9 July 2011

ISAPP 2011 - Heidelberg

Introduction to the **dark components** of the Universe

Marco Cirelli

(CERN-TH & CNRS IPhT Saclay)

in collaboration with:

A.Strumia (Pisa)
N.Fornengo (Torino)
M.Tamburini (Pisa)
R.Franceschini (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (L'Aquila + Saclay + CERN)
F.Iocco (Saclay + IAP Paris)
P.Serpico (CERN)

Reviews on Dark Matter:

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Bertone, Hooper, Silk, Phys.Rept. 405, 279-390, 2005
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Intro to Dark Matter, Dark Energy and neutrinos in cosmology

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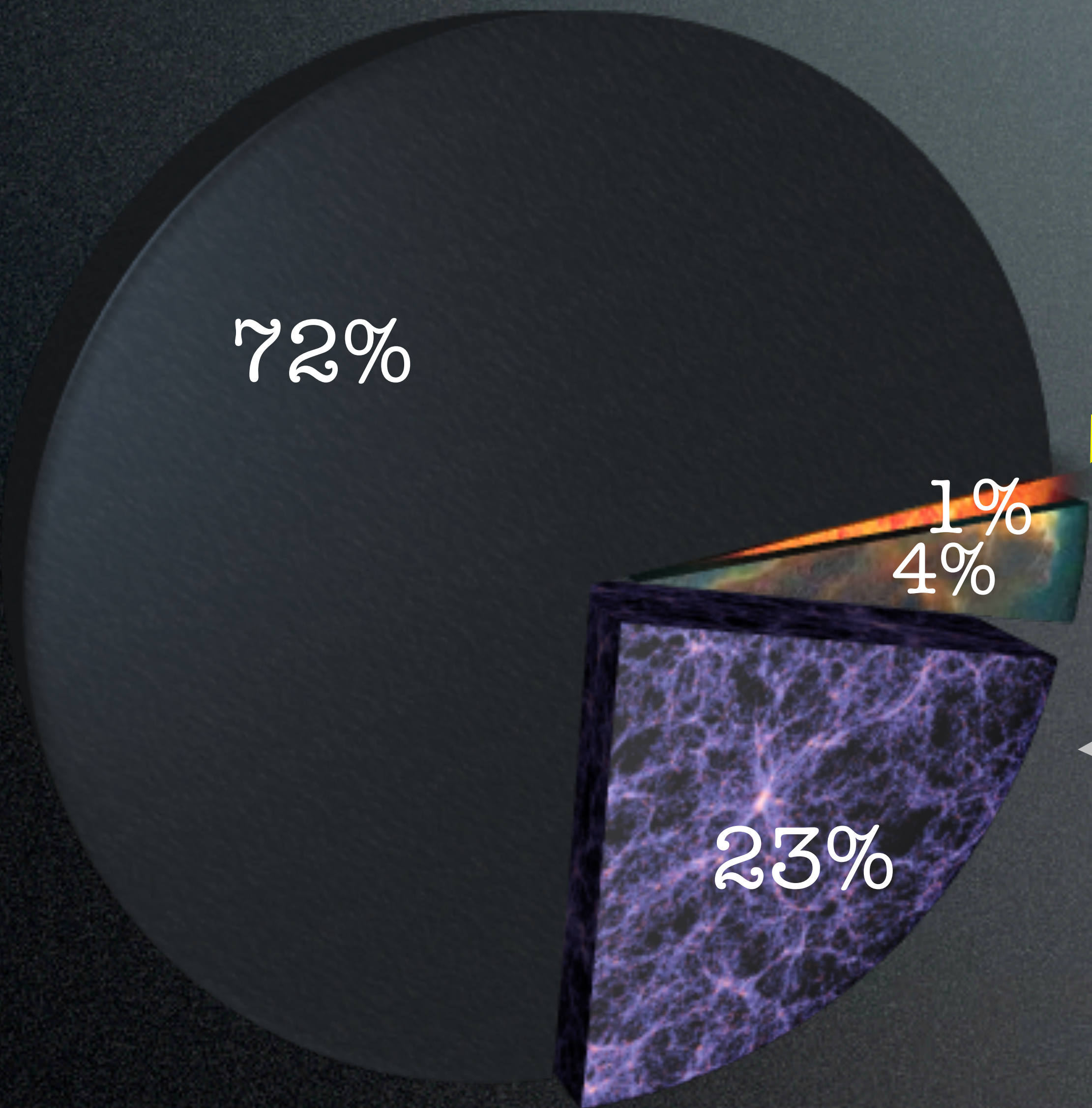
The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$ -BBN -CMB

$\Omega_{\rm DM} \sim 0.23$

$\Omega_{\rm de} \sim 0.72$
- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1\ (\text{flat});\ \text{HST}\ h = 0.71 \pm 0.07\right)$$

what's the difference between DM and DE?

The cosmic inventory

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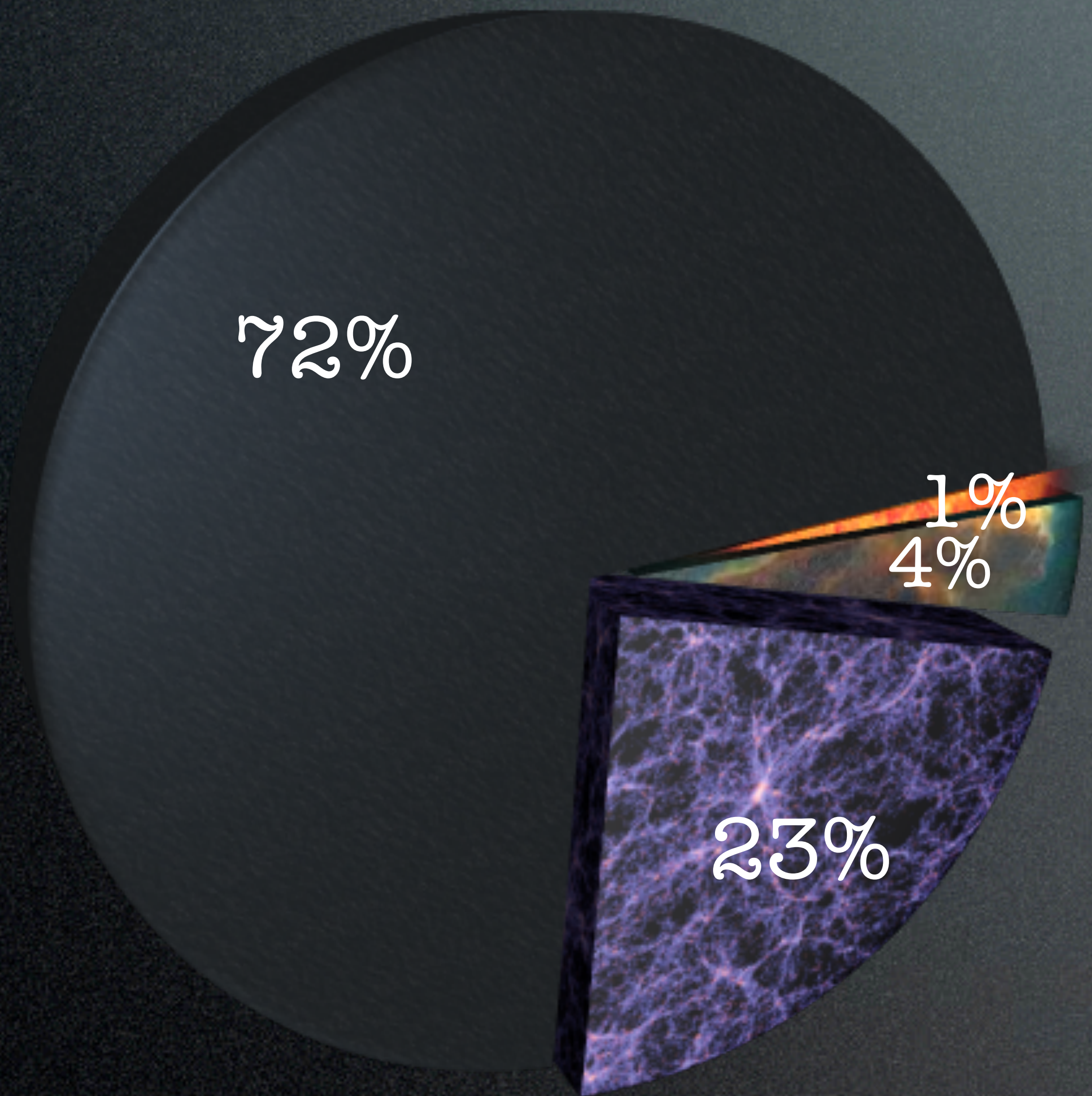


FAvgQ: what's the difference between DM and DE?

DM behaves like matter

- overall it dilutes as volume expands
- clusters gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
  (radiation has $w = -1/3$)

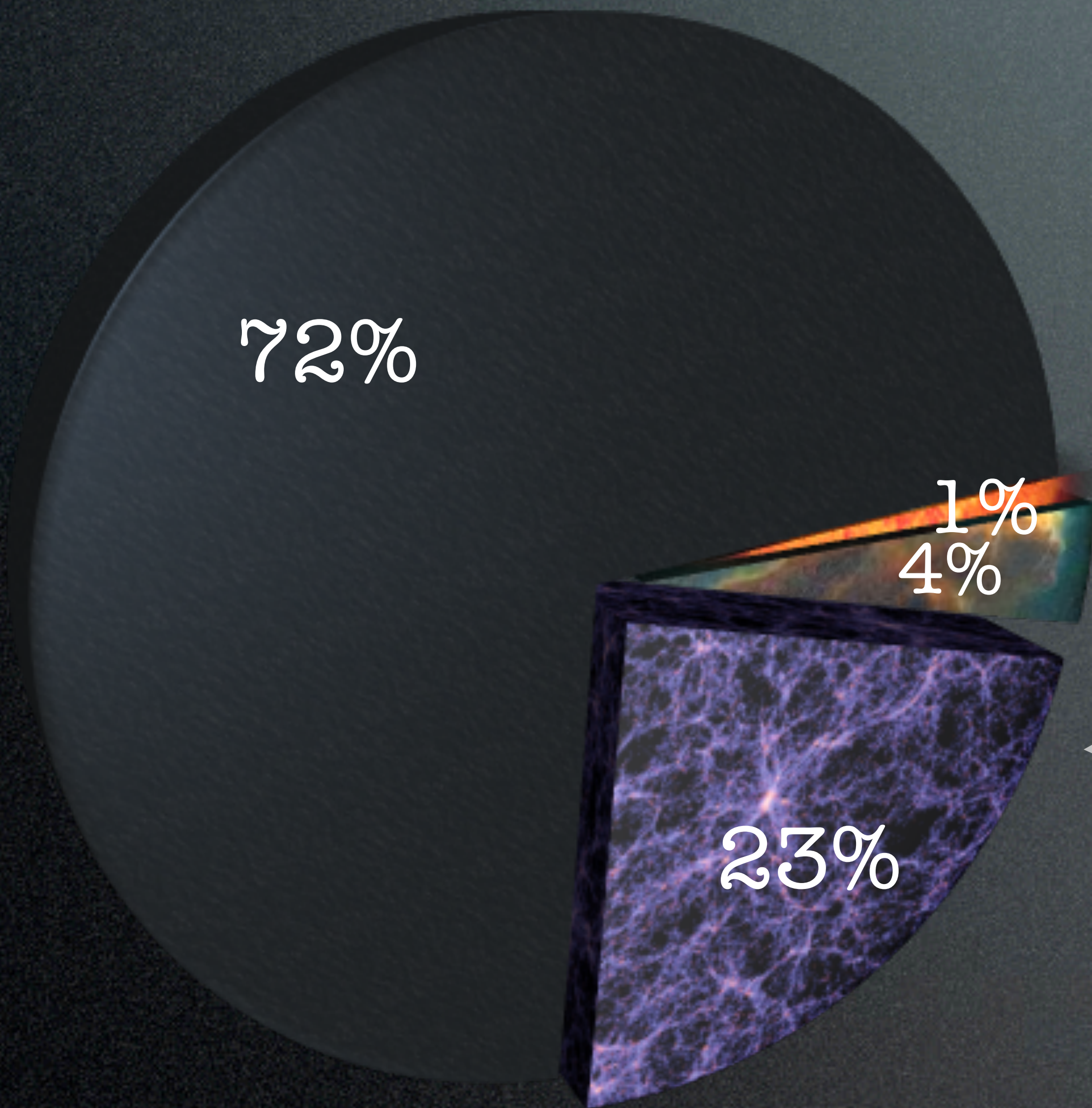
DE behaves like a constant

- it does not dilute
- does not cluster, it is prob homogeneous
- $w = P/\rho \simeq -1$
- pulls the acceleration, FRW eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_{\rm N}}{3}(1-3w)\rho$

[back]

The cosmic inventory

Most of the Universe is Dark



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particle physics $\cap$ cosmology

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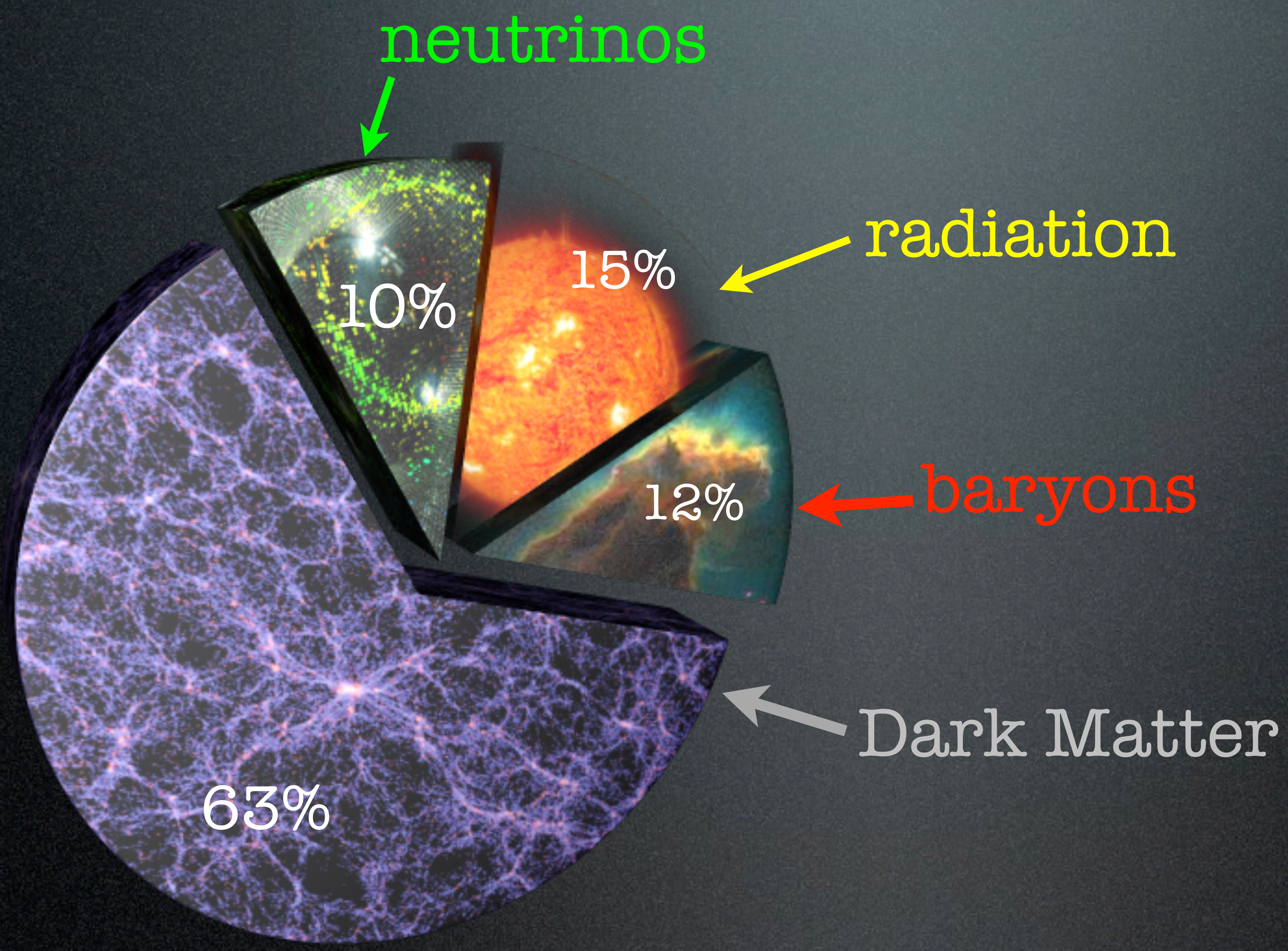


At the time of CMB formation (380 Ky)

How do we know that
Dark Matter is out there?

The Evidence for DM

1) galaxy rotation curves

$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

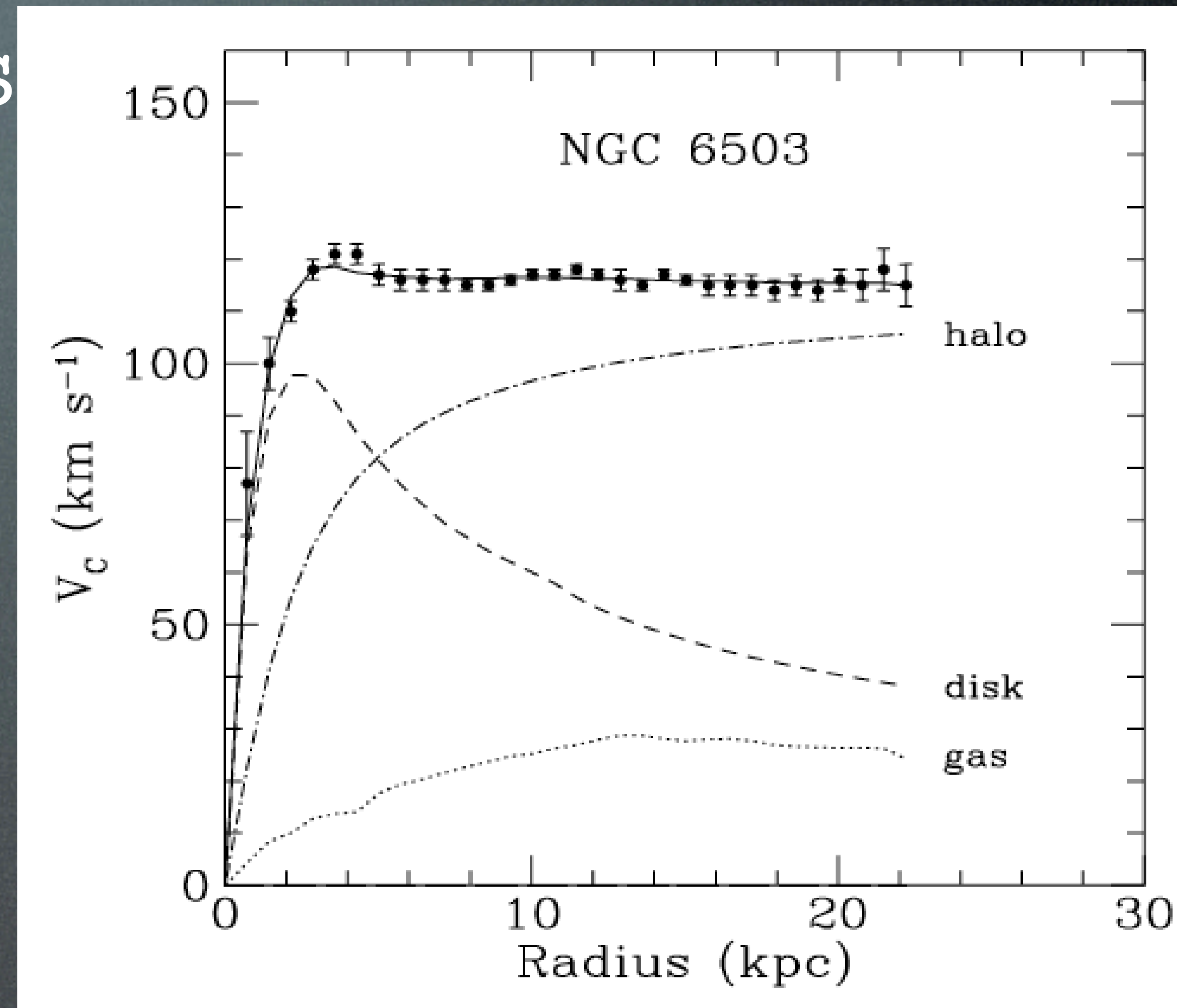
'centrifugal' 'centripetal'

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

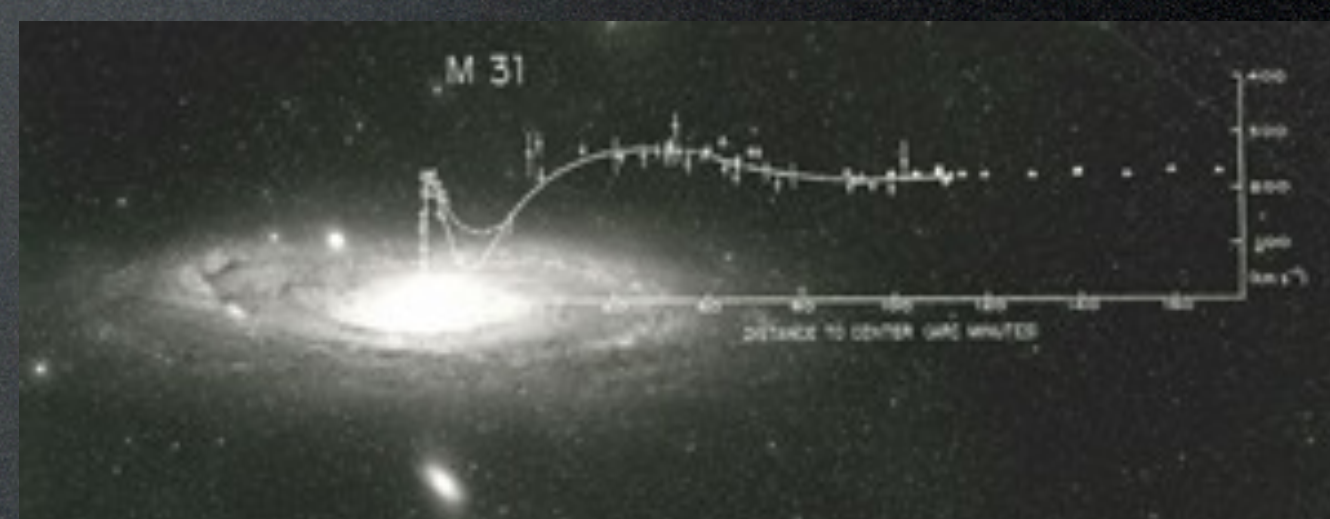
with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_{\mathrm{M}} \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



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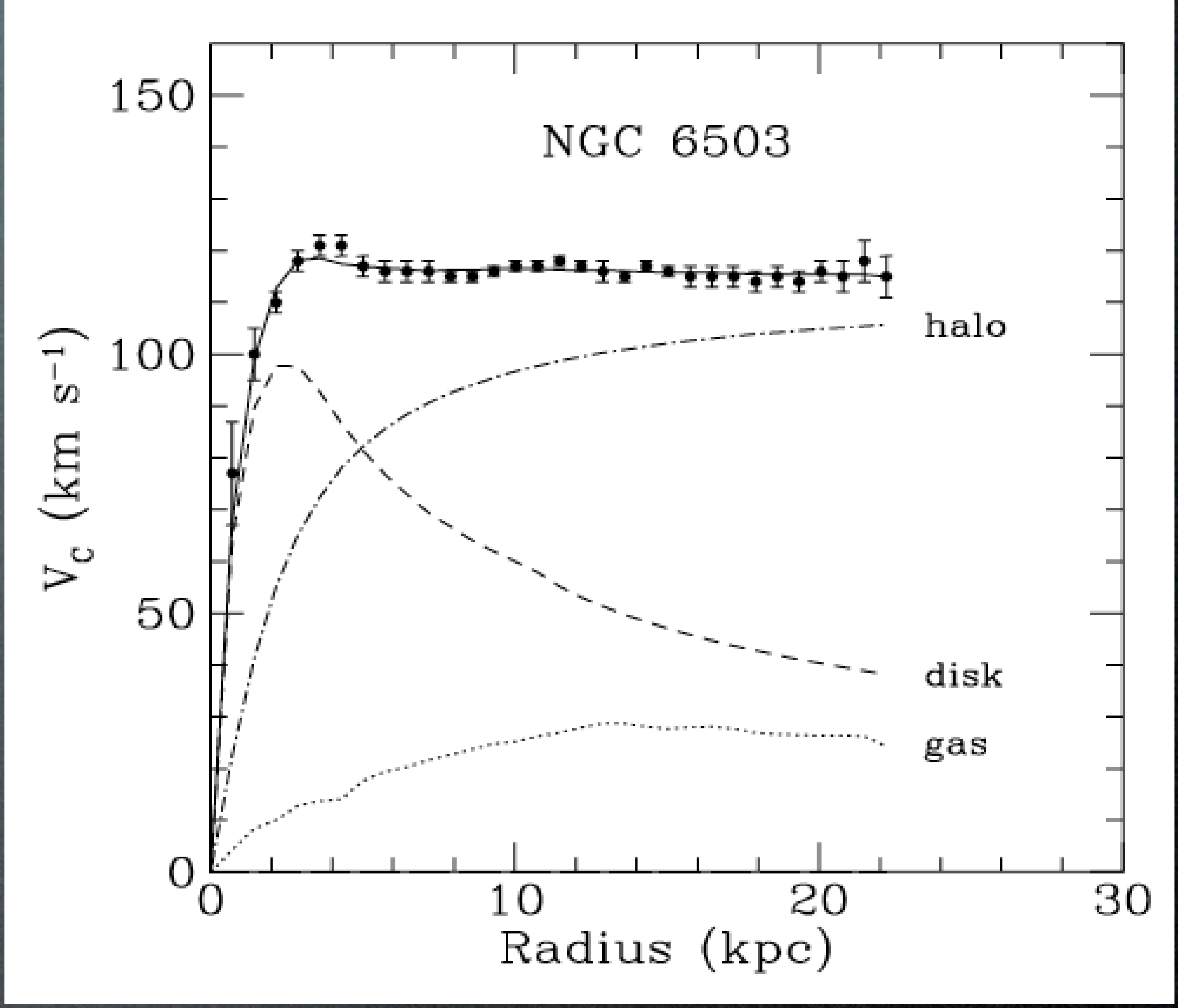

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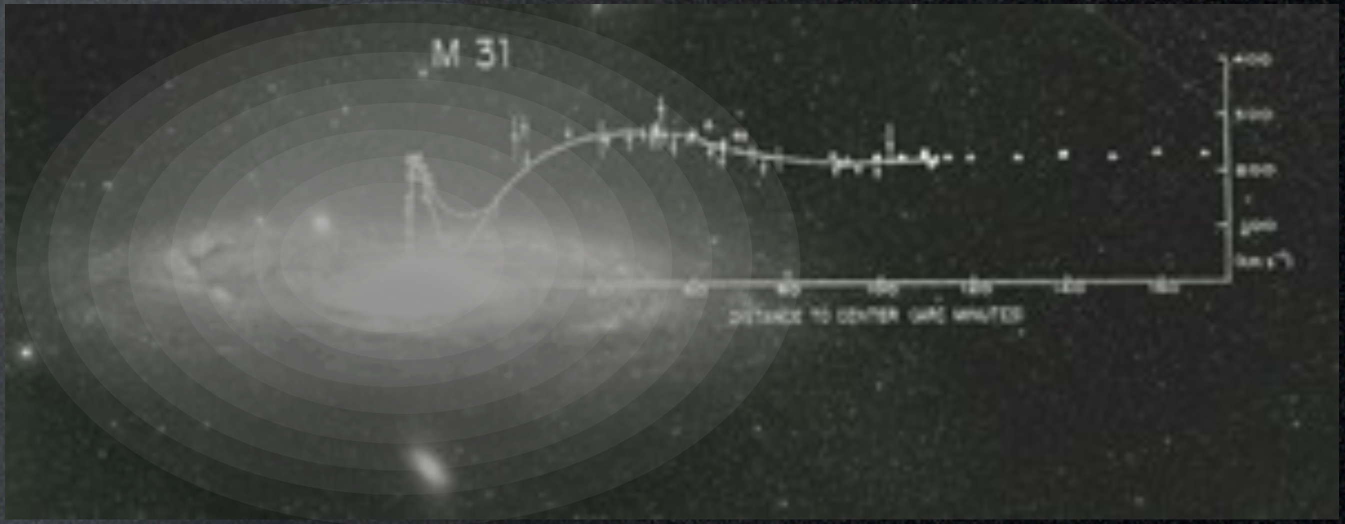

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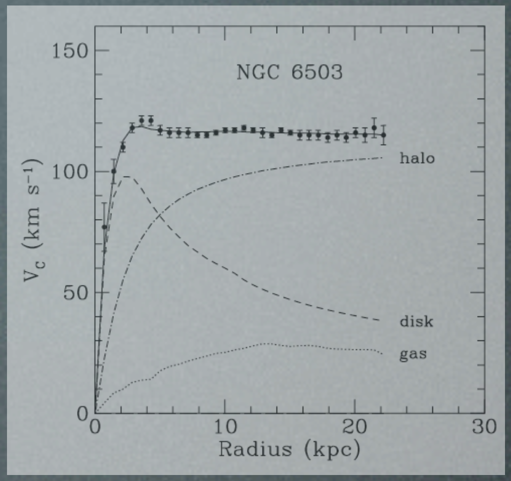

$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

$$\Omega_M \sim 0.2 \div 0.4$$

"bullet cluster" - NASA
astro-ph/0608247
[further developments]

The Evidence for DM

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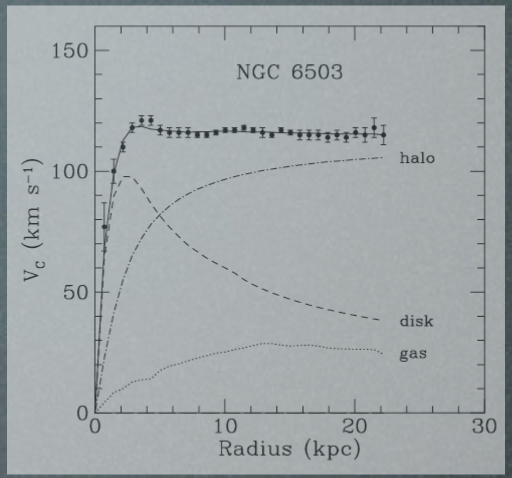

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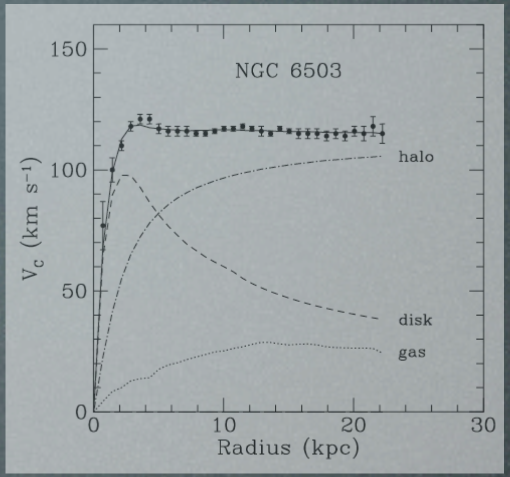

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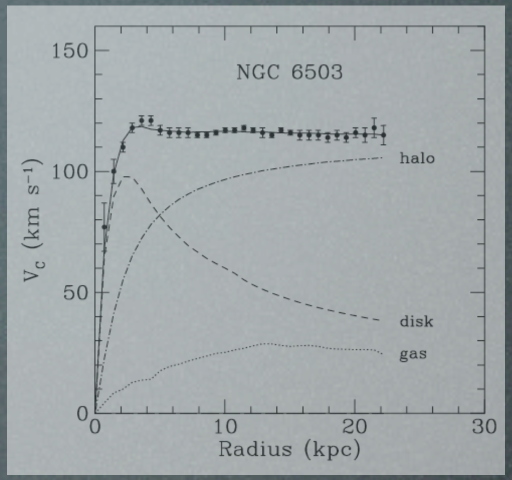

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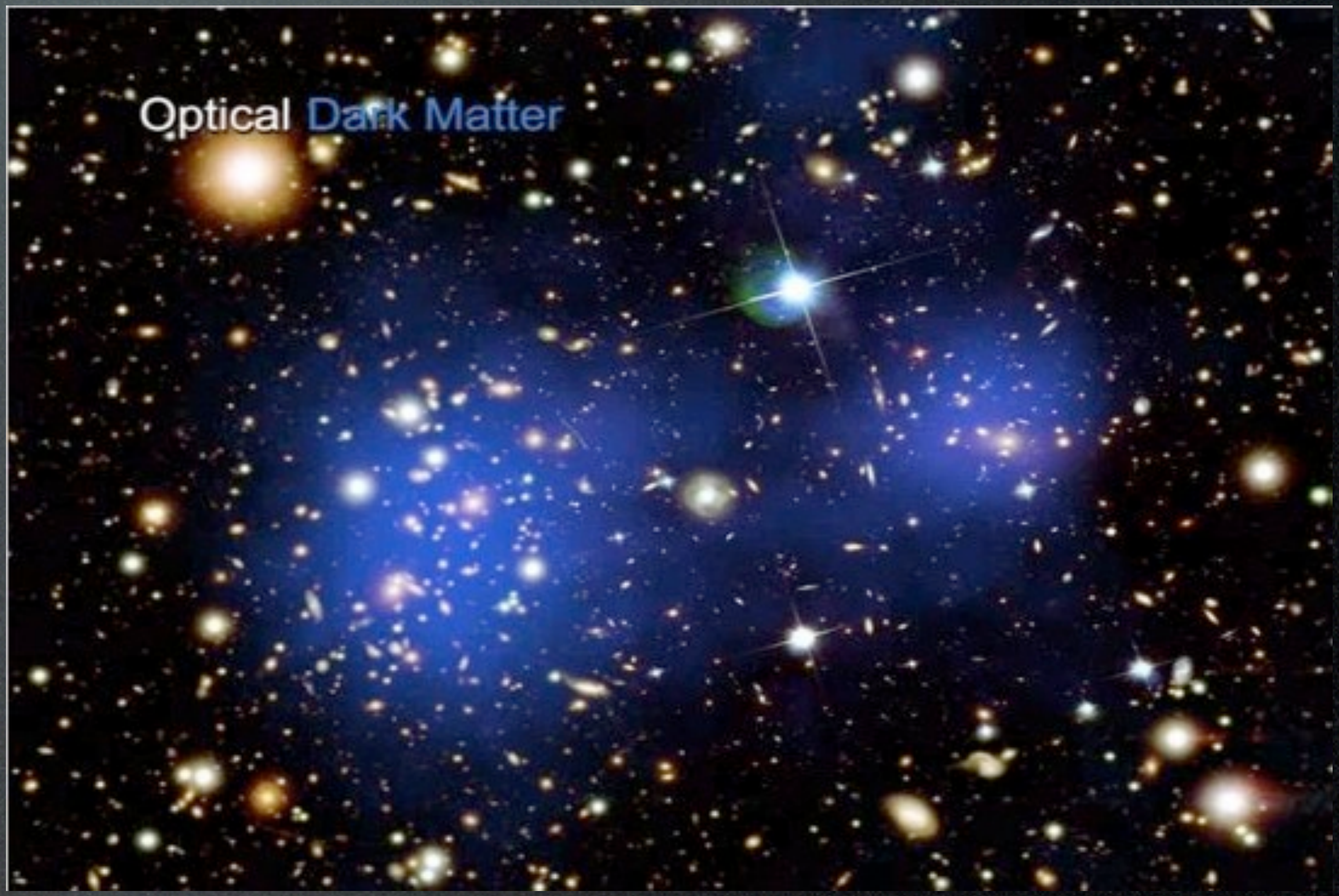

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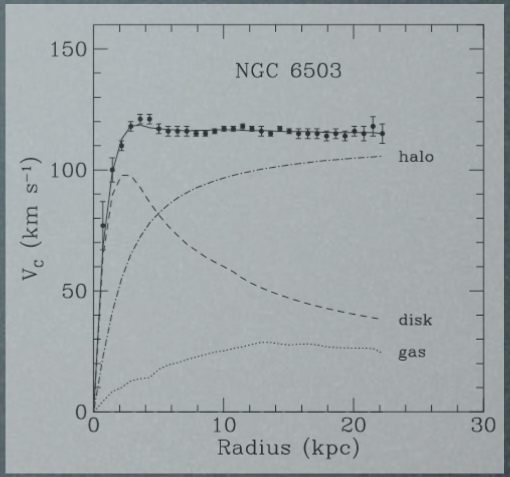

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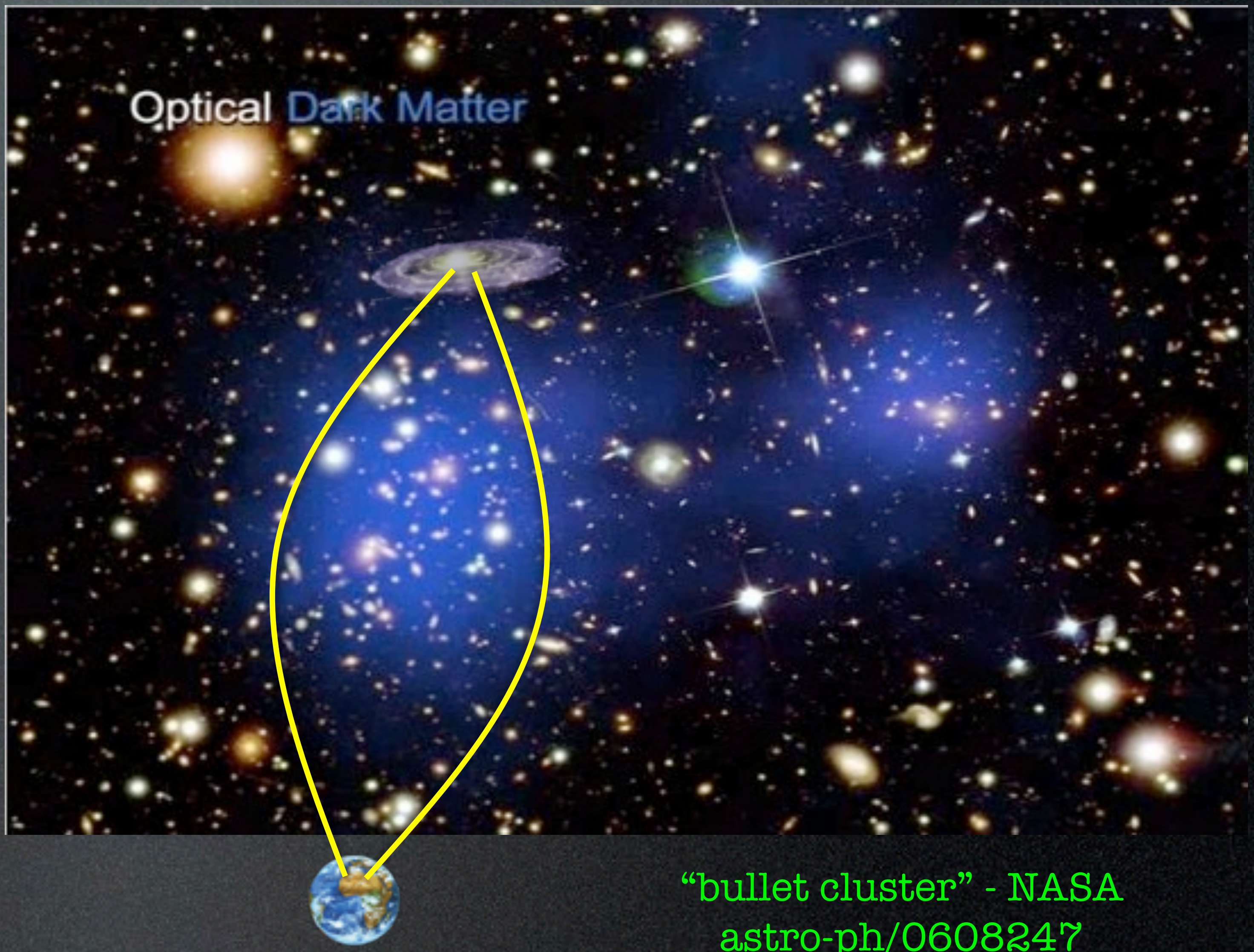

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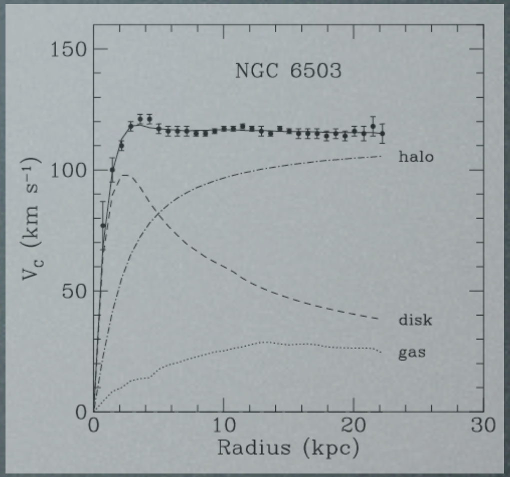

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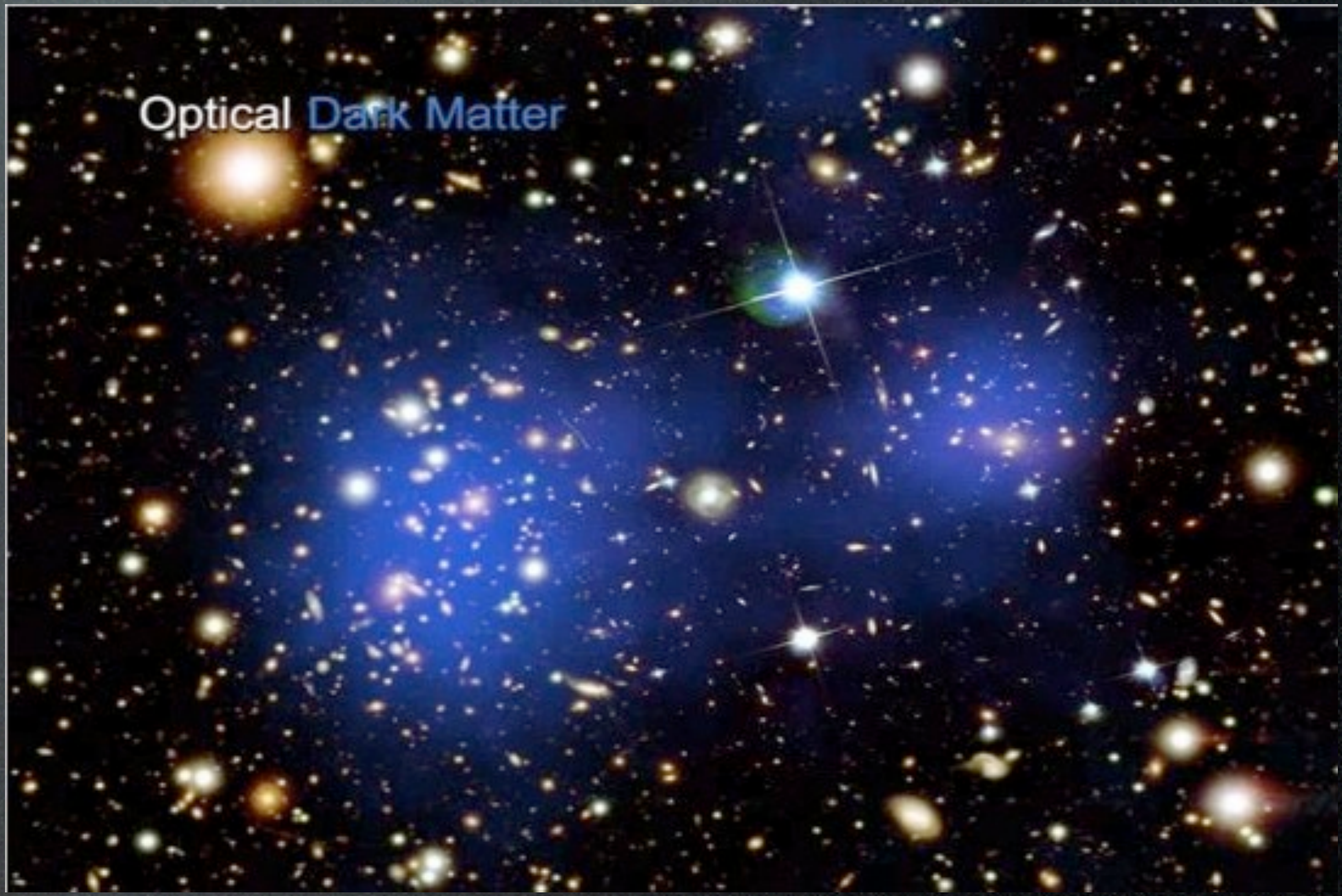

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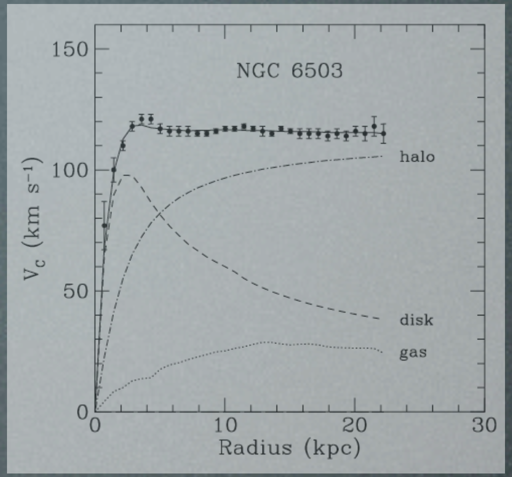

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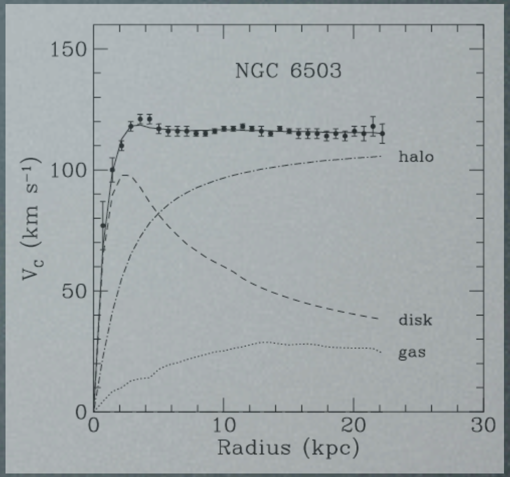

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ring of Dark Matter (2007)

The Evidence for DM

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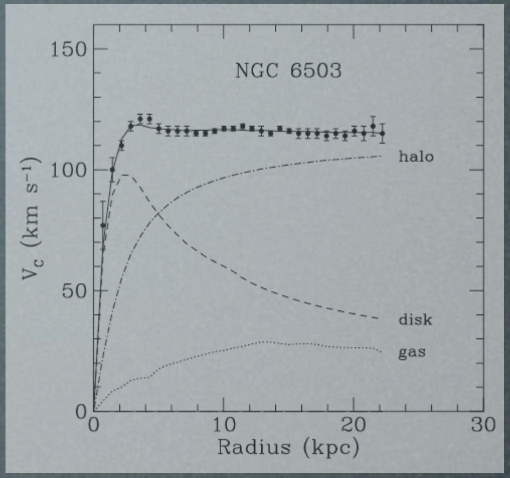

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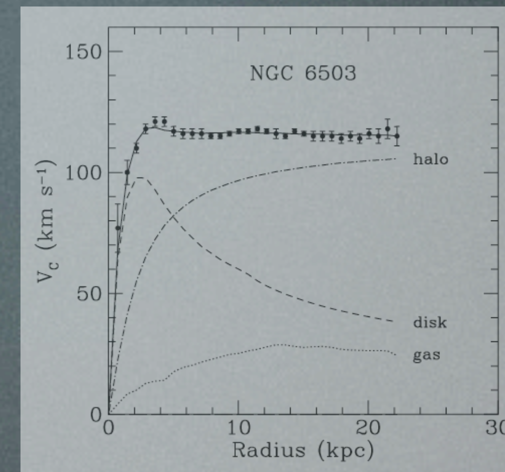

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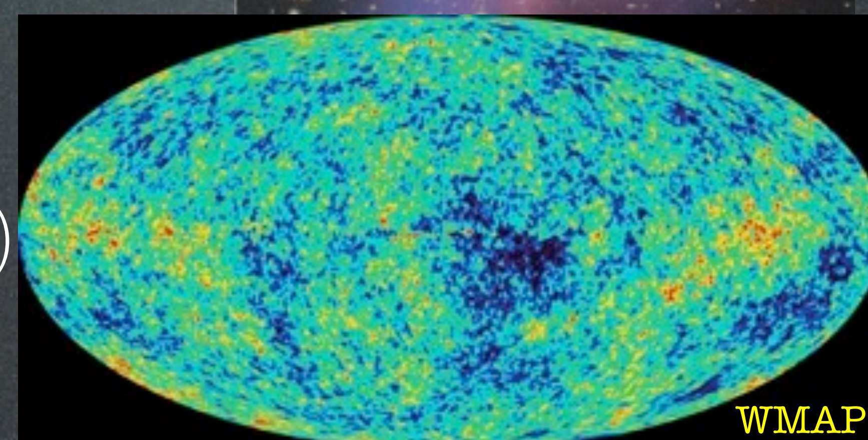
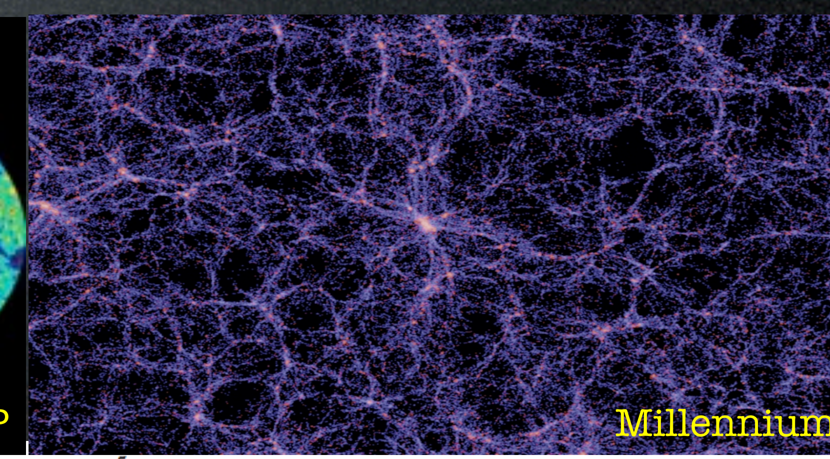
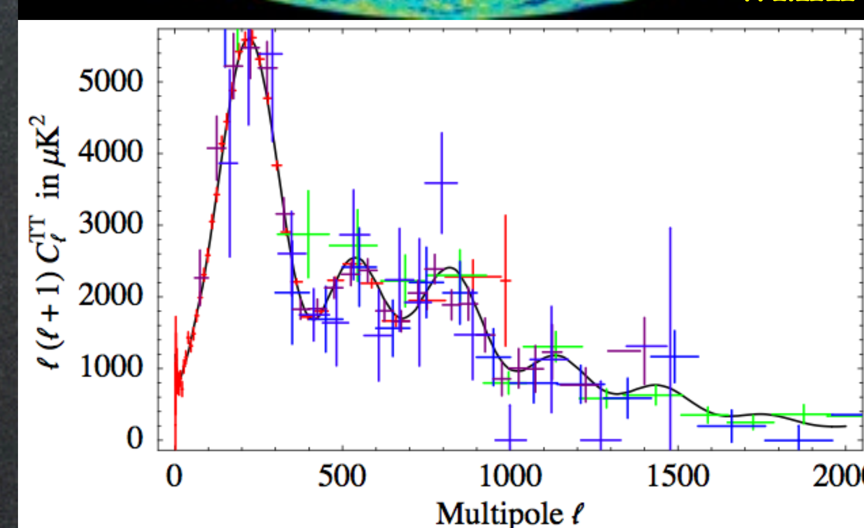
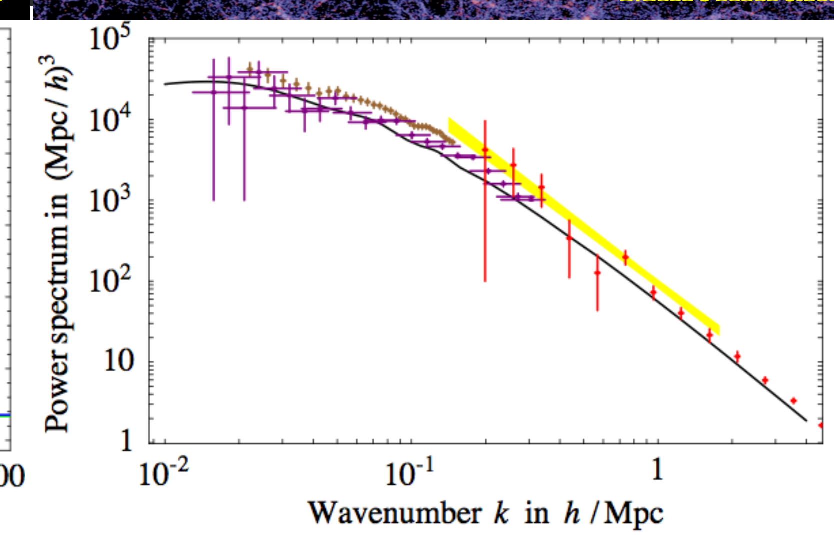
3) CMB+LSS(+SNIa:)









M.Cirelli and A.Strumia, astro-ph/0607086

DM N-body simulations

$2\ 10^6$ CDM particles, 43 Mpc cubic box

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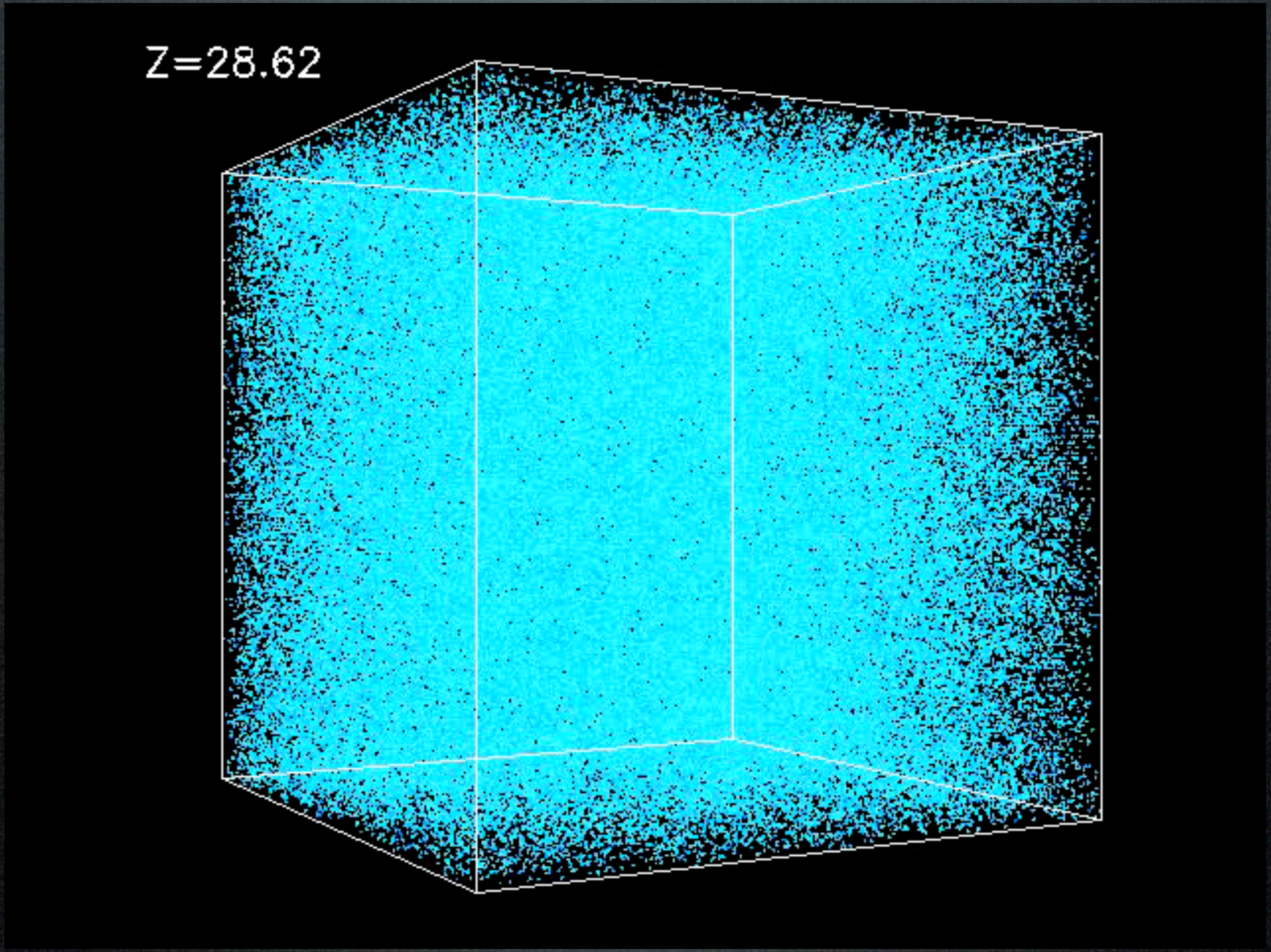

Andrey Kravtsov, cosmicweb.uchicago.edu

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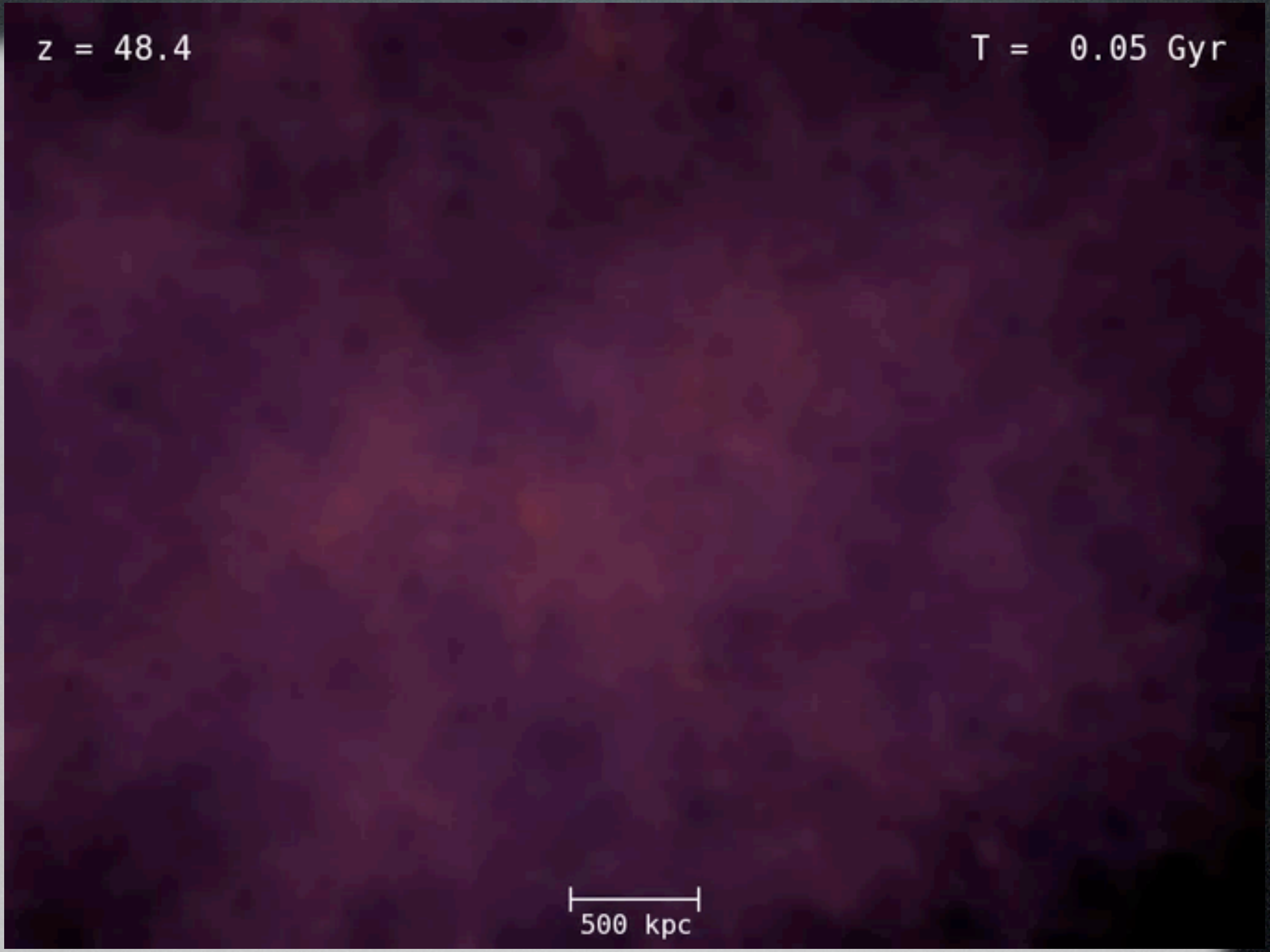
DM N-body simulations

Aquarius project of the VIRGO coll.:
1.5 10^9 CDM particles, single galactic halo

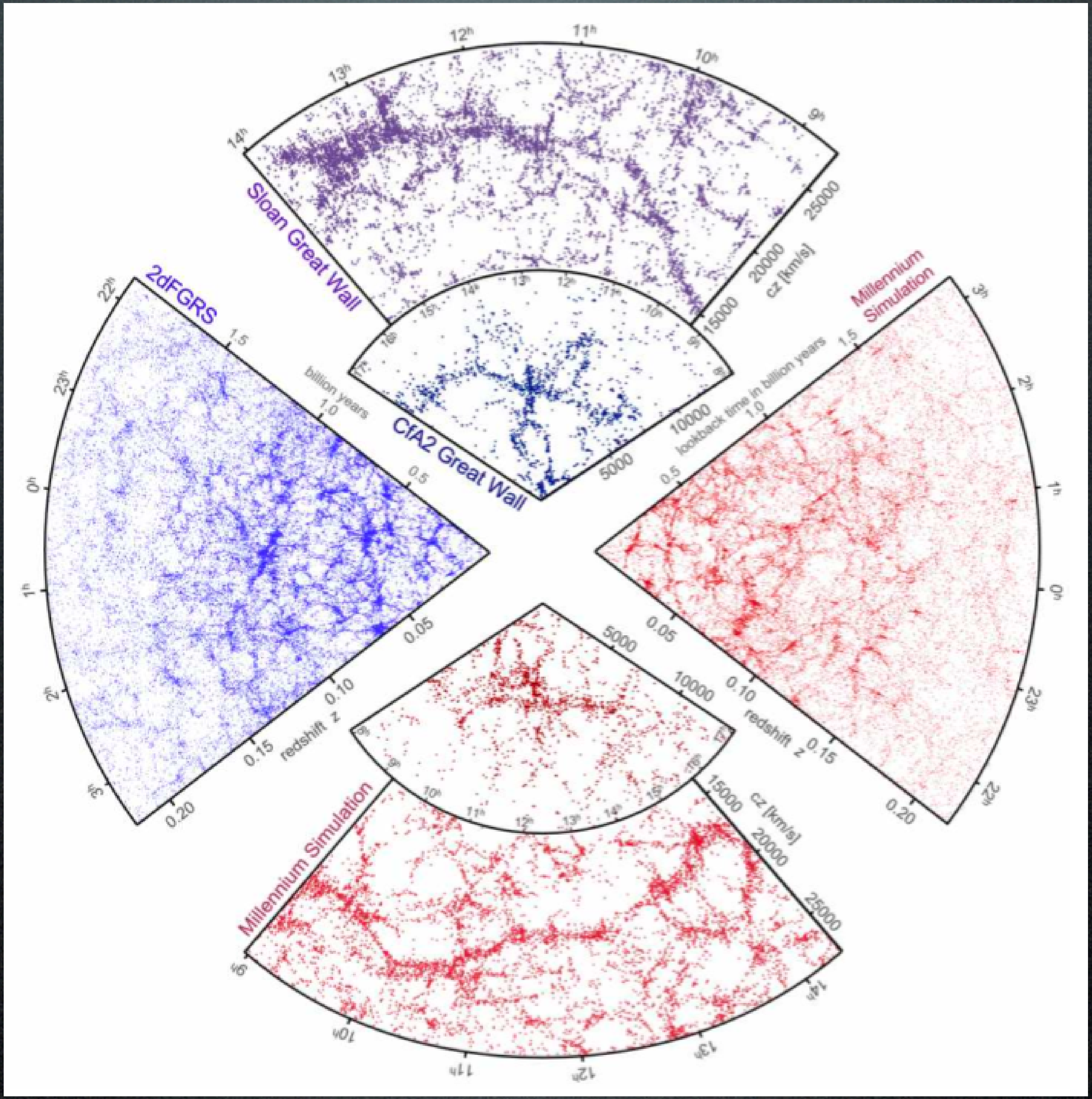


VIRGO coll., Aquarius project, www.mpa-garching.mpg.de/aquarius/ [back]

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

Millennium:
10^{10} particles,
500 h^{-1} Mpc

[back]

DM N-body simulations

2dF: 2.2 10^5 galaxies

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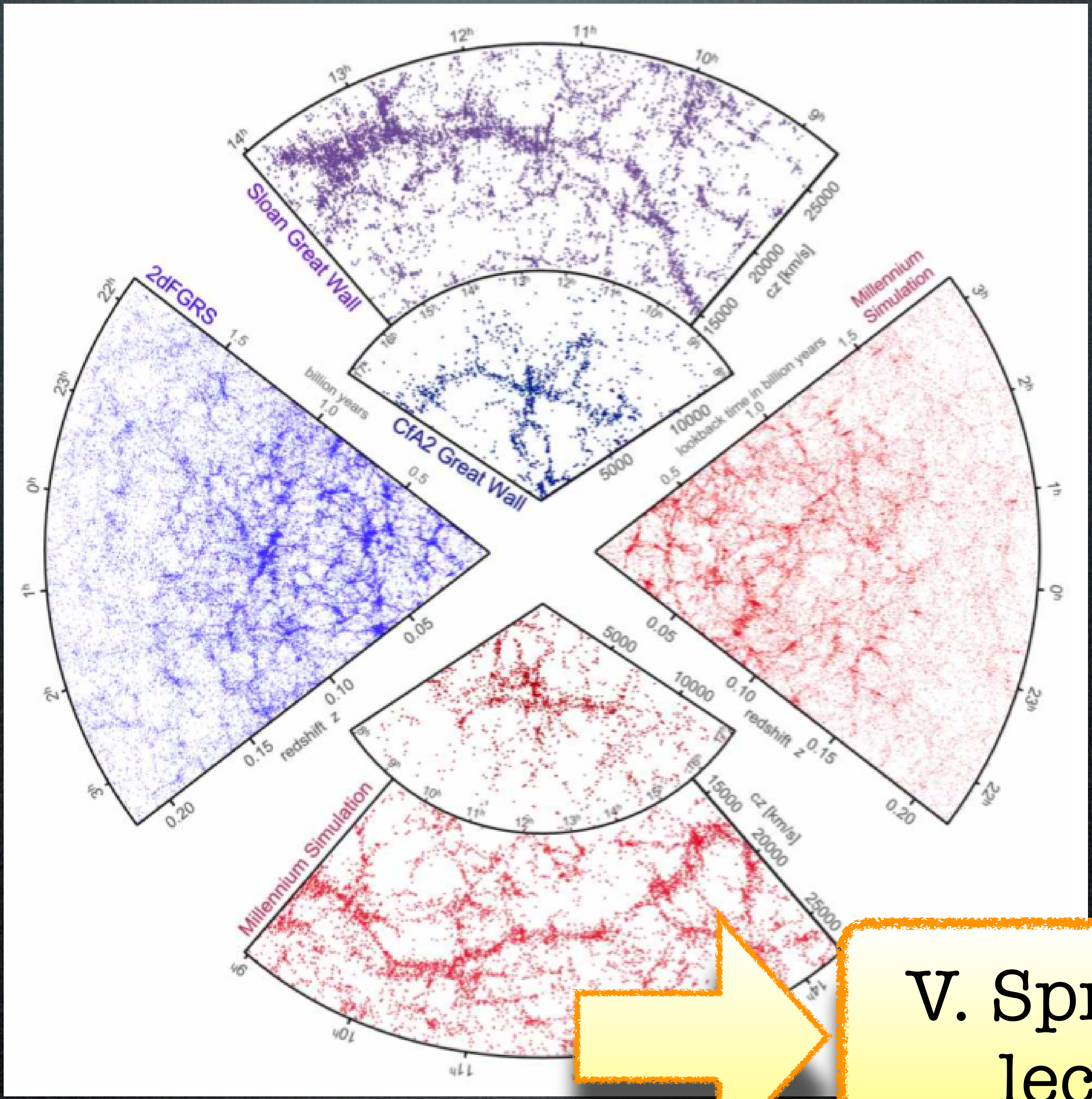
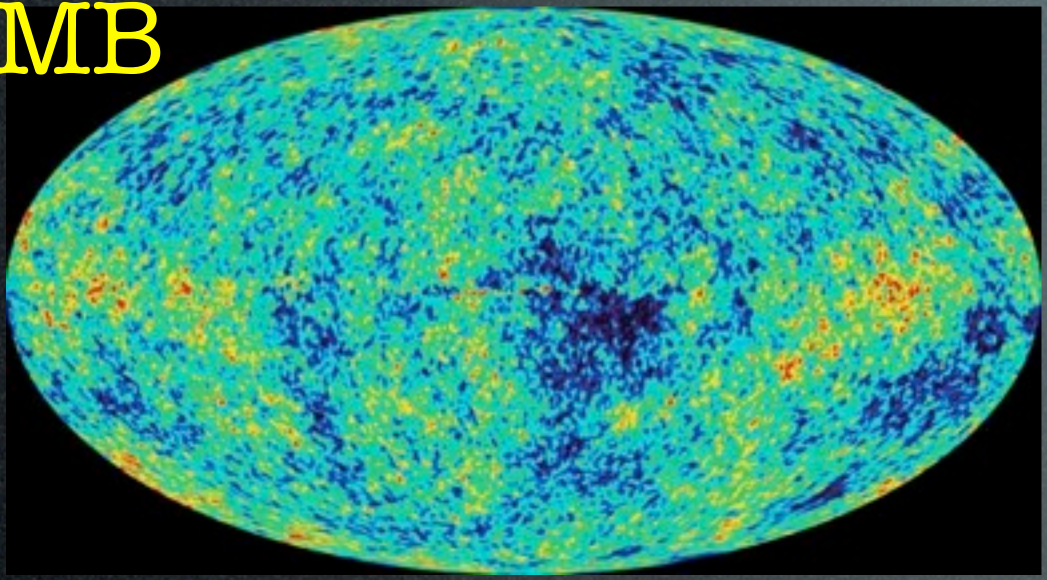


Springel, Frenk, White, Nature 4 (200

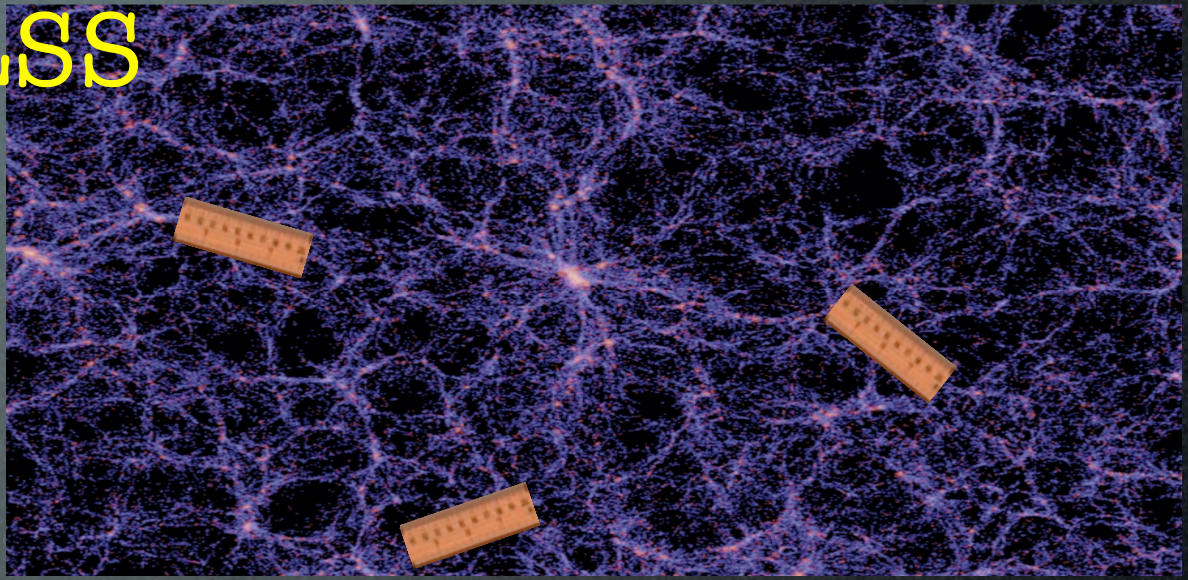
V. Springel's lecture

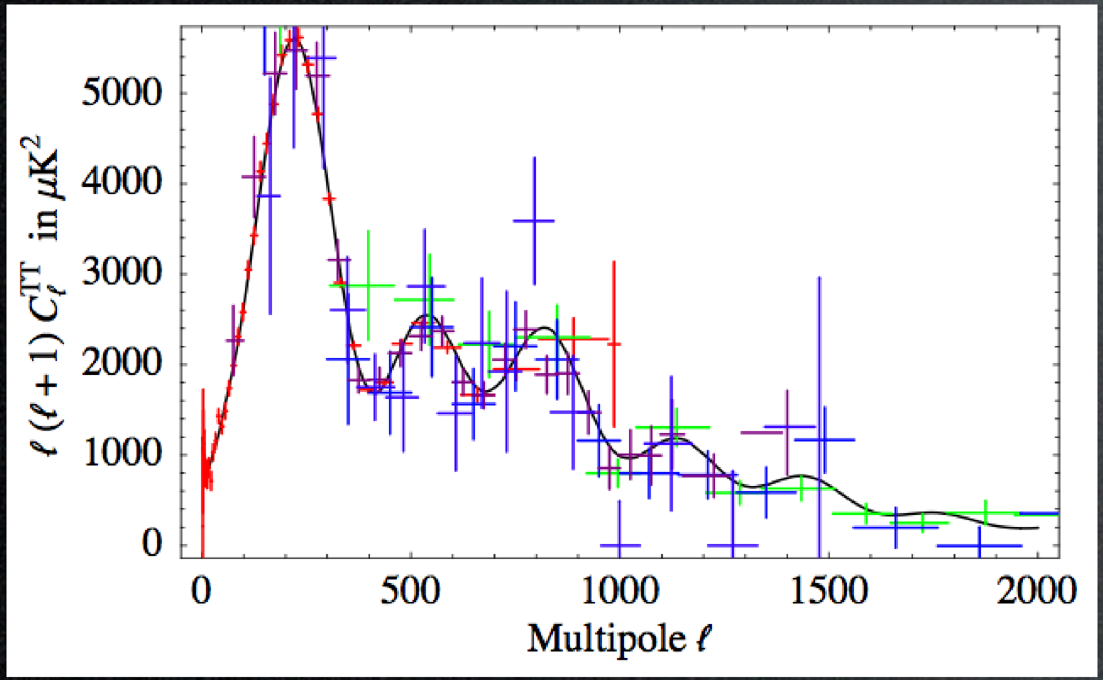
CMB & Large Scale Structure

CMB

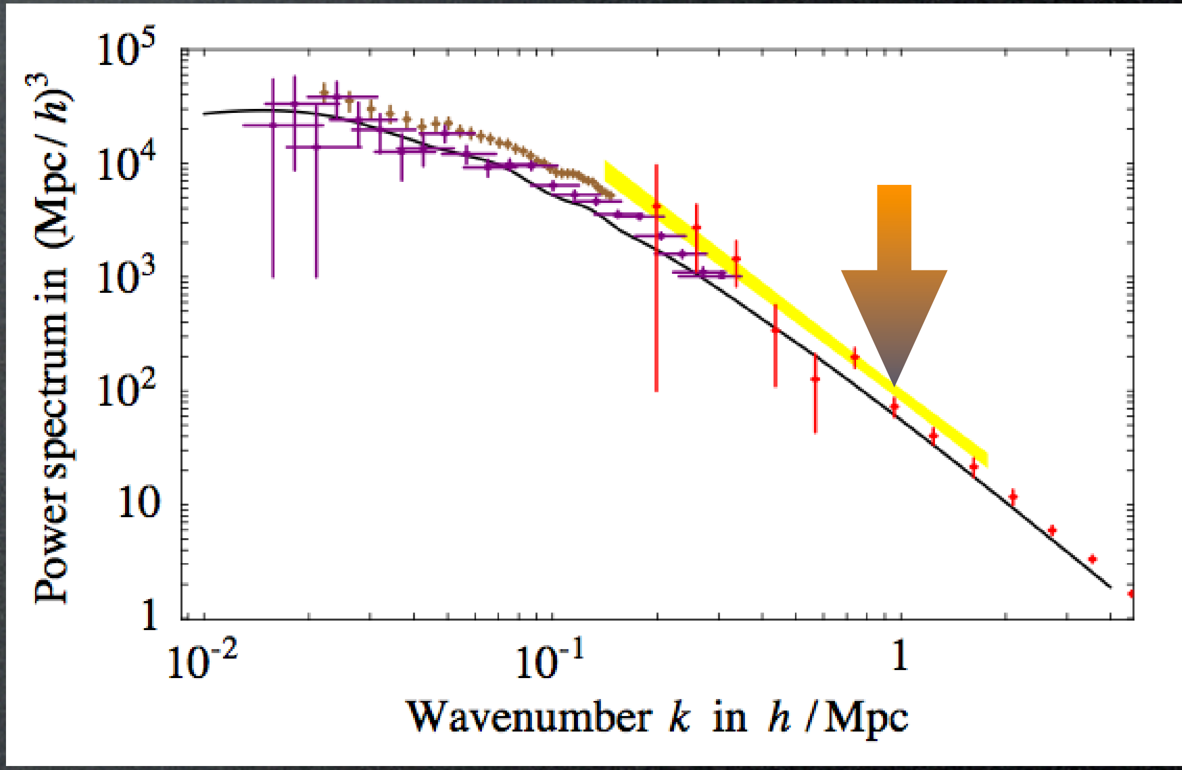


LSS



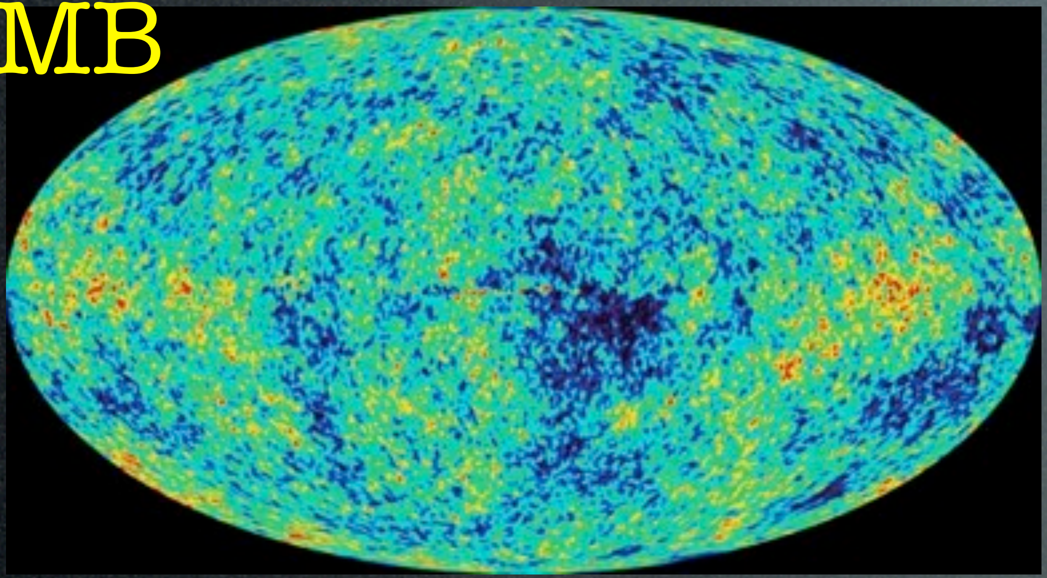


LSS matter power spectrum



CMB & Large Scale Structure

CMB



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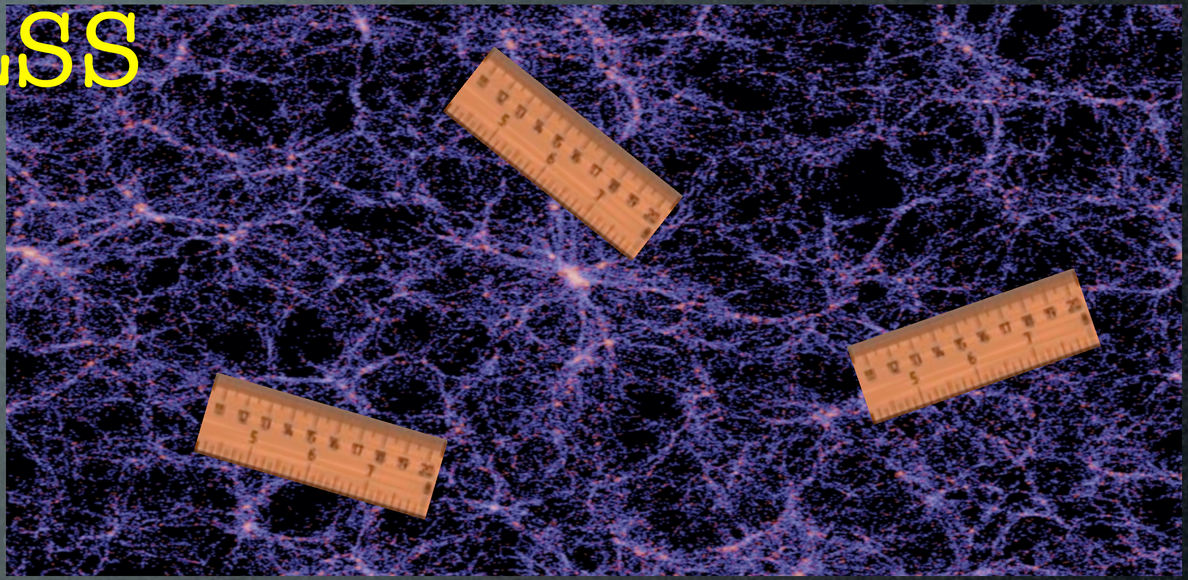

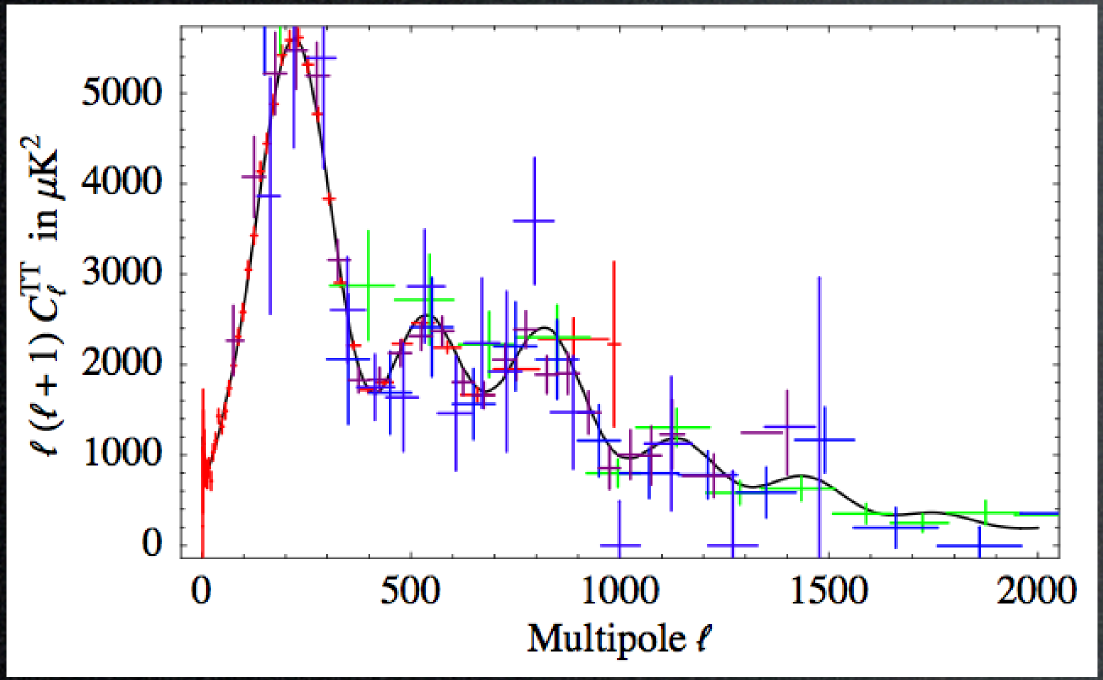

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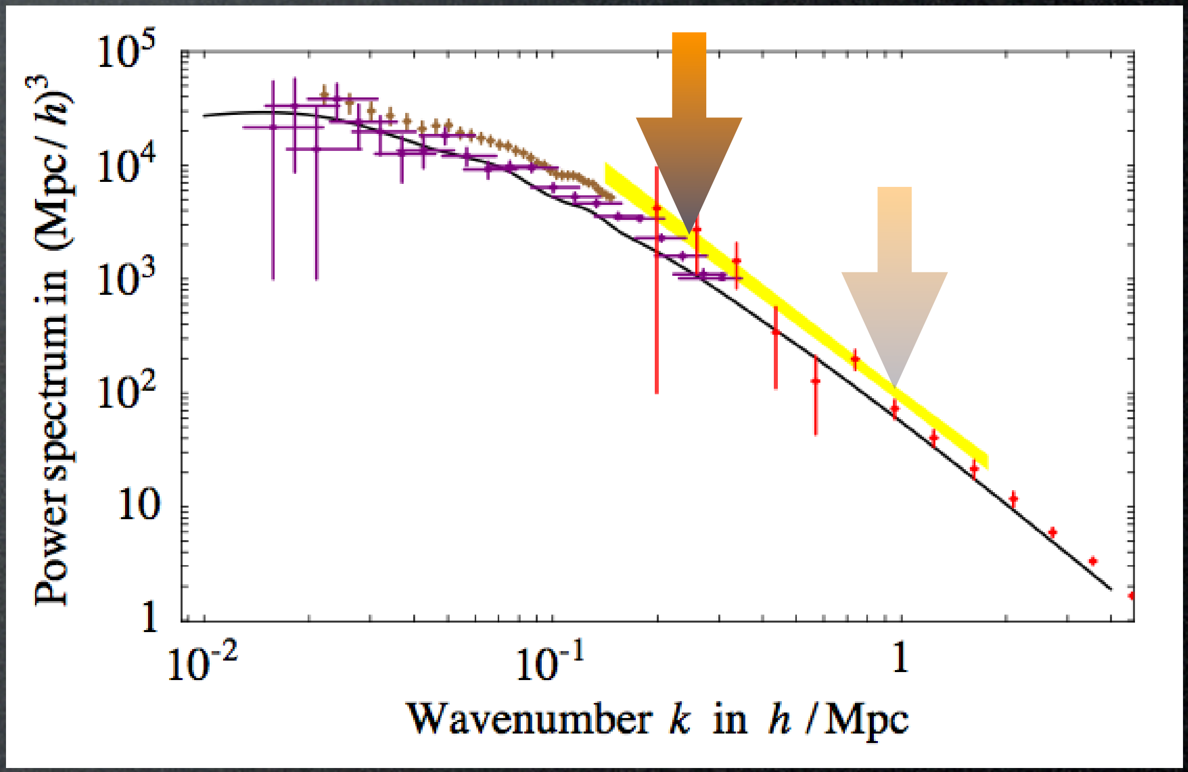

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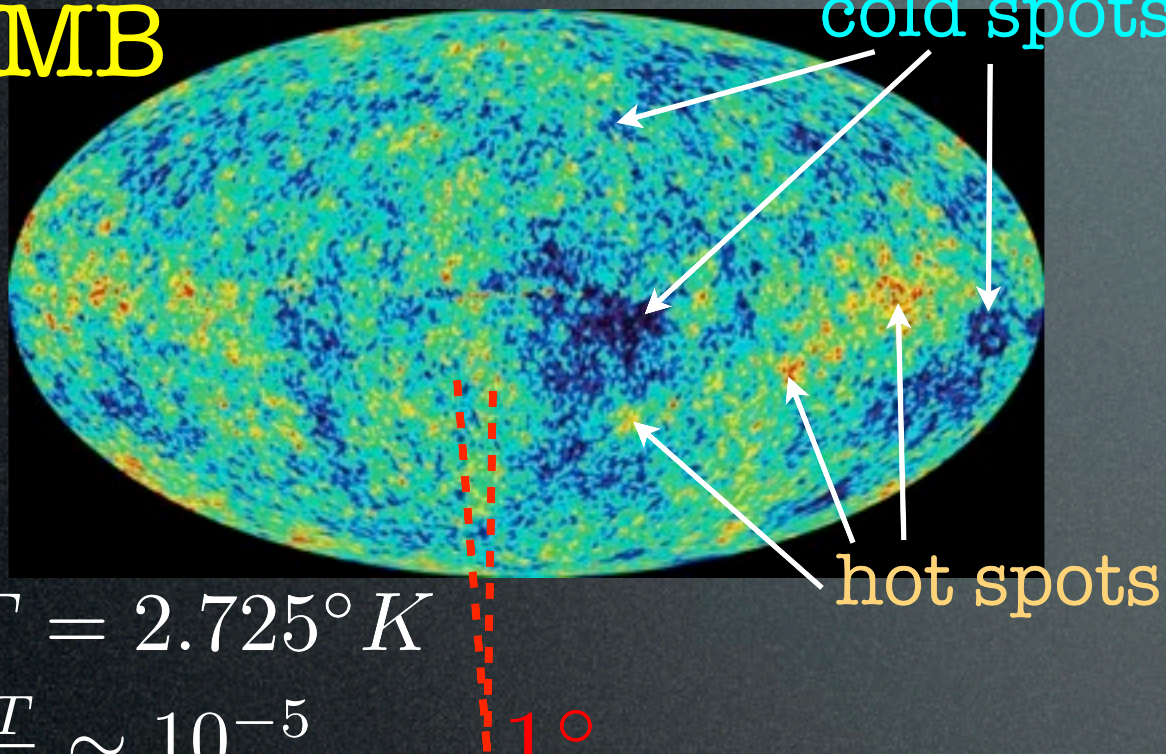
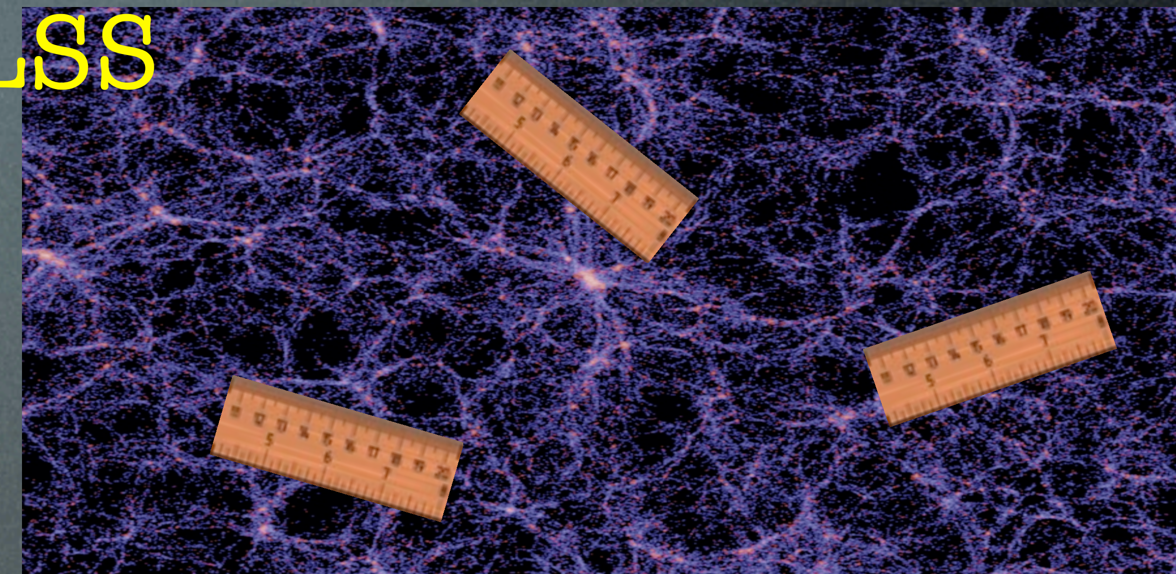


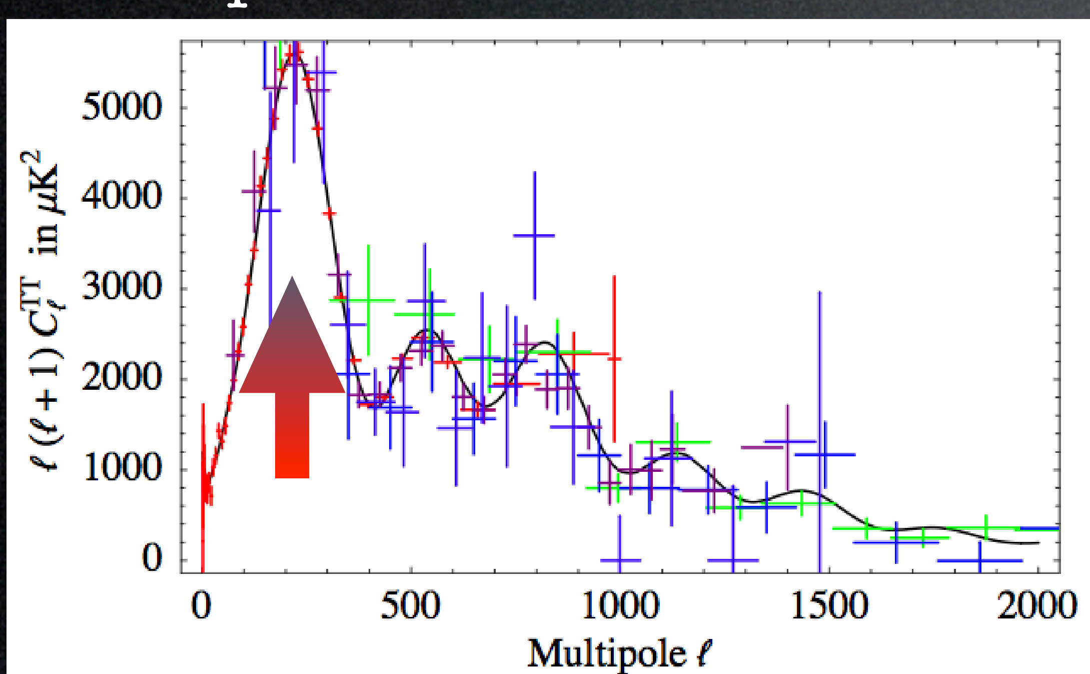
$T = 2.725° K$

$\frac{\delta T}{T} \sim 10^{-5}$

LSS



CMB spectrum



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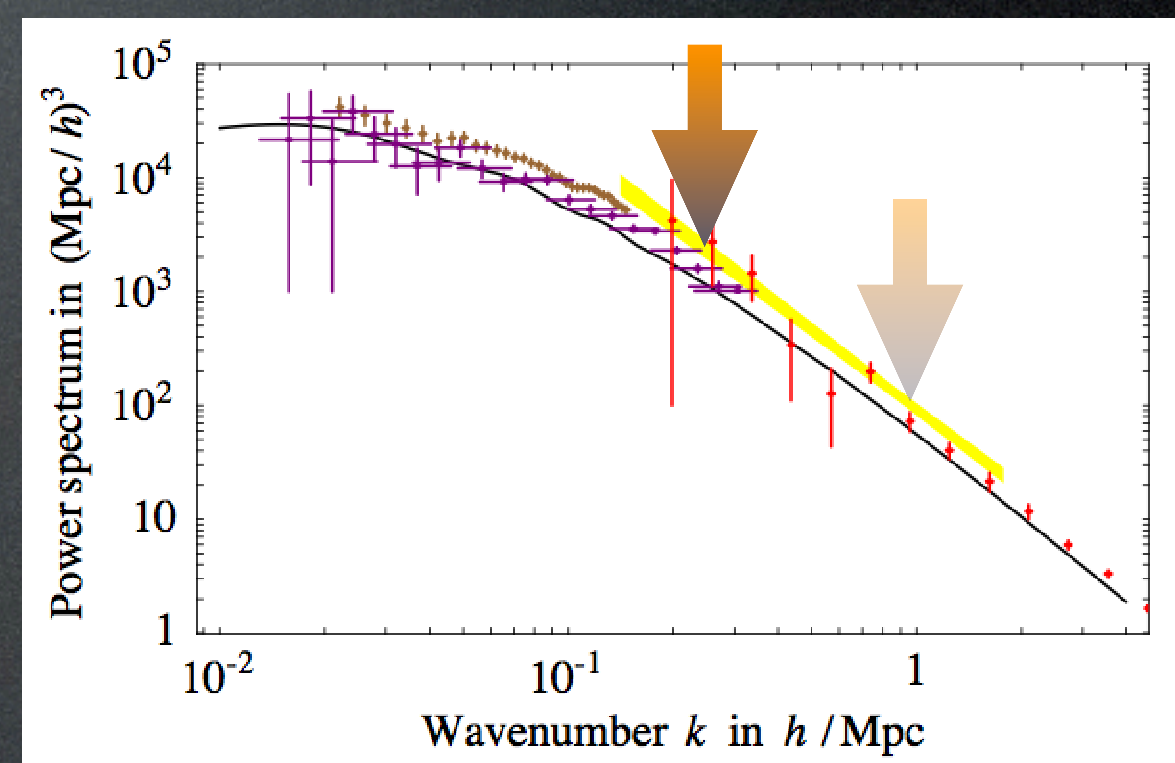
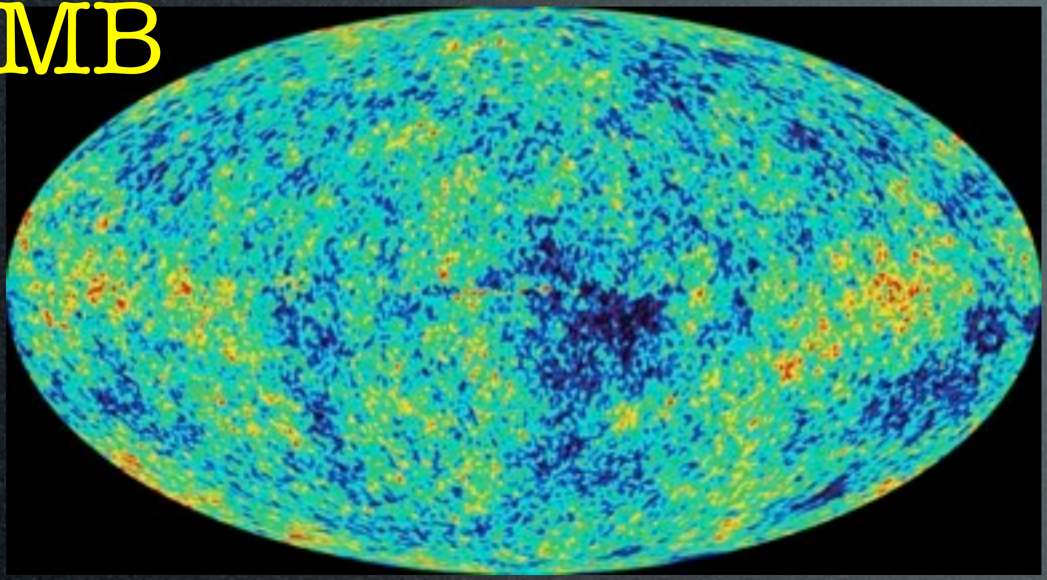


The Evidence for DM

CMB



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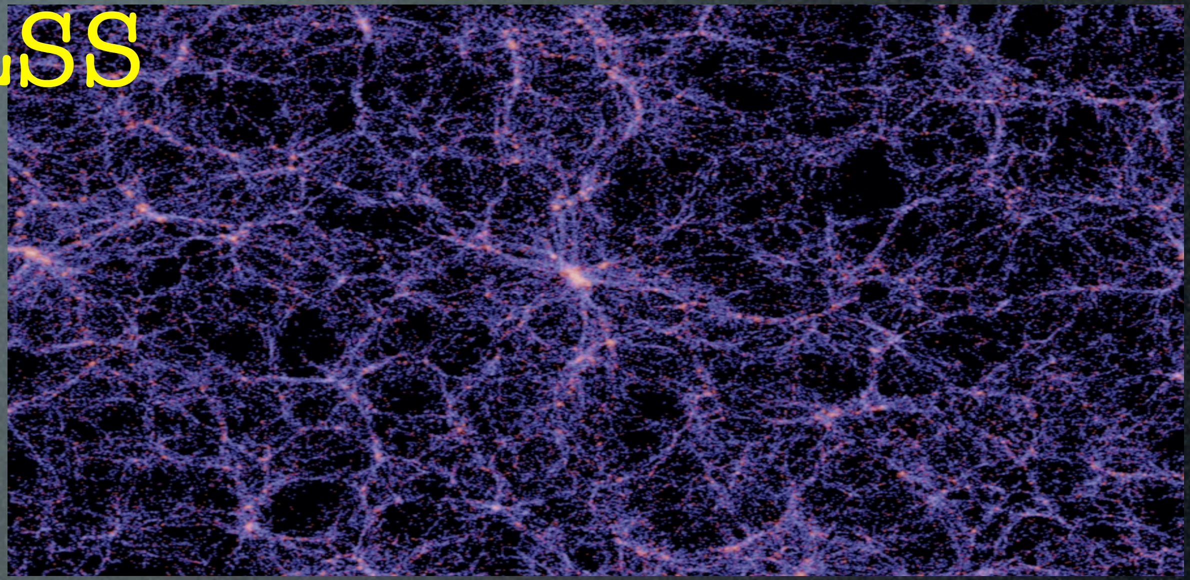
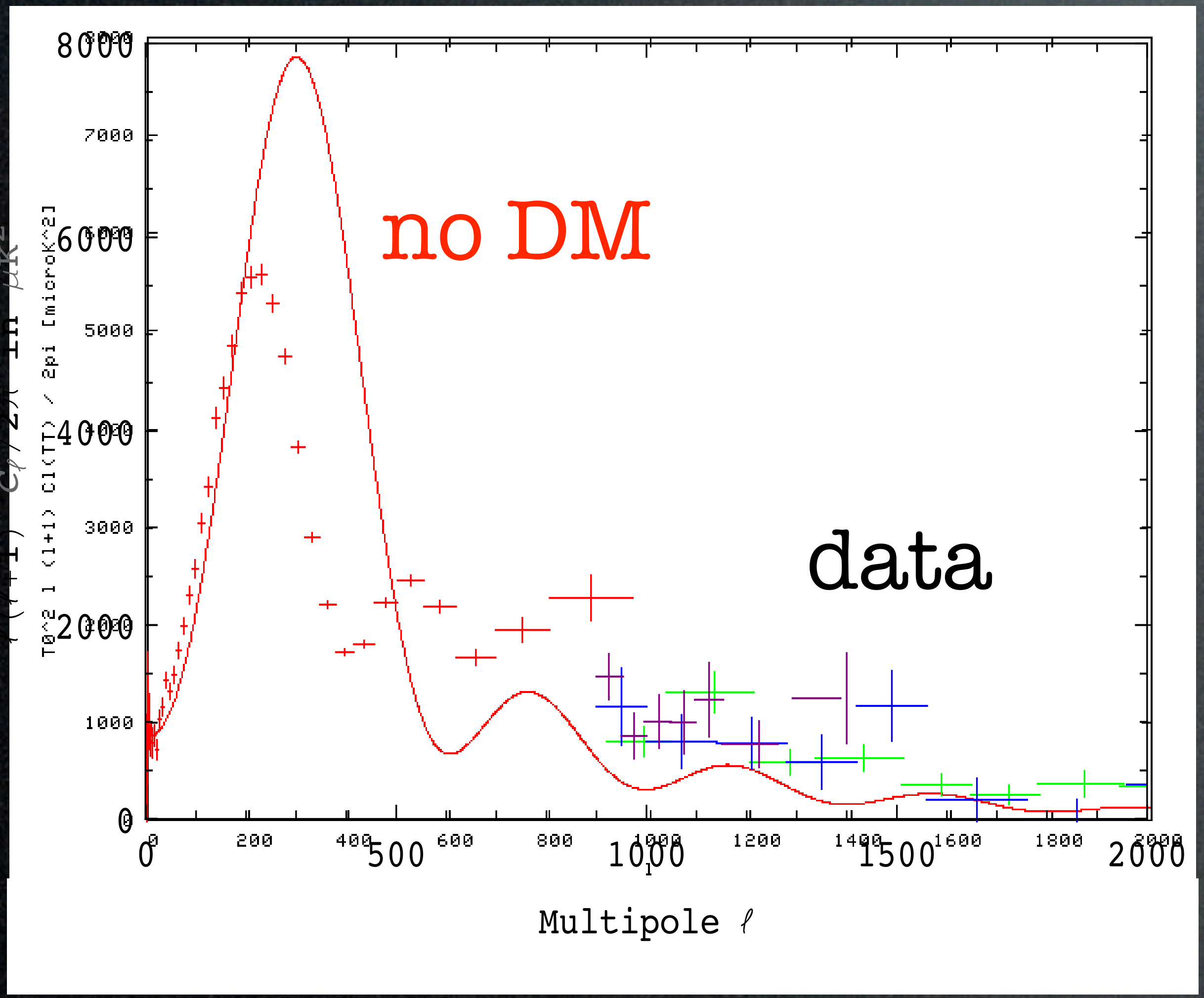
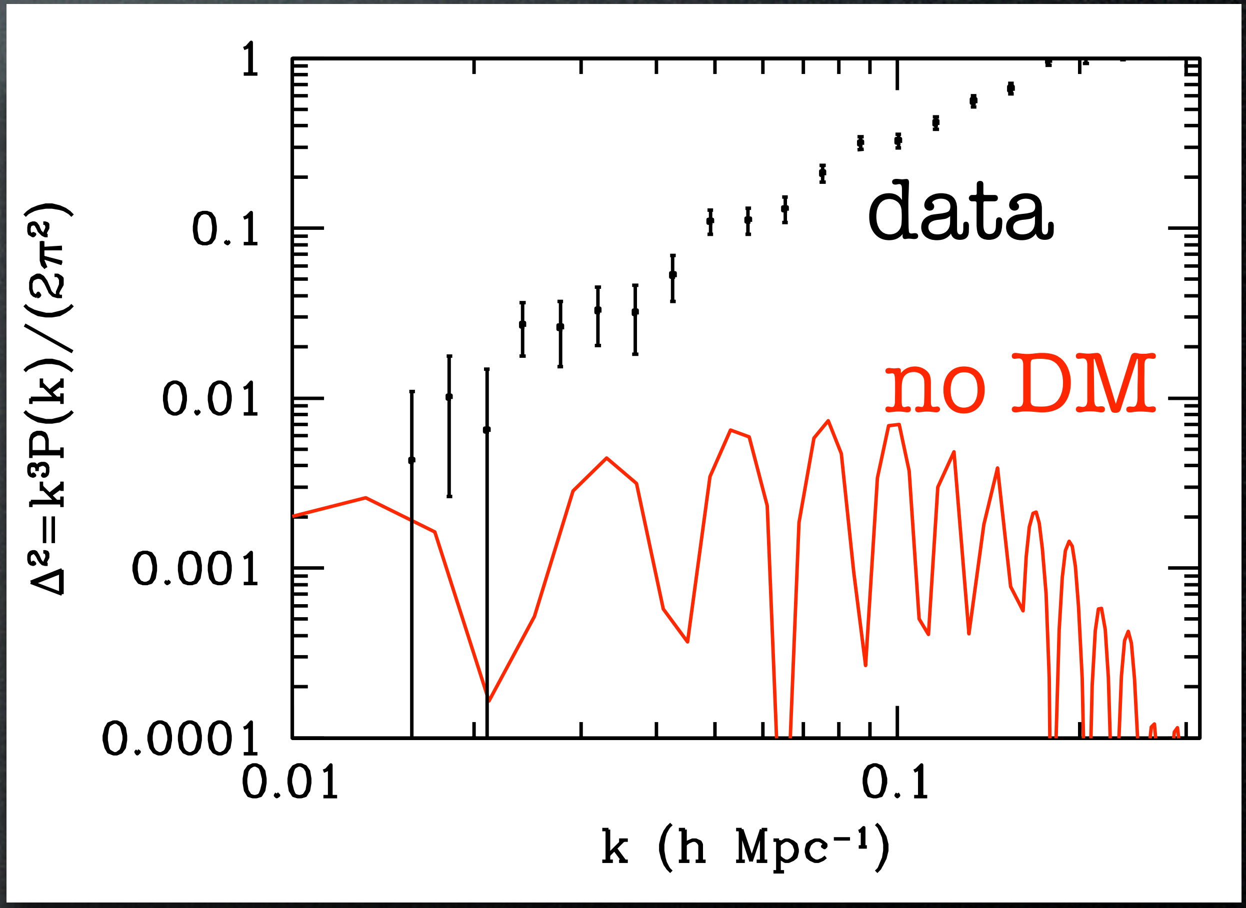


How would the power spectra be without DM? (and no other extra ingredient)



CAMB online

(in particular: no DM => no 3rd peak!)



Dodelson, Liguori 2006

(you need DM to gravitationally "catalyse" structure formation)


DETOUR

MOND? TeVeS?

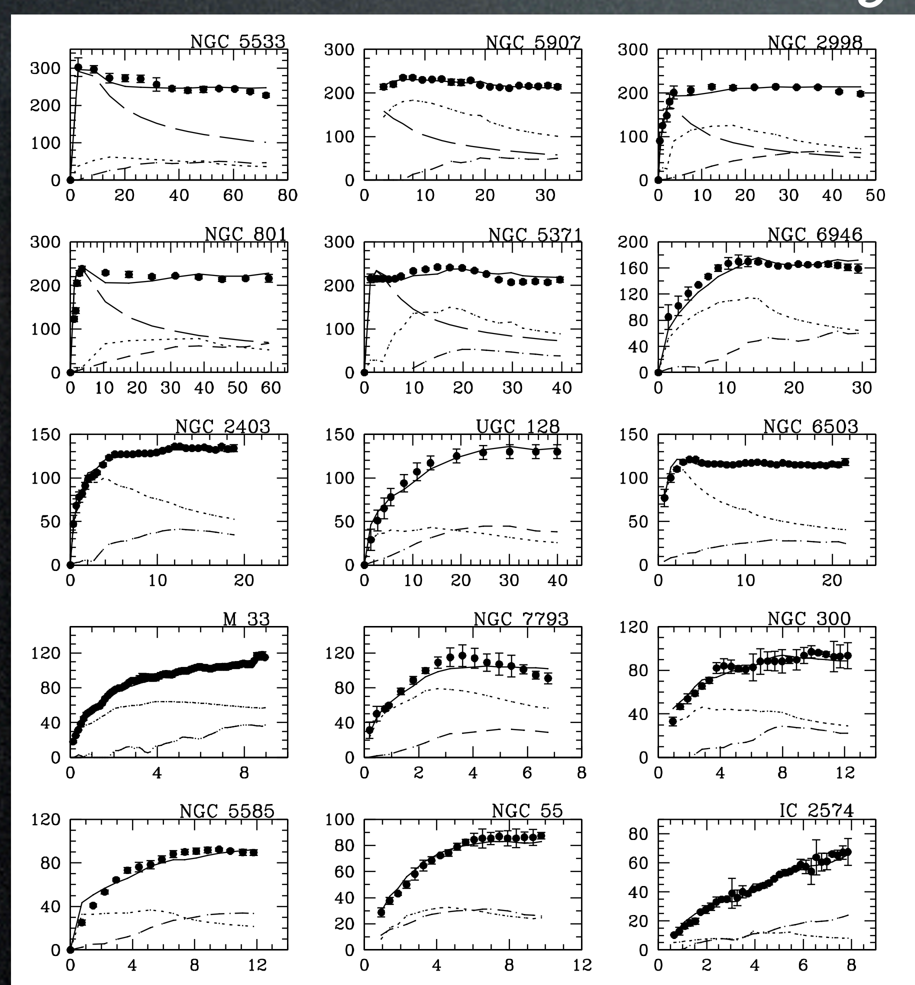
Instead of adding matter, modify Newton or GR.

$$F = m\,a \quad \longrightarrow \quad F = m\,a \cdot \mu(a) \quad \text{with} \quad \mu(a) = \begin{cases} 1 & a > a_0 \\ a/a_0 & a \sim a_0 \end{cases}$$

$$a_0 = 1.2 \cdot 10^{-10} m/s^2$$

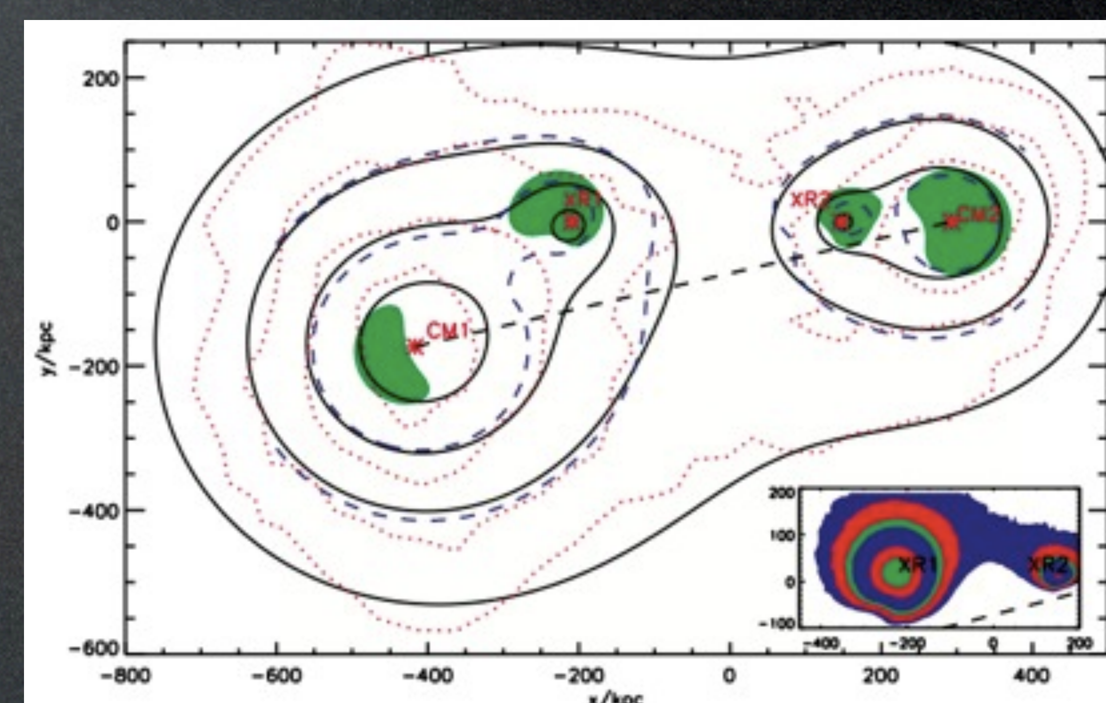
$$\underbrace{F = m\,\frac{a^2}{a_0} = \frac{GMm}{r^2}}_{\text{force balance}} \quad \Rightarrow \quad a = \frac{\sqrt{GMa_0}}{r} = \underbrace{\frac{v^2}{r}}_{\text{tangential acceleration}} \quad \Rightarrow \quad v = (GMa_0)^{1/4} = \text{const}$$

fits rotation curves very well



Sanders, McGaugh, Ann. Rev. AA, 2002

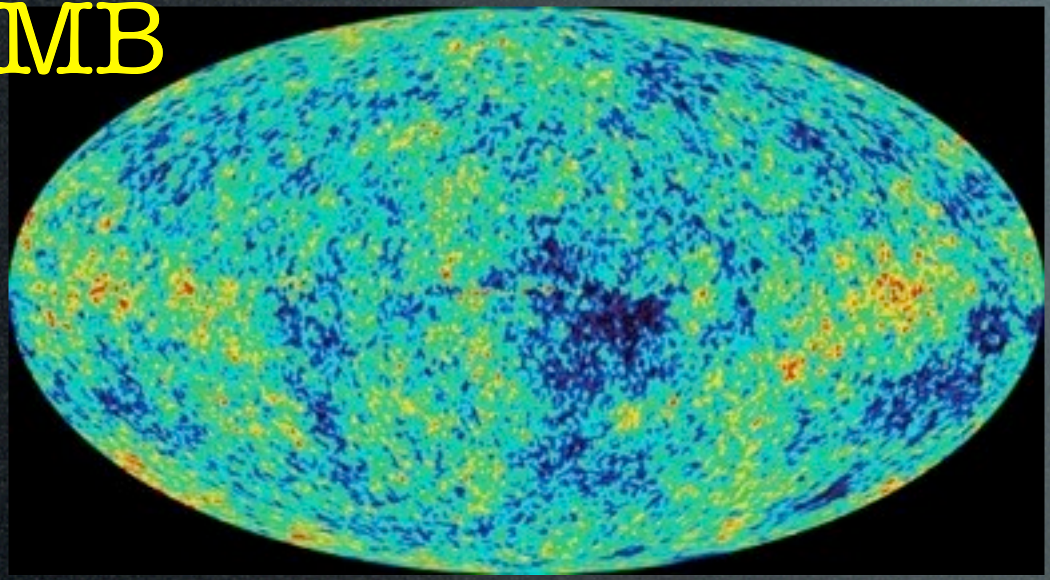
can fit (bullet) cluster if adding 2 eV neutrinos...



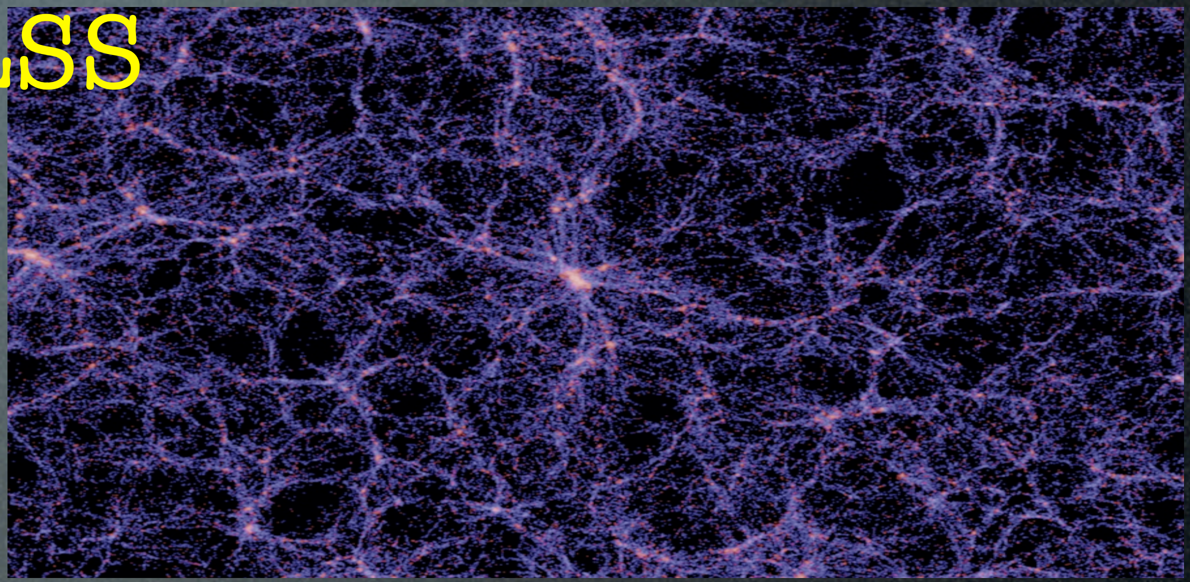
Angus et al., astro-ph/0609125

The Evidence for DM

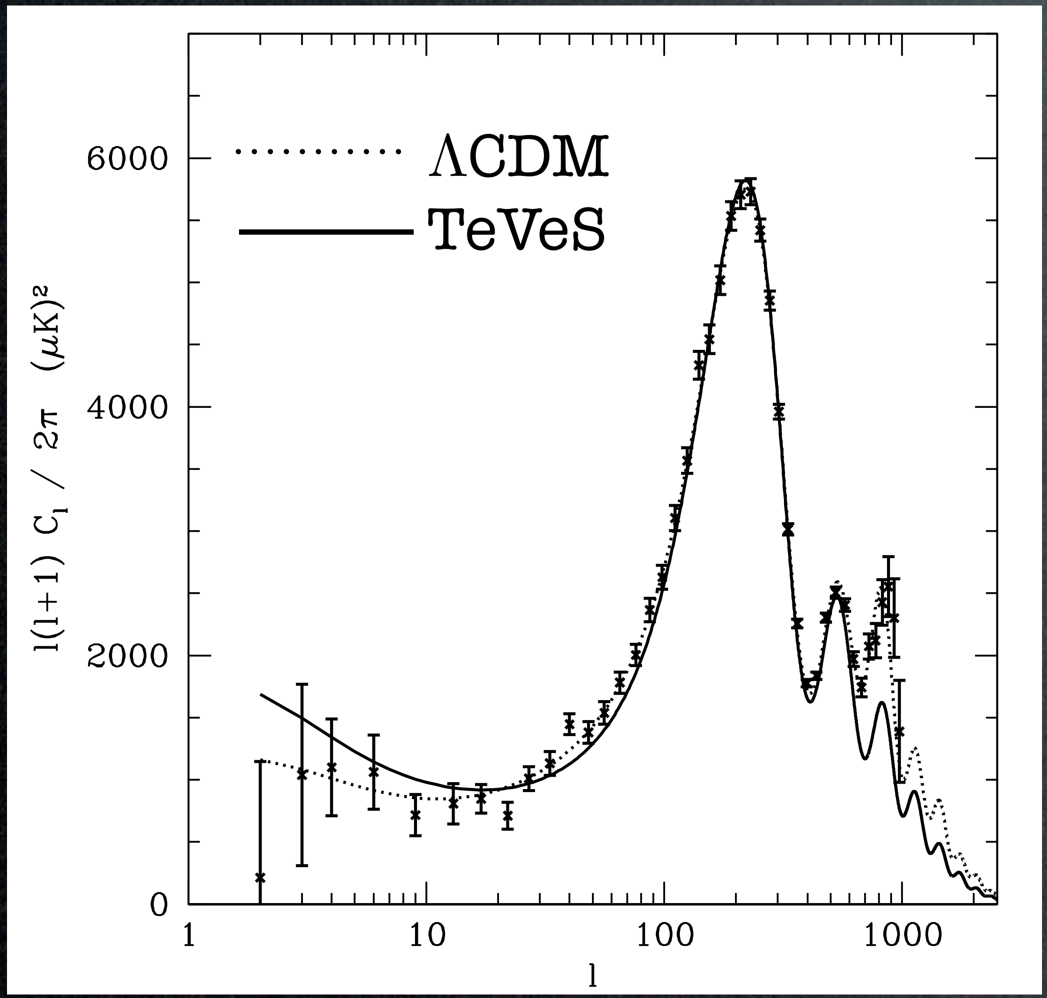
CMB



LSS

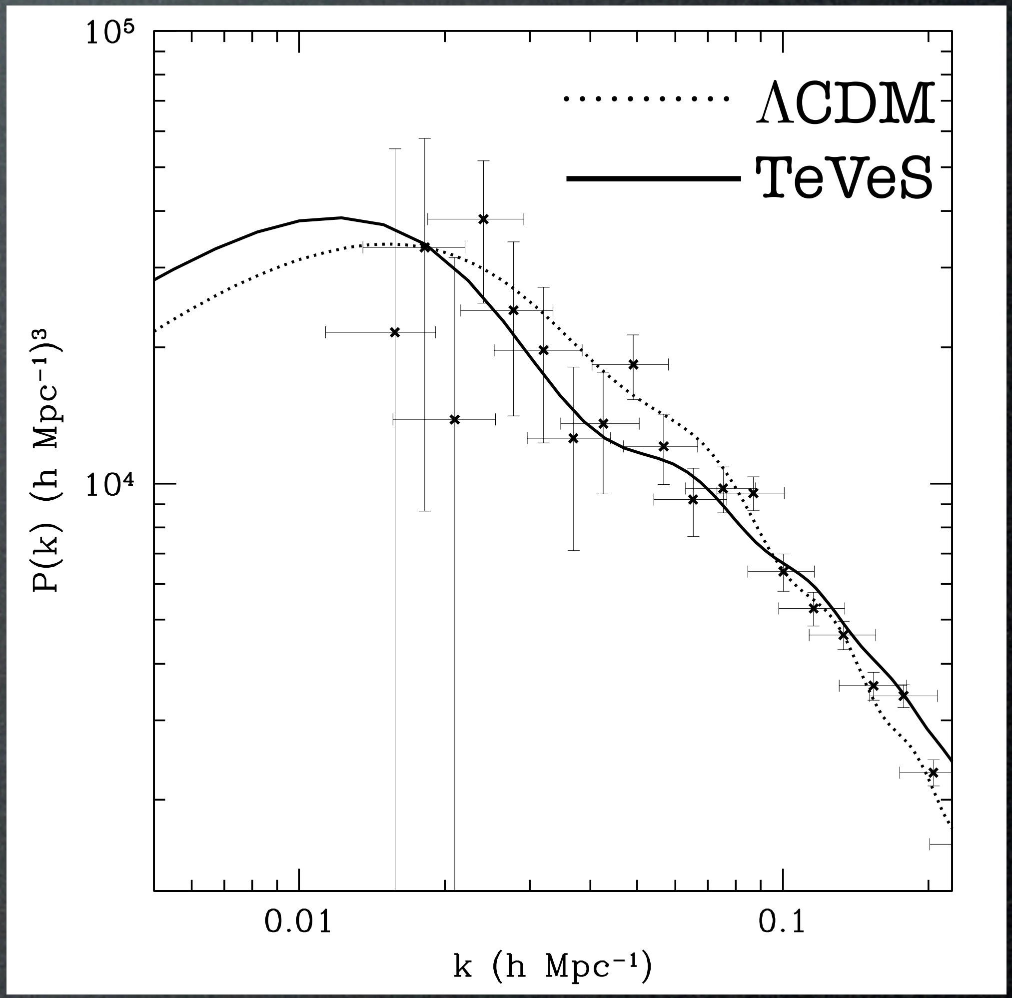


How would the power spectra be in MOND/TeVeS, without DM ?



C.Skordis, Review, 0903.3602

(in particular: no DM => no 3rd peak!)



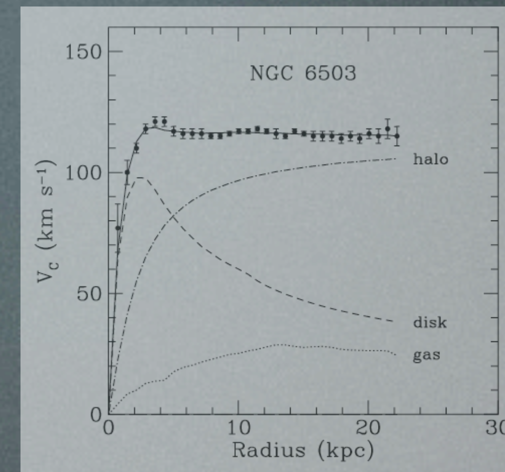
C.Skordis, Review, 0903.3602

(here you can make it)


DETOUR

The Evidence for DM

1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

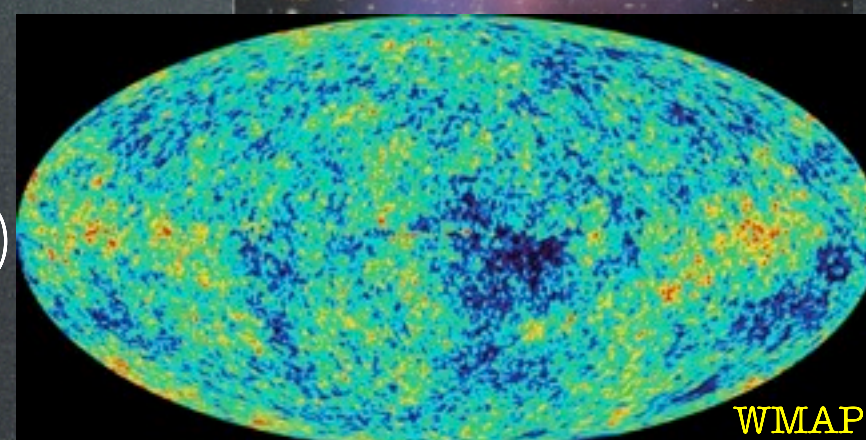
2) clusters of galaxies

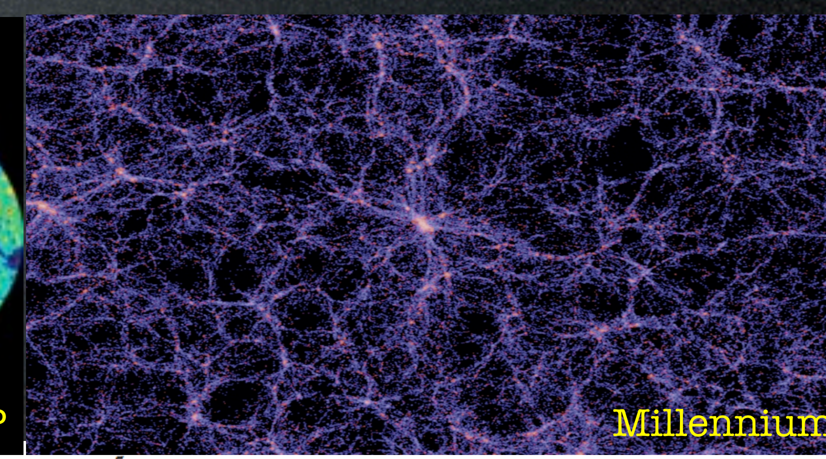
$\Omega_M \sim 0.2 \div 0.4$

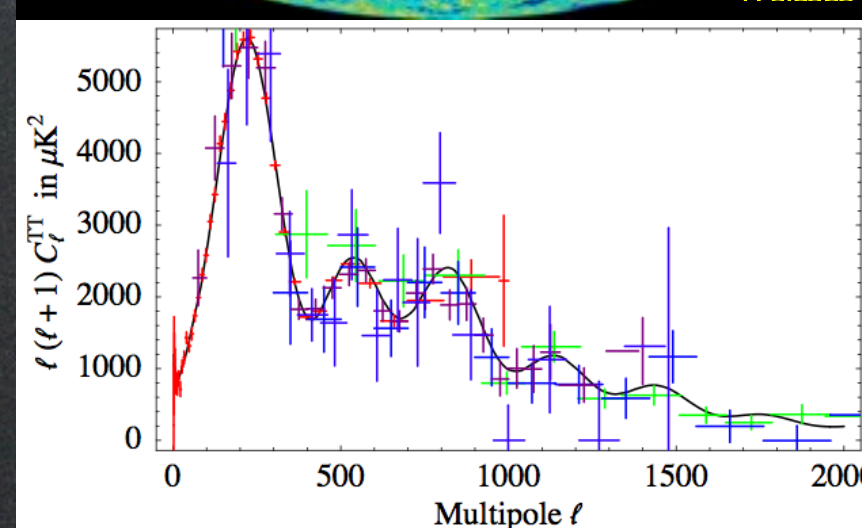
3) CMB+LSS(+SNIa:)

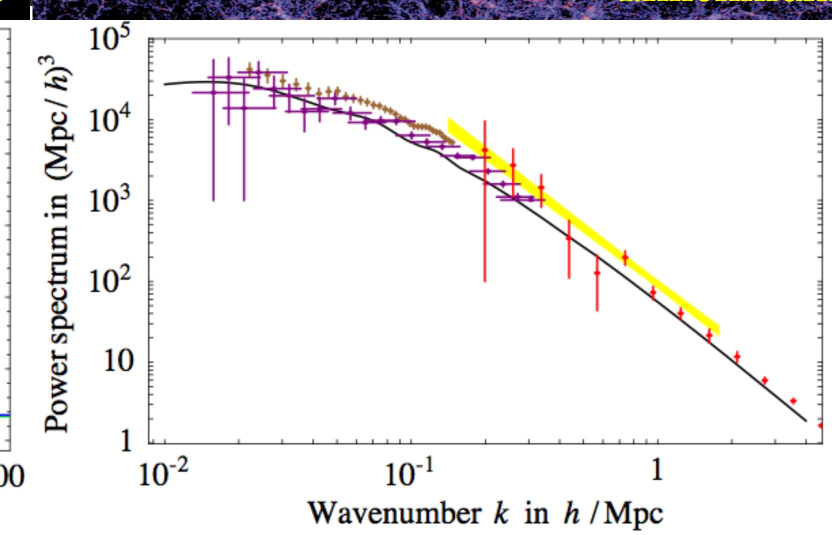
WMAP-3yr
ACbar
CBI
Boomerang
DASI
VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS









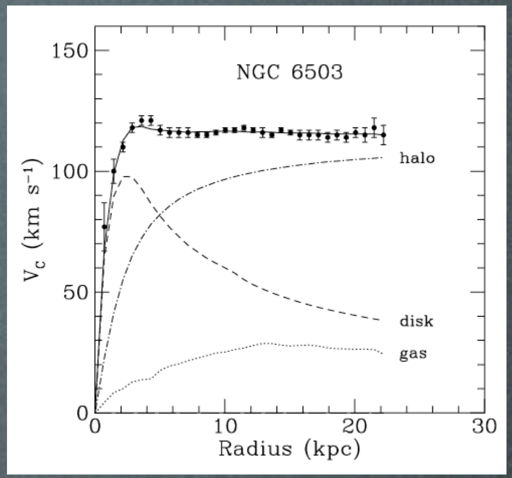
$\Omega_M \approx 0.275 \pm 0.02$

(spectra w/o DM)

M.Cirelli and A.Strumia, astro-ph/0607086

The Evidence for DM

1) galaxy rotation curves



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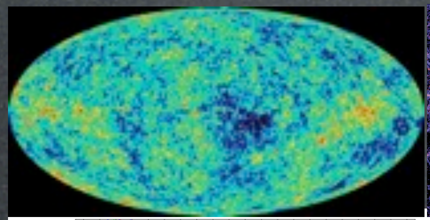

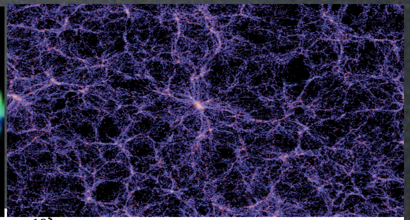

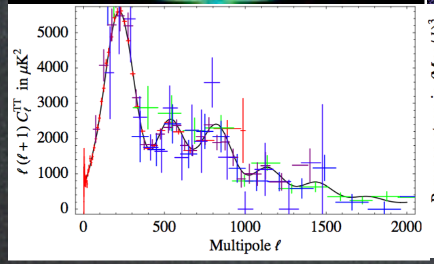

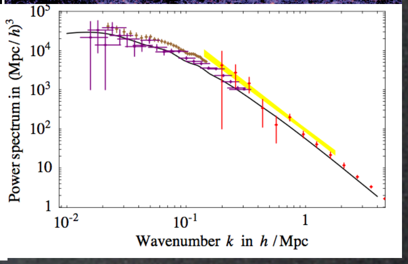

$\Omega_{\rm M} \approx 0.275 \pm 0.02$

What is the DM??

It consists of a particle.
Permeates galactic haloes.

What do we know of the particle physics properties of Dark Matter?

DM can **NOT** be:

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an astro *je ne sais pas quoi*:

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an astro *je ne sais pas quoi*:

- neutrons

- gas

- Black Holes
- brown dwarves

DM can **NOT** be:

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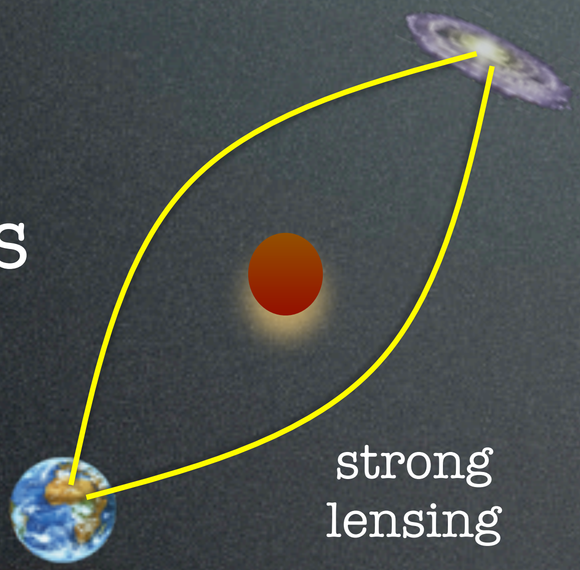

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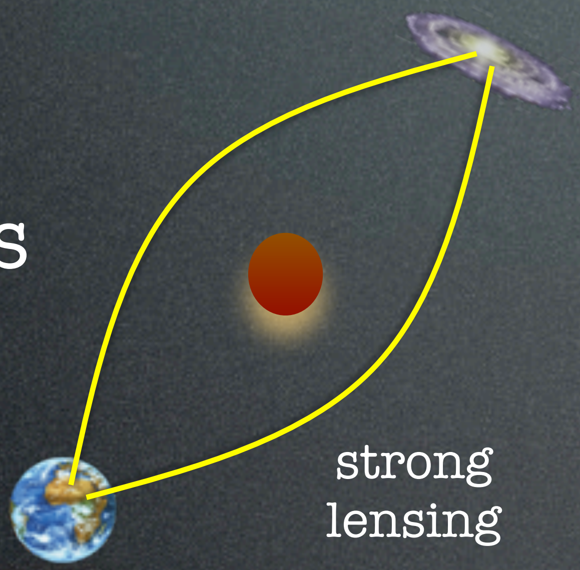

a baryon of the SM:

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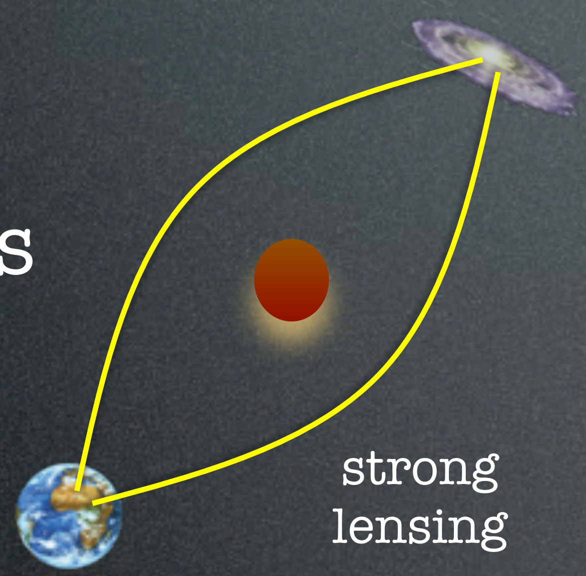

a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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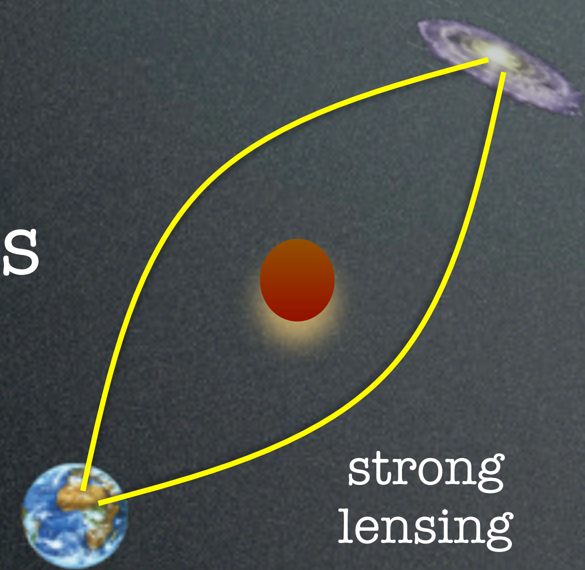

neutrinos:

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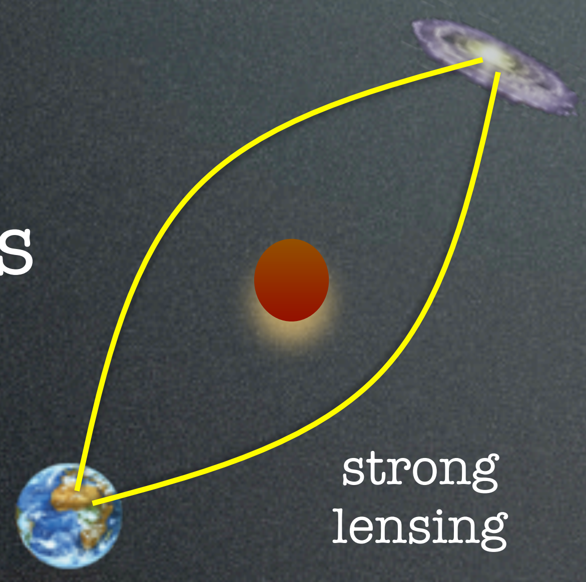

a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
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~~neutrinos~~:

too light! $m_\nu \lesssim 1\,\mathrm{eV}$

do not have enough mass to act as gravitational attractors in galaxy collapse

What are the theoretical 'beliefs'?

Likely a

weakly int., massive, neutral, stable

has the correct

relic abundance today!

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we would
have seen it!

Likely a

weakly int., massive, neutral, stable

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have seen it!

at least on cosmological
time scales, i.e.

$\tau > t_{\mathrm{universe}}$

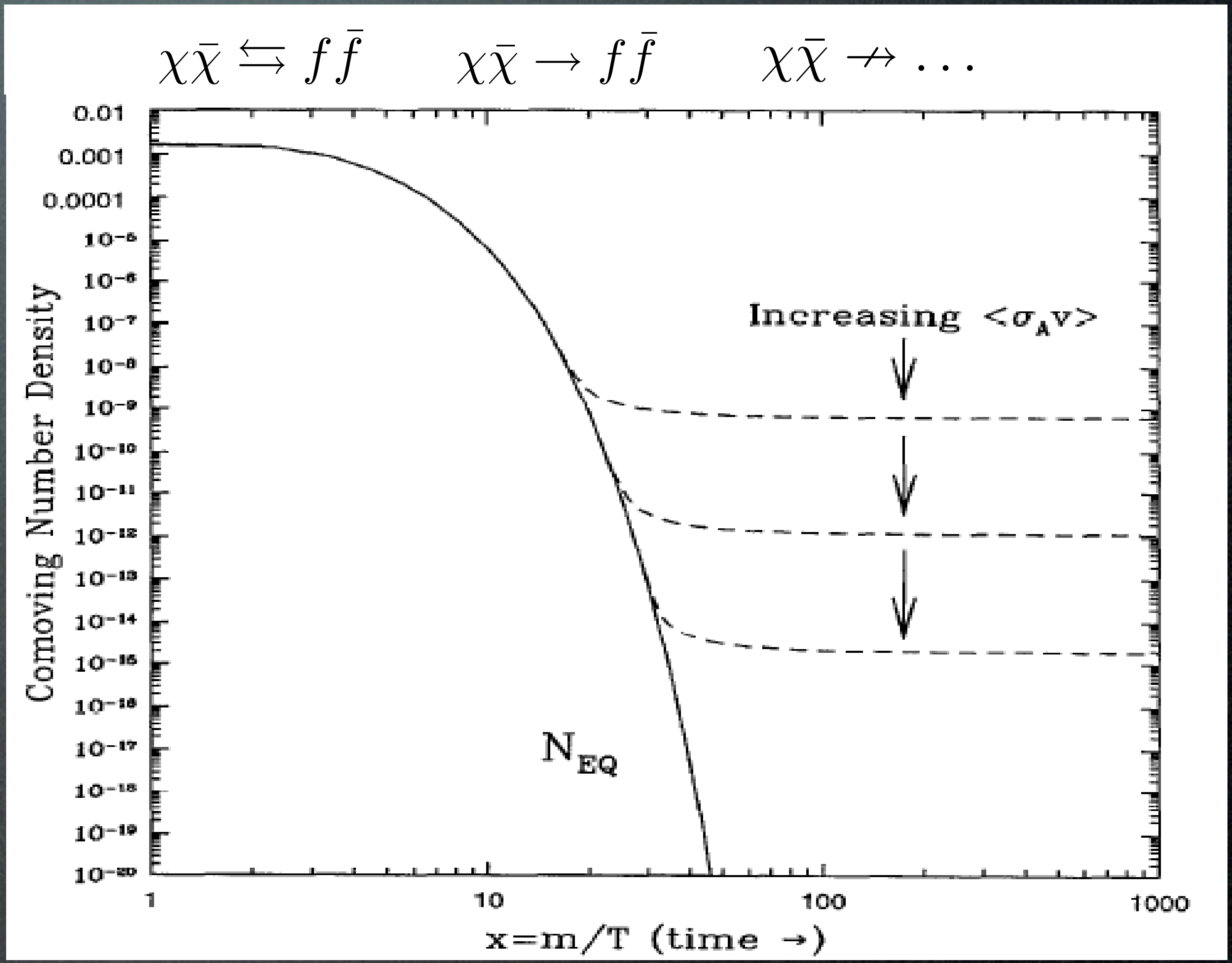
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \quad \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

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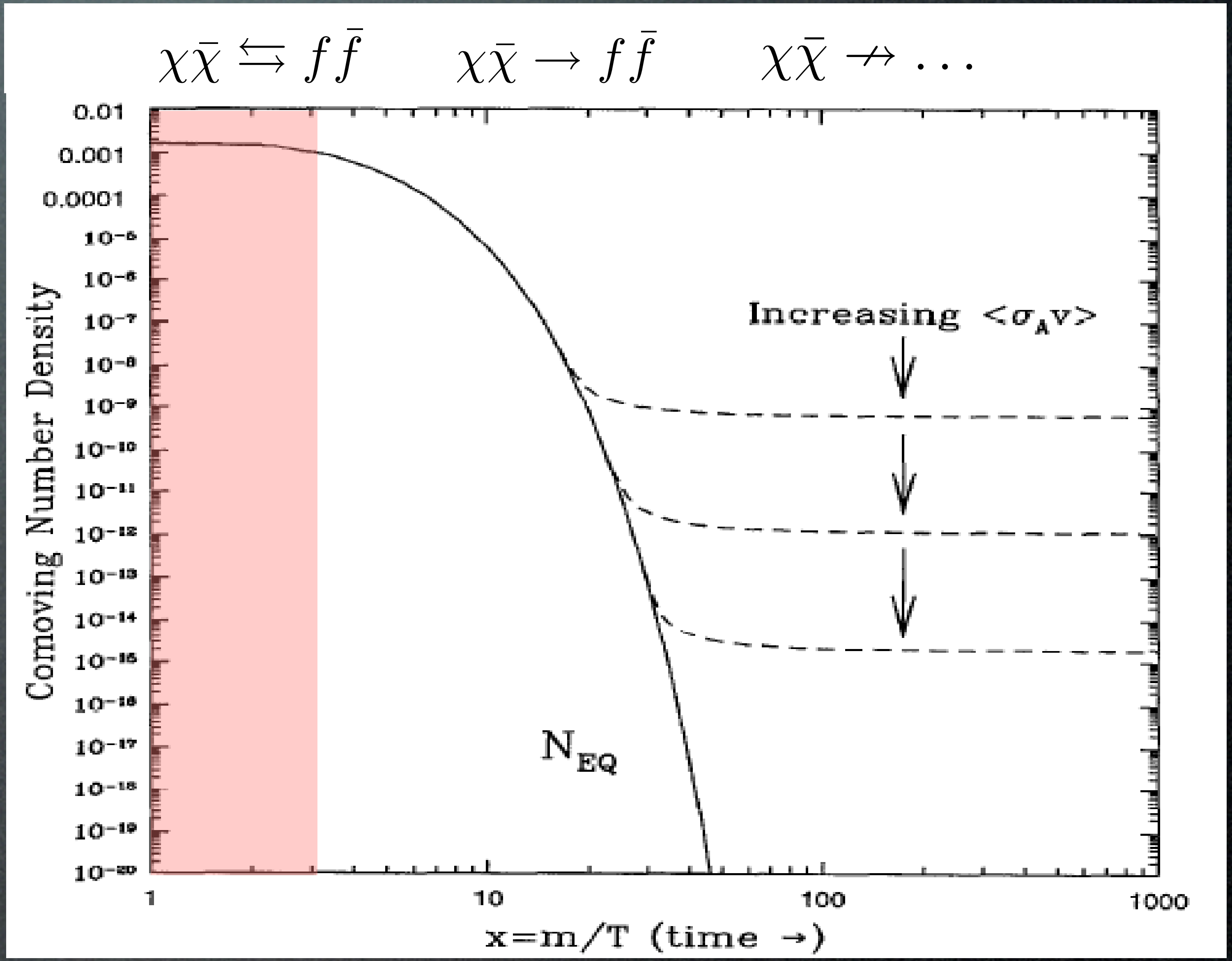

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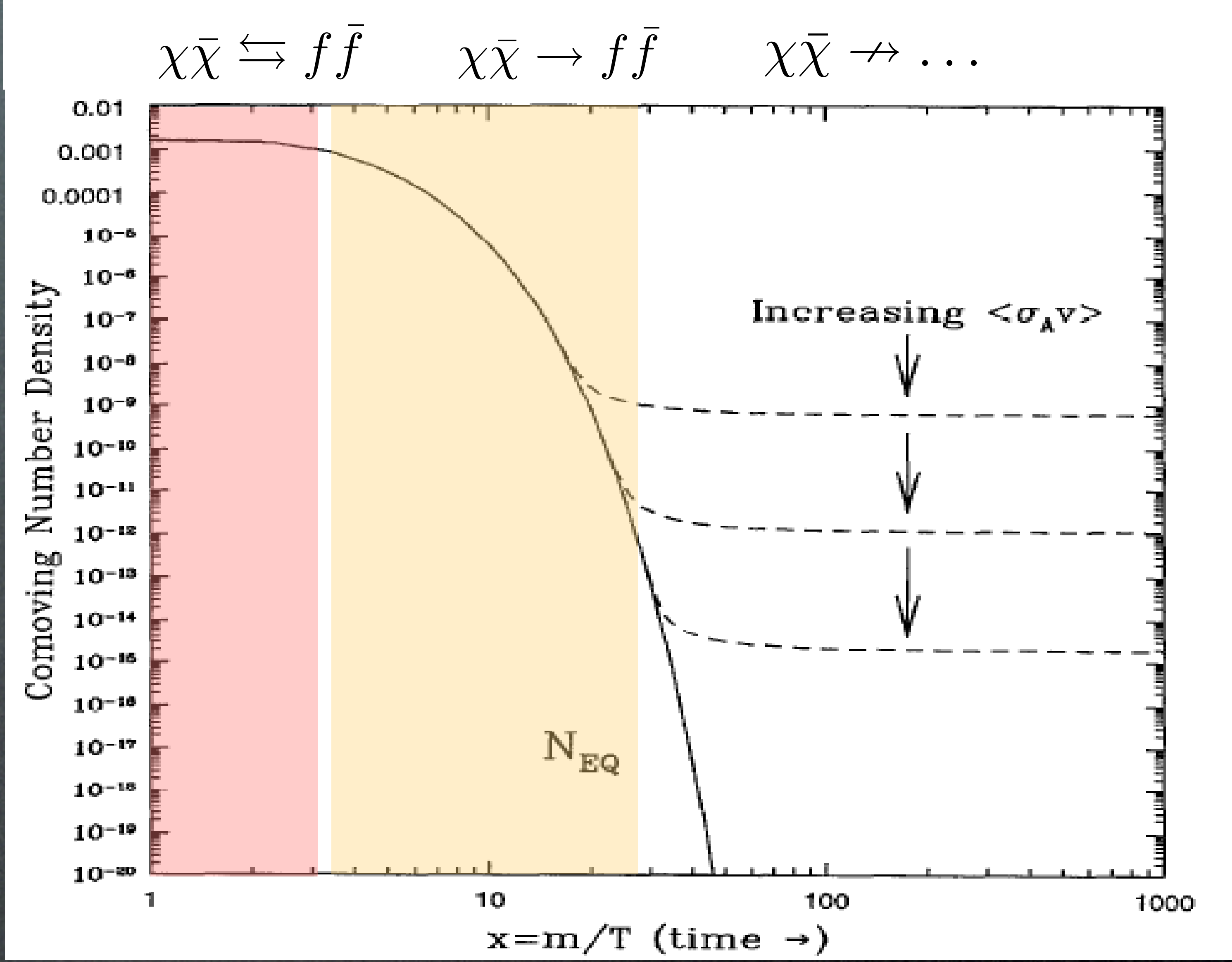

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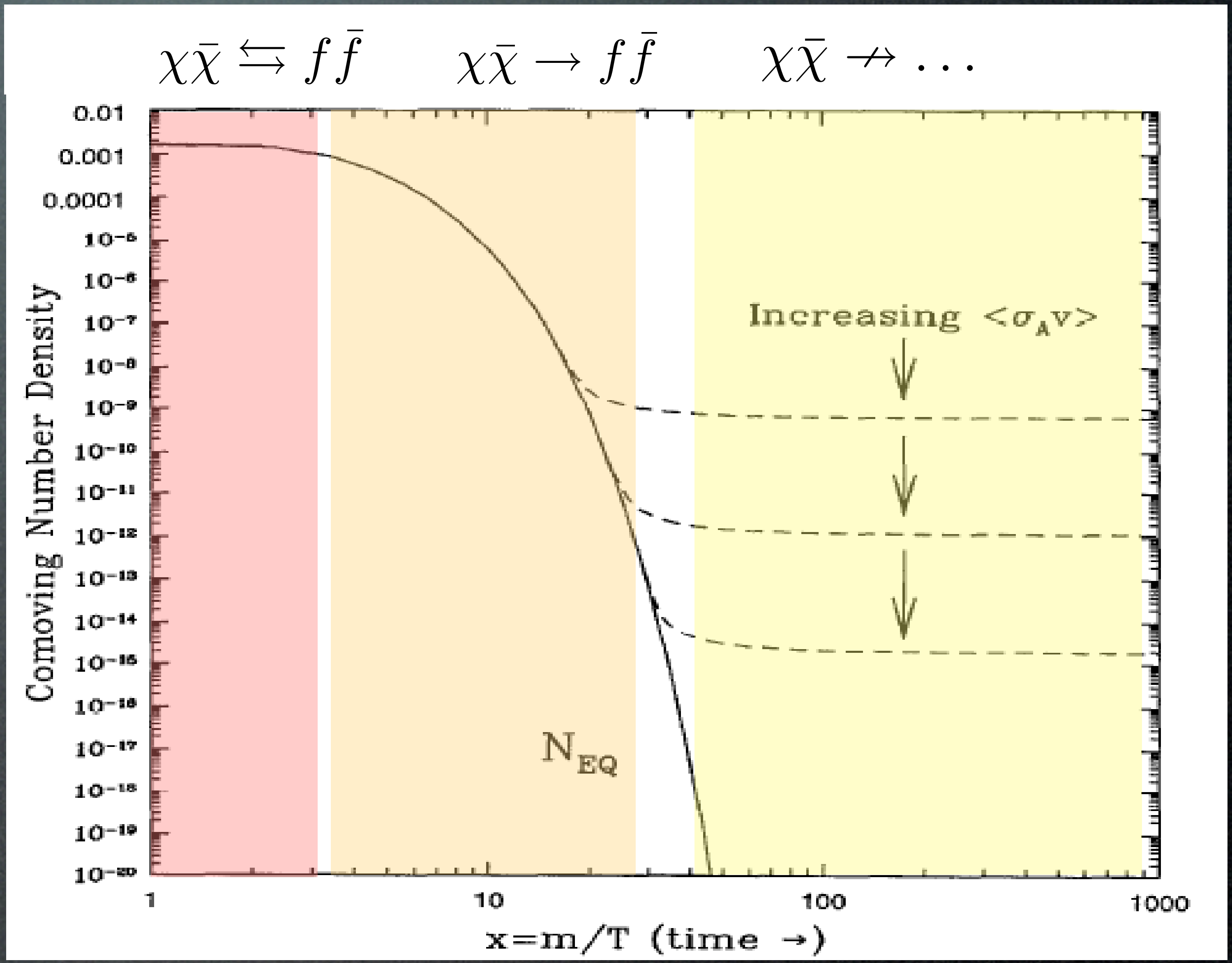

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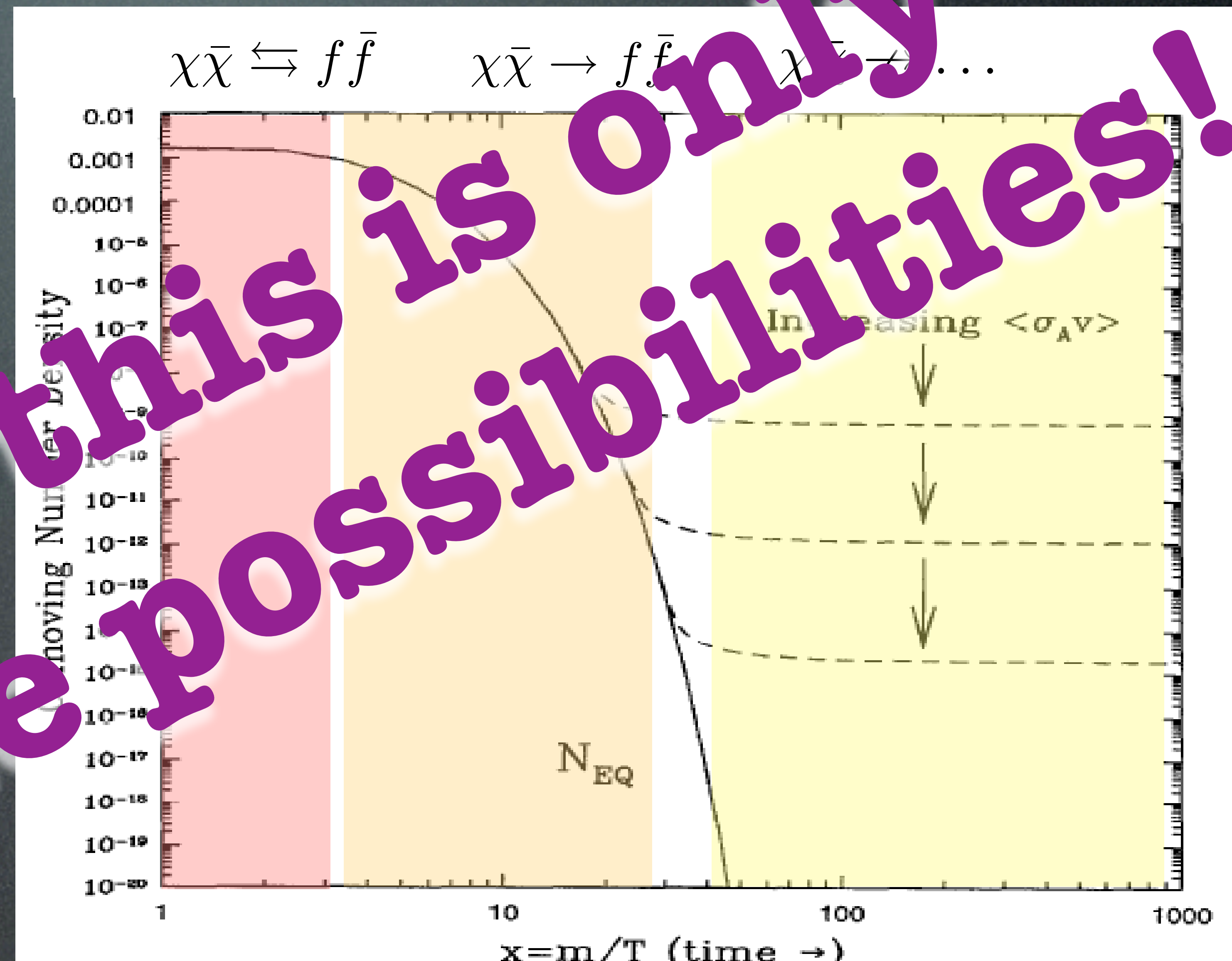

Kolb,Turner, The Early Universe, 1995

Caveat: this is only one of the possibilities!

Weak cross section:

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T. Schwetz's lectures

Roadmap

DM does not exist

it is a SM particle

DM exists

Roadmap

DM does not exist

modified gravity, TeVeS... $\neq$ many observations, difficult to modify GR consistently

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neutrons, brown dwarves, BHs... $\neq$ decay, strong lensing, BBN

neutrinos $\neq$ too light: can't make Ω, are hot and stream out

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e.m. interactions

weak interactions

other interactions

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(Champs)

weak interactions

other interactions

(axions, gravitinos, axinos,
Dirac neutrinos, RH neutrinos,
MeV Dark Matter...)

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    - SuperSymmetry
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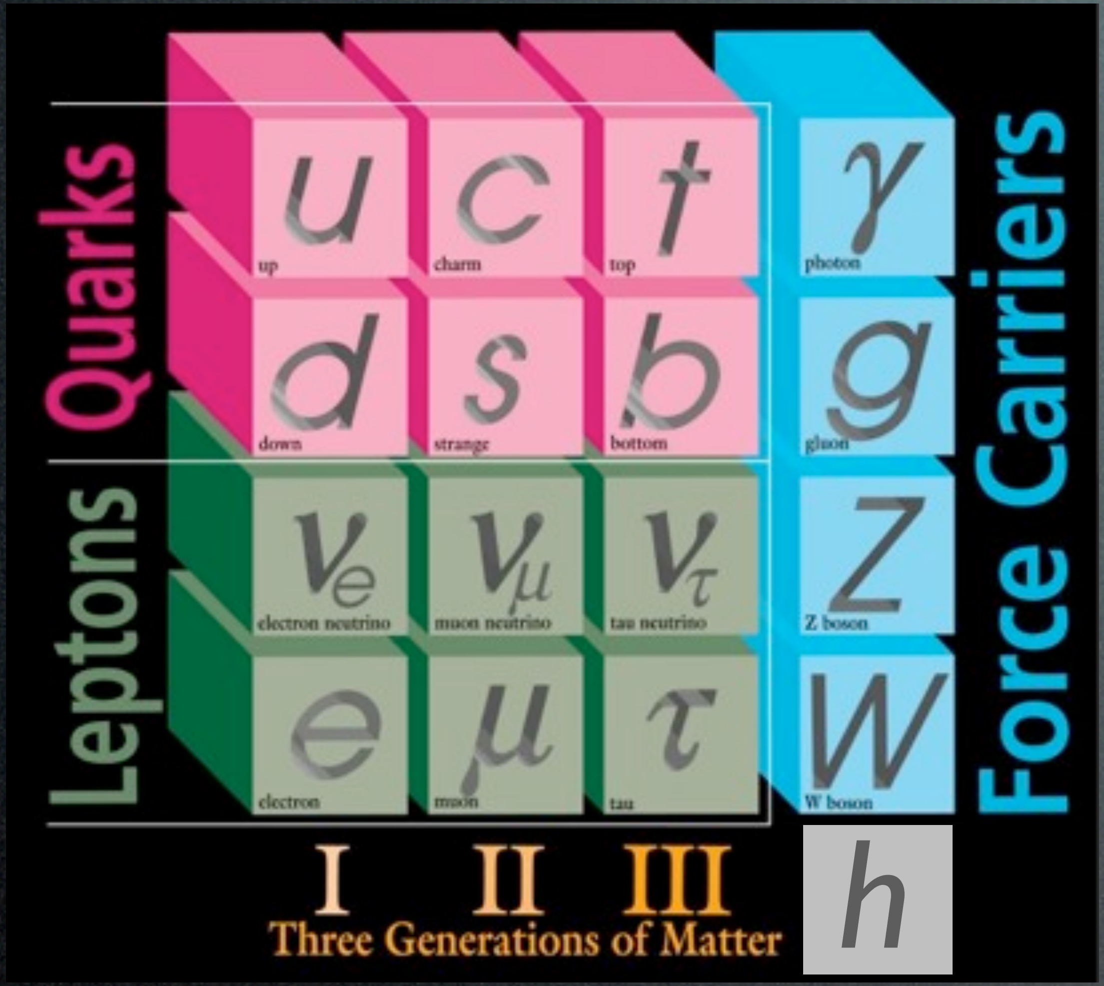
G. Servant's lecture

G. Raffelt's & M. Shaposhnikov's lectures

SuSy DM in 2 minutes



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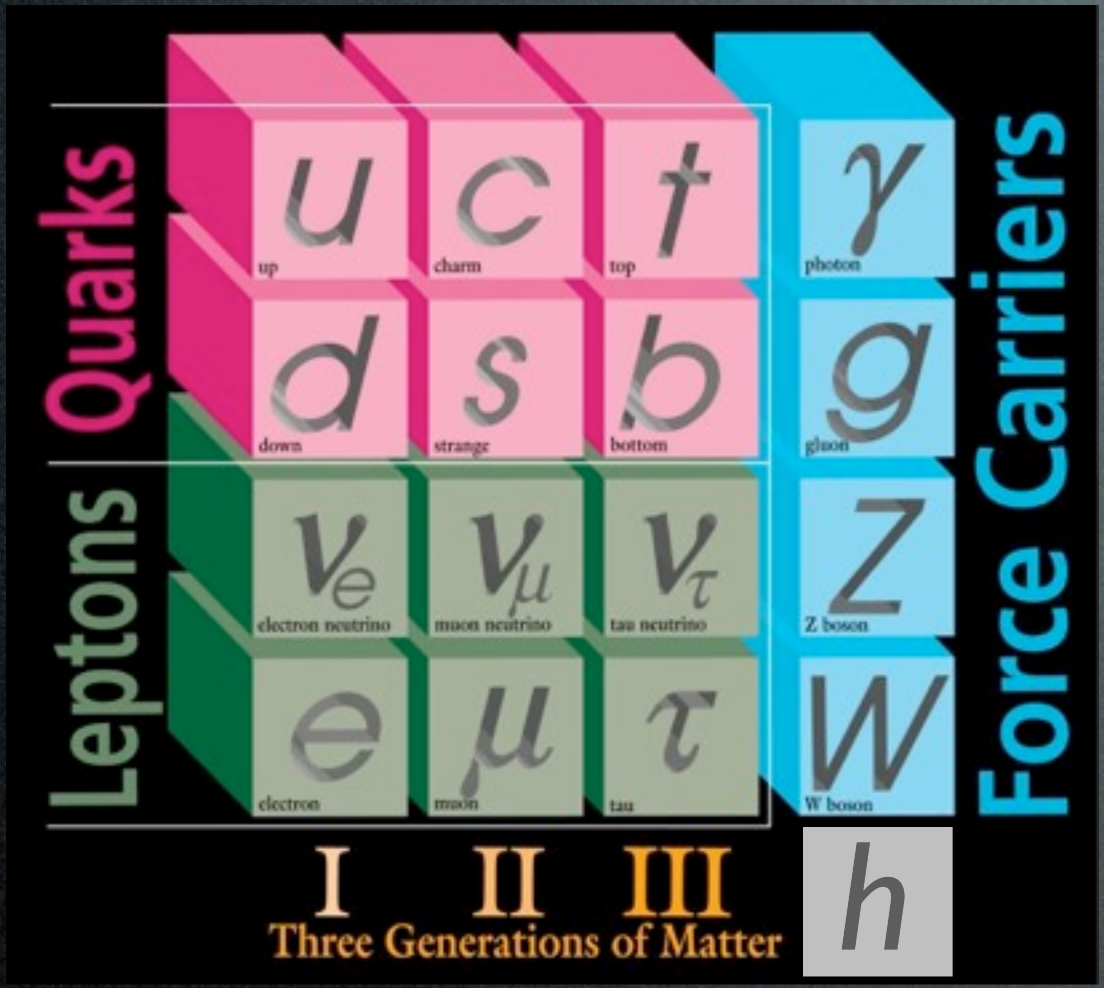

$m_{\mathrm{h}} \approx 150\ \mathrm{GeV}$

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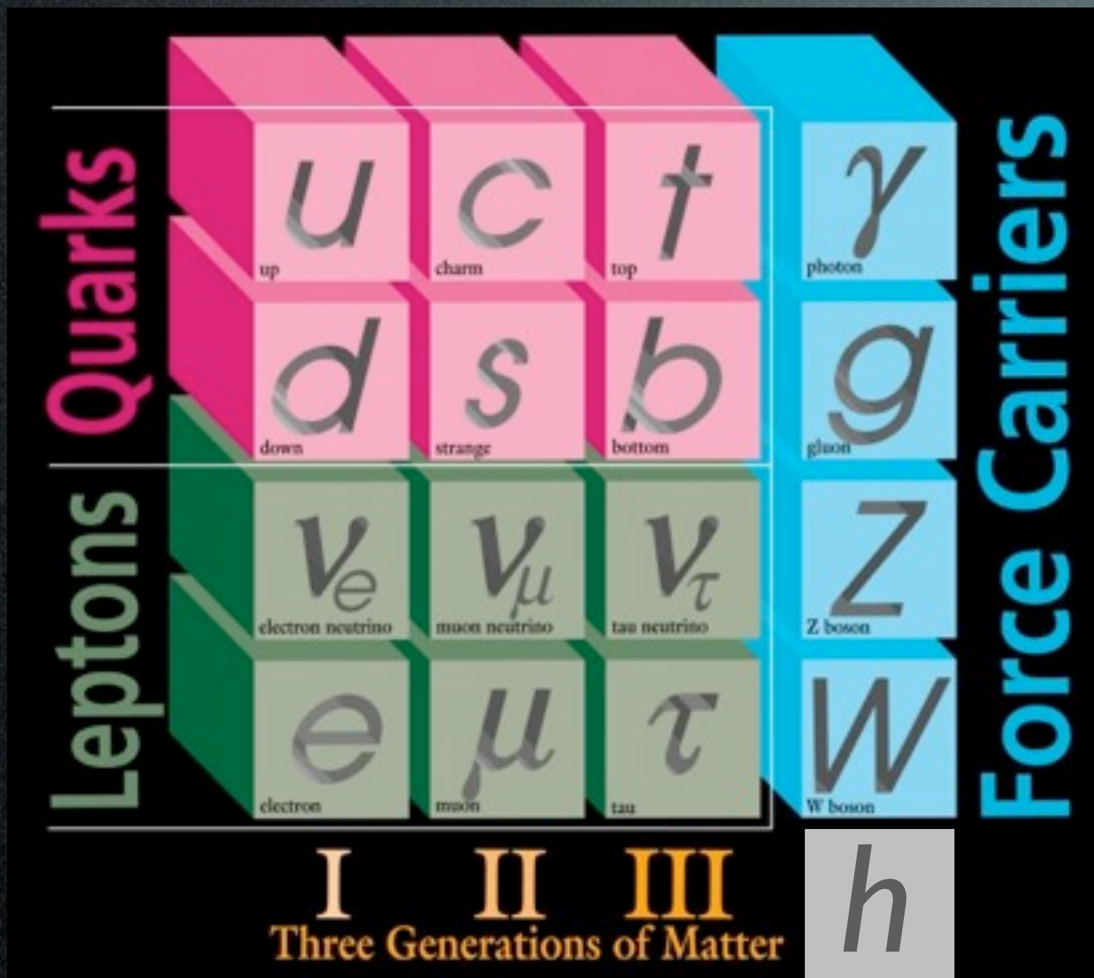

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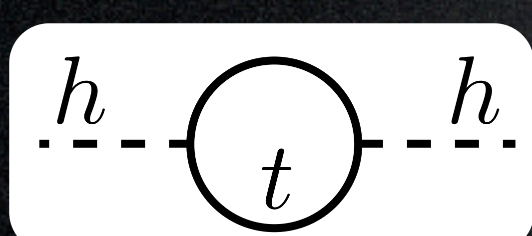
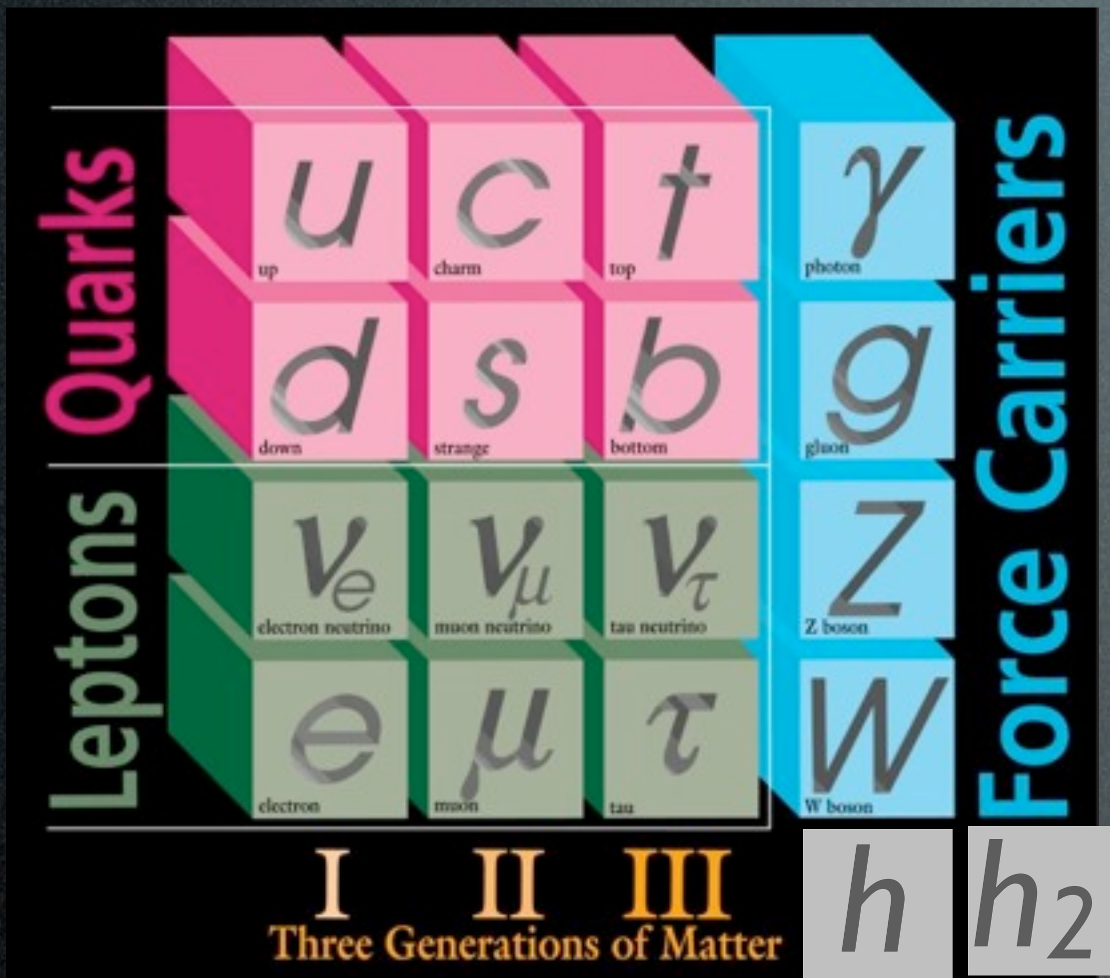
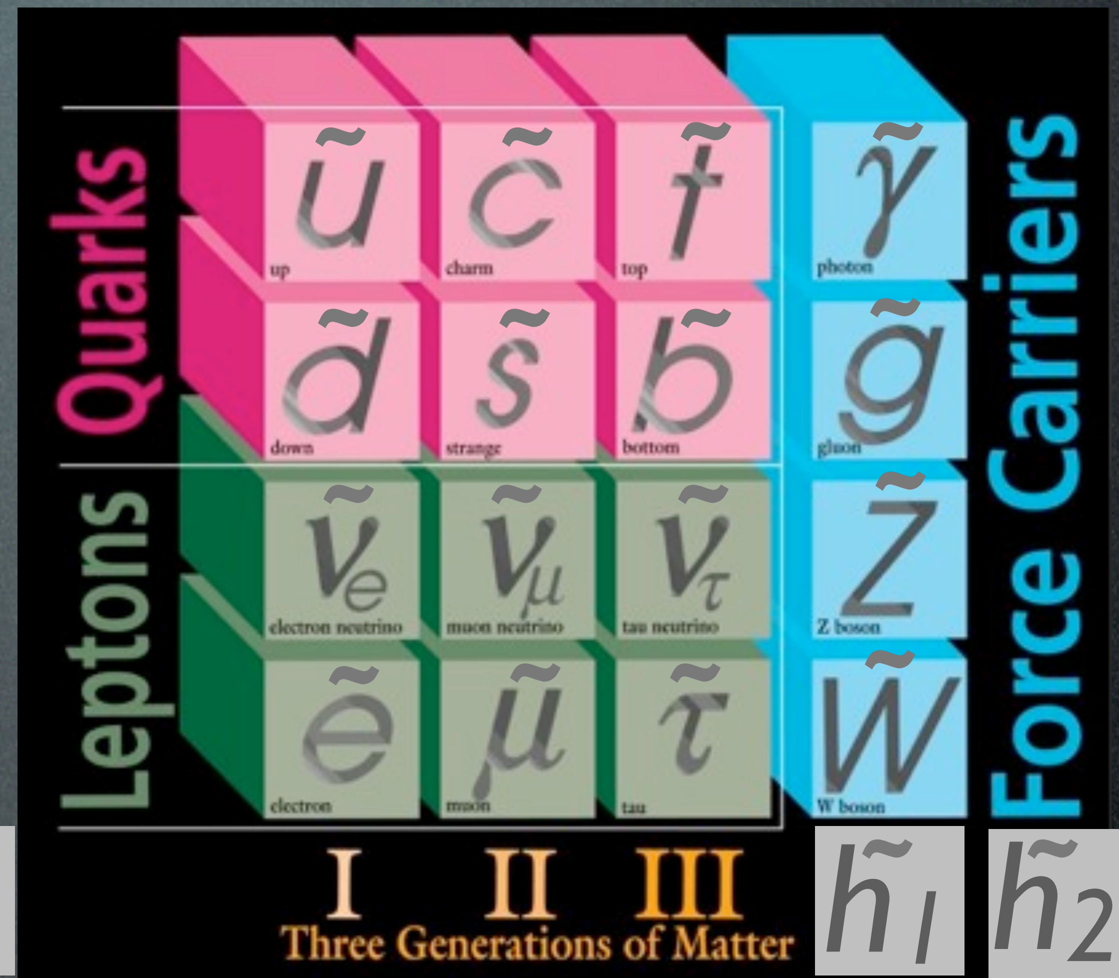


$\Delta m_{\rm h} \propto 10^{19}\ {\rm GeV}$

SuSy DM in 2 minutes





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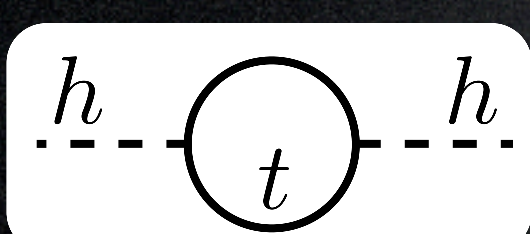

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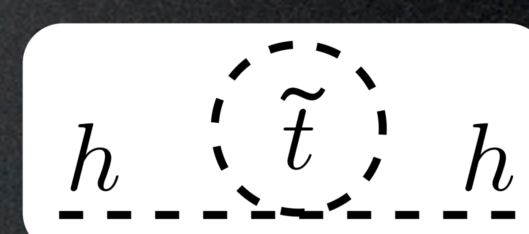
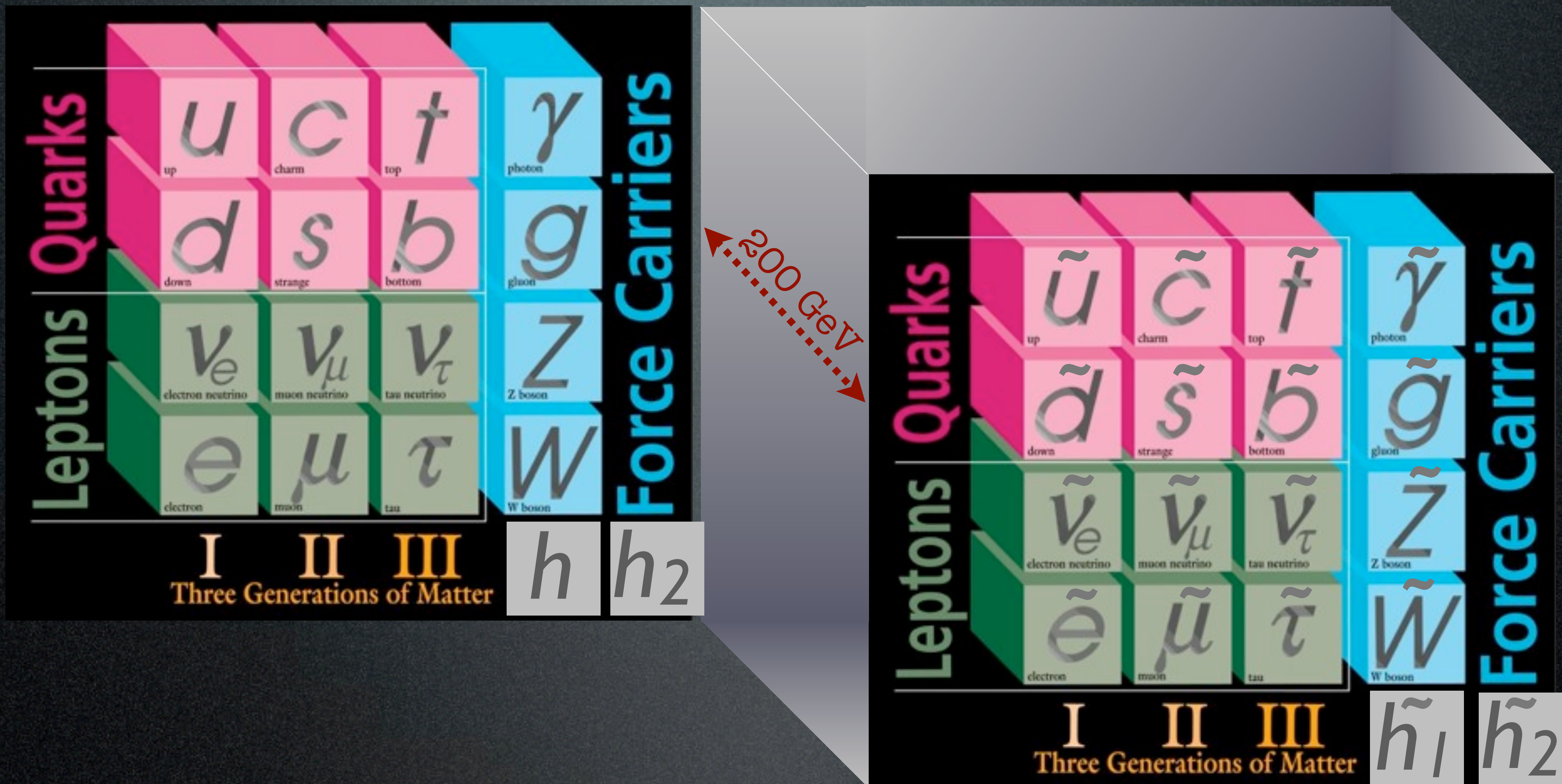


$\Delta m_\mathrm{h} \propto -10^{19}$ GeV

SuSy DM in 2 minutes



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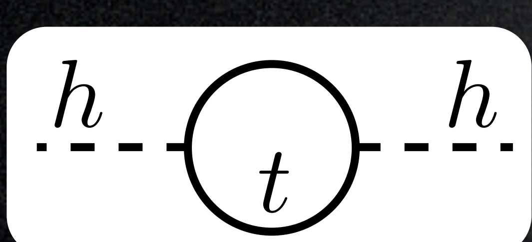

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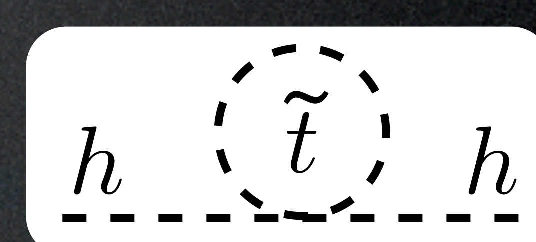

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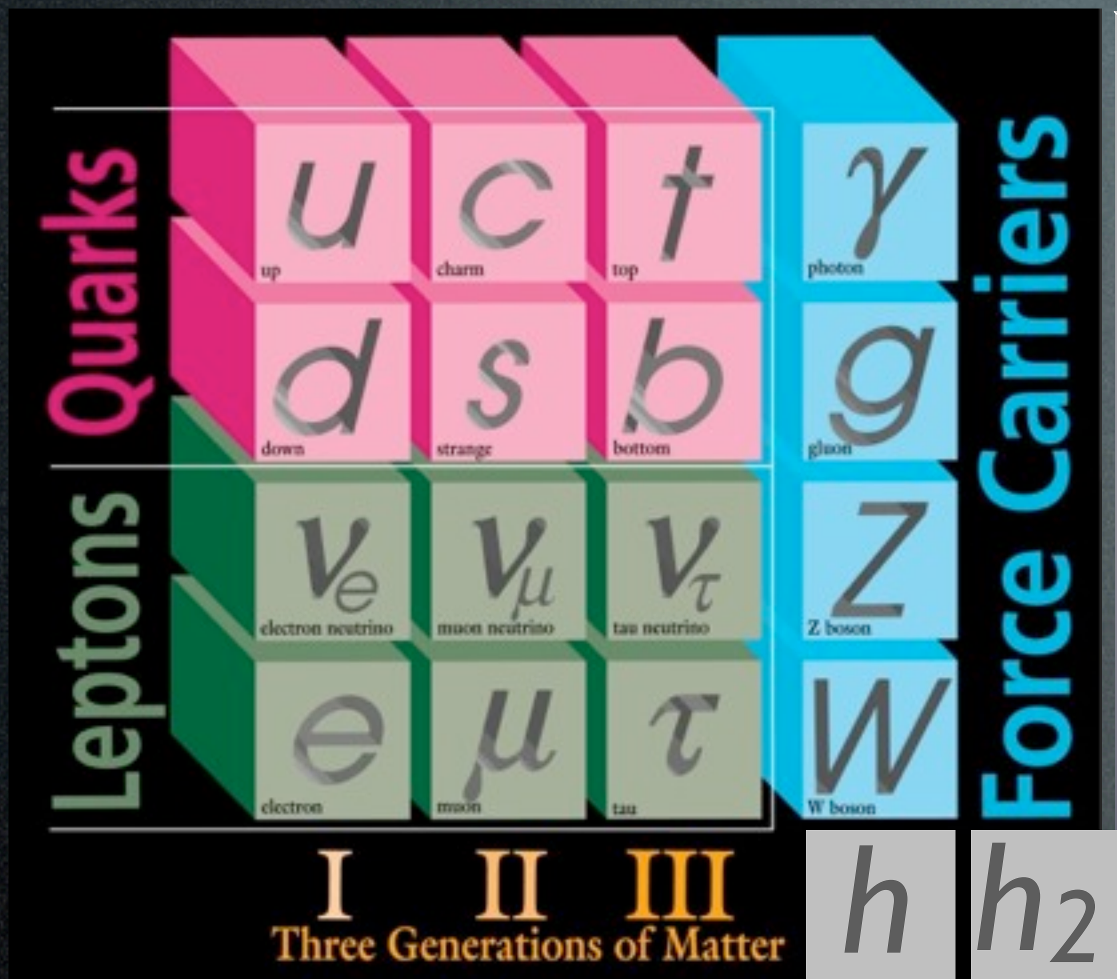
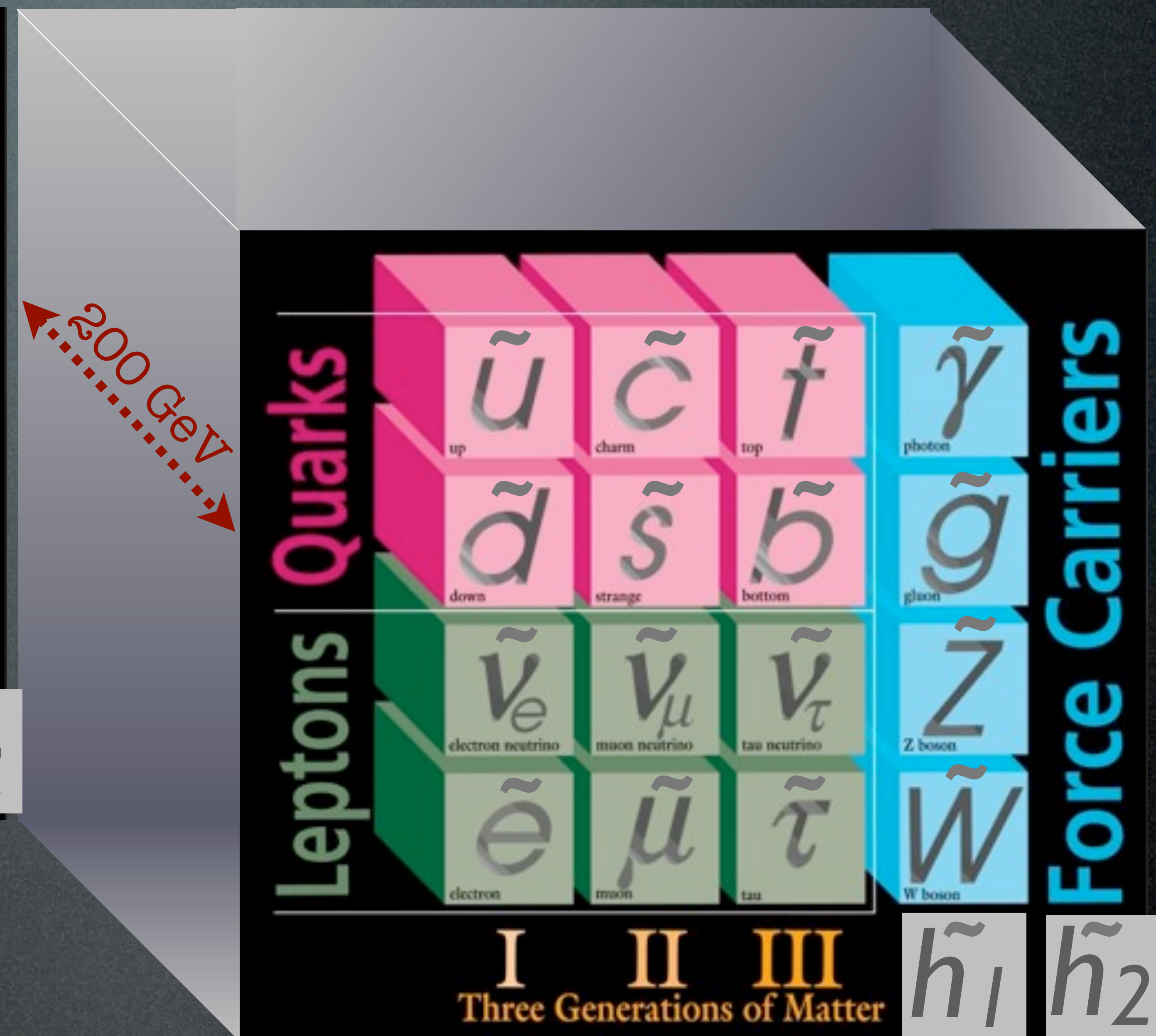
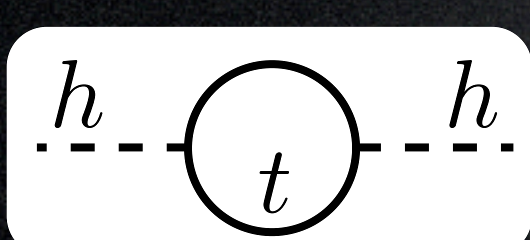




$R = +1$

$m_{\rm h} \approx 150$ GeV



$\Delta m_{\rm h} \propto 10^{19}$ GeV

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$\Delta m_{\rm h} \propto -10^{19}$ GeV

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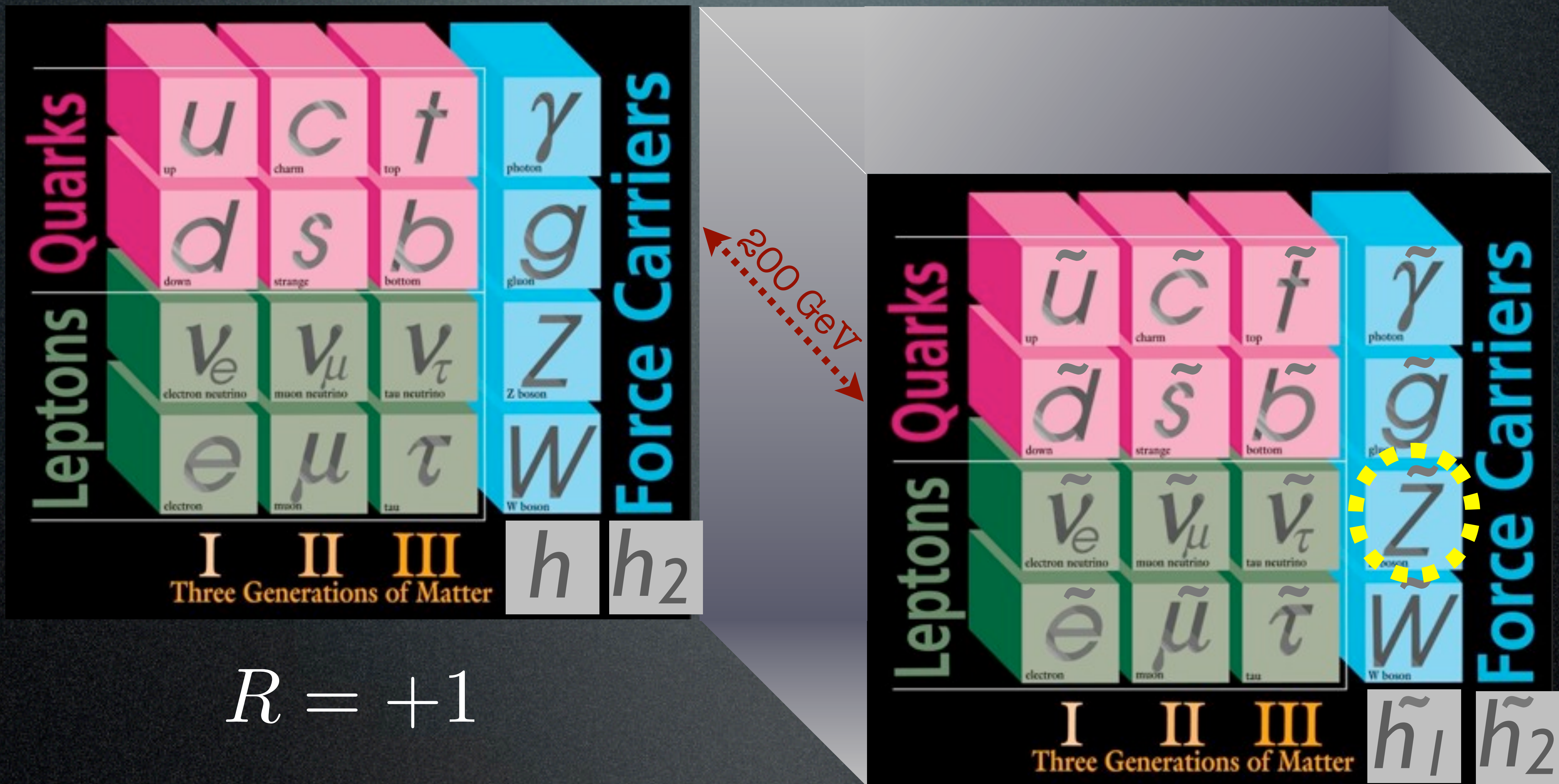

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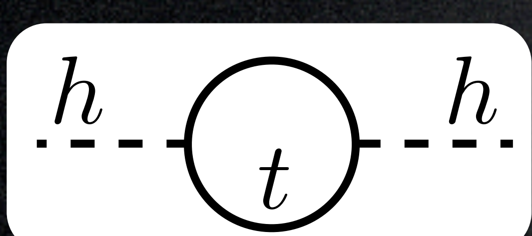

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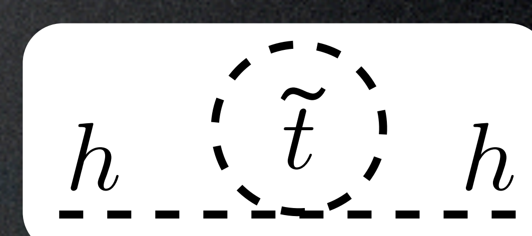

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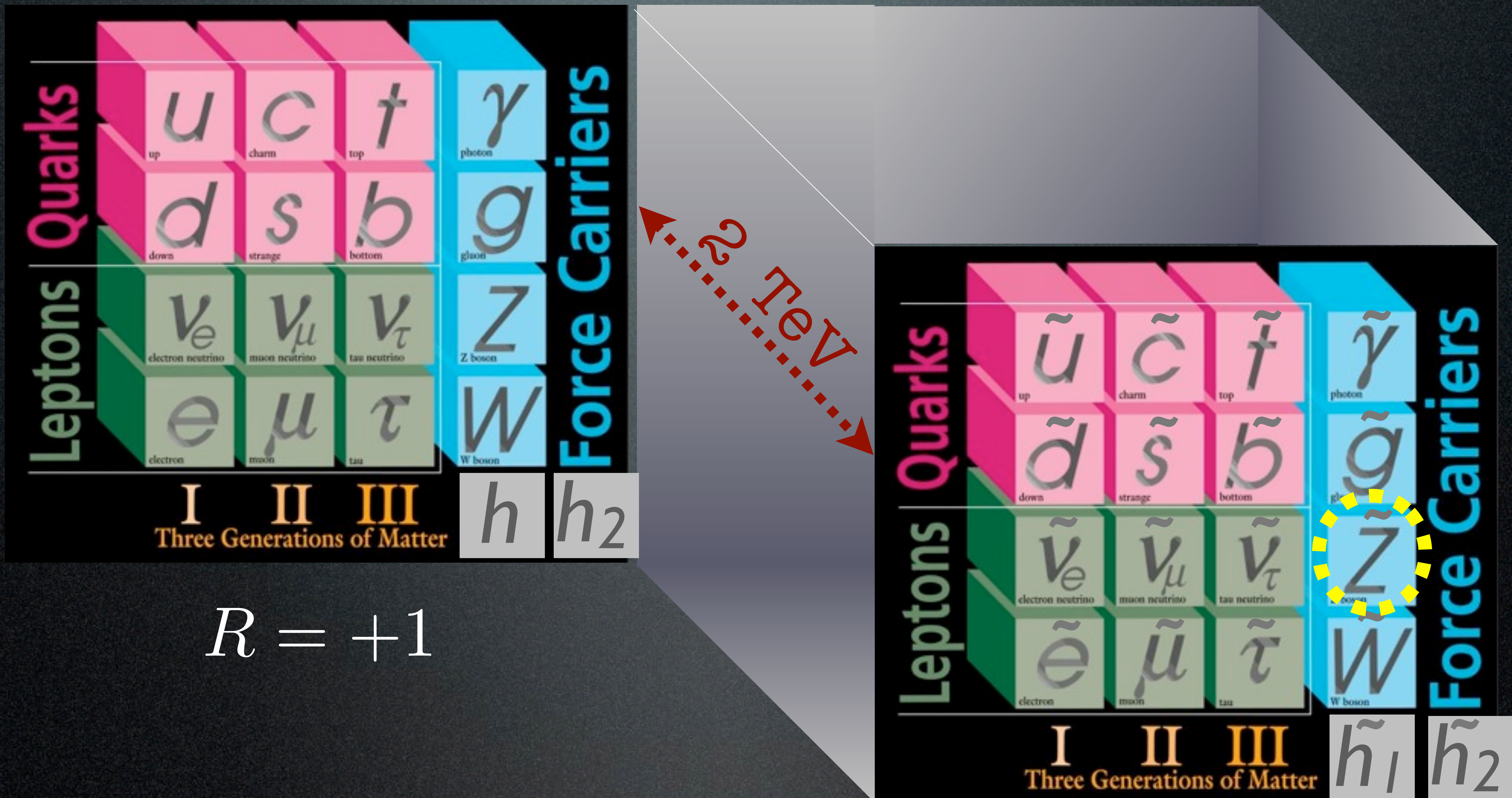

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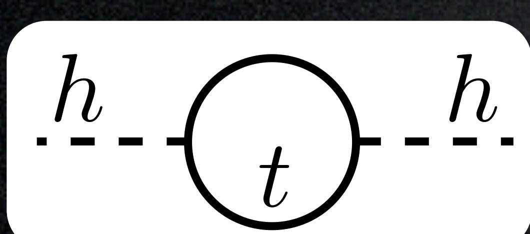

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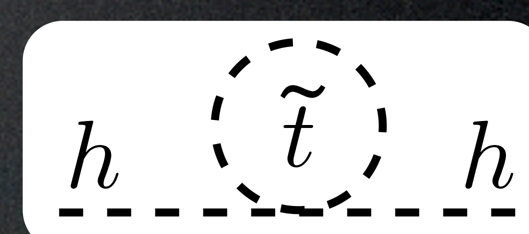
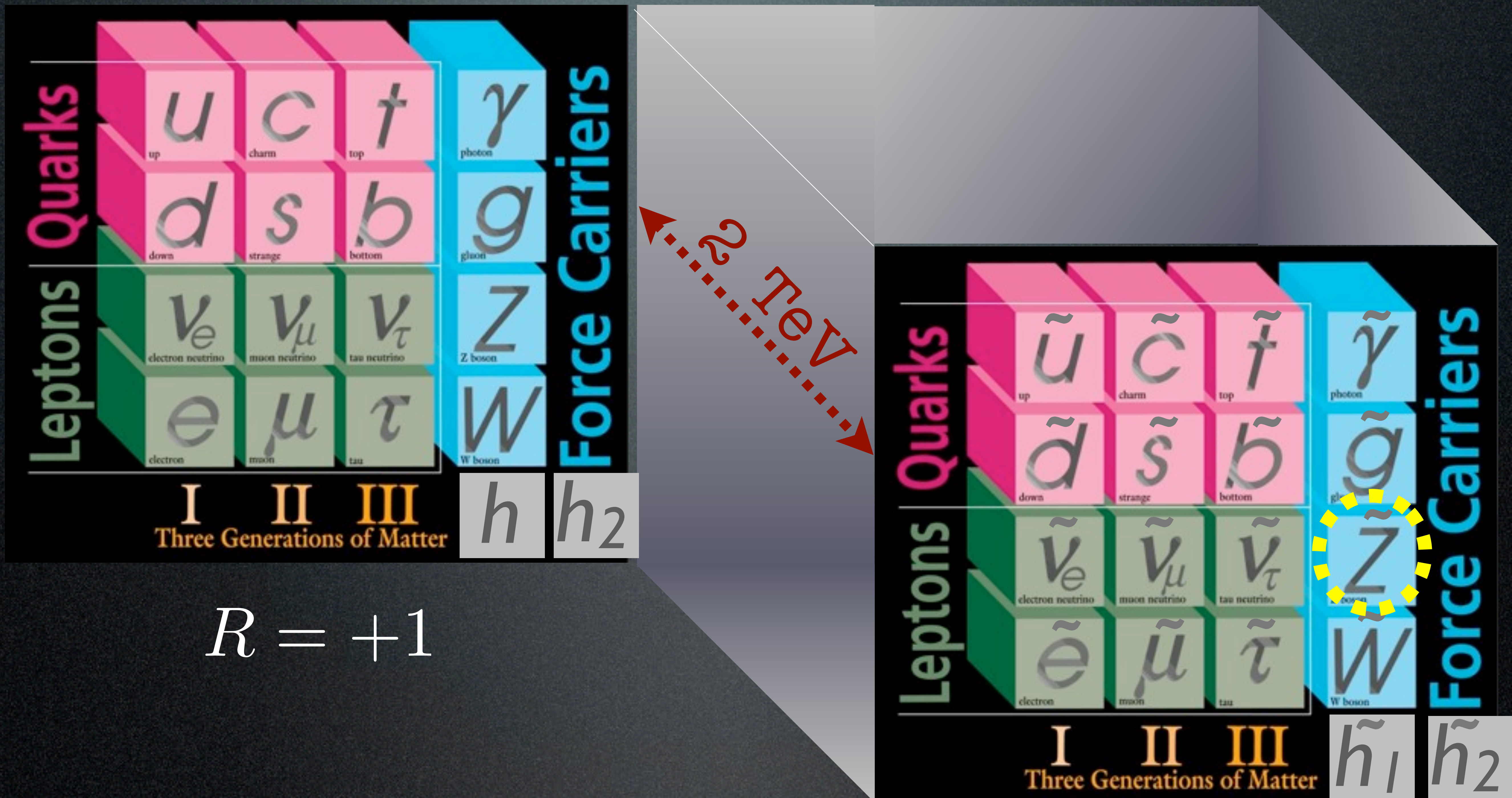


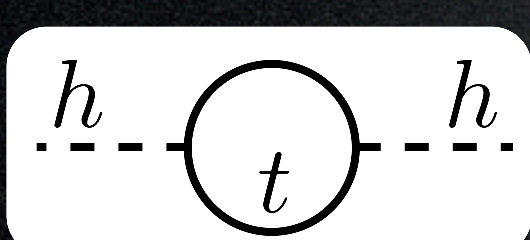
$\Delta m_{\rm h} \propto -10^{19}$ GeV

SuSy DM in 2 minutes



$$R = +1$$

$m_{\mathrm{h}} \approx 150\ \mathrm{GeV}$



$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$

A. Masiero's lecture

DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, **ATIC**, **Fermi**

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

GAPS

$\nu, \bar{\nu}$ from annihil in massive bodies

Icecube, Km3Net

DM detection

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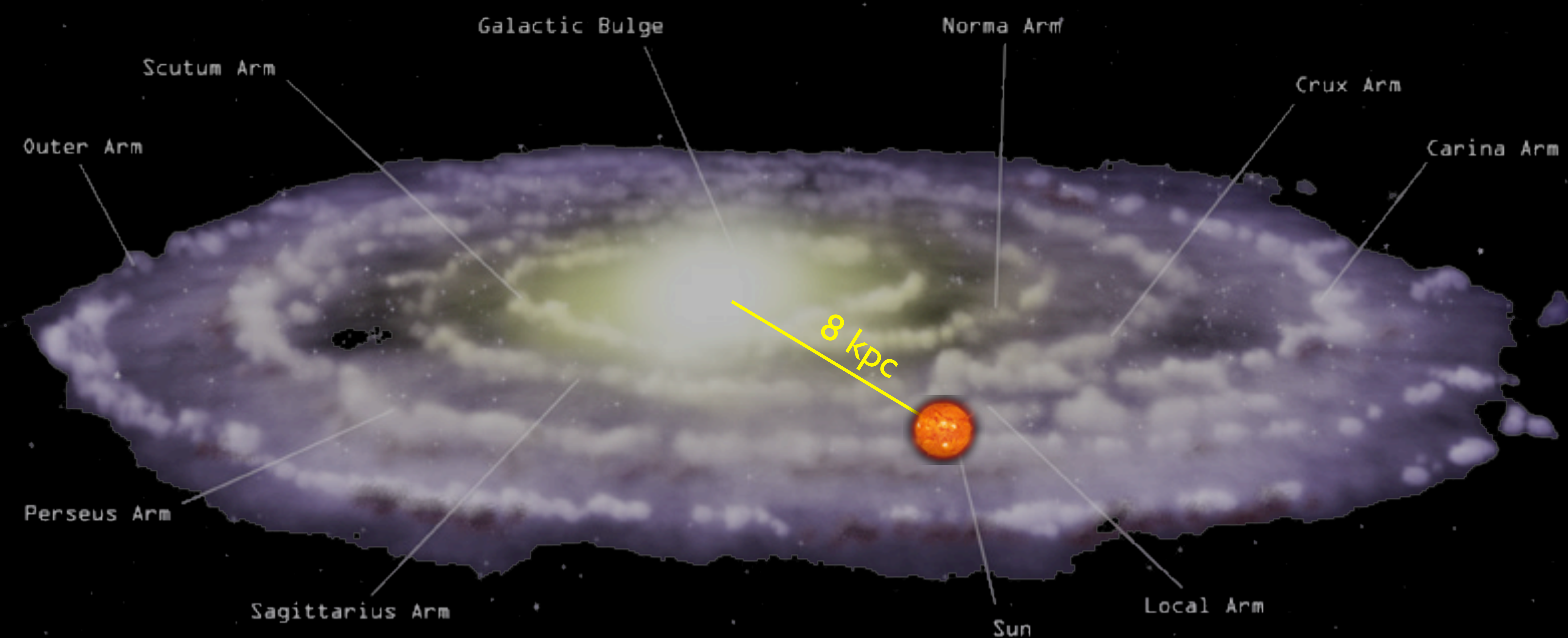
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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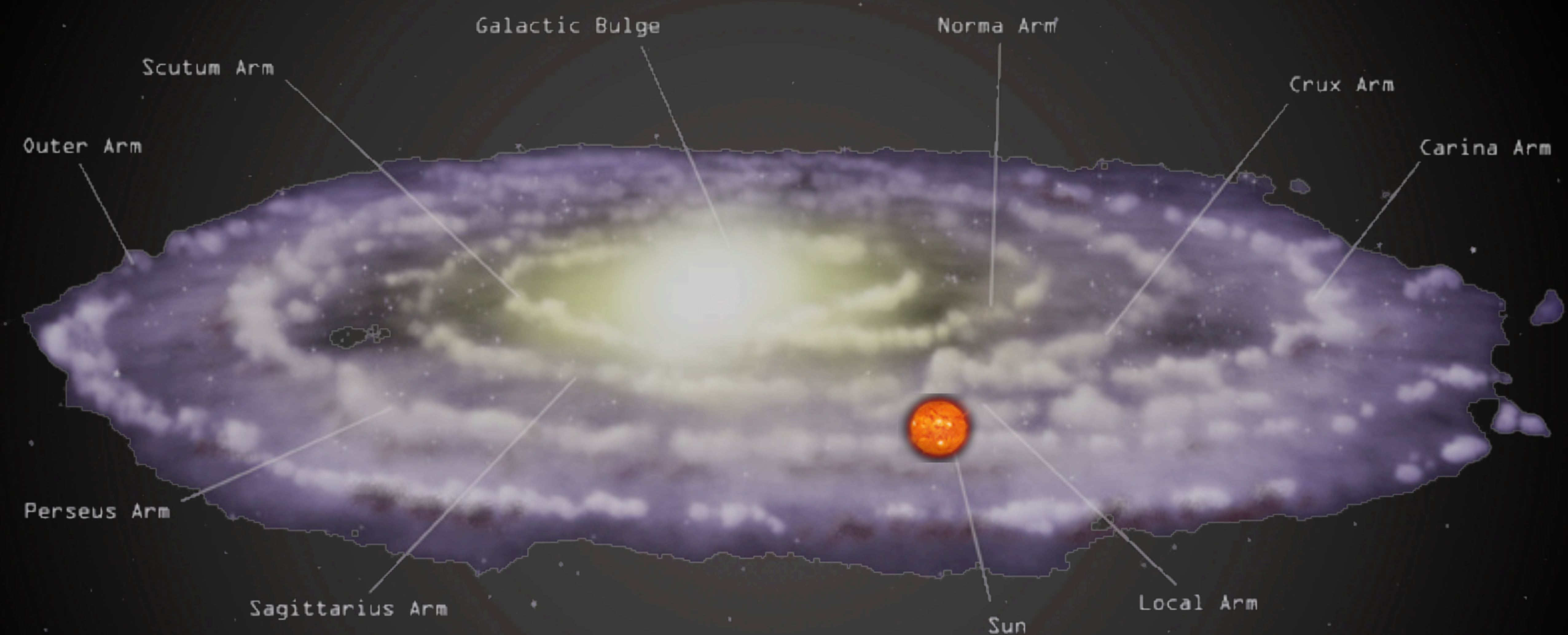

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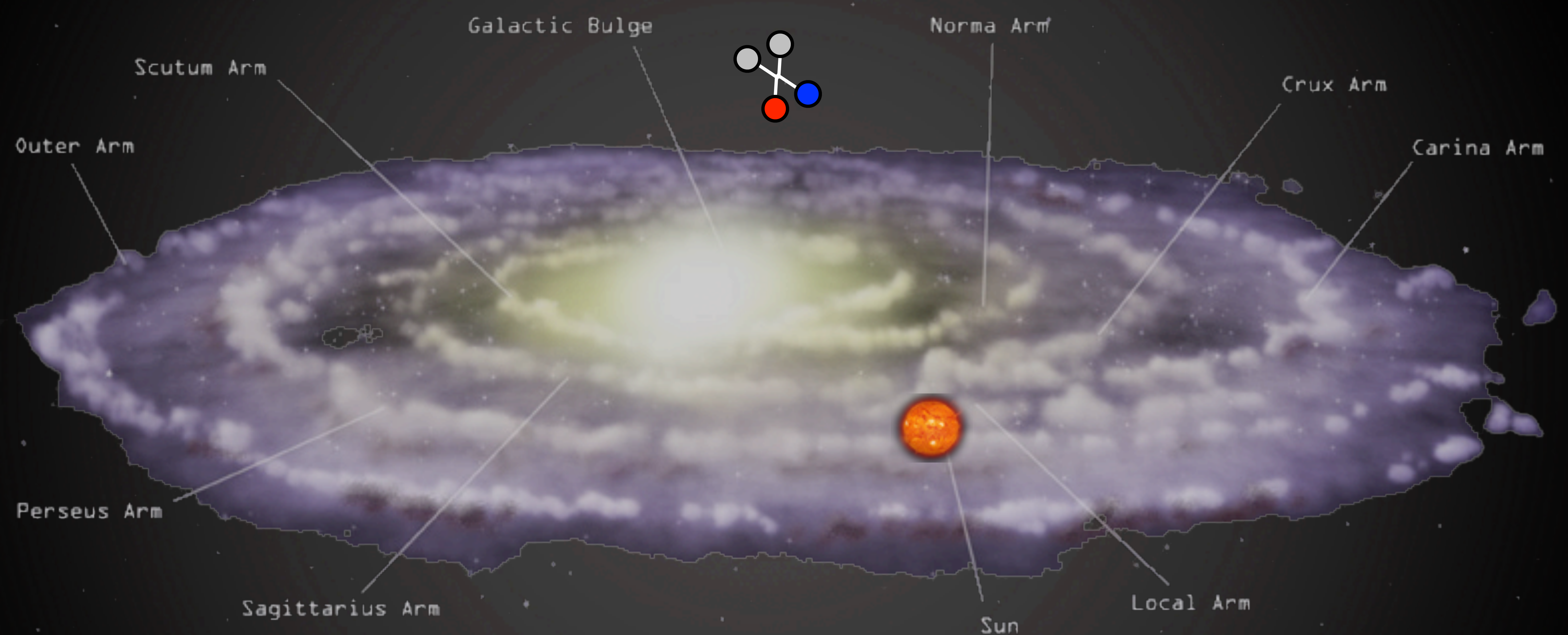

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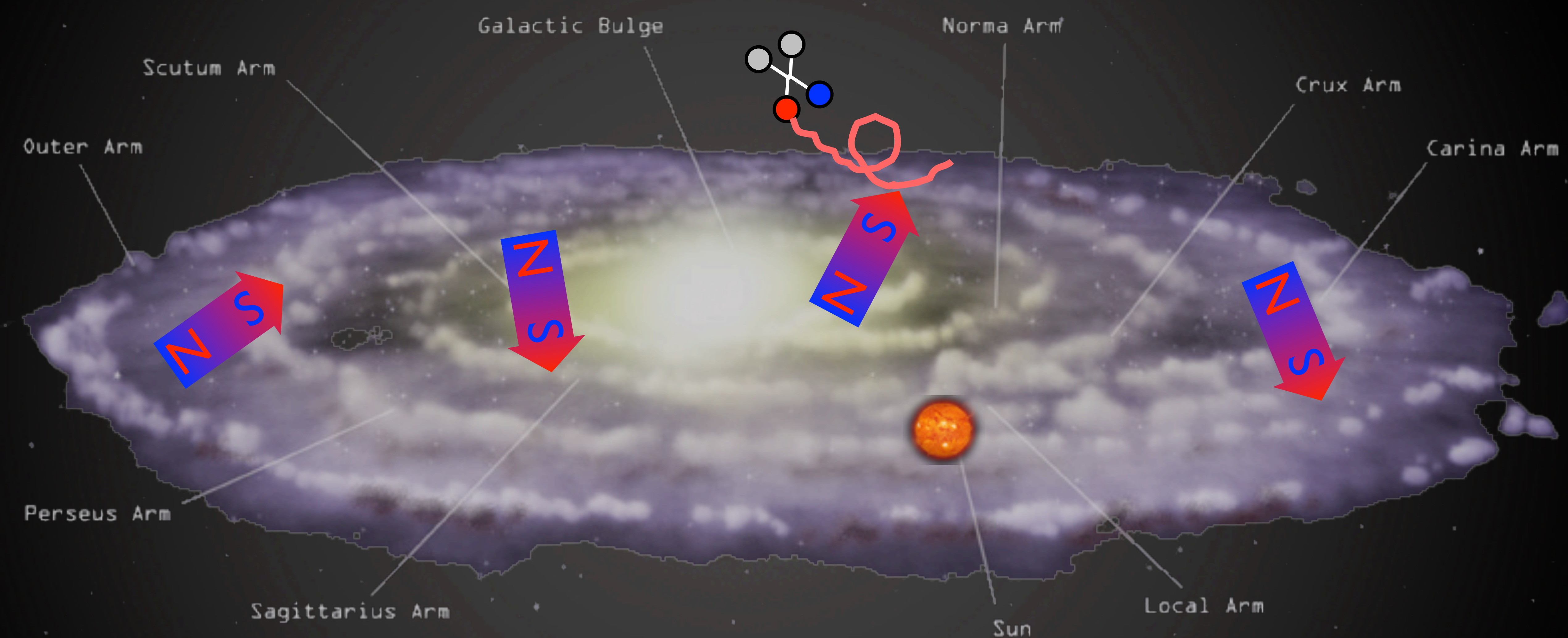

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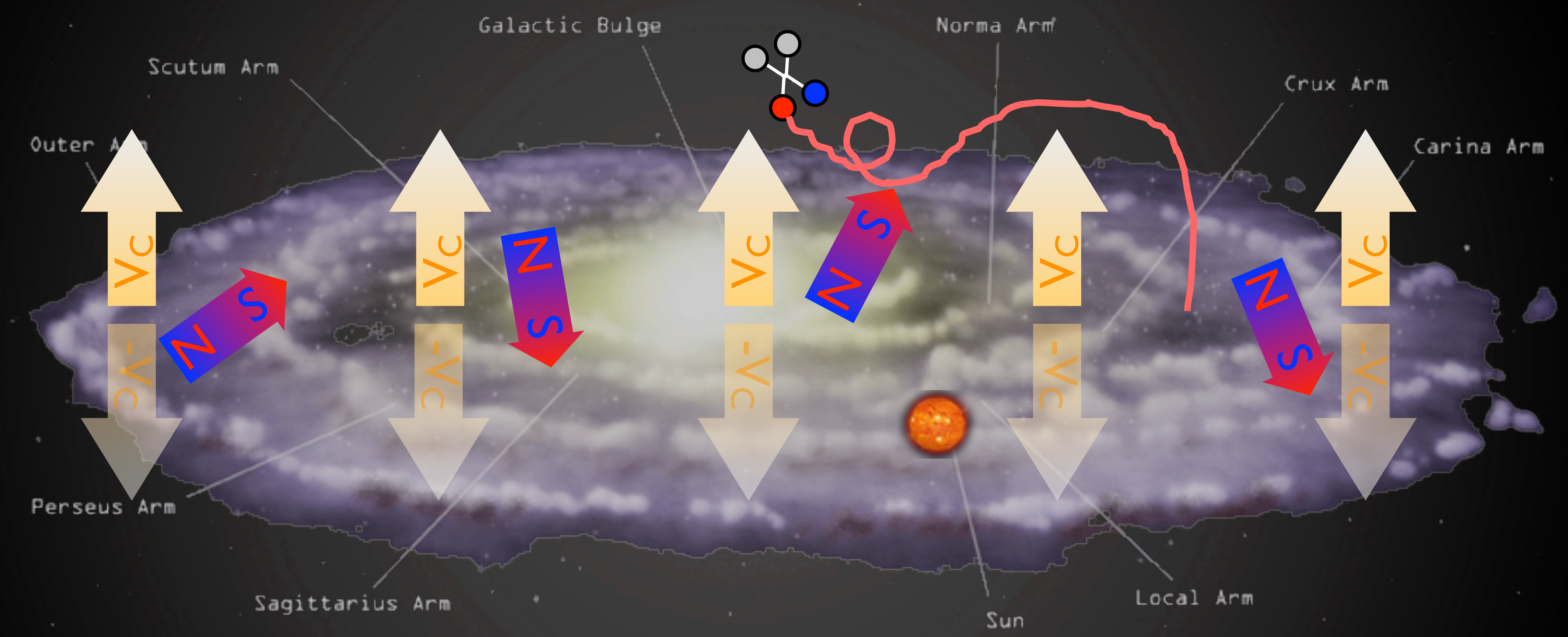

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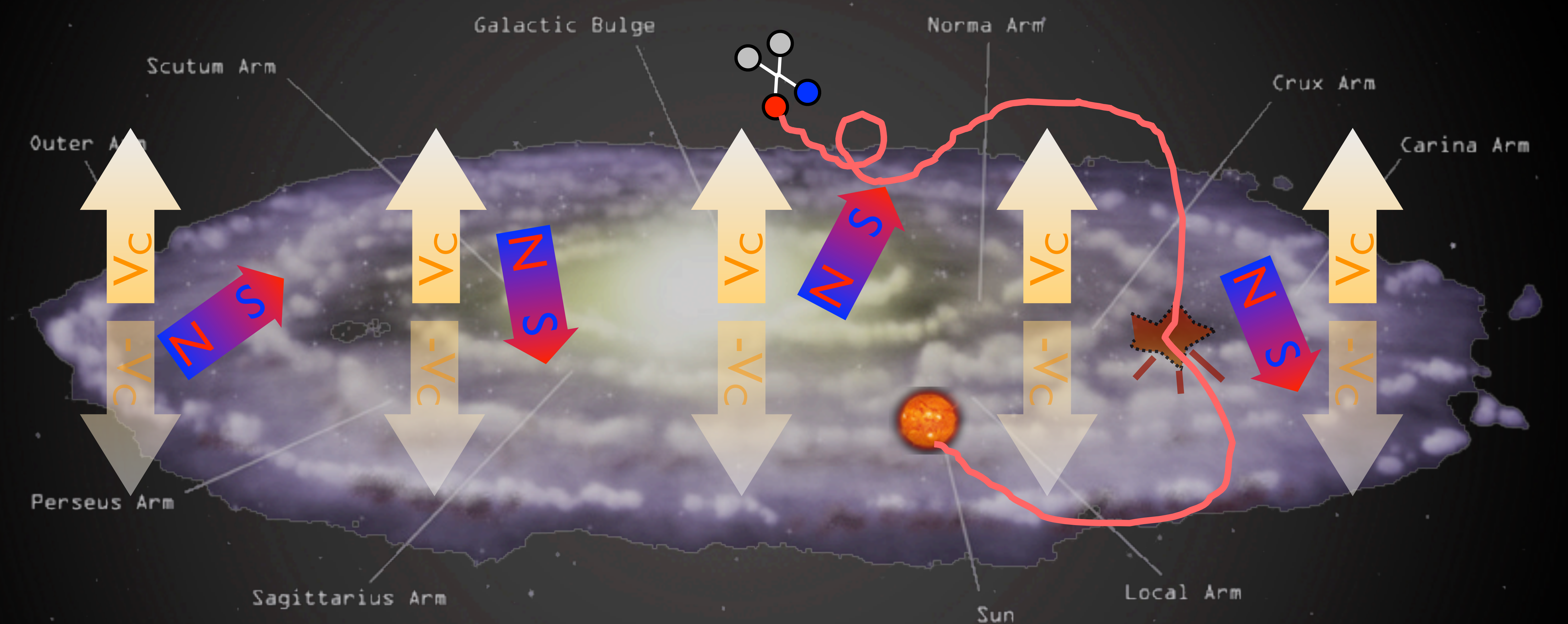

Indirect Detection: basics

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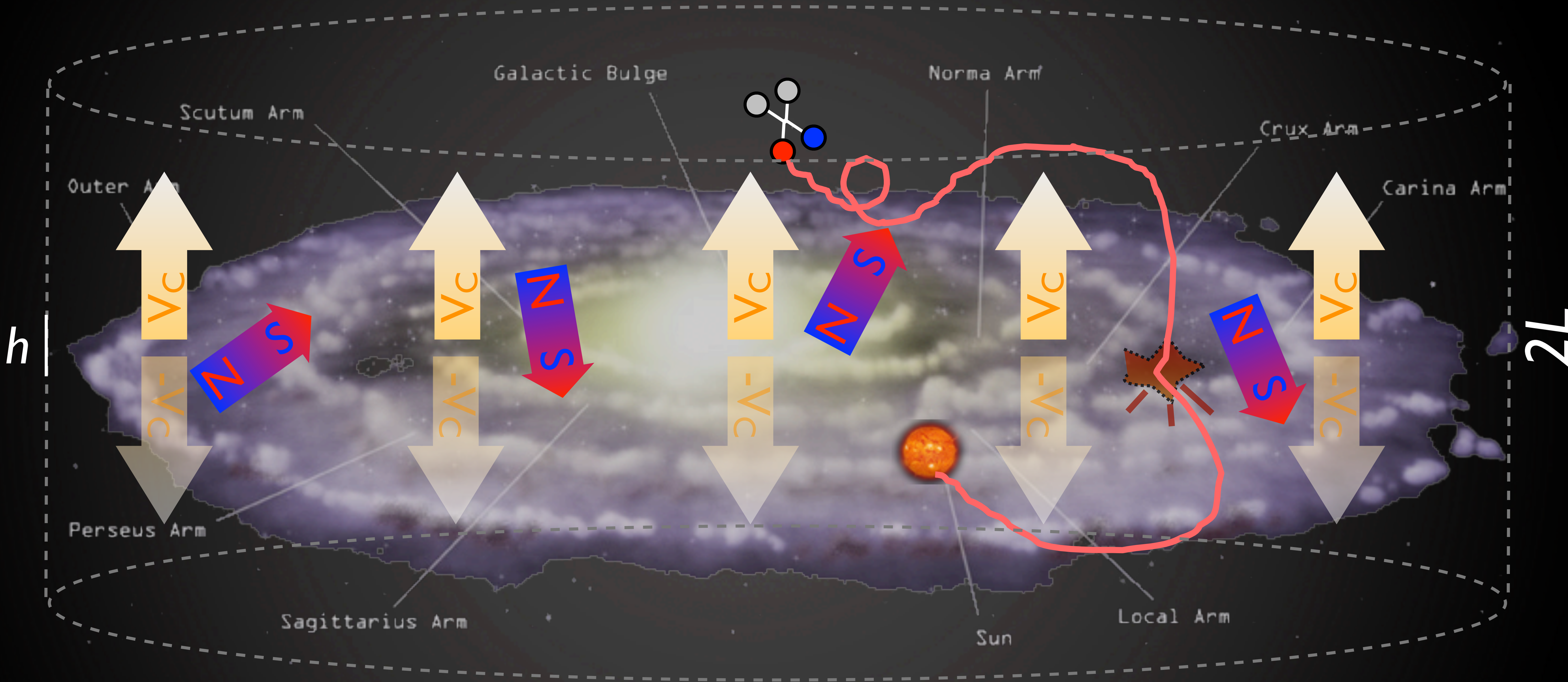


spectrum

$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

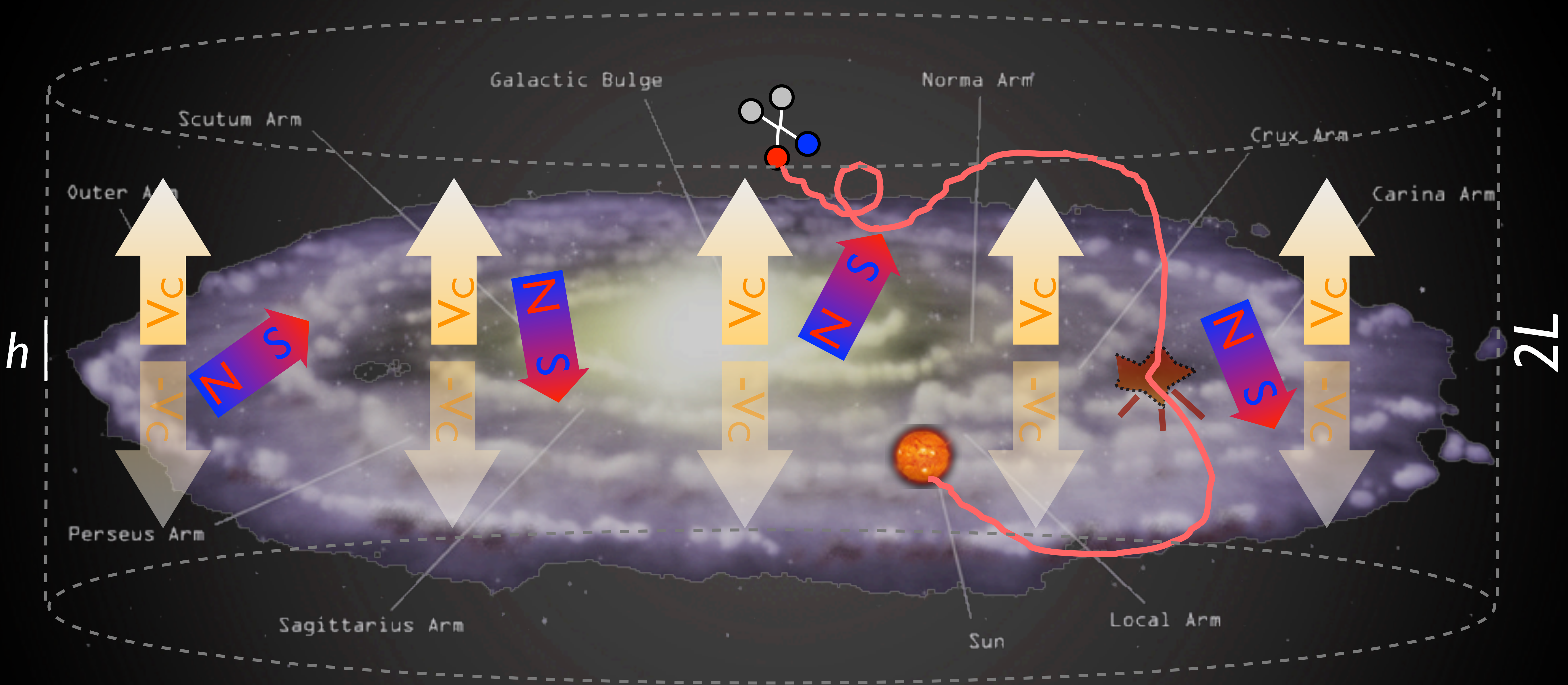
diffusion   energy loss   convective wind   source   spallations

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

[uncert]

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo

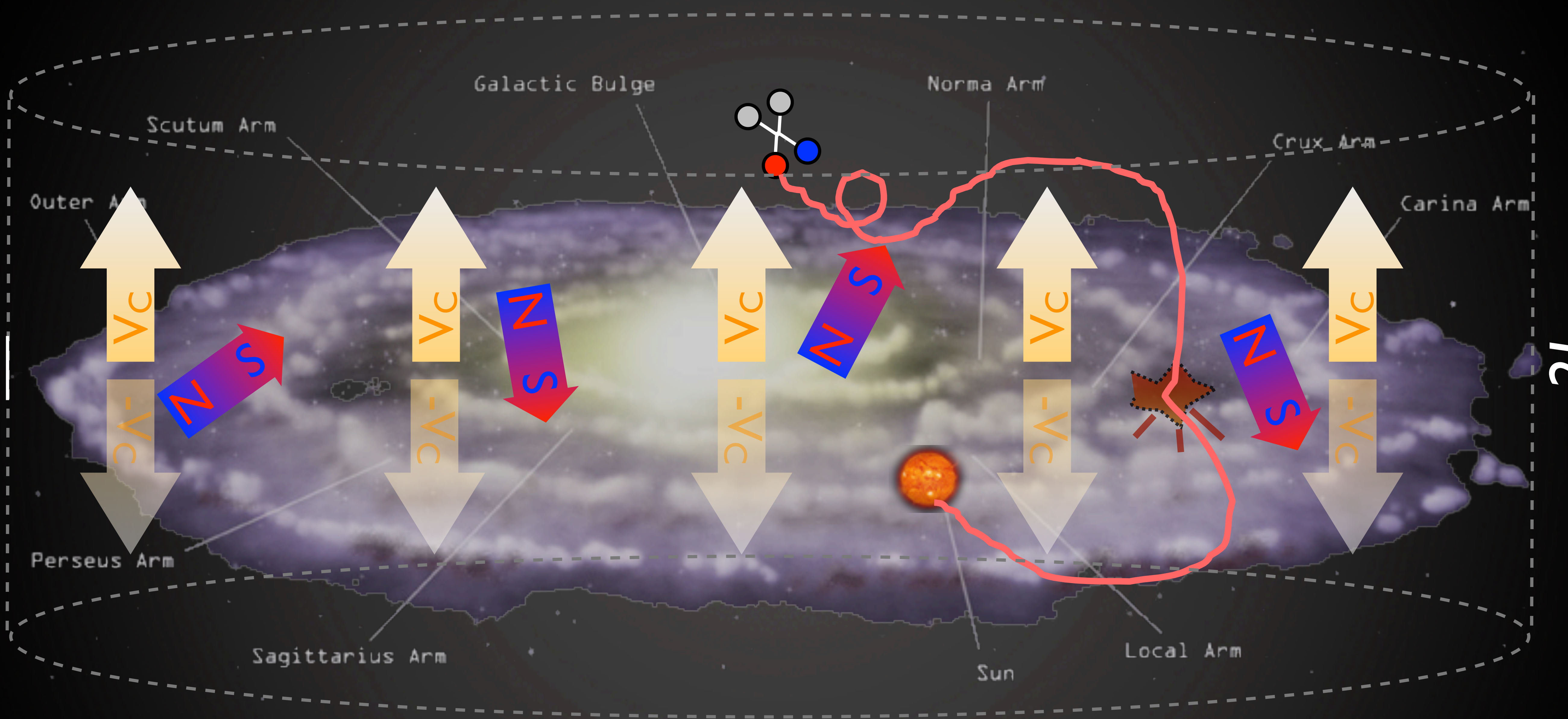


What sets the overall expected flux?

$$\text{flux} \propto n^2\, \sigma_{\text{annihilation}}$$

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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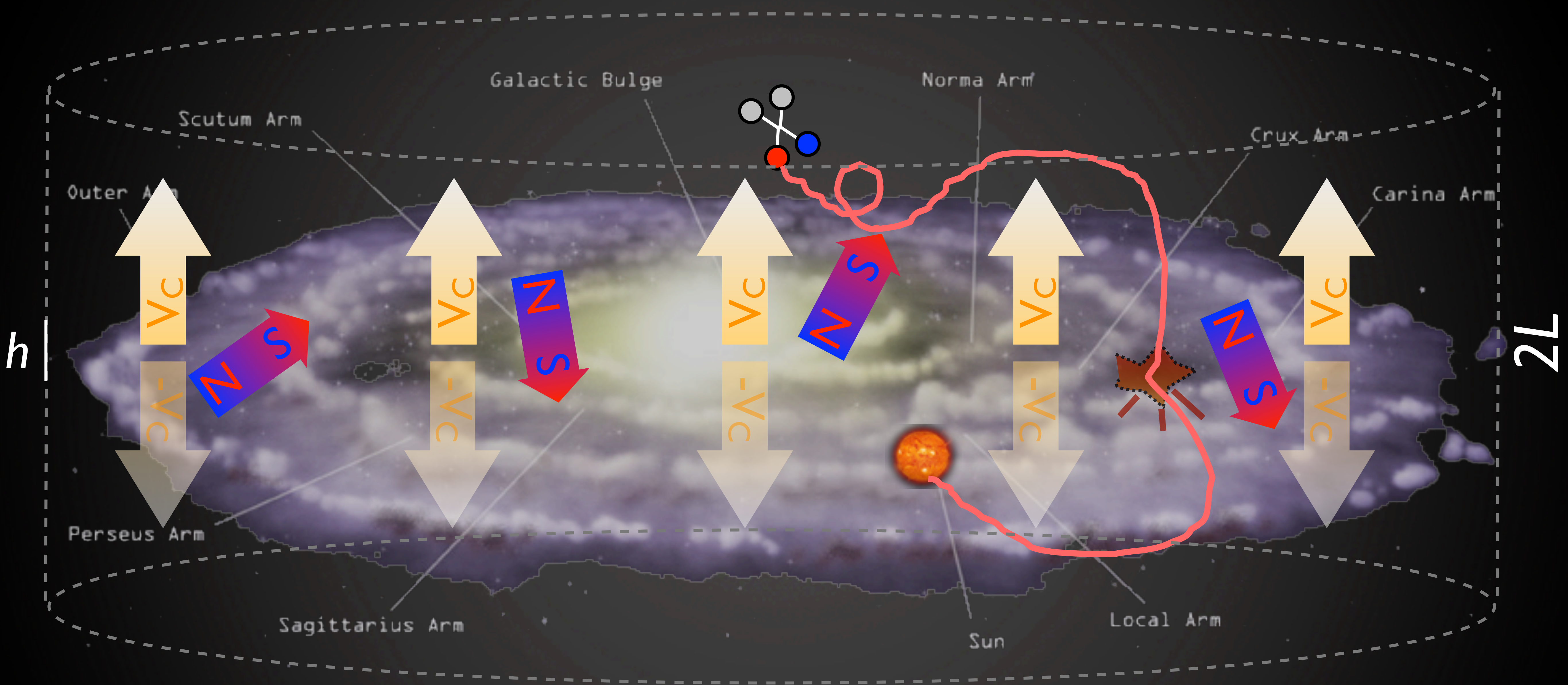
astro& cosmo

particle

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

astro& cosmo

particle

reference cross section:

$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$

DM halo profiles

From N-body numerical simulations:

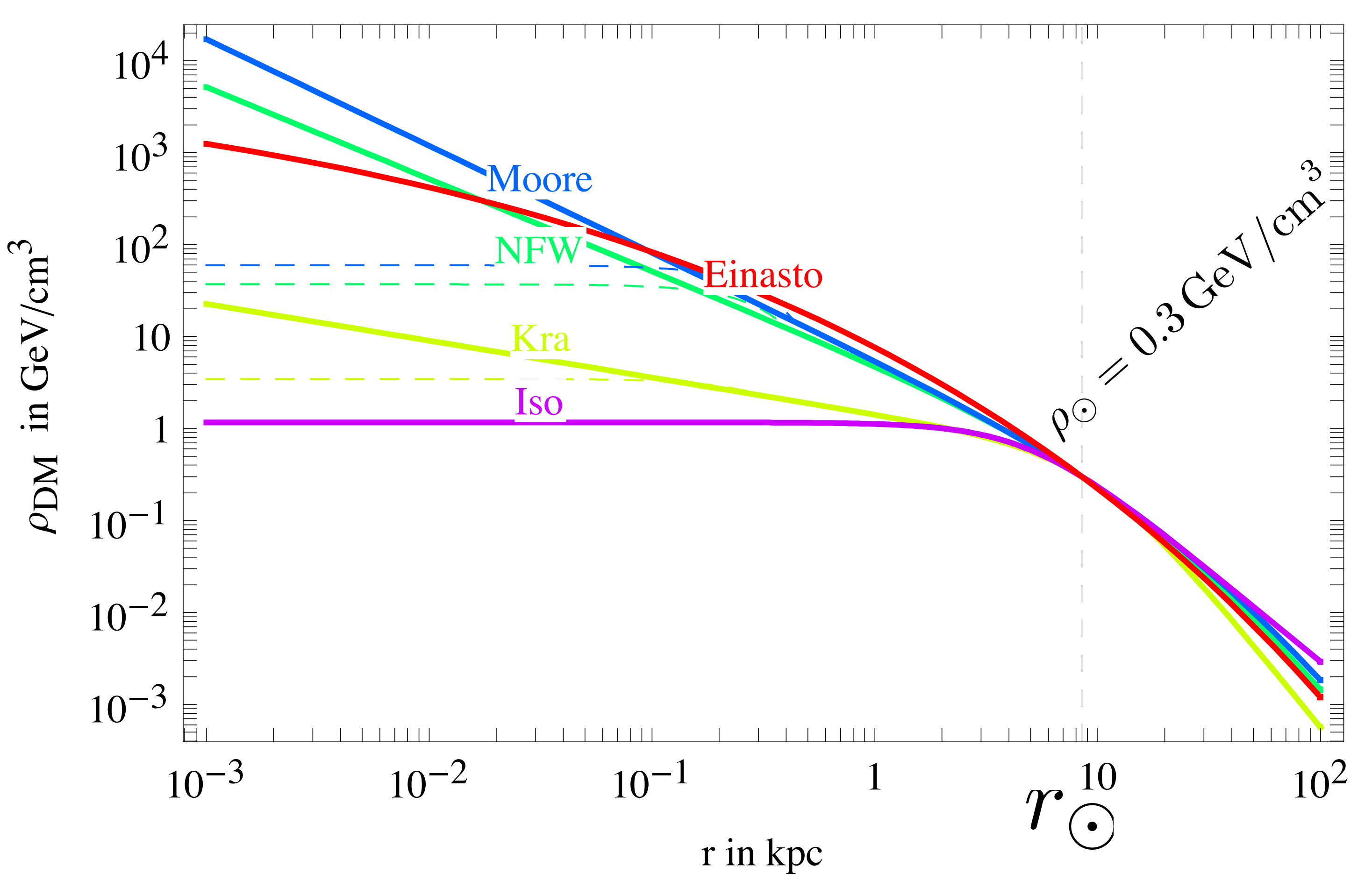
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

At small r: $\rho(r) \propto 1/r^\gamma$

$$\rho(r) = \rho_s \cdot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

Einasto | $\alpha = 0.17$ $r_s = 20\,\text{kpc}$ $\rho_s = 0.06\,\text{GeV/cm}^3$

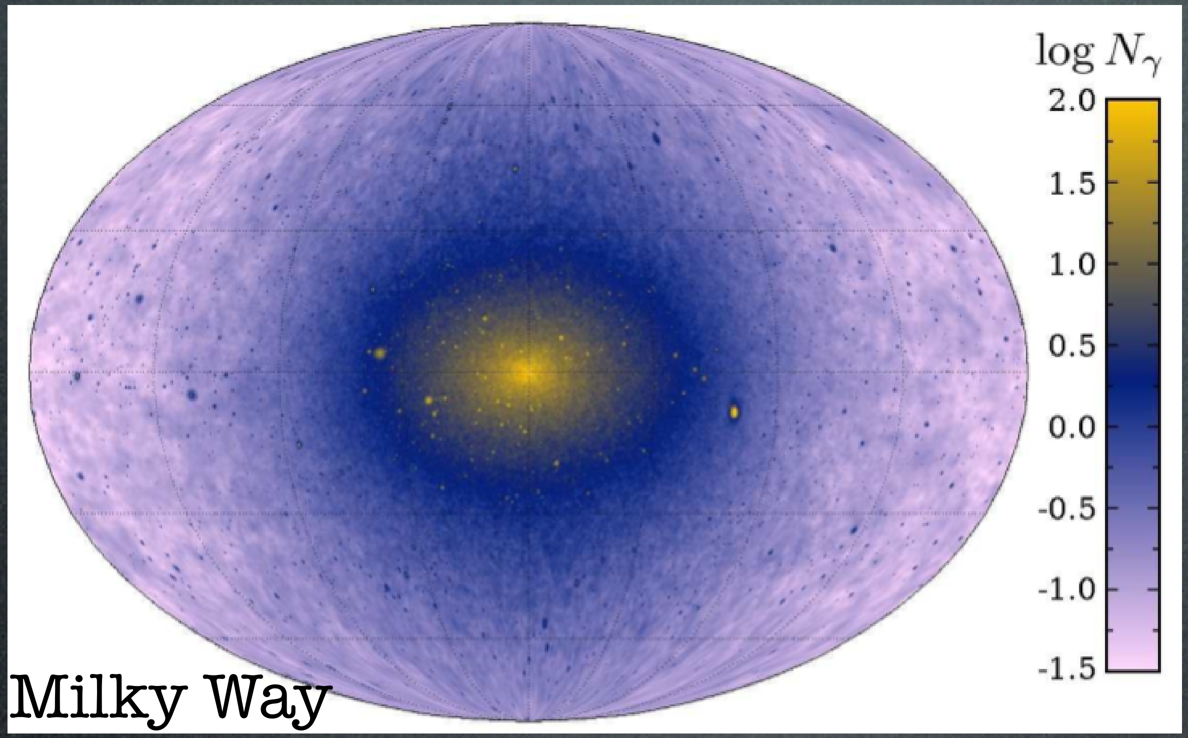


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

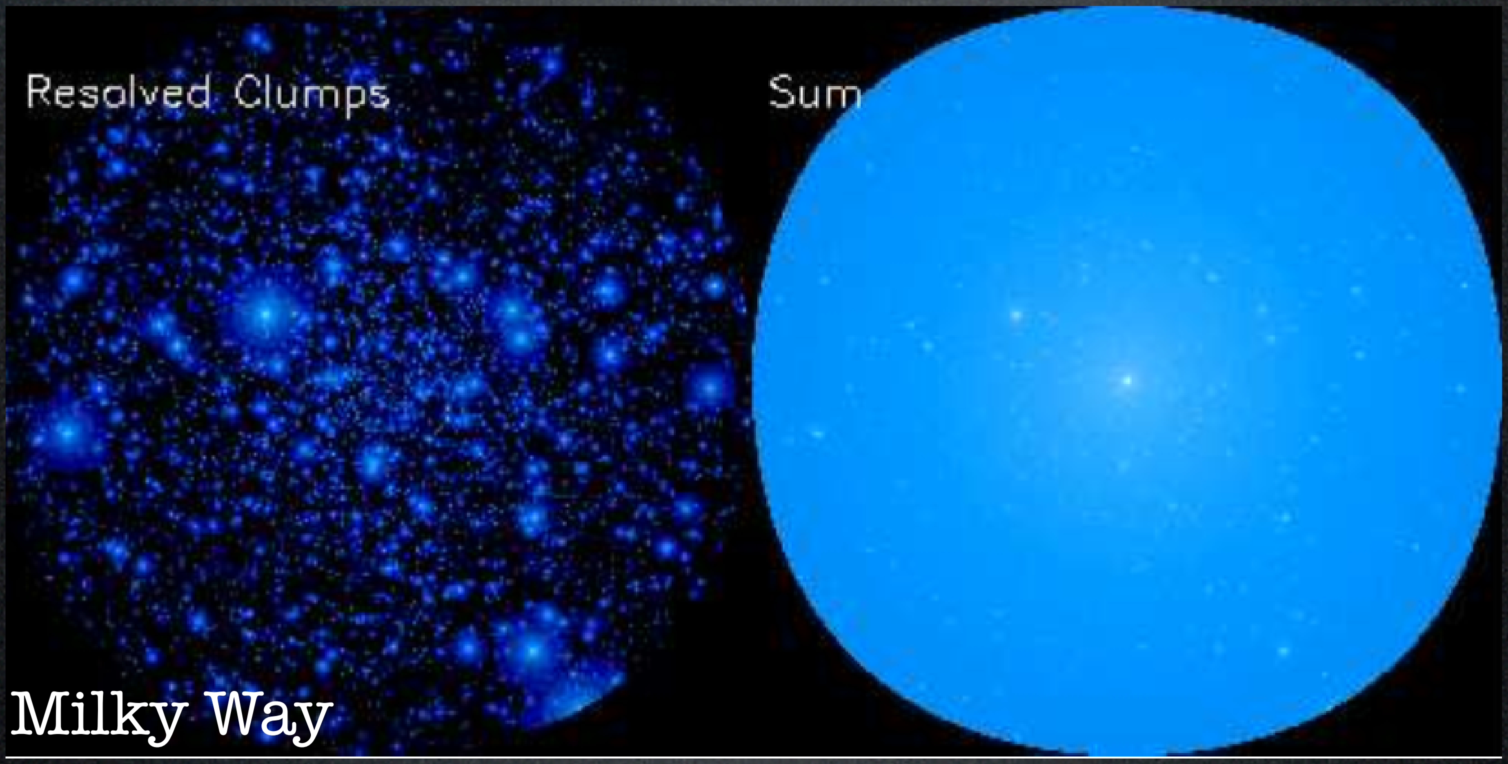
Indirect Detection

Boost Factor: local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: $B \simeq 1 \rightarrow 20$

For illustration:



Kuhlen, Diemand, Madau 2007



Pieri, Bertone, Branchini, MNRAS 384 (2008), 0706.2101

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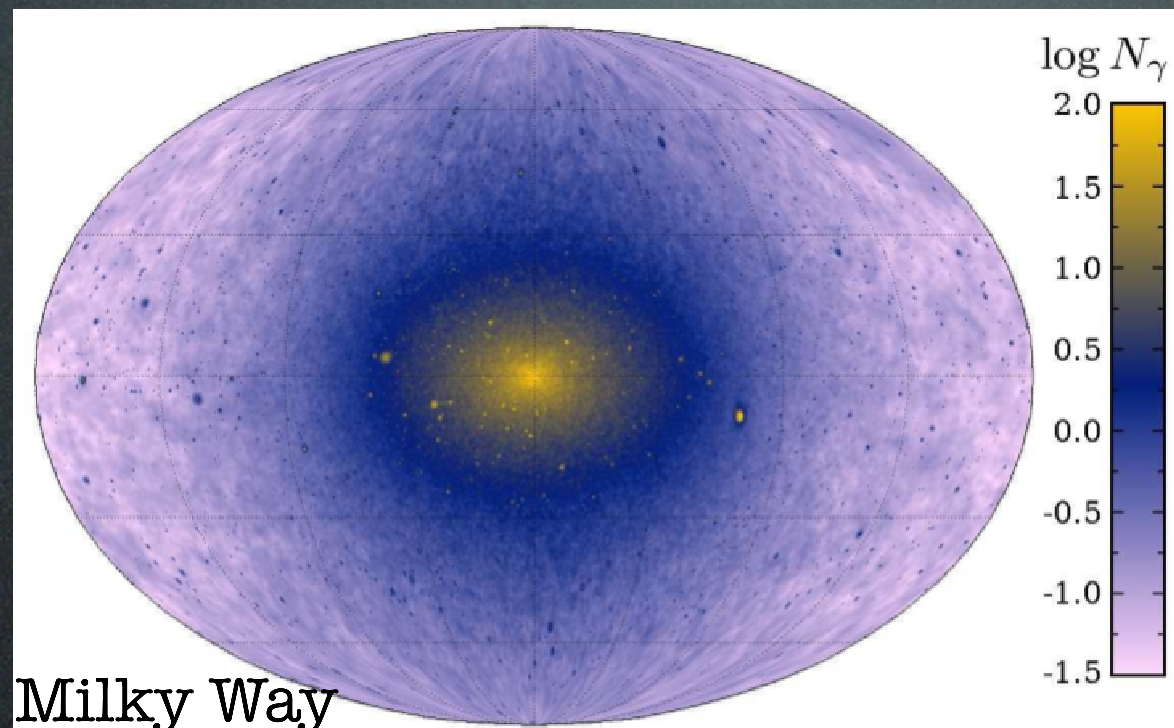
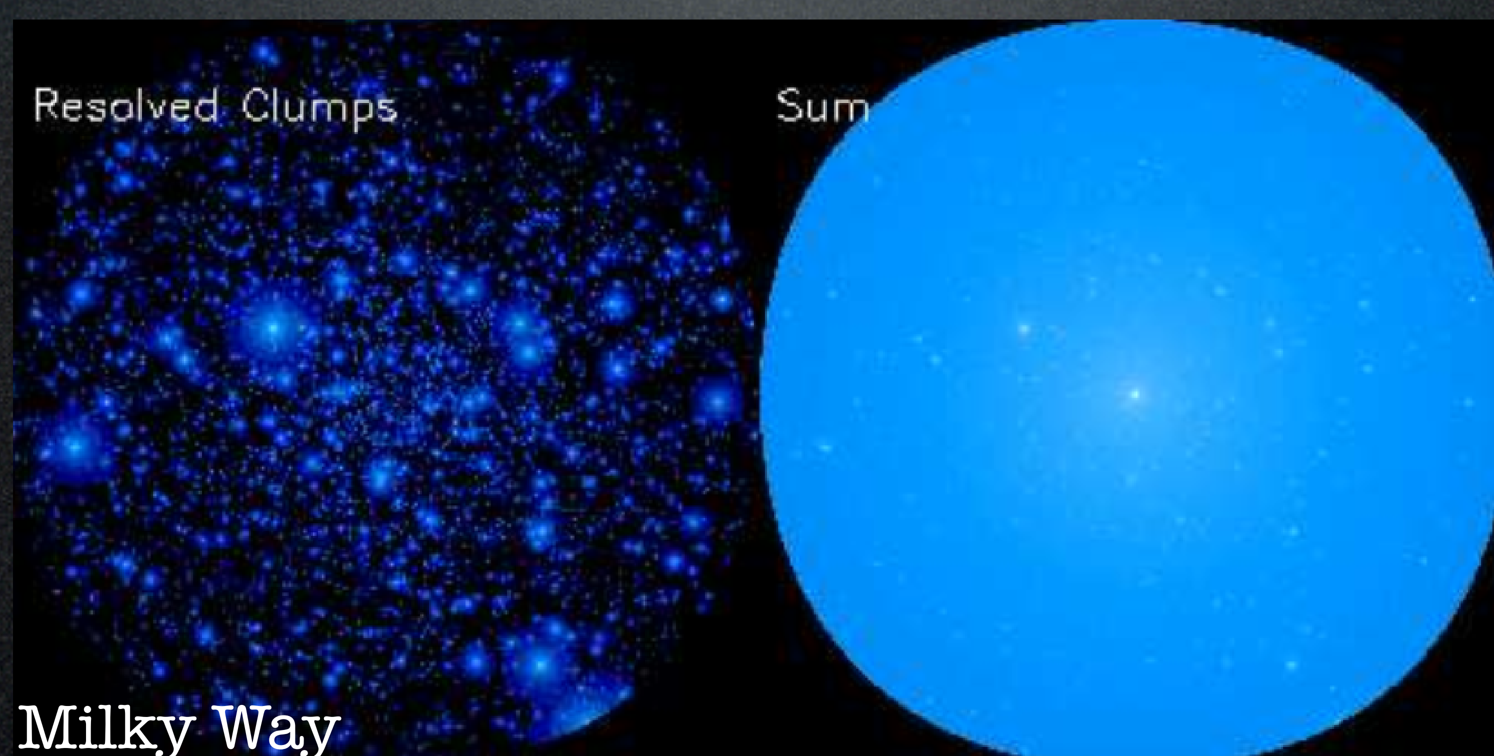


Kuhlen, Diemand, Madau 2007

But: recent simulations seem to show almost no clumps in inner 10 kpc (tidal stripping).

[Millenium Simulation, Carlos Frenk]



Pieri, Bertone, Branchini, MNRAS 384 (2008), 0706.2101

DM detection

direct detection

production at colliders

indirect

- γ from annihil in galactic center or halo and from synchrotron emission
  Fermi, HESS, radio telescopes
- e^+ from annihil in galactic halo or center
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- $\bar{p}$ from annihil in galactic halo or center
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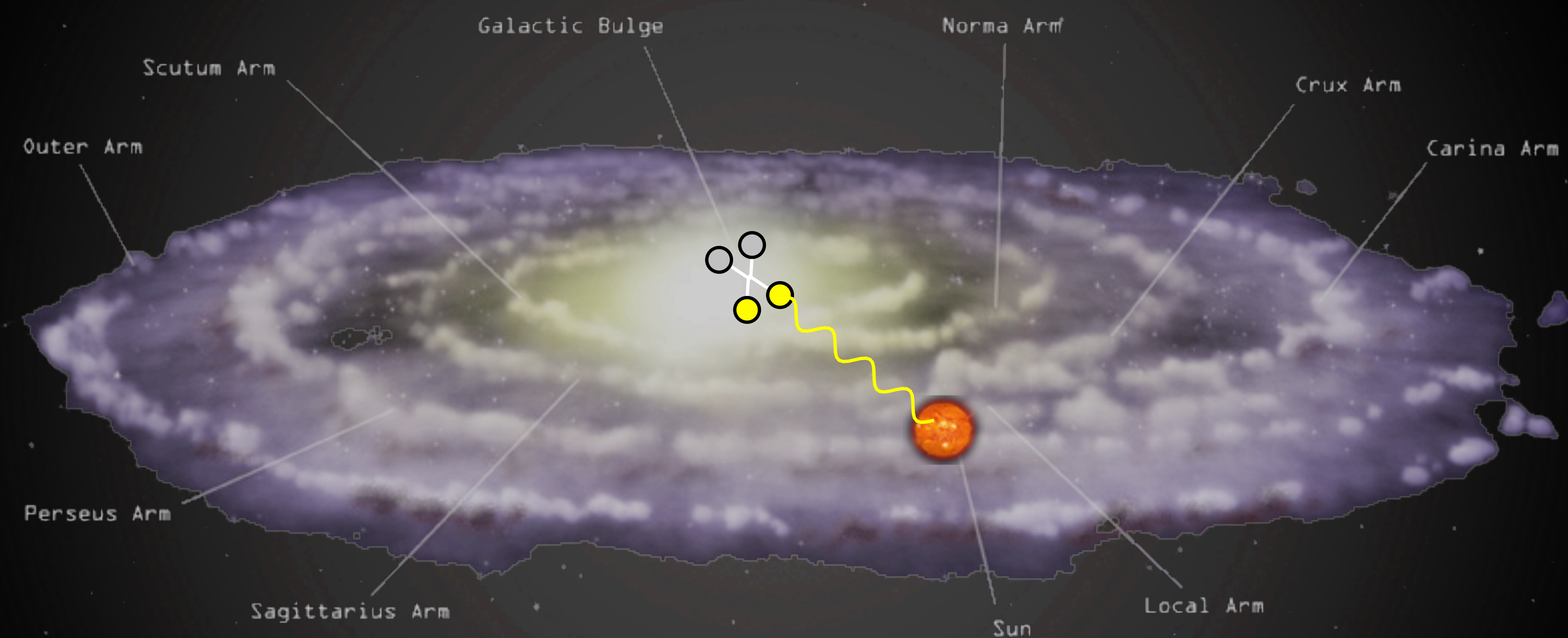
- $\nu, \bar{\nu}$ from annihil in massive bodies

Indirect Detection: constraints

γ from DM annihilations in galactic center



DM

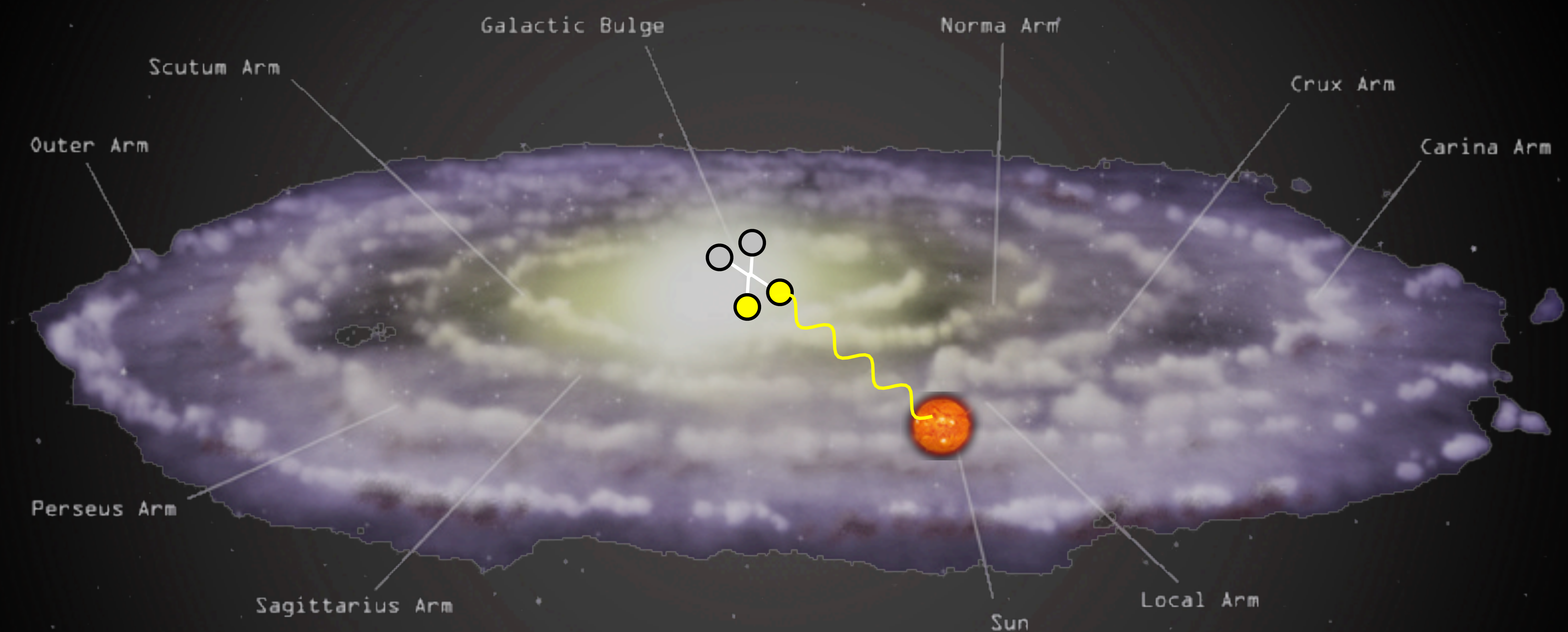
DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

Indirect Detection: constraints

a. γ from DM annihilations in galactic center



DM

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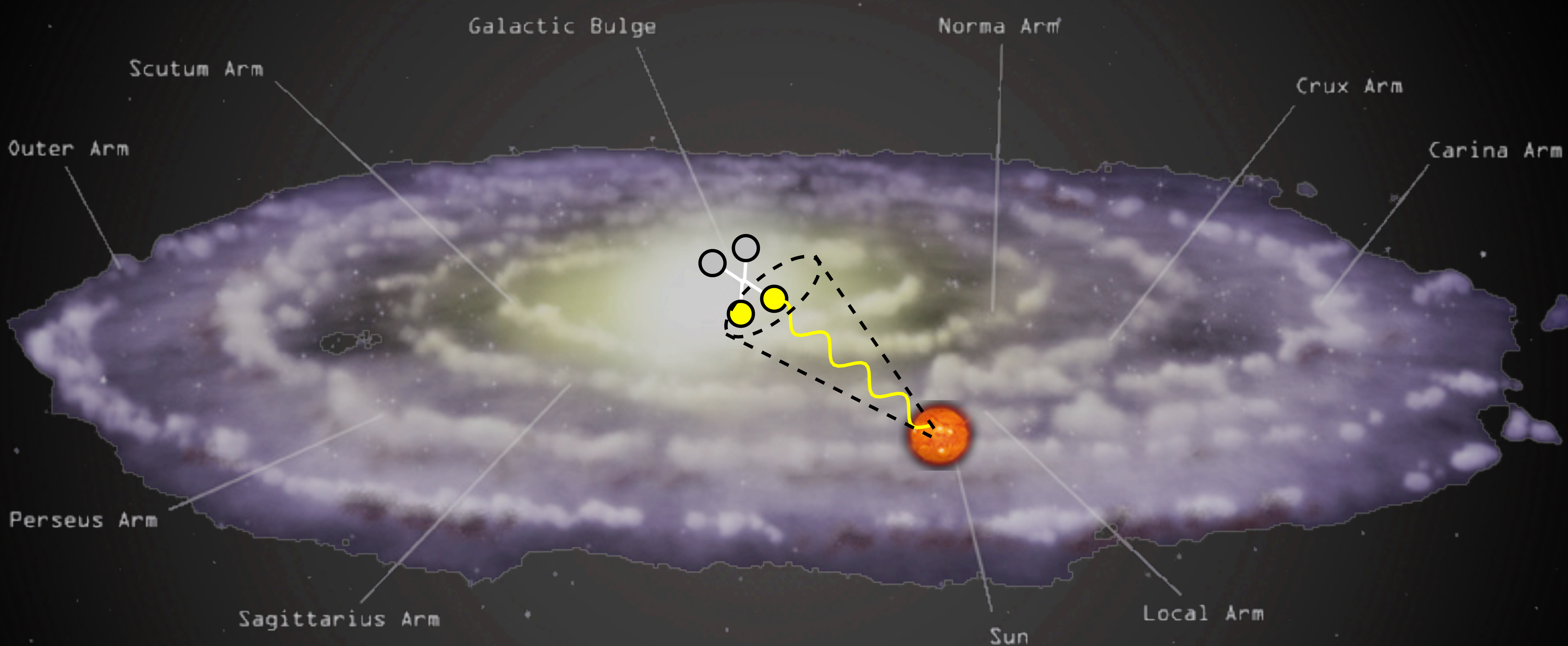

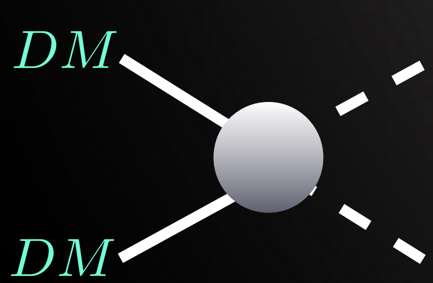

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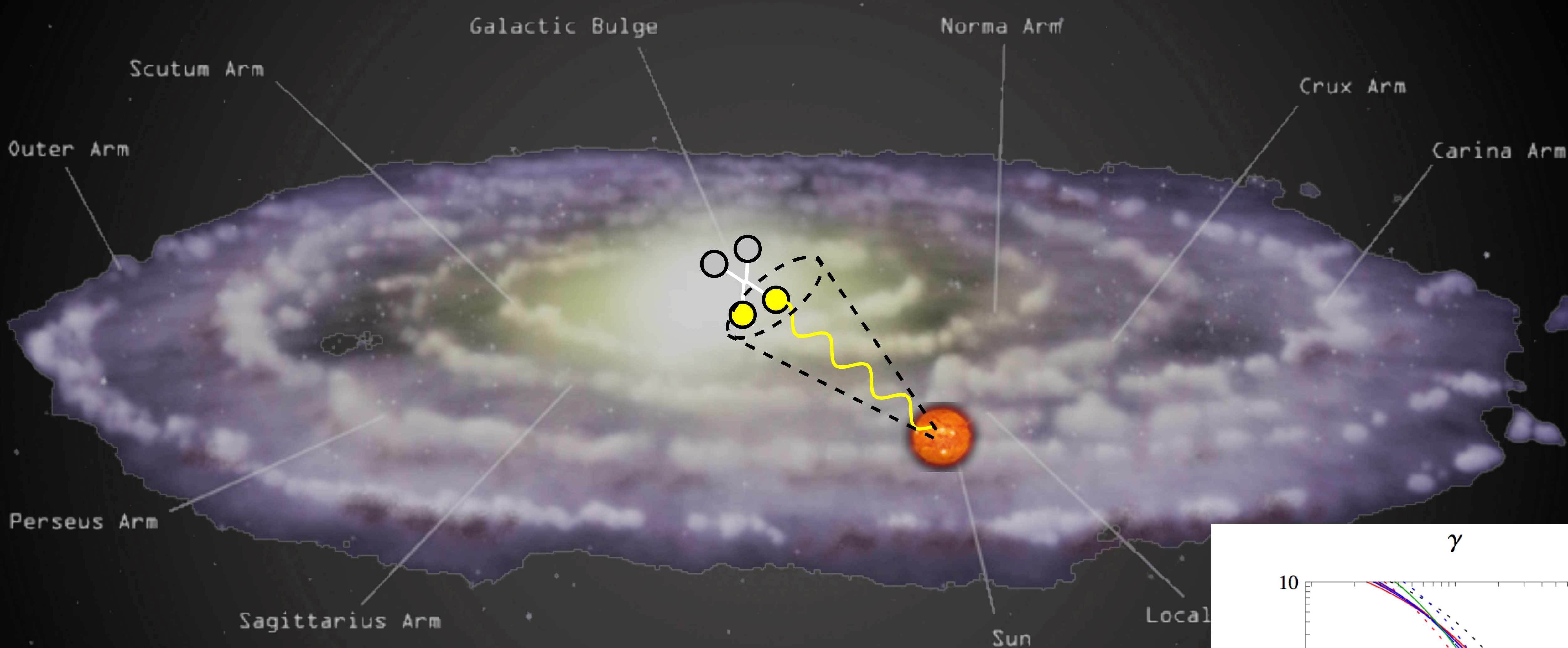

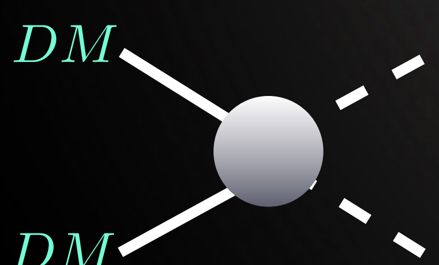

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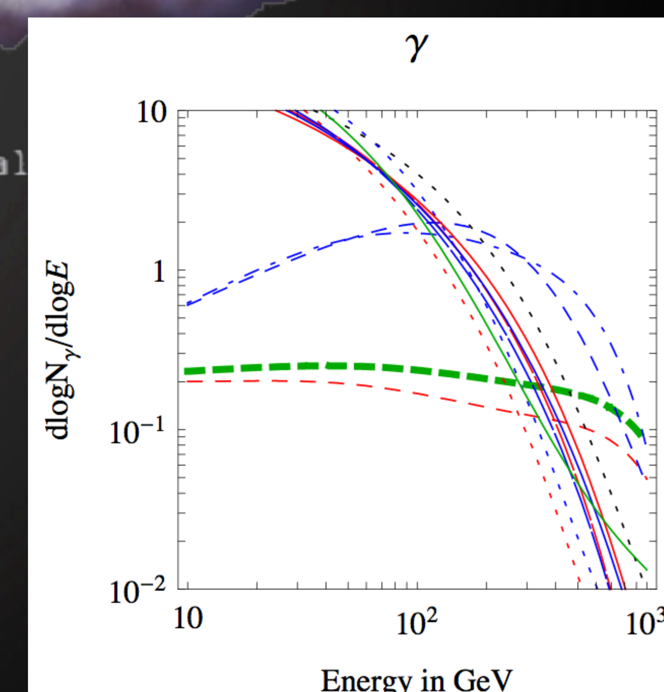
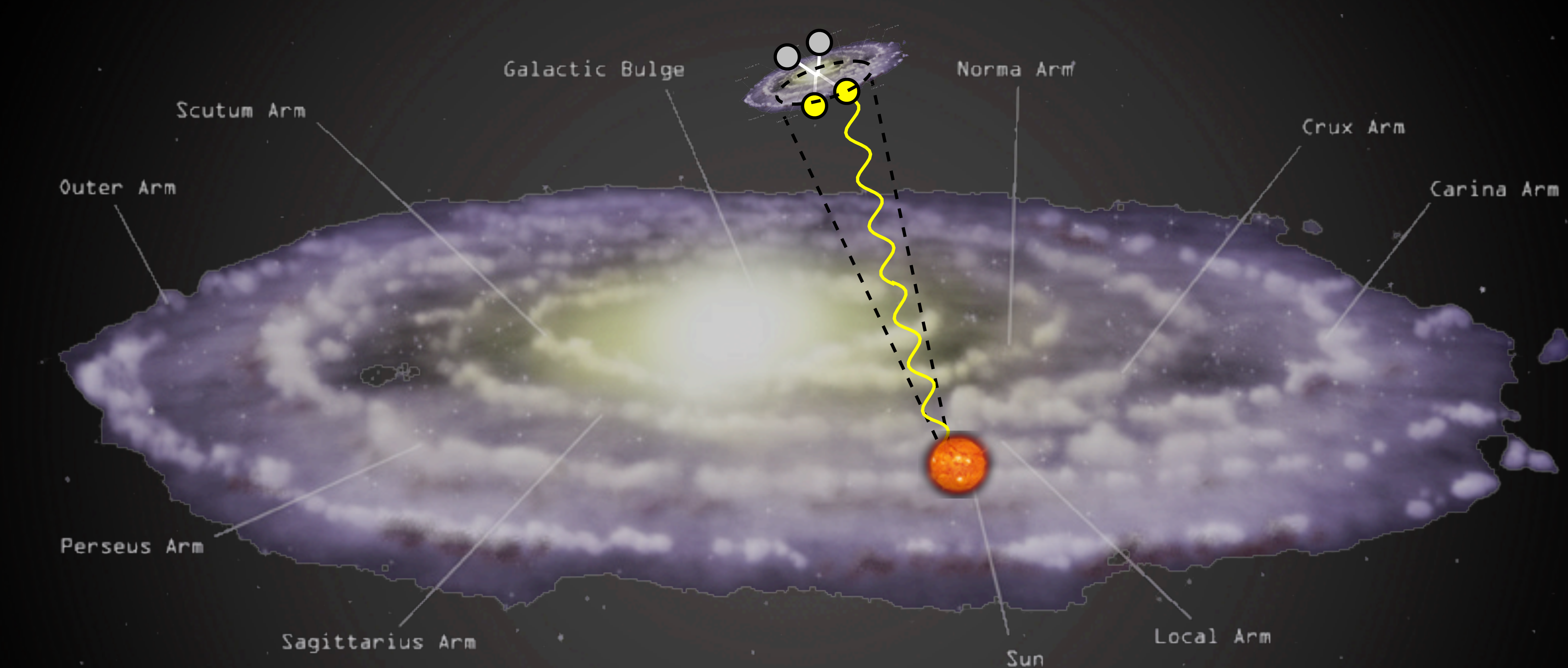
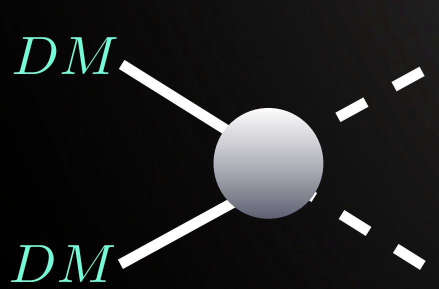


typically sub-TeV energies

Indirect Detection: constraints

b. γ from DM annihilations in Sagittarius Dwarf





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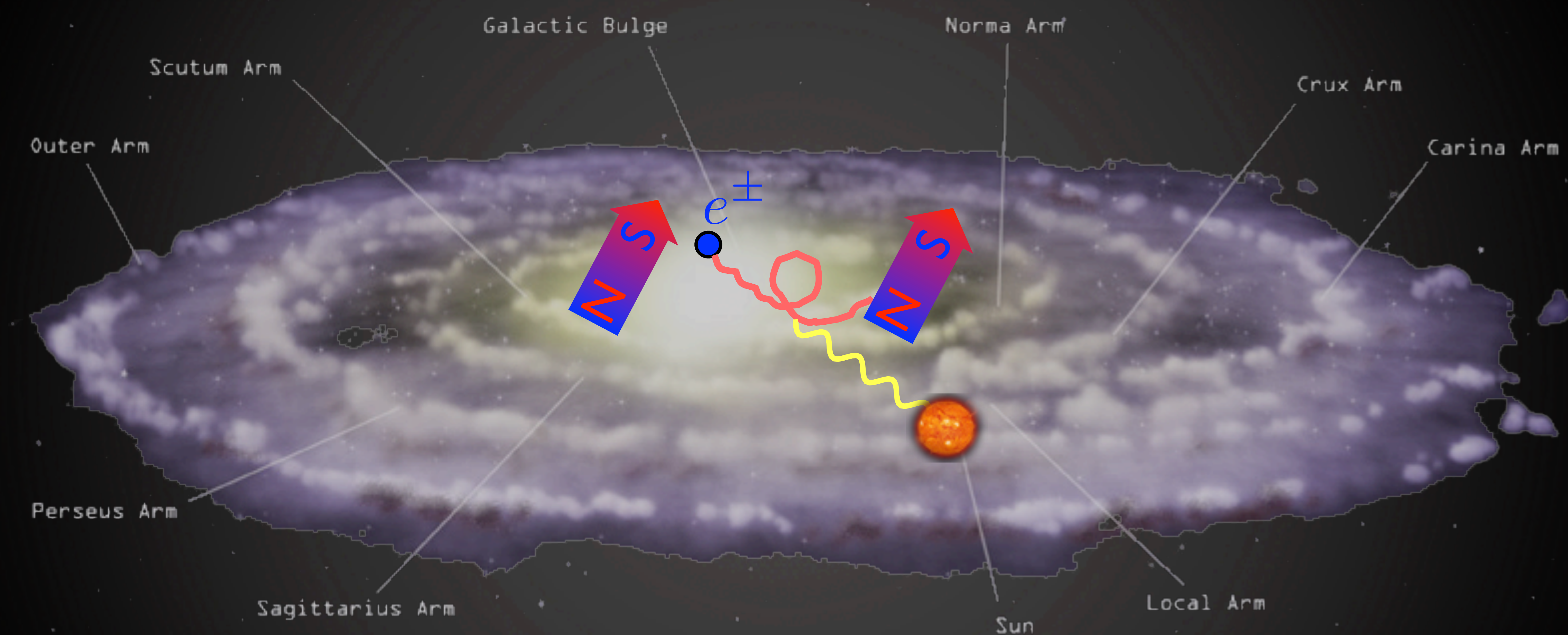
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

Indirect Detection: constraints

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



Indirect Detection: constraints

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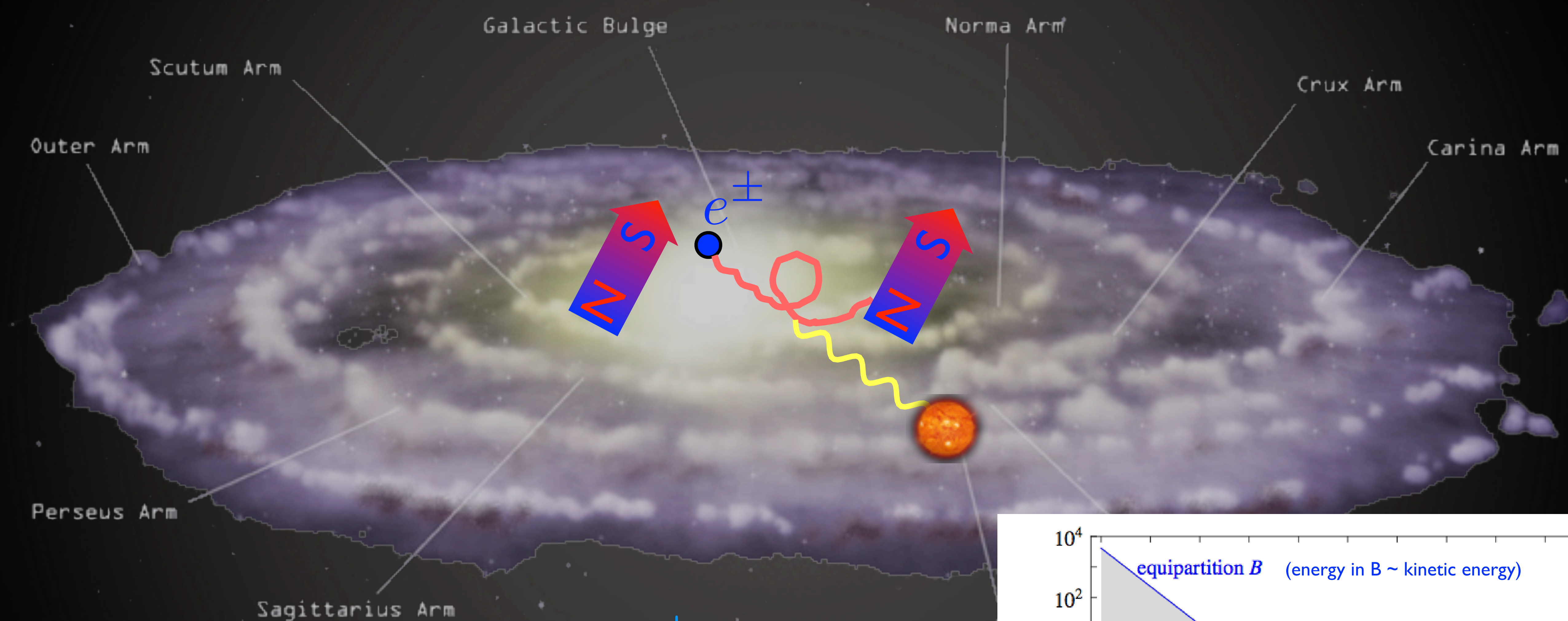
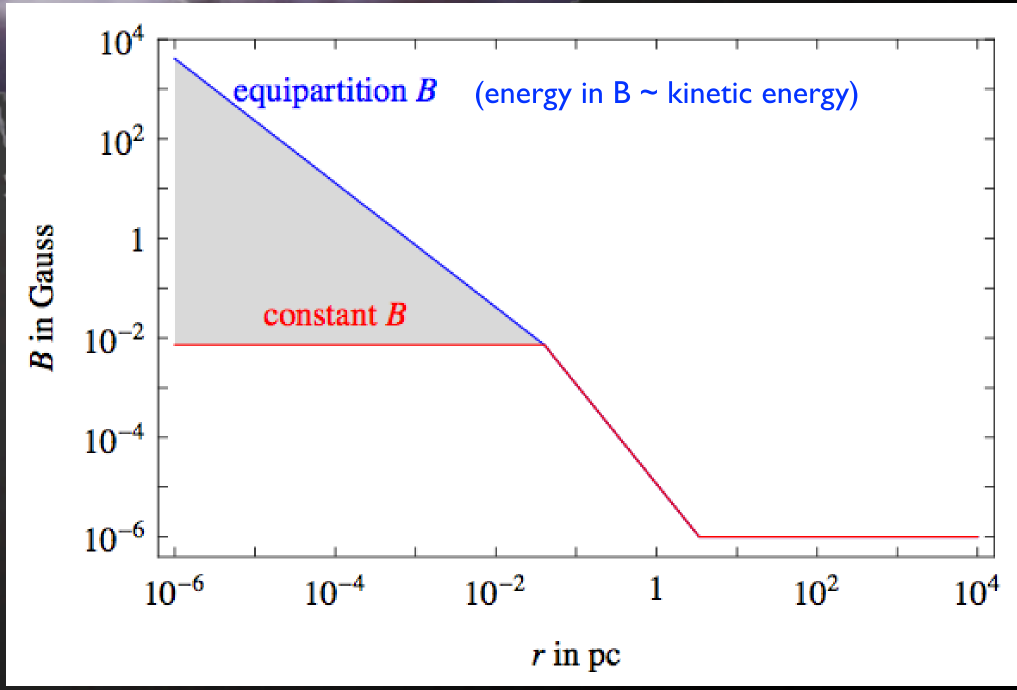


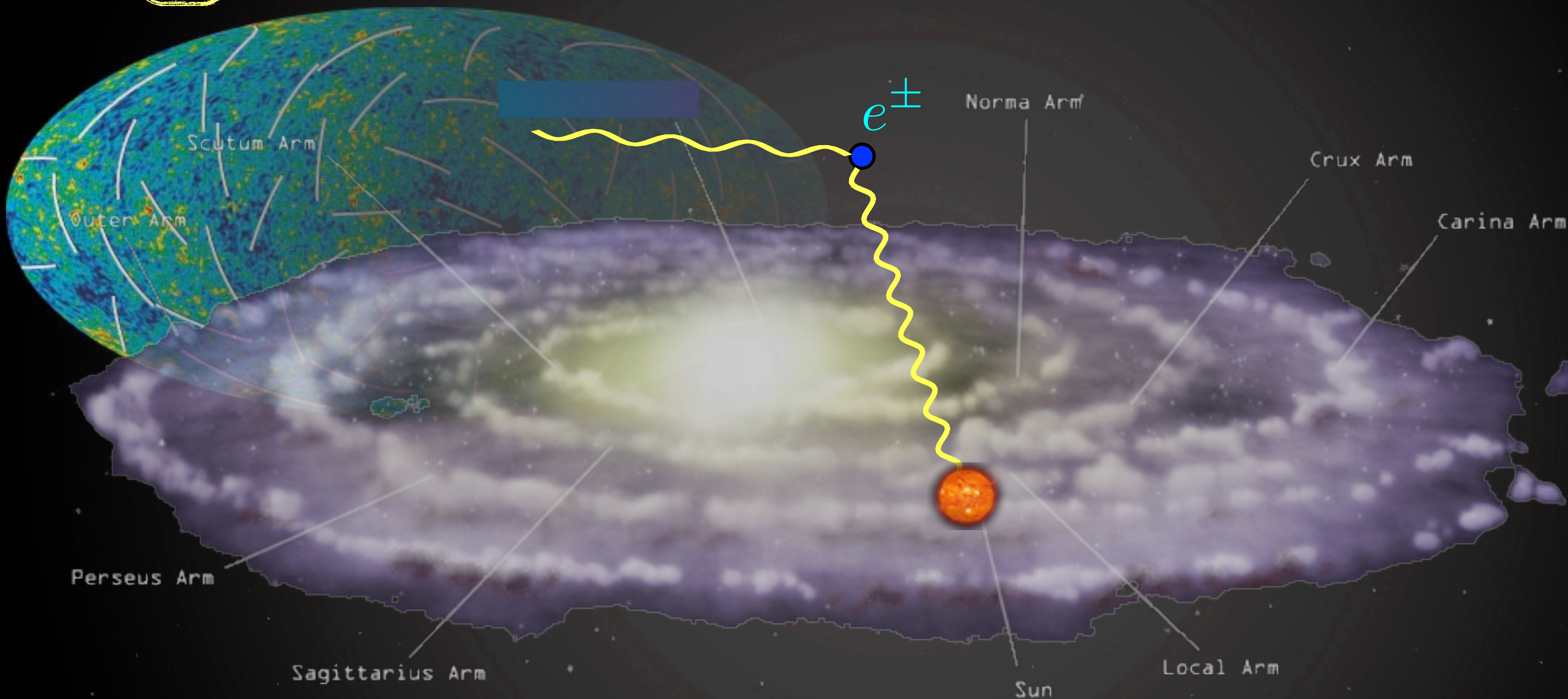
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

(assuming 'scrambled' B; in principle, directionality could focus emission, lift bounds by O(some))



Indirect Detection: constraints

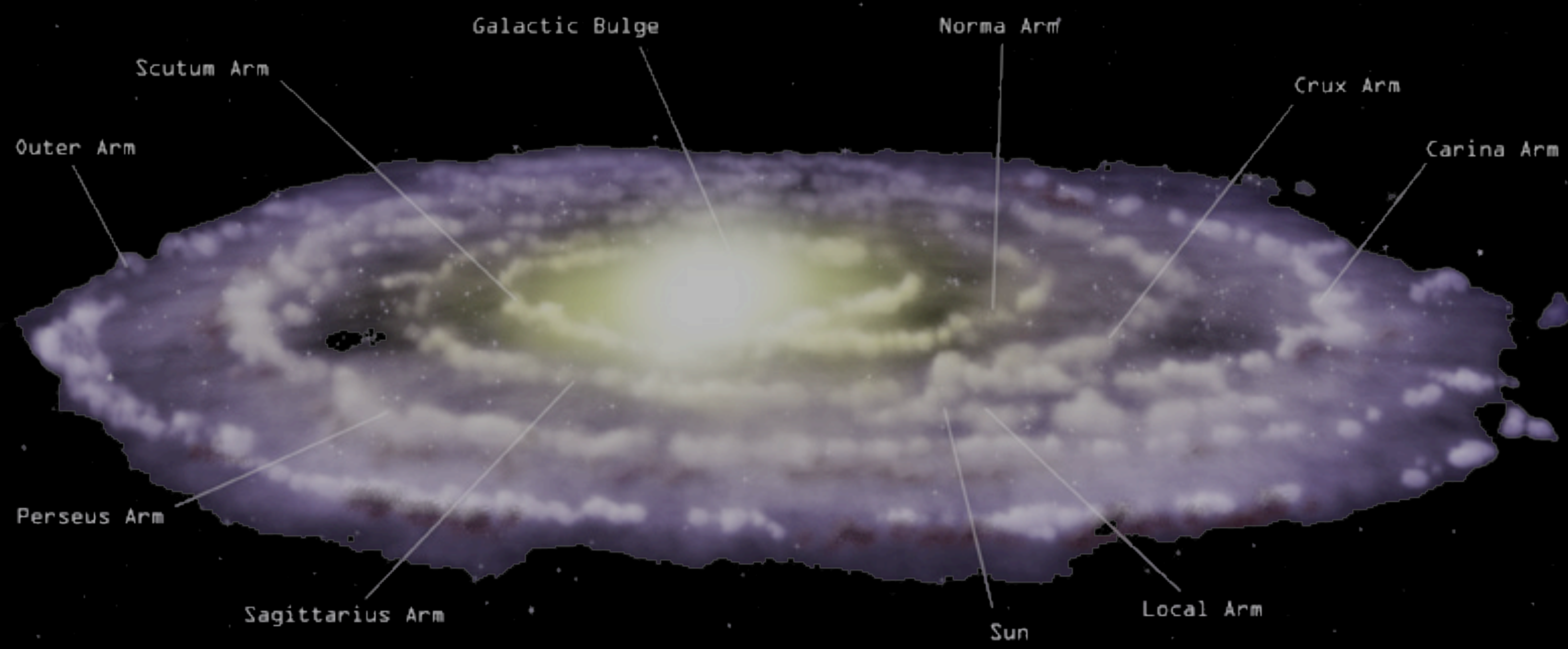
d. γ from Inverse Compton on $e^{\pm}$ in halo



- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

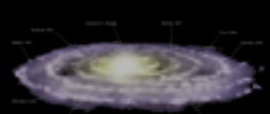
Indirect Detection: constraints

e. γ from outside the Galaxy



Indirect Detection: constraints

e. γ from outside the Galaxy

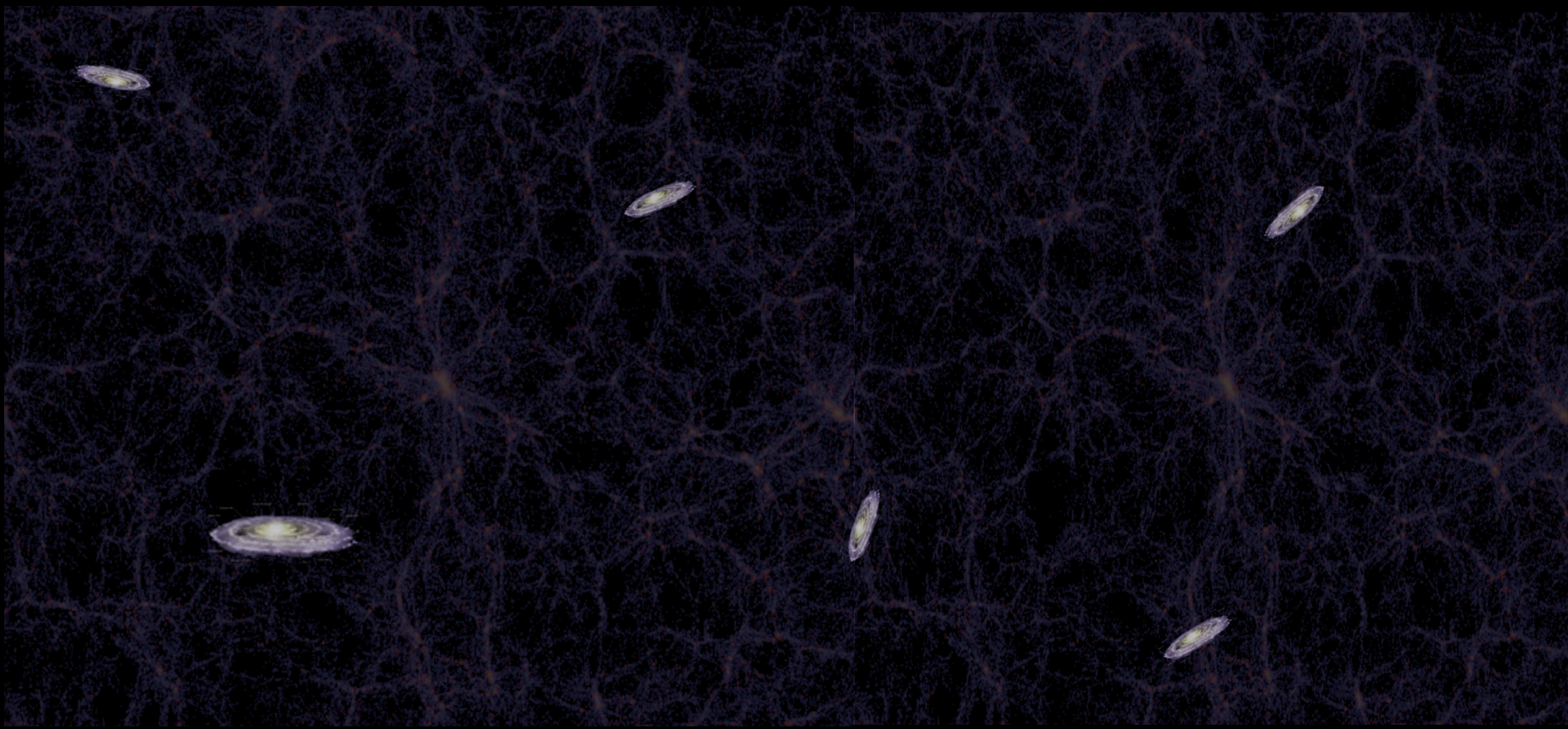


Indirect Detection: constraints

e. γ from outside the Galaxy

Indirect Detection: constraints

e. γ from outside the Galaxy



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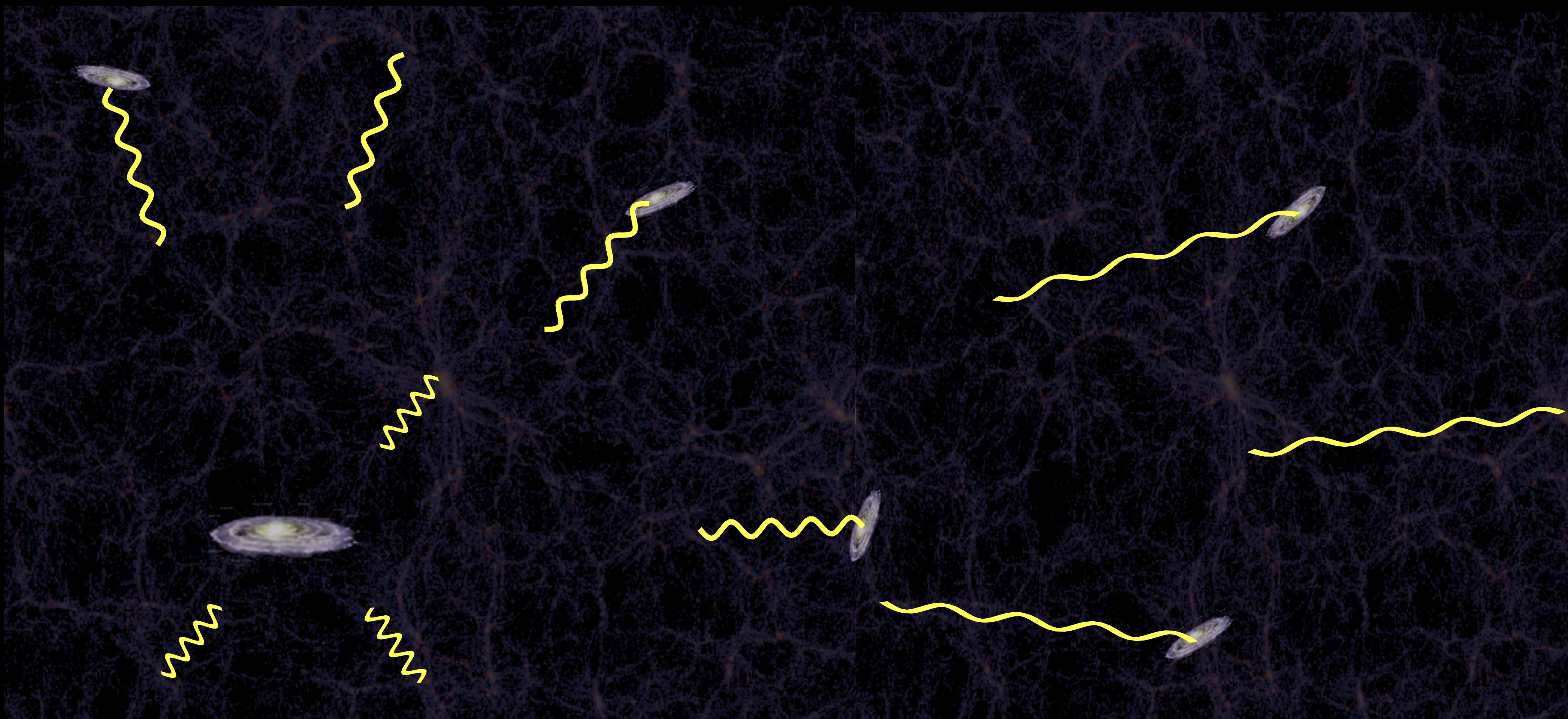

Indirect Detection: constraints

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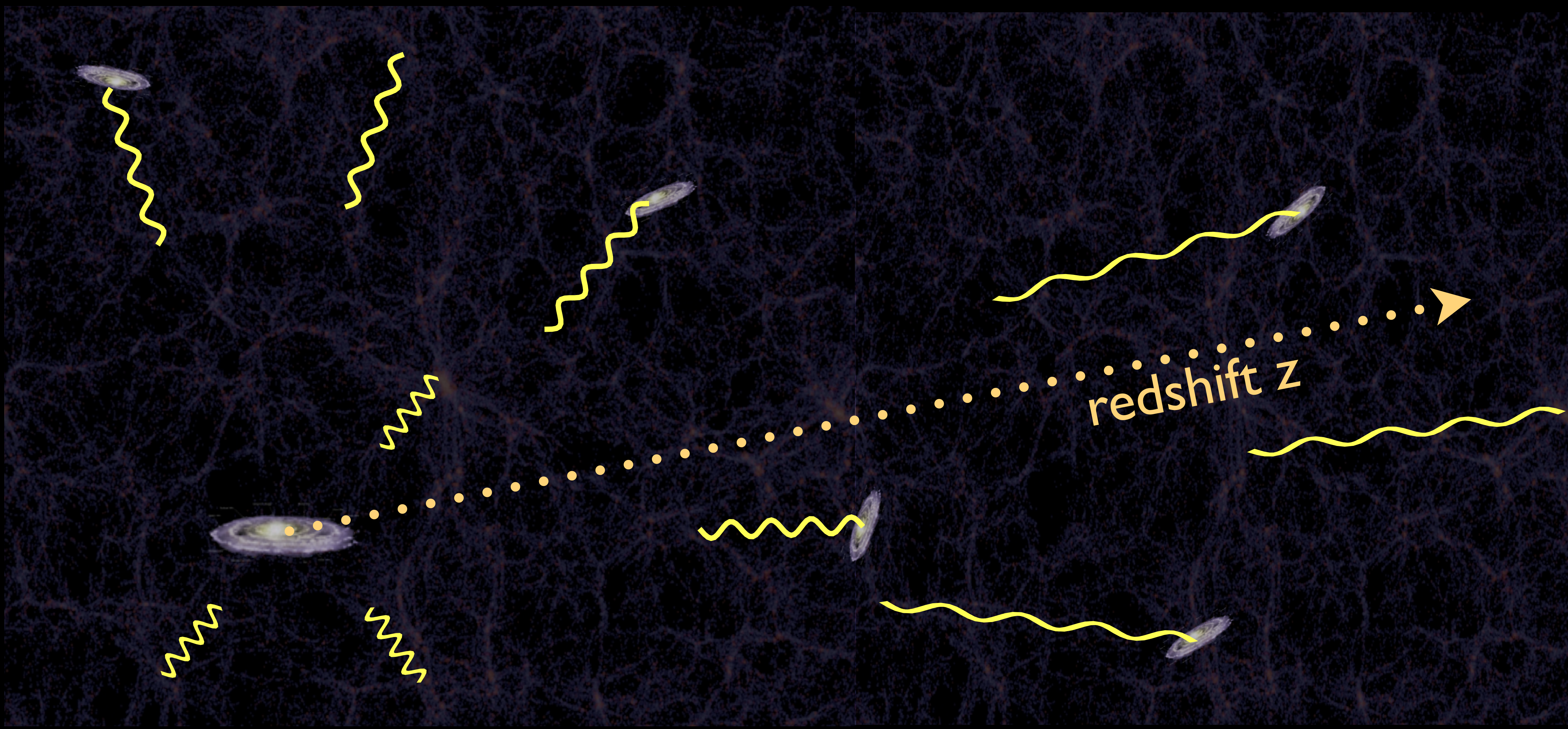

- isotropic flux of prompt and ICS gamma rays, integrated over z and r
- depends strongly on halo formation details and history

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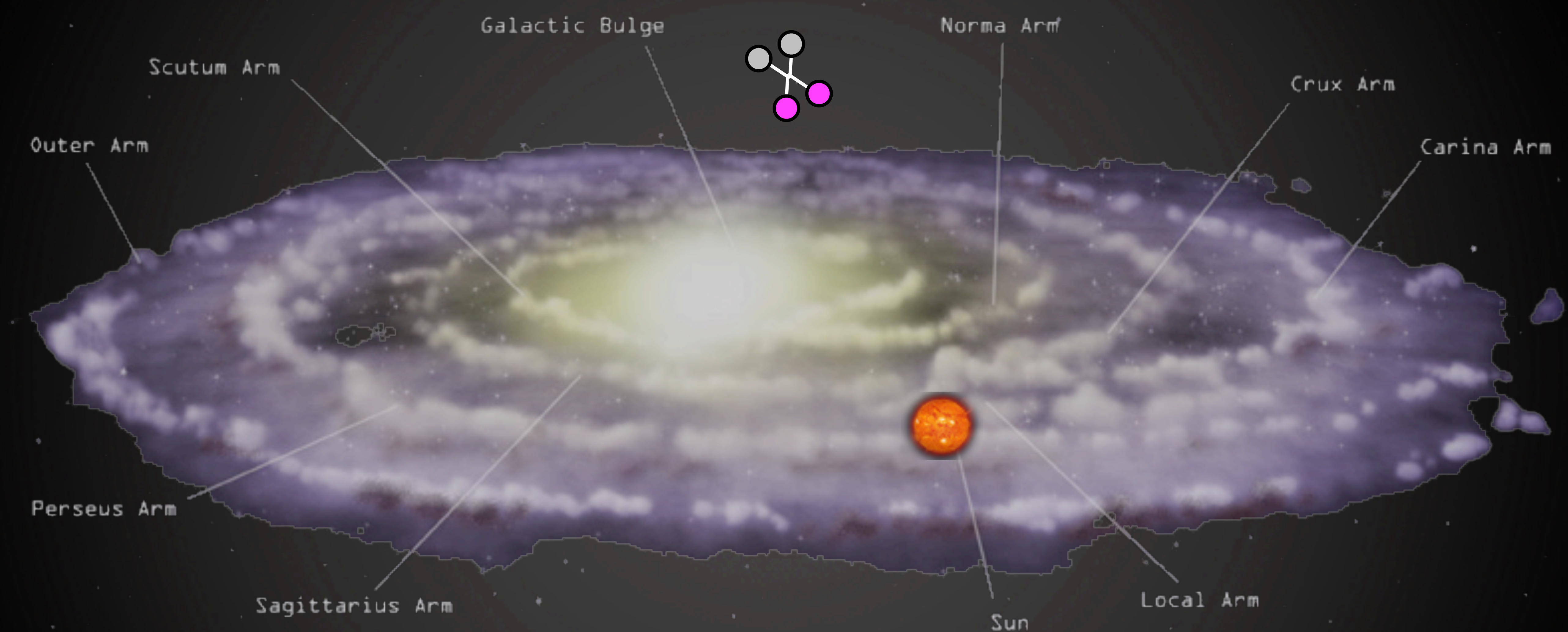
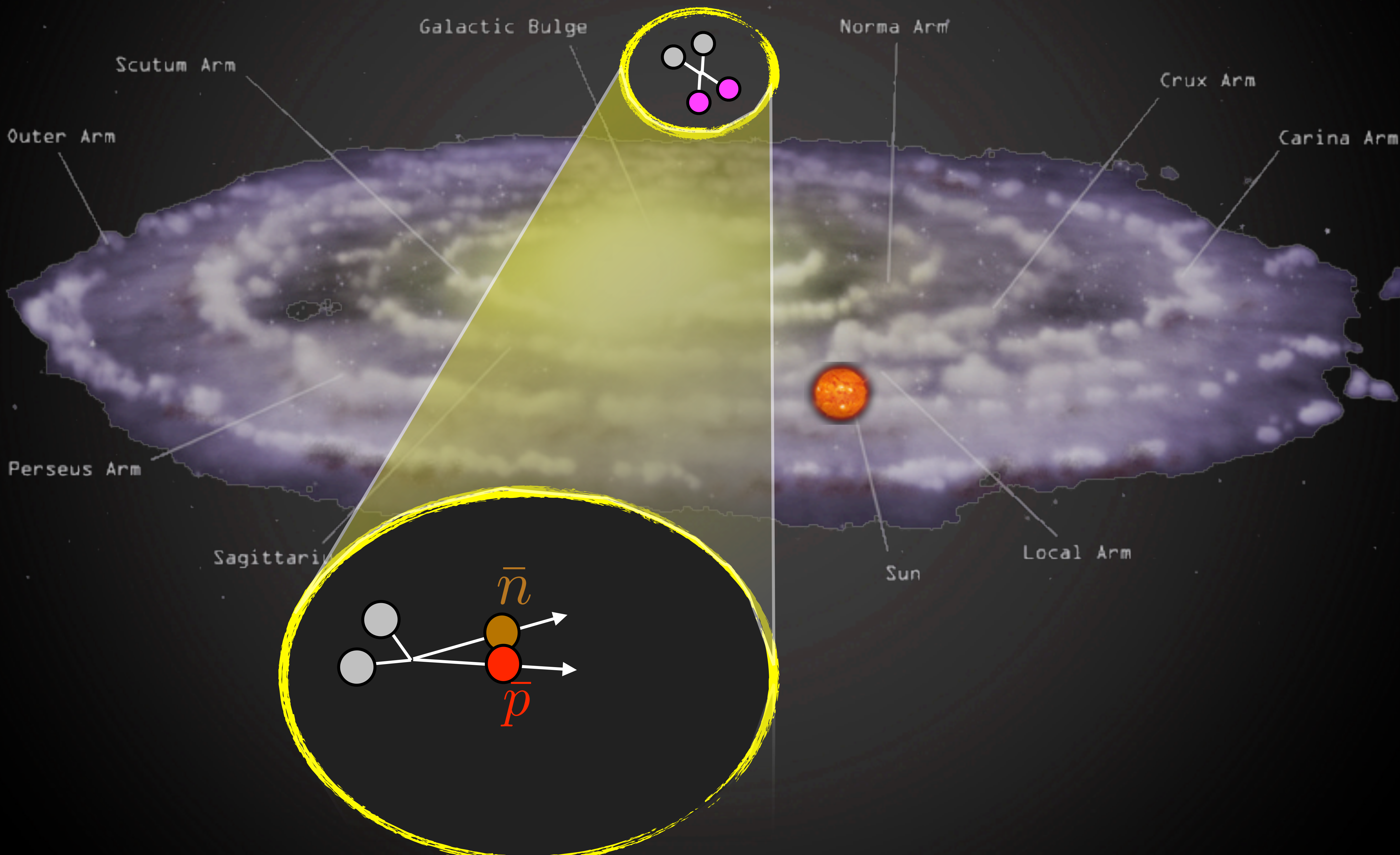
Indirect Detection

$\bar{d}$ from DM annihilations in halo



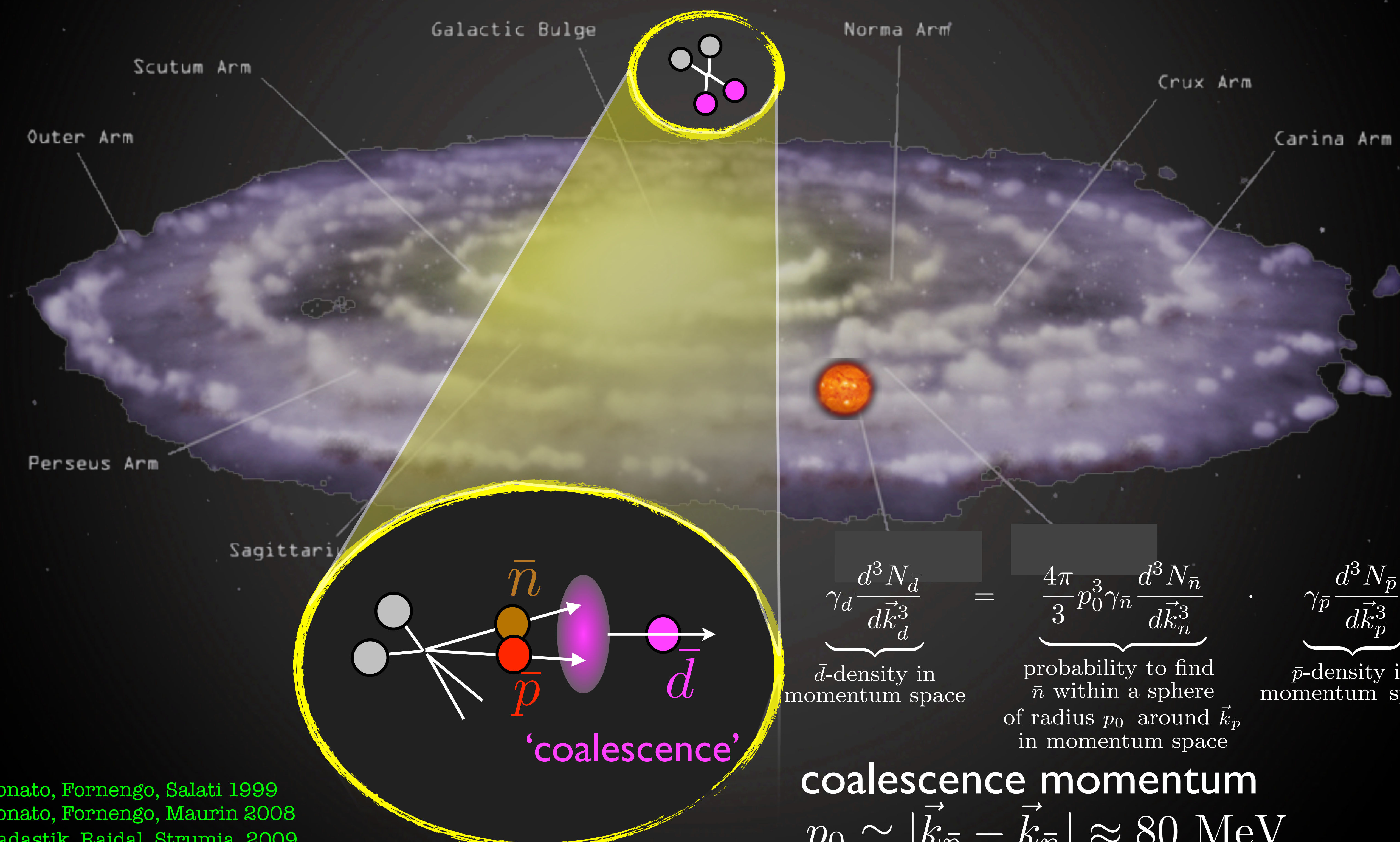
Indirect Detection

$\bar{d}$ from DM annihilations in halo



Indirect Detection

$\bar{d}$ from DM annihilations in halo



$$\underbrace{\gamma_{\bar d}\frac{d^3N_{\bar d}}{d\vec{k}^3_{\bar d}}}_{\bar{d}\text{-density in momentum space}} = \underbrace{\frac{4\pi}{3}p_0^3\,\gamma_{\bar n}\frac{d^3N_{\bar n}}{d\vec{k}^3_{\bar n}}}_{\text{probability to find } \bar{n} \text{ within a sphere of radius } p_0 \text{ around } \vec{k}_{\bar p} \text{ in momentum space}} \cdot \underbrace{\gamma_{\bar p}\frac{d^3N_{\bar p}}{d\vec{k}^3_{\bar p}}}_{\bar{p}\text{-density in momentum space}}$$

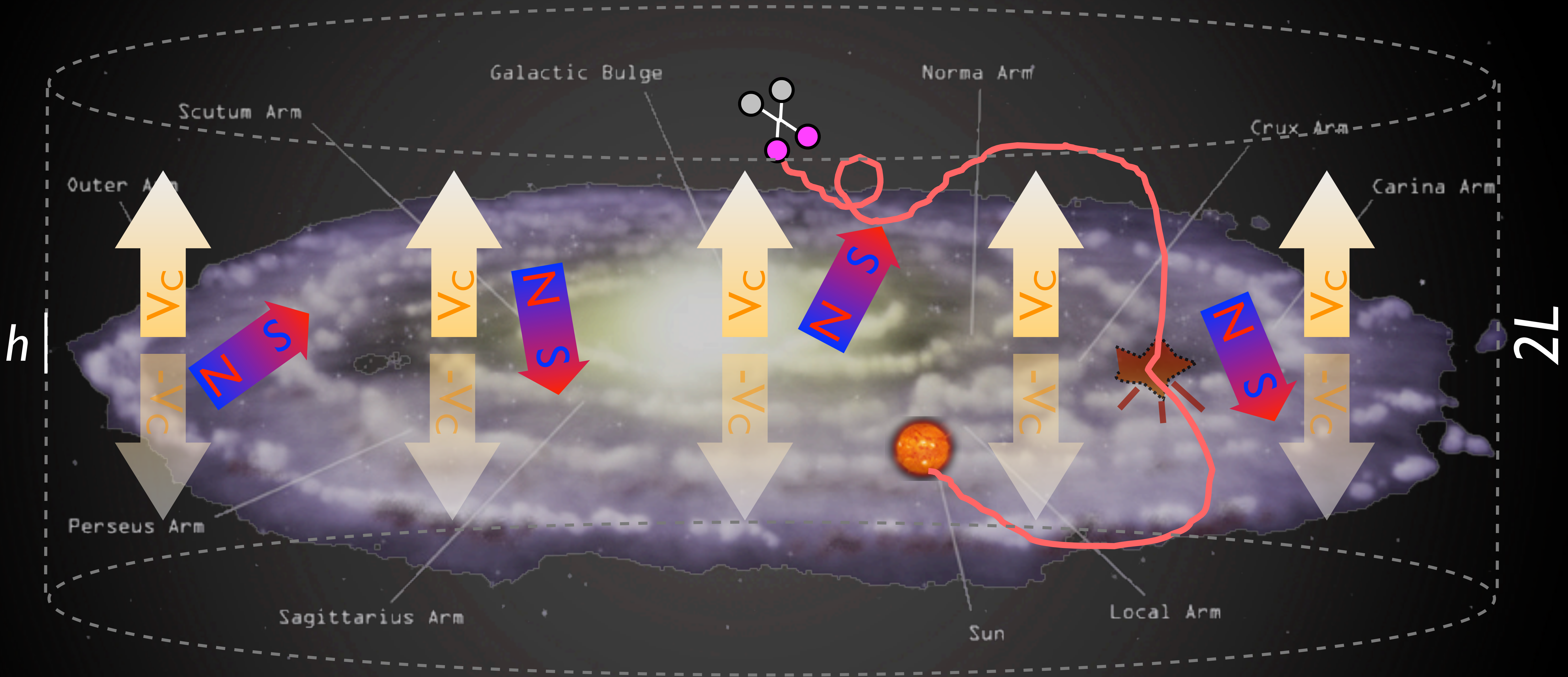
coalescence momentum

$$p_0 \simeq |\vec{k}_{\bar p} - \vec{k}_{\bar n}| \approx 80 \text{ MeV}$$

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Kadastik, Raidal, Strumia, 2009

Indirect Detection

$\bar{d}$ from DM annihilations in halo



$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

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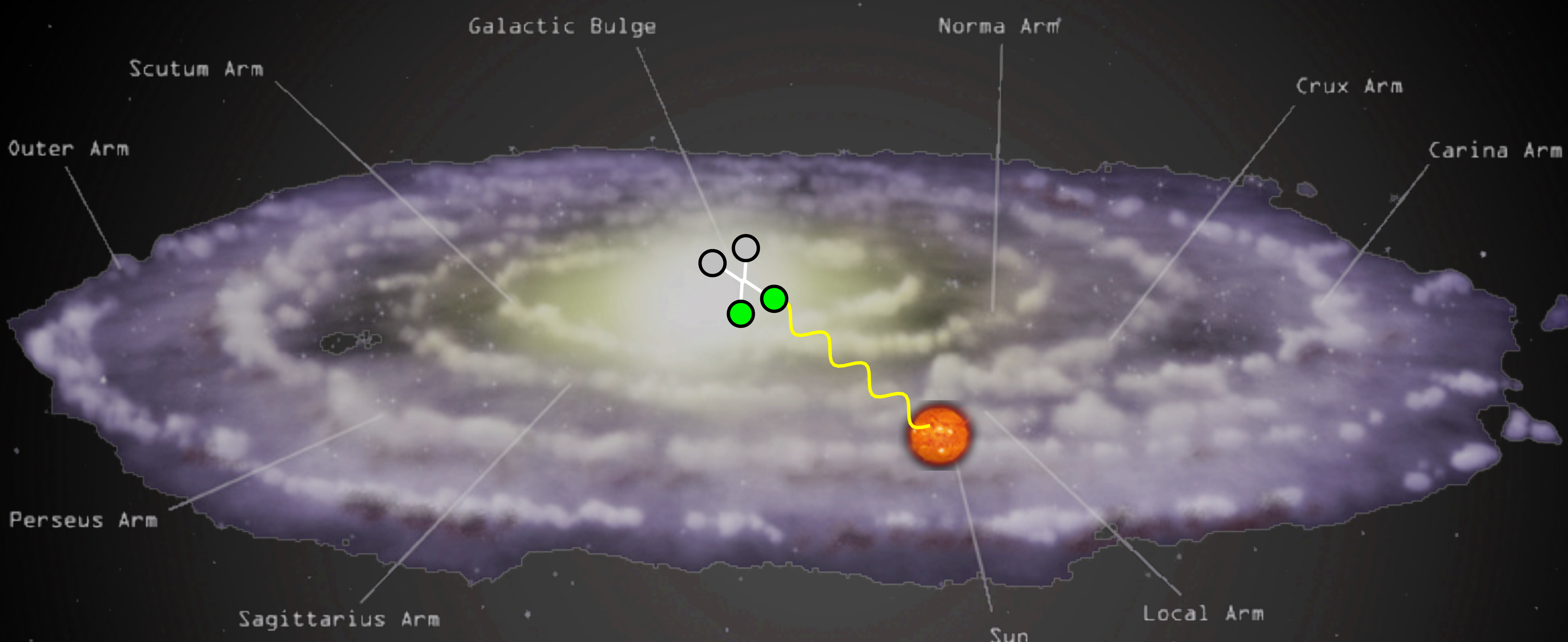
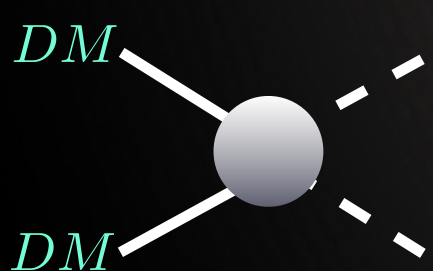
$\nu, \bar{\nu}$ from annihil in galactic center

Indirect Detection

ν from DM annihilations in galactic center

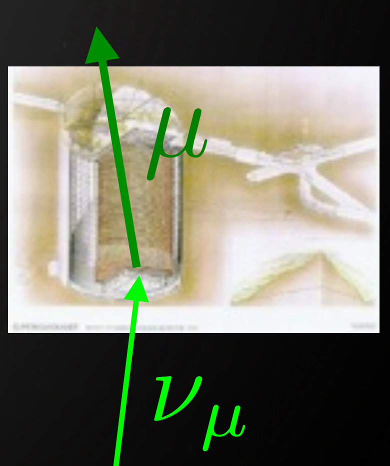




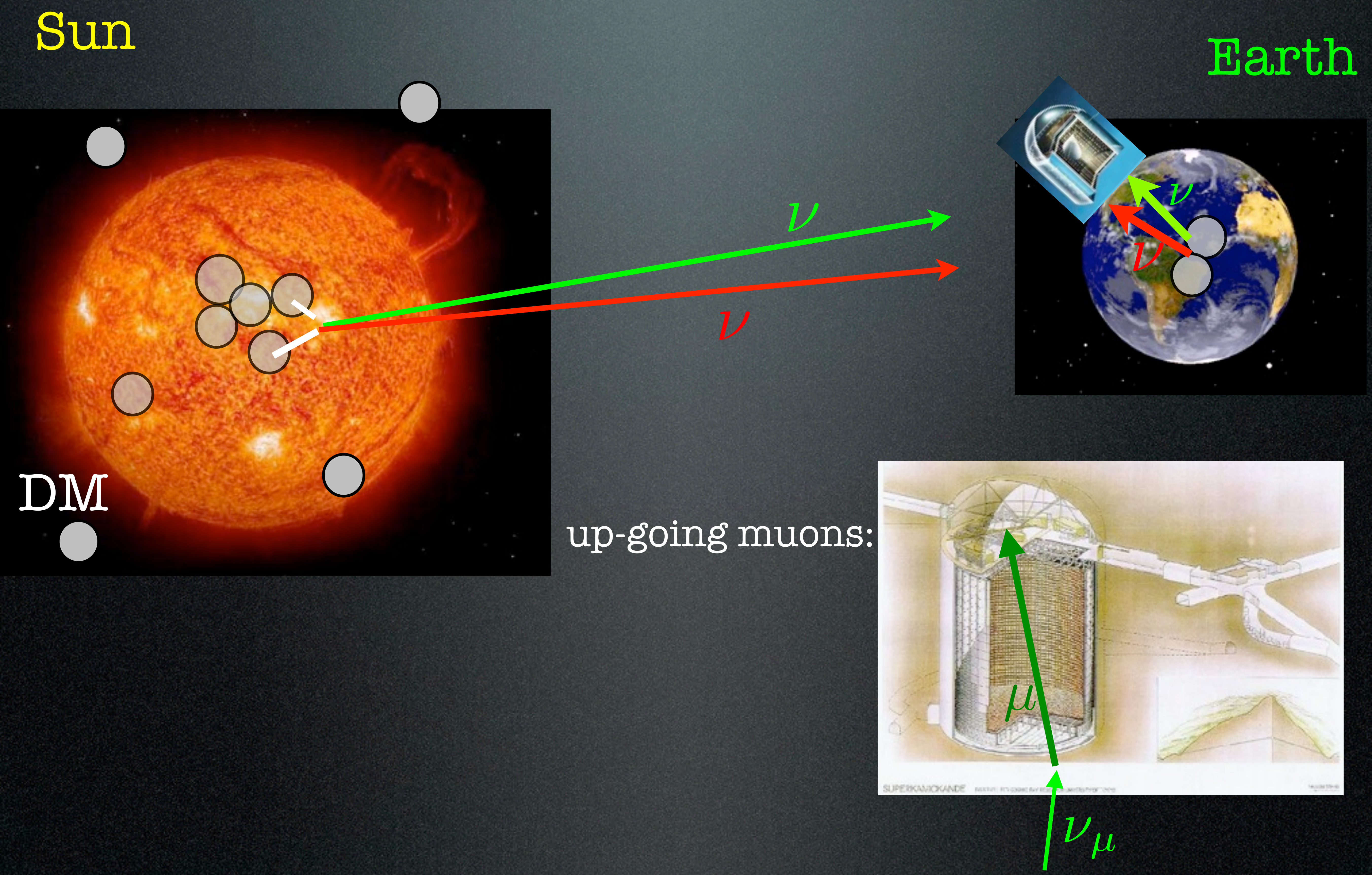
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and ν

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and ν

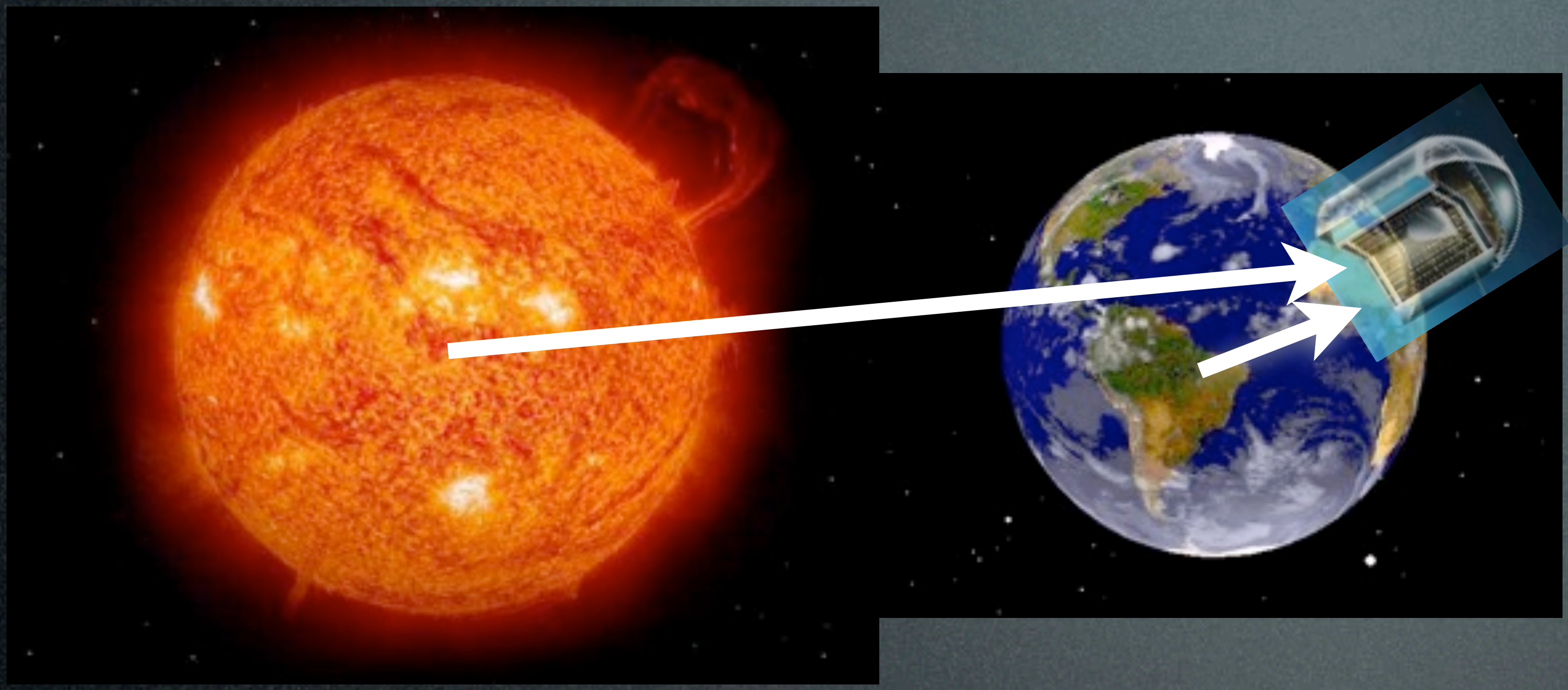
up-going muons:

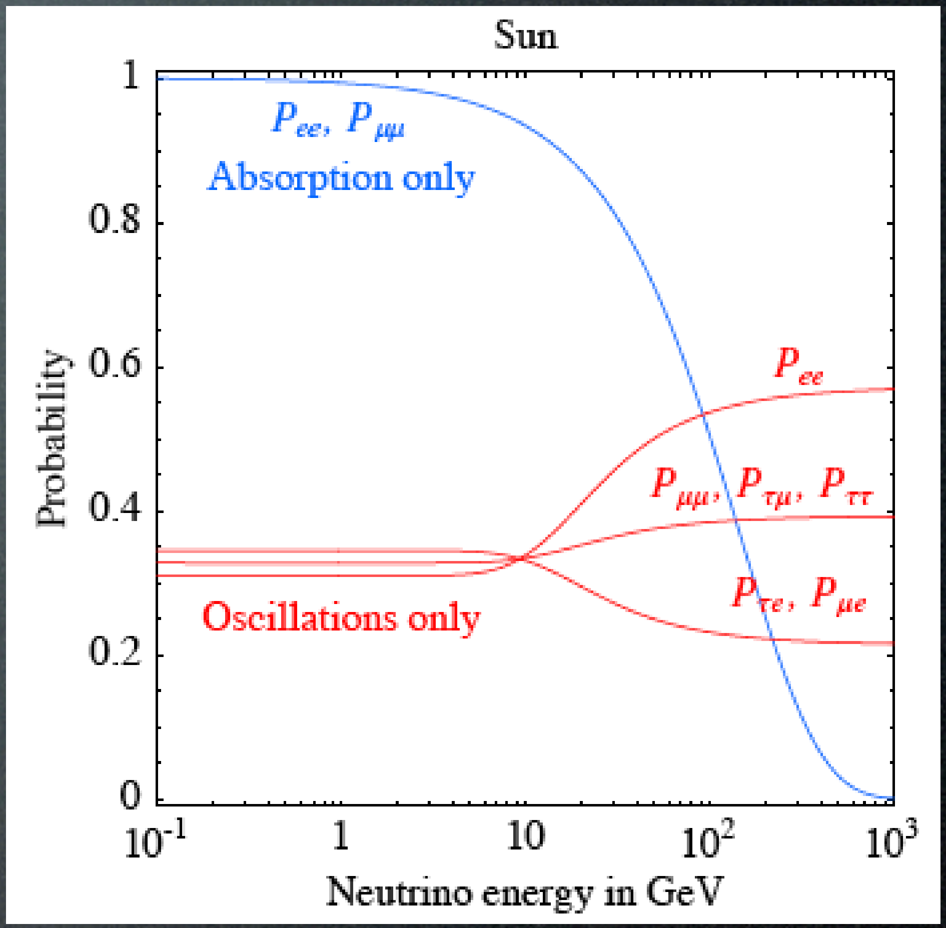


Neutrinos from DM in the Sun



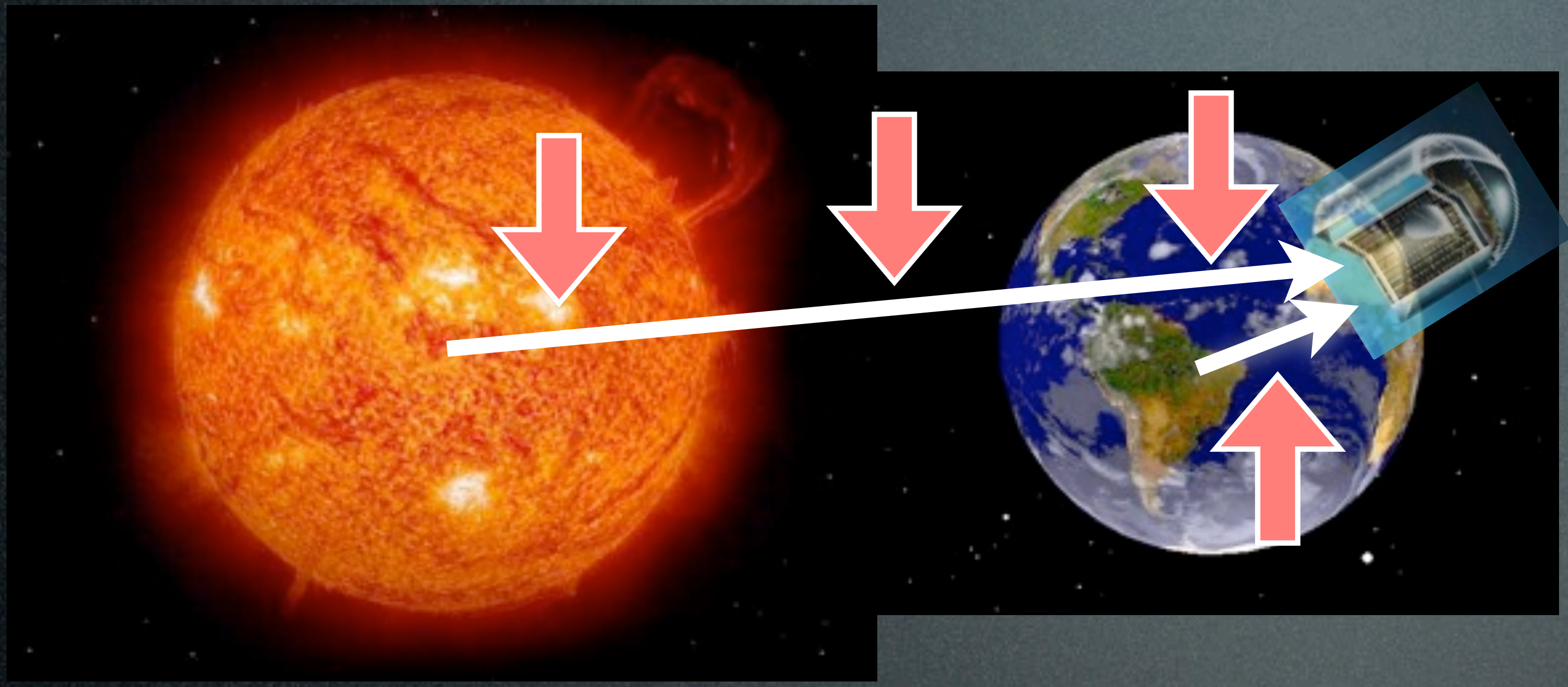
Propagation



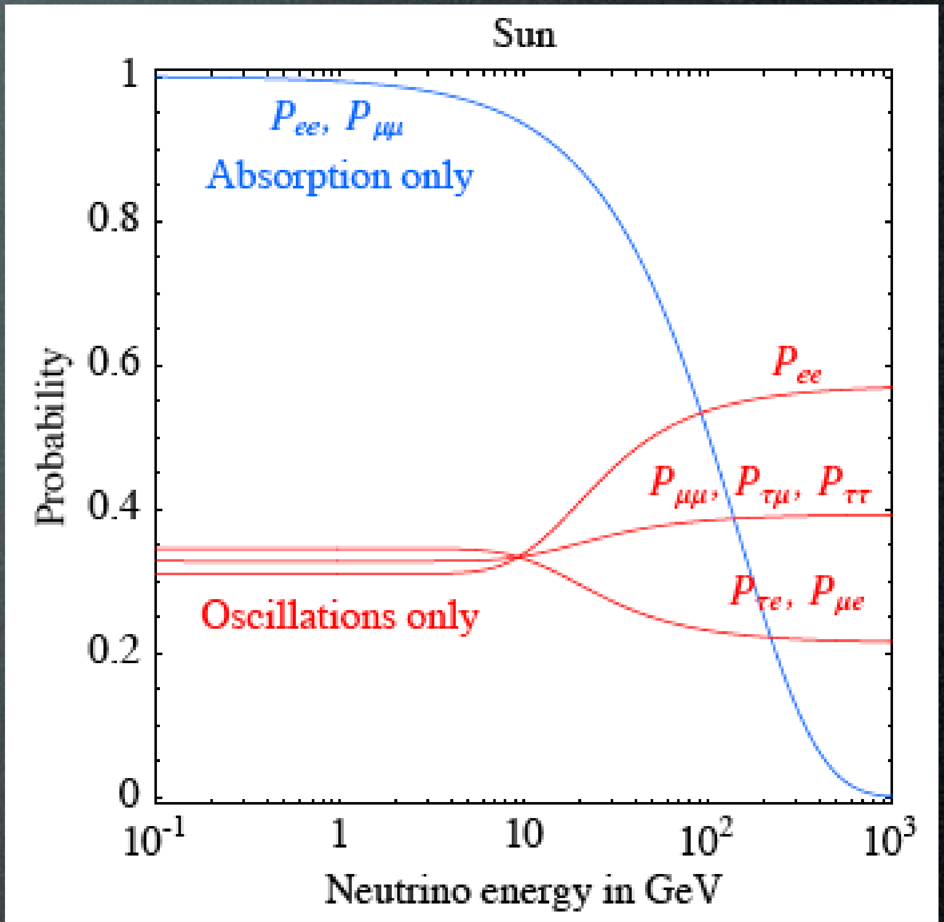


oscillations + interactions

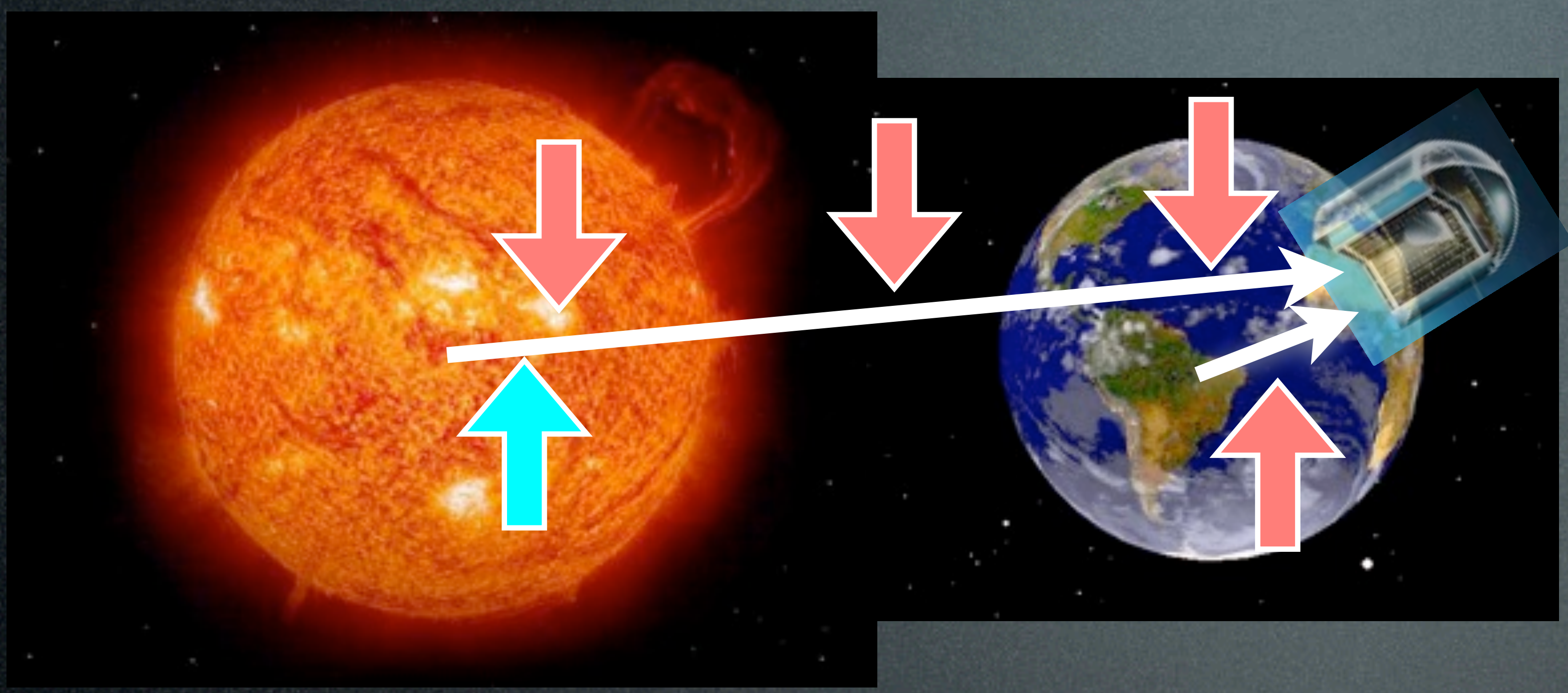
Propagation

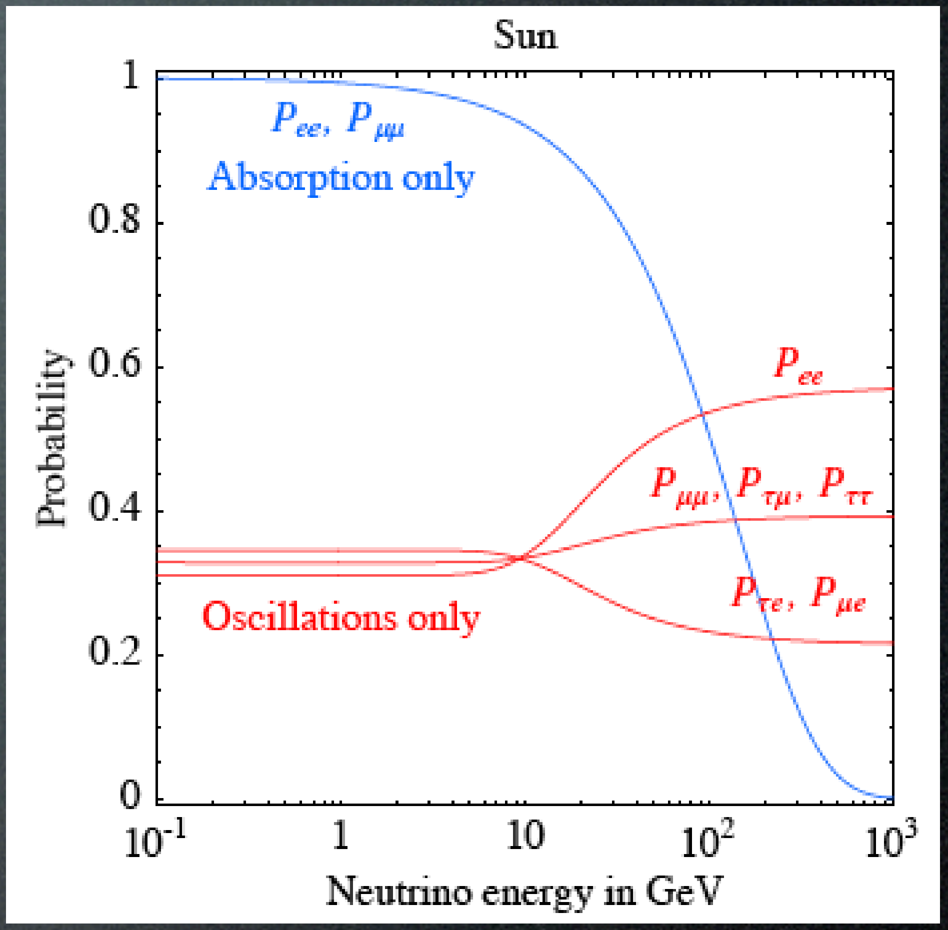


oscillations + interactions



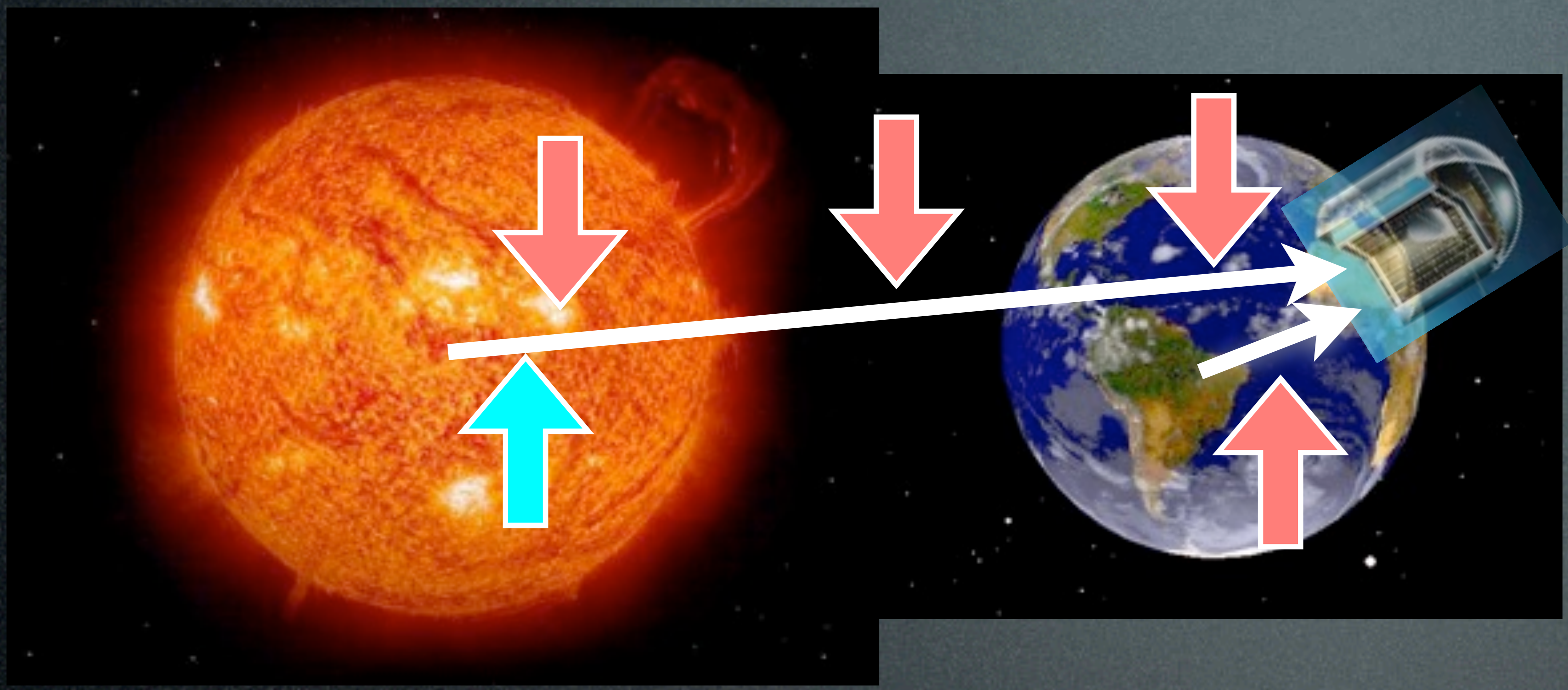
Propagation

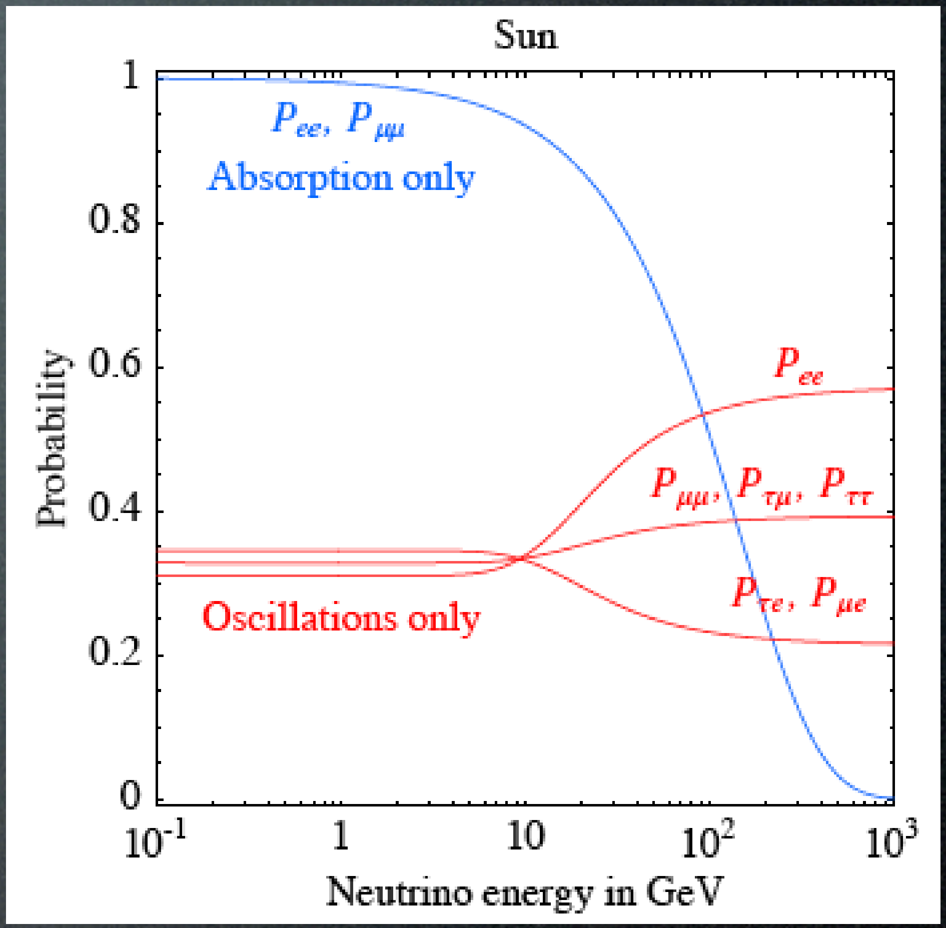




oscillations + interactions

Propagation

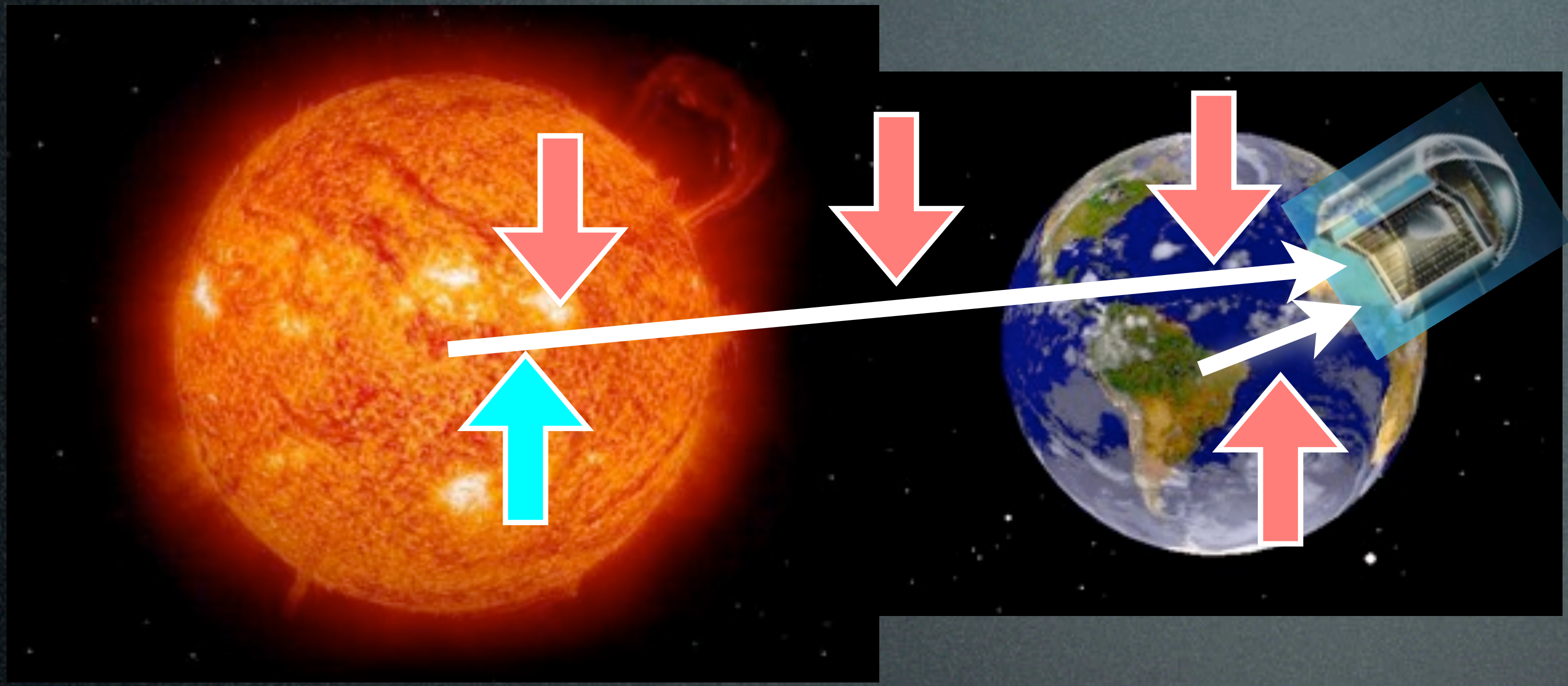


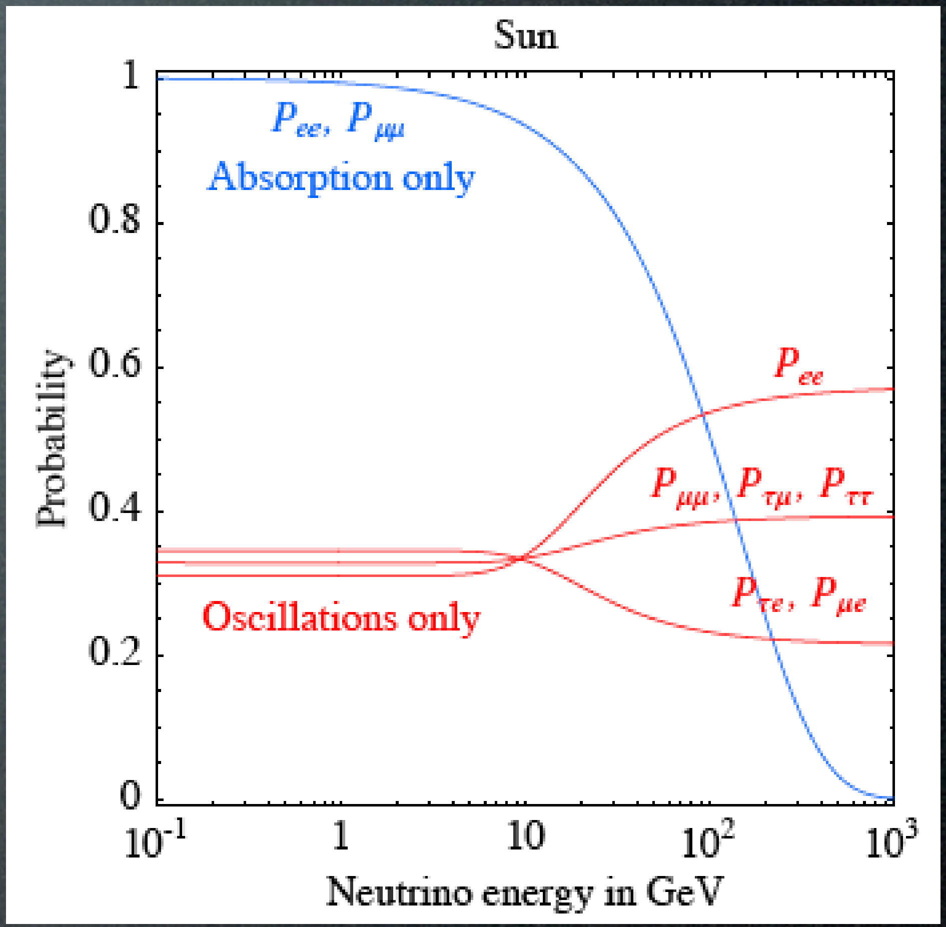


oscillations + interactions

$$\text{production} \longrightarrow \begin{pmatrix} \Phi_{\nu_e} & & \\ & \Phi_{\nu_\mu} & \\ & & \Phi_{\nu_\tau} \end{pmatrix} \longrightarrow \text{detection}$$

Propagation





oscillations + interactions

density matrix

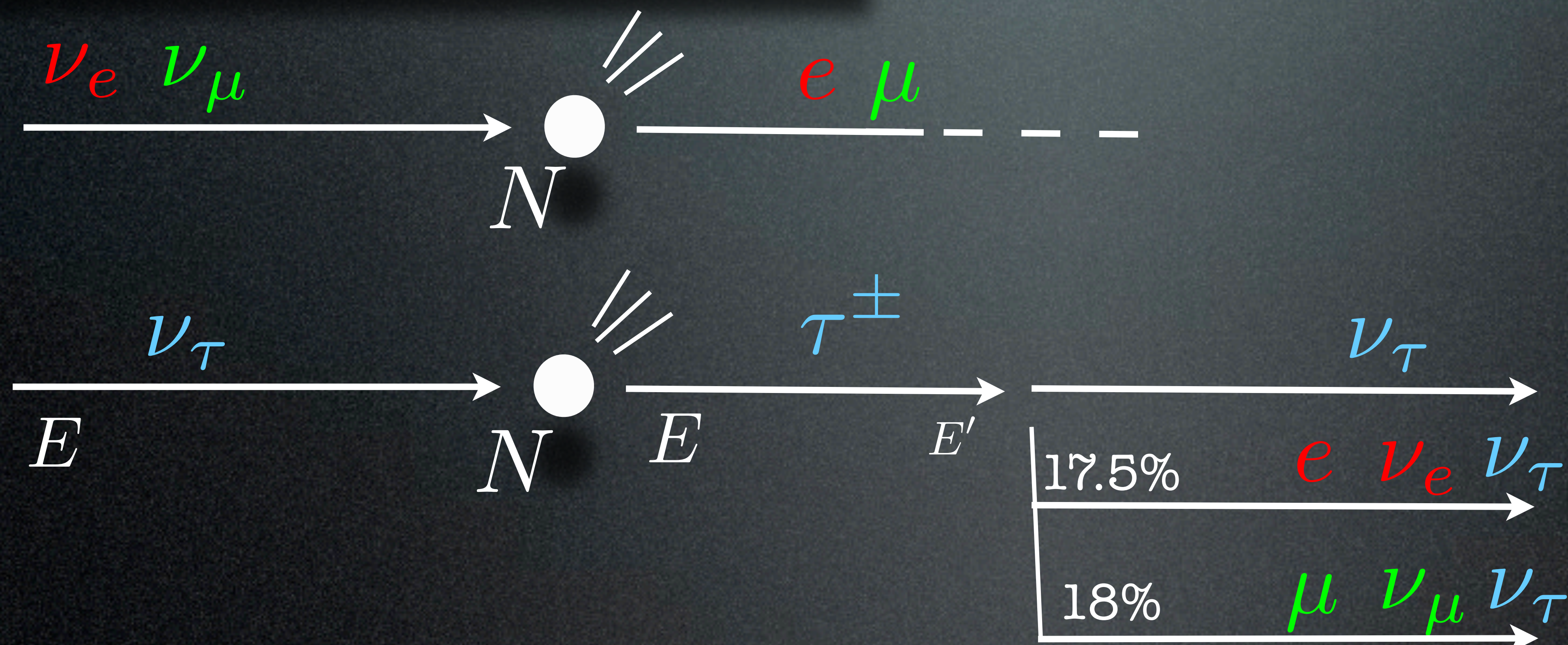
$$\boldsymbol{\rho} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

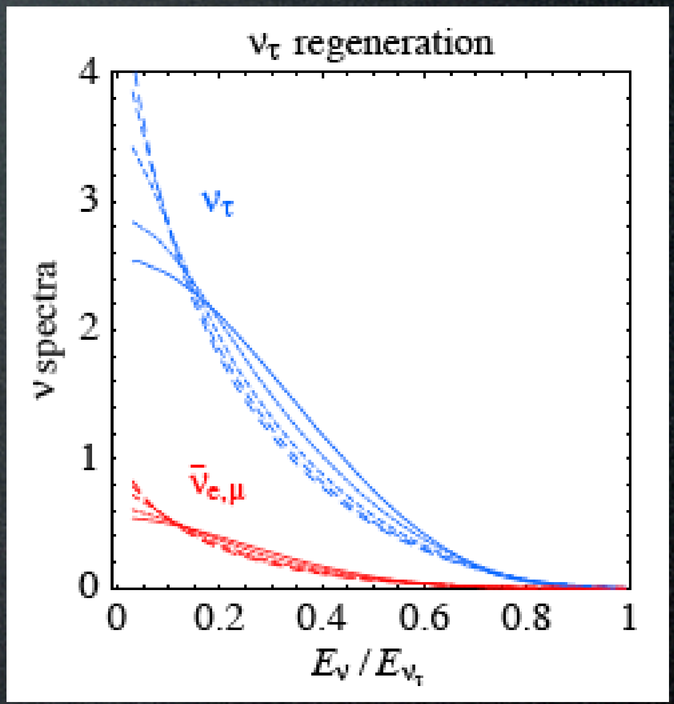
full evolution equation:

$$\boxed{\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{CC}} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{NC}} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{in}}}$$

Propagation: CC absorption and tau regeneration

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC}$$





(re)generation

$$\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} = -\frac{\{\boldsymbol{\Gamma}_{\rm CC},\boldsymbol{\rho}\}}{2} + \int \frac{dE_\nu^{\rm in}}{E_\nu^{\rm in}} \Big[\boldsymbol{\Pi}_\tau \rho_{\tau\tau}(E_\nu^{\rm in})\Gamma^\tau_{\rm CC}(E_\nu^{\rm in}) f_{\tau\to\tau}(E_\nu^{\rm in}, E_\nu) + \boldsymbol{\Pi}_{e,\mu}\bar{\rho}_{\tau\tau}(E_\nu^{\rm in})\bar{\Gamma}^\tau_{\rm CC}(E_\nu^{\rm in}) f_{\bar{\tau}\to e,\mu}(E_\nu^{\rm in}, E_\nu)\Big]$$

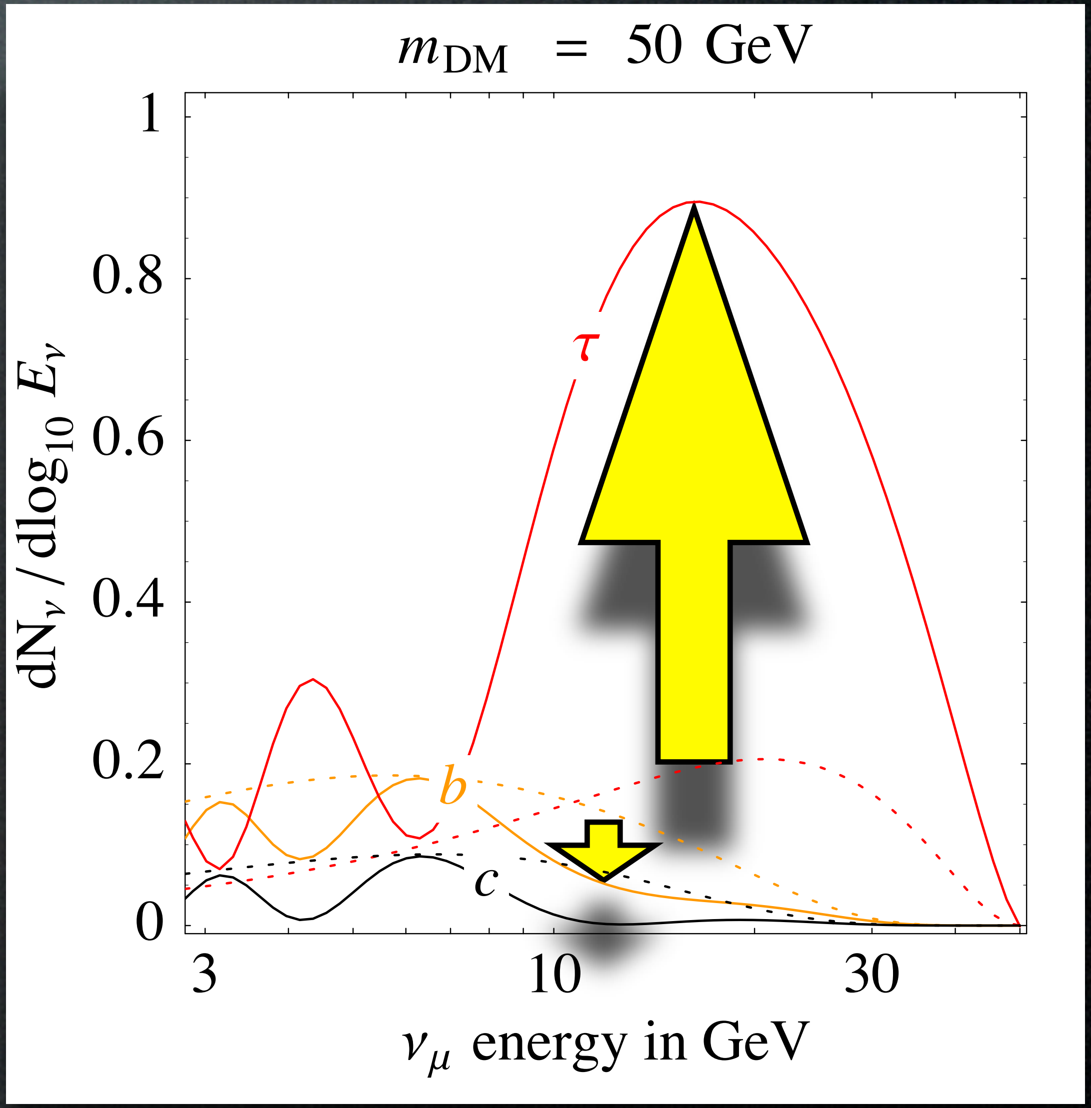
Propagation: summary

Effects of oscillations and interactions:

- reshuffle of the 3 flavors
  (oscillations and regeneration)

- attenuation of the fluxes

- degradation of energy
  (distortion of spectra)



DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

GAPS

$\nu, \bar{\nu}$ from annihil in massive bodies

C. de los Heros's lecture

DM detection

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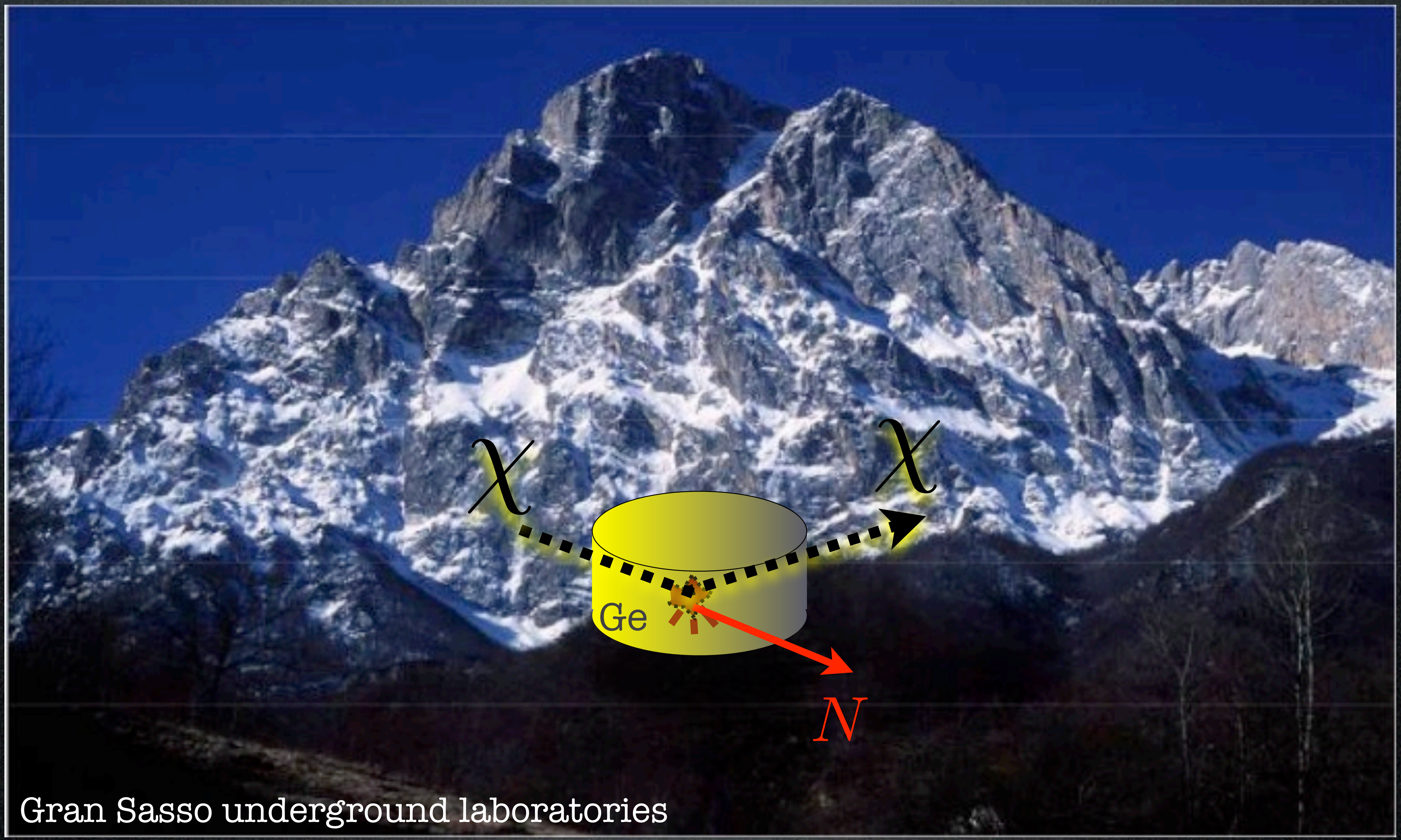
Icecube, Km3Net

Direct Detection: **basics**

Gran Sasso underground laboratories

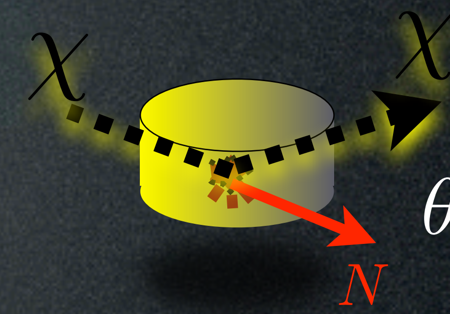
Direct Detection: basics

Direct Detection: basics



Direct Detection: basics

recoil energy $E_R = \frac{\mu_\chi^2 v^2}{m_N}(1 - \cos\theta)$



$$\mu_\chi = \frac{m_\chi \, m_N}{m_\chi + m_N} \longrightarrow \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v}) \, \mathrm{d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

$\sigma \approx \sigma_n^{\rm SI} \, A^4$ $\times$ nuclear form factors

number of events

$$N = \mathcal{E} \, \mathcal{T} \int_{E_{\rm thres}}^{E_{\max}} \frac{dR}{dE_R} \, dE_R$$

Direct Detection: basics

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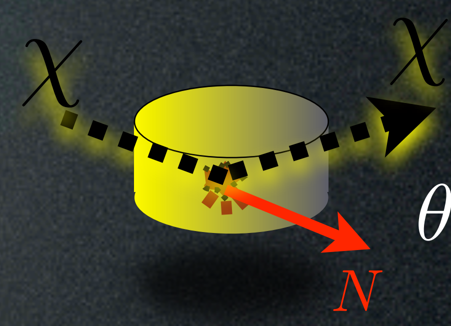

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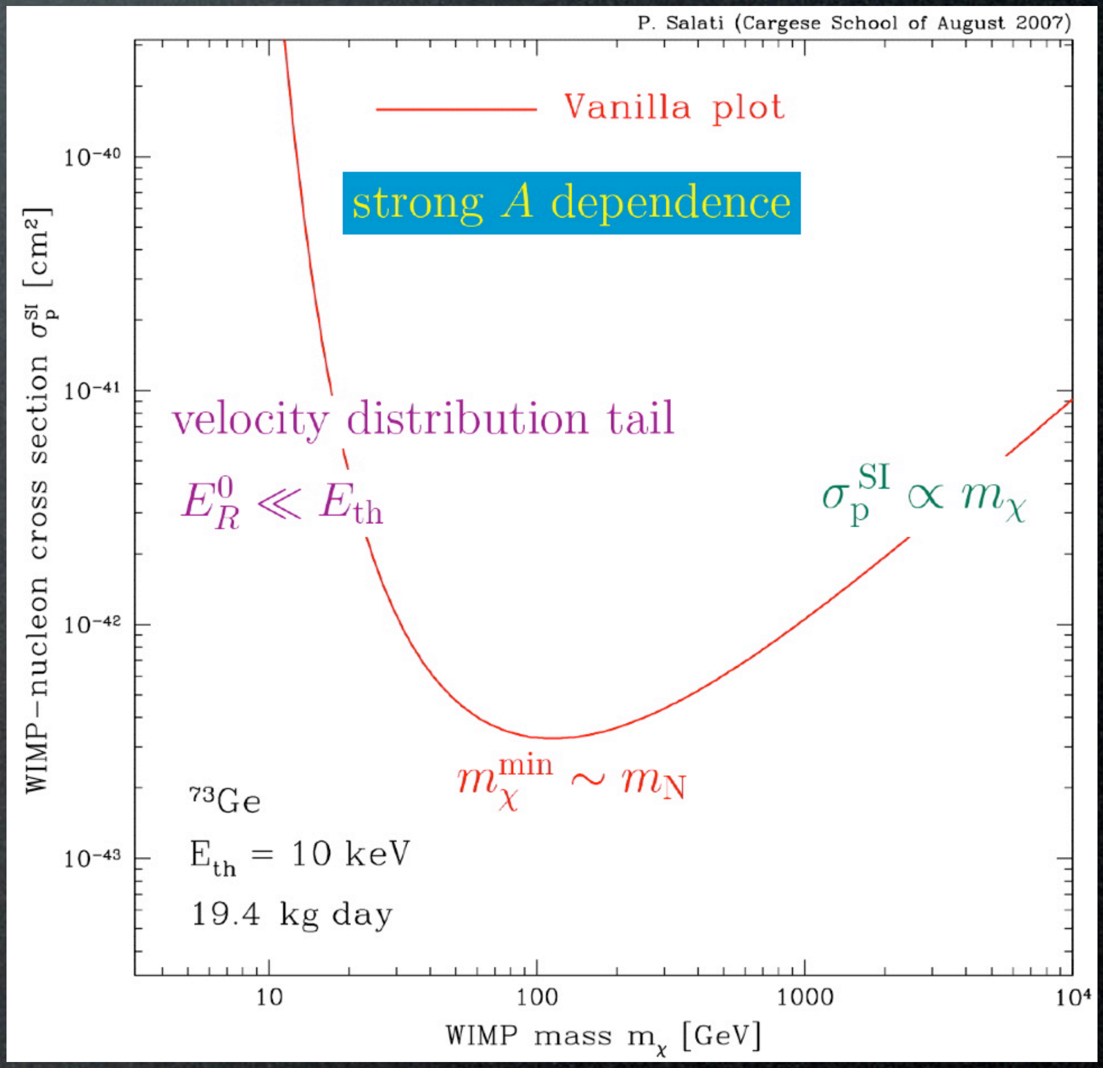
If no events



P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

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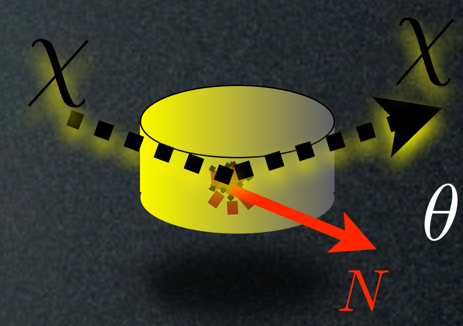

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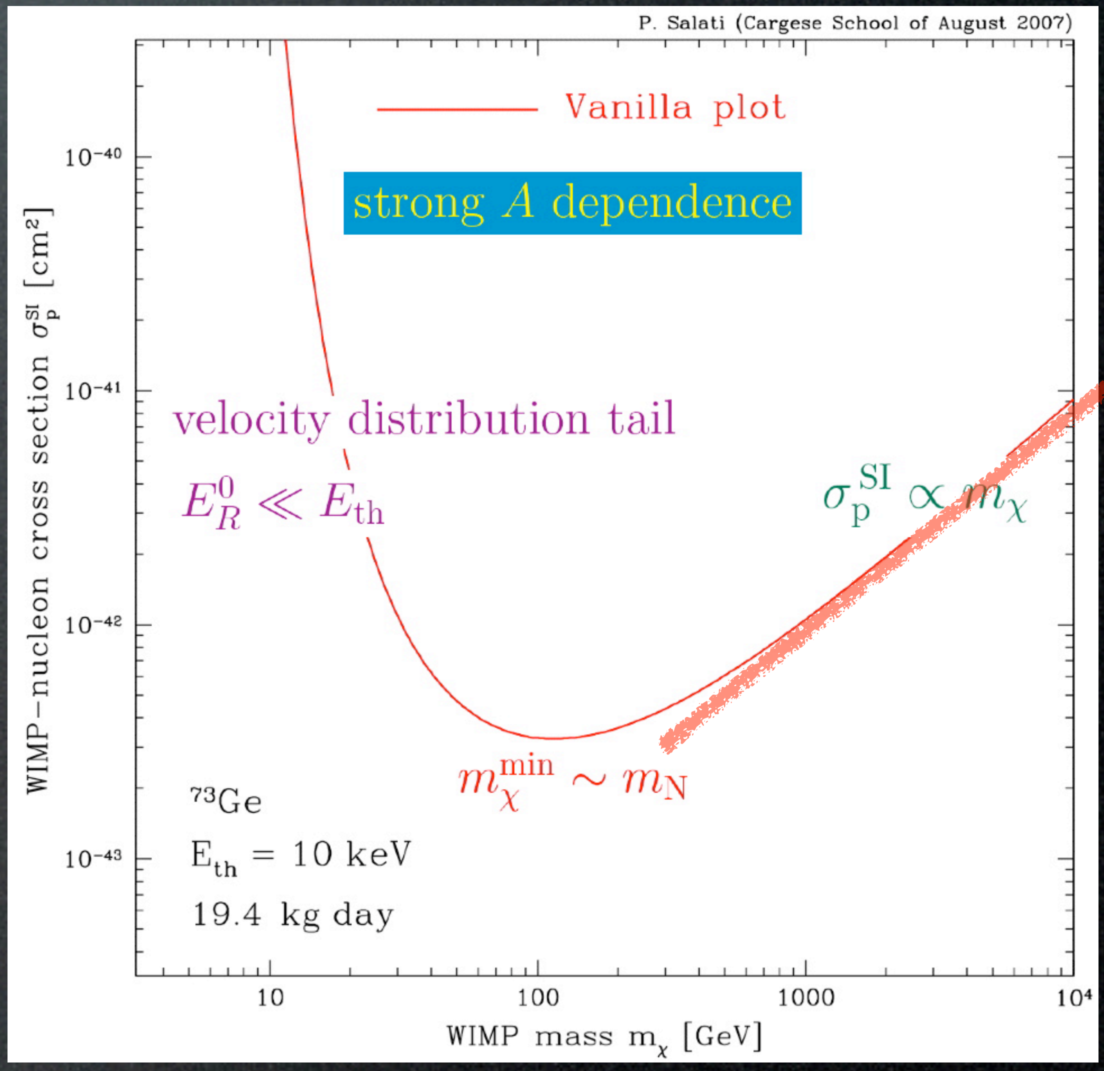
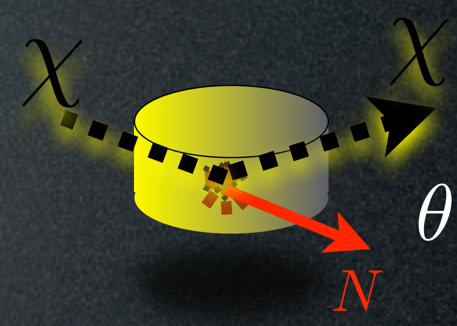


P.Salati, proceedings of Cargèse 2007

Direct Detection: basics



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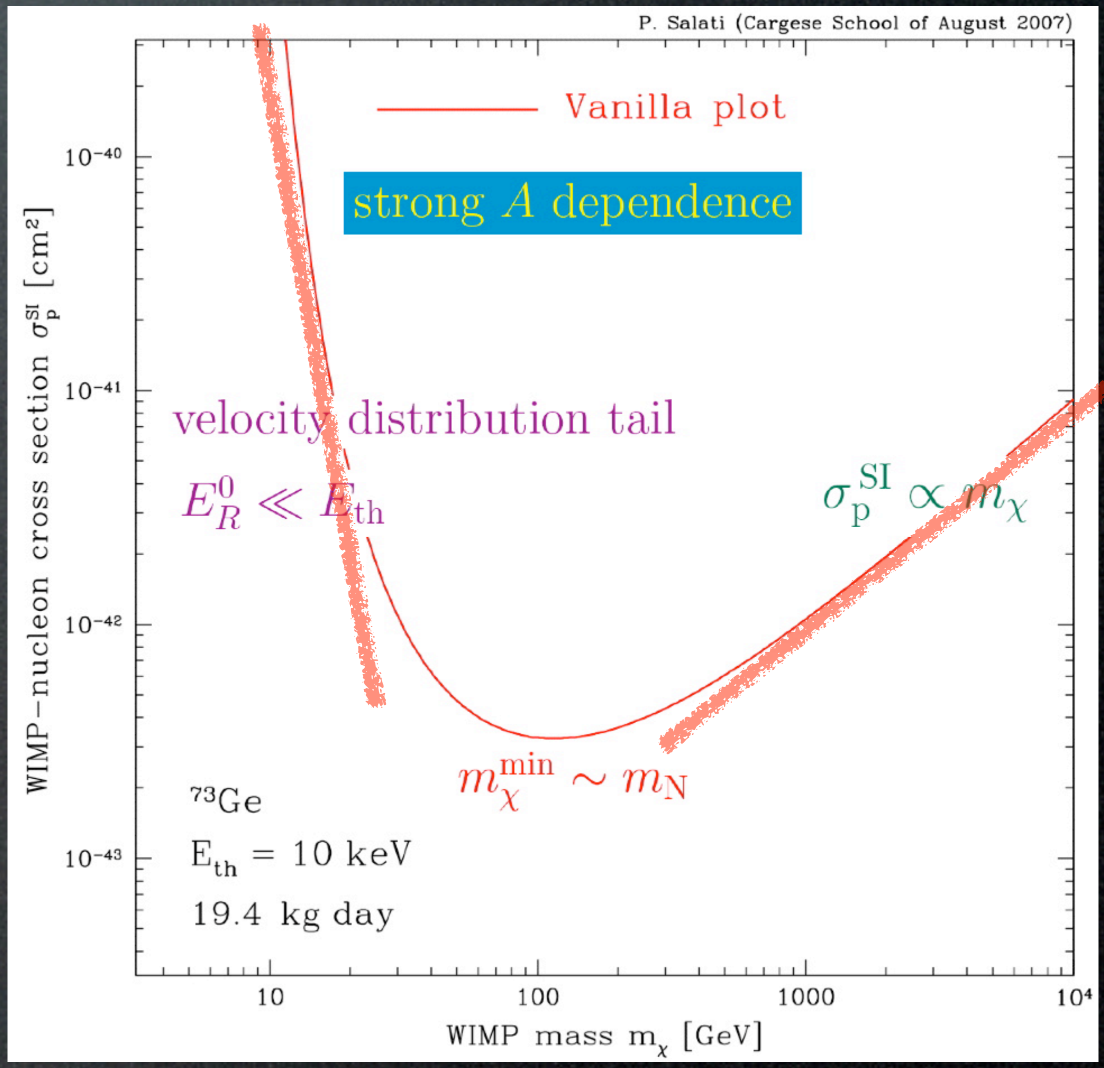

P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

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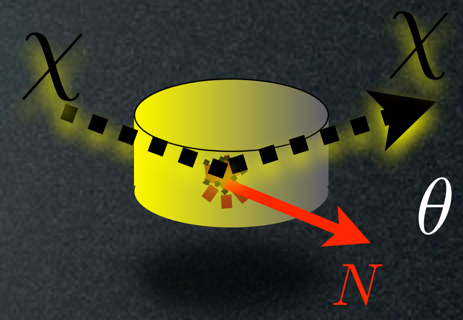

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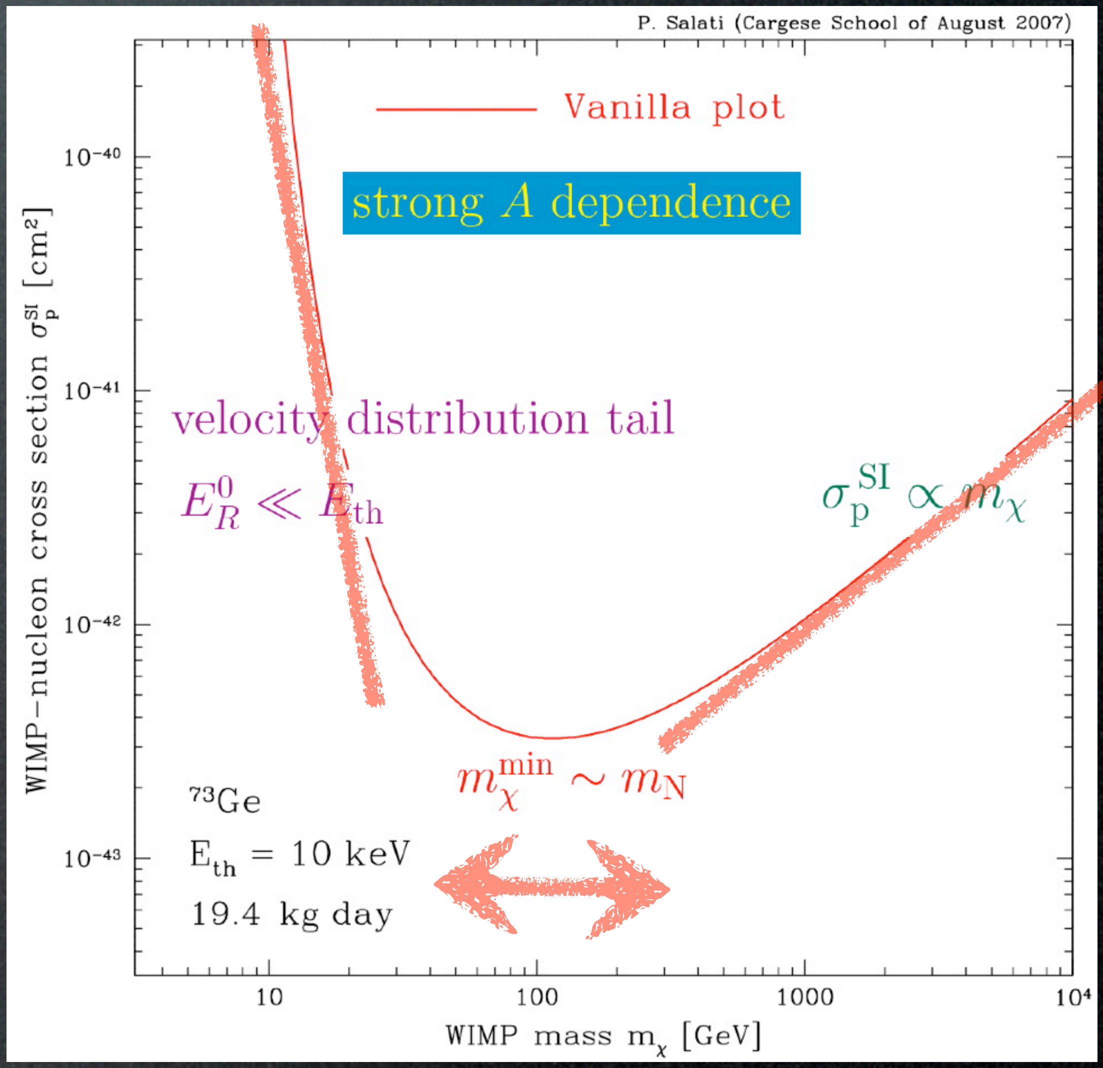

P.Salati, proceedings of Cargèse 2007

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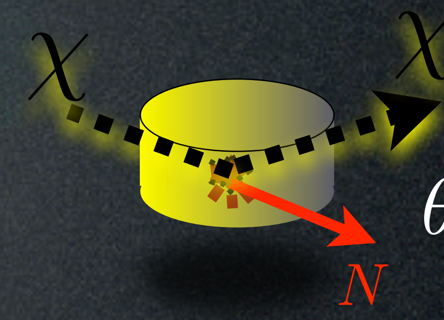

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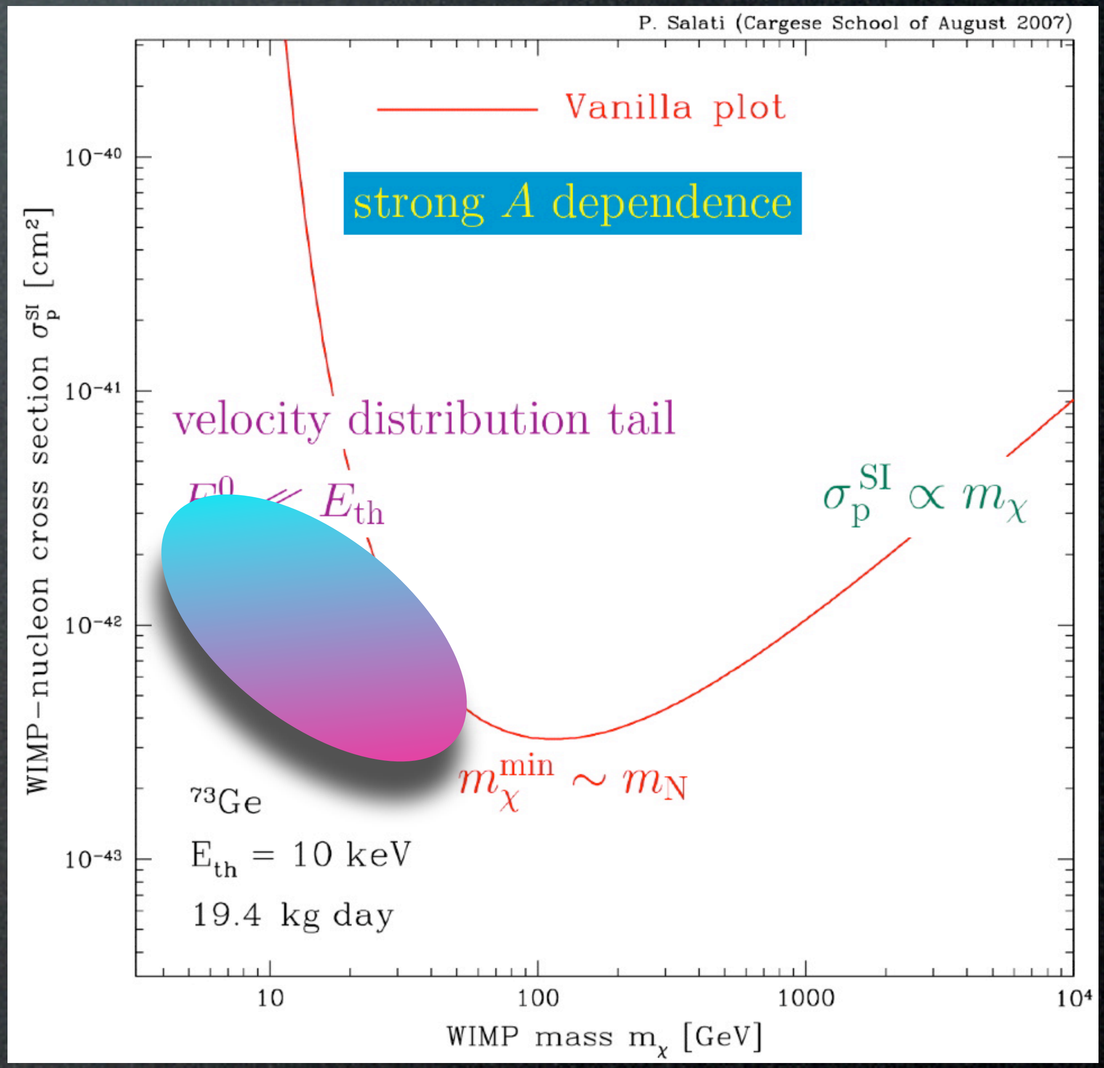
number of events

$$N = \mathcal{E}\,\mathcal{T}\int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$

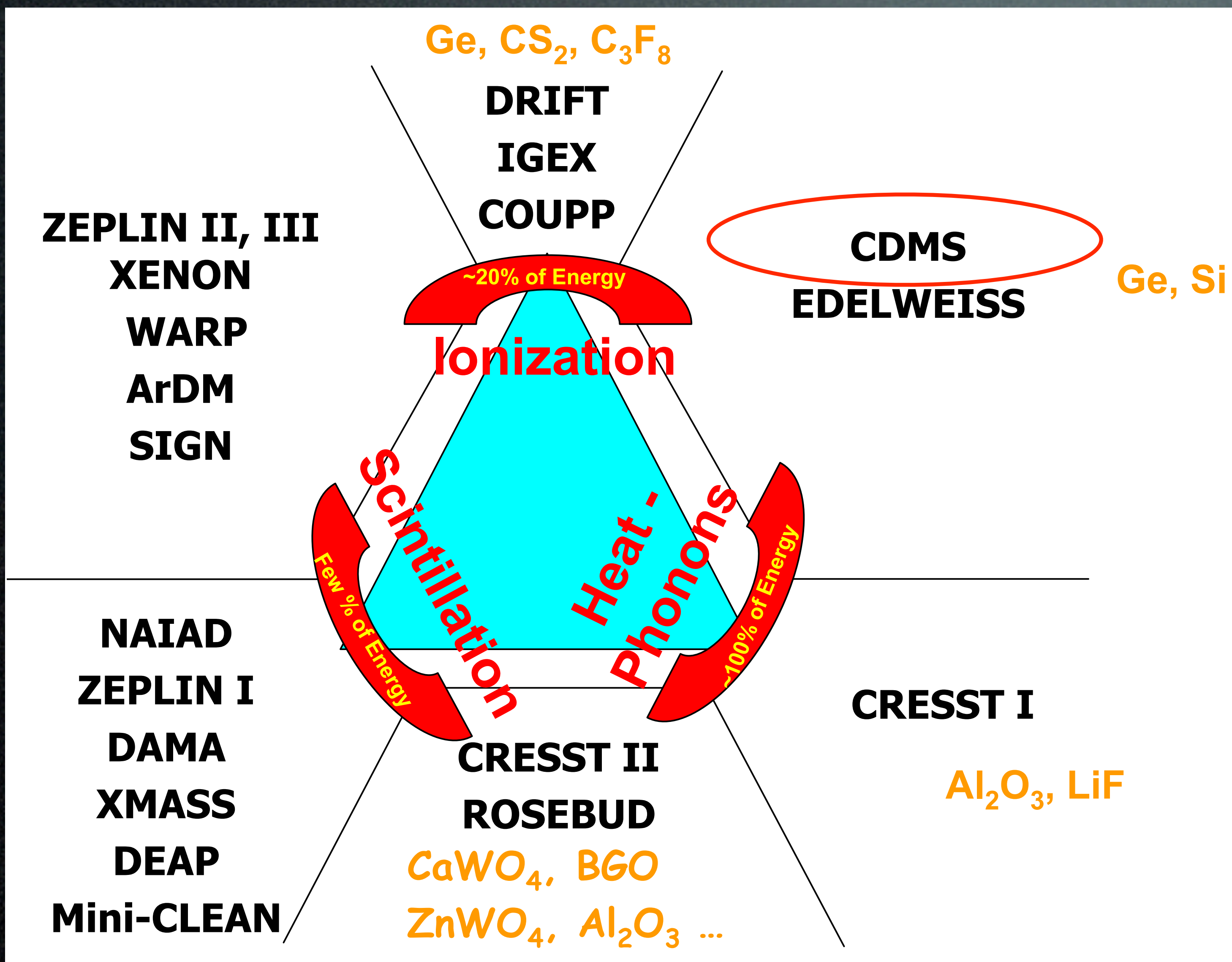
If some events



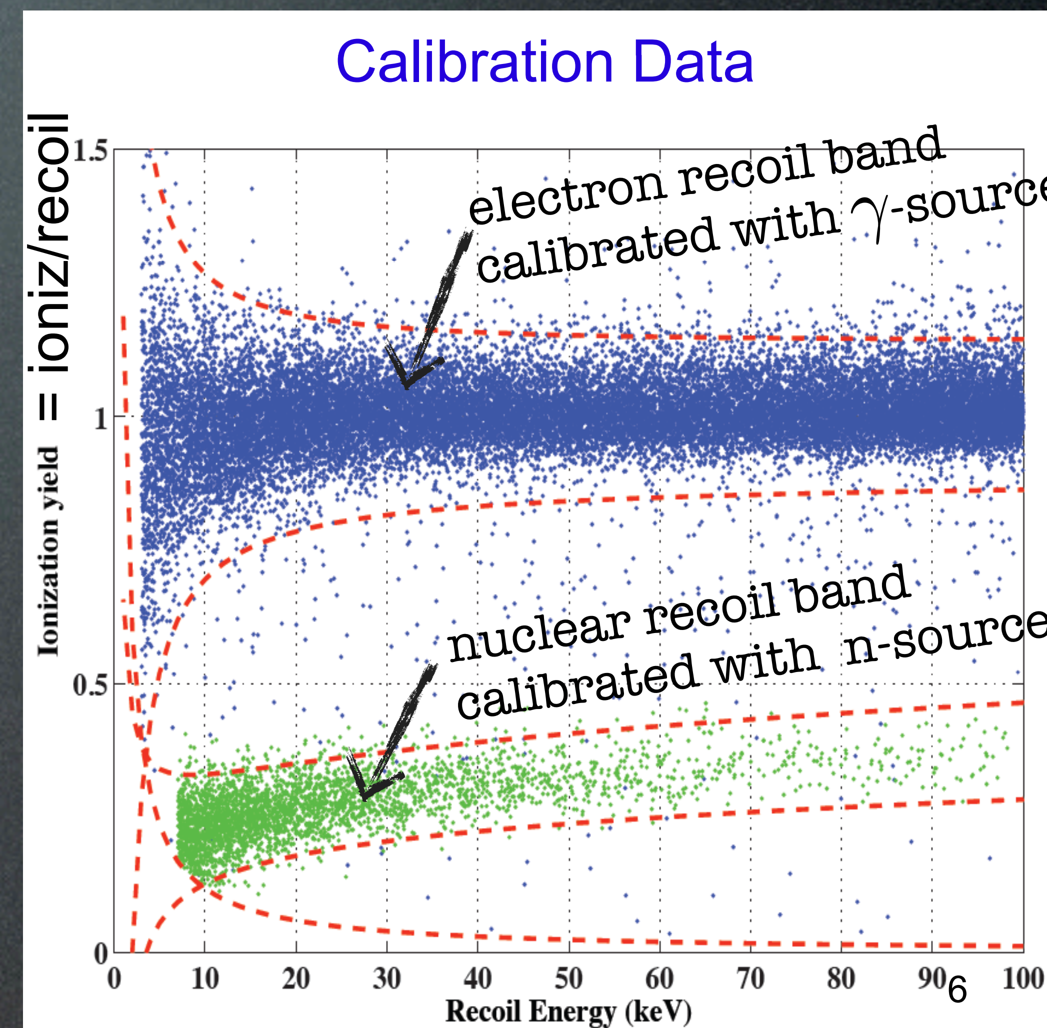
P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

Background rejection



[credit: B.Sadoulet]



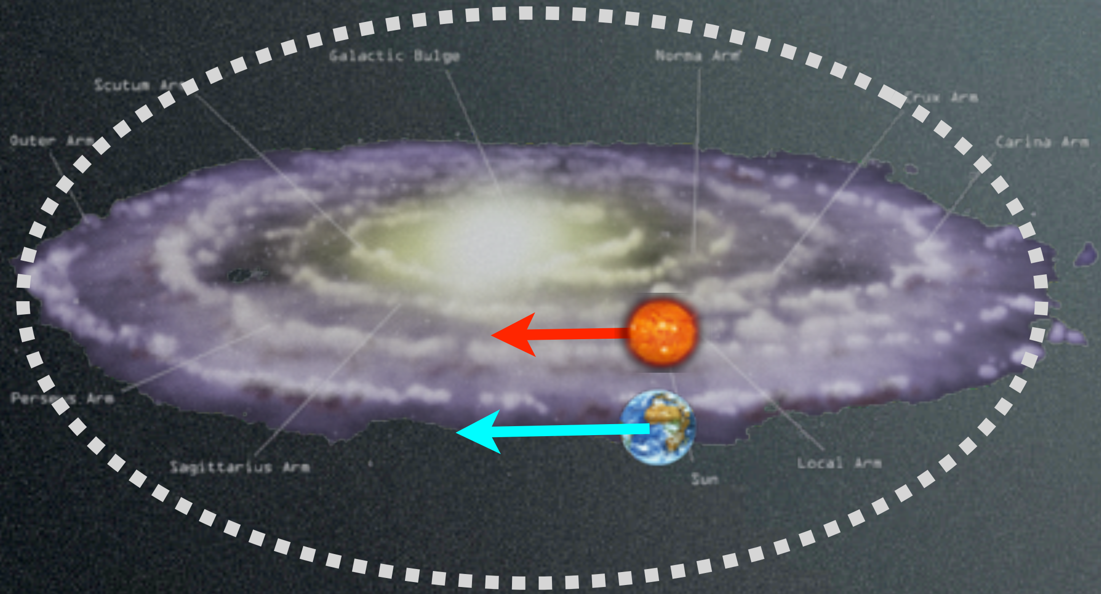
CDMS coll.

measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

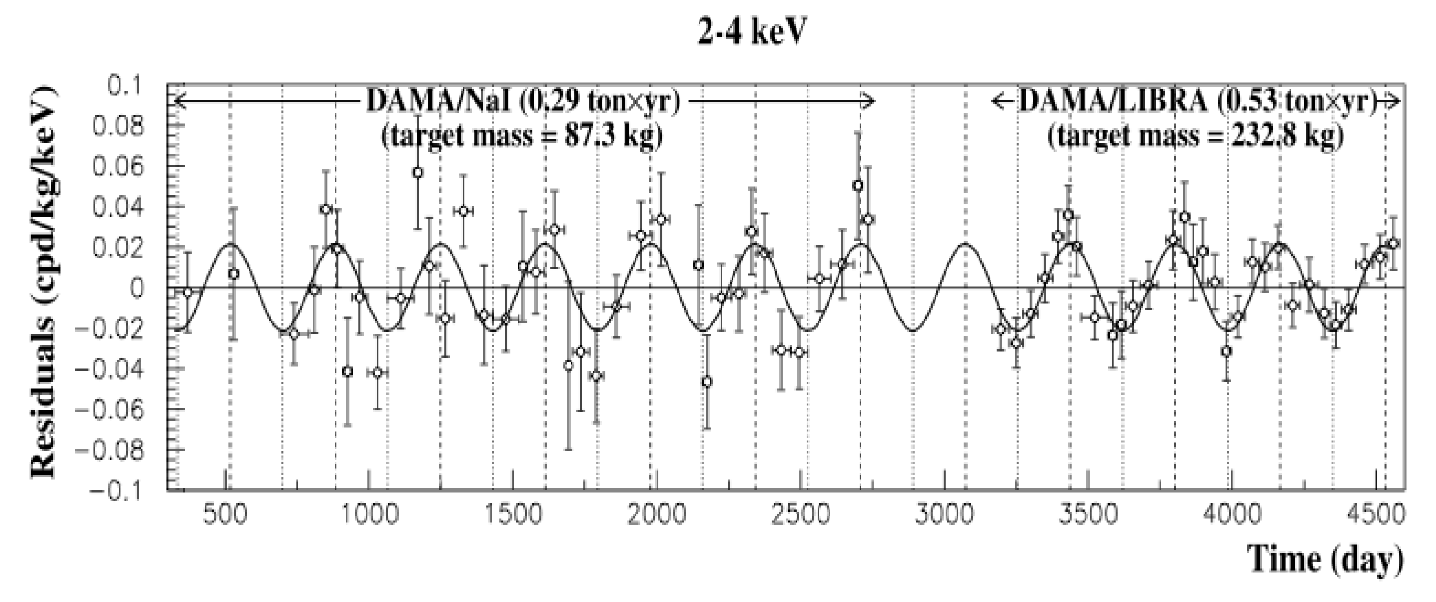
Direct Detection: hints

DAMA/Libra

NaI(Tl)



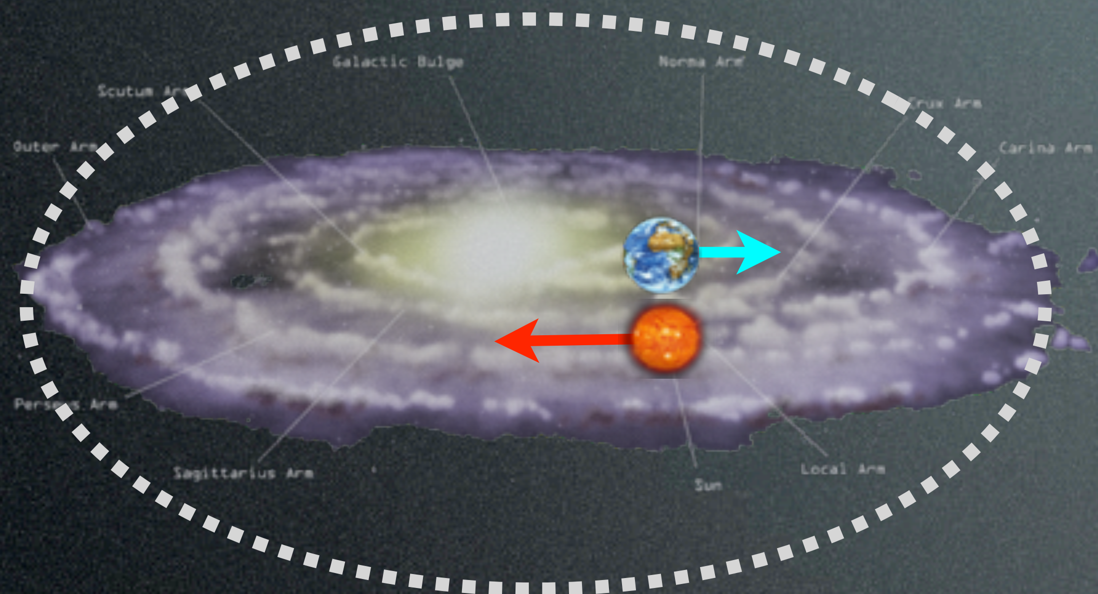
Annual modulation seen (8σ):



DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



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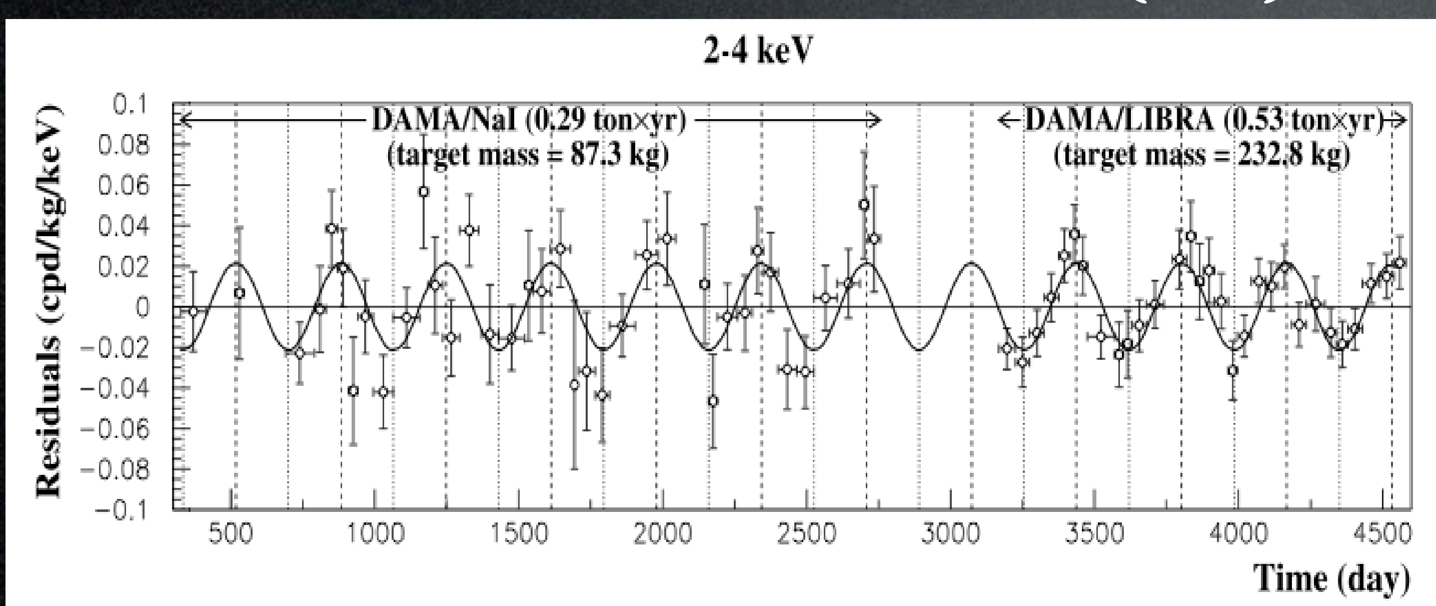
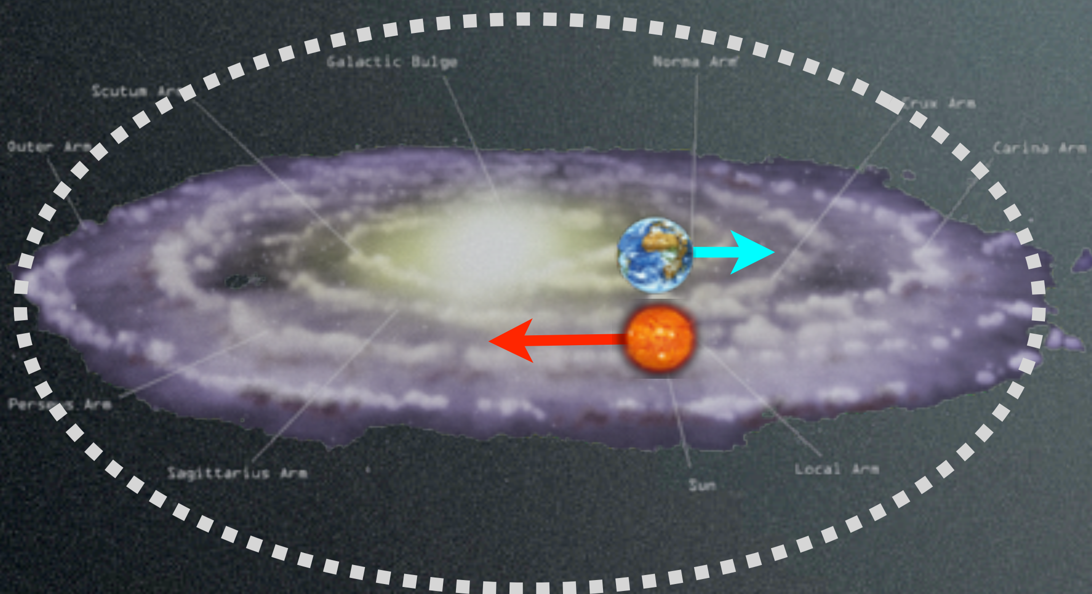


DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



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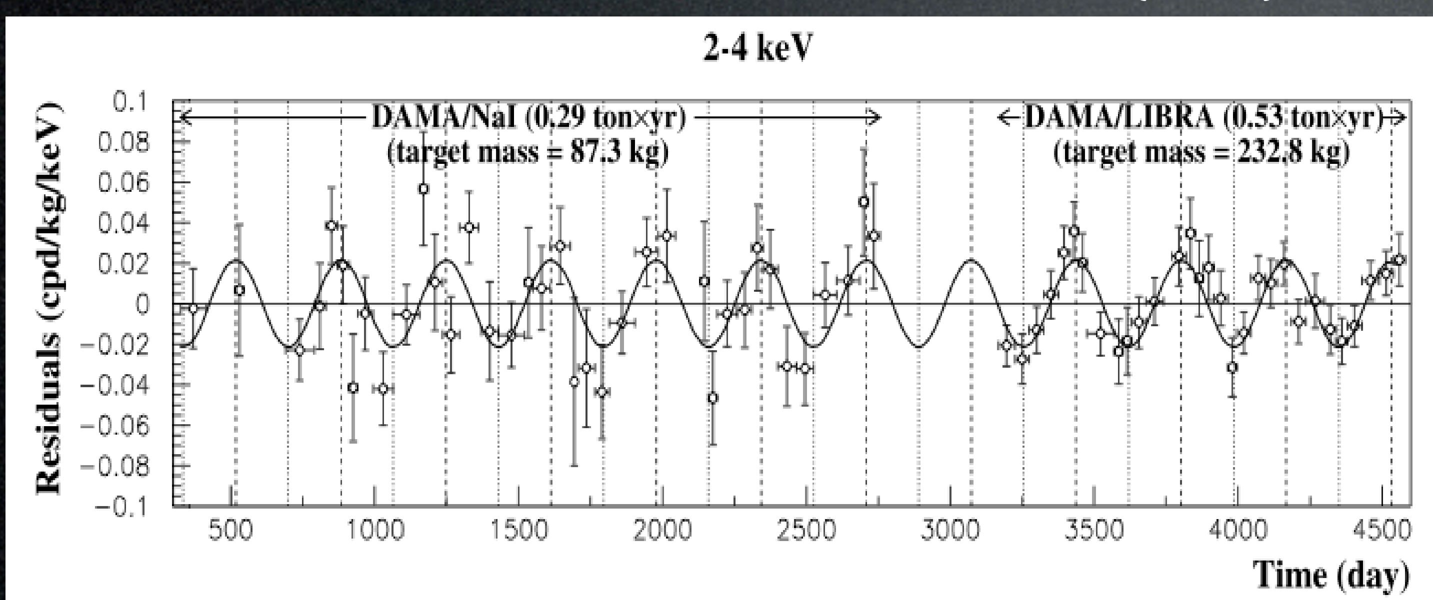


DAMA Coll., 0804.2741, 2008

An instrumental effect?

Summary of the results obtained in the additional investigations of possible systematics or side reactions
(DAMA/LIBRA – NIMA592(2008)297, EPJC56(2008)333)

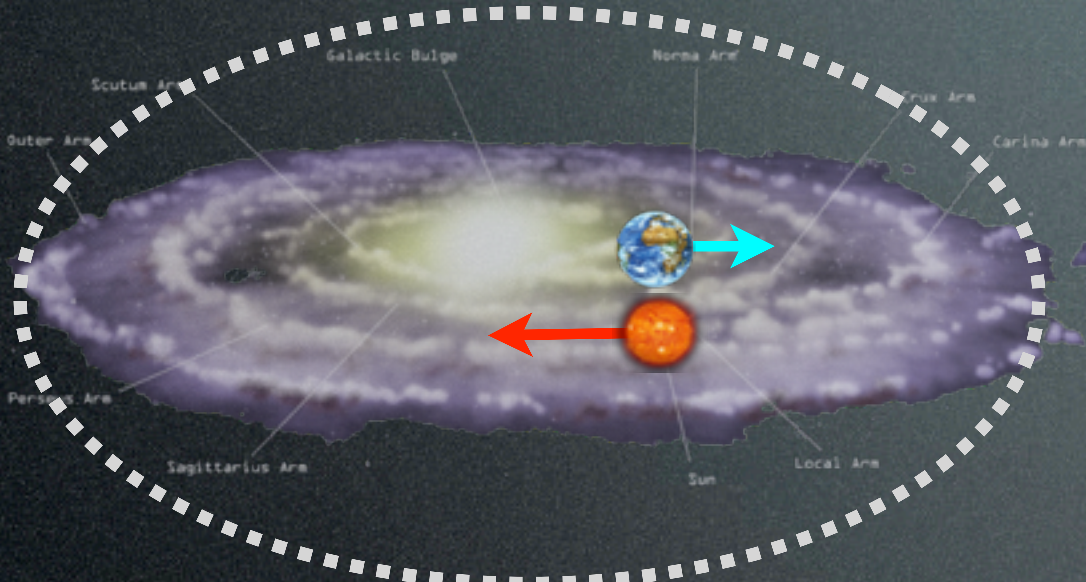
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + instrinsic calibrations	$<1\text{-}2\times10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured by MACRO	$<3\times10^{-5}$ cpd/kg/keV

+ even if larger they cannot satisfy all the requirements of annual modulation signature → Thus, they can not mimic the observed annual modulation effect

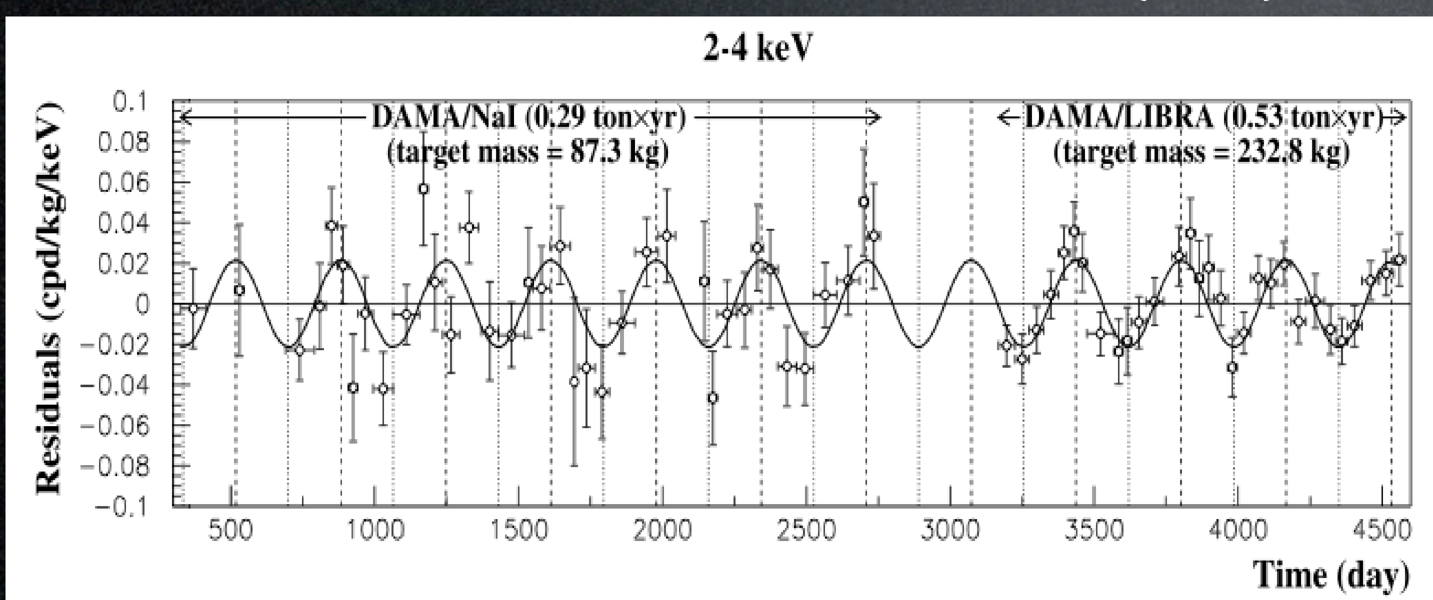
'NO!' e.g. P.Belli, KITP workshop 12.2009

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

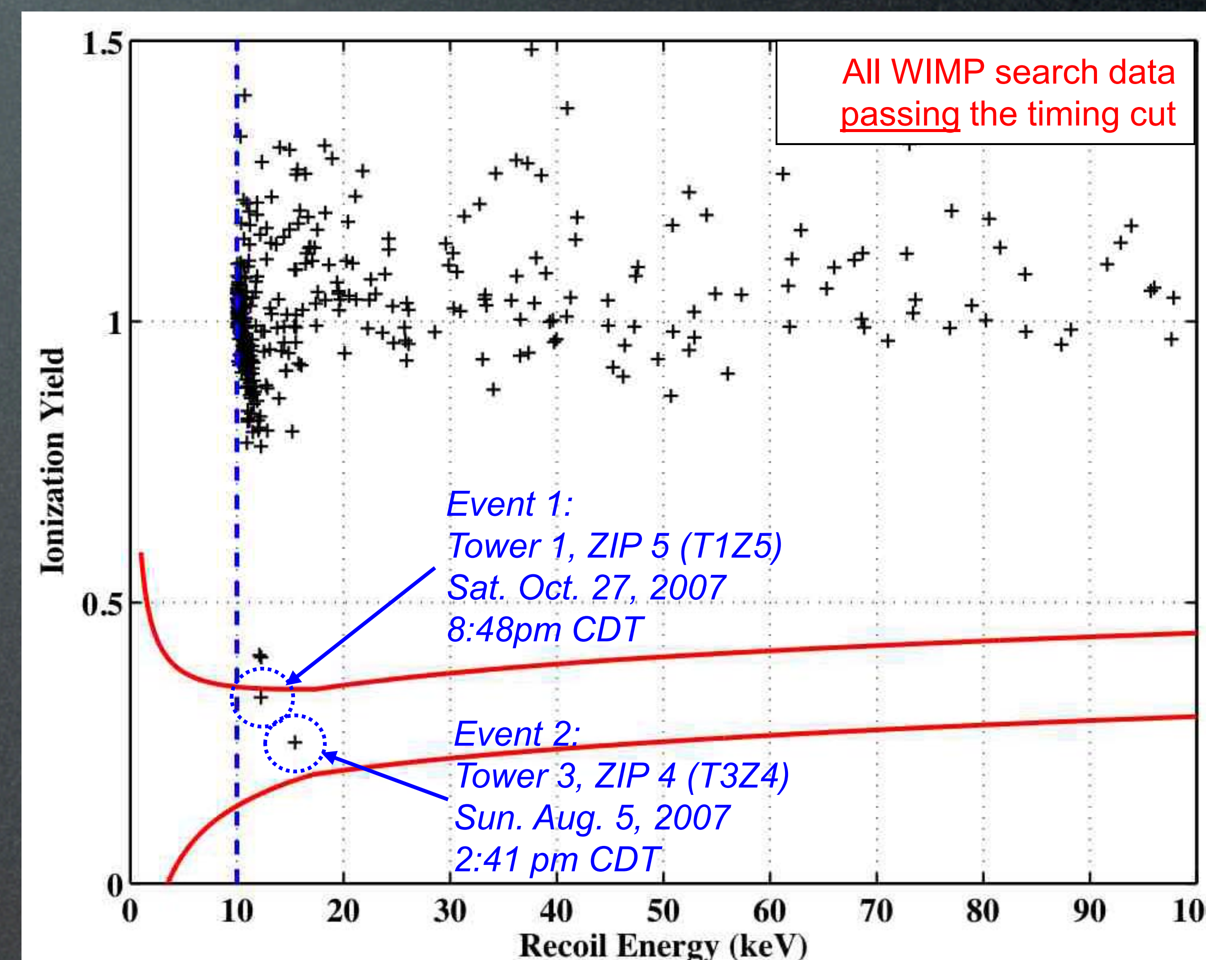


DAMA Coll., 0804.2741, 2008

CDMS

Ge+Si

2 events seen,
with 0.6 exp'd background



CDMS coll., Science 327 (2010), 0912.3592

cited 300 times

DM detection

J. Jochum's lecture

direct detection

Xenon, CDMS (Dama/Li...)

production at colliders

LHC

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

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Icecube, Km3Net

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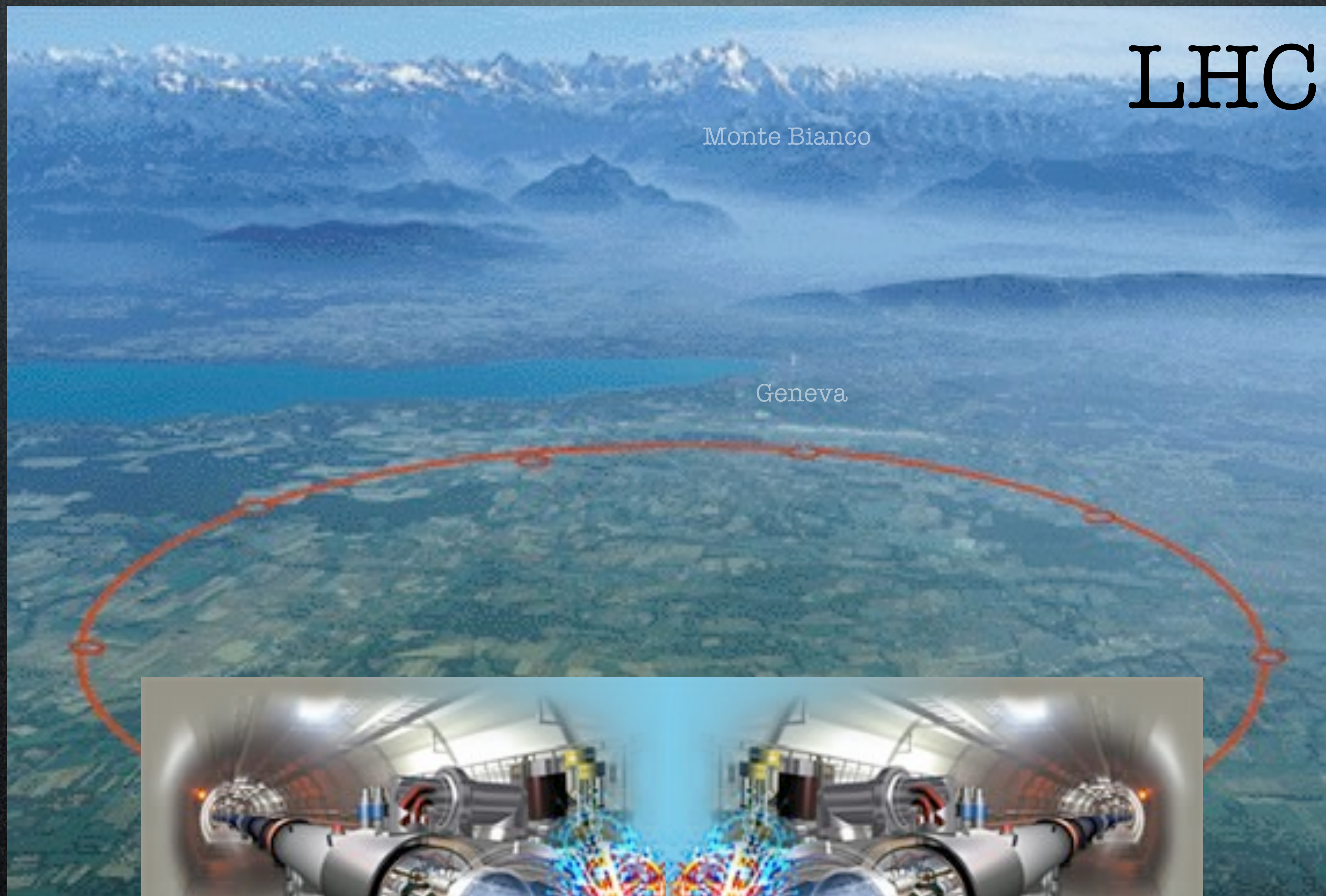
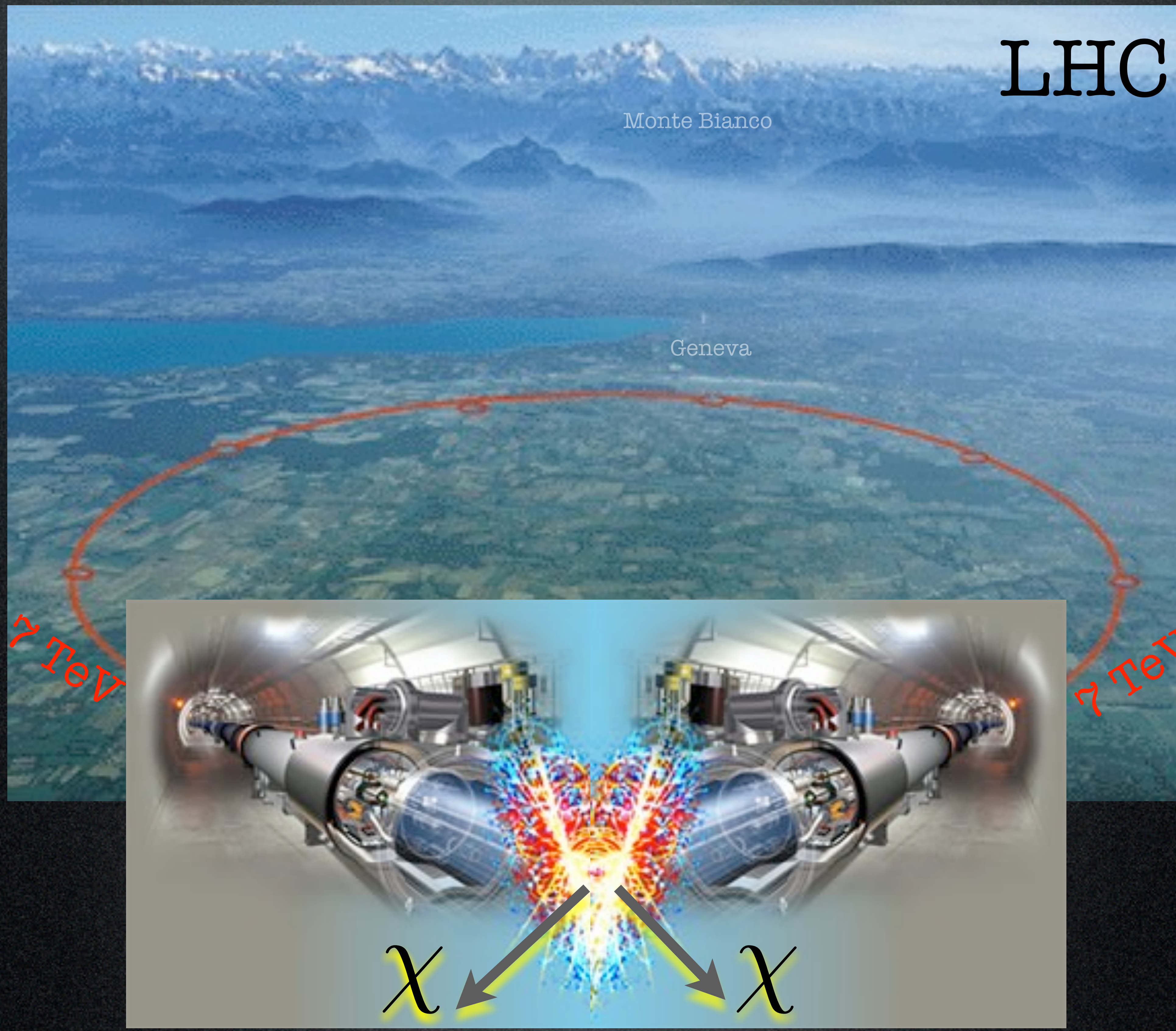
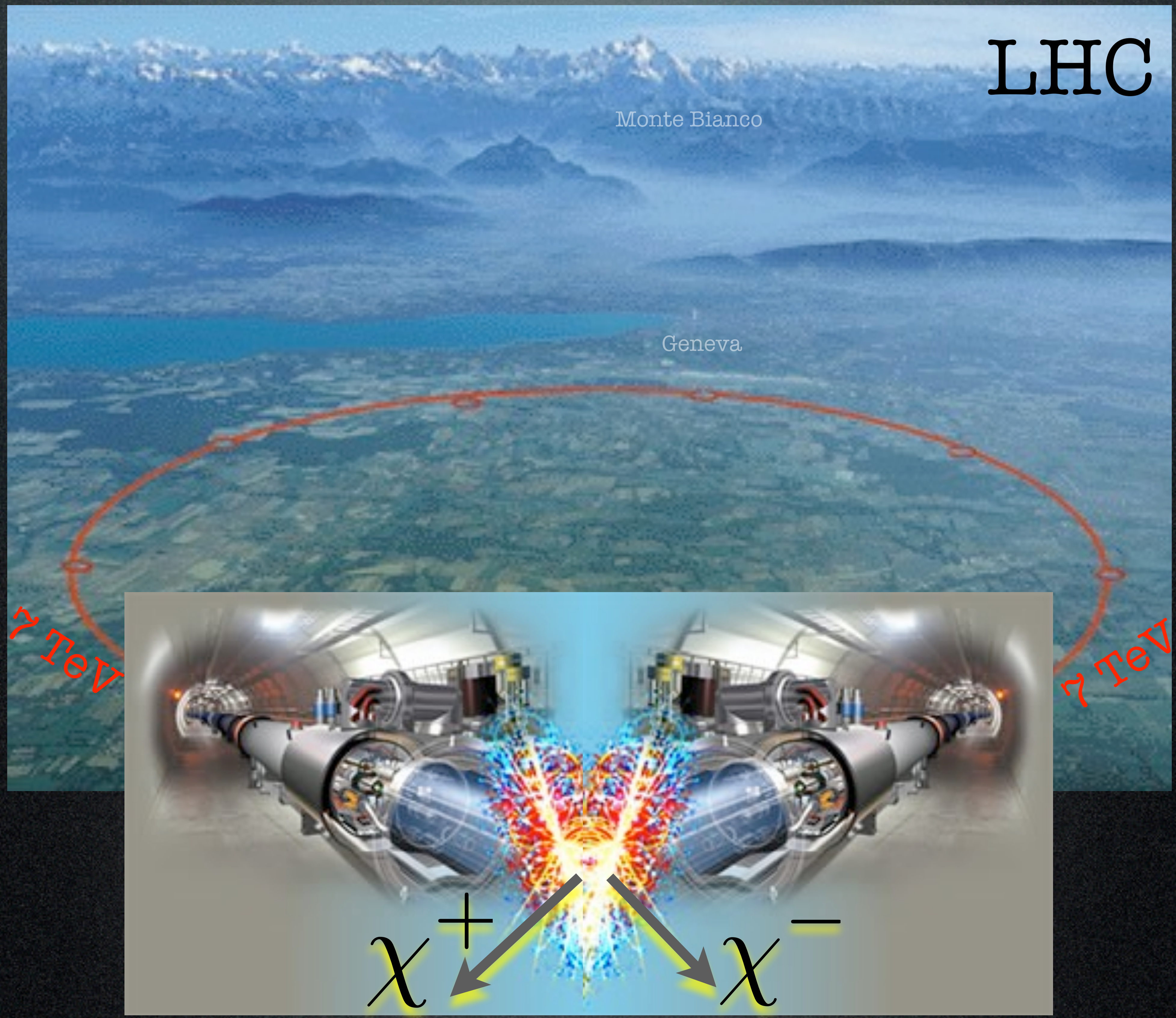


Production at colliders

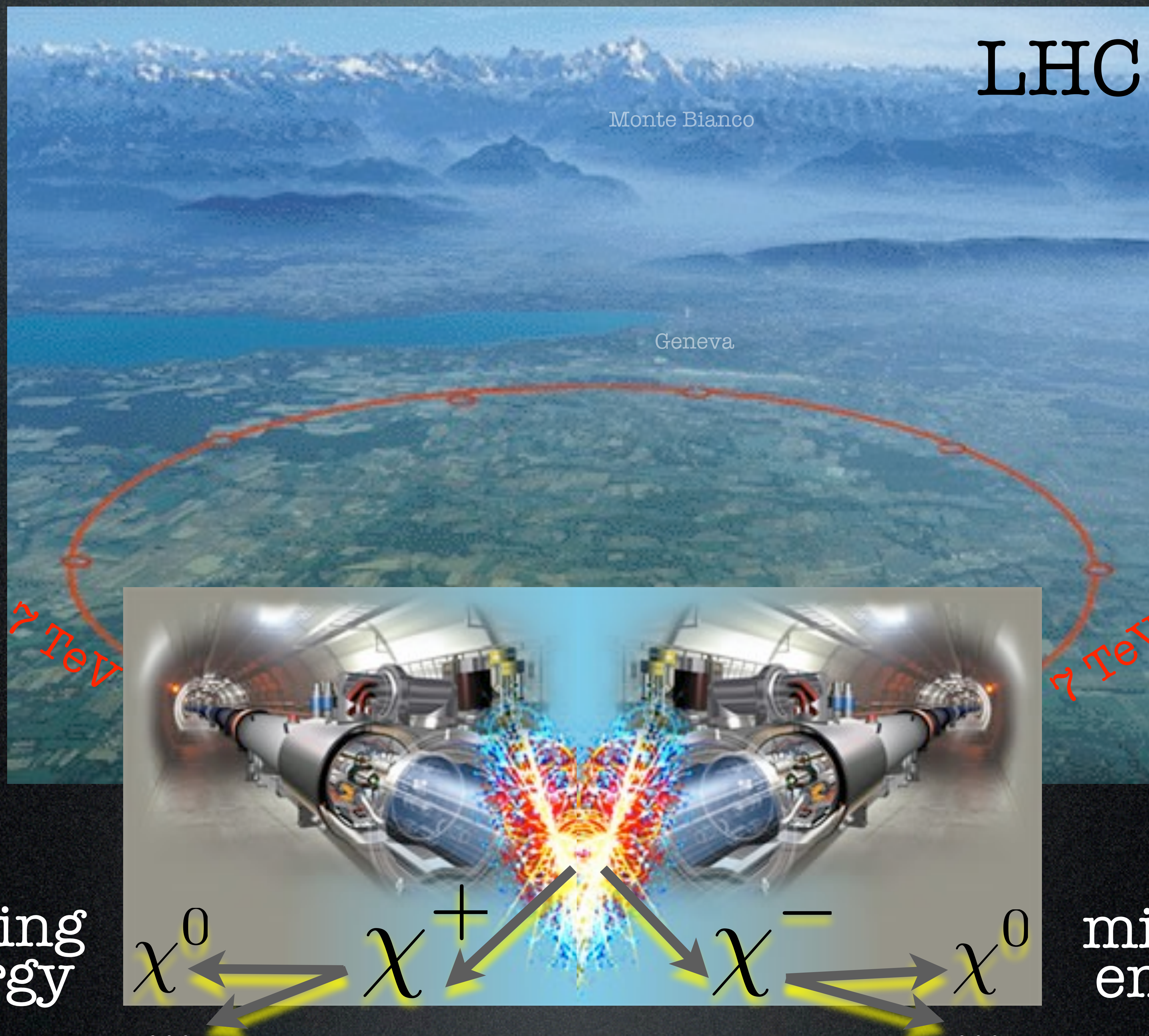


Production at colliders



Production at colliders

missing energy

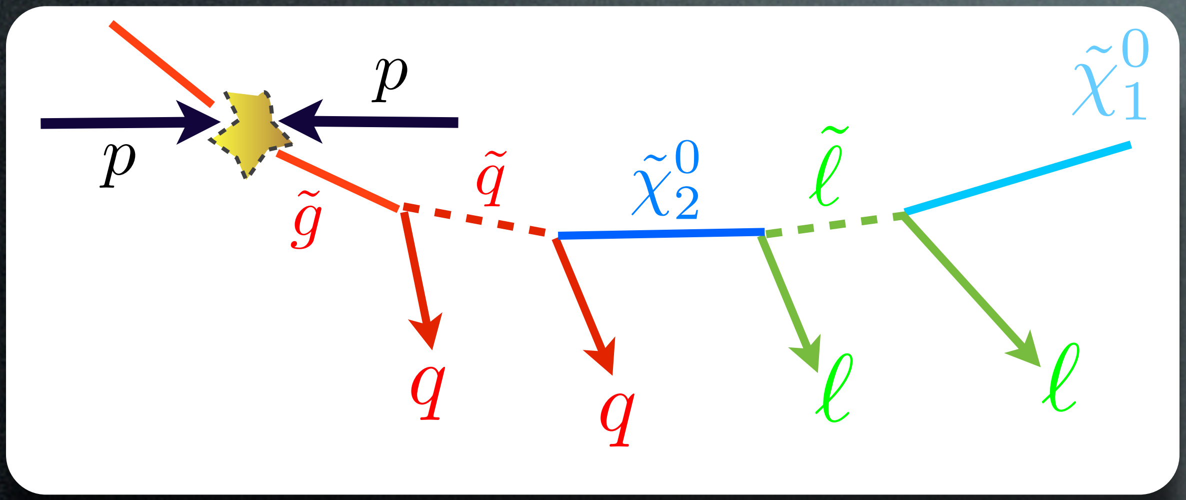


missing energy

Production at colliders

Search strategy 1:

look for decay subproducts of particles in the same theory



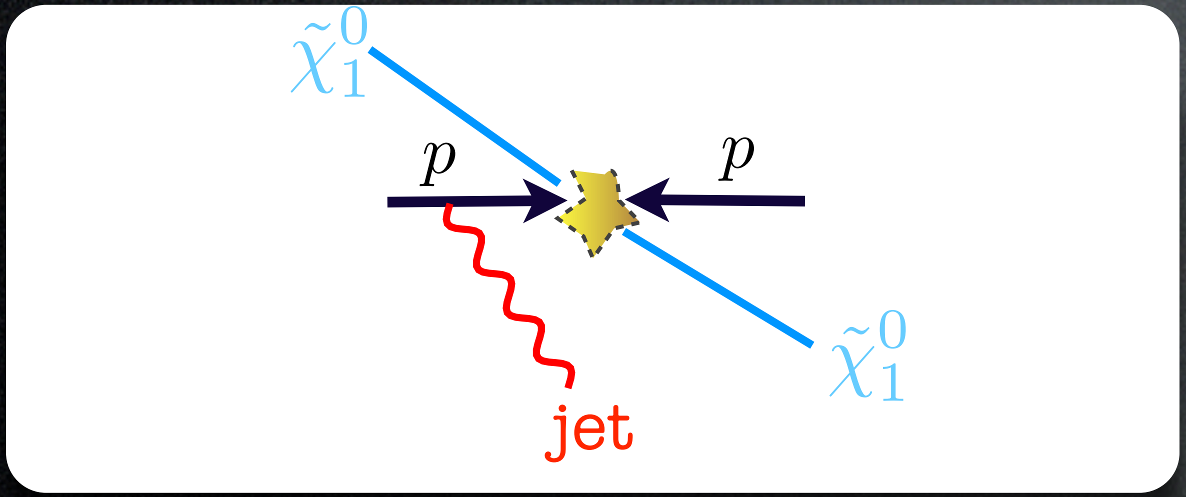
'trigger on 4j+4l+MET...'

- well studied (M_T^2...)
- model dependent

huge literature

Search strategy 2: 'monojets'

e.g. J.Goodman et al., 1008.1783



- 'new'
- more model independent

DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

T. Plehn's lecture

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

GAPS

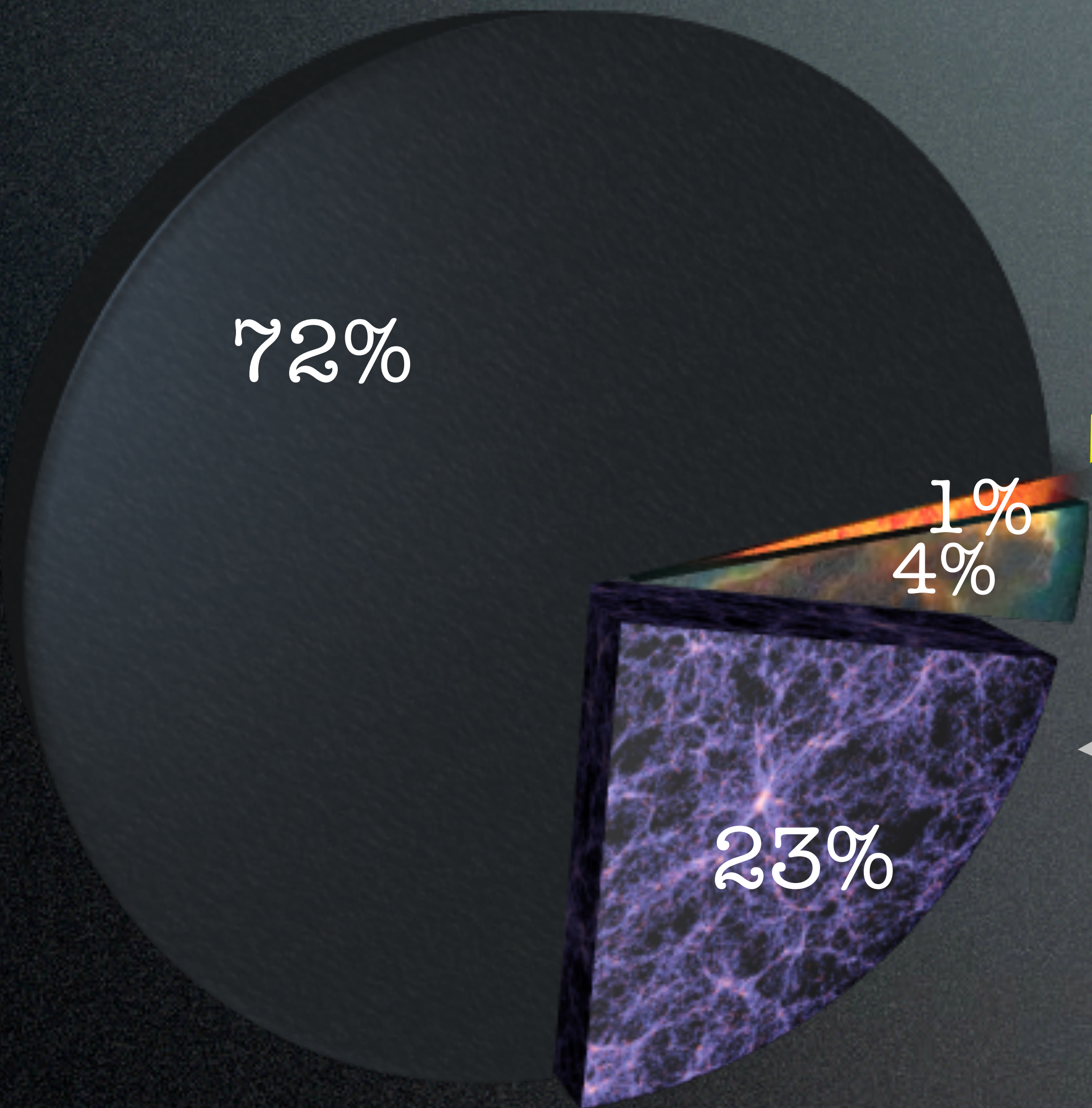
$\nu, \bar{\nu}$ from annihil in massive bodies

Icecube, Km3Net

How do we know that
Dark Energy is out there?

The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$ -BBN -CMB

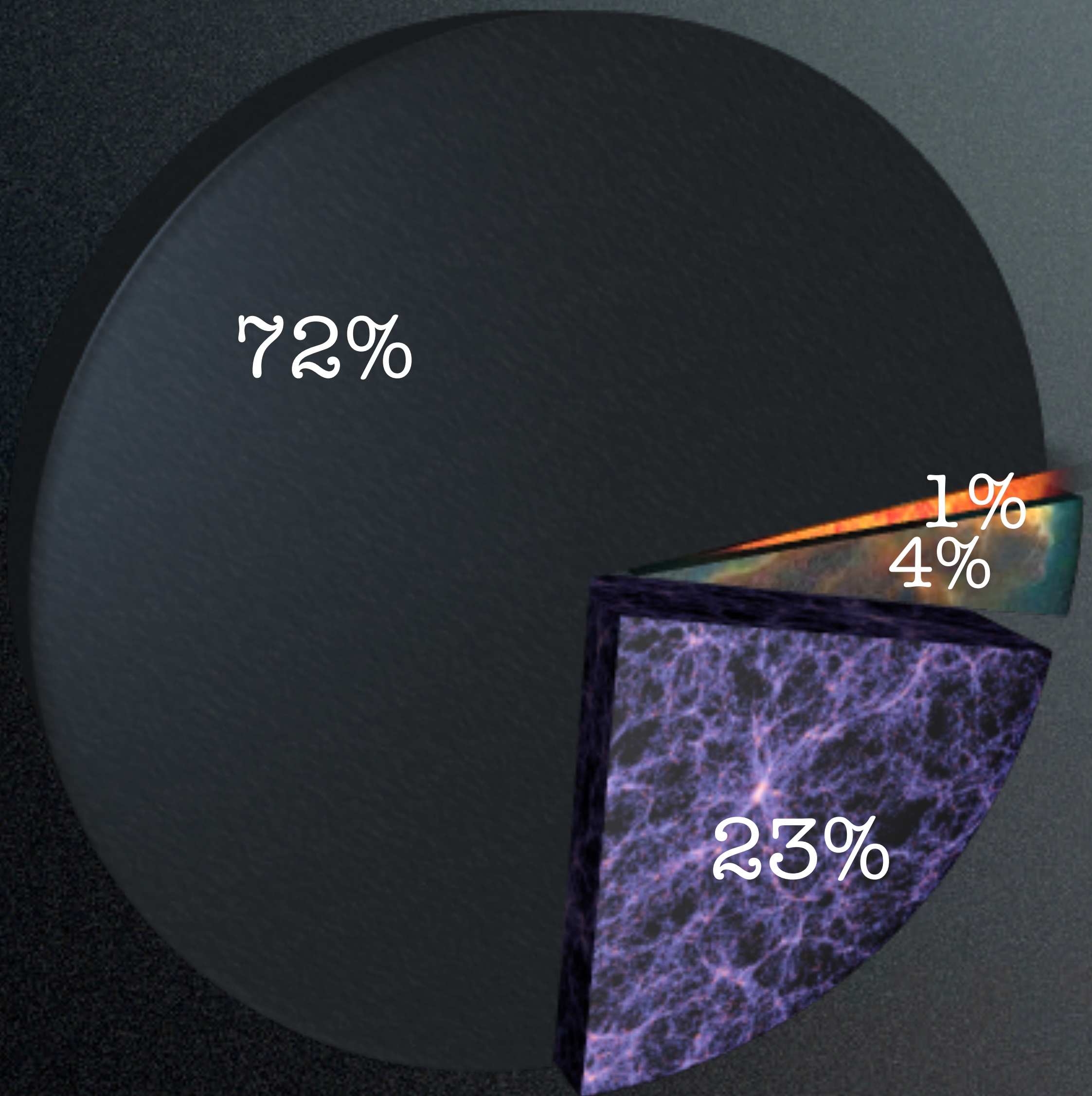
$\Omega_{\rm DM} \sim 0.23$

$\Omega_{\rm de} \sim 0.72$
- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1\ (\text{flat});\ \text{HST}\ h = 0.71 \pm 0.07\right)$$

what's the difference between DM and DE?

The cosmic inventory



‘Definition’ of Dark Energy:

FRW #2

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

if $\rho < -p/3$ i.e. $w := \frac{\rho}{p} < -\frac{1}{3}$

$\Rightarrow$ acceleration!

special case:

$\rho = -p$ i.e. $w = -1$

cosmological constant Λ

(constant as $\rho_i \propto (1+z)^{3(1+w_i)} \rightsquigarrow \text{const}$)

$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\text{tot}} = 1\ \text{(flat)};\ \text{HST}\ h = 0.71 \pm 0.07\right)$

The Evidence for DE

1) Supernovae type Ia:

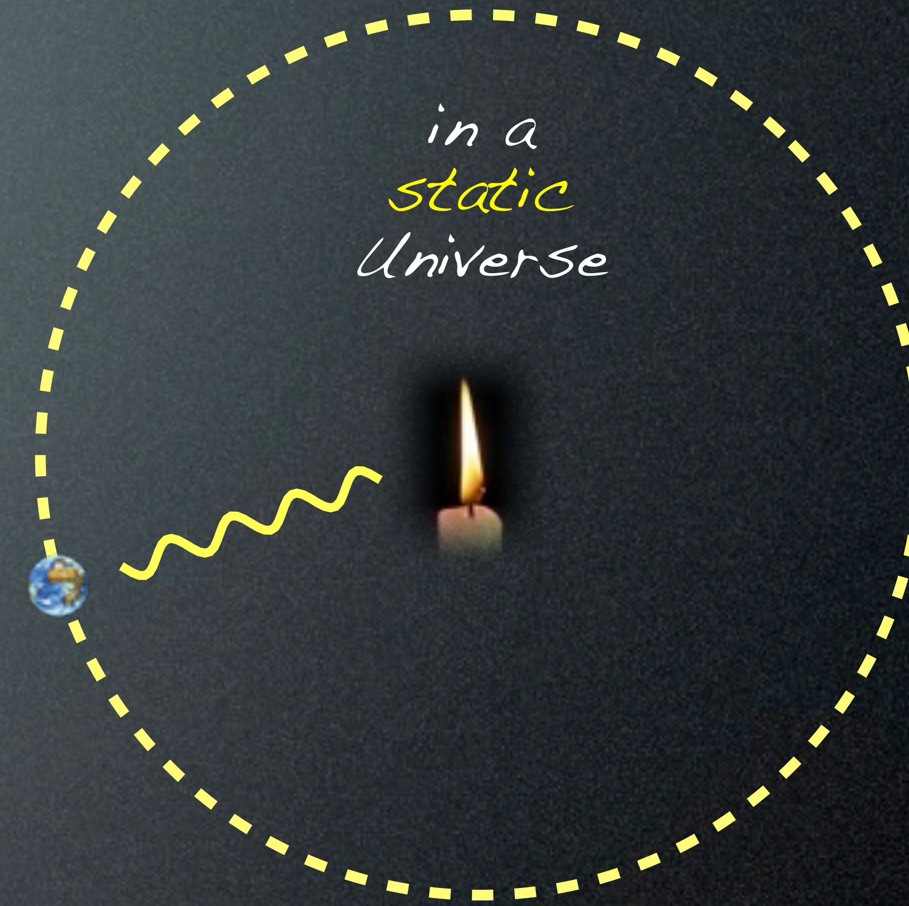
‘standard candles’

$$\mathcal{L} = 4\pi F\, d_{\rm L}^2$$

Luminosity (‘known’)

Flux (‘measured’)

Luminosity distance (‘unknown’)



The Evidence for DE

1) Supernovae type Ia:

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$(1+z)$ due to redshift
$(1+z)$ due to expansion

$$\mathcal{L} = 4\pi F\, d_{\mathrm{L}}^2 = 4\pi F\, \chi^2 (1+z)^2$$

Luminosity (‘known’)

comoving distance (‘unknown’)

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Luminosity
(‘known’)

comoving distance
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$$\chi(z) = \int_0^z \frac{dz'}{H(z)} = \int_0^z \frac{dz'}{H_0\sqrt{\Omega_{\rm M}(1+z')^3 + (1-\Omega_{\rm M})(1+z')^{3(1+w)} + \Omega_{\rm R}(1+z')^4}}$$

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so $\mathcal{L}$ as fnct of z and $\Omega_{\rm M}, \Omega_\Lambda$

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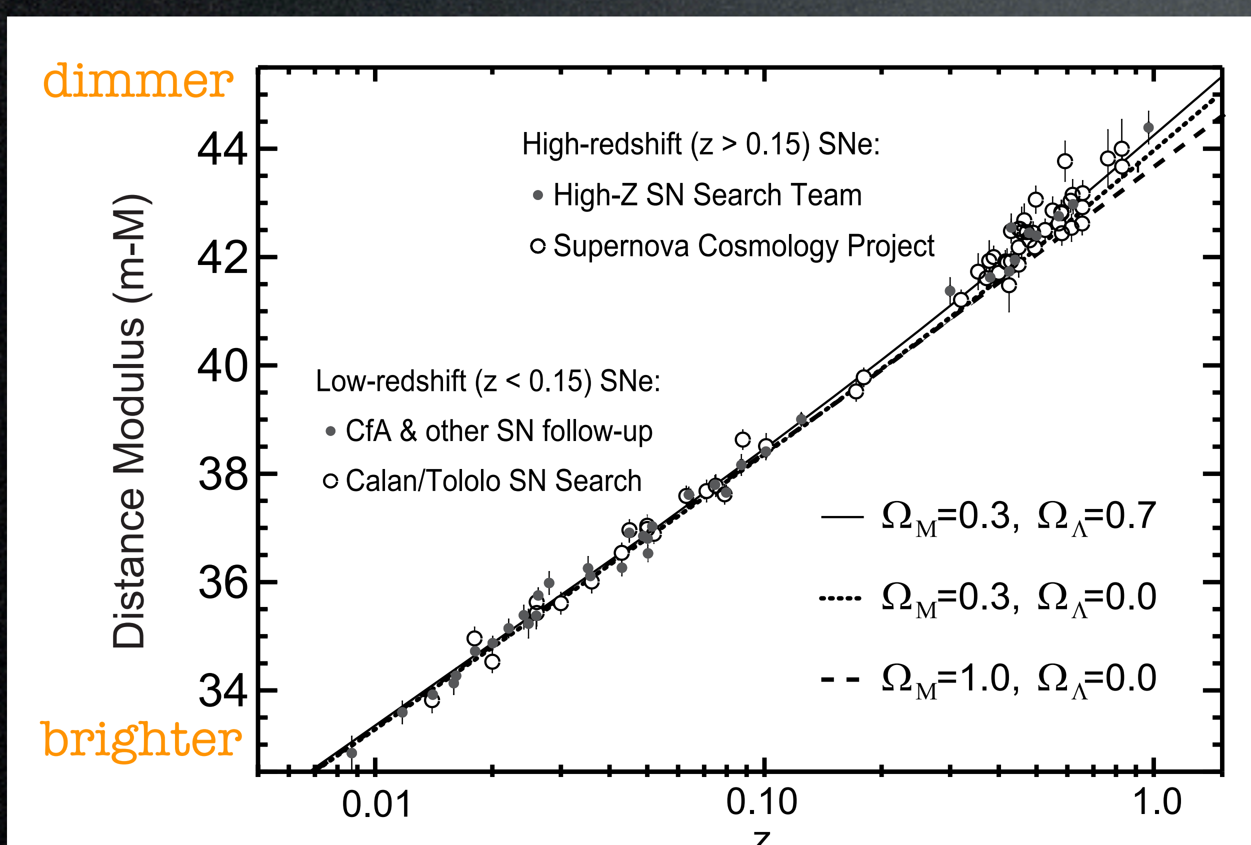
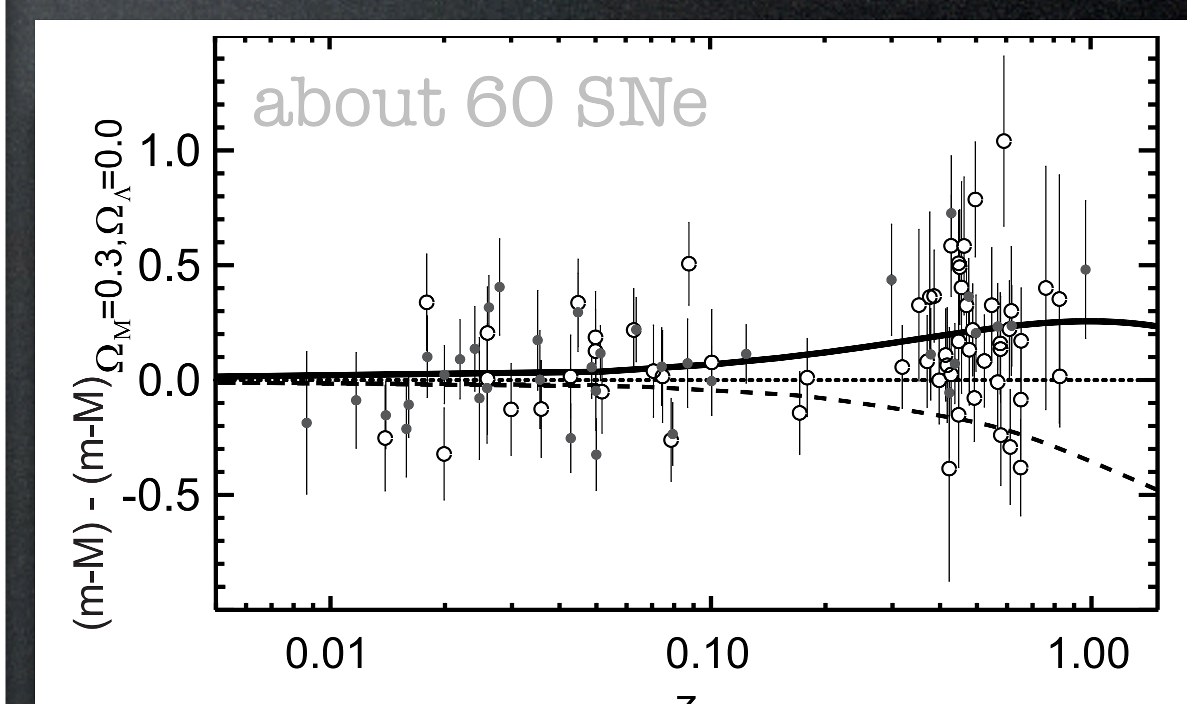


Perlmutter et al., 1999, Astrophys. J. 517
Riess et al., 1998, Astron. J. 116



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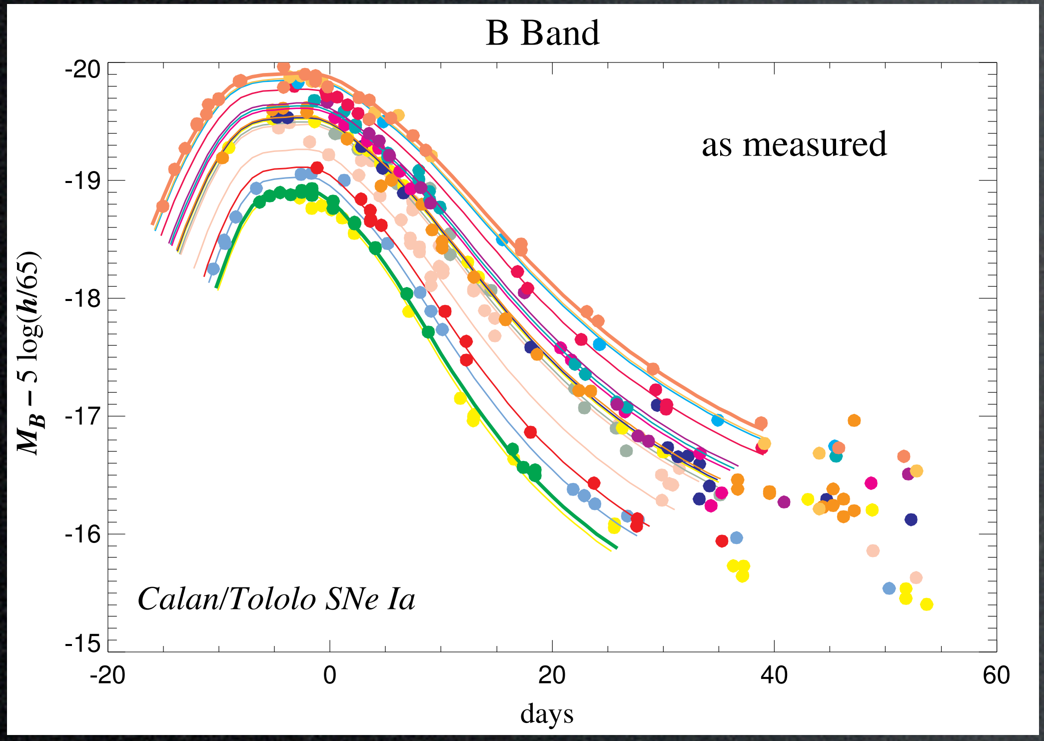
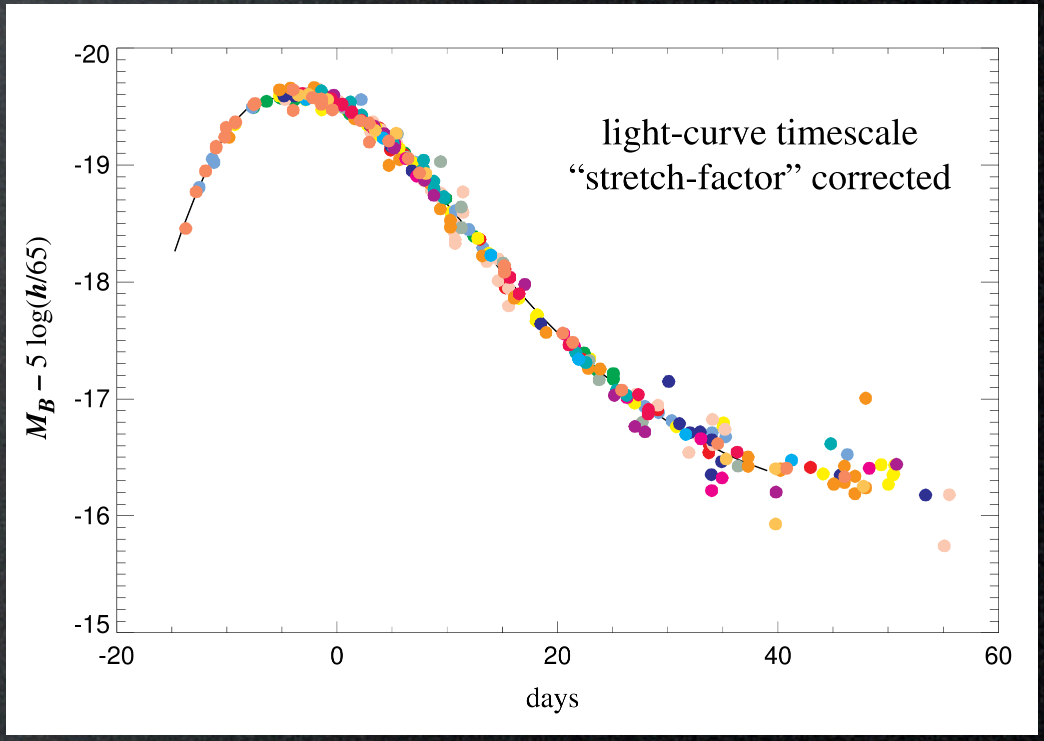
Well, they are not really standard, let’s standardize them



peak $\propto$ duration of lightcurve



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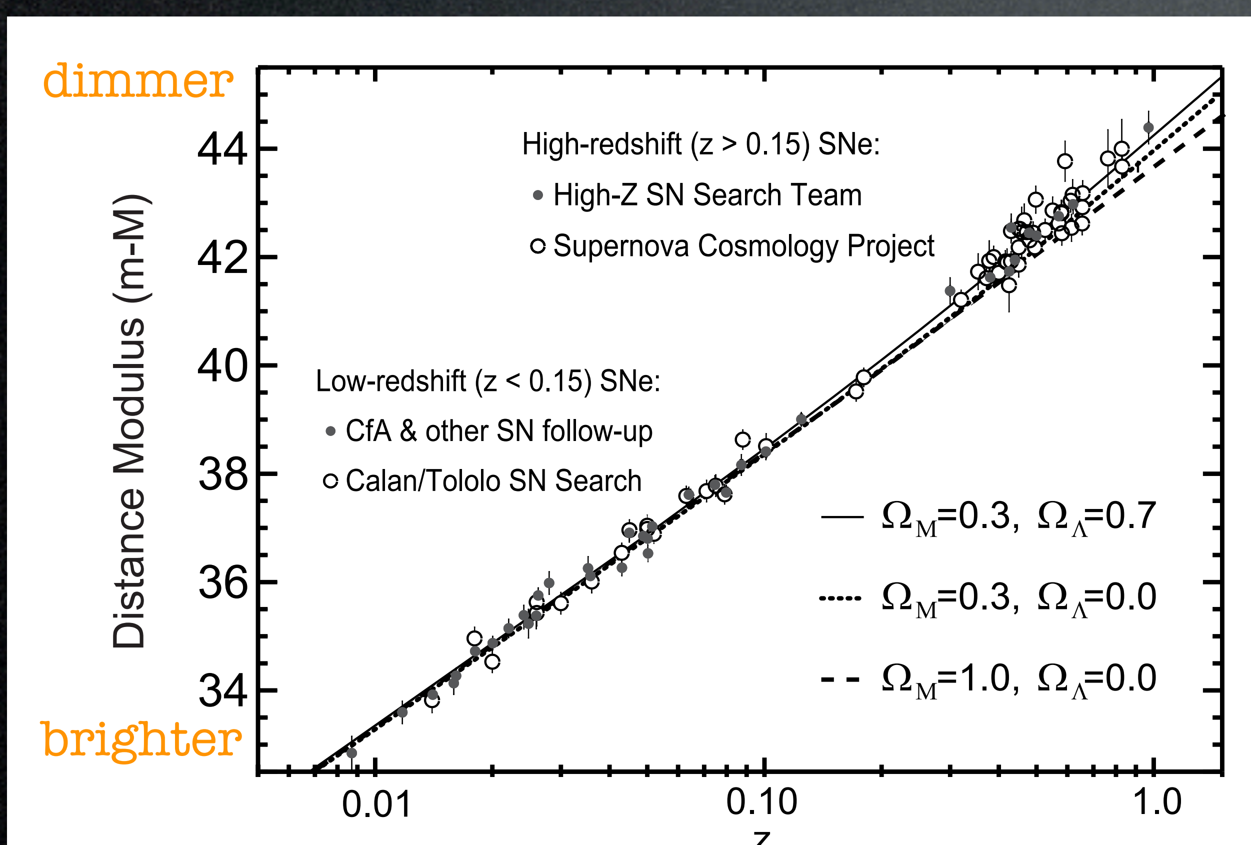

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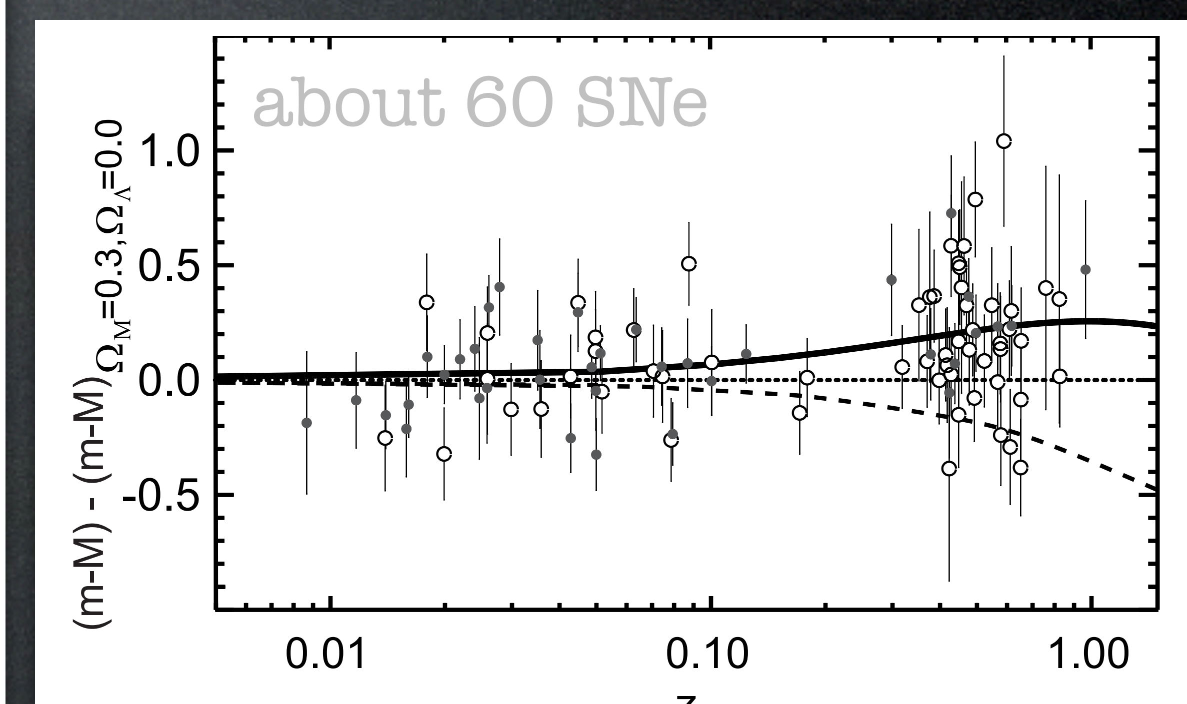

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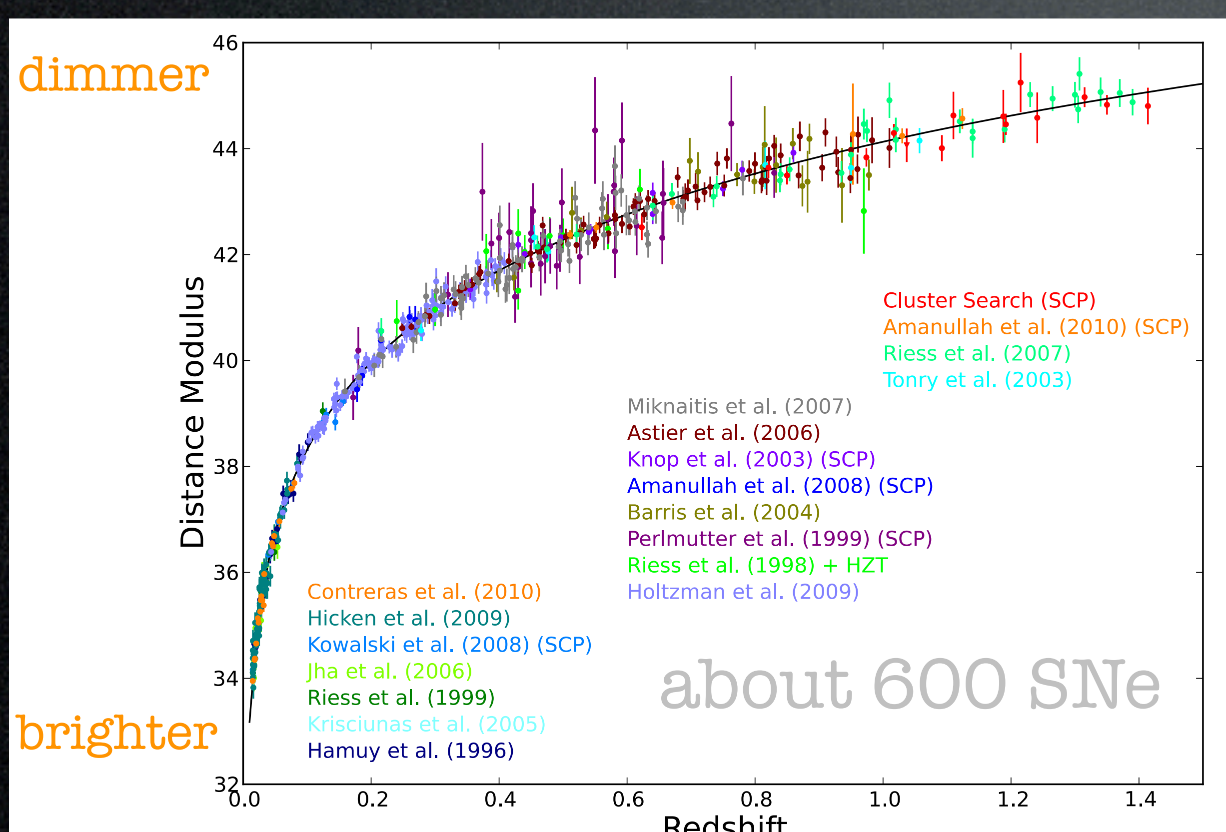


Suzuki et al., 1105.3470

Bottom line:

distant SNe appear dimmer than predicted in a Universe without DE,

the Universe has accelerated in the past 5 Gyr

The Evidence for DE

2) Baryon Acoustic Oscillations:

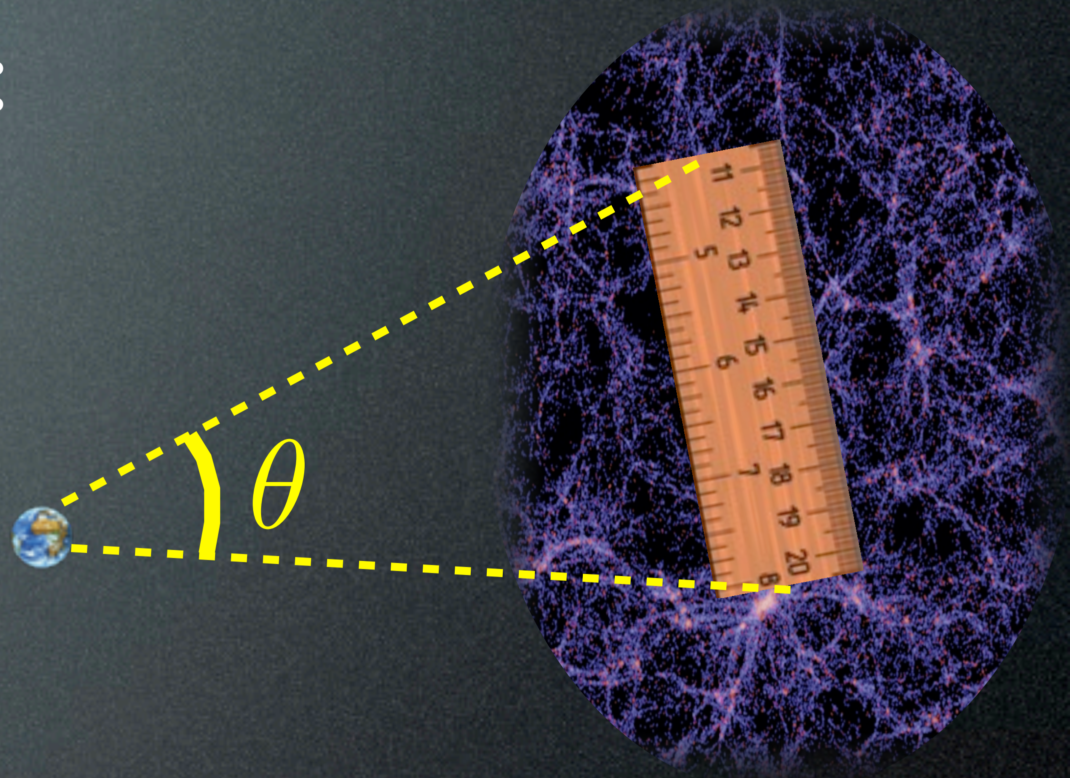
'standard ruler'

$$L = \theta \, d_{\mathrm{A}}$$

Length ('known')

Angle ('measured')

Angular distance ('unknown')



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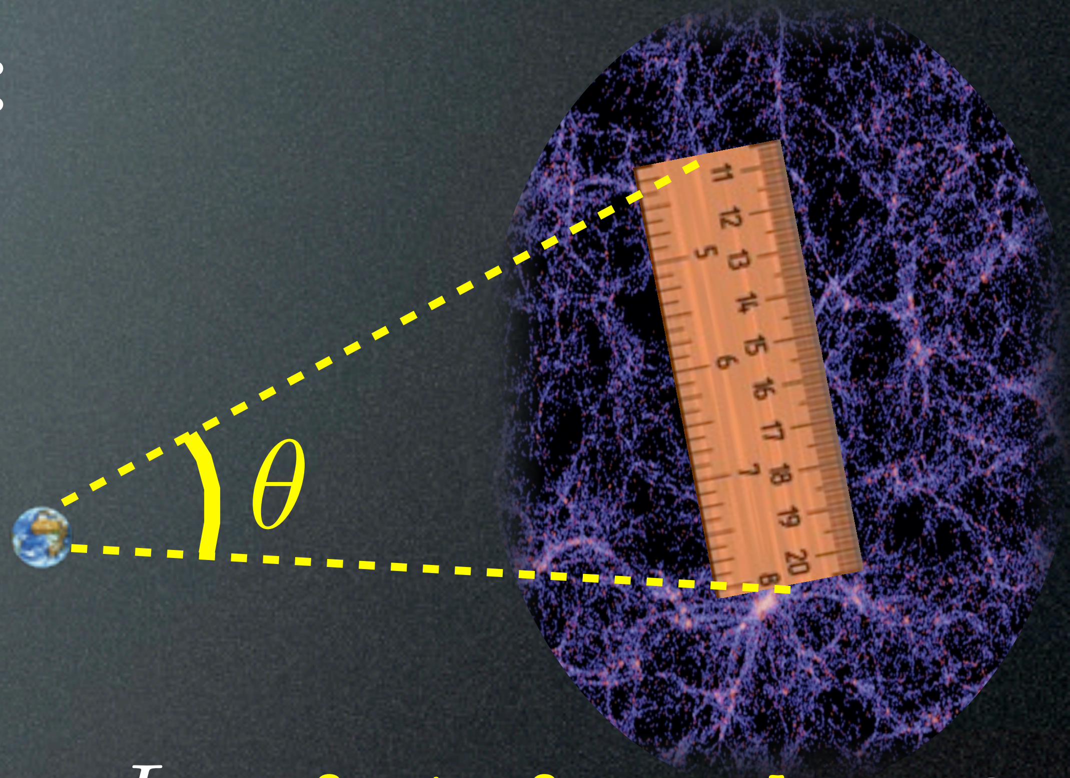

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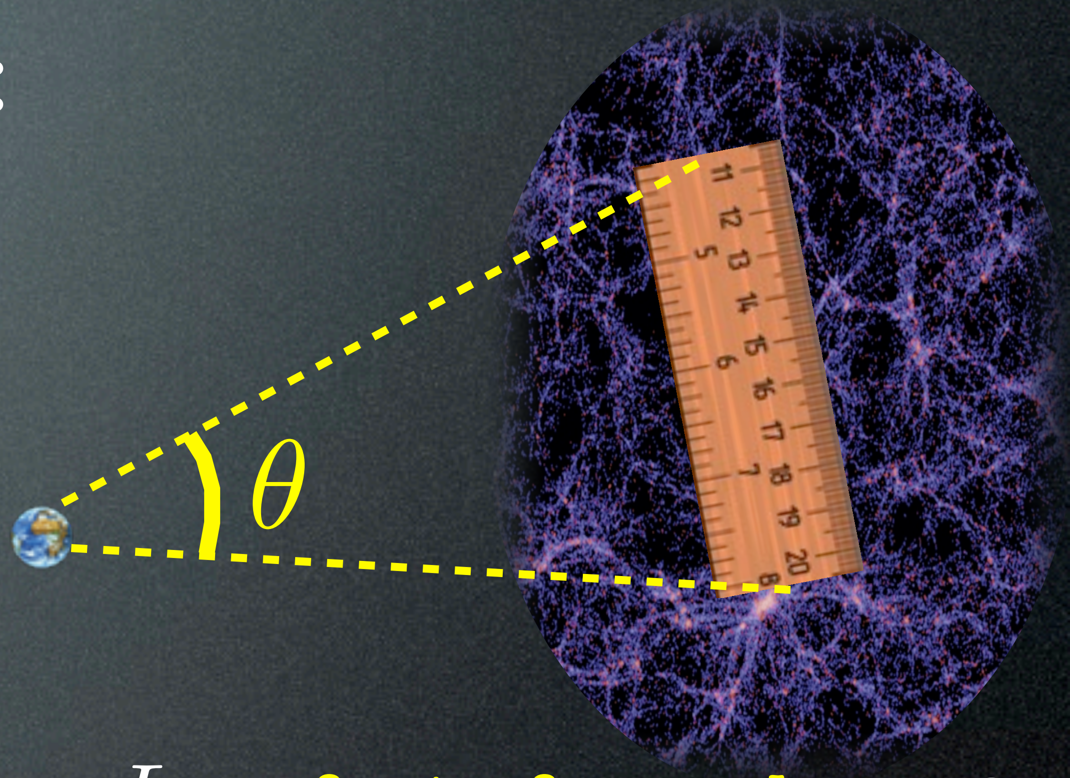

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What is the 'ruler'?

D.Eisenstein, cmb.as.arizona.edu/~eisenste/acousticpeak/

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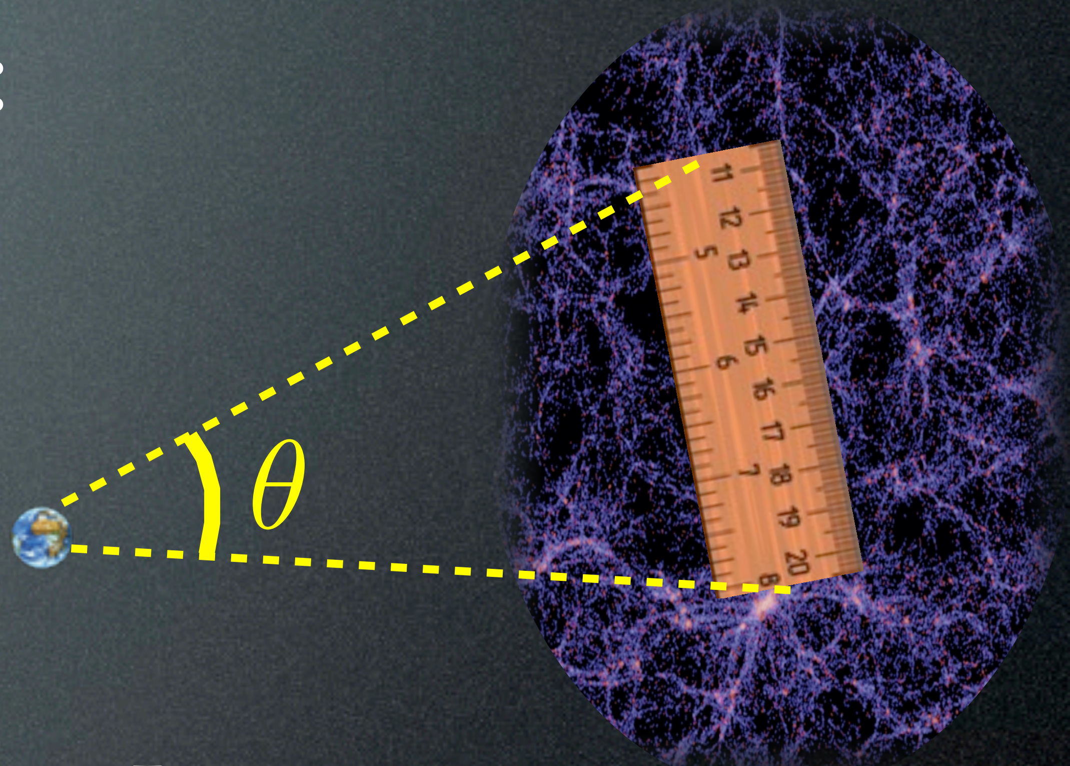

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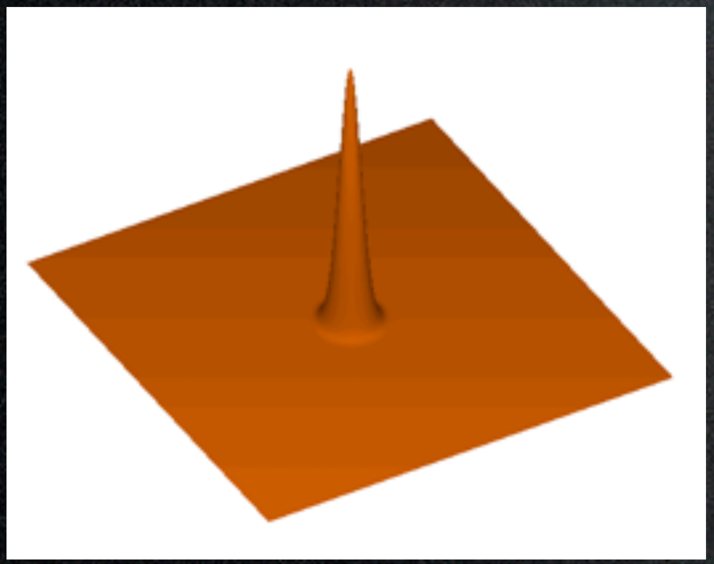

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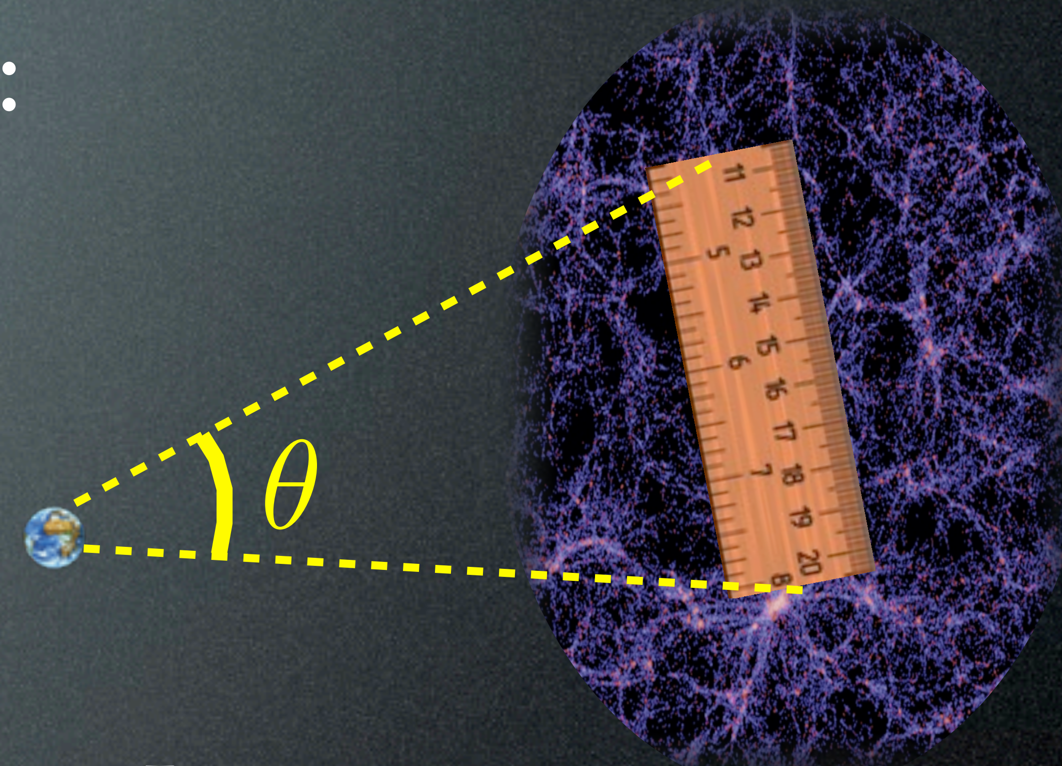

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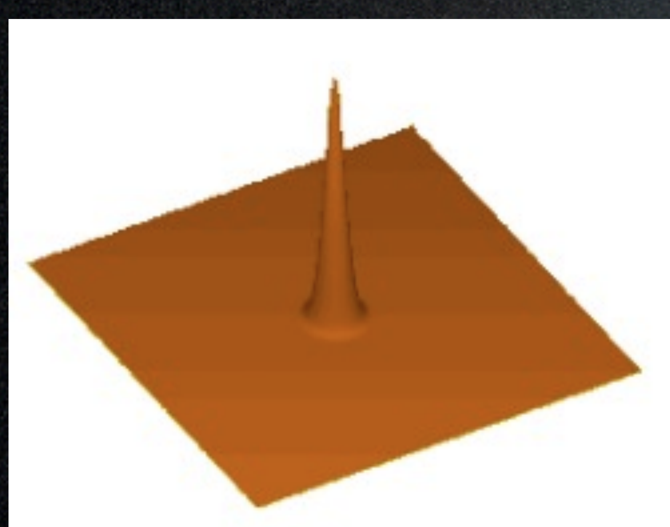

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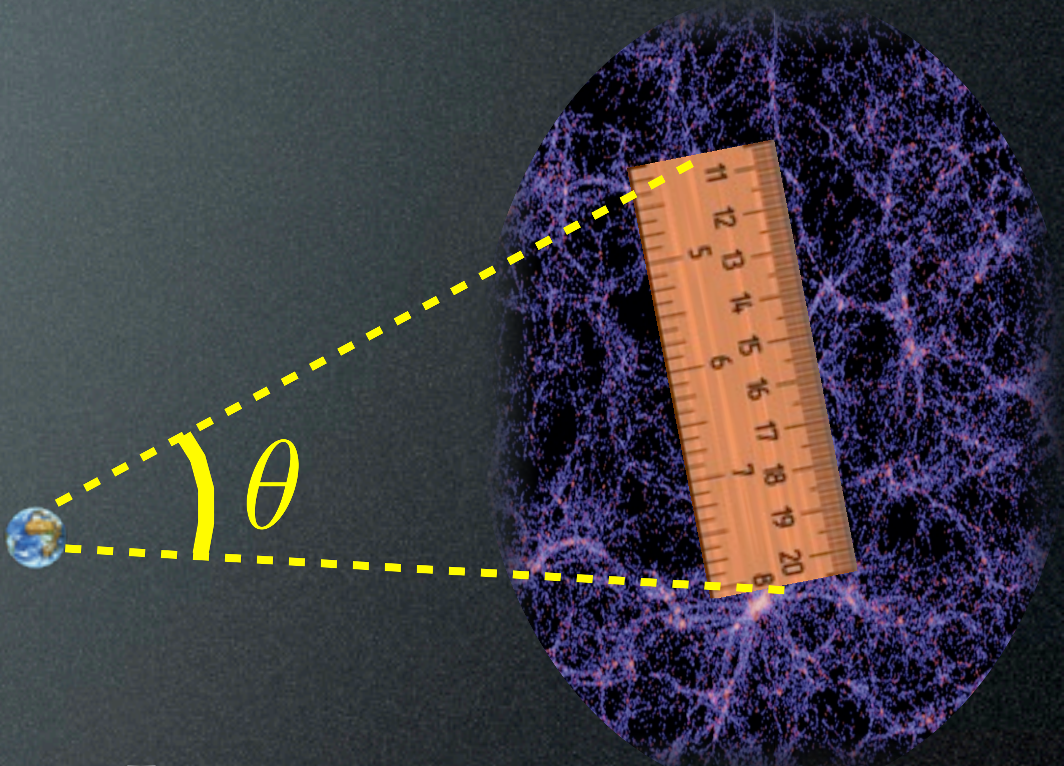

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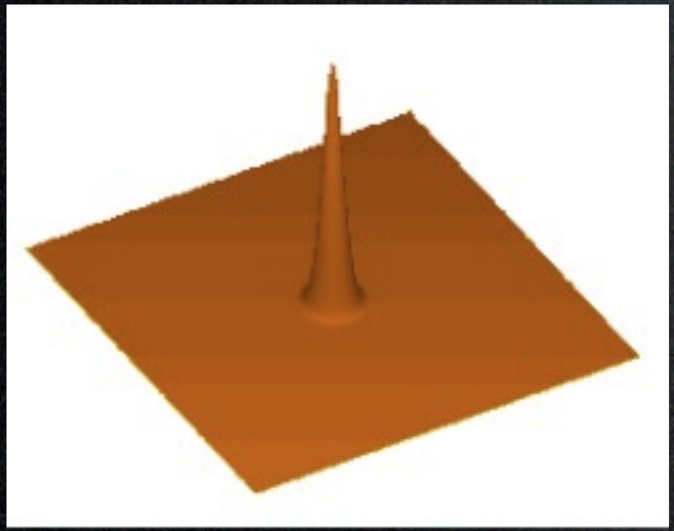

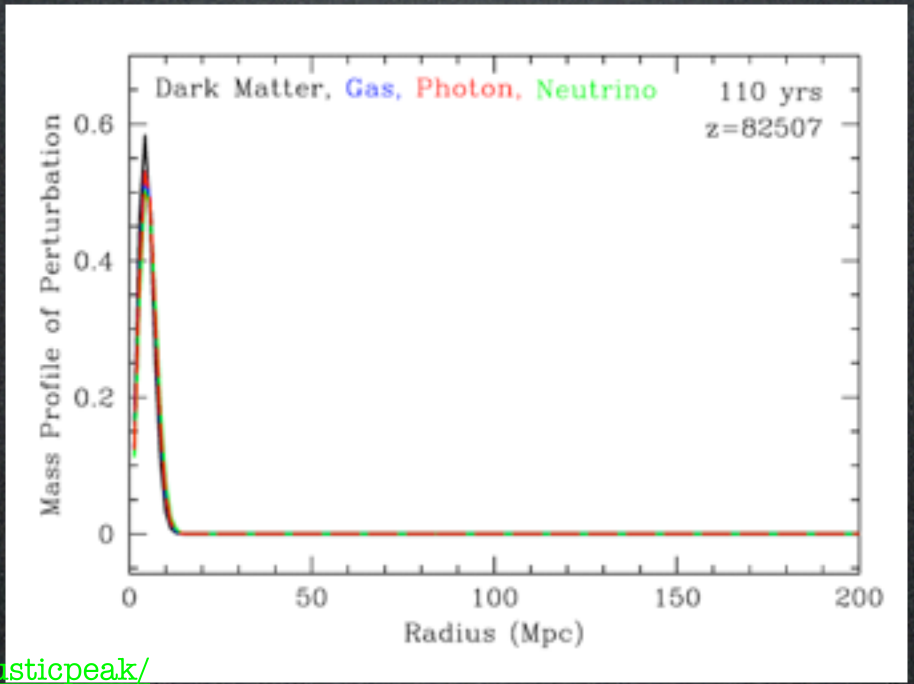

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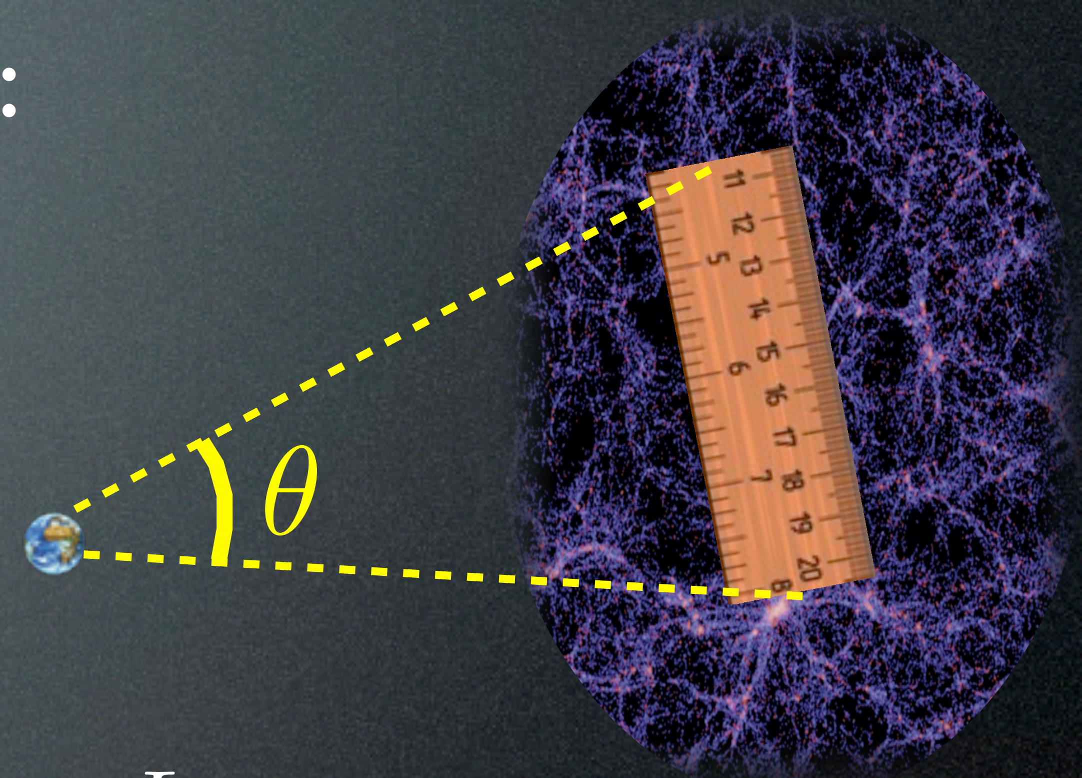

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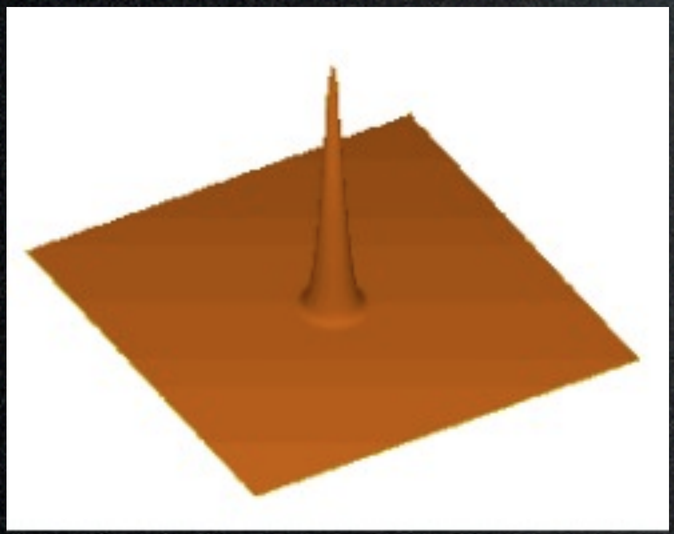

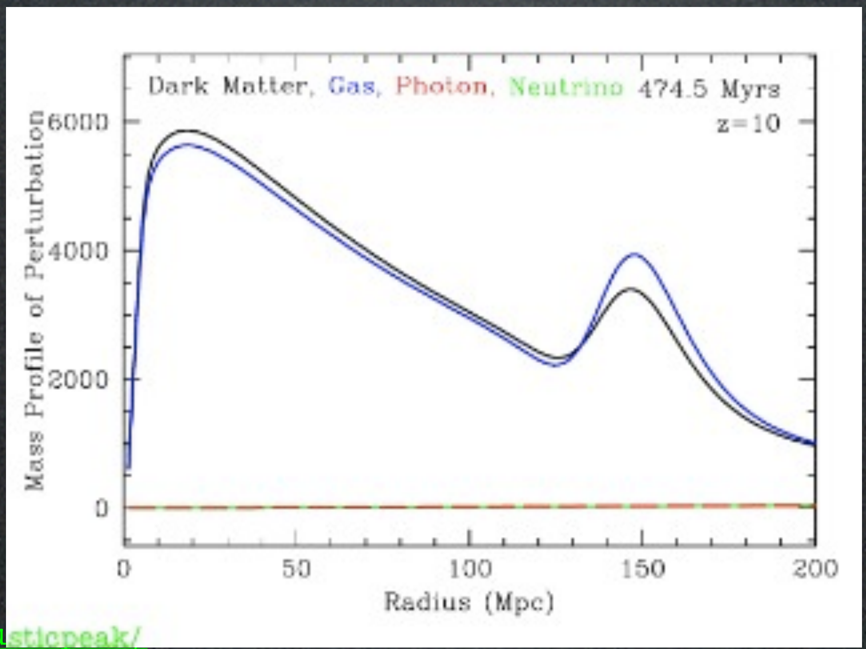

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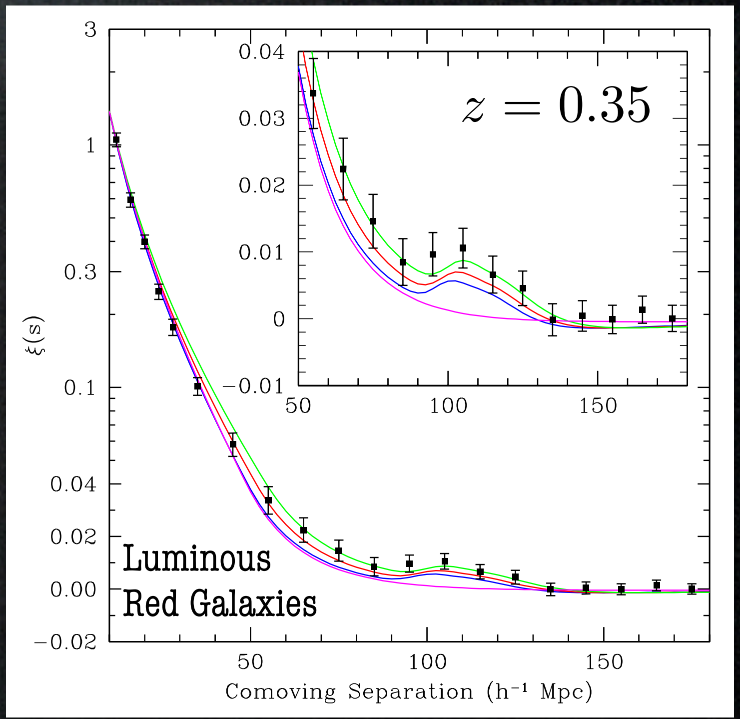

Eisenstein et al., astro-ph/0501171

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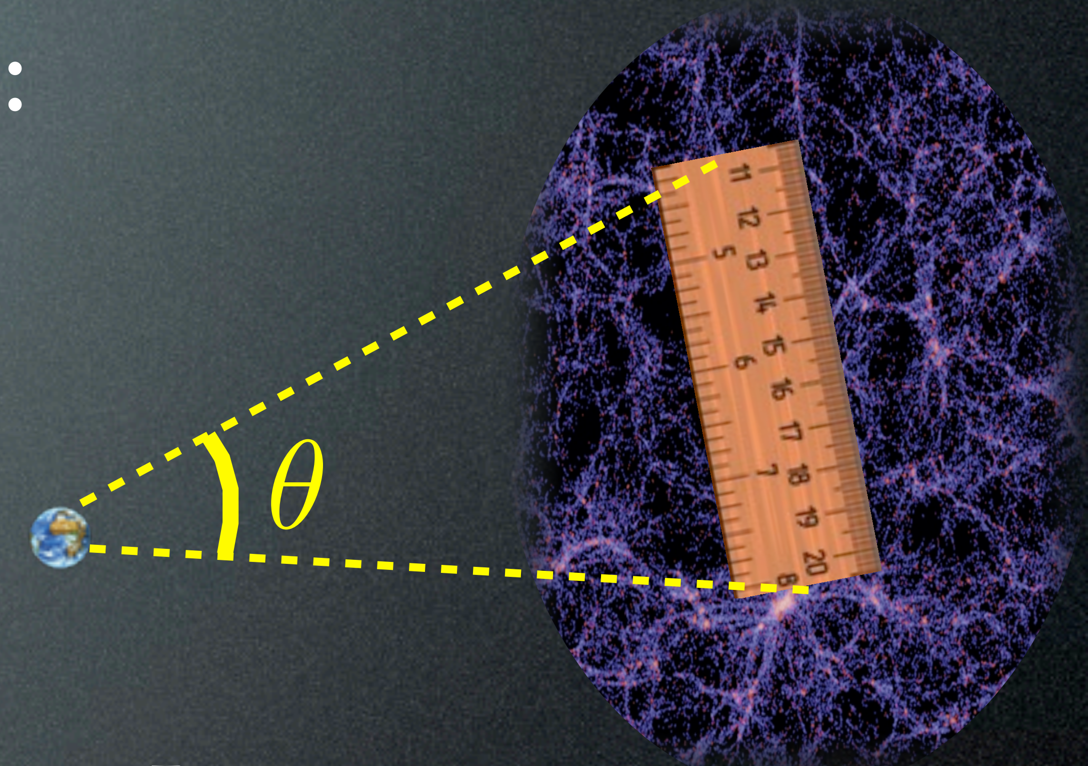
comoving distance ('unknown') → χ

Length ('known') → L



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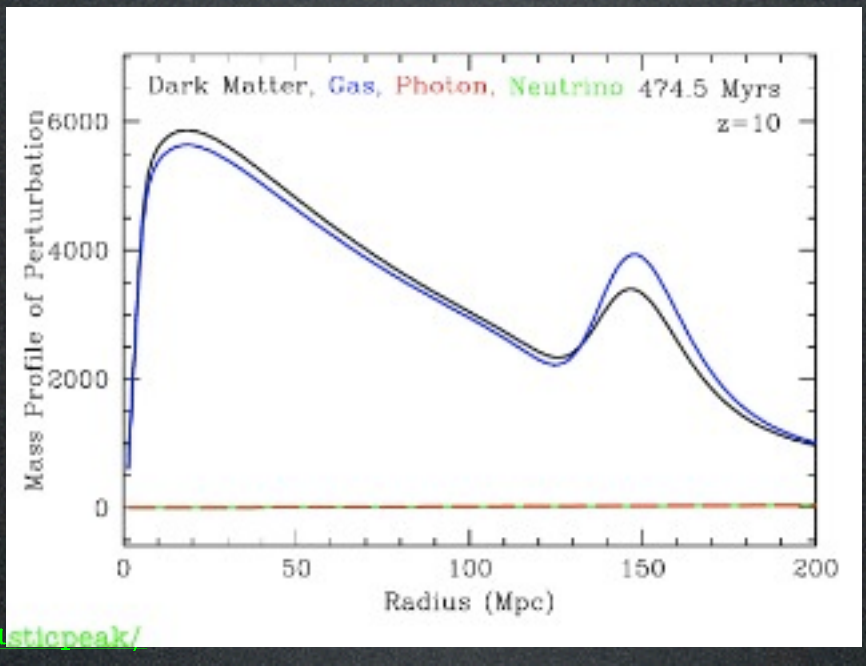
What is the 'ruler'? A pinch in the galaxy distribution



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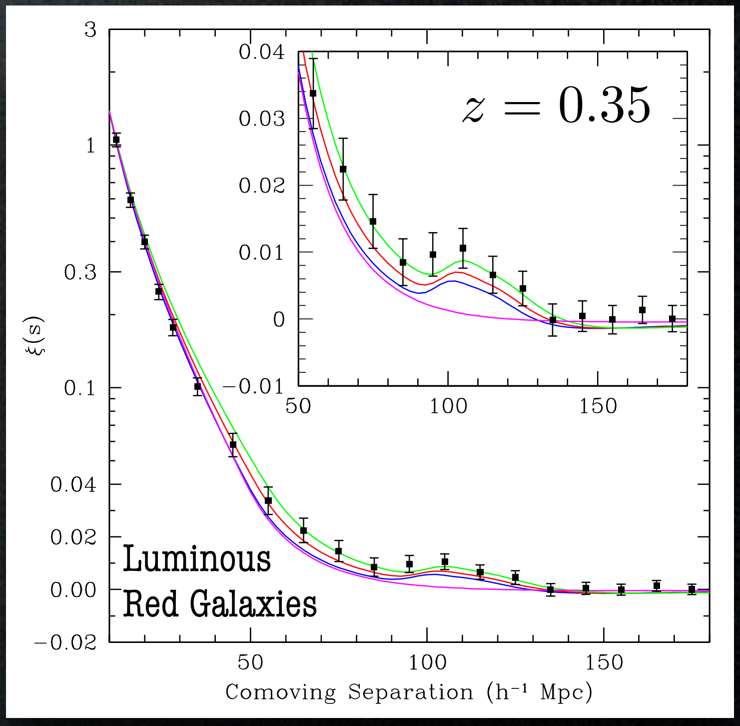

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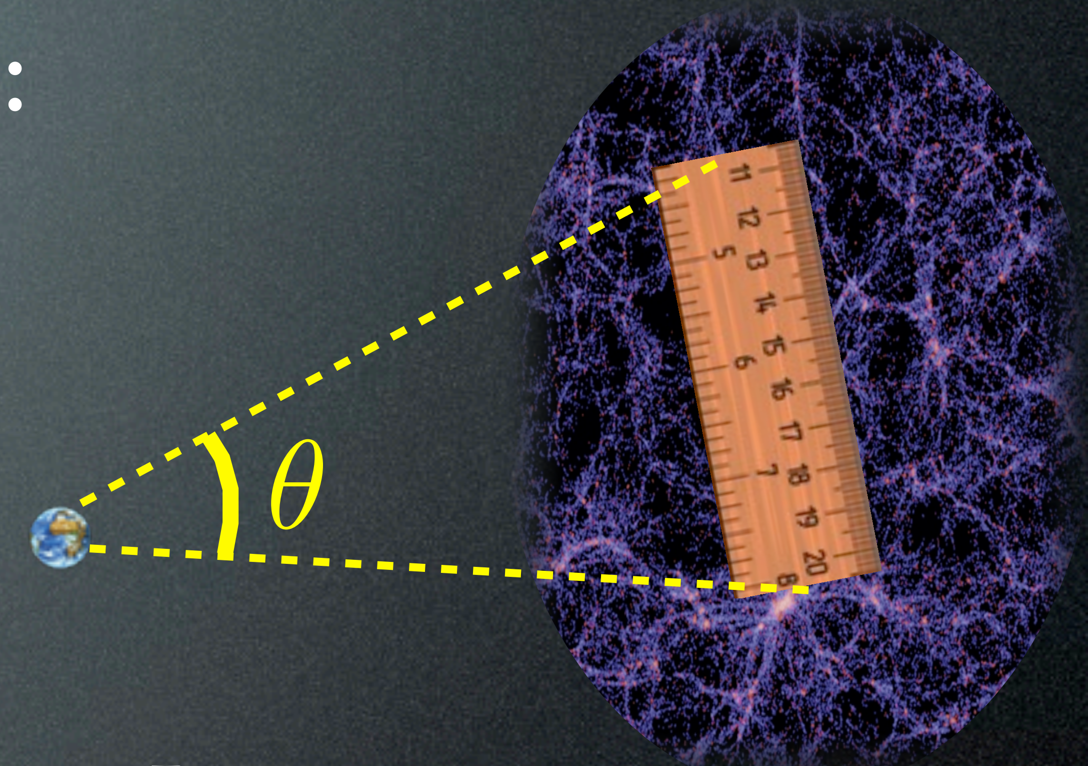

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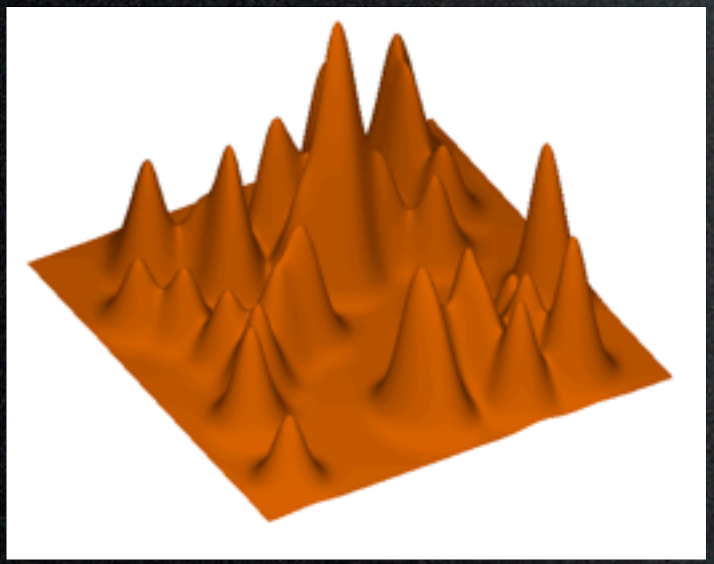

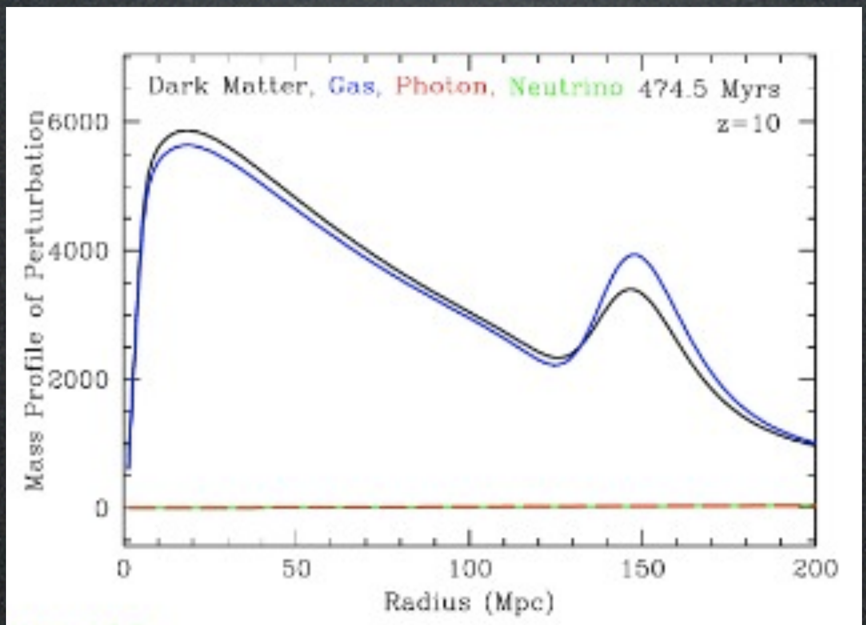

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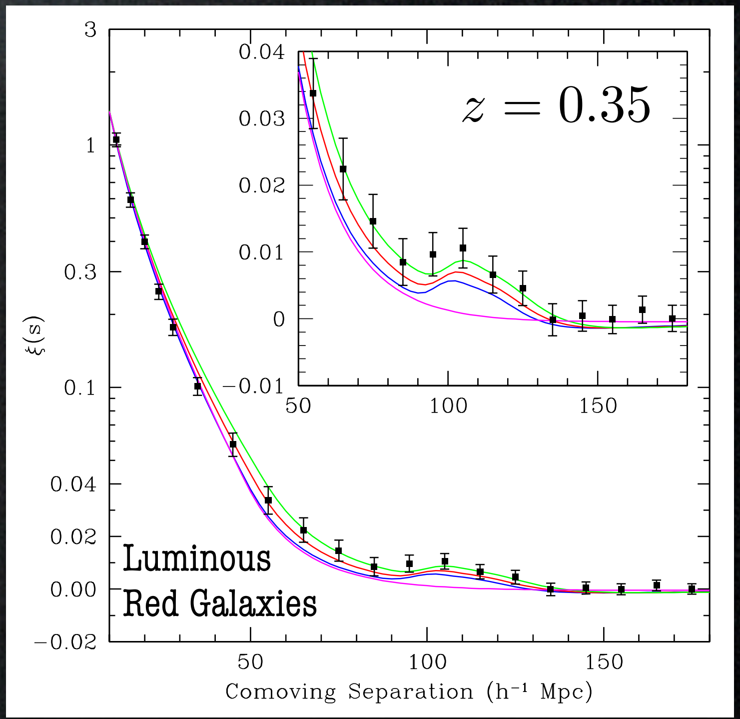

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NB: can actually do the same in z direction

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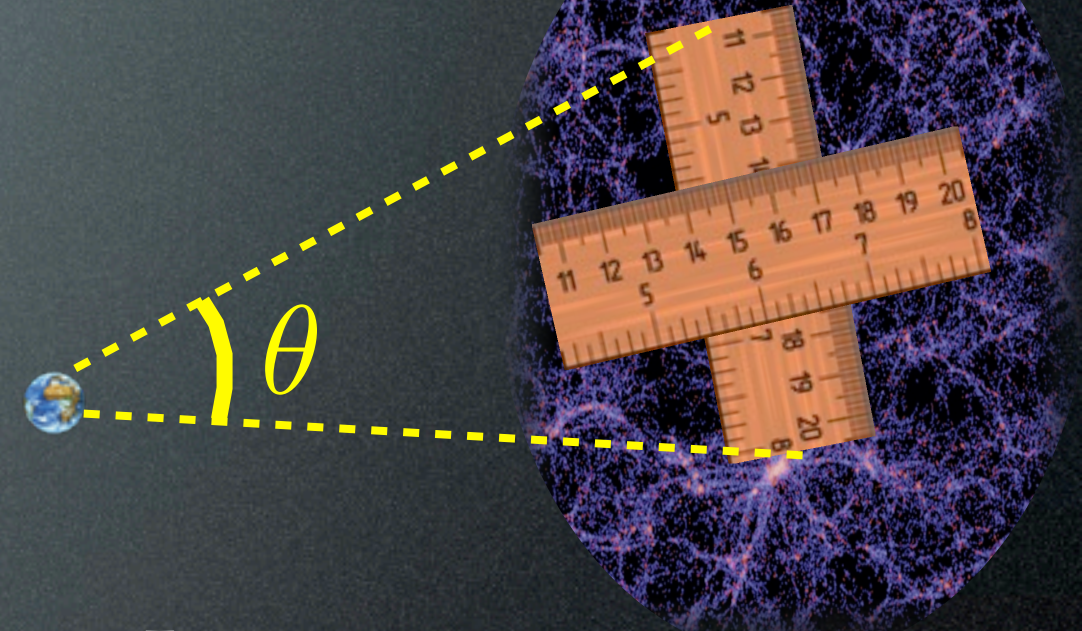

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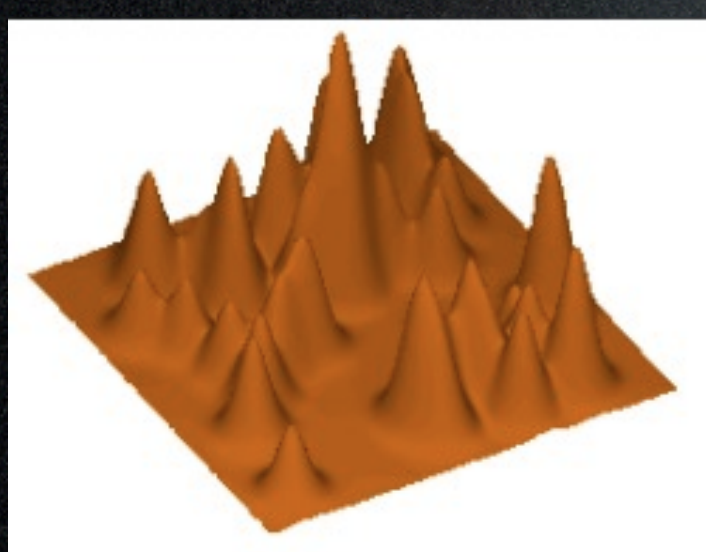

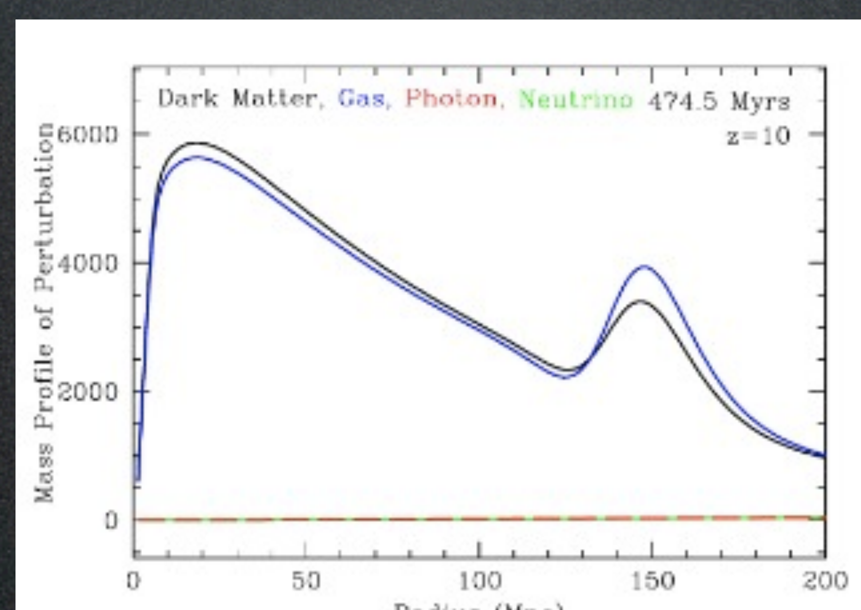

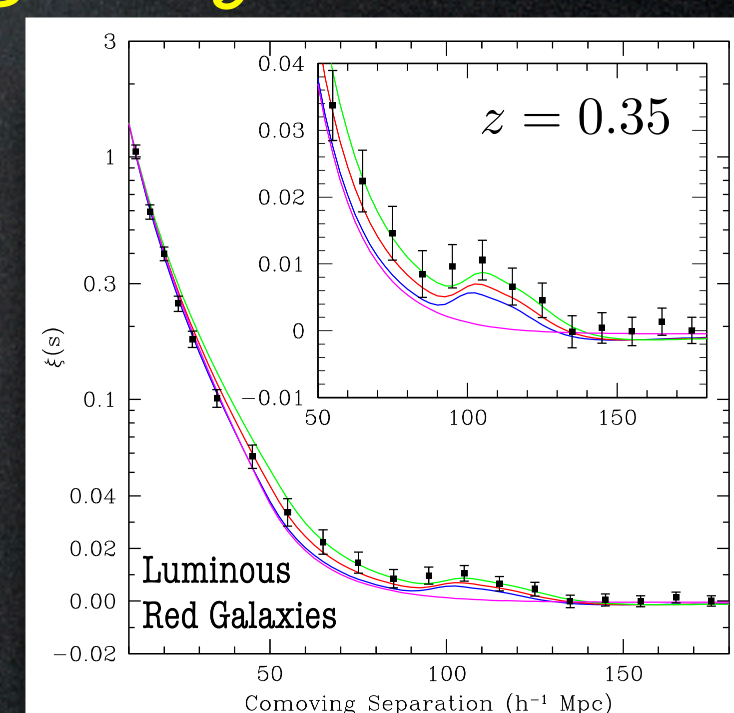

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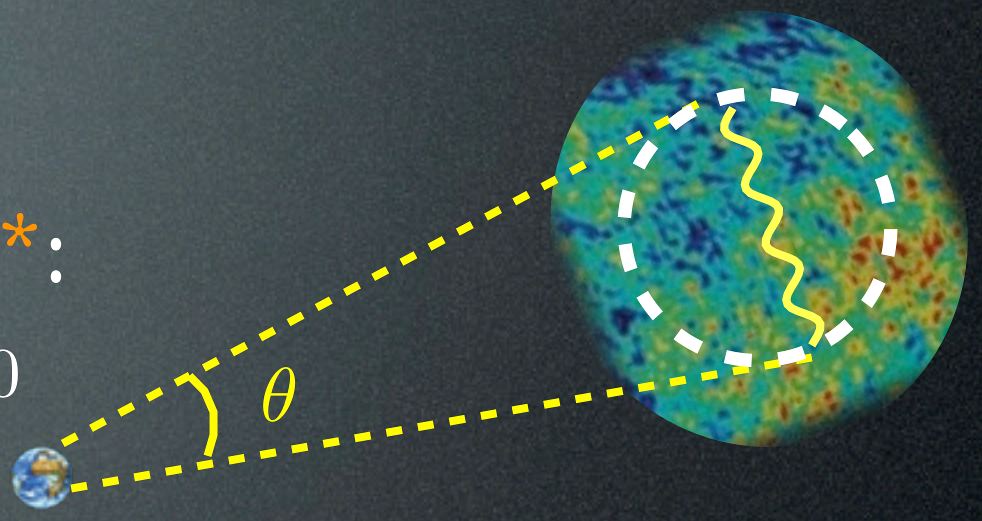
The Evidence for DE

3) CMB:

In principle: another ‘standard ruler’ *:

the size of the sound horizon at $z \simeq 1100$

$$r_s = \int c_s \, d\tau \qquad c_s \simeq c/\sqrt{3}$$



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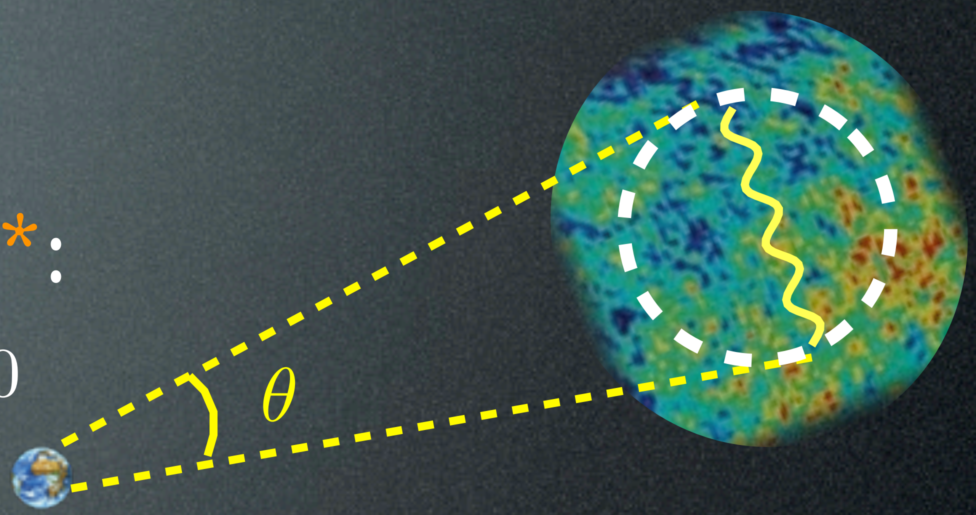

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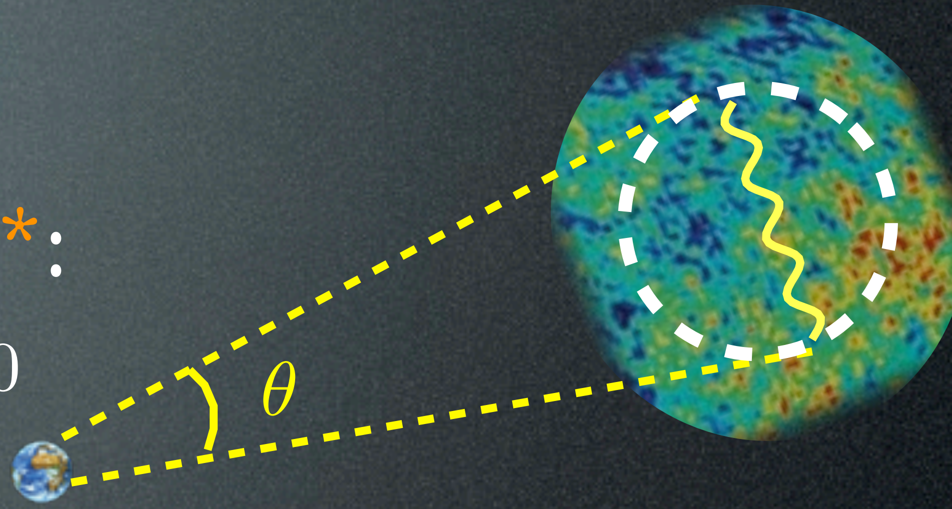

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In practice: DE is too subdominant at $z \simeq 1100$,
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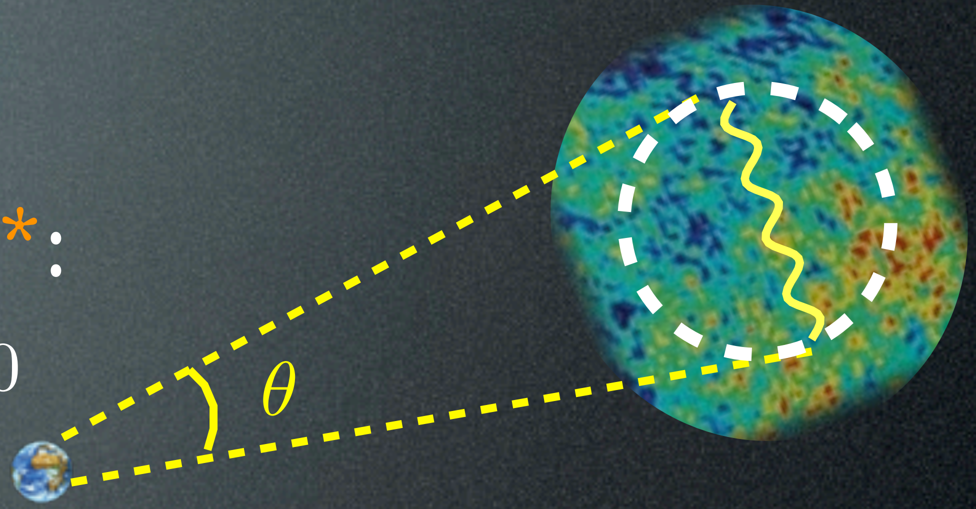

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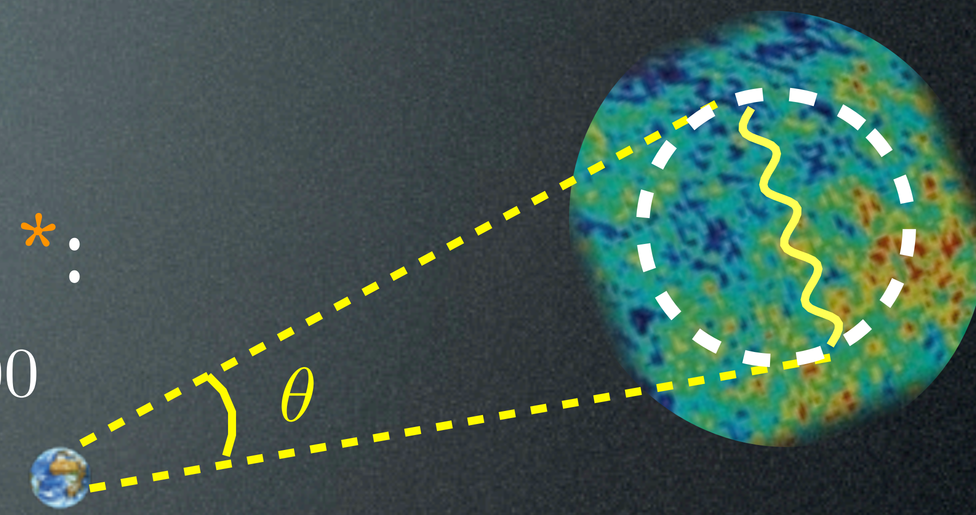
On the other hand: CMB fit gives $\Omega_{\rm tot} \simeq 1$, $\Omega_{\rm DM} \simeq 0.27$ $\Rightarrow$ $\Omega_\Lambda \approx 0.73$

The Evidence for DE

3) CMB:



In principle: another ‘standard ruler’ *:

the size of the sound horizon at $z \simeq 1100$

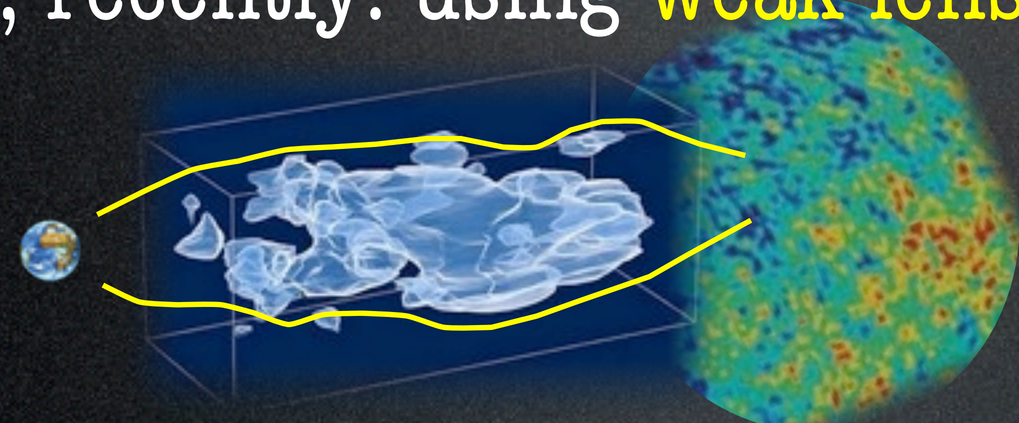
$$r_s = \int c_s \, d\tau \qquad c_s \simeq c/\sqrt{3}$$

*(actually, it’s the ‘same’ ruler as BAO!)

In practice: DE is too subdominant at $z \simeq 1100$,
there are degeneracies w other effects

On the other hand: CMB fit gives $\Omega_{\rm tot} \simeq 1$, $\Omega_{\rm DM} \simeq 0.27$ $\Rightarrow$ $\Omega_\Lambda \approx 0.73$

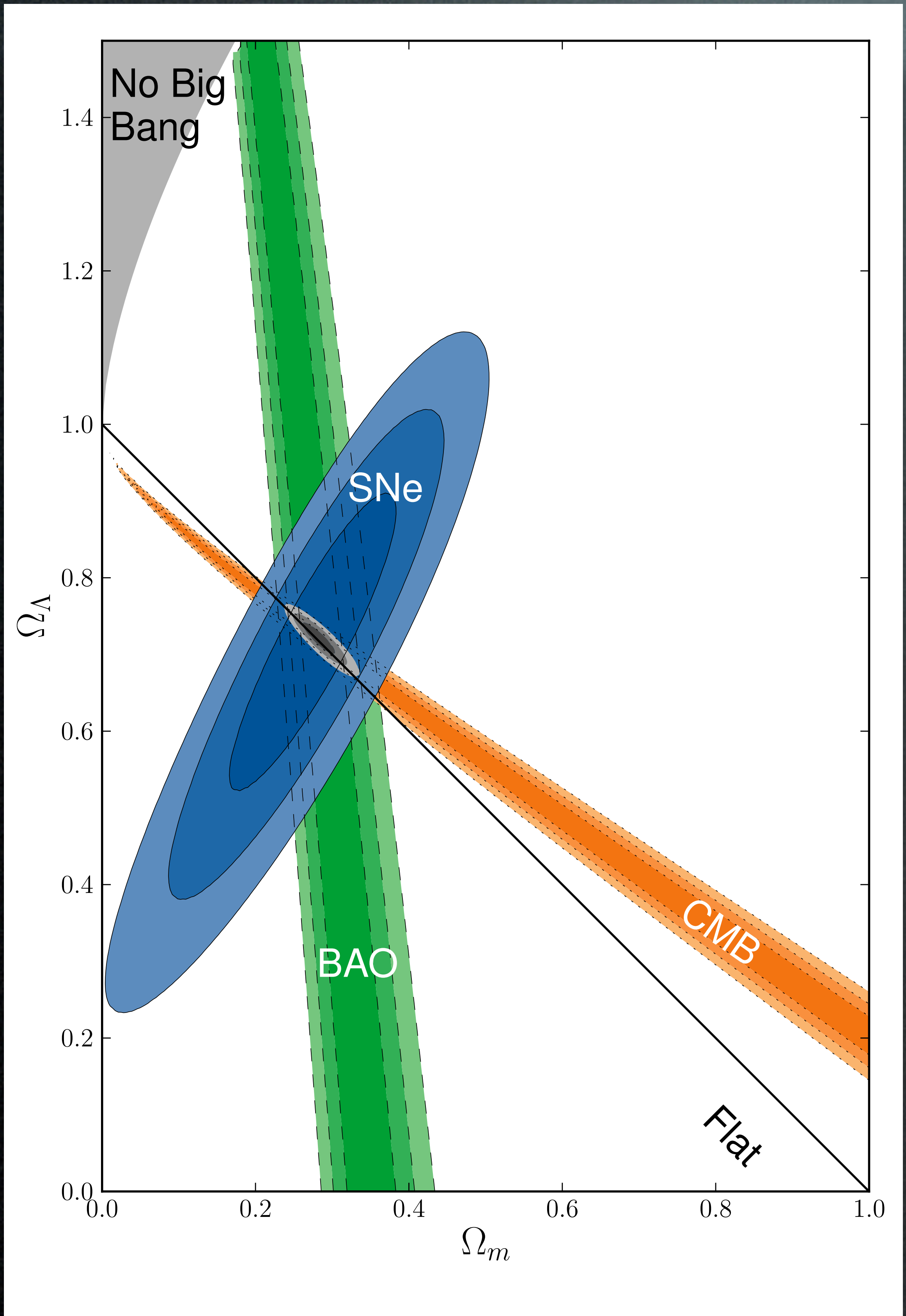
Moreover, recently: using weak lensing of CMB light



$$\Omega_\Lambda = 0.61^{+0.14}_{-0.06}$$

Sherwin et al., ACT Atacama Cosmology Telescope, 1105.0419

The Evidence for DE



Suzuki et al., 1105.3470

- complementarity
- concordance

$$\Omega_\Lambda = 0.725 \pm 0.016$$

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Other probes played / will play a role:

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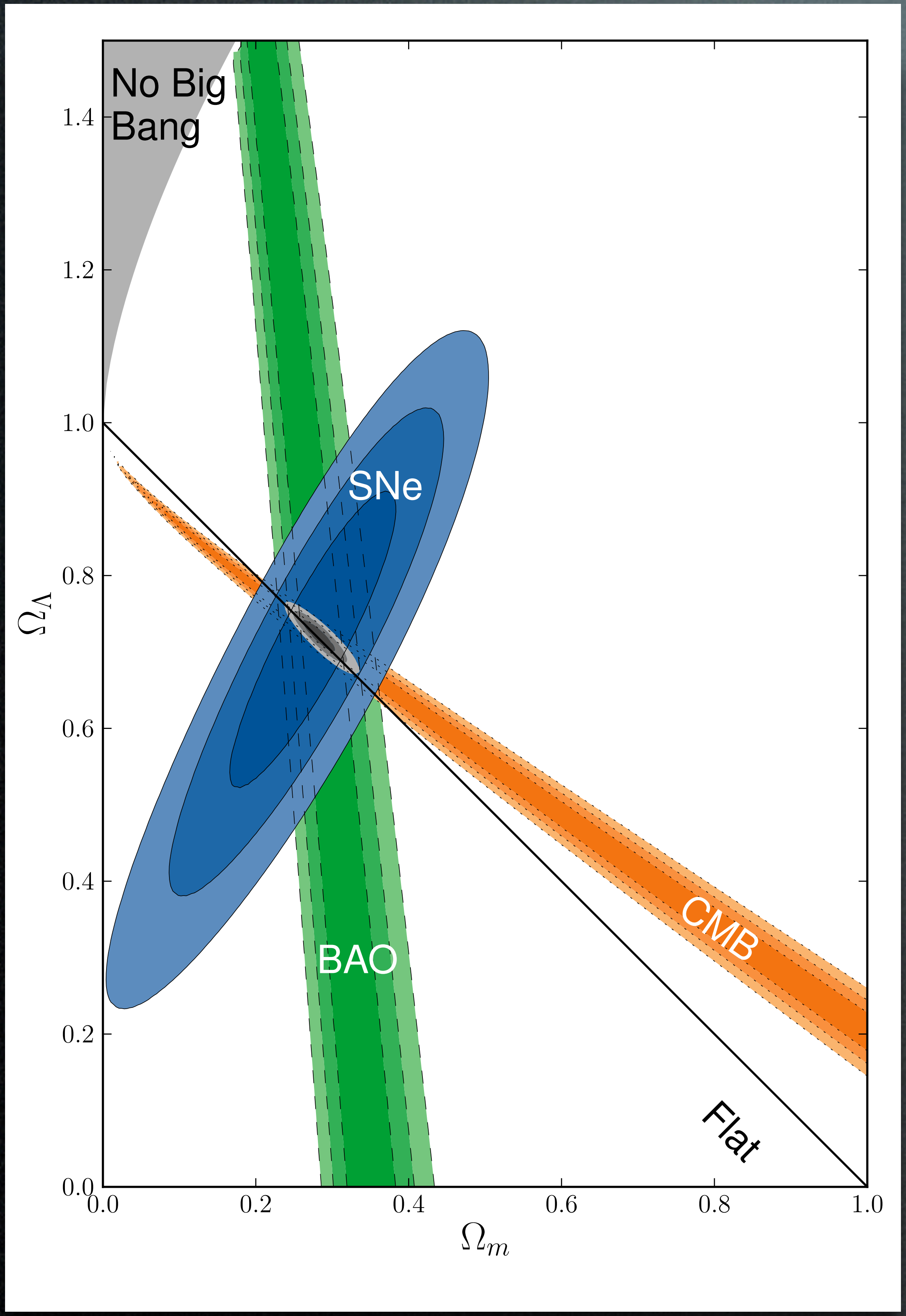

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L. Amendola's lecture

What do we know of the (particle physics) properties of Dark Energy?

Nature of DE

Λ cosmological constant, $w = -1$

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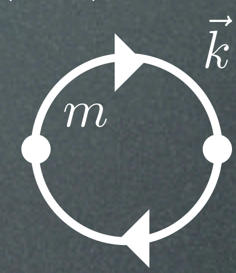
$$\simeq \sum_{\rm particles} \frac{g_i\, k_{\rm max}^4}{16\,\pi^2}$$



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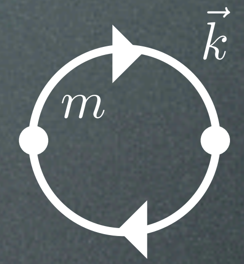

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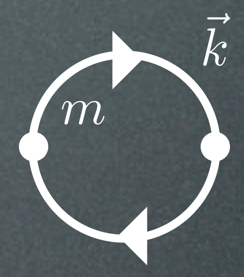

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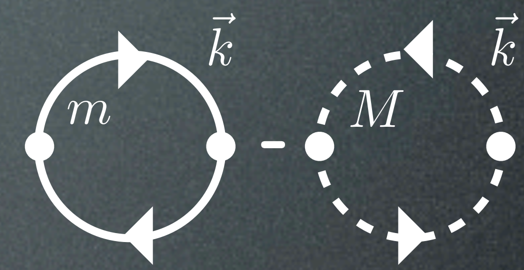

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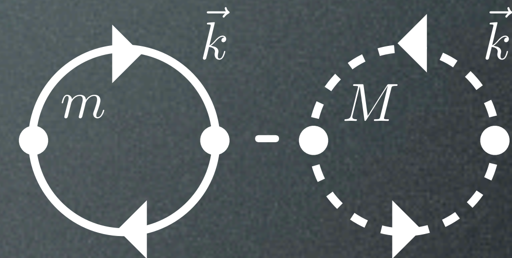

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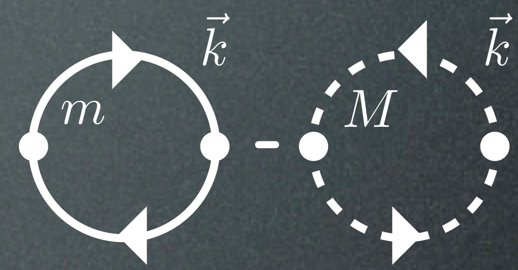

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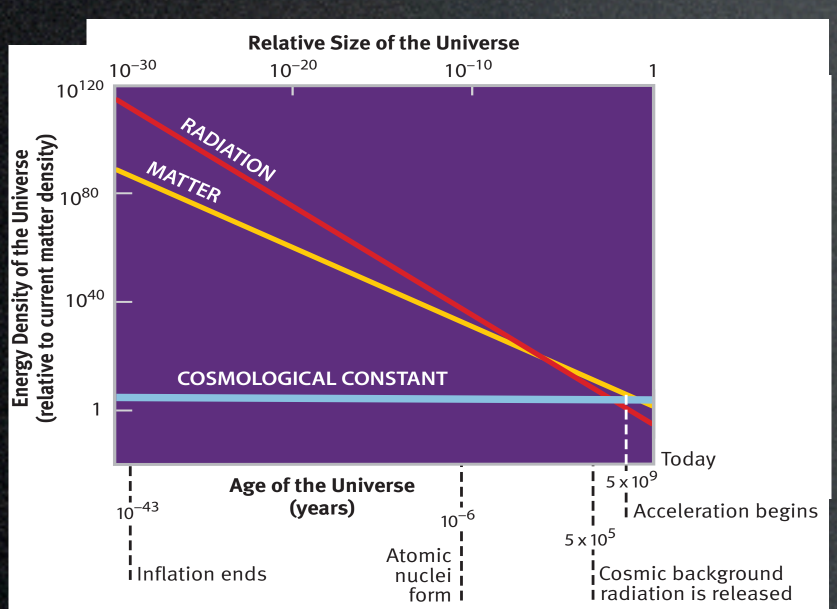

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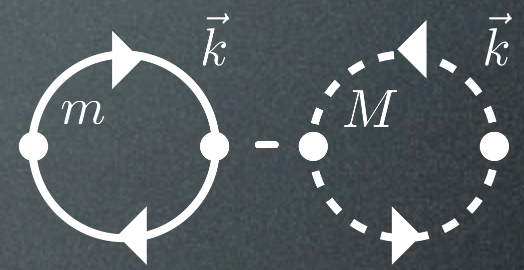

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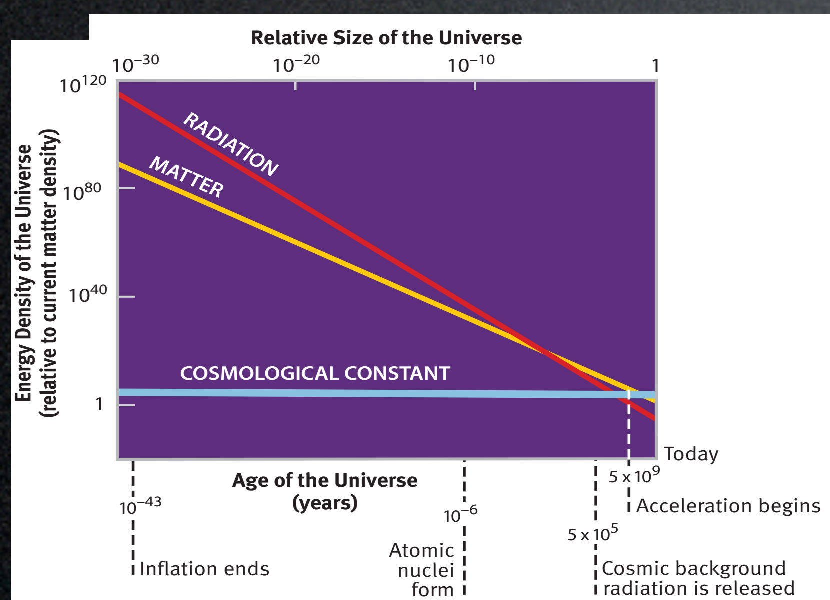

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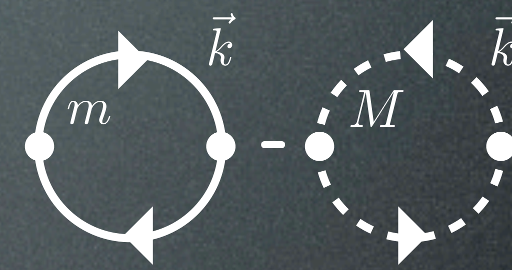

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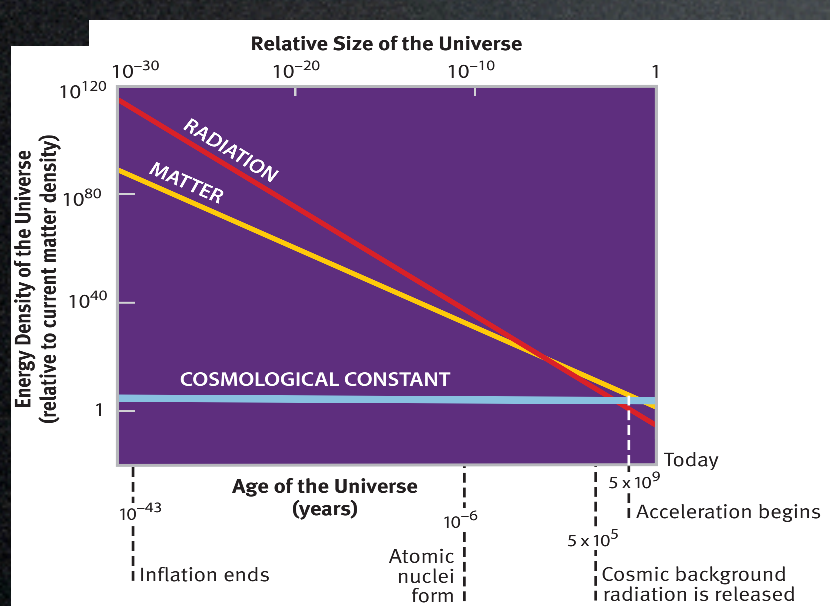

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Anthropism?

Multiverse?

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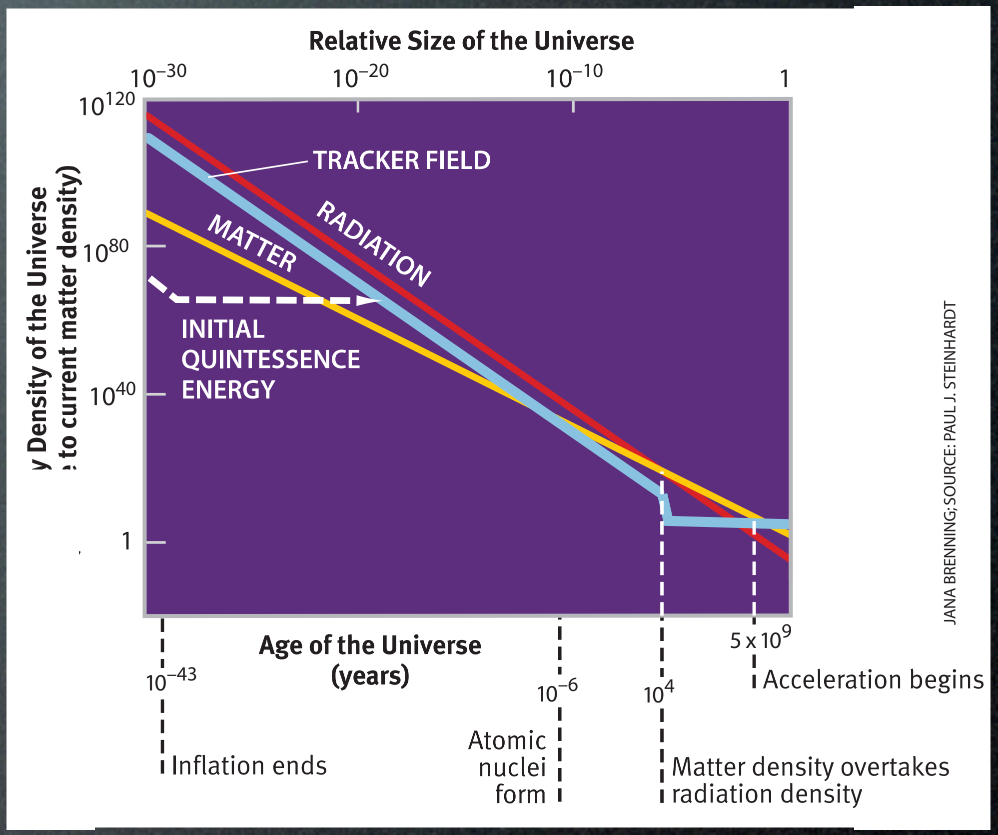

Ostriker and Steinhard, Scientific American 2000

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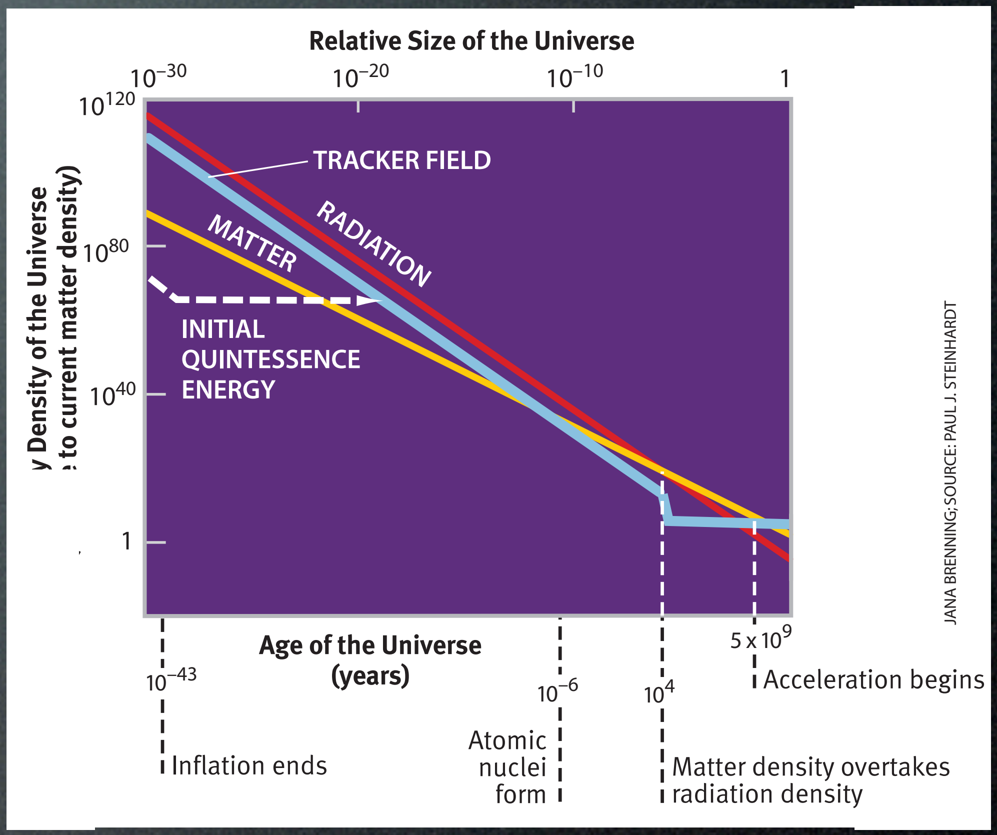

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Modified Gravity (f(R), DGP...)

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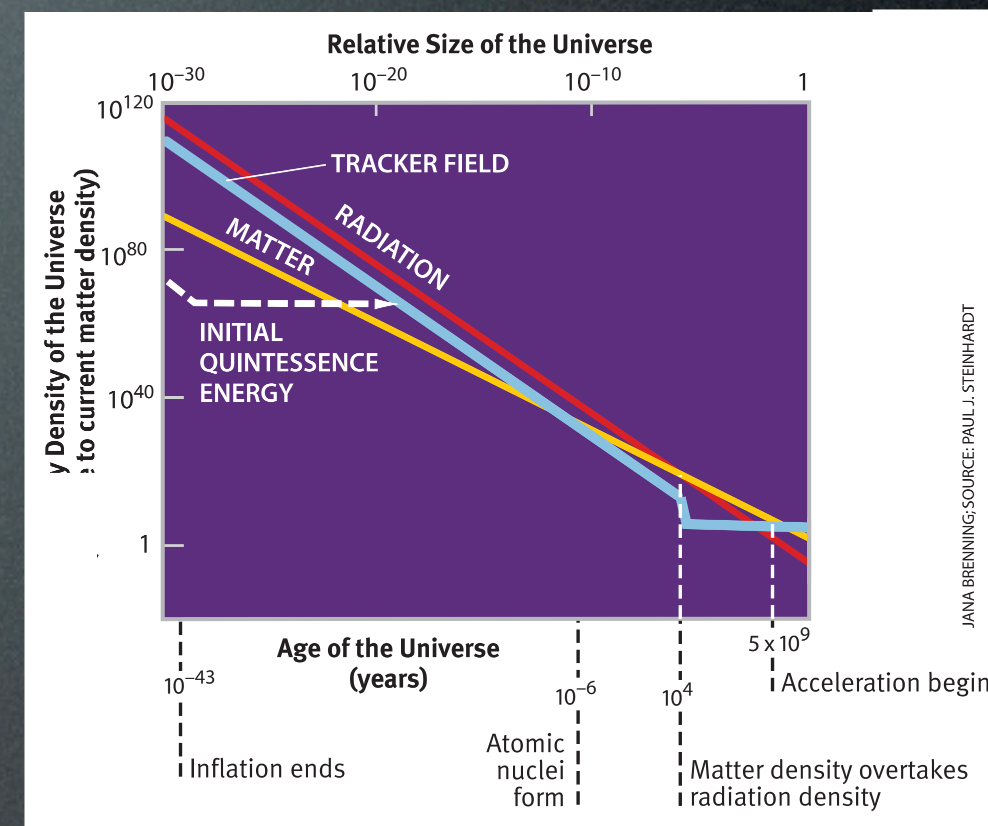

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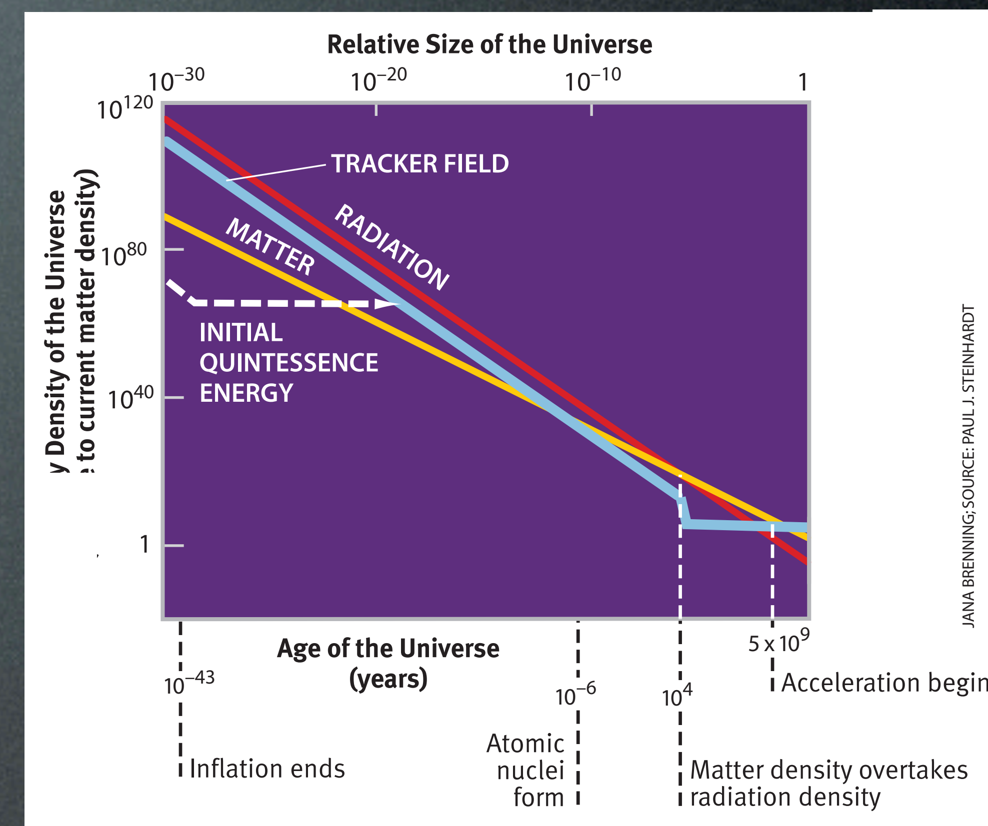

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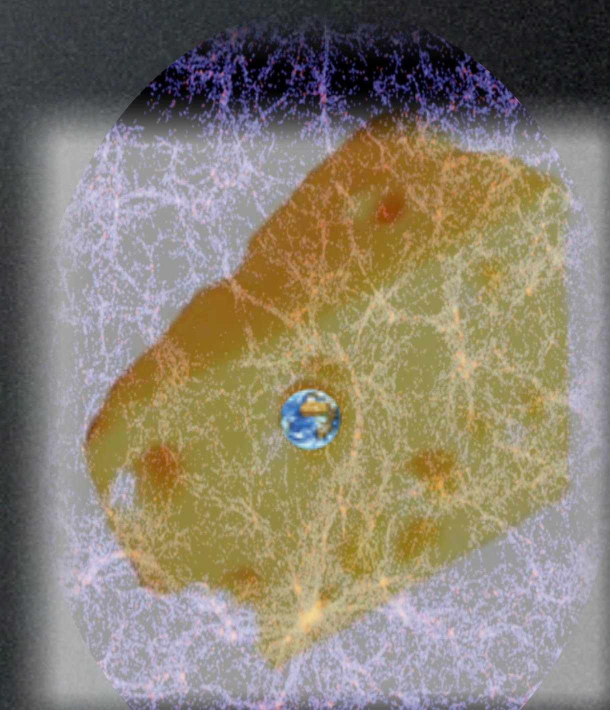

Conclusions (for today)

Dark Matter exists

Dark Energy exists

We have (almost) no clue of what they are,
but many hints and many ideas.

The ‘era of data’
is now for DM.

The ‘era of data’
is coming for DE.

May you live in exciting times.