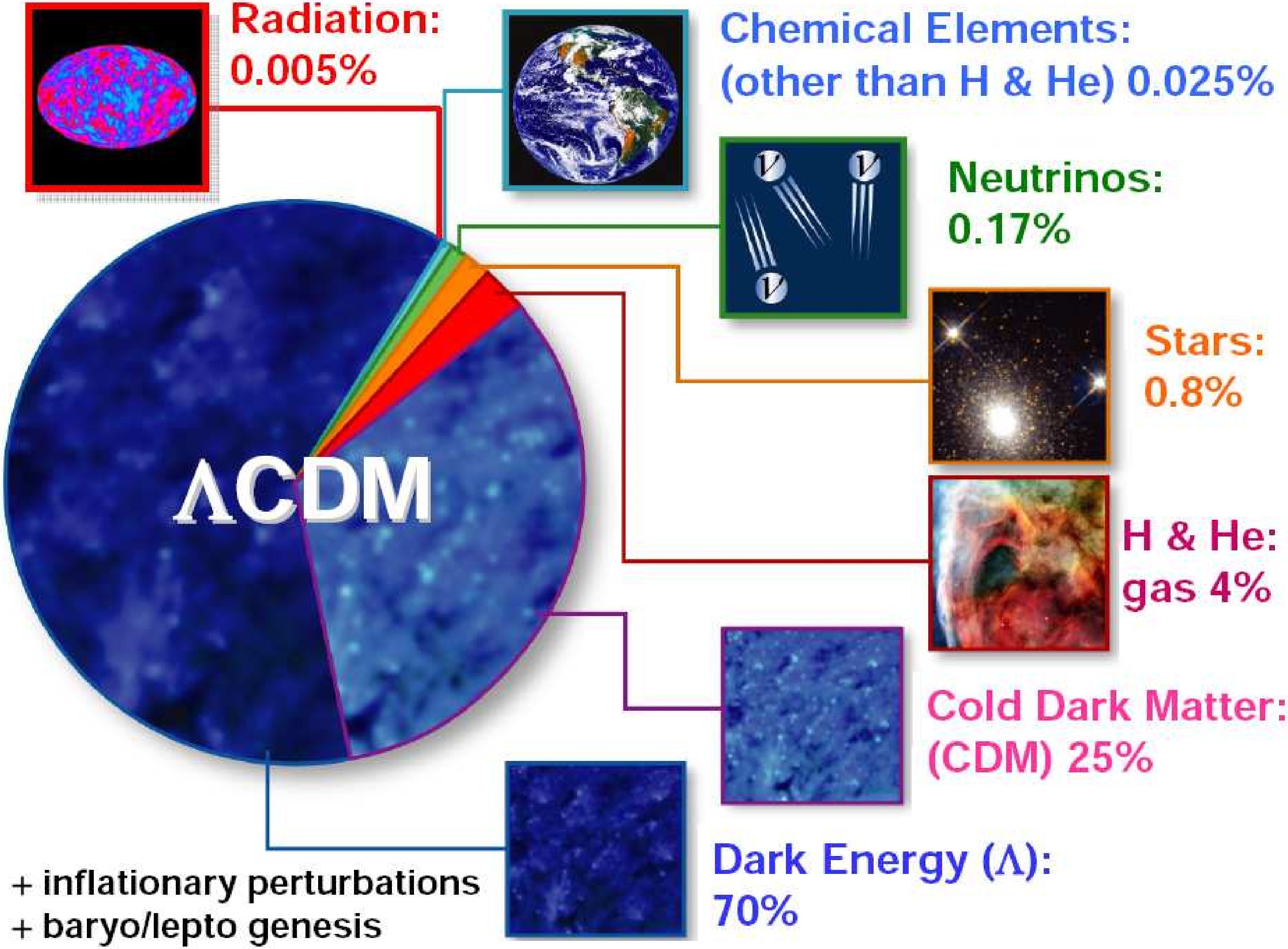
LAUNCH09

Dark Matter: Evidences, phenomenology and theoretical implications

Thomas Schwetz

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The "concordance model" of cosmology

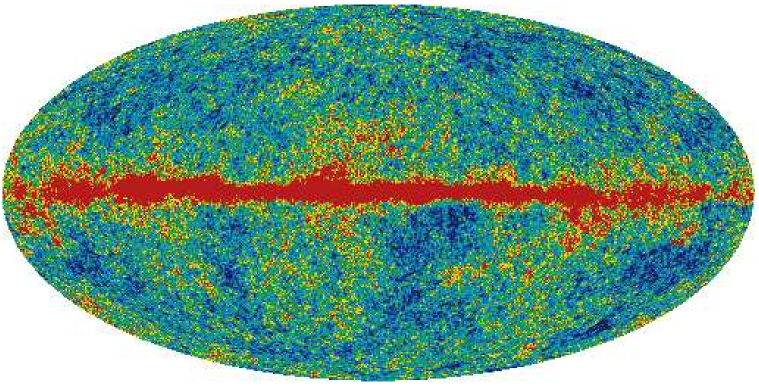


Global fit to cosmological data

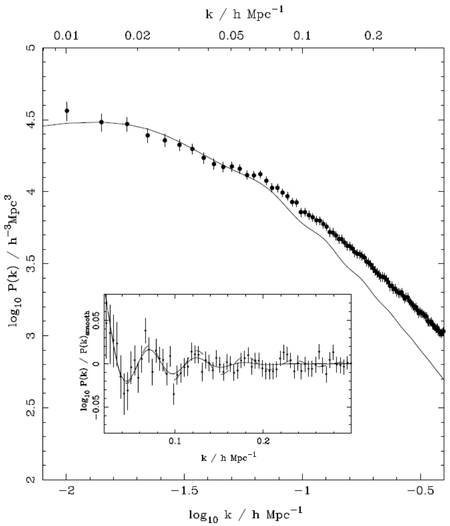
$$
\begin{aligned}
\Omega_\Lambda &= 0.726 \pm 0.015 \\
\Omega_{\rm CDM} &= 0.228 \pm 0.013 \\
\Omega_{\rm baryon} &= 0.0456 \pm 0.0015
\end{aligned}
$$

arXiv:0803.0547

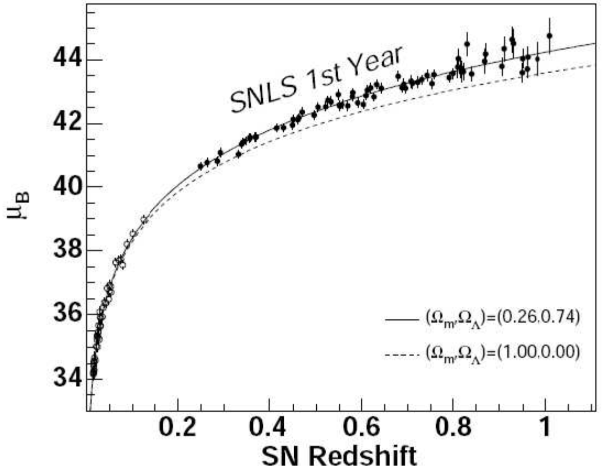
WMAP (5yr)



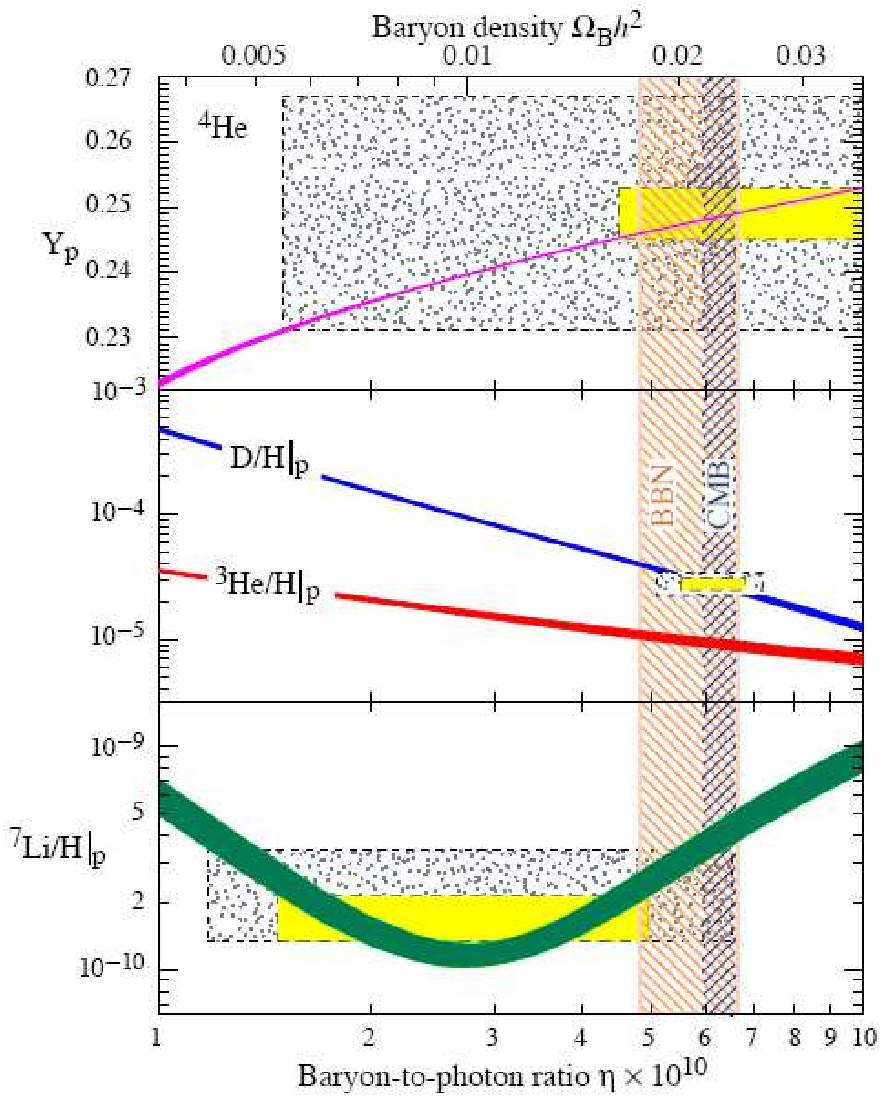
BAO



SN Ia



Density of "normal matter"



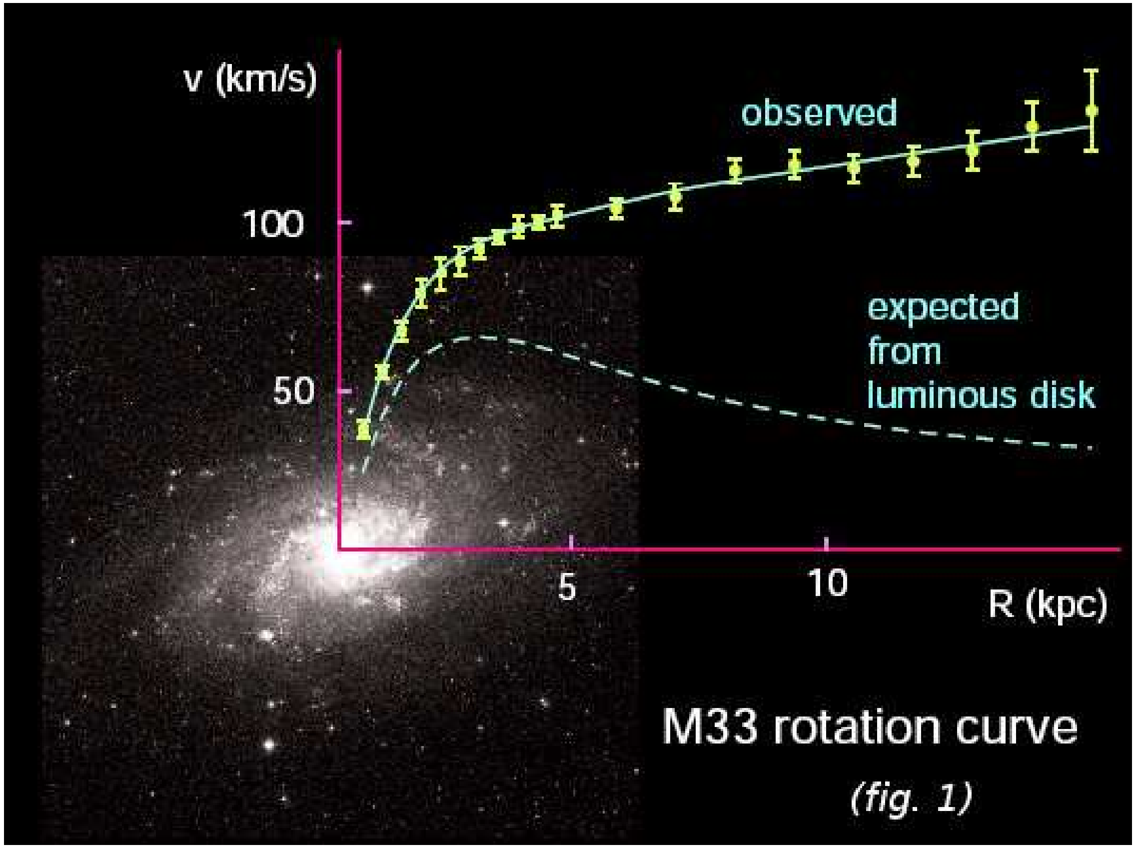
determinations of the baryon density from Big Bang Nucleosythesis and CMB are in perfect agreement:

$$\Omega_b h^2 = 0.0214 \pm 0.0020 \quad \text{(BBN)}$$

$$\Omega_b h^2 = 0.0227 \pm 0.0006 \quad \text{(CMB)}$$

The scale of galaxies and clusters of galaxies

- Rotation curves of galaxies



The scale of galaxies and clusters of galaxies

- Rotation curves of galaxies
- Virial theorem applied to galaxies and clusters

$$M \approx \frac{2\langle v^2 \rangle}{G_N \langle 1/r \rangle}$$

mass-to-light ratios:

$$\frac{M_{\text{cluster}}}{L_{\text{cluster}}} \sim 200 \frac{M_\odot}{L_\odot}, \qquad \frac{M_{\text{gal}}}{L_{\text{gal}}} \sim 10 \frac{M_\odot}{L_\odot}$$

The scale of galaxies and clusters of galaxies

- Rotation curves of galaxies
- Virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies

$\mathcal{L}_X$ depends on T and ρ_B

T and ρ_B in hydrostatic equivilibrium: balance between pressure and gravity $\rightarrow$ depends on ρ_M

$$\frac{\Omega_b}{\Omega_M} \approx 0.06 h^{-3/2}$$

$\Rightarrow$ only small fraction of the total mass in galaxy clusters emits X-rays

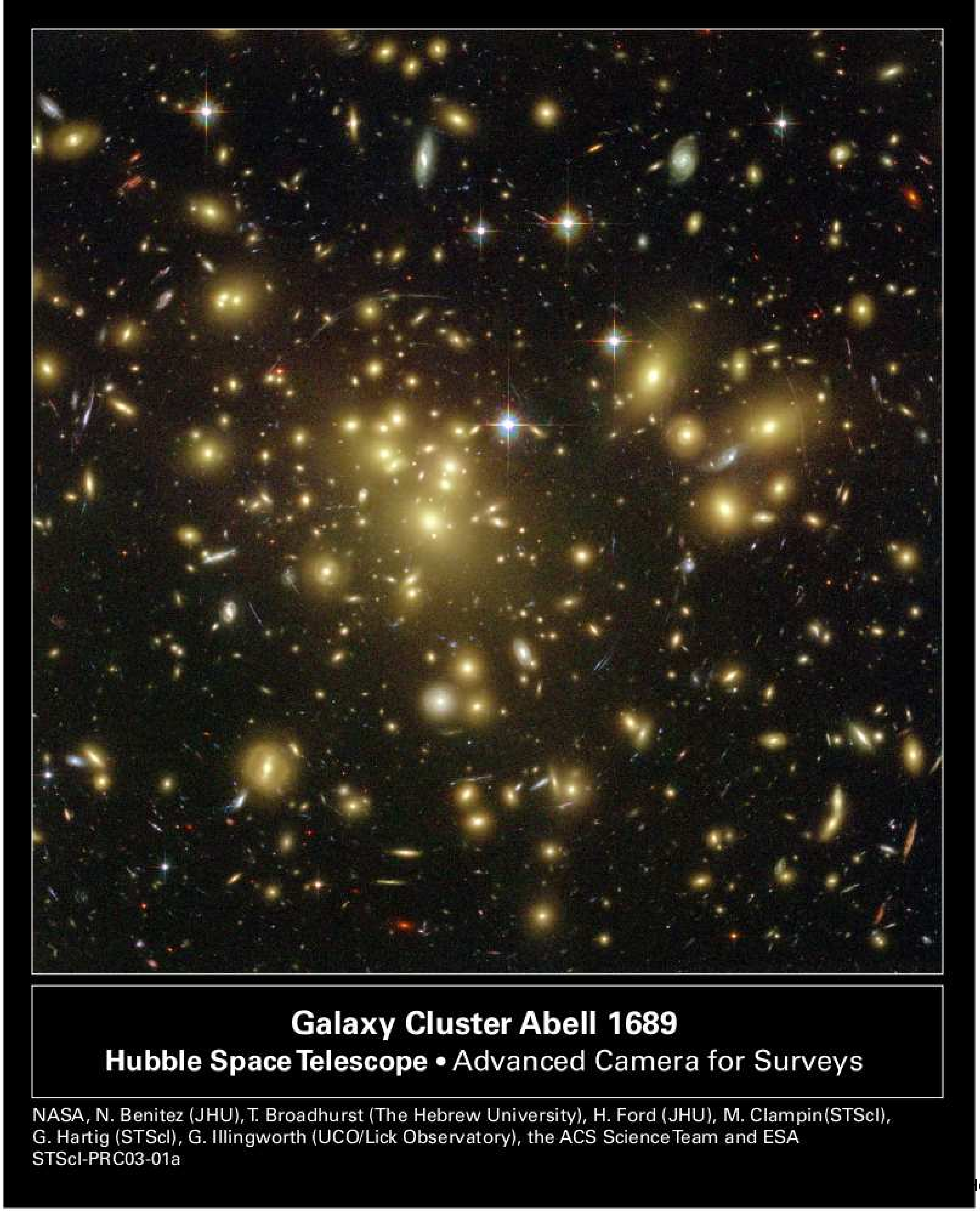
The scale of galaxies and clusters of galaxies

- Rotation curves of galaxies
- Virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies
- Gravitational lensing

  distortion of images of distant objects by gravity of intervening gravitational lense
  (multiple images, giant arcs, Einstein rings)

The sc… …laxies

- Rotati…
- Virial t… …ers
- X-rays…
- Gravit…



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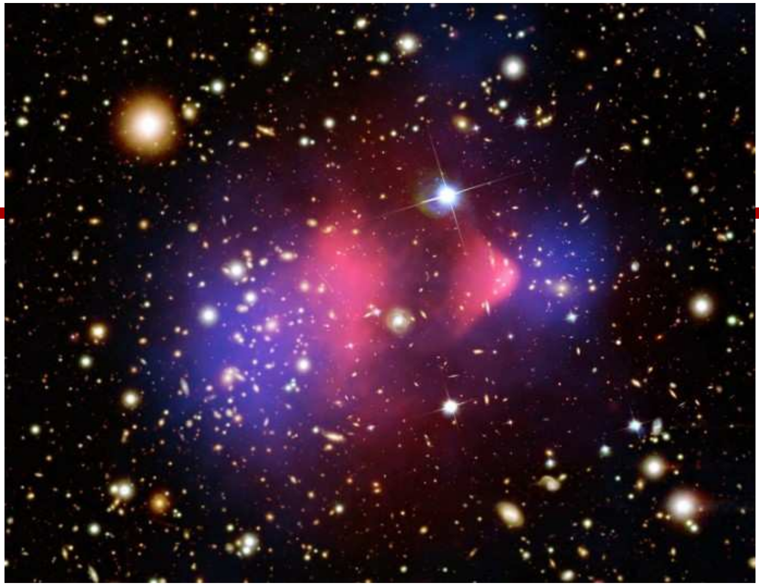
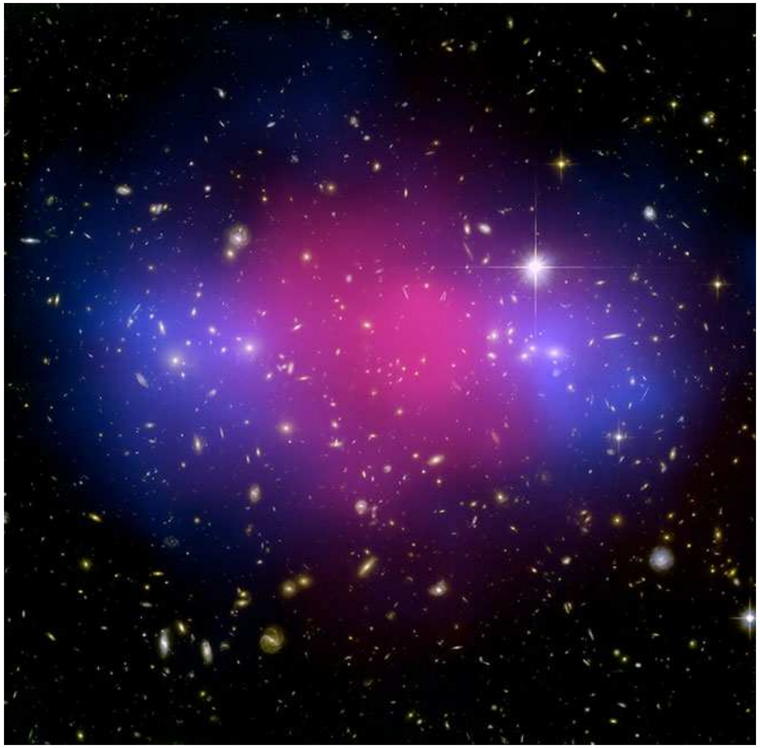
The scale of galaxies and clusters of galaxies

- Rotation curves of galaxies
- Virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies
- Gravitational lensing
- Mergers of galaxy clusters



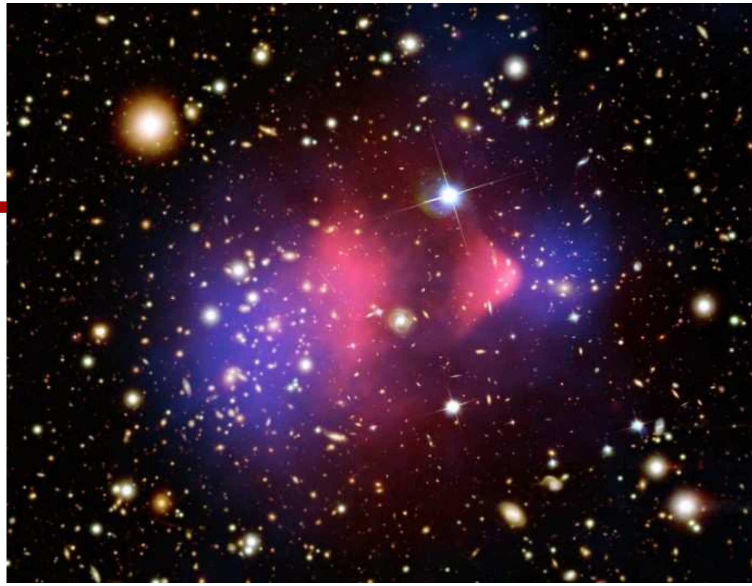
“Bullet Cluster”

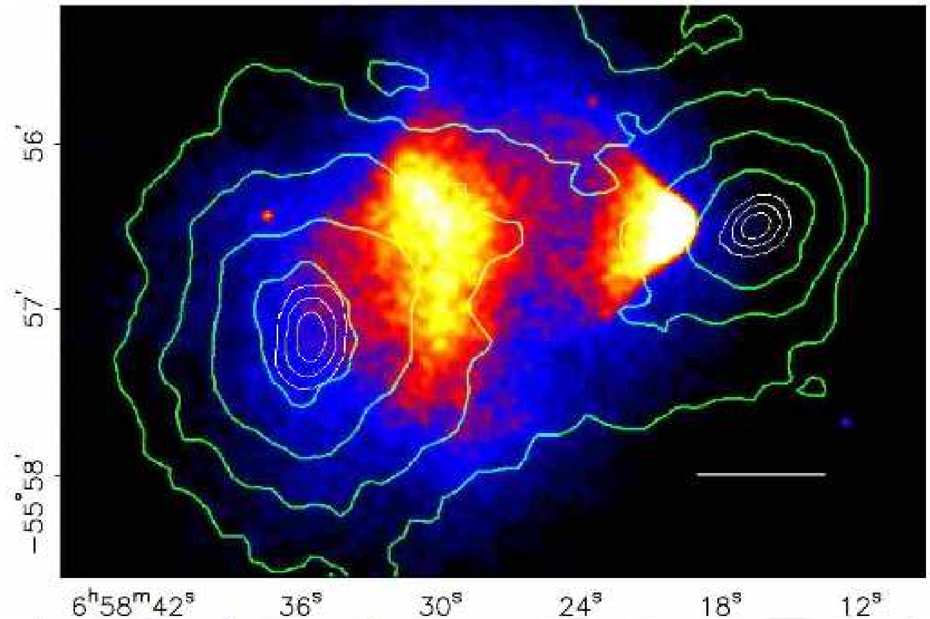
1E0657-56 (2006)

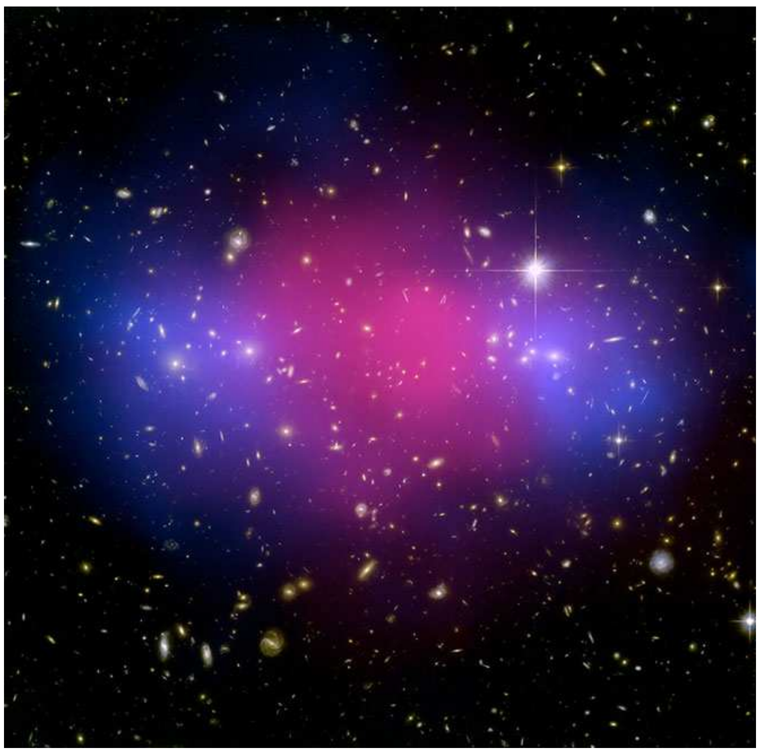


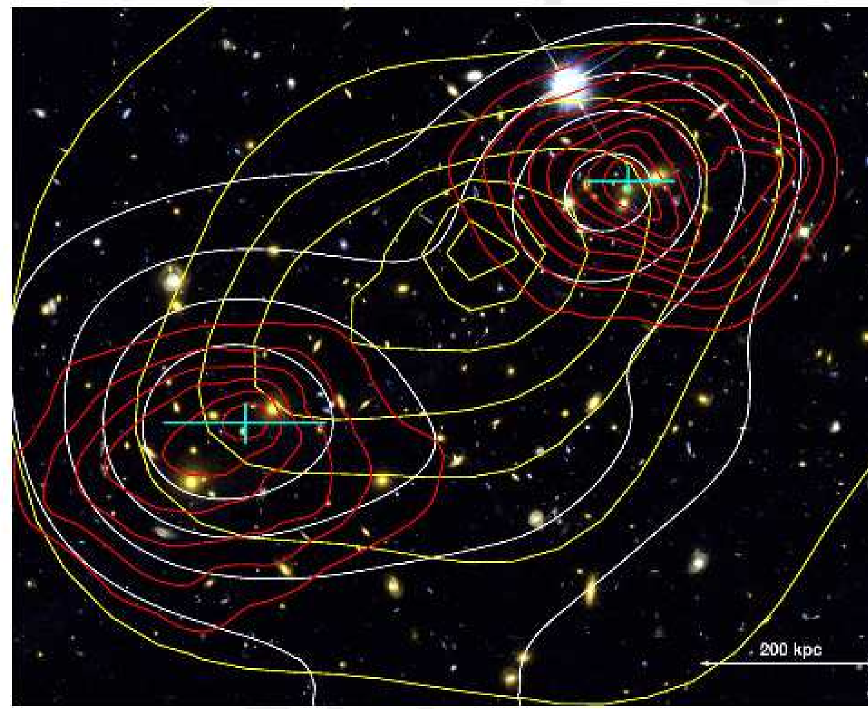
“Baby Bullet”

MACS J0025.4-1222 (2008)









X-ray emissivity from Chandra overlayed with the convergence map from strong and weak lensing data (arXiv:0704.0261, 0806.2320)

The scale of galaxies and clusters of galaxies

- Rotation curves of galaxies
- Virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies
- Gravitational lensing
- Mergers of galaxy clusters

Many independent observations are consistent
with the hypothesis that the dominating
gravitating component
of the Universe cannot be the matter we know.

Dark Matter or Modified Gravity?

We observe “anomalies” in motion of gravitational systems:

Anomalies in the orbits of

- Uranus
  lead to the discovery of a “dark object” (Neptun),
- Mercury
  lead to a modification of gravity.

Dark Matter or Modified Gravity?

Modified Gravity Theories (e.g., Bekenstein)

- successful on scales of galaxies and galaxy clusters
- can reproduce General Relativity + cosmology (require Dark Energy and neutrino mass)
- gravitational lensing data and bullet clusters require an invisible component of gravitating matter $\rightarrow$ "large" neutrino masses (m_ν of few eV)

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crucial tests from

- gravitational lensing
- absolute neutrino mass measurements

Particle Dark Matter

We need a particle which has

- the correct abundance to give $\Omega_{\text{CDM}} \approx 0.23$
  - production mechanism in the early Universe
  - has to be stable on the scale of the age of the Universe
- to be (electrically) neutral
- to fulfill constraints on
  - interactions with matter (direct detection)
  - self-interactions
  - searches for annihilation/decay products (gamma rays)
- to be consistent with structure formation
  $\longrightarrow$ "cold DM"

Particle Dark Matter

The Standard Model has one potential candidate:

the neutrino

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which, however, does not work!

- the relic density of neutrinos is

$$\Omega_\nu \approx \frac{\sum m_\nu}{93 h^2 \text{eV}}$$

$\rightarrow$ bounds on m_ν imply that neutrino density is too low

- neutrinos are “hot DM”, inconsistent with structure formation

Particle Dark Matter

The Standard Model has one potential candidate:

the neutrino

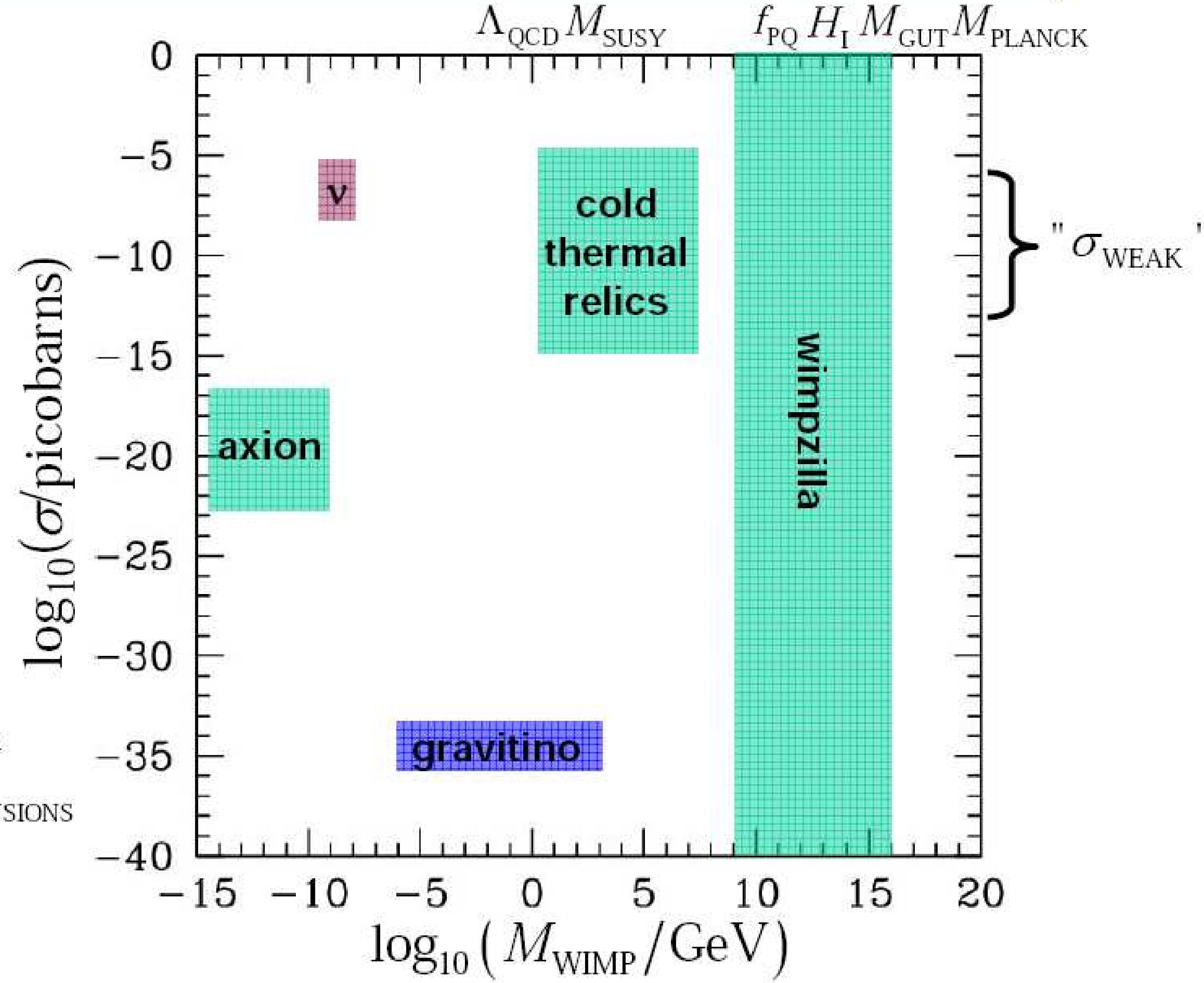
which, however, does not work!

$\Rightarrow$ Dark Matter implies

physics beyond the Standard Model

see talk of Y. Wong

Particle Dark Matter Candidates



Other Scales:

M_{EWK}

$M_{STERILE}$

M_{STRING}

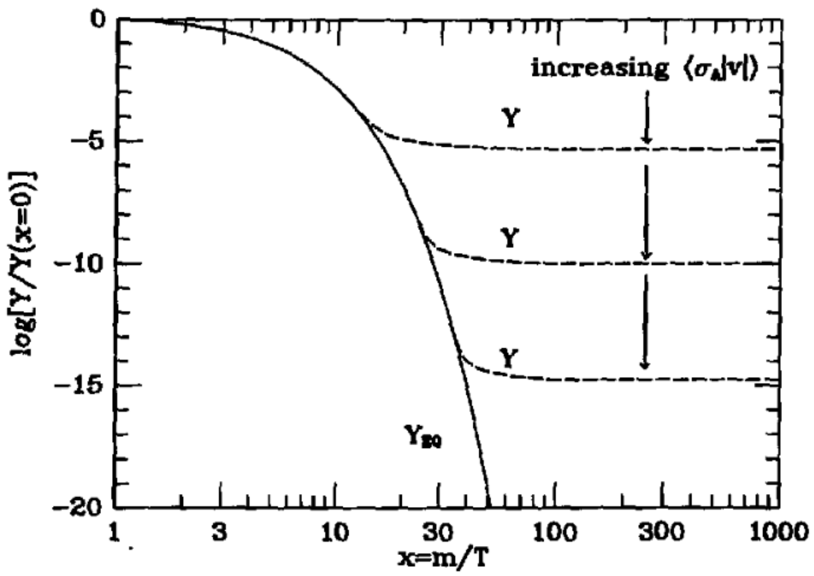
$M_{TECHNICOLOR}$

$M_{EXTRA\ DIMENSIONS}$

The "WIMP miracle"

thermal freeze-out:

$$\Omega_X h^2 \simeq \frac{10^{-37}\mathrm{cm}^2}{\langle \sigma_{\mathrm{annih}} v \rangle}$$



s-wave annihilations of a particle with mass m_X due to new physics at a scale Λ:

$$\langle \sigma_{\mathrm{annih}} v \rangle \sim \frac{g^4}{2\pi}\frac{m_X^2}{\Lambda^4} \simeq 6 \times 10^{-37}\mathrm{cm}^2\, g^4 \left(\frac{m_X}{100\,\mathrm{GeV}}\right)^2 \left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^{-4}$$

The "WIMP miracle"

We have (theoretical) reasons to believe that there is new physics around the TeV energy scale:

- stability of the SM against UV physics
- gauge coupling unification

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This new physics might provide

- a candidate particle for DM, which could
- naturally get the correct relic abundance (therm. freeze-out),
- and could be tested at LHC.

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Many of our favorite models for BSM @ the TeV scale provide such a candidate:

SUSY, Kaluza-Klein DM, Little Higgs, . . .

The "WIMP miracle"

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Many many many specific WIMP DM models:

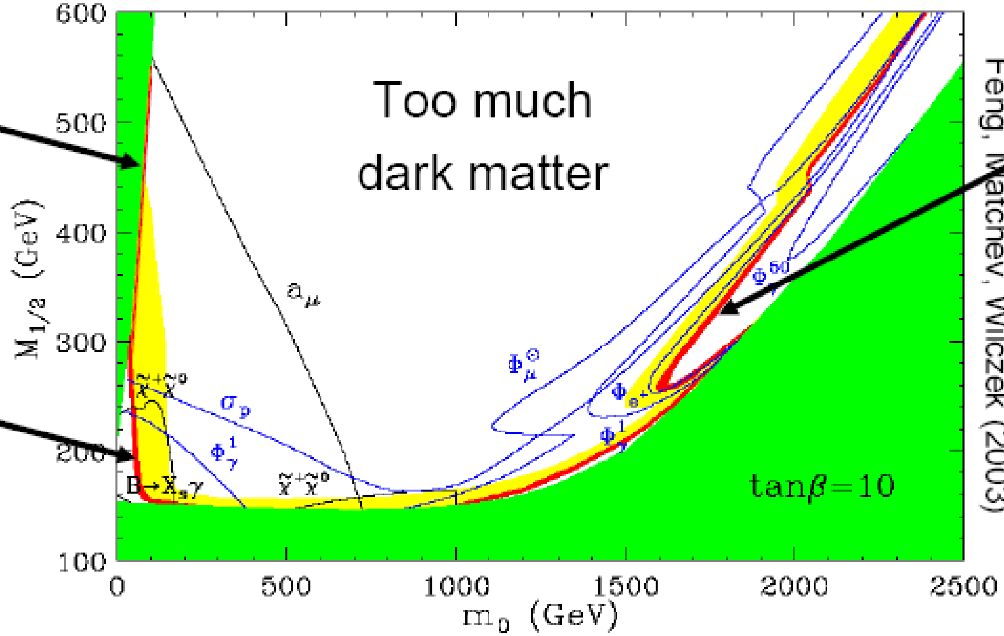
sterile neutrinos, inert Higgs, minimal DM, secluded DM, hidden sector models,. . .

Example: Neutralino DM in mSUGRA

- Ω_{DM} = 23% ± 4% stringently constrains models

Co-annihilation region

Bulk region



Focus point region

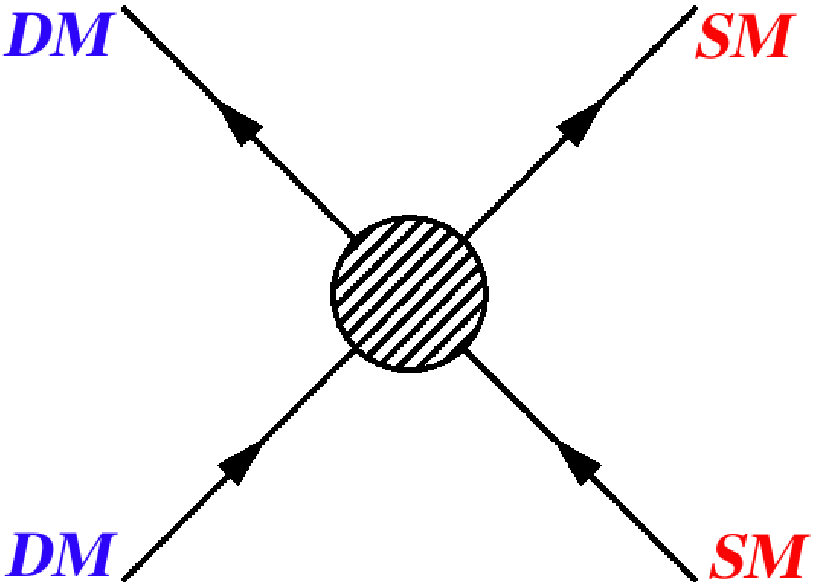
Yellow: pre-WMAP
Red: post-WMAP

- Assuming standard Big Bang, cosmology excludes many possibilities, favors certain regions

J. Feng @ COSMO 09

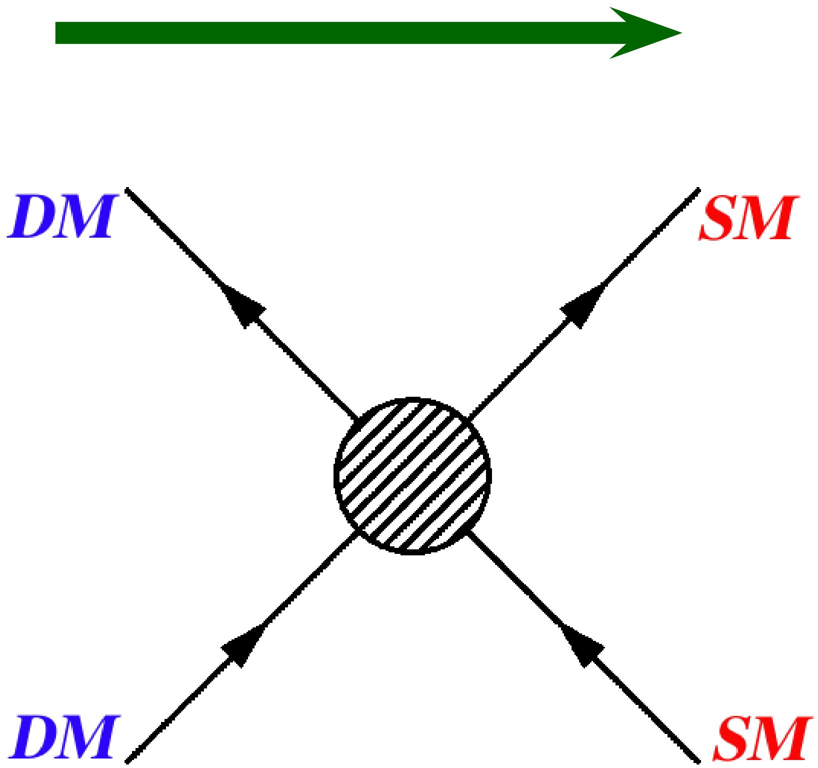
m_0: universal soft SUSY breaking scalar mass @ GUT scale
$M_{1/2}$: universal gaugino mass @ GUT scale

Testing WIMP models



Testing WIMP models

thermal freeze-out (early Univ.)
indirect detection (now)



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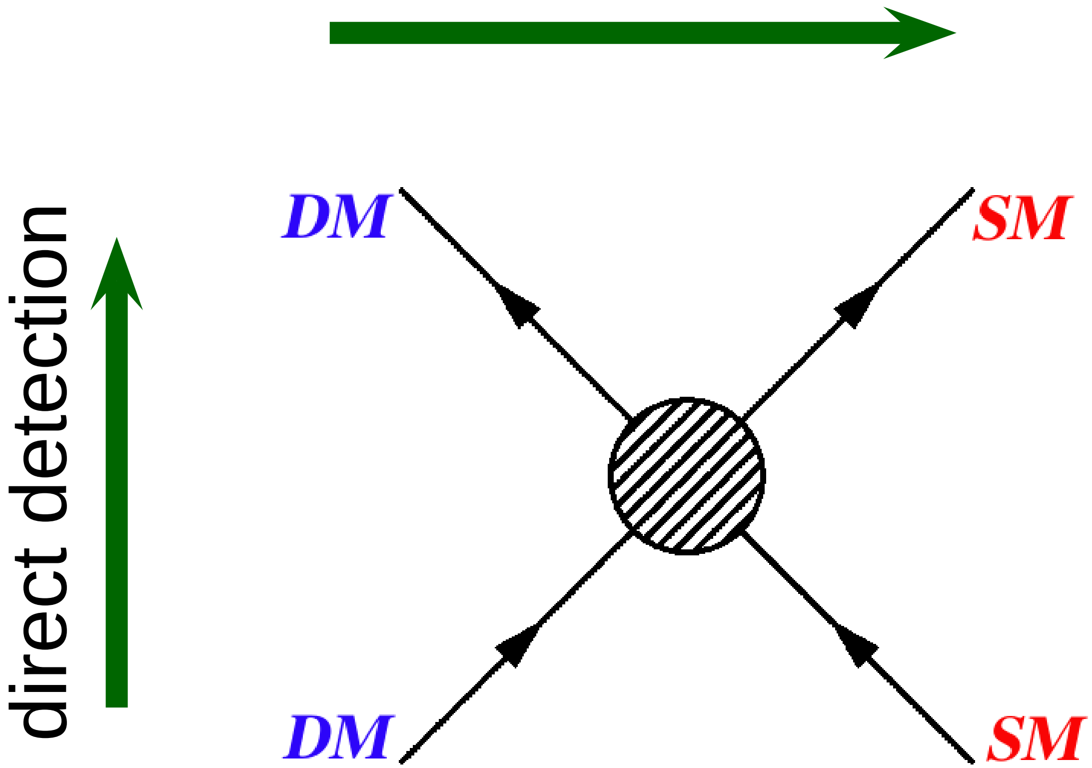

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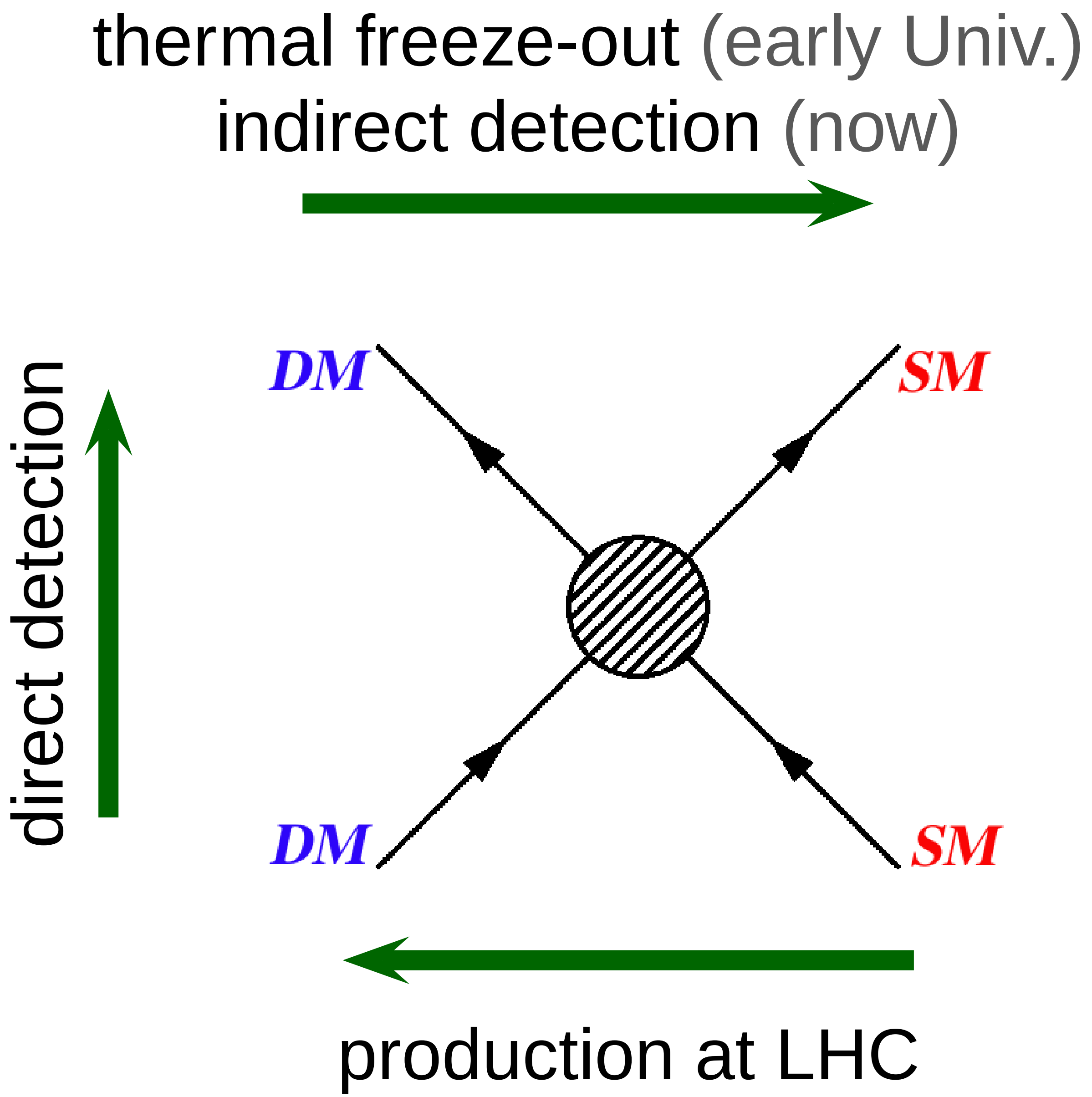

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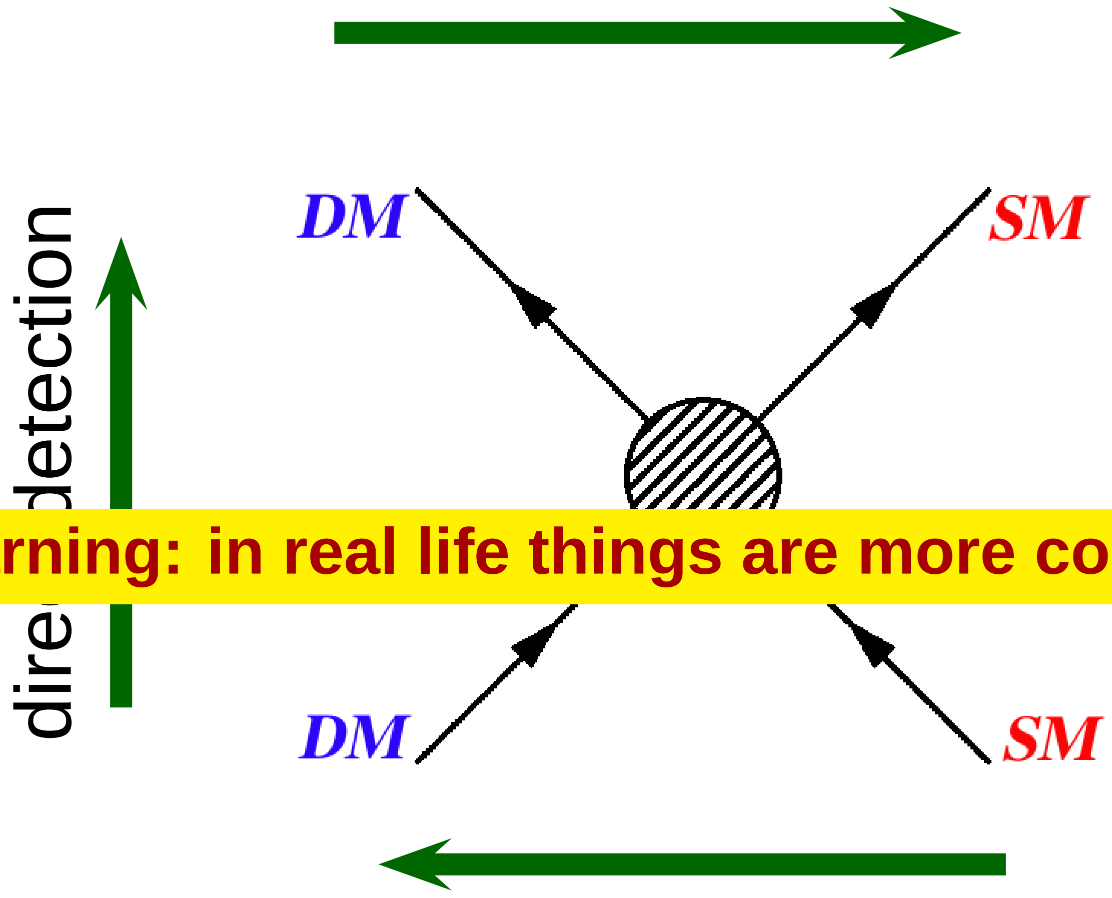
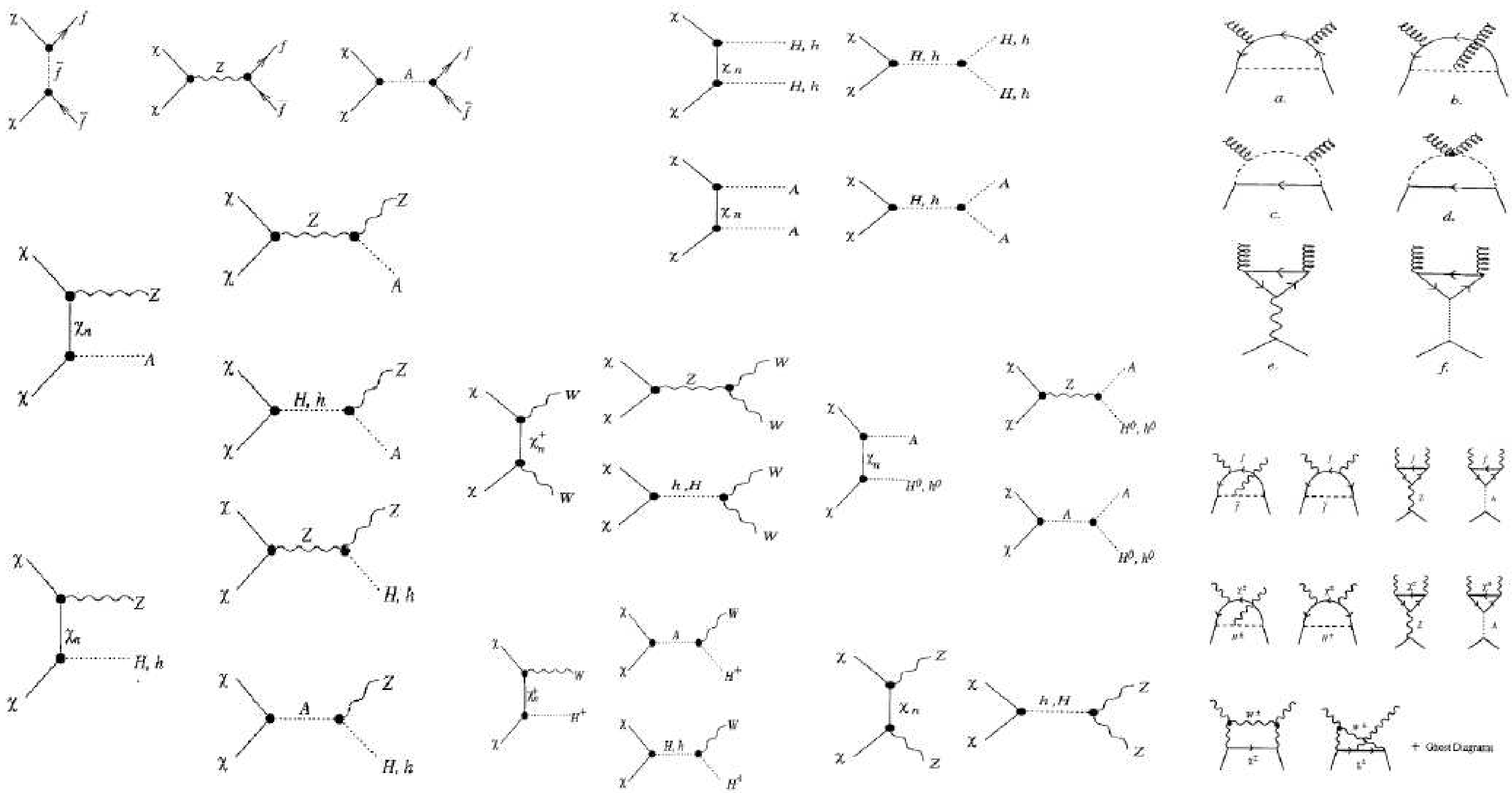


Warning: in real life things are more complicated!

production at LHC

Neutralino annihilation



Jungman, Kamionkowski, Griest, 1995

+ many 1-loop diagrams

Three ways to look for WIMPs

- Scattering off nuclei in underground detectors
  (direct detection) talks by L. Baudis, P. Belli, W. Rau

- Search for products of annihilations/decays
  (indirect detection) G. Anton, M. Simon, A. Morselli, M. Kowalski, J. Zavala

- Direct production at colliders
  (LHC) talks by S. Caron, T. Plehn

in all three cases huge progress is expected in the upcoming years

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  featureless exponential spectrum

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  uncertain astrophysical backgrounds

- Direct production at colliders (LHC) talks by S. Caron, T. Plehn missing energy

Hope for signal in all of these and explore complementarities

Three ways to look for WIMPs

- Scattering off nuclei in underground detectors (direct detection) talks by L. Baudis, P. Belli, W. Rau

  featureless exponential spectrum

  $\Rightarrow$ time or directional modulations

- Search for products of annihilations/decays (indirect detection) G. Anton, M. Simon, A. Morselli, M. Kowalski, J. Zavala

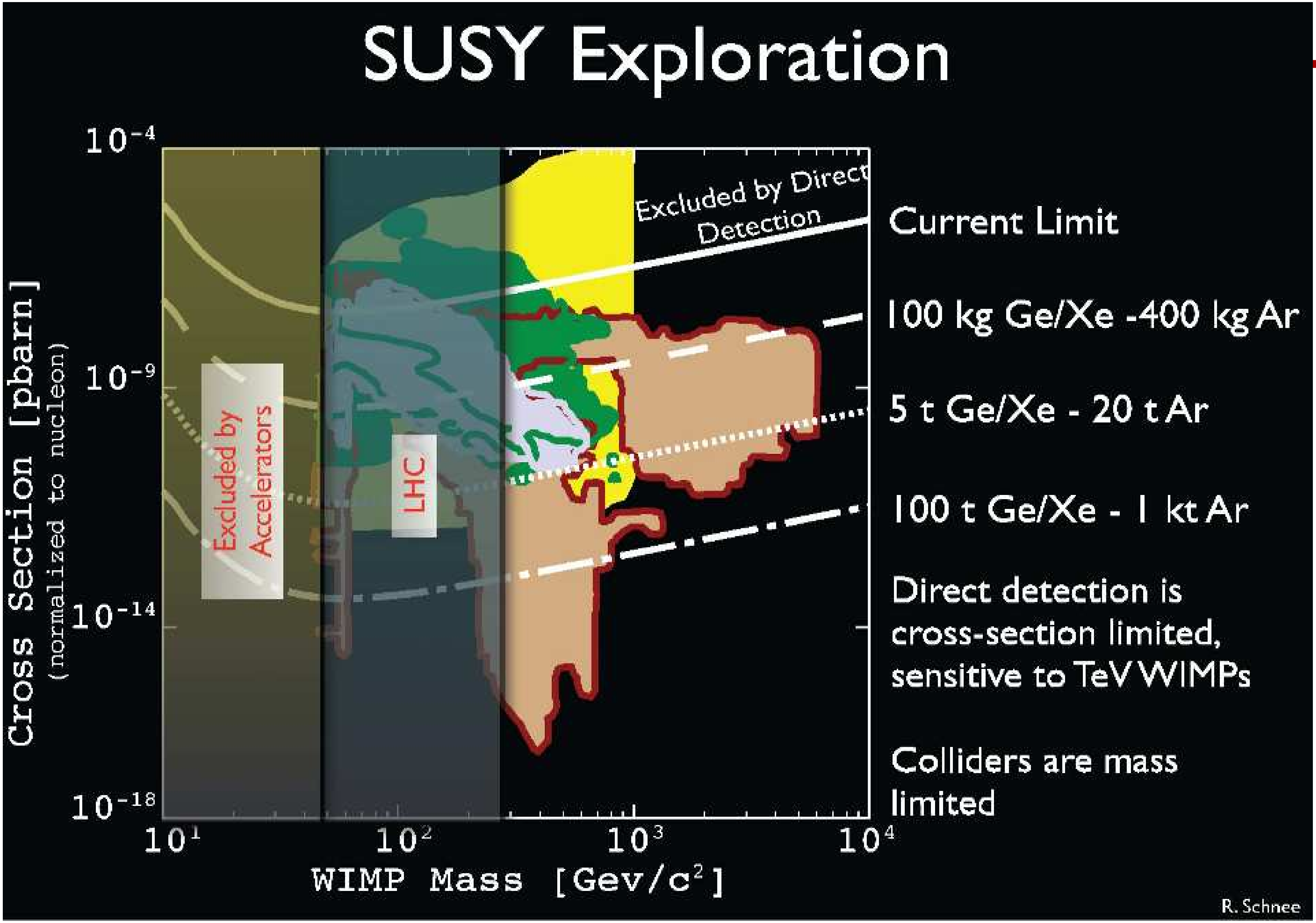
  uncertain astrophysical backgrounds

  $\Rightarrow$ “multi-messenger” searches $(\gamma, e^{\pm}, \bar{p}, \bar{D}, \nu, \ldots)$

- Direct production at colliders (LHC) talks by S. Caron, T. Plehn missing energy

Hope for signal in all of these and explore complementarities

Try to look for additional signatures


SUSY Exploration
Excluded by Direct Detection
Current Limit
100 kg Ge/Xe -400 kg Ar
5 t Ge/Xe - 20 t Ar
100 t Ge/Xe - 1 kt Ar
Excluded by Accelerators
LHC
Direct detection is cross-section limited, sensitive to TeV WIMPs
Colliders are mass limited
Cross Section [pbarn]
(normalized to nucleon)
10^-4
10^-9
10^-14
10^-18
10^1
10^2
10^3
10^4
WIMP Mass [Gev/c^2]
R. Schnee

WIMP or GIMP?

There are good arguments to assume that DM is a WIMP but there are also theoretically well motivated candidates with very small interaction strengths with SM particles (maybe only gravitational $\longrightarrow$ "GIMPs")

- Gravitino
- Axion
- Axino
- ...

see talks by W. Buchmüller, G. Raffelt

Have we seen already WIMP DM?

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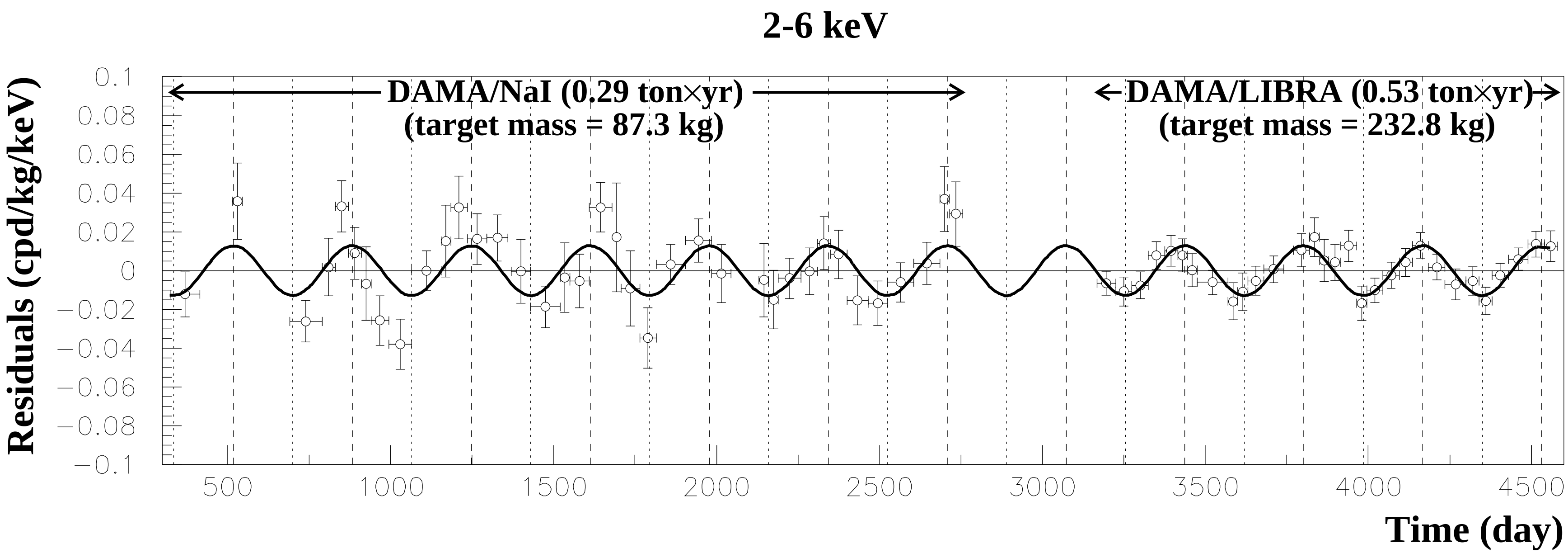
- The DAMA/LIBRA annual modulation signal?
- The PAMELA/FERMI cosmic ray anomaly?
- Anomalies from the galactic centre?

The DAMA/LIBRA annual modulation signal

The DAMA/LIBRA annual modulation signal

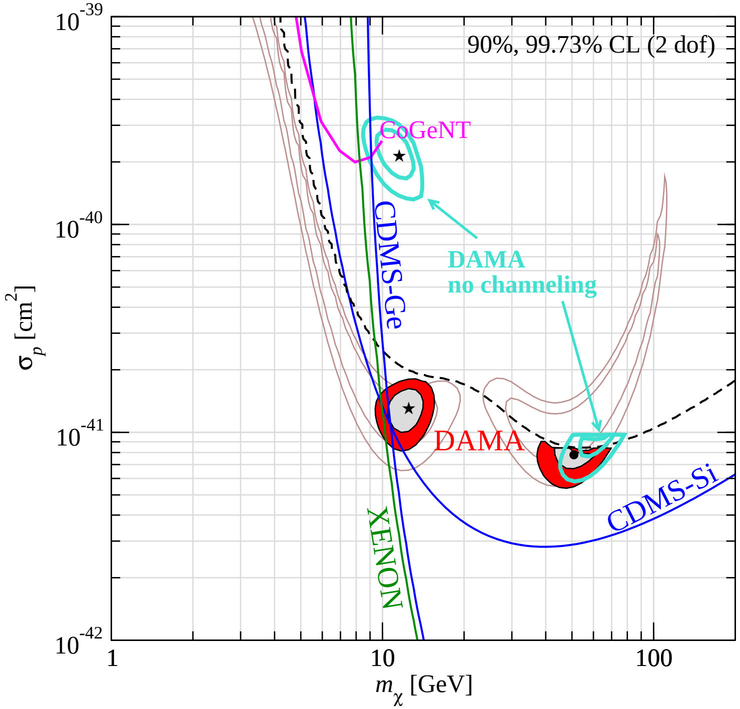
0.82 t yr exposure: 8.2σ evidence for an annual modulation of the count rate with max at day 144 ± 8 (June 2nd: 152)



Bernabei et al., 0804.2741, talk by P. Belli

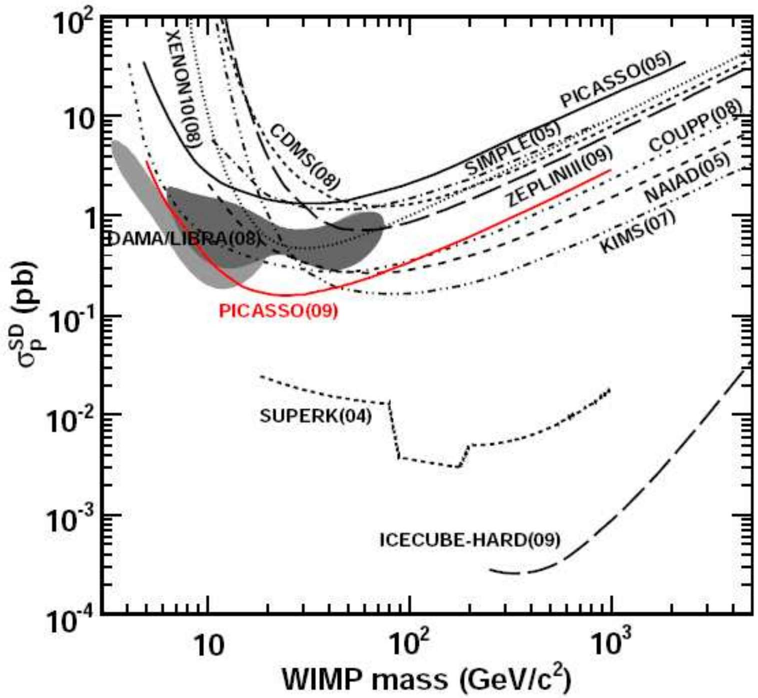
DAMA vs searches for nucl. recoils

SI elast. scattering



Fairbairn, TS, 0808.0704

SD elast. scattering



S.

Archambault et al., 0907.0307

tension between the DAMA modulation signal and bounds from nuclear recoil searches

DAMA vs searches for nucl. recoils

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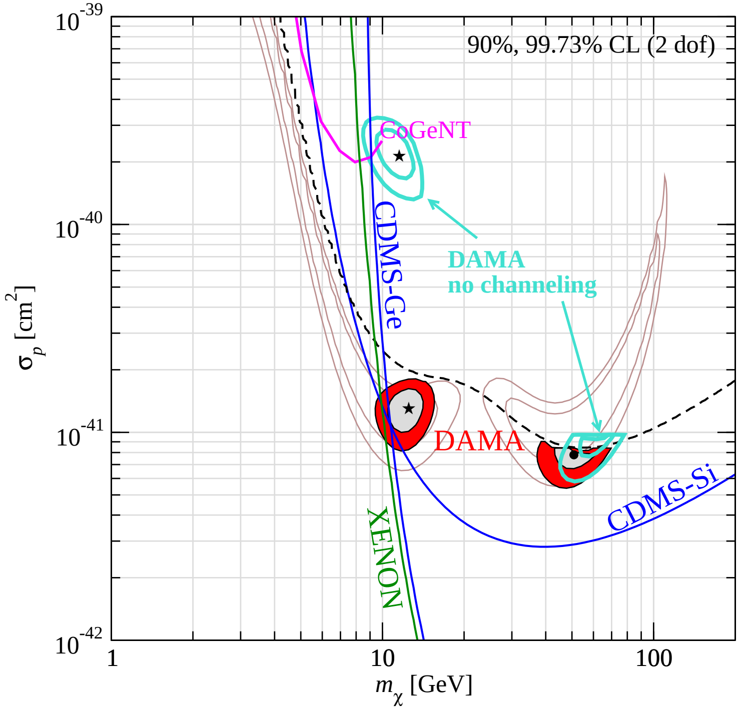

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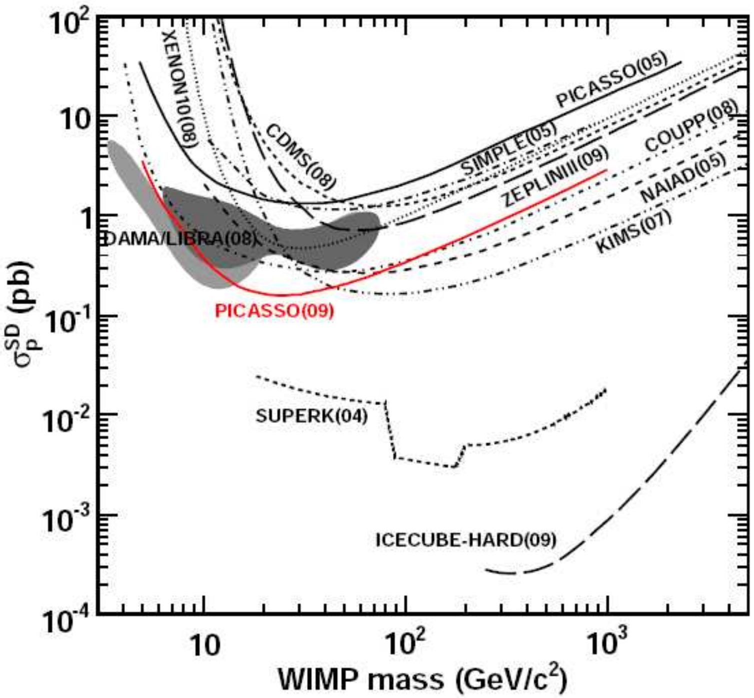

S.

Archambault et al., 0907.0307

The issue of channeling is important: for certain recoil directions in a crystal the scintillation signal is not quenched ⇒ shifts the DAMA allowed region.

DAMA vs searches for nucl. recoils

Some model-dependence in the comparison:
annual modulation of scintillation signal in DAMA versus
low-background searches for nuclear recoils

astro physics:

- non-standard halos
  Fairbairn, TS, 0808.0704; March-Russell, McCabe, McCullough, 0812.1931
- DM streams
  Gondolo, Gelmini, hep-ph/0504010; Chang, Pierce, Weiner, 0808.0196

only modest improvement in the tension is obtained by rather
extreem assumptions on DM astro physics

DAMA vs searches for nucl. recoils

Some model-dependence in the comparison:
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particle physics:

- inelastic DM scattering Tucker-Smith, Weiner, hep-ph/0101138; Chang, et al., 0807.2250; Schmidt-Hoberg, Winkler, 0907.3940; . . .
- mirror DM Foot, 0804.4518
- DM with electric/magn. moments Masso, Mohanty, Rao, 0906.1979
- resonant DM scattering Bai, Fox, 0909.2900
- momentum dep. DM scattering Chang, Pierce, Weiner, 0908.3192
- form factor DM Feldstein, Fitzpatrick, Katz, 0908.2991
- leptophilic DM Bernabei et al., 0712.0562; Kopp, Niro, Schwetz, Zupan, 0907.3159
- . . .

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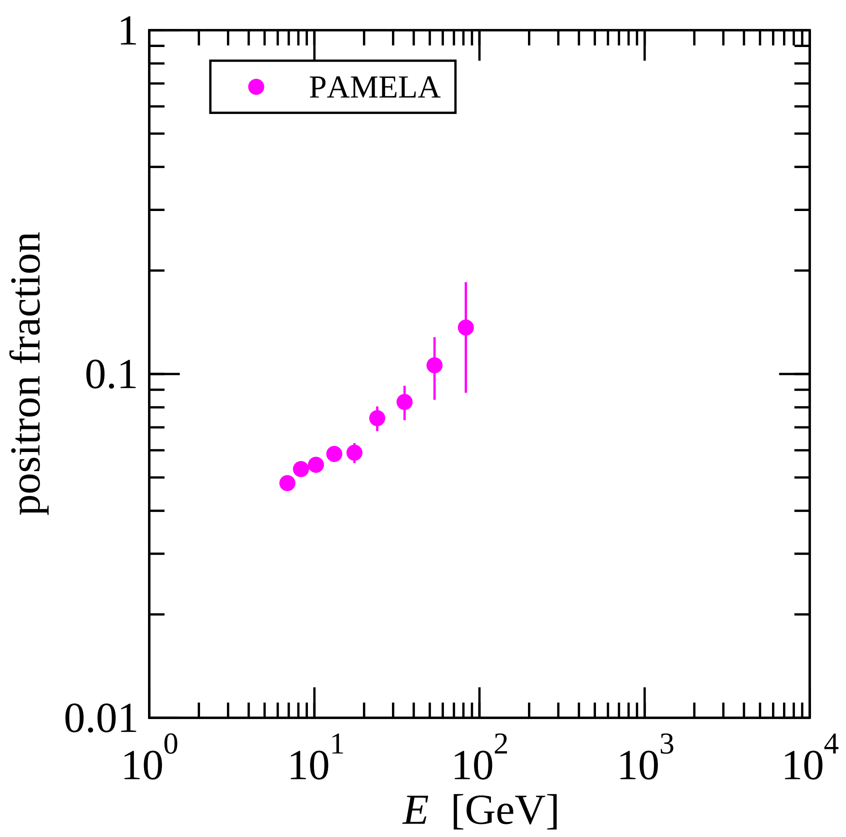
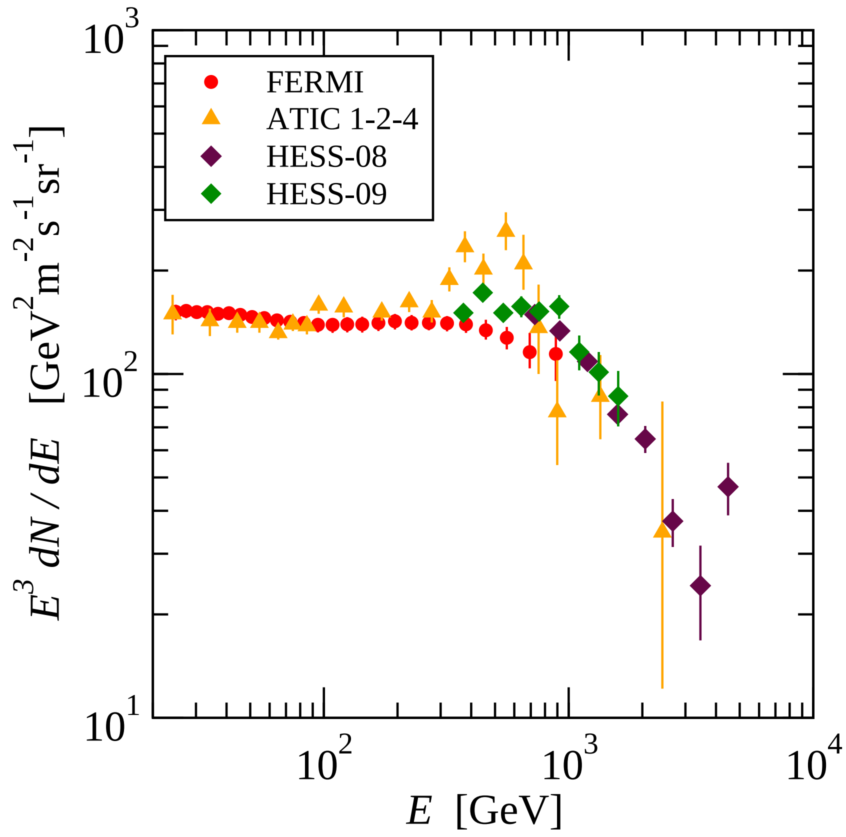
- . . .

most of these ideas work only marginally - at best . . .

Cosmic ray $e^{\pm}$ anomalies

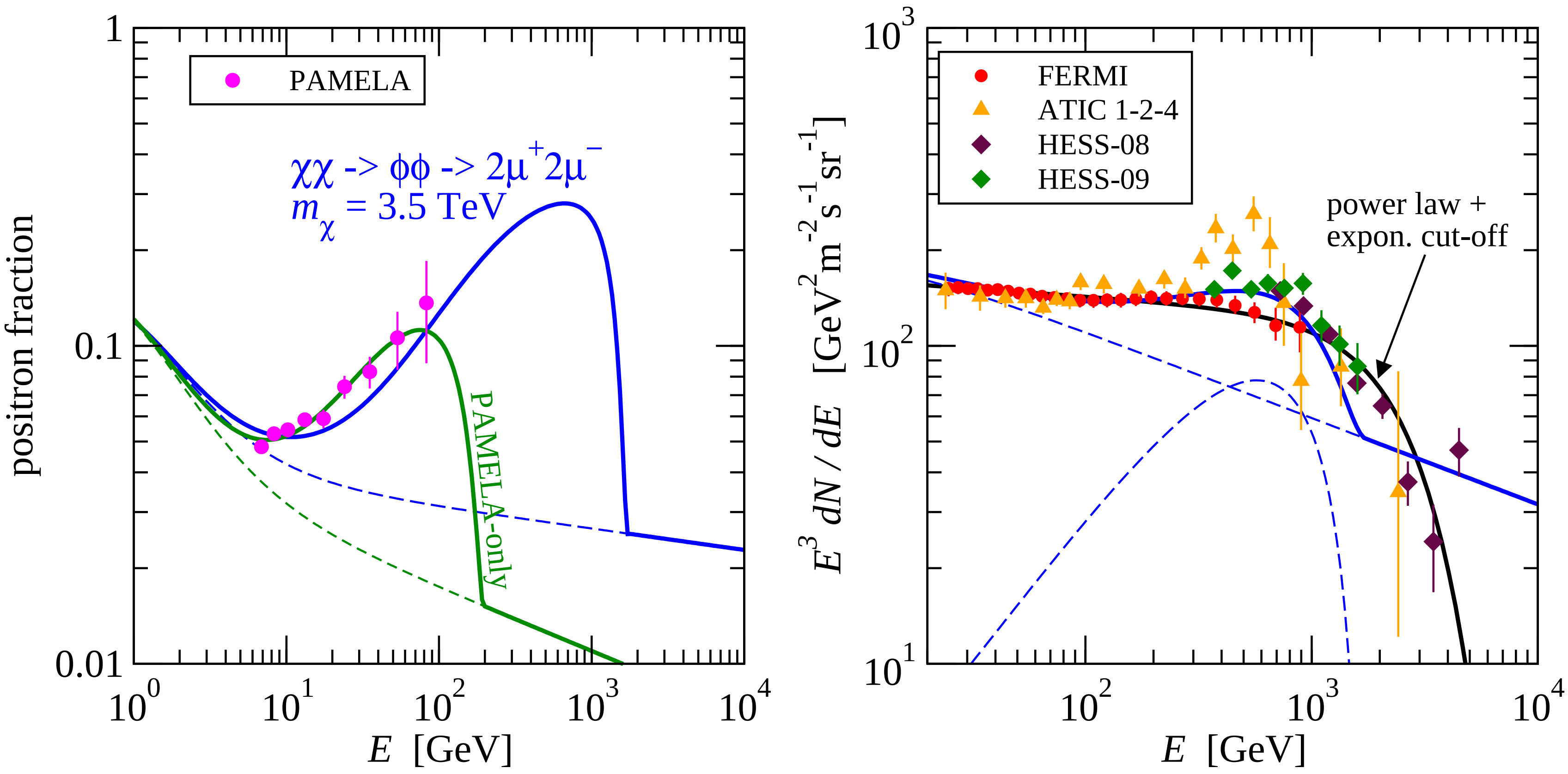
Anomalies in $e^{\pm}$ cosmic ray flux





see talks by M. Simon (PAMELA) and A. Morselli (FERMI)

Anomalies in $e^{\pm}$ cosmic ray flux



see talks by M. Simon (PAMELA) and A. Morselli (FERMI)

very active field: PAMELA paper 0810.4995 nearly 400 citations

Anomalies in $e^{\pm}$ cosmic ray flux

Data suggest a new source of primary e^{+}

Is it astro-physics or DM?

possible astro-physical sources:

- one or several local pulsars

  D. Hooper, P. Blasi, P. Serpico, 0810.1527; S. Profumo, 0812.4457

  somewhat extreeme parameters for pulsars?

- old supernova remnants

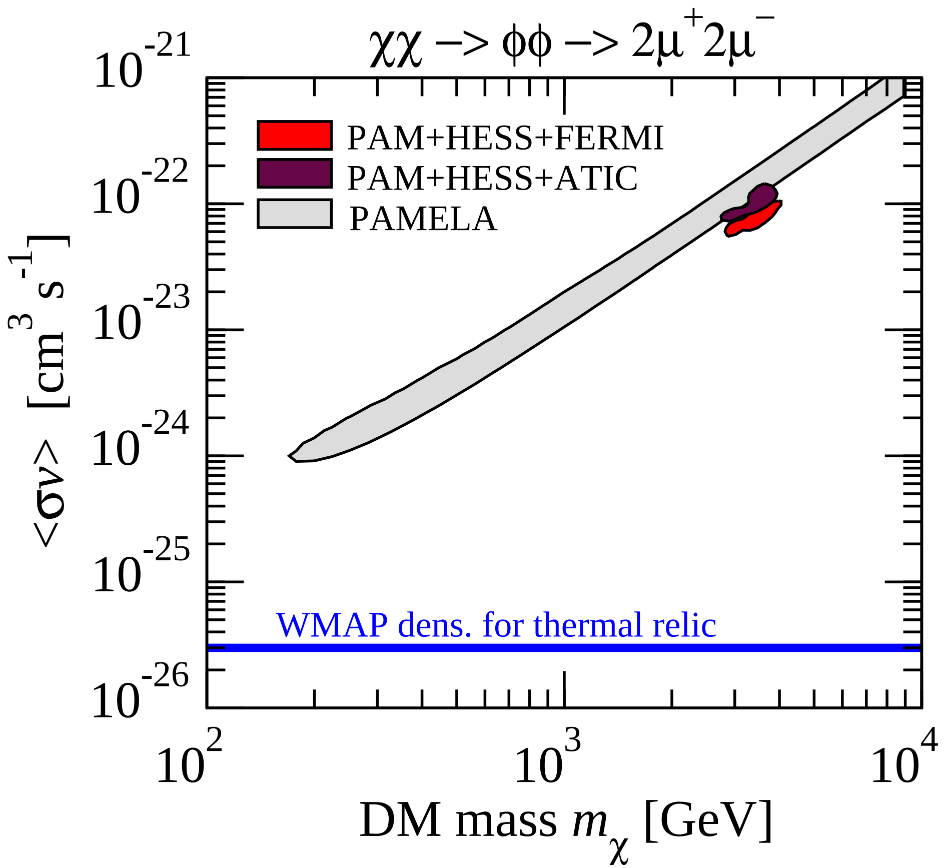
  P. Blasi, 0903.2794; P. Blasi, P. Serpico, 0904.0871

  problems with anti-protons?

Anomalies in $e^{\pm}$ cosmic ray flux

If it is DM, it has very un-expected properties:

- cross section is much larger than needed for relic density due to thermal freeze-out $\rightarrow$ "boost-factor" $\sim 100 -$ few $\times 10^3$



Rothstein, Schwetz, Zupan
0903.3116

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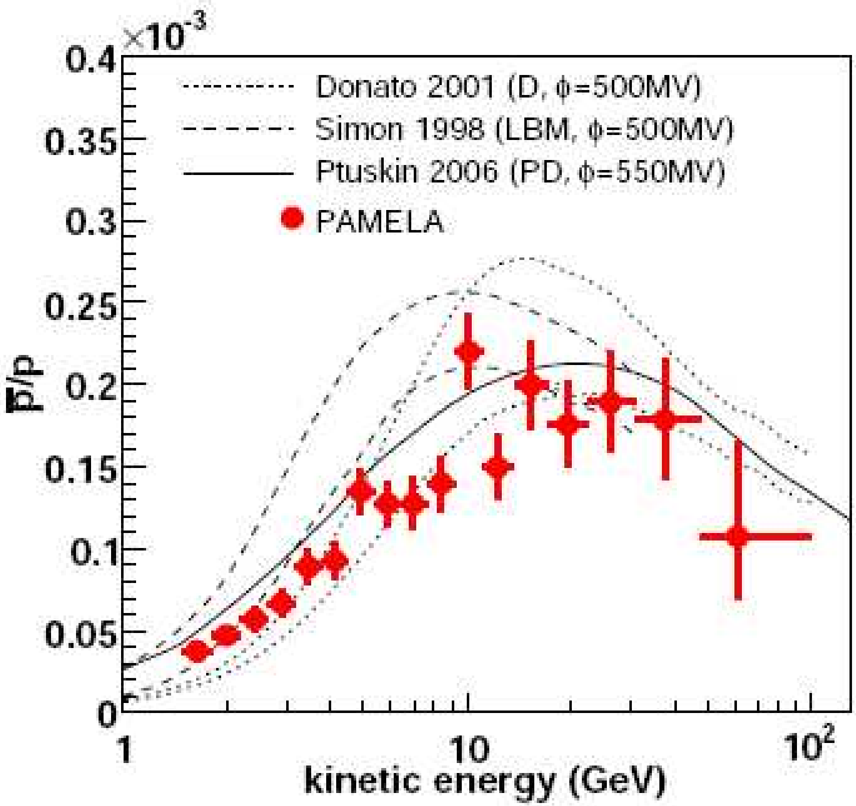
- no excess in anti-protons $\rightarrow$ annihilate into leptons



PAMELA, 0810.4994

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- no excess in anti-protons $\rightarrow$ annihilate into leptons

This looks rather different from a "standard WIMP", e.g., a SUSY neutralino!

Boost factor from astrophysics?

Annihilation rate proportional $\rho_{\rm DM}^2 \to$ DM clumps enhance rate

BUT:

- N-body simulations indicate that astrophysics allows only for boost factors $\lesssim 10$.

  Diemand et al., 0805.1244

- the probability of a nearby DM sub-halo able to explain the data is very low

  Brun, Delahaye, Diemand, Profumo, Salati, 0904.0812

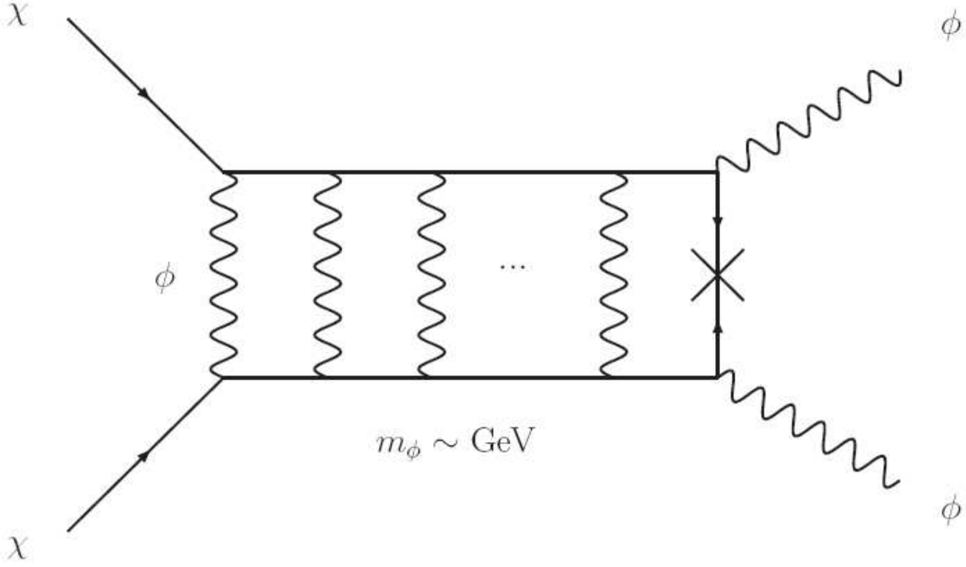
Need a particle mechanism to decouple annihilations at freeze-out and today

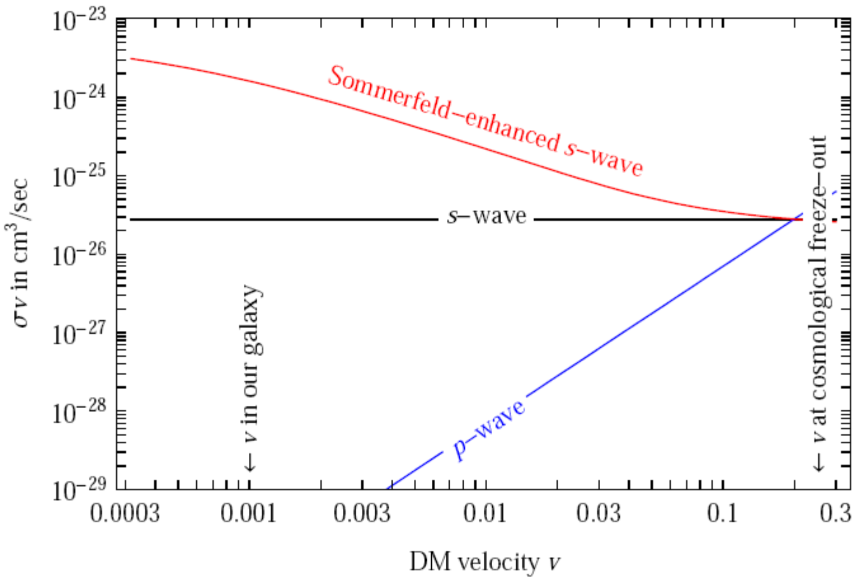
How to get such large boost factors?

- force mediator in dark sector

  (Sommerfeld enhancement / DM-bound state)

  Hisano et al., hep-ph/0307216, hep-ph/0412403, hep-ph/0610249; Cirelli et al., 0706.4071, 0809.2409; Arkani-Hamed, 0810.0713; Pospelov, Ritz, 0810.1502; . . .





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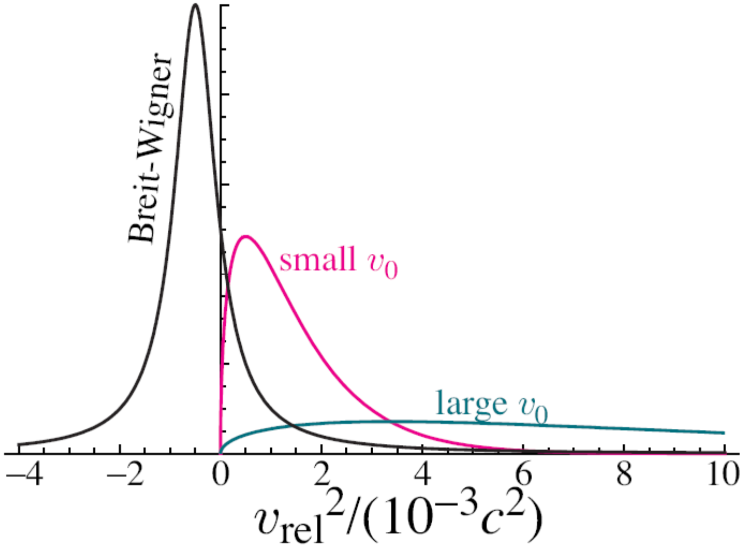
- annihilations close to a resonance

  Ibe, Murayama, Yanagida, 0812.0072



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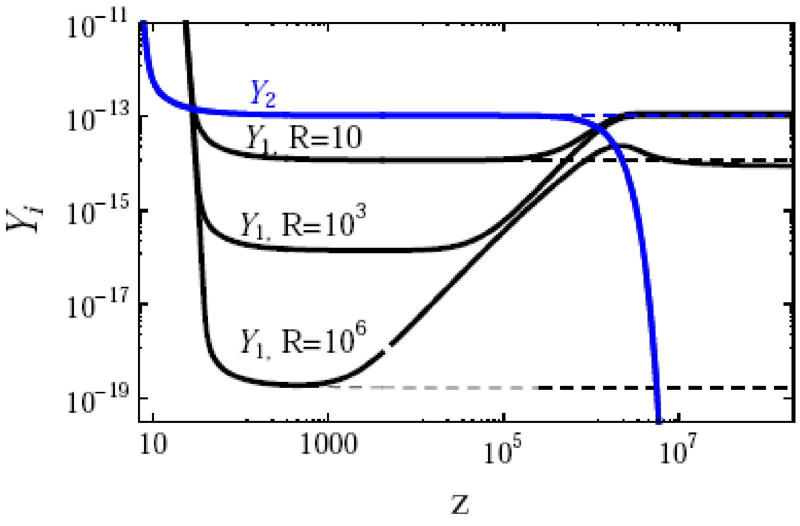

$$\frac{Y_1(\infty)}{Y_1^{\mathrm{Th.rel.}}} \simeq N_{\mathrm{dec}} R \simeq B$$

$$R = \frac{m_1}{m_2}\frac{\langle\sigma_{A1}v_1\rangle}{\langle\sigma_{A2}v_2\rangle},\ z = m_1/T,\ Y_i(z) = n_i(z)/s(z$$

How to get such large boost factors?

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  Ibe, Murayama, Yanagida, 0812.0072

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- DM decay

  Ibarra, Tran, 0709.4593, 0804.4596; Nardi, Sannino, Strumia, 0811.4153; Bertone, Büchmuller, Covi, Ibarra, 0709.2299; . . .

  - some production mechanism in early universe,

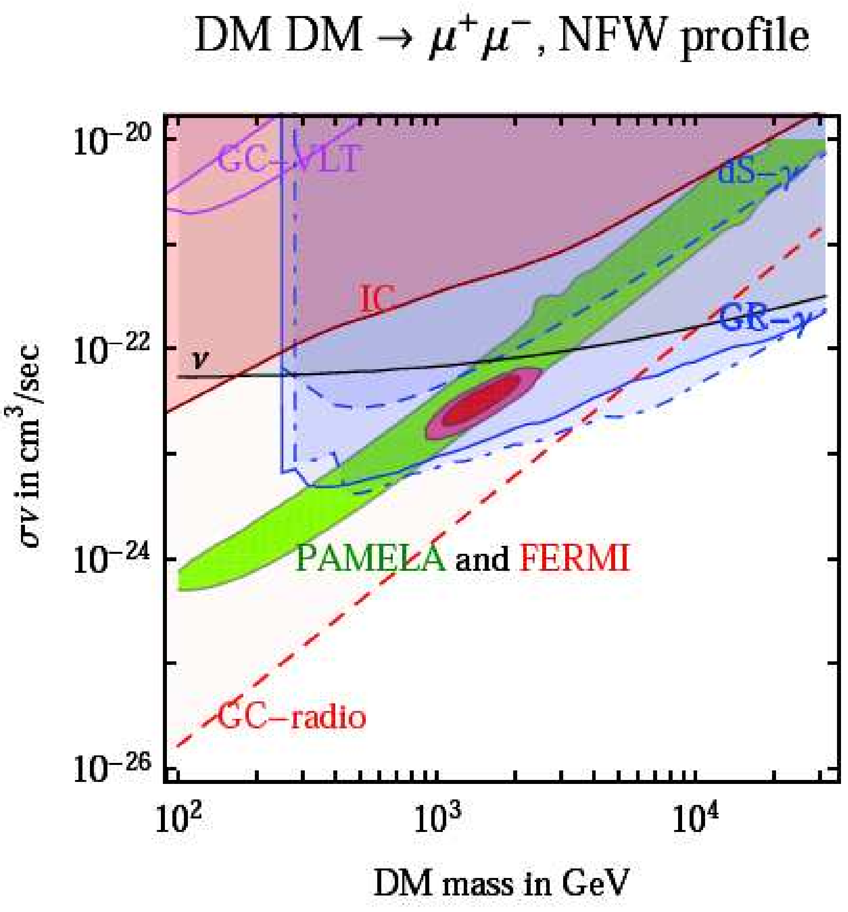
    e.g., thermal freeze-out due to $\langle\sigma_{\rm ann} v\rangle \sim 10^{-36}{\rm cm}^2$

  - indirect signal today given by decay $\Gamma \sim 10^{-26}{\rm s}^{-1}$

“multi-messenger” constraints

- anti-protons PAMELA, 0810.4994
- γ’s from final/intermed. state radiation $\rightarrow$ HESS obs. of galactic center, galactic ridge, spheroidial dwarf galaxies
  Bertone et al., 0811.3744; Bergstrom et al., 0812.3895
- synchrotron emission (radio observations of the GC)
  Bertone et al., 0811.3744; Bergstrom et al., 0812.3895
- difuse γ-rays from inverse compton scattering (ICS) on star light, CMB photons, and dust $\rightarrow$ FERMI data on difuse γ’s
  Cirelli, Panci, 0904.3830
- SuperK bound on muons from neutrinos from galactic center
  Hisano, Kawasaki, Kohri, Nakayama, 0812.0219
- distortions of the CMB power spectrum due to energy injections by DM annihilations (reionization, heating)
  Slatyer, Padmanabhan, Finkbeiner, 0906.1197; Huetsi, Hektor, Raidal, 0906.4550; Cirelli, Iocco, Panci, 0907.0719

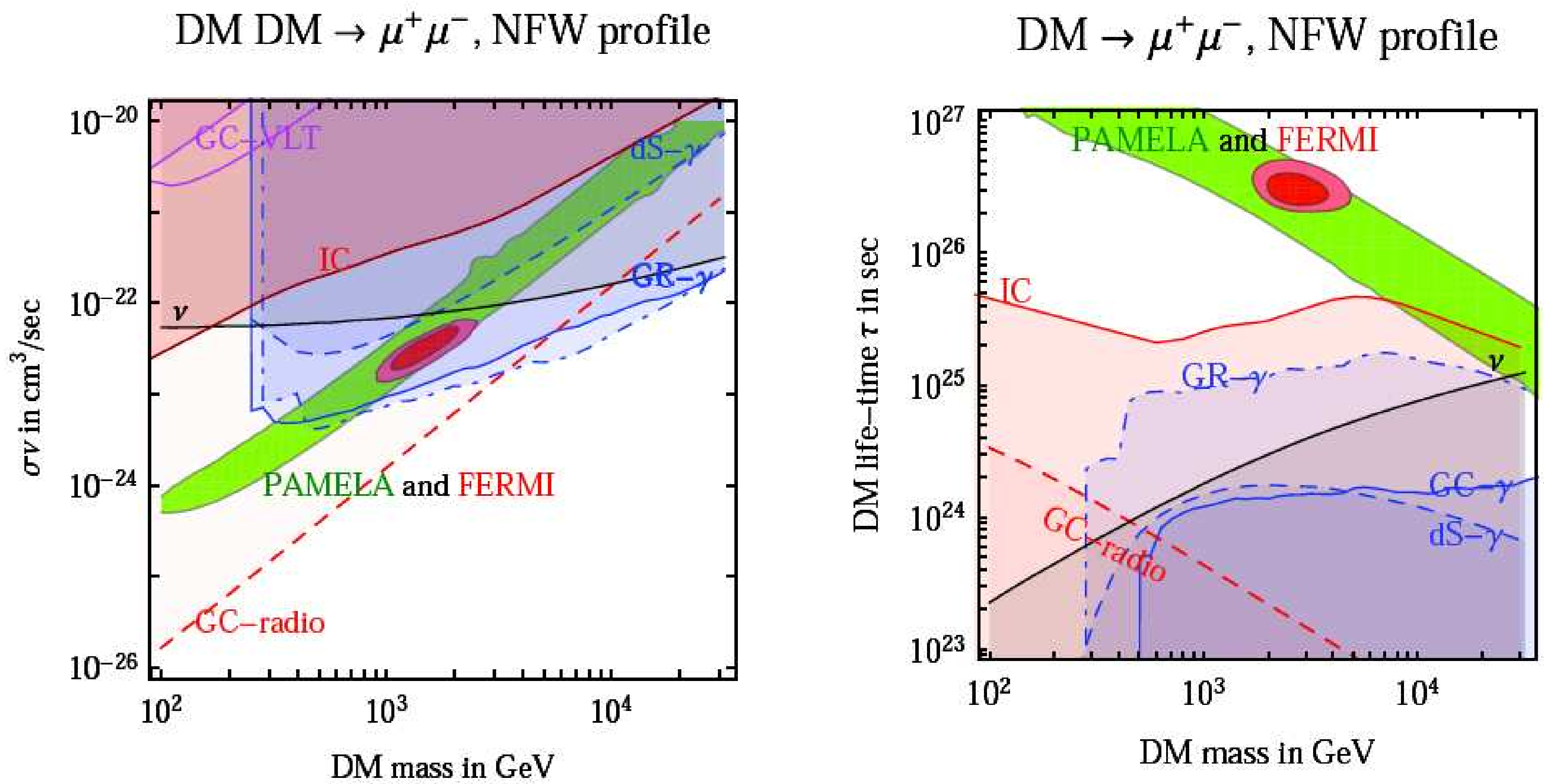
“multi-messenger” constraints



Meade, Papucci, Strumia, Volansky, 0905.0480

dependence on halo model, annihilation mode

“multi-messenger” constraints

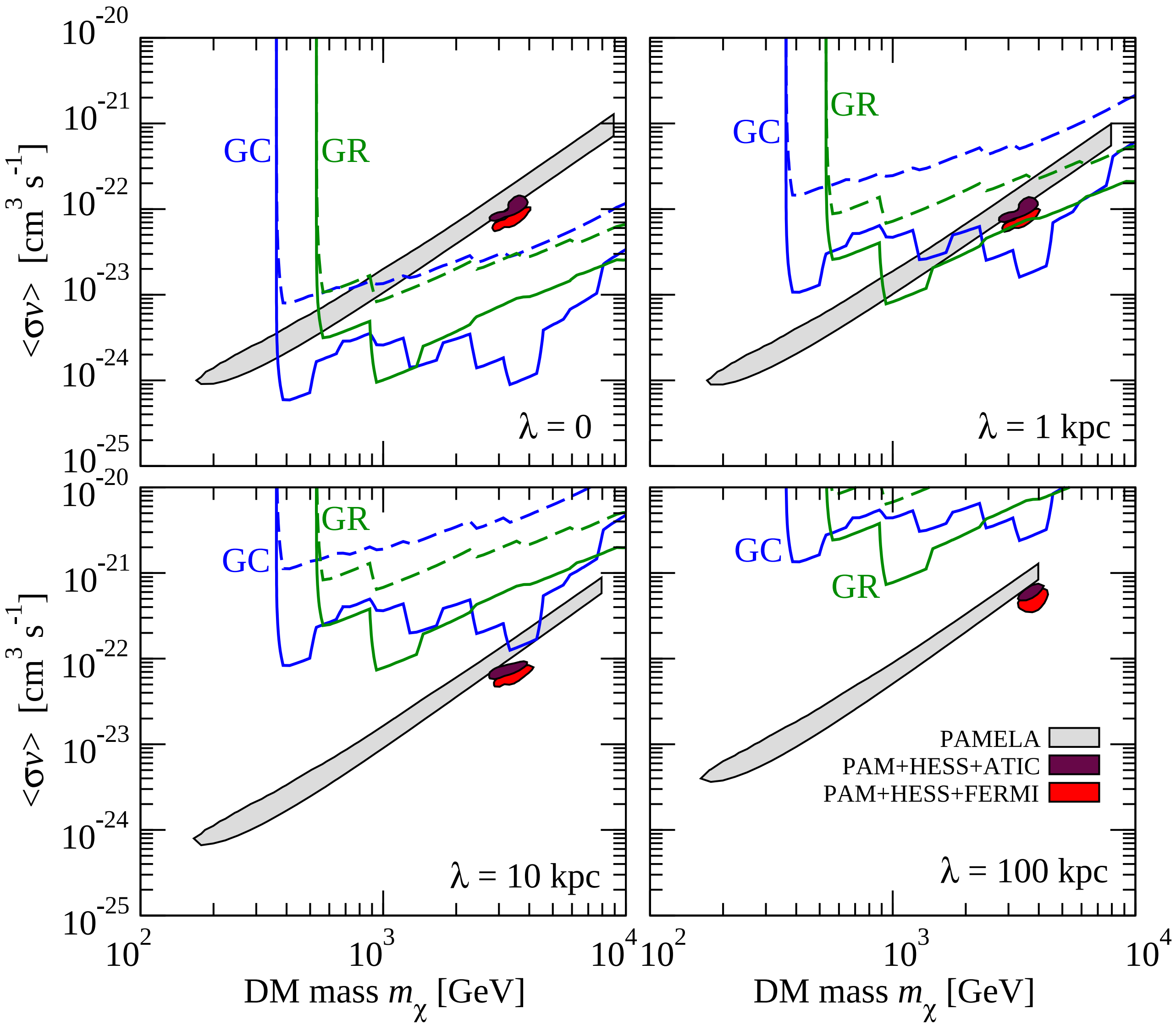


Meade, Papucci, Strumia, Volansky, 0905.0480

DM decay typically is less constrained ($\propto \rho$ instead of ρ^2)

long-lived intermediate state

γ-rays bounds can be avoided by $\chi\chi \to \phi\phi \to 2\mu^+2\mu^-$,
assuming that ϕ has a life-time corresponding to $\lambda \sim 10\,\mathrm{kpc}$



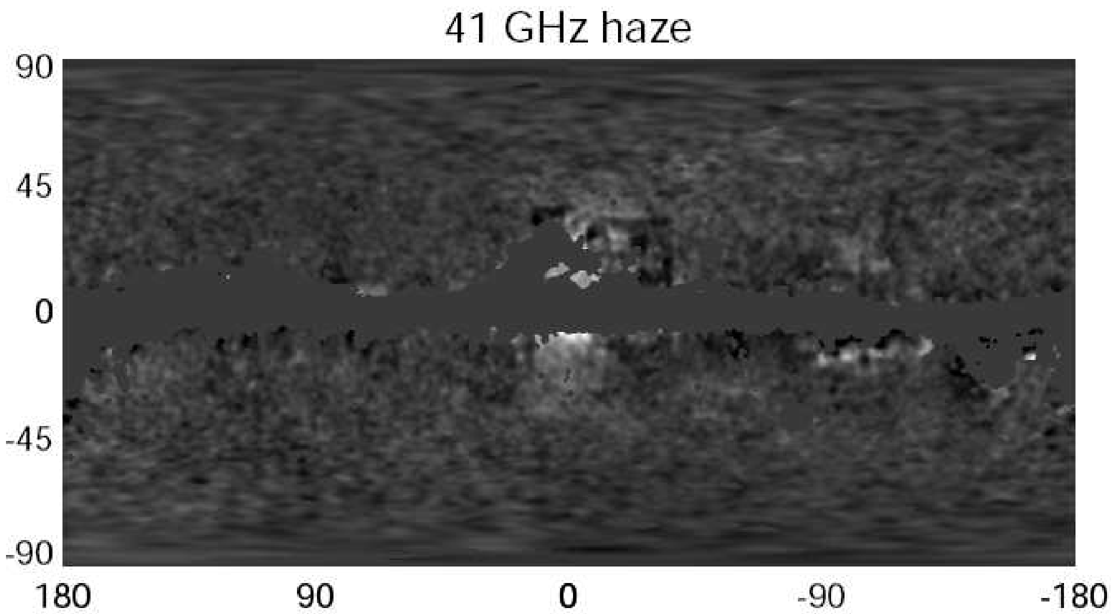
Rothstein, Schwetz, Zupan
0903.3116

PAMELA & FERMI & HESS $e^{\pm}$ anomalies. . .

- . . . seem to require rather non-standard DM (large annihilation cross section / leptonic modes)
- DM annihilations are strongly constrained (excluded?) by the lack of various photon signals
- DM decay seems to be a viable explanation

WMAP and FERMI anomalies from the galactic centre

The “Haze”



micro wave haze (WMAP)

Finkbeiner, 2004,. . .

synchrotron radiation?

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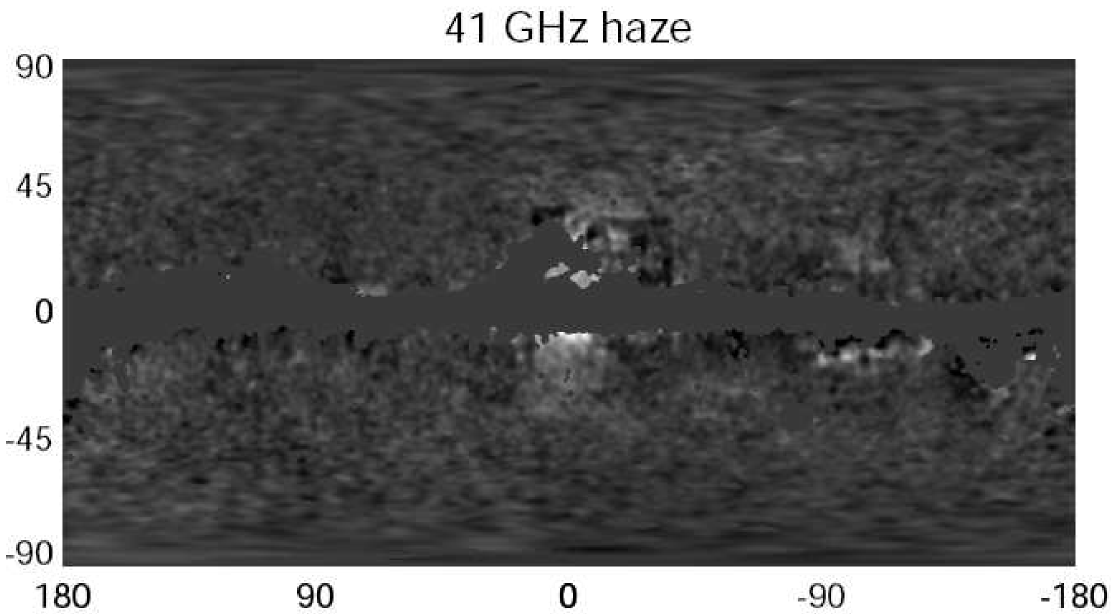

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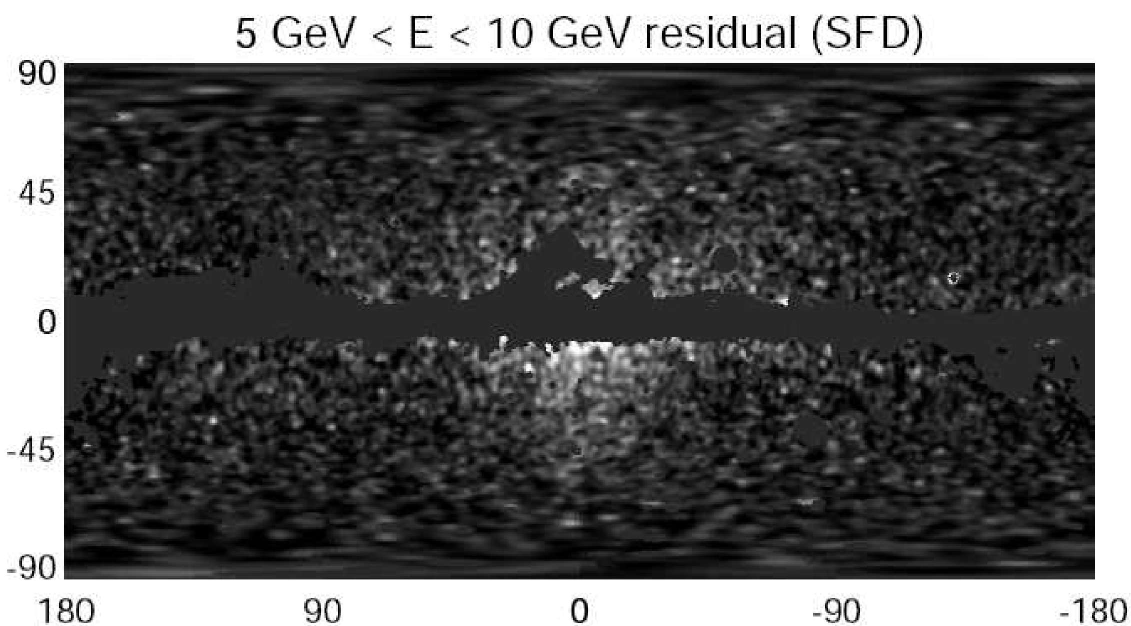

γ-ray haze (FERMI)

Dobler et al., 0910.4583

inverse compton scatt.?

Common origin of primary $e^{\mp}$?

Power of the multi-messenger approach

FERMI γ ray "excess" near the GC can be explained by $\chi\chi \to b\bar{b} \to \gamma X$ with $m_\chi \approx 28\,\mathrm{GeV}$.

L. Goodenough, D. Hooper, 0910.2998

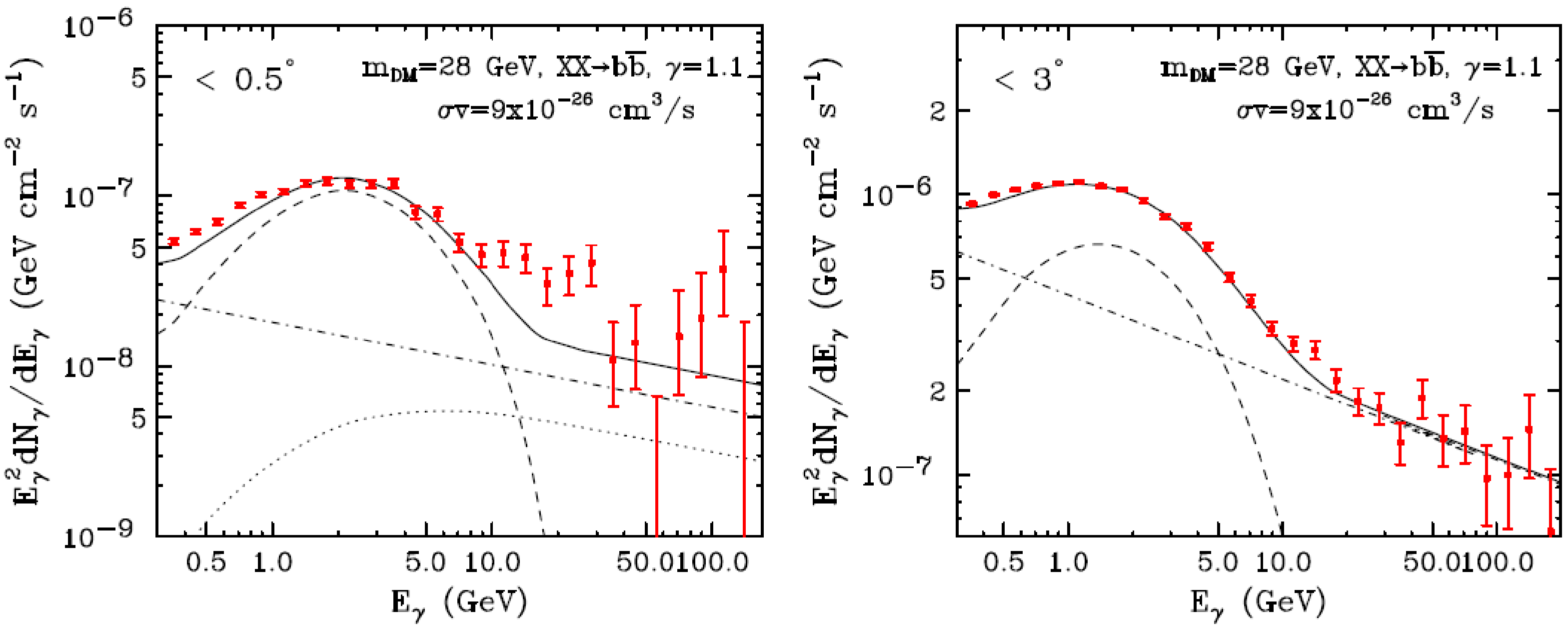

FIG. 2: The gamma ray spectrum measured by the FGST within 0.5° (left) and 3° (right) of the Milky Way's dynamical center. In each frame, the dashed line denotes the predicted spectrum from a 28 GeV dark matter particle annihilating to $b\bar{b}$ with a cross section of $\sigma v = 9 \times 10^{-26}$ cm^3/s, and distributed according to a halo profile slightly more cusped than NFW ($\gamma = 1.1$). The dotted and dot-dashed lines denote the contributions from the previously discovered TeV point source located at the Milky Way's dynamical center and the diffuse background, respectively. The solid line is the sum of these contributions.

Power of the multi-messenger approach

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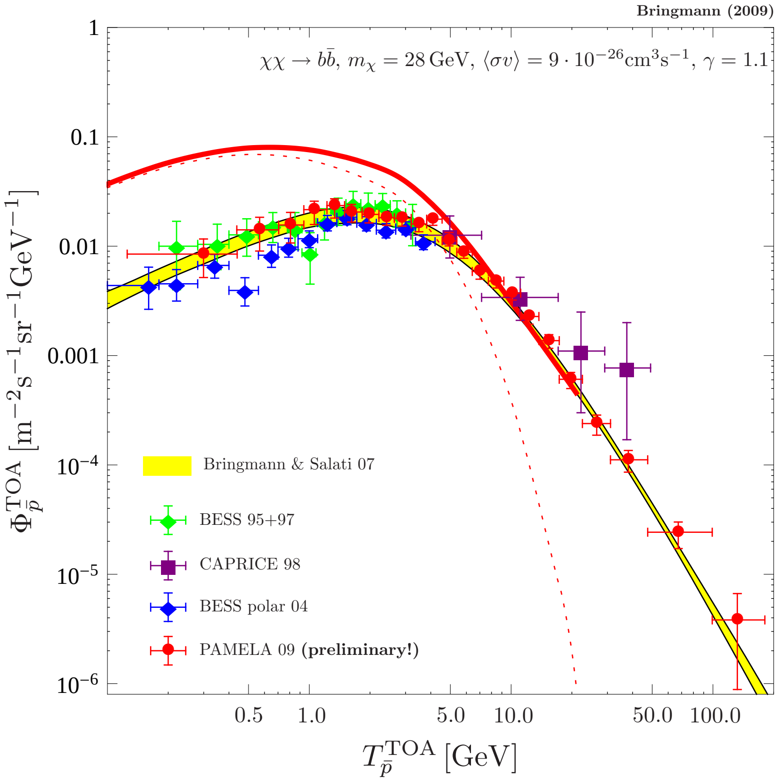
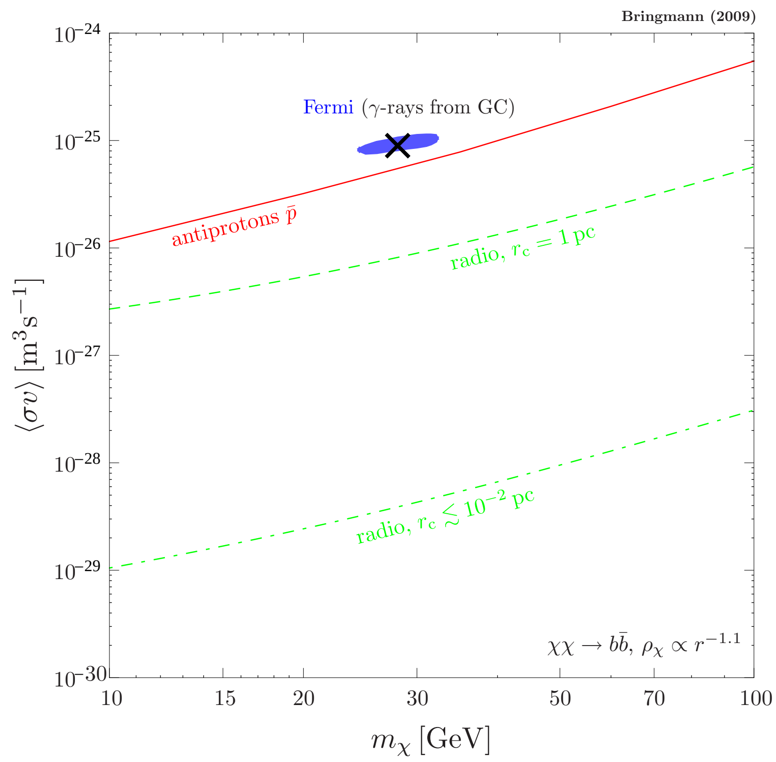
BUT: this interpretation is inconsistent with bounds from anti-protons and radio observations:





T. Bringmann
0911.1124

Concluding remarks

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- DM is a very active field with significant progress to be expected in direct, indirect and collider searches in the near future,
- has profound implications on our understanding of the universe and the theory of elementary particles,
- a few anomalies may or may not be related to non-gravitational interactions of DM $\longrightarrow$ they have triggered a lot of theoretical activity, and lead to a variety of alternative models for DM.

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Thank you for your attention!