Dark Matter and the Electroweak scale: Are they related?

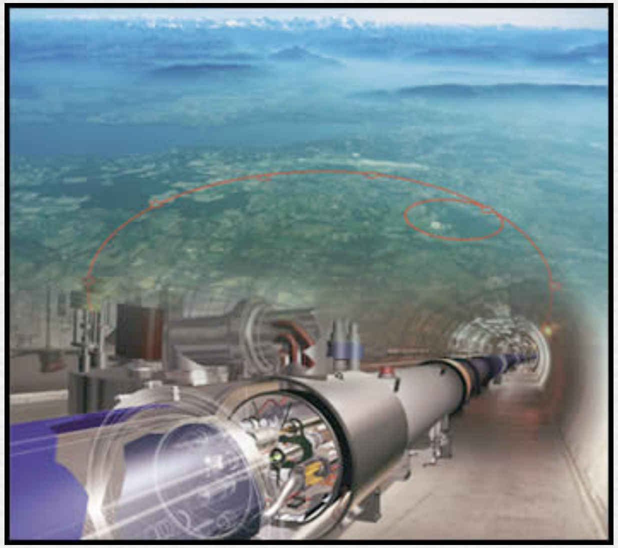
Géraldine SERVANT
CERN-Th & IPhT CEA Saclay

2010: First collisions at the LHC

Direct exploration of the TeV scale has started

main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?



The Standard Model of Particle Physics

Forces | **Matter** | **Background**

$$\mathcal{L}_{\text{Standard Model}} = -\, F^{a}_{\mu\nu} F^{a\mu\nu} + (\lambda_{ij}\, \Psi_i \Psi_j\, h + h.c) + N_i M_{ij} N_j + |D_\mu h|^2 - V(h)$$

gauge sector

flavour sector

neutrino mass sector (if Majorana)

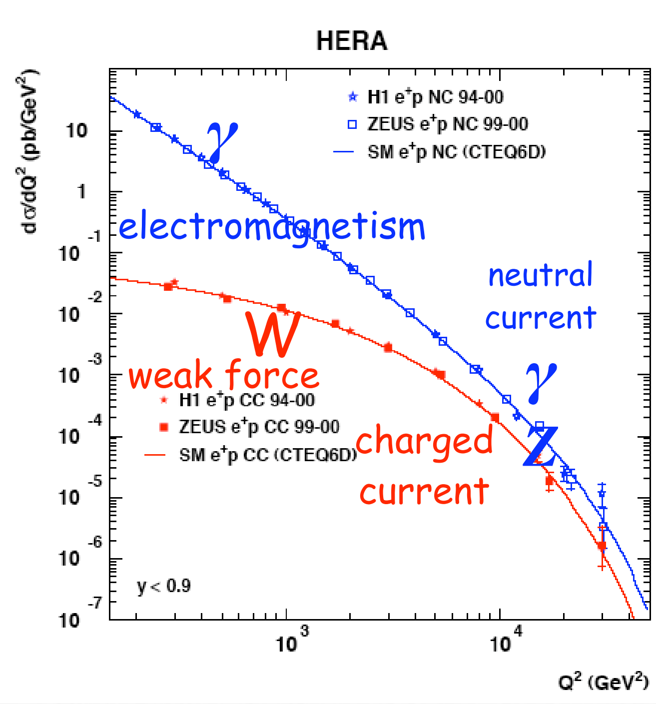
(spontaneous) electroweak symmetry breaking sector

$SU(3)_C \times SU(2)_L \times U(1)_Y$

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

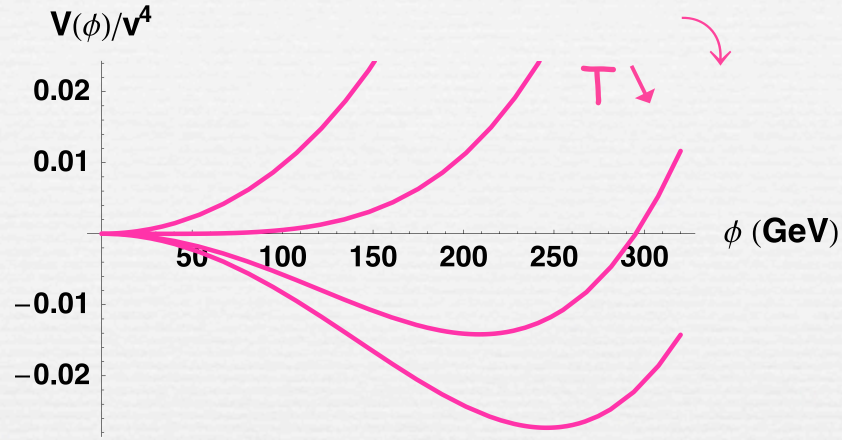
The Higgs is the only remaining unobserved piece

and a portal to new physics hidden sectors

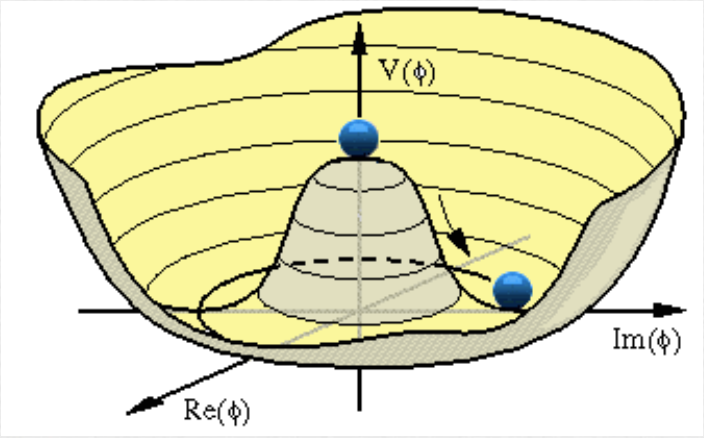


The Higgs Mechanism

EW symmetry breaking is described by the condensation of a scalar field



The Higgs selects a vacuum state by developing a non zero background value. When it does so, it gives mass to SM particles it couples to.

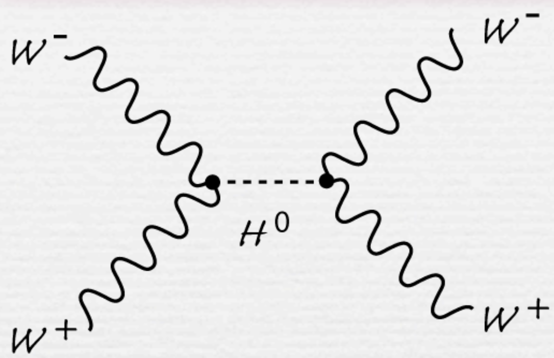


the puzzle:

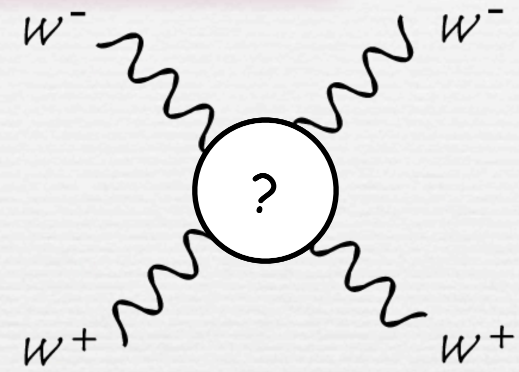
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

Electroweak symmetry breaking: 2 main questions

- ## What is unitarizing the $W_L W_L$ scattering amplitude?

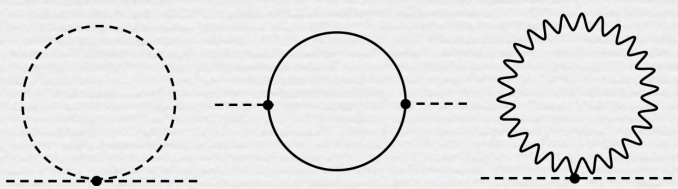


the Higgs or something else?



- ## What is cancelling the divergent diagrams?

(i.e what is keeping the Higgs light?)
: Hierarchy problem



$\Rightarrow \delta M_H^2 \propto \Lambda^2$

Λ , the maximum mass scale that the theory describes

strong sensitivity on UV unknown physics

need new degrees of freedom & new symmetries to cancel the divergences

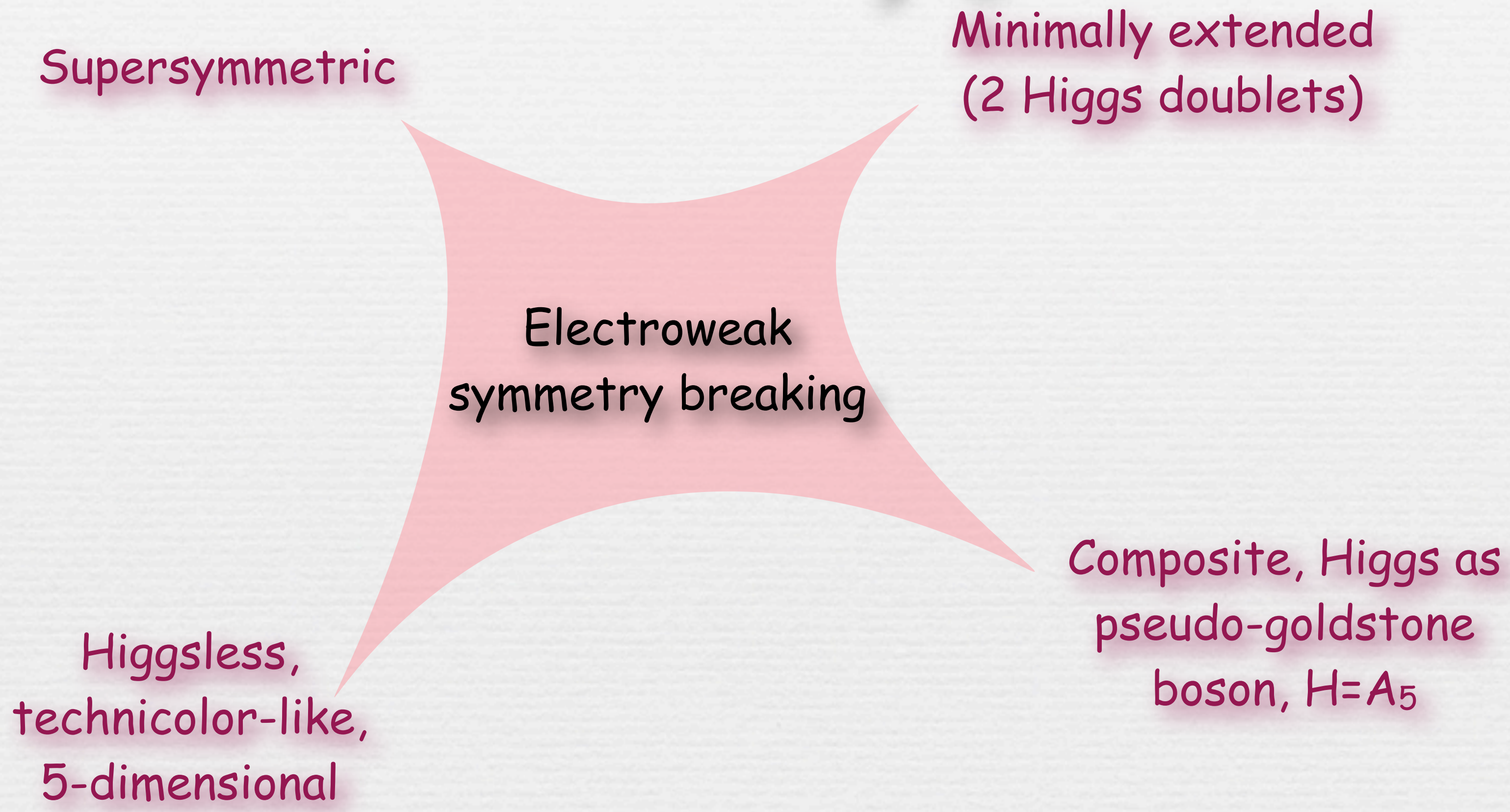
supersymmetry, gauge-Higgs unification, Higgs as a pseudo-goldstone boson...

→ theoretical need for new physics at the TeV scale

Addressing the hierarchy problem with a new symmetry

fermion	vector	scalar
$\Psi \to e^{i\theta\gamma_5}\ \Psi$	$A_\mu \to A_\mu + \partial\theta$	$H \to H + \theta$
Ψ massless: protected by chiral symmetry	A_μ massless: protected by gauge invariance	H massless: protected by a global symmetry
$\Psi \overset{\text{SUSY}}{\longleftrightarrow} H$	In 5 dimensions: $H=A_5$	

Which new physics?



In all explicit examples, without unwarranted cancellations, new phenomena are required at a scale $\Lambda \sim [3\text{-}5] \times M_{Higgs}$

and other variants ...

- Composite Higgs ?
- Little Higgs ?
- Littlest Higgs ?
- Intermediate Higgs ?
- Slim Higgs ?
- Fat Higgs ?
- Gauge-Higgs ?
- Holographic Higgs ?
- Gaugephobic Higgs ?
- Higgsless ?
- UnHiggs ?
- Portal Higgs ?
- Simplest Higgs ?
- Private Higgs ?
- Lone Higgs ?
- Phantom Higgs ?

The Hierarchy Problem has been the guideline of theorists for over 30 years

The main goal of the LHC:

Understand why $M_{EW} << M_{Planck}$

We are at a turning point. Within the next few years, we will know what is lying behind the EW scale.

Imagine what our universe would look like if electroweak symmetry was not broken

- quarks and leptons would be massless

- mass of proton and neutron (the strong force confines quarks into hadrons) would be a little changed

- proton becomes heavier than neutron (due to its electrostatic self energy) ! no more stable

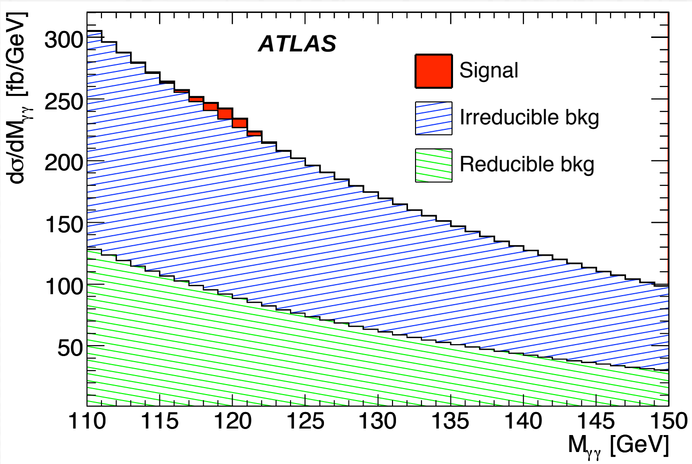
-> no hydrogen atom

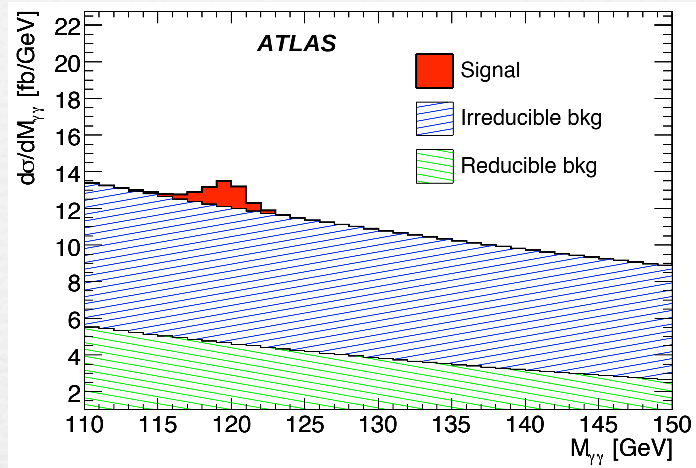
-> very different primordial nucleosynthesis

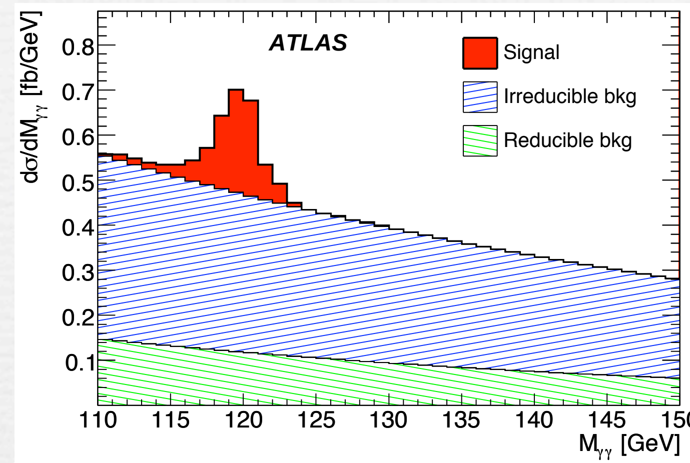
-> a profoundly different (and terribly boring) universe

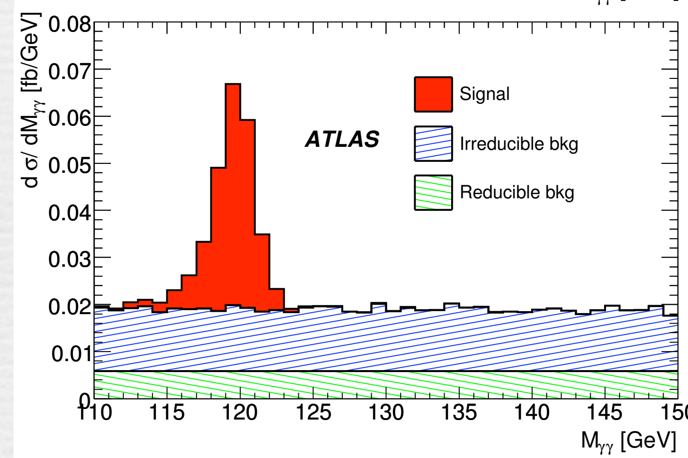
What questions the LHC experiments will try to answer :

• Does a Higgs boson exist ?









If yes :

- is there only one ?
- what are its mass, width, quantum numbers ?
- what are its couplings to itself and other particles
- Spin determination
- CP properties
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed ?

If not, be ready for

- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as W′, Z′ (KK) resonances, technicolor, etc...

• Searches for other new particles: Do they play any role in EW symmetry breaking?

LHC will most likely not provide the final answer

Searching for complementary probes of the EW symmetry breaking mechanism in cosmological observables

New TeV scale physics ⇄ **Cosmological signatures**

mainly from

- dark matter (this talk)
- baryogenesis

(see also recent interest in higgs inflation)

2 major observations unexplained by the Standard Model

that may have something to do with new physics at the electroweak scale

- the Dark Matter of the Universe

Some invisible transparent matter (that does not interact with photons) which presence is deduced through its gravitational effects

15% baryonic matter (1% in stars, 14% in gas)

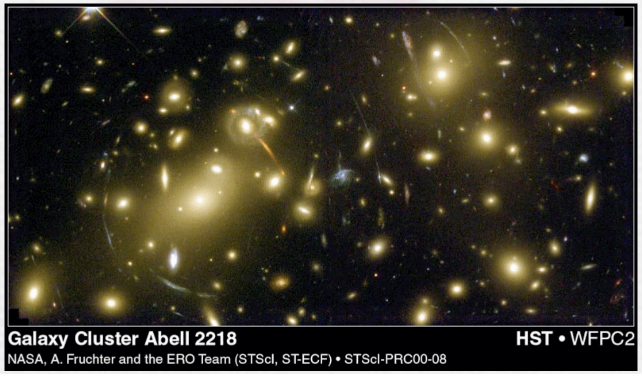
85% dark unknown matter

- the (quasi) absence of antimatter in the universe

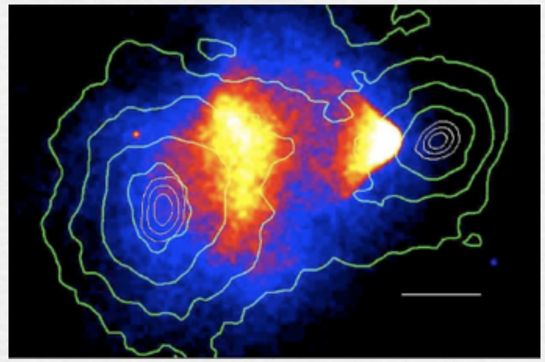
baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales

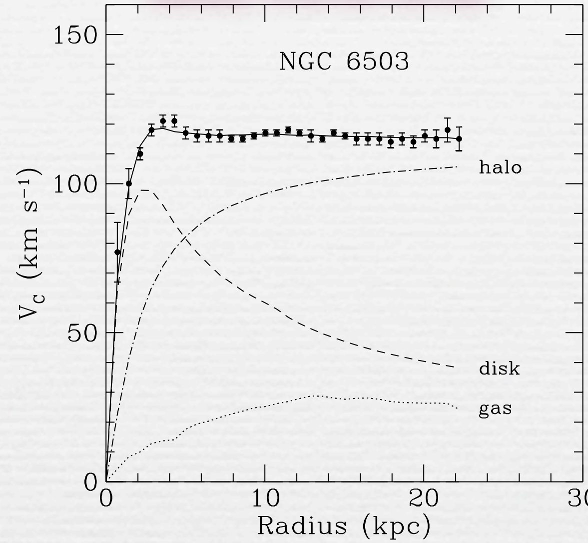
Gravitational lensing



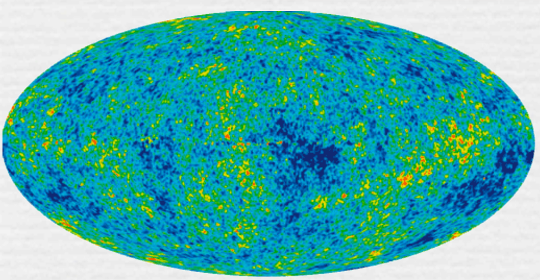
The "Bullet cluster": lensing map versus X-ray image

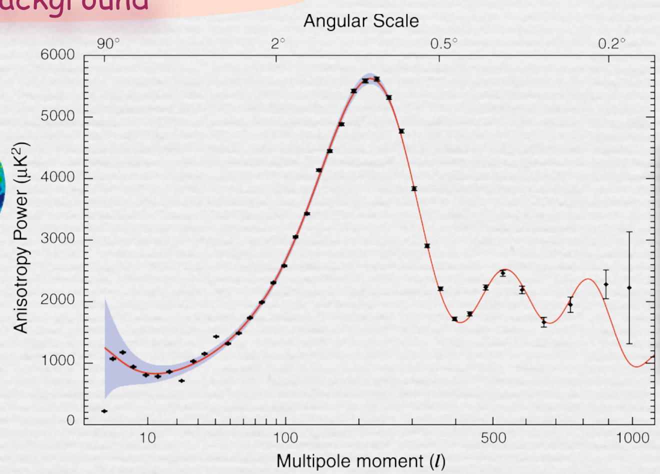


Galaxy rotation curves



Cosmic Microwave Background





... etc

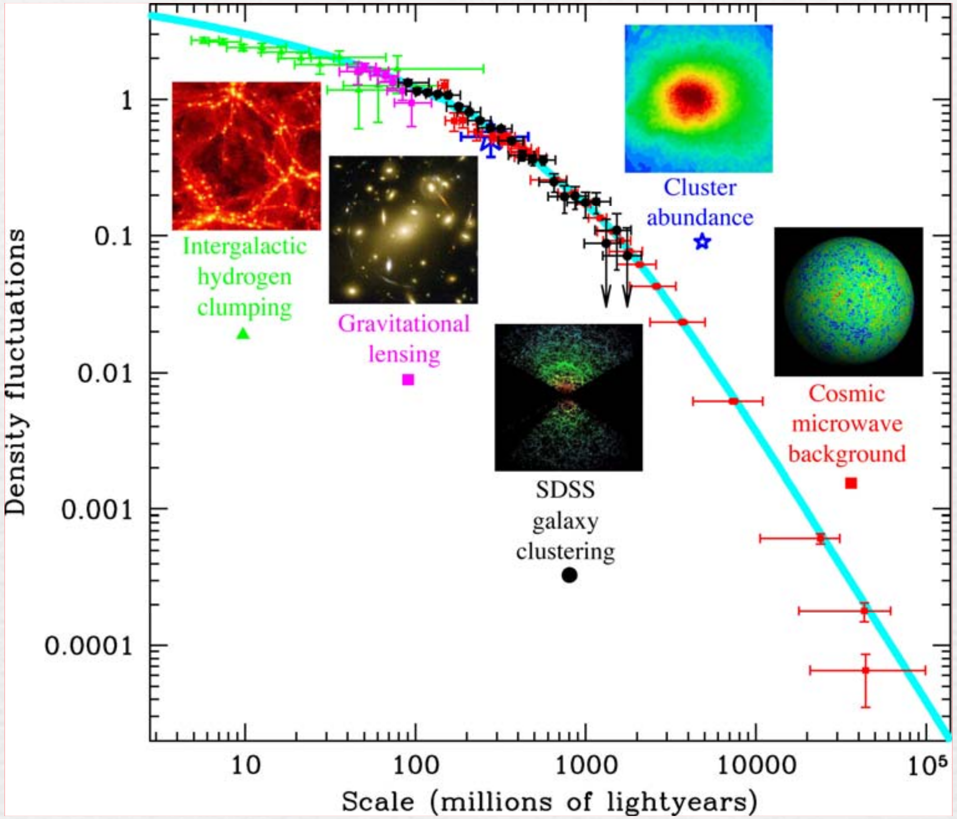
-> Fraction of the universe's energy density stored in dark matter : $\Omega_{DM} \approx 0.22$

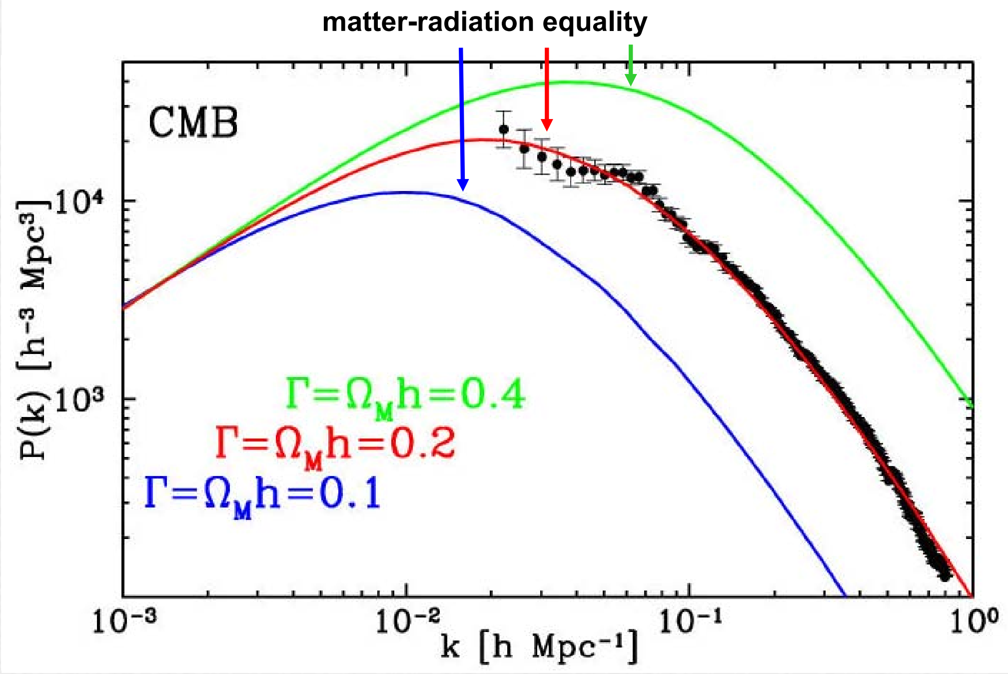
The picture from astrophysical and cosmological observations is getting more and more focussed

DM properties are well-constrained (gravitationally interacting, long-lived, not hot, not baryonic) but its identity remains a mystery

Matter power spectrum

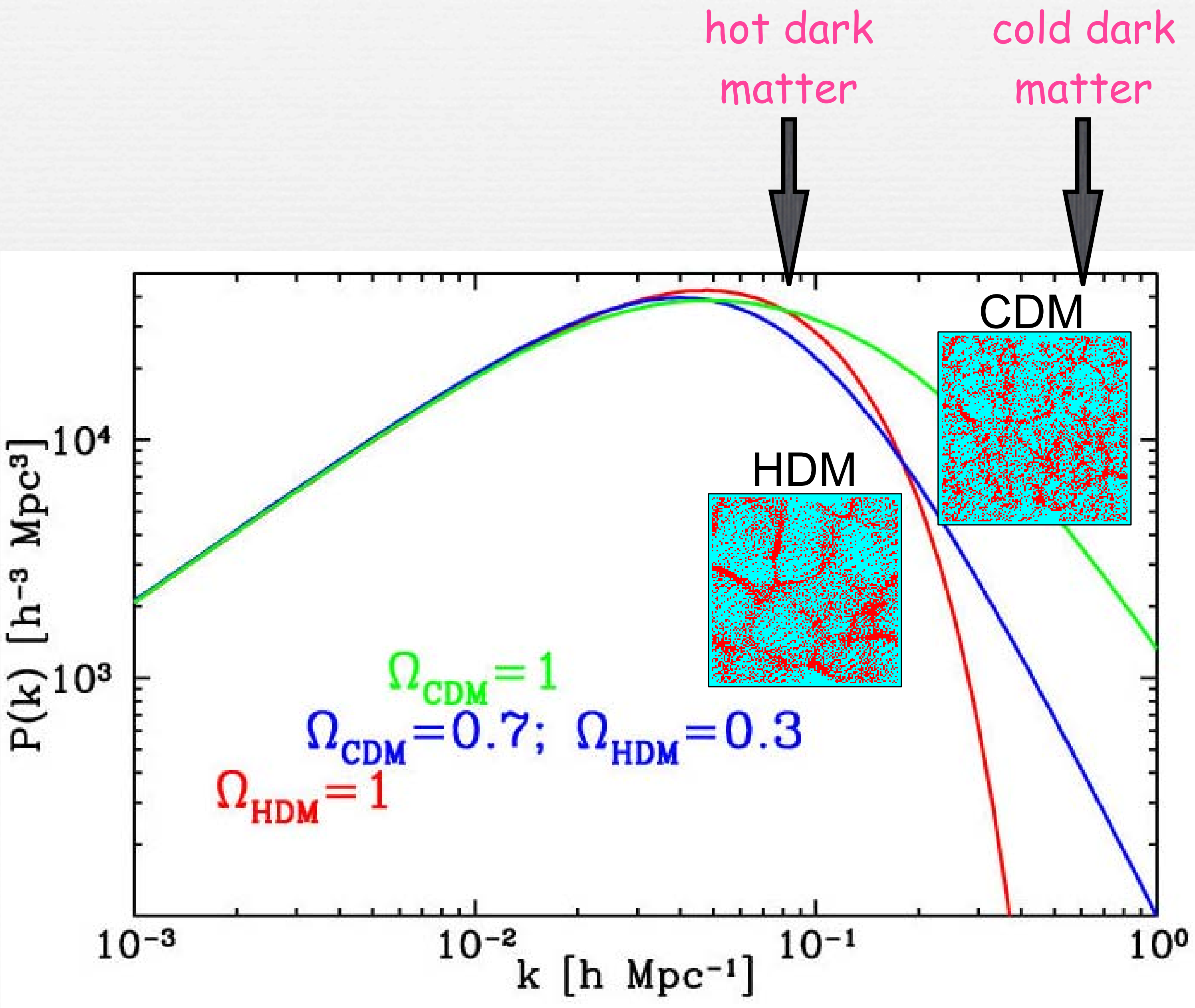
not baryonic



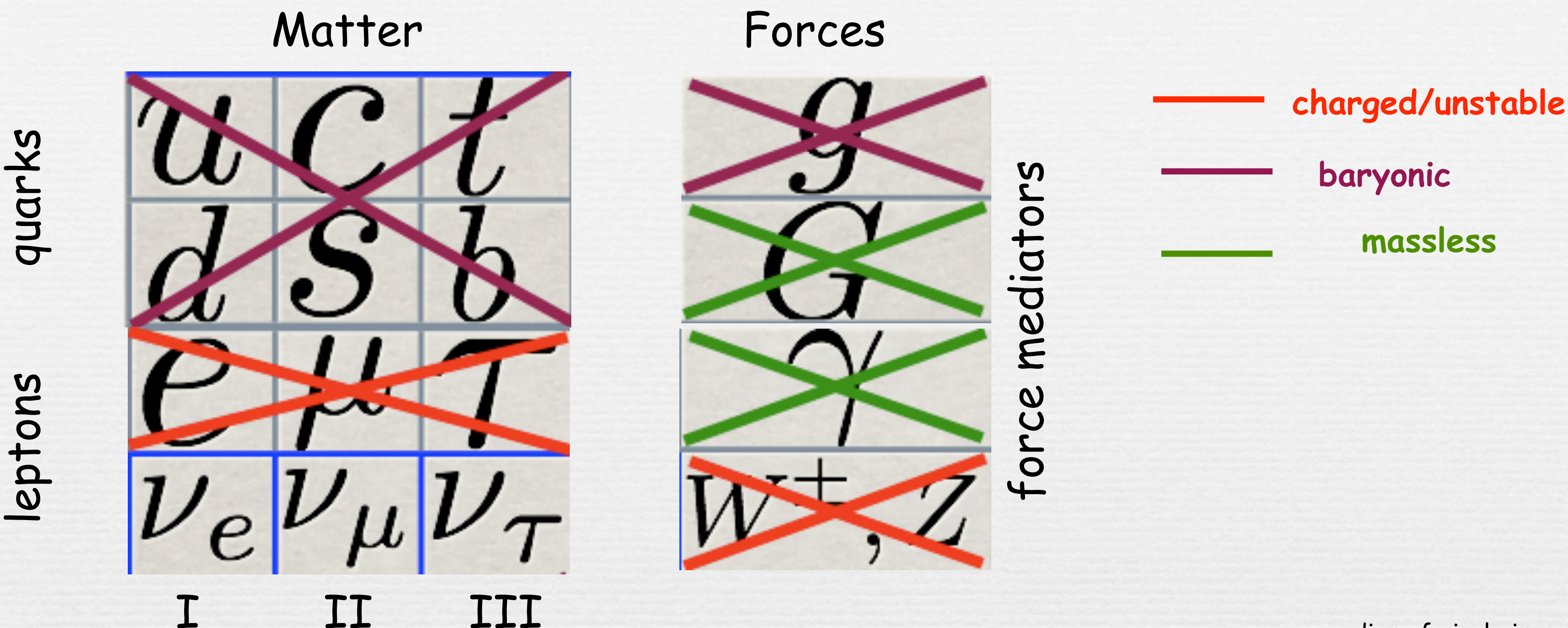


Neutrinos

not hot

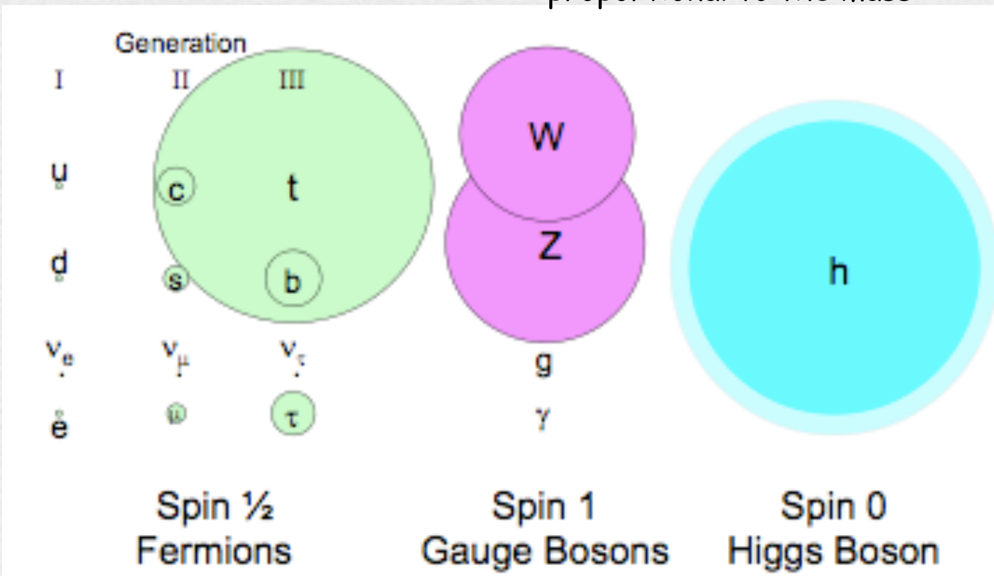


Why can't dark matter be explained by the Standard Model?



3 families of matter

radius of circle is proportional to the mass



contribution to the energy budget of the universe

Particle	Ω	type
Baryons	4 - 5 %	cold
Neutrinos	< 2 %	hot
Dark matter	20 - 26 %	cold

Dark Matter candidates

Two possibilities:

very light & only gravitationally coupled (or with equivalently suppressed couplings) -> stable on cosmological scales

sizably interacting (but not strongly) with the SM -> symmetry needed to guarantee stability

Long-lived
(stable on cosmological scales)

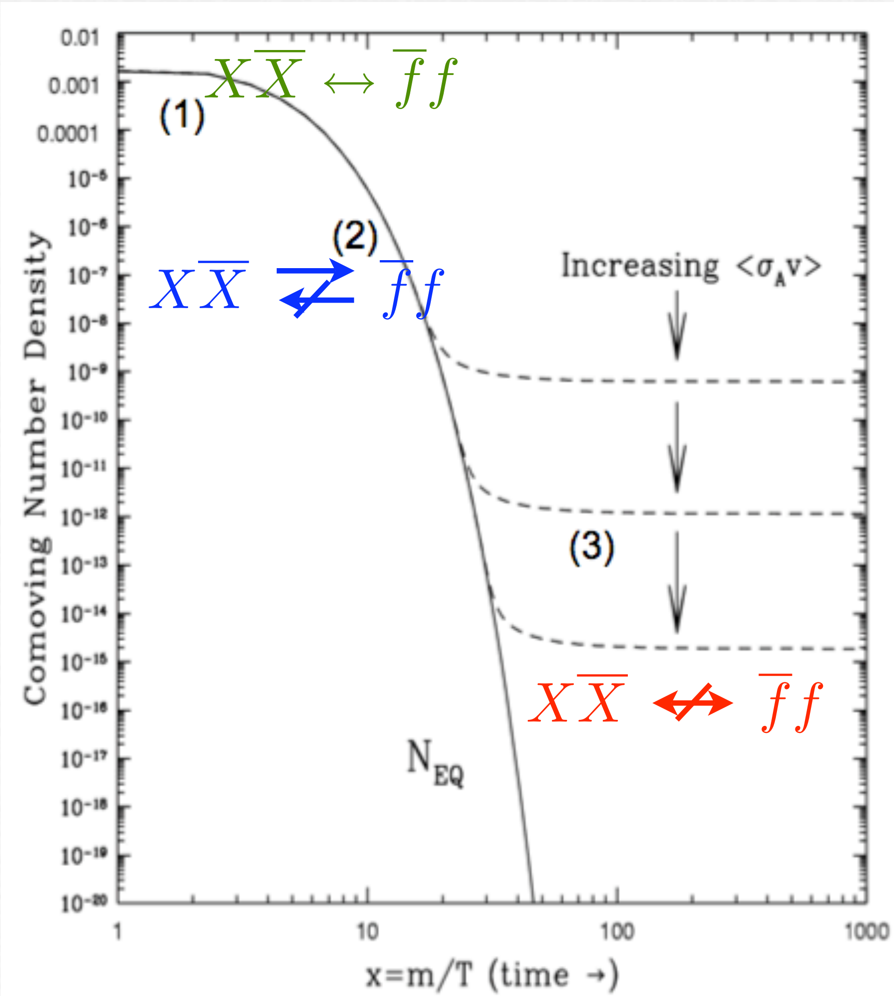
$\tau_{DM} > \tau_{universe} \sim 10^{18}$ s

stable by a symmetry

-> WIMP

The WIMP relic abundance follows from the generic thermal freeze-out mechanism in the expanding universe

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$



freese-out :

$$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}} \sim \Gamma = n\sigma v$$

Thermal relic: $\Omega h^2 \propto 1/\langle\sigma_{anni} v\rangle$

$\Rightarrow \langle\sigma_{anni} v\rangle \approx 1$ pb

$\sigma \sim \alpha^2/m^2$

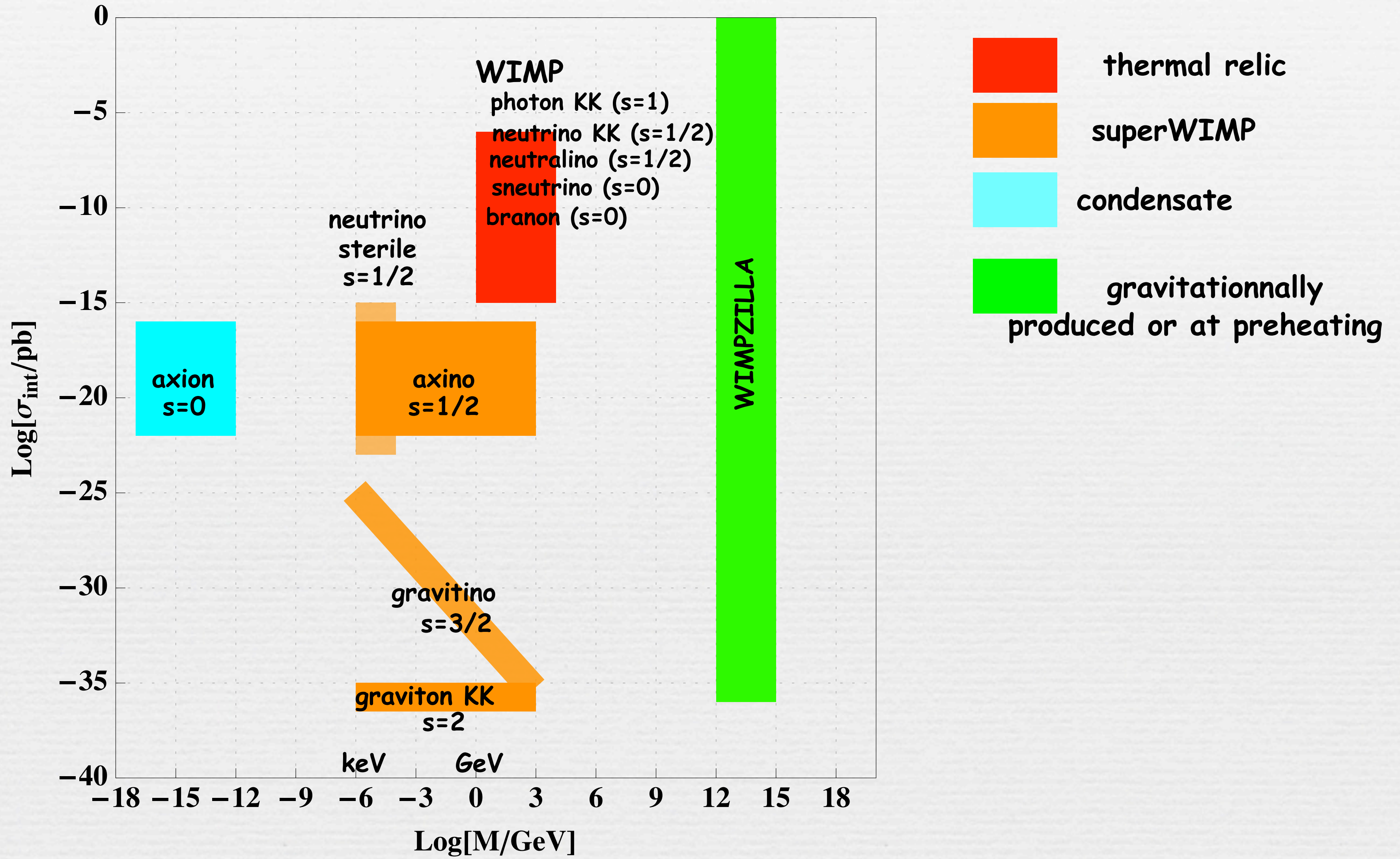
$\Rightarrow m \sim 100$ GeV

The "WIMP miracle"

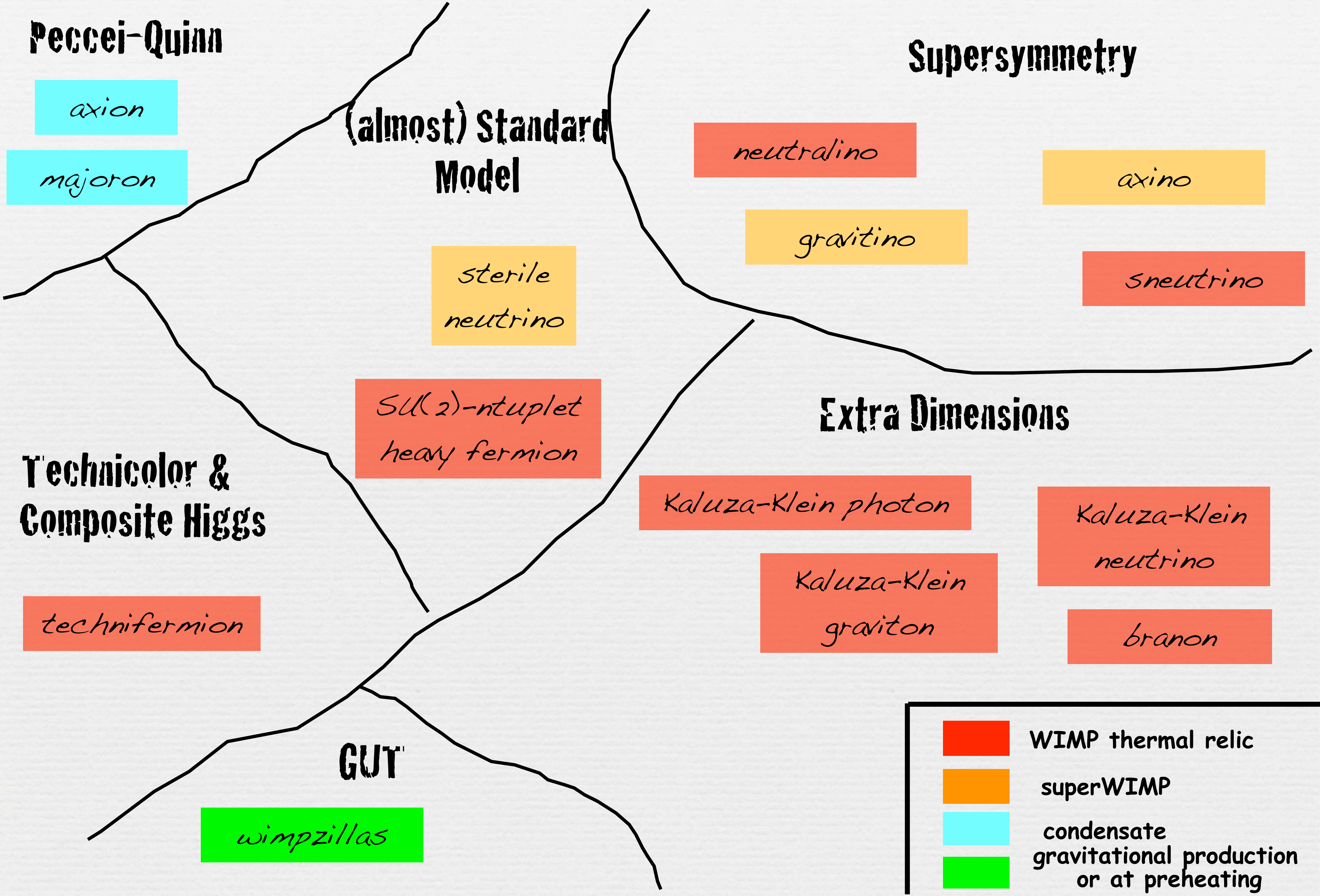
$$\Omega_{DM} \approx \frac{O(1)\ \mathrm{pb}}{\sigma_{anni}}$$

→ a particle with a typical EW-scale cross section $\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

Dark Matter Candidates Ω~1



In Theory Space

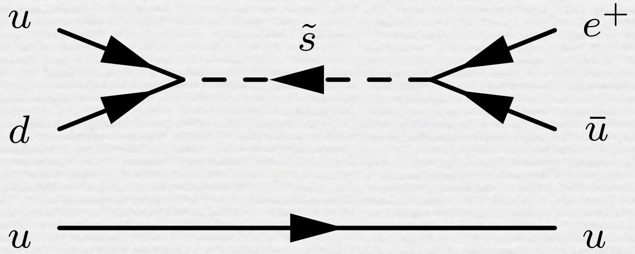


Supersymmetric Dark Matter

stable by R-parity: $$R_p = (-1)^{3B+L+2s}$$

under which SM particles are even and superpartners are odd

Primarily introduced to prevent fast proton decay in supersymmetry:



-> The Lightest Supersymmetric Particle (odd) is thus stable

New symmetries at the TeV scale and Dark Matter

to cut-off quadratically divergent quantum corrections to the Higgs mass

→ New TeV scale physics needed

↓

tension with precision tests of the SM in EW & flavor sector (post-LEP "little hierarchy pb")

↓

introduce new discrete symmetry P

R-parity in SUSY, KK parity in extra dim, T parity in Little Higgs ...

↓

Lightest P-odd particle is stable

↓

DM candidate

Work out properties of new degrees of freedom

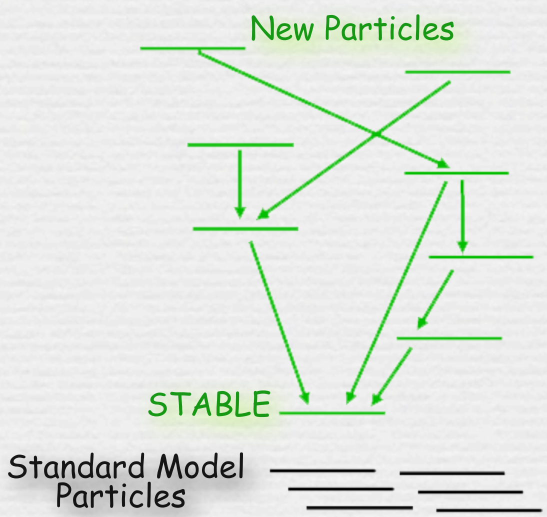
The stability of a new particle is a common feature of many models

mass spectrum, interactions

dark matter candidates

relic abundance

detection signatures & rates



Model building beyond the Standard Model: "historical" overview

	Model	Discrete symmetry	Attitude
Big hierarchy addressed	SUSY [70 ies to now]	R-parity → LSP	the attitude: Naturalness is what matters, dark matter is a secondary issue
	ADD [98-99]		
	RS [99 to now]		
Little hierarchy addressed	UED [2001 to now]	KK-parity → LKP [2002]	Lower your ambition (no attempt to explain the M_{EW}/M_{Pl} hierarchy); rather put a ~ TeV cutoff
	Little Higgs [2002-2004]	T-parity → LTP [2003]	
Big & little hierarchy pbs ignored	"Minimal" SM extensions [2004 to now]	assume discrete symmetry, typically a Z_2	Give up naturalness, focus on dark matter and EW precision tests. Optional: also require unification

Dark matter theory

dark matter model building until ~2004: mainly theory driven

largely motivated by hierarchy pb:
SUSY+R-parity,
Universal Extra Dimensions + KK parity
Little Higgs models+ T-parity

in last few years (post LEP-2)--> questioning of naturalness as a motivation for new physics @ the Weak scale

"minimal approach": focus on dark matter only and do not rely on models that solve the hierarchy problem

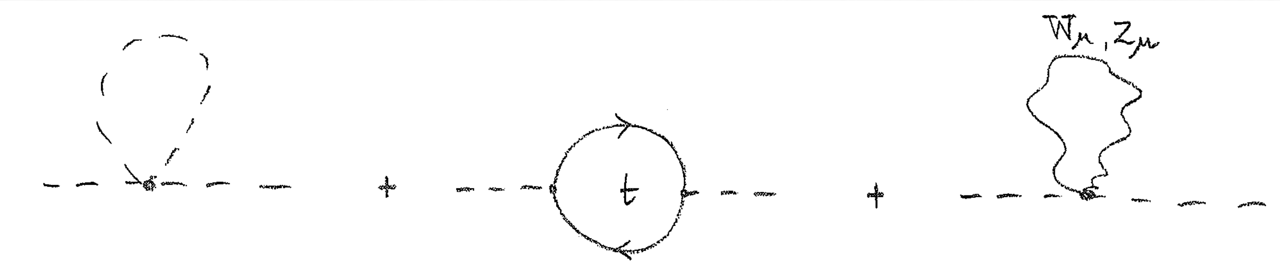
+ various "hints" (?...): DAMA, INTEGRAL, PAMELA, ATIC ...

⇒ dark matter model building since ~2008: data driven

The naturalness scale of the Standard Model

Why is the Higgs boson light?

its mass parameter receives radiative corrections



$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \sim -(0.23\ \Lambda)^2$$

(assuming the same Λ for all terms)

Λ , the maximum mass scale that the theory describes

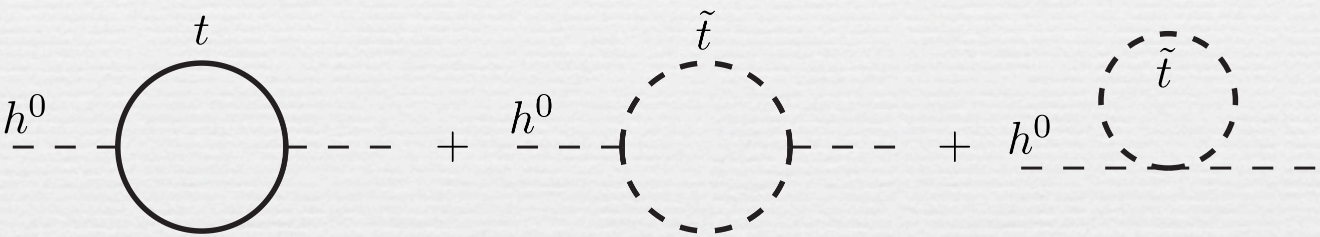
strong sensitivity on UV unknown physics

Λ=5 TeV -> cancellation between tree level and radiative contributions required by already 2 orders of magnitude

The Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry can solve the "big" hierarchy and naturalness is preserved up to very high scales if superparticle masses are at the weak scale

$\Delta(m^2_{h^0}) =$



$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

(radiative) EW symmetry breaking in the MSSM

(associated to the top Yukawa coupling)

The Higgs sector consists of two $SU(2)_L$ doublets

soft SUSY breaking parameters

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (bH_u^0 H_d^0 + c.c) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2$$

The minimization of the higgs potential leads to:

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

with $\tan\beta \equiv \langle H_u^0\rangle / \langle H_d^0\rangle$

terms in r.h.s much larger than M_Z^2

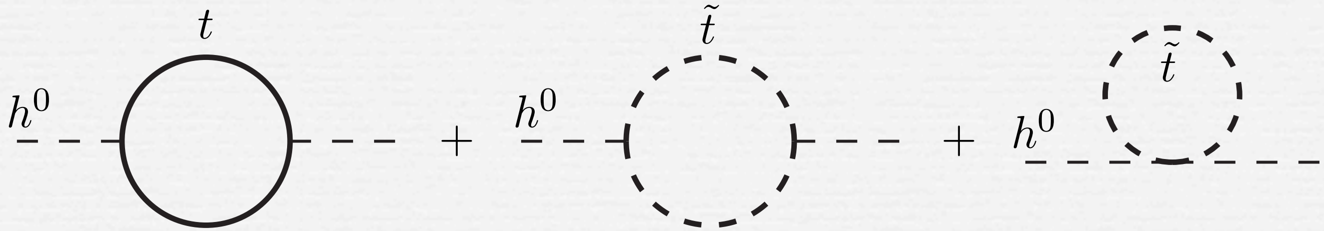
non trivial cancellation among them needed unless masses of SUSY particles are low. However:

The LEP bound on the Higgs mass , $m_h \geq 115$ GeV forces the stop mass to be large

The naturalness problem of the MSSM

The biggest problem for the MSSM: we did not see the Higgs

$\Delta(m^2_{h^0}) =$



$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

LEP limit ($m_h \gtrsim 115$ GeV) ⇛ $m_{\tilde{t}} \gtrsim$ 1 TeV

whereas the loop correction to the Higgs soft breaking mass is:

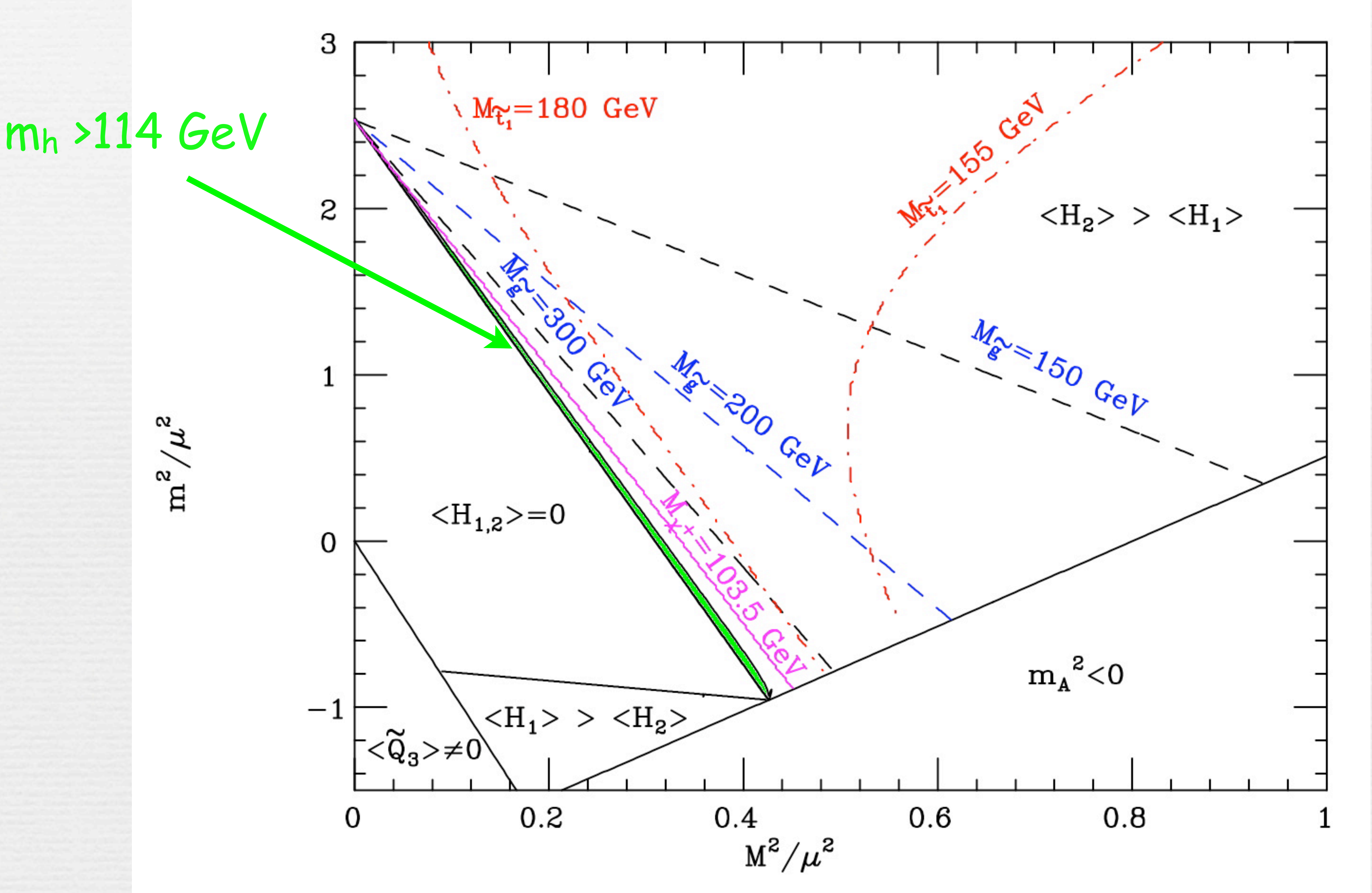
$$\Delta m^2_{H_u} = \frac{-3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}}$$

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1}$$

⇛ tuning $\equiv \dfrac{|\Delta m^2_{H_u}|}{M_Z^2} \approx \dfrac{3y_t^2}{4\pi^2 M_Z^2} m_{\tilde{t}}^2 \log\dfrac{\Lambda}{m_{\tilde{t}}} \approx 50$ for $m_{\tilde{t}} = 900$ GeV, $\Lambda = 100$ TeV

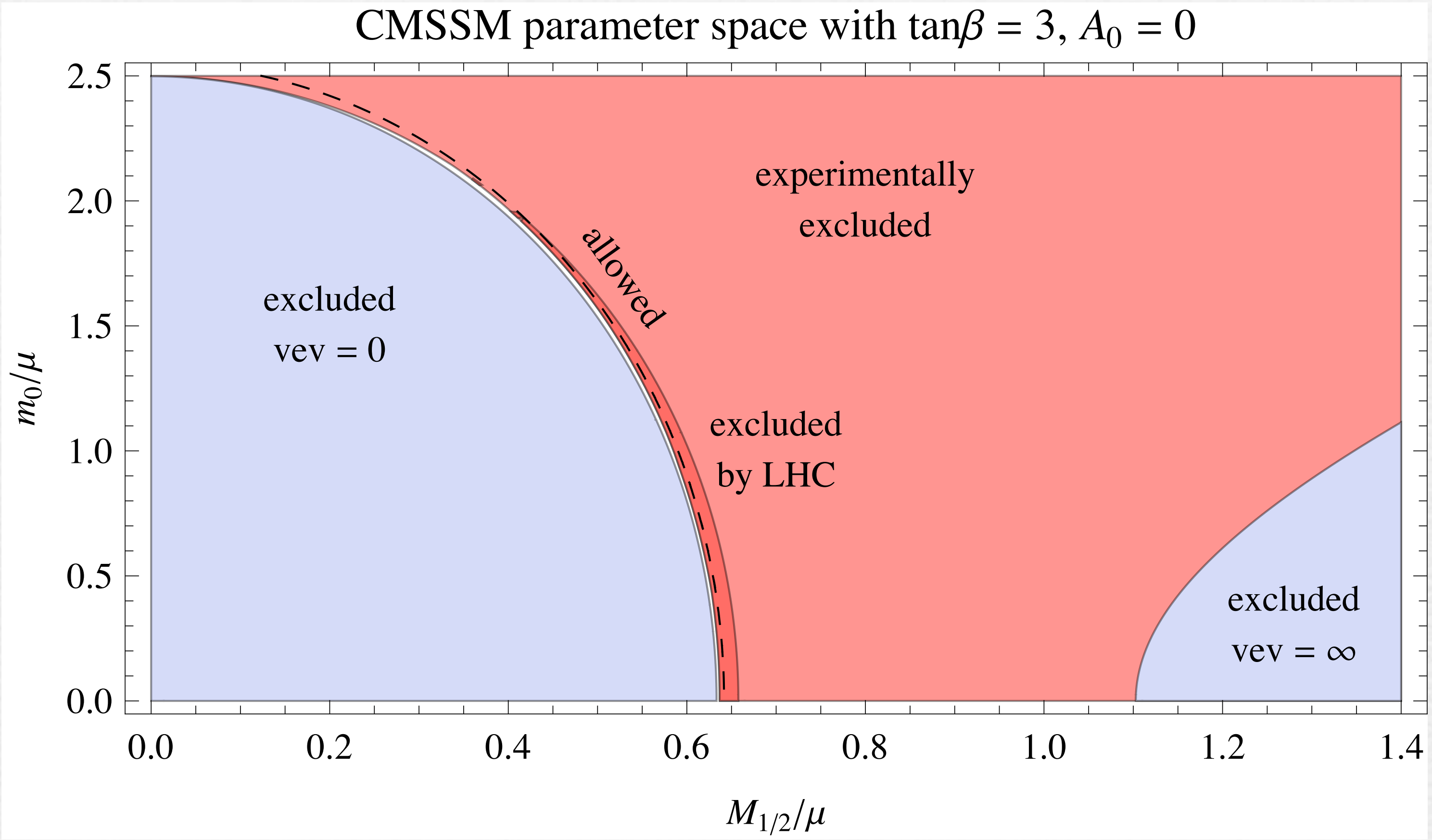
to make h heavy enough, increasing fine-tuning and superpartners increasingly harder to see

State of mSUGRA



[Giudice & Rattazzi, '06]

[Strumia, '11]



$$m_h^2 \overset{\text{tree level}}{\rightarrow} M_Z^2 \approx 0.2 m_0^2 + 0.7 M_3^2 - 2\mu^2 = (91\ \text{GeV})^2 \times 35 \left(\frac{M_3}{650\ \text{GeV}}\right)^2 + \cdots$$

Beyond the weakly coupled elementary supersymmetric Higgs boson paradigm:

The strongly coupled "Higgs": Composite Higgs or Higgsless (e.g. technicolor)

Assumption: there is a new strongly interacting sector at the Tev scale responsible for EW symmetry breaking.

if replica of QCD at the TeV scale, Higgs= $\langle Q'\bar{Q}'\rangle$ condensate

-> no light scalar playing the role of the higgs: Higgsless

->main objection: conflict with EW precision tests

->a solution: a composite light higgs arising as a pseudo-goldstone boson

The Higgs as a kind of pion
from a new strong sector?

Quantum numbers of the Goldstones fixed by the symmetry breaking pattern in the strong sector:

G-> H

Higgs scalars as pseudo-Nambu-Goldstone bosons of new dynamics above the weak scale

global symm. on u,d

strong int.

QCD: $SU(2)_L \times SU(2)_R \xrightarrow{SU(3)_c} SU(2)_V \supset U(1)_Q$

6 - 3 = 3 PNGB $\pi^{\pm}, \pi_0$

global symm. on techniquarks

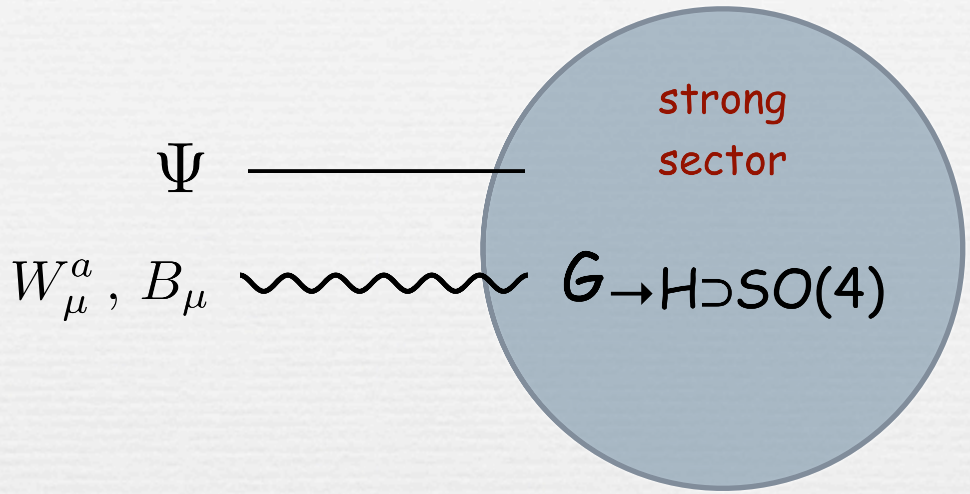
Composite Higgs: $SO(6) \times U(1)_x \xrightarrow{SU(N_c)} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

16 - 11 = 5 PNGB H, S

SO(5)/SO(4) -> SM
SO(6)/SO(5) -> SM + S
SO(6)/SO(4) -> 2 HDM

associated LHC tests

New strong sector endowed with a global symmetry G spontaneously broken to H
→ delivers a set of Nambu Goldstone bosons



$$\mathcal{L}_{int} = A_\mu J^\mu + \bar{\Psi} O + h.c.$$

custodial SO(4)≅ SU(2)×SU(2)

to avoid large corrections to the T parameter

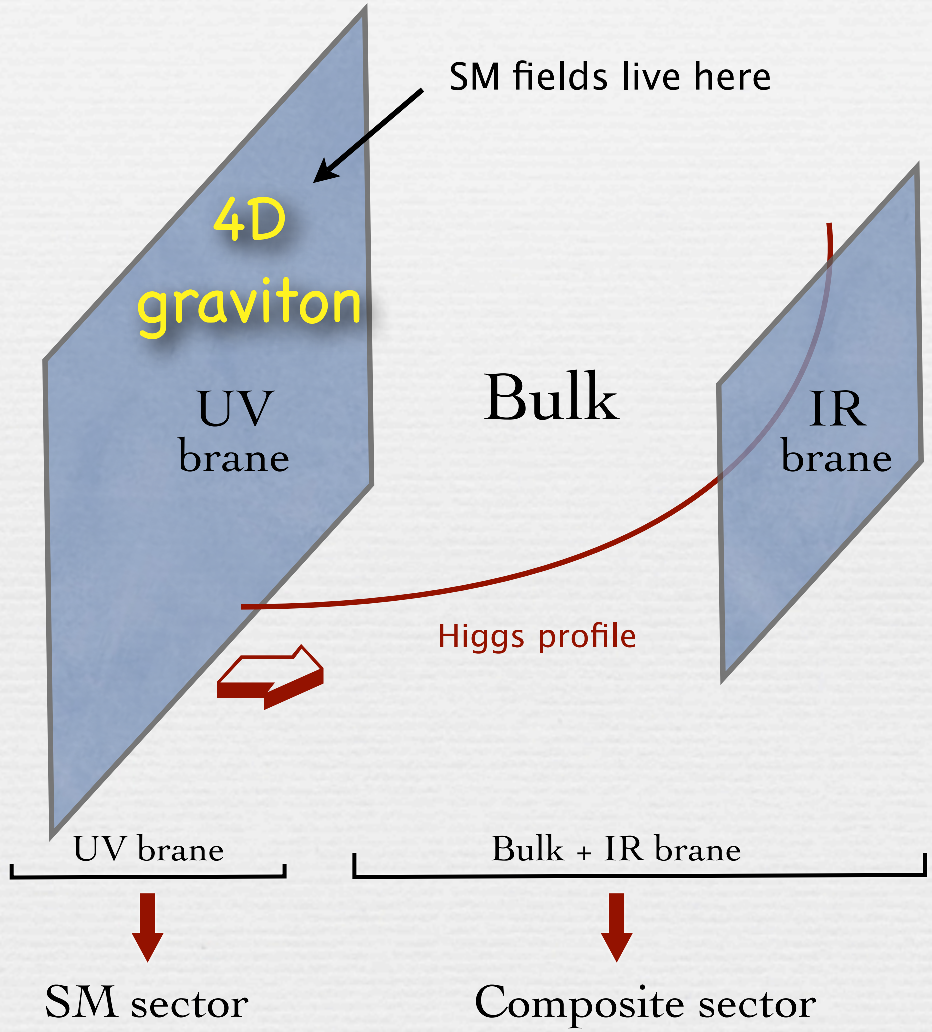
G	H	N_G	NGBs rep.$[H]$ = rep.[SU(2) × SU(2)]
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3 \times (\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2 \times (\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2 \times (\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

-> Agashe, Contino, Pomarol'05

[Mrazek et al, 1105.5403]

Extra-Dimensional point of view: Warped Geometry

Space-time is a slice of AdS_5



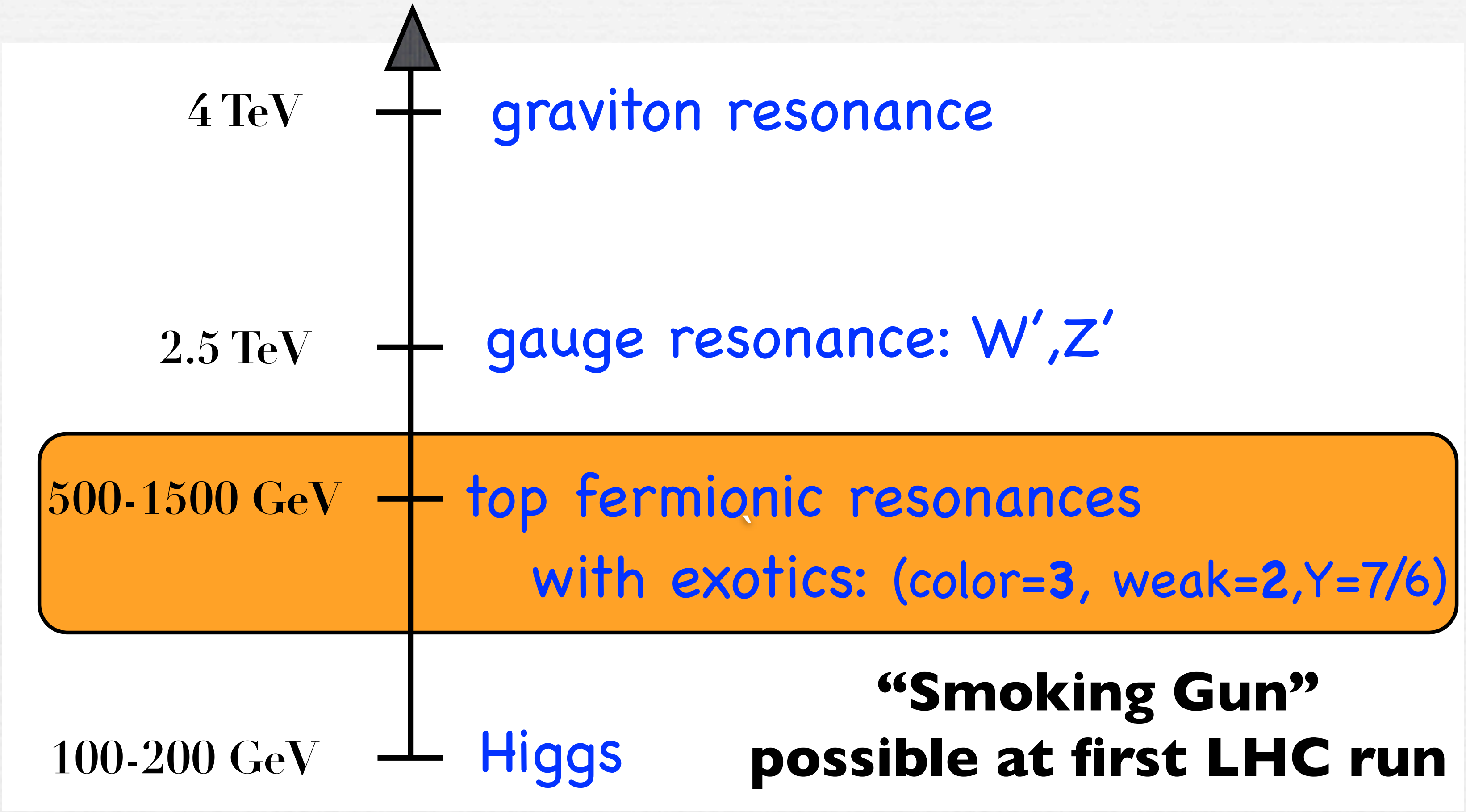
An almost CFT that becomes strongly interacting at the TeV scale & spontaneously breaks the conformal invariance

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

- Like in QCD, spectrum of resonances (Kaluza-Klein states)



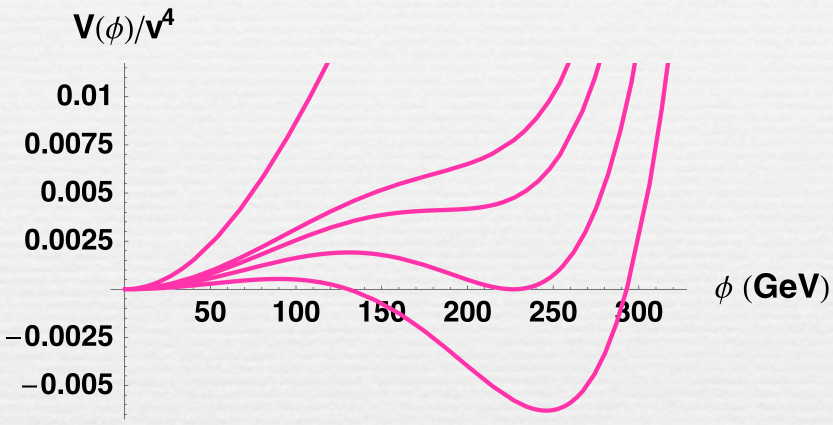
- Most natural DM candidate: The lightest Technibaryon can be stable by TechniBaryon Number conservation (as baryons in QCD).

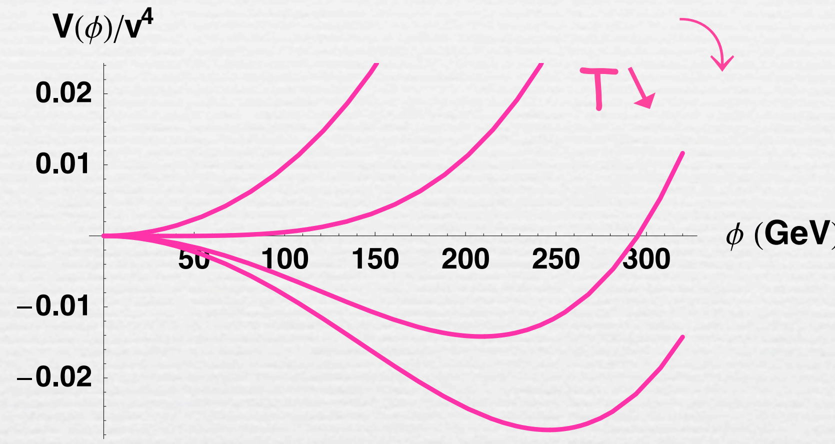
In addition to new degrees o freedom which could play the role of dark Matter, these models may exhibit a different cosmology at the weak scale.

For instance, it is not clear we can assume a radiation-dominated universe up to very high temperatures as is commonly assumed.

What is the nature of the electroweak phase transition ?

first-order or smooth cross over?





LHC will provide insight as it will shed light on the Higgs sector

Question intensively studied within the Minimal Supersymmetric Standard Model (MSSM). However, not so beyond the MSSM (gauge-higgs unification in extra dimensions, composite Higgs, Little Higgs, Higgsless...)

Nature and properties of the EW phase transition reflect information on the dynamics behind EW symmetry breaking (e.g weakly or strongly interacting).

Out -of-equilibrium dynamics during the EW phase transition may be relevant for theories of baryogeneis and dark matter production

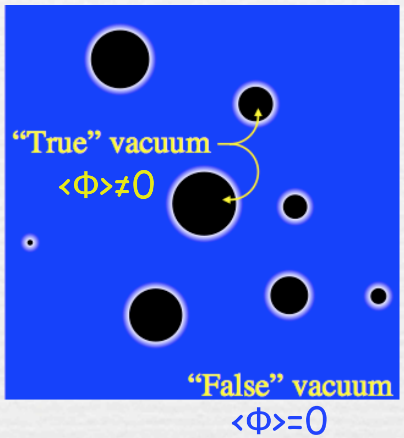
Which experimental tests of a strong 1st order phase transition?

Smoking gun signature

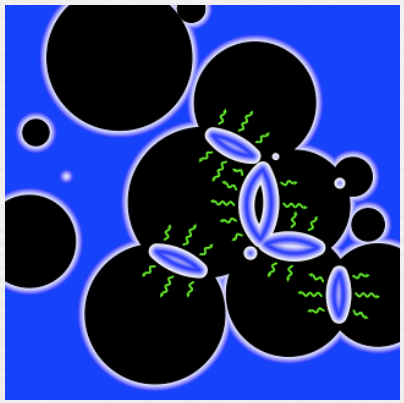
Randall-Servant'06

Konstandin,Nardini,Quiros'10

Bubble nucleation



Bubble percolation

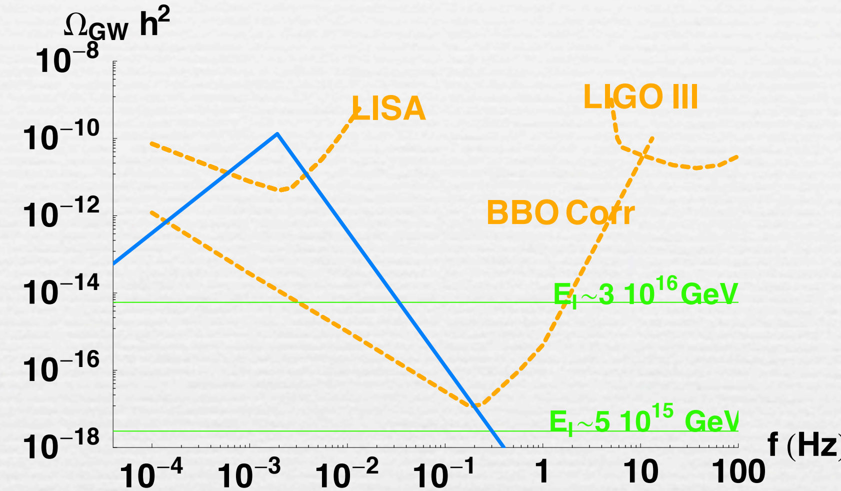


Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



violent process if $v_b \sim O(1)$

$$\Omega_{GW} \sim \frac{1}{(\beta/H)^2}\kappa^2$$

Detection of a GW stochastic background peaked in the milliHertz:
a signature of near conformal dynamics et the TeV scale

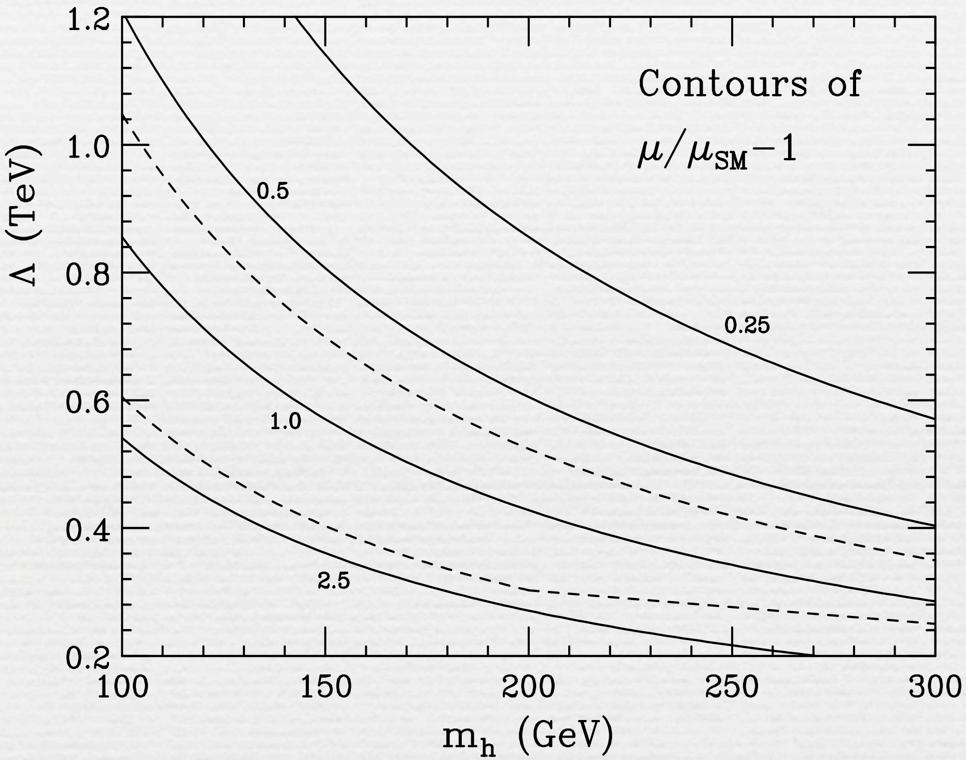
Typically large deviations to the Higgs self-couplings

$$\mathcal{L} = \frac{m_H^2}{2} H^2 + \frac{\mu}{3!} H^3 + \frac{\eta}{4!} H^4 + \ldots$$

where

$$\mu = 3\frac{m_H^2}{v_0} + 6\ \frac{v_0^3}{\Lambda^2}$$

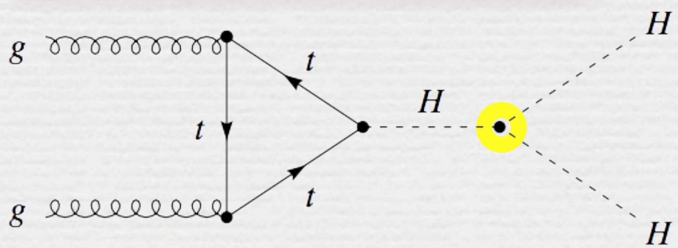
$$\eta = 3\frac{m_H^2}{v_0^2} + 36\ \frac{v_0^2}{\Lambda^2}$$



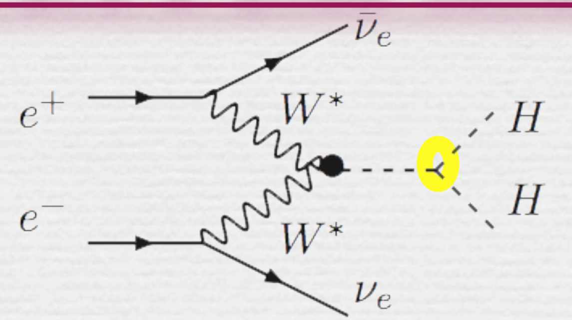
The dotted lines delimit the region for a strong 1rst order phase transition

deviations between a factor 0.7 and 2

at a Hadron Collider

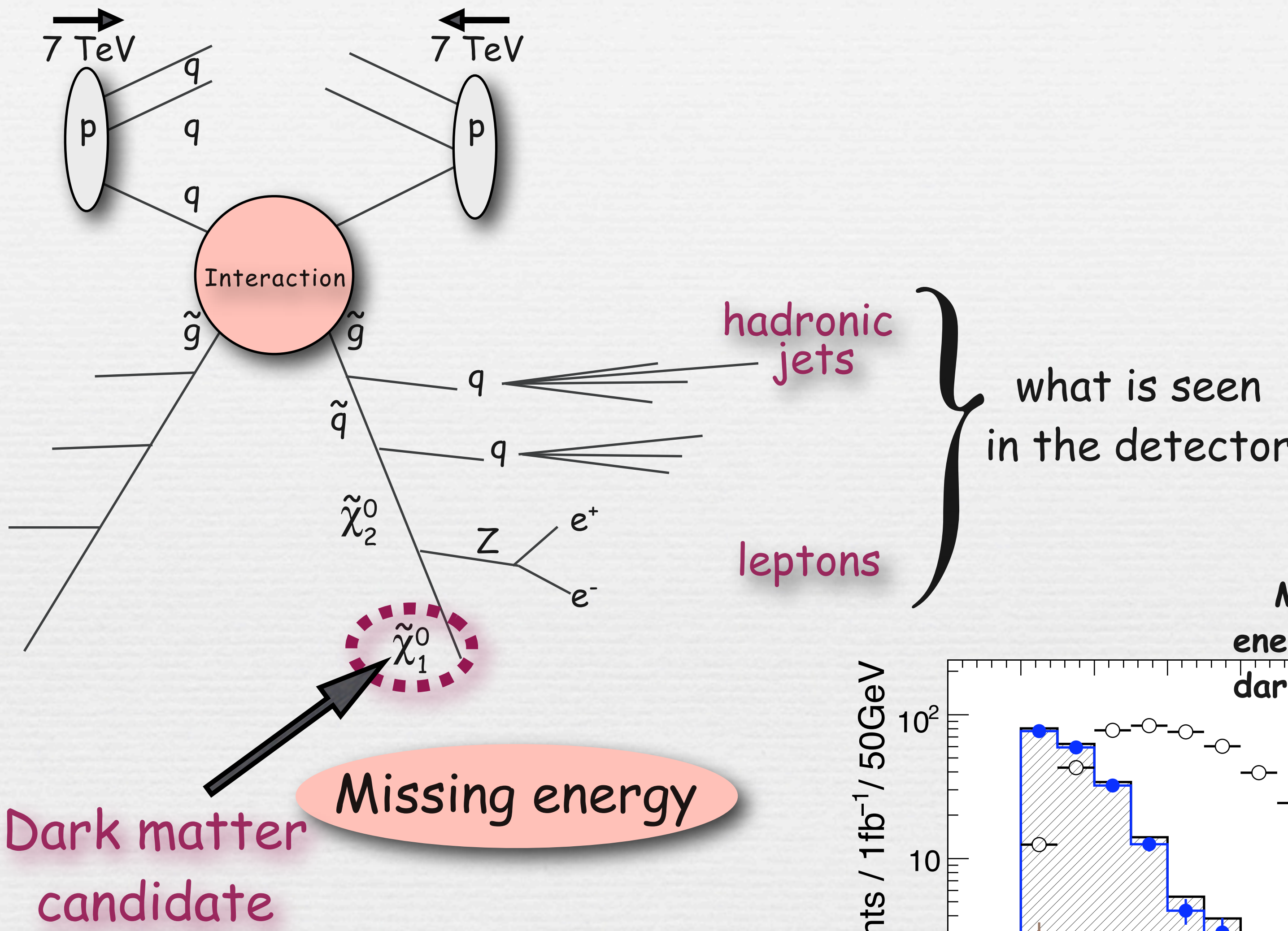


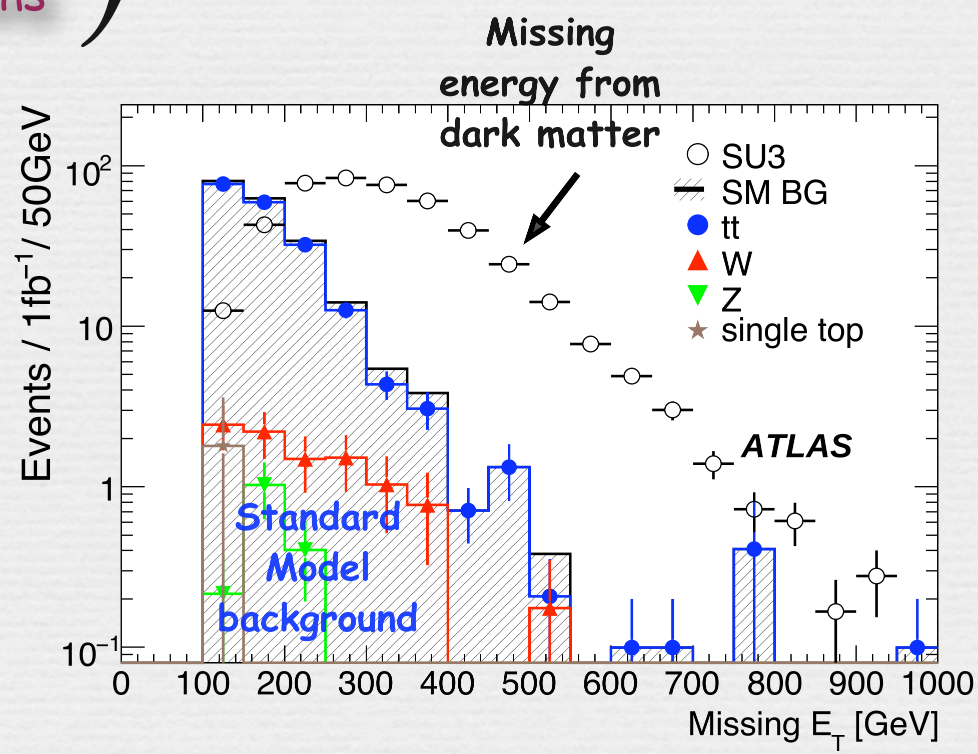
at an e⁺ e⁻ Linear Collider



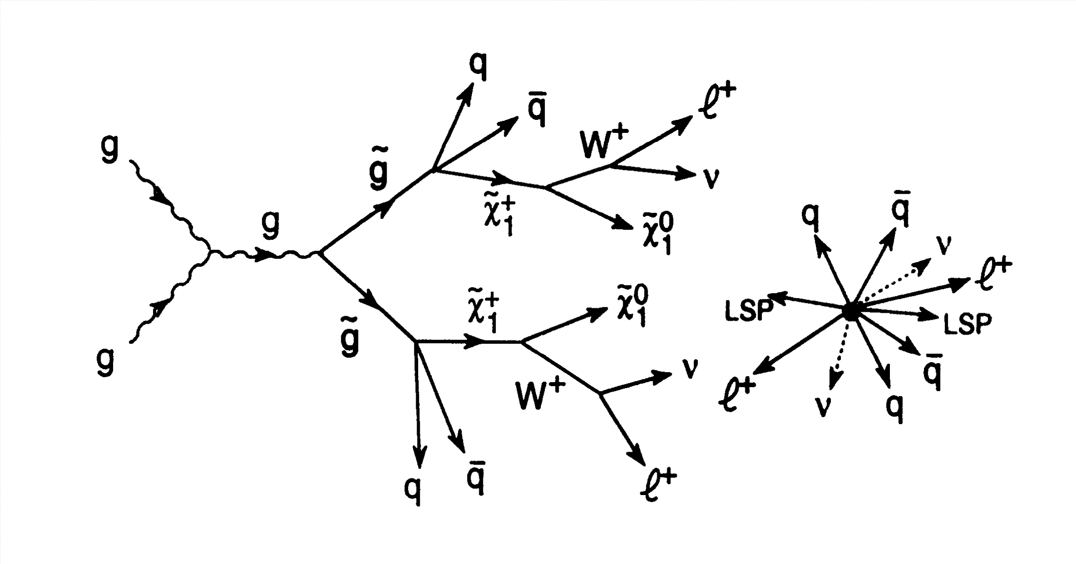
Testing the WIMP paradigm

Producing Dark Matter at LHC = "Missing Energy" events





Typical SUSY decay chain

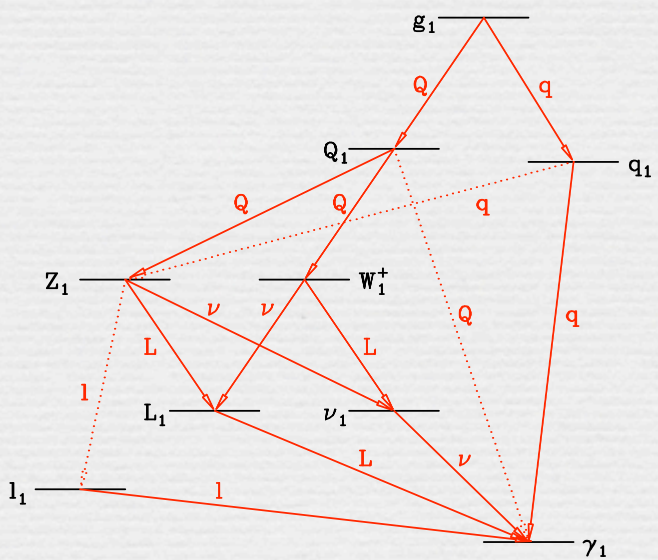


Lots of jets

Lots of leptons

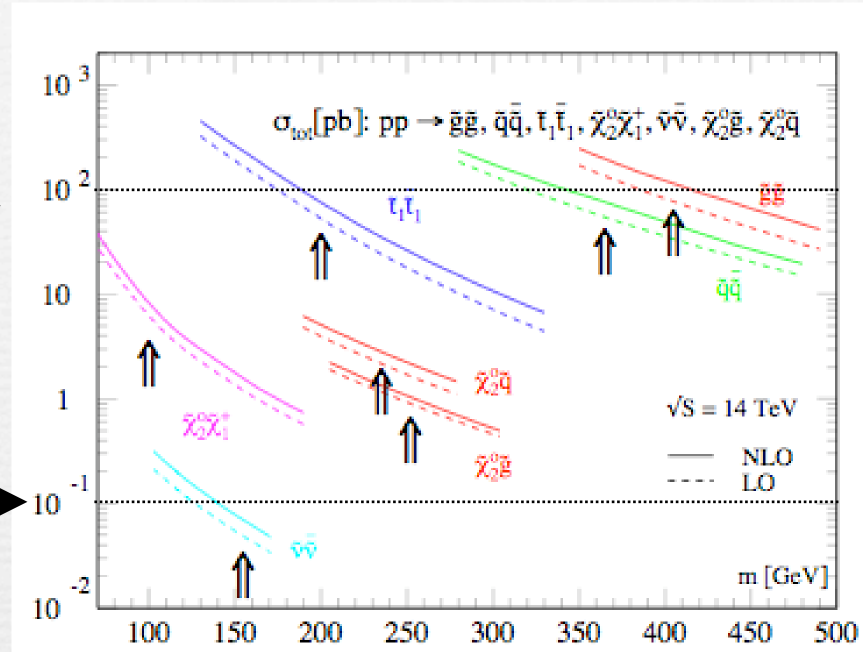
Lots of missing energy

easily mimicked by Kaluza-Klein decay chain:



Event rate

100 evts in 1 pb^{-1} →



100 evts in 1 fb^{-1} →

$L \sim 10^{33} cm^{-2} s^{-1} \sim 10\ fb^{-1}\ year^{-1}$

$\sigma \sim O(10)$ pb → $\sim 10^5$ wimps/year

Detecting large missing energy events will not be enough to prove that we have produced dark matter (with lifetime > $H^{-1} \sim 10^{17}$ s)

LHC: not sufficient to provide all answers

LHC sees missing energy events and measures mass for new particles

but what is the underlying theory?

Spins are difficult to measure (need for $e^+ e^-$ Linear Collider)

Solving the Dark Matter problem requires

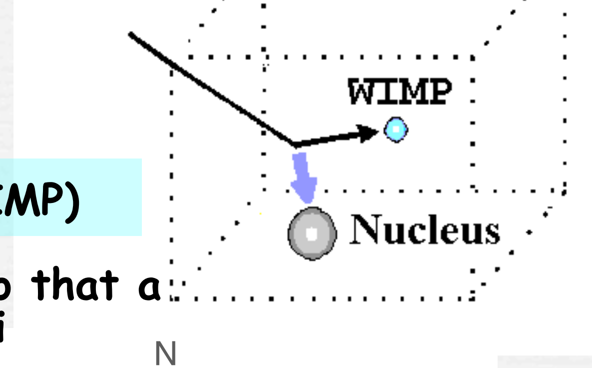
1) detecting dark matter in the galaxy (from its annihilation products)

2) studying its properties in the laboratory

3) being able to make the connection between the two

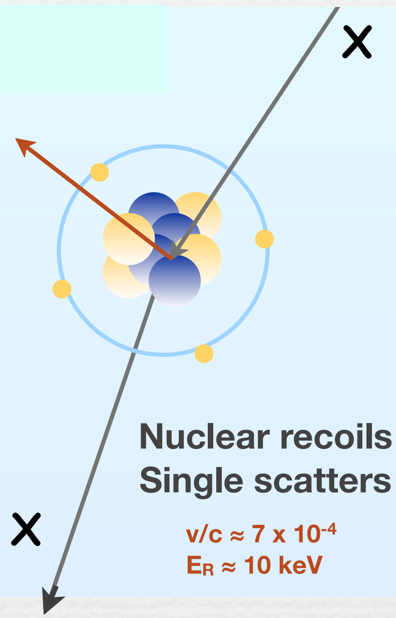
Need complementarity of particle astrophysics (direct/indirect experiments) to identify the nature of the Dark Matter particle

Direct Detection



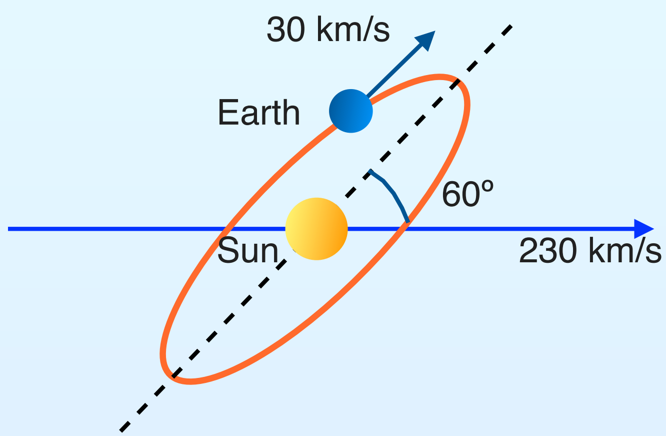
WIMP flux on Earth: ~ $10^5\ cm^{-2}s^{-1}$ (for a 100 GeV WIMP)

even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

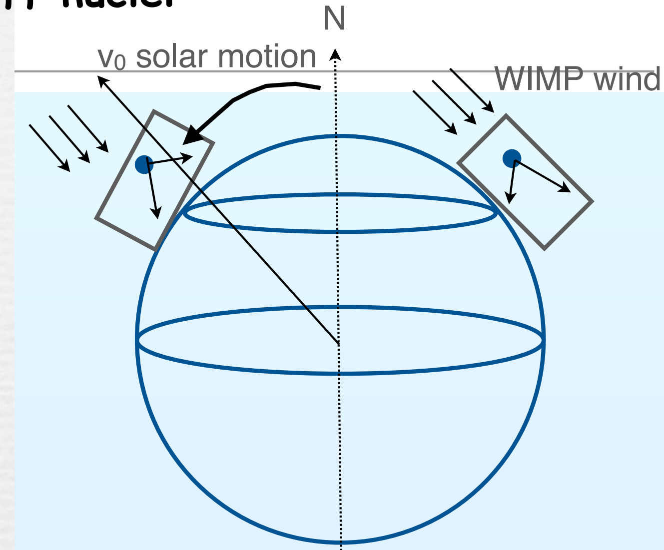


Nuclear recoils
Single scatters

$v/c \approx 7 \times 10^{-4}$
$E_R \approx 10$ keV

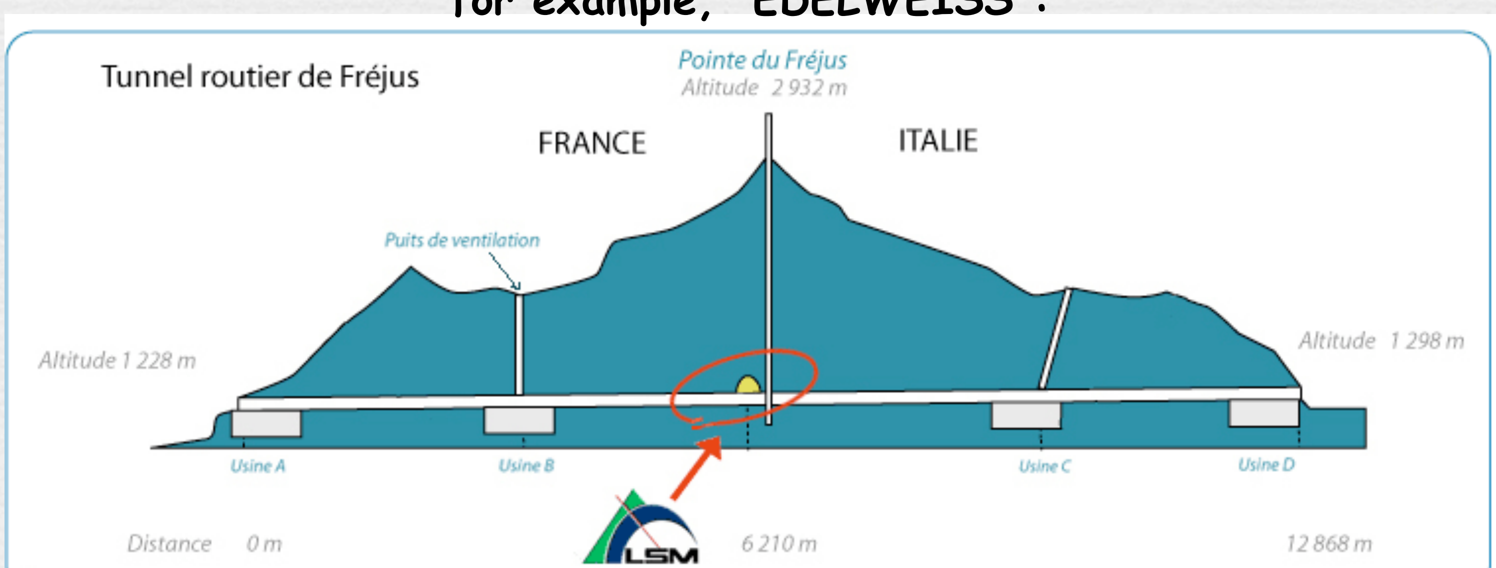


Annual rate variation
~ few % effect

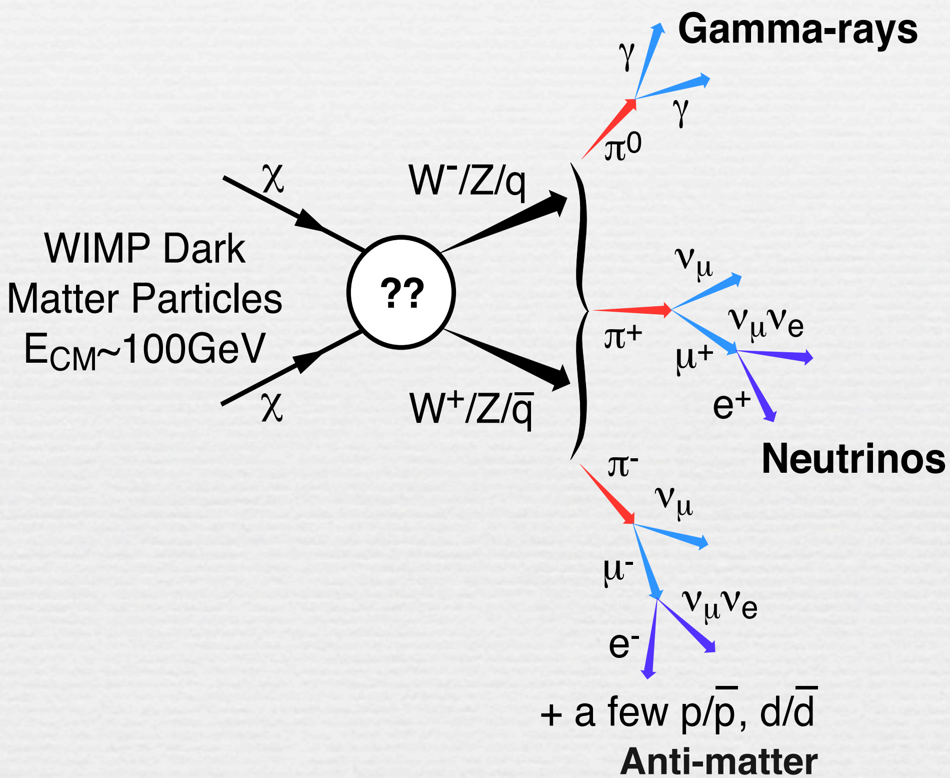


Diurnal directional modulation:
~ 50% effect

for example, “EDELWEISS”:



WIMP indirect detection



WIMP indirect detection

number of annihilation events between two wimps from the local halo

$$N \sim n^2 \sigma v . V. T$$

$$n \approx 3\ 10^{-3}\ cm^{-3} \quad \text{if } m \approx 100\ GeV$$

$$\sigma v \sim 1\ pb\ .\ 10^{-3} \sim 10^{-12}\ GeV$$

-> $N\ /year \sim\ 10^{14}\ cm^{-3}\ (GeV.cm)^{-3}\ .\ V$

(1 s ~ 10^{24} GeV^{-1} and GeV.cm~ 10^{14})

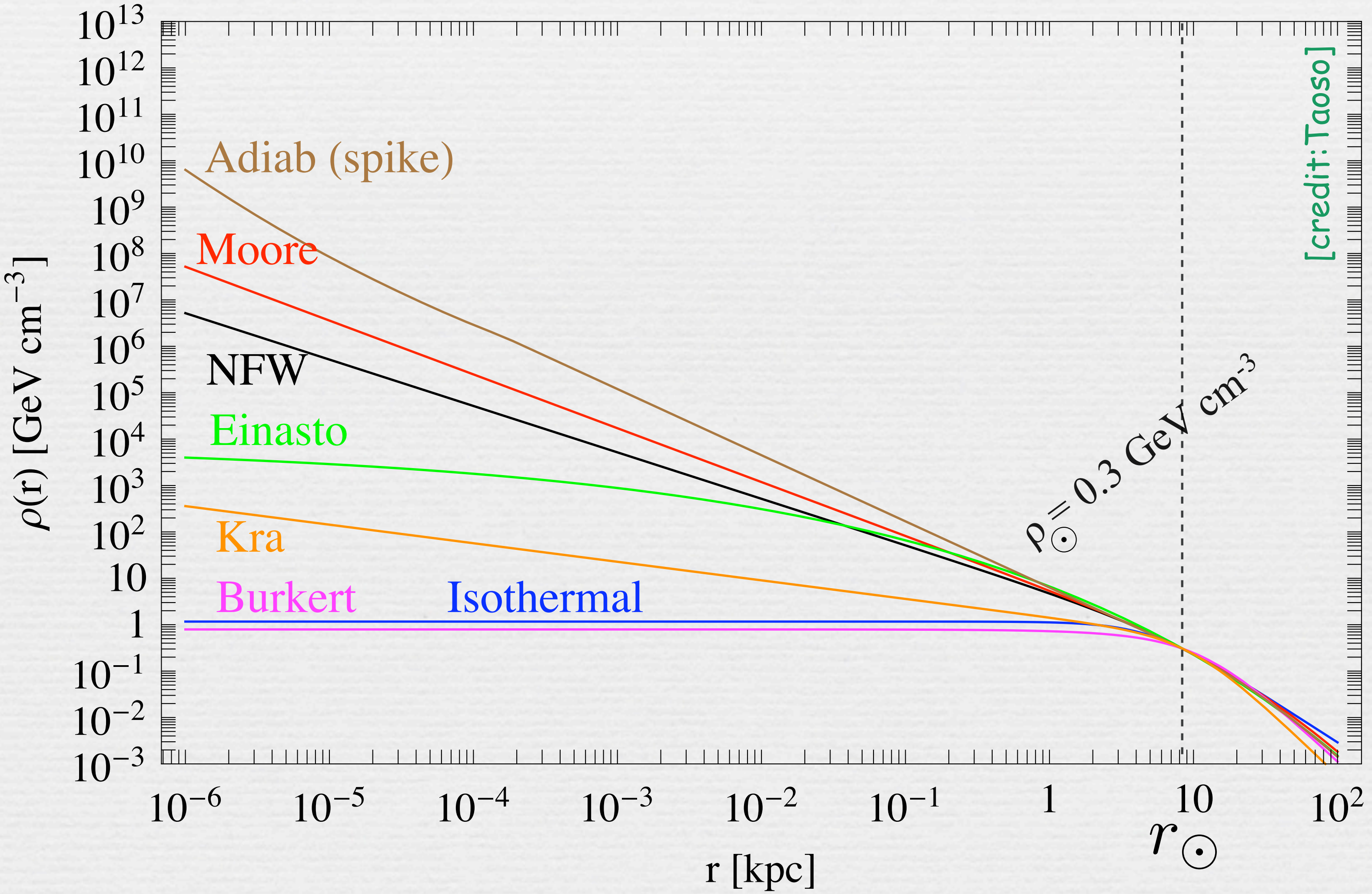
-> $N\ /year/km^3 \sim\ 10^{-13}$

--> look at regions where n is enhanced and probe large regions of the sky

$$\frac{d\Phi}{dE} \propto \int \rho^2$$

Searches focus on regions of the sky where DM clumps:
Galactic Center, dwarf galaxies...

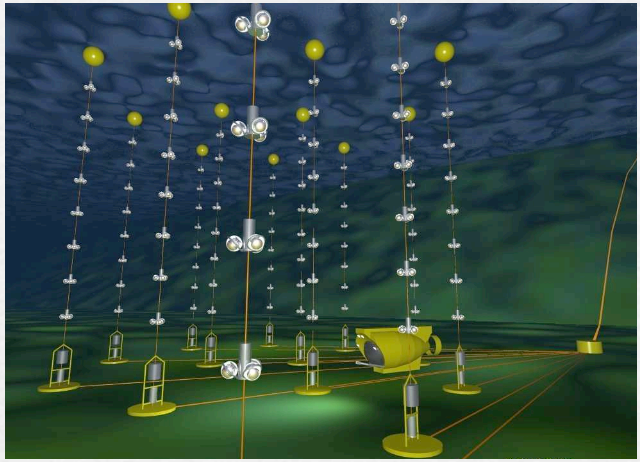
Astrophysical uncertainties on the
DM density profile



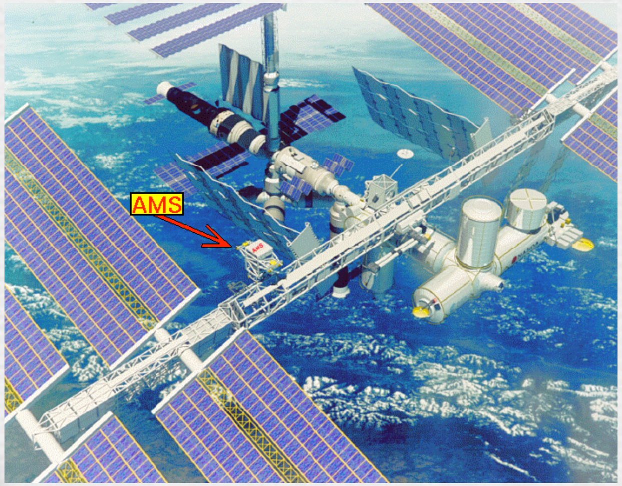
Indirect Detection

Search for neutrinos in the South Pole

In the Mediterranean



Antarès



Search for antiprotons in space

AMS

Indirect Detection

Search for dark matter photons on Earth

Hess

and in space

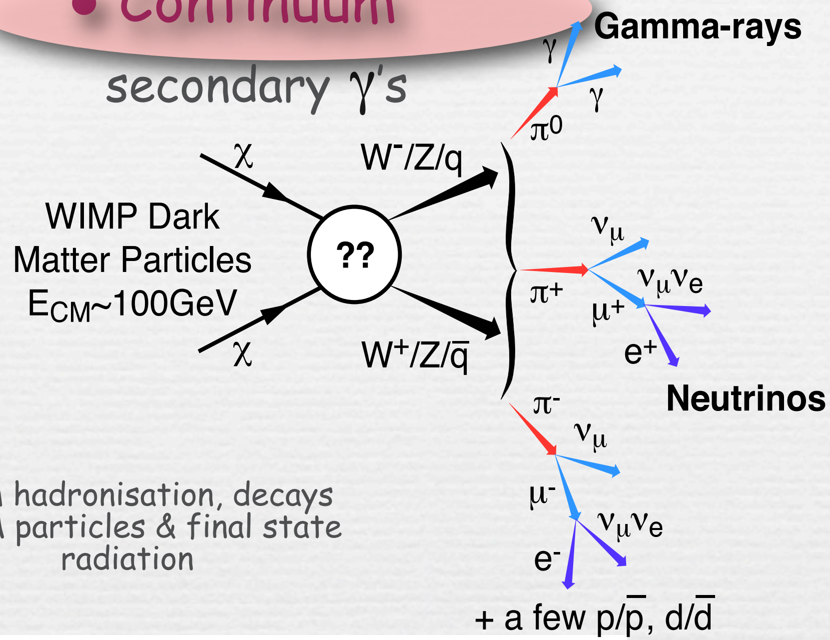
Fermi

Seeing the light from Dark Matter

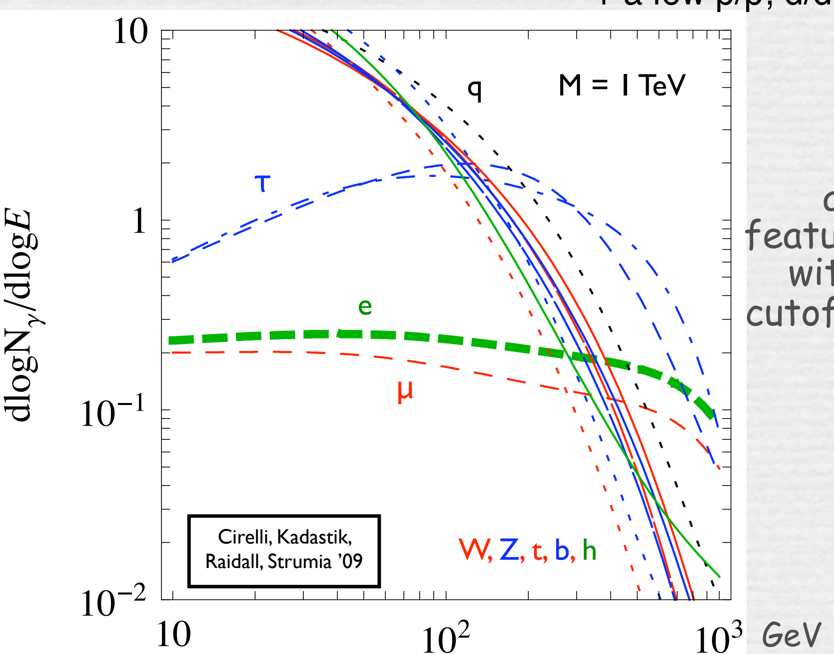
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



from hadronisation, decays of SM particles & final state radiation

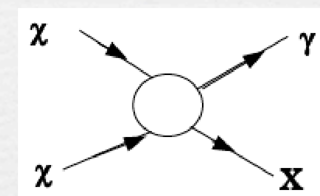


almost featureless but with sharp cutoff at Wimp mass

• Lines

primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

☺ -> striking spectral feature, SMOKING GUN signature of Dark Matter

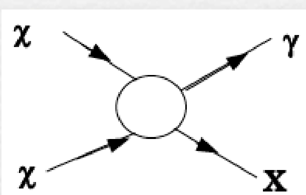
☹ lines are usually small (loop-suppressed) compared to continuum

Bergstrom, Ullio, Buckley '98

Seeing the light from Dark Matter

• detected from the ground (ACTs) and from above (FERMI)

• The position and strength of lines can provide a wealth of information about DM:



$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

→ γγ line measures mass of DM

→ relative strengths between lines provides info on WIMP couplings

→ observation of γH would indicate WIMP is not scalar or Majorana fermion

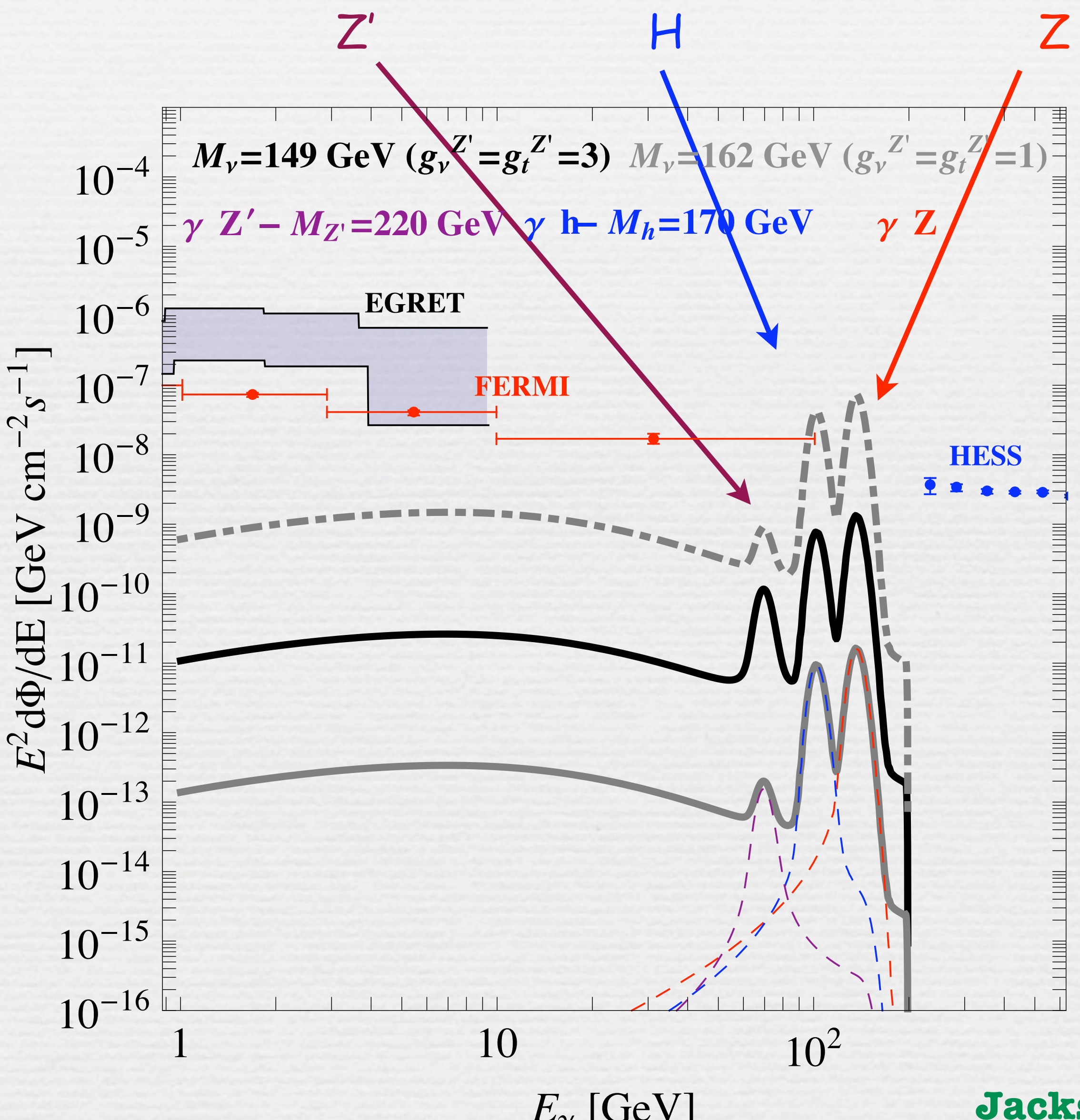
Jackson et al. '09

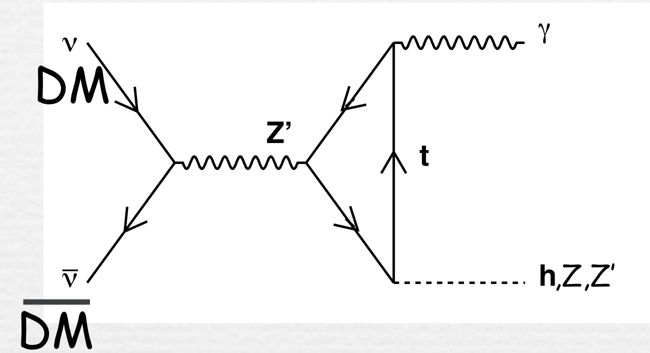
→ if other particles in the dark sector, we could possibly observe a series of lines

[the "WIMP forest", Bertone et al. '09]

Higgs in Space!

γ-ray lines from the Galactic Center $\Delta\Omega = 10^{-5}$ sr





Spectra for parameters leading to correct relic density and satisfying direct detection constraints

NFW profile

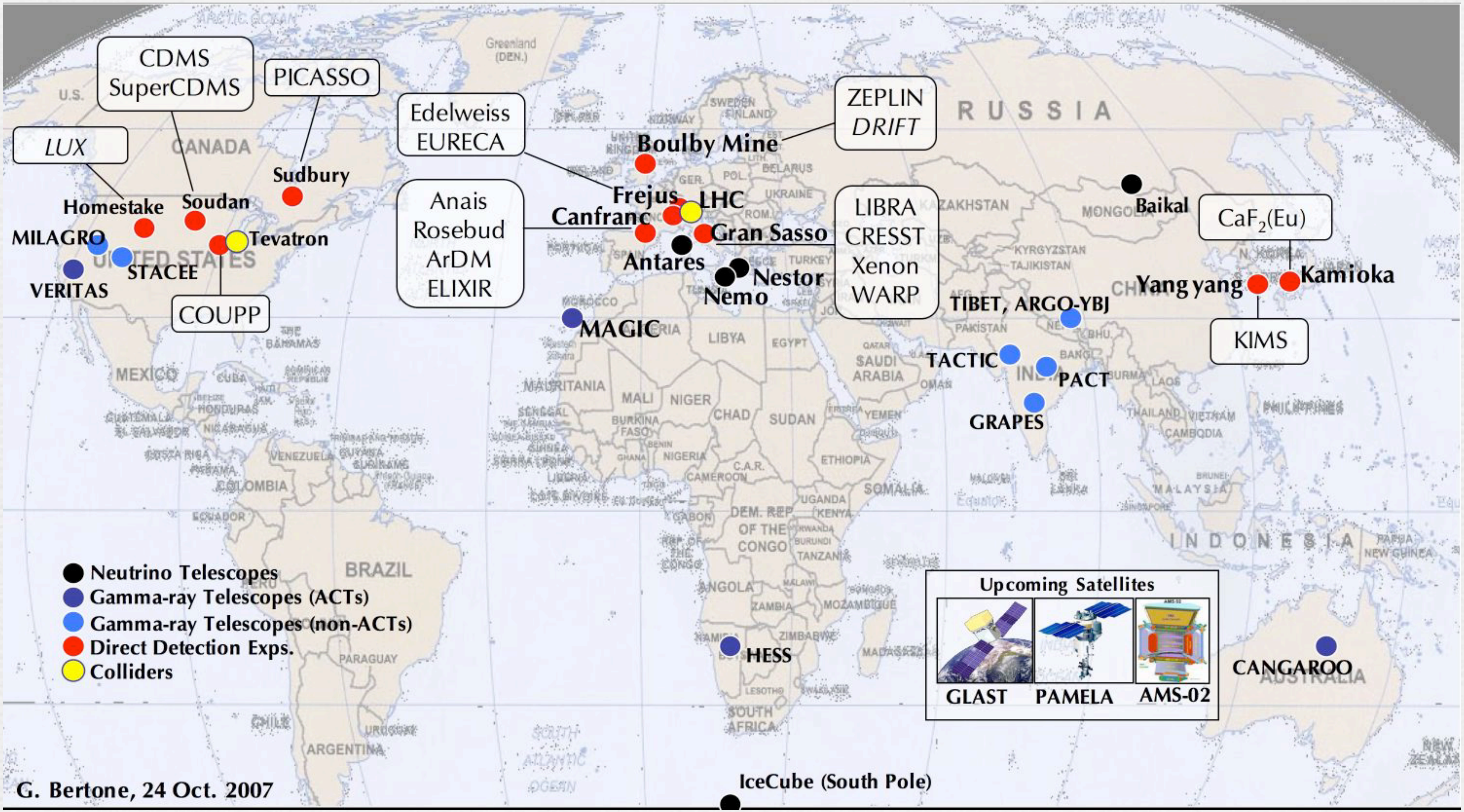
adiabatically contracted

Jackson, Servant, Shaughnessy, Tait, Taoso,'09

The Dark Matter Decade

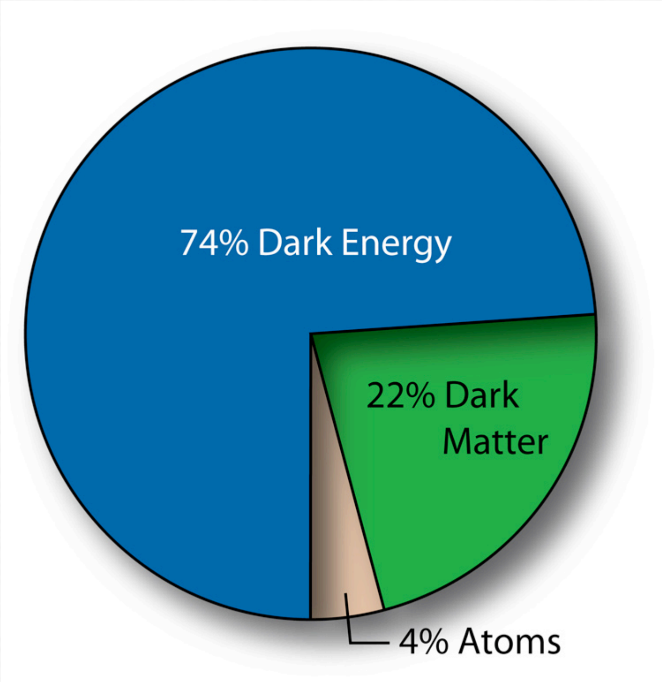
Huge experimental effort towards the identification of Dark Matter

Indirect	Direct	Collider experiments
Antimatter, Neutrinos, Gamma Rays — Signature of Annihilation in space	Elastic Scattering signature in underground labs	Missing Energy signature in high energy accelerators



beyond the standard WIMP paradigm ...

Are the Dark Matter and baryon abundances related ?



$\Omega_{DM} \approx 5\text{-}6\ \Omega_{baryons}$

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

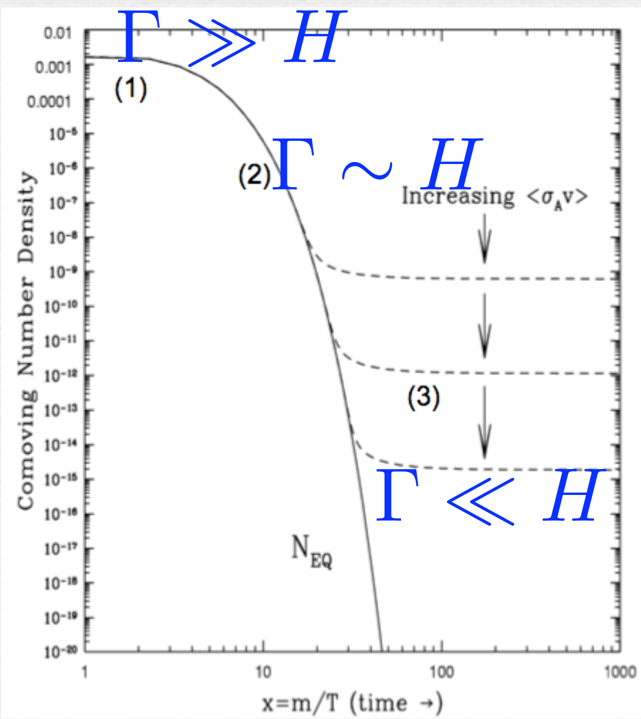
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \rightarrow \pi + \pi \rightarrow \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T} / m_\pi^2 \sim H \sim \sqrt{g_*} T^2 / m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$

then $\frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm})m_{dm}}{(n_b - \overline{n}_b)m_b} \sim C\frac{m_{dm}}{m_b}$

conservation of global charge: $Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\overline{b}})$

if efficient annihilations: $\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}}\frac{m_{dm}}{m_b}$ ⟶ typical expected mass ~ GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

(we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation ×Parity) violation

(we need to prefer matter over antimatter)

3) Loss of thermal equilibrium

In thermal equilibrium, any reaction which destroys baryon number will be exactly counterbalanced by the inverse reaction which creates it. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be erased by interactions

(we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop)

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

Baryogenesis without $\not{B}$ nor $\not{L}$ nor CP$\not{T}$

Possible if dark matter carries baryon number

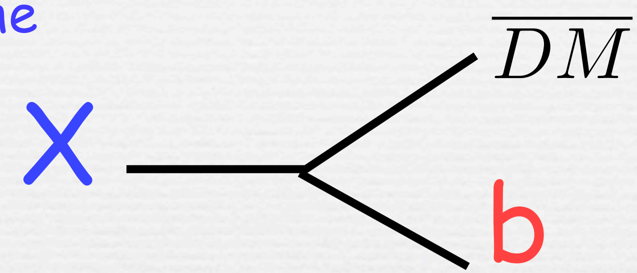
Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254
Davoudiasl et al 1008.2399

In a universe where baryon number is a good symmetry, Dark matter would store the overall negative baryonic charge which is missing in the visible quark sector

Generalization: DM & baryon sectors share a quantum number (not necessarily B)

$Q_{universe} = 0 = \underbrace{Q}_{\text{carried by baryons}} + \underbrace{(-Q)}_{\text{carried by antimatter}}$

Assume an asymmetry between b and $\bar{b}$ is created via the out-of-equilibrium and CP-violating decay :



Charge conservation leads to

$$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

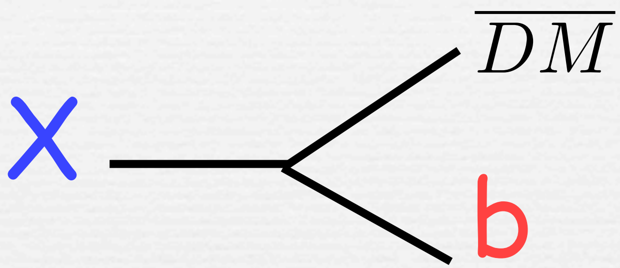
If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$:

$$\rho_{\rm DM} = m_{\rm DM} n_{\overline{\rm DM}} \approx 6\rho_b \rightarrow m_{\rm DM} \approx 6\frac{Q_{\rm DM}}{Q_b} \text{ GeV}$$

Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254
Davoudiasl et al 1008.2399
} (DM carries B number)

Kitano & Low, hep-ph/0411133
West, hep-ph/0610370
(X and DM carry Z2 charge)

asymmetry between b and $\bar{b}$ is created via the out-of-equilibrium and CP-violating decay :



$$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

out-of equilibrium and CP violating decay of X sequesters the anti baryon number in the dark sector, thus leaving a baryon excess in the visible sector

If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$

$$\rho_{\rm DM} = m_{\rm DM} n_{\overline{\rm DM}} \approx 6\rho_b \rightarrow m_{\rm DM} \approx 6\frac{Q_{\rm DM}}{Q_b}\ {\rm GeV}$$

A unified explanation for DM and baryogenesis $\quad \Omega_b \approx \frac{1}{6}\Omega_m$

turns out to be quite natural in warped GUT models...

GUT baryogenesis at the TeV scale !

Agashe-Servant-Tulin in progress

Z_3 symmetry in the SM:

Agashe-Servant'04

number of color indices

$$\Phi \longrightarrow \Phi \; e^{2\pi i \left[B - \frac{(\alpha - \bar{\alpha})}{3} \right]}$$

conserved in any theory where baryon number is a good symmetry

any non-colored particle that carries
baryon number will be charged under Z_3

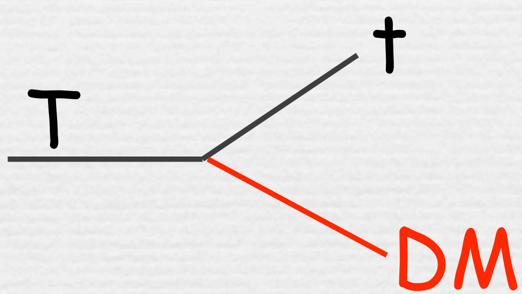
e.g warped GUTs

Z_2 versus Z_3 Dark Matter

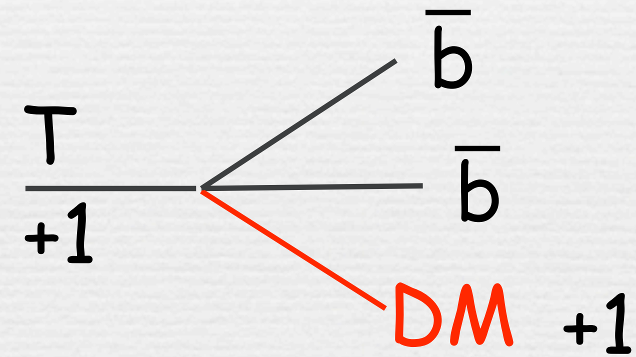
Agashe et al, 1003.0899

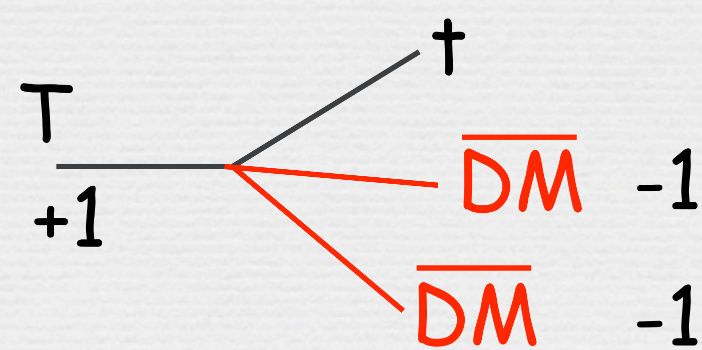
Many Dark Matter models rely on a Z_2 symmetry. However, other symmetries can stabilize dark matter. Can the nature of the underlying symmetry be tested?

Z_2



Z_3 (+1=-2)





What controls the Dark Matter abundance?

a preview of this afternoon lecture:

Conclusion

Within the next 10 years, we will probe experimentally the electroweak symmetry breaking sector as well as the WIMP paradigm and its variations

If no detection: interest will move to other candidates: axions, sterile neutrinos

[lectures by G. Raffelt & M. Shaposhnikov]