Cosmological consequences of new physics at the TeV scale

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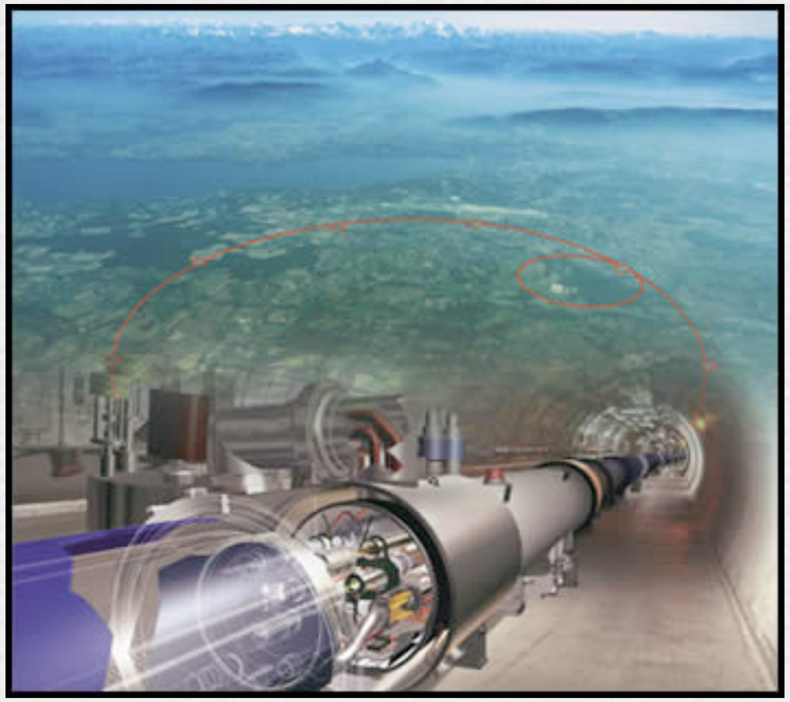
2010: First collisions at the LHC

Direct exploration of the Fermi scale has started.

main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?



The Standard Model of Particle Physics

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

gauge sector

flavour sector

neutrino mass sector (if Majorana)

electroweak symmetry breaking sector

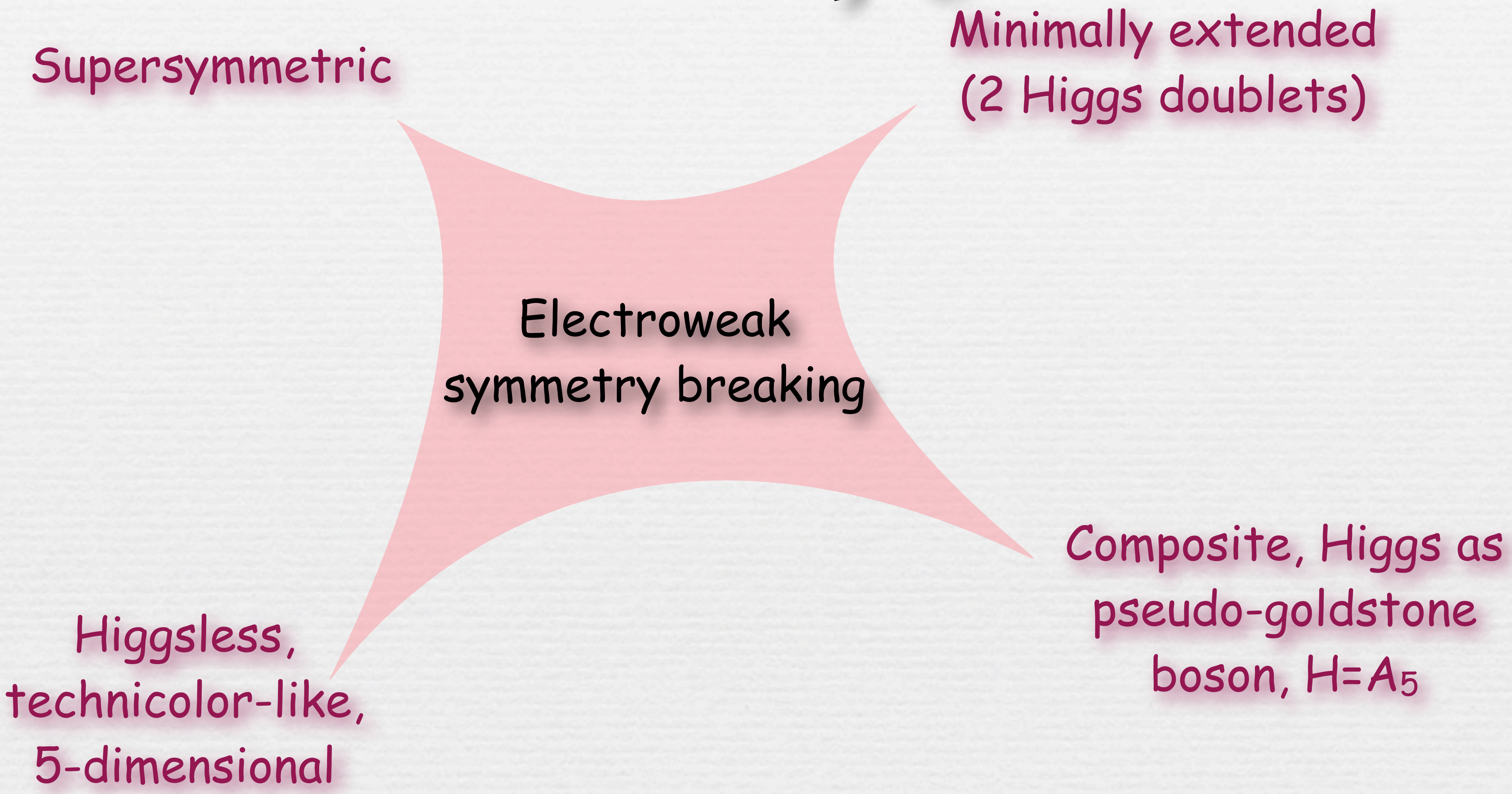
$SU(3)_C \times SU(2)_L \times U(1)_Y$

- 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

Which new physics?



In all explicit examples, without unwarranted cancellations, new phenomena are required at a scale Λ~[3-5] × M_{Higgs}

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

2 major observations unexplained by the Standard Model

- 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

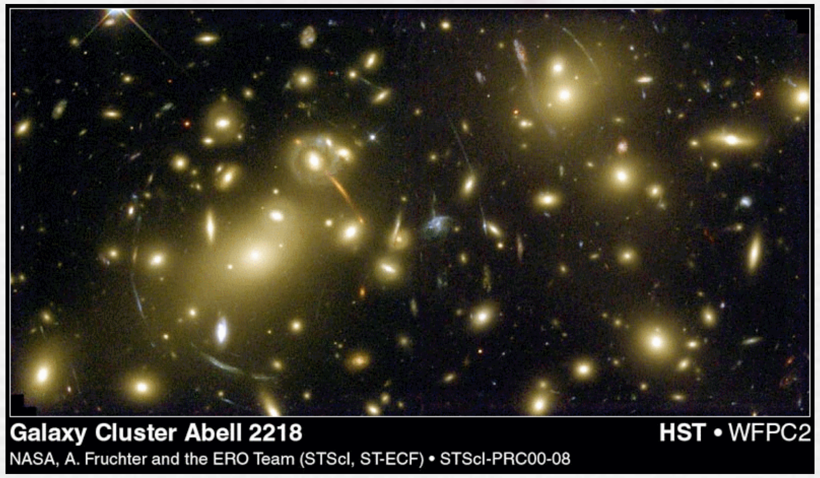
baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

→ observational need for new physics

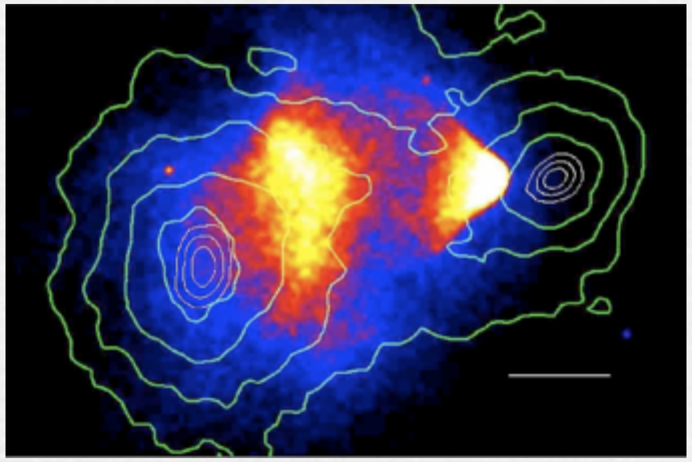
→ what does this have to do with the electroweak scale?

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

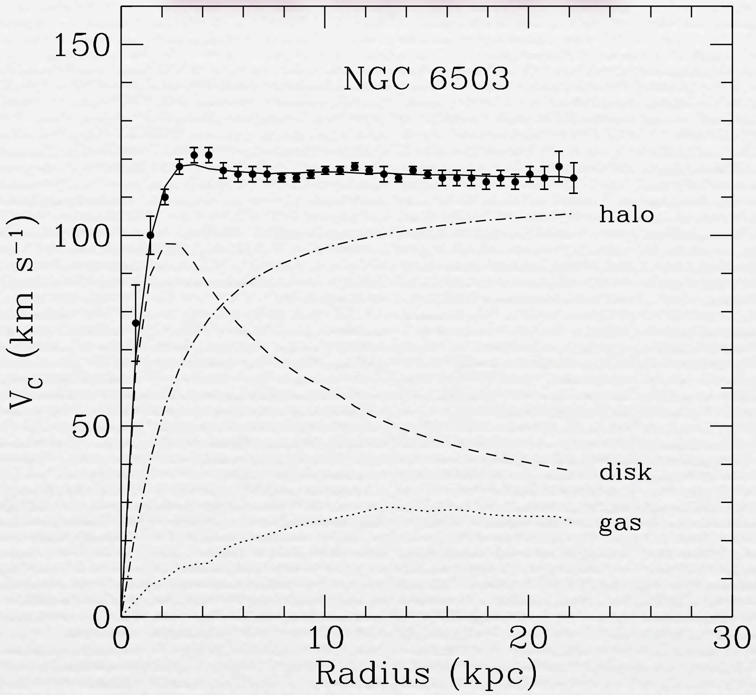
Gravitational lensing



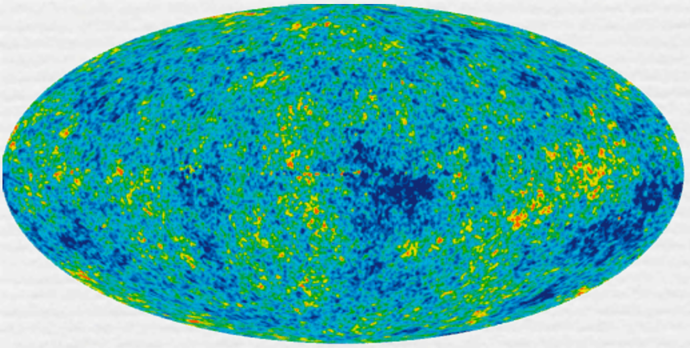
The "Bullet cluster": lensing map versus X-ray image

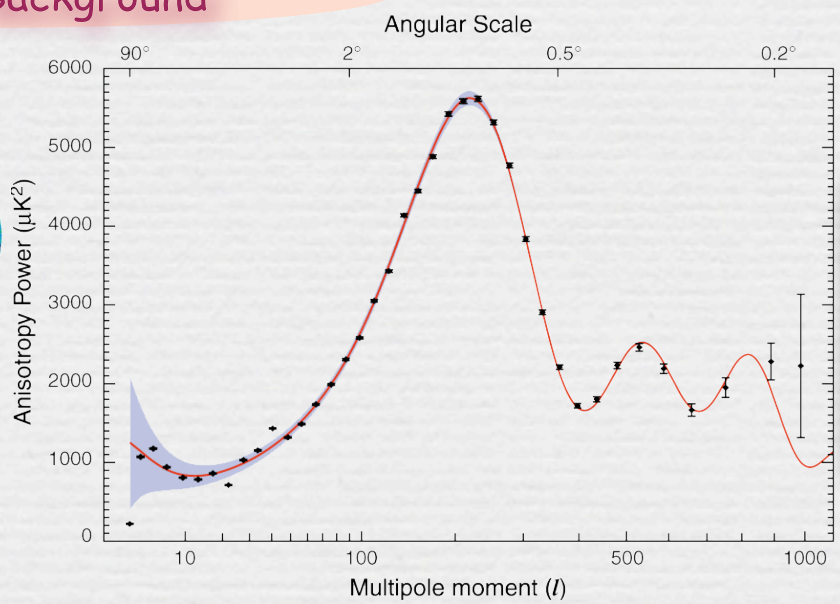


Galaxy rotation curves



Cosmic Microwave Background





... etc

-> Fraction of the universe's energy density stored in dark matter :

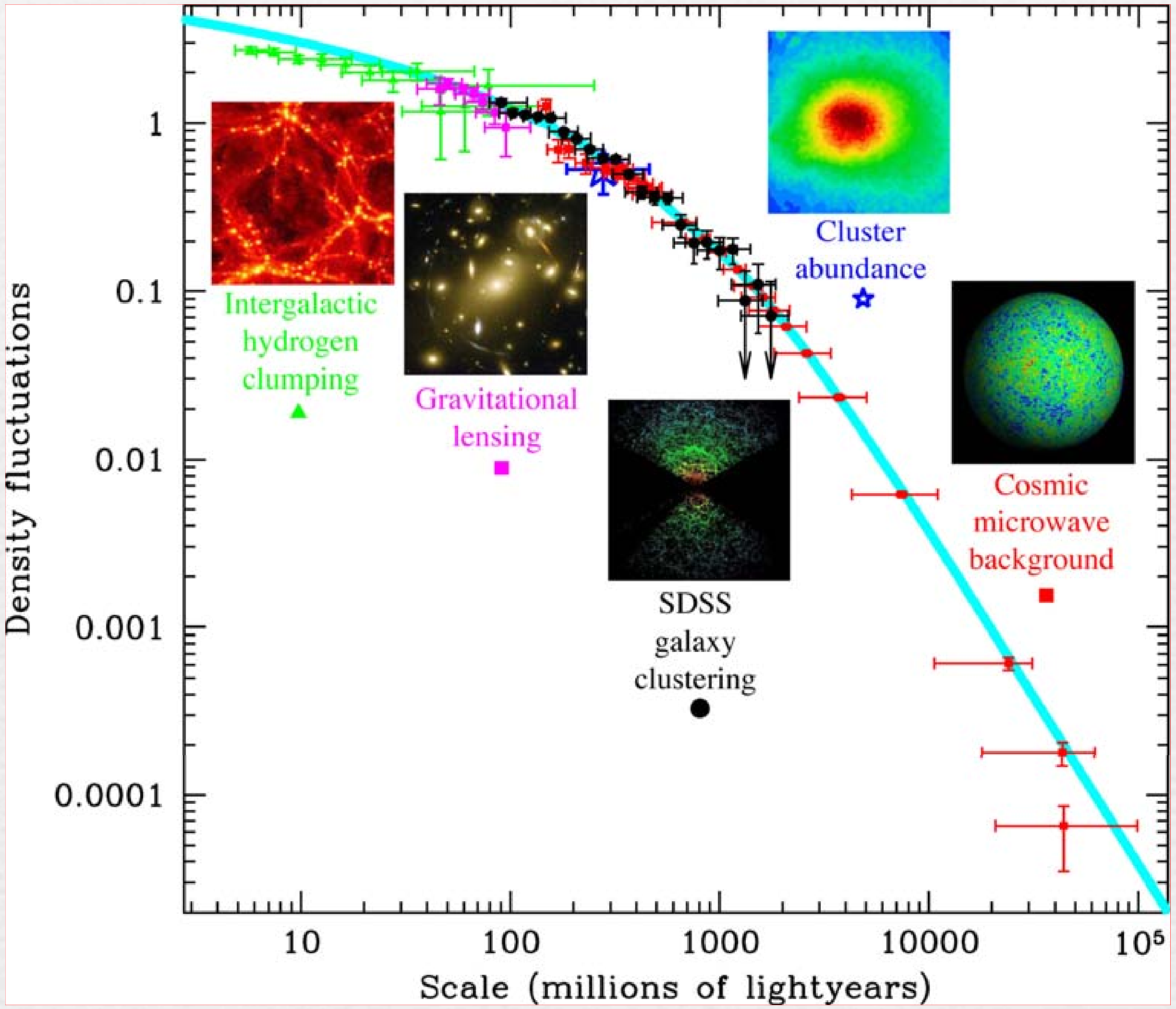
$\Omega_{DM} \approx 0.22$

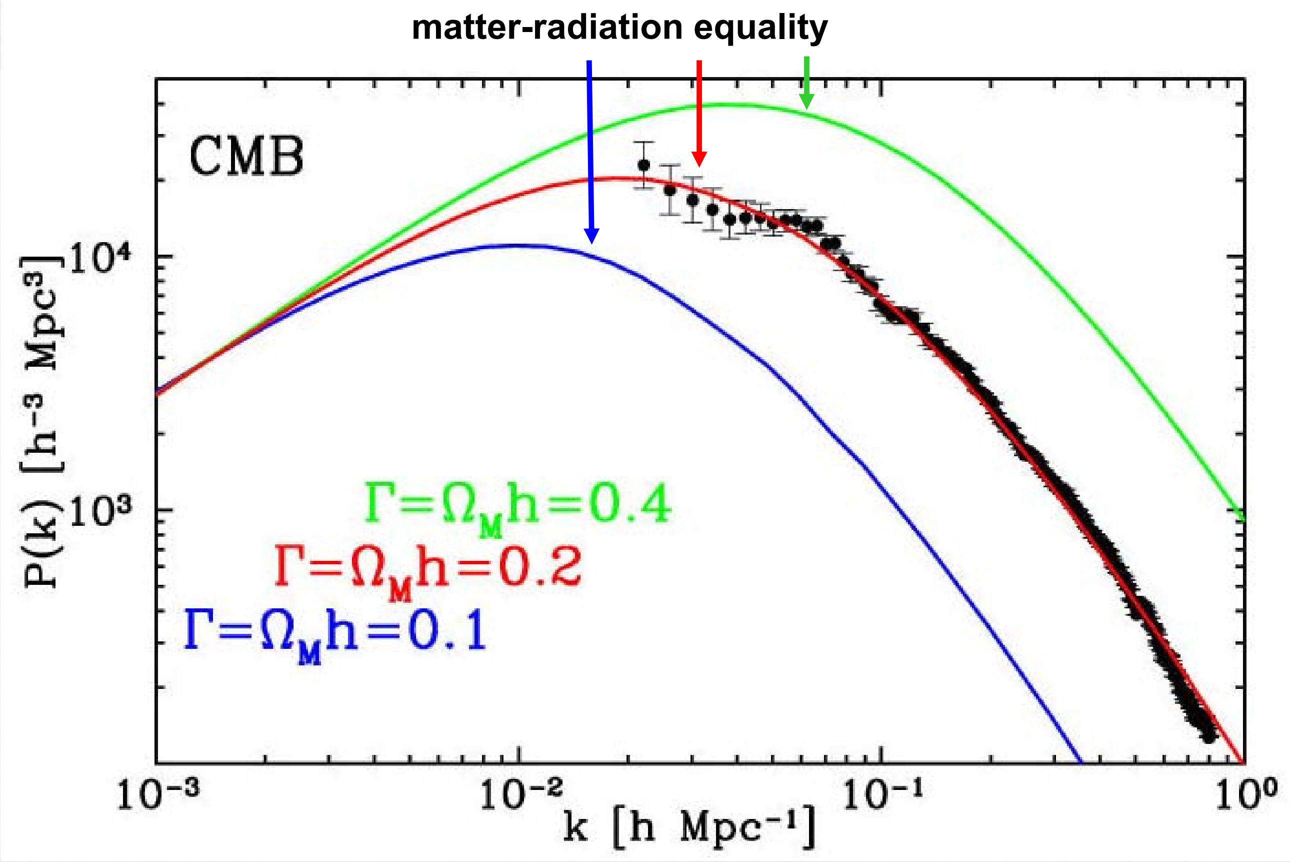
The picture from astrophysical and cosmological observations is getting more and more focussed

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

Matter power spectrum

not baryonic



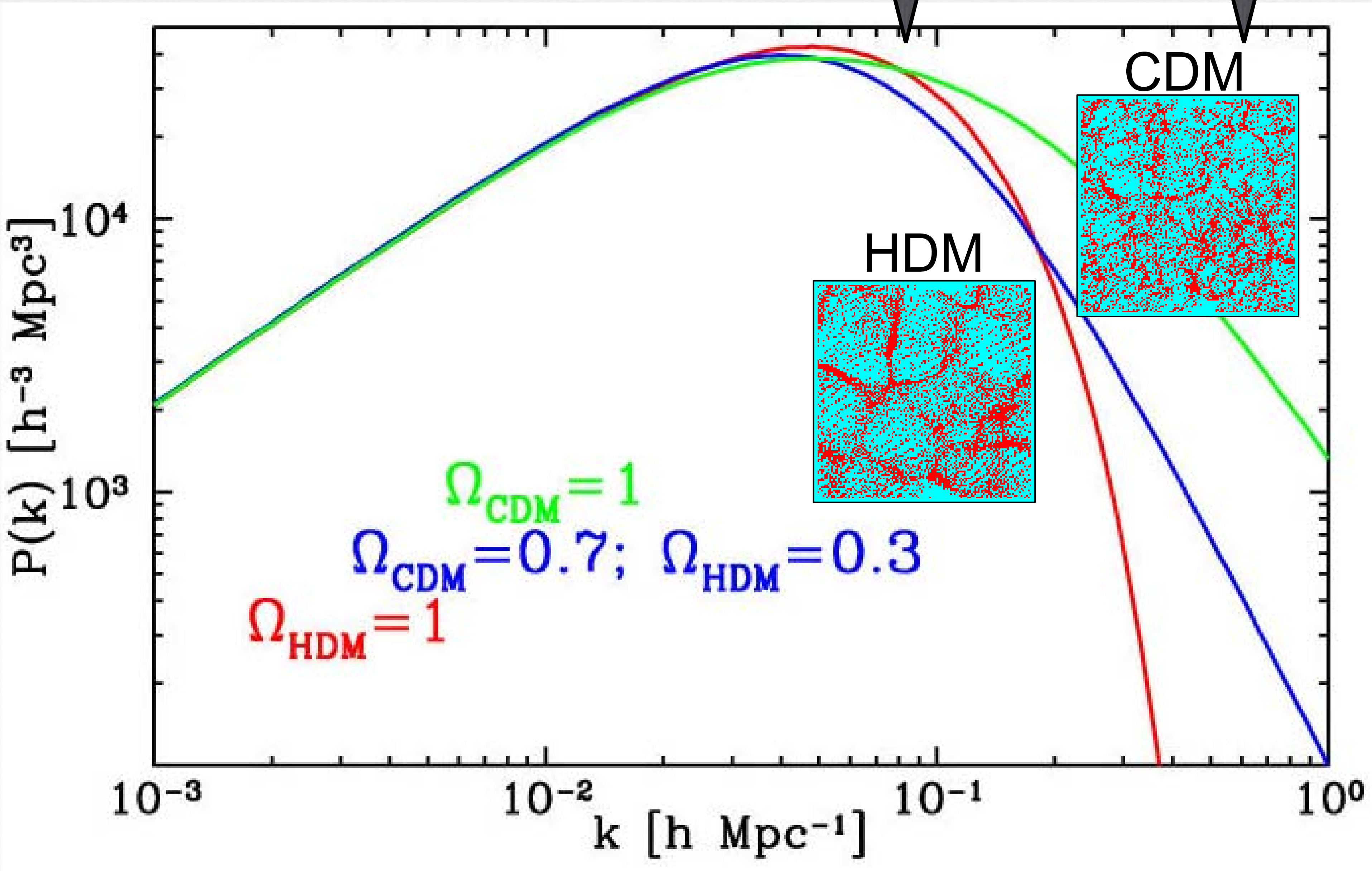


Neutrinos

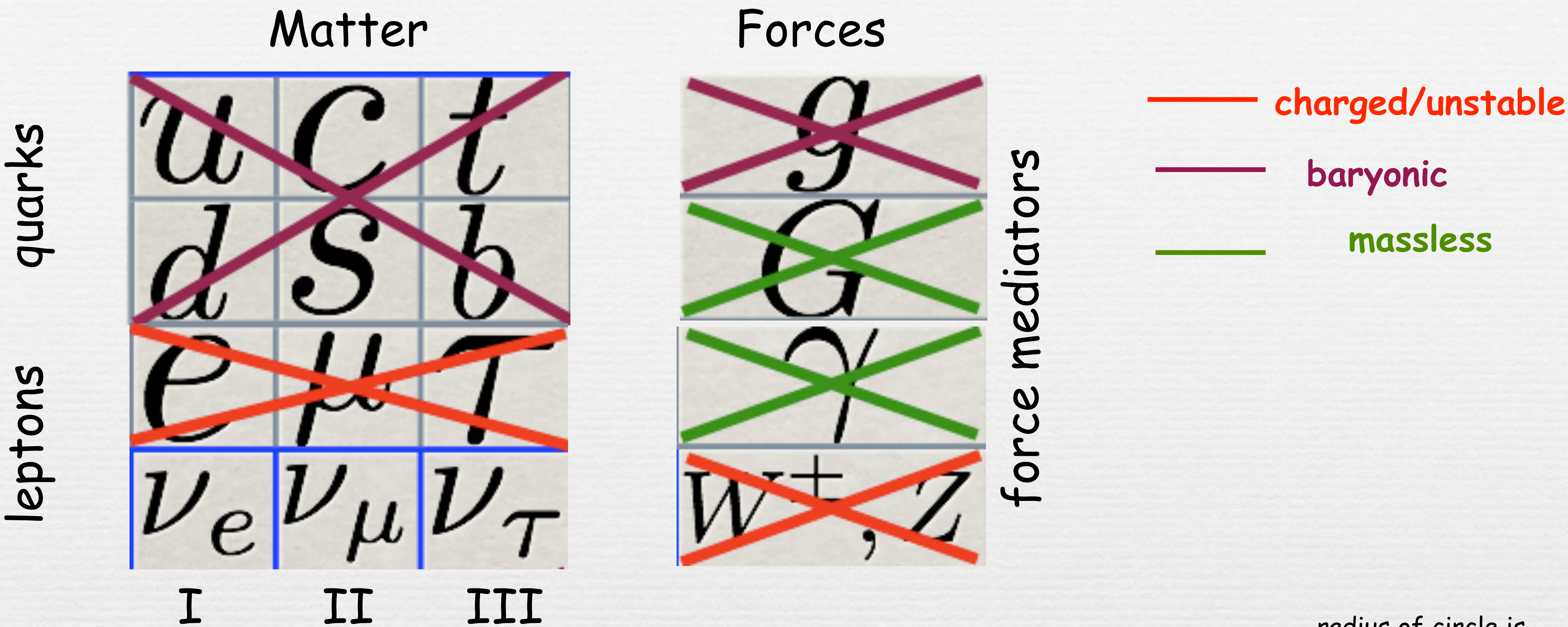
not hot

hot dark matter

cold dark matter

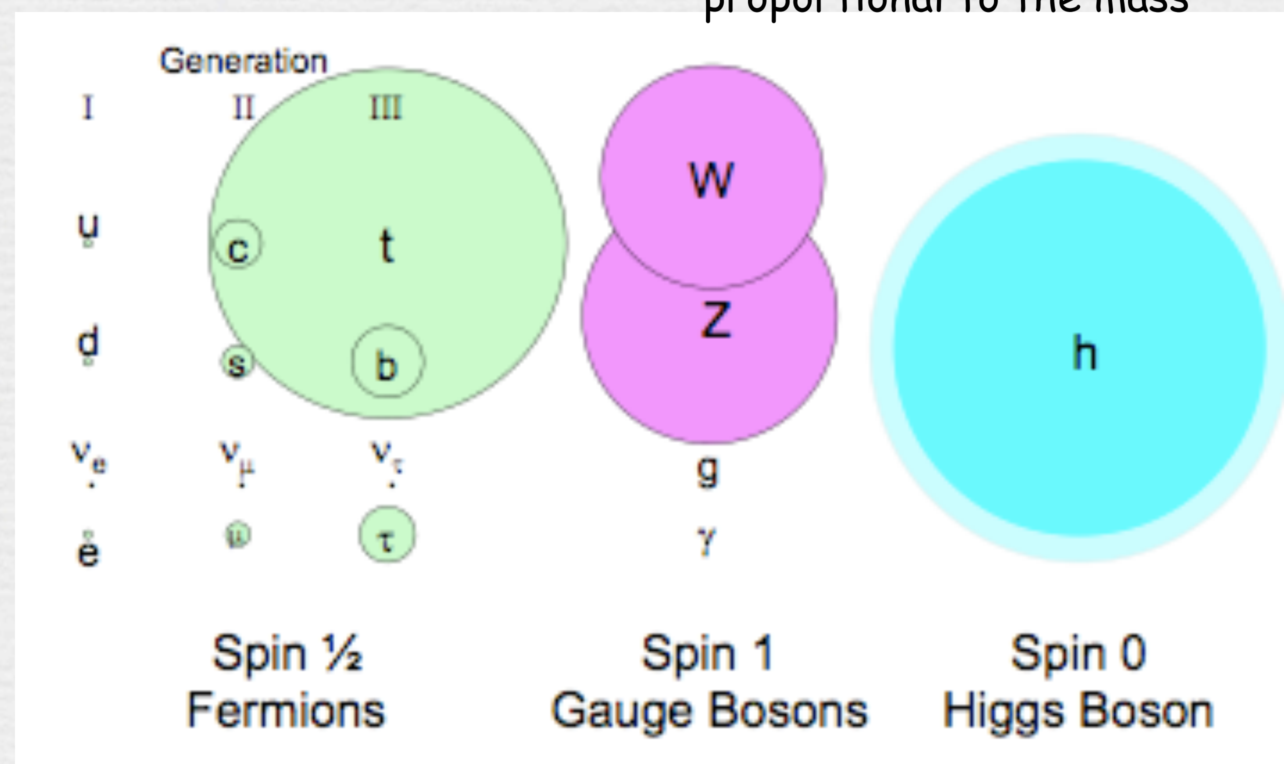


Why can't dark matter be explained by the Standard Model?



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 main possibilities

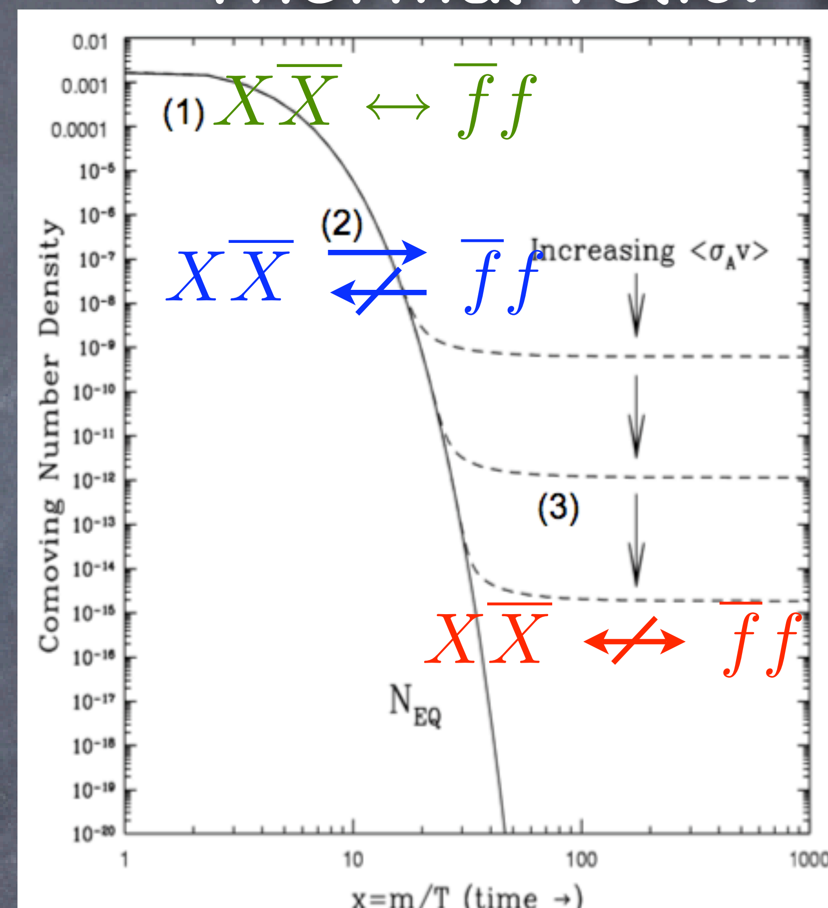
very light & only gravitationally coupled (or with equivalently suppressed couplings) -> stable on cosmological scales

sizable (but not strong) couplings to the SM -> symmetry needed to guarantee stability

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

Production mechanism is model-dependent, depends on early-universe cosmology

ex: meV scalar with $1/M_{Pl}$ couplings (radion)



$\Rightarrow \langle\sigma_{anni}\, v\rangle = 0.1$ pb

The "WIMP miracle"

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

$\Rightarrow m \sim 100$ GeV

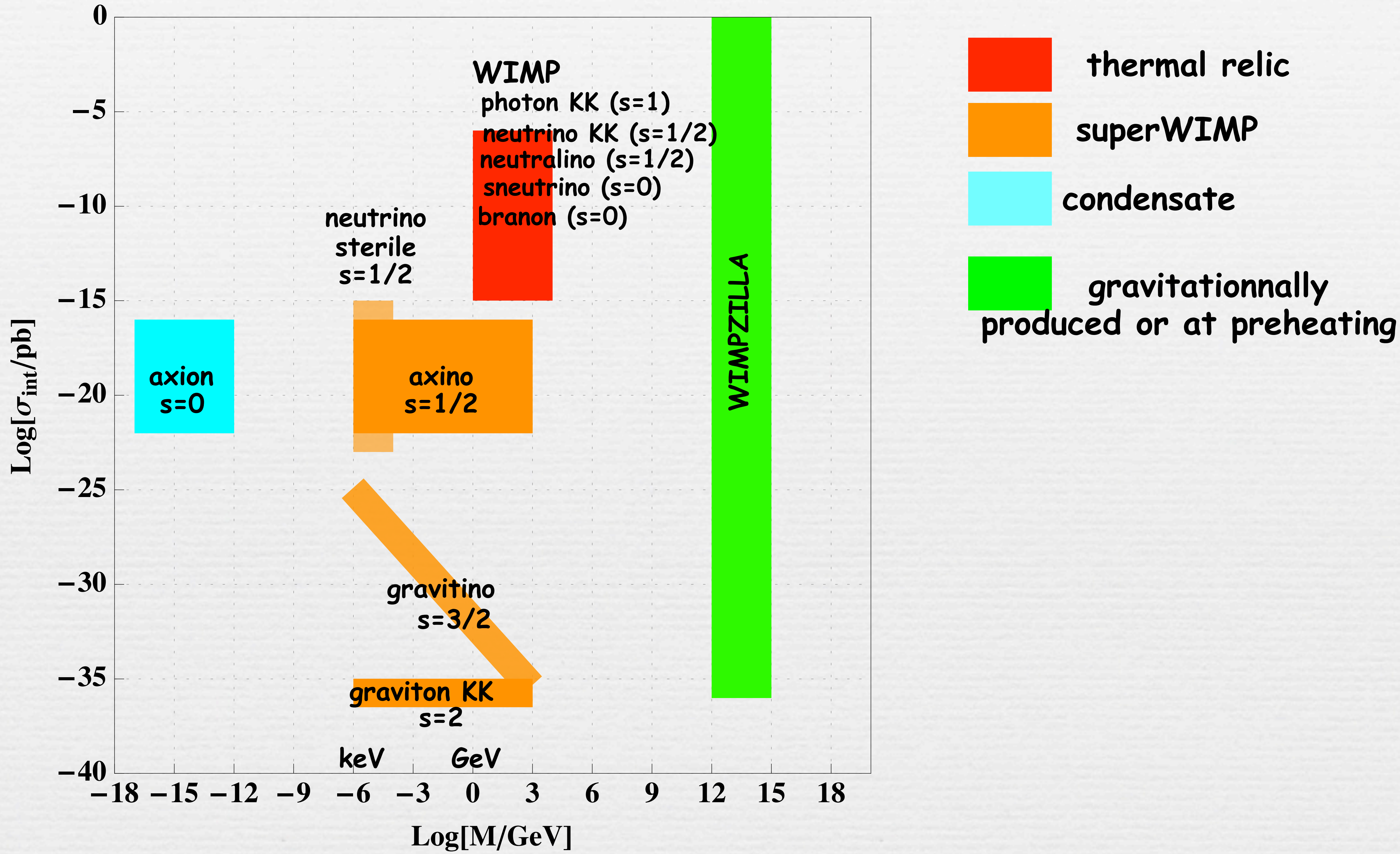
Very general, does not depend on early universe cosmology, only requires the reheat temperature to be $\geq m/25$ (= weak requirement)

an alternative: superWIMPs (where most often the above calculation is still relevant since SuperWIMPs are produced from the WIMP decay)

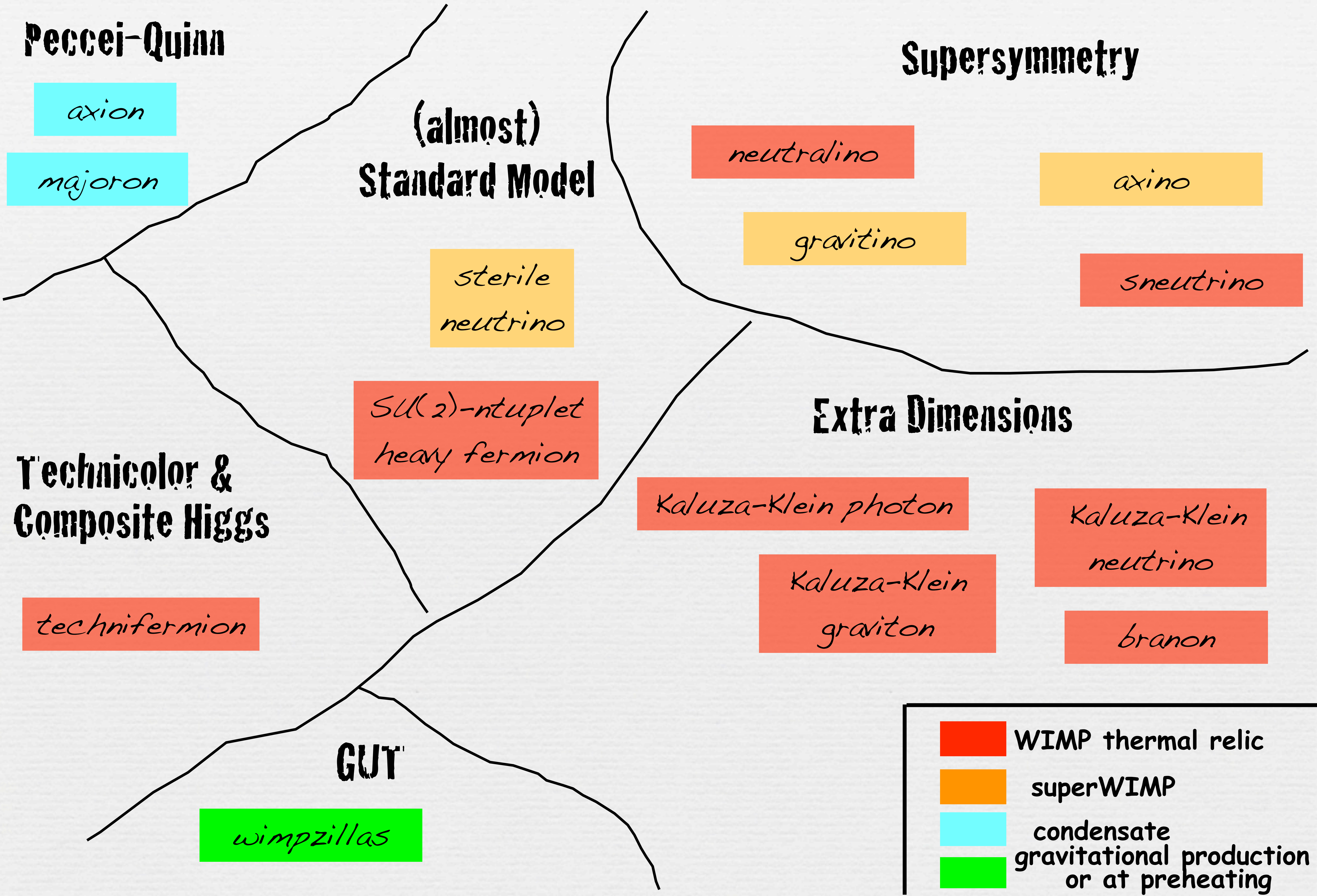
ex: gravitino, KK graviton

Dependence on reheat temperature

Dark Matter Candidates Ω~1



In Theory Space



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

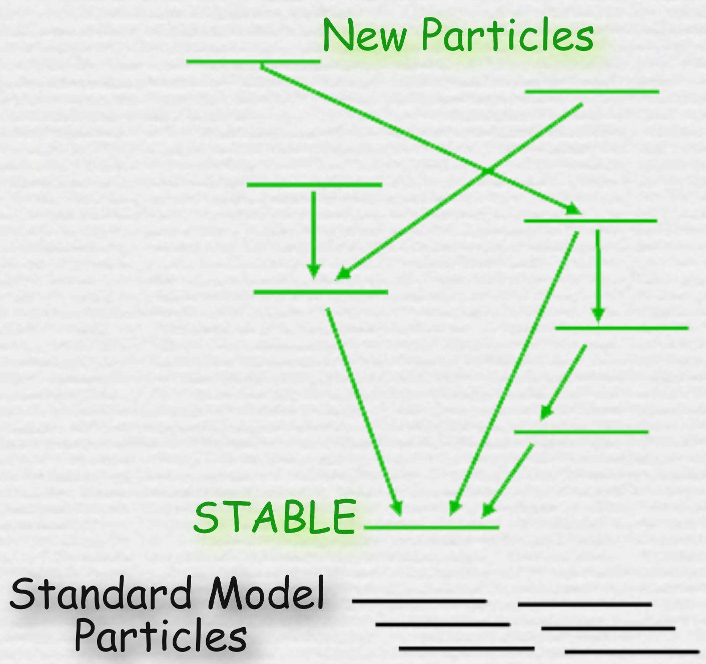
The stability of a new particle is a common feature of many models

mass spectrum,
interactions

dark matter candidates

relic abundance

detection signatures & rates



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

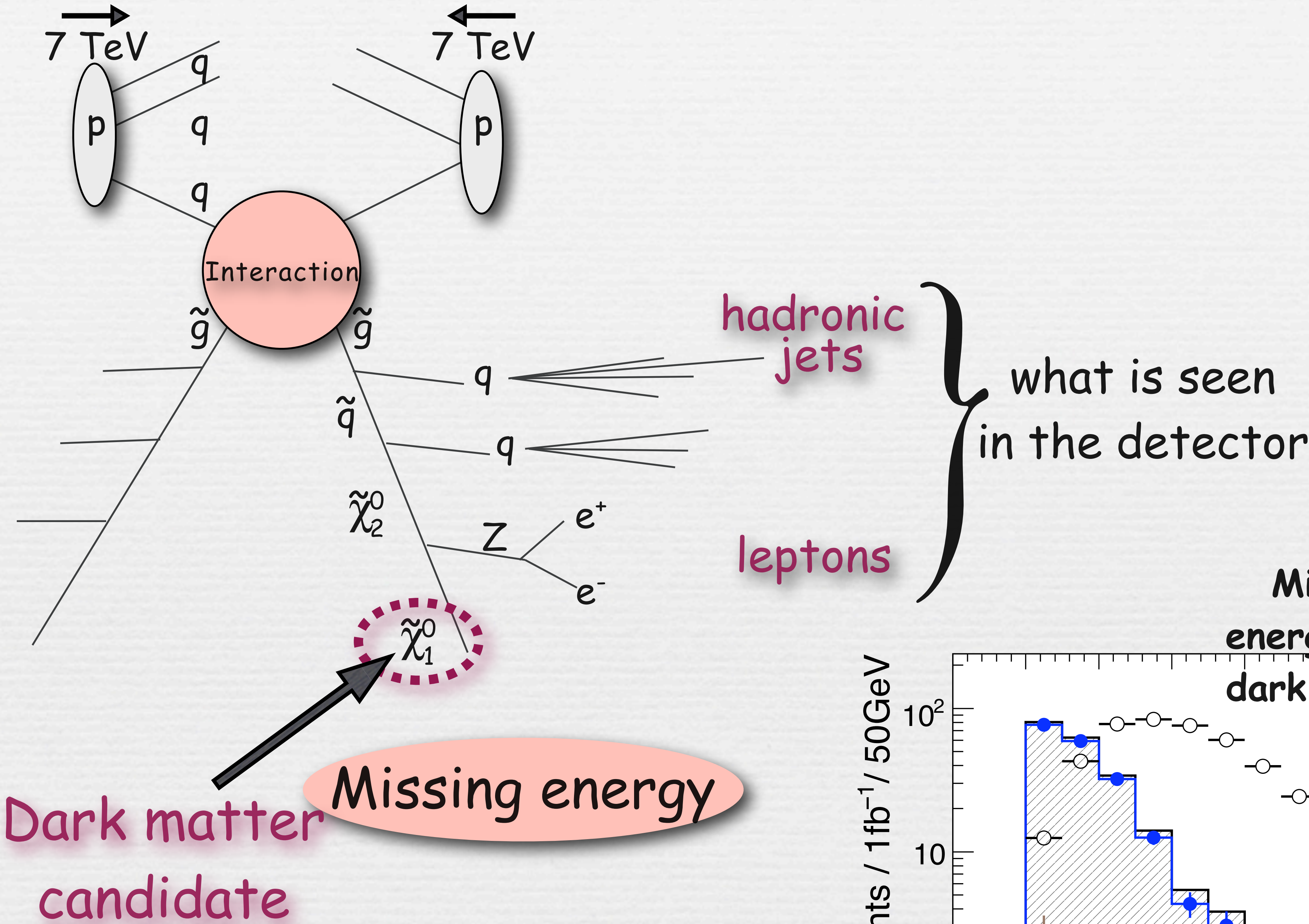
in last few years (post LEP-2)--> questioning of naturalness as a motivation for new physics @ the Weak scale

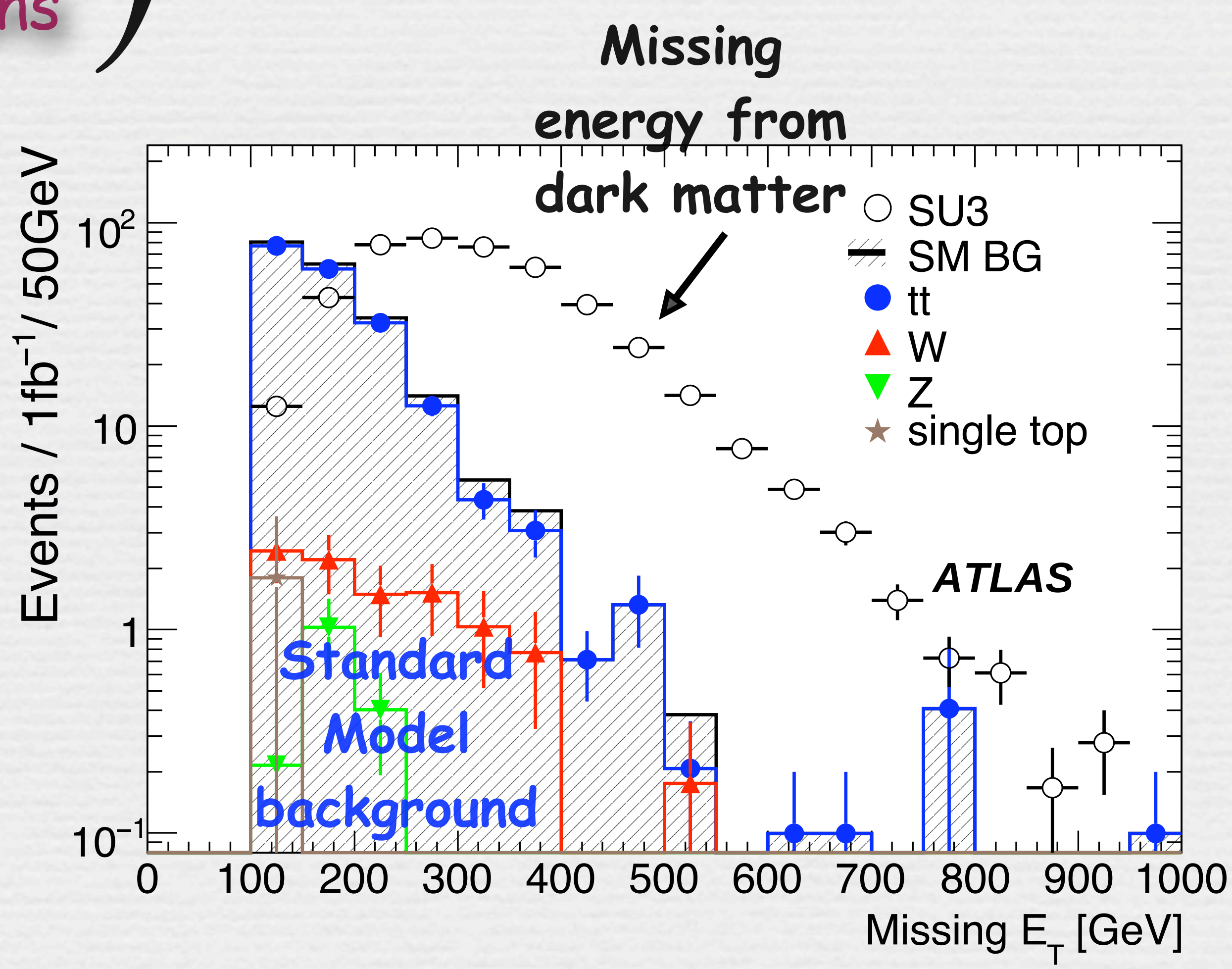
"minimal approach": focus on dark matter only and do not rely on models that solve the hierarchy problem

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

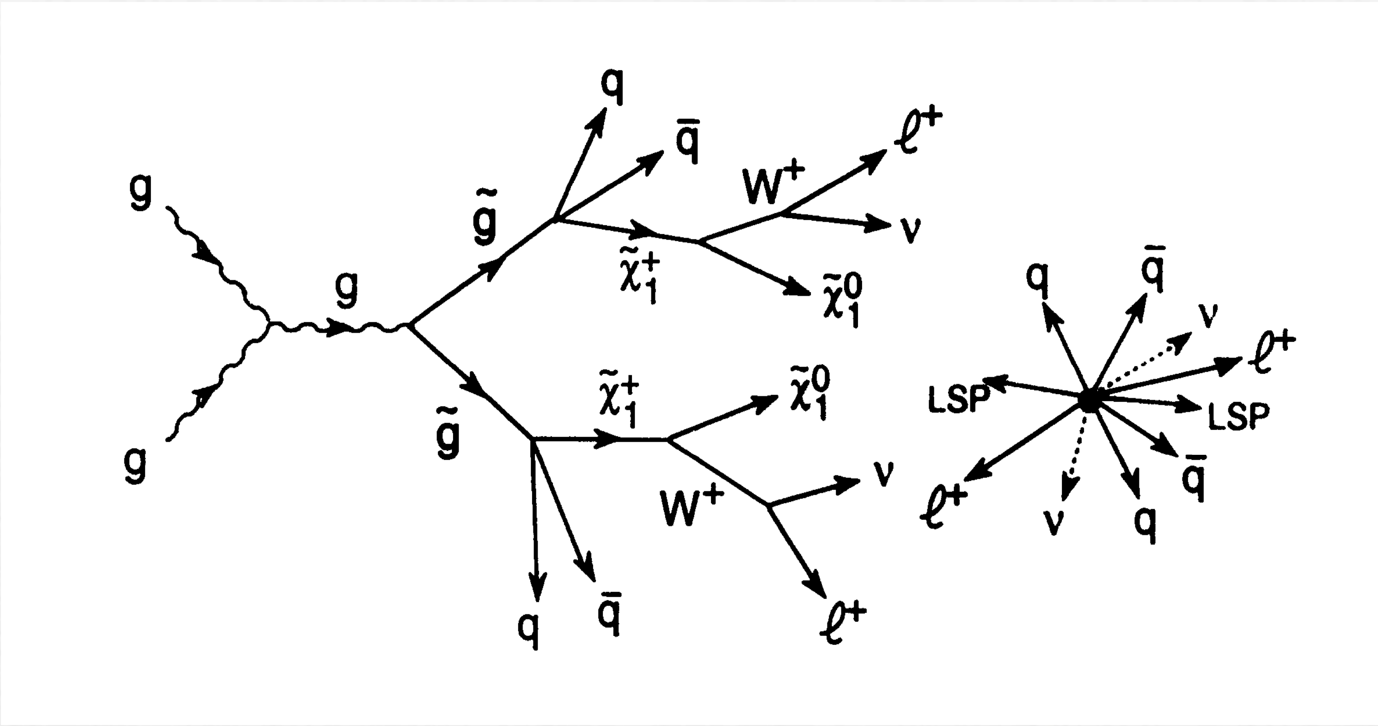
→ dark matter model building since ~2008: data driven

Producing Dark Matter at LHC = "Missing Energy" events





Typical SUSY decay chain

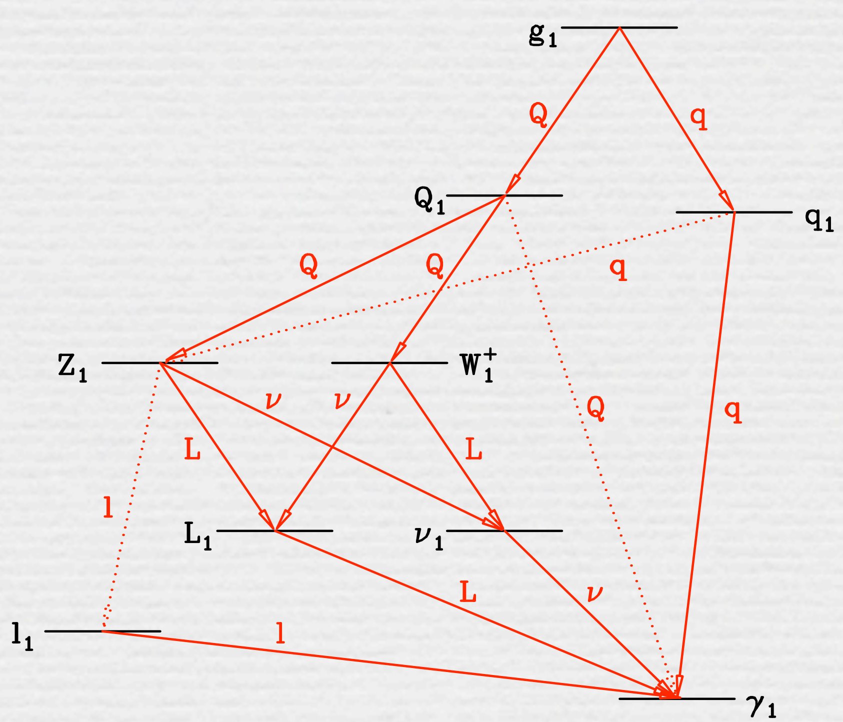


Lots of jets

Lots of leptons

Lots of missing energy

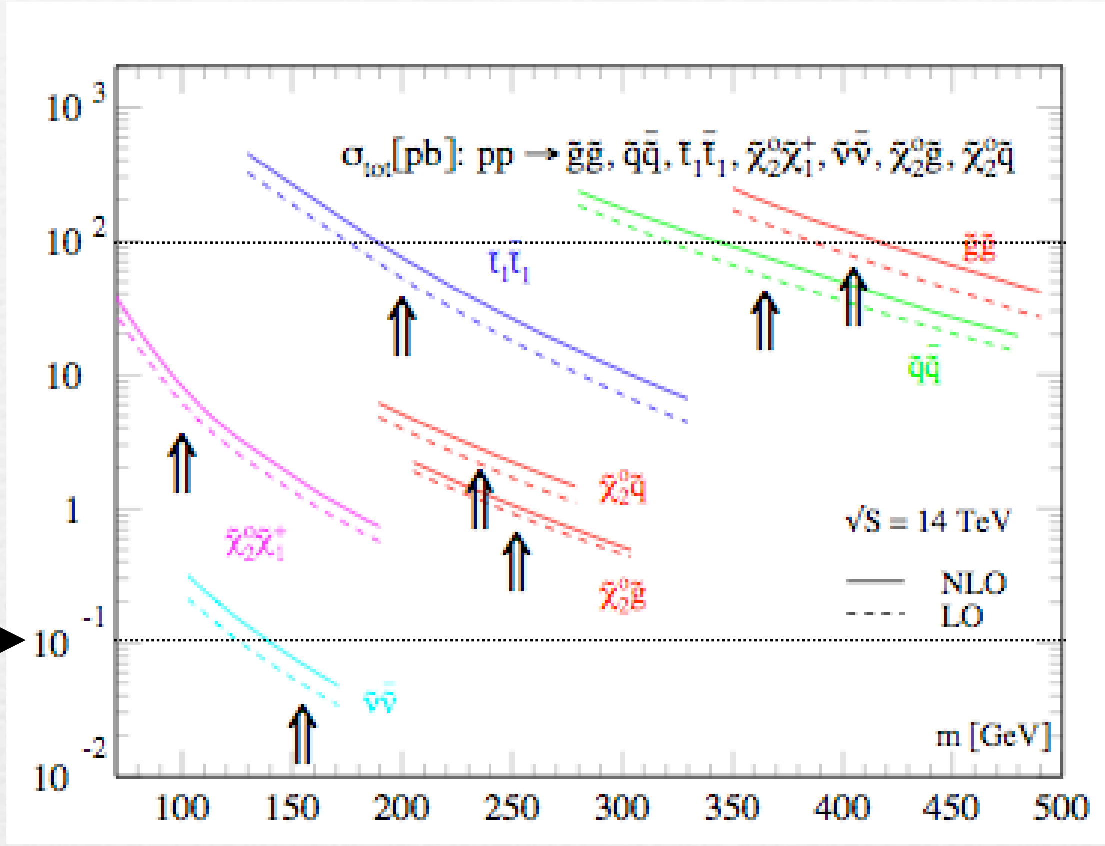
easily mimicked by Kaluza-Klein decay chain:



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)

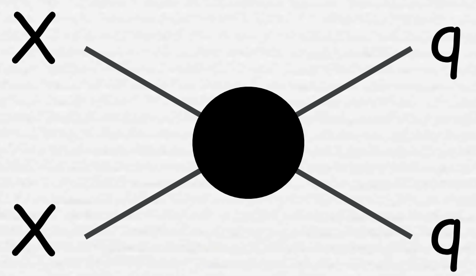
2) studying its properties in the laboratory

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

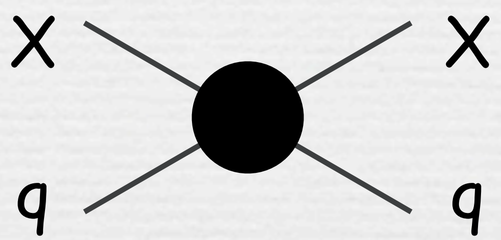
1 pb : the typical cross section

1 pb : typical annihilation cross section of wimps at freeze out for giving the correct abundance today

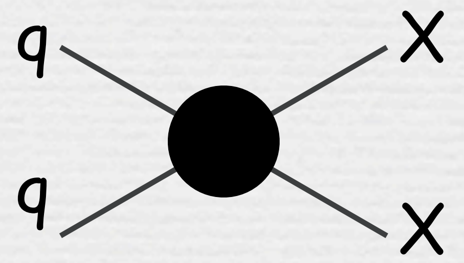


1 pb : typical scattering cross section of wimps with nuclei (-> relevant for direct detection experiments like CDMS)

[$\sigma_n \sim (m_n^2/\mu^2)/A^2$) $\sigma_0 \sim 10^{-7}$ pb]



1 pb : typical cross section for wimp production at LHC (from ~ 500 GeV gluino pair production)



WIMP direct detection

Because they interact so weakly, Wimps drifting through the Milky Way pass through the earth without much harm.

Just a few Wimps are expected to collide elastically upon terrestrial nuclei, partially transferring to them their kinetic energy.

Direct detection consists in observing the recoiled nuclei.

Energy of recoiled nuclei

An incoming wimp with velocity v interacts upon a nucleus at rest to which a momentum q is transferred. The energy deposited in the detector by this collision is:

$$E_{recoil} = \frac{|\mathbf{q}|^2}{2M_{nucleus}}$$

$$|\mathbf{q}|^2 = 2\mu^2 v^2 (1 - \cos\theta)$$

momentum transfer — reduced mass — scattering angle in center of mass frame

typical velocity: $v \sim 300\ \mathrm{km.s^{-1}} \sim 10^{-3}c$

typical recoil energy:

$$E_{recoil} \sim M_{nucleus} v^2$$ ~ 1 - 100 keV

Event rate

nuclear form factor

distribution of wimp velocities

$$\frac{dR}{dE_{recoil}} = \frac{\sigma_0\ \rho}{2\ M_{wimp}\ \mu^2} F^2\ (|\mathbf{q}|) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

dark matter density in galactic halo: $\rho \approx 0.3\ \text{GeVcm}^{-3}$

$\approx 3000\ \text{Wimps.m}^{-3}$ if $m \approx 100$ GeV

$v_{max} \sim 650$ km/s (galactic escape velocity)

$v_{\min} = \sqrt{E_{recoil} M_{nucleus}/2\mu^2}$

σ_0 : cross section at zero momentum transfer; contains model-dependent factors

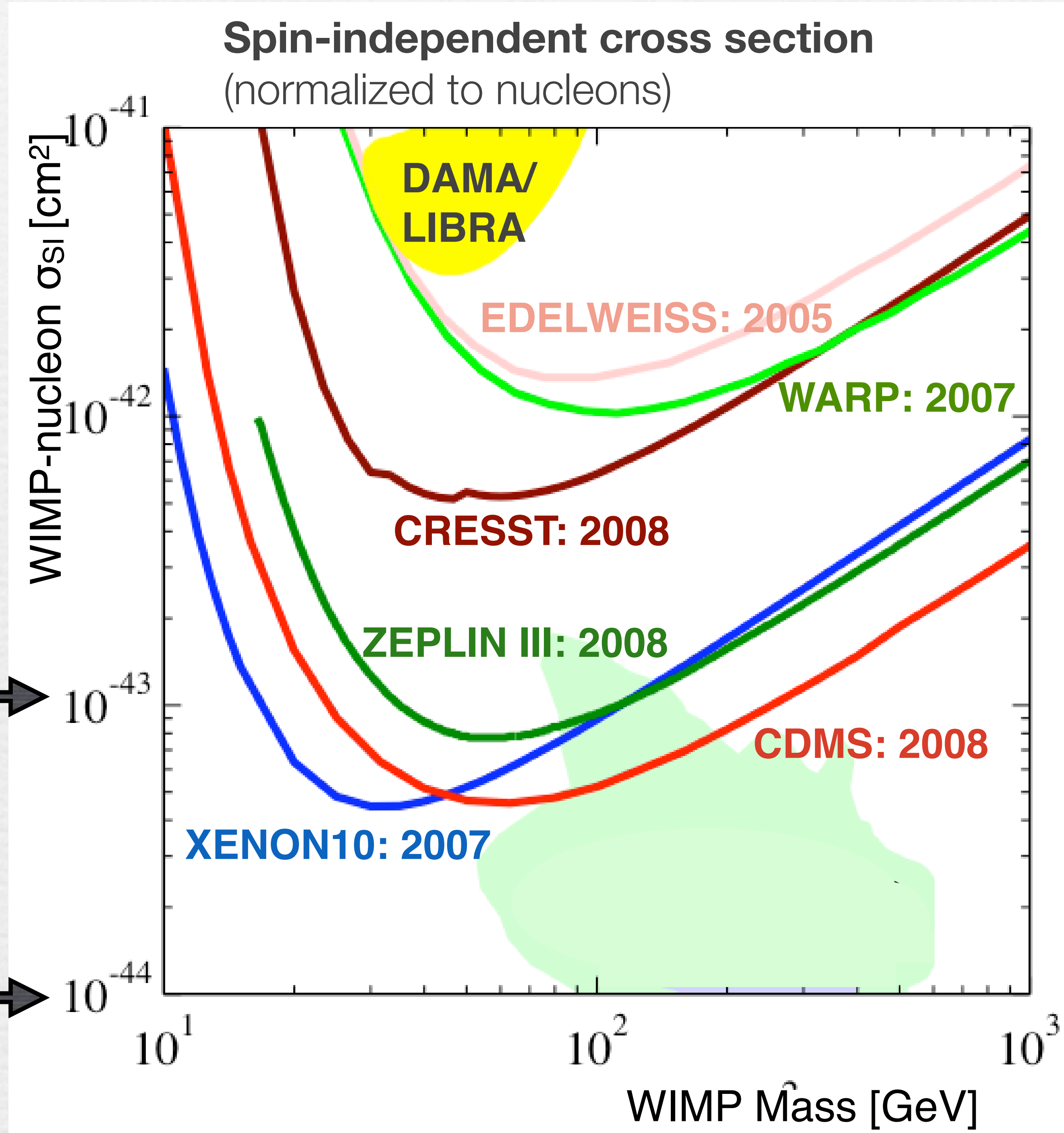
< 1 event/100kg/day if wimp-nucleon cross section is 10^{-7} pb

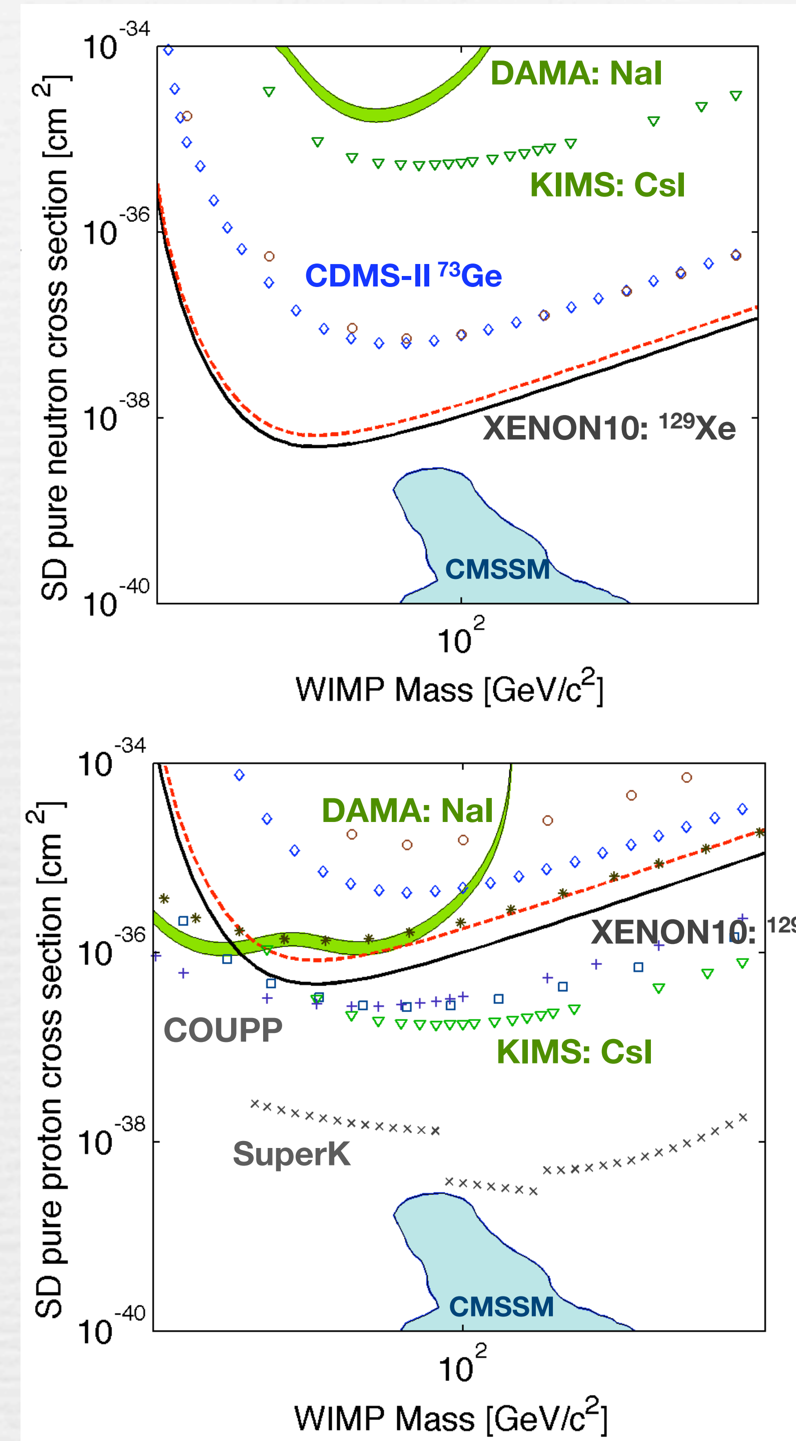
$(\sigma_n / \sigma_0 \sim (m_n^2/\mu^2)/A^2)$

Experimental results

10^{-7} pb →

10^{-8} pb →





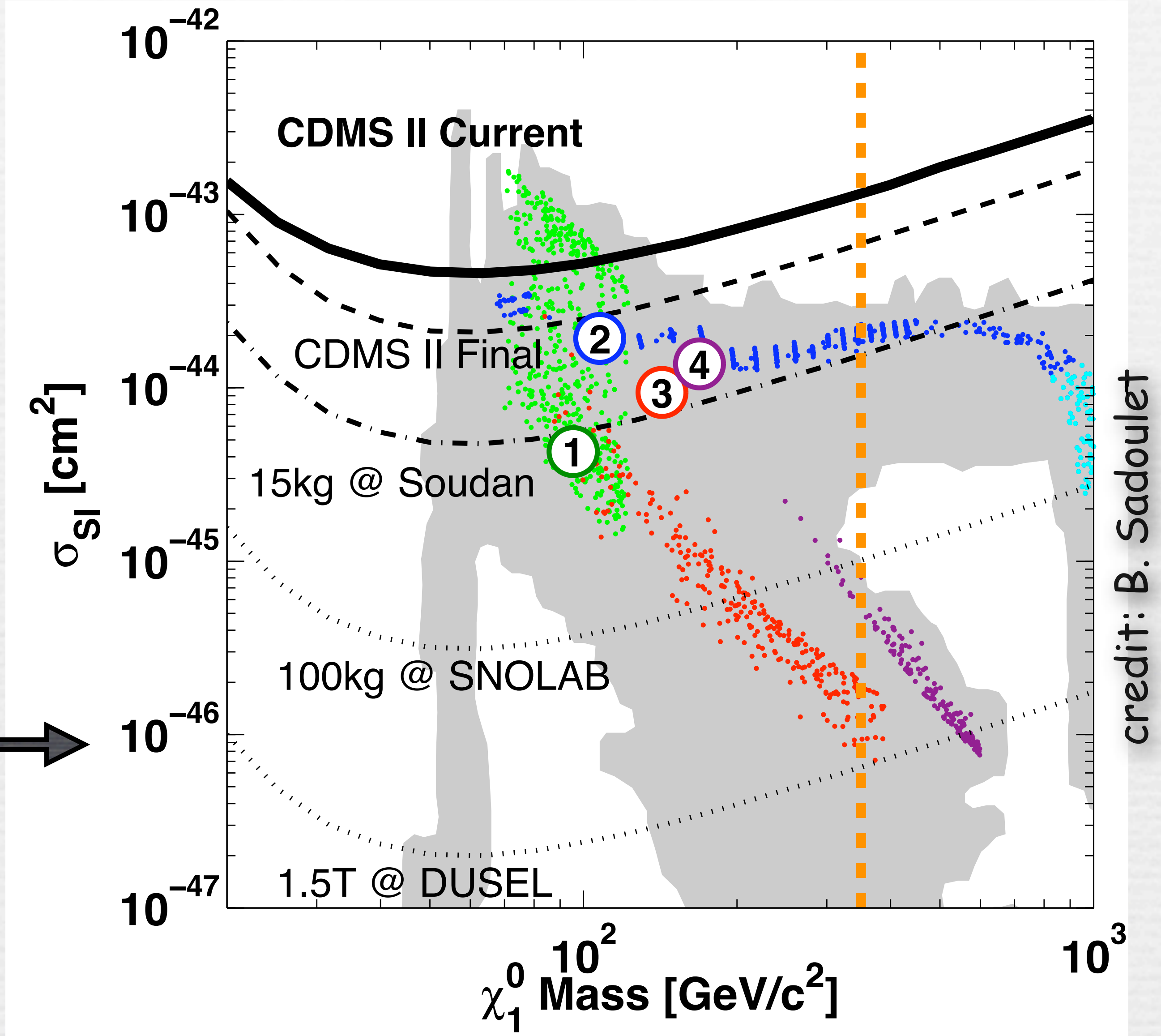
Spin-dependent

$\sigma_0^{SI} \sim A^2$, benefits from coherent scattering

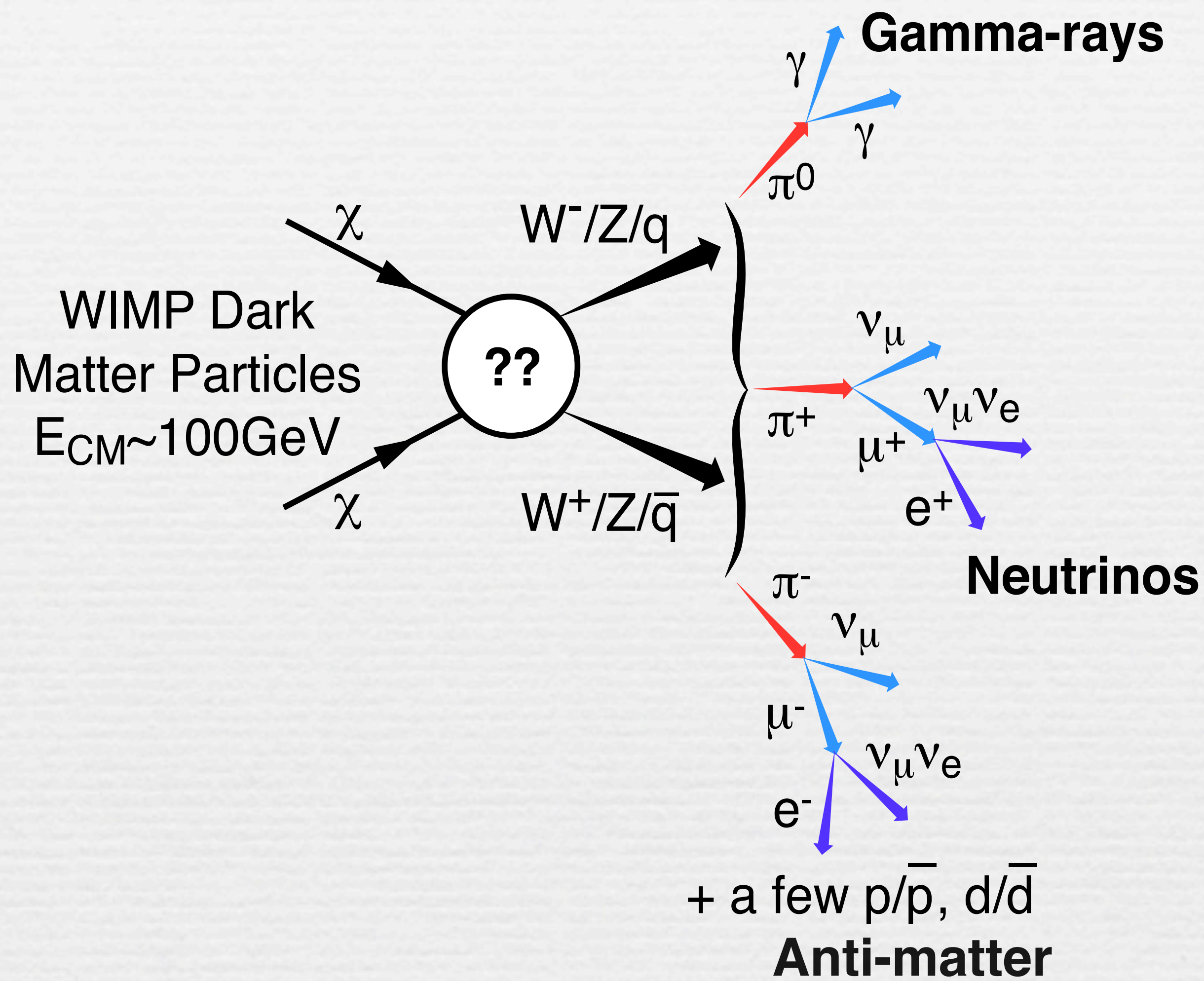
$\sigma_0^{SD} \sim J(J+1)$

Future prospects

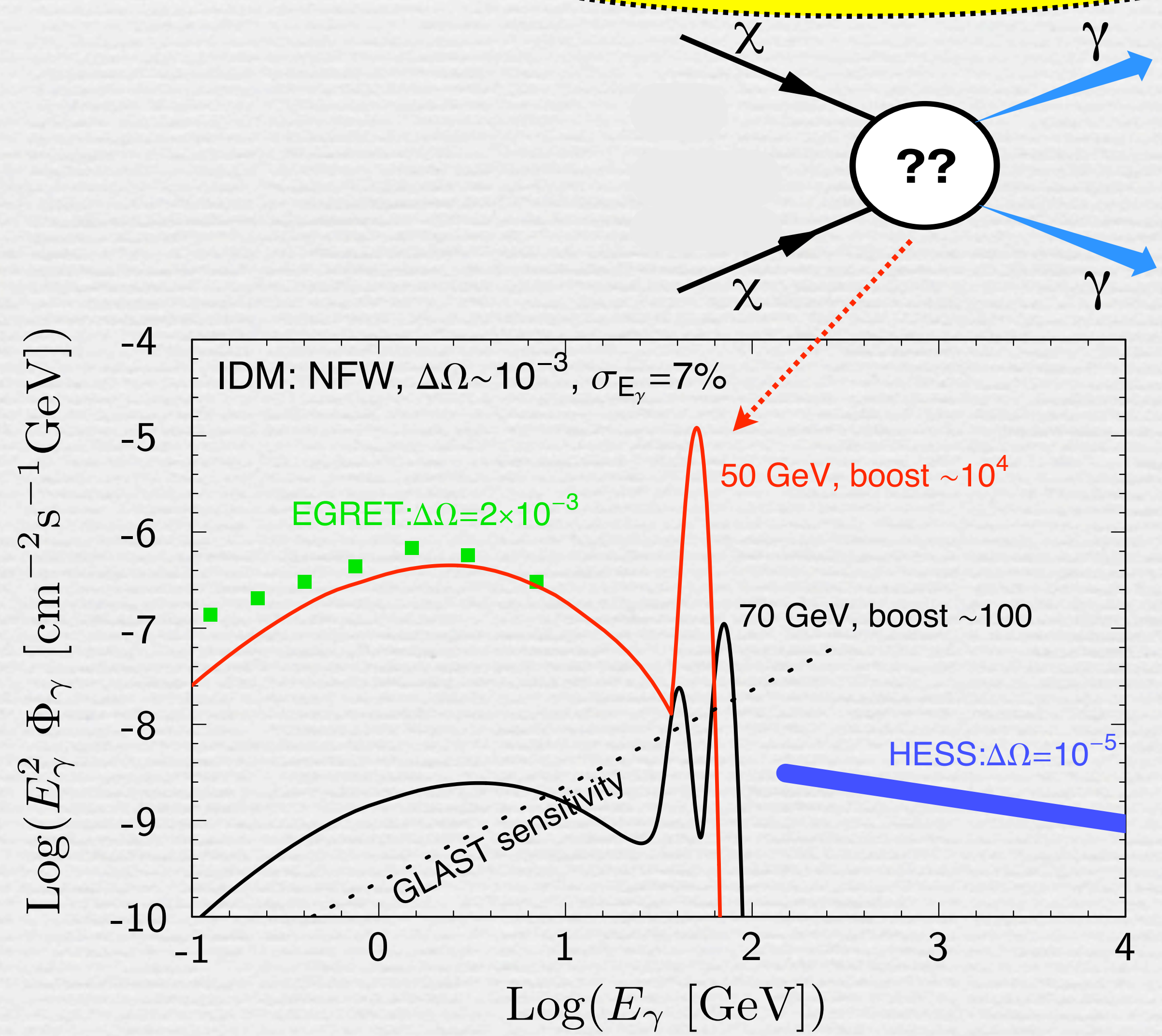
10^{-10} pb



WIMP indirect detection



smoking gun: gamma-ray line from direct anni into γγ or γZ



gamma-ray spectra (Inert doublet model)

WIMP indirect detection

number of annihilation events between two wimps from the local halo

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

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

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

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

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

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

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

Seeing the light from Dark Matter

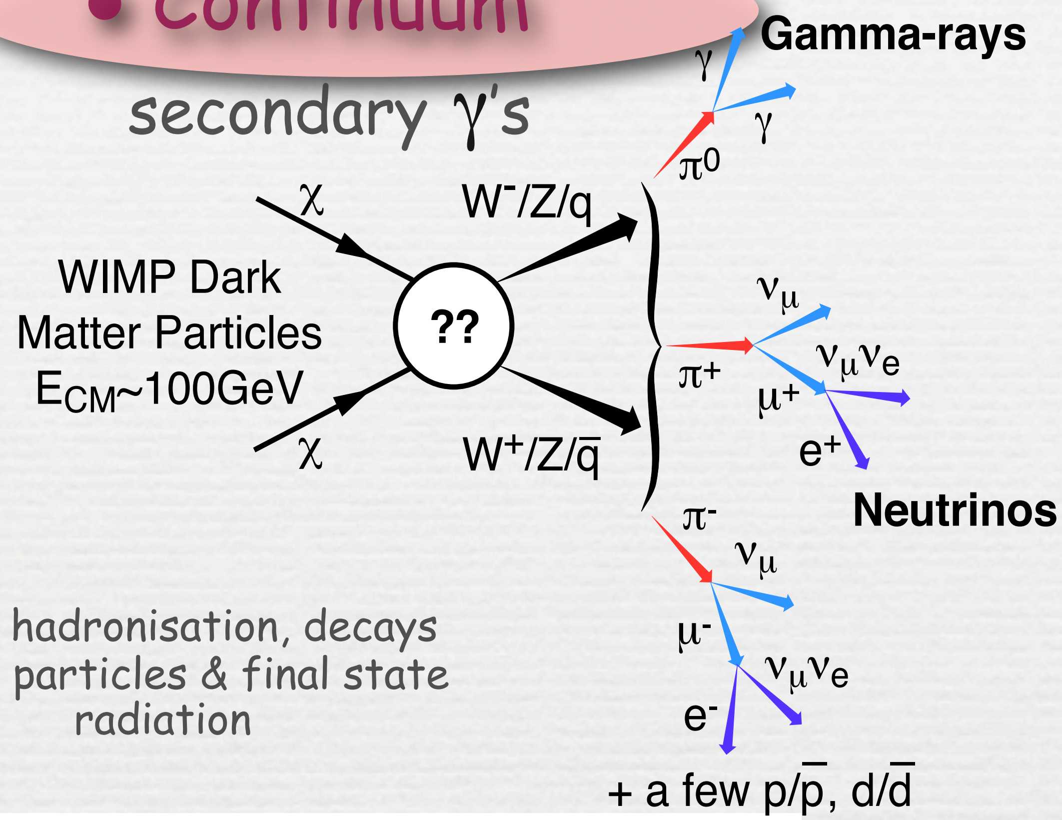
- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don't require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)

Seeing the light from Dark Matter

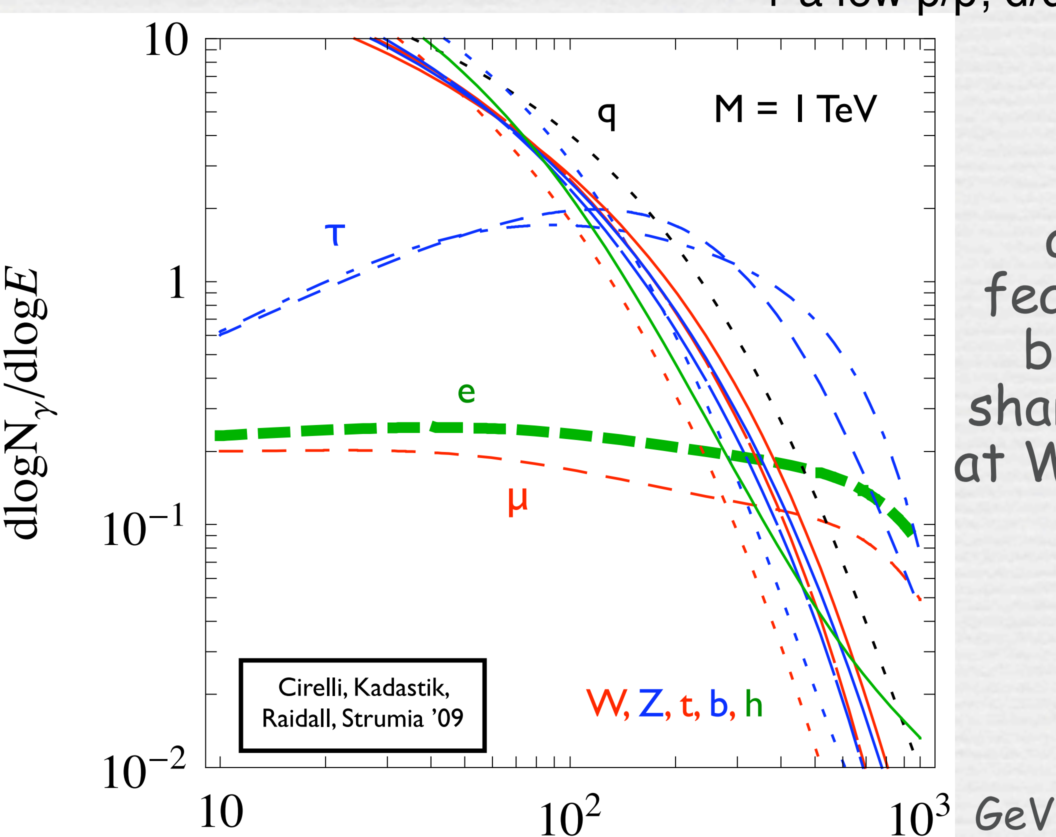
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



from hadronisation, decays of SM particles & final state radiation

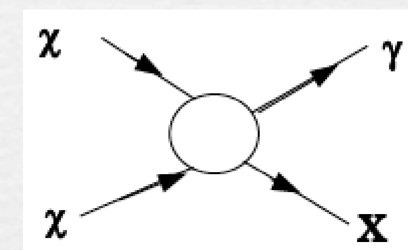


almost featureless but with sharp cutoff at Wimp mass

• 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

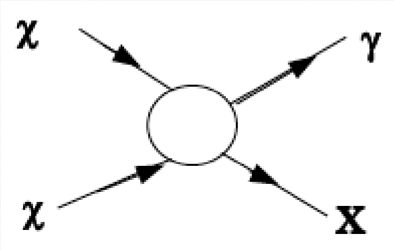
☹ lines are usually small (loop-suppressed) compared to continuum

Bergstrom, Ullio, Buckley '98

Seeing the light from Dark Matter

- What if the nature of DM is such that production of "direct" photons can be large?

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



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

→ 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]

Photon flux produced by DM annihilations

and collected from a region of angular size ΔΩ

$$\frac{d\Phi}{dE} = \frac{1}{4\pi} \frac{r_\odot \rho_\odot^2}{4M_{DM}^2} \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE} \int_{\Delta\Omega} d\Omega \int_{los} \frac{dl}{r_\odot} \left(\frac{\rho(r(l,\psi))}{\rho_\odot} \right)^2$$

includes all possible annihilation final states

$\equiv \bar{J}(\Delta\Omega)$

microphysics

astrophysics (halo profile)

Astrophysical uncertainties on the DM density profile

for DM decay:

* $\frac{\langle \sigma v \rangle}{4M_{DM}^2} \rightarrow \frac{1}{\tau M_{DM}}$

* $\rho^2 \rightarrow \rho$

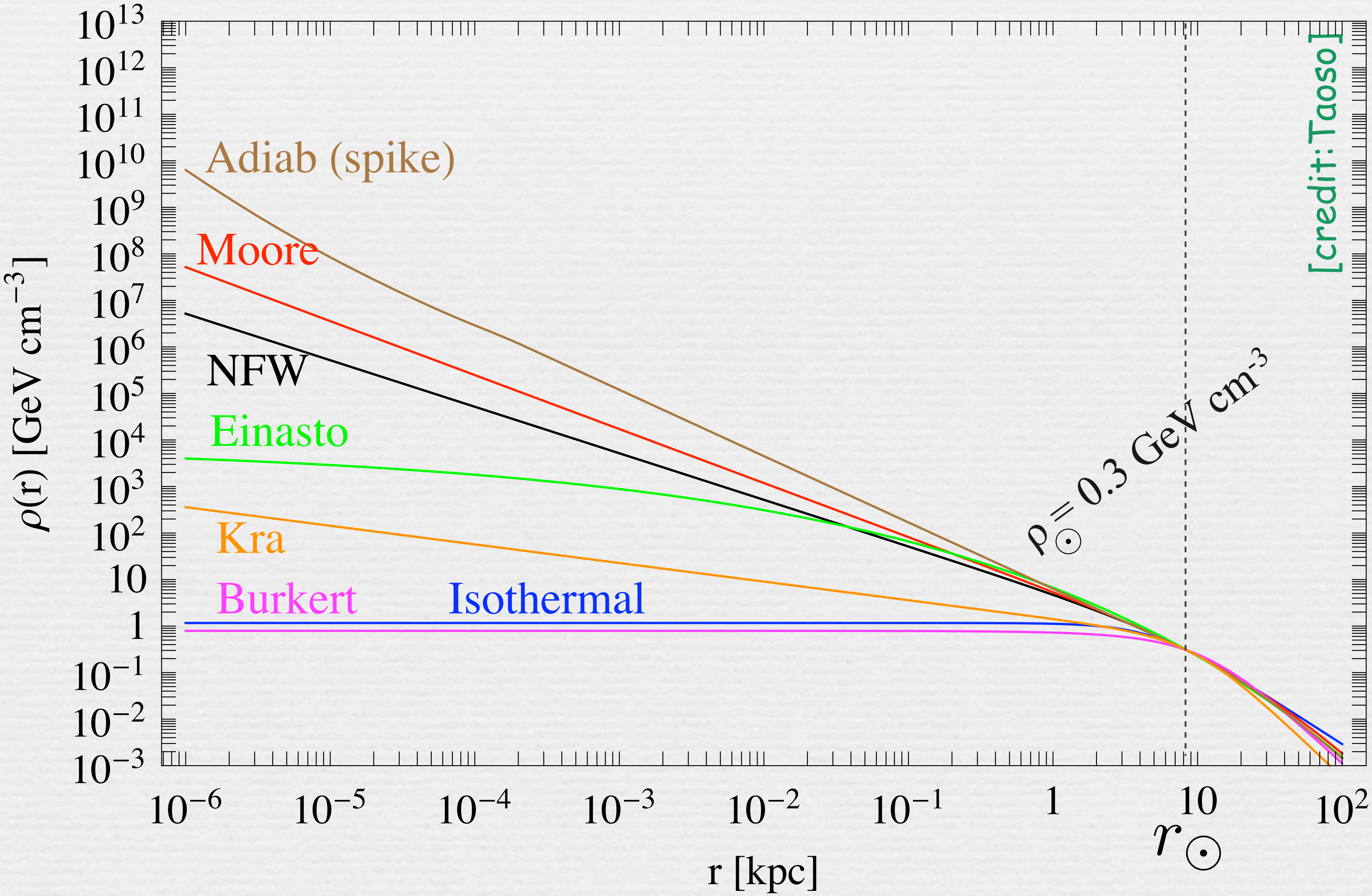
MW halo model	r_s in kpc	ρ_s in GeV/cm^3	$\bar{J}$ (10^{-5})
NFW [20]	20	0.26	$15 \cdot 10^3$
Einasto [21]	20	0.06	$7.6 \cdot 10^3$
Adiabatic[22]			$4.7 \cdot 10^7$

for observation of the galactic center region with angular acceptance ΔΩ=10^{-5}

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

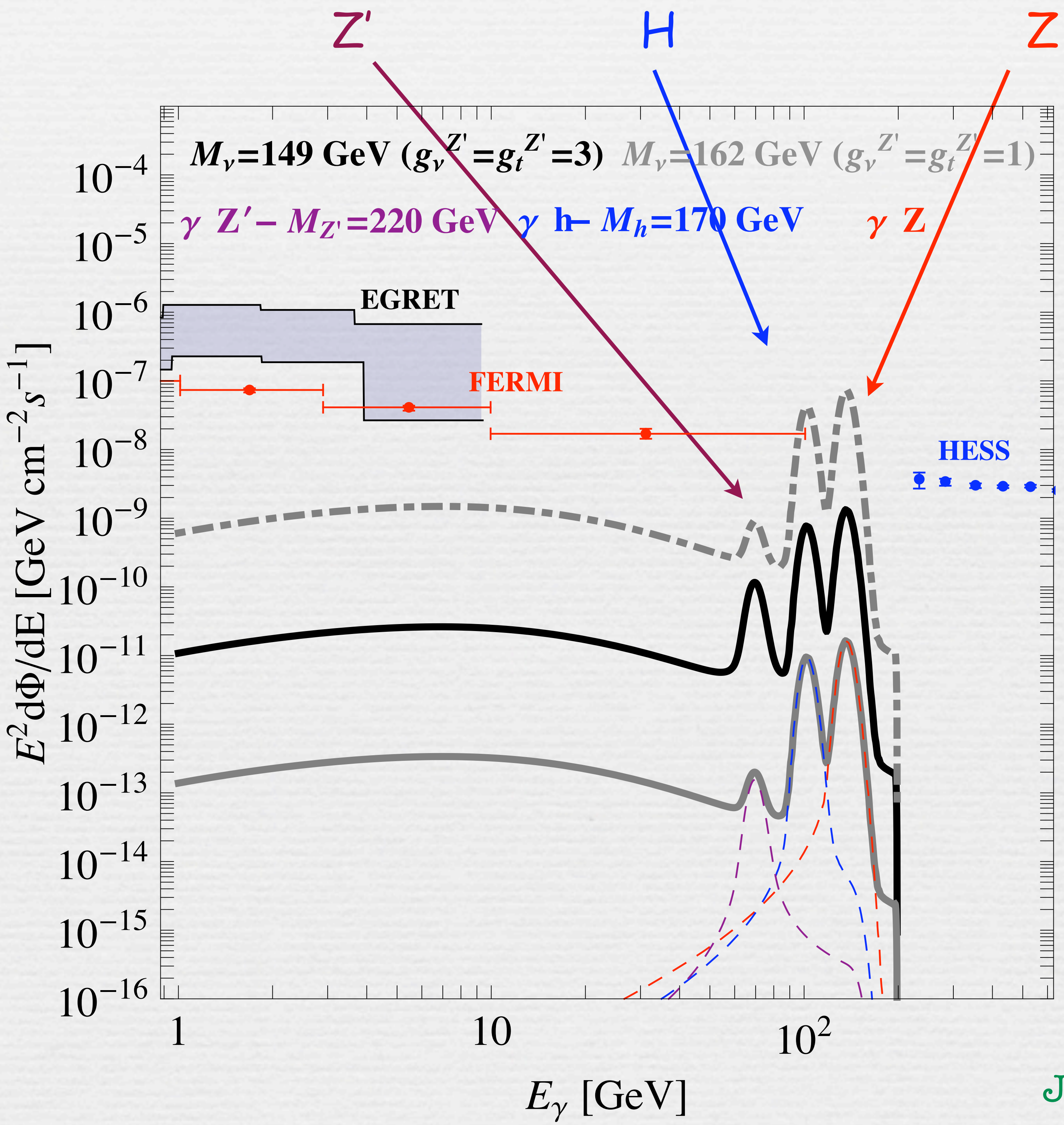
Searches focus on regions of the sky where DM clumps: Galactic Center, dwarf galaxies...

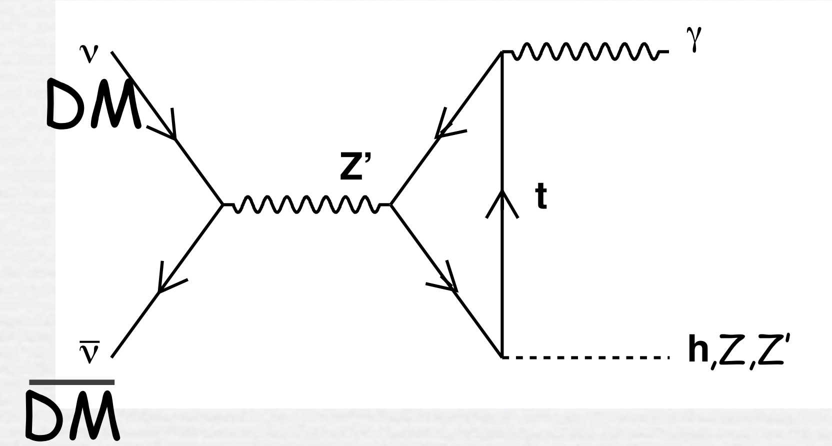
Astrophysical uncertainties on the DM density profile



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

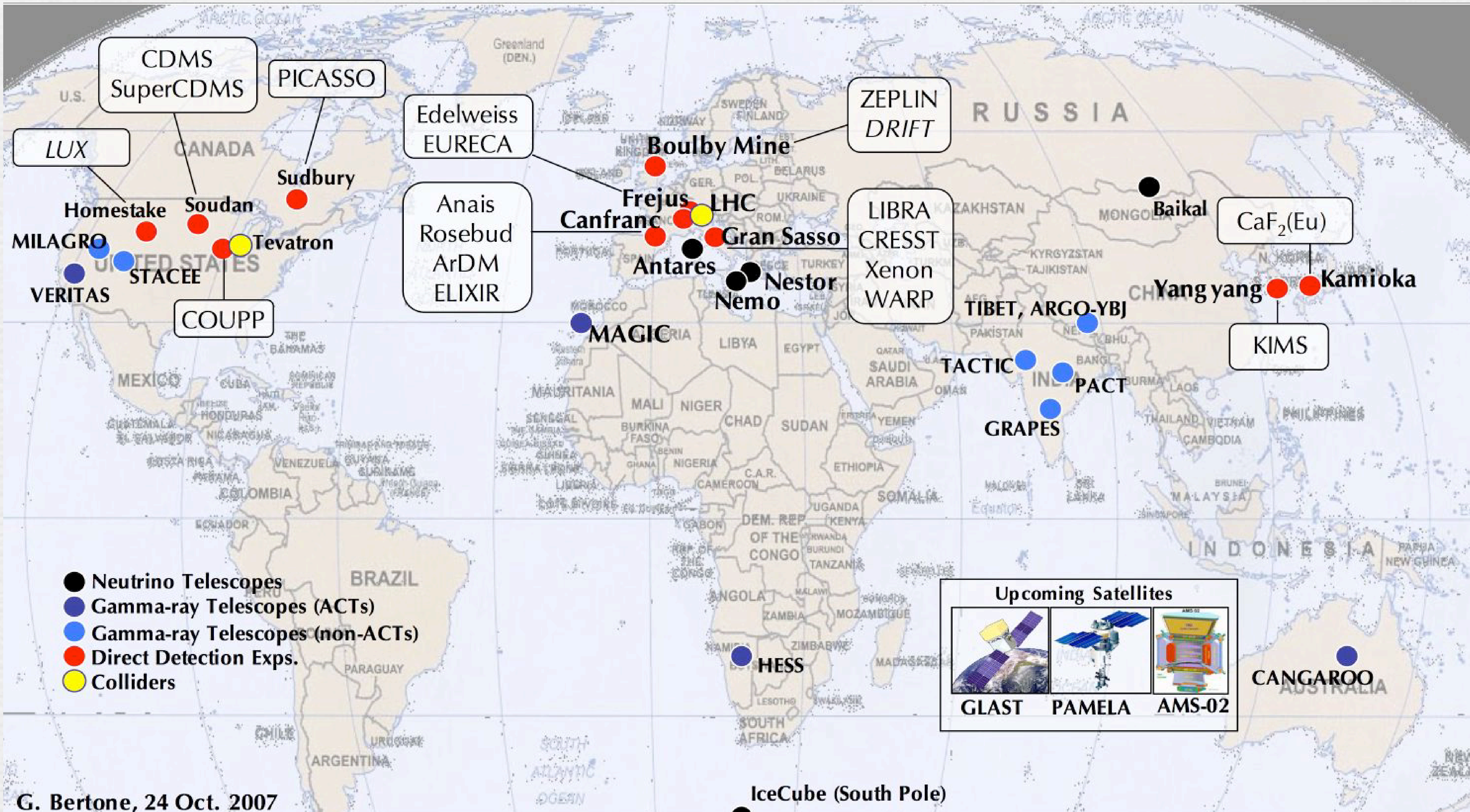
adiabatically contracted

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



Matter antimatter asymmetry

The universe we live in is made of matter (fortunately for us)

Where has the antimatter gone?

Matter Anti-matter asymmetry: Observational evidence

At the scale of the solar system: no concentration of antimatter otherwise its interaction with the solar wind would produce important source of γ's visible radiation

At the galactic scale: There is antimatter in the form of antiprotons in cosmic rays with ratio $n_{\overline{p}}/n_p \sim 10^{-4}$ which can be explained with processes such as

$$p + p \to 3p + \overline{p}$$

At the scale of galaxy clusters: we have not detected radiation coming from annihilation of matter and antimatter due to $p + \overline{p} \to \pi^0 ... \to . \gamma\gamma$

The asymmetry between matter and antimatter is characterized in terms of the baryon to photon ratio

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

The number of photons is not constant over the universe evolution. At early times, it is better to compare the baryon density to the entropy density since the n_B/s ratio takes a constant value as long as B is conserved and no entropy production takes place. Today, the conversion factor is

$$\frac{n_B - n_{\overline{B}}}{s} = \frac{\eta}{7.04}$$

Matter Anti-matter asymmetry:

characterized in terms of
the baryon to photon ratio

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

$\sim 6.\ 10^{-10}$

The great annihilation

10 000 000 001
Matter

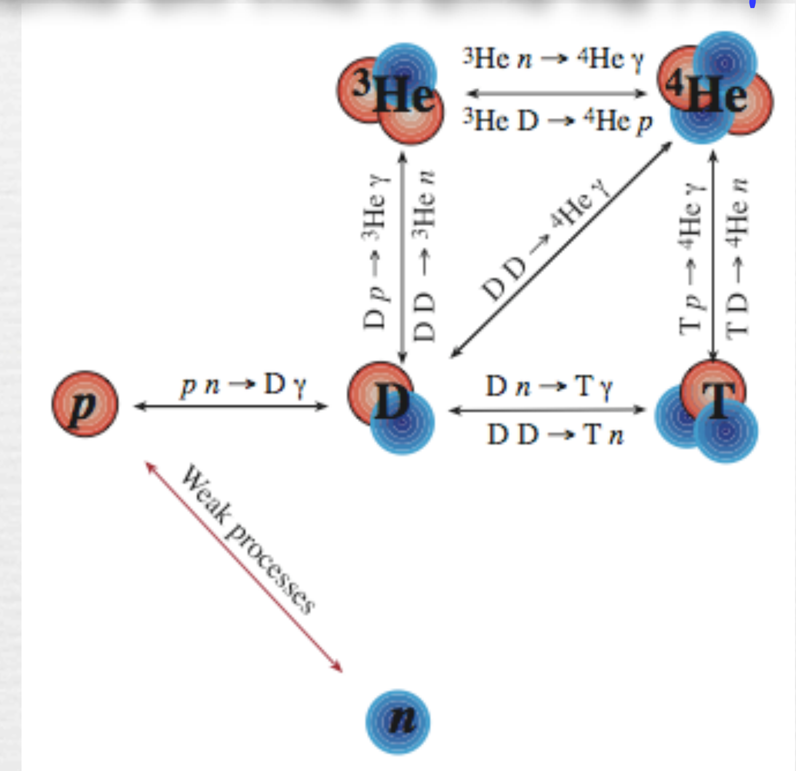
10 000 000 000
Anti-matter

1
(us)

How do we measure η ?

Counting baryons is difficult because only some fraction of them formed stars and luminous objects. However, there are two indirect probes:

1) Big Bang Nucleosynthesis predictions depend on the ratio n_B / n_γ



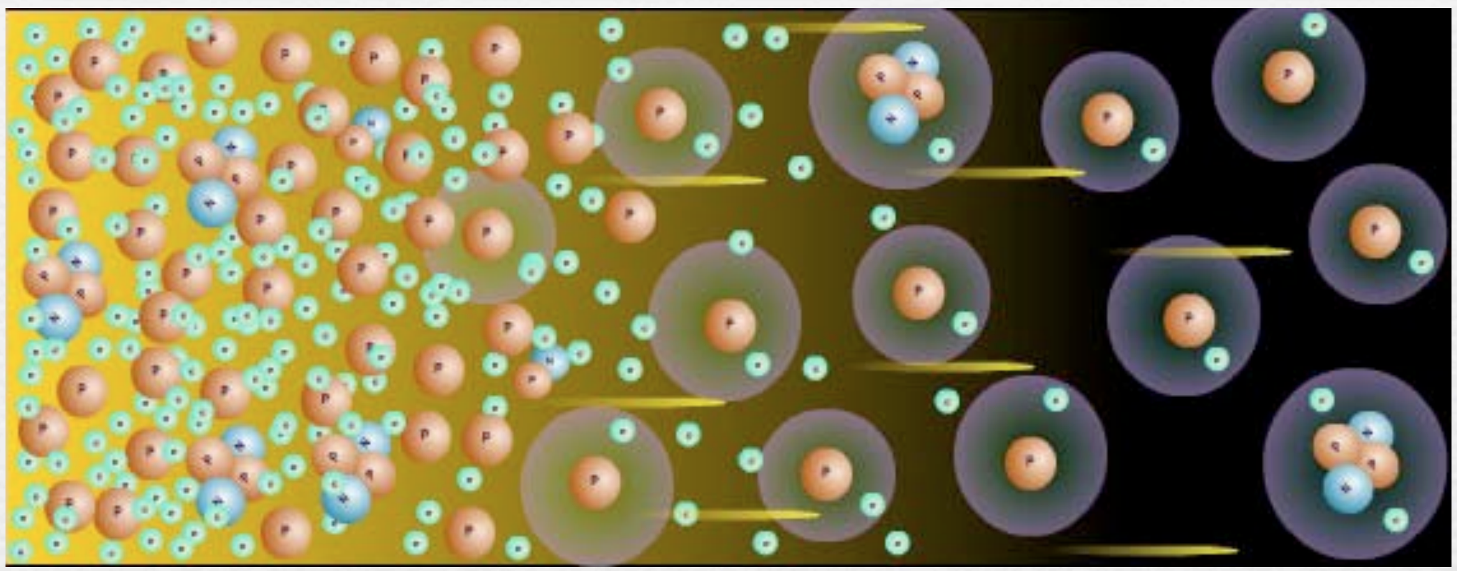
Many more photons than baryons delays BBN by enhancing the reaction D γ →pn

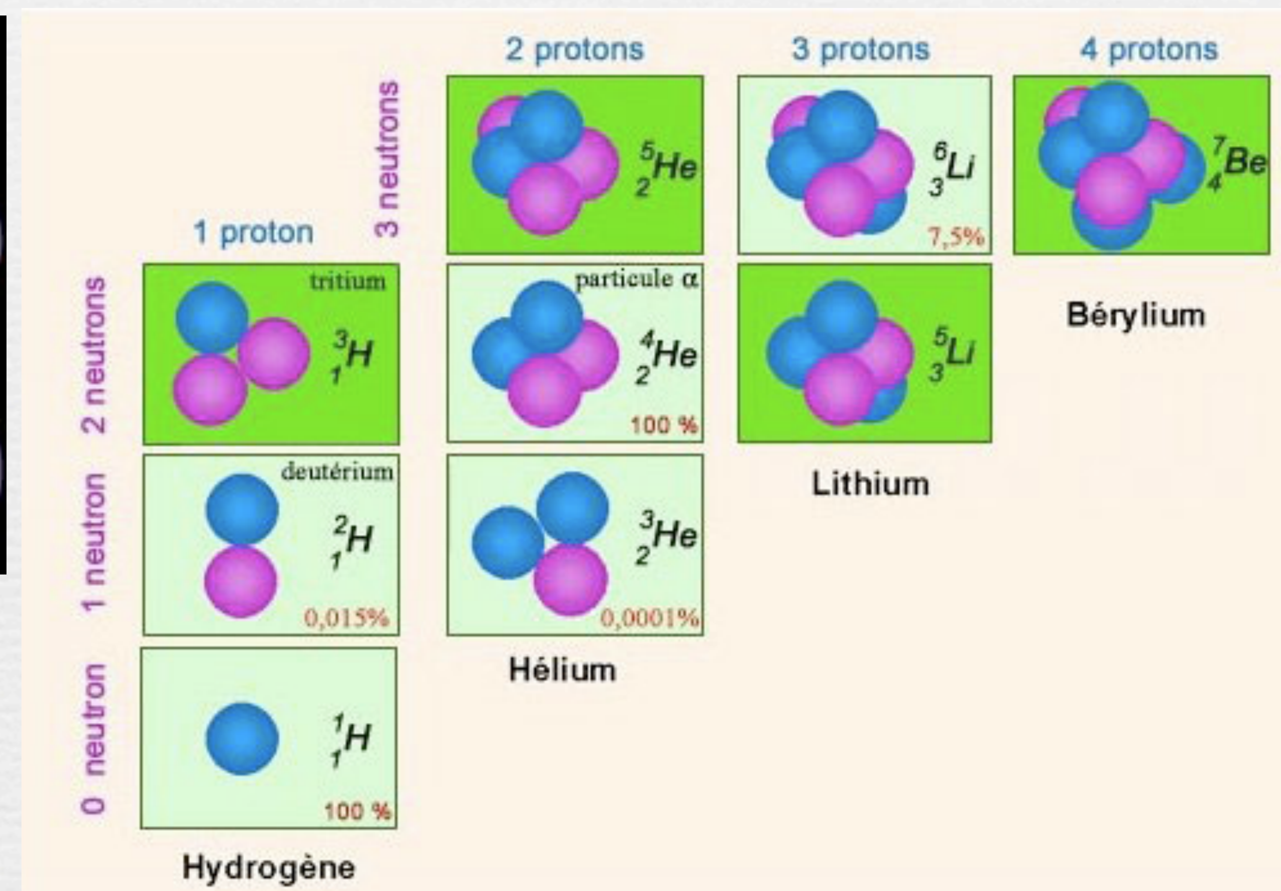
2) Measurements of CMB anisotropies

probe acoustic oscillations of the baryon/photon fluid

The amount of anisotropies depend on n_B / n_γ

The abundance of light elements (deuterium, helium, lithium) strongly depends on the amount of protons and neutrons in the primordial universe.

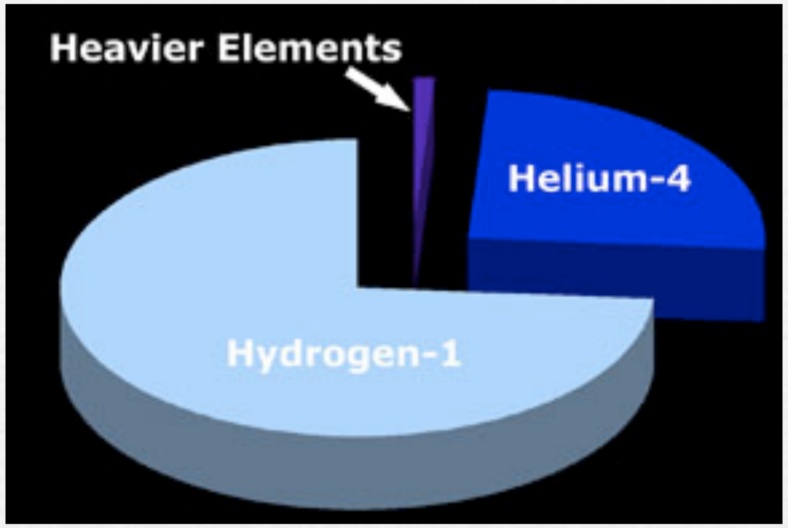


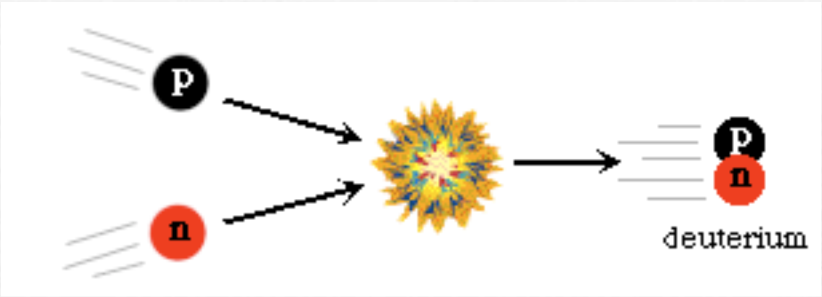


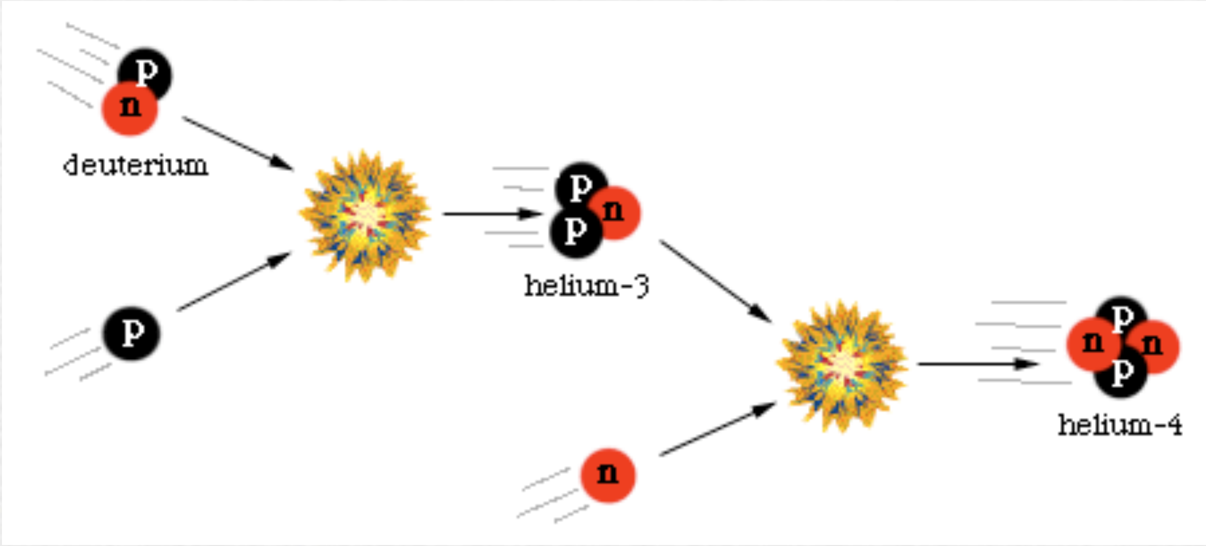
at t<1 s

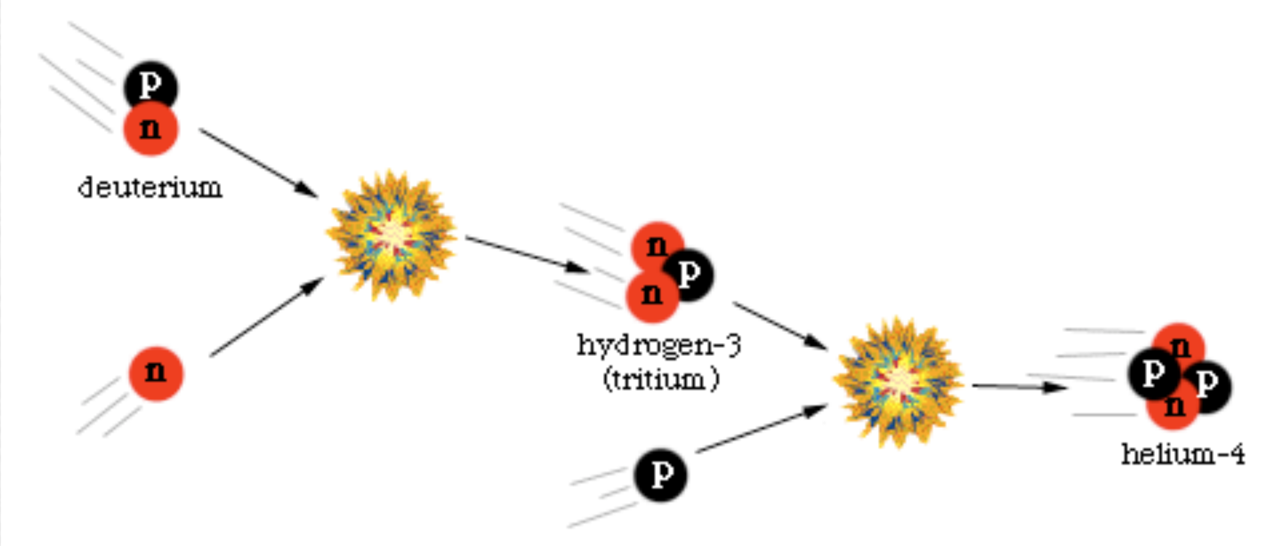
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \nu_e$$
$$n \leftrightarrow p + e^- + \overline{\nu_e}$$

Primordial nucleosynthesis







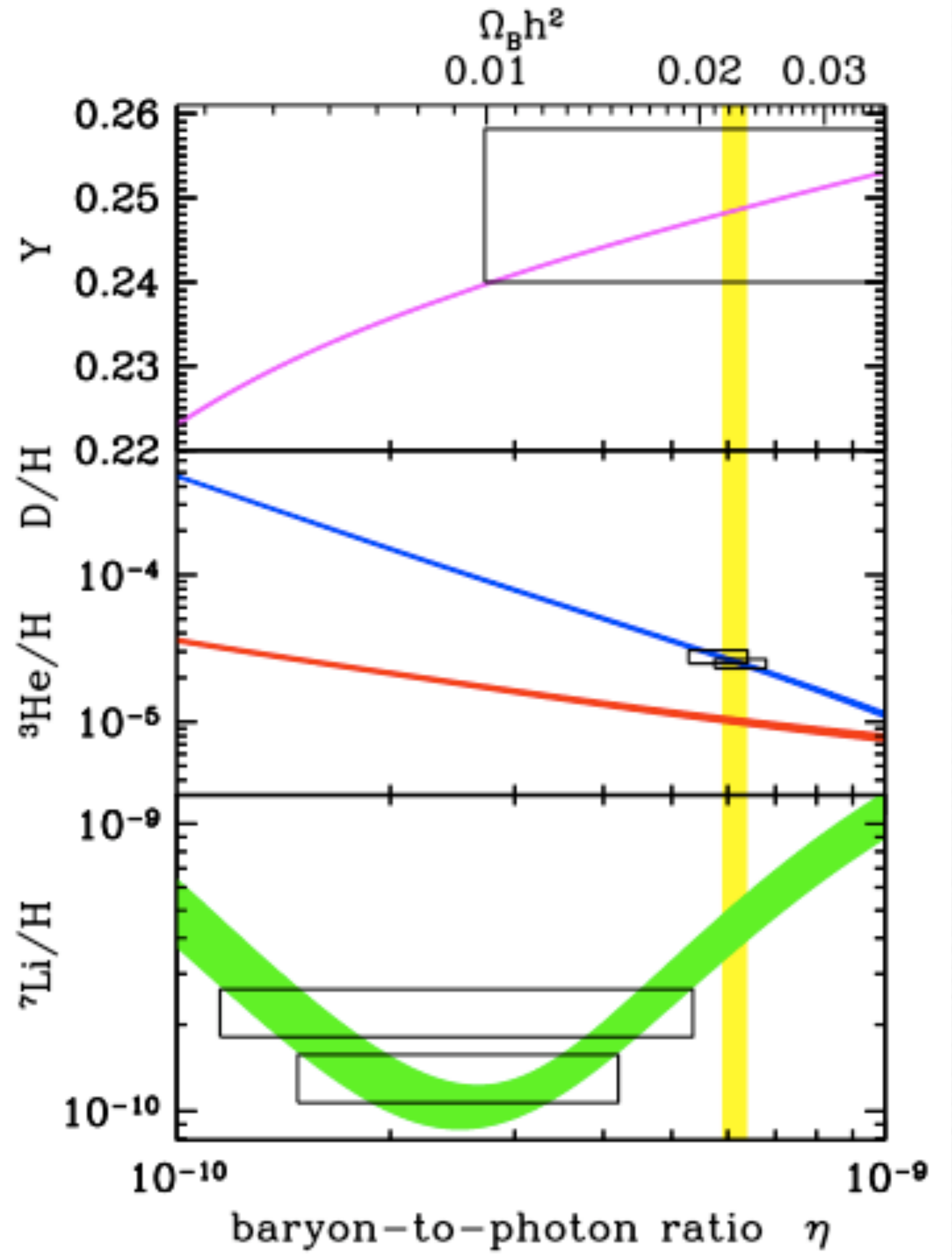


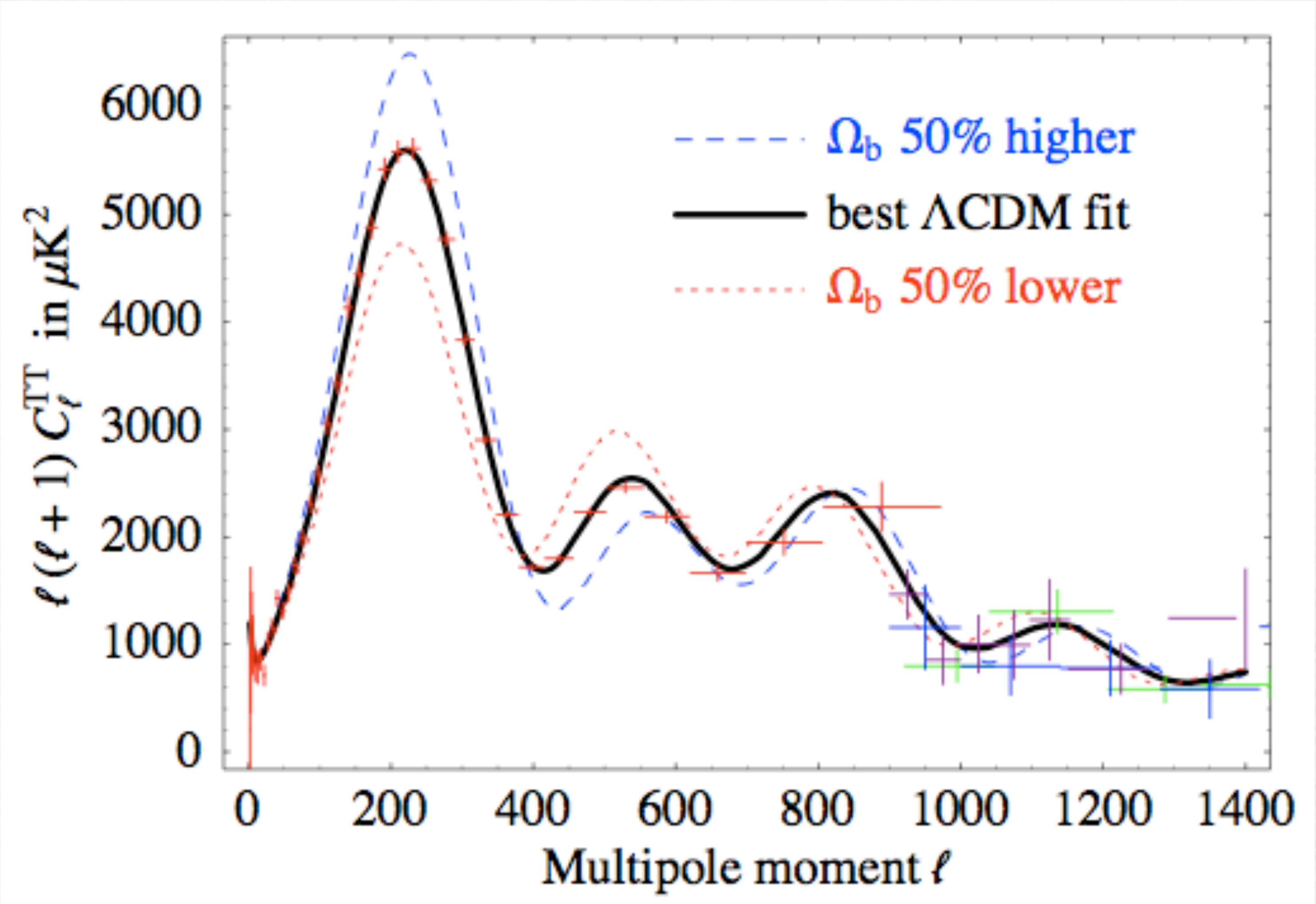
$$
\begin{array}{ccc}
\mathrm{p}+\mathrm{n} & \longrightarrow & \mathrm{D}+\gamma \\
\mathrm{D}+\mathrm{n} & \longrightarrow & {}^3\mathrm{H}+\gamma \\
\mathrm{D}+\mathrm{p} & \longrightarrow & {}^3\mathrm{He}+\gamma \\
\mathrm{D}+\mathrm{D} & \longrightarrow & {}^3\mathrm{H}+\mathrm{p} \\
\mathrm{D}+\mathrm{D} & \longrightarrow & {}^3\mathrm{He}+\mathrm{n} \\
\mathrm{D}+\mathrm{D} & \longrightarrow & {}^4\mathrm{He}+\gamma \\
{}^3\mathrm{H}+\mathrm{p} & \longrightarrow & {}^4\mathrm{He}+\gamma \\
{}^3\mathrm{He}+\mathrm{n} & \longrightarrow & {}^3\mathrm{H}+\mathrm{p} \\
{}^3\mathrm{He}+\mathrm{n} & \longrightarrow & {}^4\mathrm{He}+\gamma \\
{}^3\mathrm{H}+\mathrm{D} & \longrightarrow & {}^4\mathrm{He}+\mathrm{n} \\
{}^3\mathrm{He}+\mathrm{D} & \longrightarrow & {}^4\mathrm{He}+\mathrm{p} \\
{}^3\mathrm{He}+{}^3\mathrm{He} & \longrightarrow & {}^4\mathrm{He}+2\mathrm{p} \\
{}^4\mathrm{He}+\mathrm{D} & \longrightarrow & {}^6\mathrm{Li}+\gamma \\
{}^4\mathrm{He}+{}^3\mathrm{H} & \longrightarrow & {}^7\mathrm{Li}+\gamma \\
{}^4\mathrm{He}+{}^3\mathrm{He} & \longrightarrow & {}^7\mathrm{Be}+\gamma \\
{}^6\mathrm{Li}+\mathrm{n} & \longrightarrow & {}^7\mathrm{Li}+\gamma \\
{}^6\mathrm{Li}+\mathrm{p} & \longrightarrow & {}^7\mathrm{Be}+\gamma \\
{}^7\mathrm{Li}+\mathrm{p} & \longrightarrow & {}^4\mathrm{He}+\gamma \\
{}^7\mathrm{Be}+\mathrm{n} & \longrightarrow & {}^7\mathrm{Li}+\mathrm{p} \\
{}^7\mathrm{Be}+\mathrm{e}^- & \longrightarrow & {}^7\mathrm{Li}+\gamma
\end{array}
$$

Primordial abundances versus η

Dependence of the CMB Doppler peaks on η

(CMB temperature fluctuations)





$$\eta = 10^{-10} \times \begin{cases} 6.28 \pm 0.35 \\ 5.92 \pm 0.56 \end{cases}$$

$$\eta = 10^{-10} \times (6.14 \pm 0.25)$$

$$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$$

baryons: only a few percents of the total energy density of the universe

How much baryons would there be in a symmetric universe?

nucleon and anti-nucleon densities are maintained by annihilation processes

$$n + \overline{n} \longleftrightarrow \pi + \pi \longleftrightarrow \gamma + \gamma + \ldots$$

which become ineffective when

$$\Gamma \sim n_N / m_\pi^2 \sim H$$

leading to a freeze-out temperature

$$T_F \sim 20 \text{ MeV}$$

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

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
(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)

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

Need to go out of 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

Need for

-> Long-lived particles decays out of equilibrium

-> first-order phase transitions

Why can't we achieve baryogenesis in the Standard Model?

B is violated

C and CP are violated

but which out-of-equilibrium condition?

no heavy particle which could decay out-of-equilibrium

no strong first-order phase transition

Electroweak phase transition is a smooth cross over

Also, CP violation is too small (suppressed by the small quark masses, remember there is no CP violation if quark masses vanish)

B violation

If B was conserved : ⇛ To explain η we would have to impose arbitrary and extremely fine-tuned initial value for B, while a plausible guess is rather : $B_i = L_i = 0$ (as the total electric charge appears to be)

Any baryon asymmetry existing before inflation is diluted away and we have to produce the baryon asymmetry between the time of reheating and the time of the electroweak phase transition

⇛ Some mechanism must exist to separate baryons and antibaryons on scales larger than galaxy clusters (otherwise we would have detected gamma rays resulting from annihilation of matter and antimatter)

$$p + \overline{p} \rightarrow \pi^0 \ldots \rightarrow \gamma\gamma$$

CP violation

Let M(i->j) be the amplitude for a transition from a state i to a state j, and let $\bar{i}$ be the state obtained by applying a CP transformation to i. Then the CPT theorem implies:

$$\mathcal{M}(i \to j) = \mathcal{M}(\bar{j} \to \bar{i}) \qquad \text{(CPT invariance)}$$

CP invariance (and hence, by CPT, T invariance) demands:

$$\boxed{\mathcal{M}(i \to j) = \mathcal{M}(\bar{i} \to \bar{j}) = \mathcal{M}(j \to i)} \qquad \text{(CP invariance)}$$

The requirement of unitarity yields:

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to i)|^2 \qquad \text{(unitarity)}$$

The sum over j includes states and antistates:

$$\sum_j |\mathcal{M}(i \to j)|^2 = \boxed{\sum_j |\mathcal{M}(j \to \bar{i})|^2 = \sum_j |\mathcal{M}(j \to i)|^2} \qquad \text{(CPT+unitarity)}$$

In thermal equilibrium, interactions produce i and $\bar{i}$ in equal numbers. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be destroyed by interactions

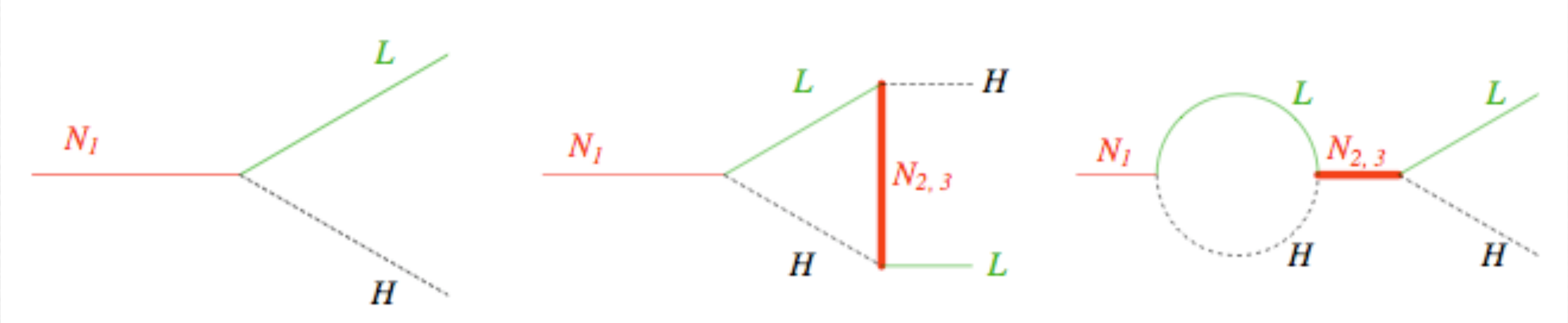
Leptogenesis

Fukugita, Yanagida

nicely connected to the explanation of neutrino masses

Majorana neutrino masses violate L and presumably CP

1) Generate L from the direct CP violation in RH neutrino decay



2) L gets converted to B by the electroweak anomaly

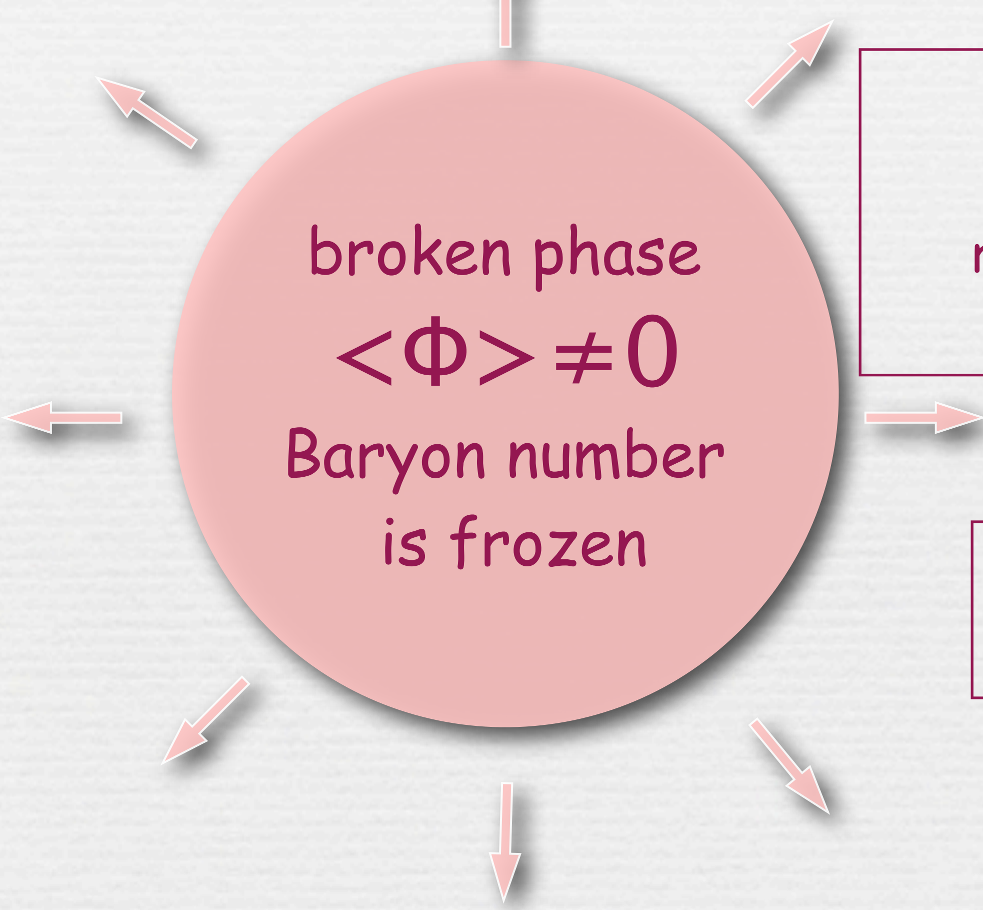
Out of equilibrium condition: $H > \Gamma \sim \lambda^2 M_1/(8\pi)$

at $T \sim M_1$, this leads to $\lambda v^2/M_1 < (8\pi)\, v^2/M_{Pl} \sim \mathrm{meV}$

see-saw formula for m_ν

Baryon asymmetry and the Fermi scale

1) nucleation and expansion of bubbles of broken phase



2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux in front of the wall

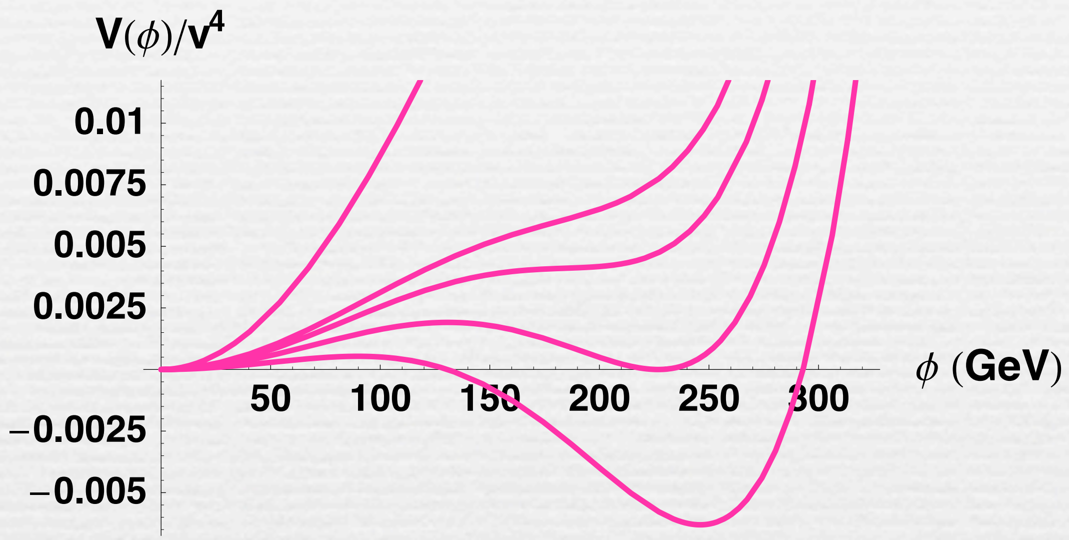
3) In symmetric phase, $<\Phi>=0$, very active sphalerons convert chiral asymmetry into baryon asymmetry

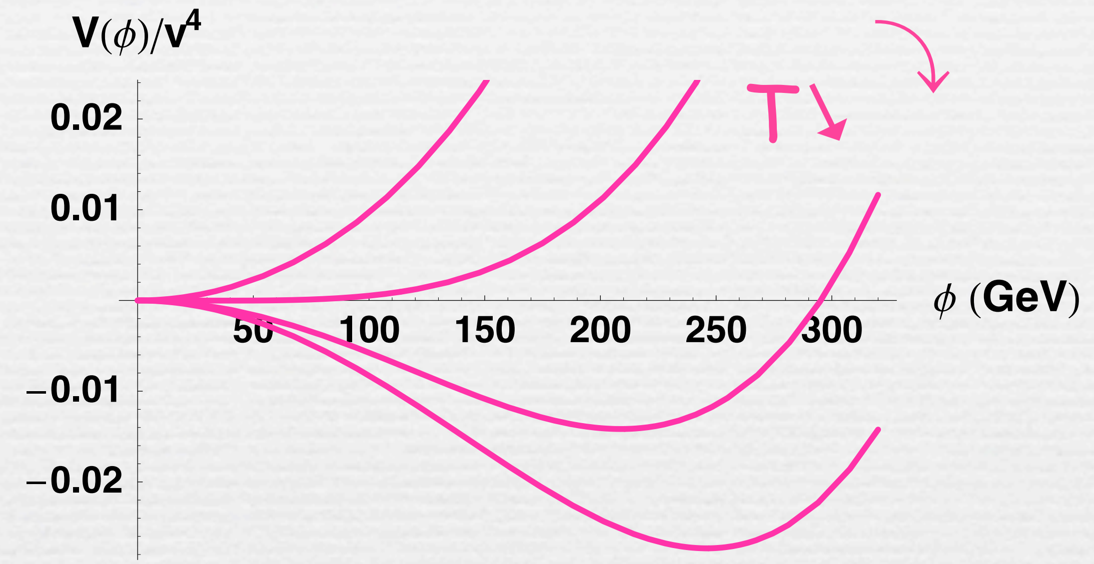
Electroweak baryogenesis mechanism relies on a first-order phase transition

What is the nature of the electroweak phase transition?

Work out the nature of the electroweak phase transition

first-order or second-order?





indispensable for reliable computations of the baryon asymmetry

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...)

Beyond the beaten paths

Dirac Leptogenesis

Lindner et al '99;
Murayama & Pierce '02

No need to violate Lepton number for leptogenesis !
and leptogenesis can be achieved with Dirac neutrinos

Disadvantage: no obvious relationship between the mechanism responsible for the generation of the lepton asymmetry and the smallness of neutrino masses

Like in traditional leptogenesis, assume the CP-violating decay of a heavy particle into leptons

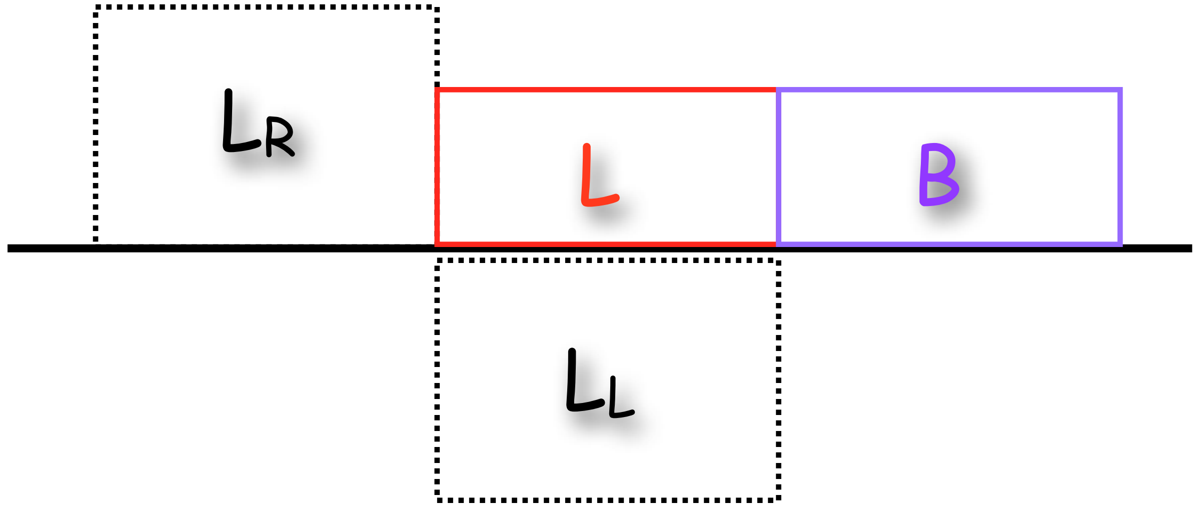
-> results in a non-zero lepton number for LH particles and an equal and opposite lepton number for RH particles :

$$n_R - n_{\overline{R}} = n_{\overline{L}} - n_L$$

For most SM species, Yukawa interactions between the LH and RH particles are sufficiently strong to cancel these two stores of lepton number rapidly

Only Lepton number in LH sector is processed into baryon number by sphalerons

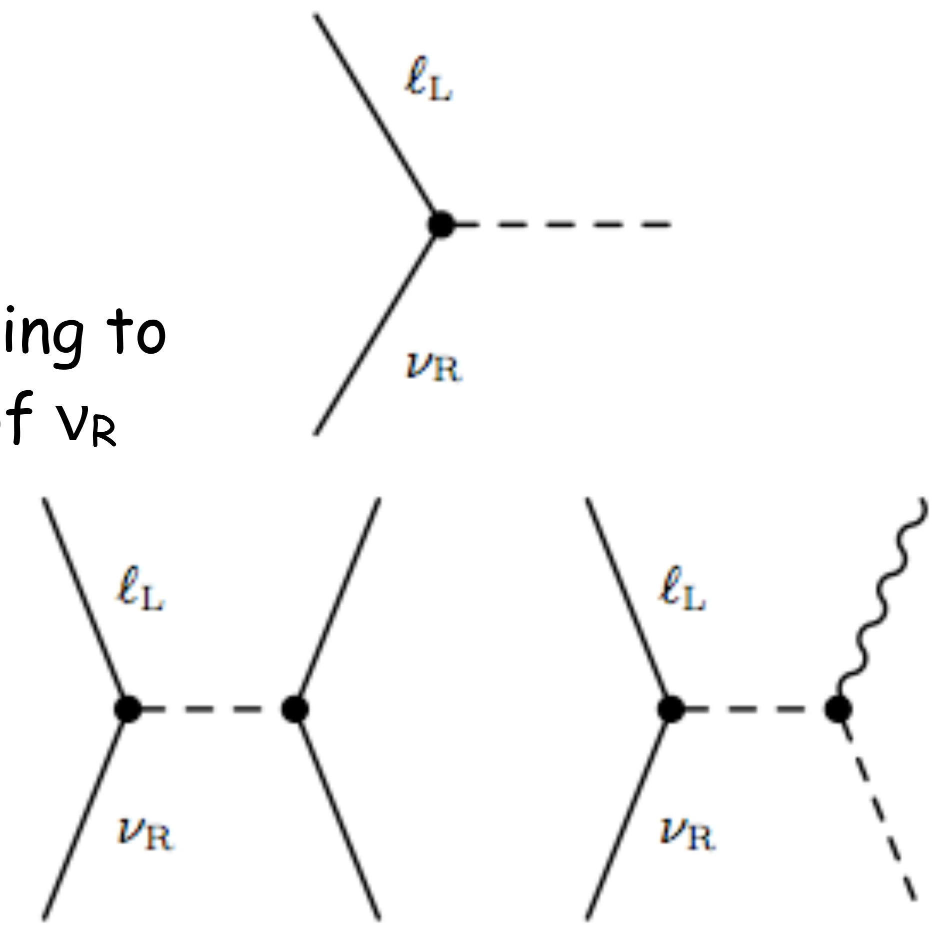
However, the interactions of ν_R are exceedingly weak and equilibrium between LH lepton number and RH lepton number will not be reached until T << weak scale



$$n_B = n_L = -\frac{28}{79} n_{\nu_R}$$

$$\begin{aligned} S &\leftrightarrow 3q + \ell \\ \phi &\leftrightarrow q + \bar{u} \\ \bar{\phi} &\leftrightarrow q + \bar{d} \\ \bar{\phi} &\leftrightarrow \ell + \bar{e} \end{aligned}$$

Processes contributing to the equilibration of ν_R



$$\Gamma \sim \lambda^2 g^2 T$$

Condition for non-equilibration

$\Gamma \lesssim H \sim T^2/M_{Pl}$

$\longrightarrow$ $\lambda \lesssim \sqrt{(T_c / M_{Pl})} \sim 10^{-8}$

T_c : T at electroweak phase transition

$m \sim \lambda\, T_c \lesssim 1$ keV

related idea:
baryogenesis without B-L violation

see Gonzales-Garcia, Racker & Rius 0909.3518

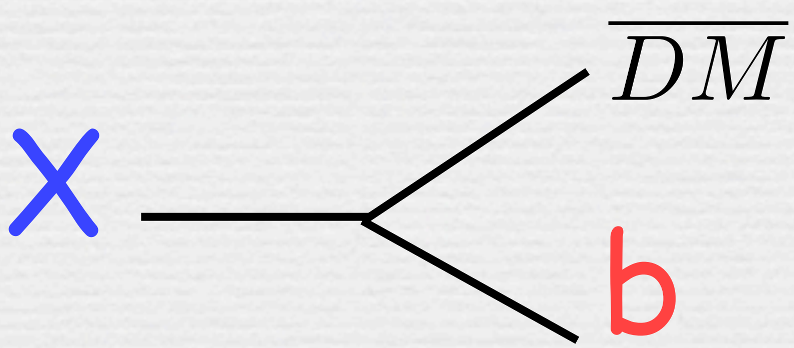
Baryogenesis without $\cancel{B}$ nor $\cancel{L}$ nor $C\cancel{P}T$

Possible if dark matter carries baryon number !

Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254

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!

naturally arises in warped GUTs where
DM is a heavy RH neutrino carrying baryon number



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

A unified explanation for DM and baryogenesis !
can also explain the coincidence $\Omega_b \approx \frac{1}{6}\Omega_m$

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

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

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

$$X \to \overline{DM} + b$$

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 $\bar{b}$:

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

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

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

Back to electroweak baryogenesis

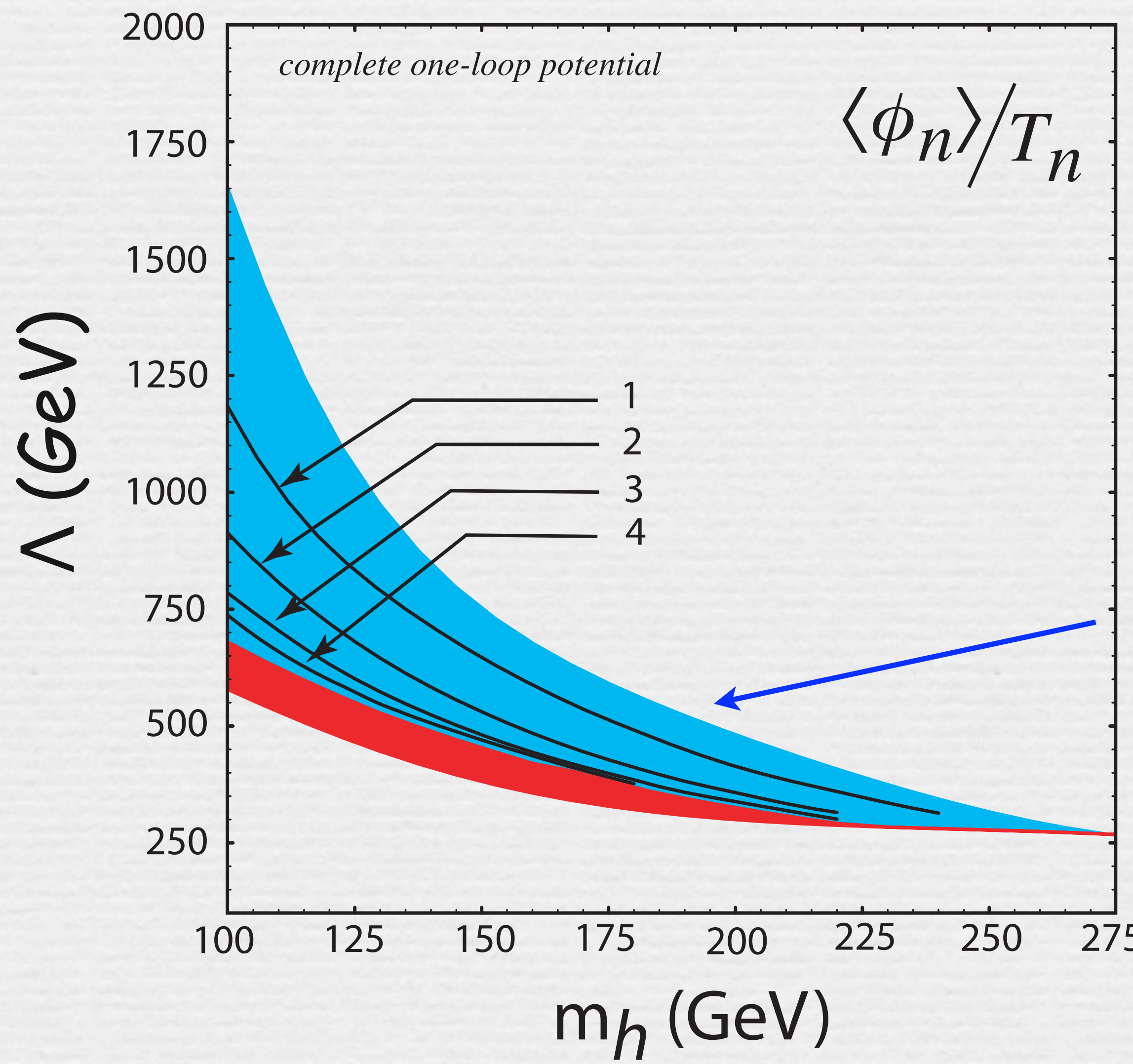
Effective field theory approach

add a non-renormalizable Φ^6 term to the SM Higgs potential and allow a negative quartic coupling

$$V(\Phi) = \mu_h^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{|\Phi|^6}{\Lambda^2}$$

"strength" of the transition does not rely on the one-loop thermally generated negative self cubic Higgs coupling

strong enough
for EW baryogenesis
if $\Lambda \lesssim 1.3$ TeV



region where EW phase transition is 1st order

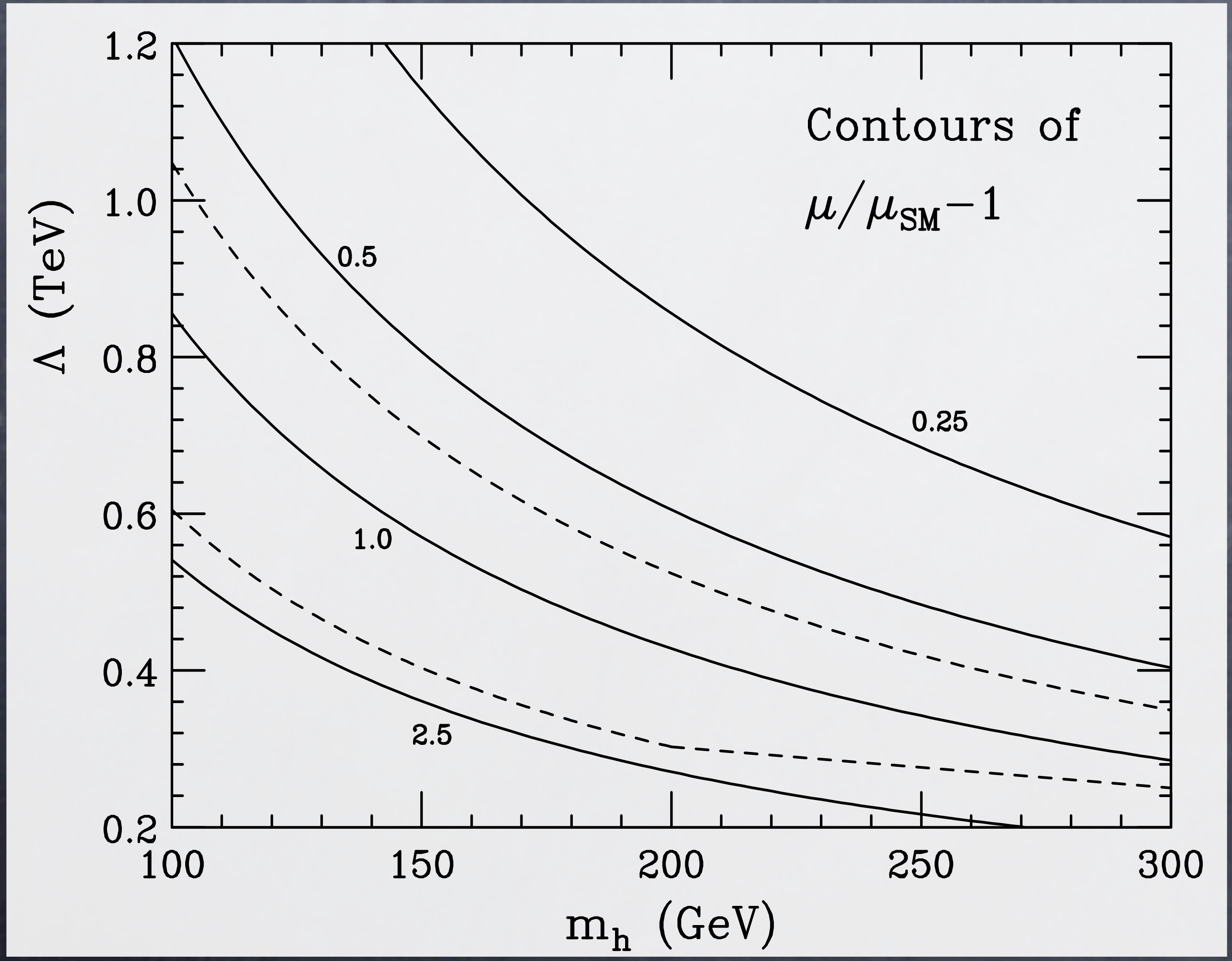
Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

This scenario predicts large deviations to the Higgs self-couplings

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

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

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

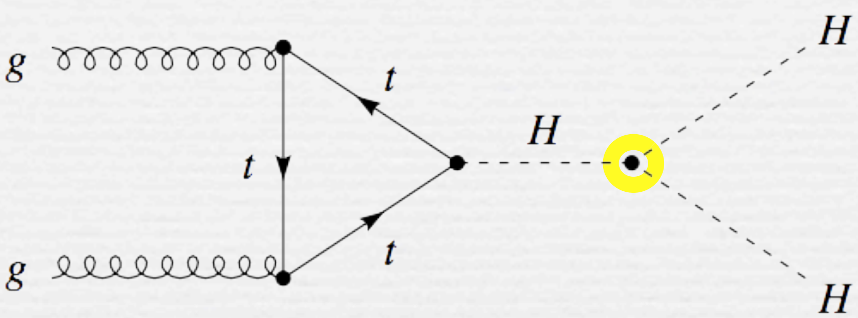


The dotted lines delimit the region for a strong 1rst order phase transition

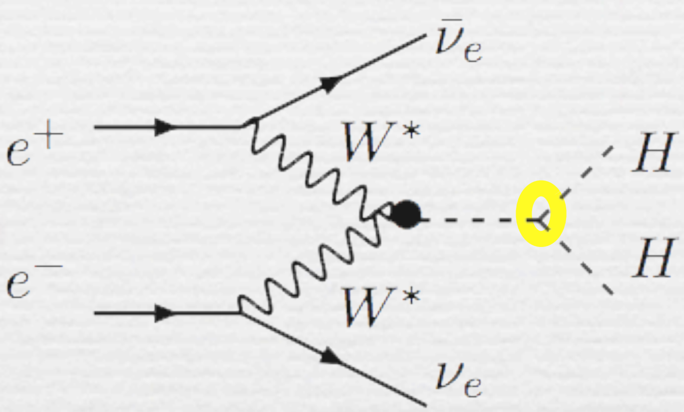
deviations between a factor 0.7 and 2

Experimental tests of the Higgs self-coupling

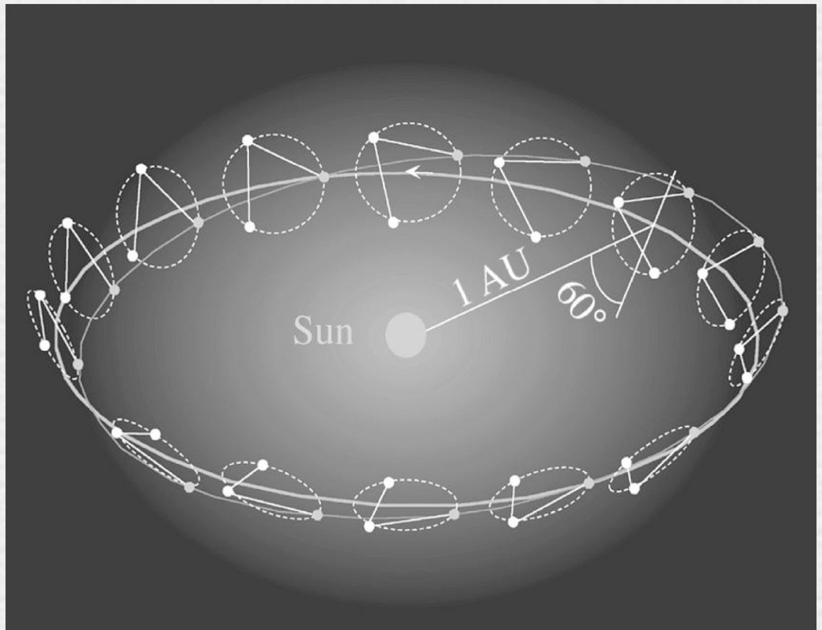
at a Hadron Collider

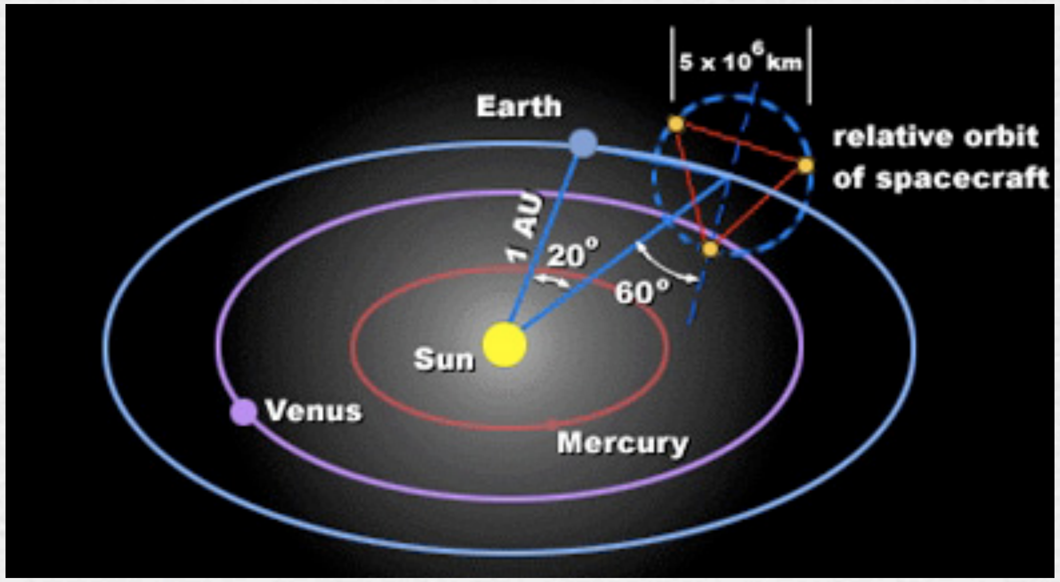


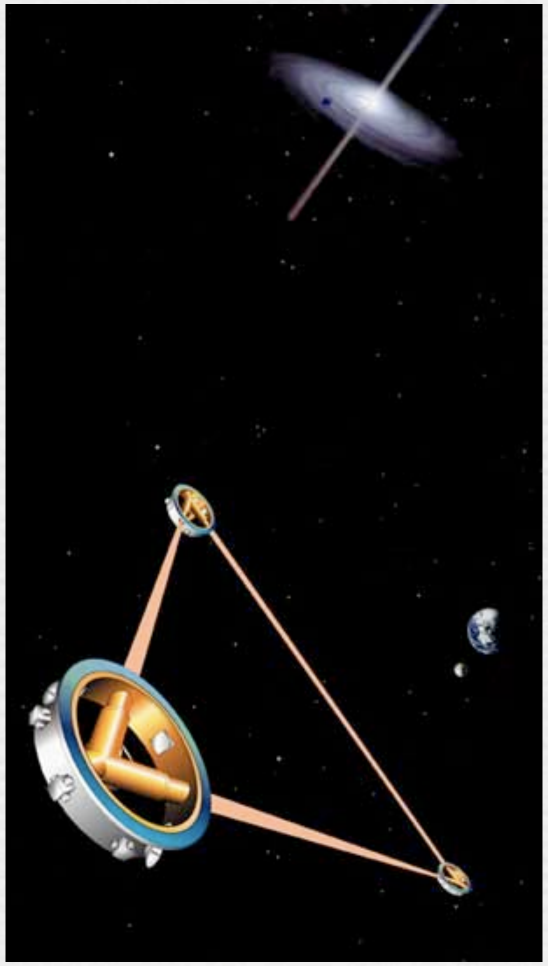
at an $e^+ e^-$ Linear Collider



... or at the gravitational wave detector LISA

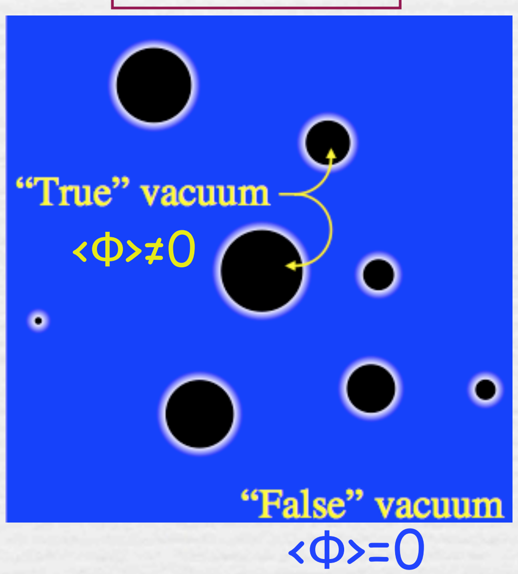




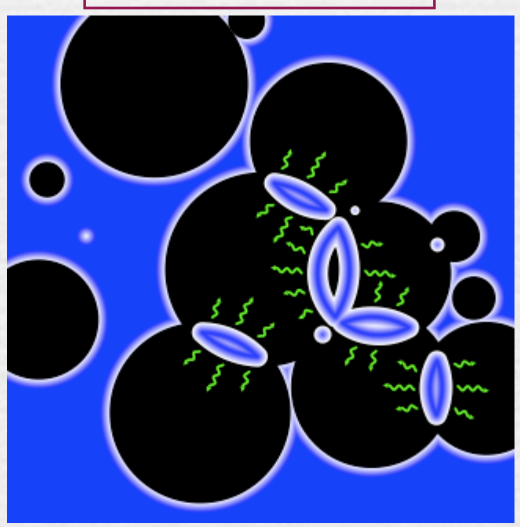


Gravitational Wave Spectrum of the electroweak phase transition

Bubble nucleation



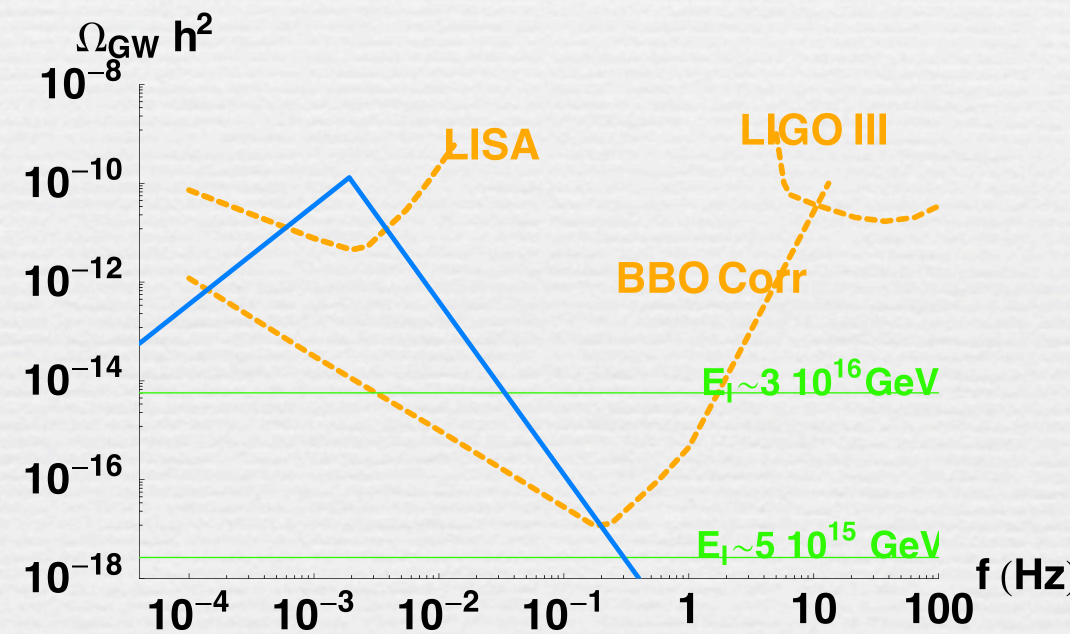
Bubble percolation



Fluid flows

Magnetic fields

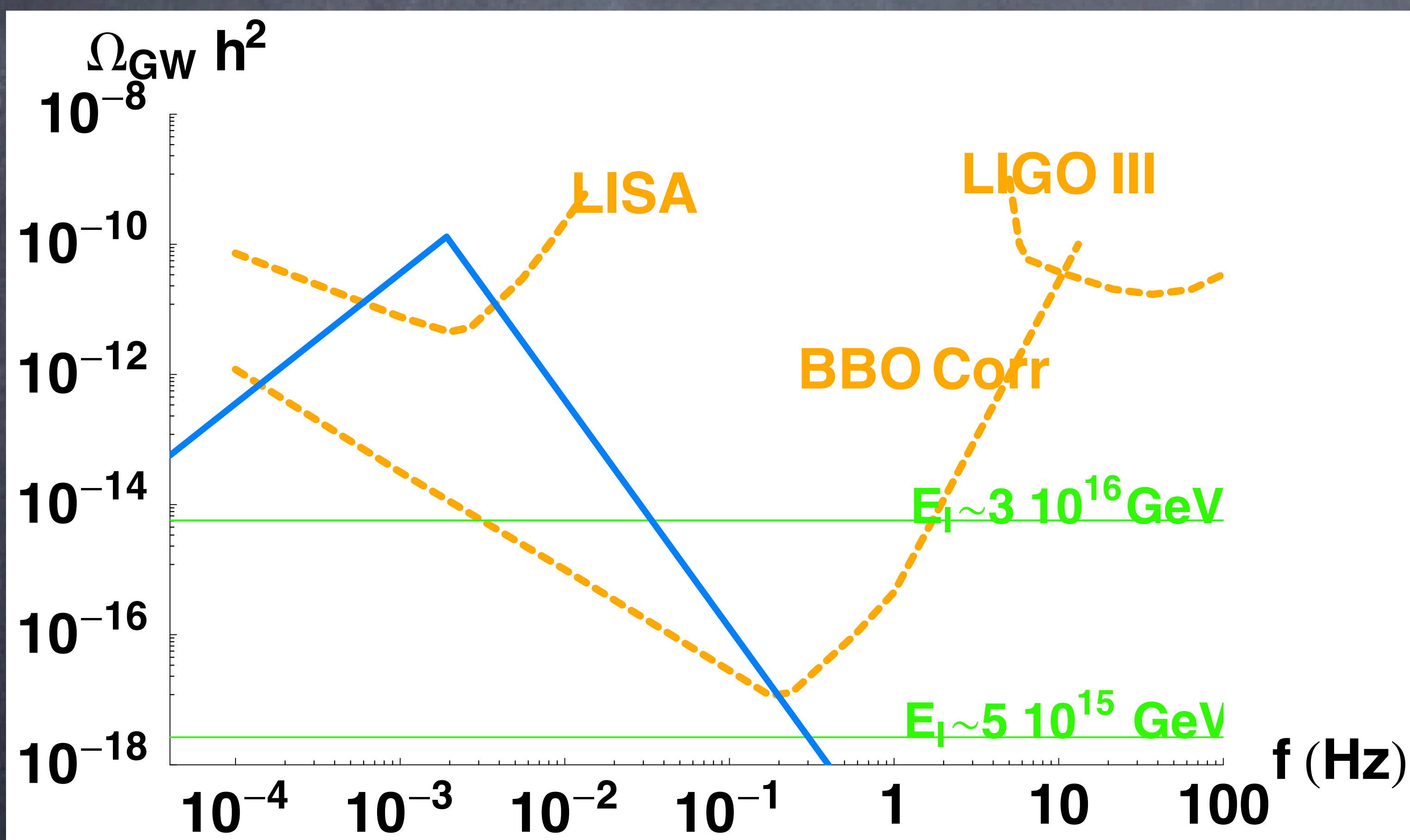
Stochastic background of gravitational radiation



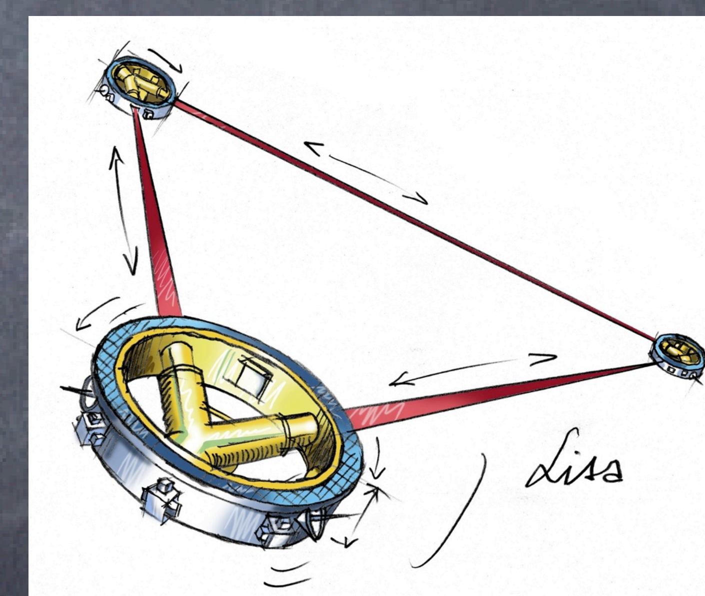
Why should we be excited about mHZ freq.?

$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3}\mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$

LISA: Could be a new window on the Weak Scale



LISA band:
$10^{-4} - 10^{-2}$ Hz

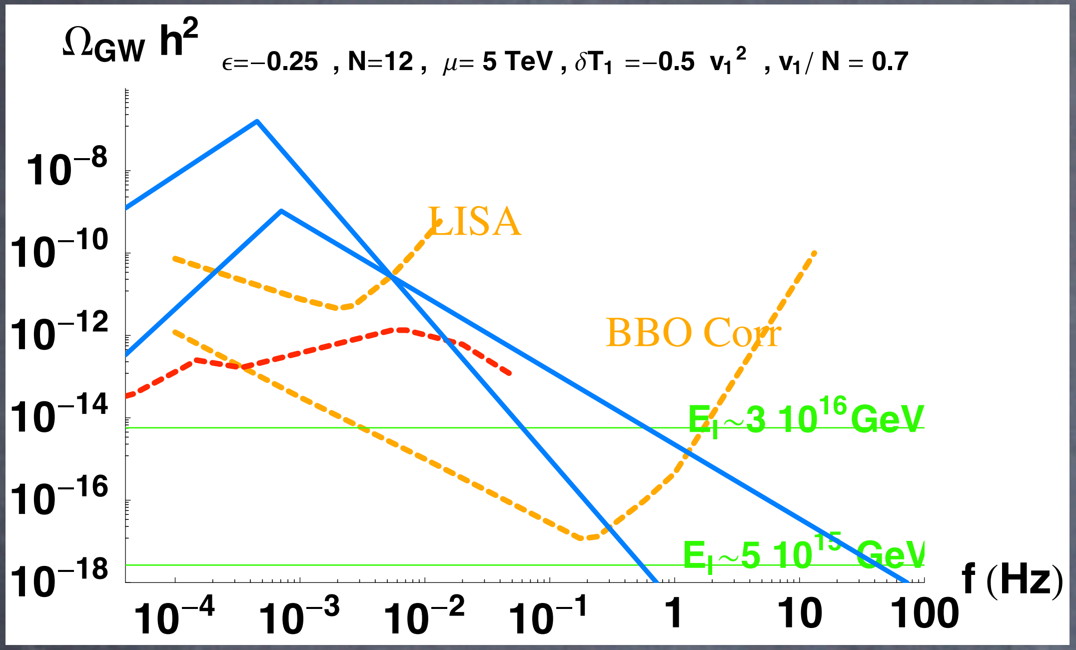


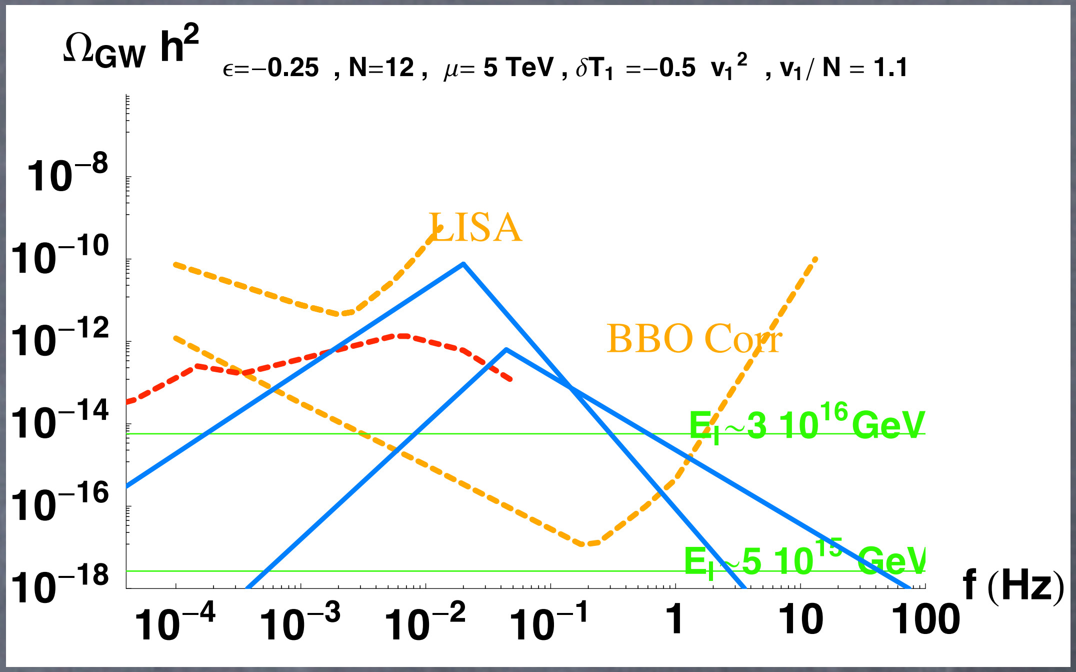
complementary to collider informations

Cosmology of the Randall-Sundrum model

Gravitational Waves from "3-brane" nucleation:

Signal versus LISA's sensitivity





Randall-Servant'06

Signature in GW is generic,

i.e. does not depend whether Standard Model is in bulk or on TeV brane

but crucially depends on the radion properties

Conclusion

We might be learning something about the Higgs/radion
by looking at the sky

Bulk flow & hydrodynamics

higgs vaccuum energy is converted into :

- -kinetic energy of the higgs,
- -bulk motion
- - heating

$$\Omega_{GW} \sim \kappa^2(\alpha, v_b) \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2$$

fraction that goes into kinetic energy

$$\alpha = \frac{\epsilon}{\rho_{rad}}$$

$$\frac{\beta}{H} = \frac{1}{T}\frac{dS}{dT}$$

fraction κ of vacuum energy density ϵ converted into kinetic energy

$$\kappa = \frac{3}{\epsilon \xi_w^3} \int w(\xi) v^2 \gamma^2 \xi^2 \, d\xi$$

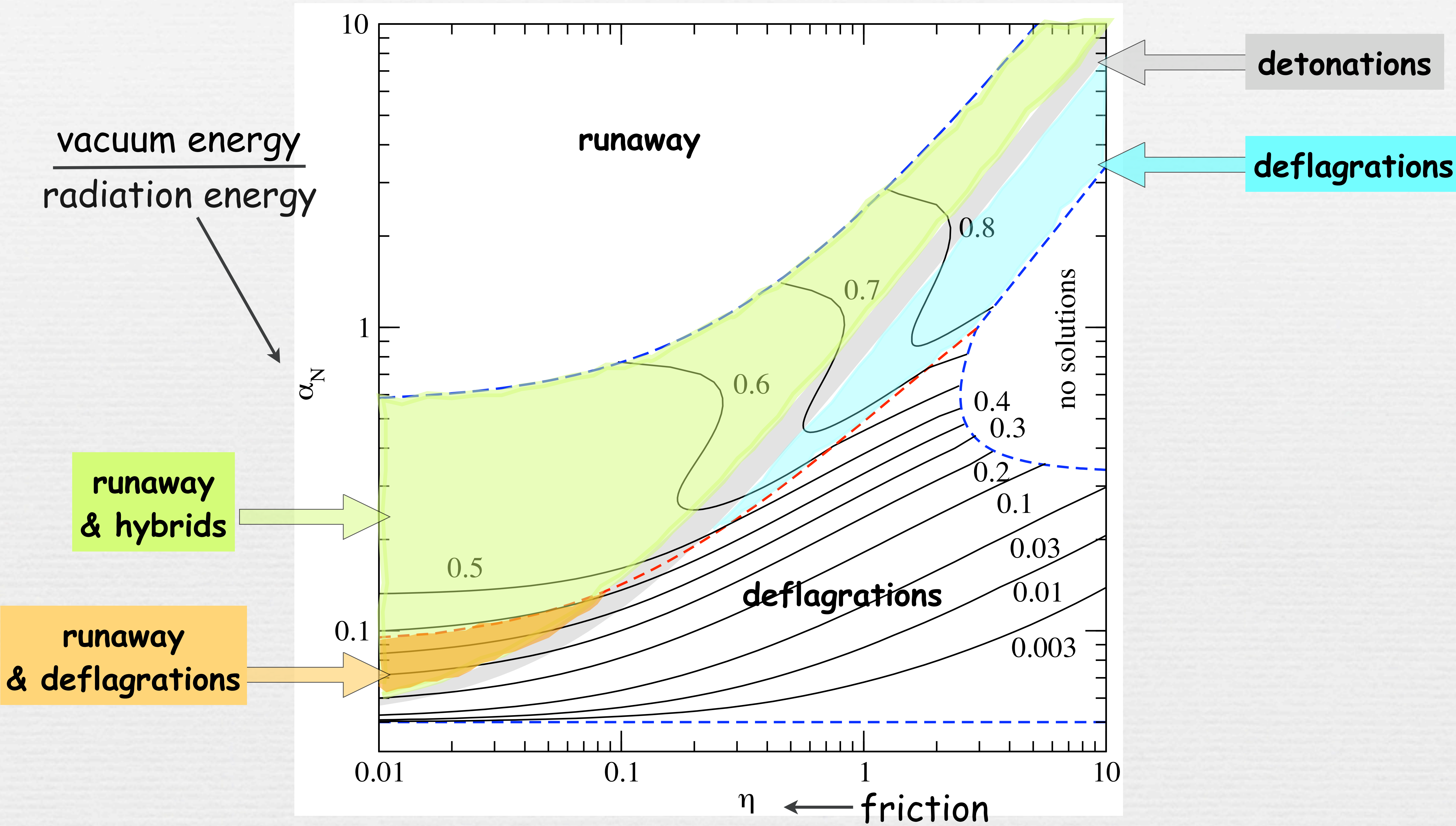
wall velocity

fluid velocity

-> all boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

Model-independent κ contours

Espinosa, Konstandin, No, Servant'10



$$\eta_{\rm SM} \sim 10^{-3}$$

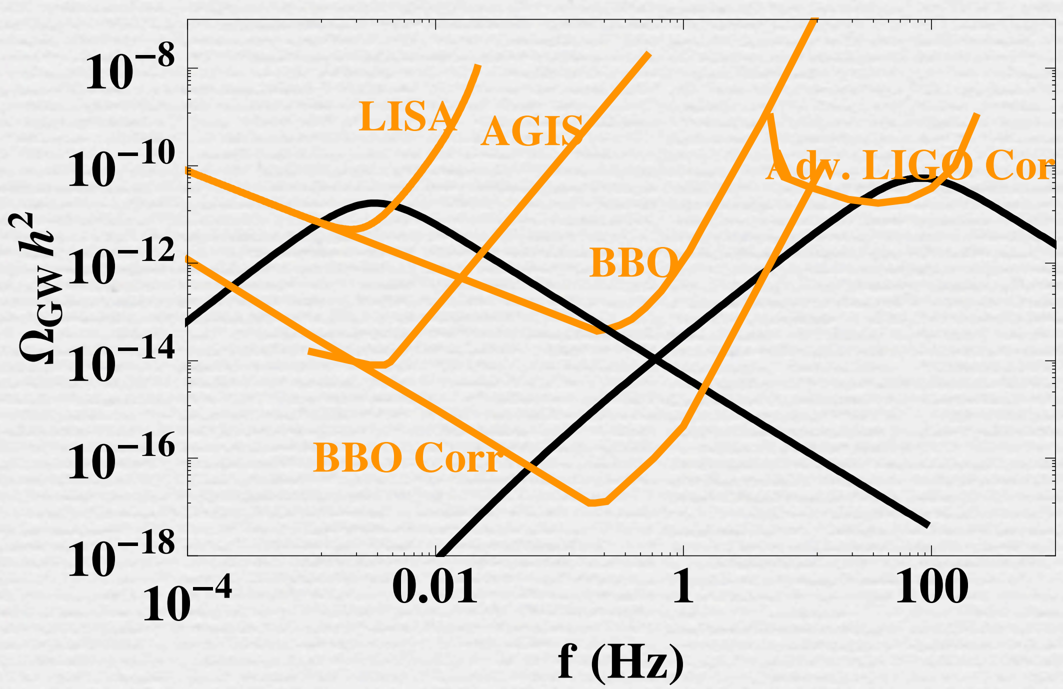
$$\eta_{\rm MSSM} \sim 10^{-2} \qquad v \sim 0.05 - 0.1$$

Summary

The nature of the EW phase transition is unknown & it will take time before we can determine whether EW symmetry breaking is purely SM-like or there are large deviations in the Higgs sector which could have led to a first-order PT

It is an interesting prospect that some TeV scale physics could potentially be probed by LISA

Discussion applies trivially to any other 1st order phase transition (only shift peak frequency, amplitude and shape of signal do not depend on the absolute energy scale of the transition)

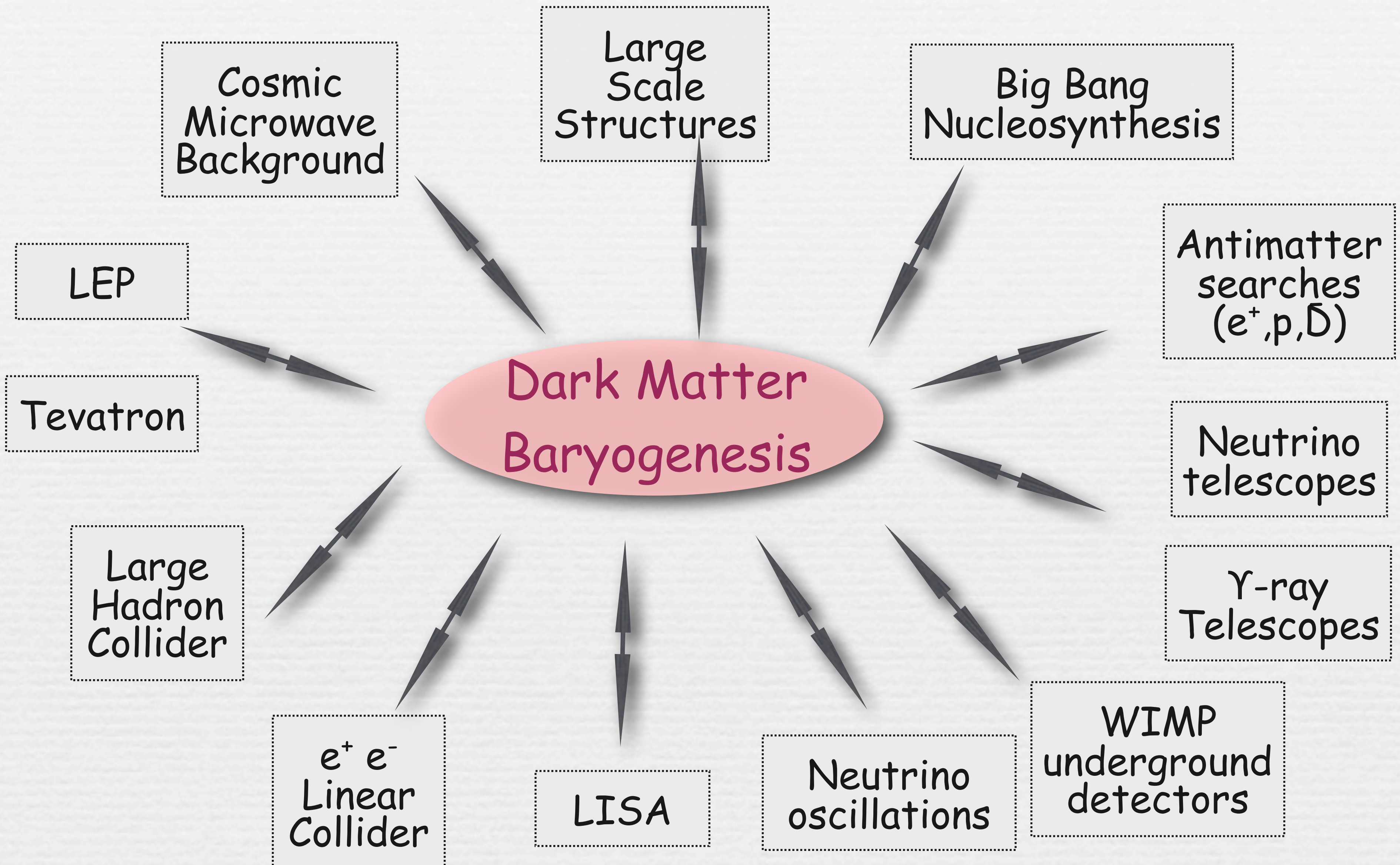


Conclusion:

The Standard model of Particle Physics is incomplete:
It cannot explain the dark Matter nor the matter-antimatter asymmetry of the universe

New Physics is needed.

Cosmic connections of electroweak symmetry breaking: A multi-form and integrated approach



To conclude

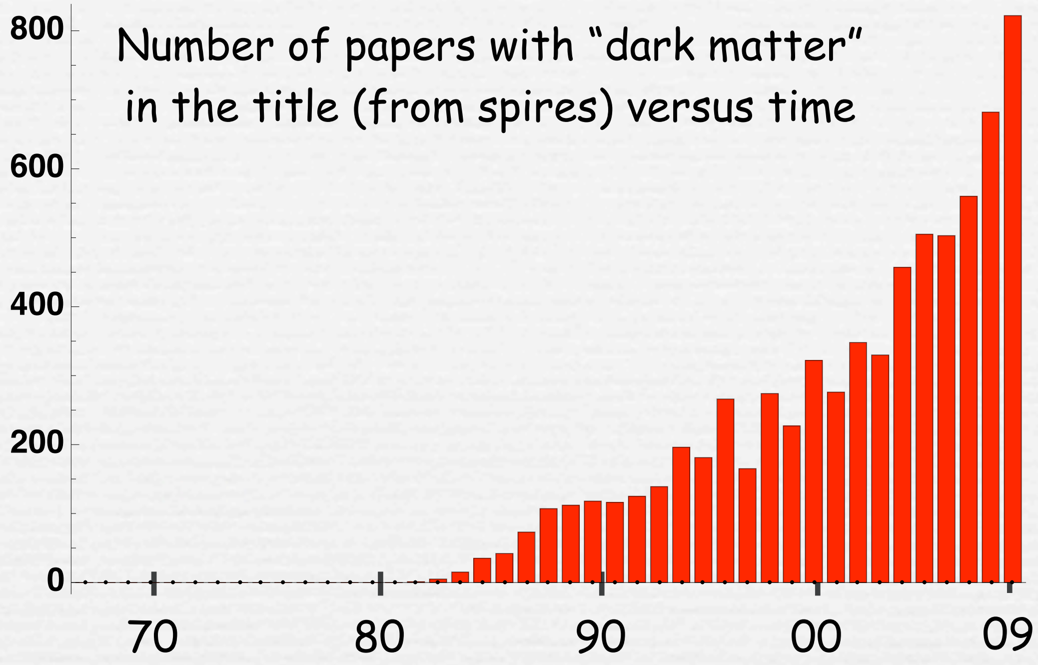
A blooming field

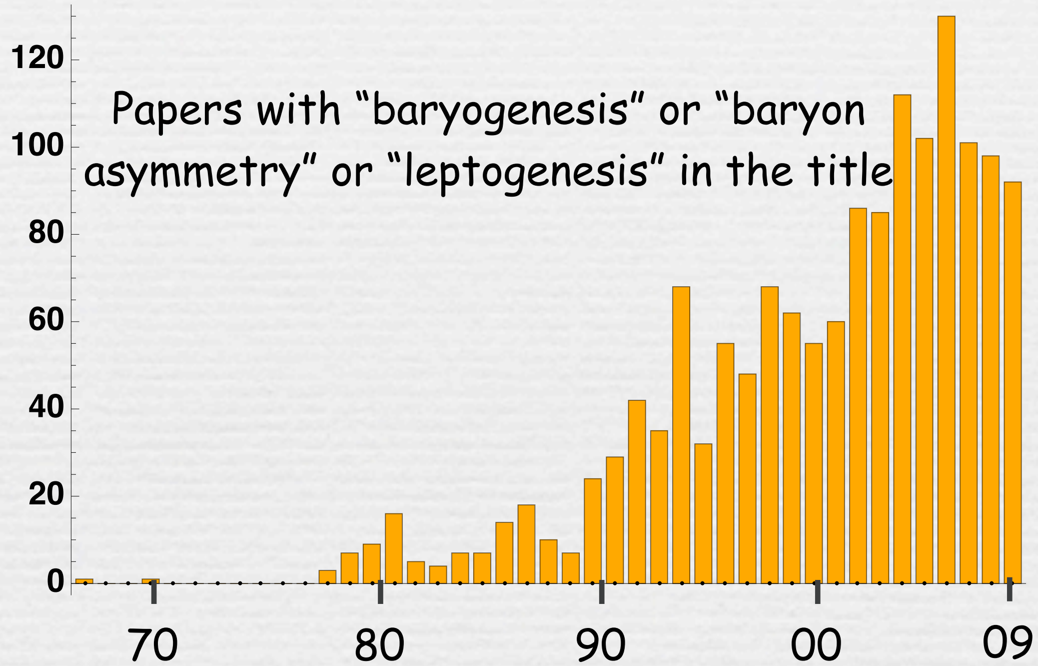
Abundance of experimental activity related to dark matter searches

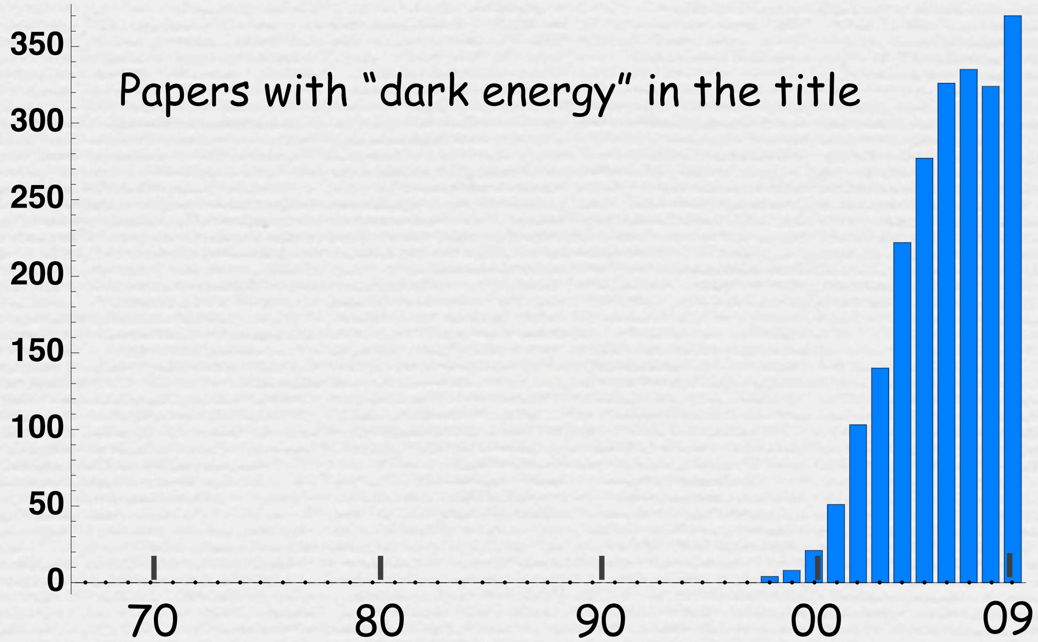
still much activity in model building

many viable alternatives to LSPs
LKPs, LZPs, LTPs, IDM ...

with a large variety of signatures



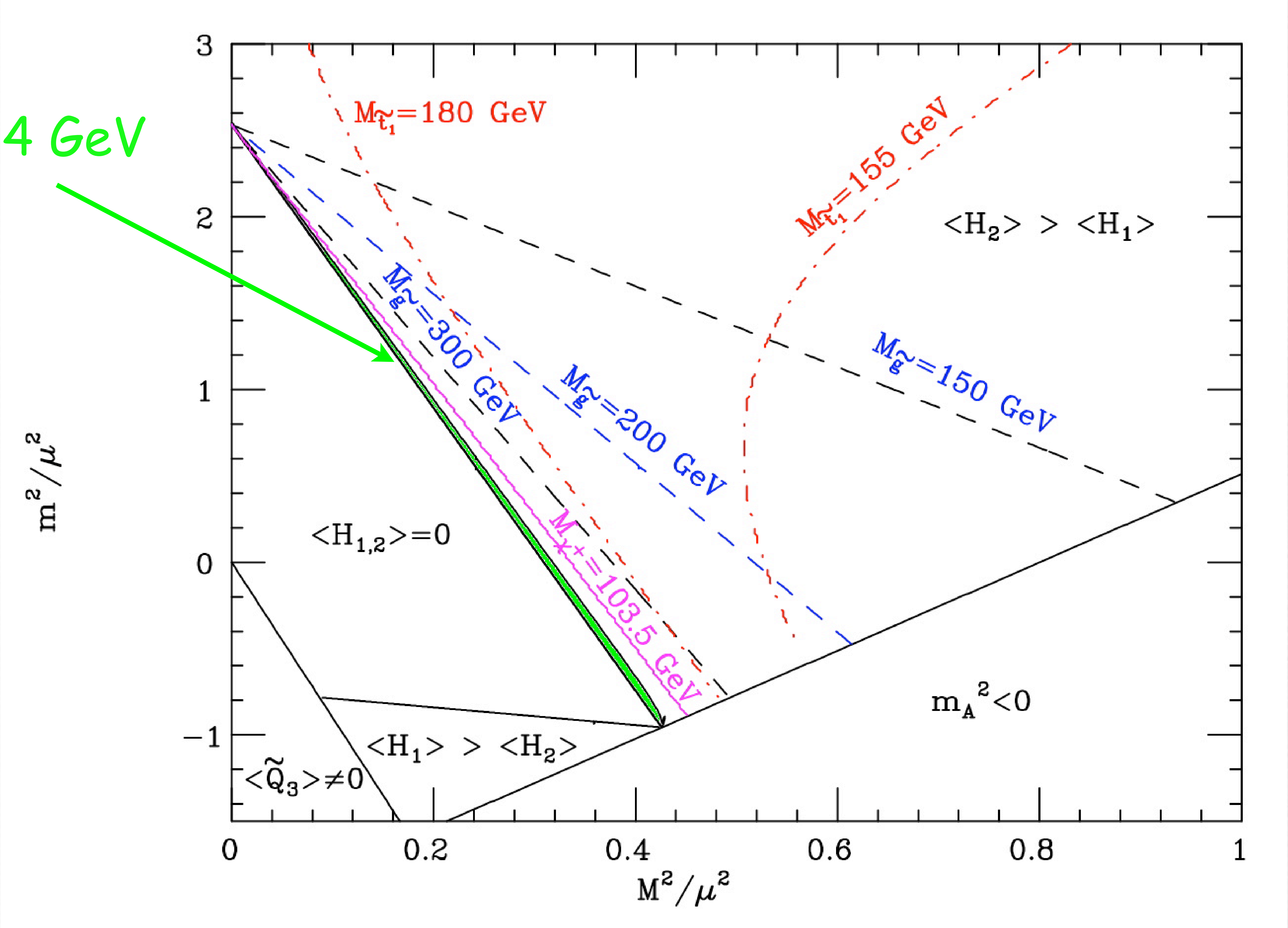




Annexes

State of mSUGRA

m_h >114 GeV



[Giudice & Rattazzi, '06]