Cosmology and the Particle Accelerator Connection

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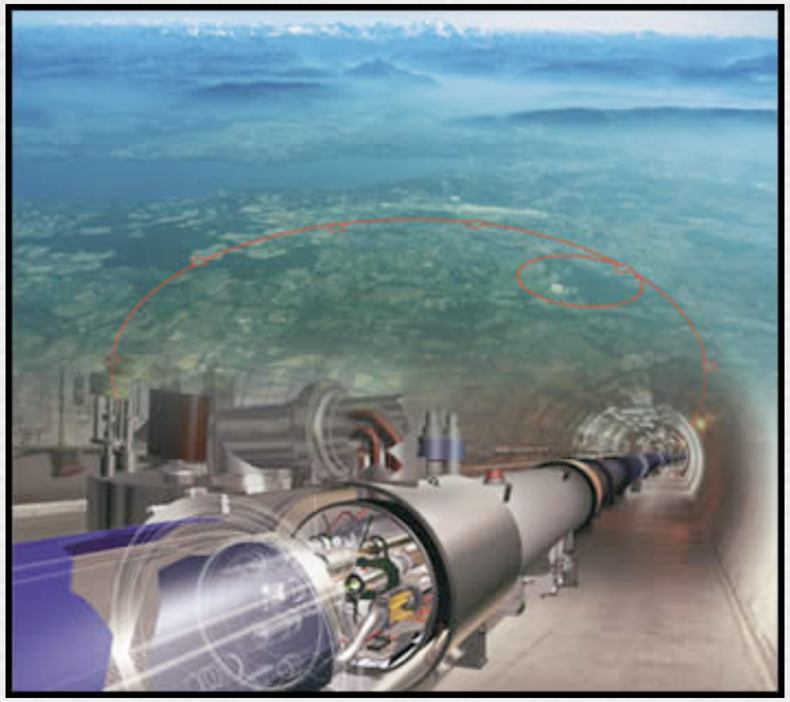
2010: First collisions at the LHC ?

Direct exploration of the Fermi scale starts.

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

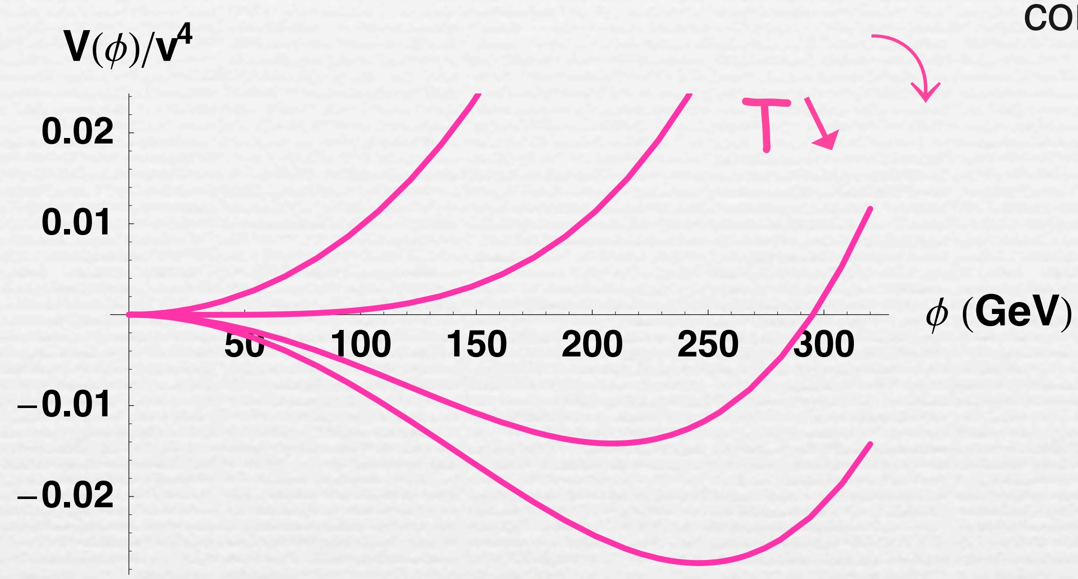
$SU(3)_C \times SU(2)_L \times U(1)_Y$

- 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

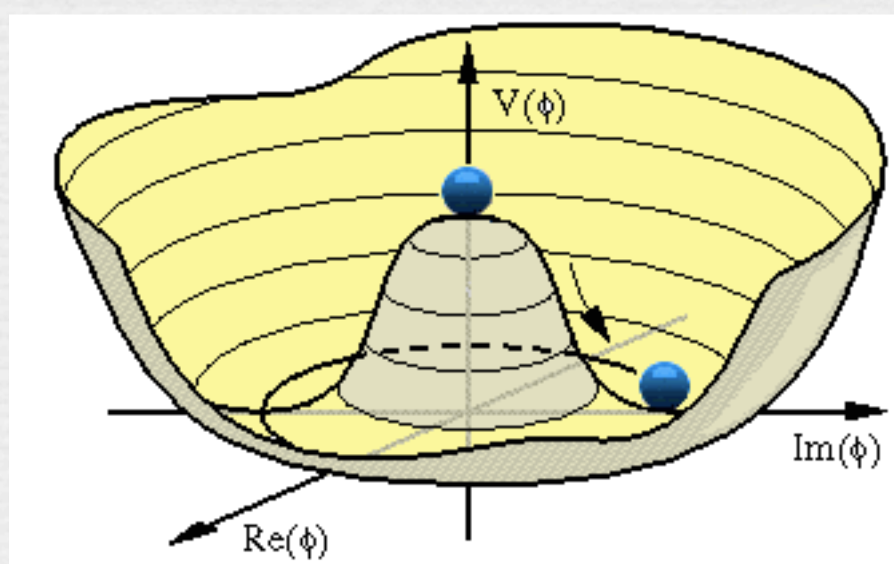
and a portal to new physics hidden sectors

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.

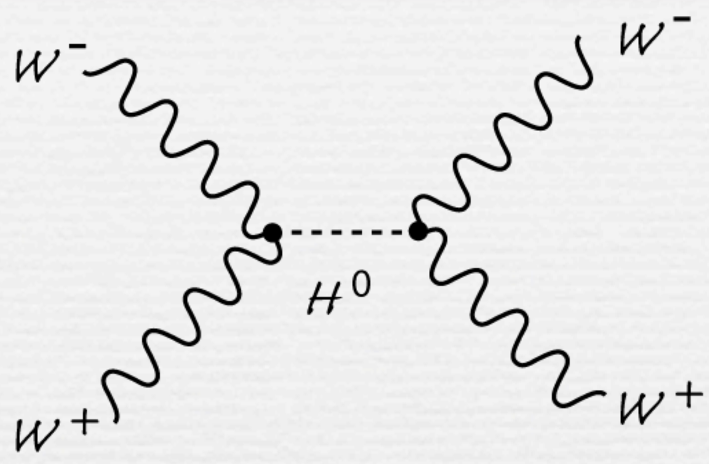


the puzzle:

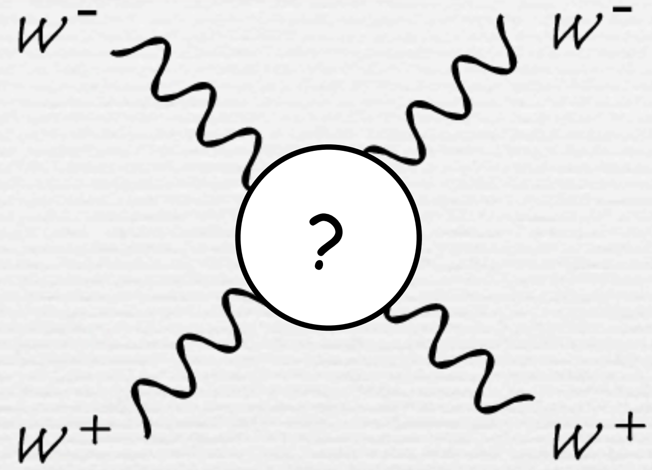
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

Electroweak symmetry breaking: 2 main questions

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

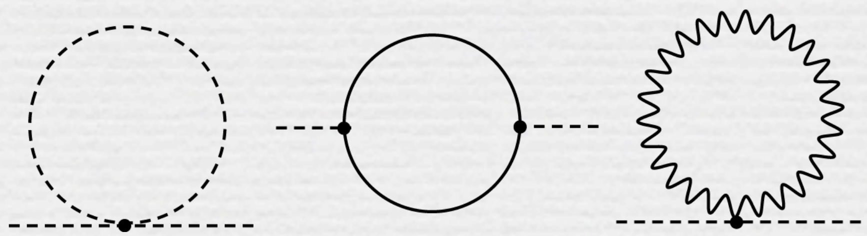


the Higgs or something else?



- **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

Which new physics?

Supersymmetric

Minimally extended
(2 Higgs doublets)

Electroweak
symmetry breaking

Composite, Higgs as
pseudo-goldstone
boson, $H=A_5$

Higgsless,
technicolor-like,
5-dimensional

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

Which Higgs ?

- 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 ?

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

- quarks and leptons would be massless

-mass of proton and neutrons (QCD confines quarks into color singlet hadrons) would be a little changed

-proton becomes heavier than neutron! no more stable

-> no hydrogen atom

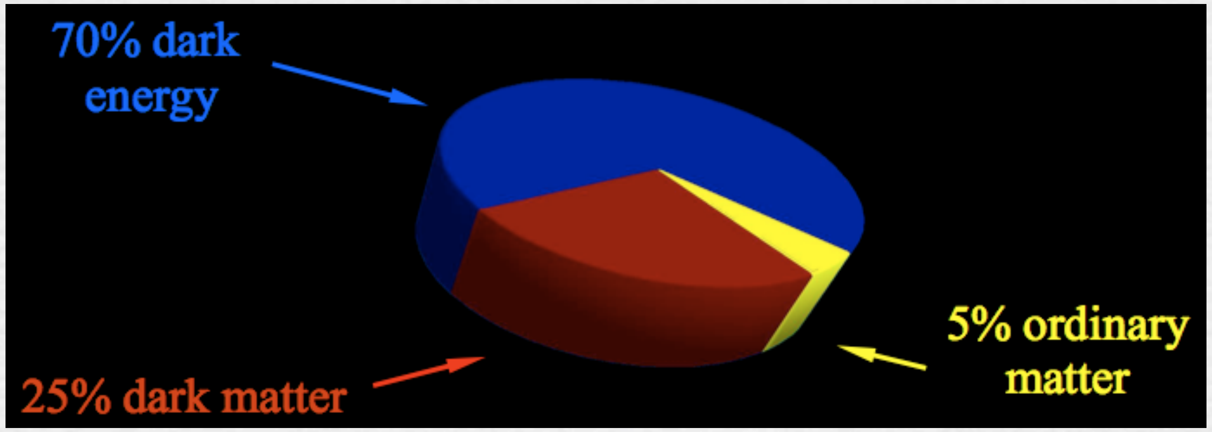
-> very different primordial nucleosynthesis

-> a profundly different (and terribly boring) universe

Most recent experimental successes

- top discovery
- Solar, atmospheric & terrestrial neutrino oscillations
- Direct CP violation in K mesons
- CP violation in B mesons
- Validation of quantum properties of Standard Model
- Observation of accelerated expansion of the universe
- Determination of the energy/matter content of the universe

Nevertheless:
We're lacking the understanding of 95 % of the energetic content of the universe



2 major observations unexplained by the Standard Model

- the Dark Matter of the Universe

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

85% dark unknown matter

- the (quasi) absence of antimatter in the universe

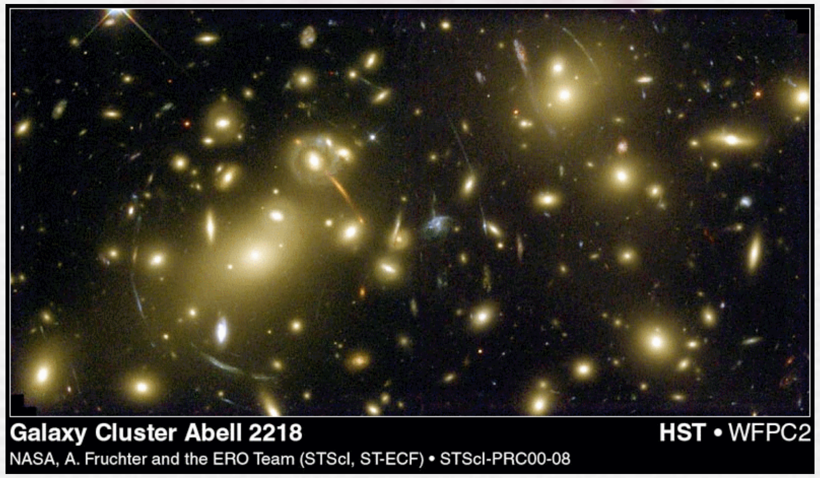
baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

→ observational need for new physics

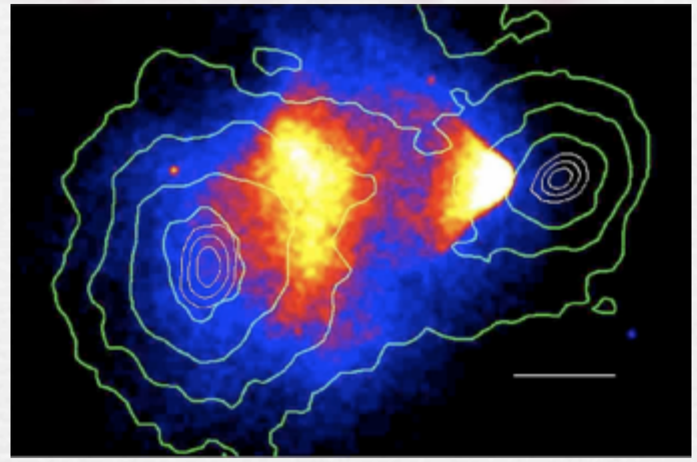
→ what does this have to do with the TeV scale?

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

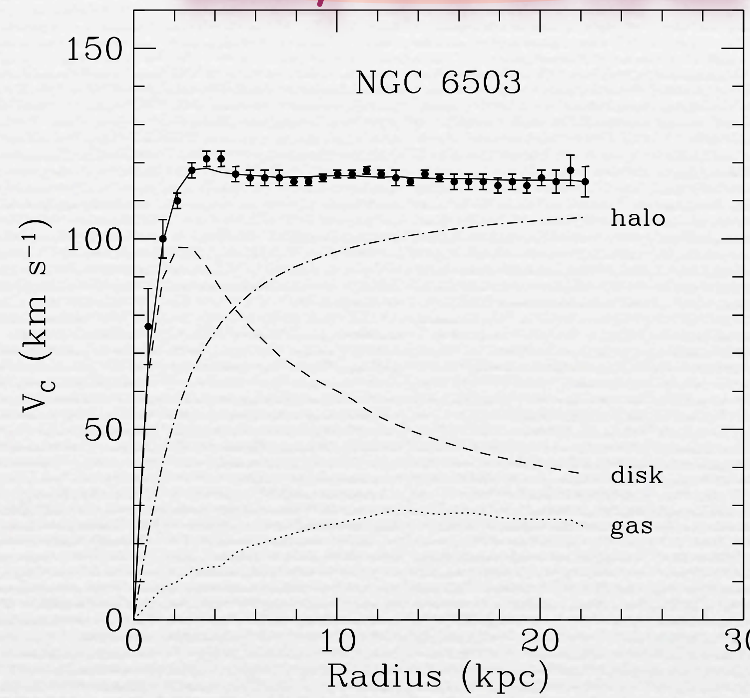
Gravitational lensing



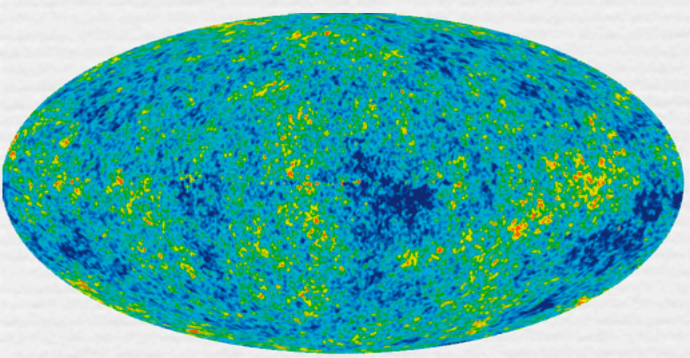
The "Bullet cluster": lensing map versus X-ray image

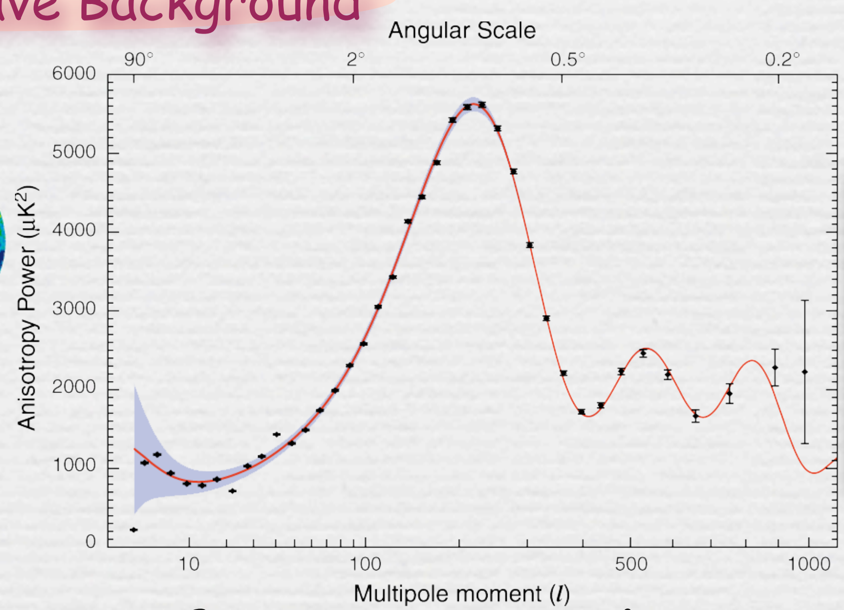


Galaxy rotation curves



Cosmic Microwave Background





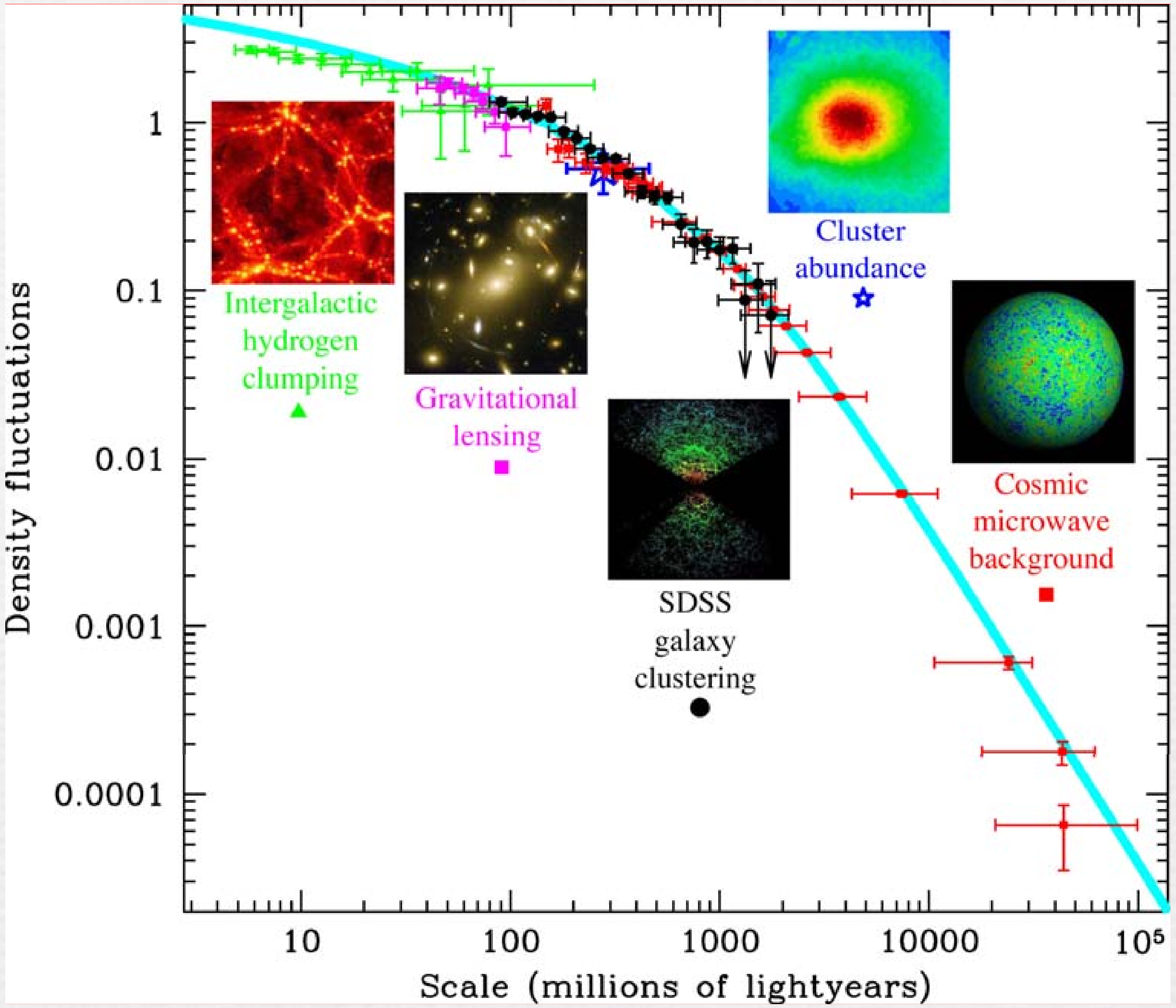
... etc

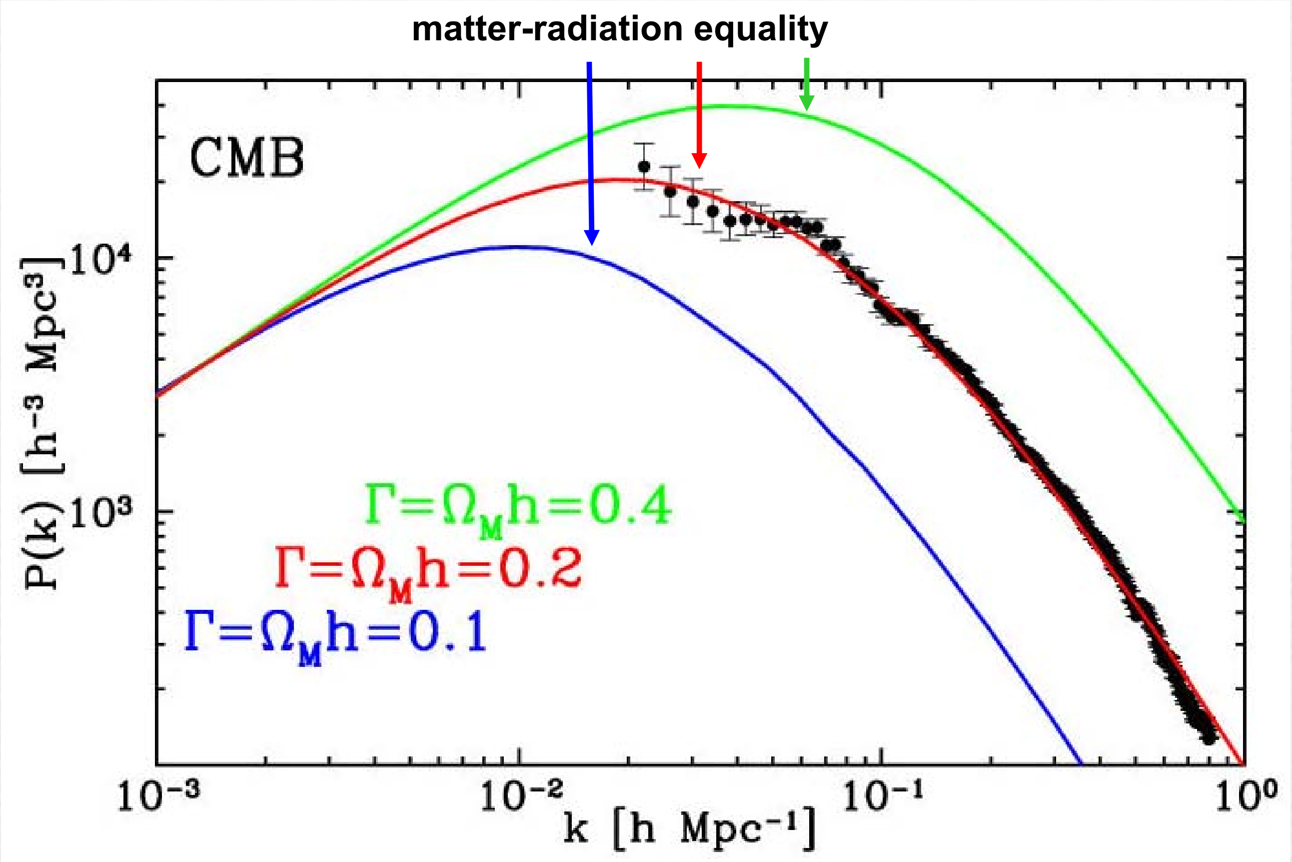
-> Fraction of the universe's energy density stored in dark matter : $\Omega_{DM} \approx 0.22$

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

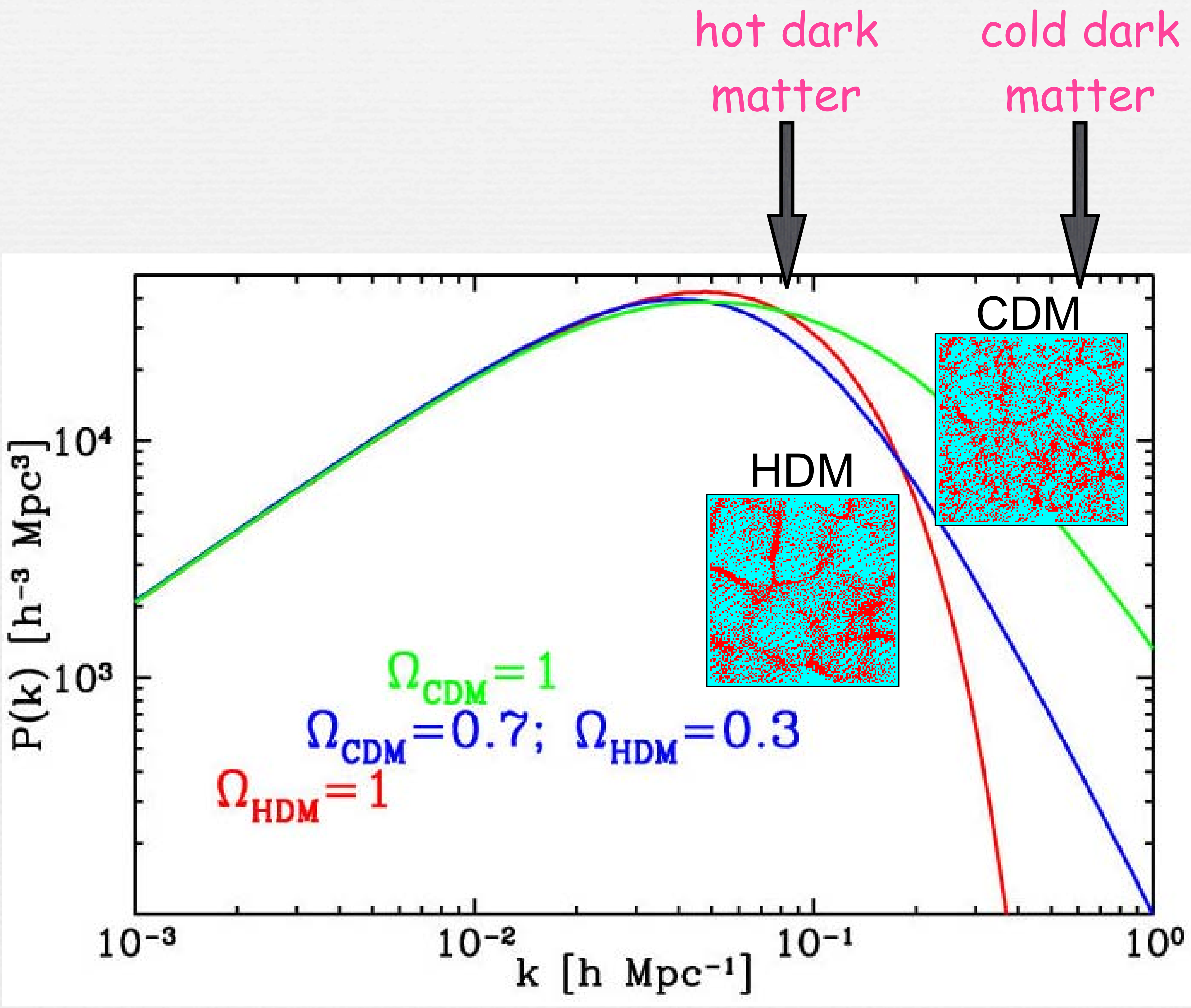
DM properties are well-constrained (gravitationally interacting, long-lived, not hot, not baryonic) but its identity remains a mystery

Matter power spectrum





Neutrinos



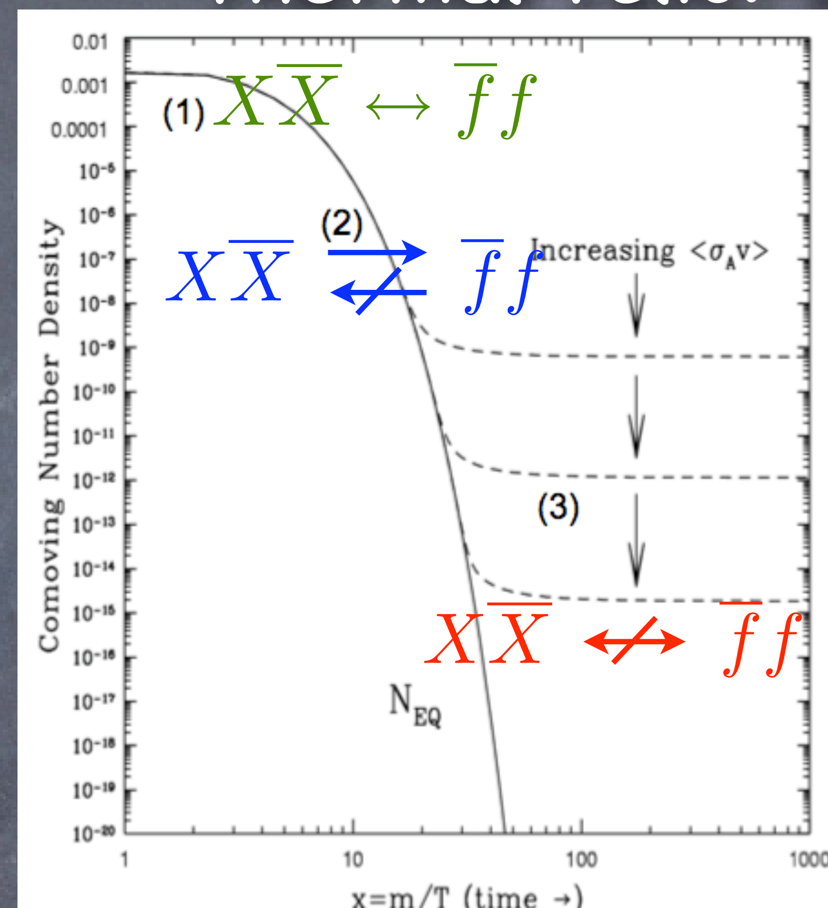
hot dark matter
cold dark matter
CDM
HDM
$\Omega_{CDM}=1$
$\Omega_{CDM}=0.7;\ \Omega_{HDM}=0.3$
$\Omega_{HDM}=1$
10^4
10^3
P(k) [h^{-3} Mpc^3]
10^{-3}
10^{-2}
10^{-1}
10^0
k [h Mpc^{-1}]

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



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

The "WIMP miracle"

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

$\Rightarrow m \sim 100$ GeV

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

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

Very general, does not depend on early universe cosmology, only requires the reheat temperature to be ≥ 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 and the Fermi scale

Fraction of the universe's energy density stored in a stable massive thermal relic:

$$\Omega_{DM} \approx \frac{0.2\ \text{pb}}{\sigma_{anni}}$$

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

a compelling coincidence
(the "WIMP miracle")

Which particle? How to test this hypothesis?

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

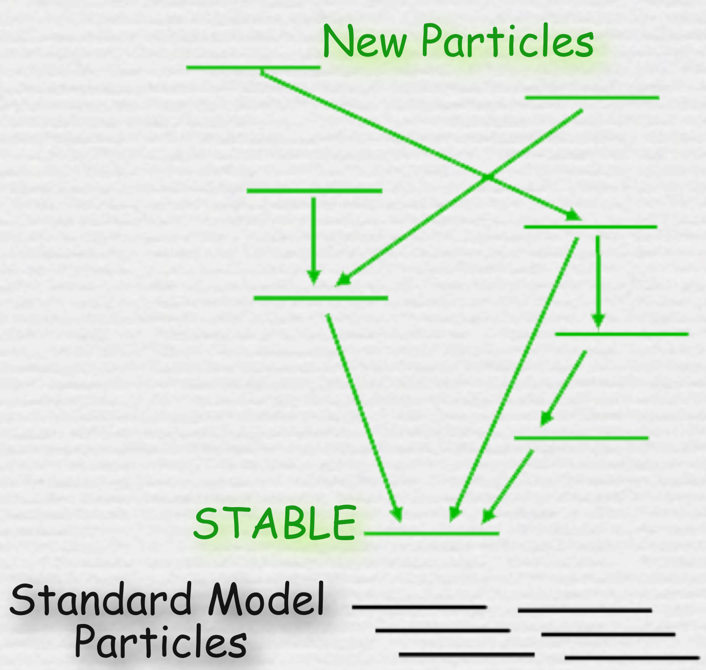
mass spectrum,
interactions

→

dark matter candidates

↓ relic abundance

↓ detection signatures & rates



Model building beyond the Standard Model: "historical" overview

Big hierarchy adressed	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 adressed	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 Candidates

	M_{EW}/M_{Pl} hierarchy adressed	little hierarchy adressed(∼TeV cutoff)	Hierarchy pb ignored
SPIN 0			
- axion }(not wimps)	×		×
- radion	?		
- branon	?		
- singlet scalar			×
- adjoint scalar (=spinless photon)		×	
SPIN 1/2			
- Dirac neutrino	× (in RS)		
- SU(2) p-uplet			×
- neutralino	×		
- axino	×		
SPIN 1			
- Heavy photon (KK or B-partner in Little Higgs)		×	
SPIN 3/2			
- Gravitino	×		
SPIN 2			
- KK Graviton		× (in UED)	

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 --> 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

a typical example of
the "minimal approach": *The Inert Doublet Model (IDM)*

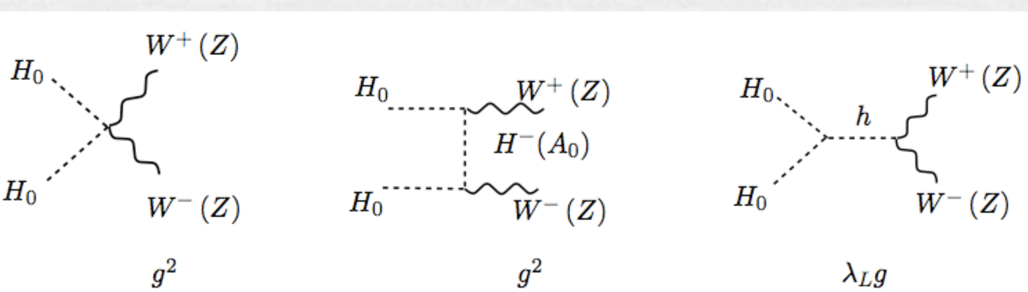
Deshpande-Ma'78; Barbieri-Hall-Rychkov 06
Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07 ; Hambye, Tytgat 07 .....

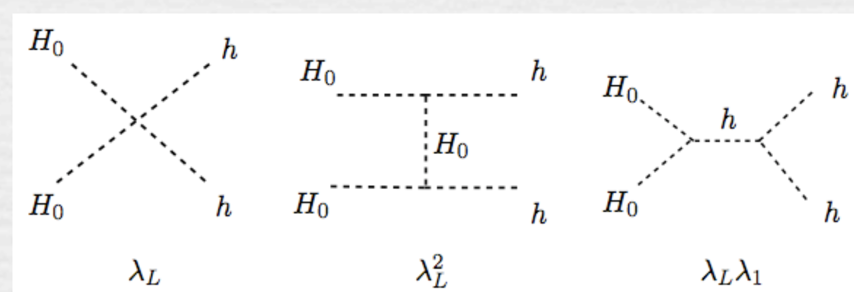
A two-Higgs extension of the SM with an unbroken Z_2 symmetry

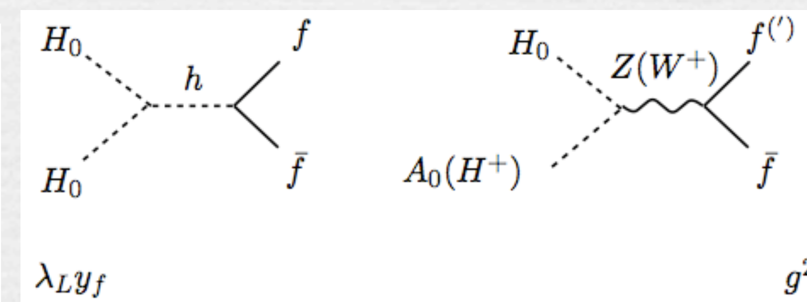
$H_1 \to H_1$ and $H_2 \to -H_2$ (and all SM fields are even)

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

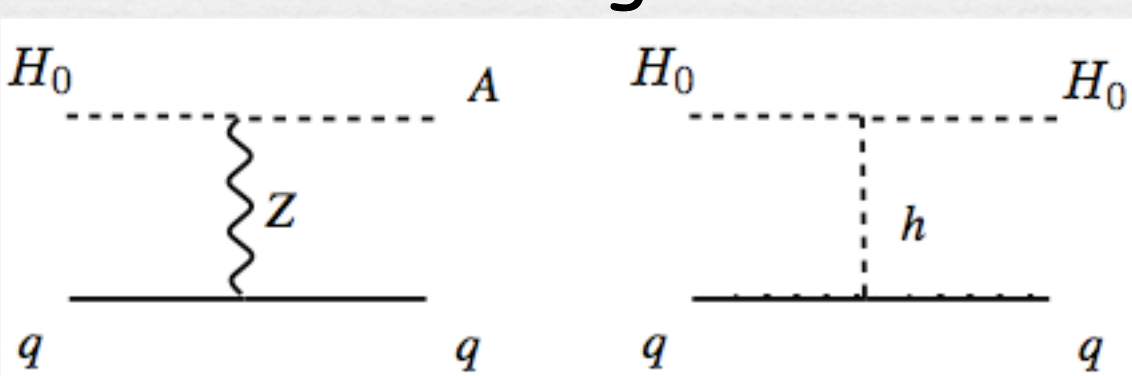
Annihilation:





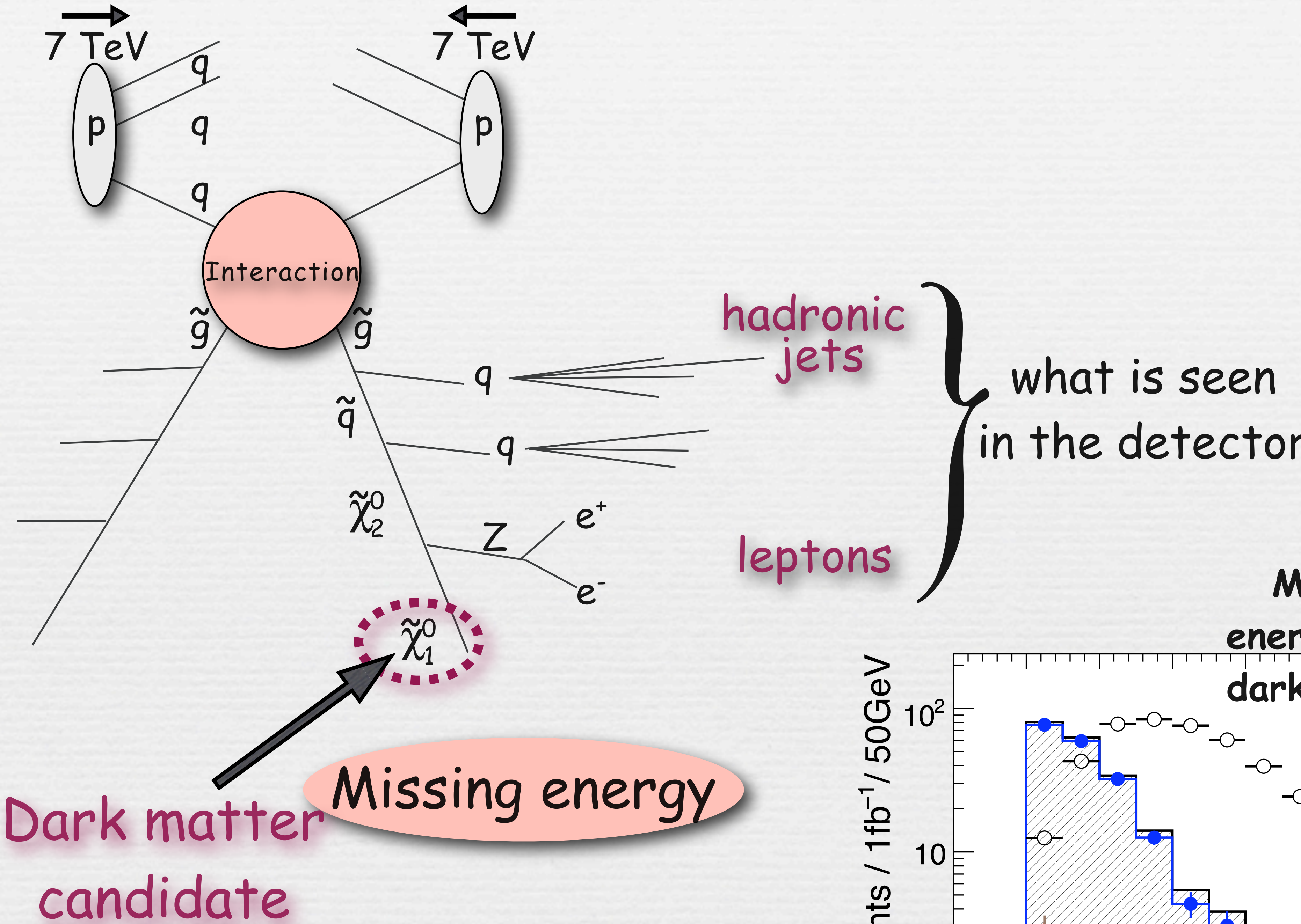


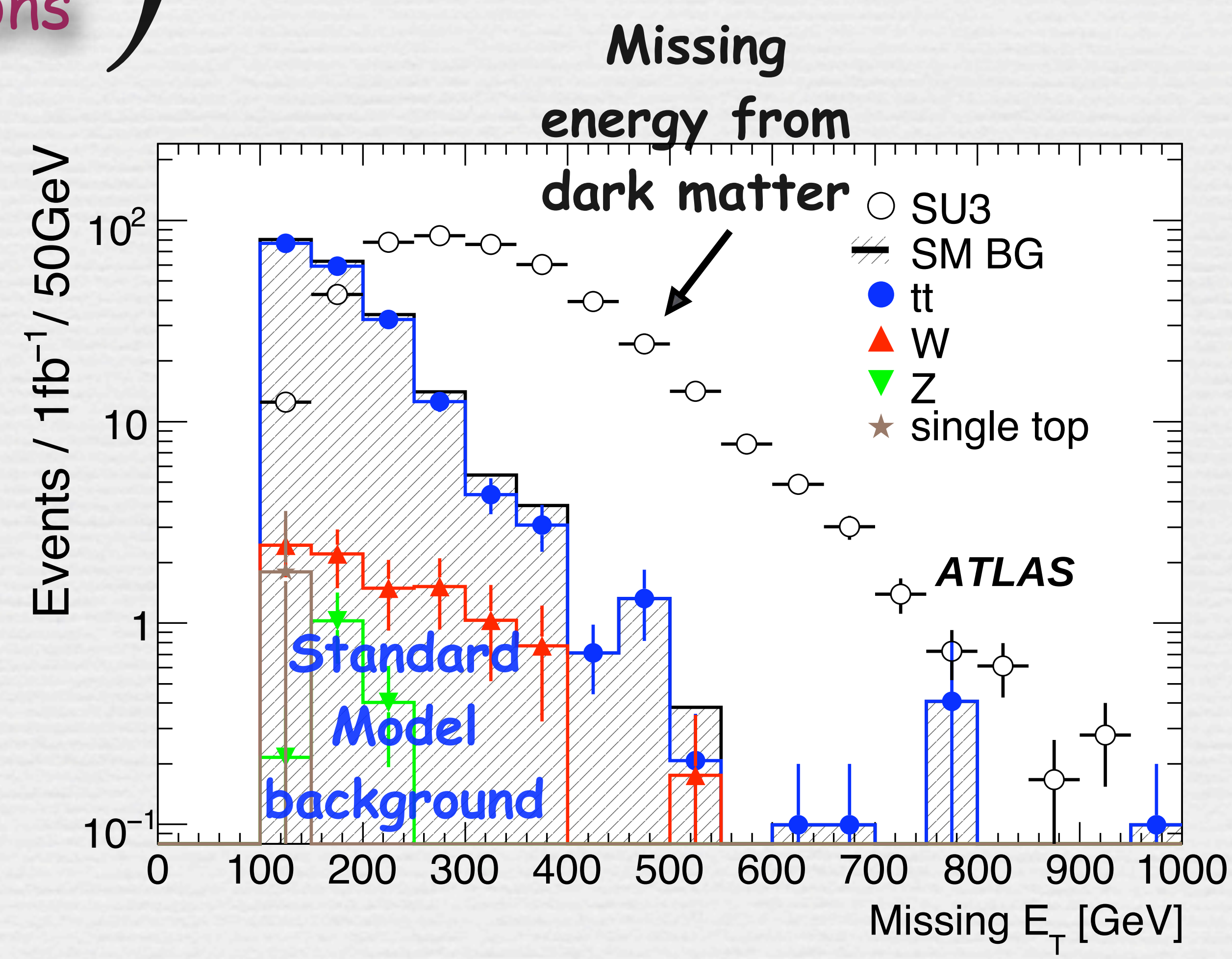
Elastic scattering:



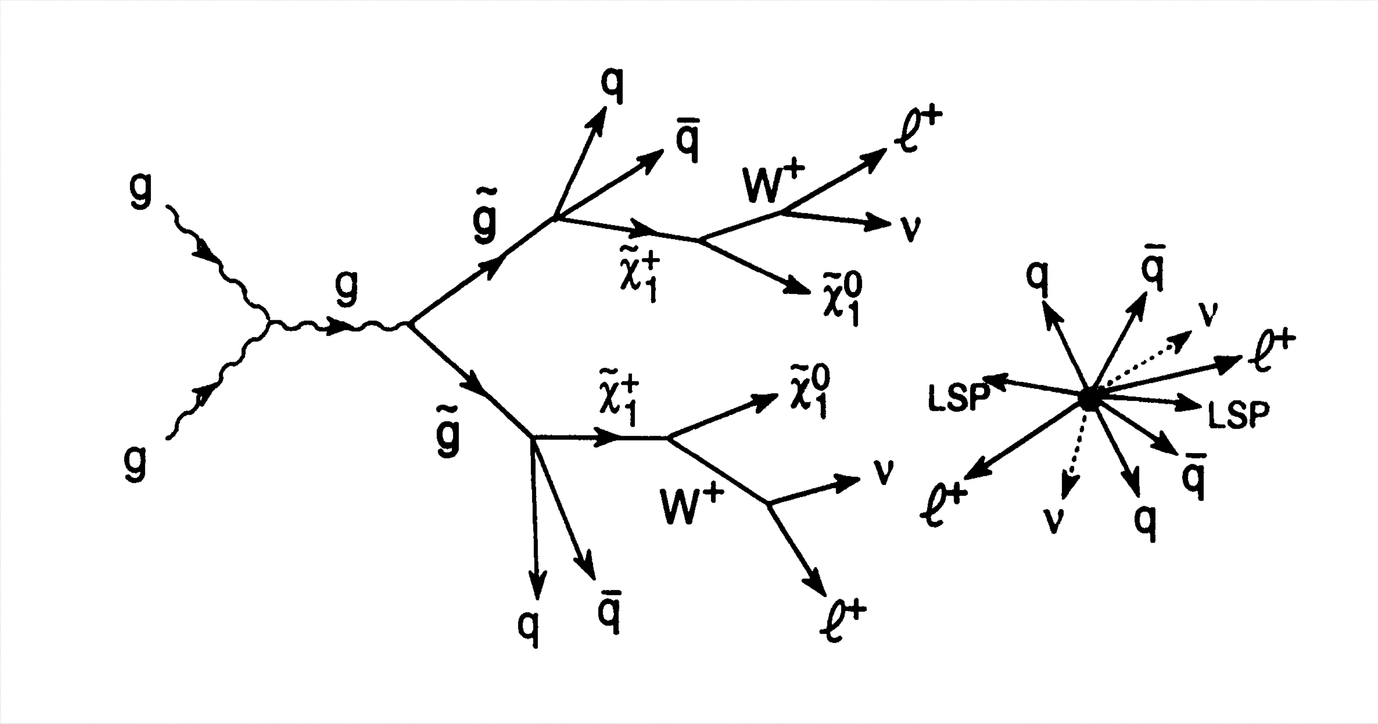
σ~ $O(10^{-9})$ pb, within sensitivity of future experiments

Producing Dark Matter at LHC = "Missing Energy" events





Typical SUSY decay chain

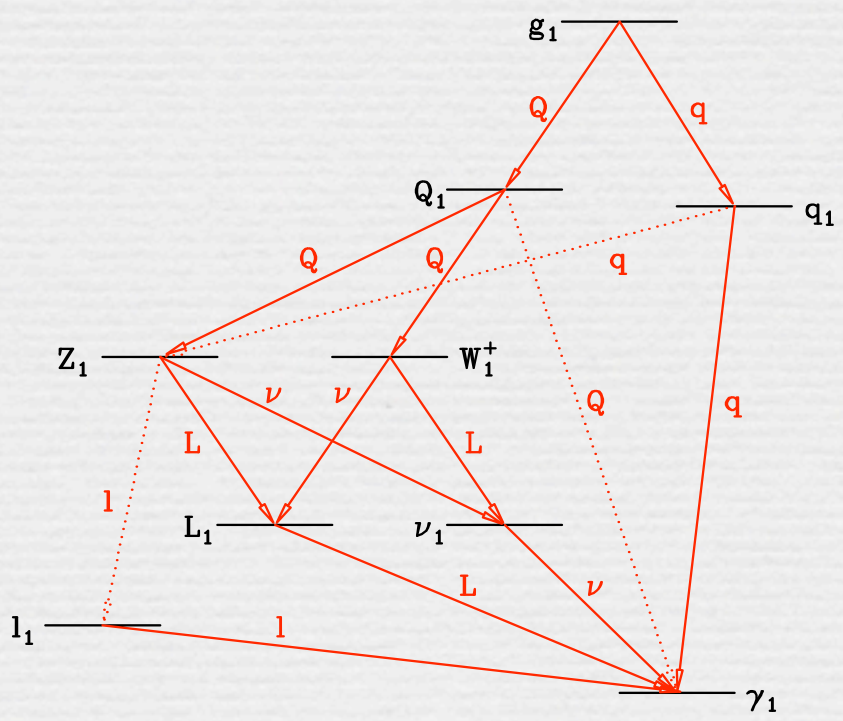


Lots of jets

Lots of leptons

Lots of missing energy

easily mimicked by Kaluza-Klein decay chain:



Example of a common signature:

$$t\,\bar{t} + \text{large } \not{E}_T$$

from pair-production of top partners that decay into DM

SUSY: $\tilde{t} \rightarrow \chi_0\ t$

Little Higgs: $T \rightarrow A_H\ t$

Universal extra dimensions: $t^{(1)} \rightarrow B^{(1)}\ t$

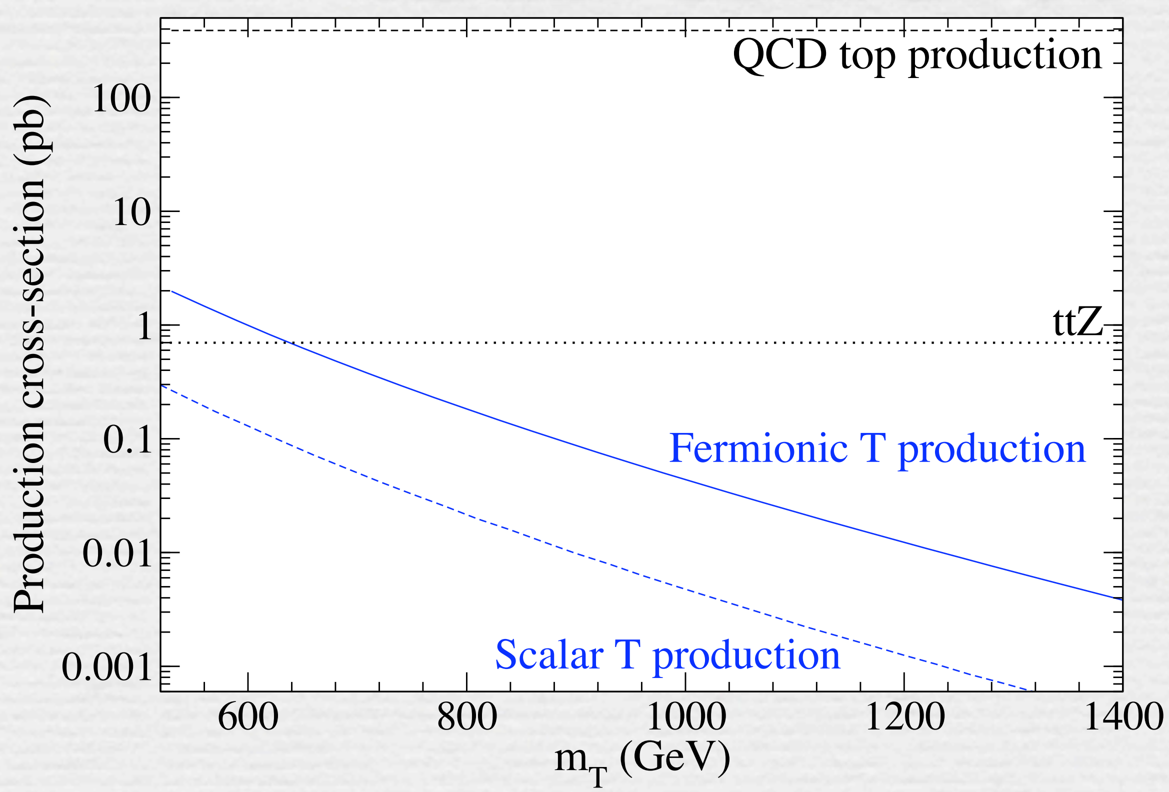
Randall-Sundrum GUTs: $t^{(1)'} \rightarrow \nu^{(1)'}\ \overline{\nu}^{(1)'}\ t$

scalar ($\tilde{t}$)

Majorana fermion (χ_0)

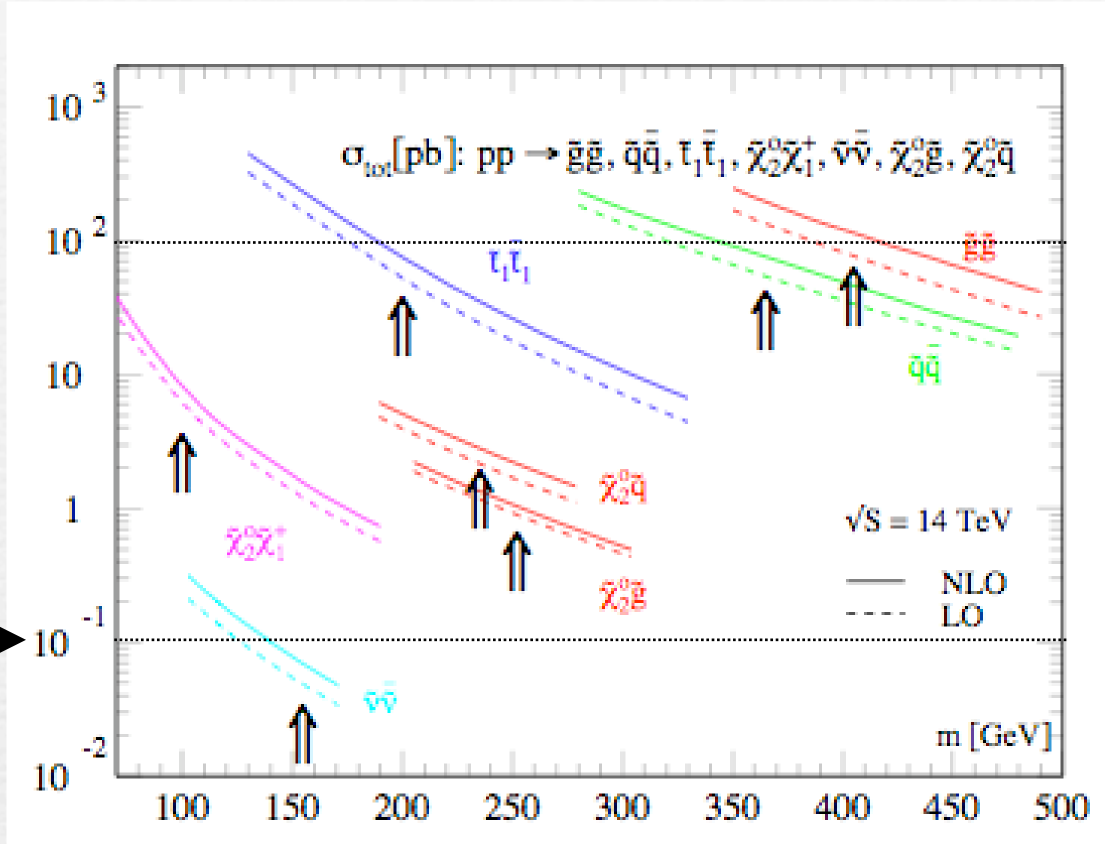
Gauge bosons (A_H, $B^{(1)}$)

Dirac fermions (T, $t^{(1)}$, $t^{(1)'}$, $\nu^{(1)'}$, $\overline{\nu}^{(1)'}$)



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)

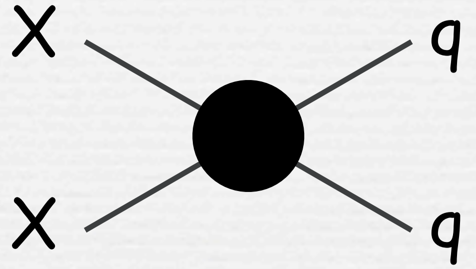
2) studying its properties in the laboratory

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

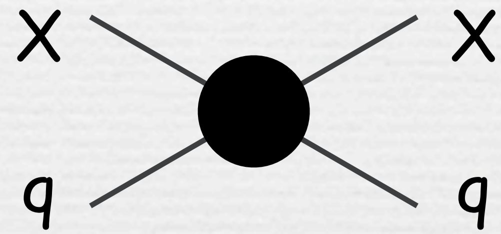
1 pb : the typical cross section

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

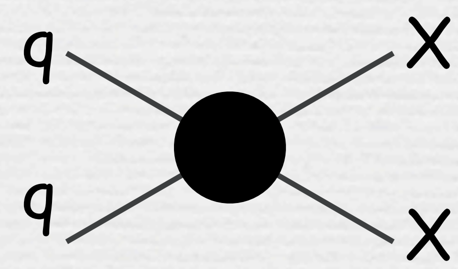


1 pb : typical scattering cross section of wimps with nuclei (-> relevant for direct detection experiments like CDMS)

$[\sigma_n \sim (m_n^2/\mu^2)/A^2\ )\ \sigma_0 \sim 10^{-7}$ 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 ~ 300 km.s^{-1} ~ 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:

$\rho \approx 0.3\ \mathrm{GeVcm^{-3}}$

$\approx 3000\ \mathrm{Wimps.m^{-3}}$ 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

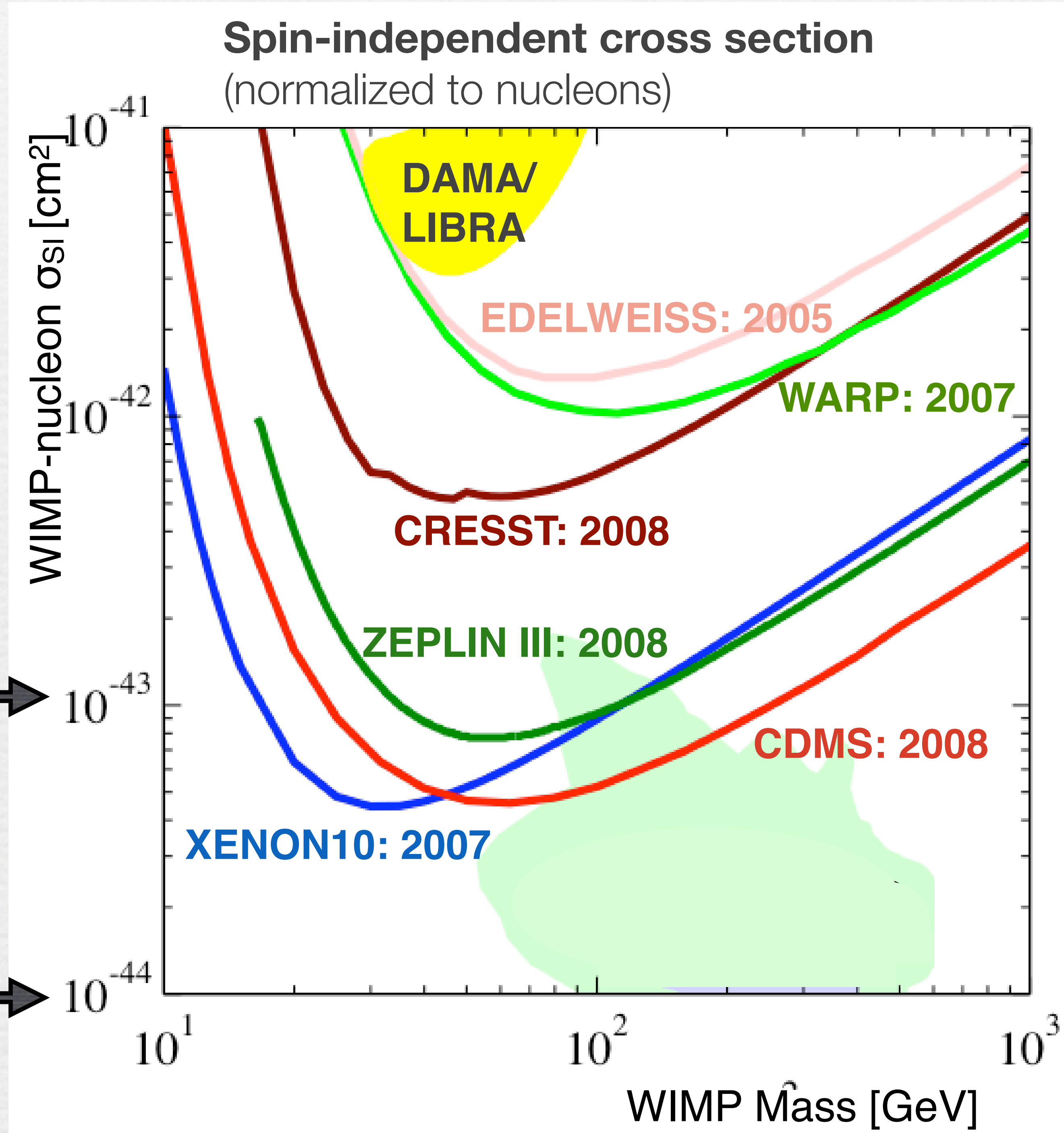
< 1 event/100kg/day if wimp-nucleon cross section is 10^{-7} pb

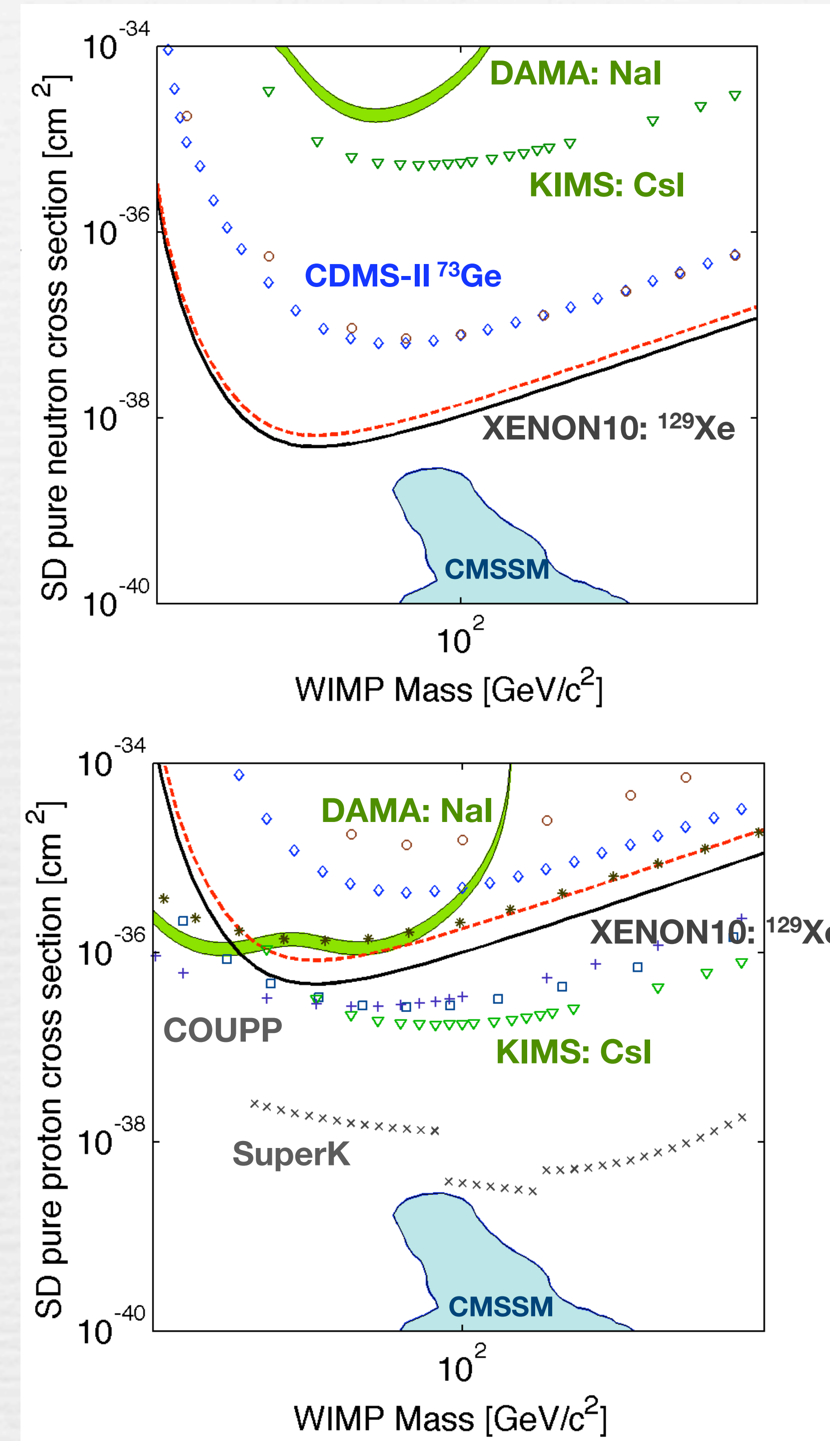
$(\sigma_n / \sigma_0 \sim (m_n^2/\mu^2)/A^2)$

Experimental results

10^{-7} pb →

10^{-8} pb →





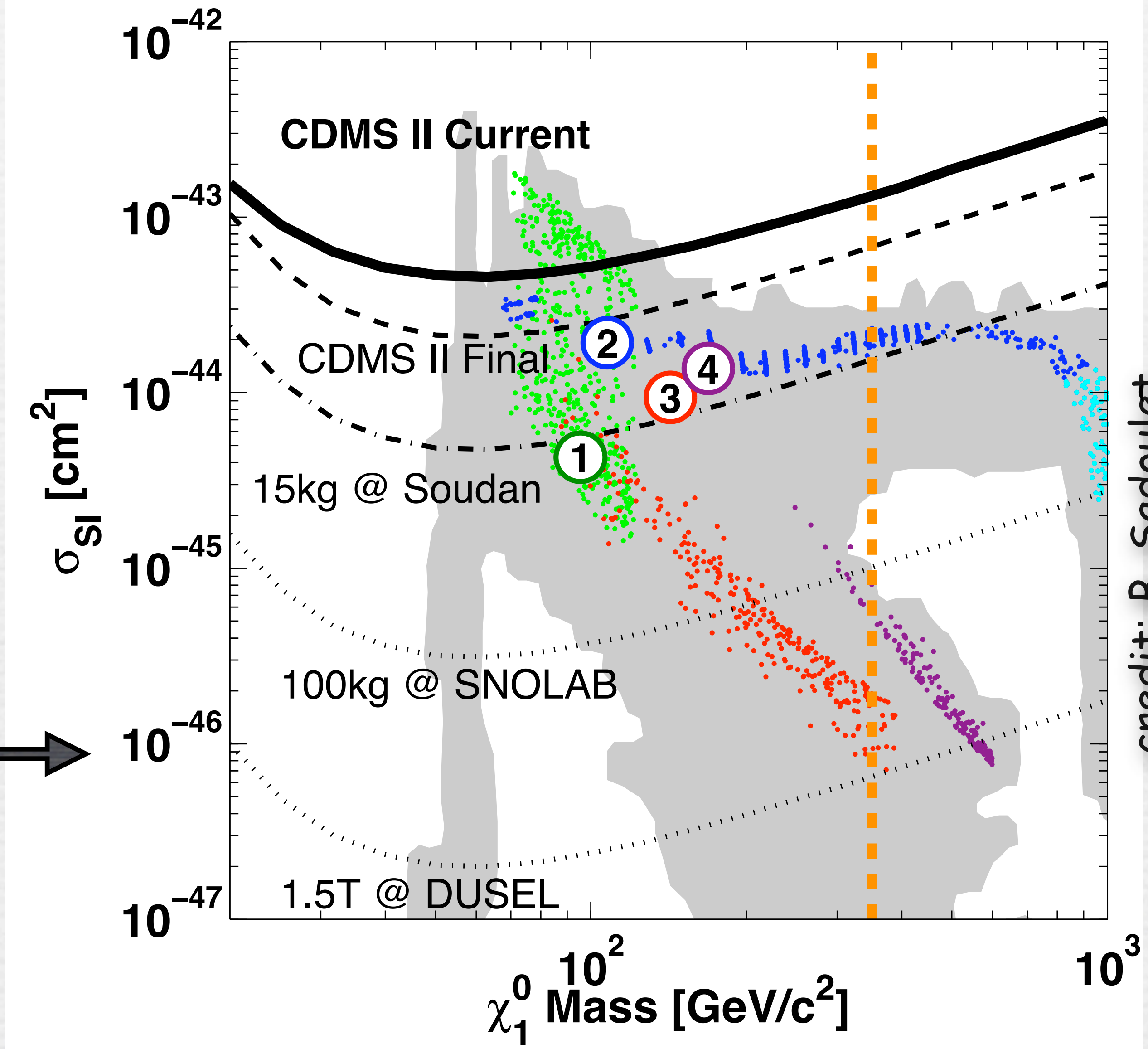
Spin-dependent

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

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

Future prospects

10^{-10} pb



WIMP indirect detection

number of annihilation events between two wimps from the local halo

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

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

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

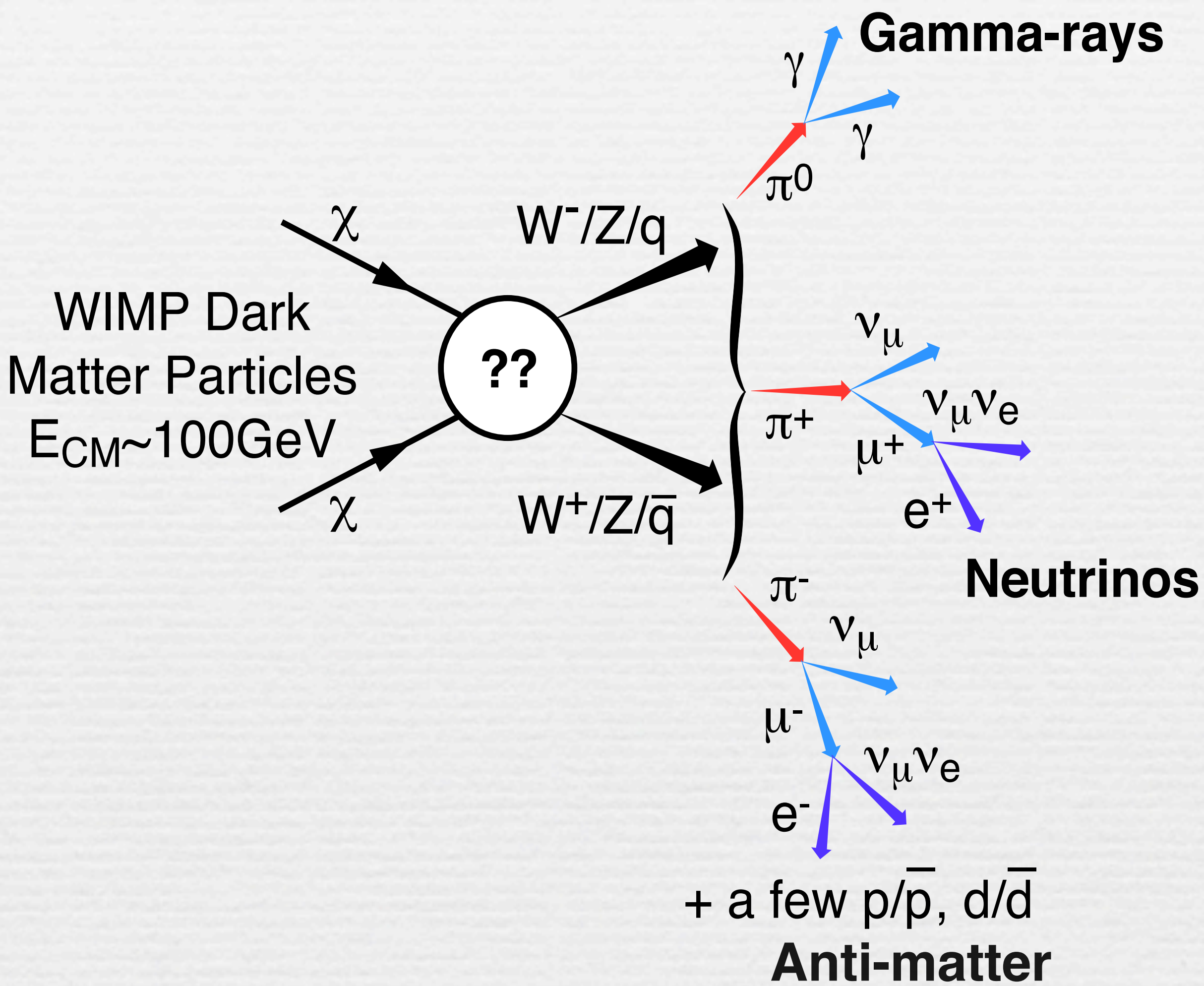
-> $N\ /year \sim\ 10^{14}\ cm^{-3}\ (GeV.cm)^{-3}\ .\ V$

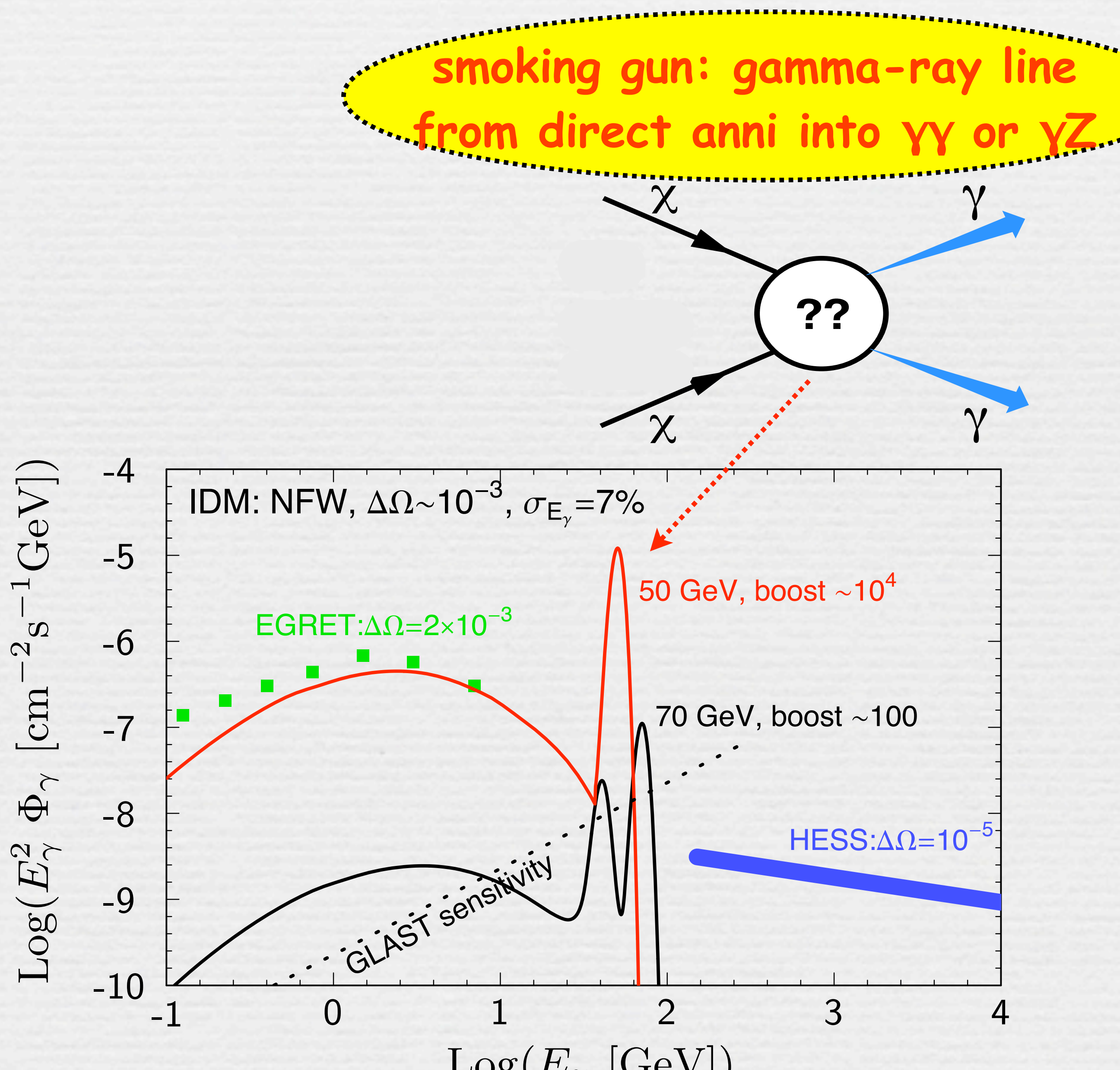
(1 s ~ $10^{24}\ GeV^{-1}$ and GeV.cm~ 10^{14})

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

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

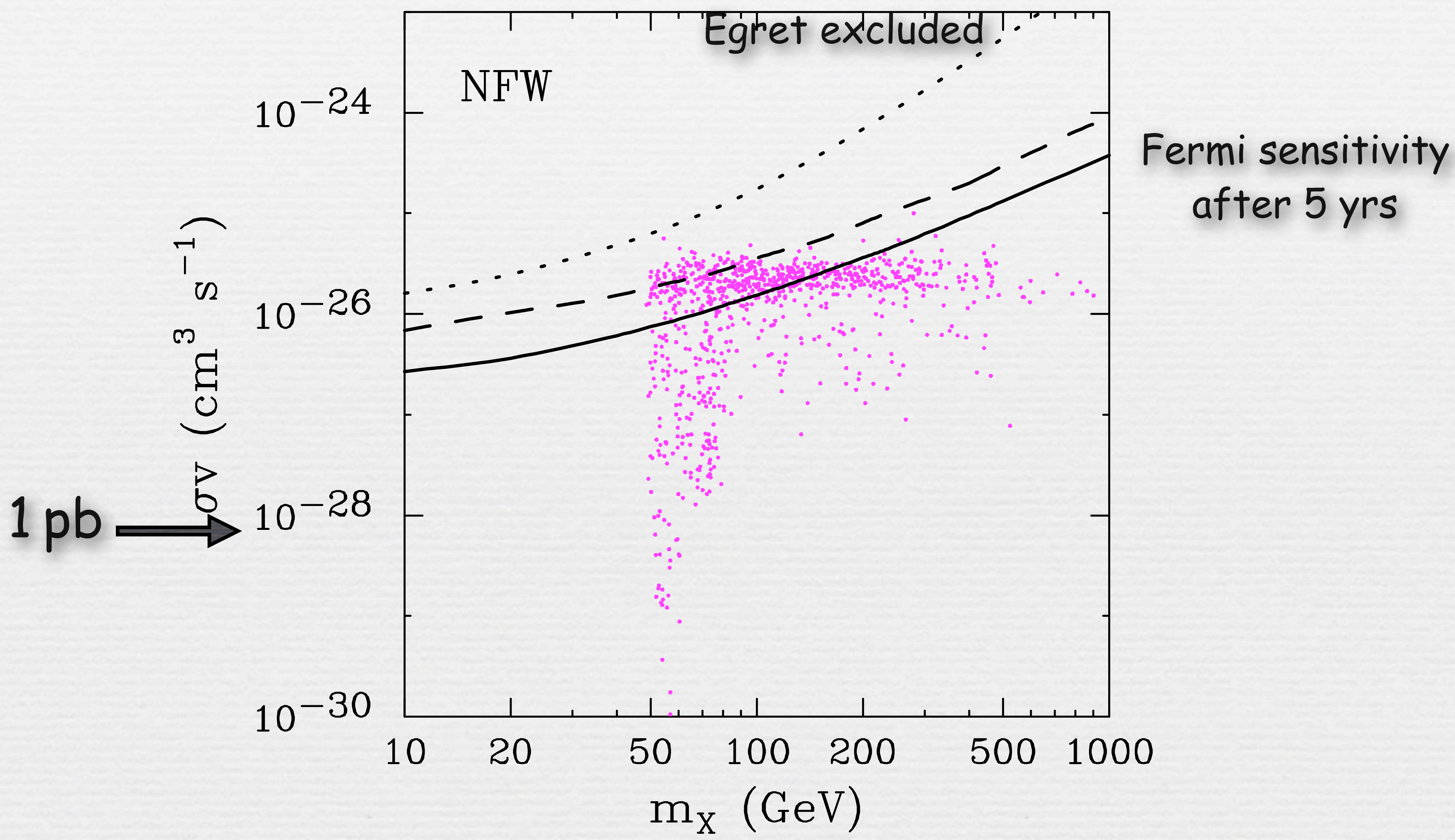
WIMP indirect detection





gamma-ray spectra

(Inert doublet model)

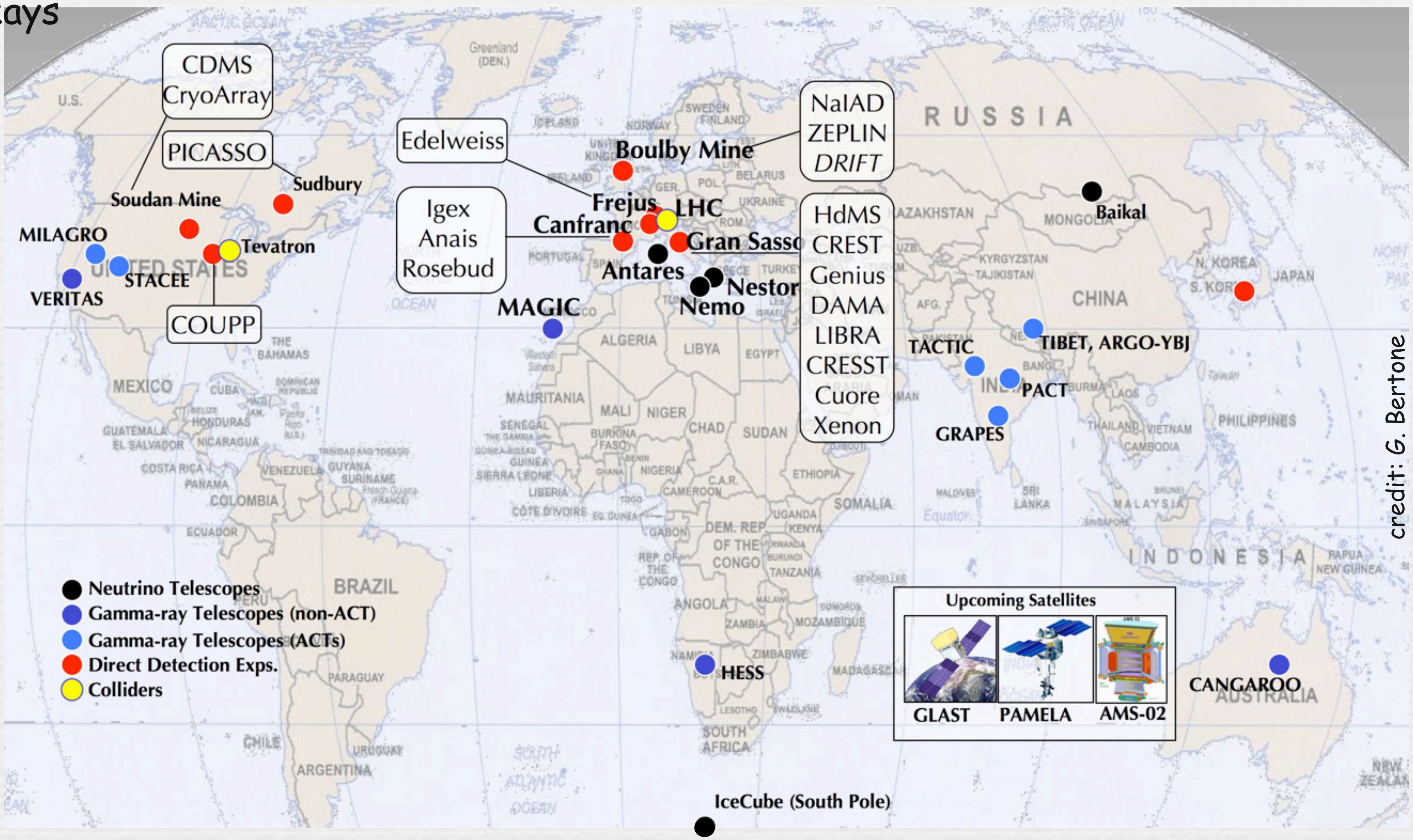


Egret excluded
NFW
Fermi sensitivity
after 5 yrs
1 pb
10^{-24}
10^{-26}
10^{-28}
10^{-30}
σv (cm^3 s^{-1})
10
20
50
100
200
500
1000
m_X (GeV)

Huge experimental effort towards the identification of Dark Matter

Indirect	Direct	Collider experiments
Signature of Annihilation	Elastic Scattering signature	Missing Energy signature

Antimatter
Neutrinos
Gamma Rays



credit: G. Bertone

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

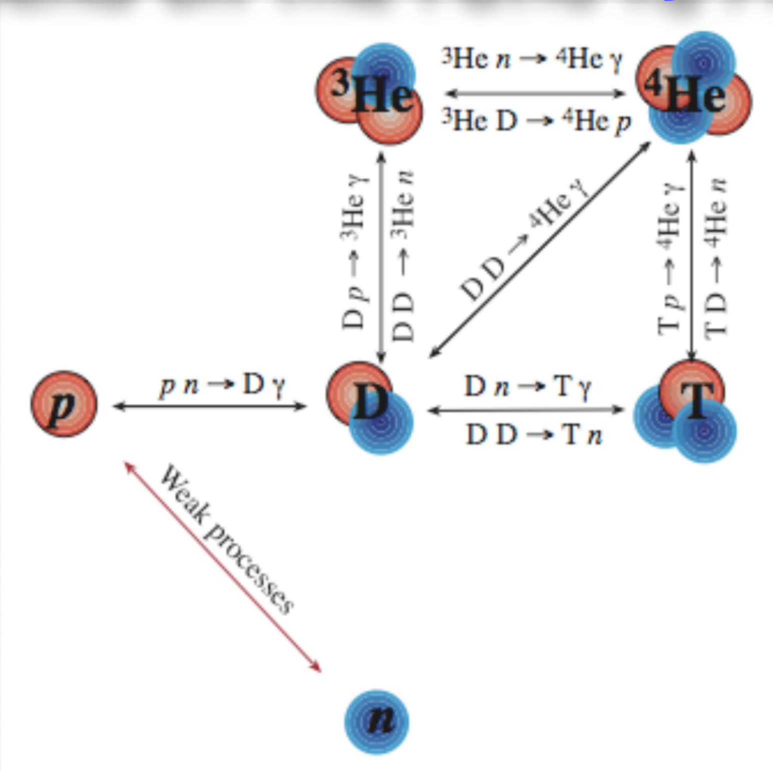
$$\frac{n_B - n_{\overline{B}}}{s} = \frac{\eta}{7.04}$$

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

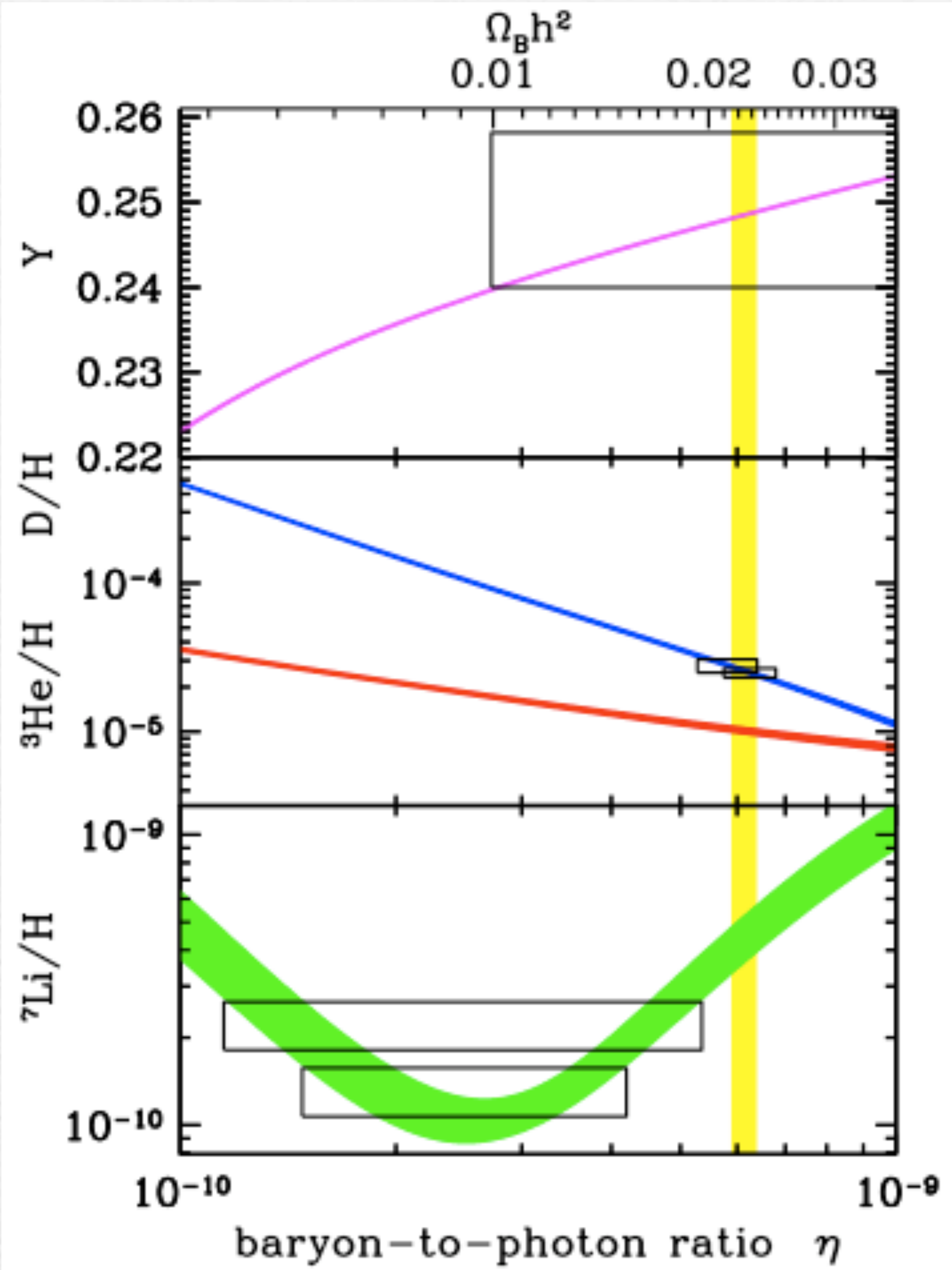
probe acoustic oscillations of the baryon/photon fluid

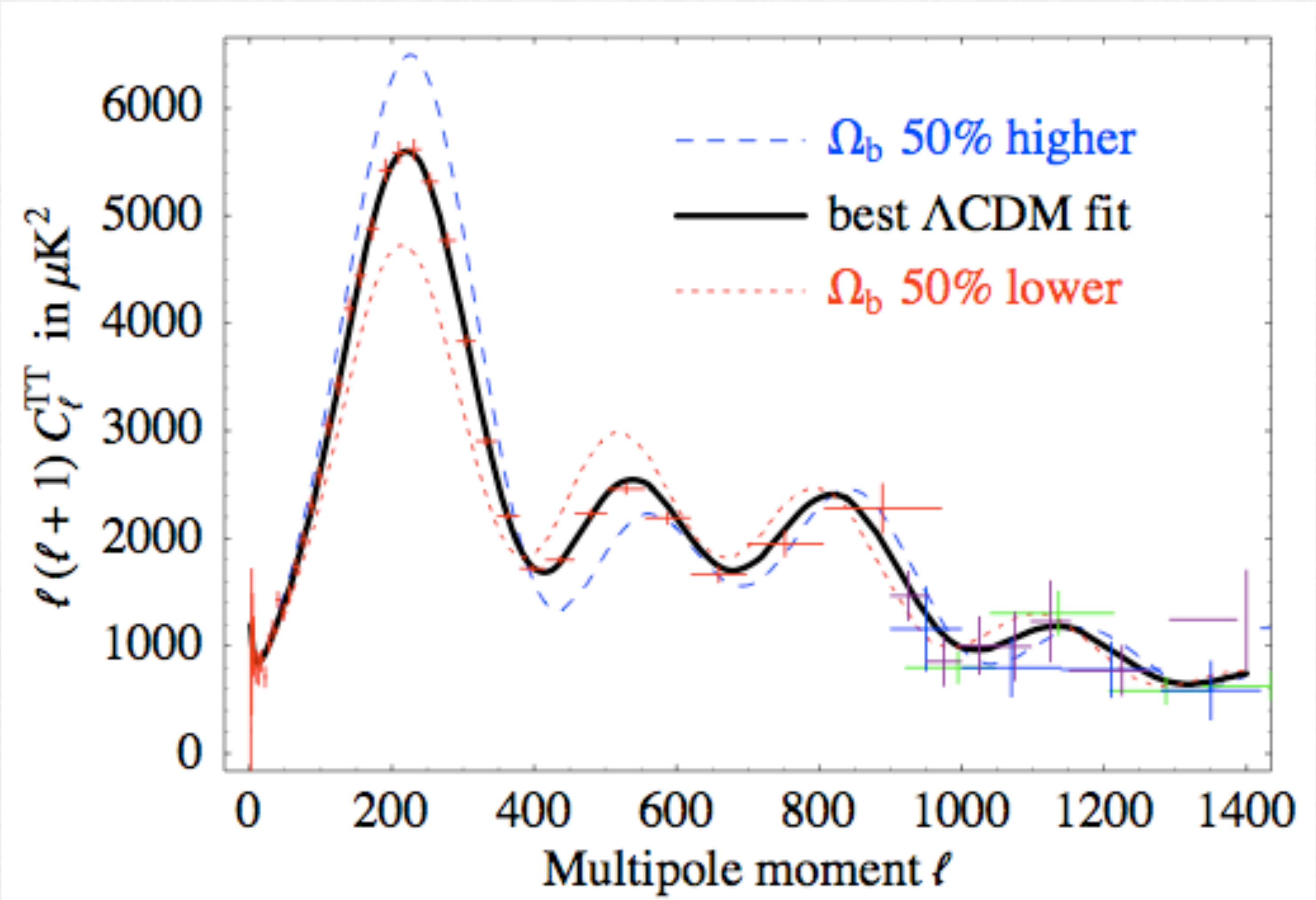
The amount of anisotropies depend on n_B / n_γ

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

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

↓

1
(us)

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) B violation

2) C and CP violation

3) Loss of thermal equilibrium

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

Why can't we achieve baryogenesis in the SM?

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)

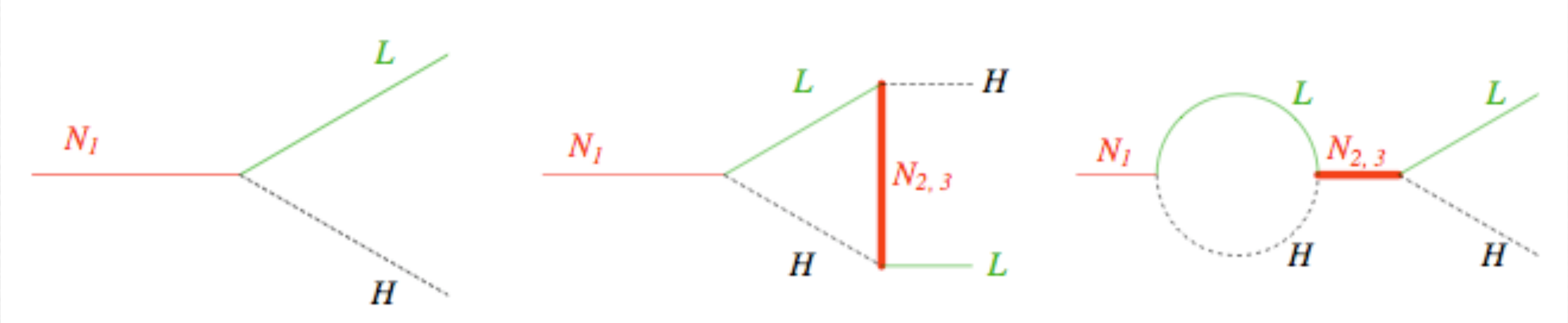
Leptogenesis

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

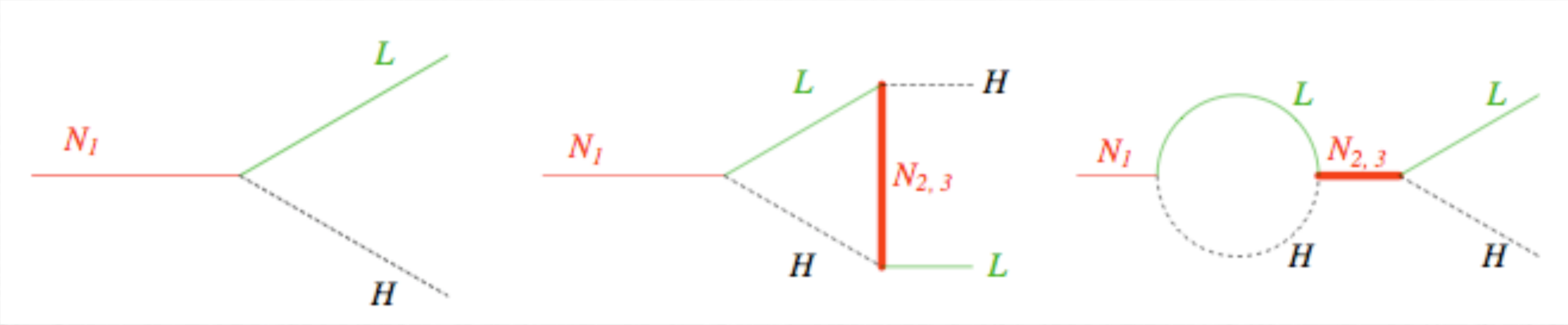
at $T \sim M_1$, this leads to $\lambda v^2/M_1 < (8\pi)\ v^2/M_{Pl} \sim$ meV

see-saw formula for m_ν

The basic physics

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{N}_1 i\partial\!\!\!/ N_1 + \lambda_1 N_1 H L + \frac{M_1}{2} N_1^2 + $$
$$+\bar{N}_{2,3} i\partial\!\!\!/ N_{2,3} + \lambda_{2,3} N_{2,3} H L + \frac{M_{2,3}}{2} N_{2,3}^2 + \text{h.c.}$$

One can redefine fields in such a way that the ineliminable CP-violating phase is in $\lambda_{2,3}$



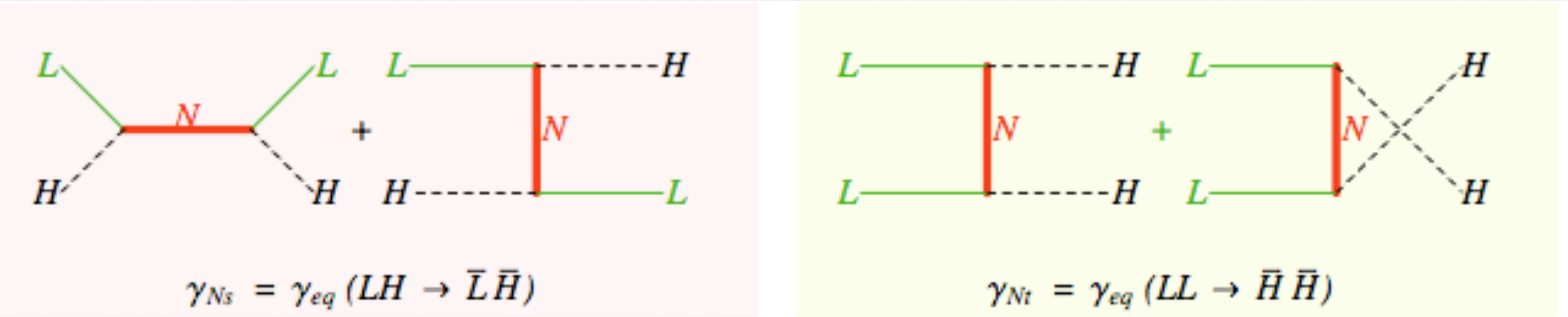
$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \overline{LH})}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \overline{LH})} \sim \frac{1}{4\pi} \frac{M_1}{M_{2,3}} \text{Im}\lambda_{2,3}^2$$

and $$\frac{n_B}{n_\gamma} \approx \frac{\epsilon_1 \eta}{g_{SM}}$$

efficiency

depends on how much decays are out-of-equilibrium and on washout of L by scatterings

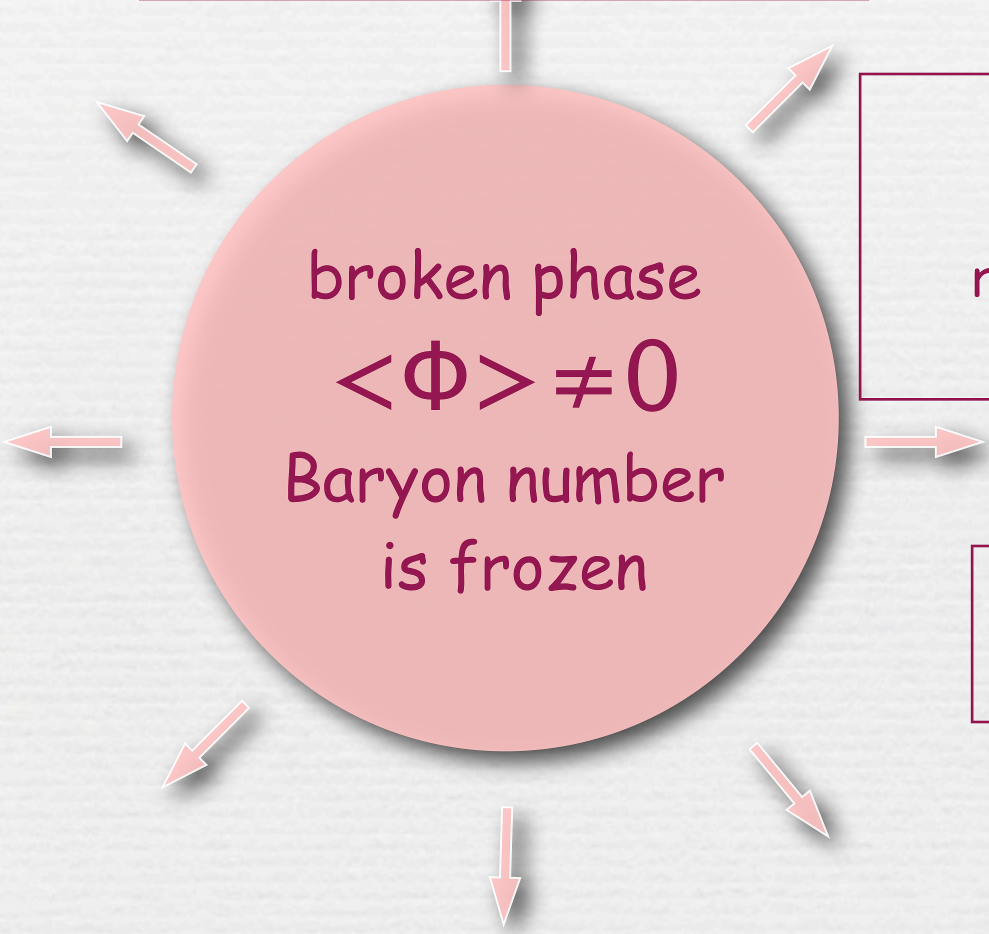
Wash-out $LH \leftrightarrow \overline{LH}$ and $LL \leftrightarrow \overline{HH}$ ΔL=2 scatterings



relevant only if $M_1 > 10^{14}$ GeV

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, $\langle\Phi\rangle = 0$, 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?

EW baryogenesis is natural ...

$$n_{\rm B} = \int_{-\infty}^{+\infty} \frac{dn_{\rm B}}{dt}\frac{dz}{v_z}$$

$$\frac{dn_{\rm B}}{dt} \sim n_{\rm B}\frac{\Gamma_{sph}}{T^3}$$

$$n_{\rm B} \propto \frac{\Gamma_{sph}}{T^3 v_z}\int_{-\infty}^{0} n_L\, dz$$

$$\Gamma_{sph} \sim 25\,\alpha_w^5 T^4 \sim \alpha_w^4 T^4 \quad \longrightarrow \quad \frac{n_{\rm B}}{s} \sim \frac{\alpha_w^4}{g_*}\epsilon_{\rm CP} \sim 10^{-10}$$

$$\longrightarrow \quad \epsilon_{\rm CP} \gtrsim 10^{-2}$$

If CP violating effects are large at weak energies, we obtain the right amount of baryon asymmetry

Rate of B violation in the EW broken phase

$$\Gamma = 2.8 \times 10^5 (\frac{\alpha_W}{4\pi})^4 \kappa C^{-7} \; T^4 \left(\frac{E_{sph}}{T}\right)^7 e^{-E_{sph}/T}$$

Arnold-McLerran'87
Khlebnikov-Shaposhnikov'88
Carson-McLerran'90
Carson-Li-McLerran-Wang'90

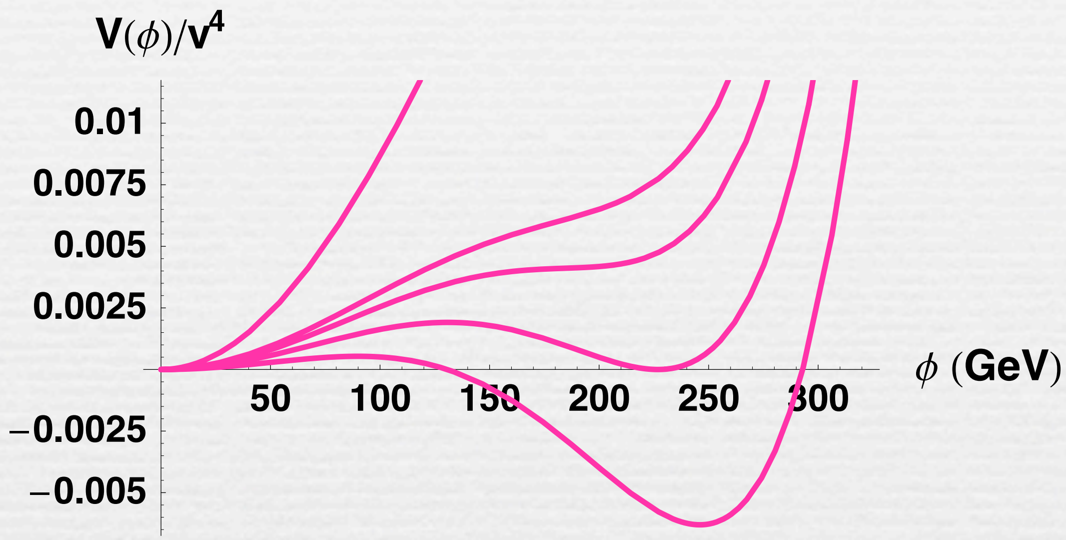
Out-of-equilibrium condition:

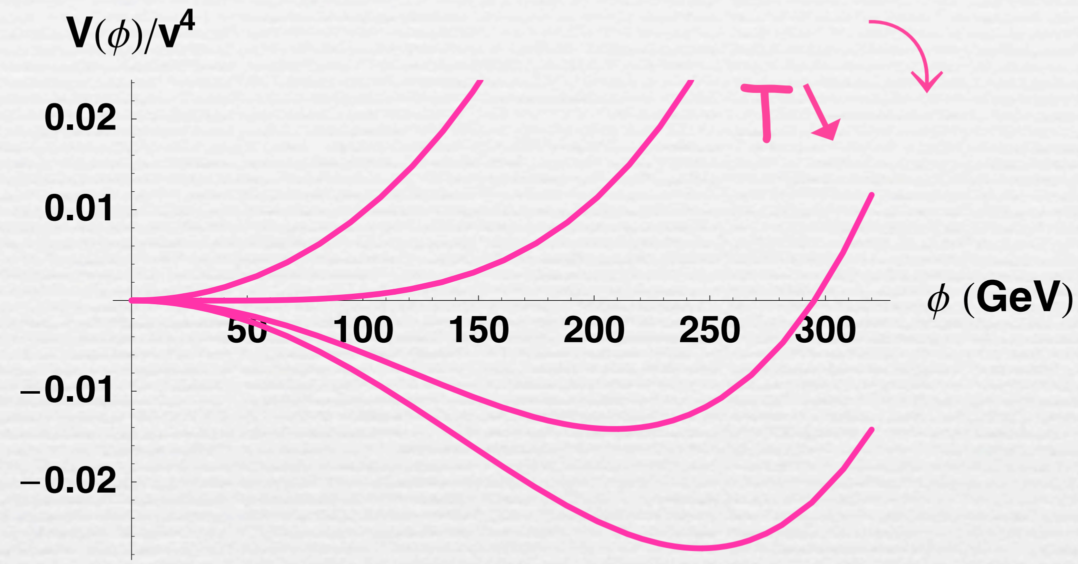
$$\frac{\Gamma}{T^3} < H \sim \frac{\sqrt{\rho}}{m_{Pl}} \quad \Rightarrow \quad \left.\frac{\langle\phi\rangle}{T}\right|_{T_c} > 1$$

=` sphaleron bound '

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...)

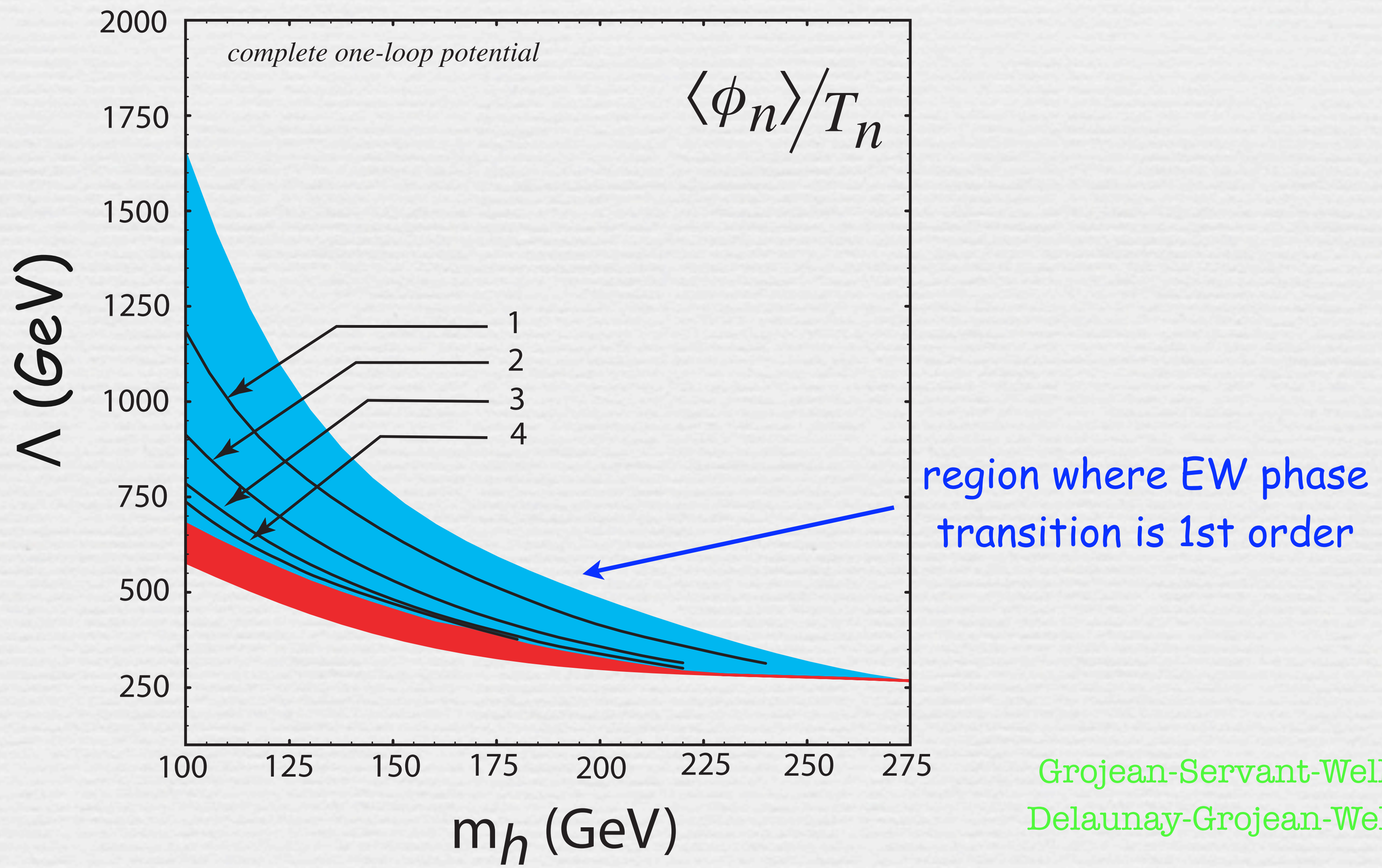
Effective field theory approach

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



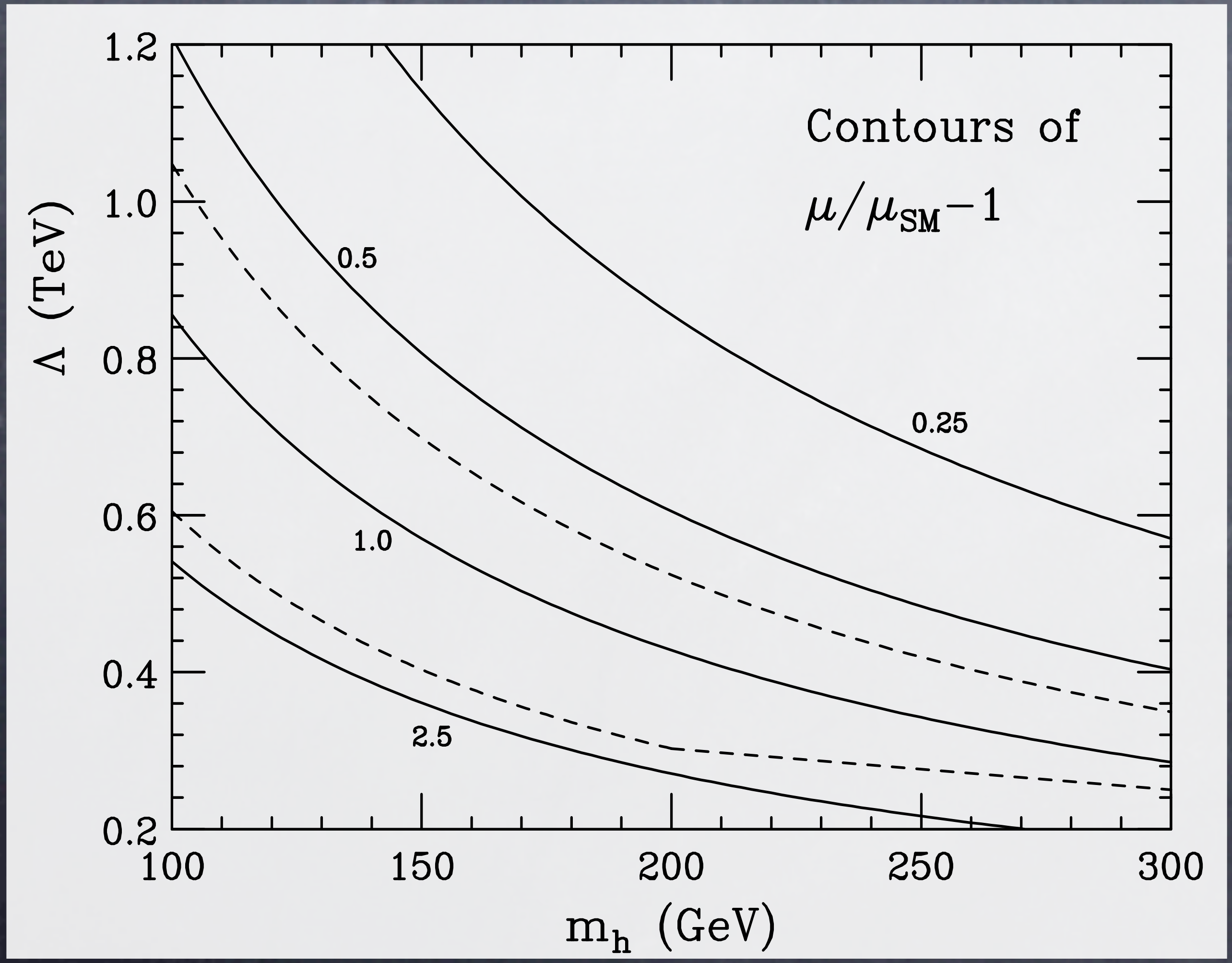
Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

This scenario predicts large deviations to the Higgs self-couplings

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

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

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

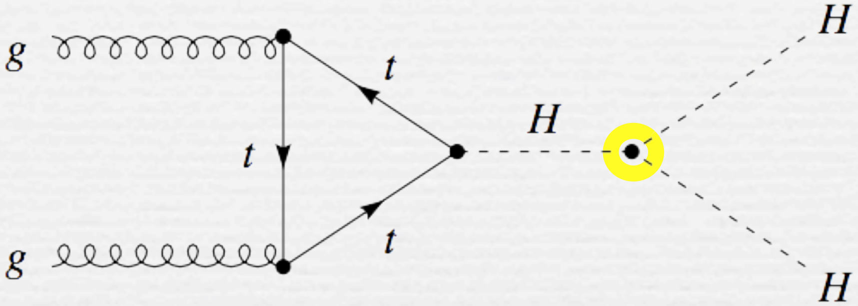


The dotted lines delimit the region for a strong 1rst order phase transition

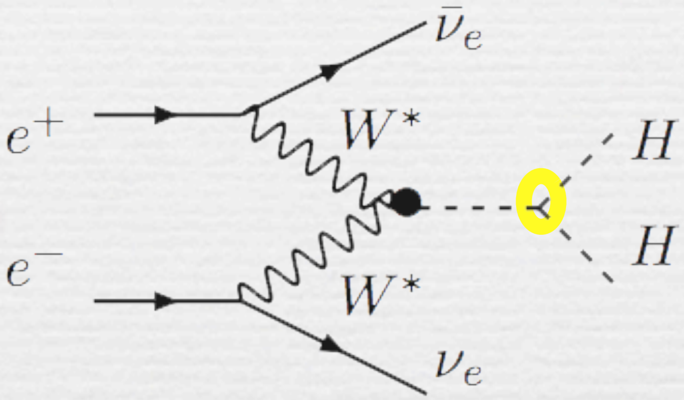
deviations between a factor 0.7 and 2

Experimental tests of the Higgs self-coupling

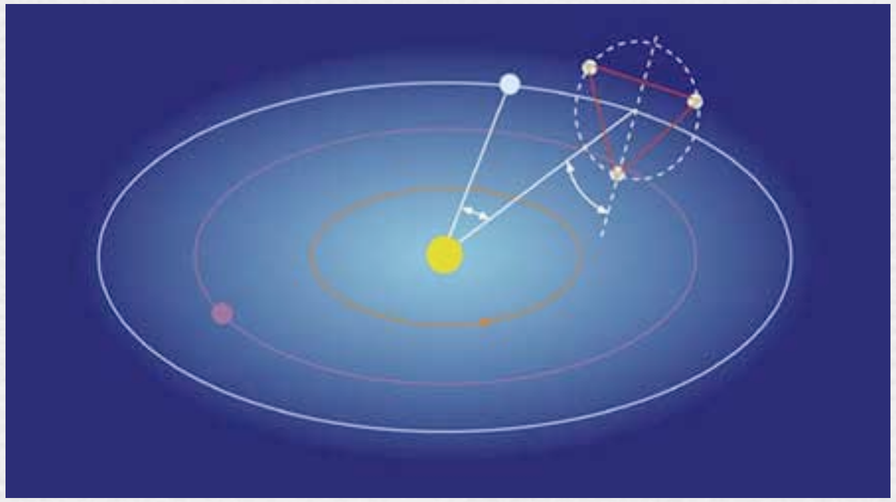
at a Hadron Collider

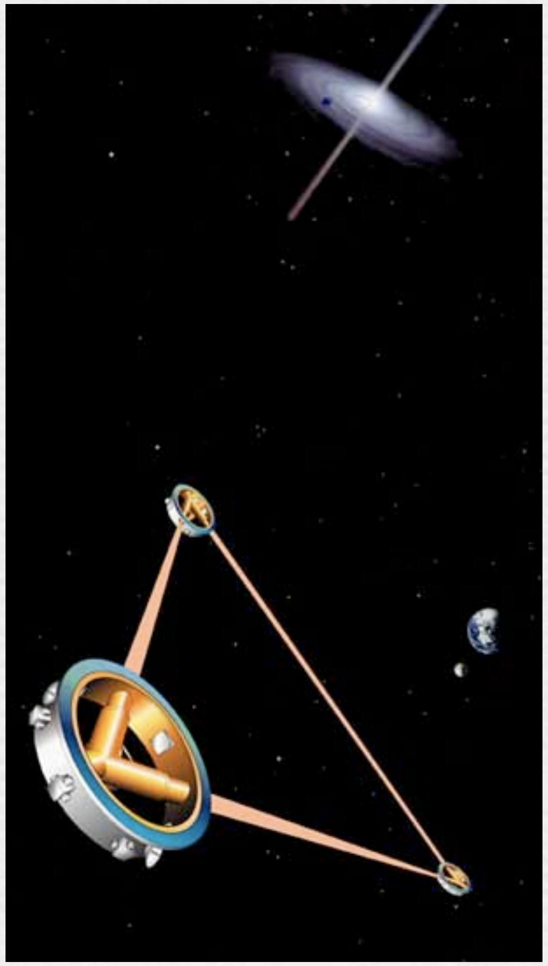


at an $e^+ e^-$ Linear Collider



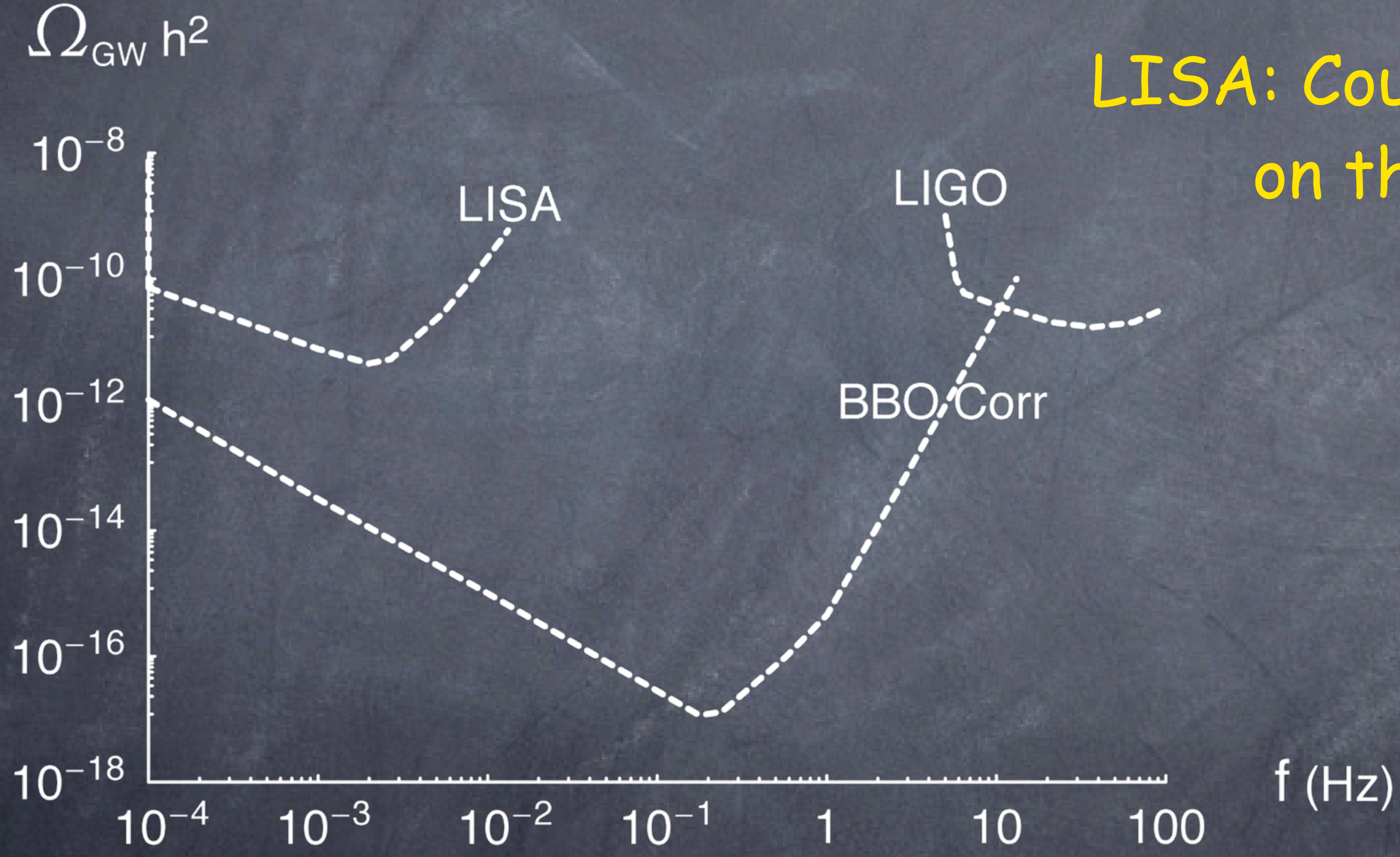
... or at the gravitational wave detector LISA





Something exciting about the milliHertz frequency

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



LISA: Could be a new window on the Weak Scale

LISA band:

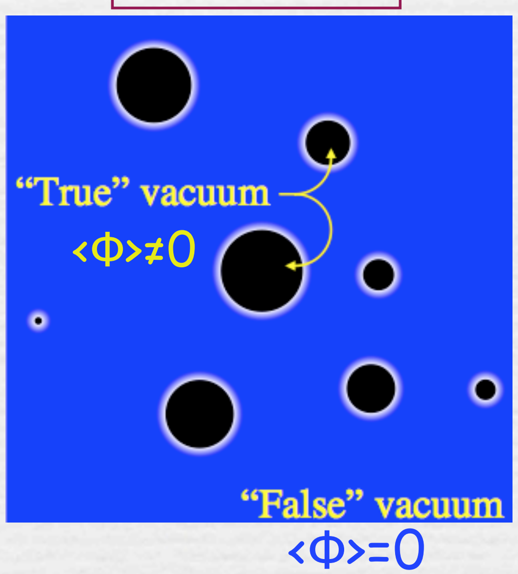
$10^{-4} - 10^{-2}$ Hz

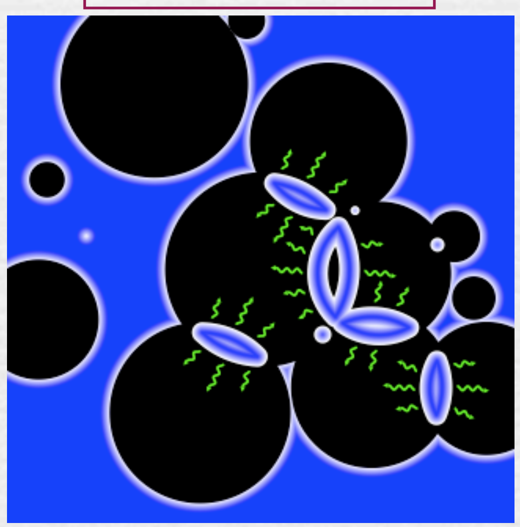
complementary to collider informations

Gravitational Wave Spectrum of the electroweak phase transition

Bubble nucleation

Bubble percolation

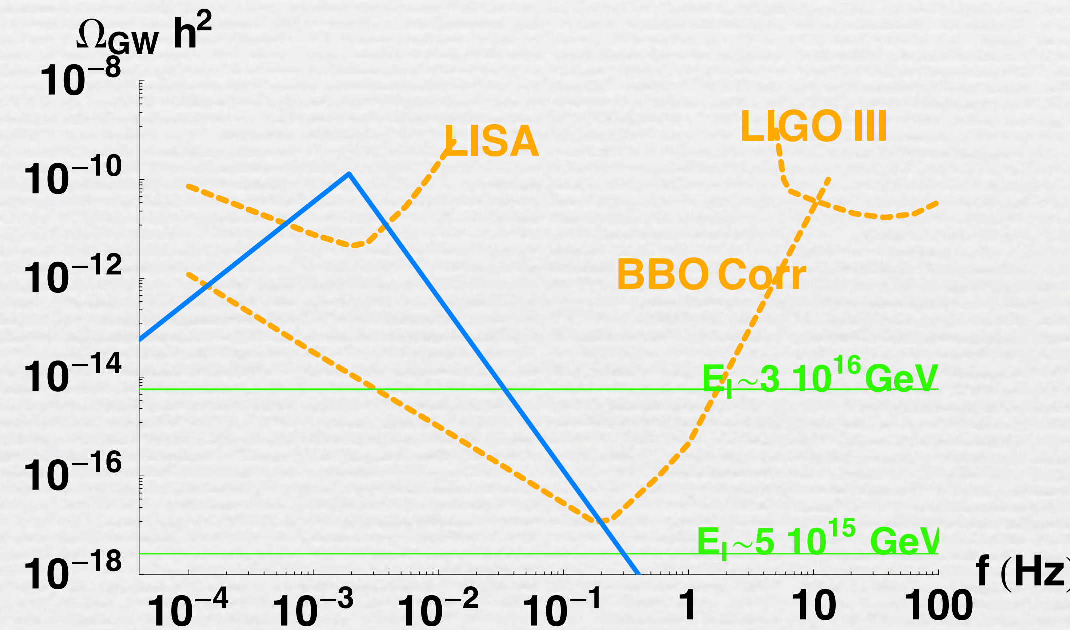




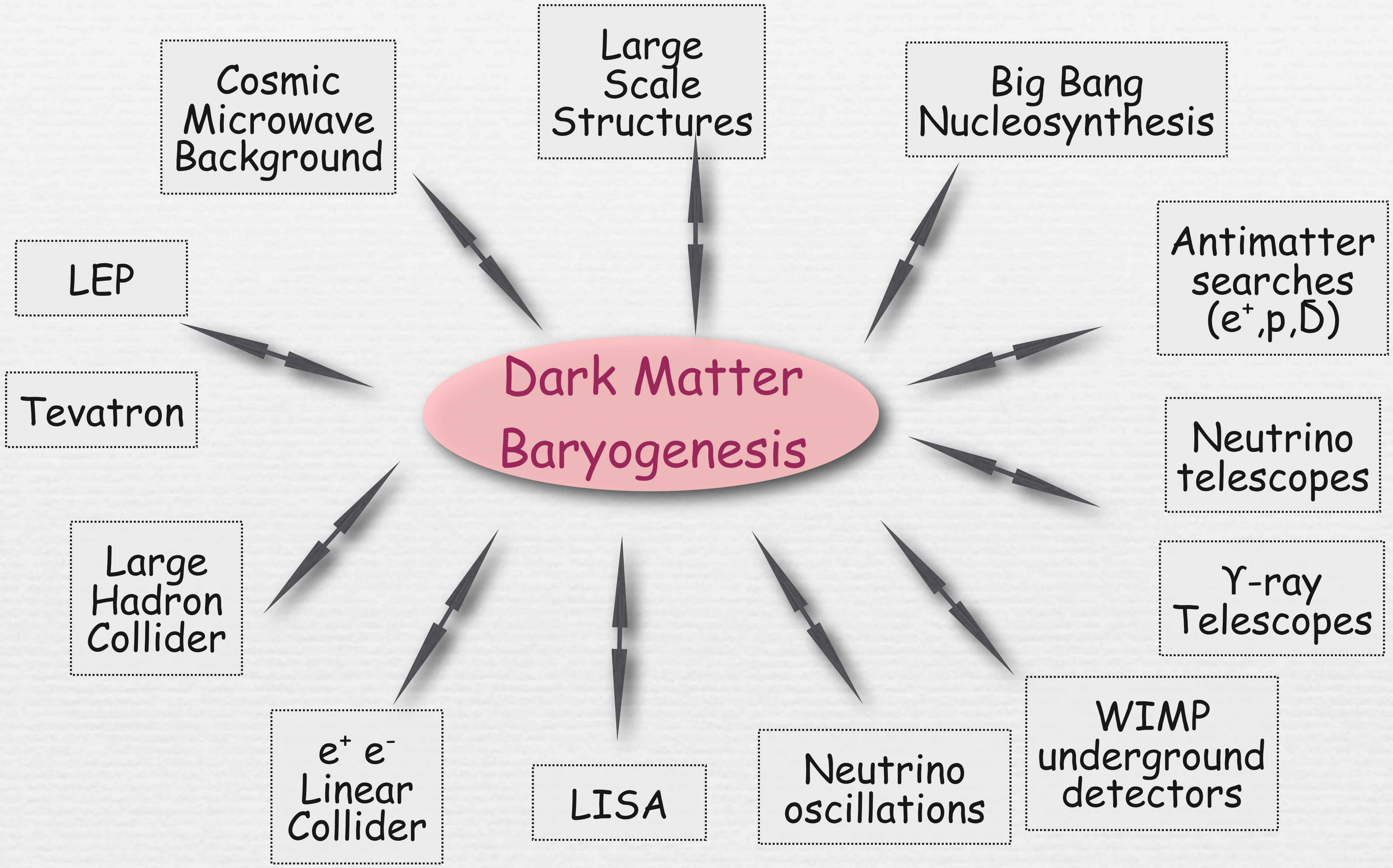
Fluid flows

Magnetic fields

Stochastic background of gravitational radiation



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



An opportunity to enjoy interdisciplinarity

To conclude

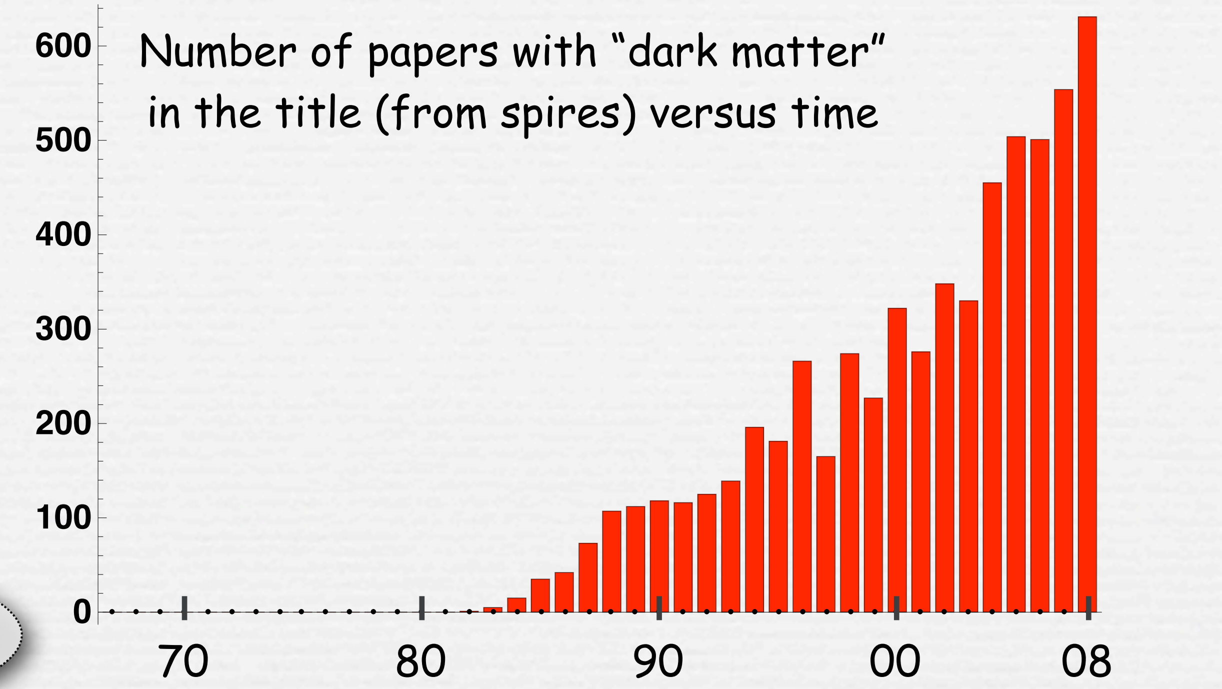
A blooming field

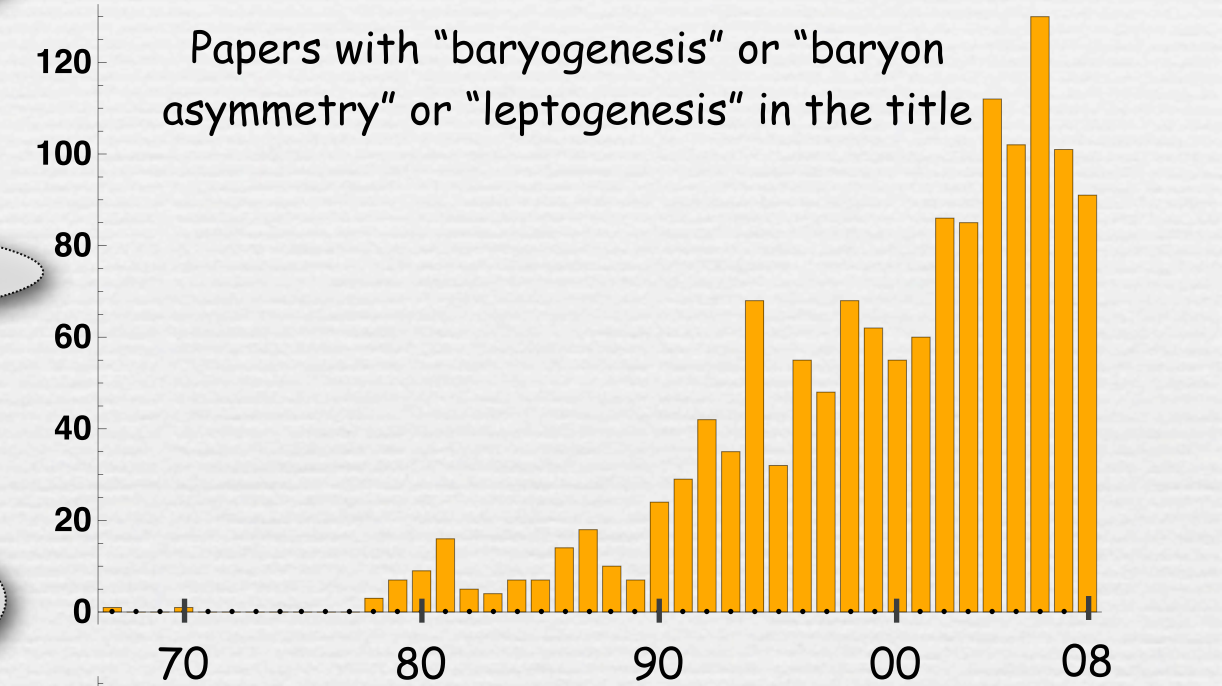
Abundance of experimental activity related to dark matter searches

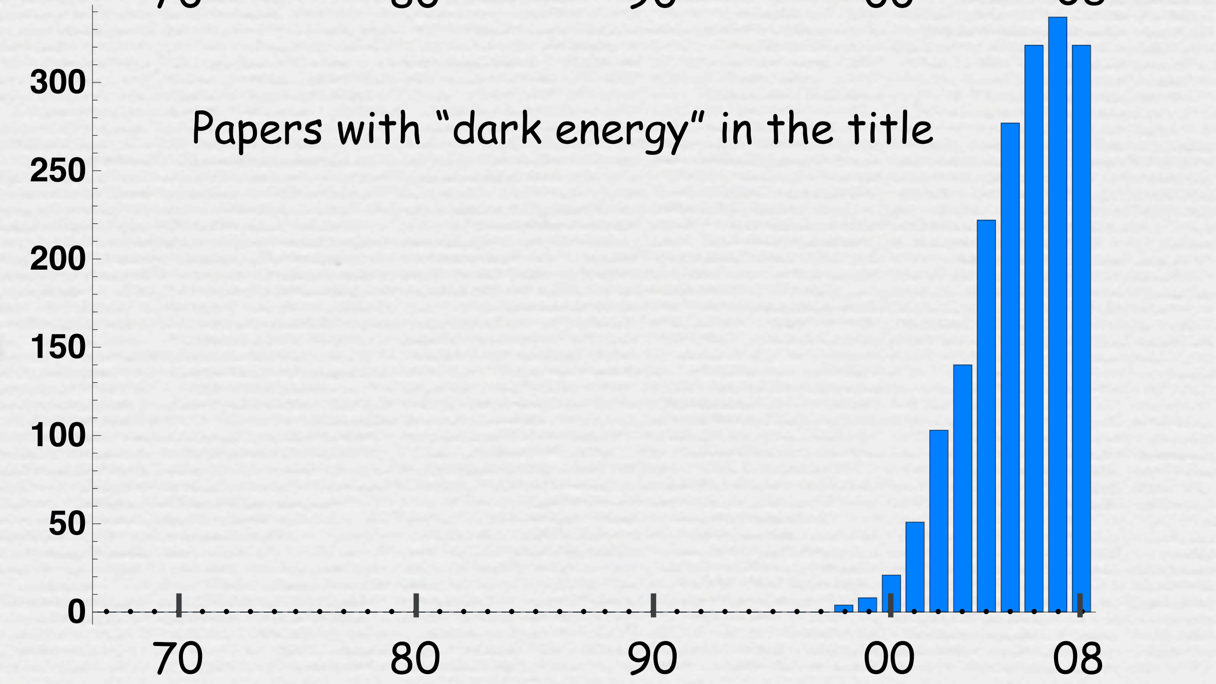
still much activity in model building

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

with a large variety of signatures



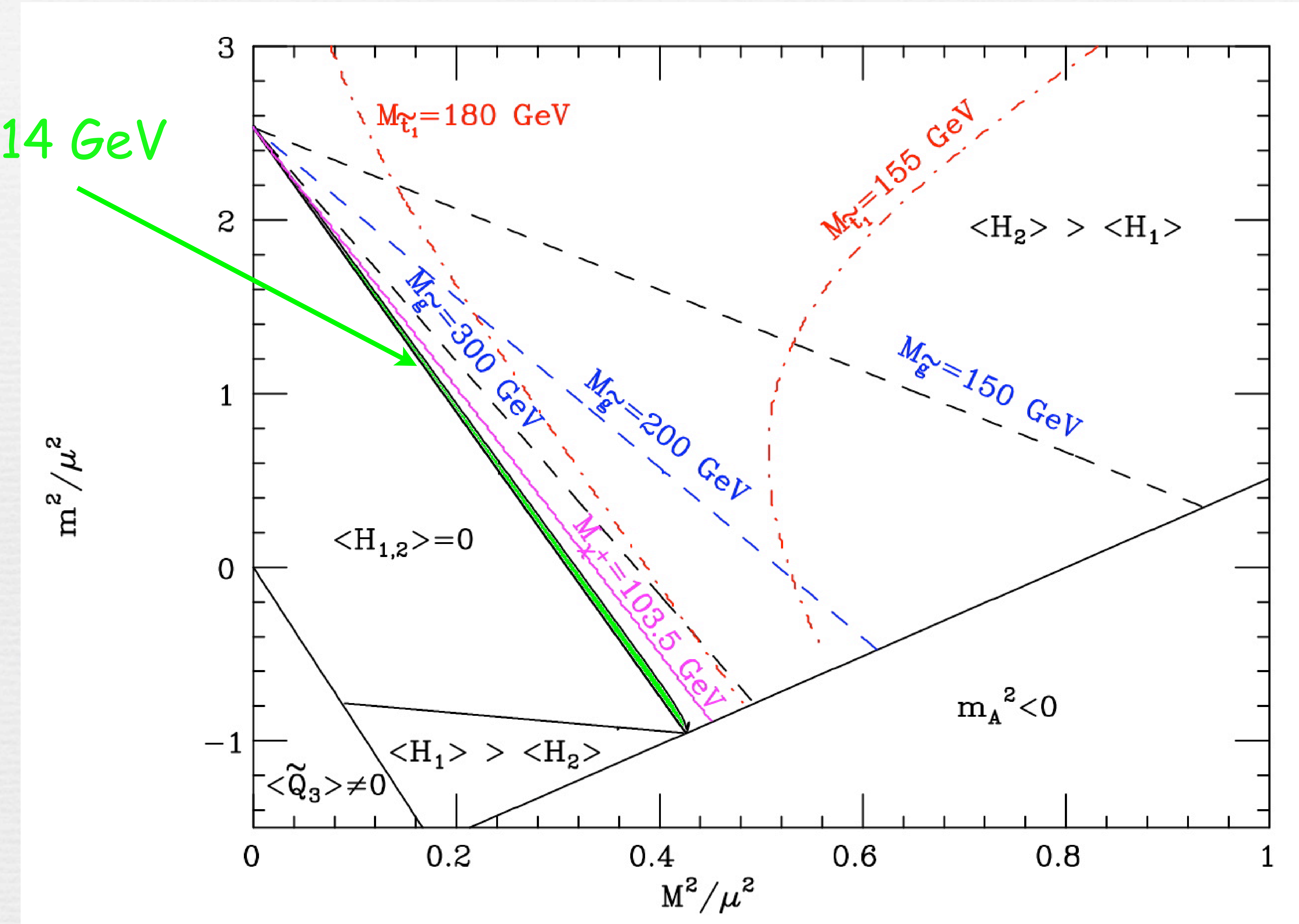




Annexes

State of mSUGRA

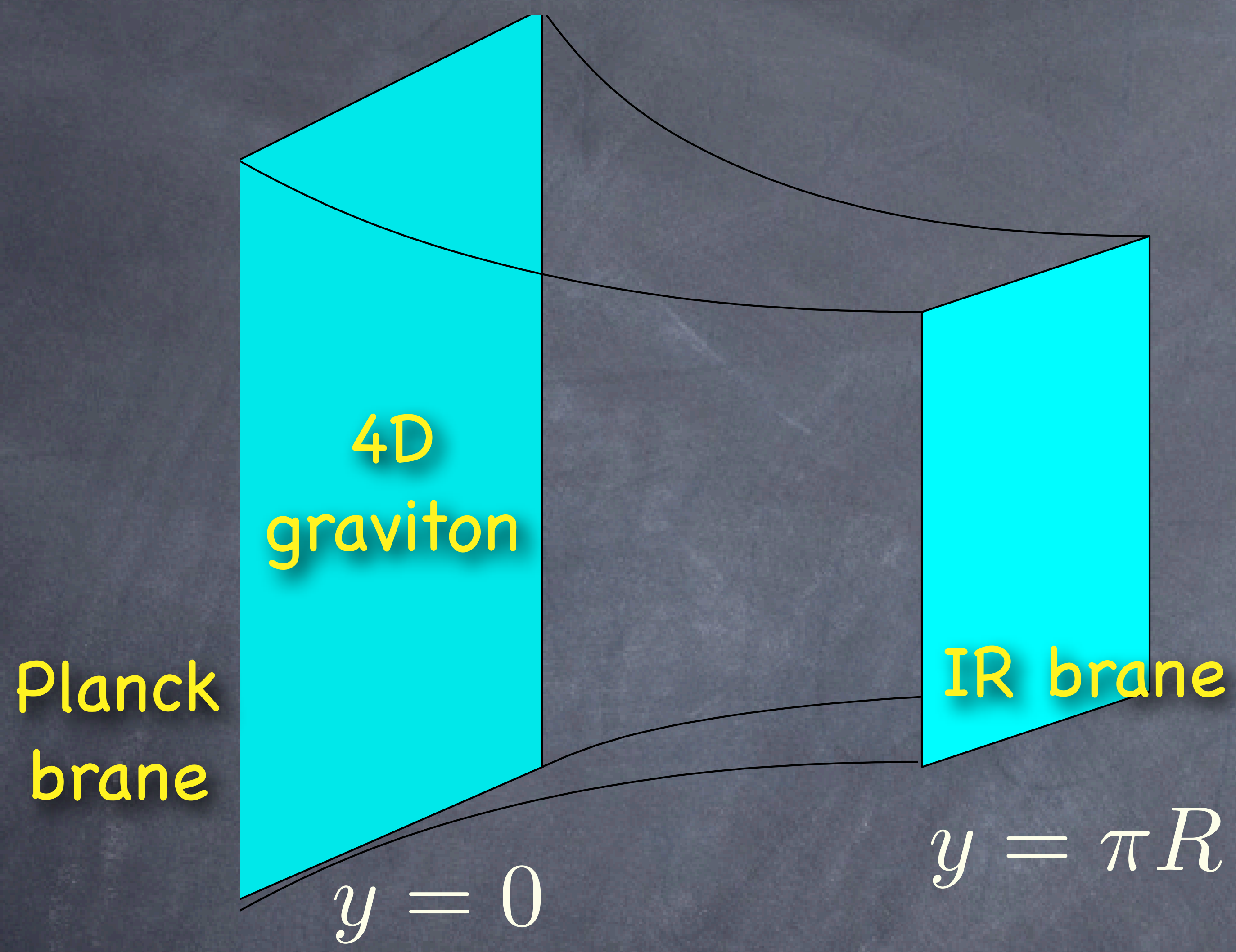
$m_h > 114$ GeV



[Giudice & Rattazzi, ‘06]

Space-time is a slice of AdS_5

[Randall, Sundrum '99]



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

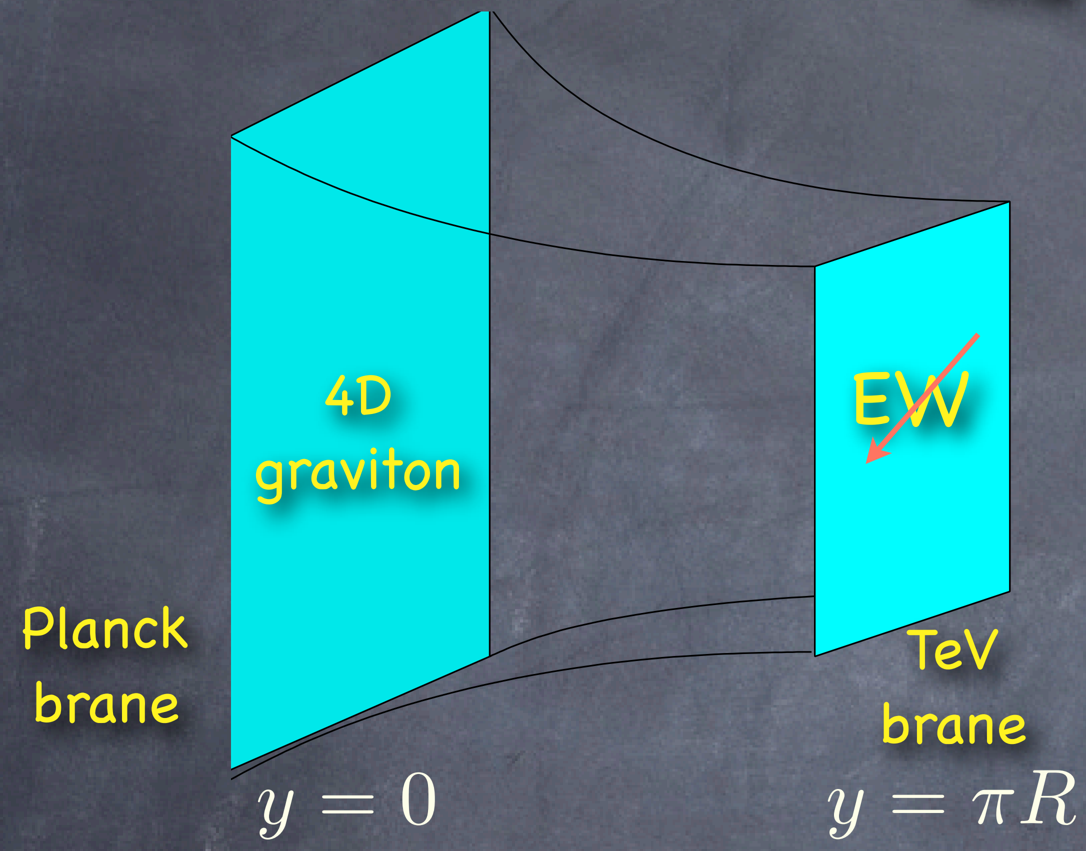
$$M_{Pl}^2 \sim \frac{M_5^3}{k}$$

The effective 4D energy scale varies with position along 5th dimension

RS1 (has two branes) versus RS2 (only Planck brane)

Solution to the Planck/Weak scale hierarchy

The Higgs (or any alternative EW breaking) is localized at y=πR, on the TeV (IR) brane



After canonical normalization of the Higgs:

$$v_{\text{eff}} = v_0 e^{-k\pi R}$$

parameter in the 5D lagrangian

$$k\pi R \sim \log\left(\frac{M_{Pl}}{\text{TeV}}\right)$$

Exponential hierarchy from O(10) hierarchy in the 5D theory

One Fondamental scale : $M_5 \sim M_{Pl} \sim k \sim \Lambda_5/k \sim r^{-1}$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

Warped hierarchies are radiatively stable as cutoff scales get warped down near the IR brane