Cosmological consequences of new physics at the TeV scale

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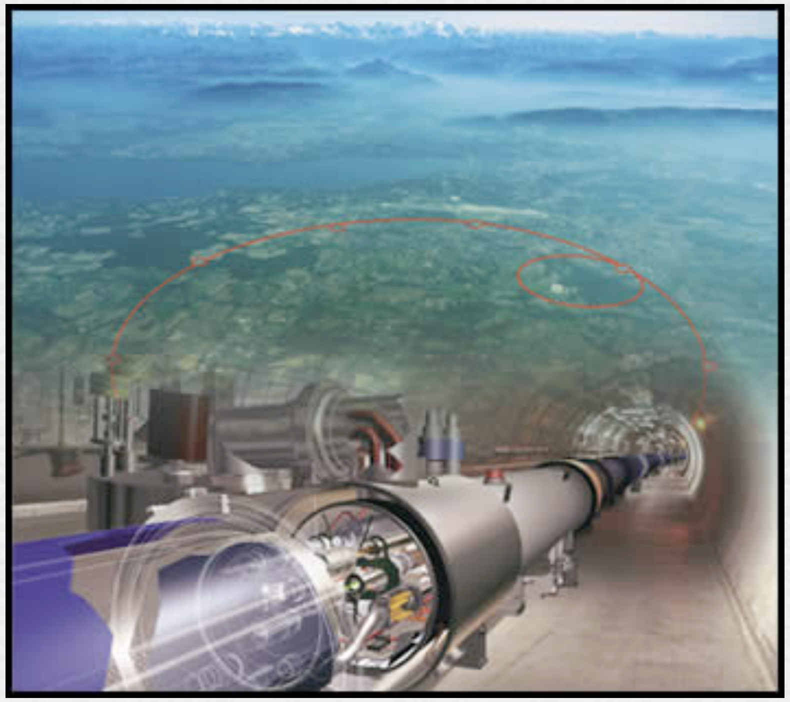
2010: First collisions at the LHC

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

Forces — **Matter** — **Background**

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

gauge sector

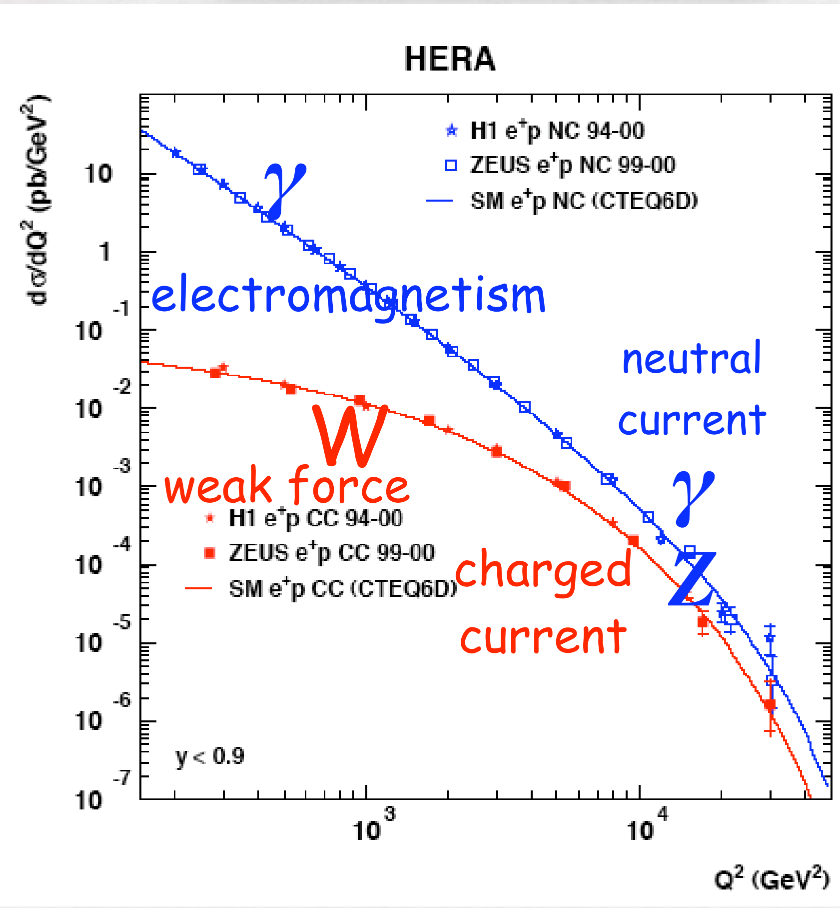
flavour sector

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

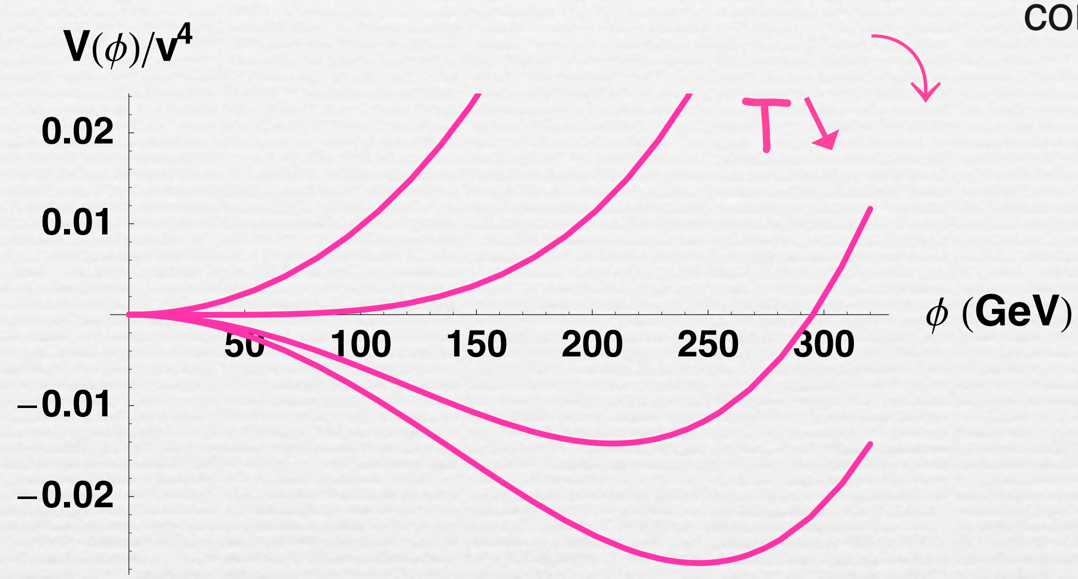


The Higgs is the only remaining unobserved piece

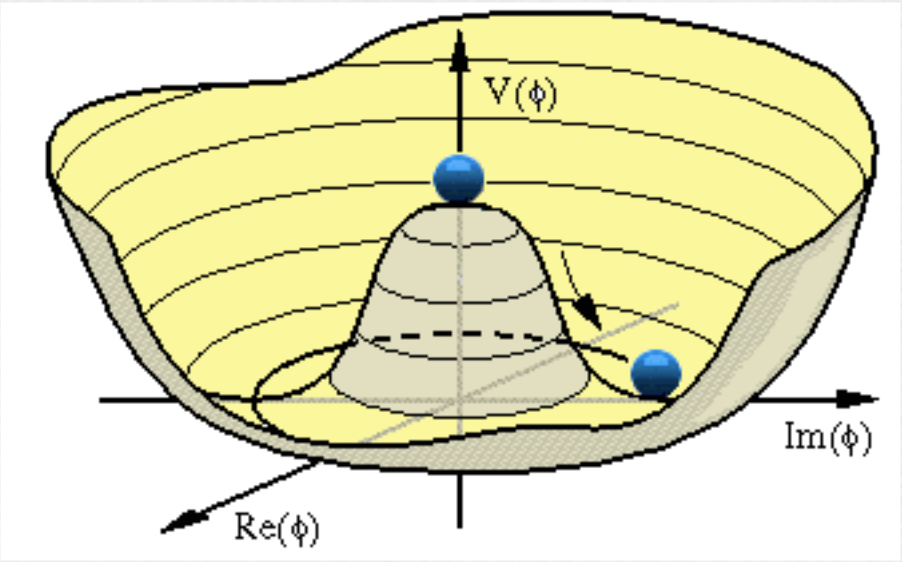
and a portal to new physics hidden sectors

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.

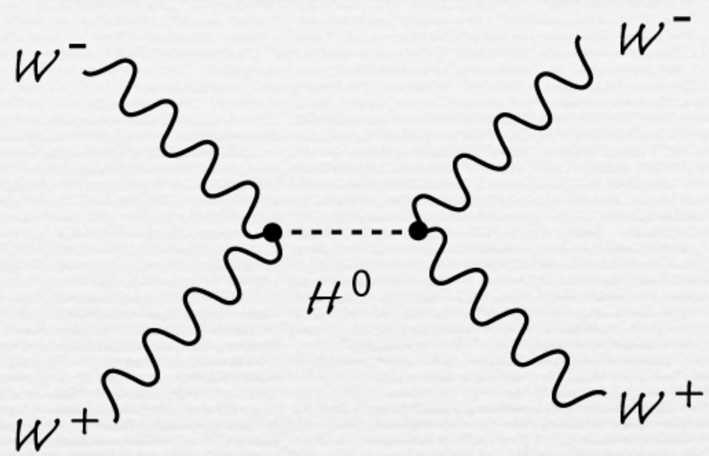


the puzzle:

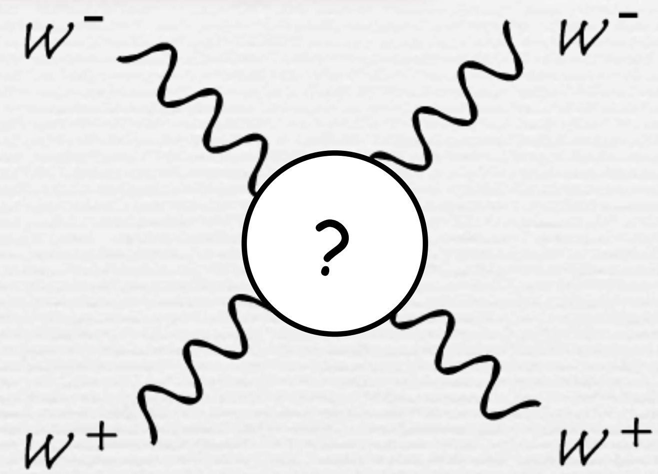
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

Electroweak symmetry breaking: 2 main questions

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

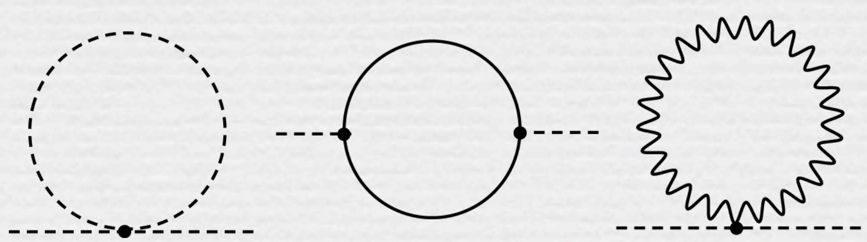


the Higgs or something else?



- **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...

$\boxed{\rightarrow \text{ theoretical need for new physics at the TeV scale}}$

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 ?

What questions the LHC experiments should try to answer :

Does a Higgs boson exist ?

If yes :

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

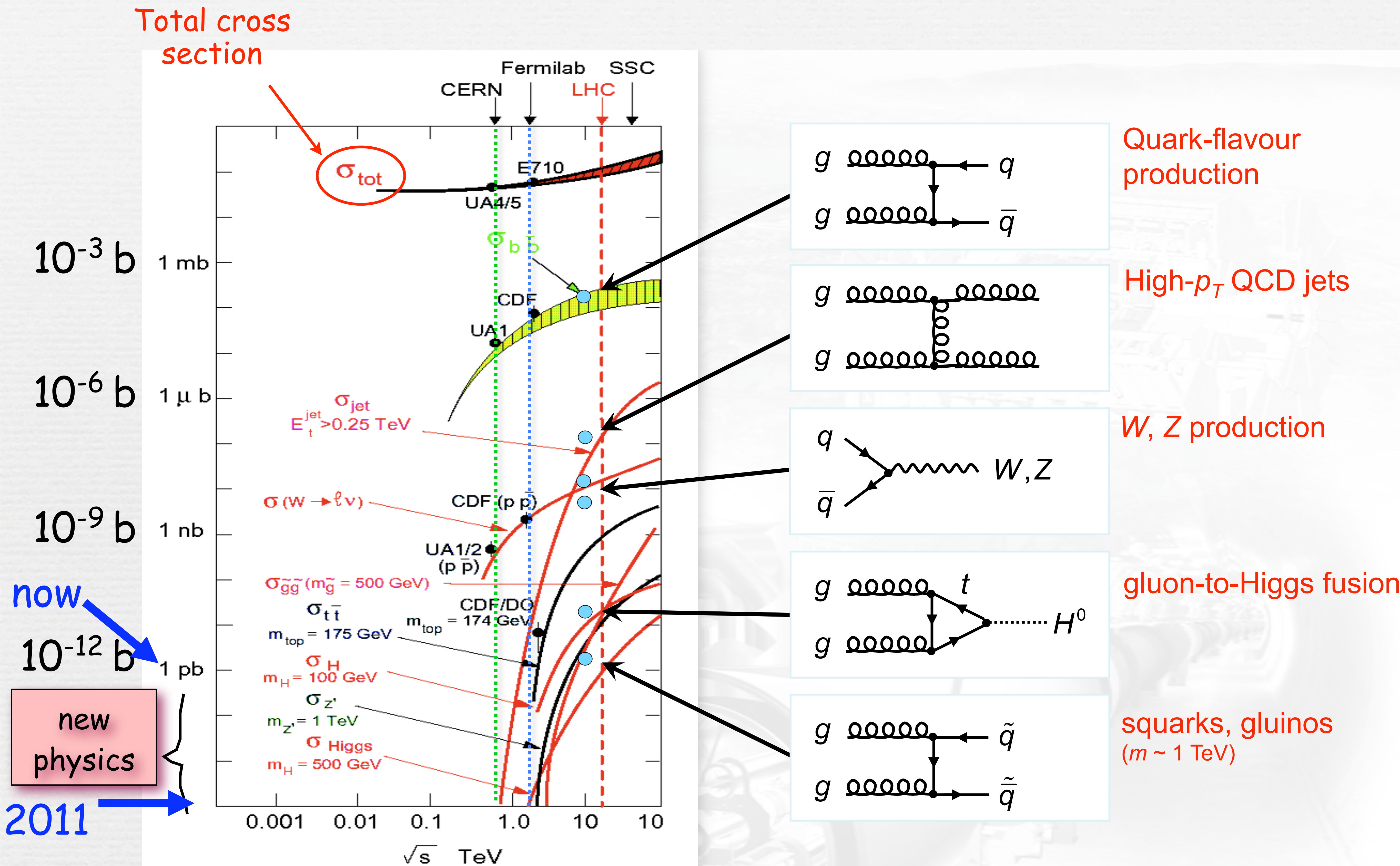
If no :

be ready for

- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as

W’, Z’ (KK) resonances, technicolor, etc...

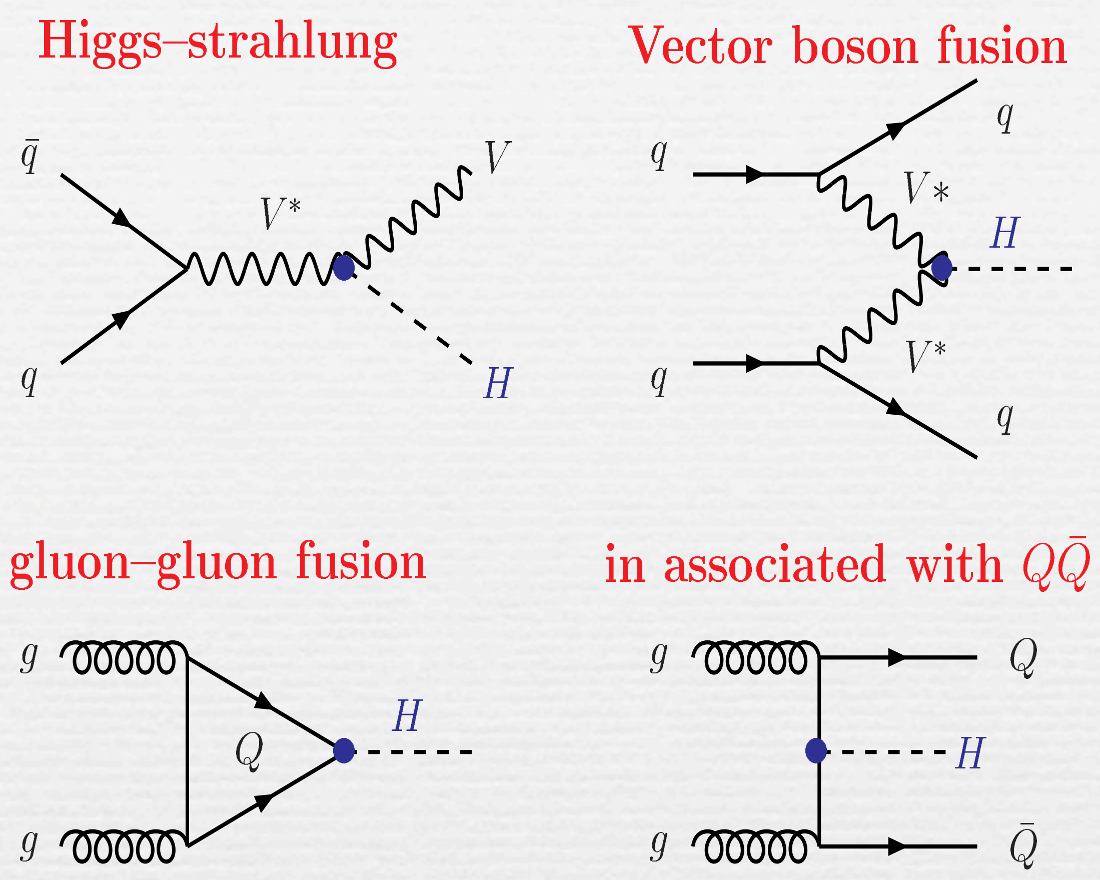
Event rate at hadron ($p\overset{(-)}{p}$) colliders

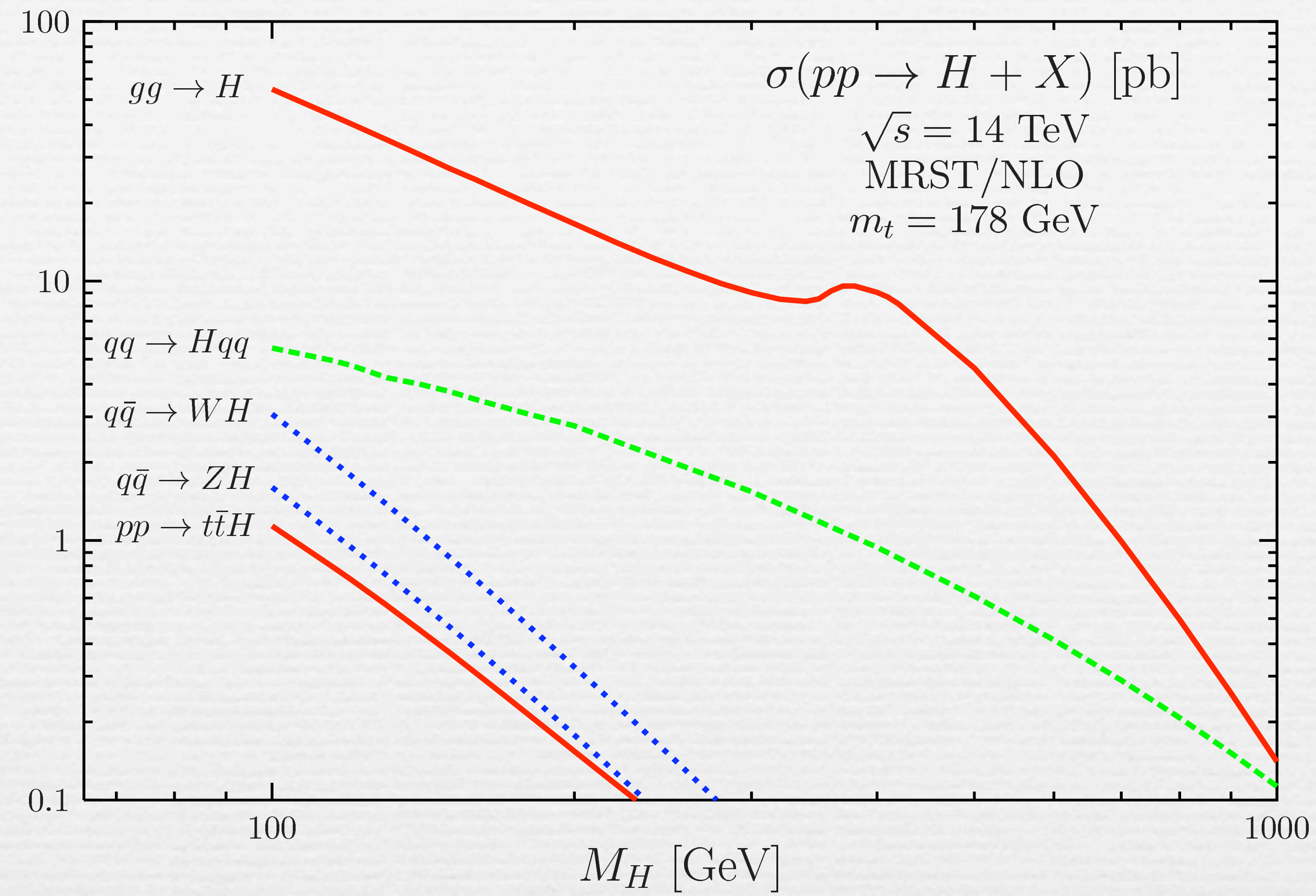


Higgs event= 1/(10 billions)

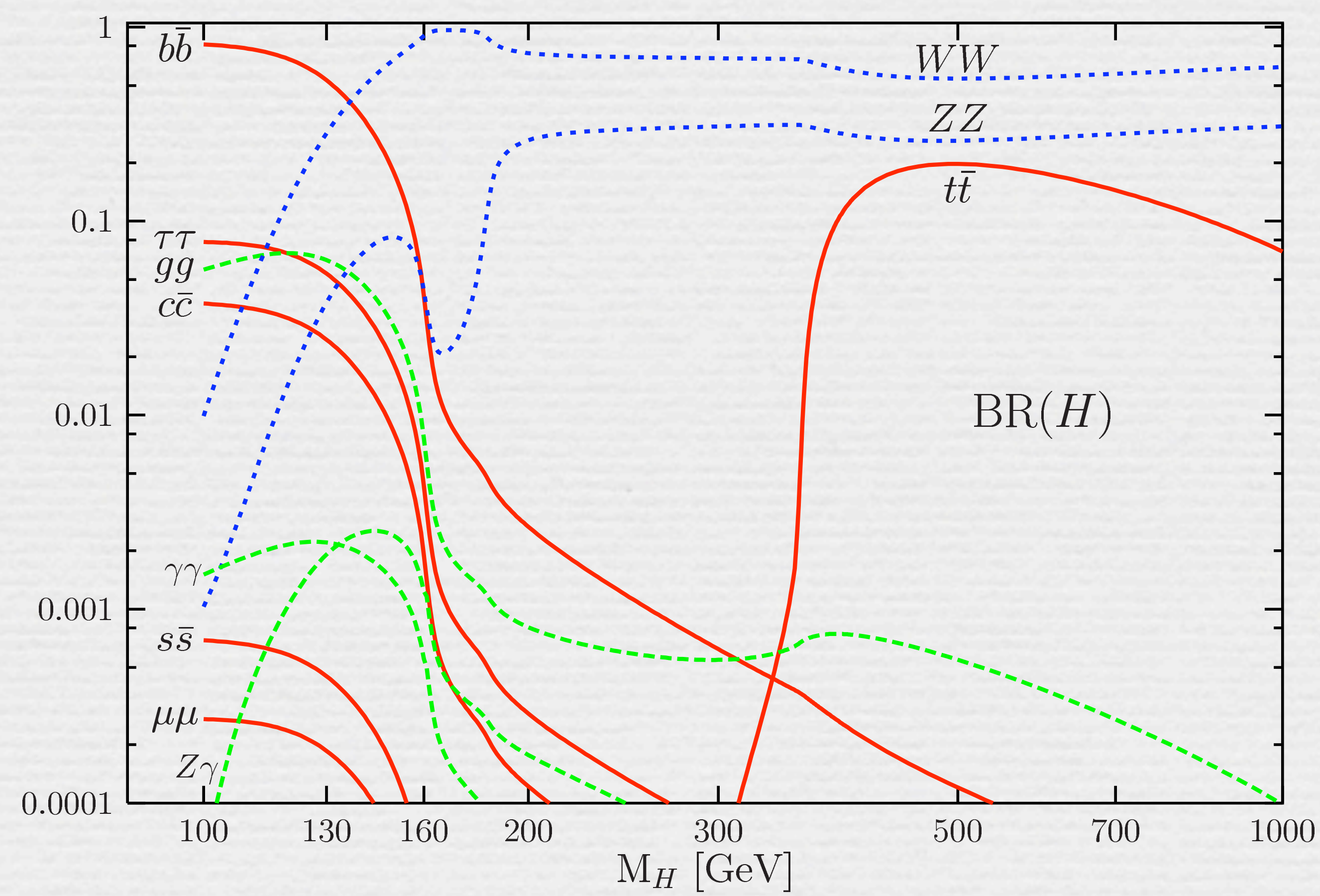
searching for the Higgs is like searching for a specific corn grain in a very large corn field ...

SM higgs production at the LHC

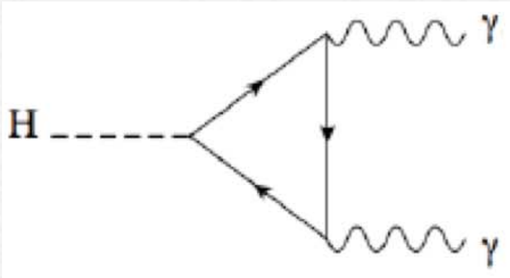


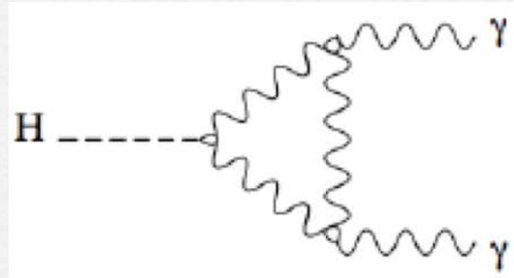


SM branching ratios

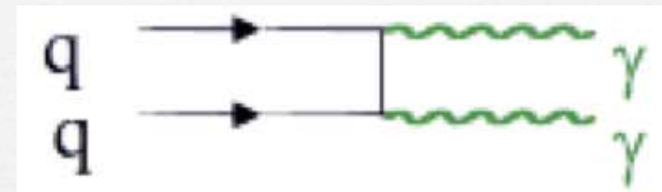


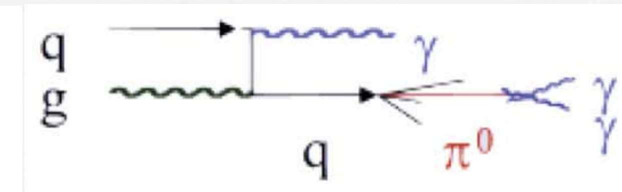
higgs to gamma gamma





main background





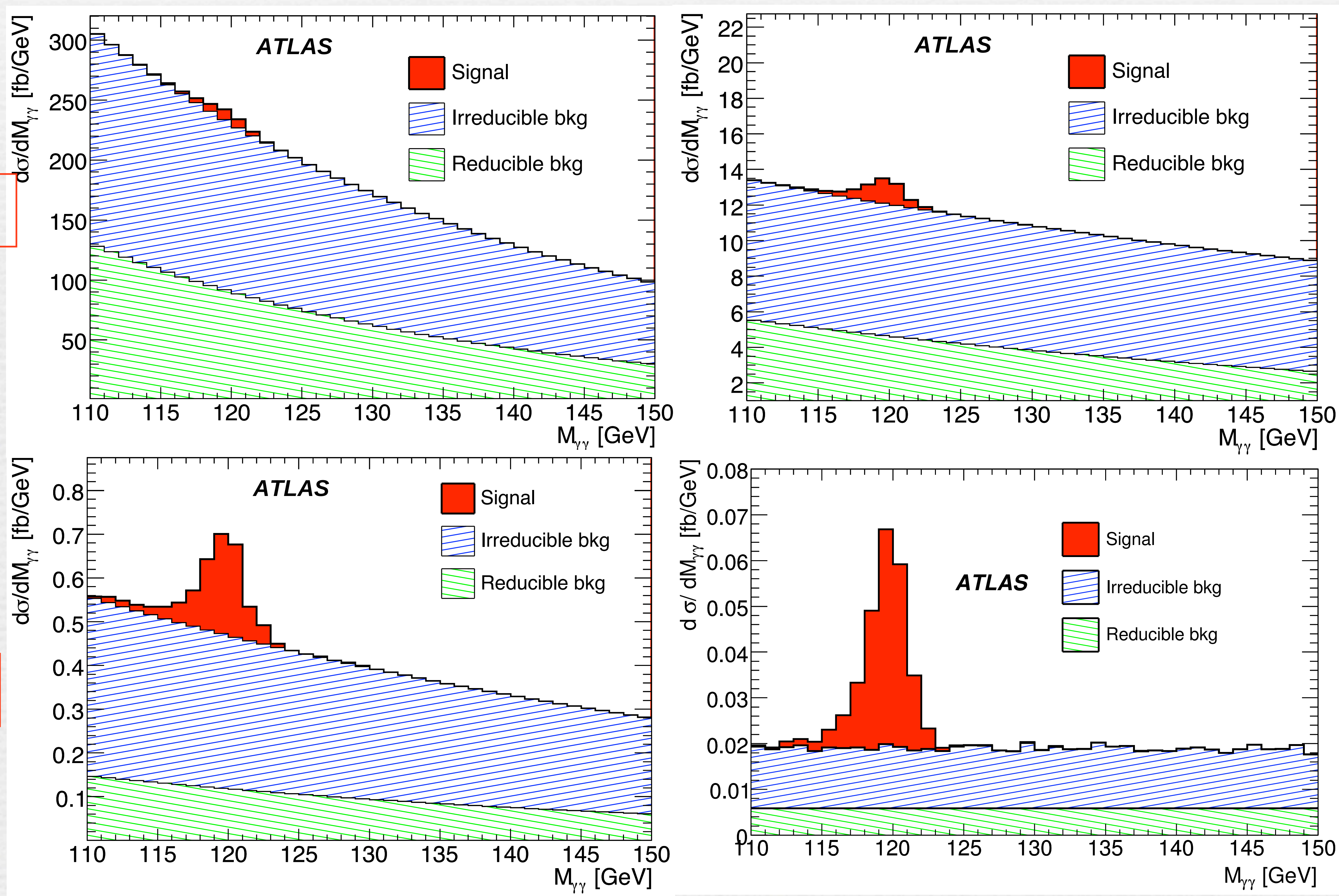
for different final states (gh,qqh,Wh,Zh) , different S/B

inclusive

H + 1j

H + 2 j

H + E_T^{miss}



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

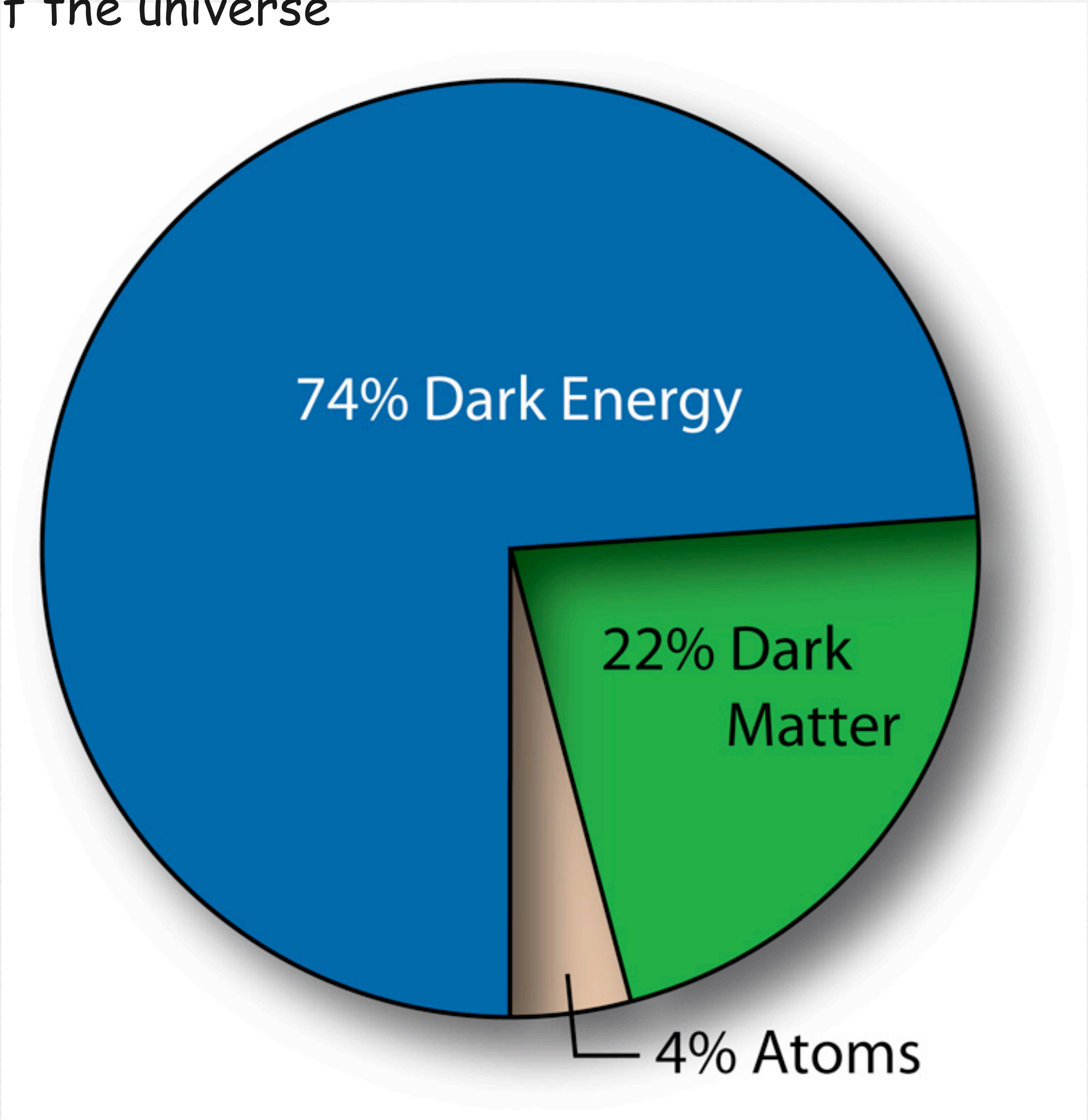
-> a profoundly different (and terribly boring) universe

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 96 %
of the energy budget of the universe



Precision Cosmology

WMAP Cosmological Parameters

Model: lcdm+sz+lens

Data: wmap7

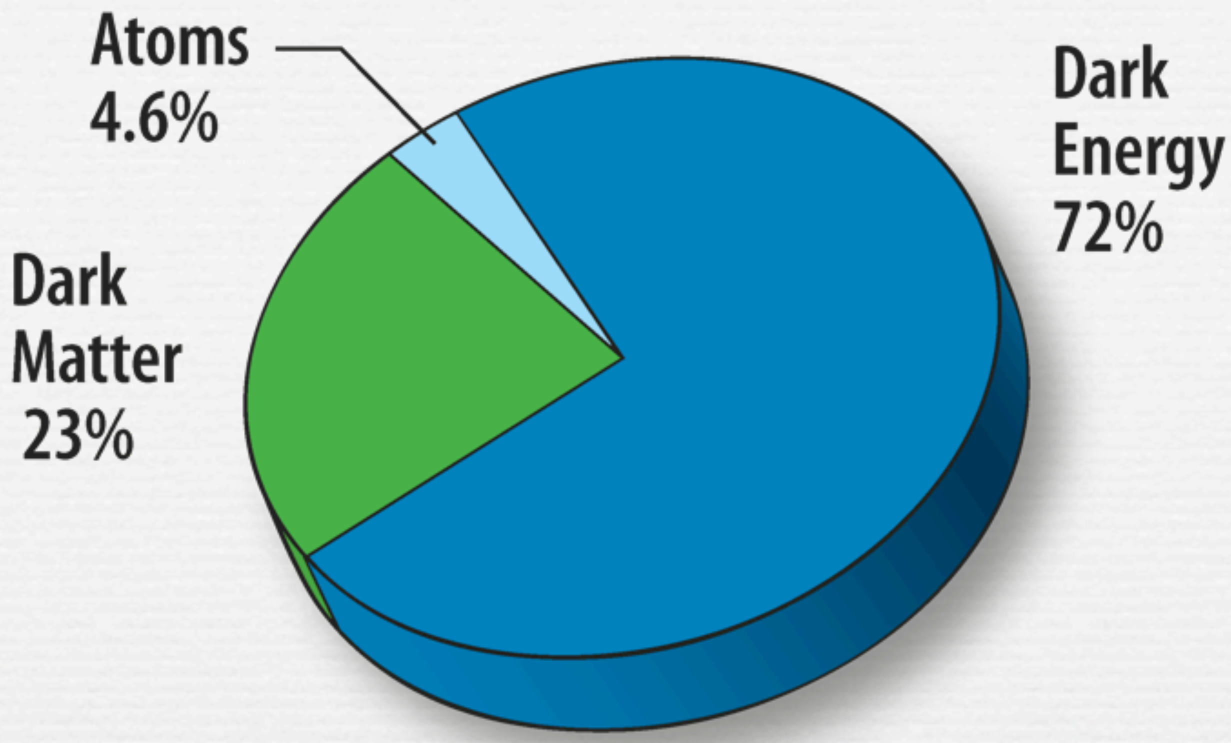
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1 - n_s$	0.037 ± 0.014
$1 - n_s$	$0.0079 < 1 - n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
$k_{\rm eq}$	$0.00974^{+0.00041}_{-0.00040}$	$\ell_{\rm eq}$	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\rm hor}(z_{\rm dec})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z = 0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z = 0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
$A_{\rm SZ}$	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	0.5952 ± 0.0016 °	t_*	379164^{+5187}_{-5243} yr
$z_{\rm dec}$	1088.2 ± 1.2	z_d	1020.3 ± 1.4
$z_{\rm eq}$	3196^{+134}_{-133}	$z_{\rm reion}$	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		

fraction of the total energy density in "dark energy"

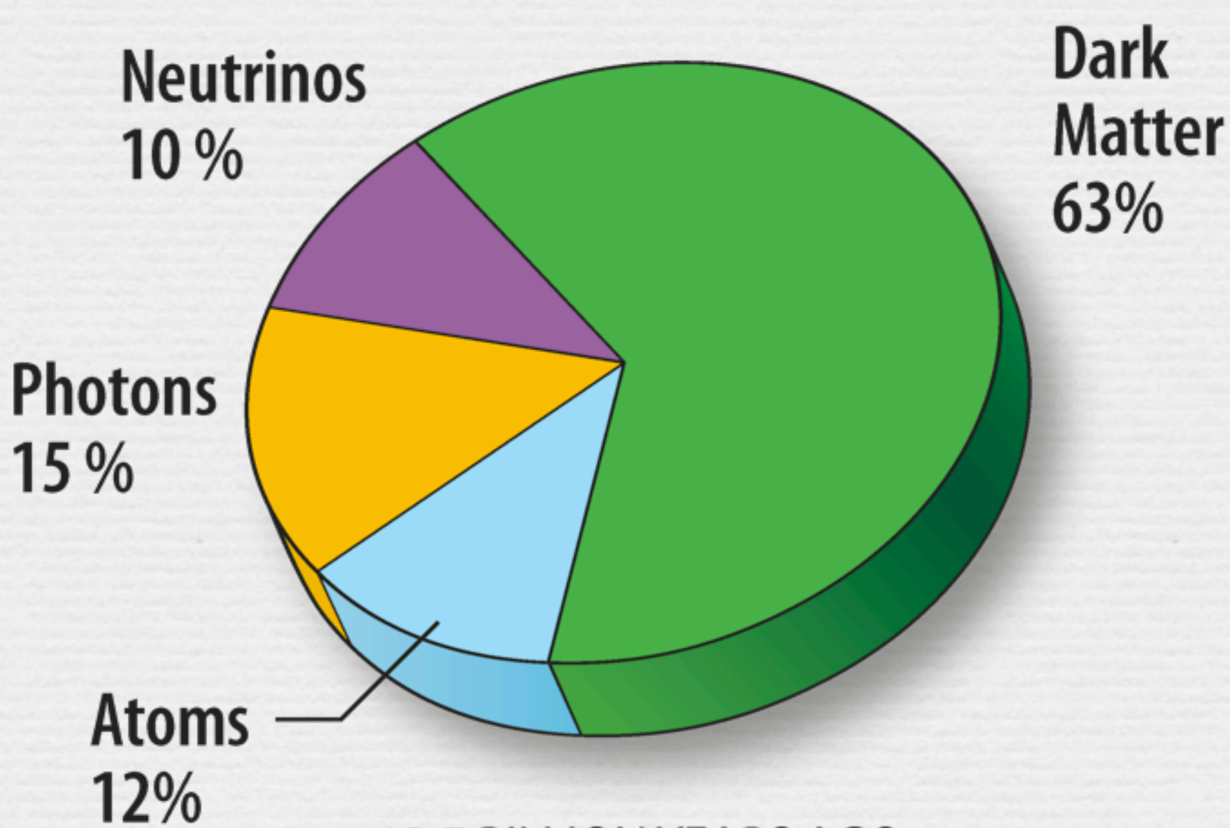
expansion rate

fraction of the total energy density in matter

age of the universe

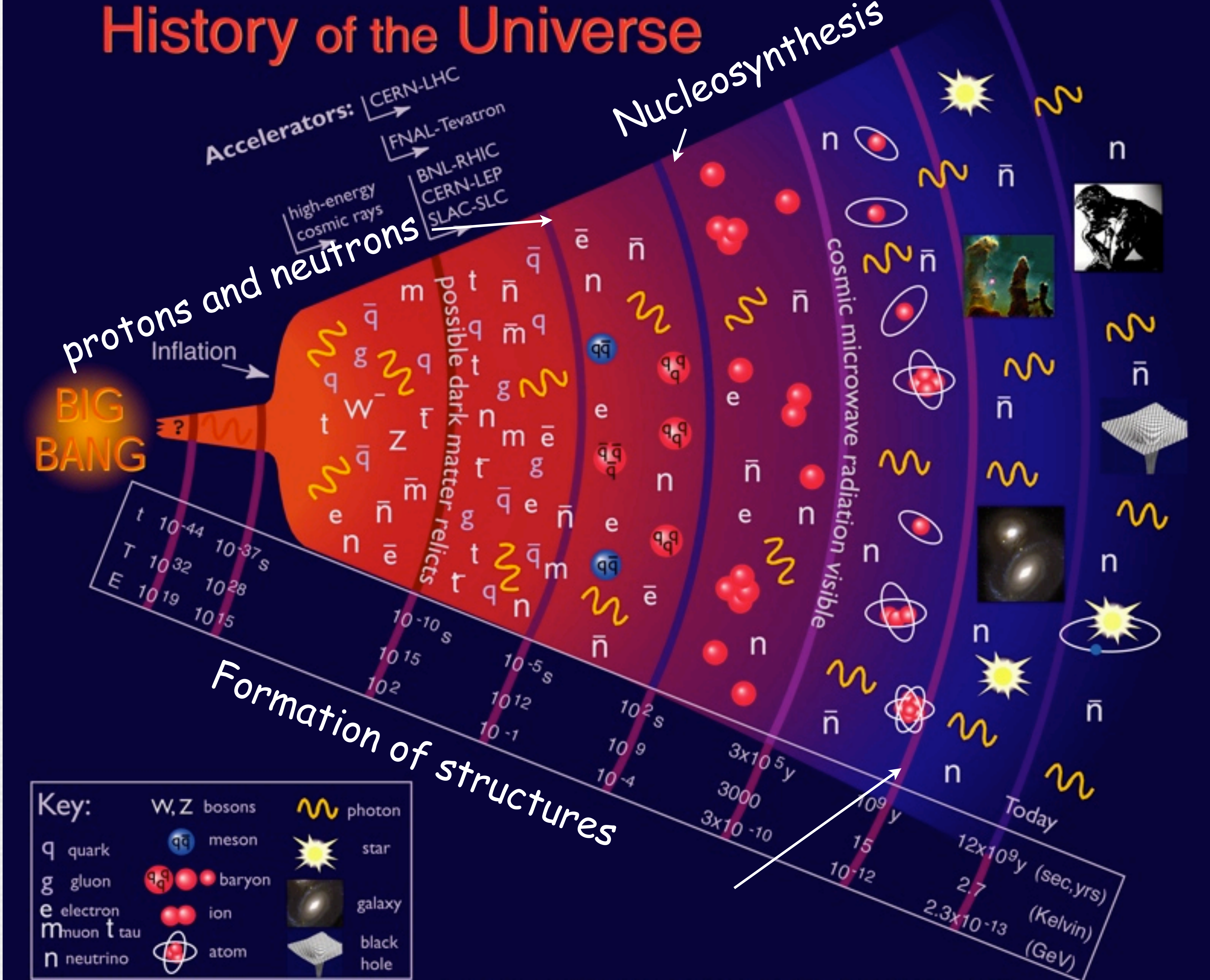


TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)


History of the Universe
Nucleosynthesis
protons and neutrons
Formation of structures
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

Three major experimental facts are still lacking a theoretical explanation :

- ✳ The mass of elementary particles (gauge bosons, quarks & leptons)
- ✳ dark matter (stable, non-baryonic, non-relativistic, neutral particle)
- ✳ the matter - antimatter asymmetry (the three Sakharov conditions)

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

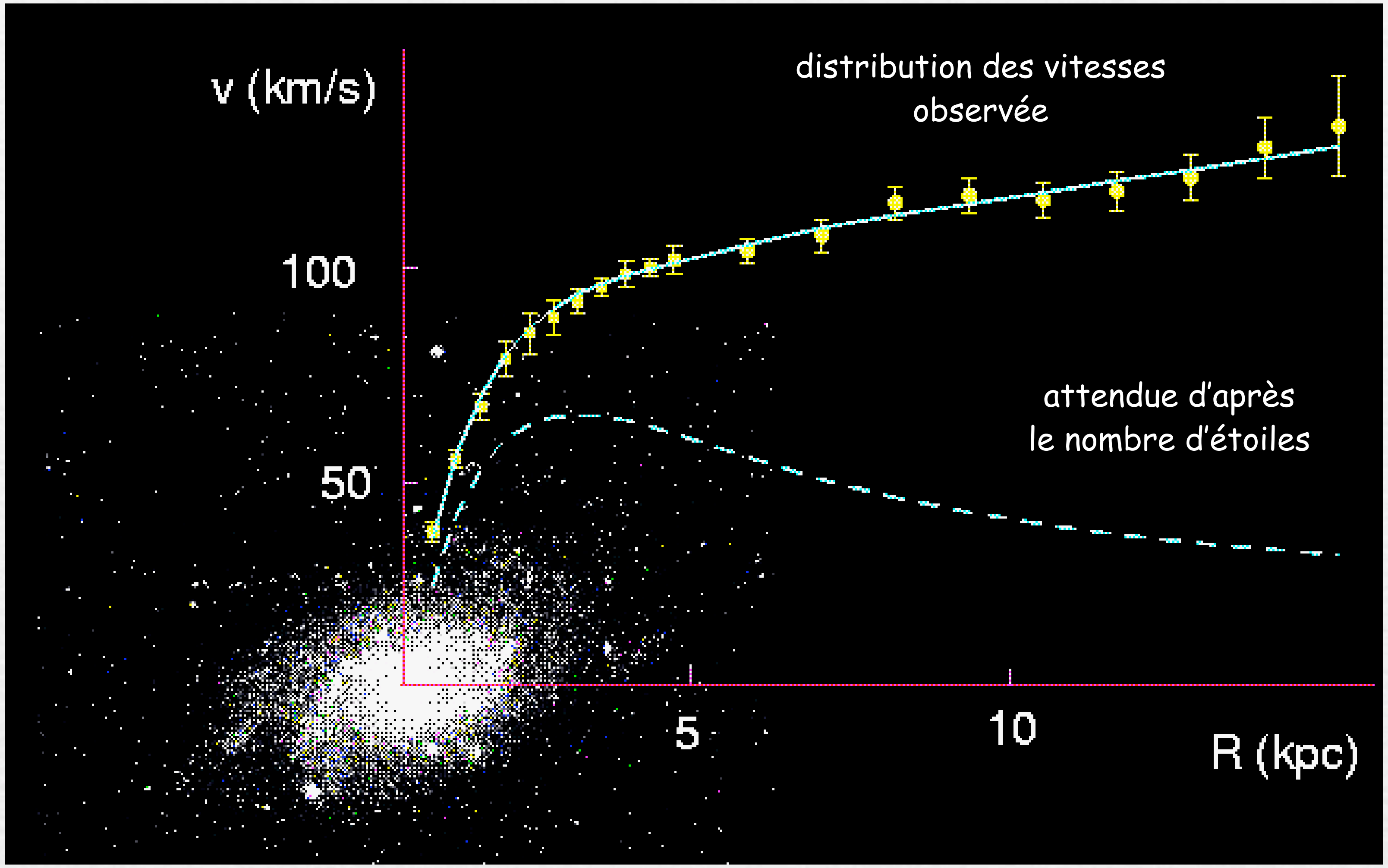
- the (quasi) absence of antimatter in the universe

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?

galaxy rotation curves



$$M(<r) = \frac{v^2 r}{G_N}$$

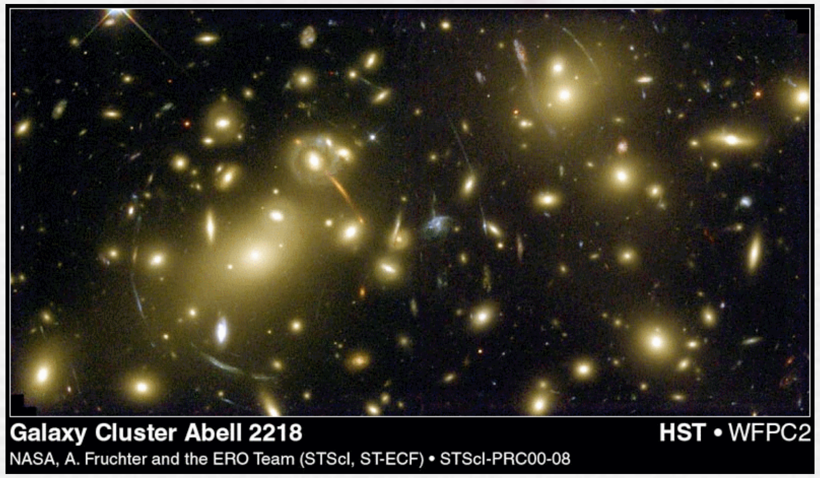
At large distances from the center, beyond the edge of the galaxy, the velocity would be expected to all as 1/sqrt(r) if most of the matter is contained in the optical disk while it was observed to remain constant, implying the existence of an extended dark halo

gravitational lensing

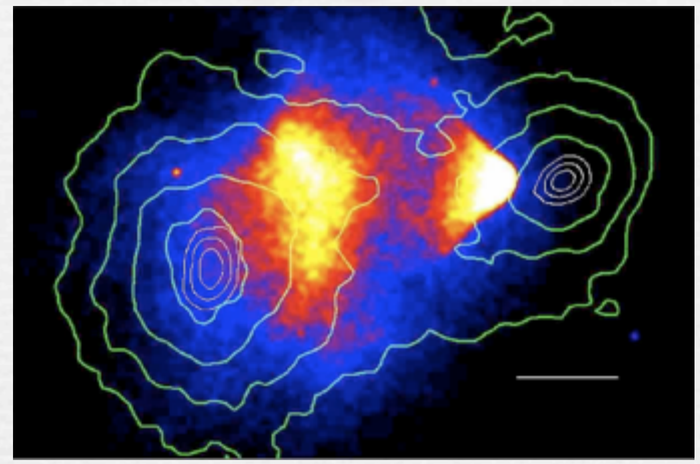
Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

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

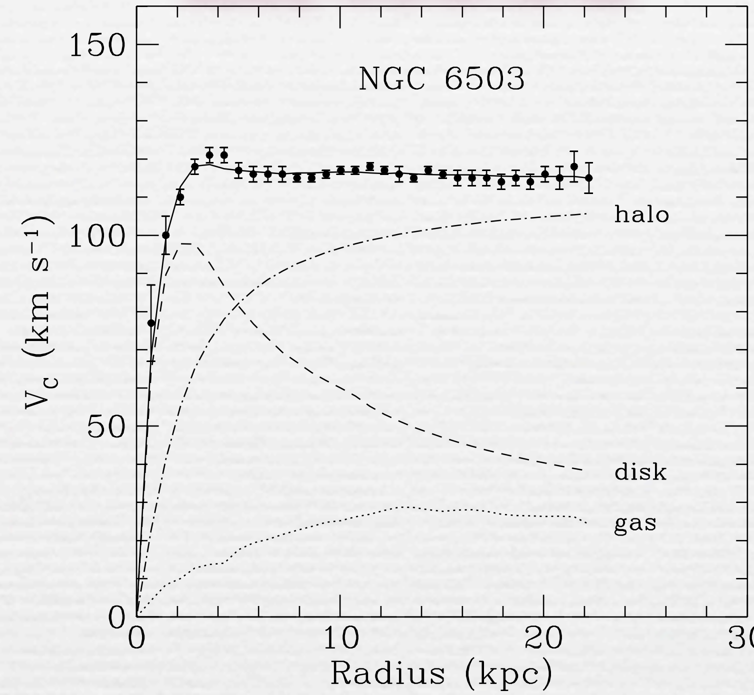
Gravitational lensing



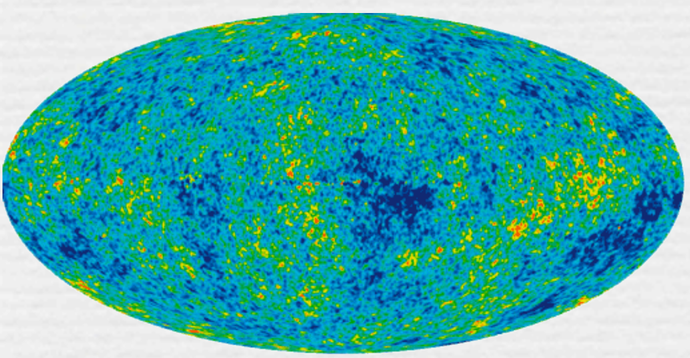
The "Bullet cluster": lensing map versus X-ray image

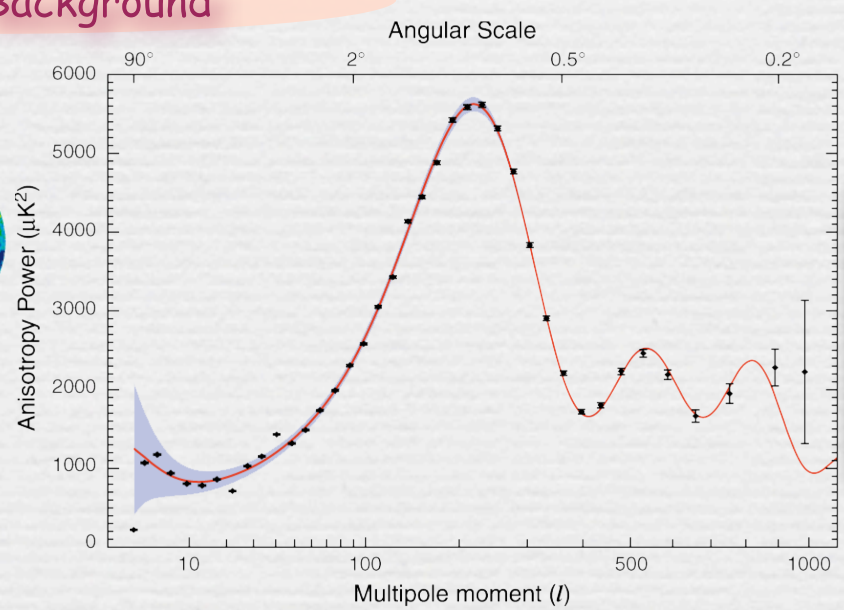


Galaxy rotation curves



Cosmic Microwave Background





... etc

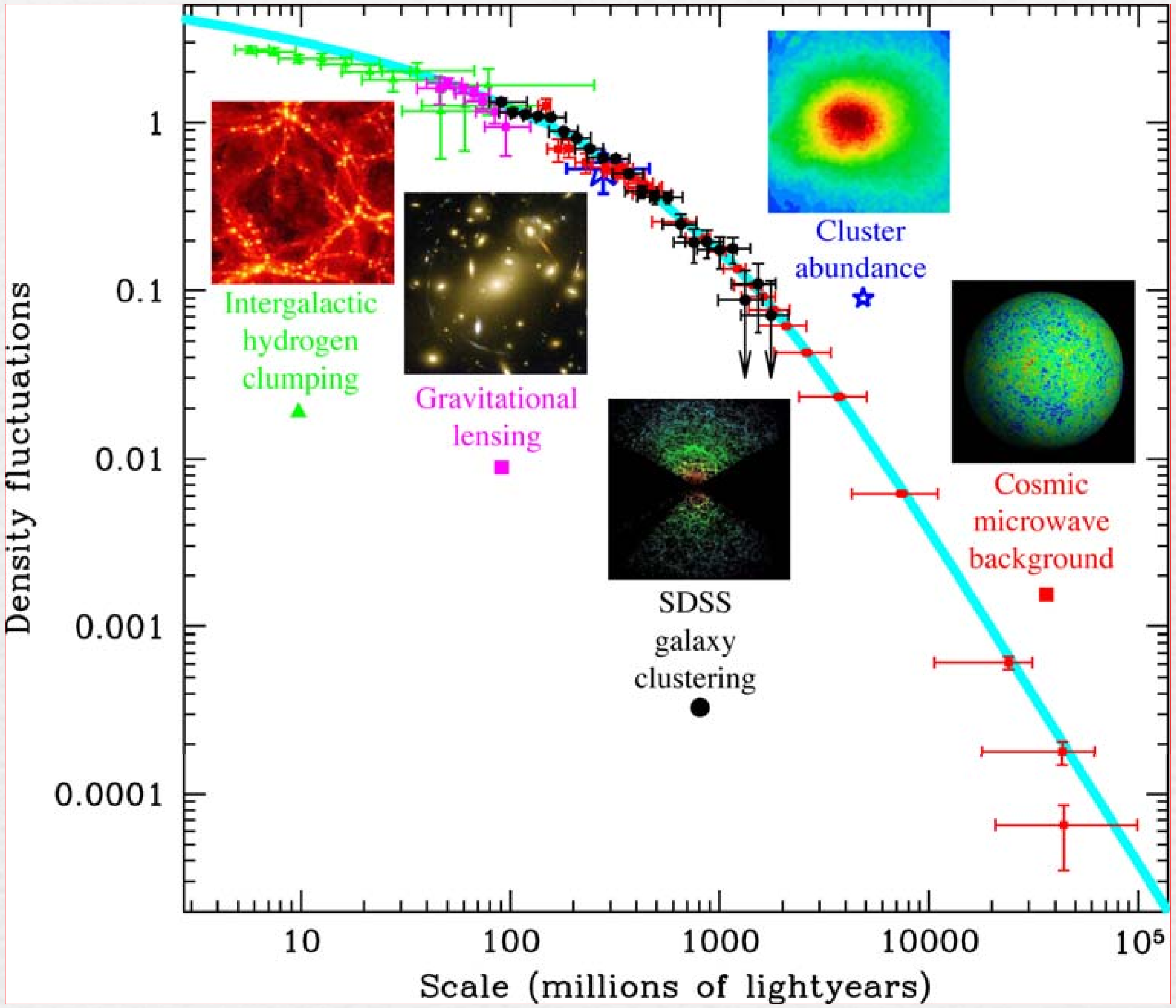
-> Fraction of the universe's energy density stored in dark matter : $\Omega_{DM} \approx 0.22$

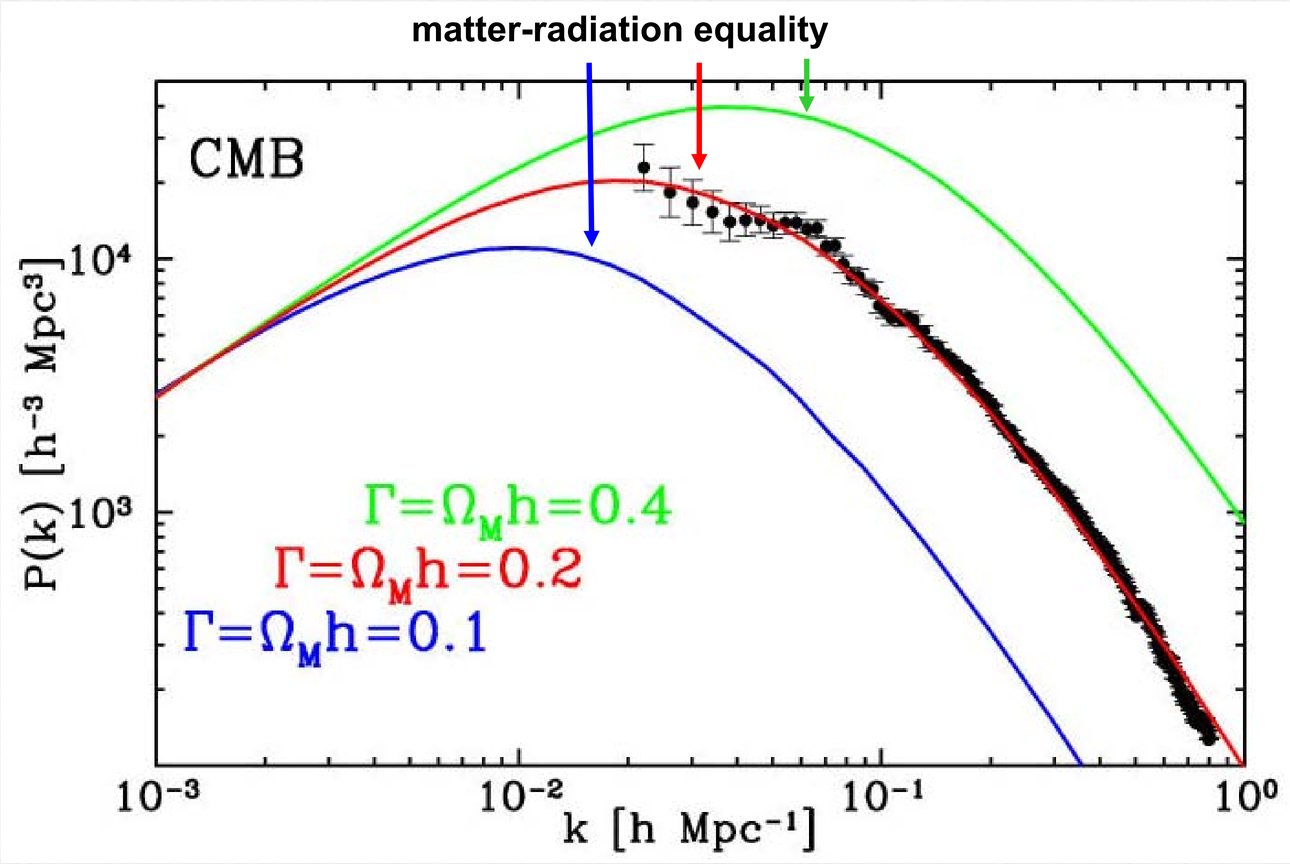
The picture from astrophysical and cosmological observations is getting more and more focussed

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

Matter power spectrum

not baryonic



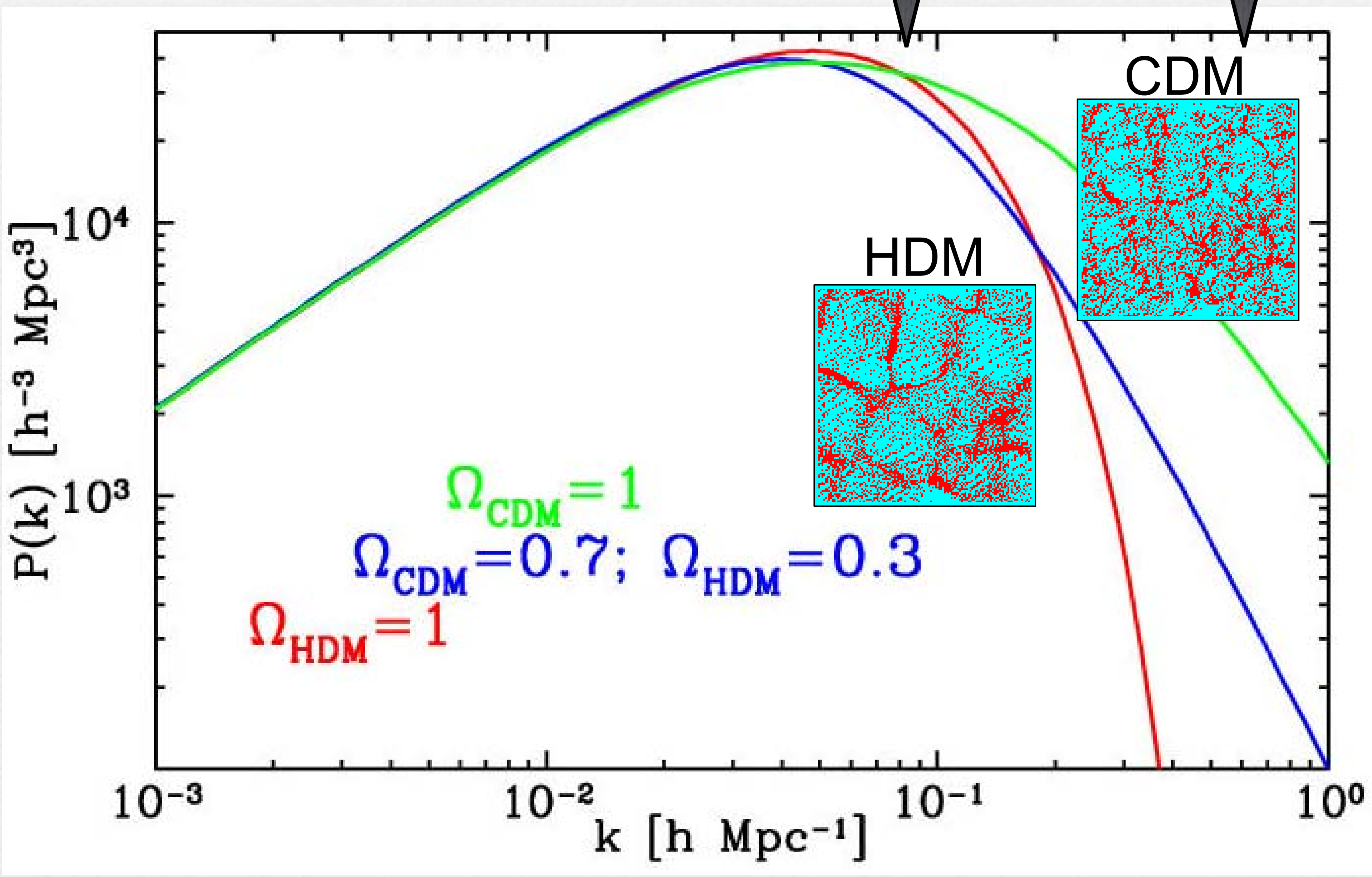


Neutrinos

not hot

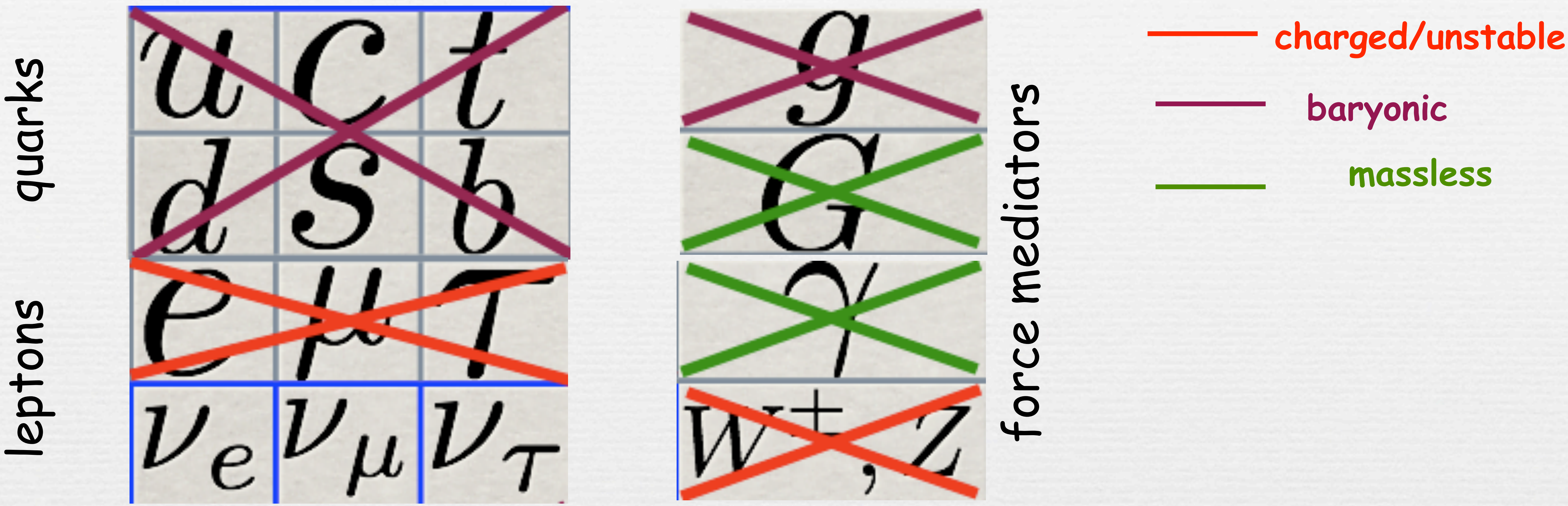
hot dark matter

cold dark matter



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

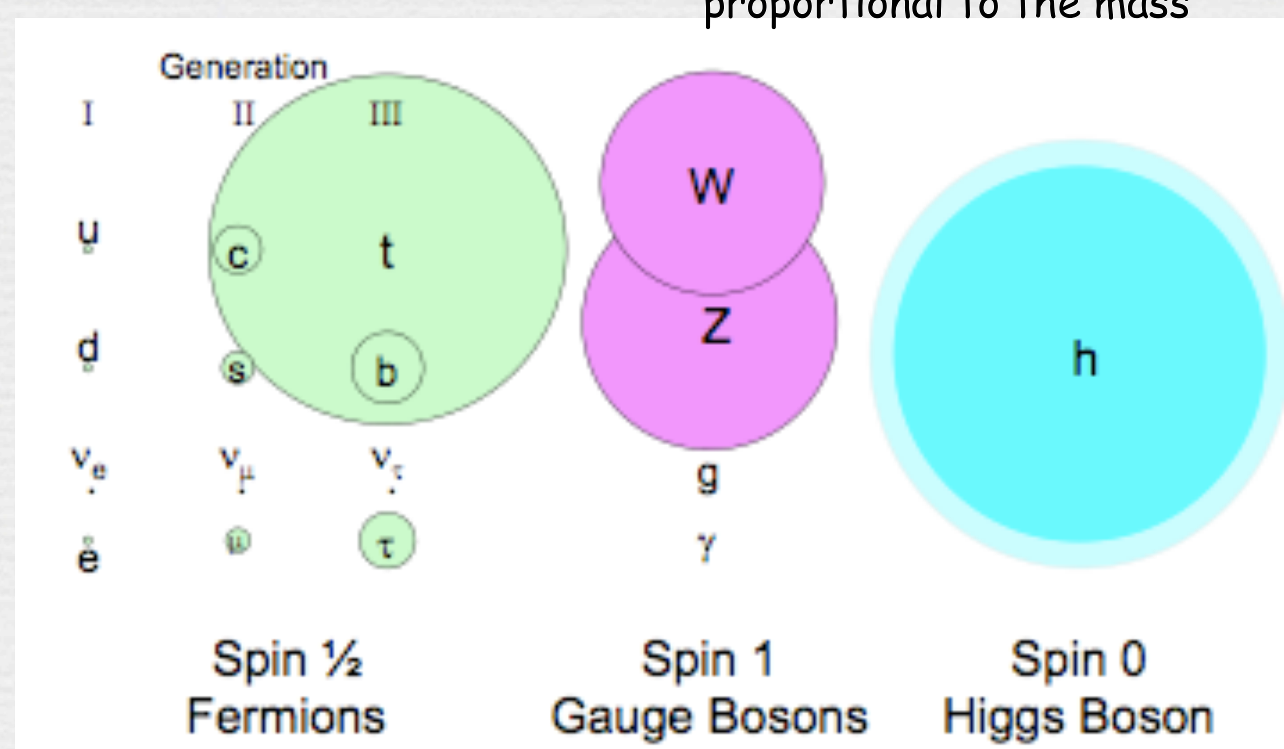
Matter Forces



I II III

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

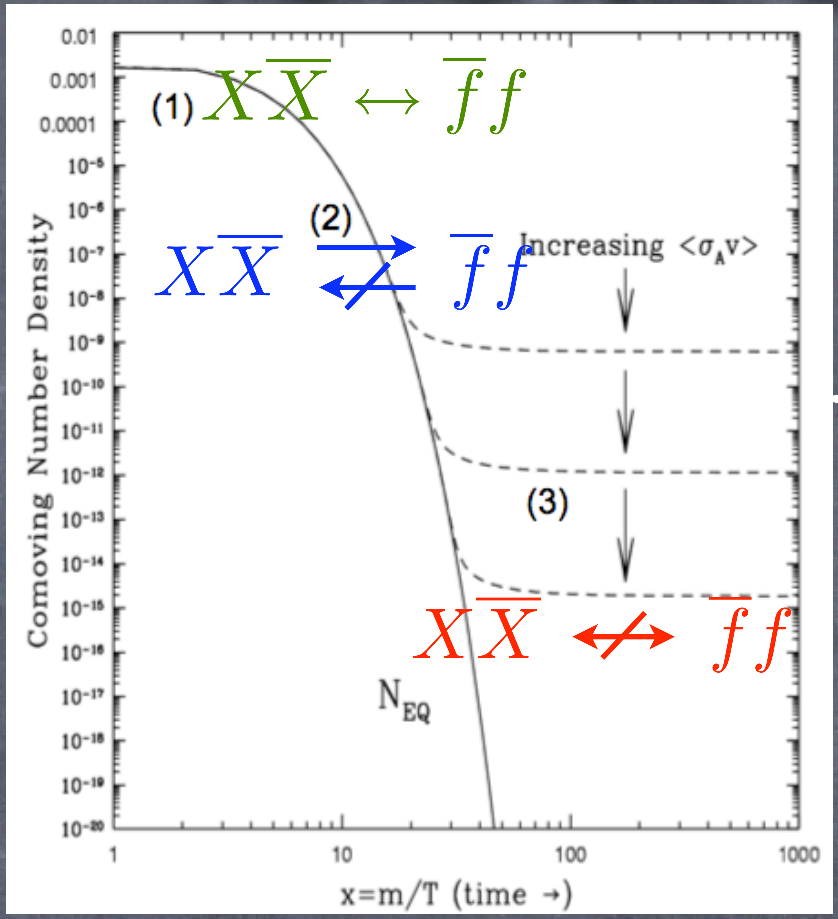
very light & only gravitationally coupled (or with equivalently suppressed couplings) -> stable on cosmological scales

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

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

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

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

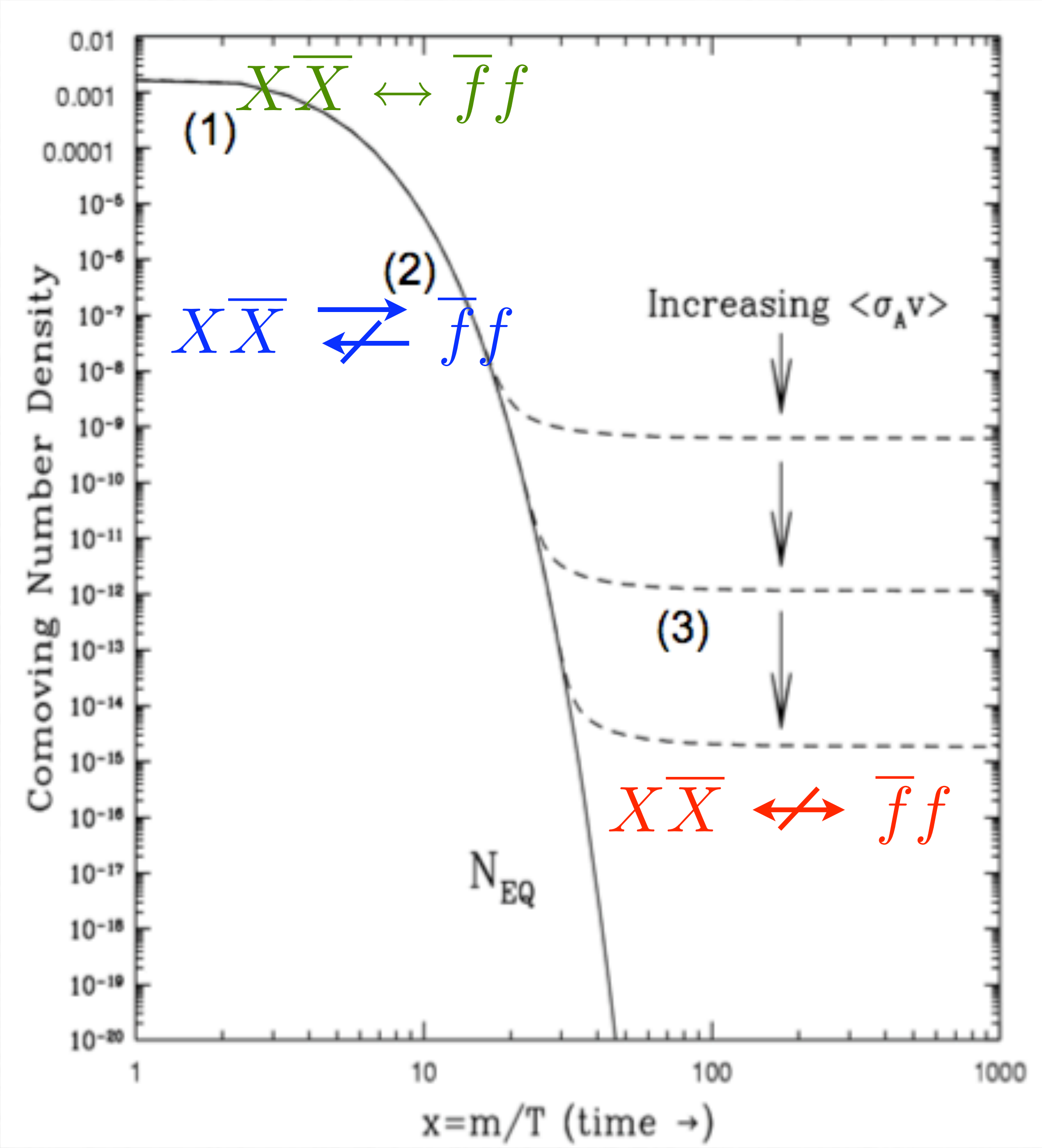
Dependence on reheat temperature

The "WIMP miracle"

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

freese-out :

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



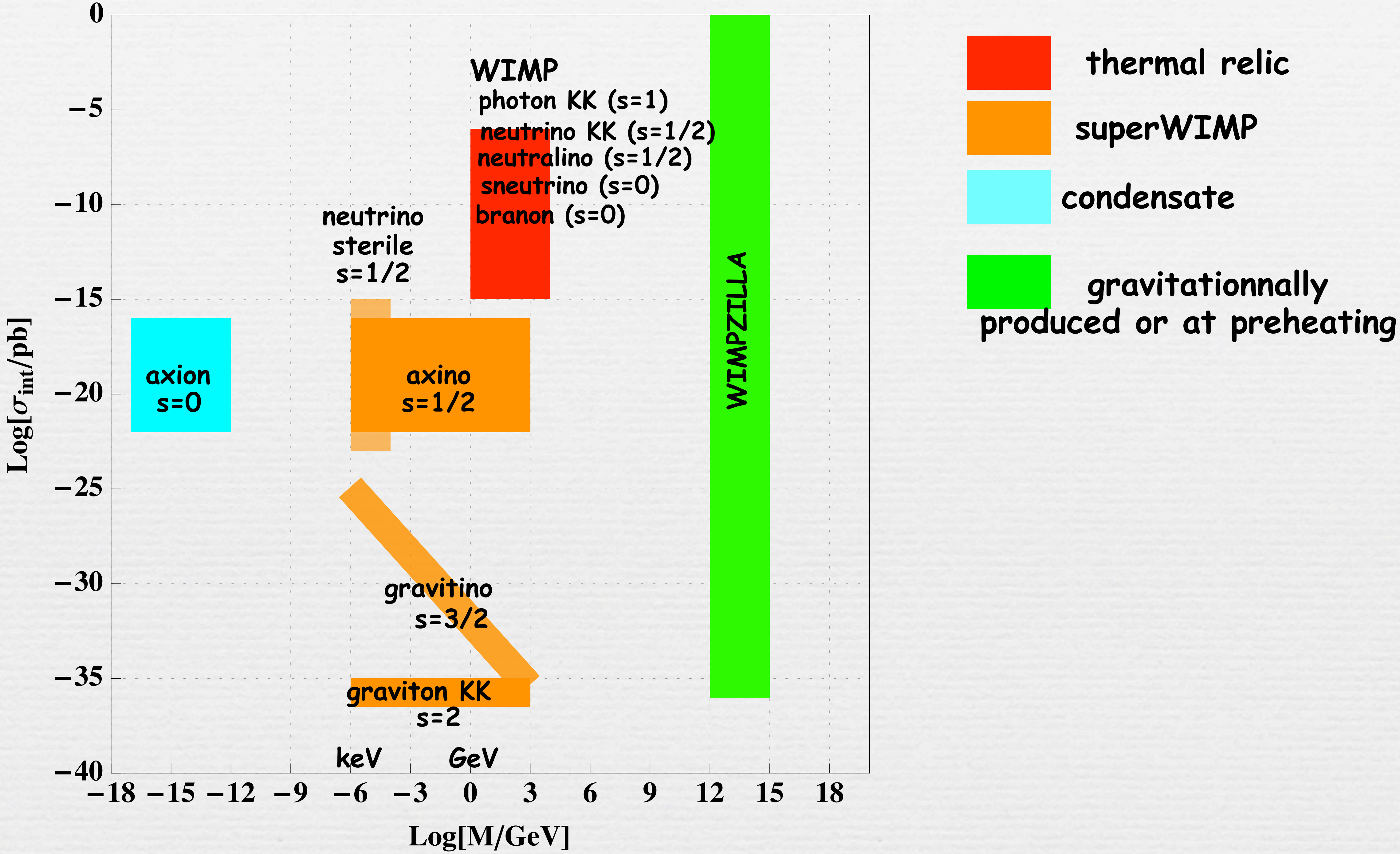
Thermal relic: $\Omega\, h^2 \propto 1/\langle\sigma_{anni}\, v\rangle$

$\Rightarrow \langle\sigma_{anni}\, v\rangle = 0.3$ pb

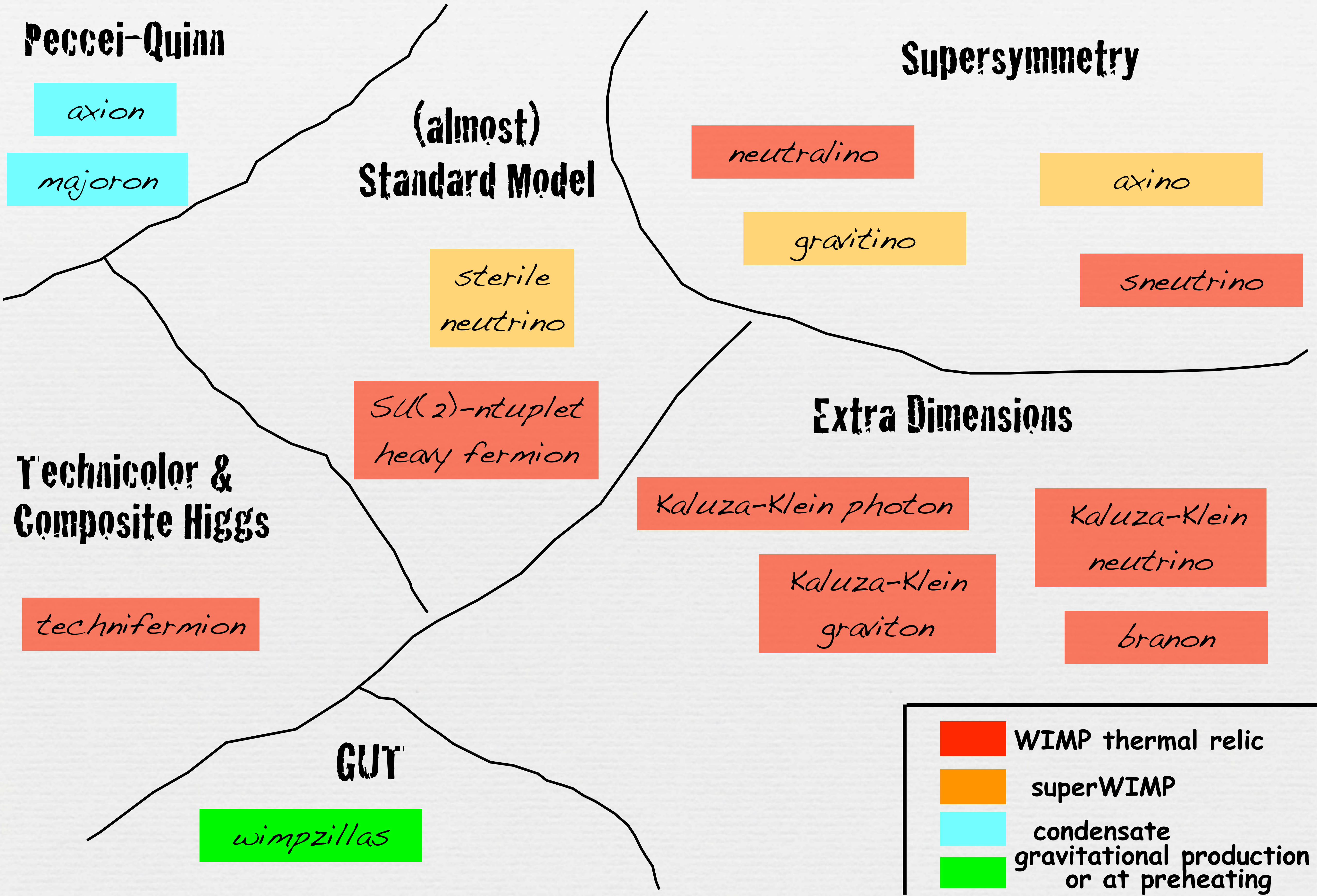
$\sigma \sim \alpha^2/m^2$

$\Rightarrow m \sim 100$ GeV

Dark Matter Candidates Ω~1



In Theory Space



Dark Matter and the Fermi scale

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

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

→ 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")

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

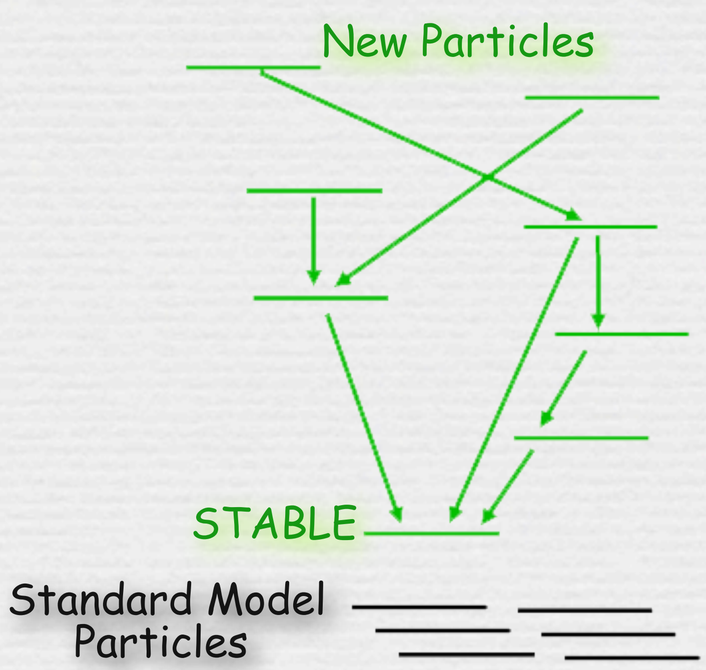
The stability of a new particle is a common feature of many models

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

ADD
[98-99]

RS
[99 to now]

the attitude: Naturalness is what matters, dark matter is a secondary issue

Little hierarchy adressed

UED
[2001 to now]

KK-parity→ LKP
[2002]

Little Higgs
[2002-2004]

T-parity→ LTP
[2003]

Lower your ambition (no attempt to explain the M_{EW}/M_{Pl} hierarchy); rather put a ~ TeV cutoff

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

a typical example of
the "minimal approach":

The Inert Doublet Model (IDM)

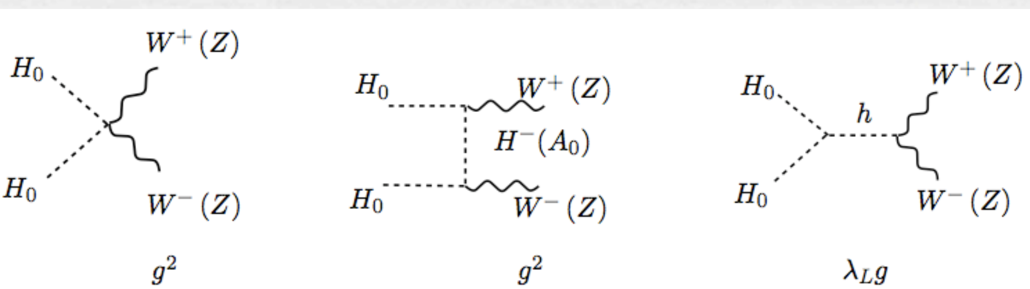
Deshpande-Ma'78; Barbieri-Hall-Rychkov 06
Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07 ; Hambye, Tytgat 07 .....

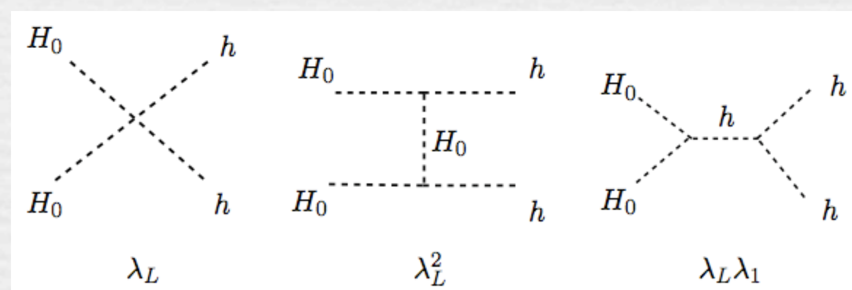
A two-Higgs extension of the SM with an unbroken Z_2 symmetry

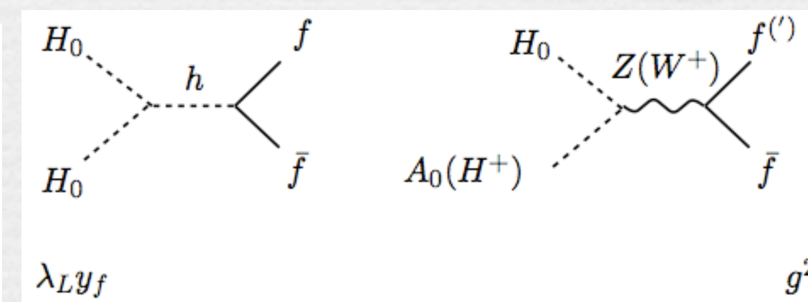
$H_1 \to H_1$ and $H_2 \to -H_2$ (and all SM fields are even)

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

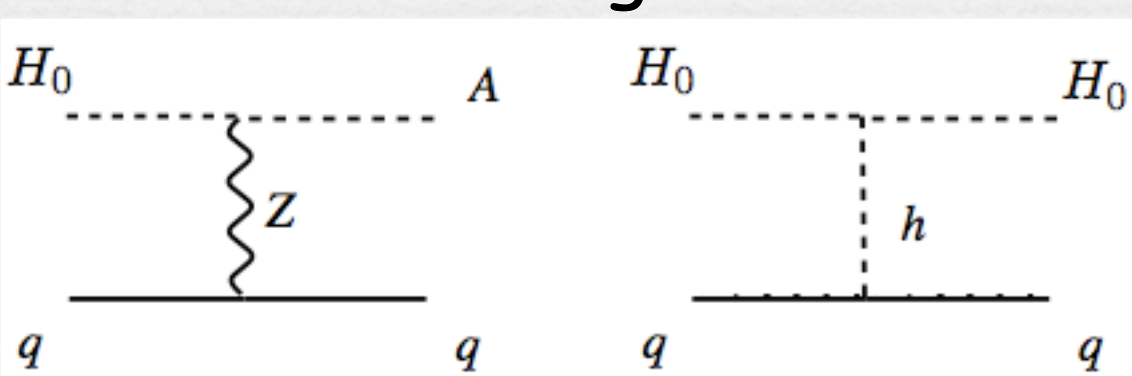
Annihilation:





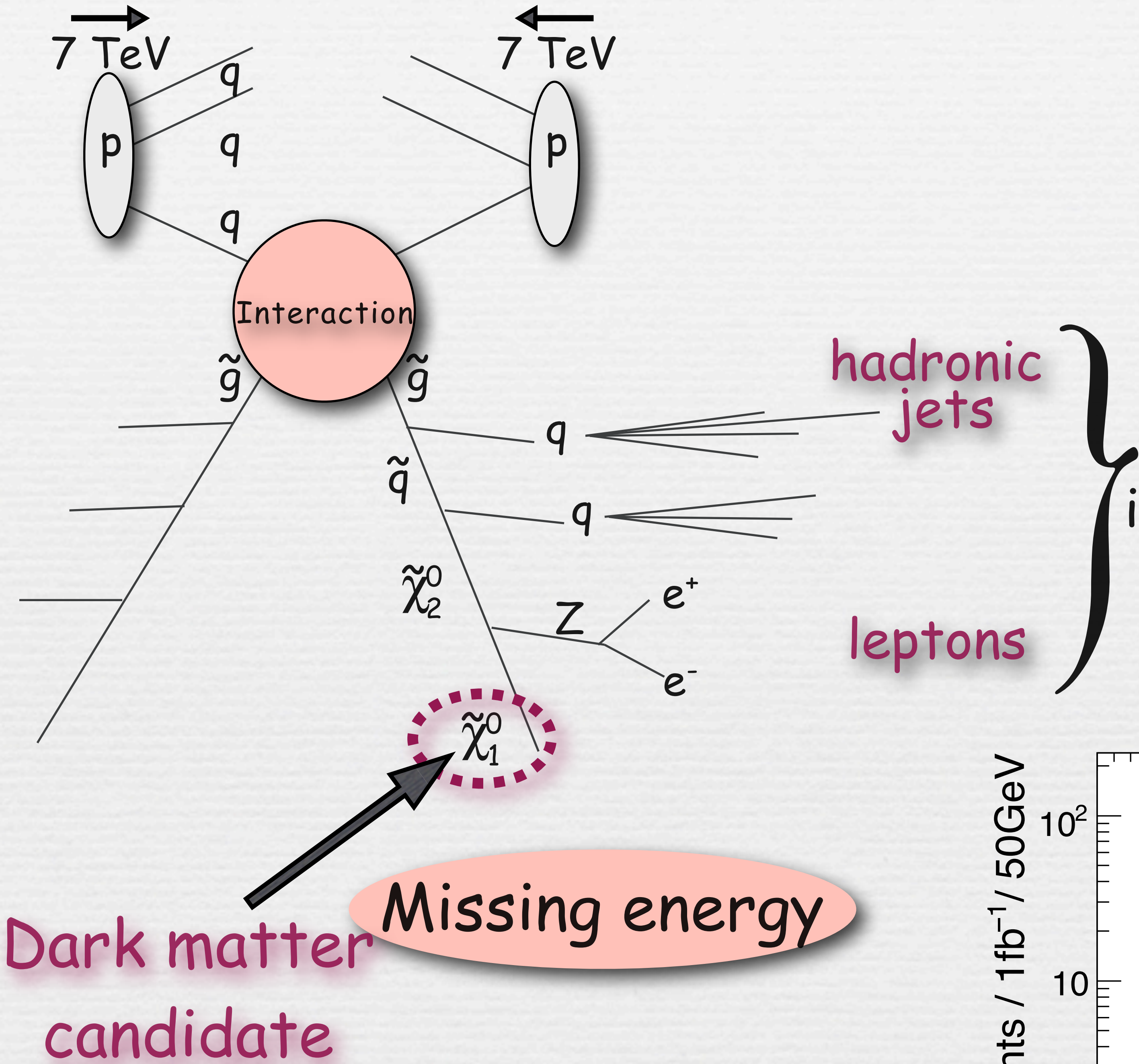


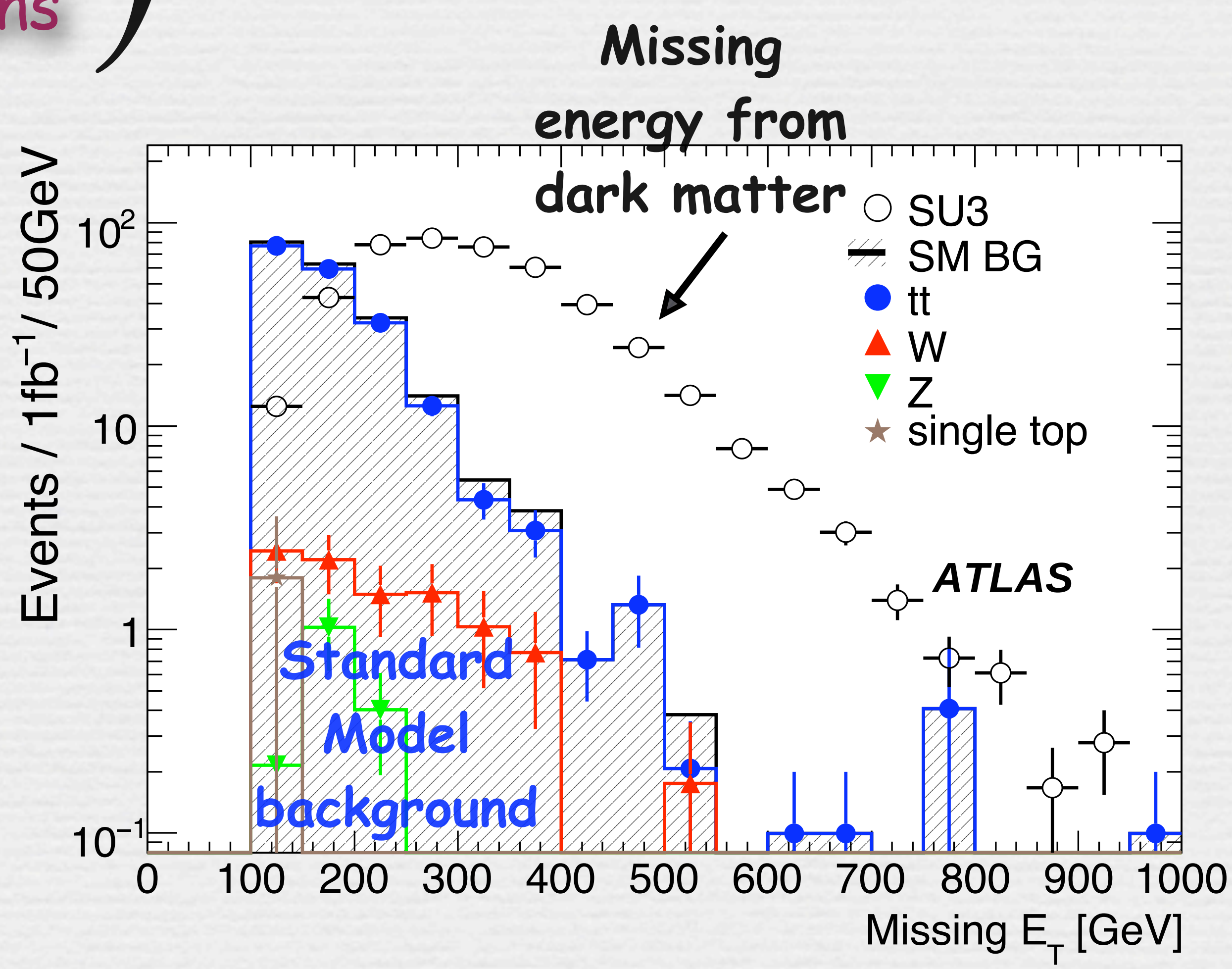
Elastic scattering:



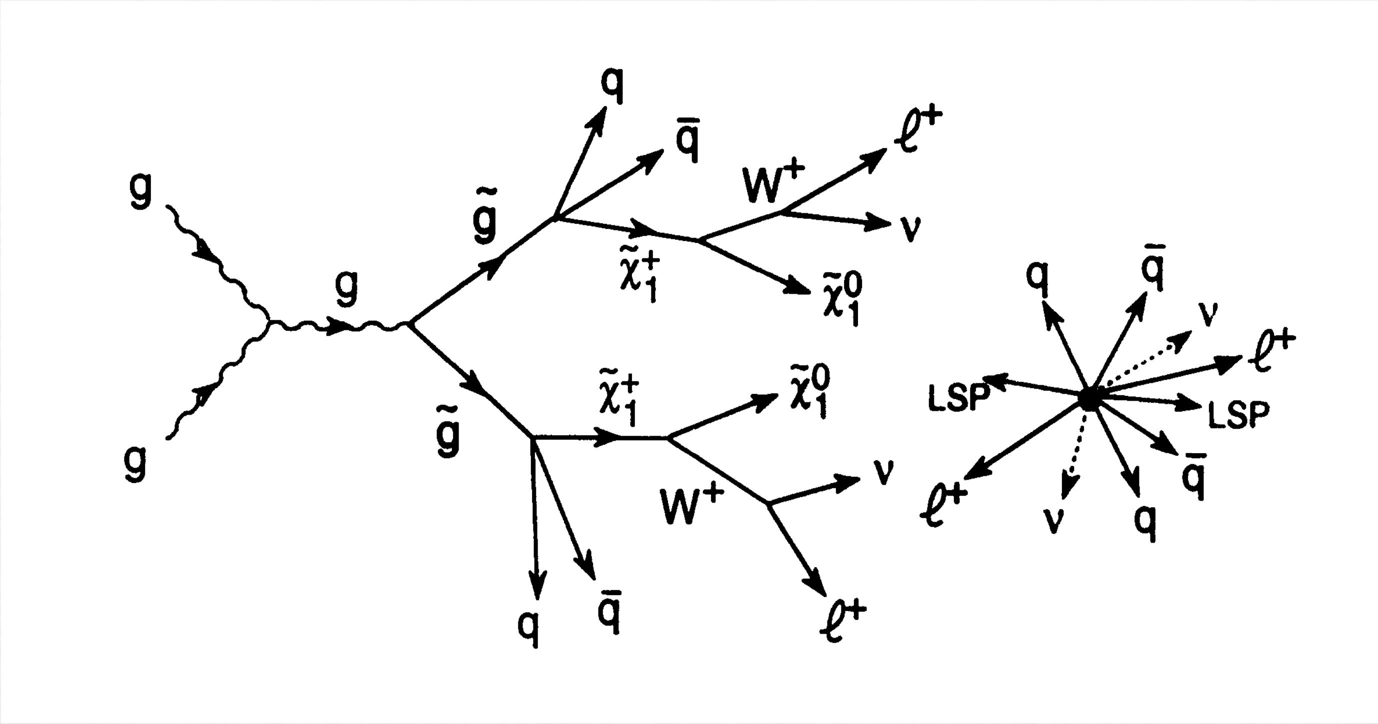
σ~ O(10^{-9}) pb, within sensitivity of future experiments

Producing Dark Matter at LHC = "Missing Energy" events





Typical SUSY decay chain

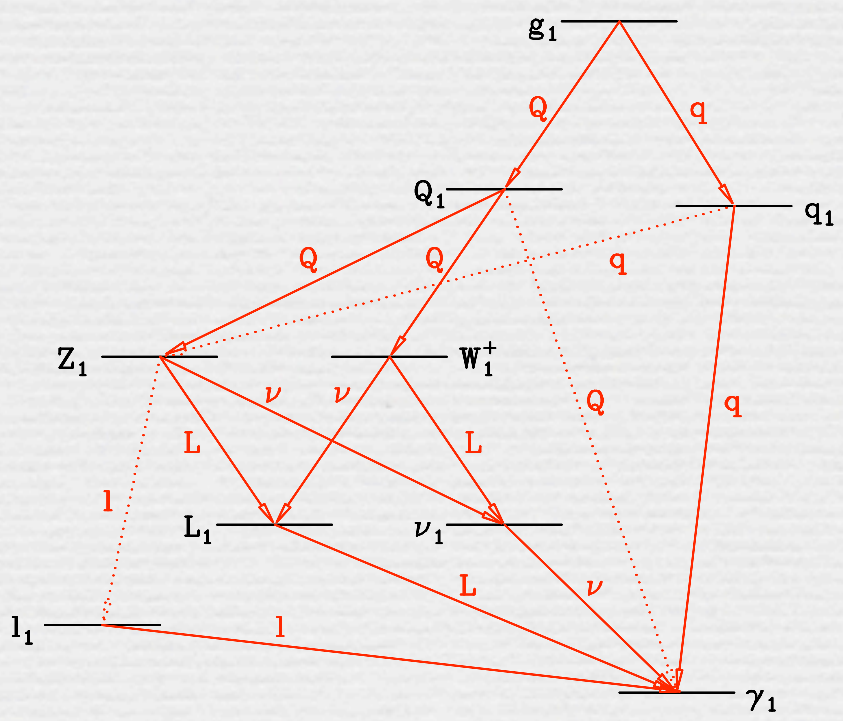


Lots of jets

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

scalar

Majorana fermion

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

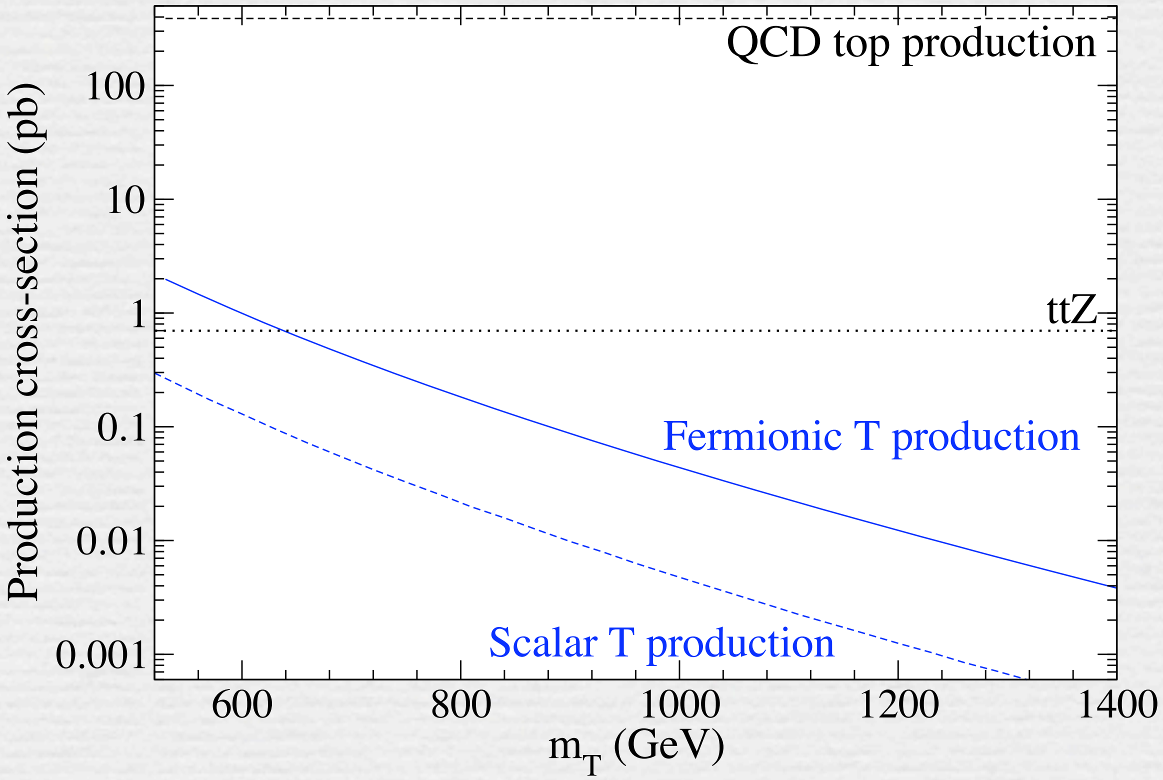
Little Higgs $T \longrightarrow A_H\ t$

Gauge bosons

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

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

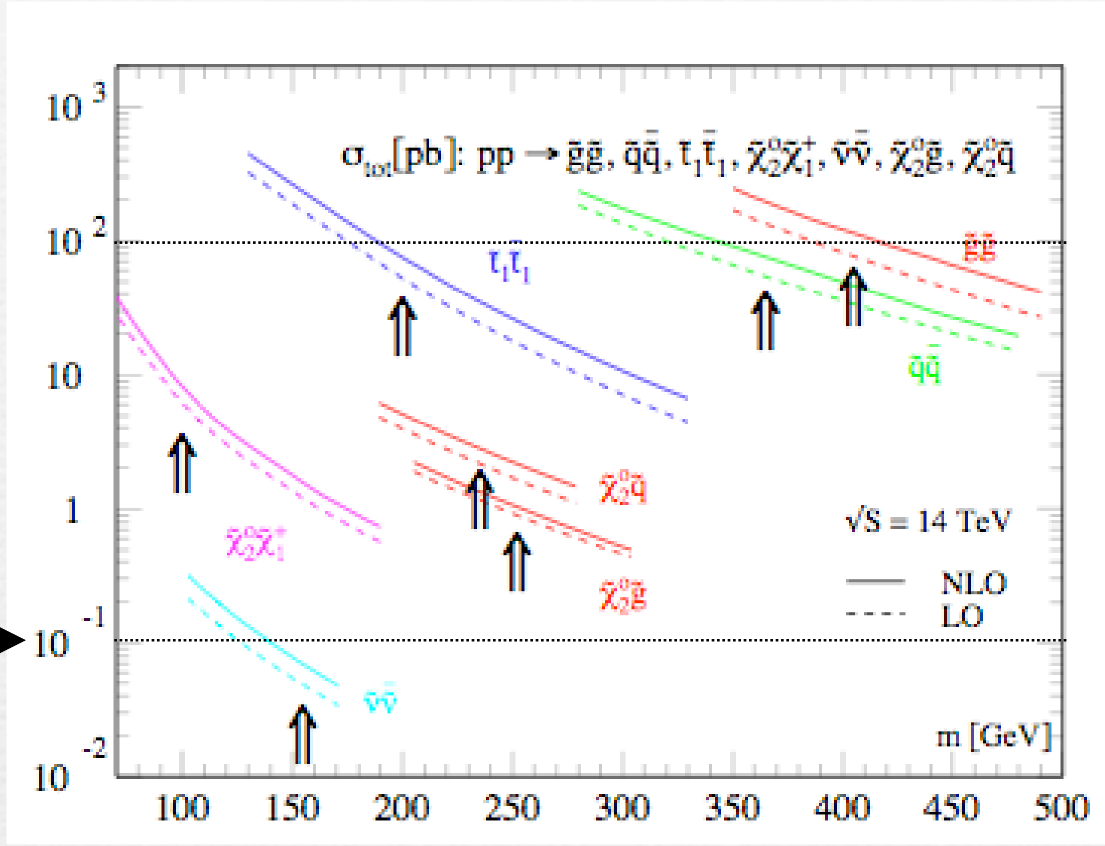
Dirac fermions



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)

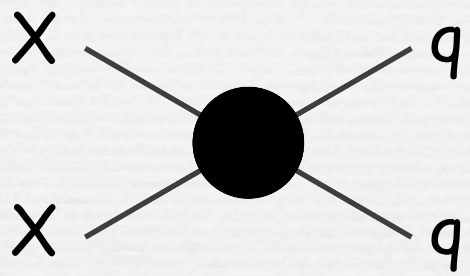
2) studying its properties in the laboratory

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

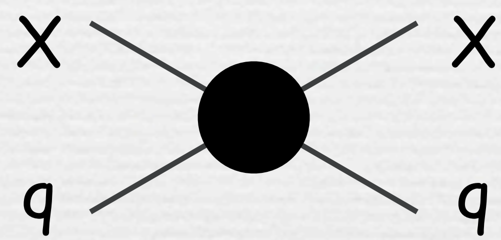
1 pb : the typical cross section

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

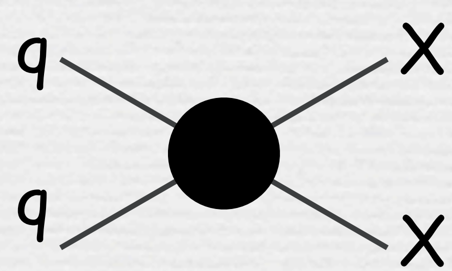


1 pb : typical scattering cross section of wimps with nuclei
(-> relevant for direct detection experiments like CDMS)

[$\sigma_n \sim (m_n^2/\mu^2)/A^2$) $\sigma_0 \sim 10^{-7}$ 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: $v \sim 300$ 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:

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

≈ 3000 Wimps.m^{-3} if m≈100 GeV

v_{max} ~ 650 km/s (galactic escape velocity)

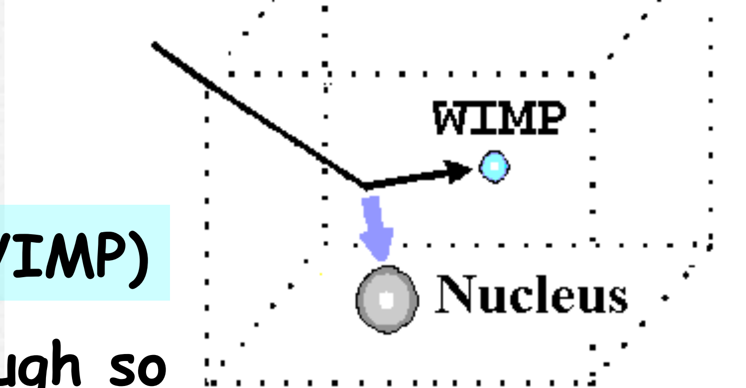
$$v_{\min} = \sqrt{E_{recoil} M_{nucleus}/2\mu^2}$$

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

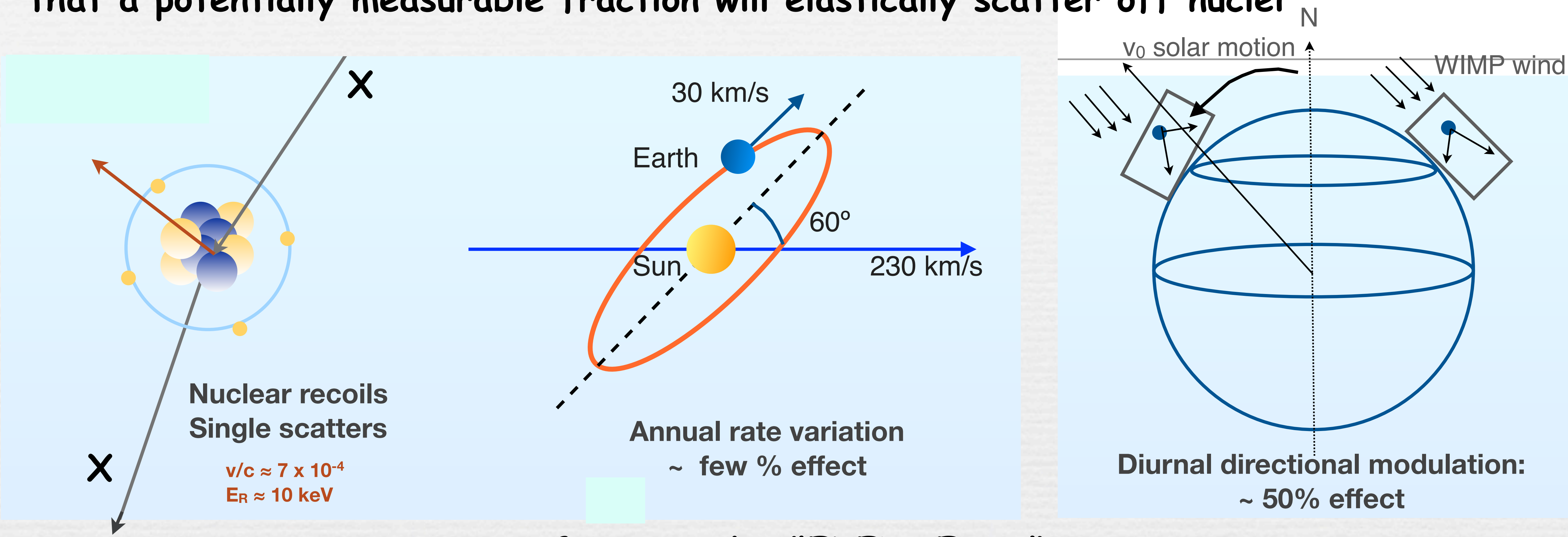
($\sigma_n / \sigma_0 \sim (m_n^2/\mu^2)/A^2$)

Direct Detection

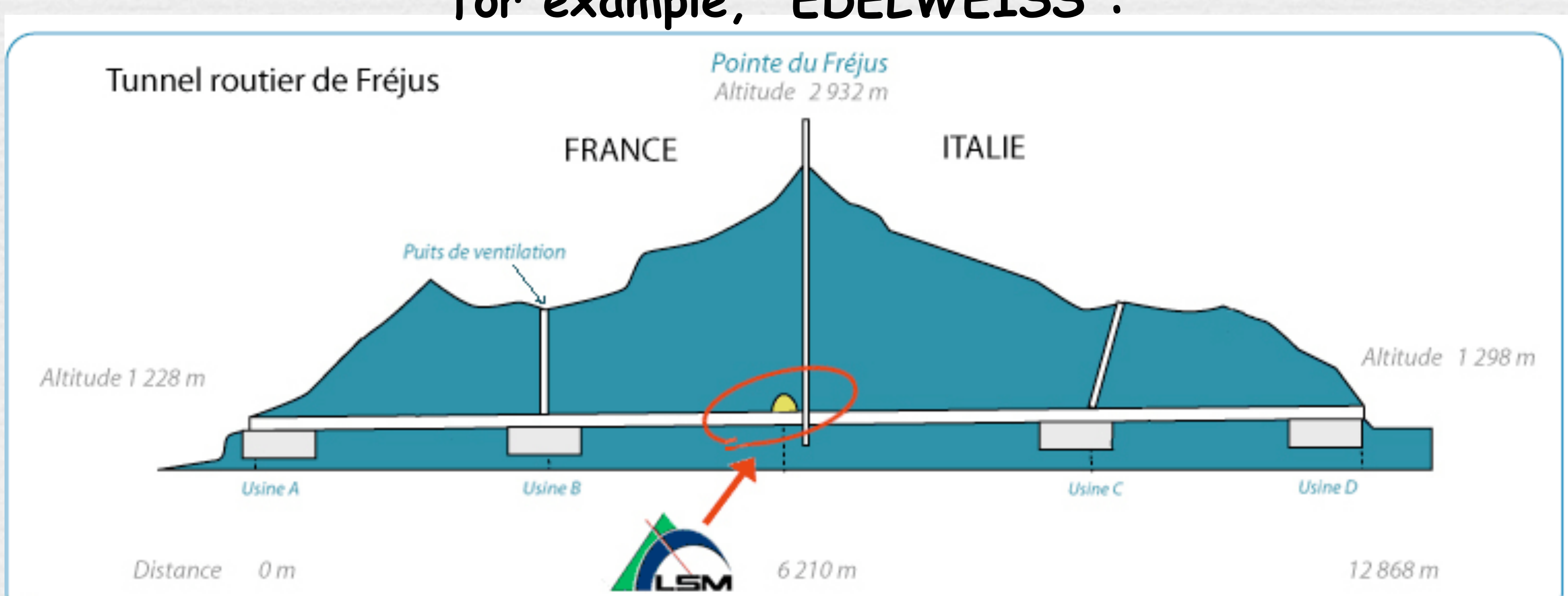


WIMP flux on Earth: ~ 10^5 cm^{-2}s^{-1} (for a 100 GeV WIMP)

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



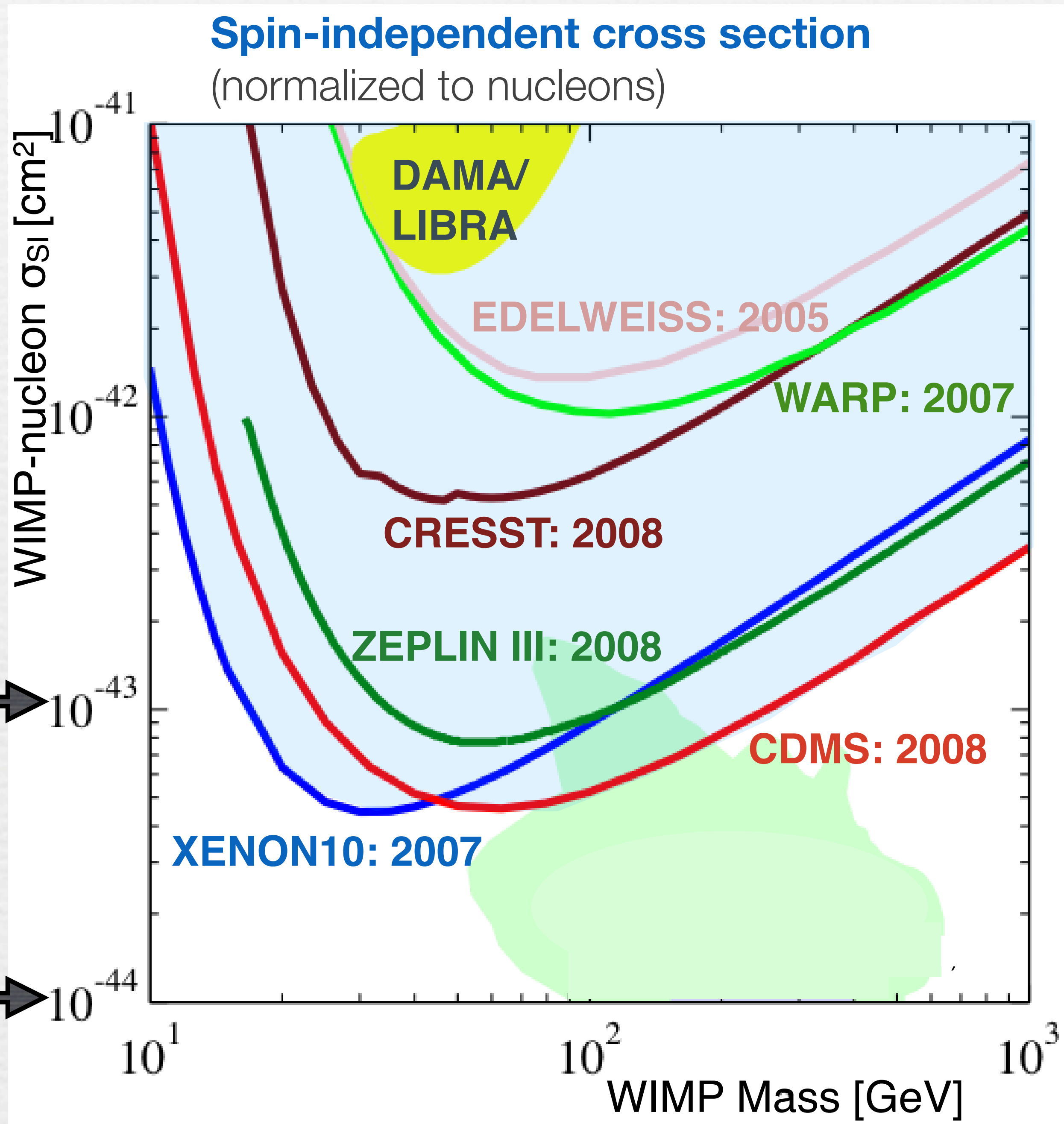
for example, "EDELWEISS":



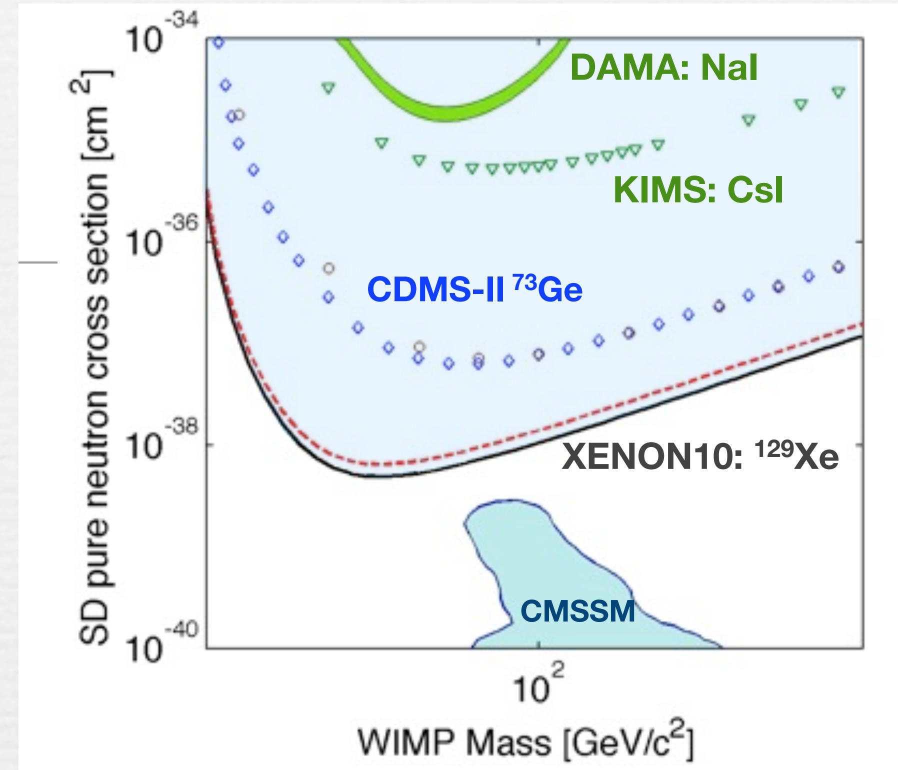
Experimental results

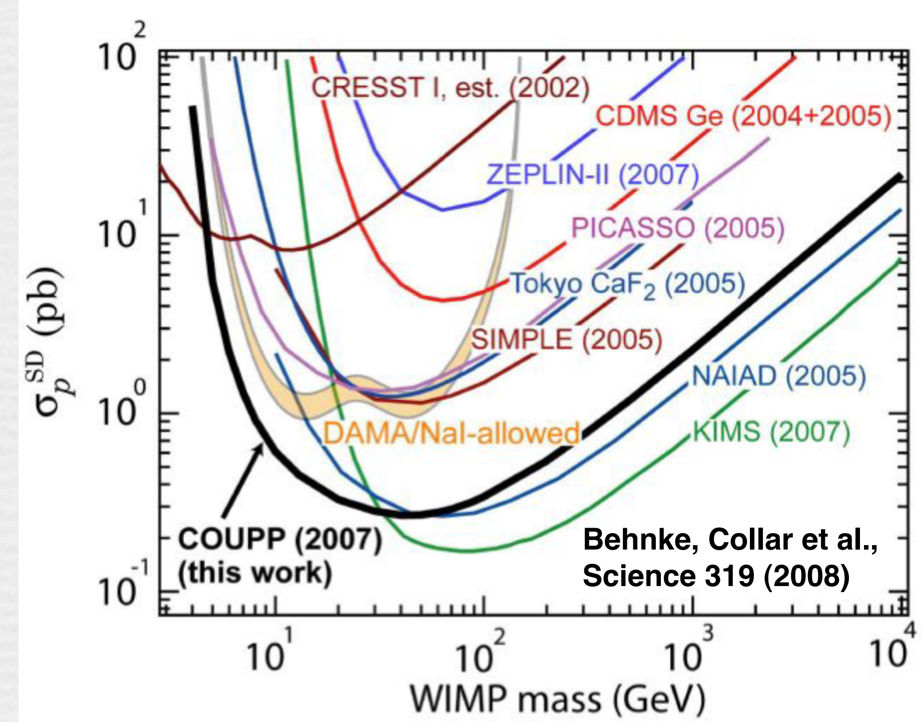
10^{-7} pb →

10^{-8} pb →



Spin-dependent



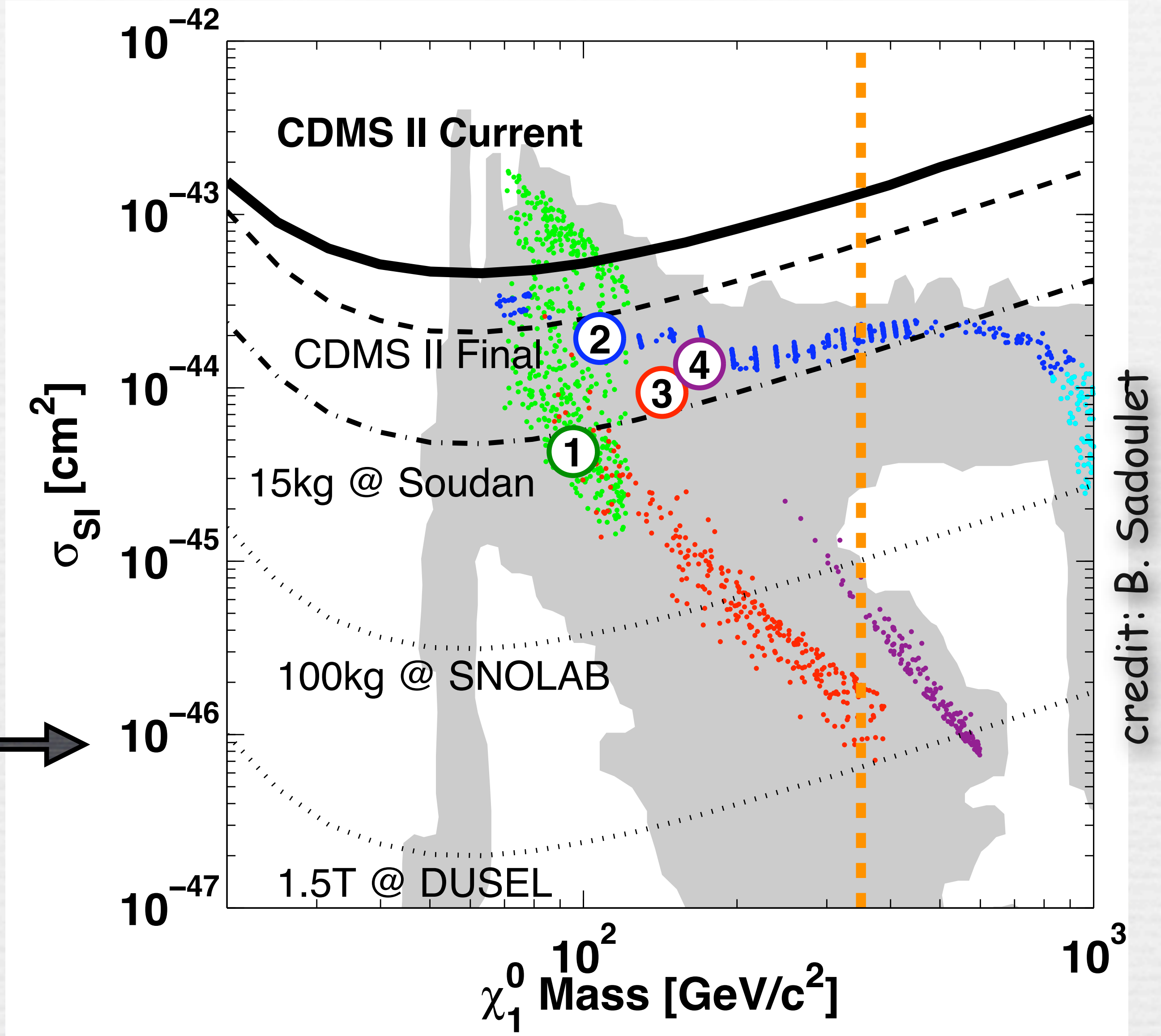


$\sigma_0^{SI} \sim A^2$, benefits from coherent scattering

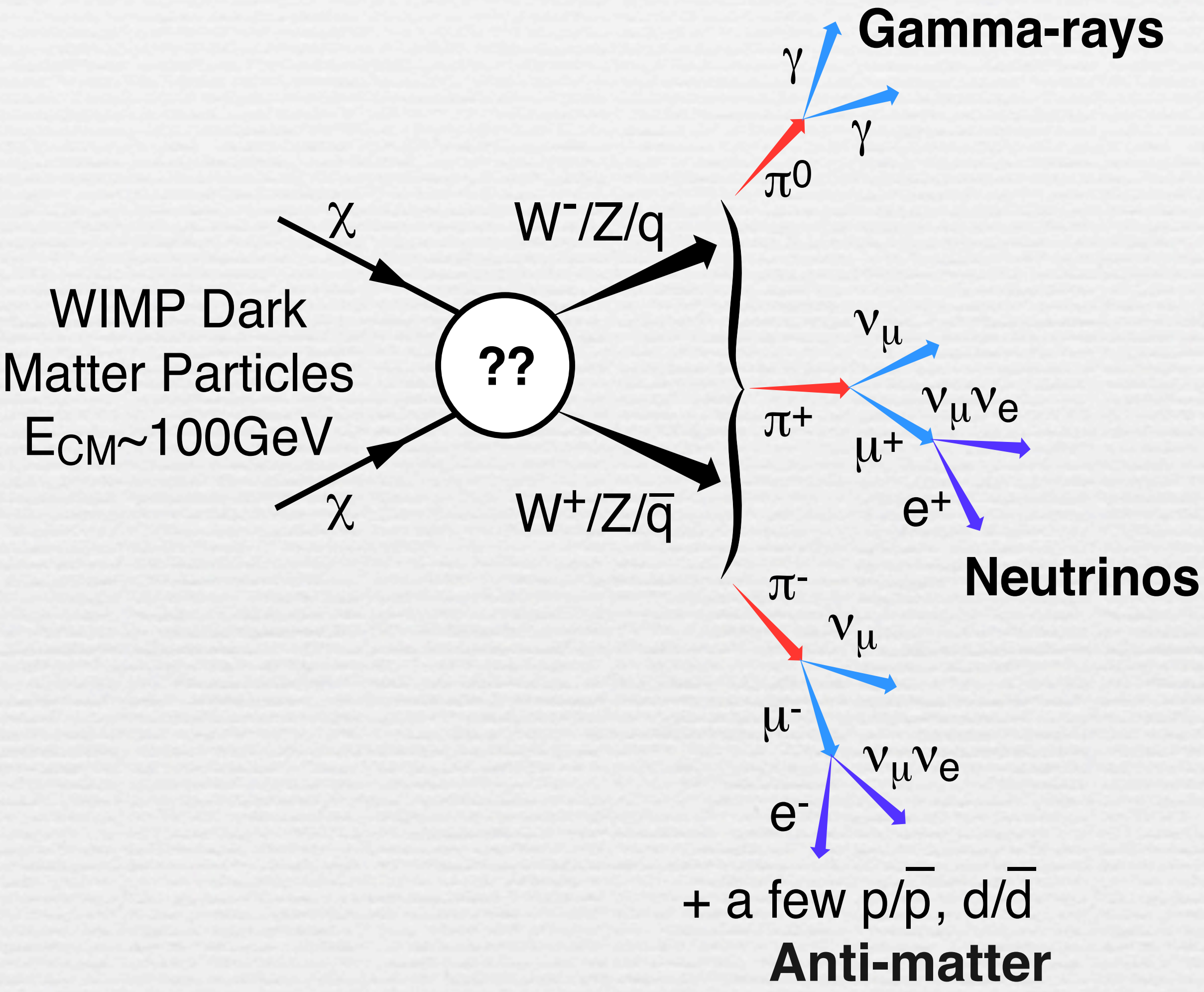
$\sigma_0^{SD} \sim J(J+1)$

Future prospects

10^{-10} pb



WIMP indirect detection



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})

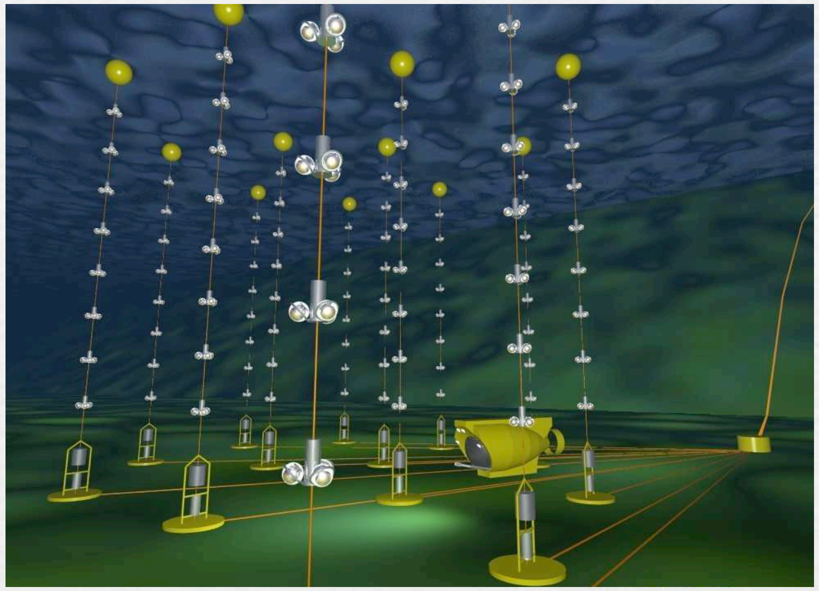
-> $N\ /year/km^3 \sim 10^{-13}$

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

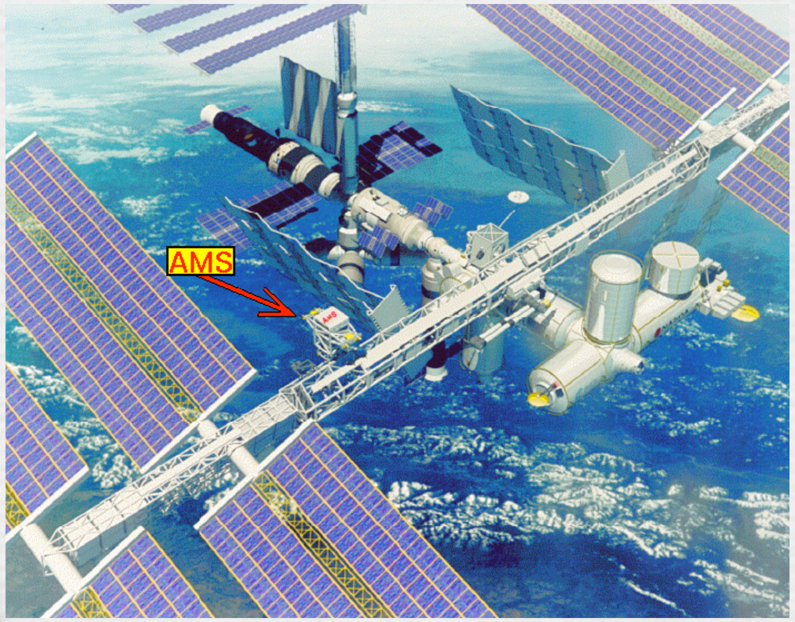
Indirect Detection

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

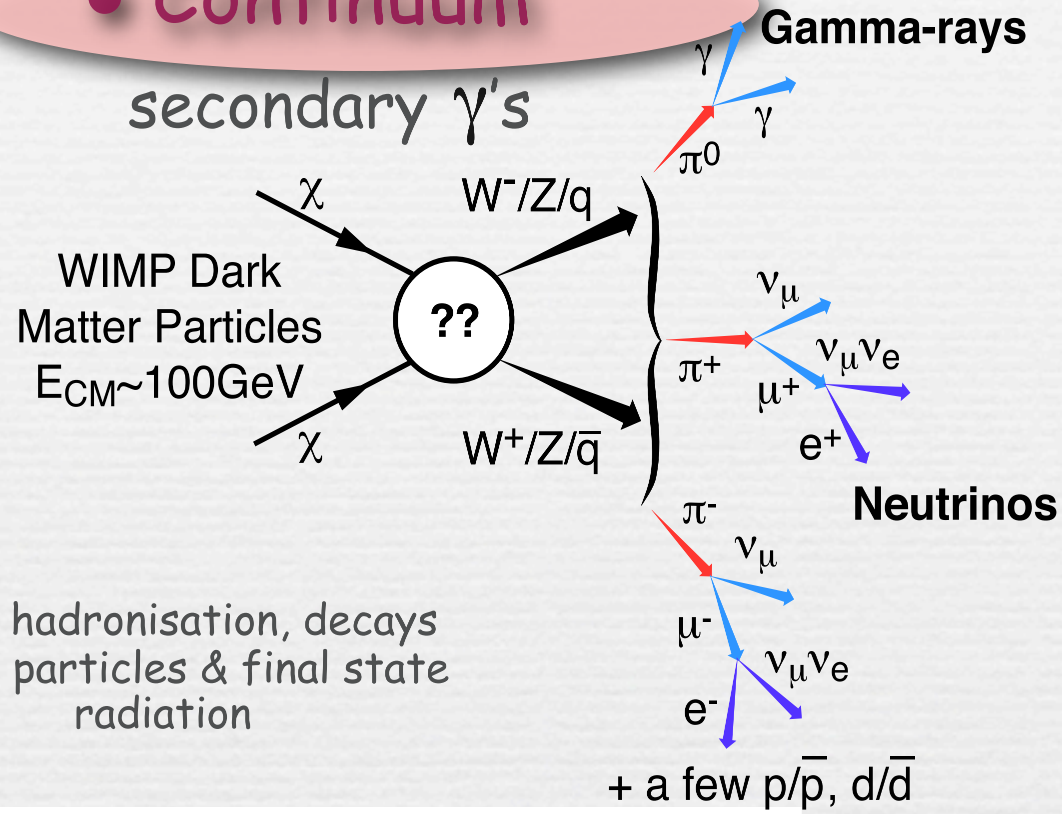
- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don't require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)

Seeing the light from Dark Matter

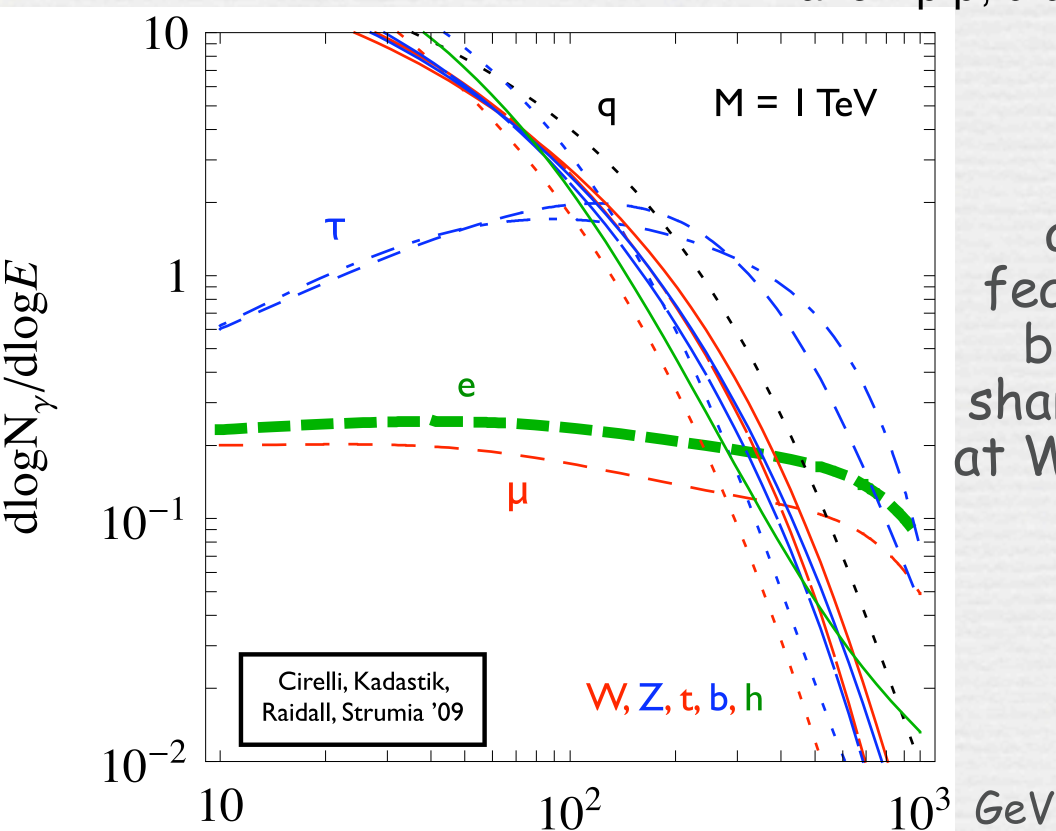
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



from hadronisation, decays of SM particles & final state radiation

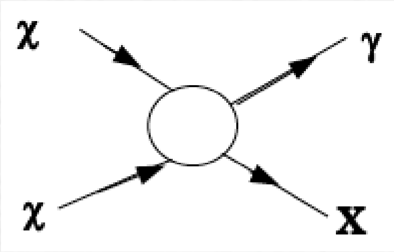


almost featureless but with sharp cutoff at Wimp mass

• Lines

primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

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

☺ smoking gun signature: gamma-ray line from direct anni into γγ, γZ or γH

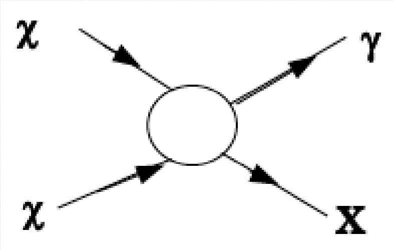
☹ lines are usually small (loop-suppressed) compared to continuum

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:



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

→ $\gamma\gamma$ 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

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

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

includes all possible annihilation final states

microphysics

astrophysics (halo profile)

Astrophysical uncertainties on the DM density profile

for DM decay:

* $\dfrac{\langle\sigma v\rangle}{4M_{DM}^2} \longrightarrow \dfrac{1}{\tau M_{DM}}$
* $\rho^2 \longrightarrow \rho$

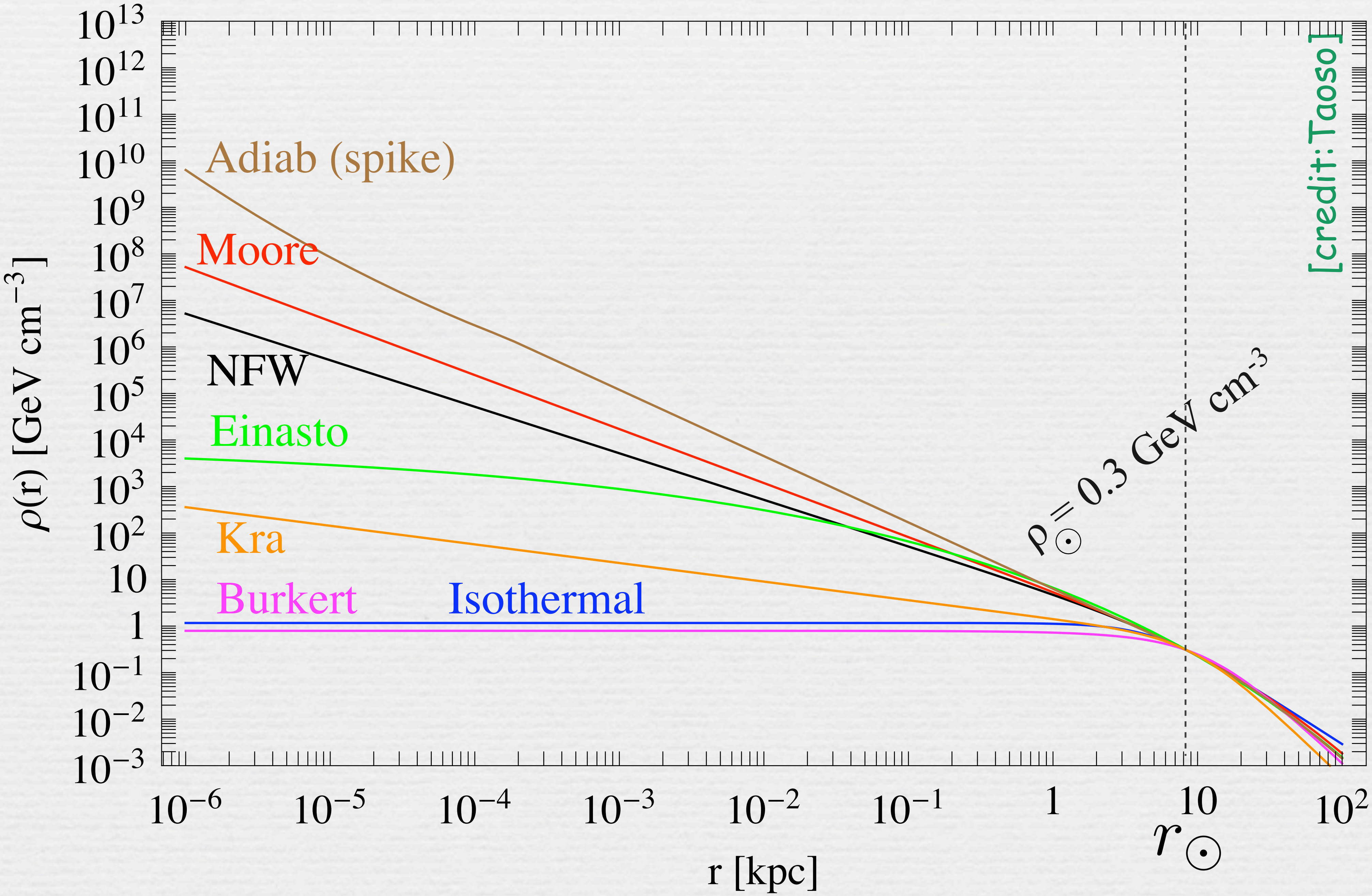
MW halo model	r_s in kpc	ρ_s in GeV/cm^3	$\bar{J}$ (10^{-5})
NFW [20]	20	0.26	$15 \cdot 10^3$
Einasto [21]	20	0.06	$7.6 \cdot 10^3$
Adiabatic[22]			$4.7 \cdot 10^7$

for observation of the galactic center region with angular acceptance $\Delta\Omega = 10^{-5}$

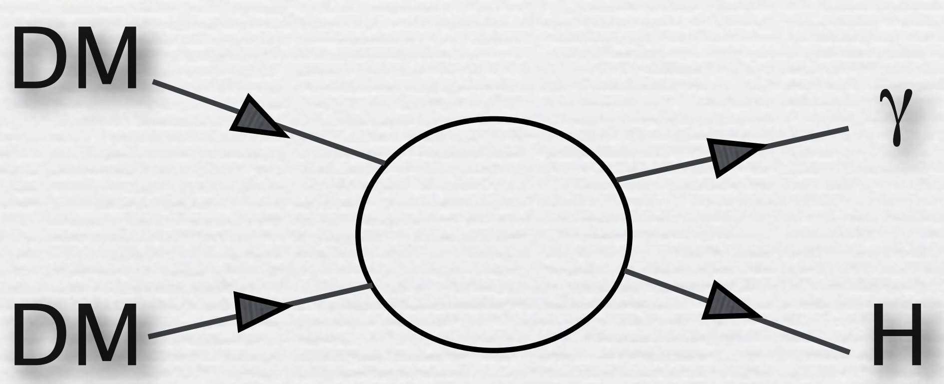
$$\frac{d\Phi}{dE} \propto \int \rho^2$$

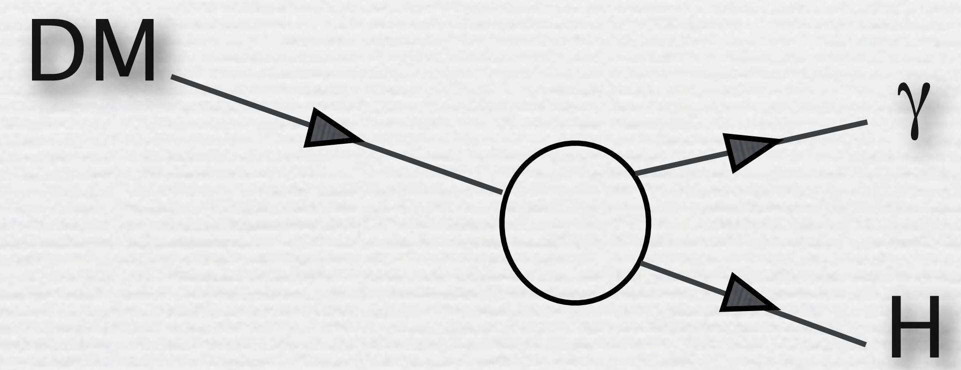
Searches focus on regions of the sky where DM clumps: Galactic Center, dwarf galaxies...

Astrophysical uncertainties on the DM density profile



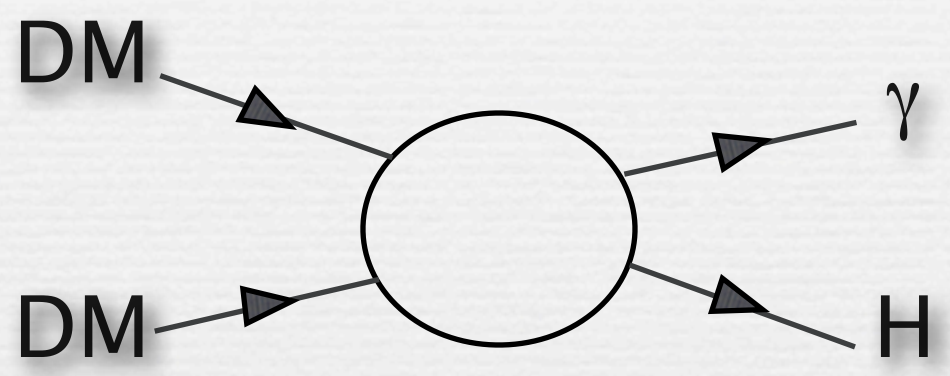
What about Higgs production today in
Dark Matter annihilations or Dark Matter decays?





Indirect probes of the Higgs in space

Discovery of a gamma-ray line produced by WIMP annihilations in space and whose energy reflects the mass of the Higgs (and the WIMP)



could even allow the first direct observation of a Higgs production process

if the WIMP hypothesis is correct: likely to be connected to the physics of EW symmetry breaking and may have enhanced couplings to massive states

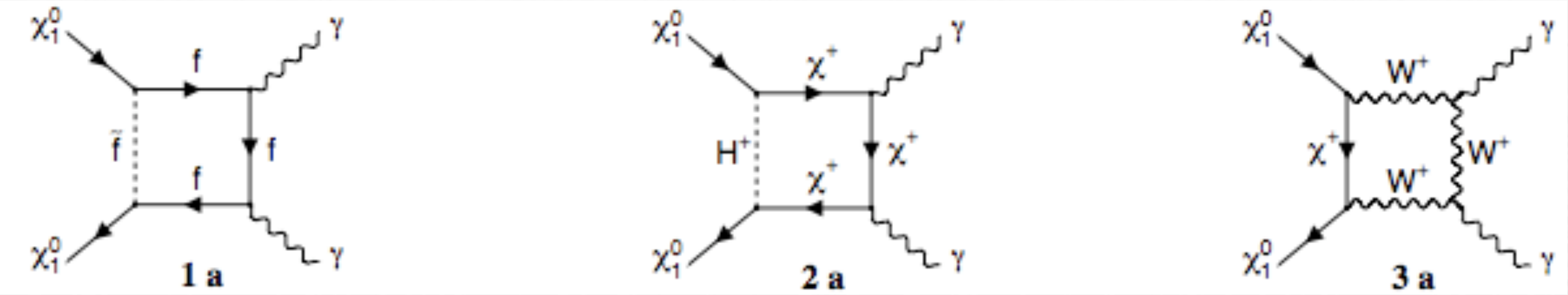
γ-lines from DM

Past results

SUPERSYMMETRY

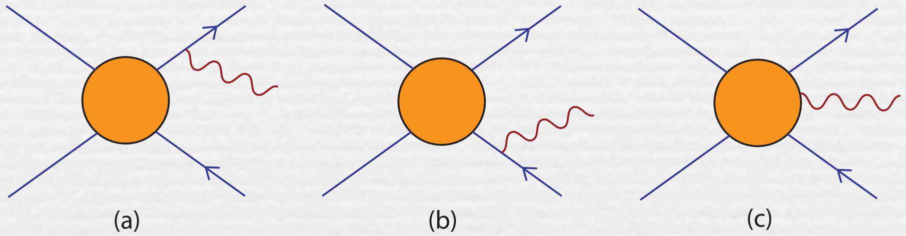
Bergstrom, Ullio, Buckley' 98
Bringmann, Bergstrom & Edsjo '08
...

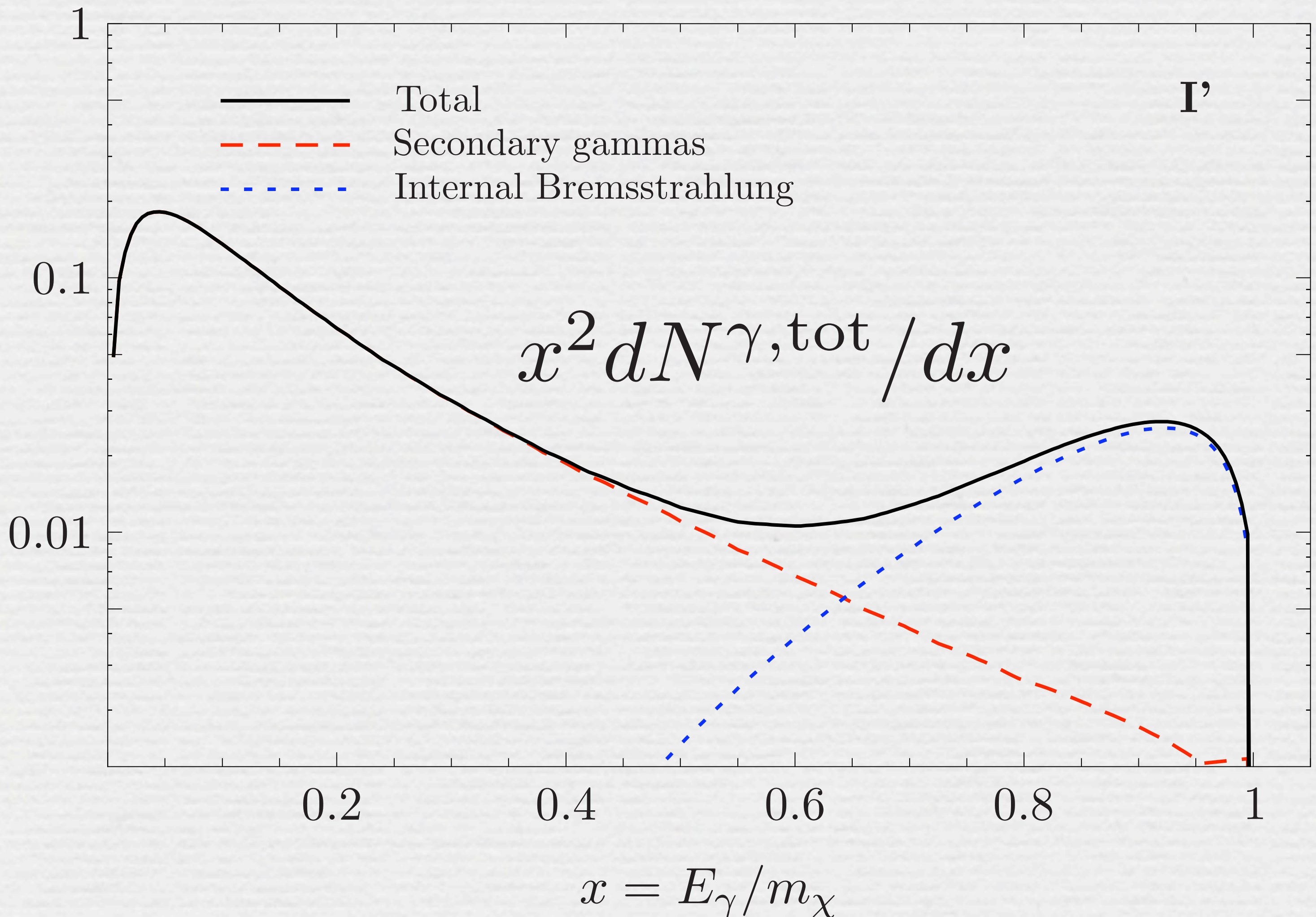
annihilations into $\gamma\gamma$ & γZ :



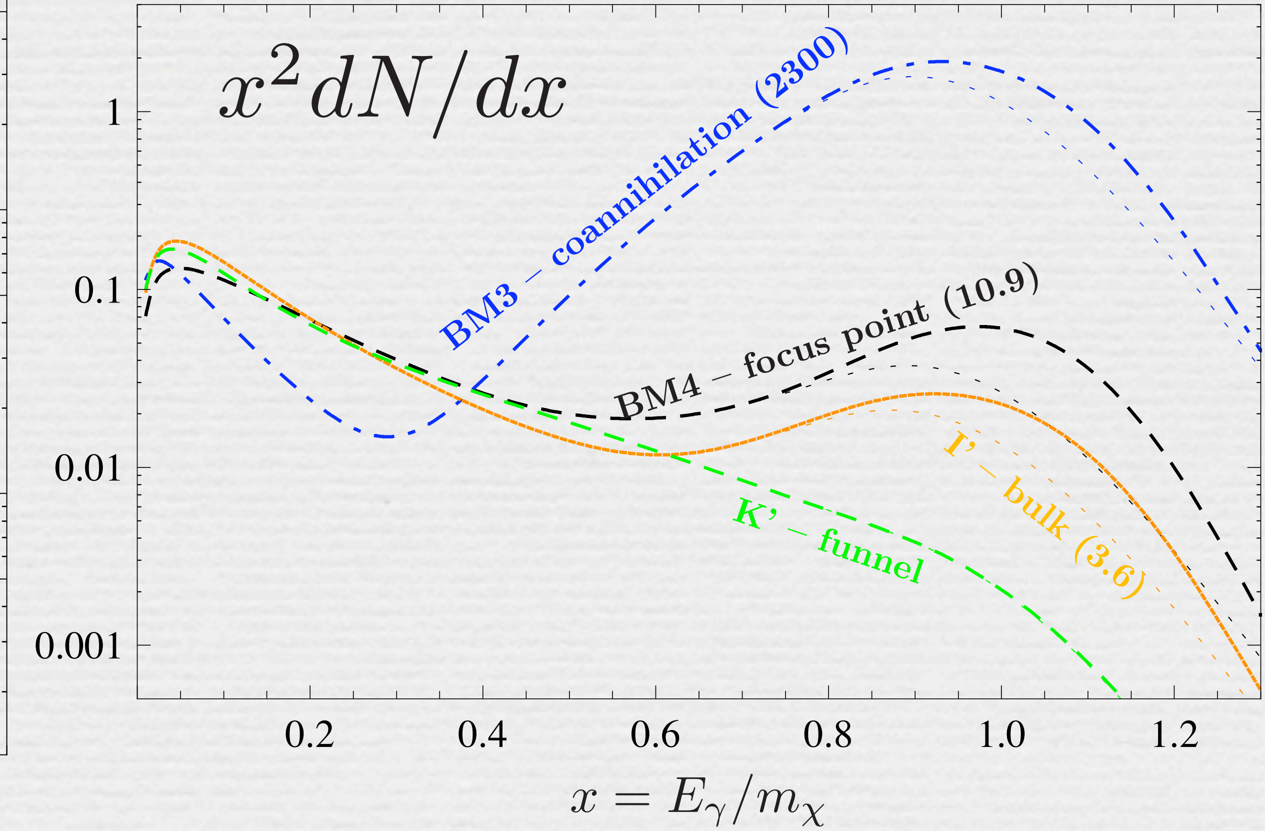
"Standard"Continuum suppressed by Majorana nature of WIMP (light fermion states chirally suppressed)

wever, as recently reexamined: large enhancements from internal bremsstrahlung





No line feature



The Inert Doublet Model (IDM)

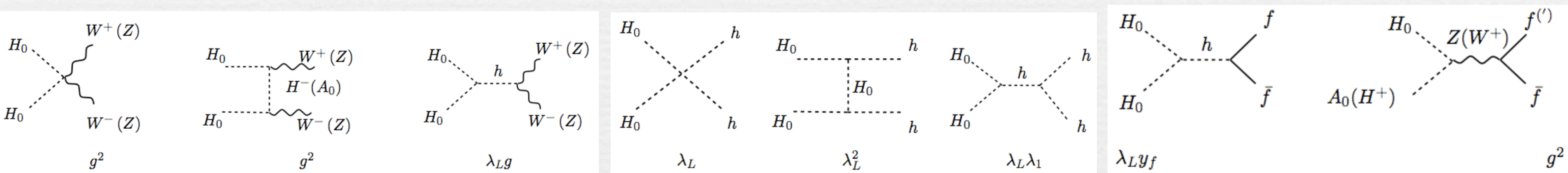
Deshpande-Ma'78; Barbieri-Hall-Rychkov 06; Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07 ; Hambye, Tytgat 07 .....

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)

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

Scalar WIMP with $M_{DM} \sim M_W$



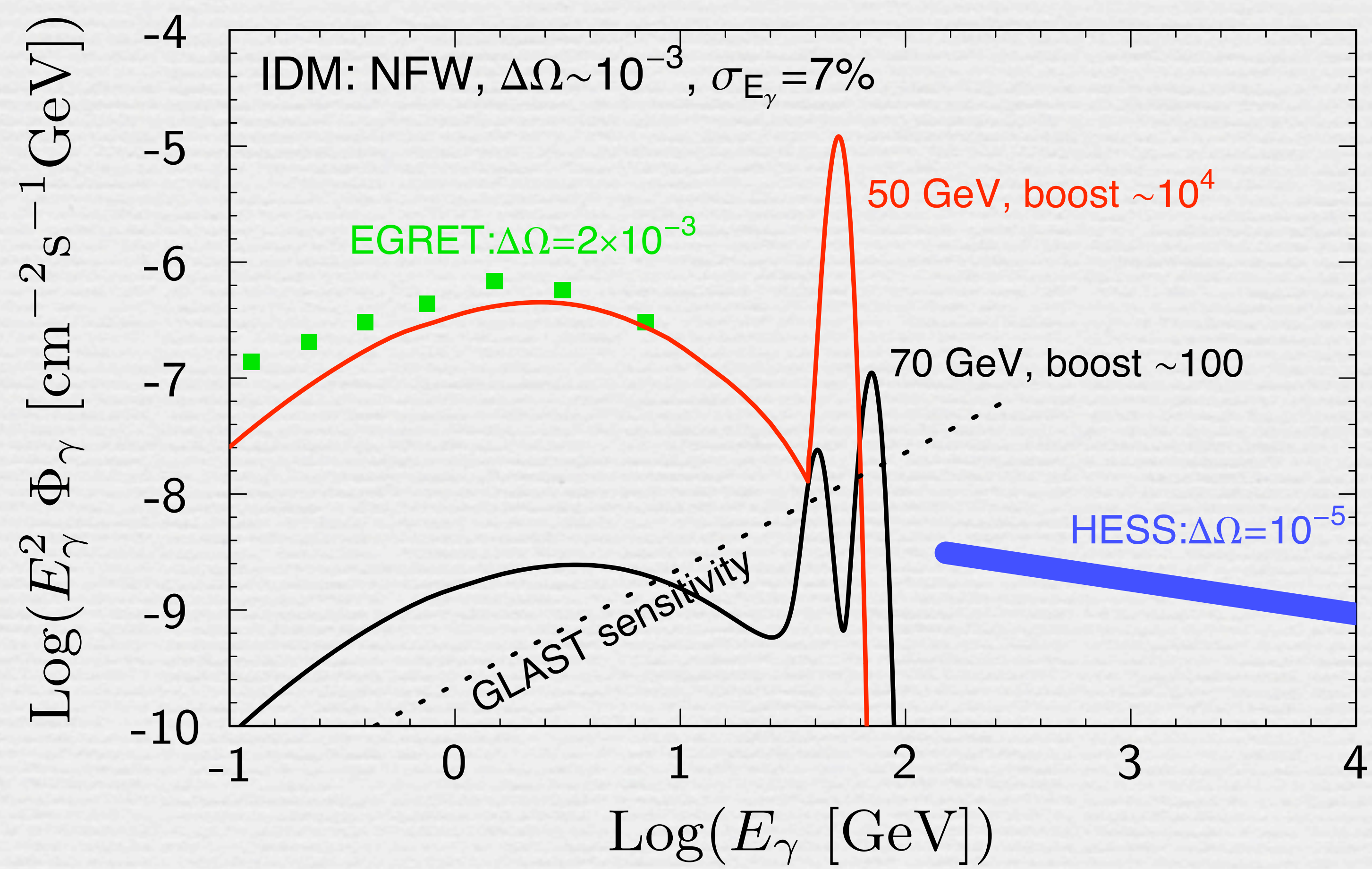
annihilations into $\gamma\,\gamma$ & $\gamma\,Z$

mainly through loops of W

Gustaffsson et al. '07

virtual W nearly on-shell

threshold enhancement

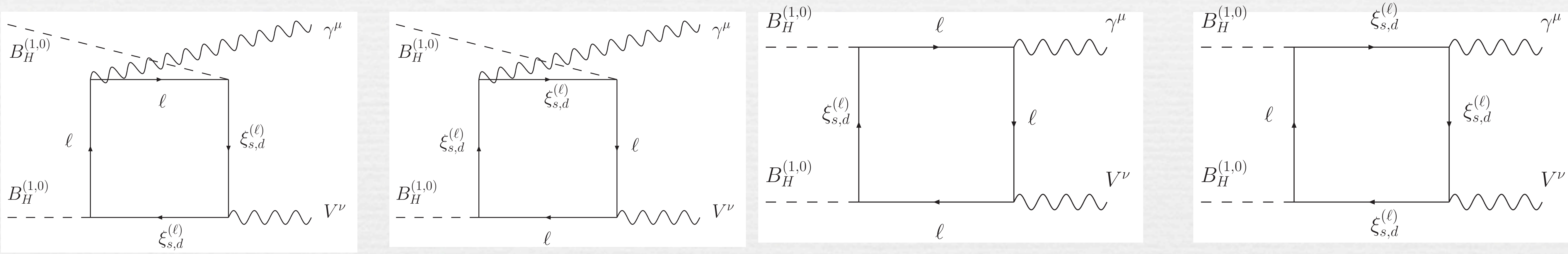


Lines from 6D Universal Extra Dimensions (the "Chiral square")

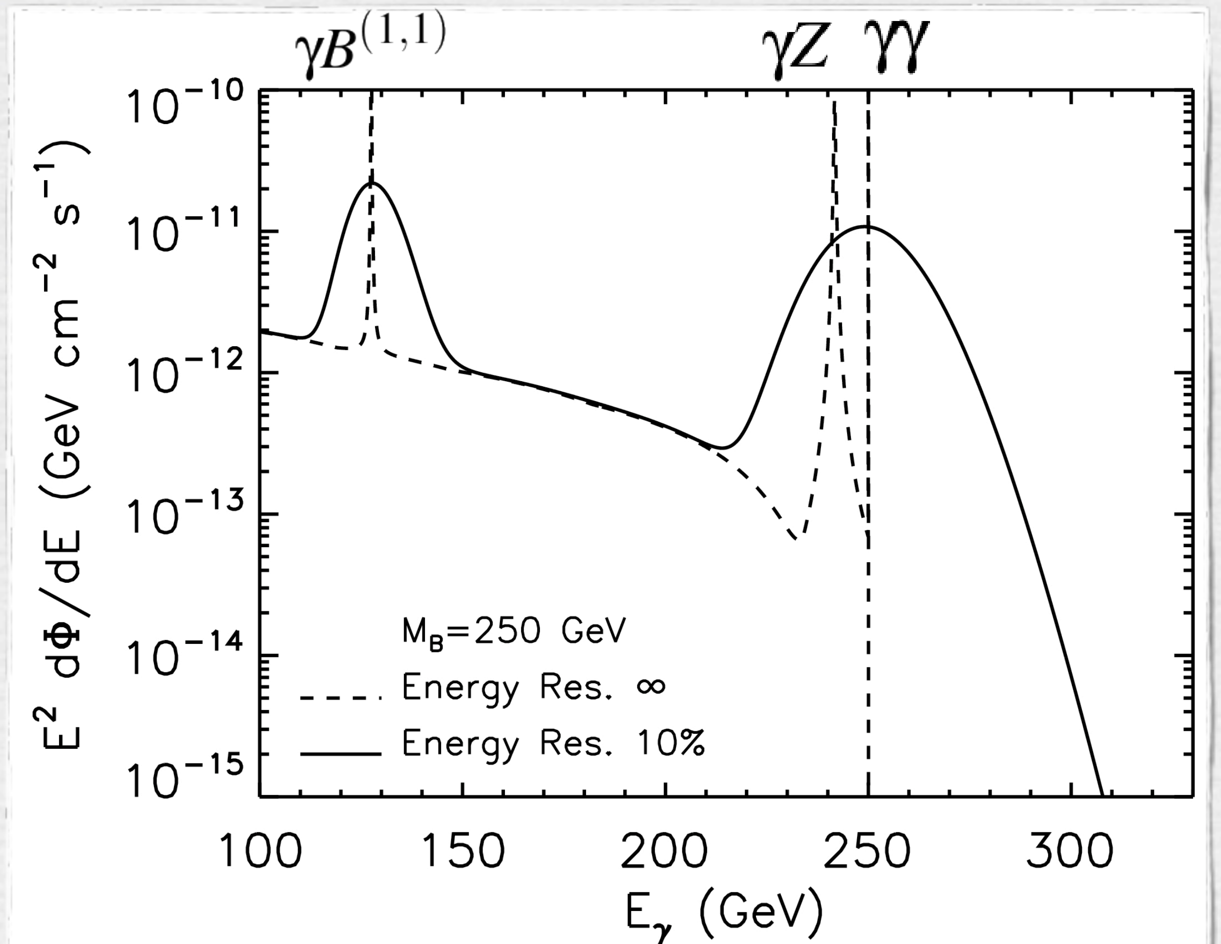
WIMP=scalar B_H ("spinless photon") with M~200-500 GeV

Burdman, Dobrescu, Ponton'05
Dobrescu, Hooper, Kong, Mahbubani '07

$B_H B_H \to \gamma V$ where V= γ, Z and $B^{(1,1)}$



Bertone, Jackson, Shaughnessy, Vallinotto, Tait. '09



Annihilations into γ H?

Scalar DM ☹

e.g. "Chiral Square" (6D UED model), Inert Doublet Model ...

Non-relativistic scattering of 2 scalars ⇛ The initial state angular momentum is zero

OK if 2 vectors in the final state but vector+scalar final state requires initial state orbital angular momentum ⇛ higher order in v^2

Majorana fermion DM ☹

e.g. neutralino in SUSY

Must also annihilate at higher order in v^2 (initial state S=0)

→ Vector DM ☺

e.g. KK photon in 5D UED, heavy photon in Little Higgs models

OK in principle but if it annihilates via s-channel scalar exchange: still v^2 -suppressed; if t-channel (box diagrams), this is typically suppressed by couplings and masses (e.g. in UED or Little Higgs)

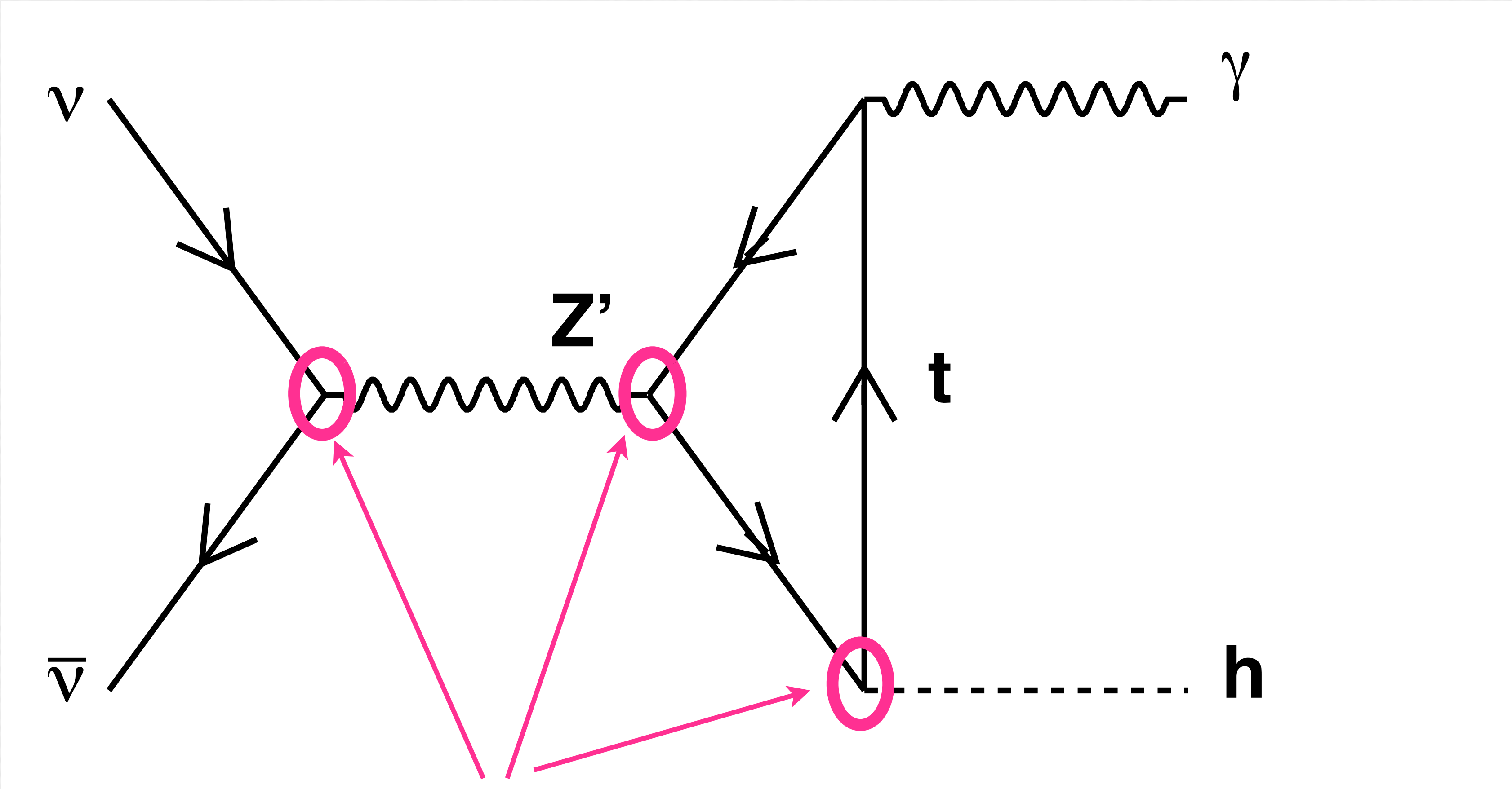
→ Dirac Fermion DM ☺

e.g. Agashe-Servant '04; Belanger-Pukhov-Servant '07

The top quark-Dark Matter connection

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

Dirac Dark Matter annihilation into γ H



~ O(1) couplings

A very simple effective theory

Jackson, Servant, Shaughnessy,Tait, Taoso,'09
Agashe-Servant '04; Belanger-Pukhov-Servant '07

There is a new spontaneously broken U(1)'.
The WIMP is a Dirac fermion, ν, singlet under the SM, charged under U(1)'

The only SM particle with a large coupling to the Z' is the top quark

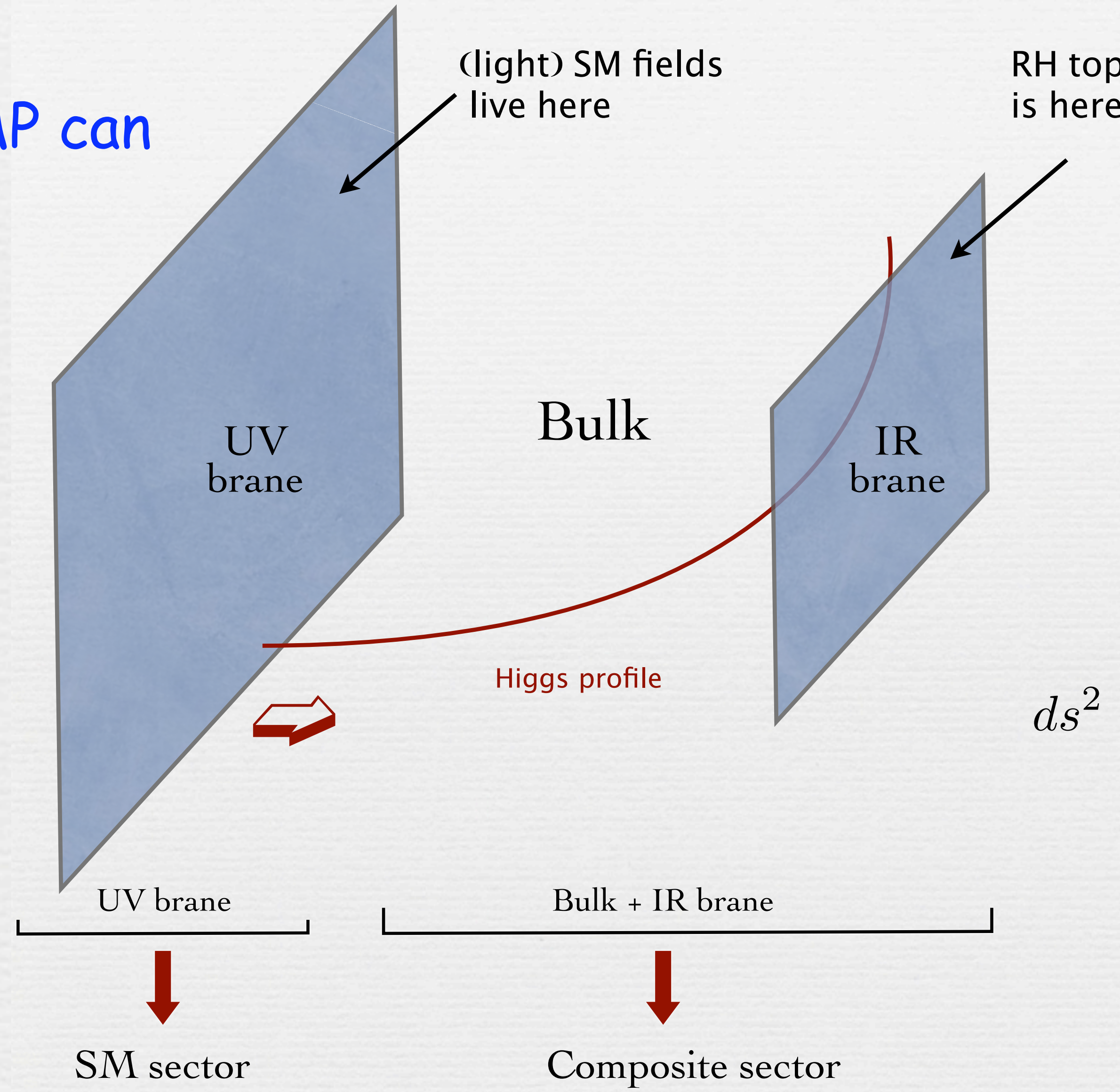
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + M^2_{Z'}Z'_\mu Z'^\mu + \underbrace{i\bar{\nu}\gamma^\mu D_\mu \nu}_{\text{DM}} + g^t_R \bar{t}\gamma^\mu P_R Z'^\mu t + \frac{\chi}{2}F'_{\mu\nu}F^{\mu\nu}_Y$$

$$D^\mu \equiv \partial_\mu - i\left(g^\nu_R P_R + g^\nu_L P_L\right) Z'^\mu$$

There is no SM state the WIMP can decay into: ν is stable.

This model is inspired by the Randall-Sundrum setup (warped extra dimension):

TeV KK modes (such as Z') have enhanced couplings to RH top quark



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

More generally, in models of partial fermion compositeness, natural to expect that only the top couples sizably to a new strongly interacting sector.

Proton stability & Stable GUT partner in Warped GUTs

Agashe-Servant'04

DM is RH neutrino from 16 of SO(10)

$$\begin{pmatrix} Q'_L \\ u^c_R \\ d^c_R \\ L'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}$$

multiplet has B=1/3

bulk fermion with (-+) BC -> light!

number of color indices

stable under $Z_3 : \Phi \longrightarrow \Phi \; e^{2\pi i\left[B - \frac{\alpha - \overline{\alpha}}{3}\right]}$

Has enhanced couplings to TeV KK modes (such as Z') and top quark

UV	SO(10)	IR
light SM fermions	warping $\longrightarrow$	t_R Higgs DM

Mass spectrum of KK fermions

Depends on:

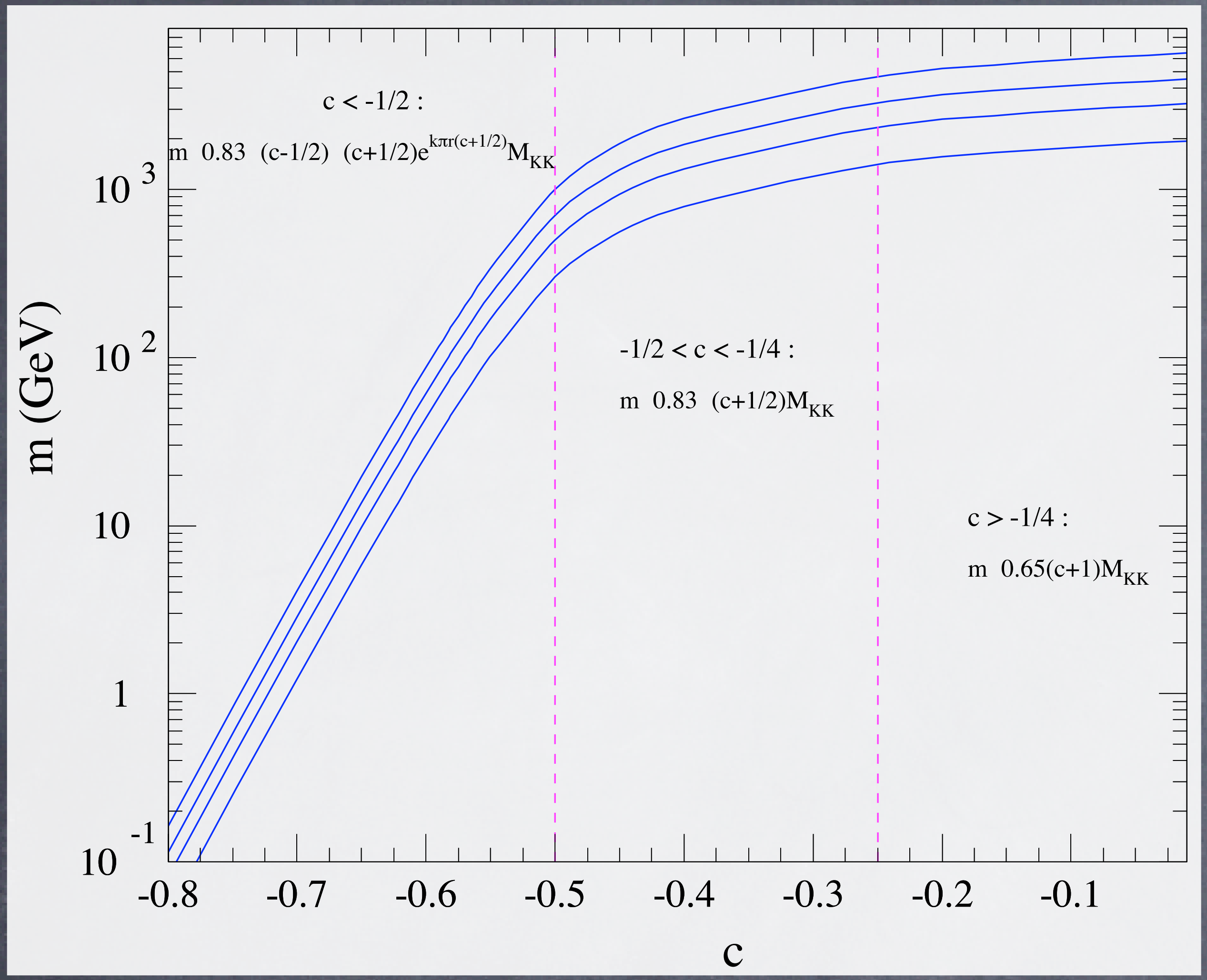
✔ type of boundary conditions on TeV and Planck branes

✔ c-parameter (=5D bulk mass)
(=localization of zero-mode wave function)

For certain type of boundary conditions on fermions, there can be a hierarchy between the mass of KK fermion and the mass of KK gauge bosons

$\Rrightarrow$ Not a single KK scale

Mass spectrum of lightest KK fermion



10 TeV
7 TeV
5 TeV
3 TeV

← M_{KK} value

c= 5D fermion mass in Planck units

Agashe-Servant hep-ph/0403143, hep-ph/0411254

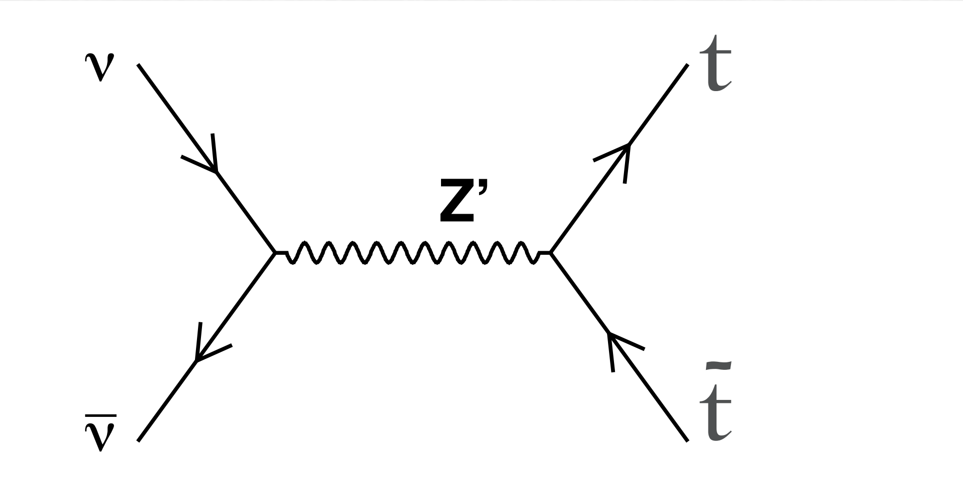
Right-handed top quark has c ≈ -1/2 ⇛ (-+) KK modes in its multiplet have mass of a few hundreds of GeV: Accessible at LHC!

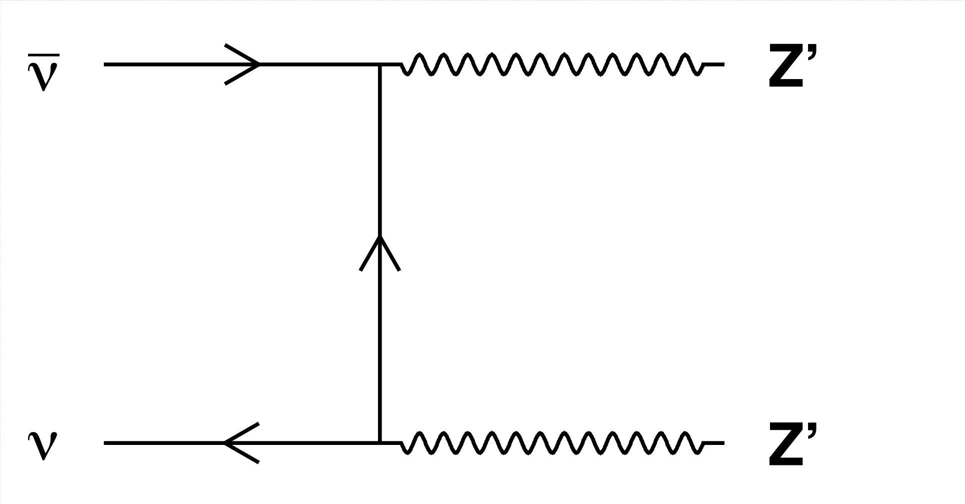
Light KK fermions are expected as a consequence of the heaviness of the top quark

Relic density calculation

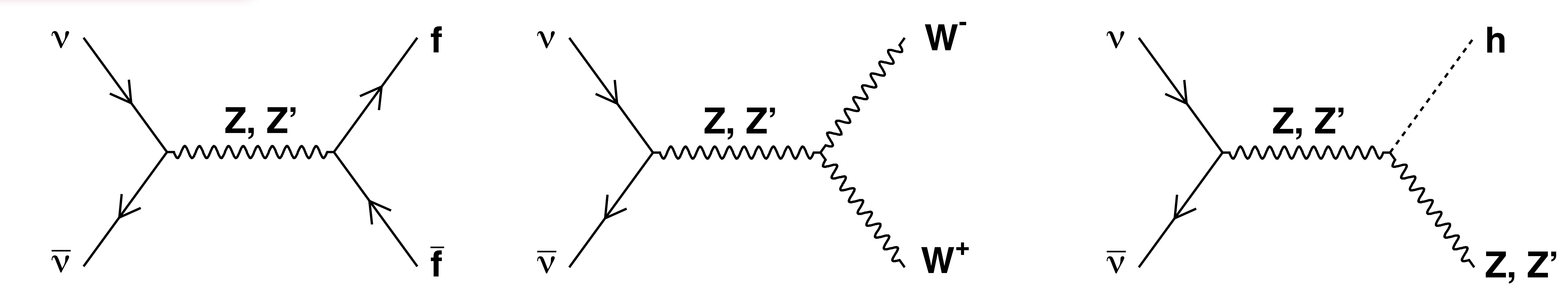
(assuming no $\nu\,\bar{\nu}$ asymmetry)

dominant channels





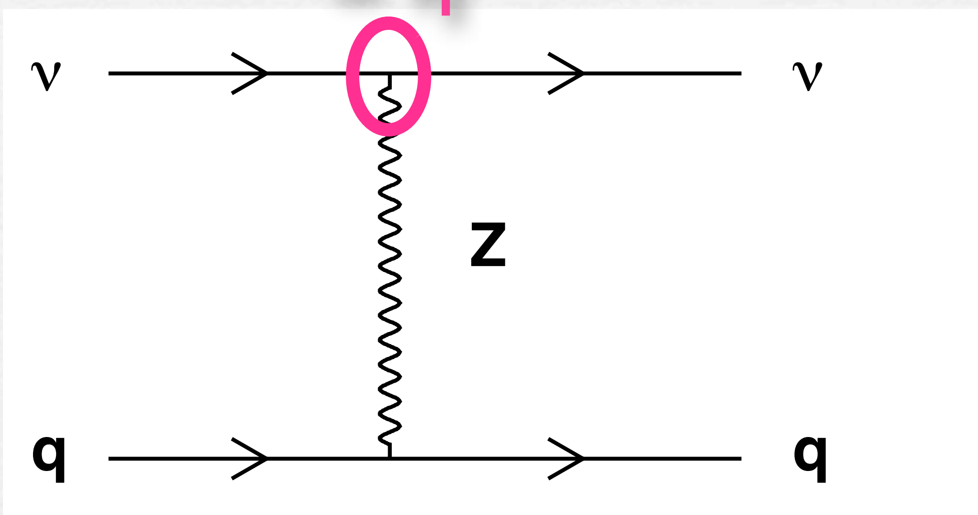
suppressed channels



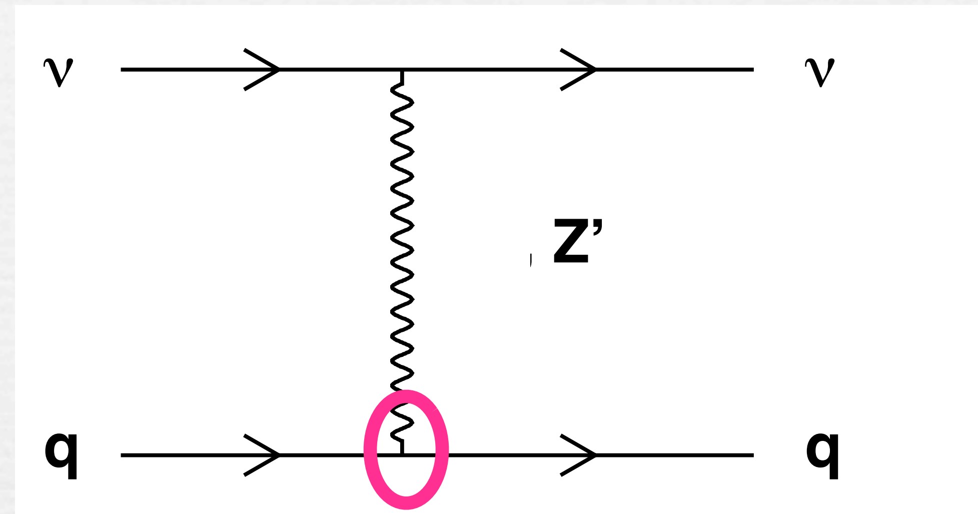
Direct detection constraints

η: kinetic mixing

$\propto \eta$



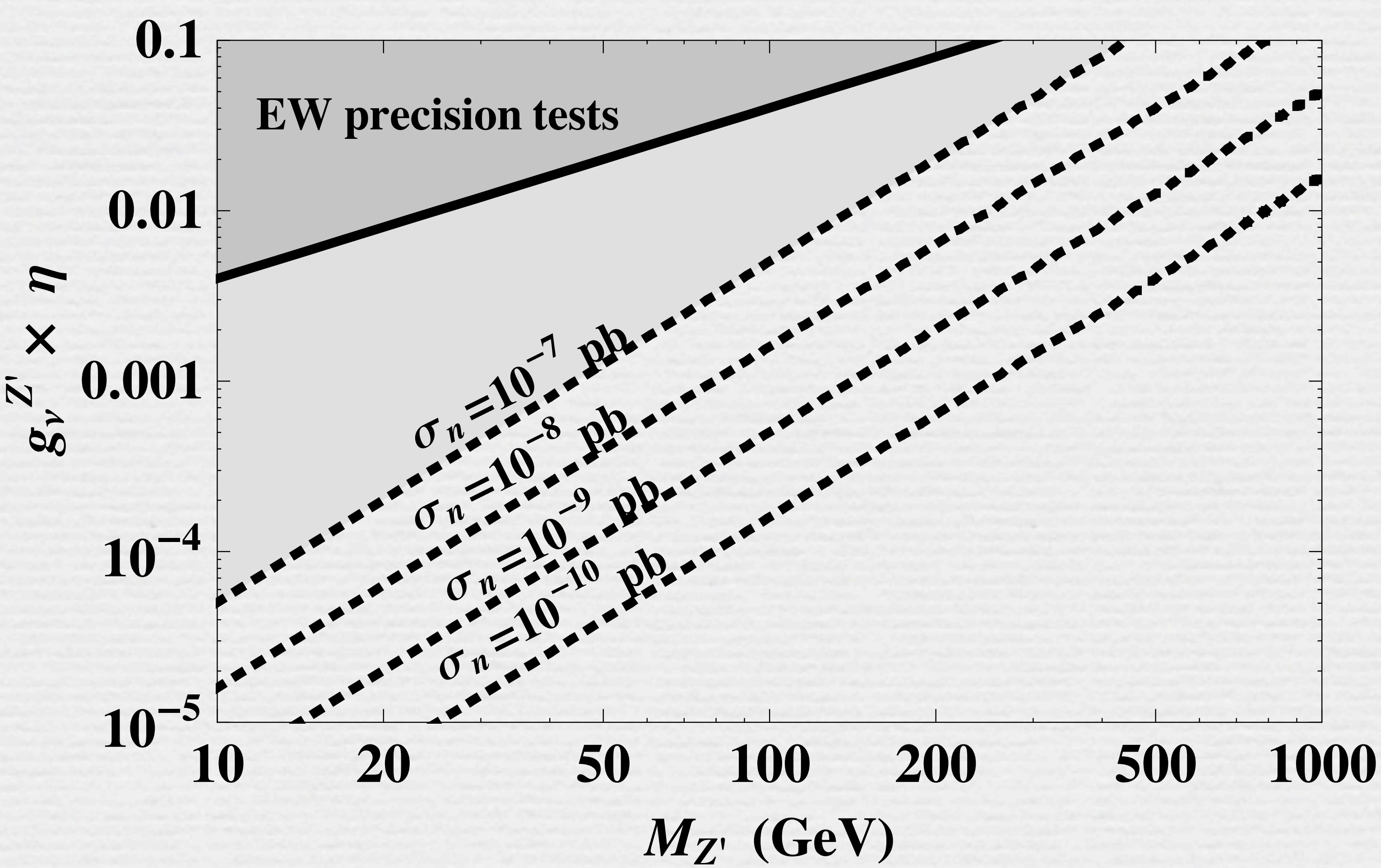
+



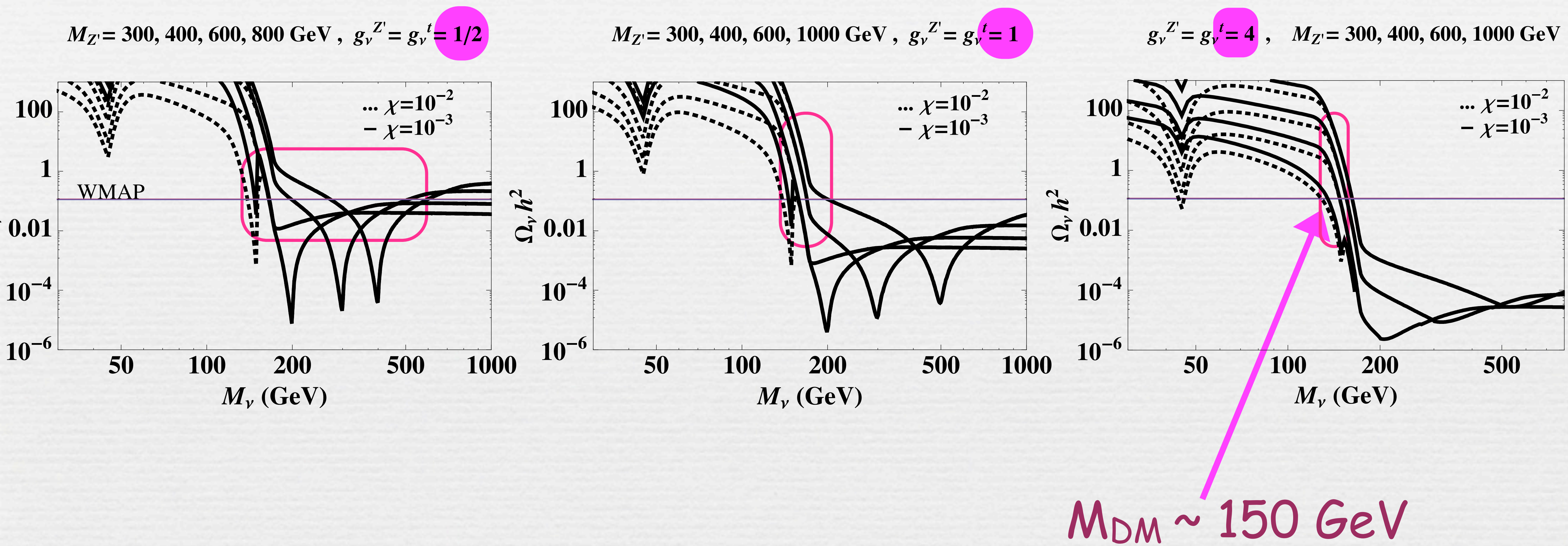
$\propto \eta$

$\rightarrow \sigma \propto \eta^2$

ν-nucleon elastic scattering cross section contours



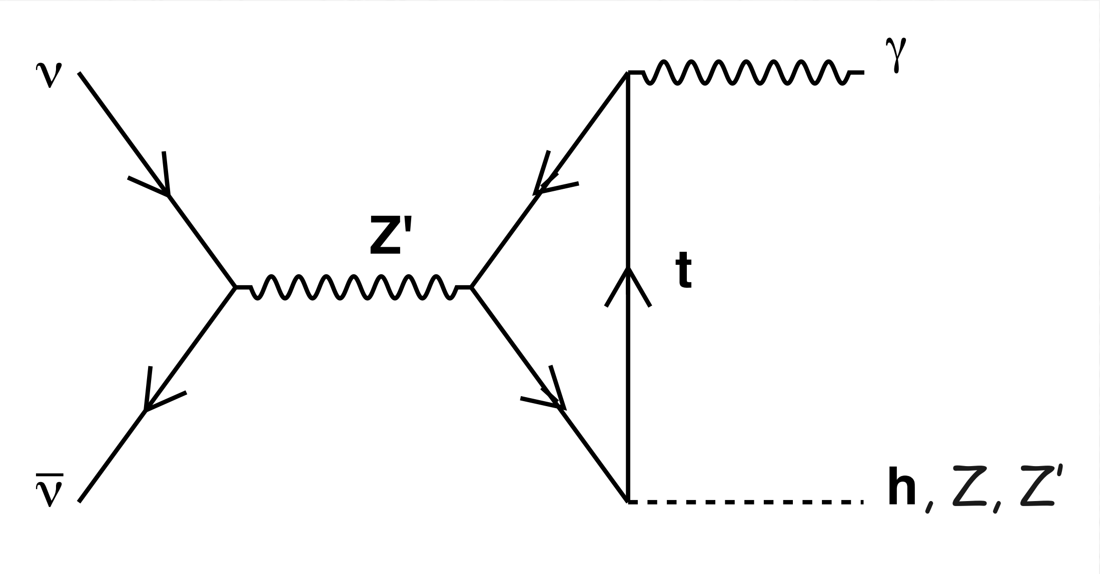
Dark matter mass from relic density calculation



as the Z' coupling to top and ν increases, the prediction for MDM gets narrower -> MDM ~ 150 GeV

for $g_\nu^{Z'}, g_t^{Z'} \gtrsim 1$

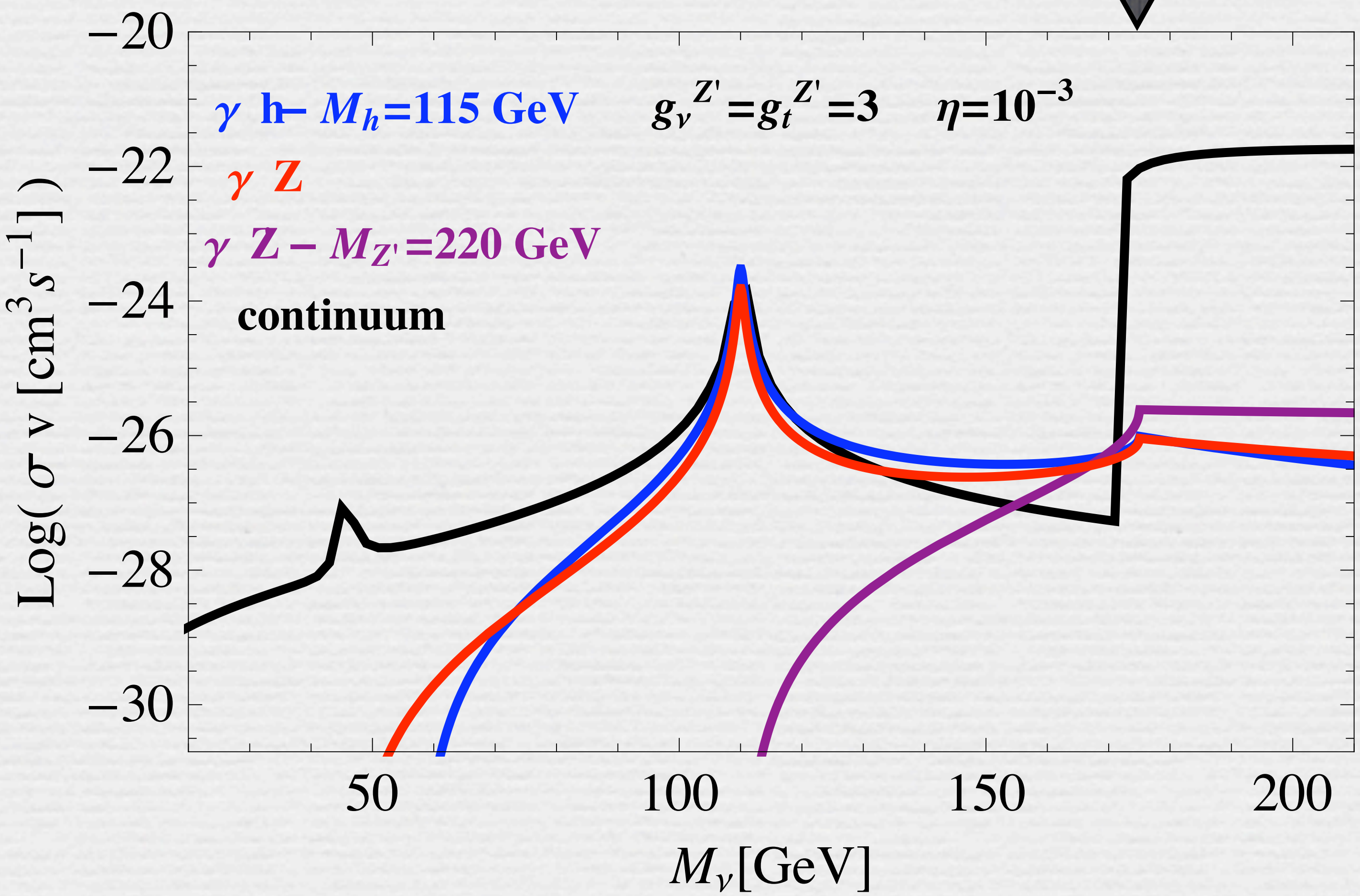
γ signal from ν annihilation



Note: no γγ line as dictated by Landau-Yang theorem (Z' being the sole portal from the wimp sector to the SM)

Lines not suppressed compared to continuum

continuum jumps due to opening of $t\bar{t}$ channel



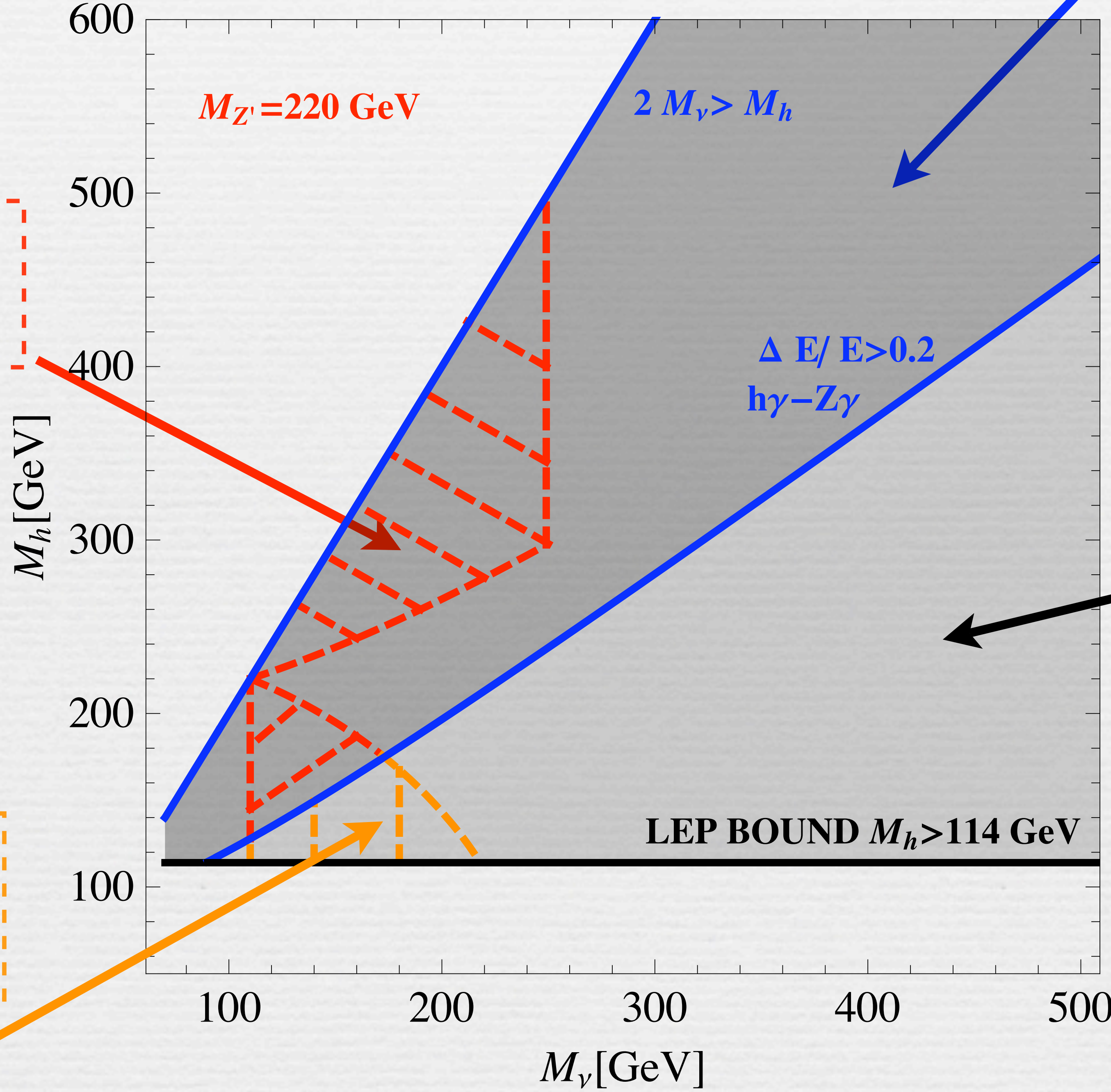
How many lines?

region where 2 lines are visible

(Hγ and Zγ)

region where the 3 lines are visible

(Hγ, Zγ and Z'γ)



region with 1 line (Hγ and Zγ lines are merged)

region with 2 lines (H/Zγ and Z'γ)

assuming energy resolut

of 10%

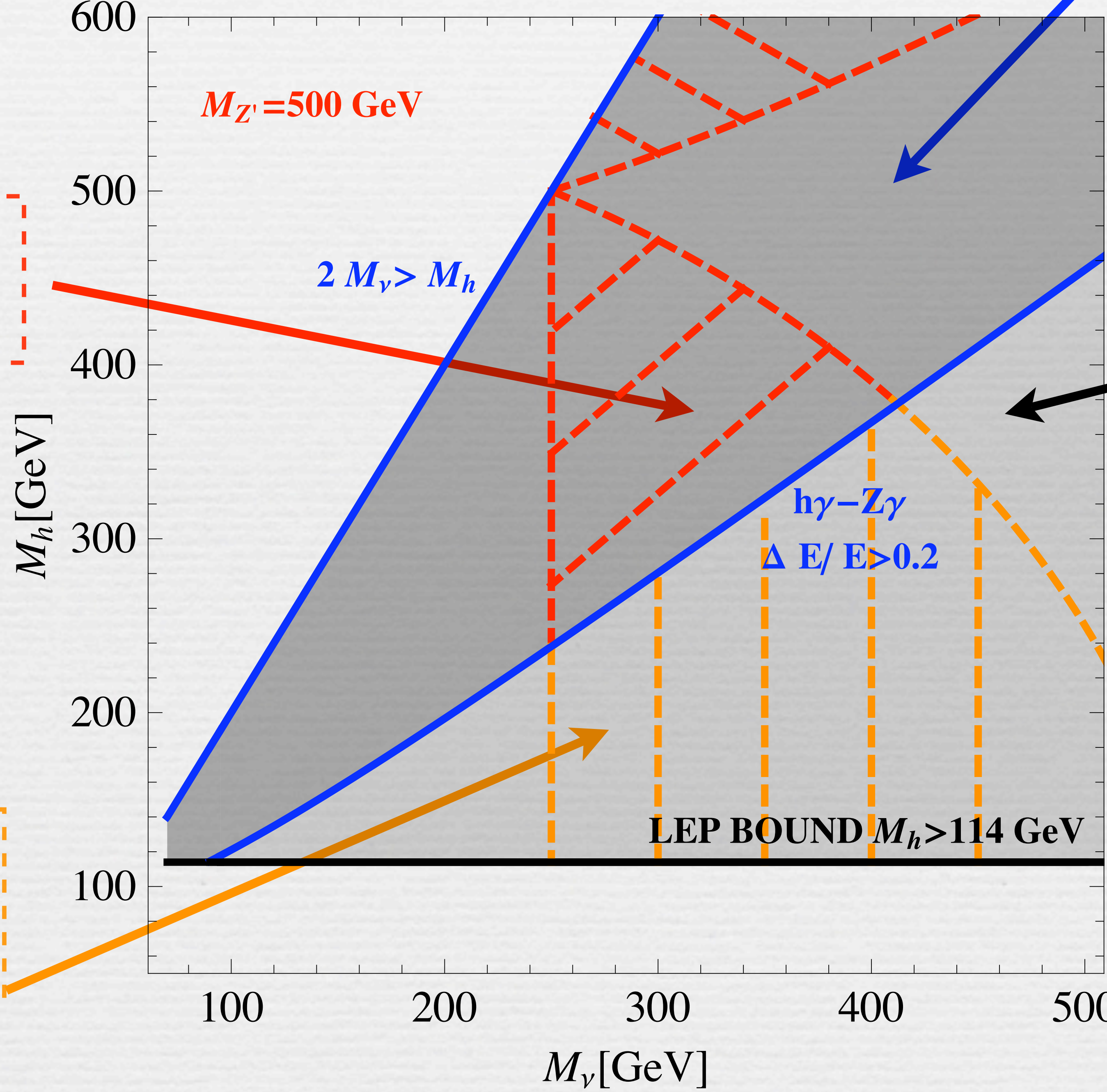
Line observability in the (M_{DM} - M_H) plane

region where 2 lines are visible

($H\gamma$ and $Z\gamma$)

region where the 3 lines are visible

($H\gamma$, $Z\gamma$ and $Z'\gamma$)



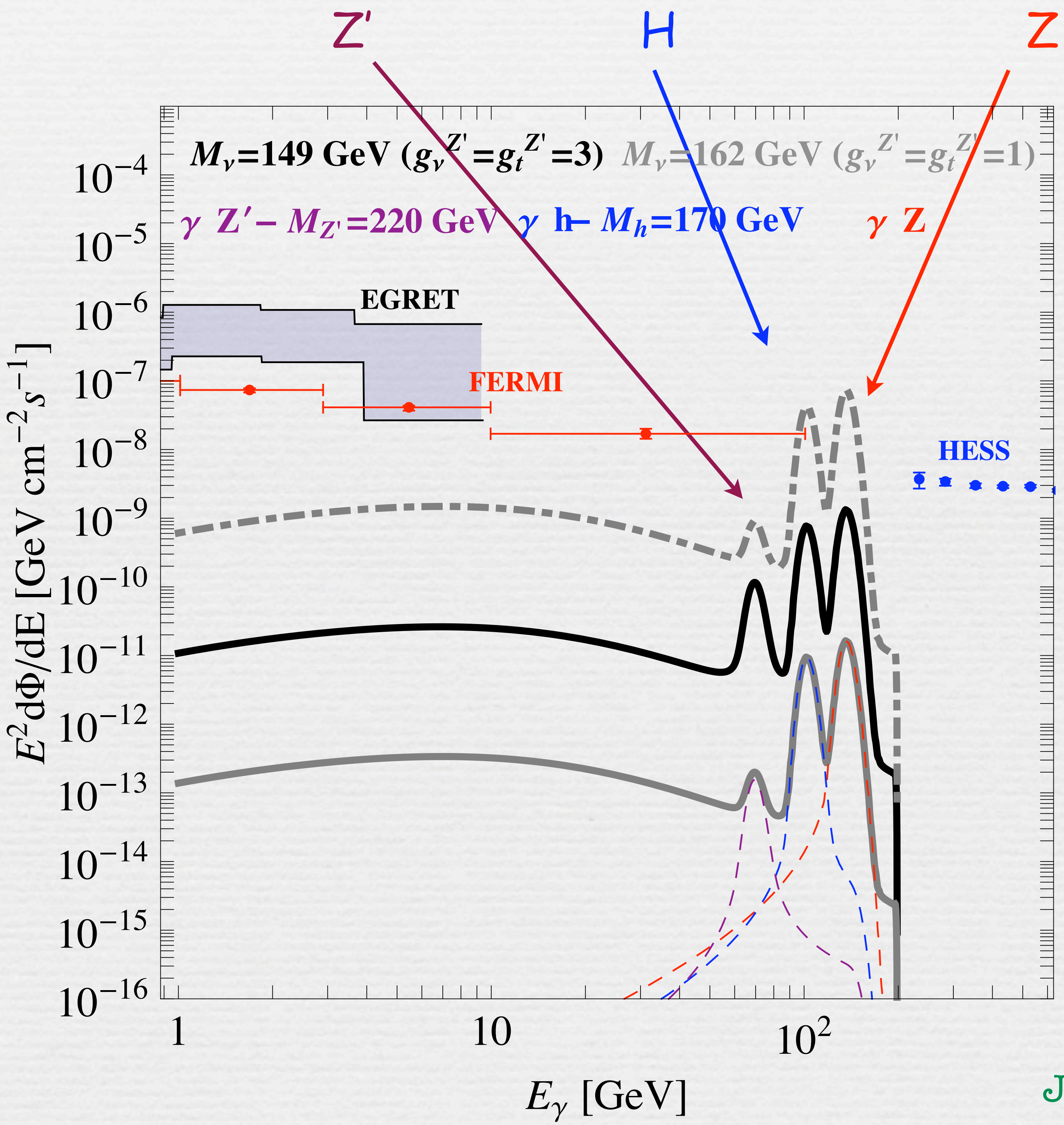
region with 1 line ($H\gamma$ and $Z\gamma$ lines are merged)

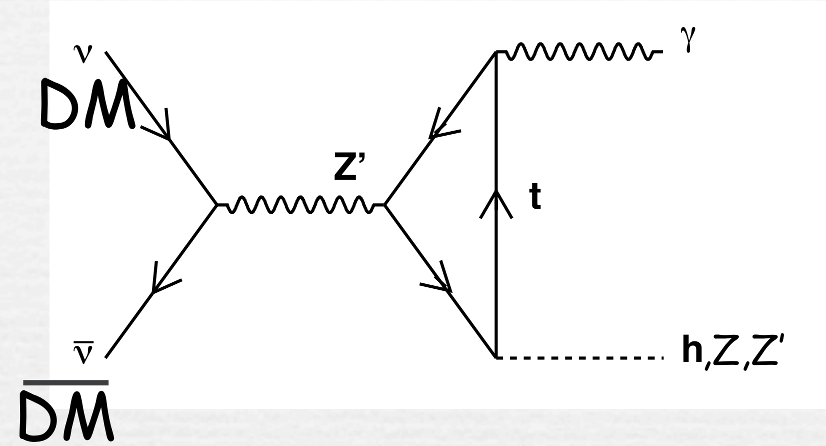
region with 2 lines ($H/Z\gamma$ and $Z'\gamma$)

assuming energy resolut of 10%

Higgs in Space!

γ-ray lines from the Galactic Center ΔΩ= 10^{-5} sr





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

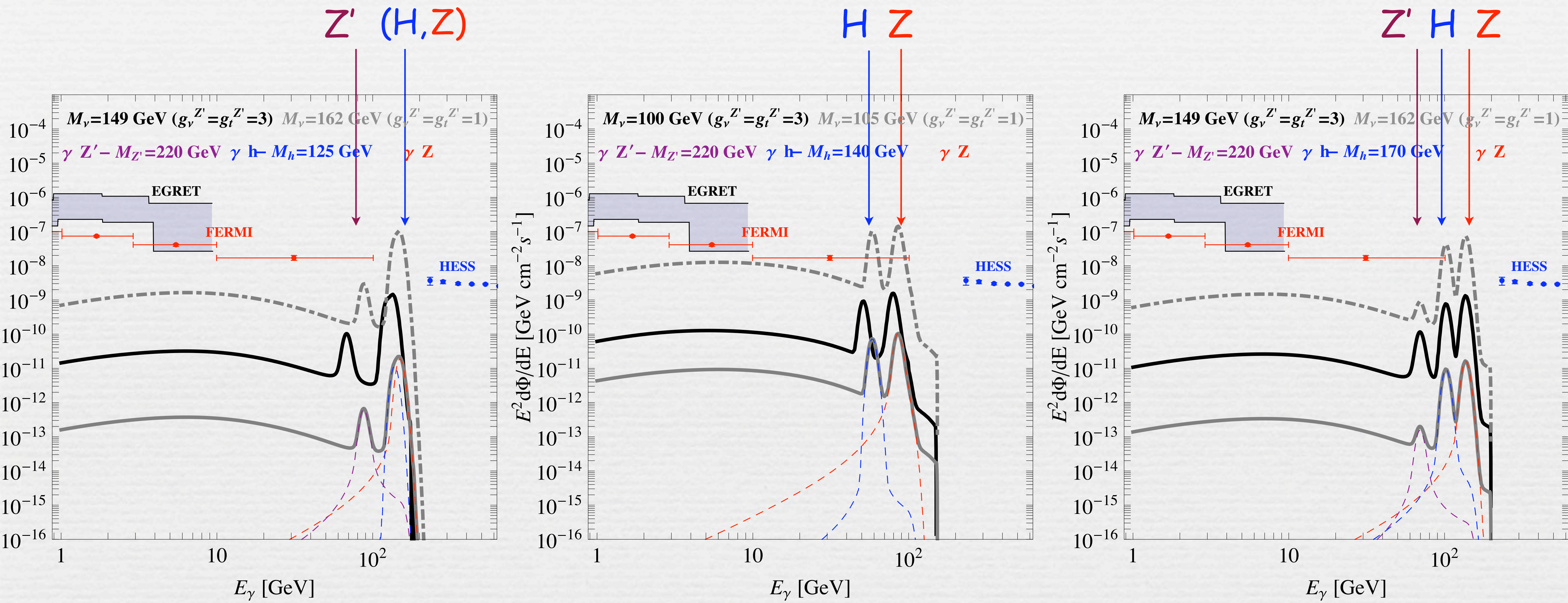
NFW profile

adiabatically contracted

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

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

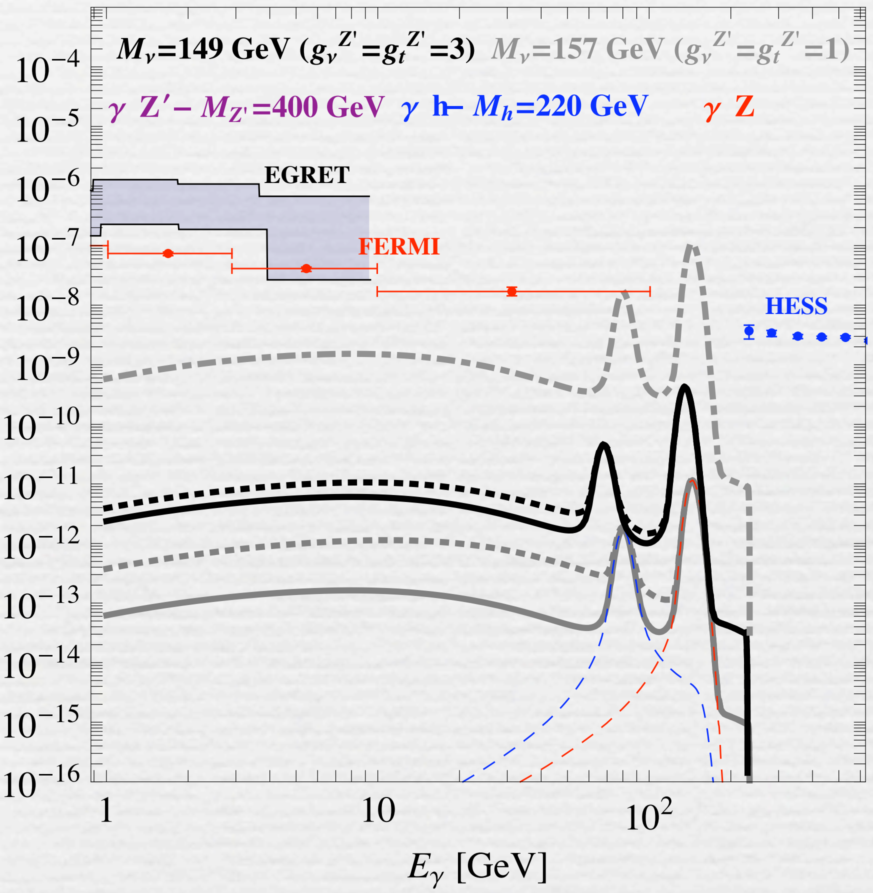


NFW profile

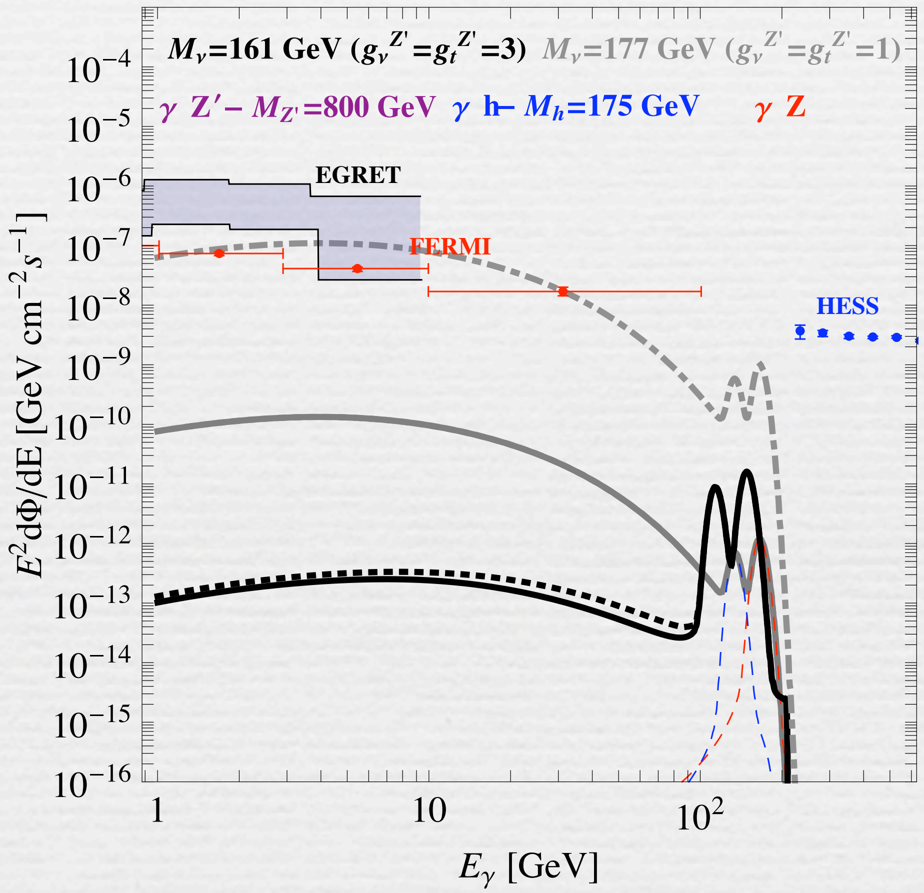
adiabatically contracted

Increasing $M_{Z'}$

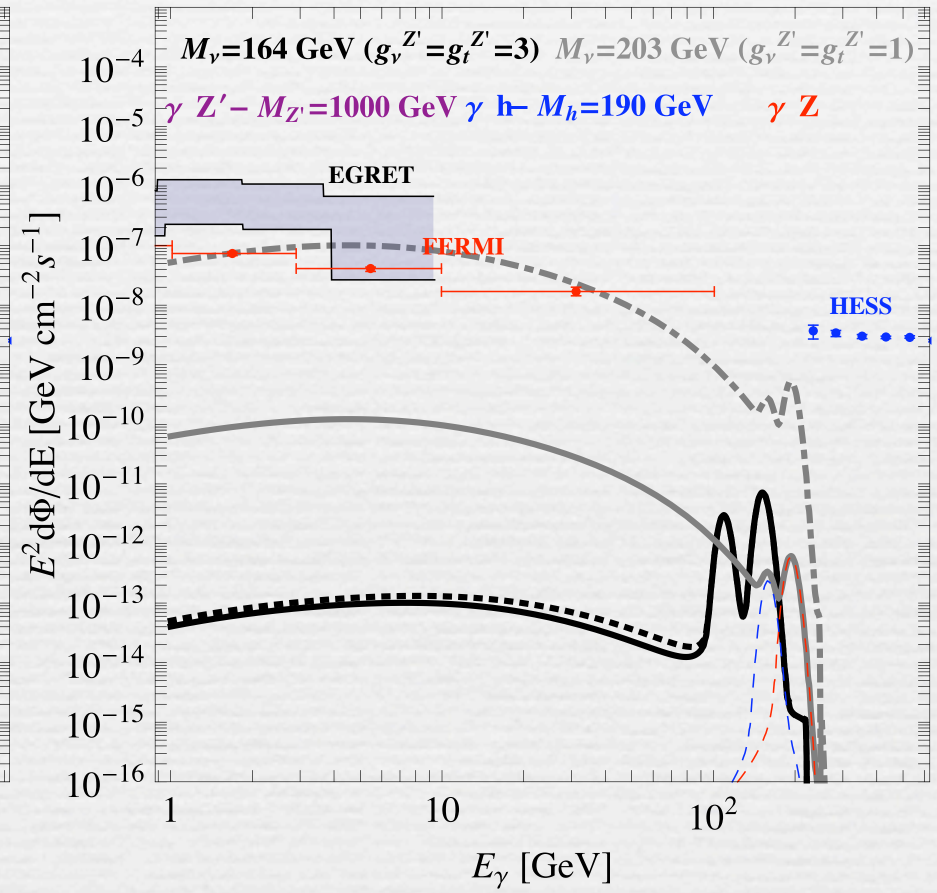
$M_{Z'}$ = 400 GeV



$M_{Z'}$ = 800 GeV



$M_{Z'}$ = 1 TeV



To recap:

DM almost decouples from light fermions while still having large couplings to top

$M_{DM} < M_t$ since the strong coupling to top would otherwise give a too low relic density (for O(1) couplings).

DM mass is below kinematic threshold for top production in the zero velocity limit

Virtual top close to threshold can significantly enhance loop processes producing monochromatic photons.

A simple 4d UV completion

All SM fermions are uncharged under U(1)'

in addition to ν, add $\tilde{T}$ (vector-like) charged under U(1)'
with same gauge SM quantum numbers as t_R

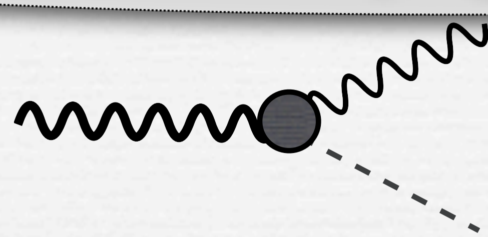
to realize coupling of top quark to Z' and h:

$$y H \overline{Q}_3 t_R + \mu \overline{\tilde{T}}_L \tilde{T}_R + Y \Phi \overline{\tilde{T}}_L t_R$$

higgs of U(1)'

the light mass eigen state identified with top
quark is an admixture of t and $\tilde{T}$

γh line from decaying vector dark matter



Arina, Hambye, Ibarra, Weniger 0912.4496

hidden sector non-abelian group $SU(2)_{HS}$ broken by ϕ

$$\mathcal{L} = \mathcal{L}^{SM} - \frac{1}{4} F^{\mu\nu} \cdot F_{\mu\nu} + (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) - \lambda_m \phi^\dagger \phi H^\dagger H - \mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2$$

A_i^μ : stable because of accidental SO(3)

stability broken by non-renormalizable operators:

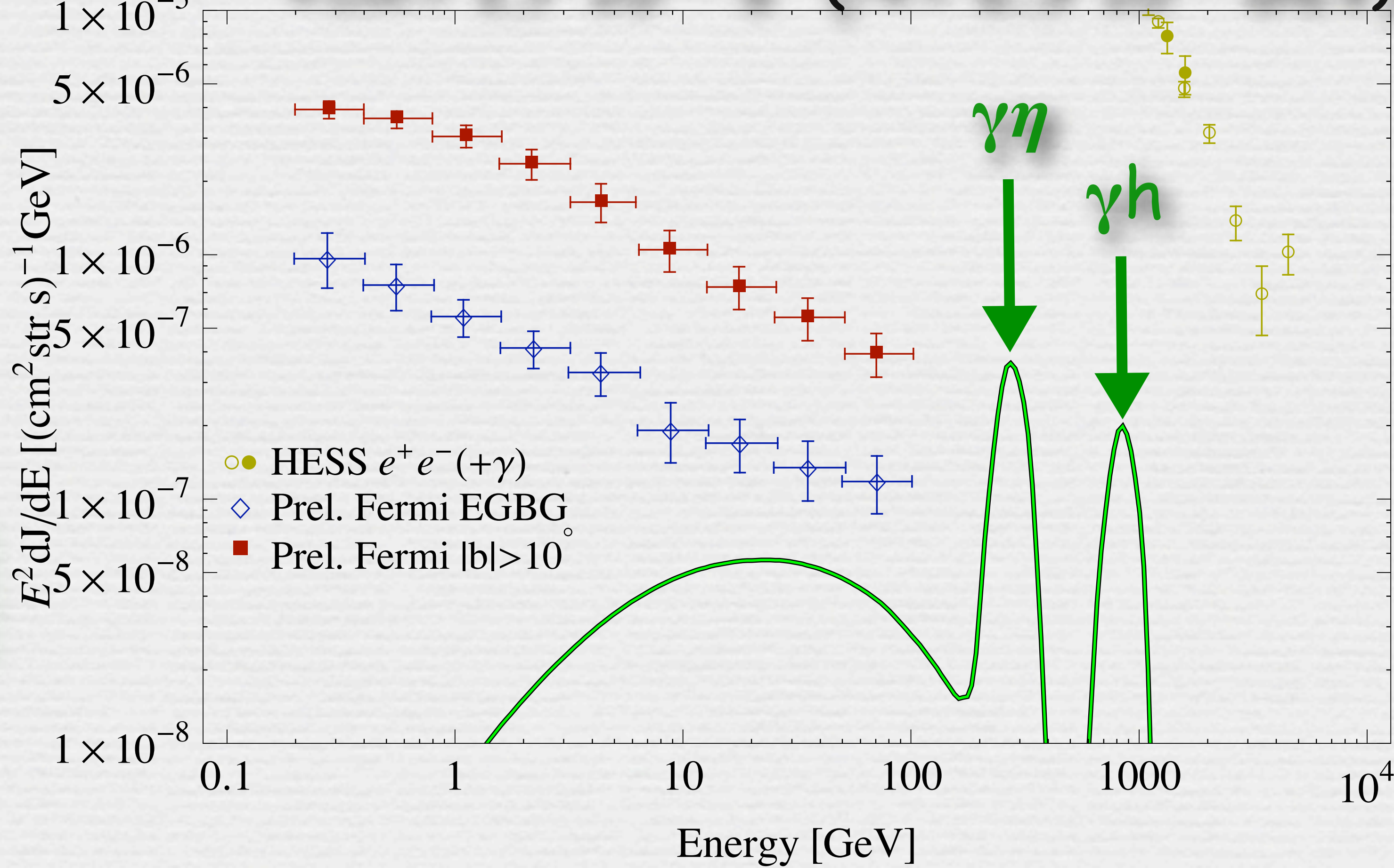
$$\frac{1}{\Lambda^2} \mathcal{D}_\mu \phi^\dagger \phi \; \mathcal{D}_\mu H^\dagger H \qquad \frac{1}{\Lambda^2} \mathcal{D}_\mu \phi^\dagger \mathcal{D}_\nu \phi \; F^{\mu\nu Y}$$

$$\frac{1}{\Lambda^2} \mathcal{D}_\mu \phi^\dagger \phi \; H^\dagger \mathcal{D}_\mu H \qquad \frac{1}{\Lambda^2} \phi^\dagger F^a_{\mu\nu} \frac{\tau^a}{2} \phi F^{\mu\nu Y}$$

late decay of DM → γh & γη lines :

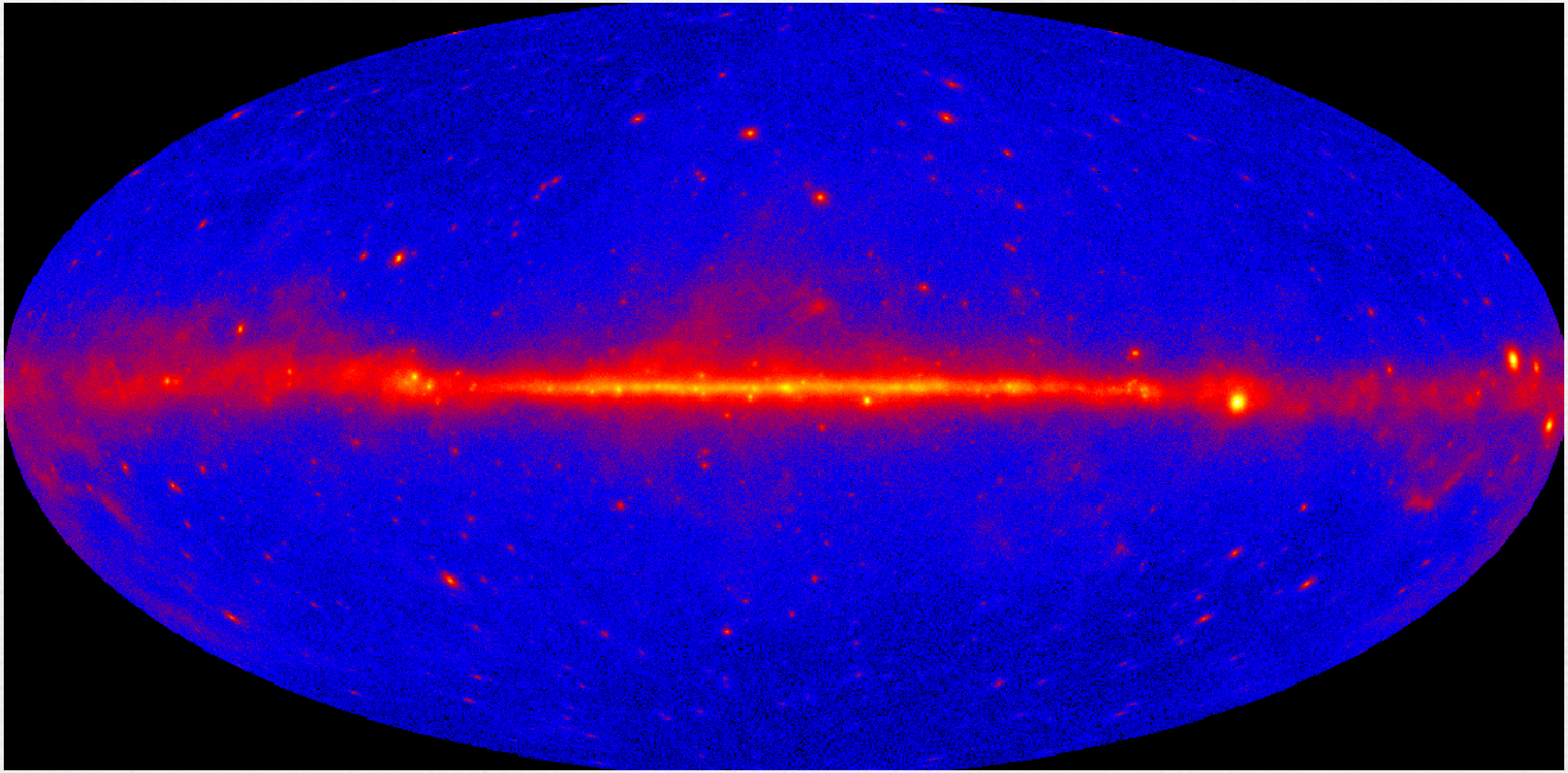
(η:hidden sector scalar)

τ_{DM} = 1.7 10^{28} s (Λ = 2.9 10^{15} GeV)



Detectability

Fermi-LAT 1 year Gamma-Ray Skymap



E_γ =100 MeV-300 GeV

~ 80% of gamma-rays produced by cosmic ray interactions with interstellar gas and radiation field

to assess upper limit on contribution from DM, need a very accurate bgd model

Gamma background:

- diffuse emission of our galaxy modeled using GALPROP

Strong, Moskalenko, Reimer '00

in agreement with Fermi-LAT data at mid-latitudes

due to interactions of cosmic rays with galactic gas

-bremsstrahlung

-π_0 decay

-inverse Compton

depends on location in the sky

strongest in galactic disk

- For the GC center analysis, the dominant background will be from sources in the vicinity of the GC.

many different kinds of objects whose spectra and distributions are not well understood

signal extraction from background in GC:challenging

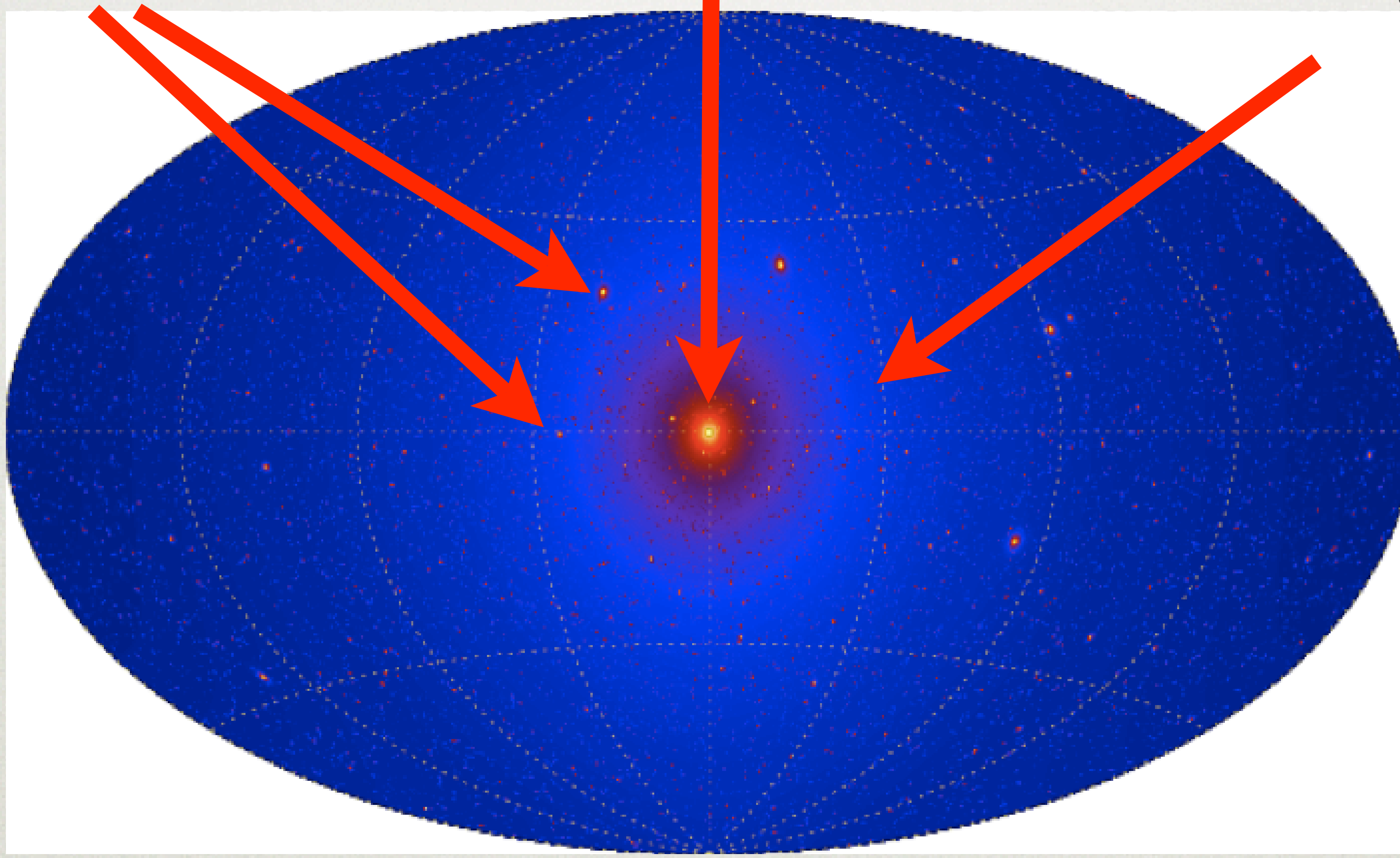
Search Strategies

[Credit: S. Murgia, Fermi Symposium ‘Nov 09]

Satellites:
Low background and good source id, but low statistics

Galactic center:
Good statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And electrons!

Anisotropies

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Galaxy clusters:
Low background but low statistics

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

What’s best?
See discussions in

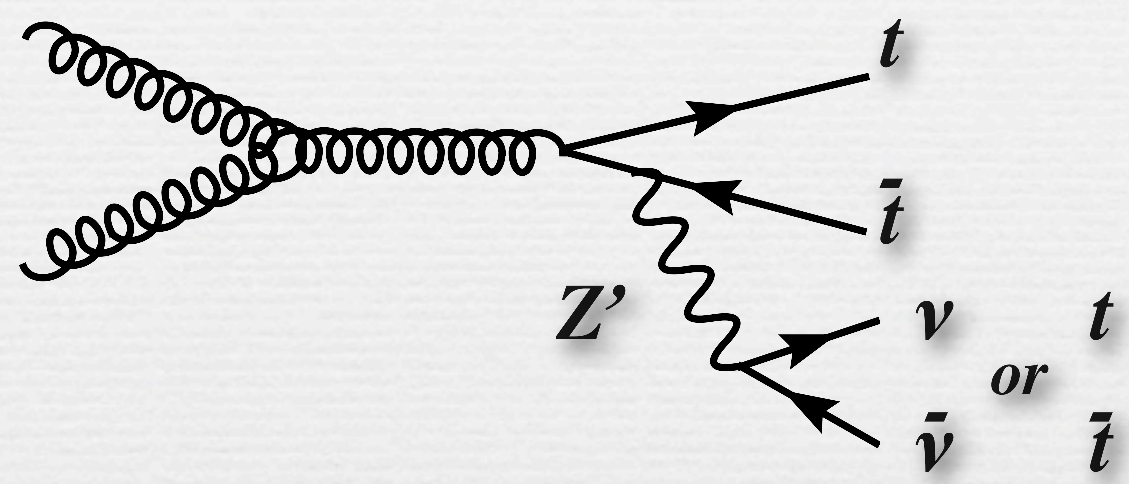
Dodelson, Hooper, Serpico’07; Serpico, Zaharijas’08
Dodelson, Belikov, Hooper, Serpico’09; Serpico, Hooper’09 ....

Collider signatures of a top (and DM)-philic Z'

- $\cancel{f\overline{f} \to Z' \to t\bar{t}}$

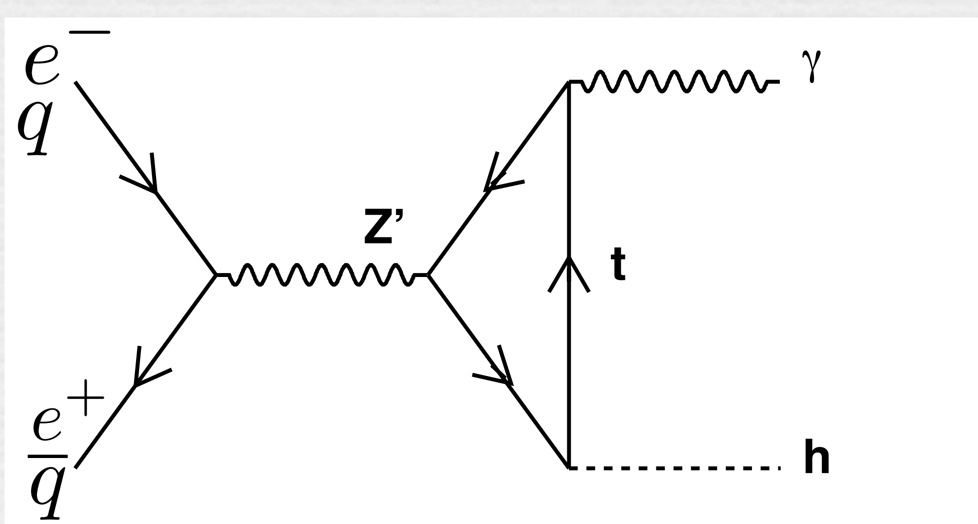
Z' has suppressed couplings to light quarks
-> no observable $t\bar{t}$ resonances

- $gg \to t\bar{t} + Z'$ $\xrightarrow{Z' \to \nu\bar{\nu}}$ $t\bar{t} + \not{E}_T$
- $gg \to t\bar{t} + Z'$ $\xrightarrow{Z' \to t\bar{t}}$ $t\bar{t}t\bar{t}$



- $f\overline{f} \to Z' \to \gamma H$

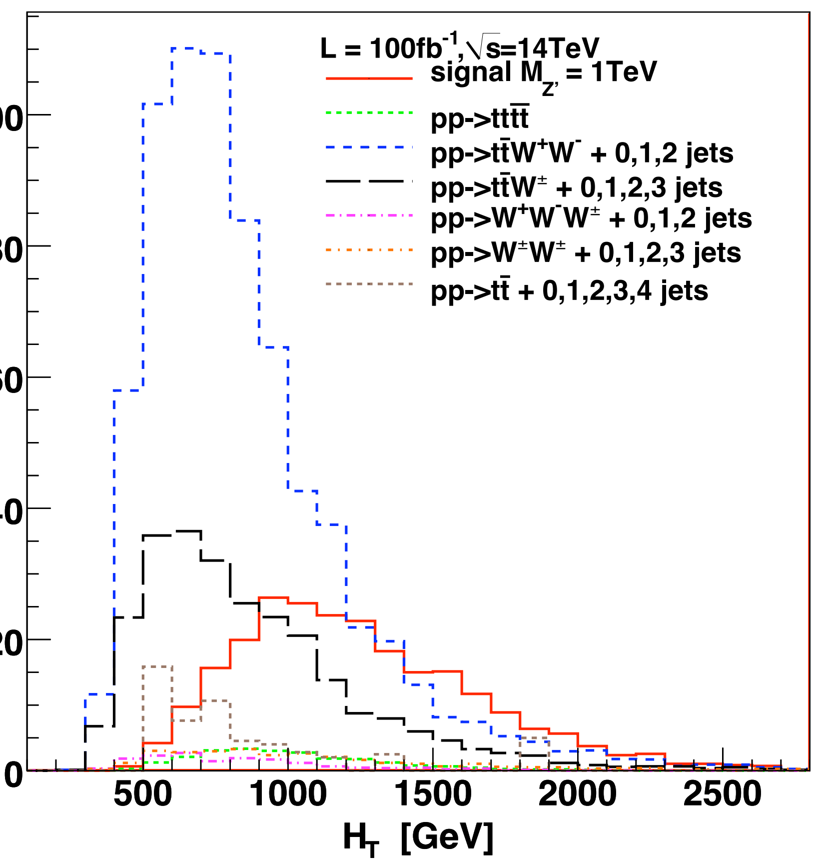
energetic monochromatic γ

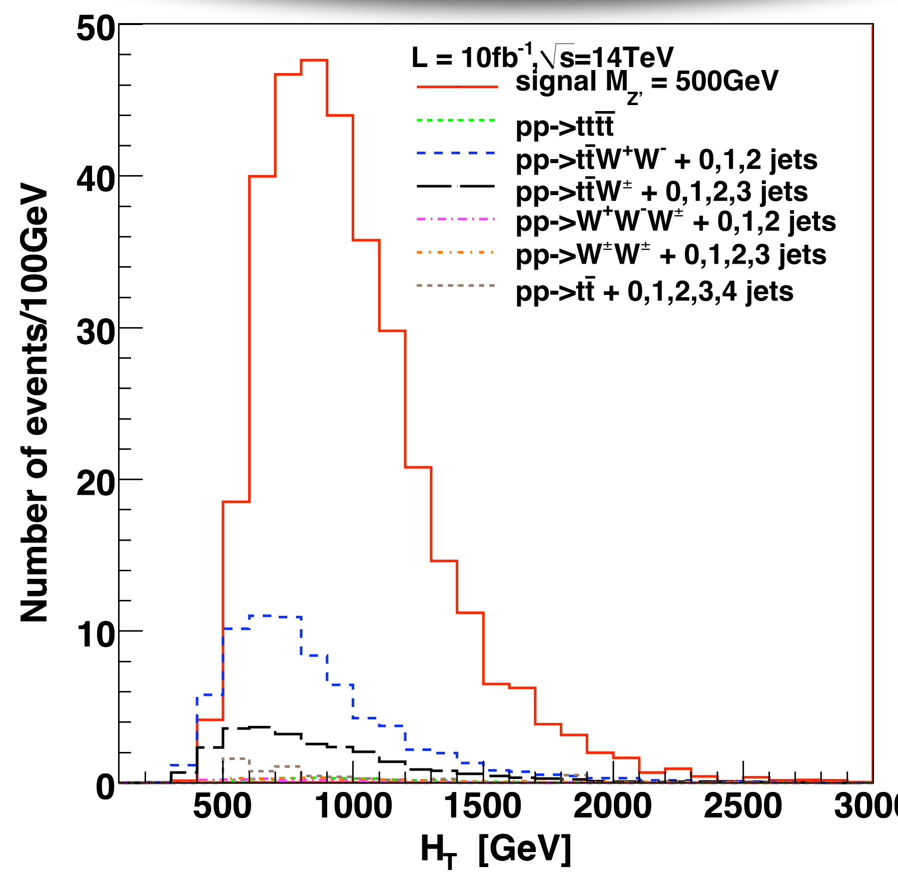


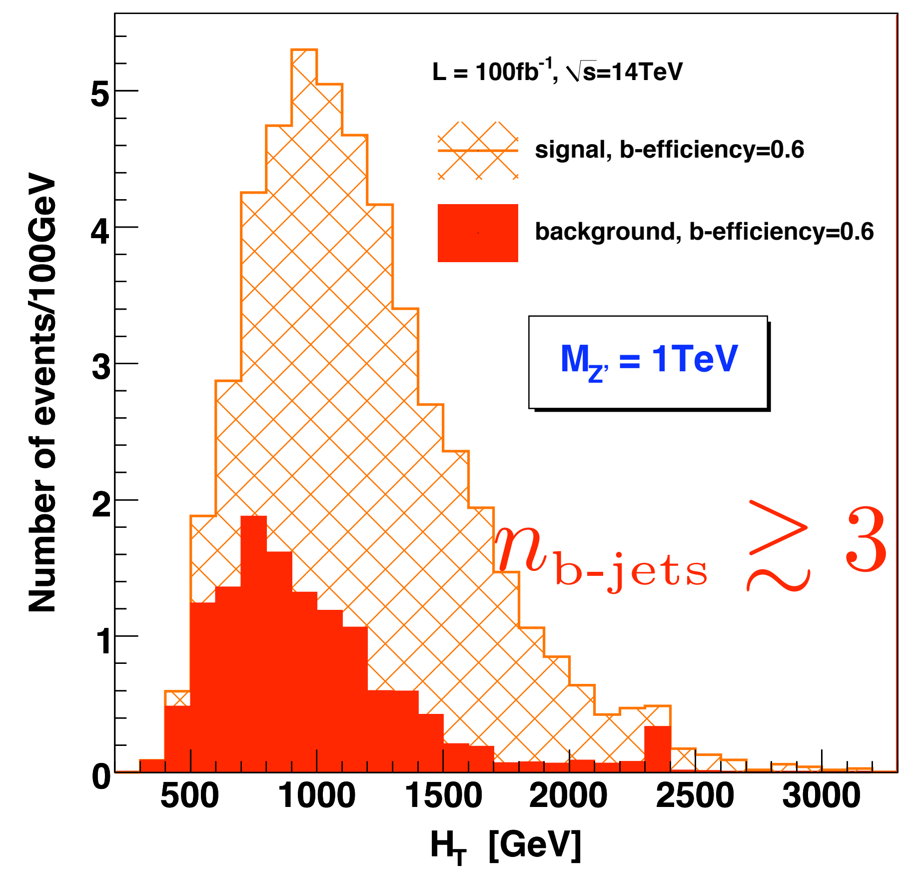
$n_j \geq 6, p_T > 30$ GeV

pp → $t\bar{t}t\bar{t}$ @ 14 TeV LHC

in same-sign dilepton channel

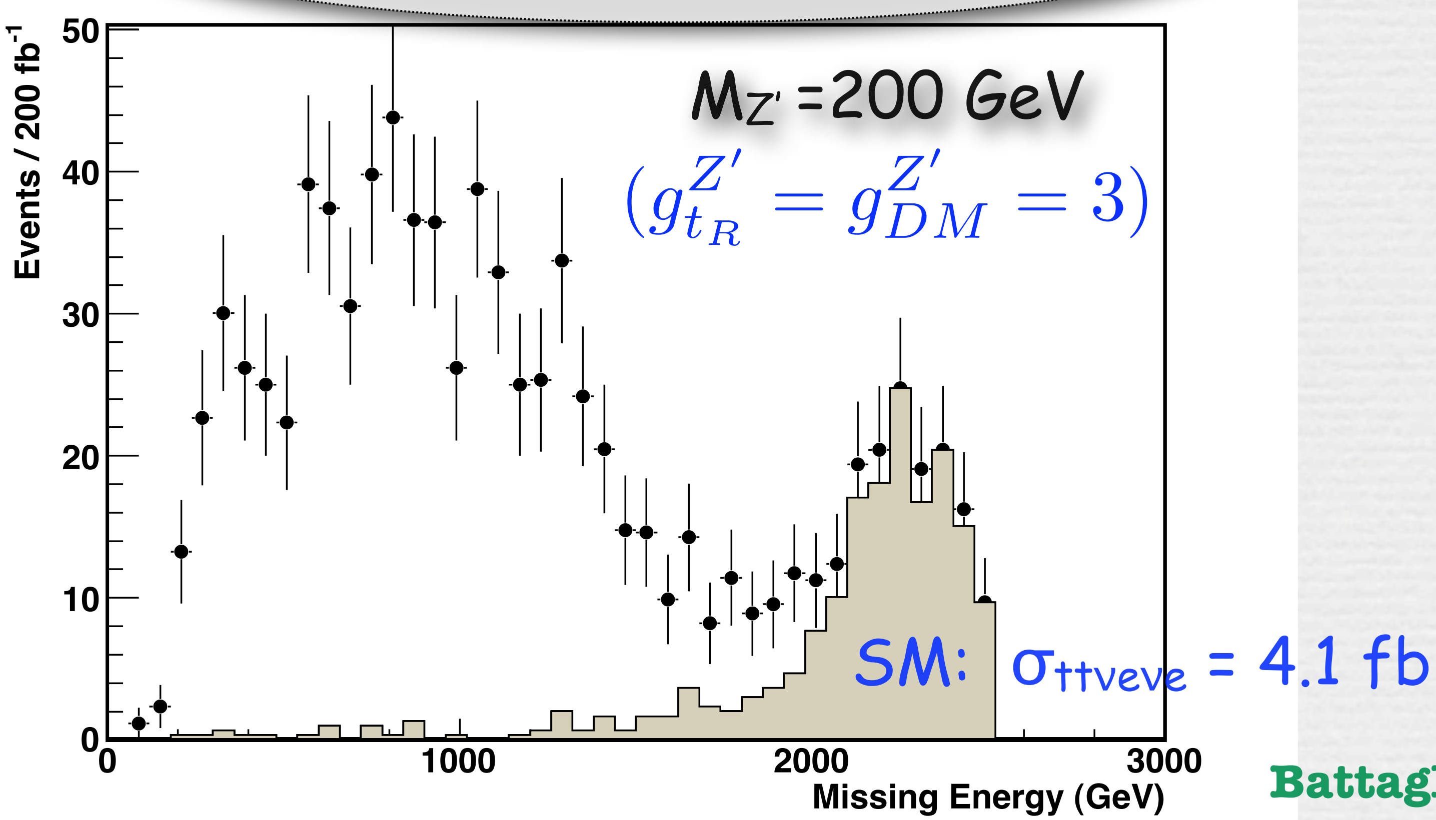






Gauthier-Servant

$e^+ e^- \to t\,\bar{t} + \not{E}_T$ @ 3 TeV CLIC



Battaglia-Servant 1005.4632

Summary

Are DM and EW symmetry breaking related ? If so, wimps may have enhanced couplings to massive states, top, W/Z, H etc.

DM-Top quark connection (RS and composite Higgs inspired)

Signals of a Higgs from γ rays

Observation of γ H would indicate that the WIMP is not a scalar nor a Majorana fermion but most likely a Dirac fermion or a vector

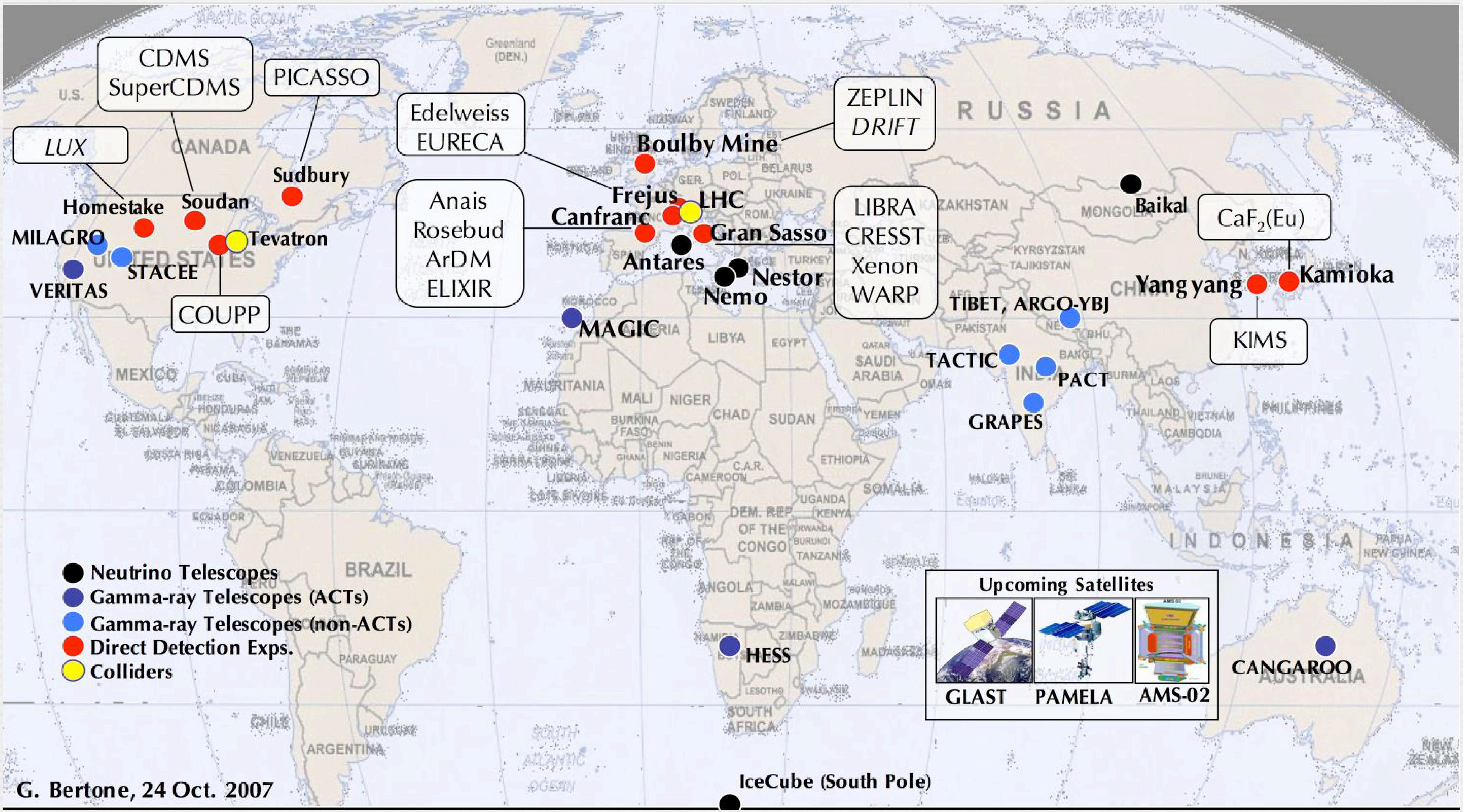
Worth checking whether Higgs is hiding in gamma-ray telescope's data (Fermi, Magic, Hess, Cangaroo, Veritas...)

Complementary Collider signatures (e.g. four-top events)

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

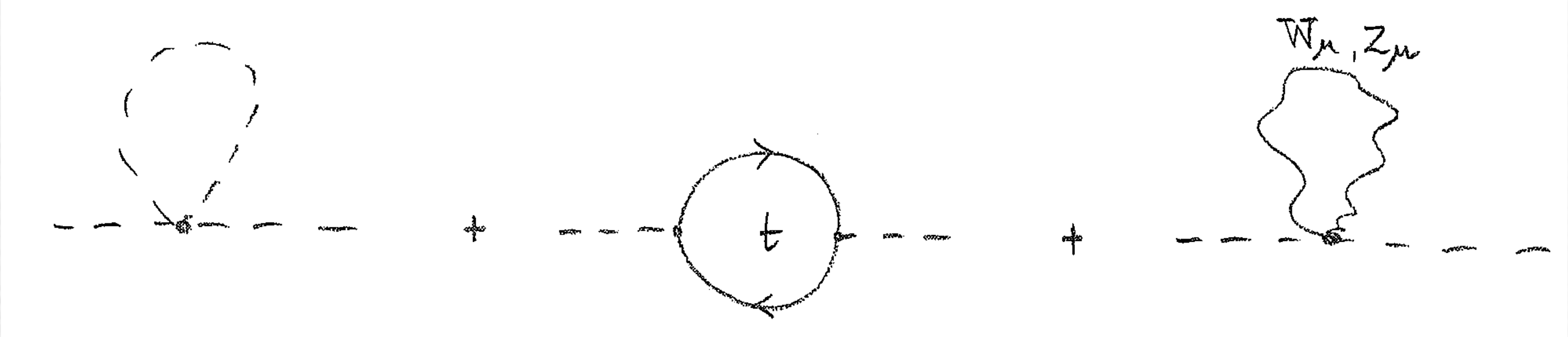


Annexes

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

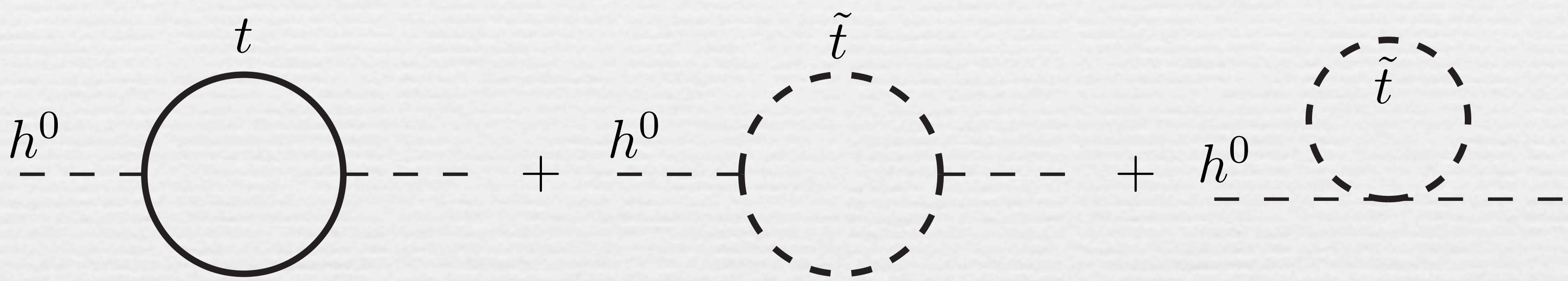
strong sensitivity on UV unknown physics

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

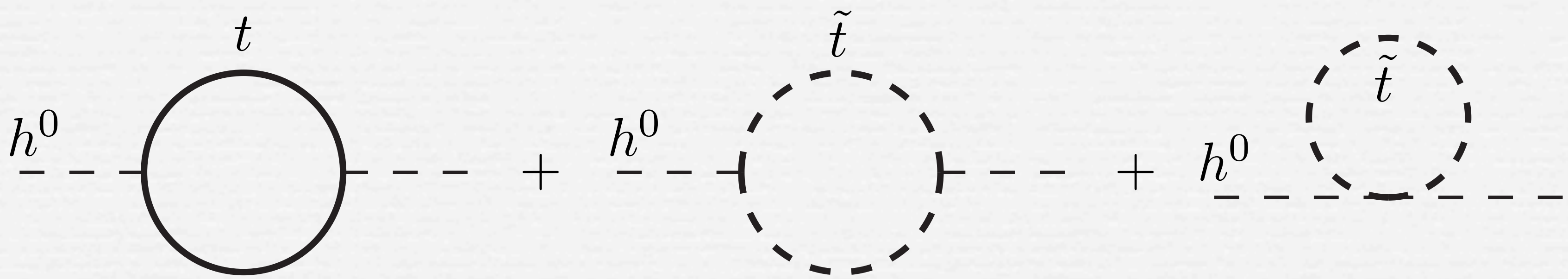
non trivial cancellation among them needed unless masses of SUSY particles are low. However:

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) $\Rrightarrow$ $m_{\tilde{t}} \gtrsim 1$ TeV

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

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

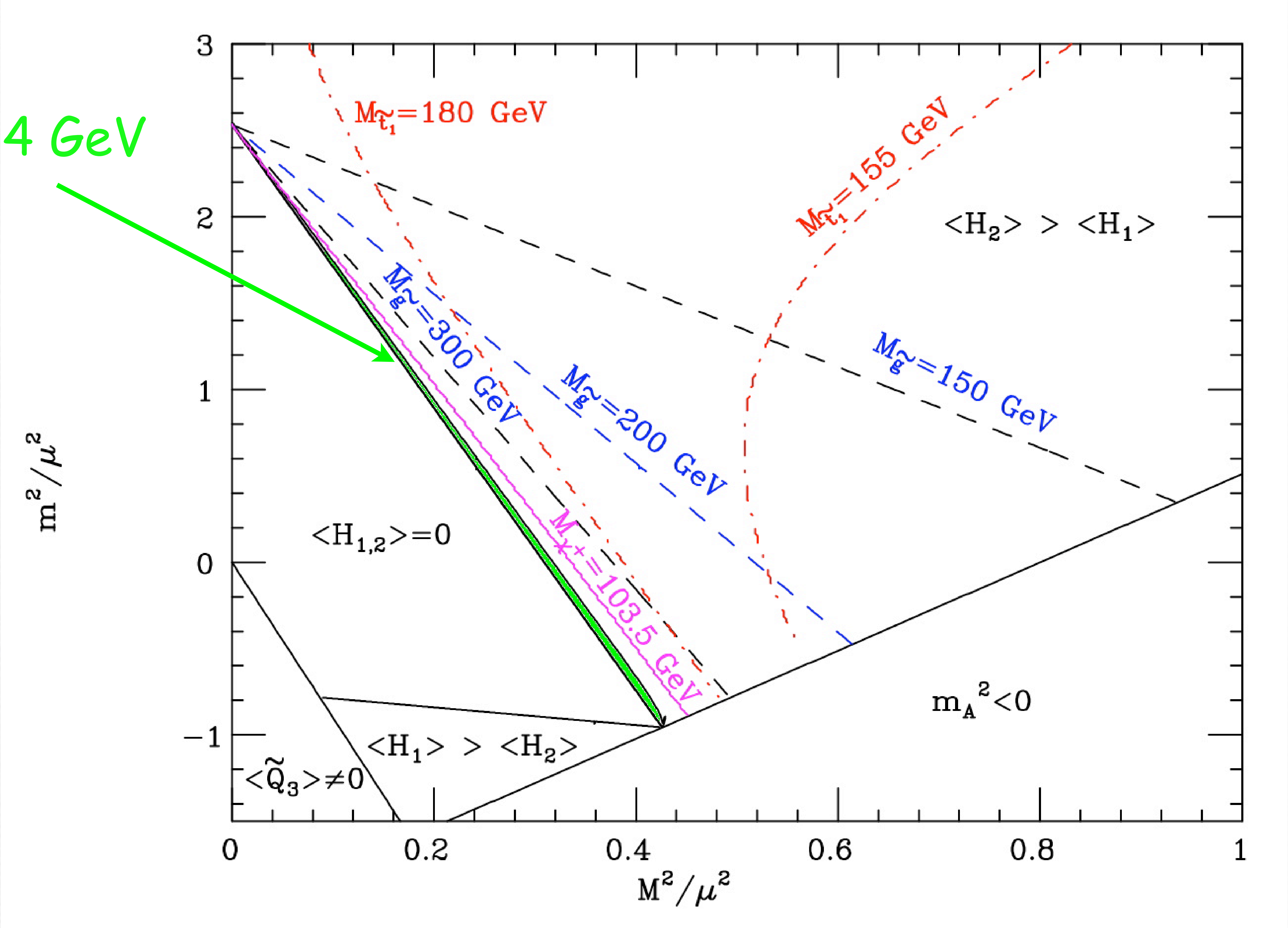
$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

$\Rrightarrow$ tuning $\equiv \dfrac{|\Delta m_{H_u}^2|}{M_Z^2} \approx \dfrac{3y_t^2}{4\pi^2 M_Z^2} m_{\tilde{t}}^2 \log\dfrac{\Lambda}{m_{\tilde{t}}} \approx 50$ 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

m_h >114 GeV



[Giudice & Rattazzi, ‘06]