(Some theory about) Dark Matter searches (especially) at LHC

Alessandro Strumia, VI WI pp@LHC, Genova, May 9, 2013

Testing weak scale DM

'Weak scale' expectations based on two speculations:

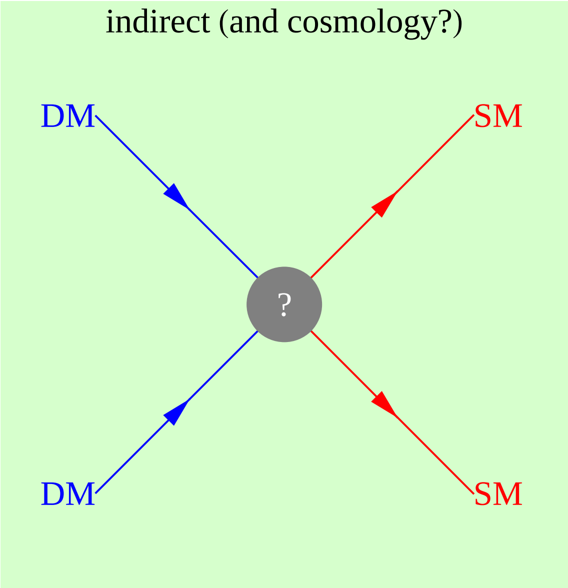
1) Dark Matter as a thermal relic: $M_{\rm weak} \lesssim g_{\rm DM}\sqrt{T_{\rm now}\cdot M_{\rm Pl}} \lesssim 10\,{\rm TeV}$

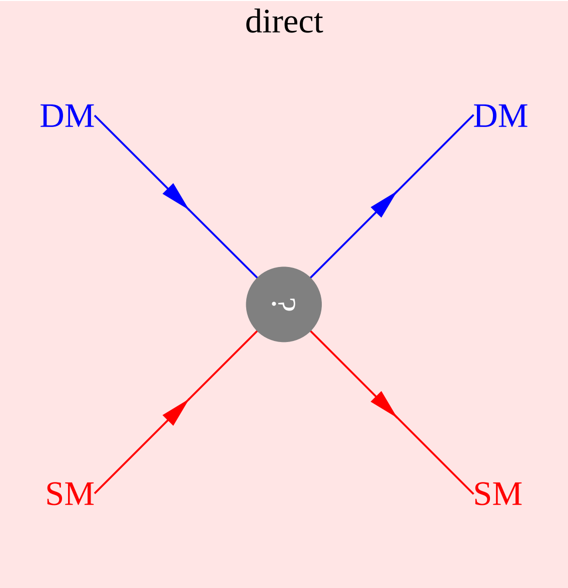
2) Naturalness of the Higgs mass: $M_{\rm colored} \lesssim 400\,{\rm GeV}\times\sqrt{\bf FT}$

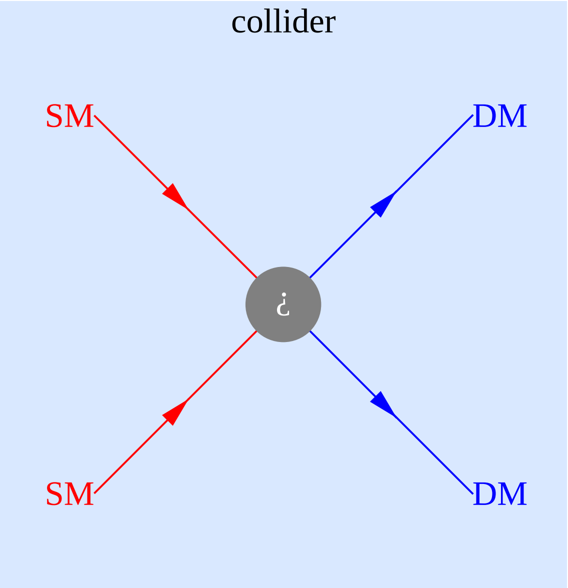
from the sky

from the underworld

from CERN







DM at colliders

DM at colliders, what signal?

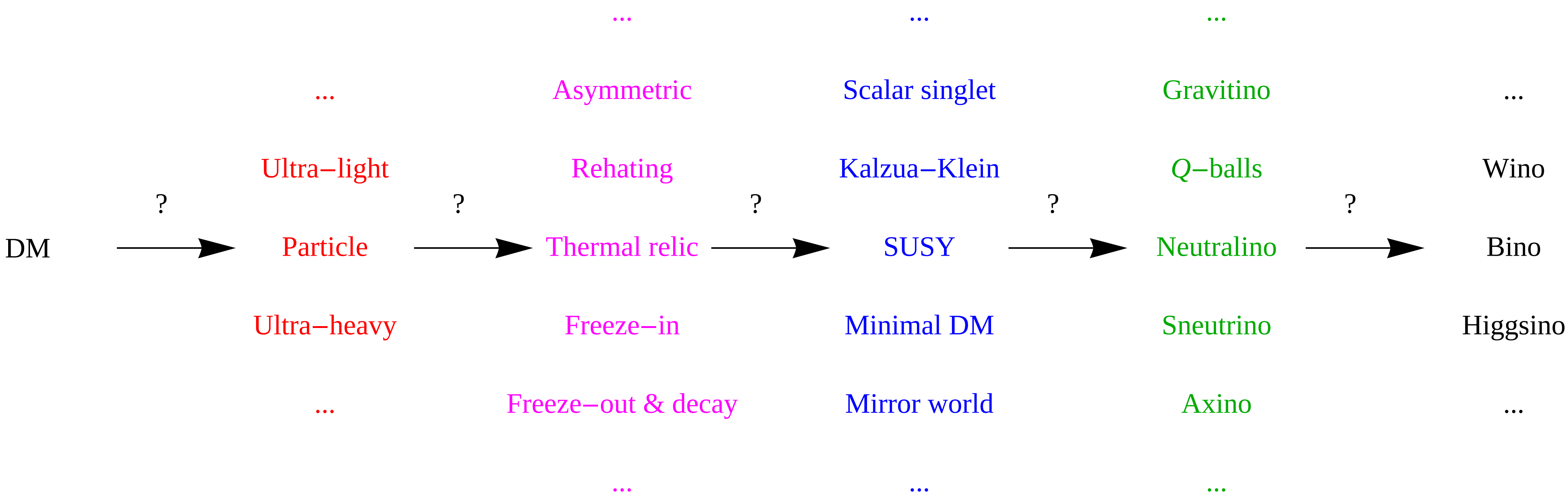
Safe concrete expectations are well-known and trivial:

- DM is probably stable thanks to a Z_2 symmetry: **DM produced in pairs**.
- DM behaves like ν: DM carries away **missing transverse momentum** $\not{p}_T$.
- Maybe DM comes alone giving $\not{p}_T j$ and $\not{p}_T \gamma$ from initial state radiation.
- Maybe DM comes with other particles giving better signals.

It would be wise to stop here.

Anti-pedagogical presentation

The rest is a list of disconnected speculations mostly based on 1+2



Like cleaning stains from a jaguar...

Politically Correct Dark Matter

According to the ideology that dominated past decades, the Higgs mass has a hierarchy problem solved by many new particles at the weak scale.

The most popular solutions are the supersymmetric sparticles. SUSY ruins B, L conservation, so theorists add a new Z_2 symmetry (R-parity, KK parity):

$$\text{SM} \to \text{SM} \qquad \text{new} \to -\text{new}$$

which makes the lightest new particle stable: DM candidate if neutral!
WIMP miracle: the thermal abundance of a weak particle can reproduce $\Omega_{\rm DM}$!!

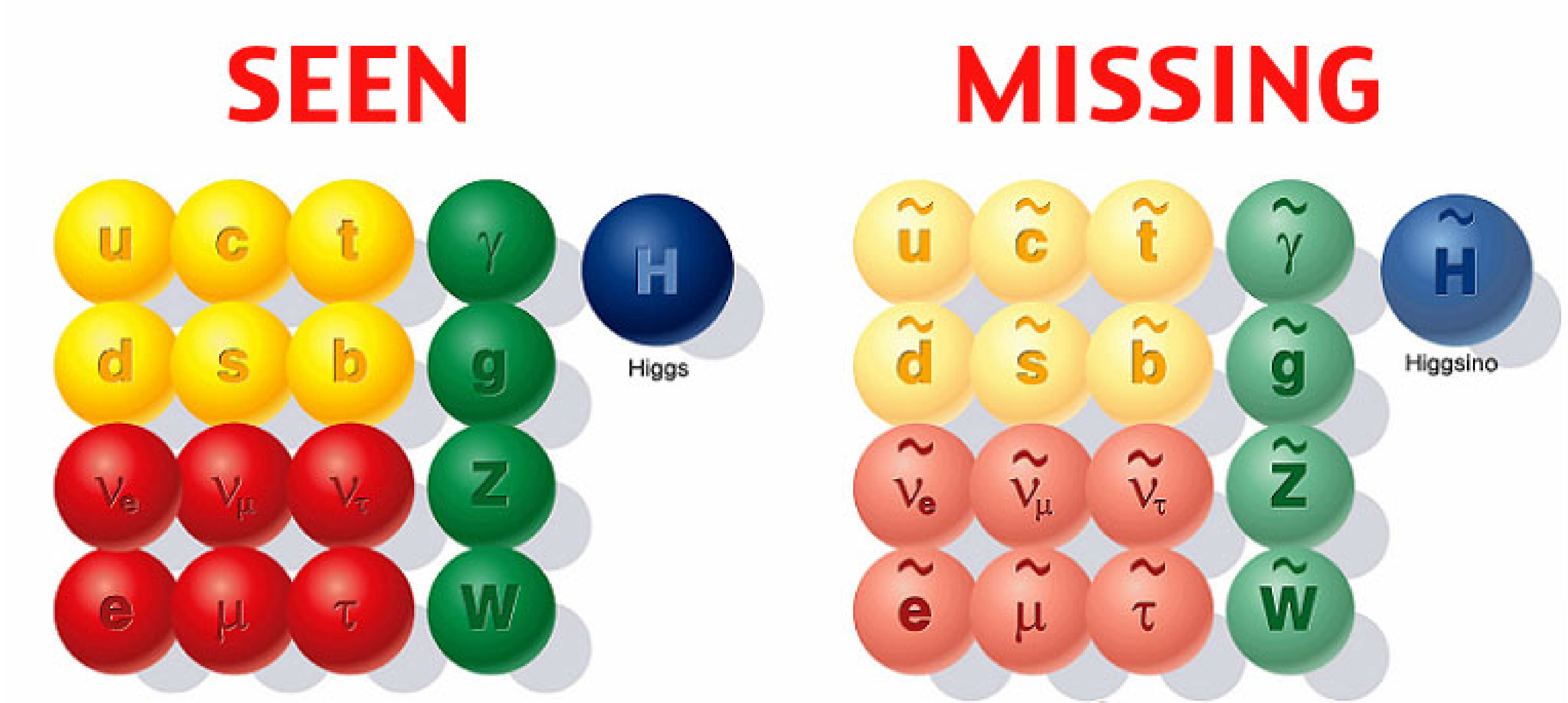
"Neutralino" is often used as a synonymous of "Dark Matter"!!!

Big signals! DM is the last step of a decay chain that starts with $g/\tilde{q}$ production

$$\tilde{g} \to g\tilde{q} \to g\ell\chi \to g\ell\ell N$$

Many authors proposed kinematical variables to reconstruct intermediate masses...

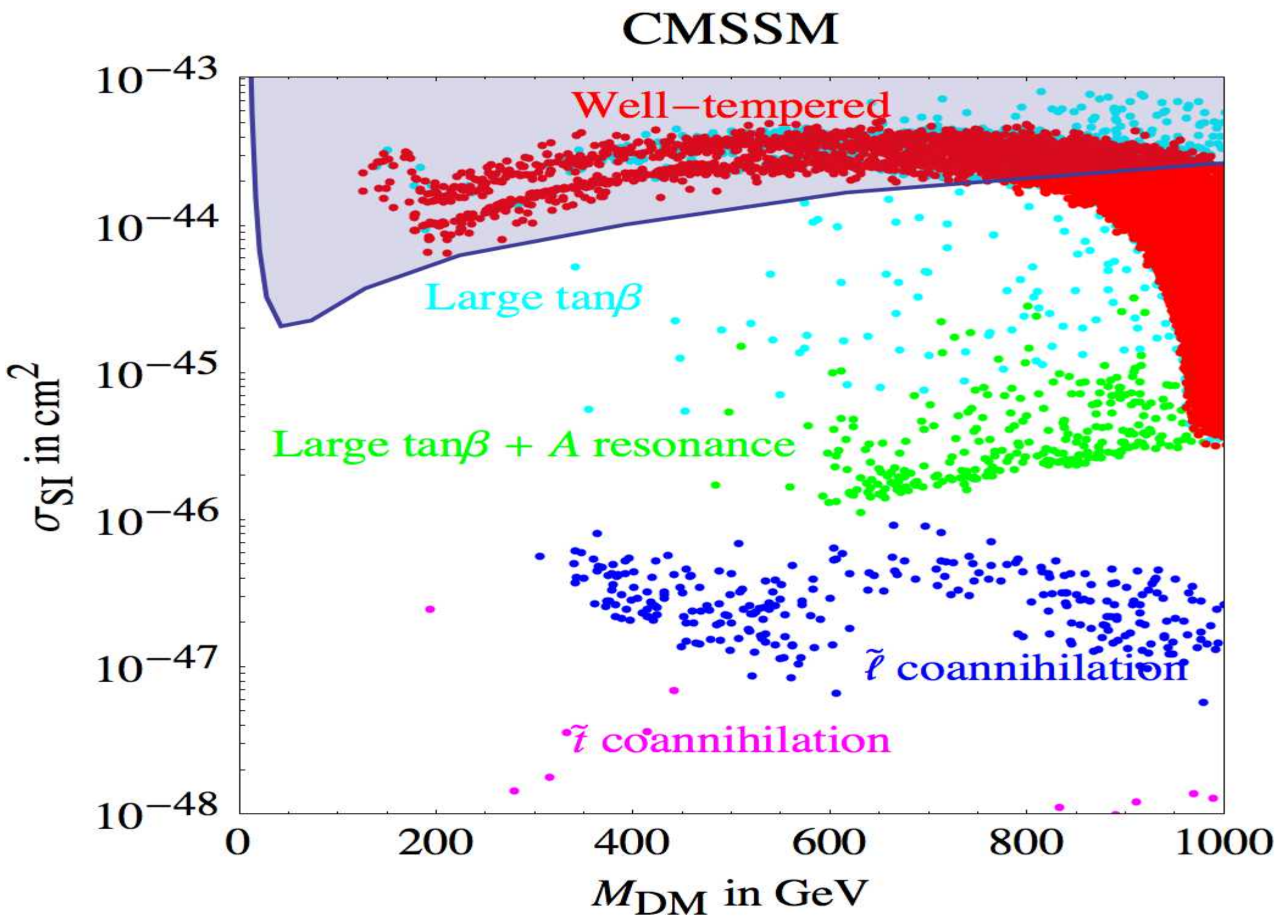
But next LHC was turned on and nothing like this has been seen so far

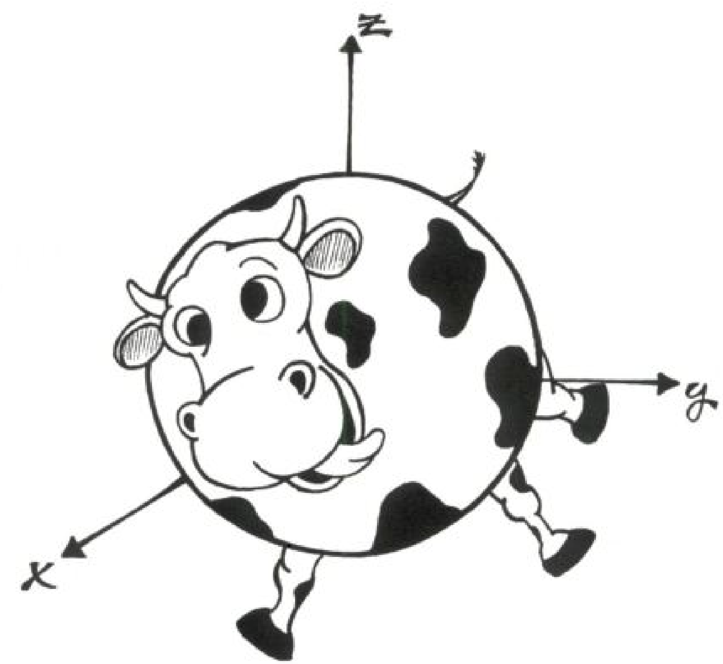


The missing super-partner problem

Dark Matter in the CMSSM

$\Omega_{\rm DM}$ suggested neutralino annihilations via sleptons up to a few crazy regions.



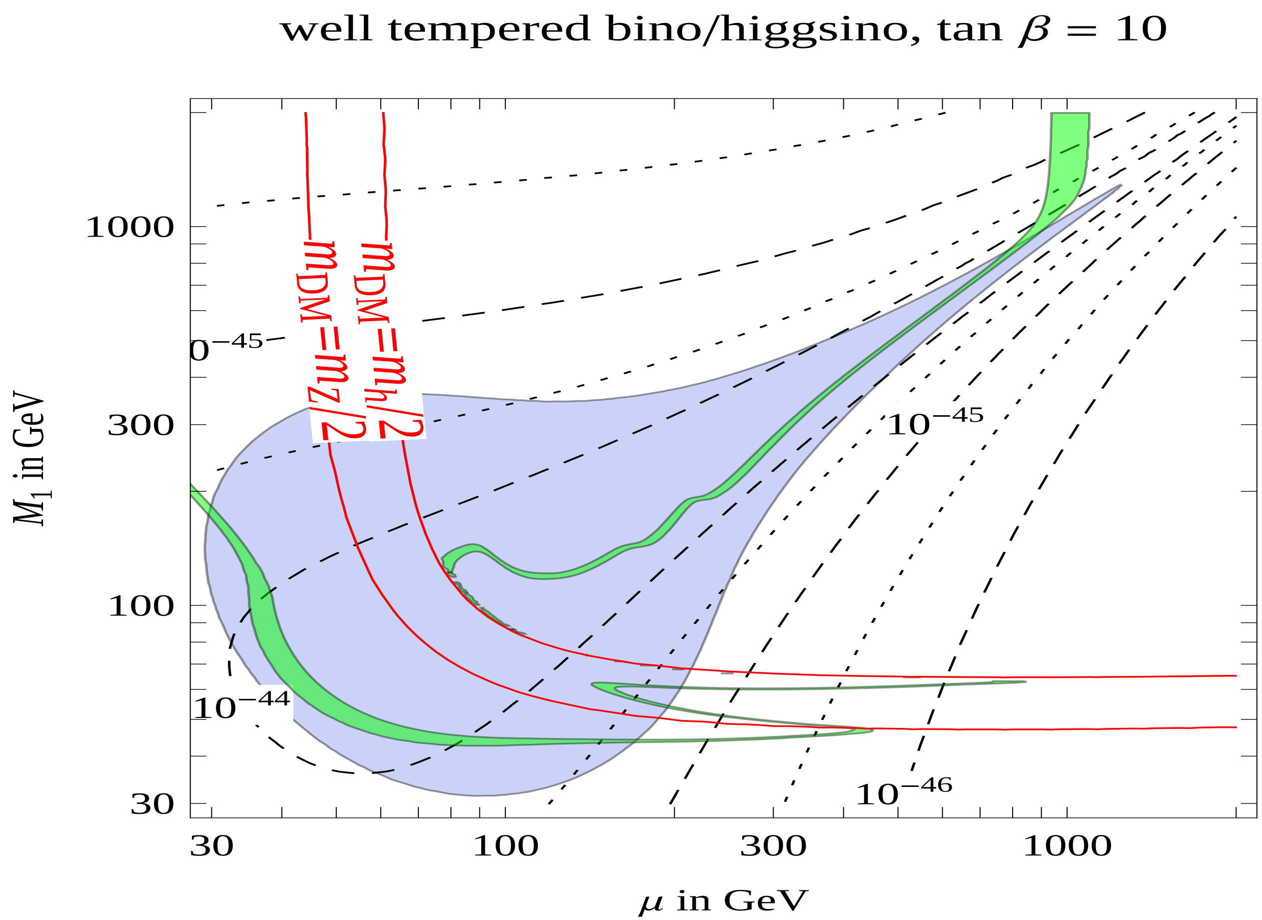


The 'bulk' region got excluded leaving the tail, the nose: **only special mechanisms can give $\Omega_{\rm DM}$:** $\tilde{\ell}$ co-annihilations, H, A resonance, h, H, A at large $\tan\beta$, $\tilde{t}$ co-annihilations, well-tempered $\tilde{B}/\tilde{H}$ (excluded by Xenon for $\mu > 0$), h resonance (excluded by LHC, $M_3 > 3m_h$). Like dissecting the spherical cow.

Well-tempered neutralinos

If $M \lesssim$ TeV winos and higgsinos annihilate too much, binos annihilate too little. Like in the 3 bear fable, the observed thermal $\Omega_{\rm DM}$ is obtained by mixing them.

Wino/bino ($M_1 \simeq M_2$) is not detectable. Wino/higgsino ($M_2 \simeq \mu$) is less plausible. Higgsino/bino ($M_1 \simeq |\mu|$, green strip) has been disfavoured by Xenon (dark region) if $\mu > 0$; cancellations are possible for $\mu < 0$



Stop co-annihilations

A neutralino and a stop can give the correct thermal $\Omega_{\rm DM}$ via co-annihilations, which needs

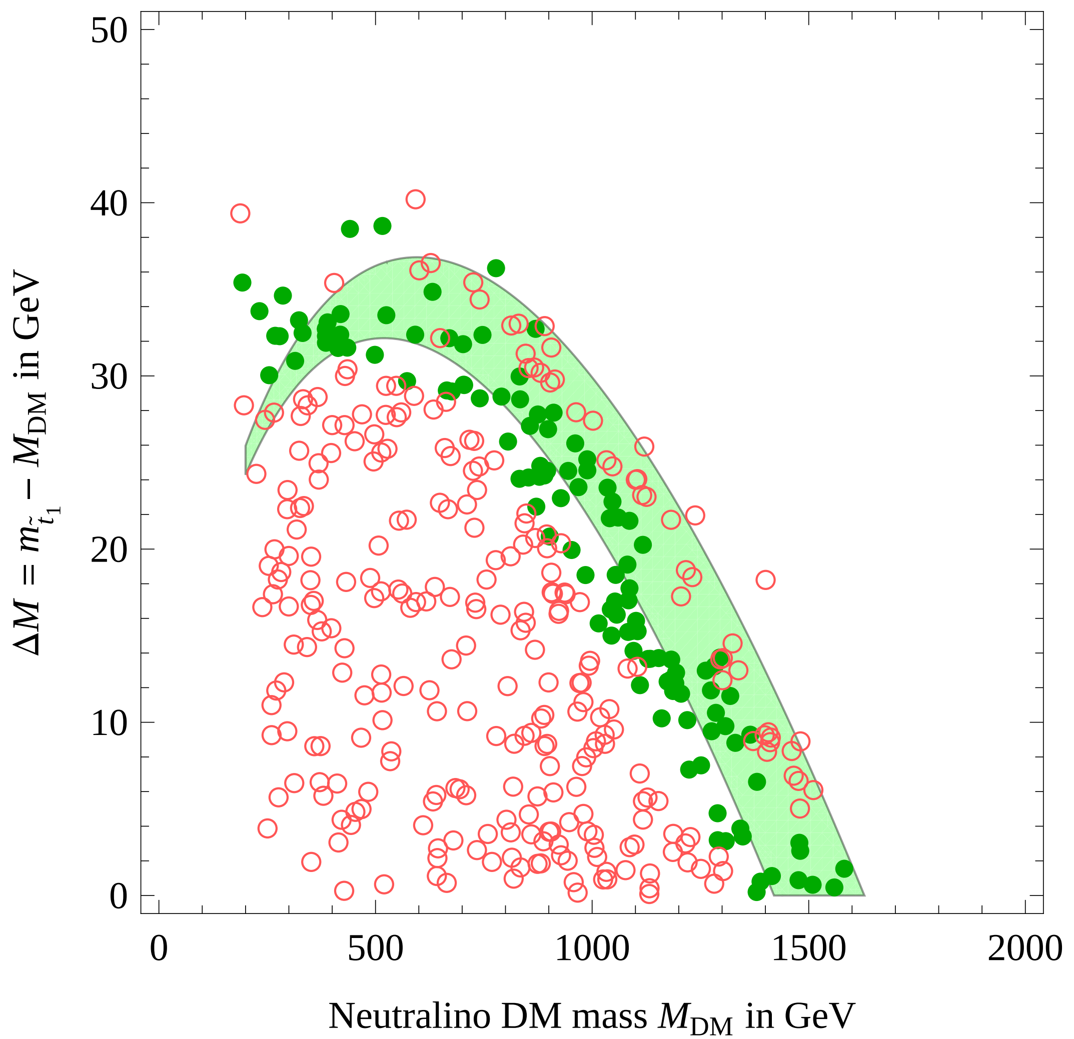
$$\sigma v = \overbrace{\frac{3}{8} e^{-2\Delta M/T}}^{\text{co}-\text{annihilation}} \times \overbrace{\frac{7\, g_3^4}{216\pi\, m_{\tilde{t}_1}^2}}^{\sigma(\tilde{t}\tilde{t}^*\to gg)v}$$

$$\approx 2.3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$$

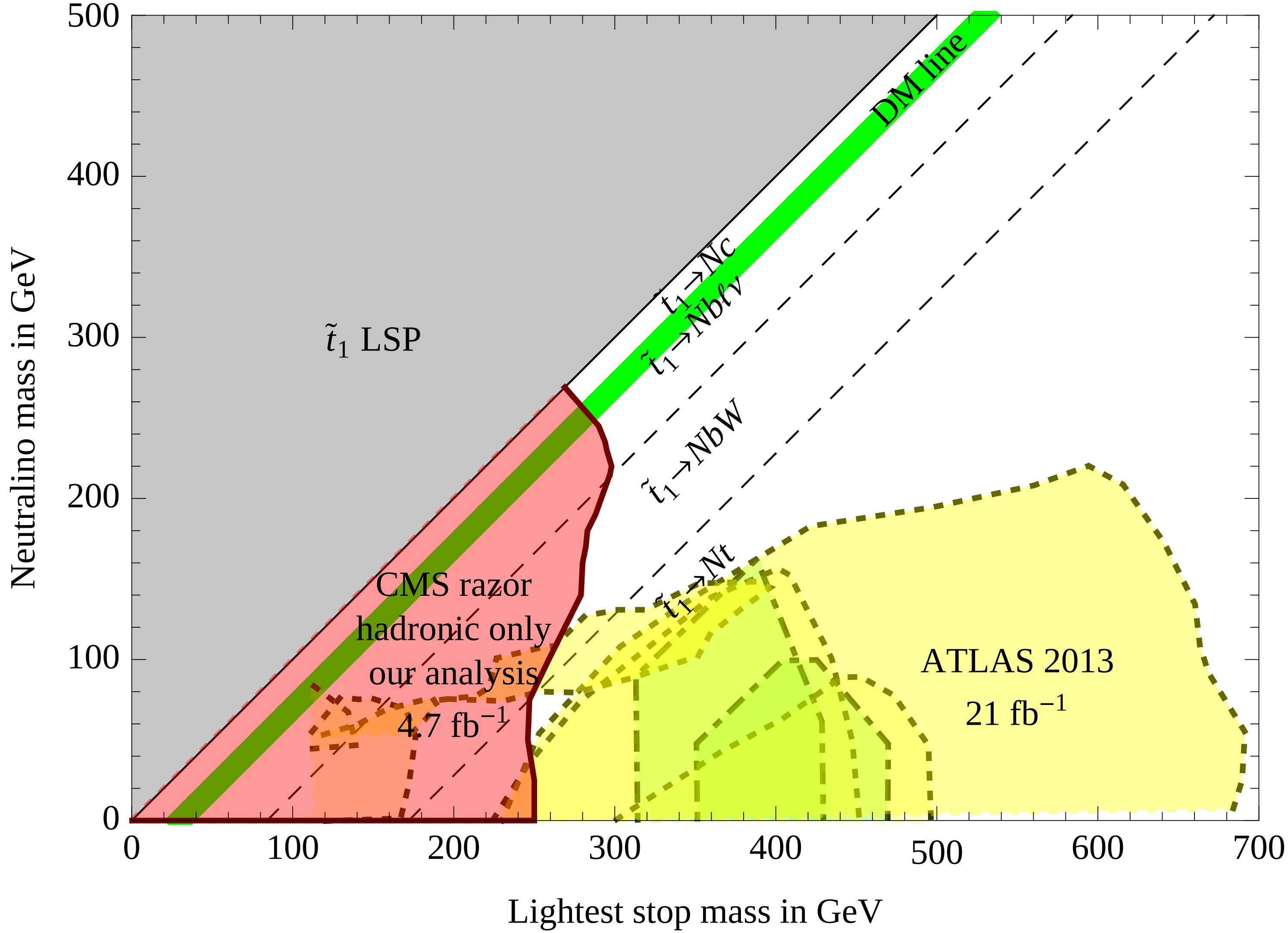
i.e.

$$\Delta M = m_{\tilde{t}} - M_{\rm DM} \approx 30\,\text{GeV}$$

for $m_{\tilde{t}} < 1.5\,\text{TeV}$.



Stop bounds



New fully model independent bound (theorist analyses of 7 TeV data) enters the main region where $\tilde{t}$ decays are ≈invisible, relying on **jet initial state radiation**. Good sensitivity at LHC thanks to big $\sigma(pp \to \tilde{t} + \tilde{t}^* + \text{jets})$ from QCD.

Can SUSY mania damage DM searches?

One-letter extensions of the MSSM:

AMSSM, BMSSM, CMSSM, DMSSM, EMSSM, FMSSM, GMSSM, HMSSM, IMSSM, KMSSM, MMSSM, NMSSM, OMSSM, PMSSM, QMSSM, RMSSM, SMSSM, TMSSM, UMSSM, VMSSM, XMSSM, YMSSM, ZMSSM

All of them have kilo-fine-tuning problems, so it is good that SUSY covers many possibilities: "it doesn't matter whether a cat is white or black, as long as it catches mice".

The LSP could decay into the graviton. If τ if slow enough, charged tracks and secondary vertices if the LSP is charged or coloured. If very slow, LSP could decay while the beam is off... LSP might decay into a light dark sector, that finally decays back to light SM particles making things like 'muon jets'...

Etc etc... Furthermore, natural scenarios alternative to SUSY are sometimes considered, especially universal extra dimensions and Little Higgs.

Is nature natural?

The good possibility of naturalness is in trouble

The bad possibility is that the Higgs is light due to ant**pic reasons. Then, one would expect that H is the only light scalar, so weak-scale DM must be a fermion. This lead to consider 'split SUSY' i.e. neutralino/wino/higgsino DM.

The ugly possibility is that quadratic divergences should be ignored. They are unphysical: nobody knows if they vanish or not. The answer is chosen by the unknown physical cut-off. Maybe it behaves like dimensional regularization.

Then the SM satisfies 'finite naturalness' (FT ≈ 0.12).

To preserve finite naturalness, new physics motivated by data, such as DM, must be not much above the weak scale. Consider: scalar/fermion DM and DM with/without SM gauge interactions.

DM with EW gauge interactions

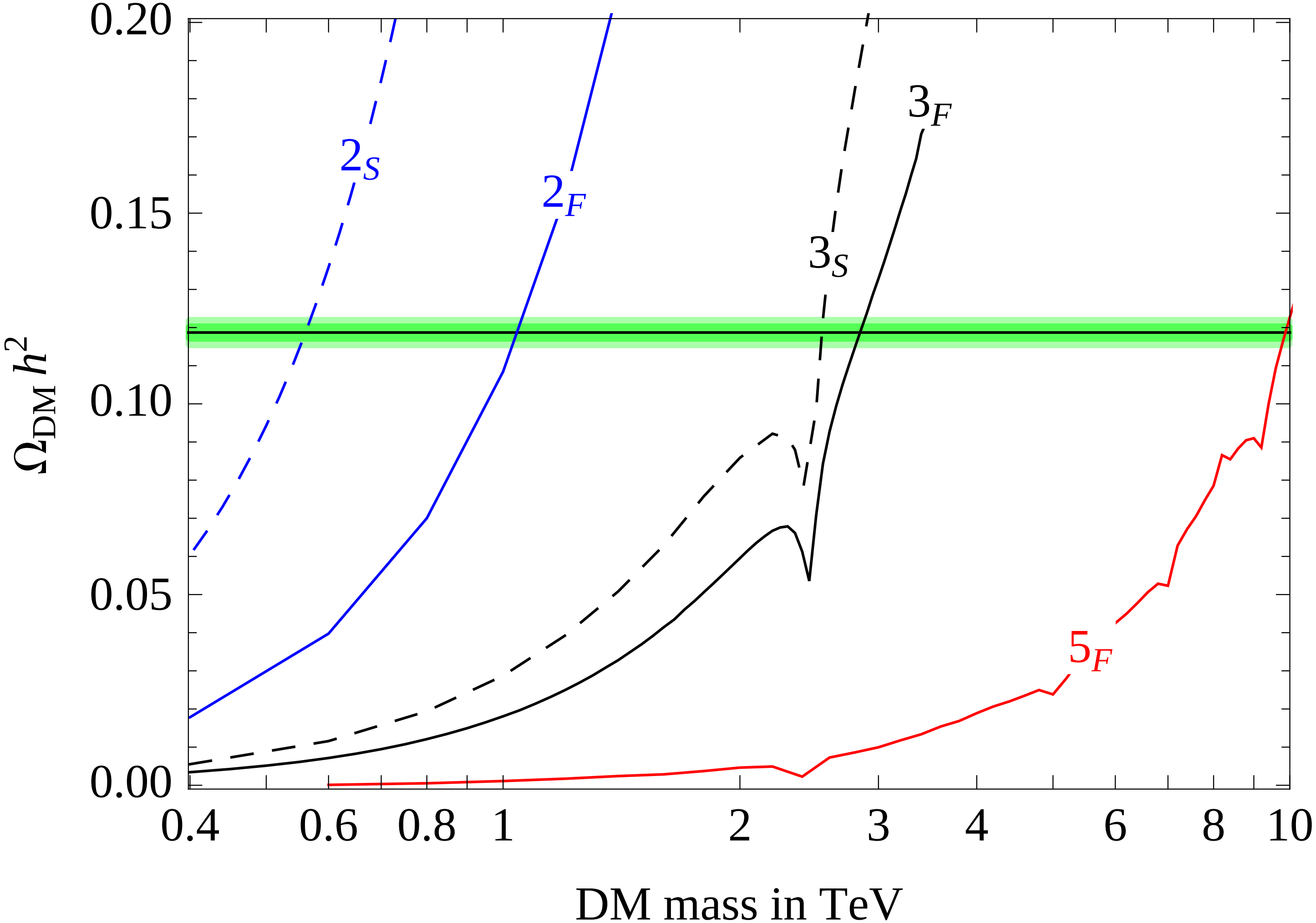
Consider Minimal Dark Matter: **one** electroweak multiplet containing a neutral DM particle with **only gauge** interactions. The neutral component gets lighter by $\approx 166\,$MeV. Finite naturalness: 2-loop quantum corrections to M_h^2

$$\delta m^2 = \frac{cnM^2}{(4\pi)^4}\left(\frac{n^2-1}{4}g_2^4 + Y^2 g_Y^4\right) \times \begin{cases} 6\ln\frac{M^2}{\Lambda^2} - 1 & \text{for a fermion} \\ \frac{3}{2}\ln^2\frac{M^2}{\Lambda\mu^2} + 2\ln\frac{M^2}{\Lambda^2} + \frac{7}{2} & \text{for a scalar} \end{cases}$$

Quantum numbers SU(2)$_L$	U(1)$_Y$	Spin	DM could decay into	DM mass in TeV	$m_{\rm DM^\pm} - m_{\rm DM}$ in MeV	Finite naturalness bound in TeV, $\Lambda \sim M_{\rm Pl}$	$\sigma_{\rm SI}$ in $10^{-46}\,$cm^2
2	1/2	0	EL	0.54	350	$0.4\times\sqrt{\Delta}$	$(2.3\pm0.3)\,10^{-2}$
2	1/2	1/2	EH	1.1	341	$1.9\times\sqrt{\Delta}$	$(2.5\pm0.8)\,10^{-2}$
3	0	0	HH^*	$2.0\to2.5$	166	$0.22\times\sqrt{\Delta}$	0.60 ± 0.04
3	0	1/2	LH	$2.4\to2.7$	166	$1.0\times\sqrt{\Delta}$	0.60 ± 0.04
3	1	0	HH, LL	$1.6\to?$	540	$0.22\times\sqrt{\Delta}$	0.06 ± 0.02
3	1	1/2	LH	$1.9\to?$	526	$1.0\times\sqrt{\Delta}$	0.06 ± 0.02
4	1/2	0	HHH^*	$2.4\to?$	353	$0.14\times\sqrt{\Delta}$	1.7 ± 0.1
4	1/2	1/2	(LHH^*)	$2.4\to?$	347	$0.6\times\sqrt{\Delta}$	1.7 ± 0.1
4	3/2	0	HHH	$2.9\to?$	729	$0.14\times\sqrt{\Delta}$	0.08 ± 0.04
4	3/2	1/2	(LHH)	$2.6\to?$	712	$0.6\times\sqrt{\Delta}$	0.08 ± 0.04
5	0	0	(HHH^*H^*)	$5.0\to9.4$	166	$0.10\times\sqrt{\Delta}$	5.4 ± 0.4
5	0	1/2	stable	$4.4\to10$	166	$0.4\times\sqrt{\Delta}$	5.4 ± 0.4
7	0	0	stable	$8\to25$	166	$0.06\times\sqrt{\Delta}$	22 ± 2

Thermal Dark Matter

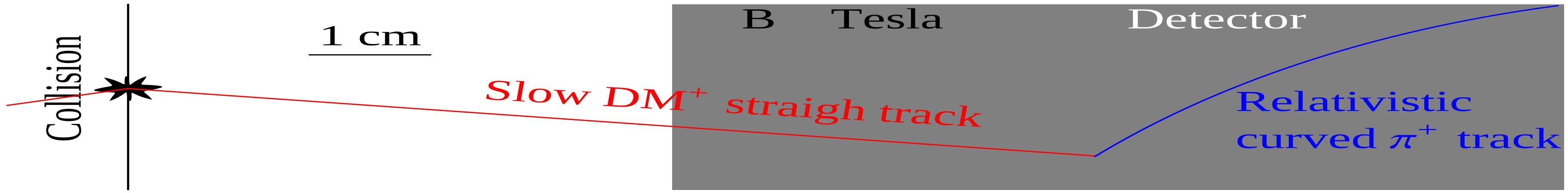
MDM reproduces as a thermal relic reproduces the observed $\Omega_{\rm DM}$ for $M \approx$ TeV



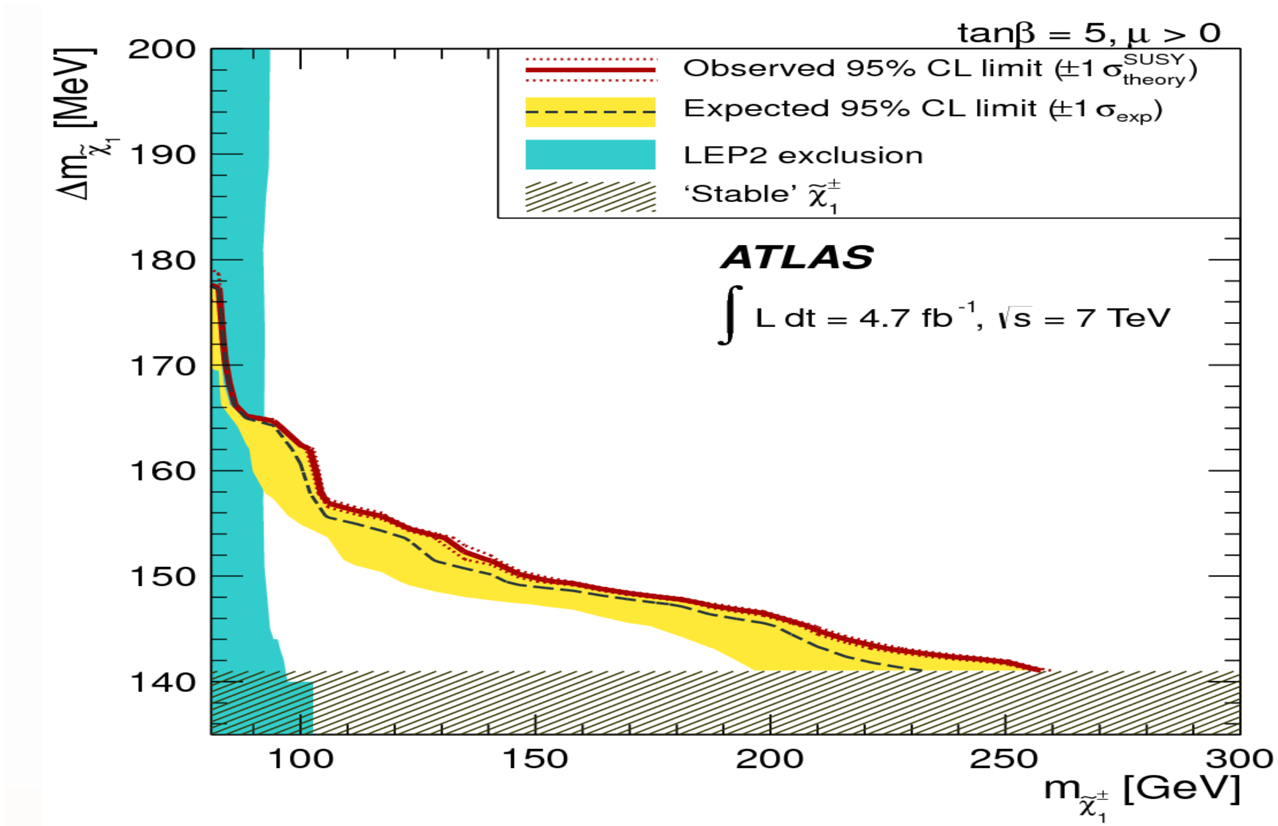
(Non-relativistic DM DM annihilations are Sommefeld enhanced if $M \gtrsim M_W/\alpha$)

Wino/MDM searches

$$\Gamma(\mathrm{DM}^\pm \to \mathrm{DM}^0\pi^\pm) = (n^2-1)/44\,\mathrm{cm} = 0.977\,\Gamma(\mathrm{DM}^\pm) \qquad \Delta M = 166\,\mathrm{MeV}$$

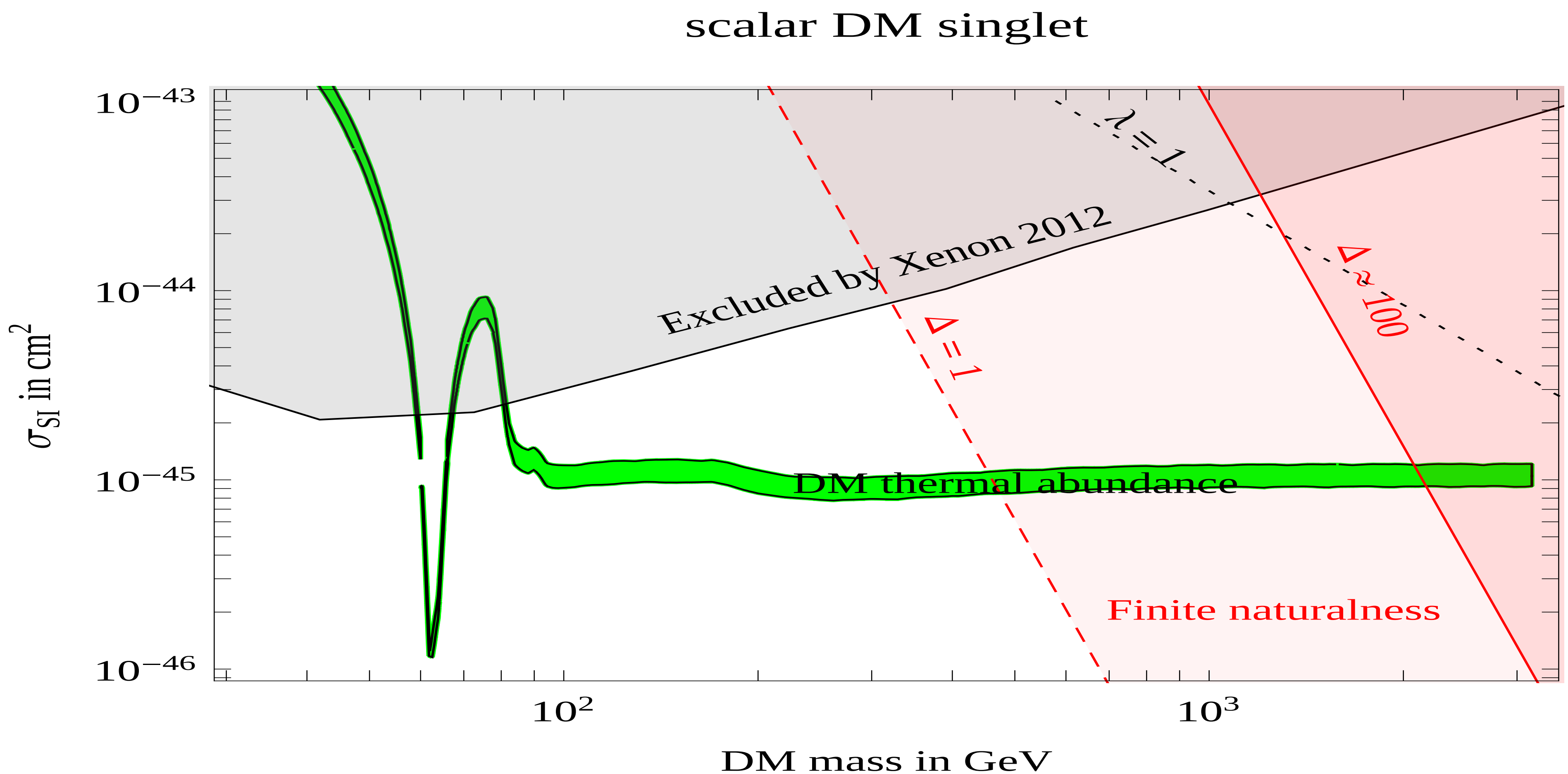


Trigger on initial state radiation and missing energy, LHC better than LEP!



Singlet Scalar DM

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{(\partial_\mu S)^2}{2} - \frac{m_S^2}{2}S^2 - \lambda_{HS}S^2|H|^2 - \frac{\lambda_S}{4}S^4$$

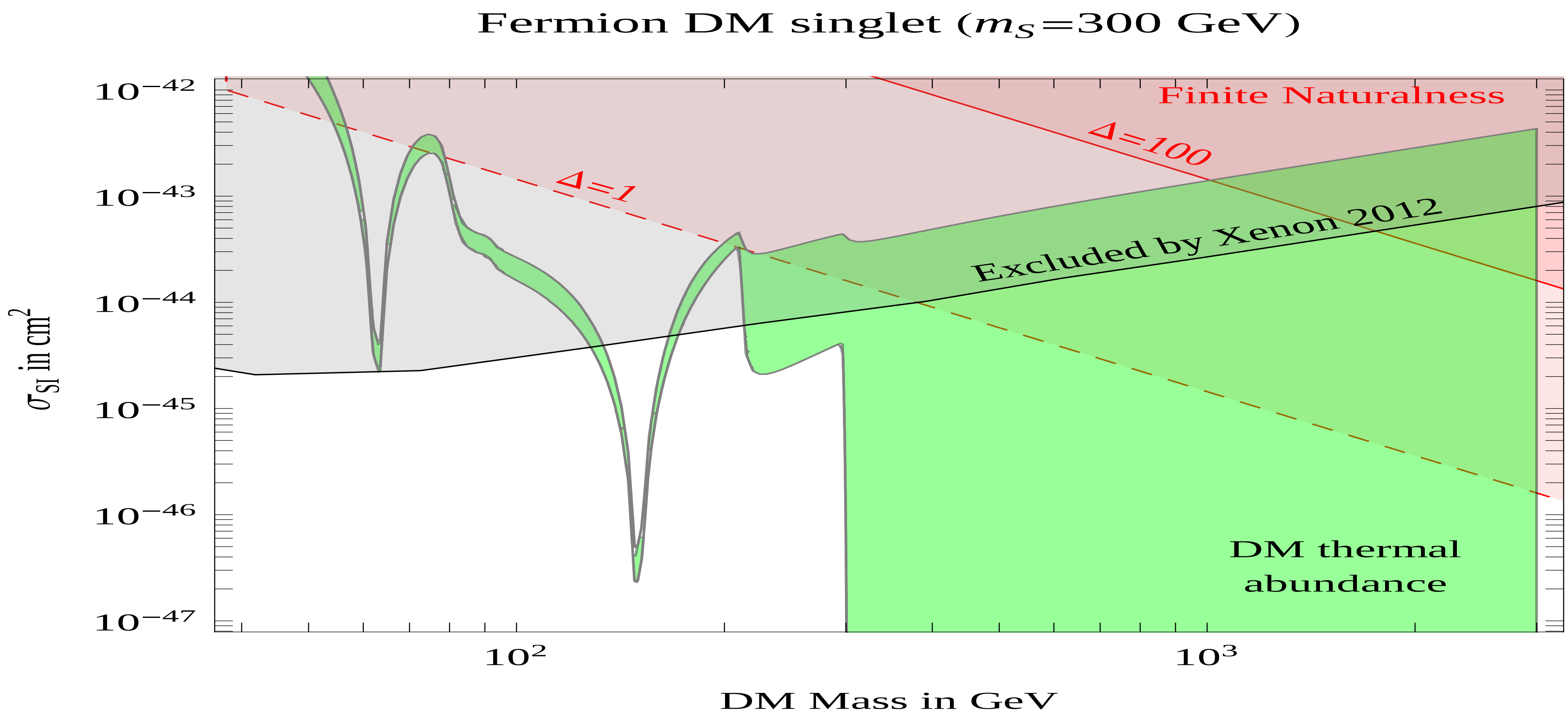


$$\sigma_{\rm SI} = \frac{\lambda_{HS}^2 m_N^4 f^2}{\pi M^2 M_h^4} \qquad \delta m^2 = -\frac{2\lambda_{HS}^2}{(4\pi)^2}M^2(\ln\frac{M^2}{\bar{\mu}^2} - 1) < \Delta \times M_h^2$$

Singlet Fermion DM

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{(\partial_\mu S)^2}{2} + \bar\psi i \partial\!\!\!/ \psi - \frac{m_S^2}{2}S^2 - \frac{\lambda_S}{4}S^4 - \lambda_{HS}S^2|H|^2 + \frac{y}{2}S\psi\psi + \frac{M_\psi}{2}\psi\psi + \text{h.c.}$$

Communicate via S. Thermal annihilations are p-wave, so $\sigma_{\rm SI}$ is often too large.



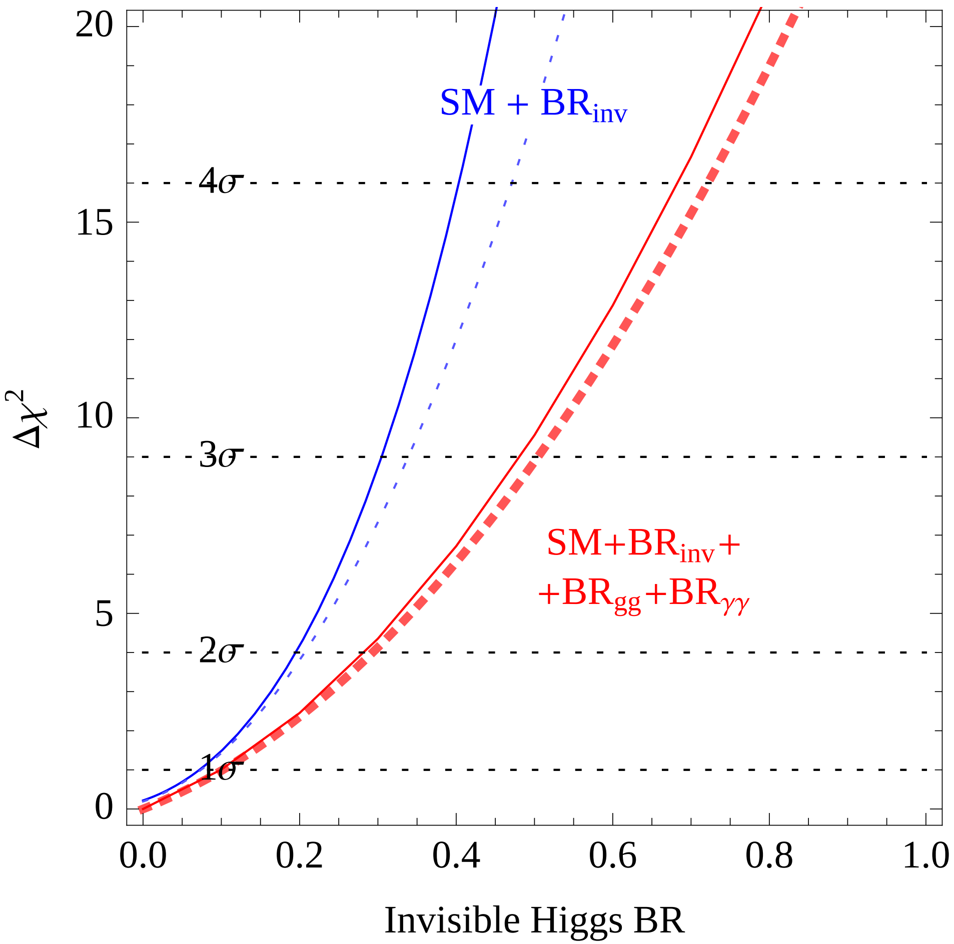
$$\sigma_{\rm SI} = \frac{y^2 \sin^2 2\alpha}{8\pi}\frac{m_N^4 f^2}{v^2}\left(\frac{1}{M_h^2} - \frac{1}{M_S^2}\right)^2 \qquad \delta m^2 = \frac{6y^2\sin^2\alpha}{(4\pi)^2}M^2(\ln\frac{M^2}{\bar\mu^2} - \frac{1}{3})$$

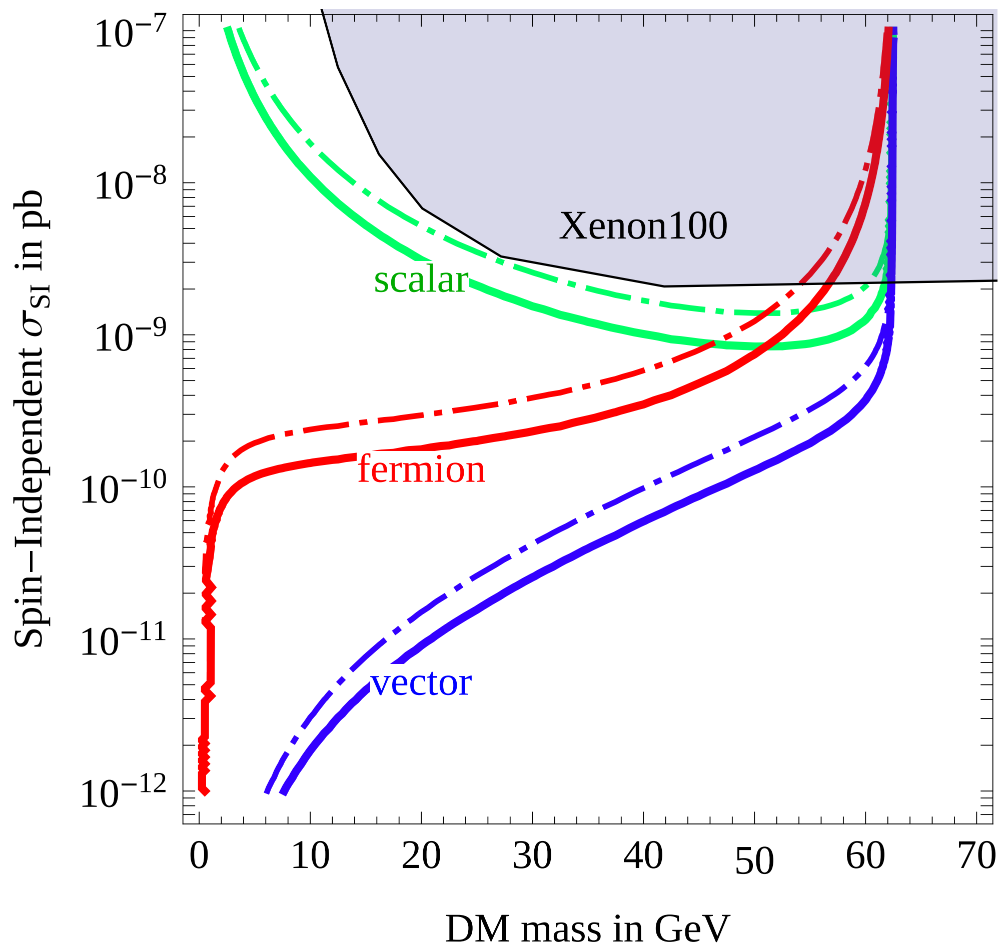
DM and Higgs decays

Consider scalar (S) or fermion (F) or vector (V) DM coupled to the Higgs as

$$r_S \frac{2m_S^2}{V} hSS + r_f \frac{m_f}{V} h\bar{f}f + r_V \frac{2m_V^2}{V} hV_\mu V_\mu$$

where $r = 1$ if DM gets mass only from $\langle h \rangle = V$. Invisible Higgs decays are a great signal for $M < M_h/2$: $\text{BR}_{\text{inv}} \lesssim 19 - 28\%$ at 95% CL constrains σ_{SI}





Effective operator description?

Assume that the physics that couples DM to SM is so heavy that it can be integrated out leaving effective operators of the form

$$\frac{1}{\Lambda^2}[\bar{\Psi}_{\rm DM}\gamma_\mu\Psi_{\rm DM}][\bar{\Psi}_{\rm SM}\gamma^\mu\Psi_{\rm SM}]$$

General framework where everything is computed in terms of Λ and M, e.g.

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm exp}} = \frac{(\Lambda/700\,{\rm GeV})^4}{(M/150\,{\rm GeV})^2} \qquad \sigma_{\rm SI} \approx 5\ 10^{-39}\,{\rm cm}^2 \left(\frac{M}{m_N+M}\right)^2\left(\frac{700\,{\rm GeV}}{\Lambda}\right)^4$$

CMS and ATLAS $j\not{E}_T$ and $\gamma\not{E}_T$ searches imply $\Lambda > 700\,{\rm GeV}$ for $M \ll \Lambda$. But:

1. "Model free" rather than "model independent"?
   The growth of $\sigma \sim E^2/\Lambda^4$ is crucial in getting competitive collider "bounds" on $\sigma_{\rm SI}$. But DM/SM interactions "usually" are mediated by light Z, h, W... rather than by hypothetical heavy particles ($\tilde{\ell}$?) as $1/\Lambda^2 \approx y_?^2/M_?^2$.

2. In-validity of the the effective operator approximation?
   For any collider the limit will be $\Lambda \ll \sqrt{s}$, because the invisible signal needs extra j or γ. What LHC would really see is the heavy mediator particle.

Detectable Dark Matter below a TeV?

DM above a TeV is too heavy for LHC and for δm_h^2. DM below a TeV with weak gauge interactions annihilates too much leaving a too low Ω_{DM}, unless:

- Extra solution at $M < M_W$ such that too large $\sigma(\text{DM}\,\text{DM} \to W^+W^-)$ is kinematically suppressed. Not fully excluded by LEP. E.g. 'inert doublet'

- Mix interacting ($M \gg v$) with singlets ($M \to 0$): get any intermediate M.

- DM as singlet + extra coupling e.g. bino$_{\text{DM}}$-lepton-slepton Yukawa in SUSY works if sleptons are around or below the LEP bound. Small extra couplings can be resonantly enhanced, e.g. DM DM $\to A \to b\bar{b}$ in SUSY if $M_A = 2M$.

DM at colliders: summary

Simplest scenario: only DM is produced, an initial state jet allows to see

$$\not{p}_T + \text{soft jet}$$

Plausible scenario: DM could be the lightest of a new set of particles (like in SUSY). LHC dominantly produces heavier colored particles (gluino, squarks) that decay down to DM. The signal depends a lot on the decay chains

$$\not{p}_T \;+ \text{hard jets or leptons or...}$$

Possible scenario: the lightest sparticle is charged or colored and decays into "gravitinos" or "axino" DM with life time $\tau \gtrsim$m

charged tracks, decays after the collisions

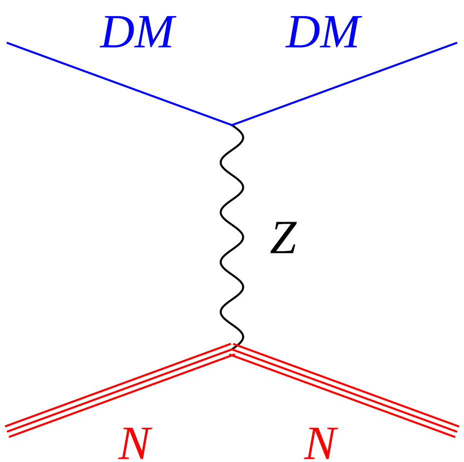
etc etc etc but nothing seen in data so far

Direct DM detection

Direct DM detection: key parameter

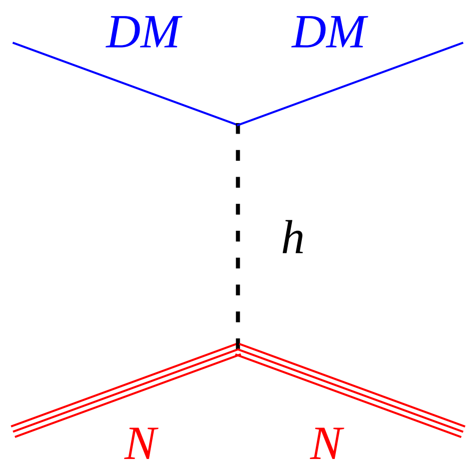
$\sigma_{\rm SI}$ = spin-independent DM-nucleon cross section

allows to compare experiments: DM/nucleus cross section $\sigma_{\mathcal{N}} = A^2 \sigma_{\rm SI}$.



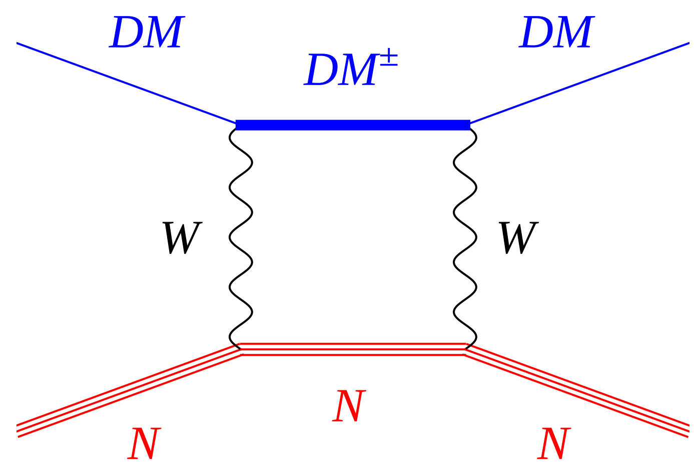
tree, vector

$$\sigma_{\rm SI} \approx \frac{\alpha^2 \, m_N^2}{M_Z^4}$$



tree, scalar

$$\sigma_{\rm SI} \approx \frac{\alpha^2 \, m_N^4}{M_h^6}$$

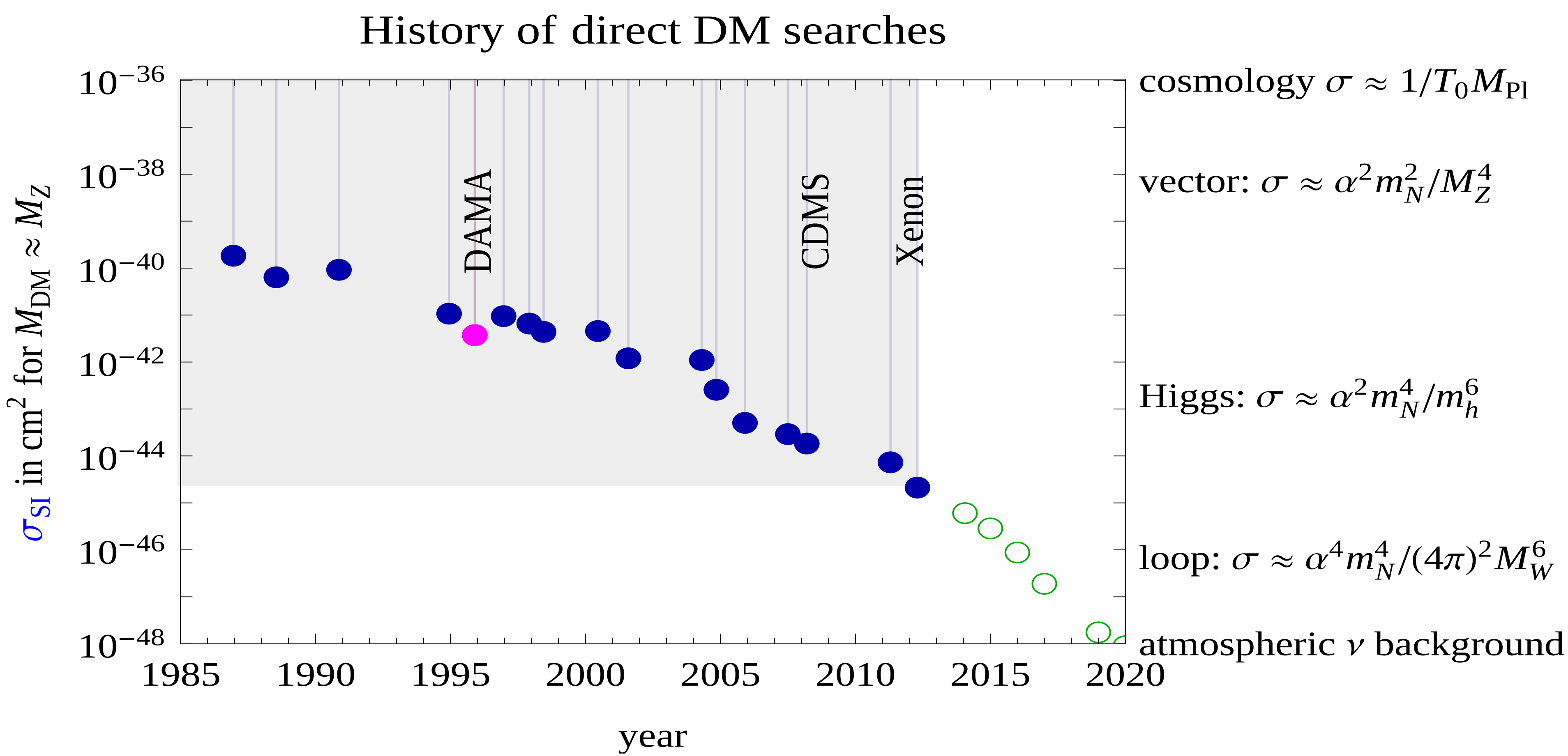


loop

$$\sigma_{\rm SI} \approx \frac{\alpha^4 \, m_N^4}{M_W^6}$$

The vector effect vanishes if DM is real (e.g. a Majorana fermion).

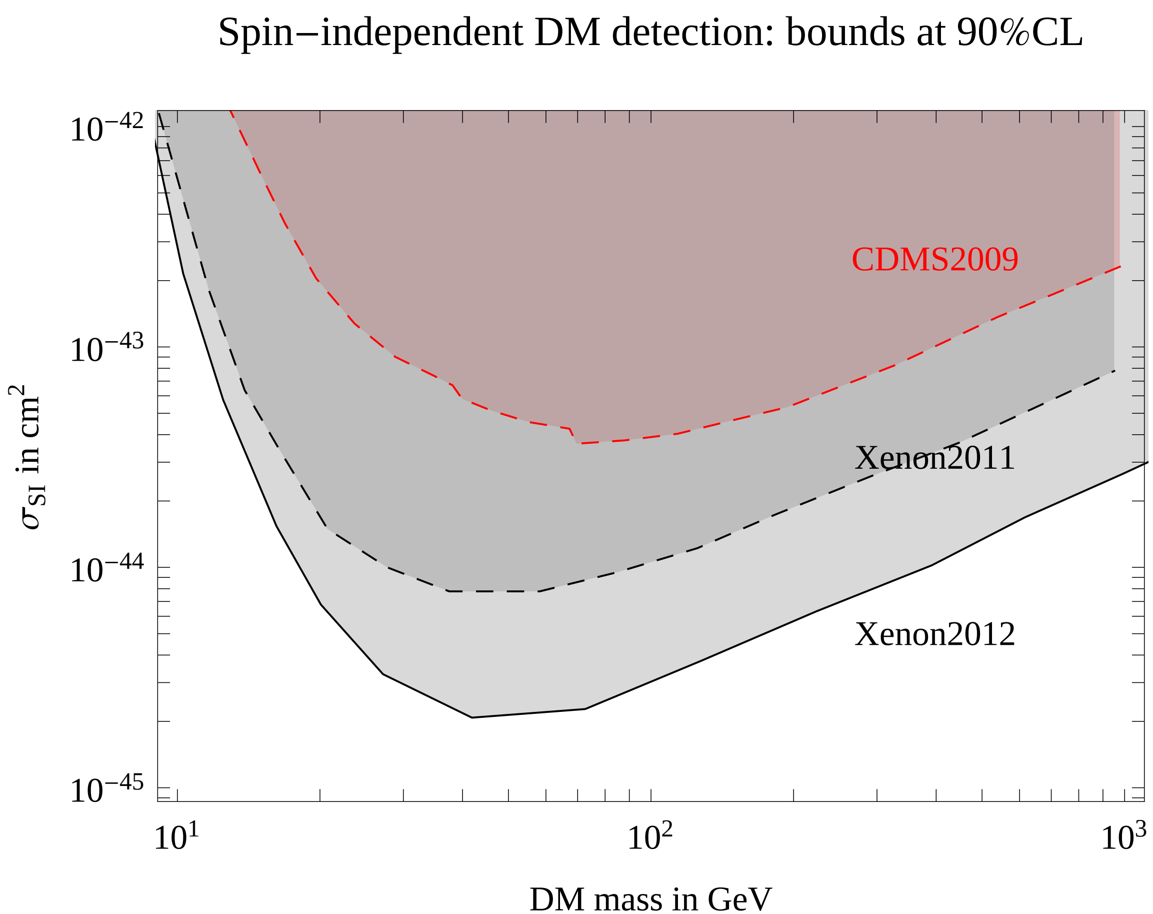
Experimental progress



DM must be neutral under the γ, g and almost neutral under the Z

‘Anomaly-free’ Dark Matter

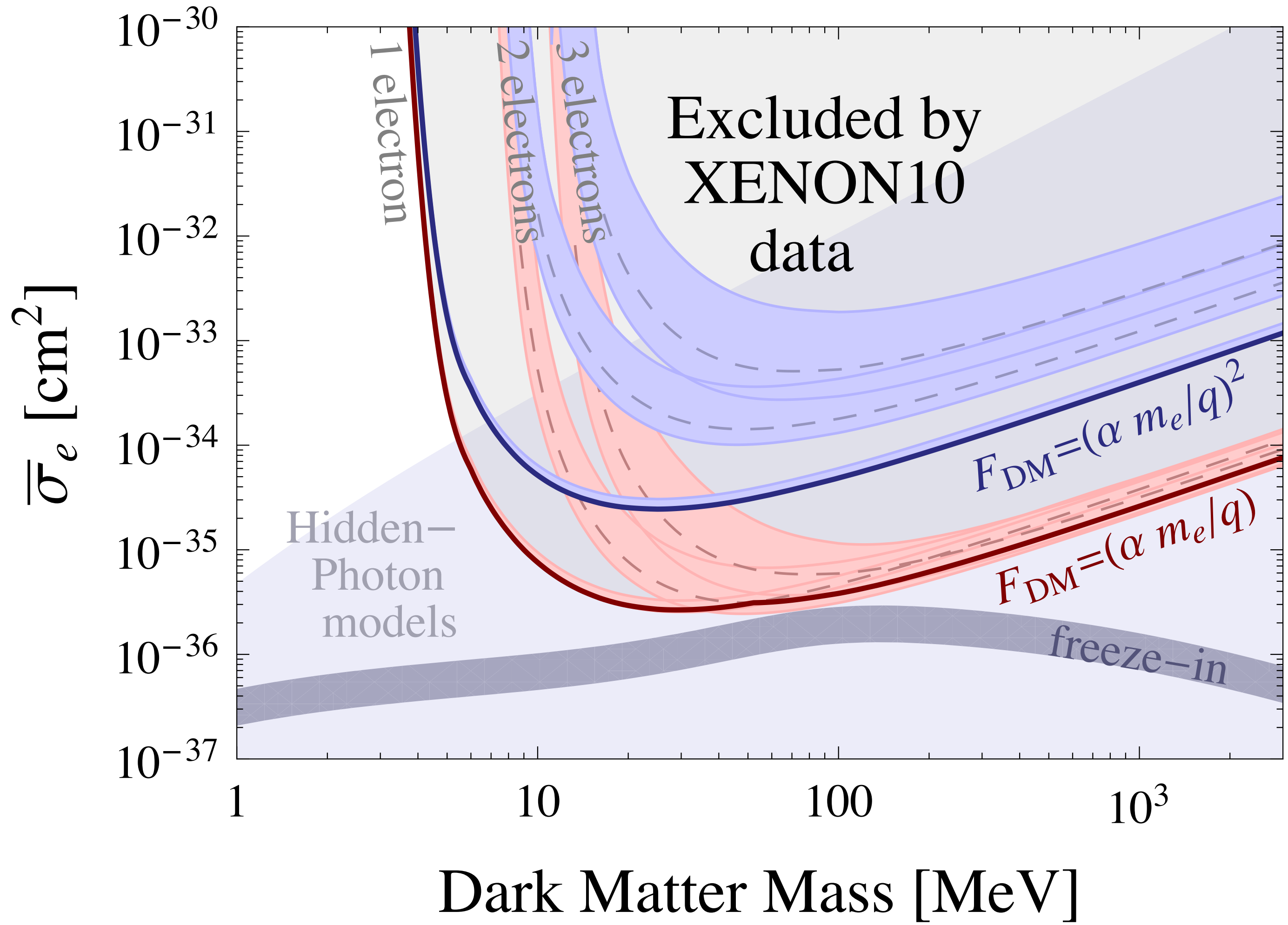
Ignoring experiments that claim ‘anomalous’ results, this is the present status:



[Below a few GeV is ≈ terra incognita]

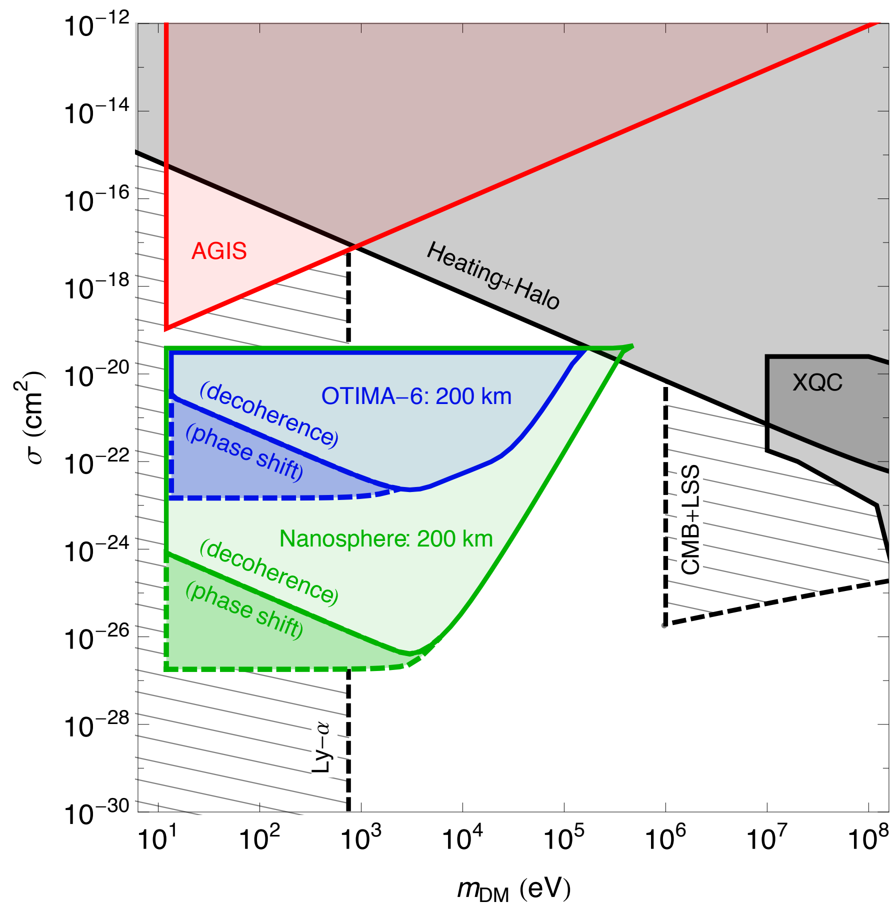
Sub GeV DM

When nuclear recoil $E_R \sim E_{\rm DM}(m_N/M)$ becomes too small, $E_{\rm DM} = \frac{M}{2}v^2 \sim 50\,{\rm eV}(M/100\,{\rm MeV})$ can lead to (a) e ionization; (b) e excitation; (c) molecular dissociation giving individual e or γ or ion or phonons. First bound:



Ultra-light DM

If DM is so light that its scatterings are too soft even for atomic physics, DM can still be detected via quantum interference! Experimentalists are able of splitting the wave functions of nucleons or atoms by a small distance (nm to cm). Quantum interference is lost if one of them interacts with DM. Experiments are done with a few atoms for a few seconds, so the bound is N_A weaker



Indirect DM detection

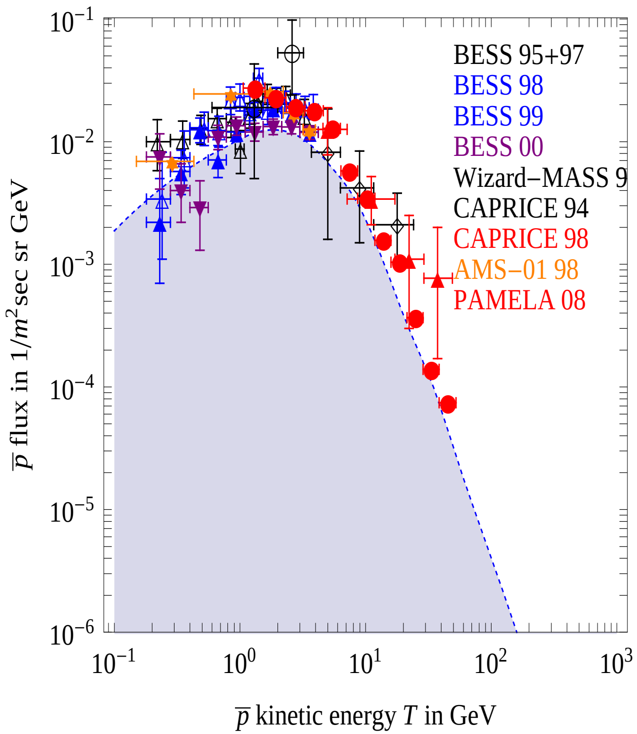
  

Indirect signals of Dark Matter

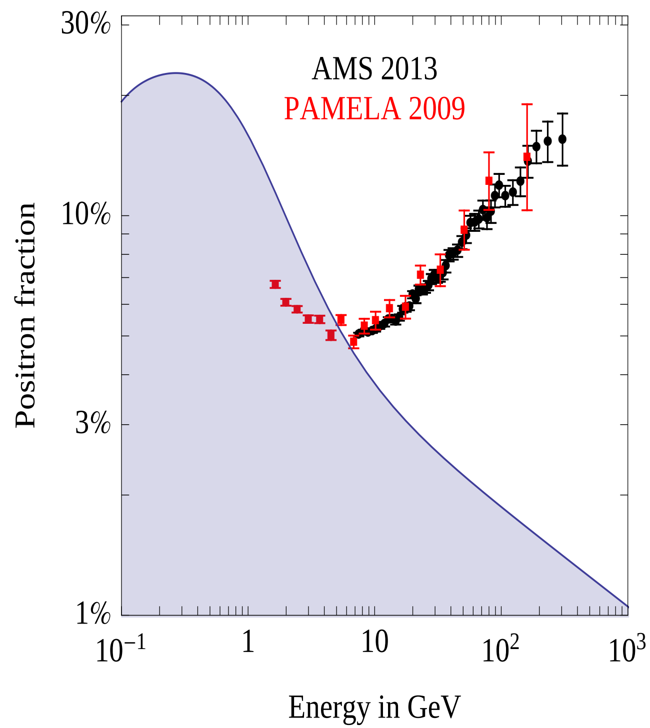
DM DM annihilations in our galaxy might give detectable γ, e^+, $\bar{p}$, $\bar{\mathrm{d}}$.

Measurements of charged cosmic rays

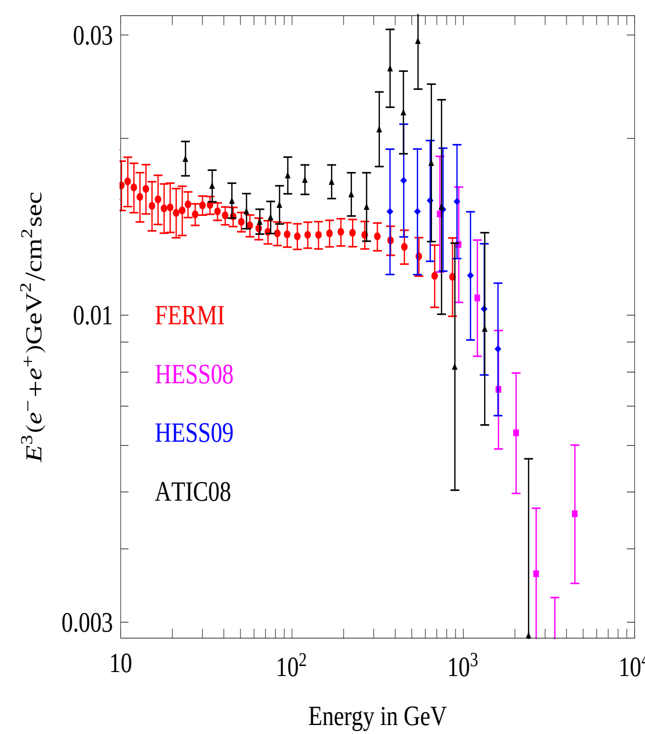
$\bar{p}$



$e^+/(e^+ + e^-)$



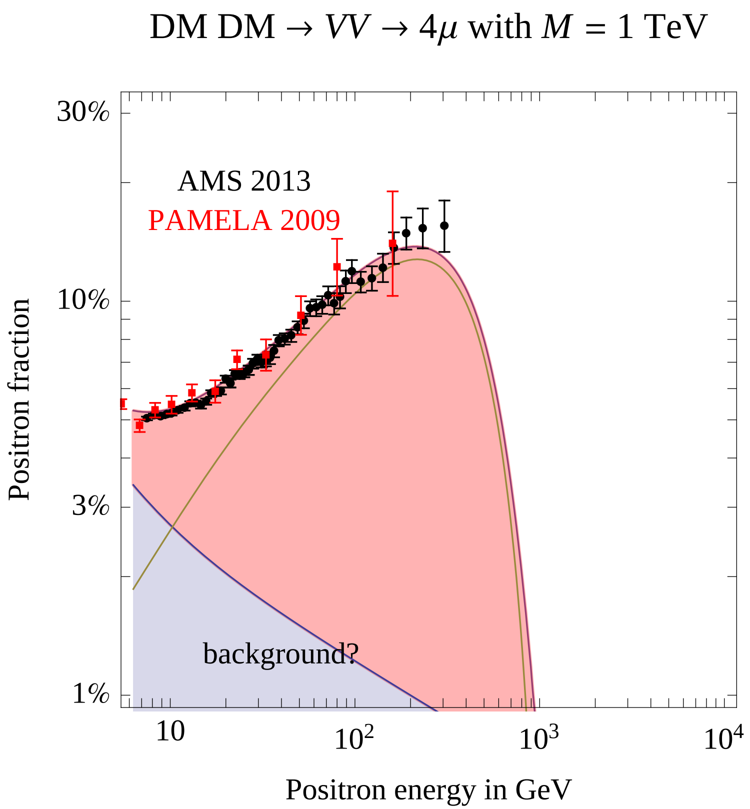
$e^+ + e^-$

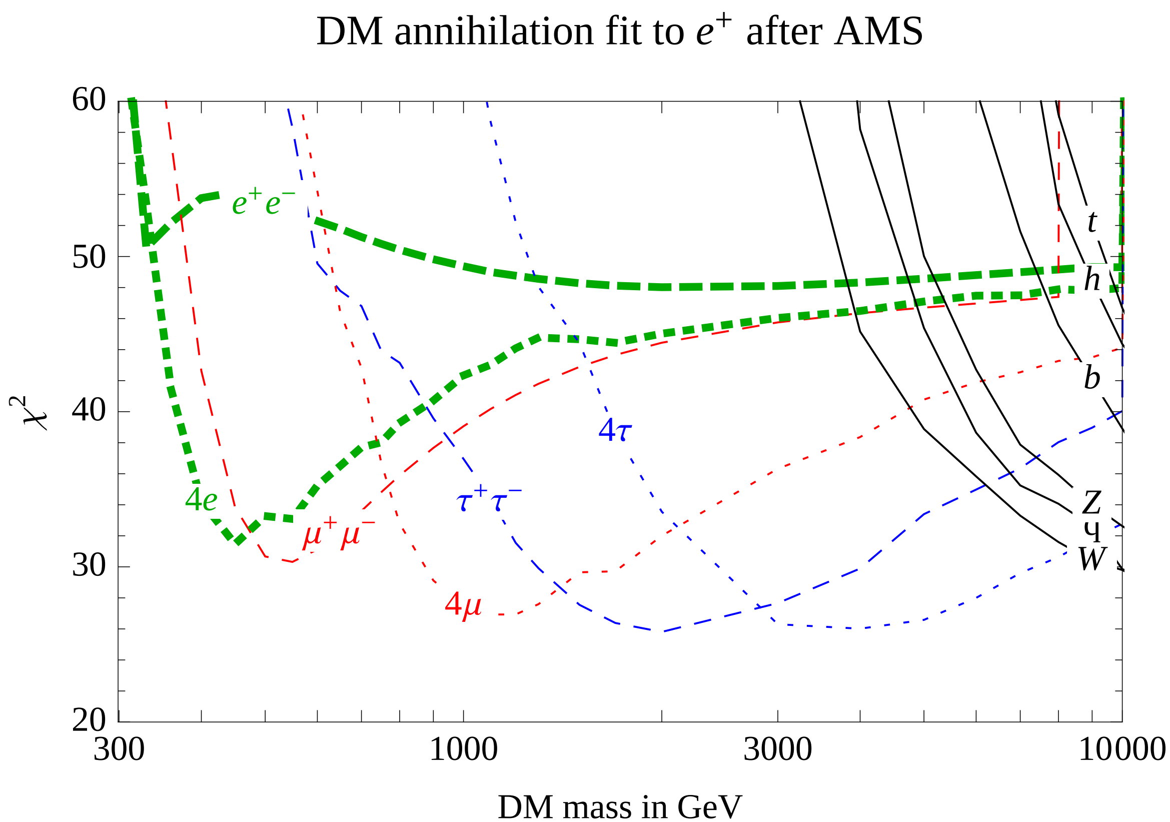


Explaining the e^+ excess

Due to astrophysics? Maybe pulsars or primary e^+? Due to DM?

e^+ spectrum reproduced if DM annihilates into leptons with $\sigma v \sim 10^3 \sigma v_{\rm cosmo}$



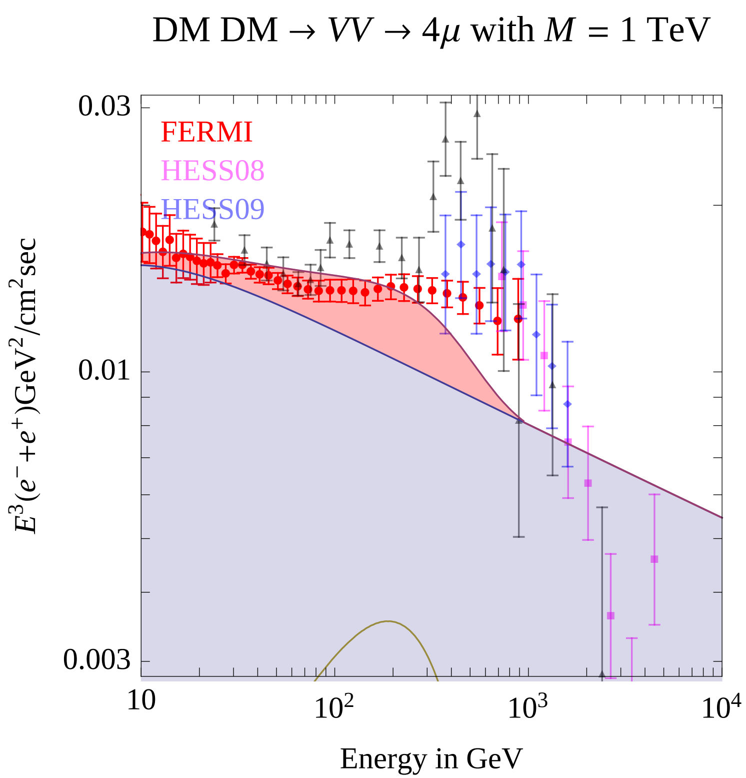


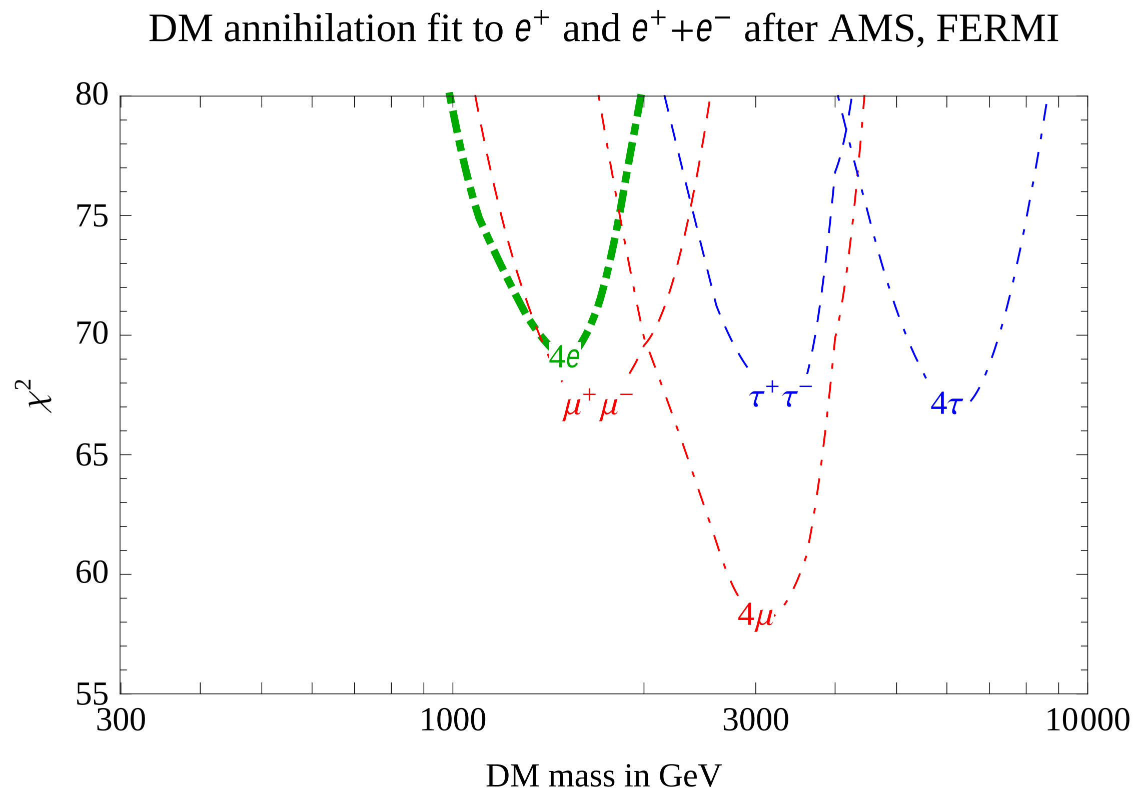
AMS hint of a flattening favours $M \sim$ TeV

Not seen in $\bar{p}$: leptonic modes again. Not seen in γ: needs quasi-constant $\rho(r)$.

Explaining the $e^{\pm}$ excesses

Hints of drops in $e^+/(e^+ + e^-)$ and in $e^+ + e^-$ **but** at different energies





AMS can clarify measuring very precisely the $e^+ + e^-$ spectrum

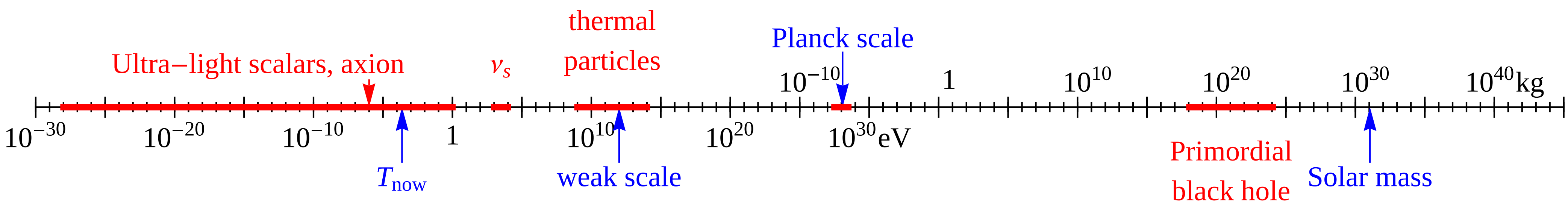
Dark Matter: what it is?

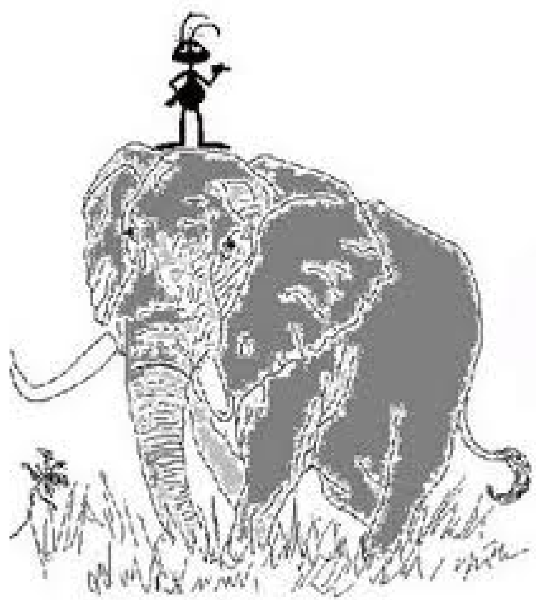
Why DM should be a weak scale particle, if new physics must not be there?

Dark Matter: how heavy?

DM exists, but so far we have seen only its gravity

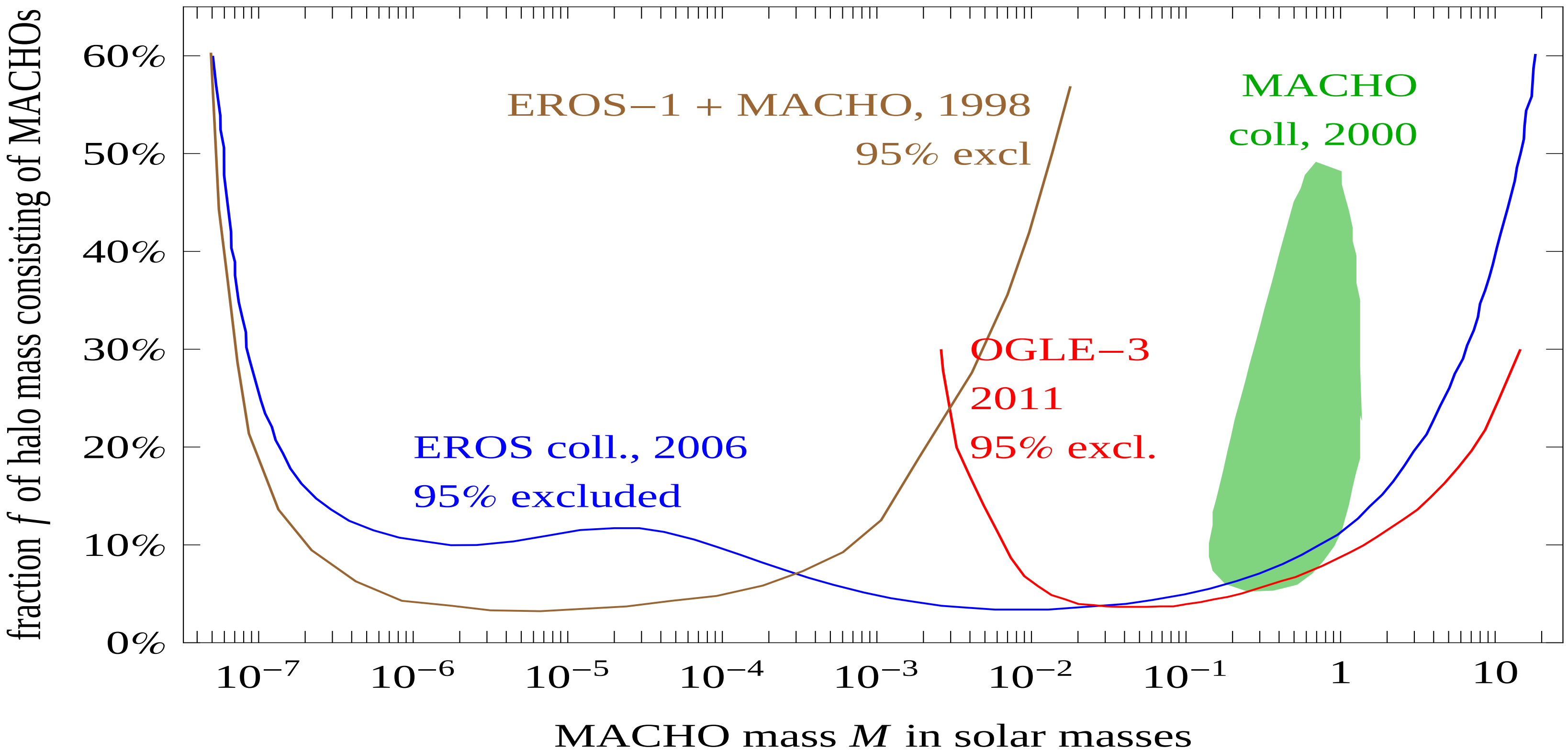
Decades of theoretical work restricted the DM mass to a range of 100 orders of magnitude. We do not even know if DM is astro-physics or particle physics





DM as ultra-heavy objects (MACHO)?

Dead stars, planets, Black Holes... must be either non-baryonic (mirror world?) or made before BBN (primordial BH?). DM 'particles' are lighter than small galaxies so $M < 10^5 M_\odot$ where $M_\odot = 2\ 10^{33}$ g is the solar mass. Microlensing surveys imply that MACHO Milky Way fraction is $< 20\%$ around $M \sim M_\odot$.



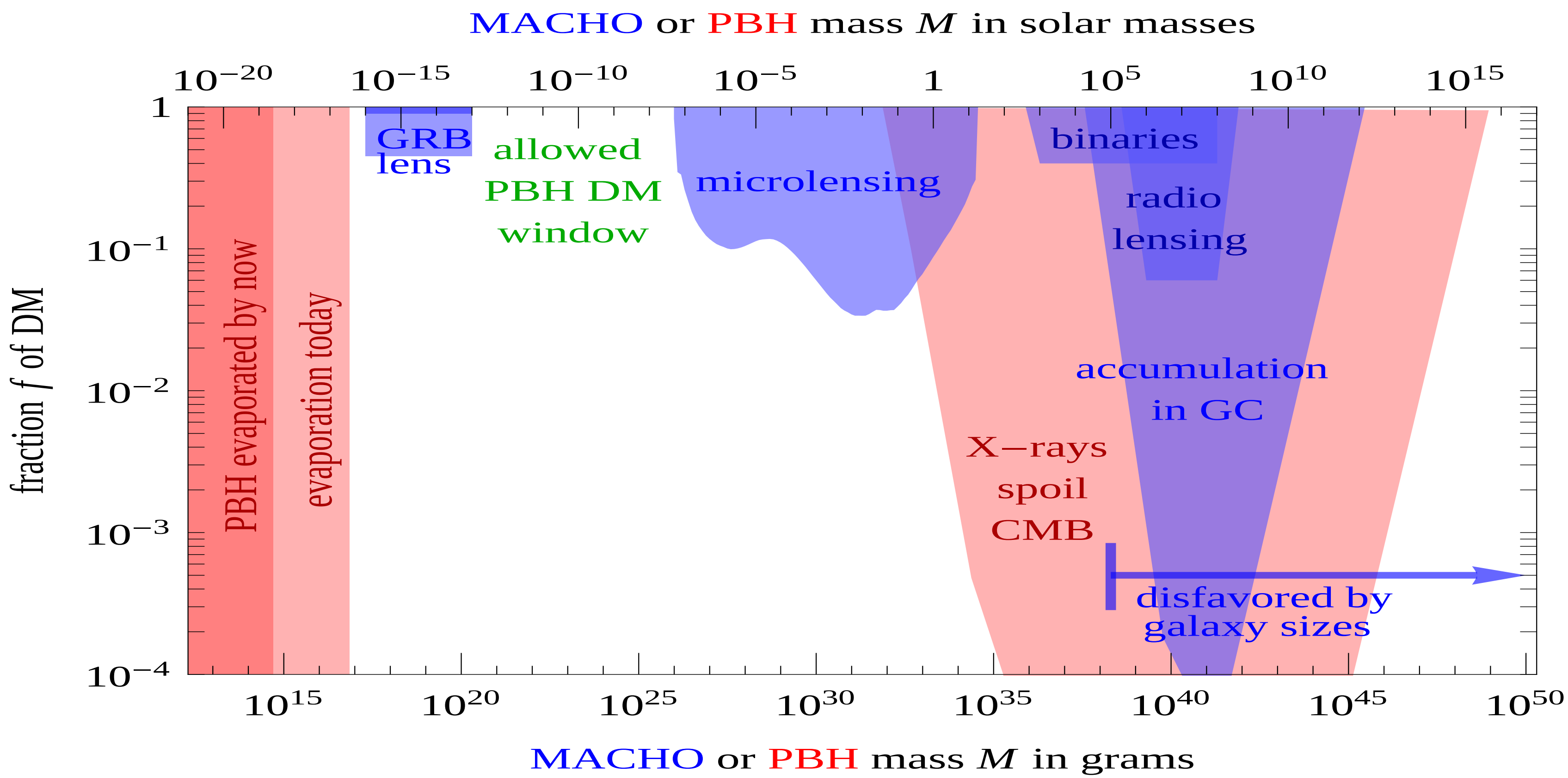
DM as Primordial Black Holes (PBH)?

PBH are not predicted by standard cosmology because primordial fluctuations have small amplitude $\delta_k \sim 10^{-5} \ll 1$. Allowed mass range:

$$10^{-13}\, M_\odot \lesssim M \lesssim 10^{-7}\, M_\odot$$

A BH cannot be too light because it emits photons evaporating in a time $\sim G_N^2 M^3$.

Non-observation of microlensing nor of X-ray emission from matter falling into BH.

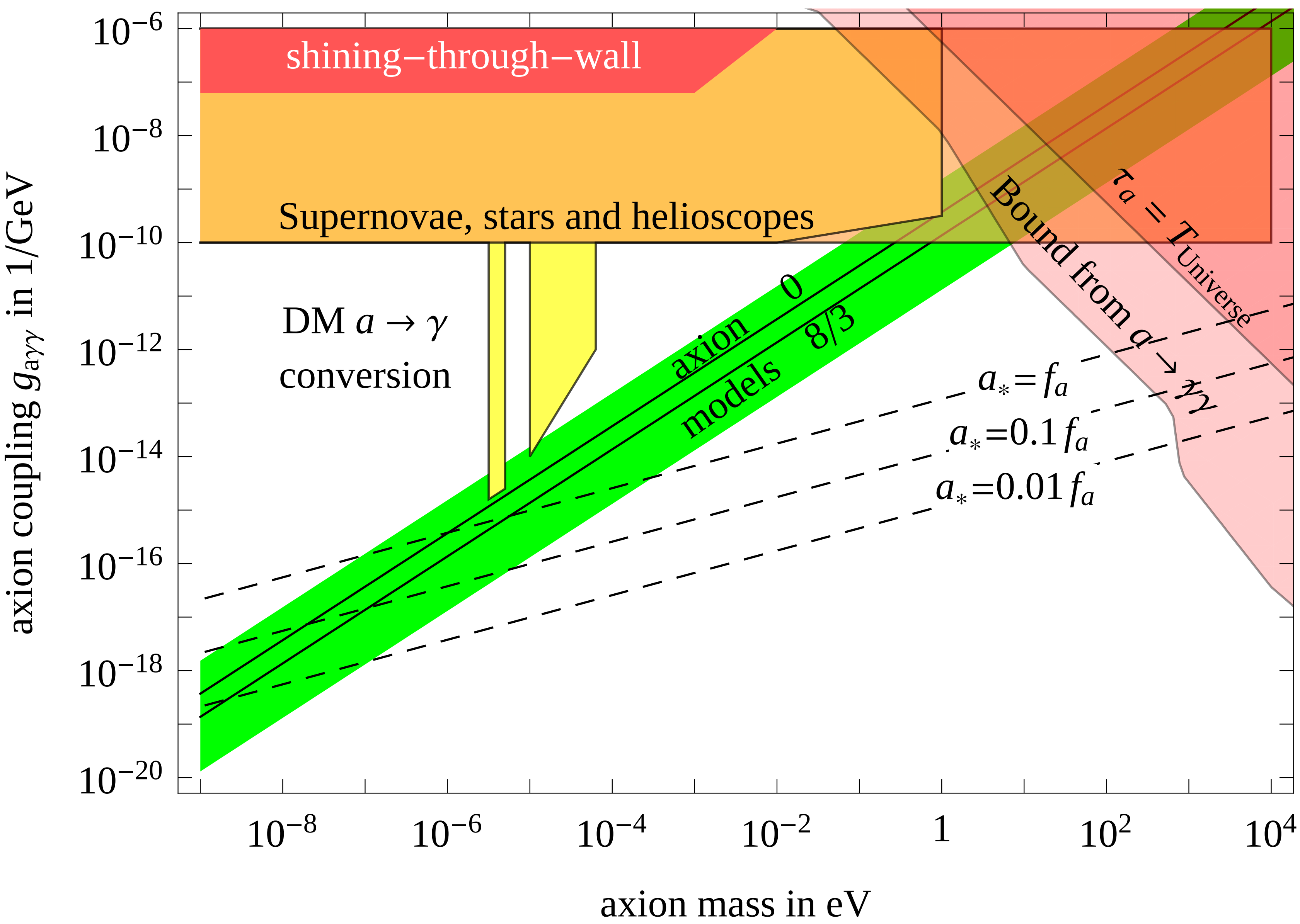


Axions as ultra-light scalar DM

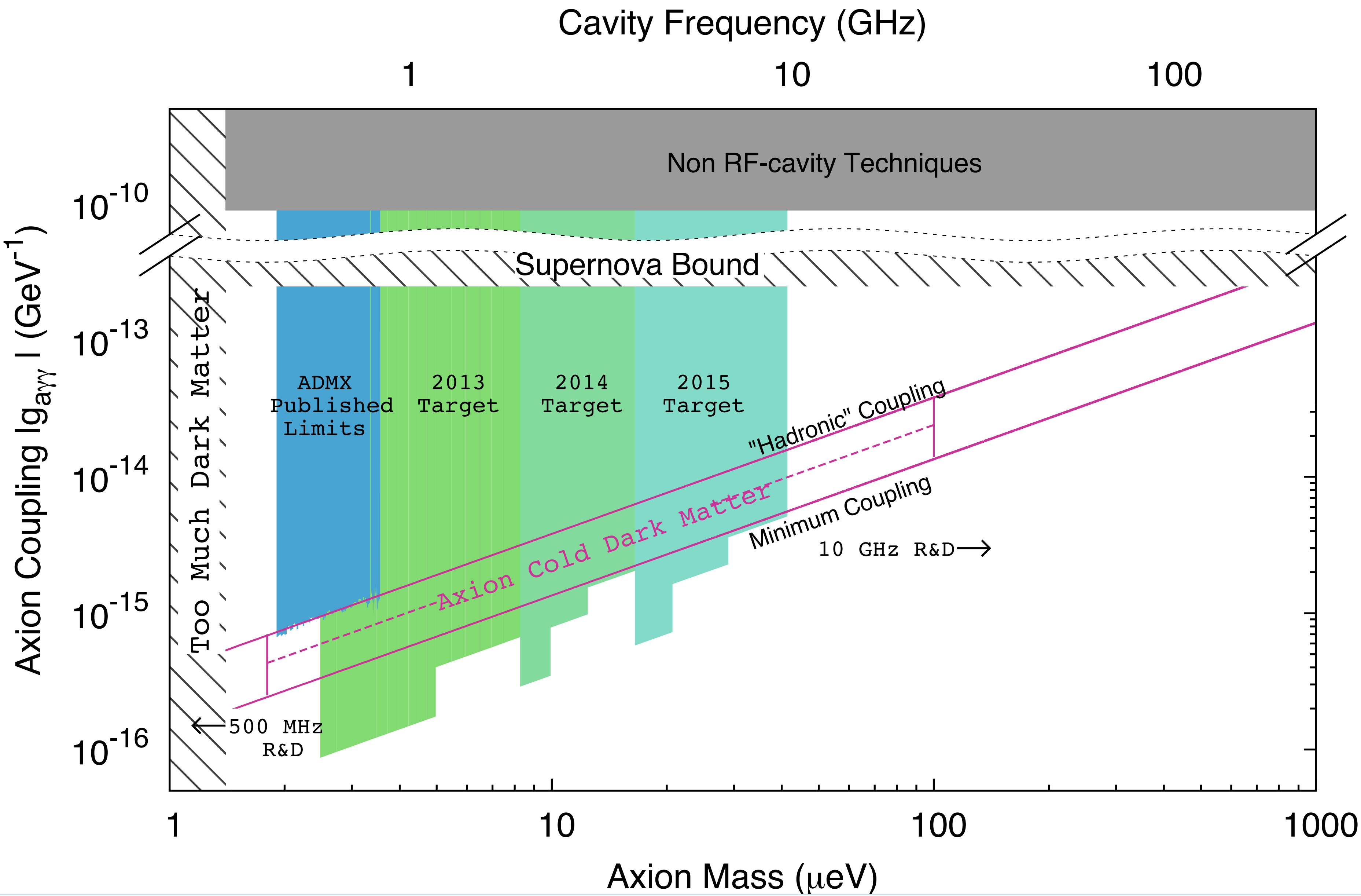
Practical summary: the axion a is a well-motivated particle with

$$
\begin{aligned}
m_a &= \frac{m_\pi f_\pi / f_a}{\sqrt{(1+m_u/m_d)(1+m_d/m_u+m_d/m_s)}} \approx 0.6\,\mathrm{meV}\frac{10^{10}\,\mathrm{GeV}}{f_a} \\
g_{a\gamma\gamma} &= \frac{\alpha_{\mathrm{em}}}{2\pi f_a}\left(\frac{\sum q^2}{T^2} - \frac{2}{3}\frac{4+m_u/m_d+m_u/m_s}{1+m_u/m_d+m_u/m_s}\right) \\
\Omega_{\mathrm{DM}} &\approx \sqrt{\frac{m_a}{\mathrm{eV}}}\left(\frac{a_*}{10^{11}\,\mathrm{GeV}}\right)^2
\end{aligned}
$$

Axion searches



ADMX



Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
Supernova Bound
Too Much Dark Matter
ADMX Published Limits
2013 Target
2014 Target
2015 Target
"Hadronic" Coupling
Axion Cold Dark Matter
Minimum Coupling
10 GHz R&D
500 MHz R&D
Axion Coupling |gaγγ| (GeV-1)
10-10
10-13
10-14
10-15
10-16
1
10
100
1000
Axion Mass (μeV)

Axions and LHC

Like fish and bicycle

Experiments demand $f_a > 10^9$ GeV so "normally" axions models employ ultra-heavy new fermions (KSVZ) or scalars (DFSZ). Out of range for LHC.

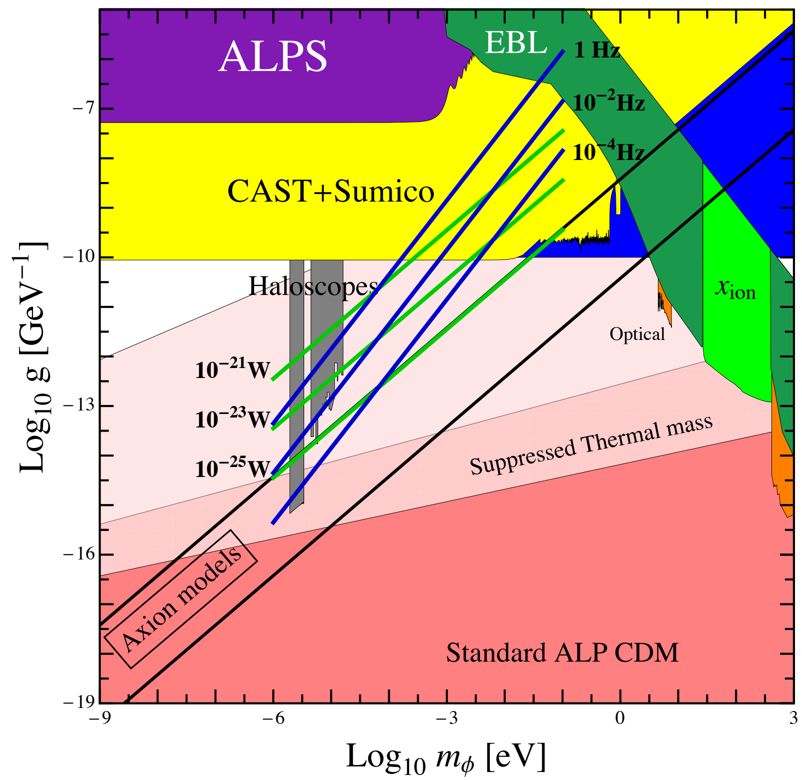
If "finite naturalness" holds, such particles can and must be light:

$$M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74\,\text{TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5\,\text{TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1\,\text{TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}$$

The axion is the phase of the mass M of KSVZ heavy quarks Ψ. Given that $f_a \gtrsim 10^9$ GeV, at LHC they would behave as ordinary heavy quarks.

New ideas for axion detection

DM axions passing through a magnetic fields make an electric field with $\omega = m_a$. If a metallic surface is also present, an electromagnetic wave is emitted perpendicularly to it. Using a spherical surface, such waves can focused in the centre, and detected. Detectors sensitive to powers of 10^{-25} W would start to probe the axion strip for all masses down to $\approx 1/\text{m}$. [1212.2970]



Axions with $f \sim M_{\text{Pl}}$ could be detected as oscillating neutron electric dipole or by angular momentum loss of rotating black holes due to axion emission...

Axion DM already observed!?

Three big claims from Sikivie and others:

1) Axions interact form a coherent Bose-Einstein condensate;
2) This leads to caustics in the DM galactic densities $\rho(r)$ at special radii;
3) Such caustics are supported by data.

Step 1) is based on interactions rates *linear* in the axion couplings, either gravity or a small quartic. This is derived as a consequence of the large axion occupation numbers, such that short-time axion scatterings would not conserve energy. I don't understand what is the sense of this.

Axion coherence should hold at most for times $t \sim 1/m_a\beta^2$.

Conclusions / last slide

1) DM exists.
2) LHC overcovers natural models, they would have given great DM signals.
3) LHC undercovers thermal DM searches, is sensitive now to EW multiplets.
4) We no longer believe we know where to look for DM.
5) Watch axions