Dark matter theory
(pheno oriented)

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LPTHE Univ. Paris 6 and CNRS

LHC days in Split, 23 September 2016

Cooking a Dark Matter model: constraints

"**Particle**" properties

- feels **Gravity**
- CMB (& not spoil BBN,…) = **non-baryonic**
- Invisible now = almost **electrically neutral**
- **stable** enough

"**Historical**" properties

How much?	$\Omega_{\rm DM} \simeq 0.26$	(Planck satellite)
Since when?	enough **before CMB**	
How fast?	**Non-relativistic**	

Constraints + rules of the game + creativity =

The Standard Model has no DM candidate → Beyond the Standard Model!

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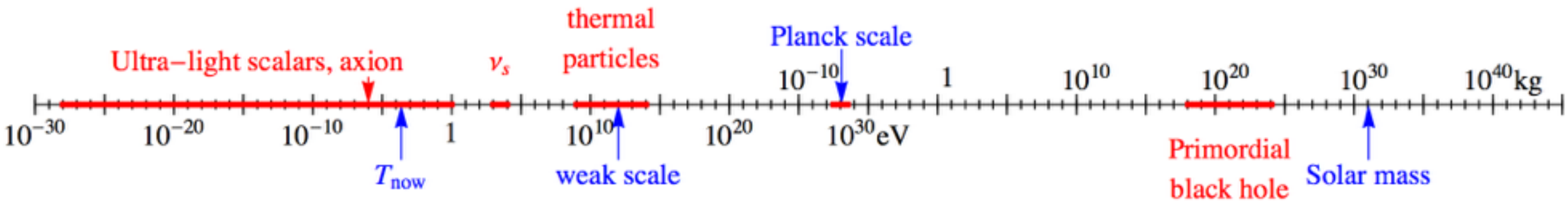

(courtesy of Marco Cirelli)

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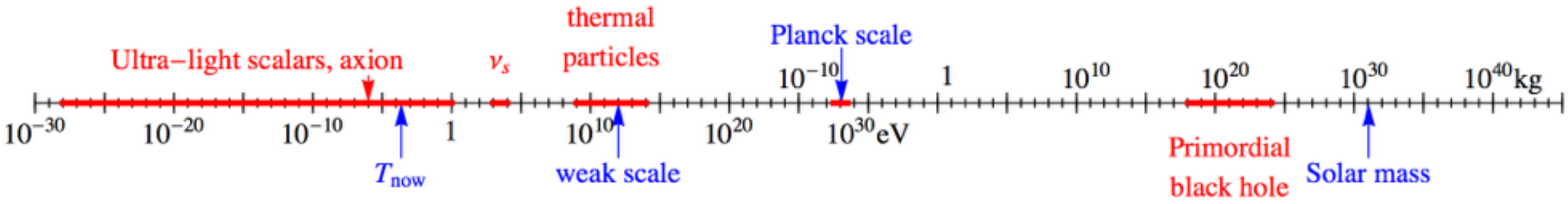

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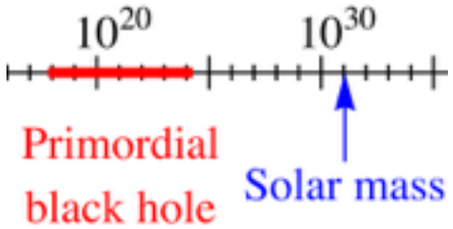
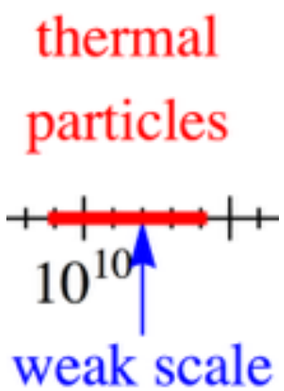


Possibly the “least conventional" candidate



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Apologies for not mentioning all the rest…

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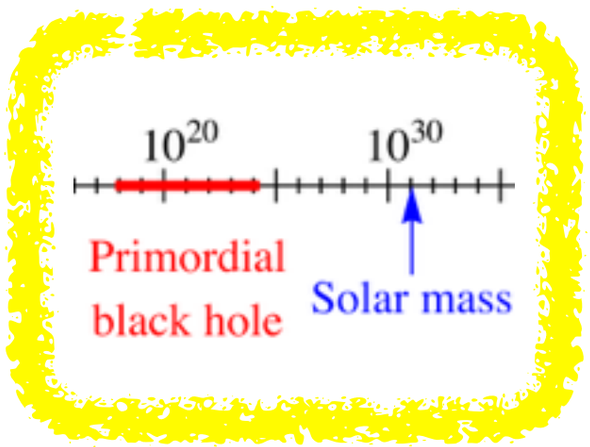

Primordial black holes (?)

- ☑ Gravity (and nothing else: non baryonic + electrically neutral)
- ☑ Stable enough (provided they did not evaporate)
- ☑ How to have them? How to have them at BBN??? See e.g. Anne Green 1403.1198
  - Large density perturbations from inflation
  - Cosmic strings loops
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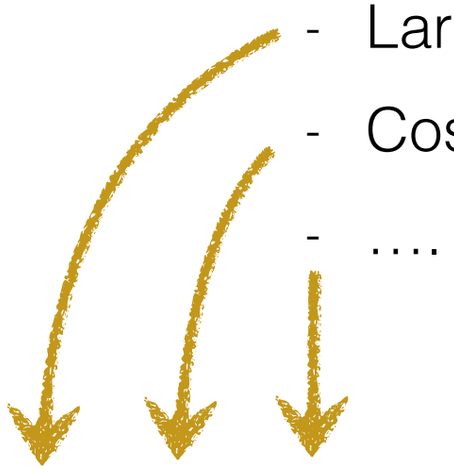

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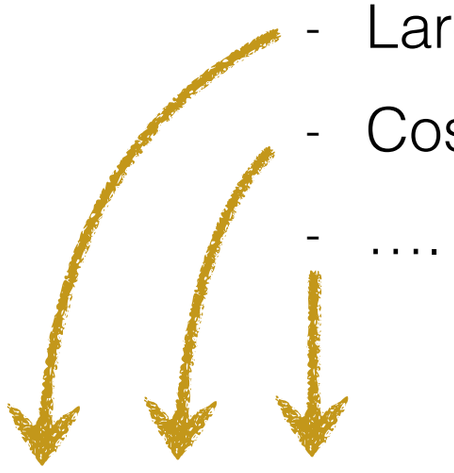

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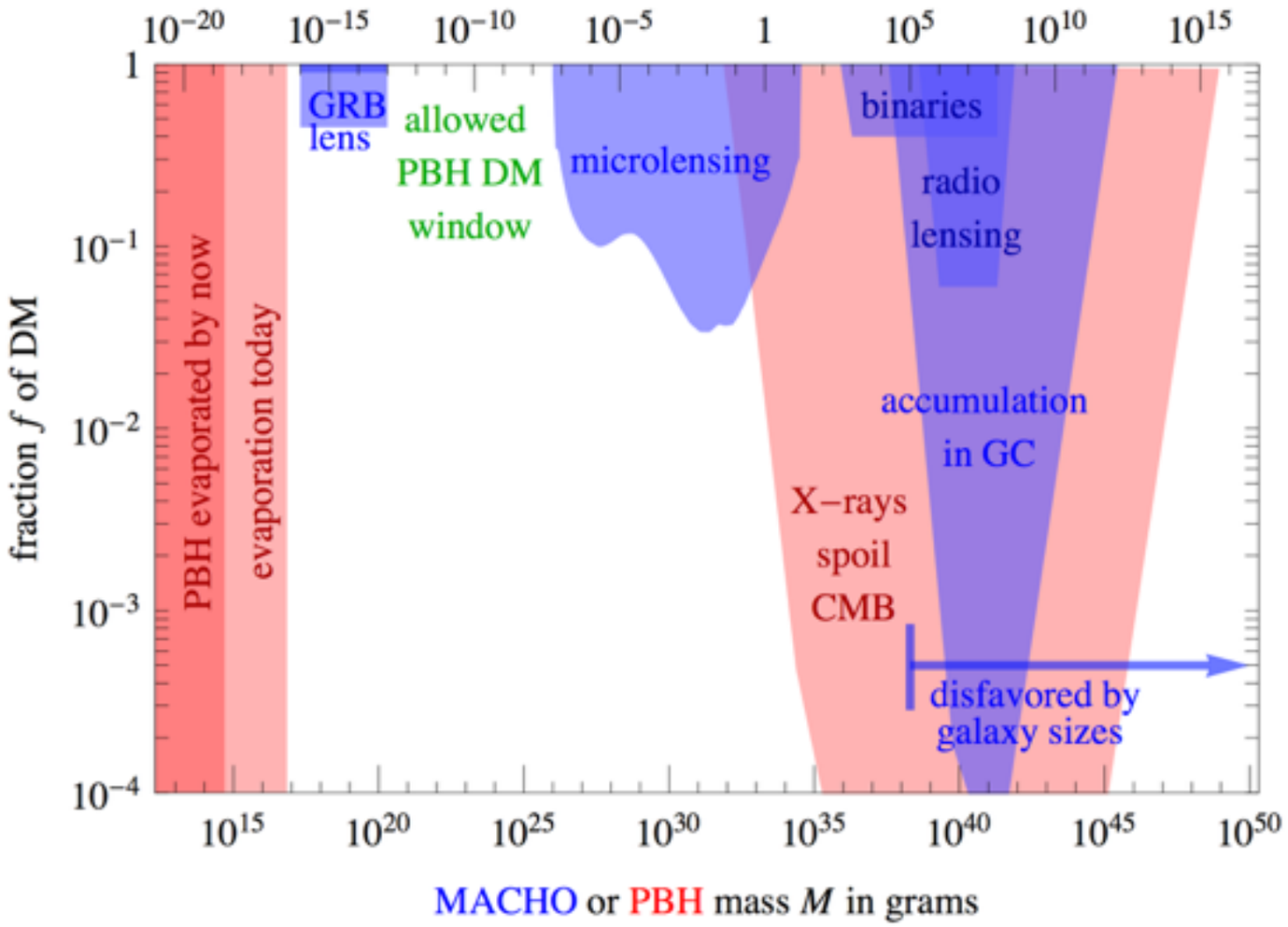
Still we have gravity to probe them!

Dark Matter detection I: PBH

See e.g. review Carr Kuhnel Sandstad 1607.06077



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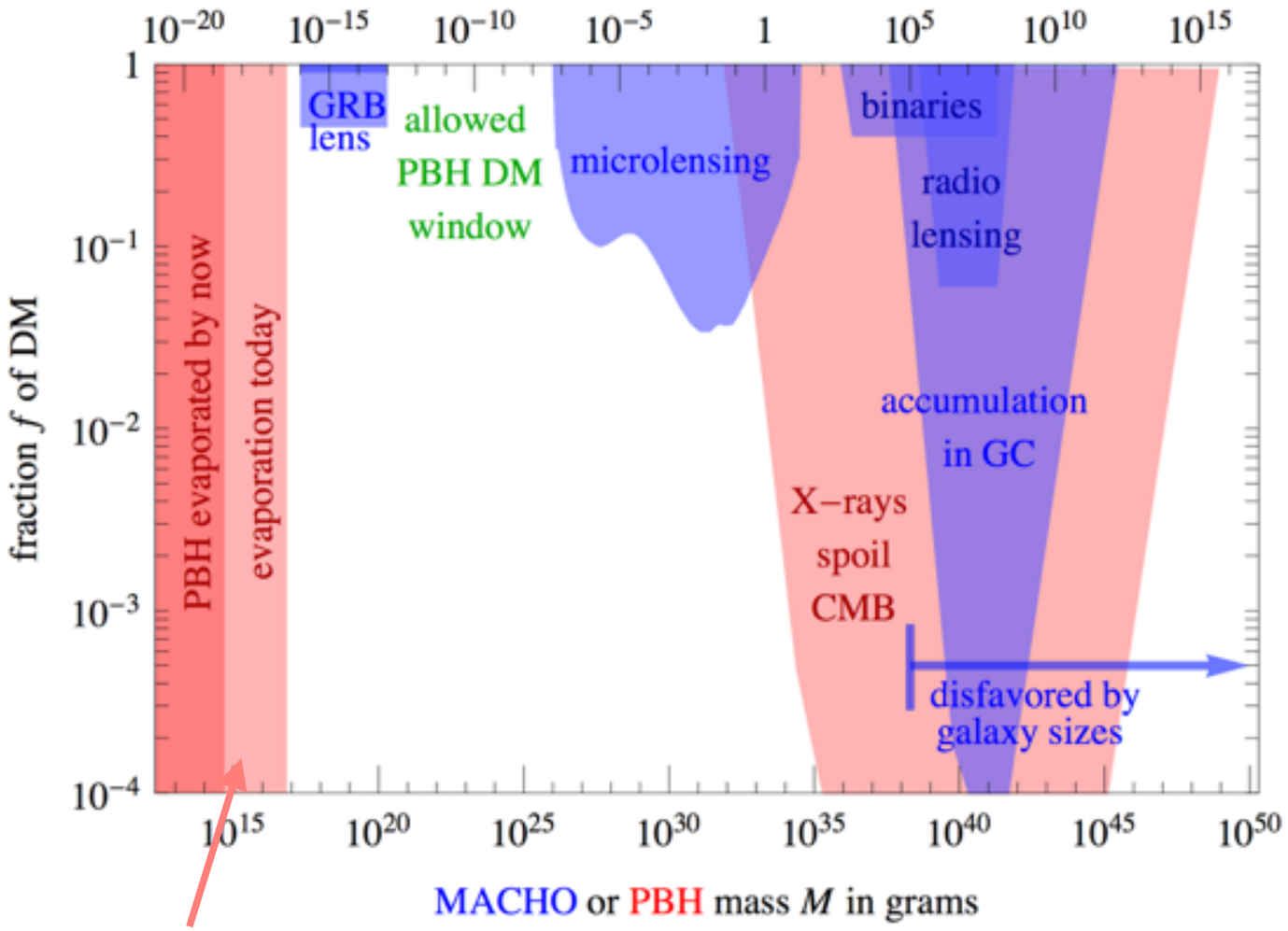

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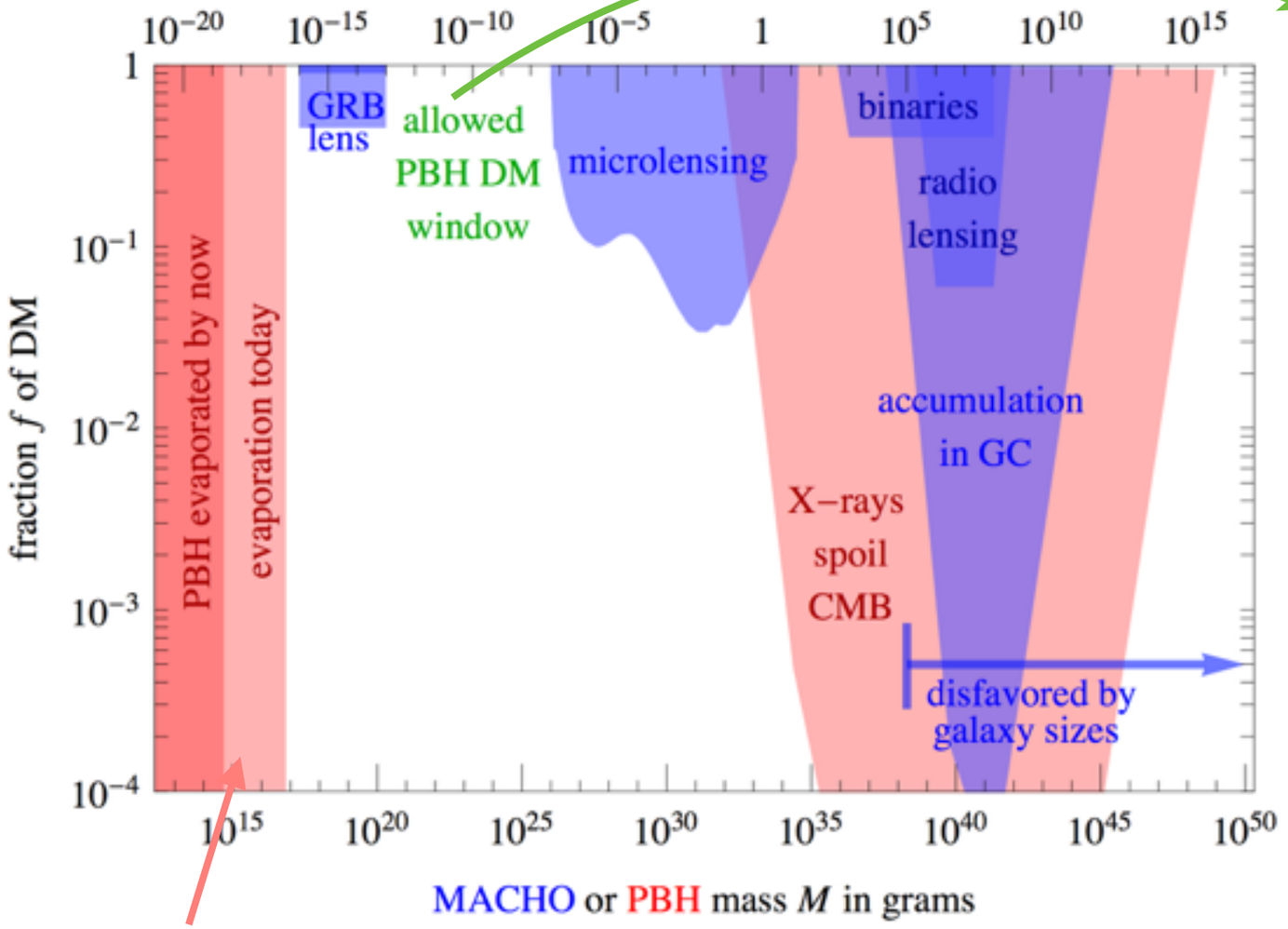

Allowed window: mass < Moon

size < 1 mm

Pani Loeb 1401.3025

Strong claim of exclusions via capture in (and disruption of) neutron stars

Claim eventually confuted

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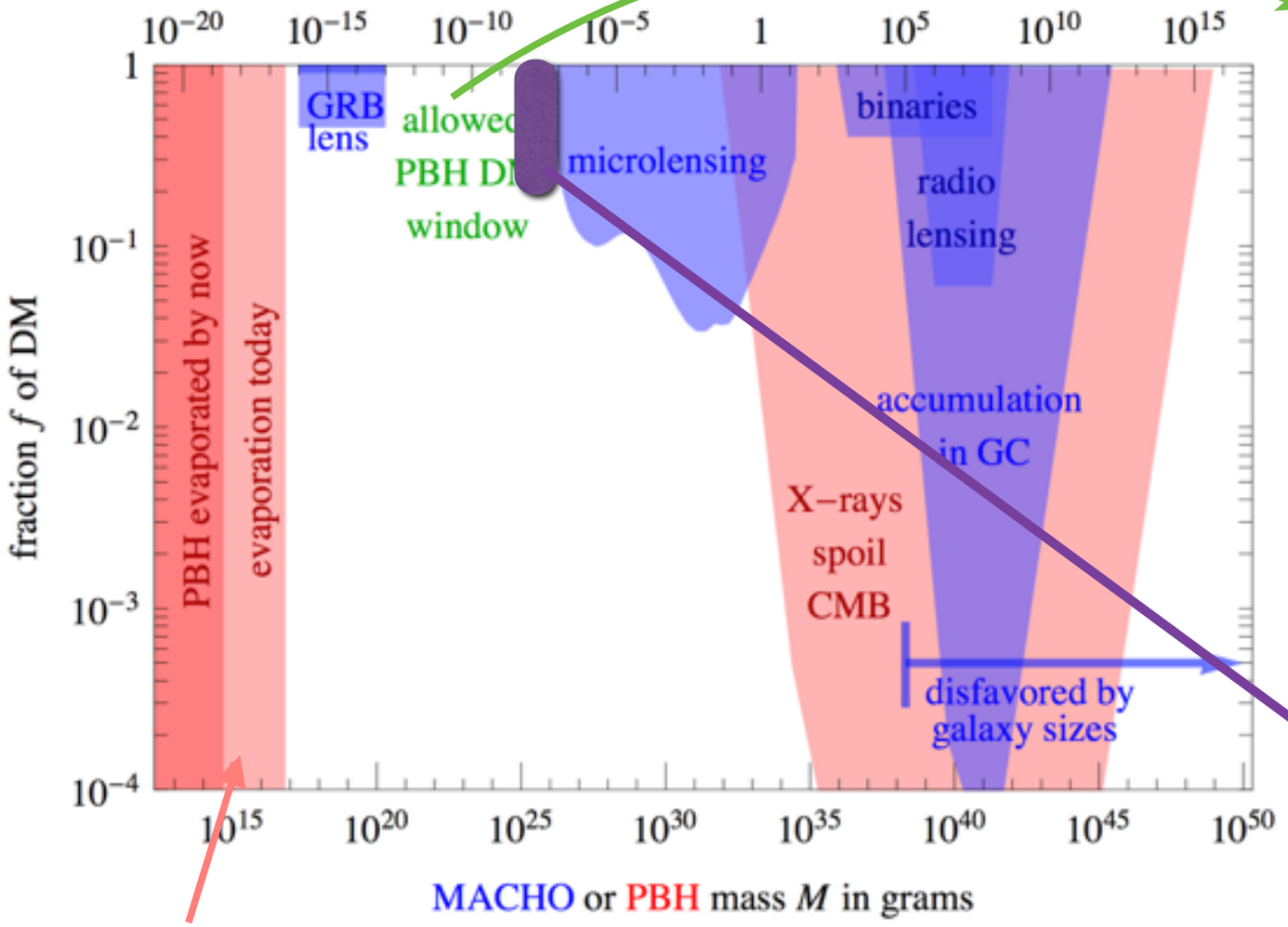

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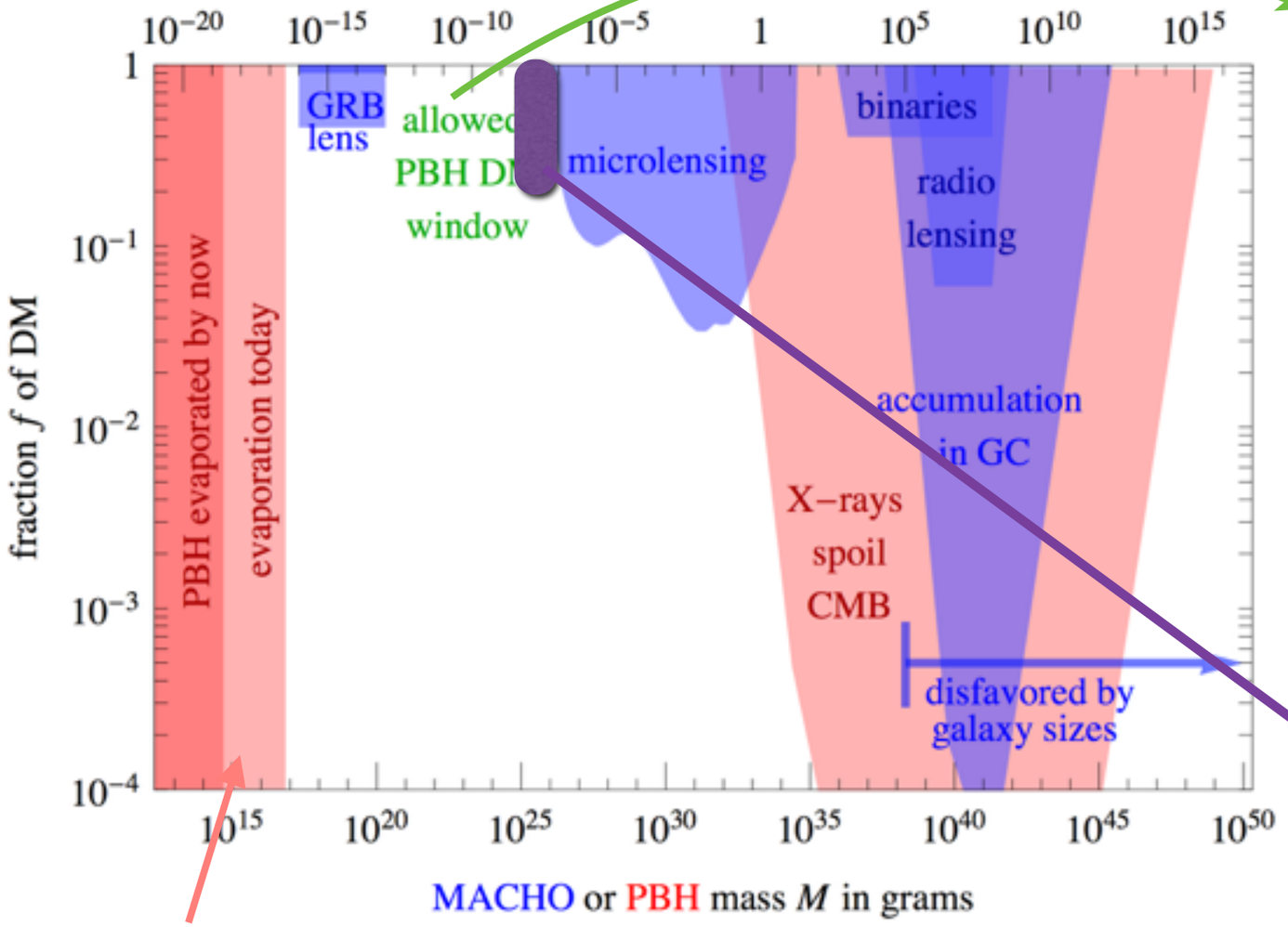

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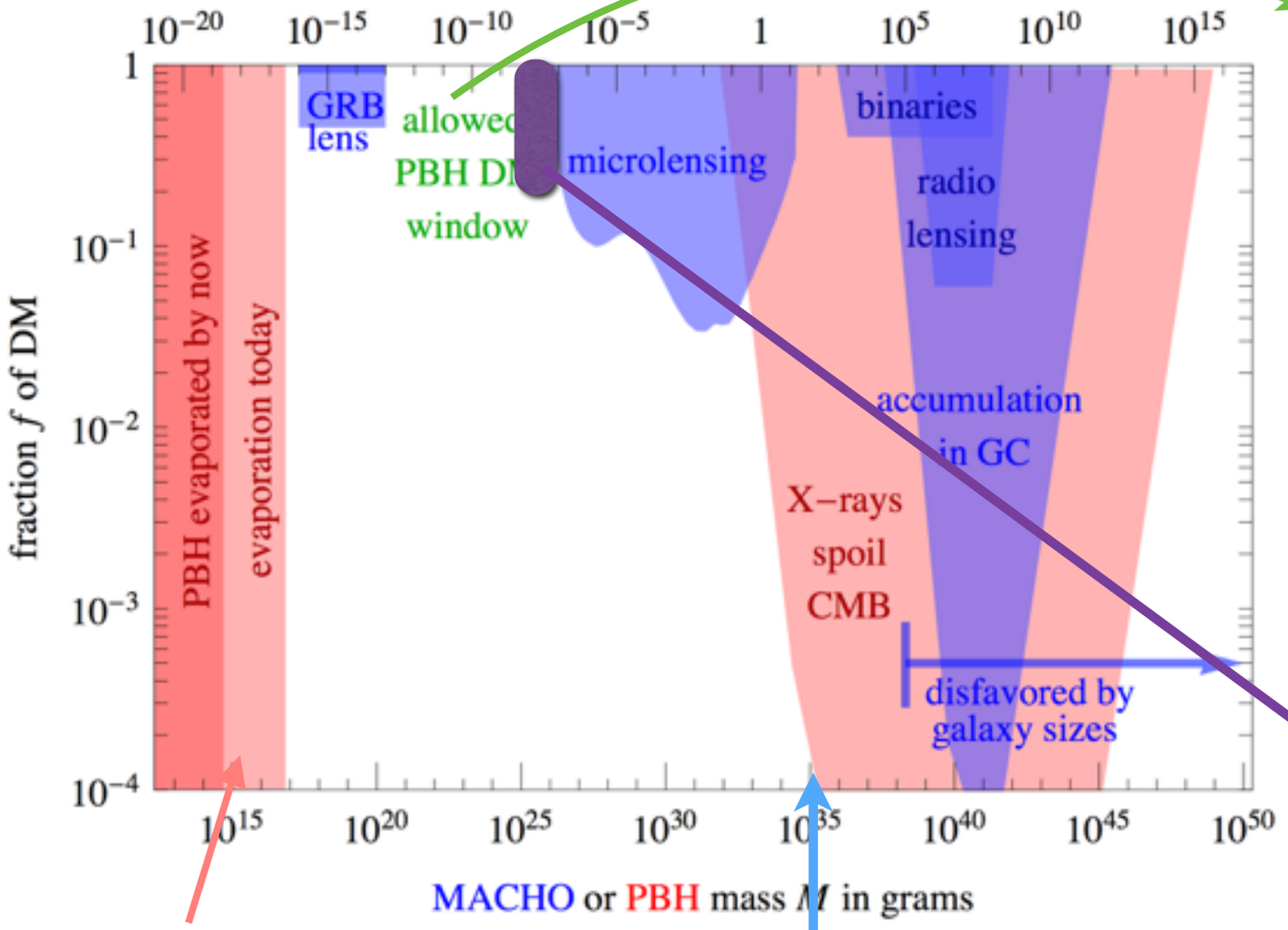

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IF you do not believe CMB constraints on PBH can LIGO have observed Dark Matter?

YES Bird+7 et al. 1603.00464

NO Sasaki et al. 1603.08338

Graham et al. 1505.04444

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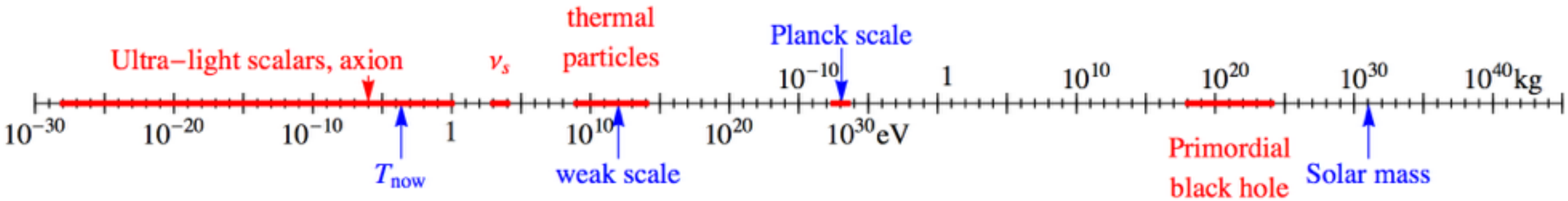
Outline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Primordial black hole
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Solar mass
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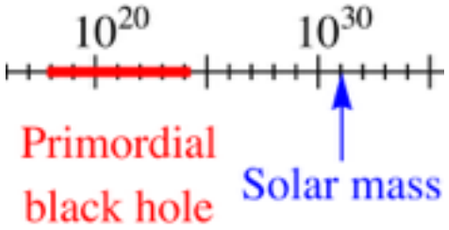
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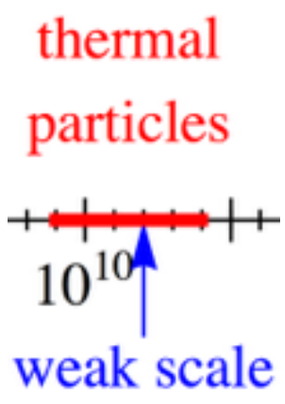
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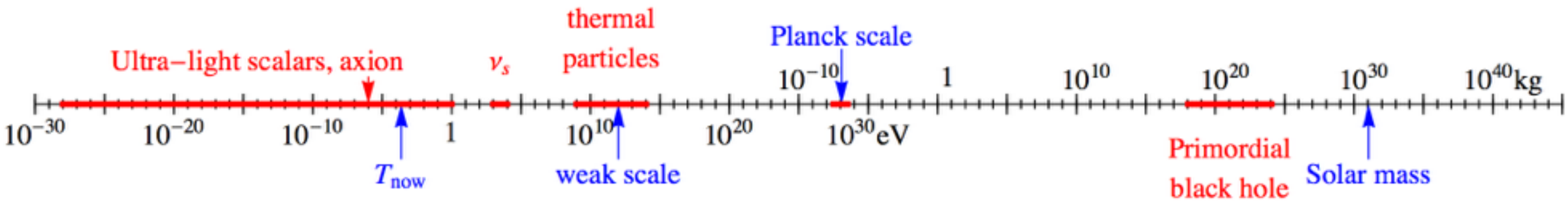
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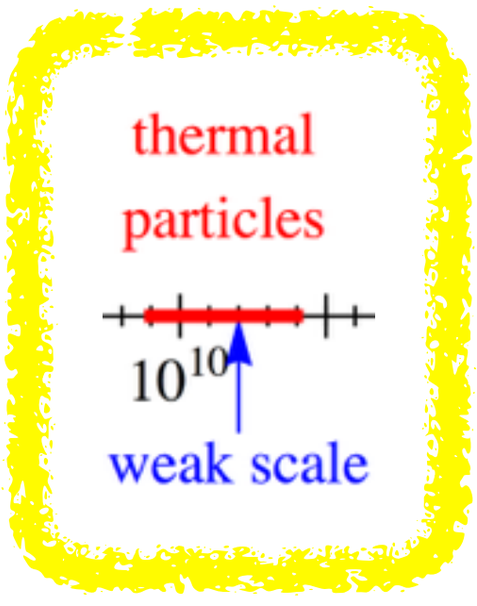
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Weakly Interacting Massive Particles

Weak = SM weak force, DM charged under $SU(2)_w \times U(1)_Y$

(or = whatever interaction with the SM, provided $\alpha = 10^{-3} - 10^{-1}$)

Particle properties: **massive** $U(1)_{\rm em}$**neutral** **stable** **not a baryon**

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Nothing said yet about **history**: how produced?
how abundant?
how cold?

The answer to these questions is the main classification criterium

Examples: thermal relic freeze-in asymmetric …

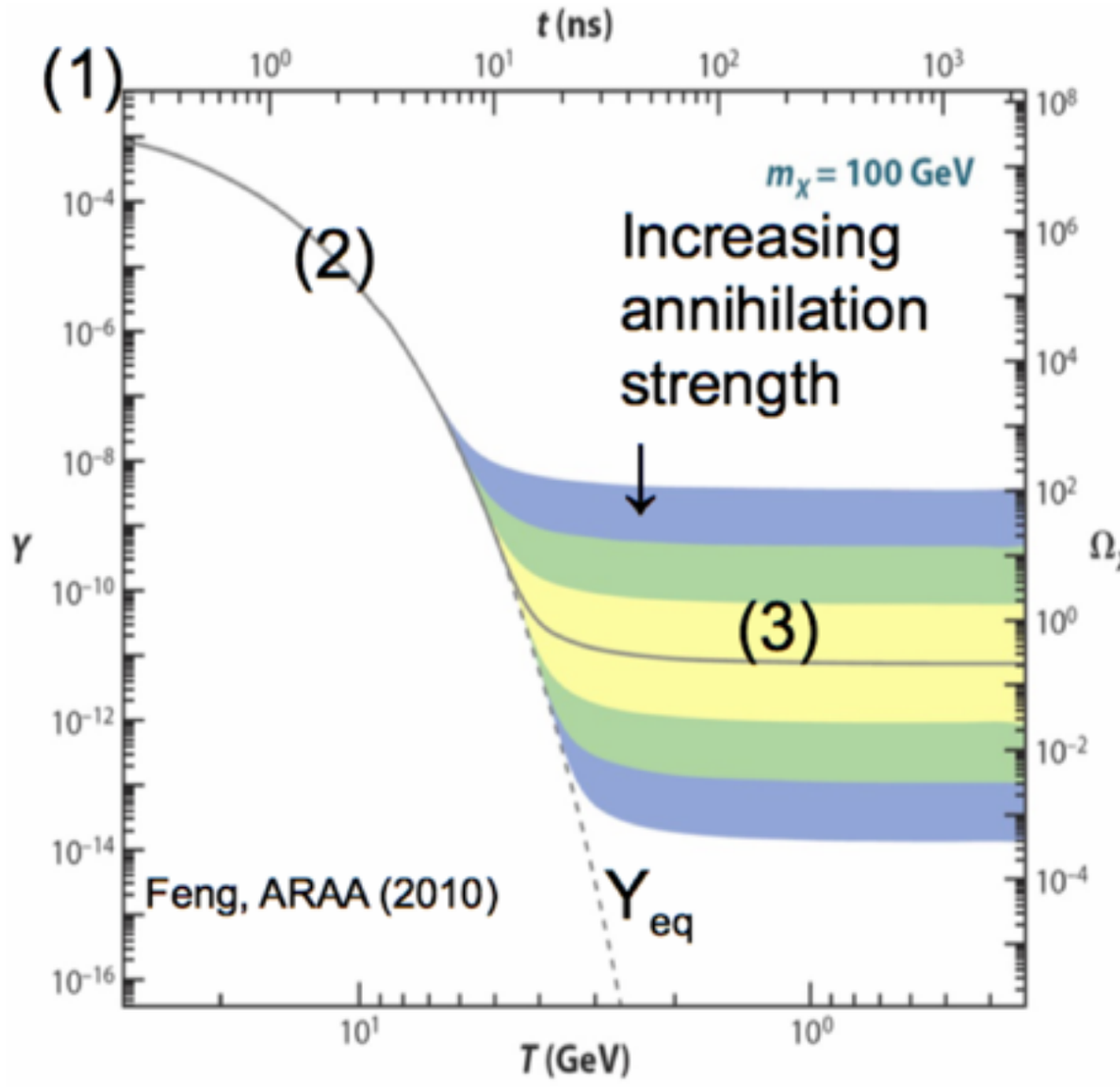
Most told WIMP history: thermal relics

(1) Thermal equilibrium DM DM ⟷ SM SM

(2) Universe cools DM DM → SM SM

(3) Universe expands DM DM SM SM

Abundance from annihilation cross section!



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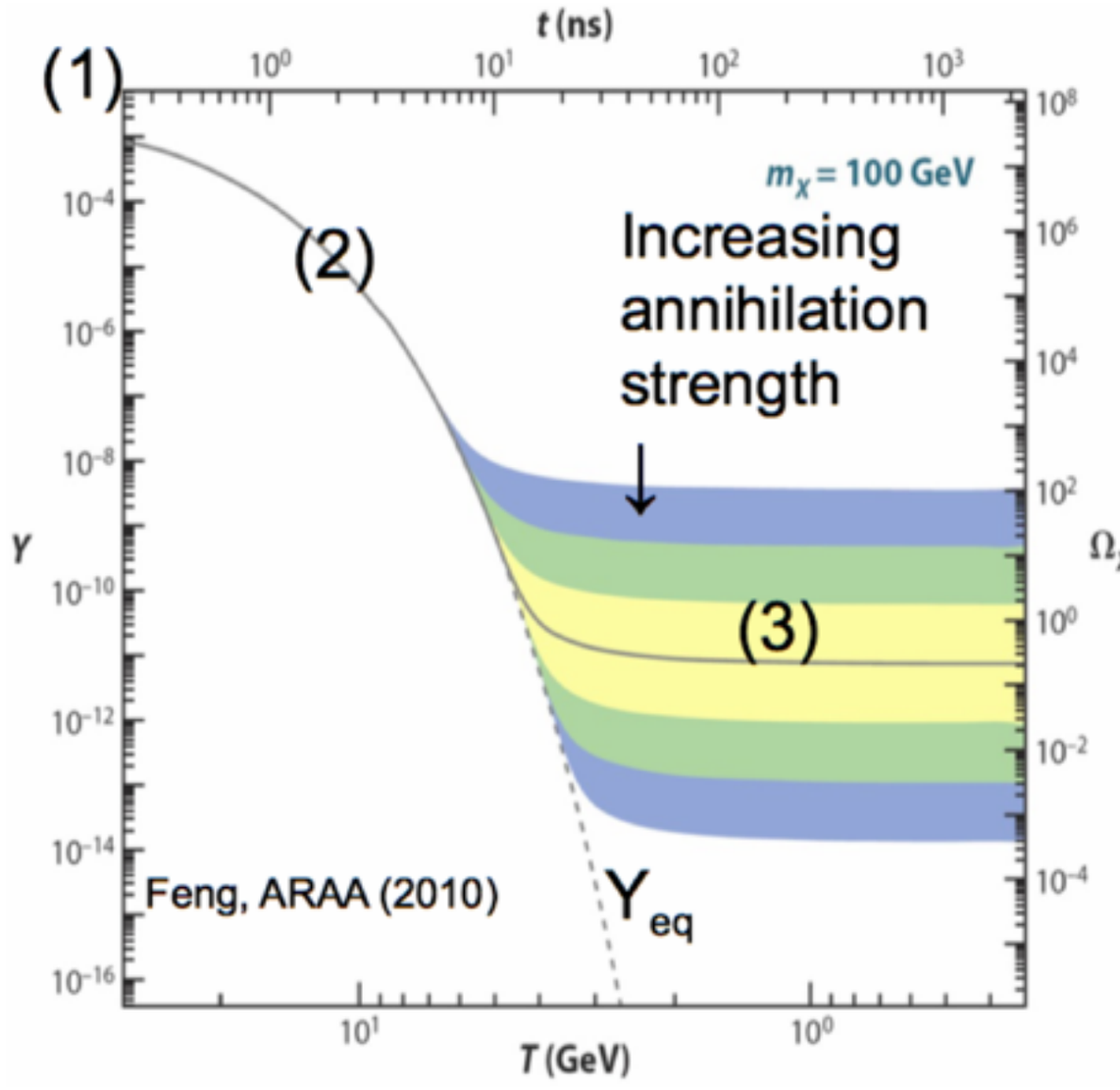

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"**WIMP miracle**"

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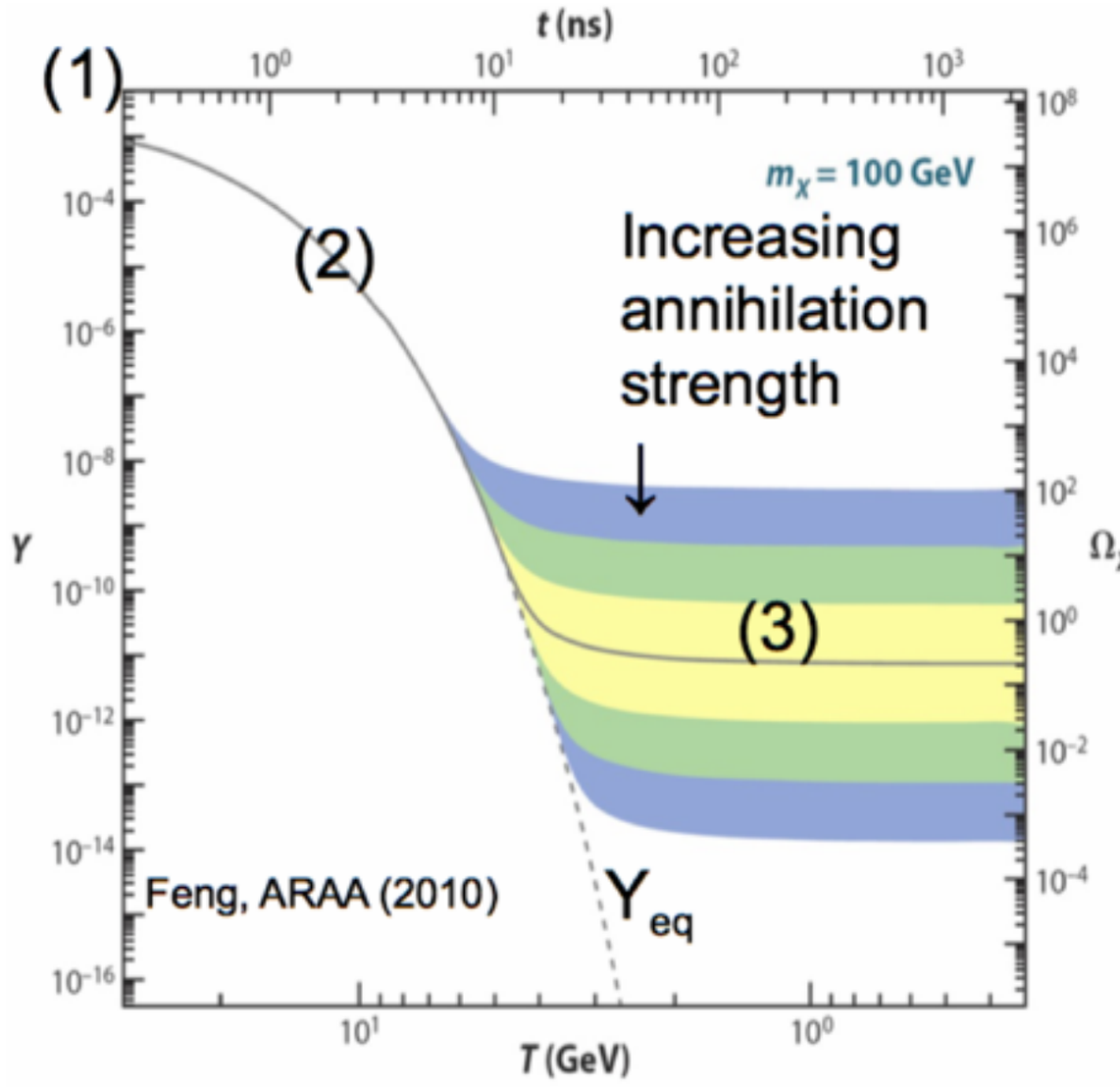

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WIMP miracle motivates BSM at the weak scale!

WIMPs and theories: one slide overview

BSM needed at the weak scale to solve other problems

and WIMPs came out for free!

SUSY neutralino!!

("the original" motivation of WIMPs)

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why not $M_{W,Z} \simeq M_{\rm BSM}$? (e.g. $M_{\rm BSM} = M_{\rm Planck}$)

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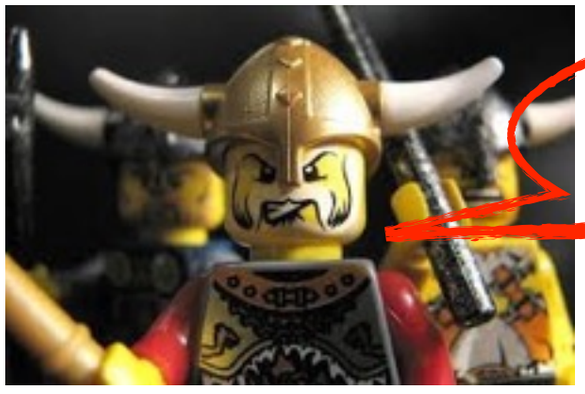

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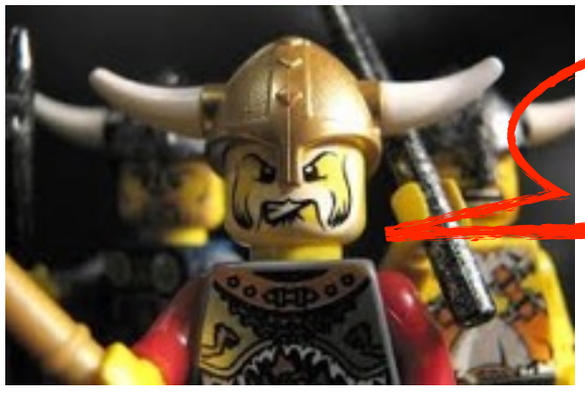

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Absence of BSM data encourages open mind, sure…but:

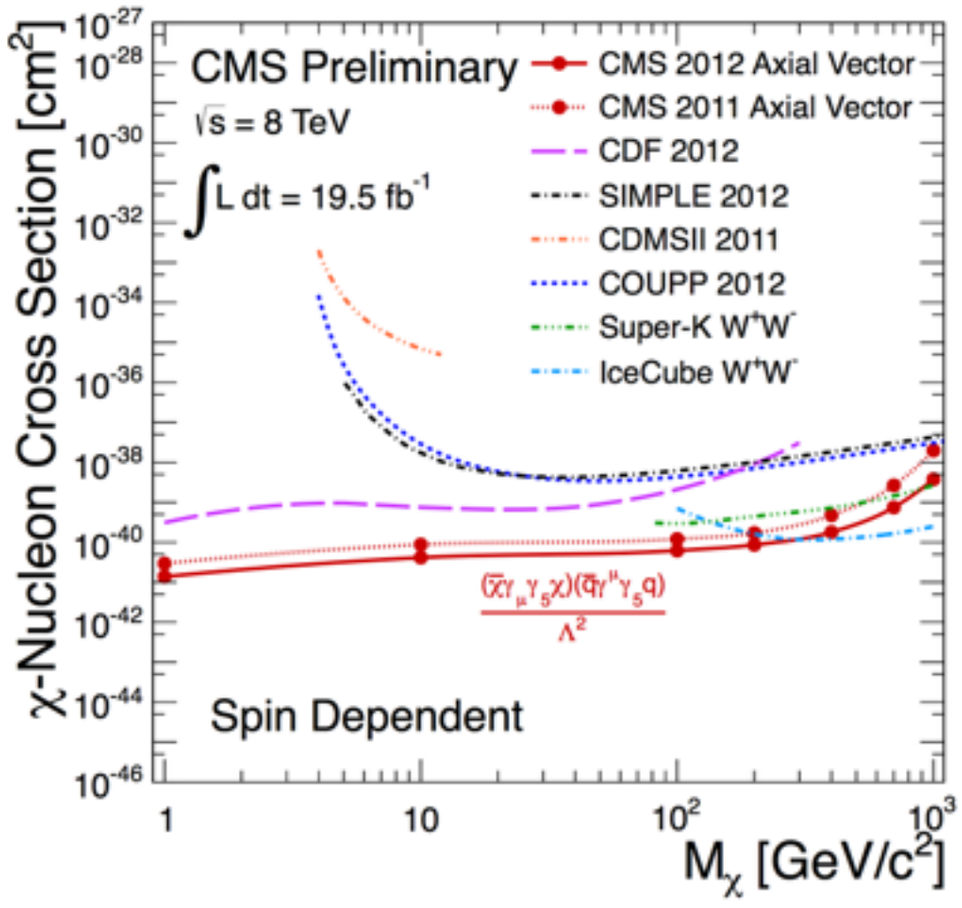
1. WIMPs are motivated *independently of naturalness*!
2. Also models of non-natural SUSY have WIMP candidates!

OK, how can we probe WIMPs?

More ambitious: can we probe thermal WIMP paradigm?

General strategy: effective field theories?

- ☺ Model-independent
- ☺ easy comparison collider - direct detection



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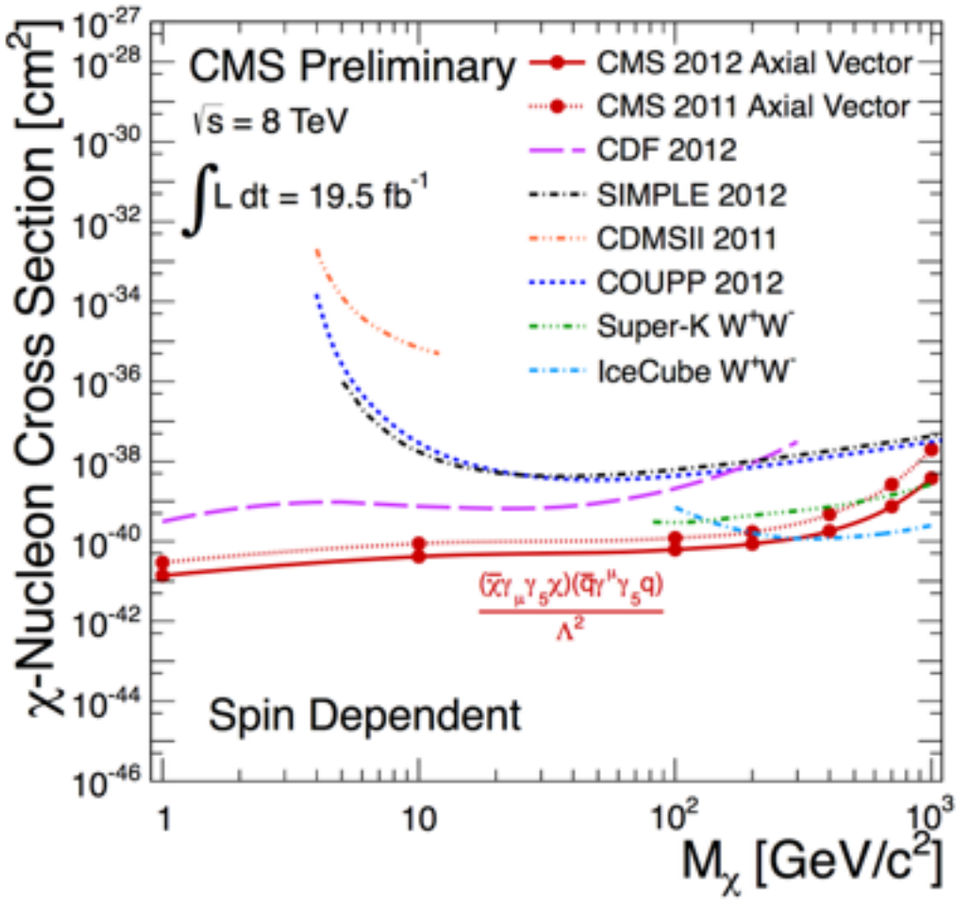
often momentum transfer $Q_{\rm tr}$ > suppression scale M_*

Busoni et al 1307.2253 and 1402.1275, Buchmuller et al 1308.6799, Abdallah et al 1409.2893, Racco Wulzer Zwirner 1502.04701,…



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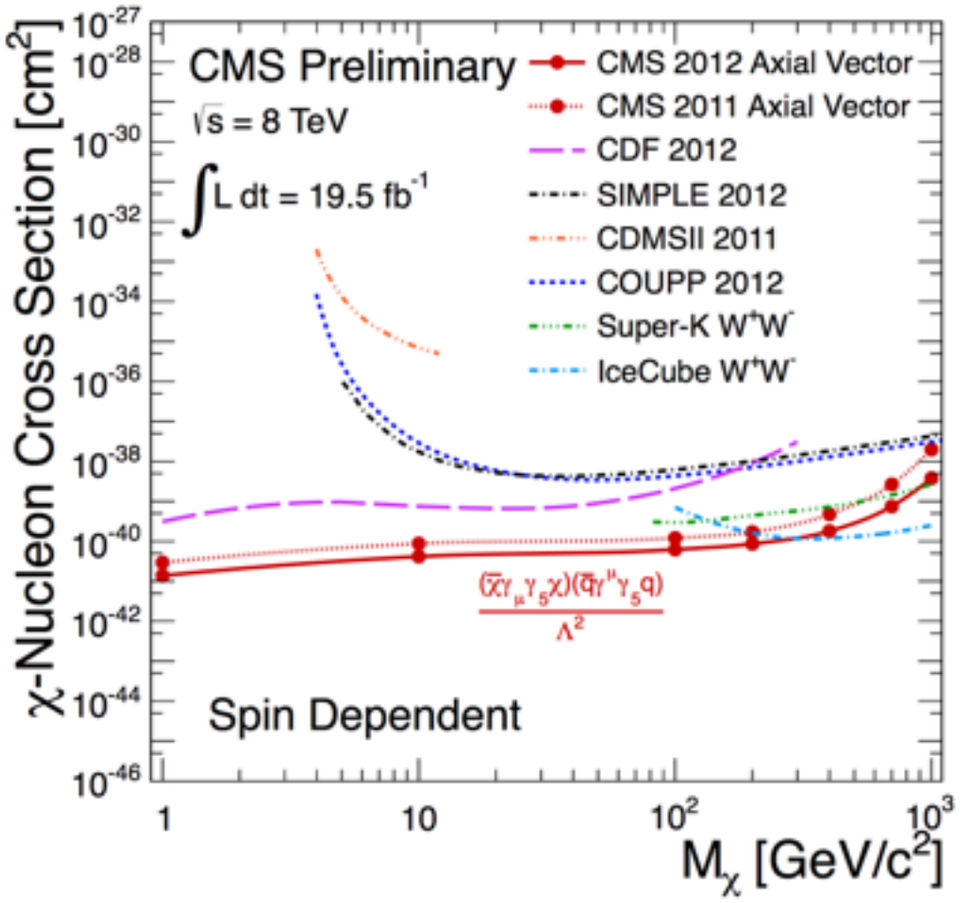

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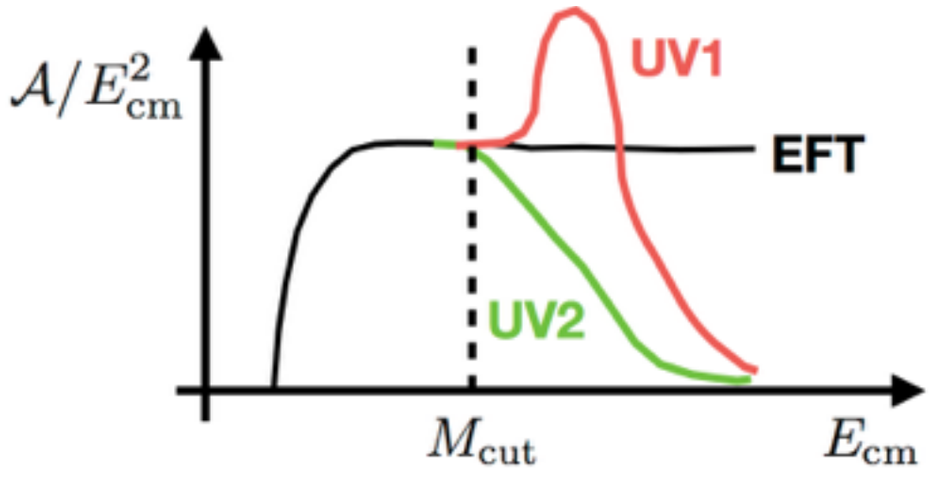

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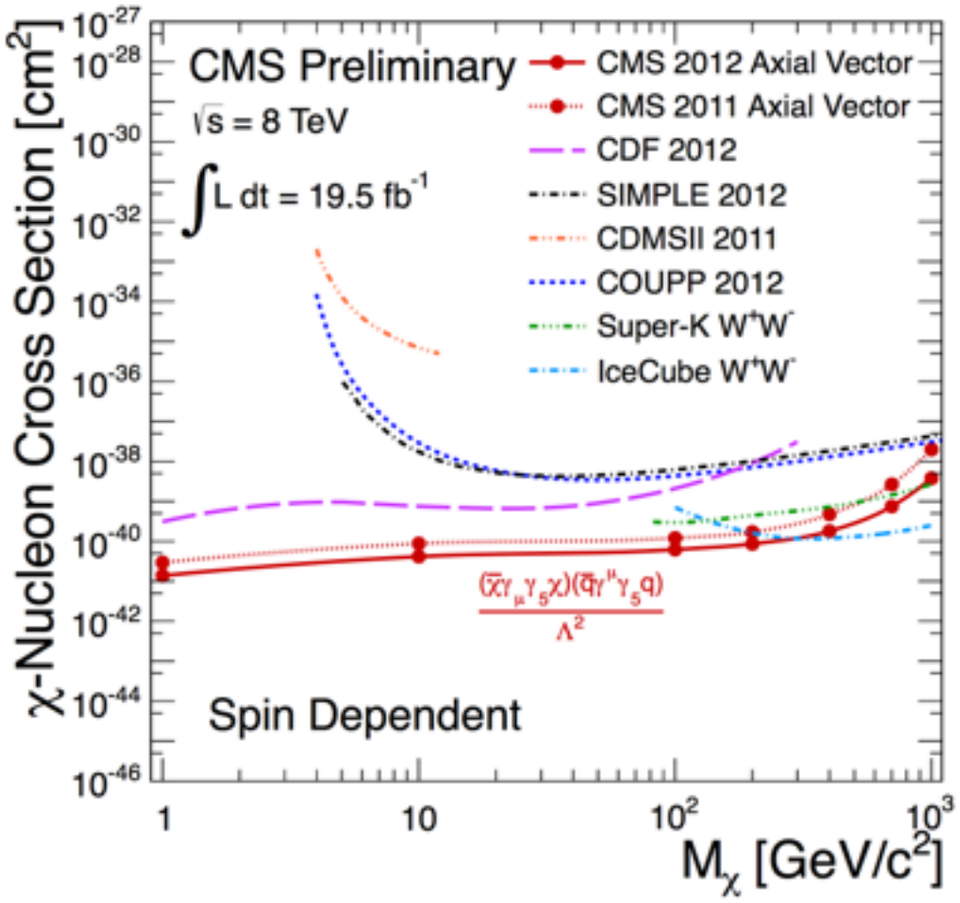

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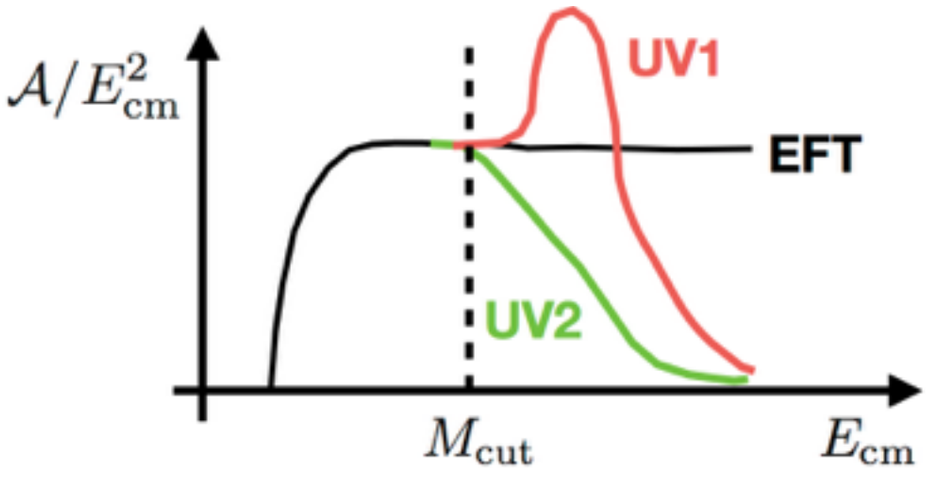

2. Go to benchmark/simplified models!

Quantum numbers		
$SU(2)_L$	$U(1)_Y$	Spin
3	0	F
5	0	F

An EW fermion multiplet

Aka the “prototype" of a WIMP

and a good excuse to tell you interesting phenomena & theory

Why an EW fermion multiplet? (besides WIMP prototype)

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Minimal Dark Matter
Cirelli Fornengo Strumia hep-ph/0512090

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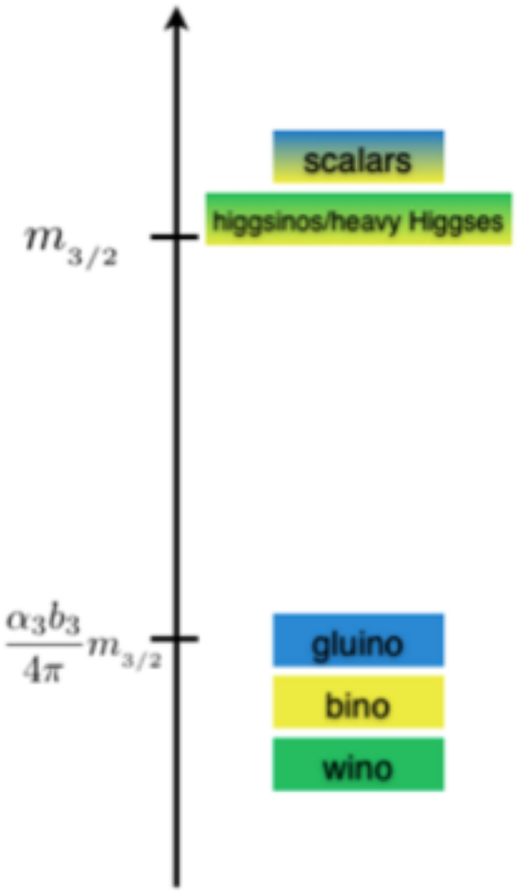

Supersymmetry with heavy scalars James Wells hep-ph/0306127

All good SUSY features (DM, unification of gauge couplings,…)

Hierarchy problem? Go anthropic

Wino LSP candidate for Dark Matter!

See also Arkani-Hamed Dimopoulos hep-th/0405159
Giudice Romanino hep-ph/0406088
...
D'Eramo Hall Pappadopulo 1409.5123

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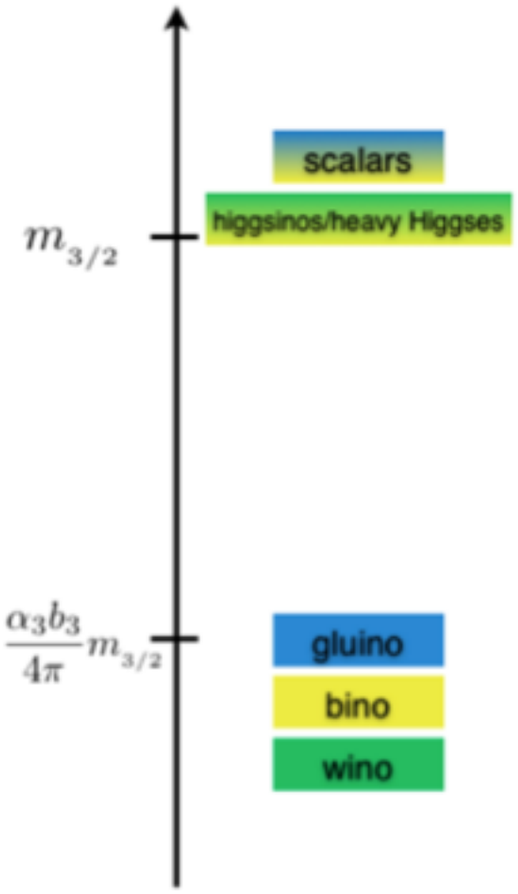


Supersymmetry with heavy scalars James Wells hep-ph/0306127

All good SUSY features (DM, unification of gauge couplings,…)

Hierarchy problem? Go anthropic

Wino LSP candidate for Dark Matter!

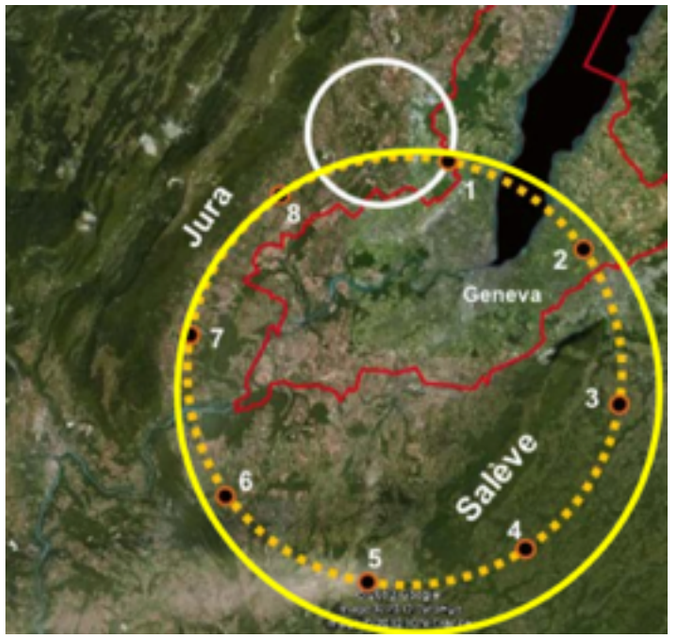
See also Arkani-Hamed Dimopoulos hep-th/0405159
Giudice Romanino hep-ph/0406088
…
D'Eramo Hall Pappadopulo 1409.5123

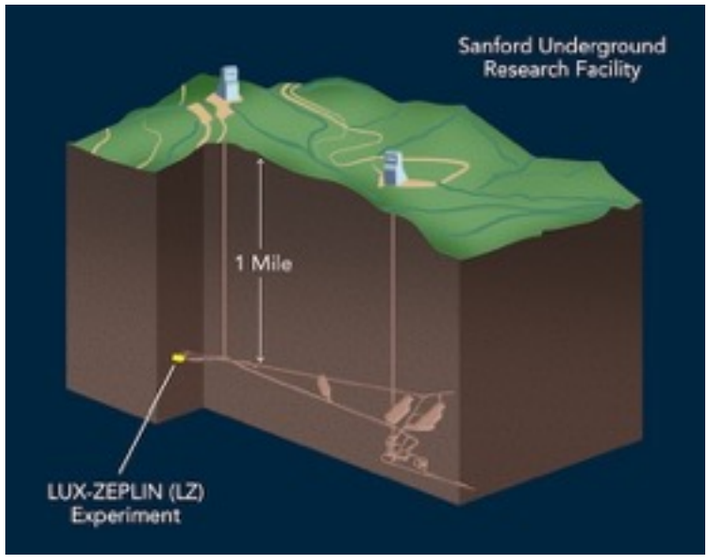
Phenomenology

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \tfrac{1}{2}\,\bar{\chi}\big(i\hat{D} - M_\chi\big)\chi$$

M_χ is **the only free parameter**, fixed to **multi-TeV** if we impose thermal relic
(we'll keep an open mind on DM mass)

Phenomenology





EW multiples at colliders: disappearing tracks

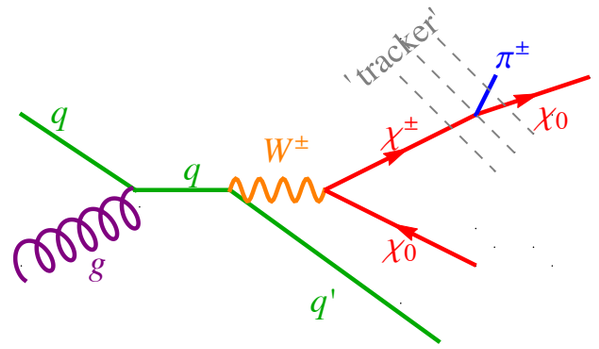
Feng et al 1999,…

$M_{\chi^{\pm},\pm\pm} - M_{\chi 0} \gtrsim m_\pi$ ⟹ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

almost all $\chi^{\pm}$ & $\chi^{\pm\pm}$ decay to $\chi 0$ + soft pions before reaching the detector

Both ATLAS and CMS performed this analysis

current strongest limits on EWmultiplets $M_{\chi 0} \gtrsim 270\ \mathrm{GeV}$



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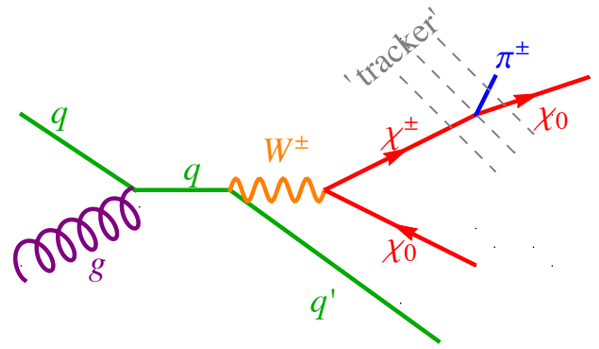
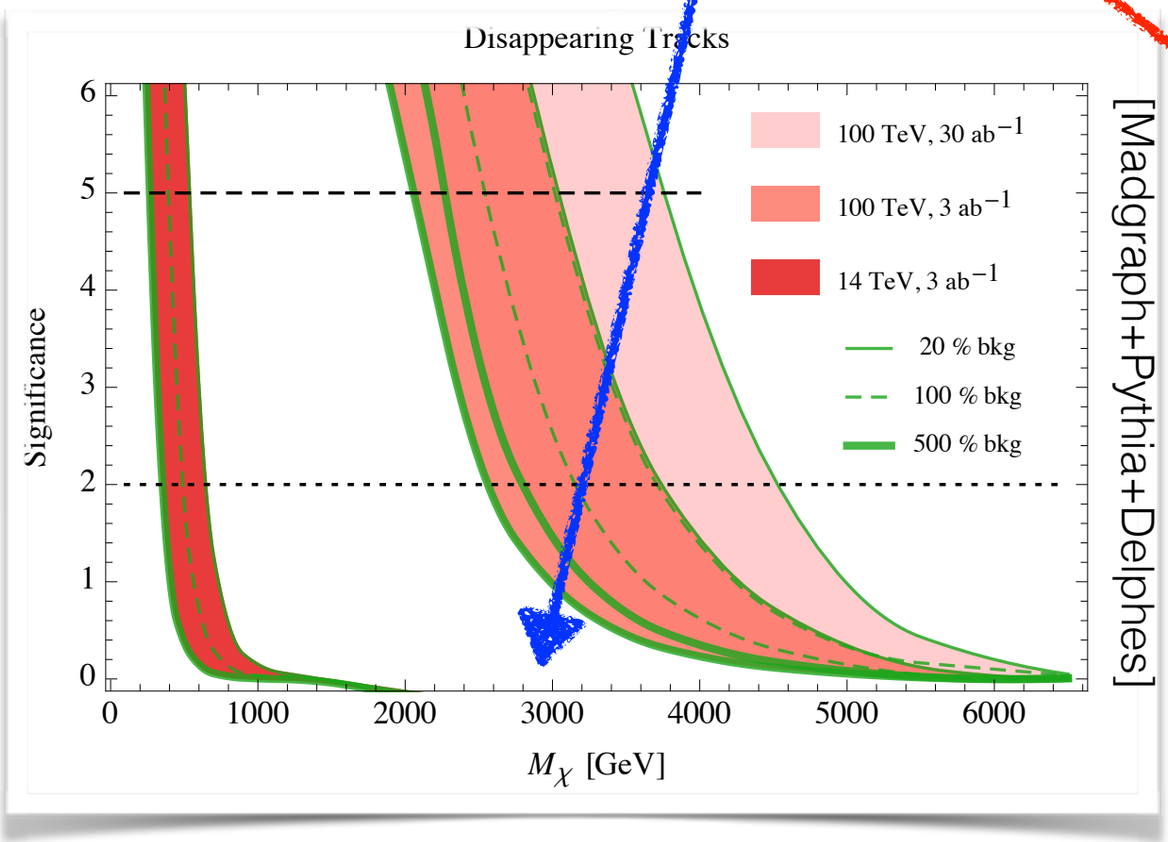
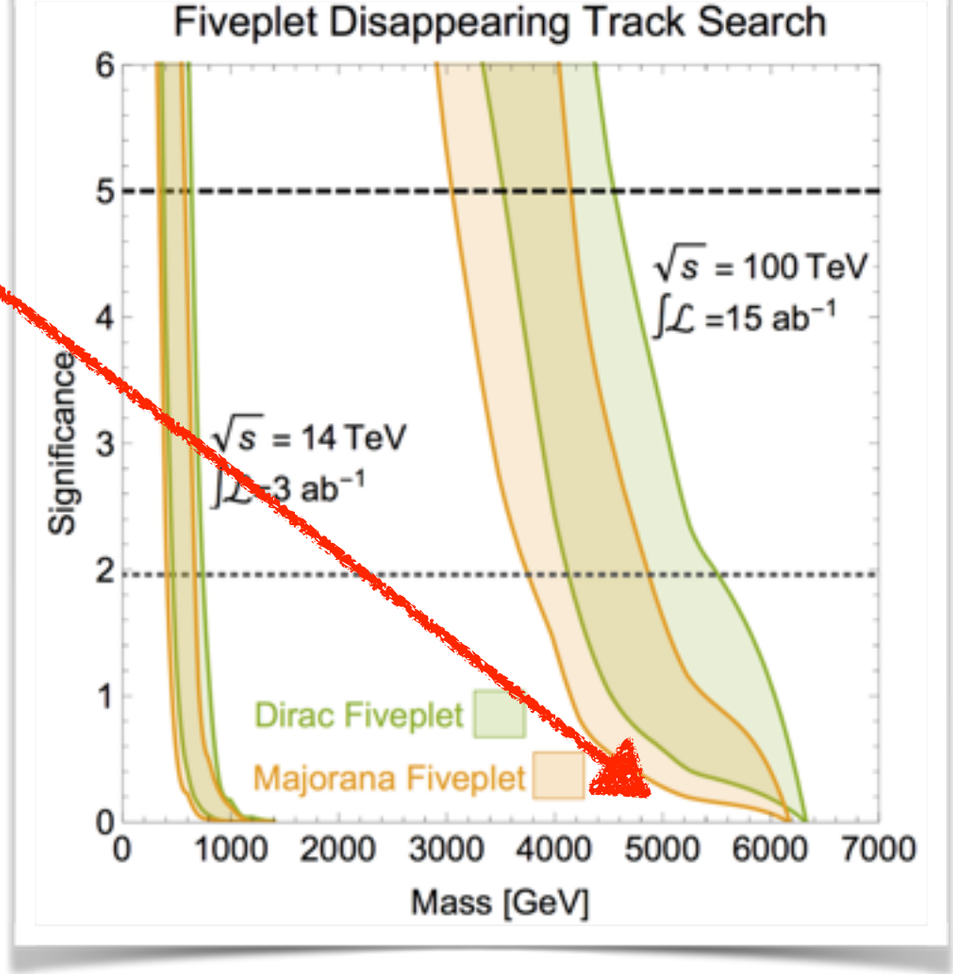
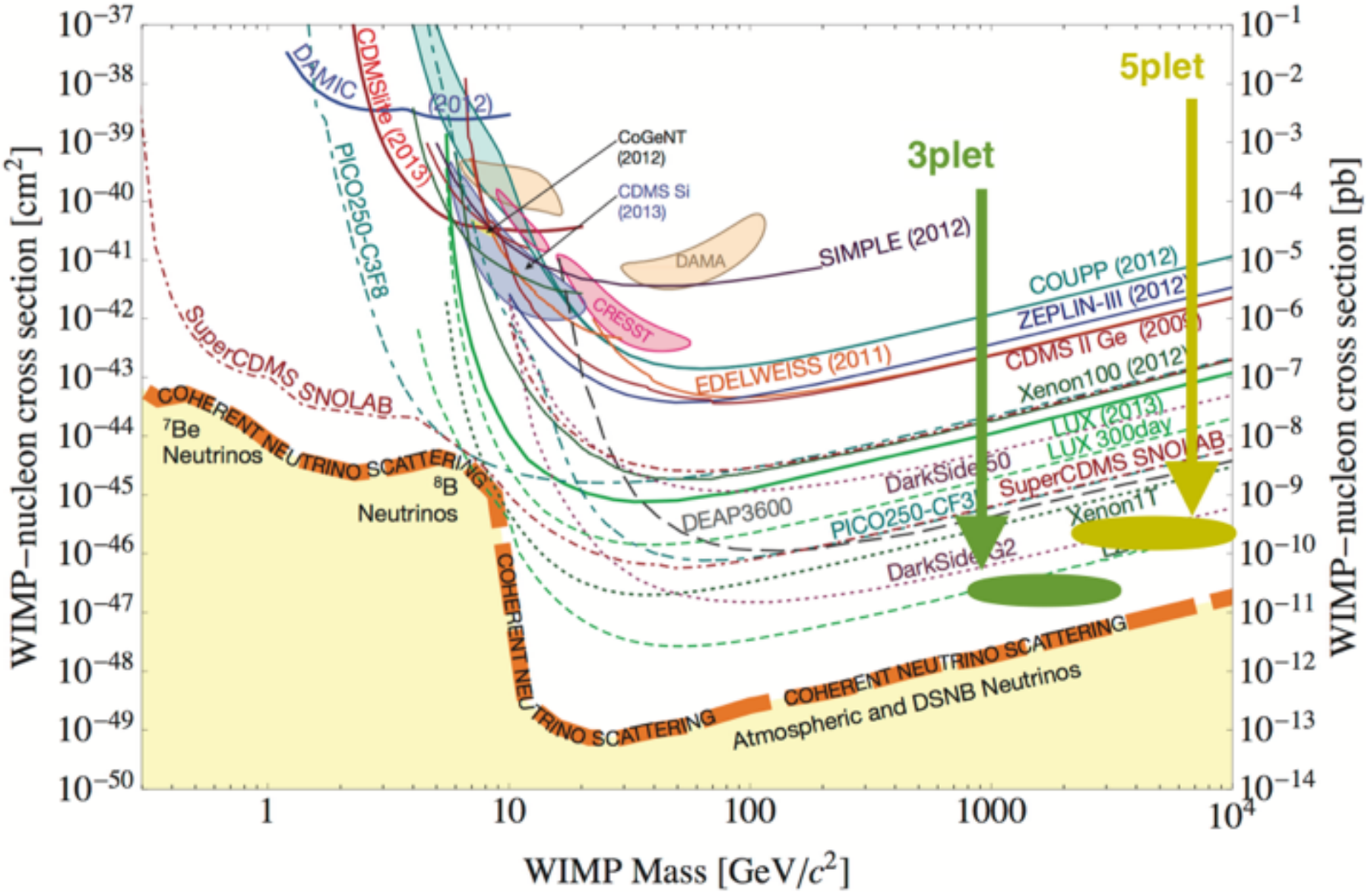


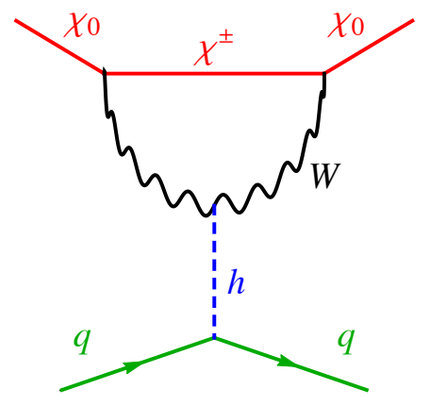
FCC-hh will likely probe the 3plet, not the 5plet

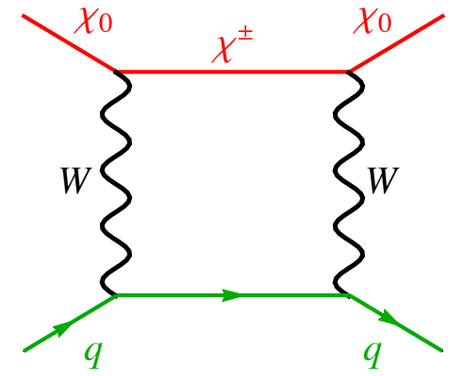




Direct detection







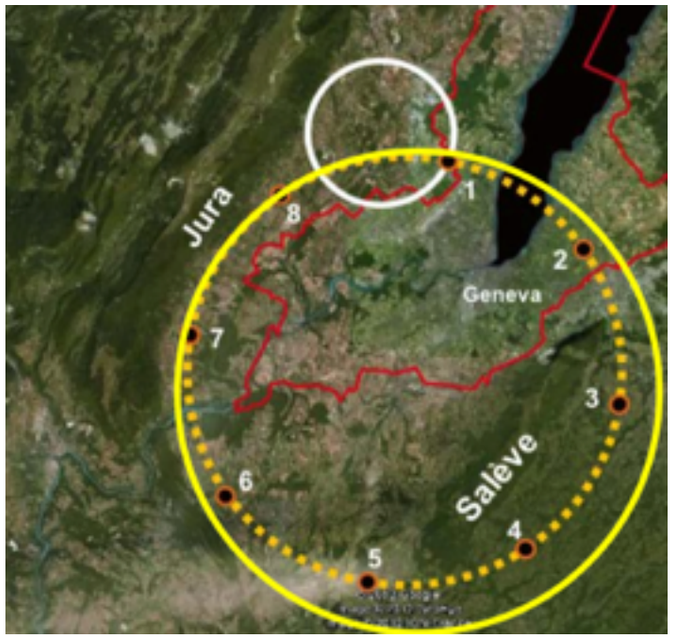
Hisano et al. 1504.00915:

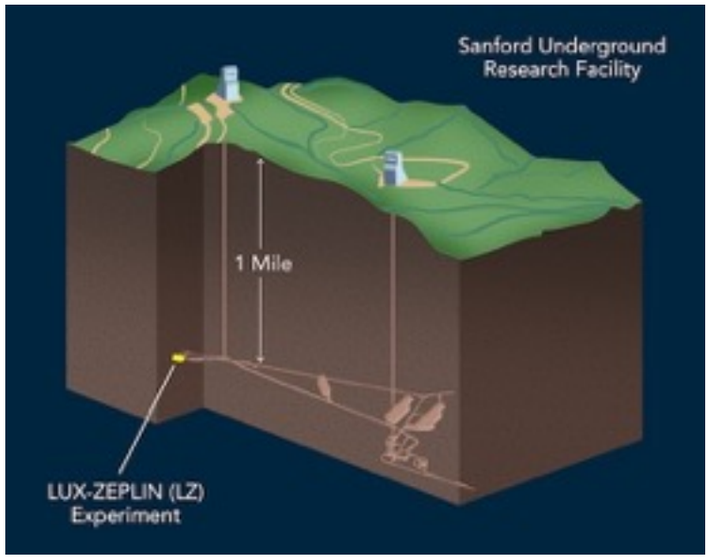
$$\sigma_{\rm SI}^{\rm 5plet} = 1.9 \times 10^{-46}\ {\rm cm}^2$$

$$\sigma_{\rm SI}^{\rm 3plet} = 2.3 \times 10^{-47}\ {\rm cm}^2$$

Full NLO in α_S, O(50%) uncertainties

Phenomenology





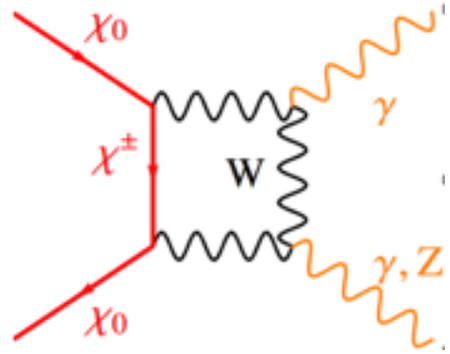
5plet: little hopes to reach $M_{\rm thermal}$ before DARWIN (= Next Generation in DD, 2025?)

3plet: little hopes before DARWIN or 100 TeV collider (2040?)

Phenomenology

Gamma-ray lines

Wino&lines since Cohen et al 1307.4082, Fan Reece 1307.4400



$$E_\gamma = M_{\rm DM}$$

FERMI

up to a few x 100 GeV

space-based

covers all sky

HESS, CTA

up to a few x 10 TeV,

ground based (Namibia, Chile + Canaries)

need to choose target (Galactic Center? dwarf galaxies?)

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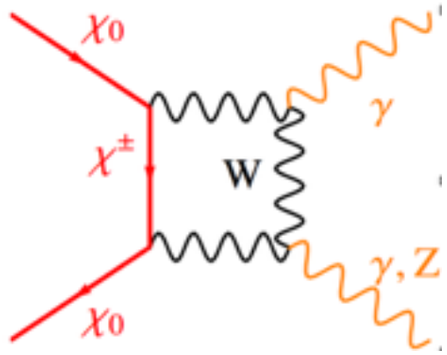

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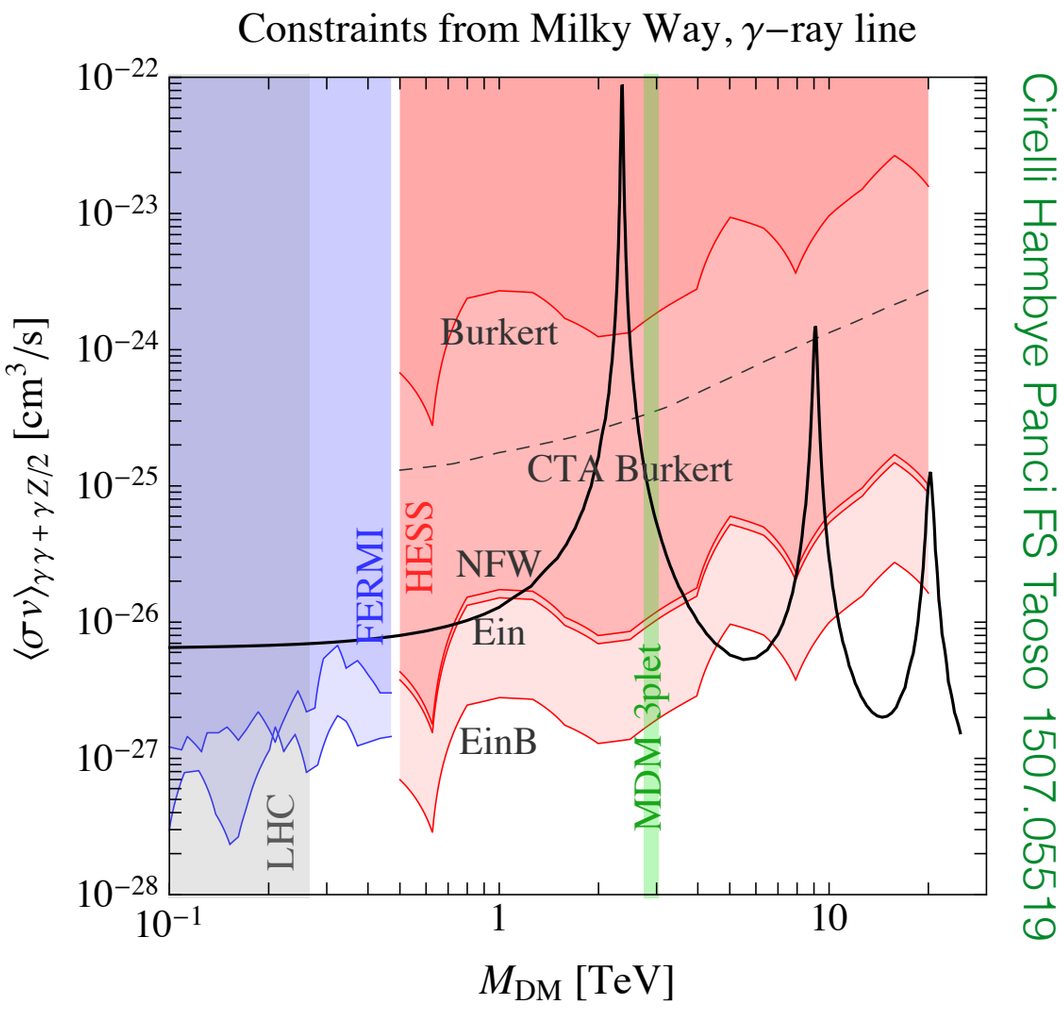

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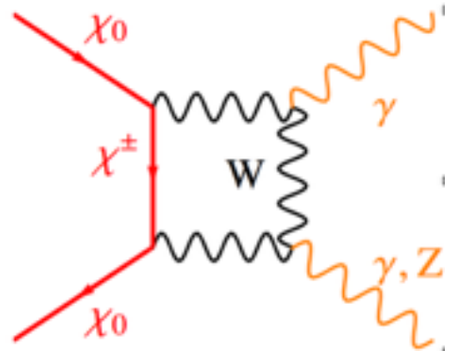

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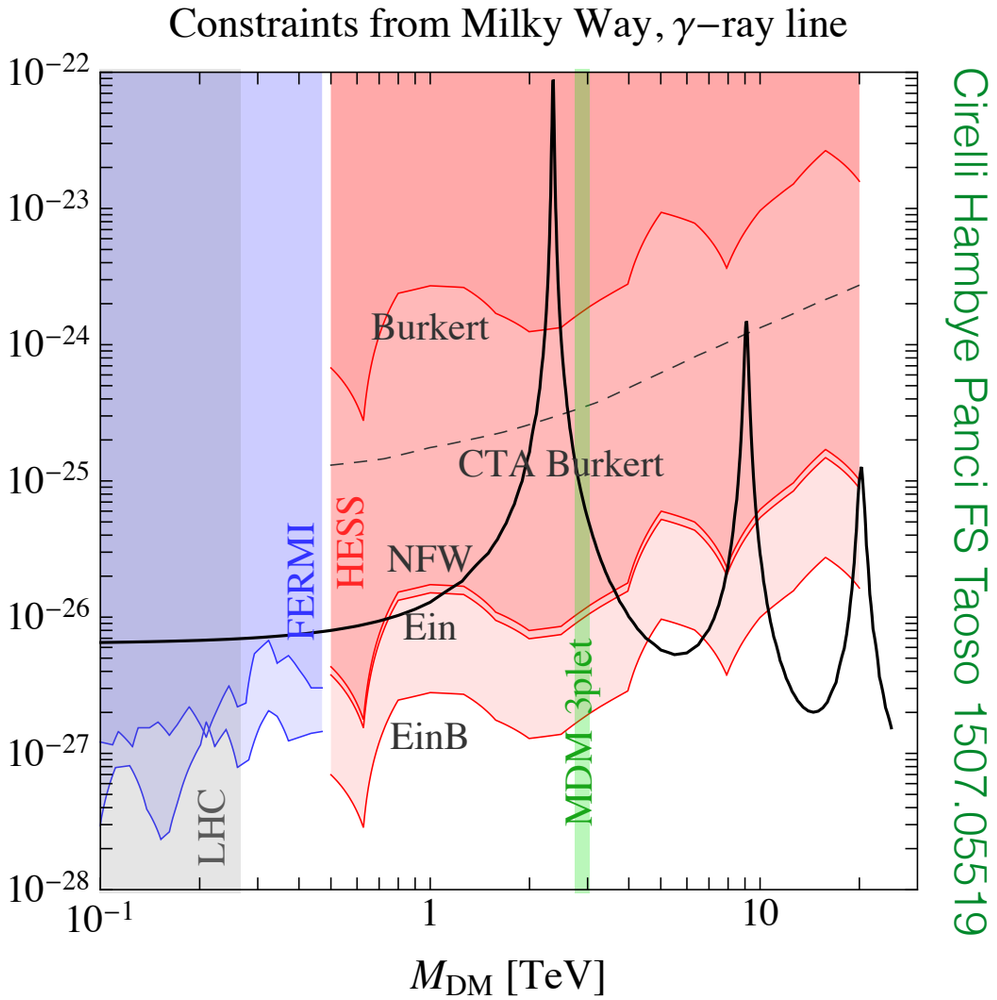
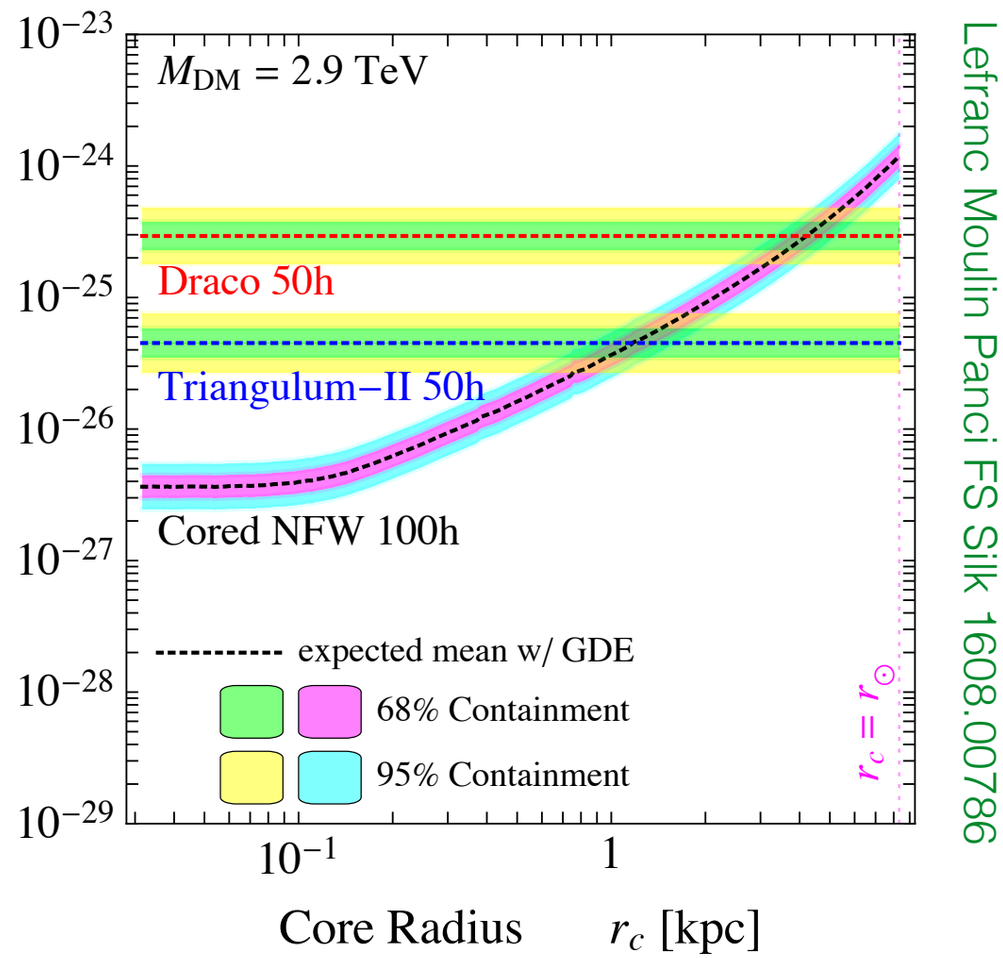
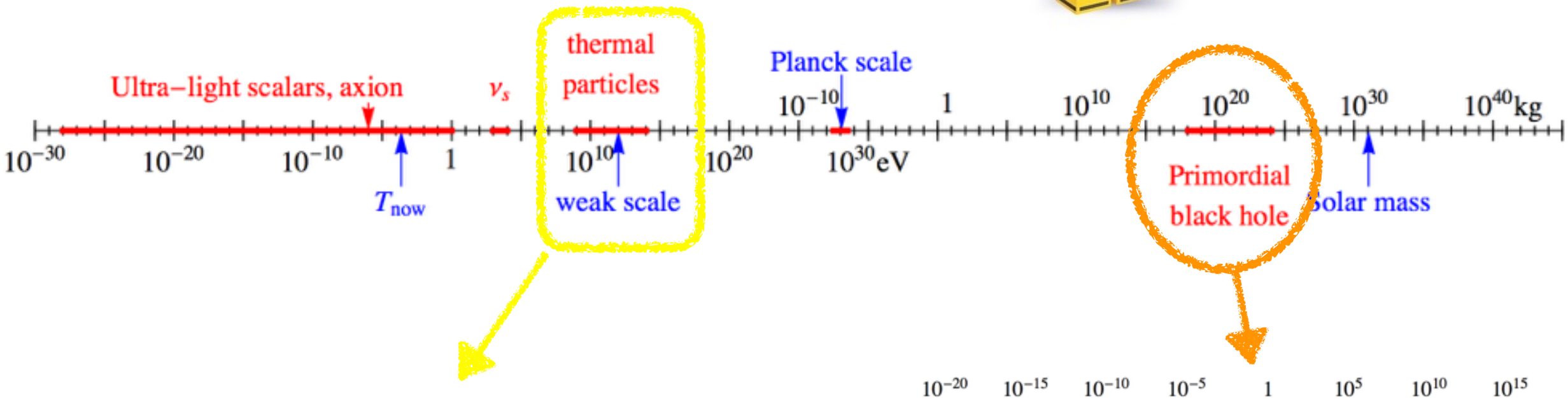
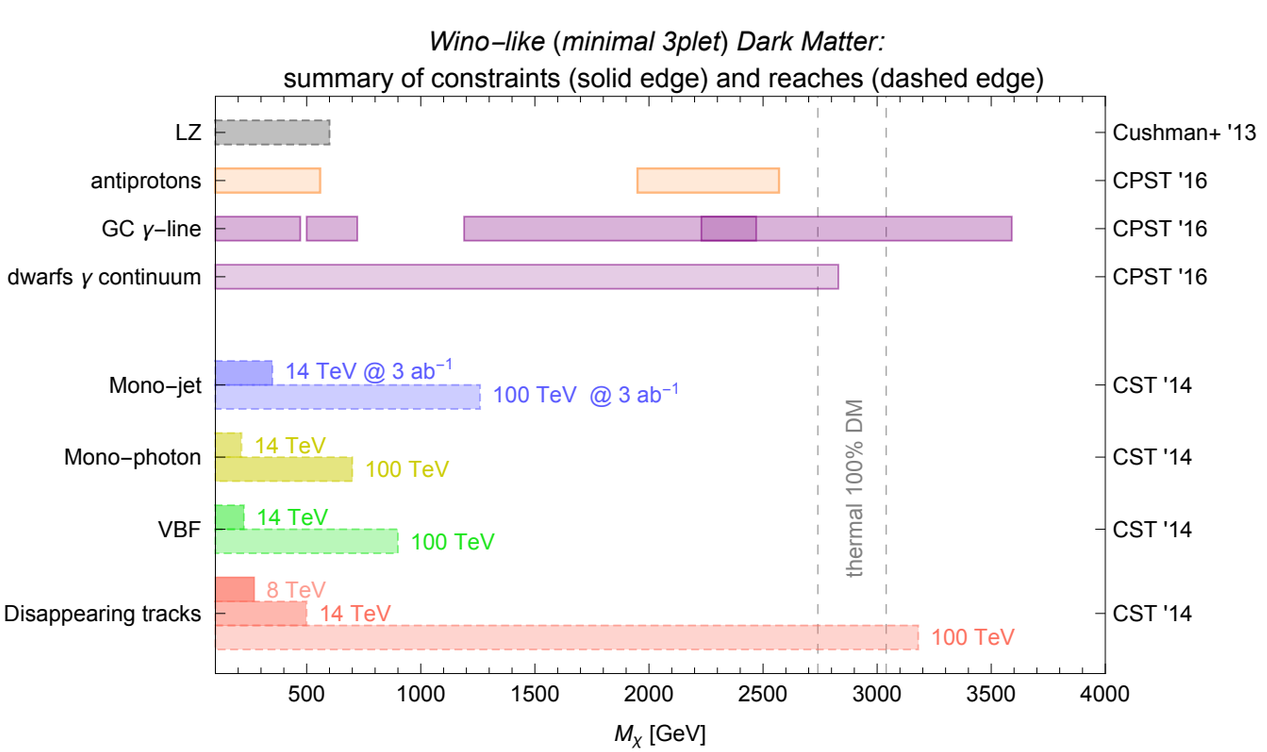


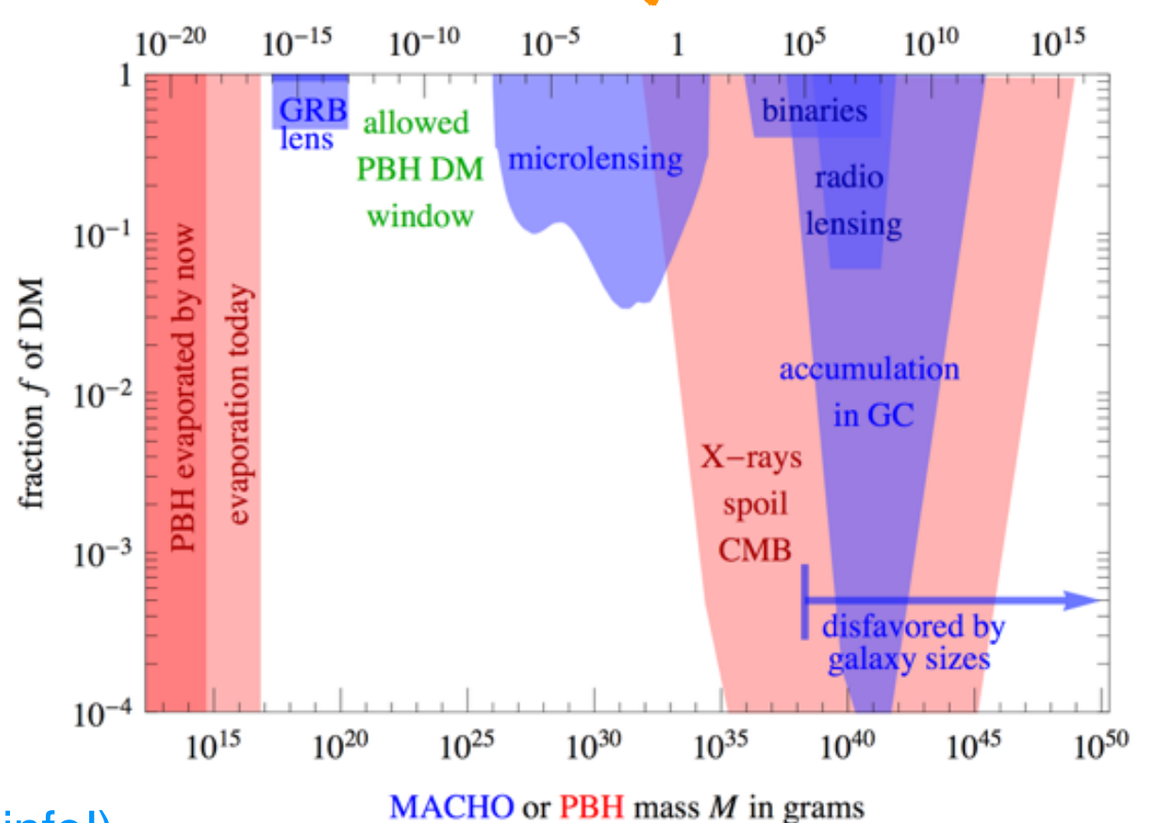


Astro input necessary, of interest also for future colliders studies!

Conclusion: keep exploring!







(WARNING: benchmarks are good, but keep giving more info!)

Back-up slides

Filippo Sala LPTHE Paris

LHC days in Split 2016

Why an EW fermion multiplet?

Minimal Dark Matter Cirelli Fornengo Strumia hep-ph/0512090

Philosophy: focus on DM, and try to preserve SM successes (flavour & CP,…)

+ DM stability, adding the least possible ingredients to the theory

Approach: add to the SM an extra particle

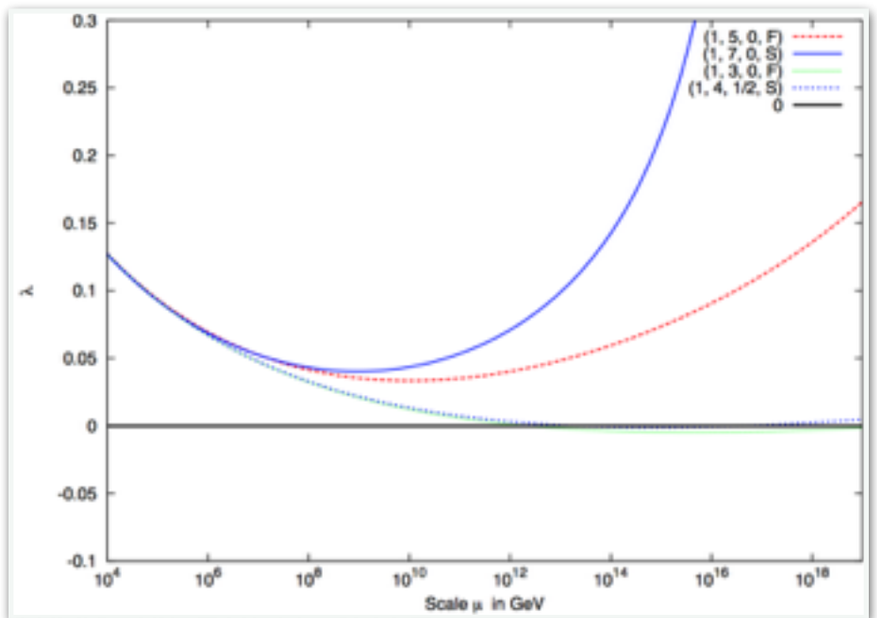
and determine its “good" quantum numbers

“good" = i) stable ii) lightest component neutral iii) allowed

Result: 5plet, 3plet [but add symmetry, like B-L or L or subgroup…]

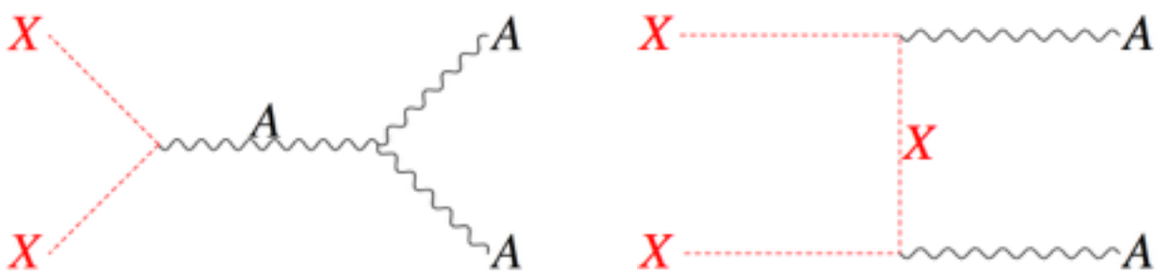
Other “minimal" virtues

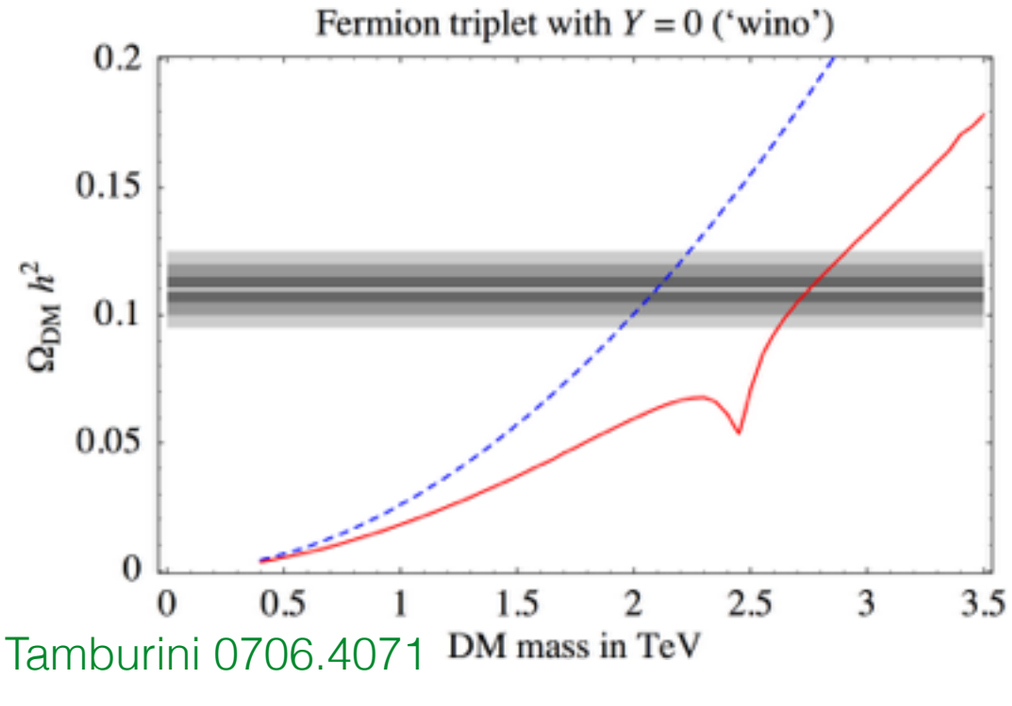
- ☺ Makes SM vacuum stable
  Chao et al. 1210.0491
- ☺ Helps with gauge coupling unification
  [See e.g. “split SUSY without SUSY” Frigerio Hambye 0912.1545]
- ☺ …



Thermal relic WIMPs

Prototypical WIMP candidate $\longrightarrow$ $M_{\rm DM} \sim {\rm TeV}$



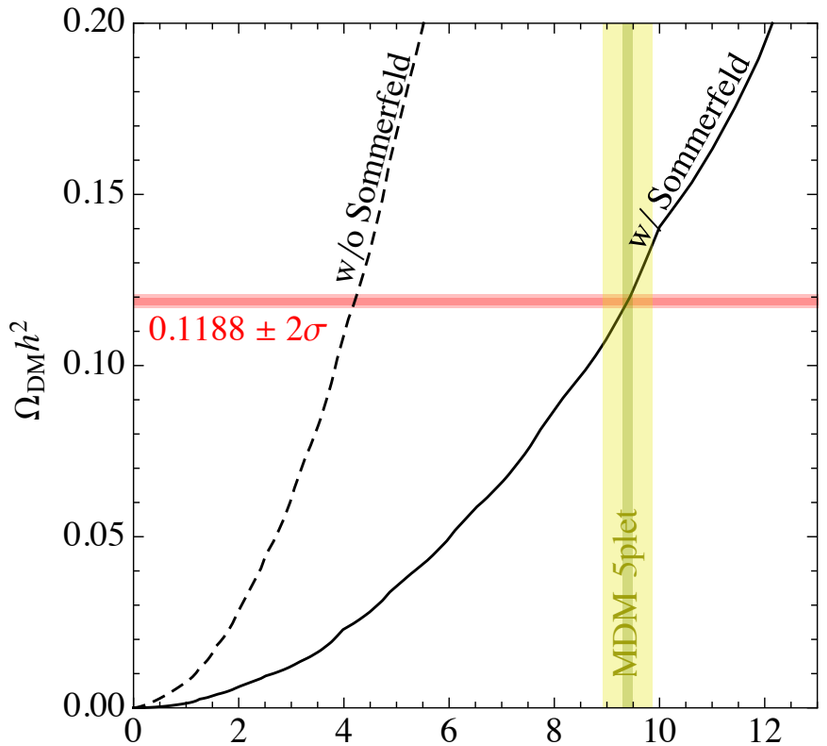


Cirelli Strumia Tamburini 0706.4071

Important to include:

- ☑ Coannihilations
- ☑ Sommerfeld enhancement
- ☐ Bound states formation (& maybe NLO)

$$M^{\rm 3plet}_{\rm thermal} \simeq 3\ {\rm TeV} \qquad M^{\rm 5plet}_{\rm thermal} \simeq 9.5\ {\rm TeV}$$



Cirelli et al. 1507.05519

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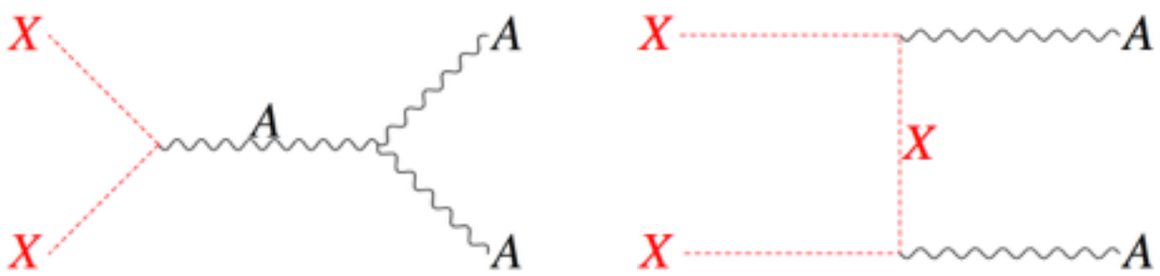

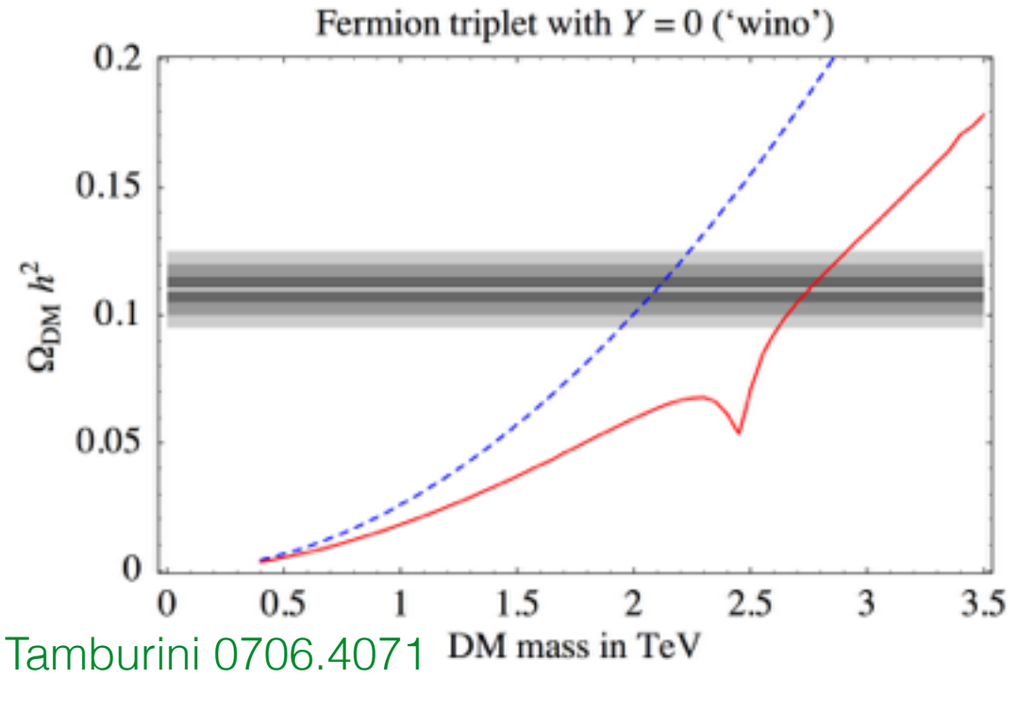

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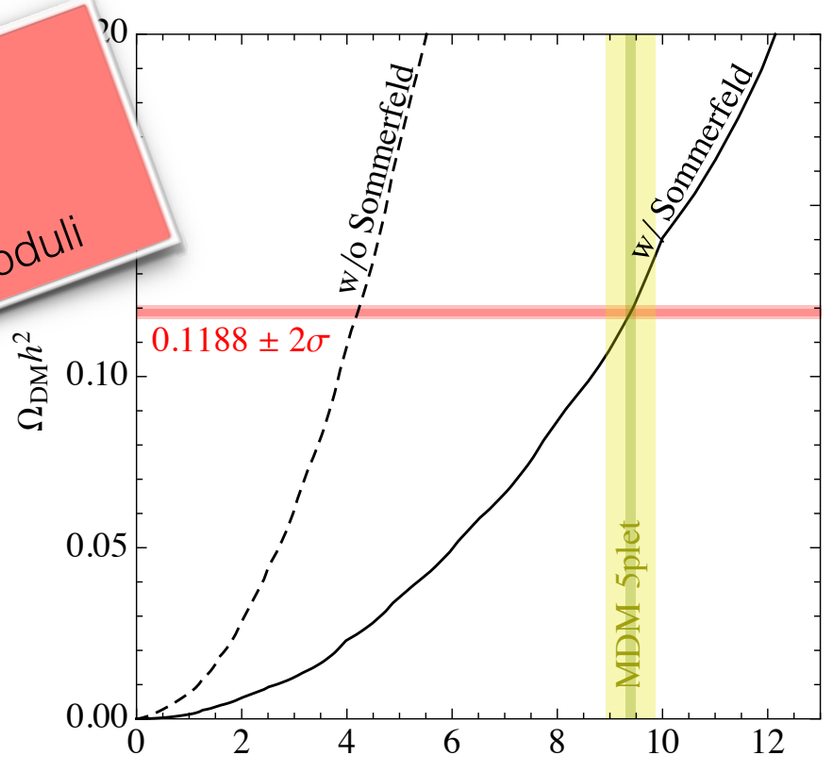
Important to include:

- ☑ Coannihilations
- ☑ Sommerfeld enhancement
- ☐ Bound states

An open mind on DM mass

see e.g. Moroi Randall hep-ph/9906527 for Wino (3plet) abundance from decay of pseudomoduli

$$M^{\rm 3plet}_{\rm thermal} \simeq 3 \quad M^{\rm 5plet}_{\rm thermal} \simeq 9.5\ {\rm TeV}$$



Cirelli et al. 1507.05519

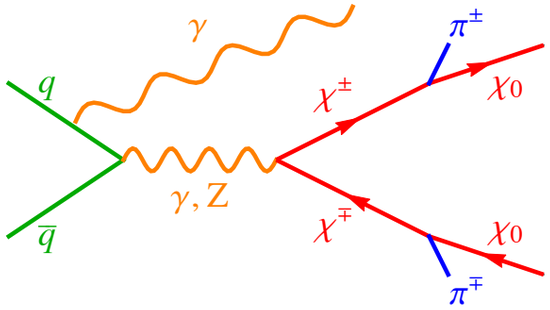
EW multiples at colliders

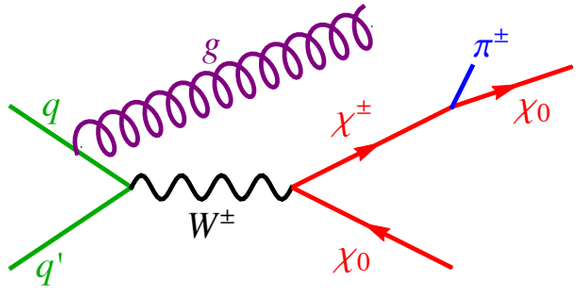
DM does not interact with detectors: look for missing energy + SM radiation

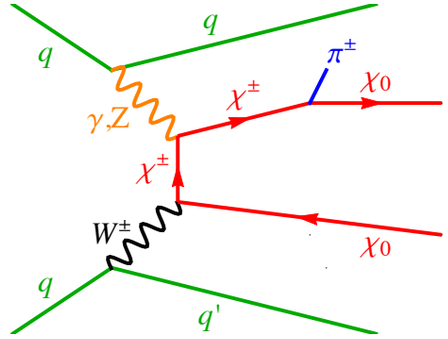
Pure EW multiplets: $\chi^{\pm}$ & $\chi^{\pm\pm}$ add to the signal!

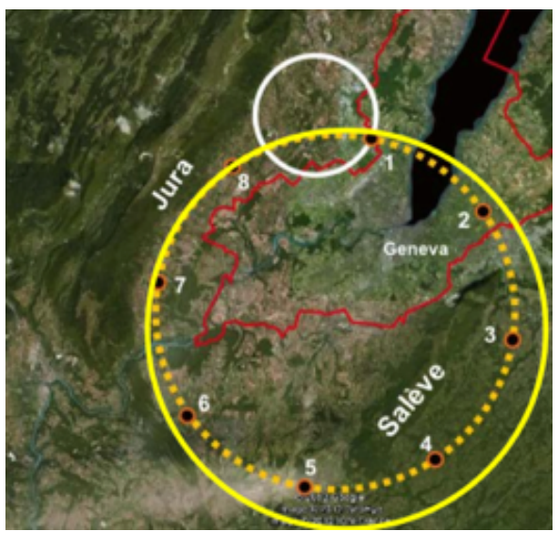
In fact $M_{\chi^{\pm,\pm\pm}} - M_{\chi 0} \gtrsim m_\pi$ ⟹ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

⟹ almost all $\chi^{\pm}$ & $\chi^{\pm\pm}$ decay to $\chi 0$ + soft pions before reaching the detector









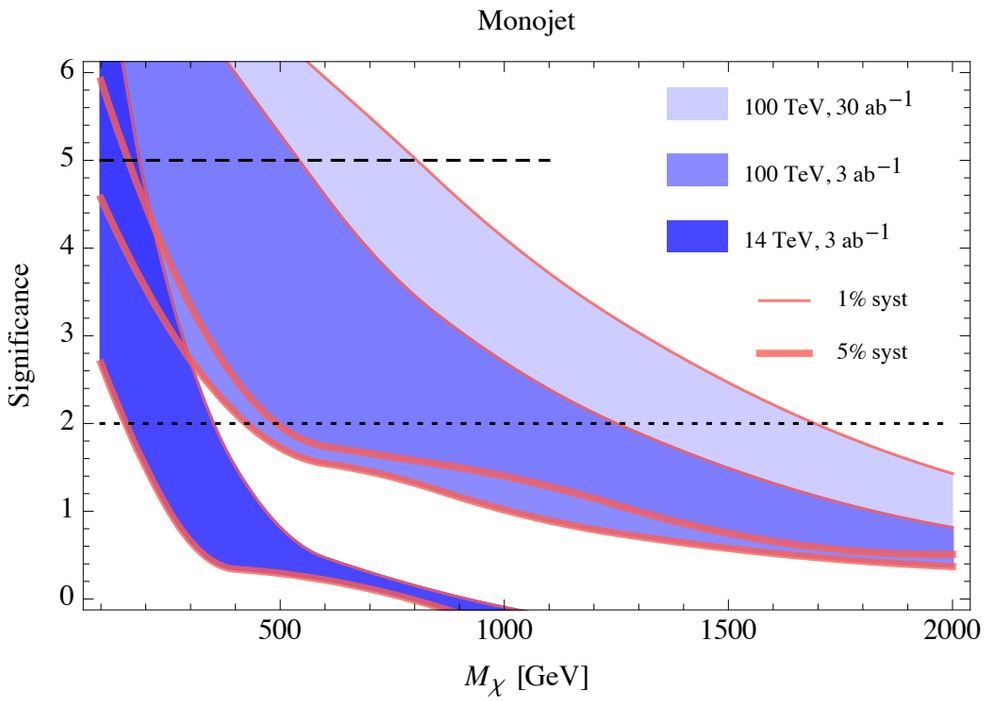
SM radiation: - monojet
- monophoton
- (forward) dijets - aka "Vector Boson Fusion"

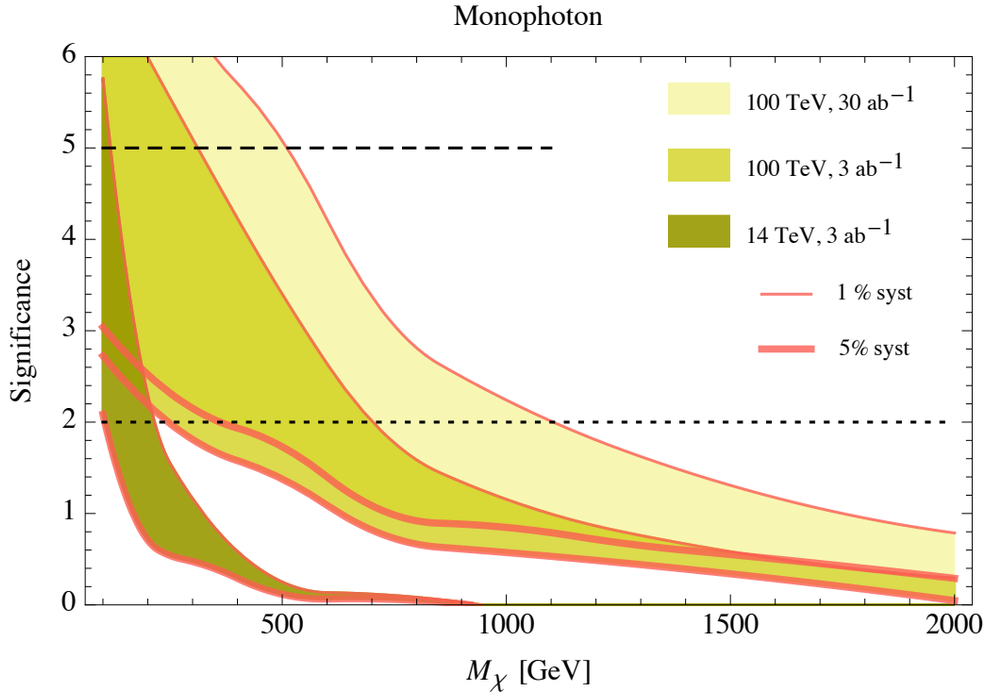
LHC8: hopeless to get even close to multi-TeV thermal masses

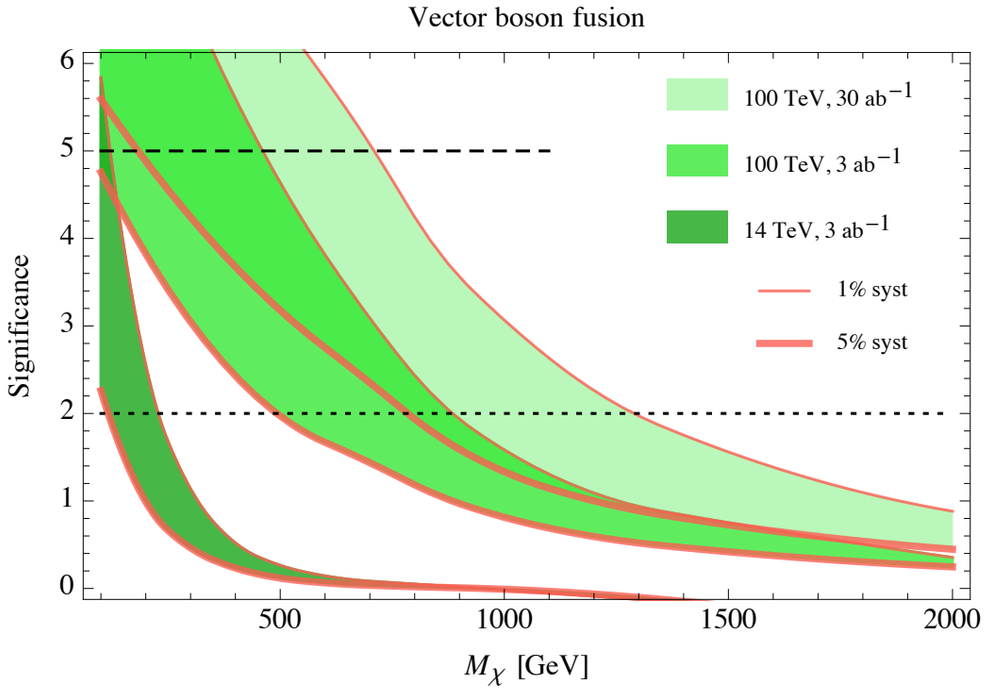
Need higher energies ⟹ **HL-LHC** (14 TeV) & **FCC-hh** (100 TeV)

Missing energy + SM radiation

Plots for 3plet (Wino) from Cirelli Sala Taoso 1407.7058
see also Low Wang 1404.0682, Berlin et al. 1502.05044







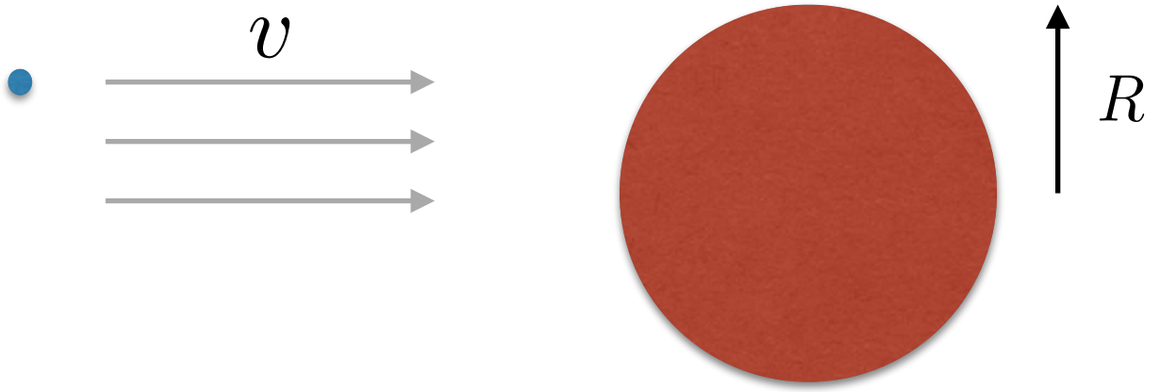
- **Will not cover thermal relic masses**
- systematics understanding will be crucial (today we are at ~ 5%, not 1%!)
- going from 14 to 100 TeV will increase mass reach by a factor of 3 - 4

Same conclusions for 5plet

Sommerfeld enhancement

Sommerfeld 1931,
Hisano et al. hep-ph0412403 (first time DM), ….
Arkani-Hamed et al. 0810.0713 for nice explanation

Classical analogous



$$\sigma_0 = \pi R^2$$

If slow, gravity becomes important:

$$\sigma = \sigma_0 \left(1 + \frac{v_{\rm esc}^2}{v^2}\right)$$

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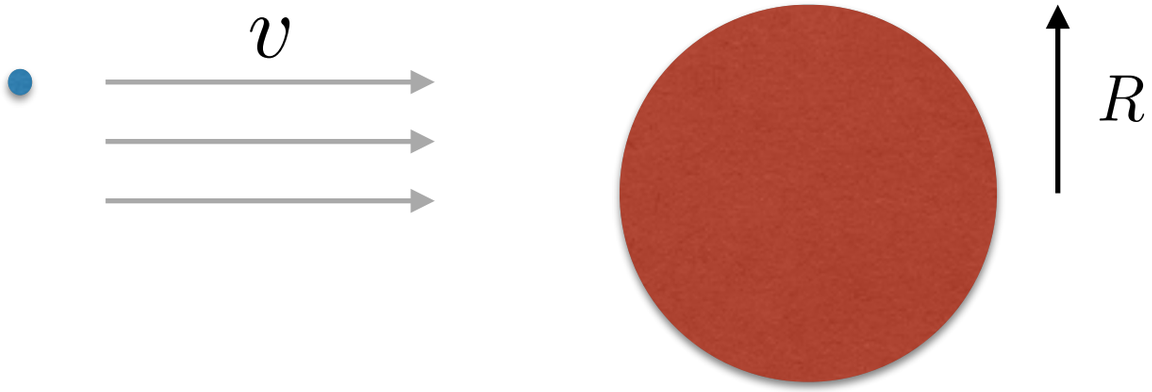

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Quantum: like in classical example, to have (Sommerfeld) enhancement requires

- slow particles $v \ll c$
- long-range attractive force $M_{\rm mediator} < \alpha\, M_{\rm DM}$

DM mass for SM weak force? $\alpha_{\rm w} \sim 1/30$

$$M_{\rm DM} \gtrsim 30\, M_{W,Z} \simeq 2.5\ {\rm TeV}$$

A bit more technical:
quantum field theory computations assume particles are “free" (=plain waves) at $r = +\infty$
BUT: if potential V is important also there (long-range!) you have to **solve Schroedinger eq.**

EW multiples in the gamma sky

Sommerfeld enhancement

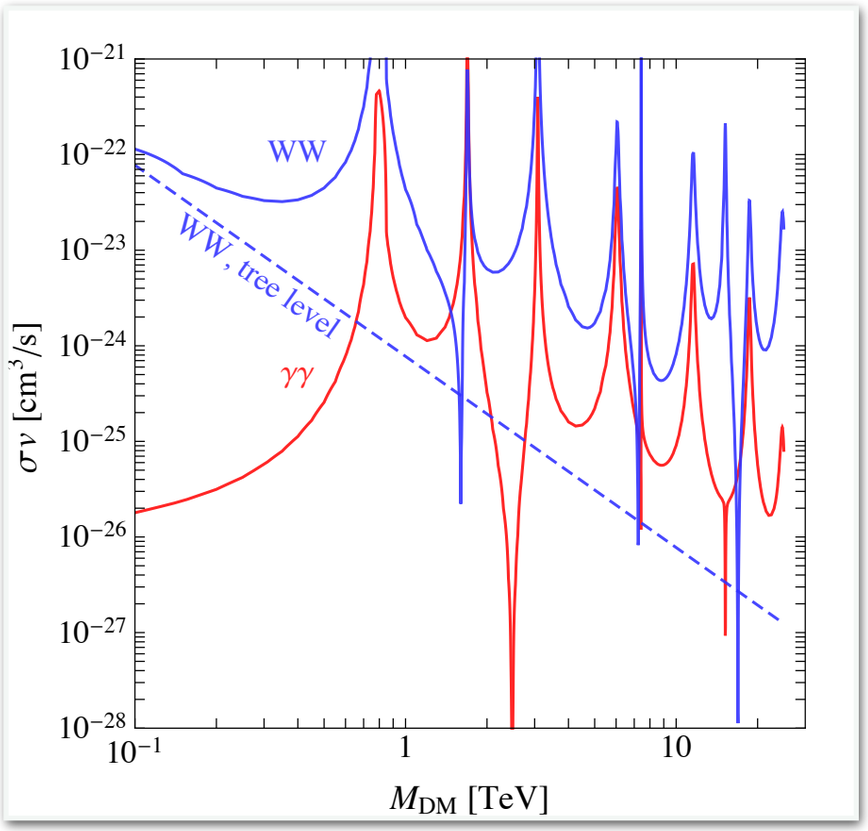
at low velocities non-relativistic attractive potential

Milky Way $v \sim 10^{-3}$ c

Dwarf spheroidals $v \sim 1 - 5 \times 10^{-5}$ c

σv saturates at $v \sim 10^{-2}$ c

5plet, $\chi_0\chi_0 \to WW, \gamma\gamma$



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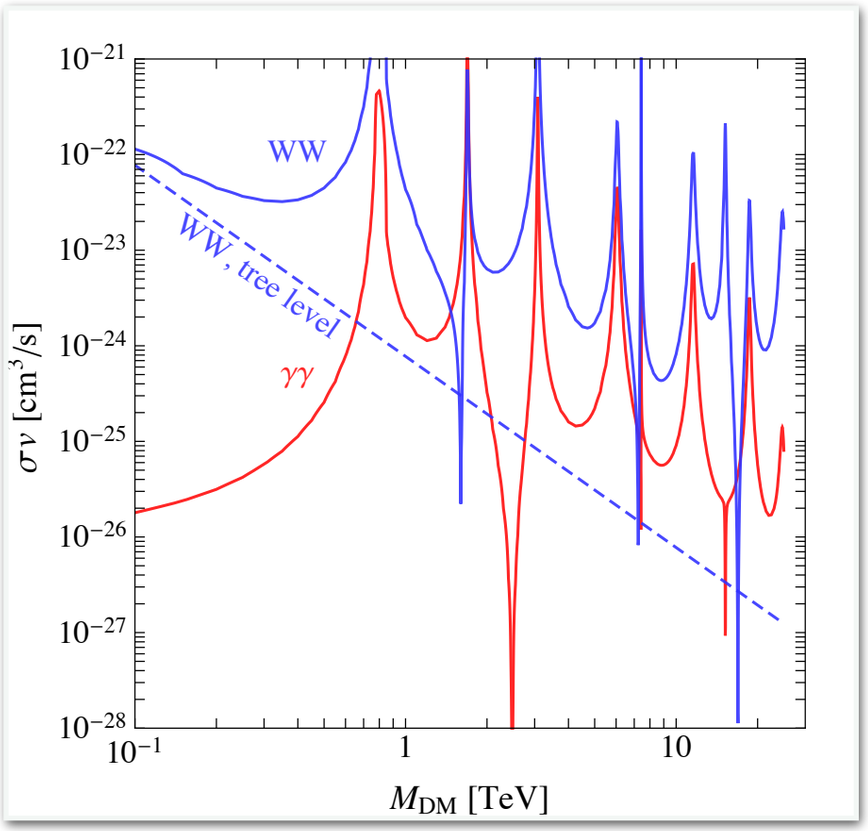
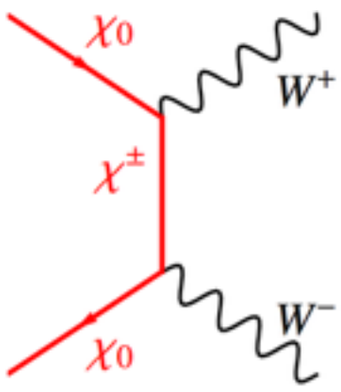
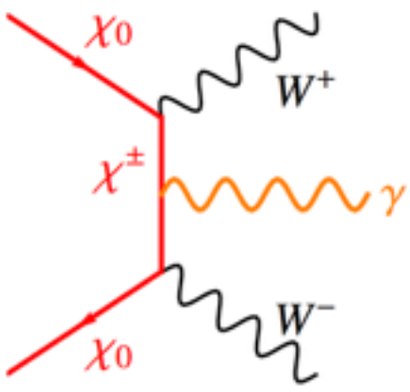
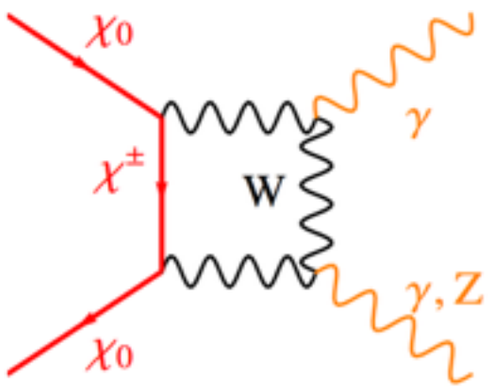








$\bar{p},\ e^+,\ \nu,\ \gamma, \ldots$

"continuum"

γ-ray lines: smaller cross sections

but features in γ-spectrum enhance sensitivities!

A primer on Dwarf Spheroidal Galaxies (dSph)

- Gravitationally linked to our galaxy
- DM dominated objects → this is why they are good targets!
- Often member stars ("tracers") are just a few → uncertainties on DM properties

with respect to Milky Way:
- ☺ almost no bkg: few stars, ~ no gas
- ☺ we are discovering more and more of them! (GC is only one…)

Dark Matter annihilation from dSph

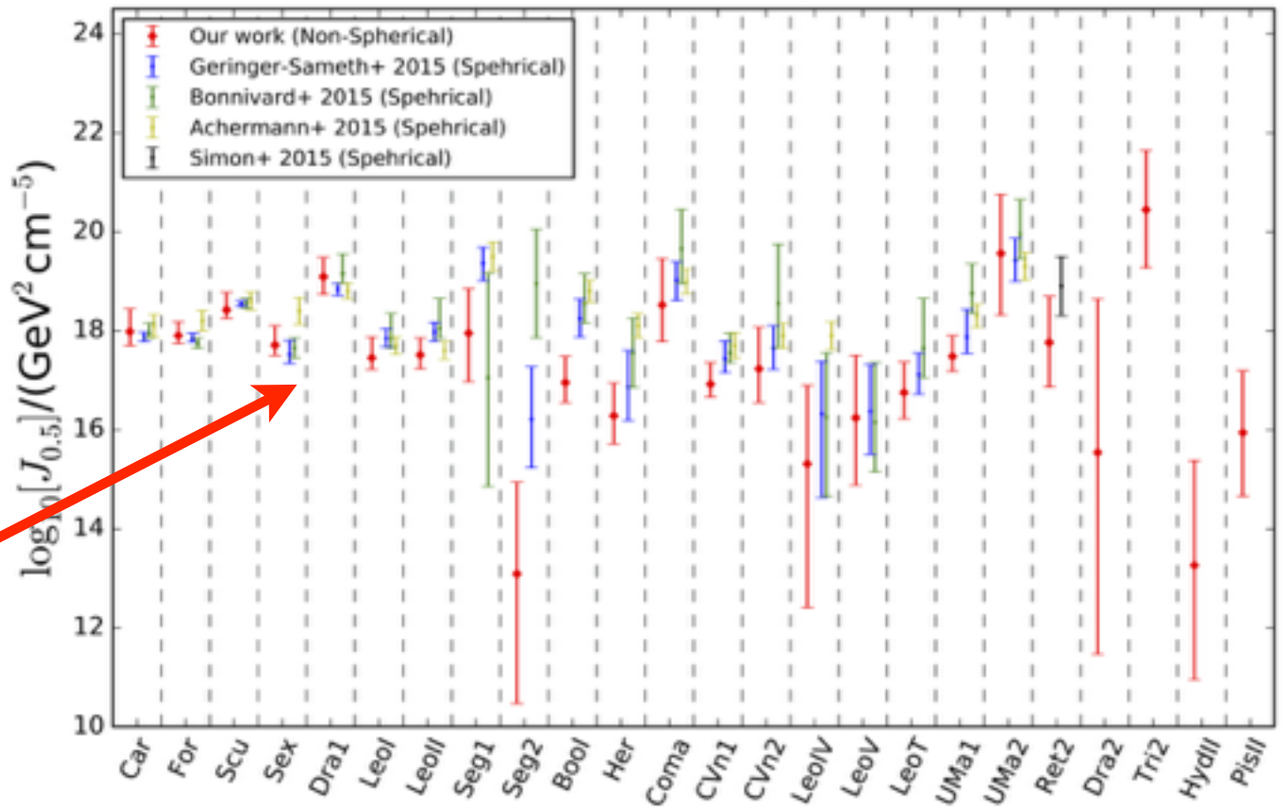
$$\text{Signal} \propto J = \int_{\Delta\Omega} \int_{\text{l.o.s.}} d\ell \, d\Omega \; \rho^2(\ell, \Omega)$$

First estimates of J-factors didn't include
- systematics (i.e. stellar foregrounds)
- non-sphericity
- …..

But interesting progress in recent months!

See also Ullio Valli 1603.07721
Evans et al. 1604.05599, 1604.05493
Genina Fairbairn 1604.00838, …

Hayashi et al 1603.08046



Continuum from dSphs

FERMI: 15 dwarves, assumes $\Delta J < 40\%$

HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)

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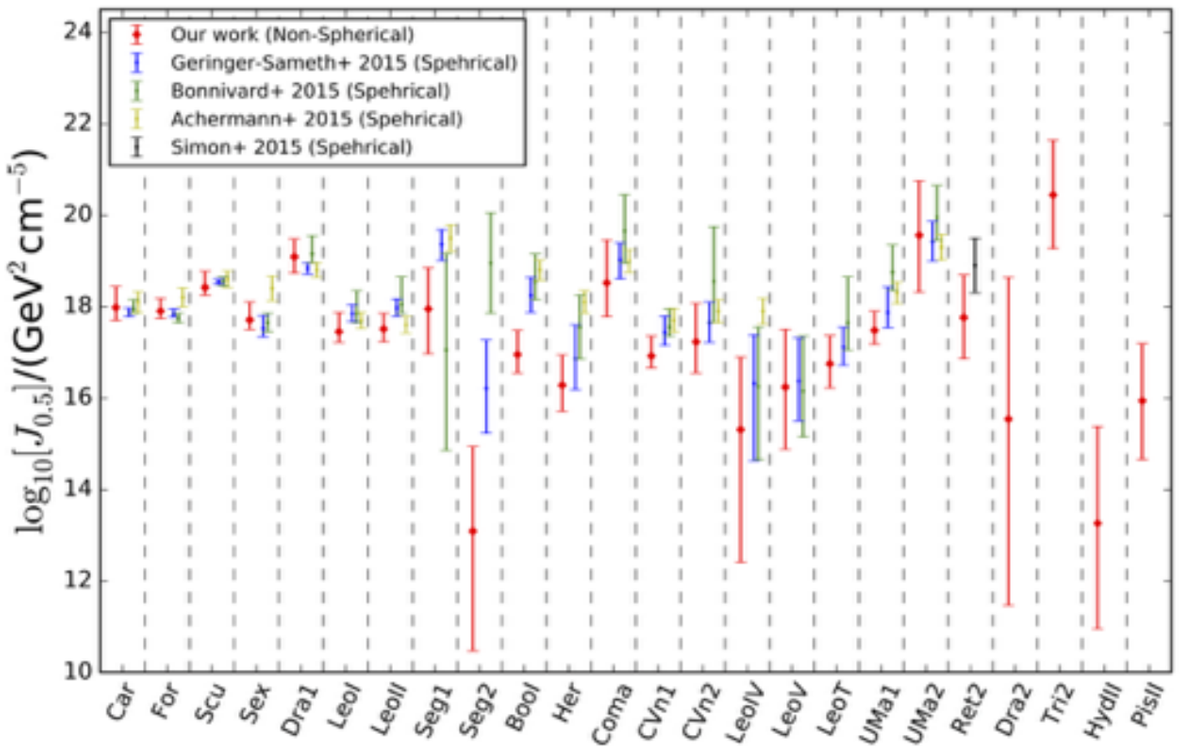

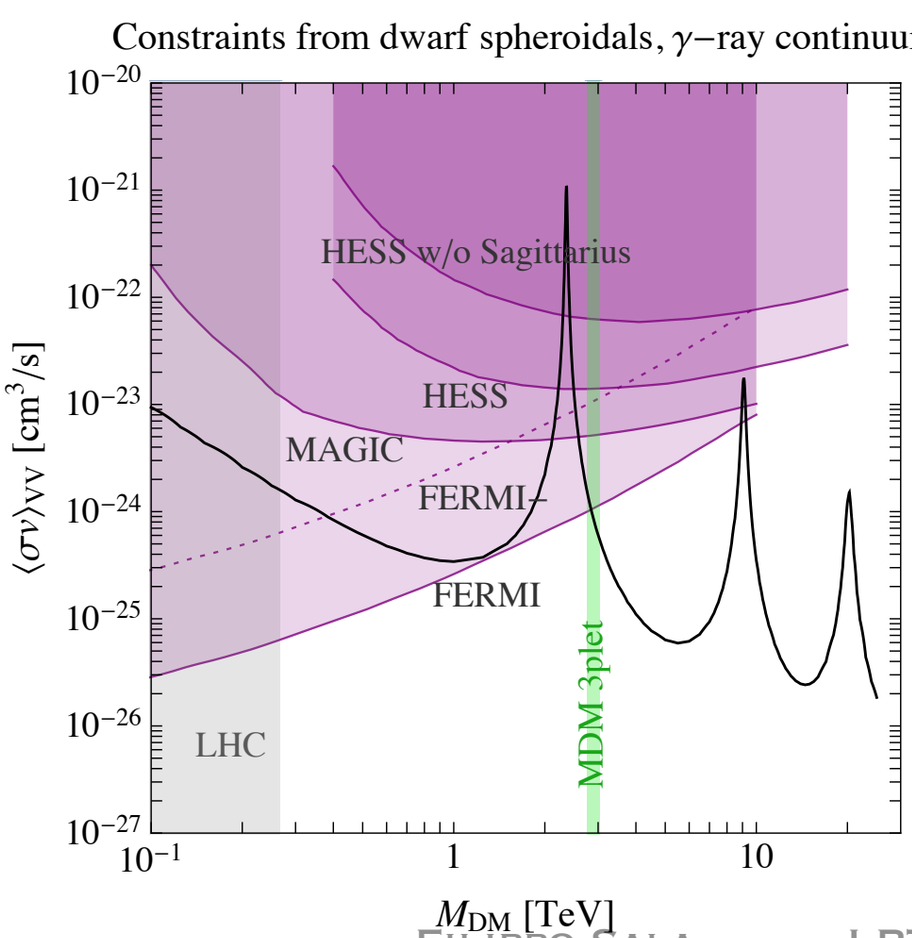

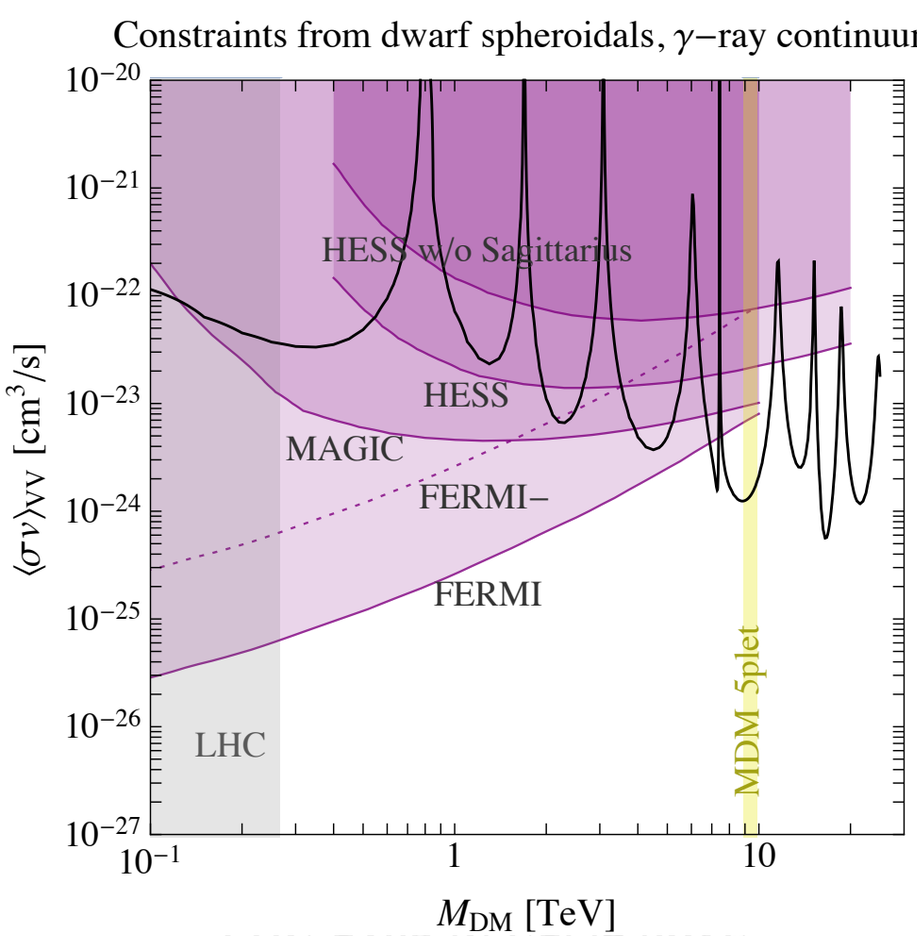

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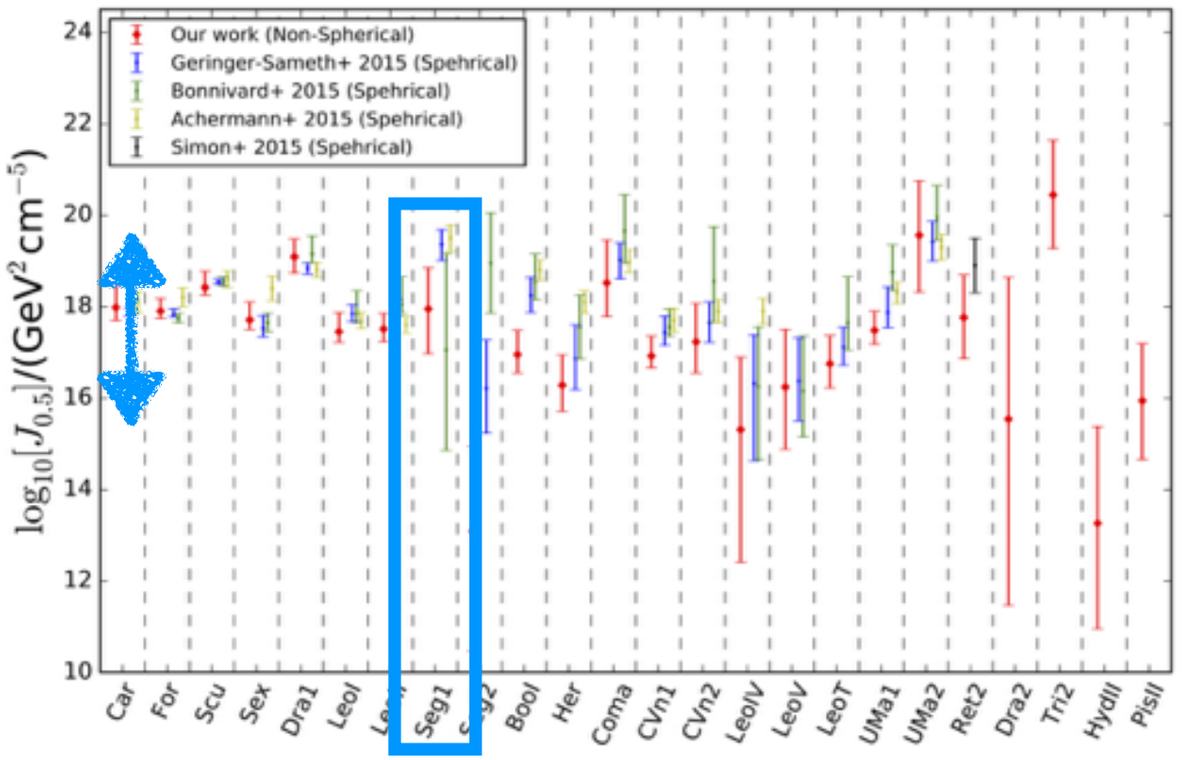
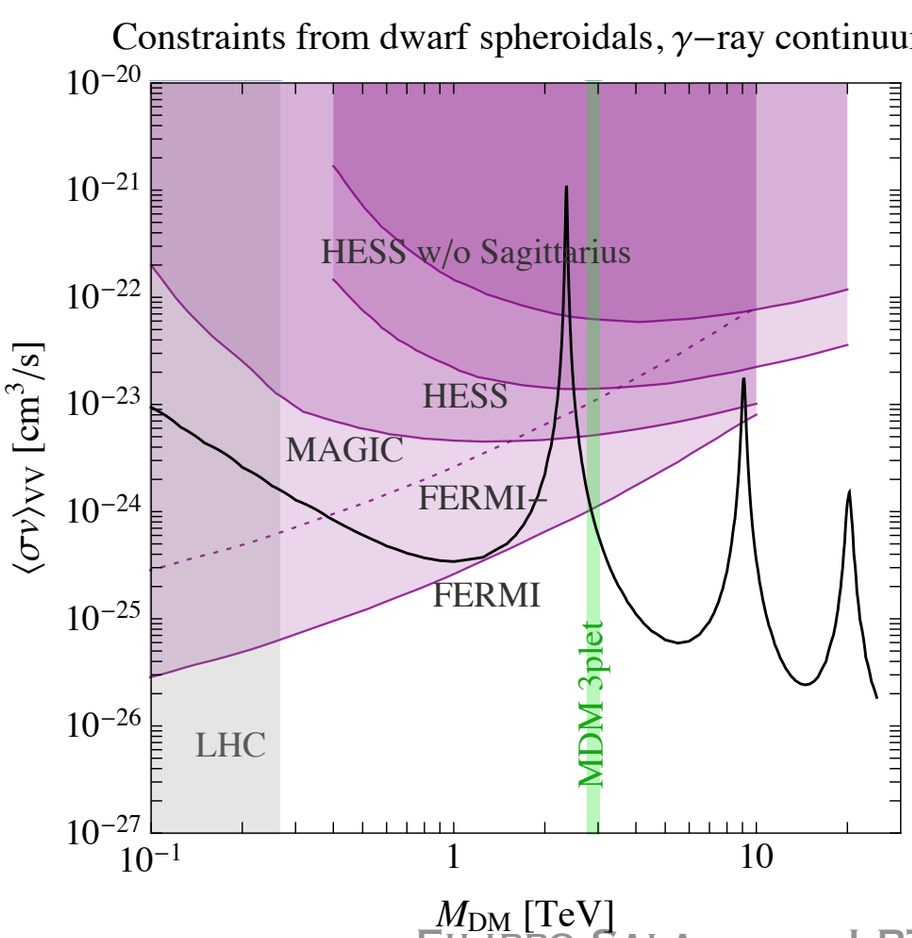
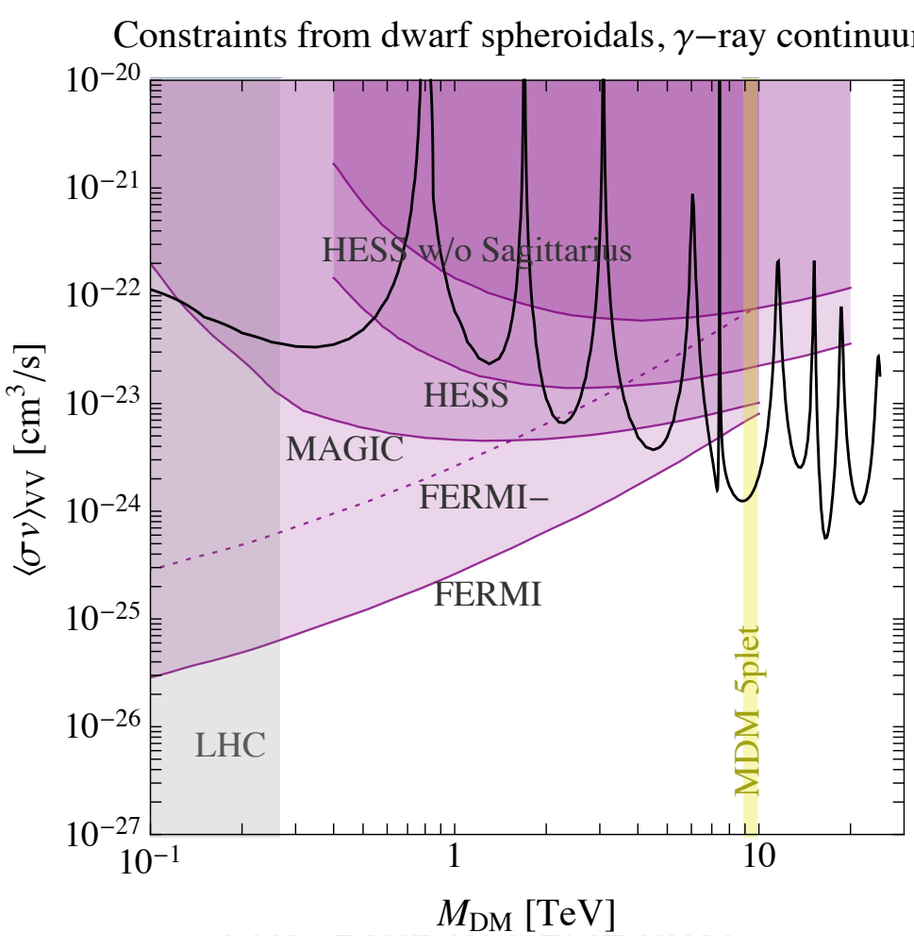
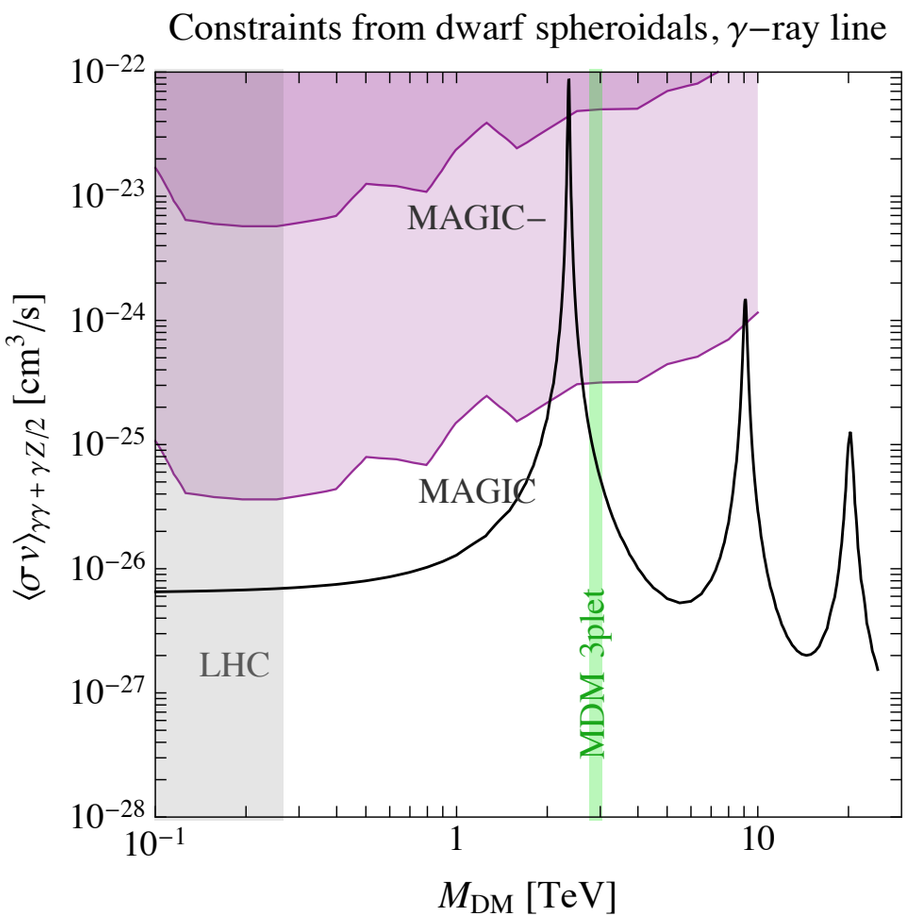


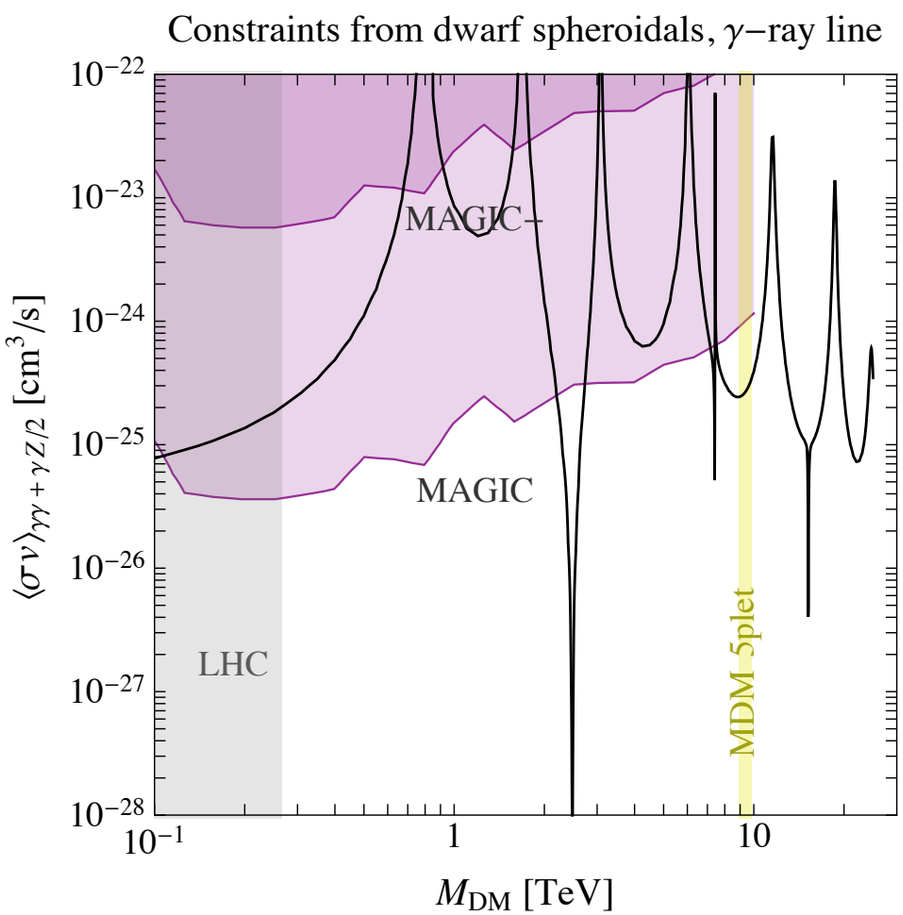




Gamma-ray lines from dSphs

Only MAGIC performed this analysis, and was unlucky…





What about the future? How long should Cherenkov telescopes point dwarves?

Continuum with FERMI

- FERMI measures γ fluxes from all sky
- We “conservatively" estimate astrophysical backgrounds
- We divide the sky into regions, and extract bounds from each one

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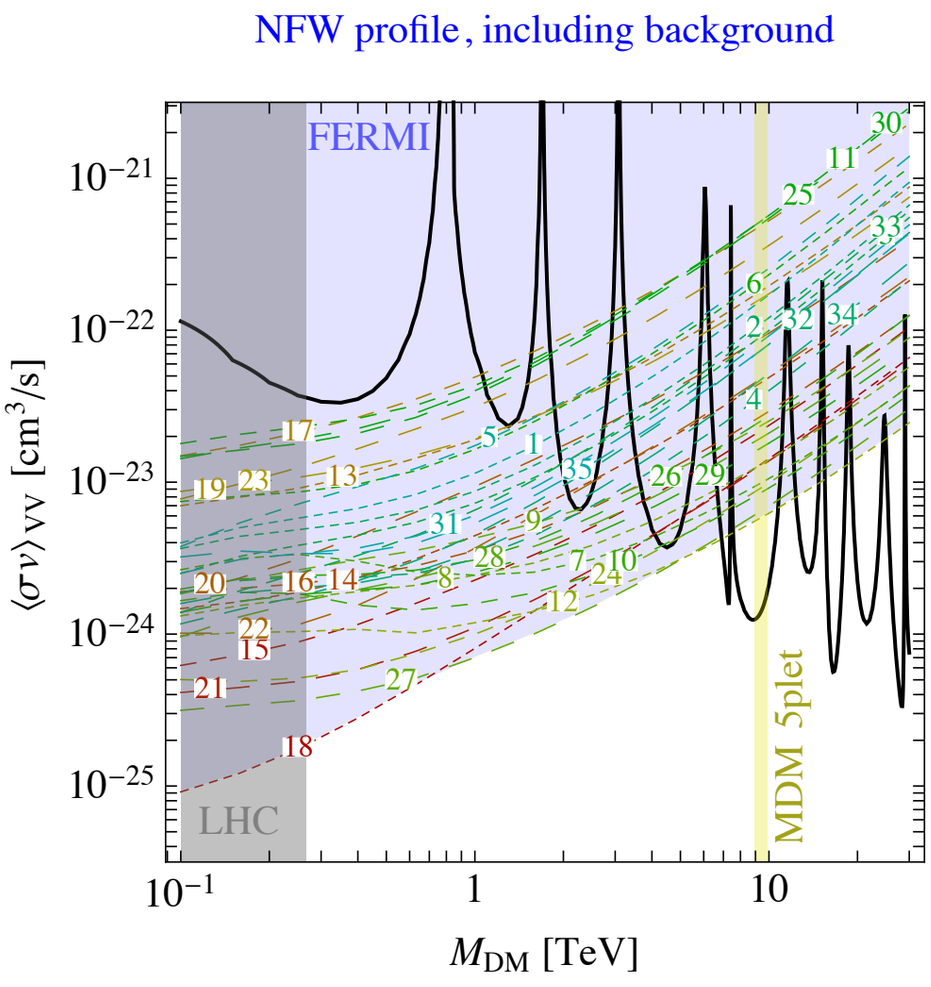

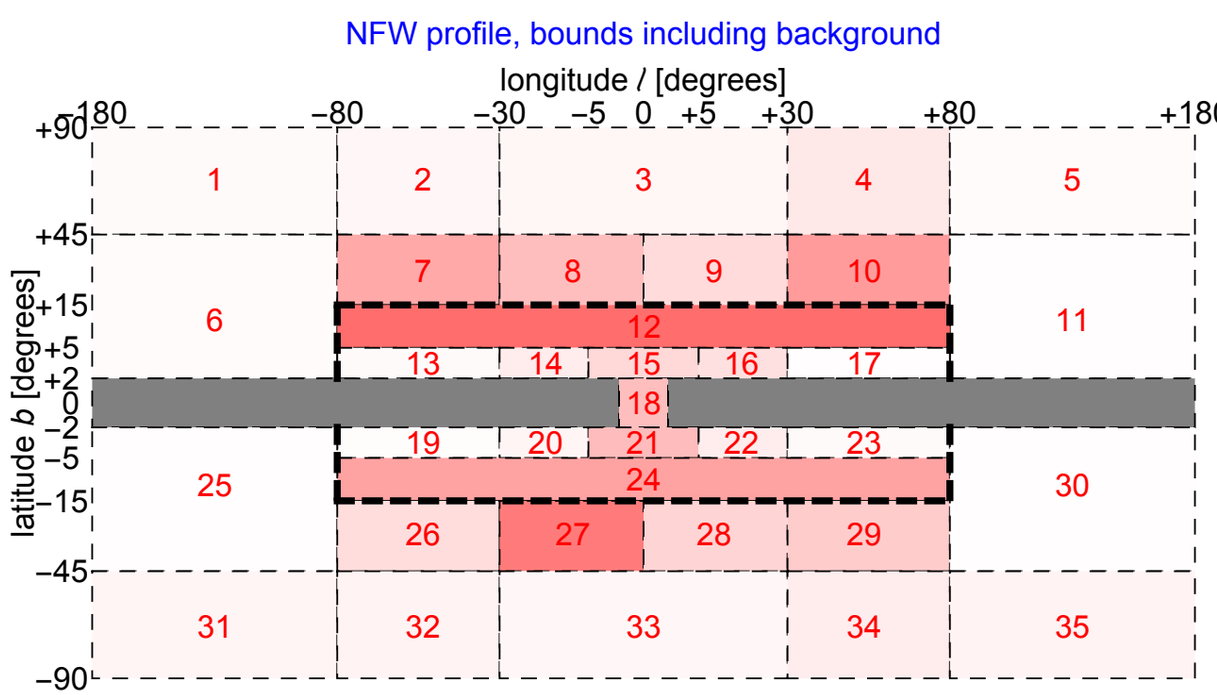

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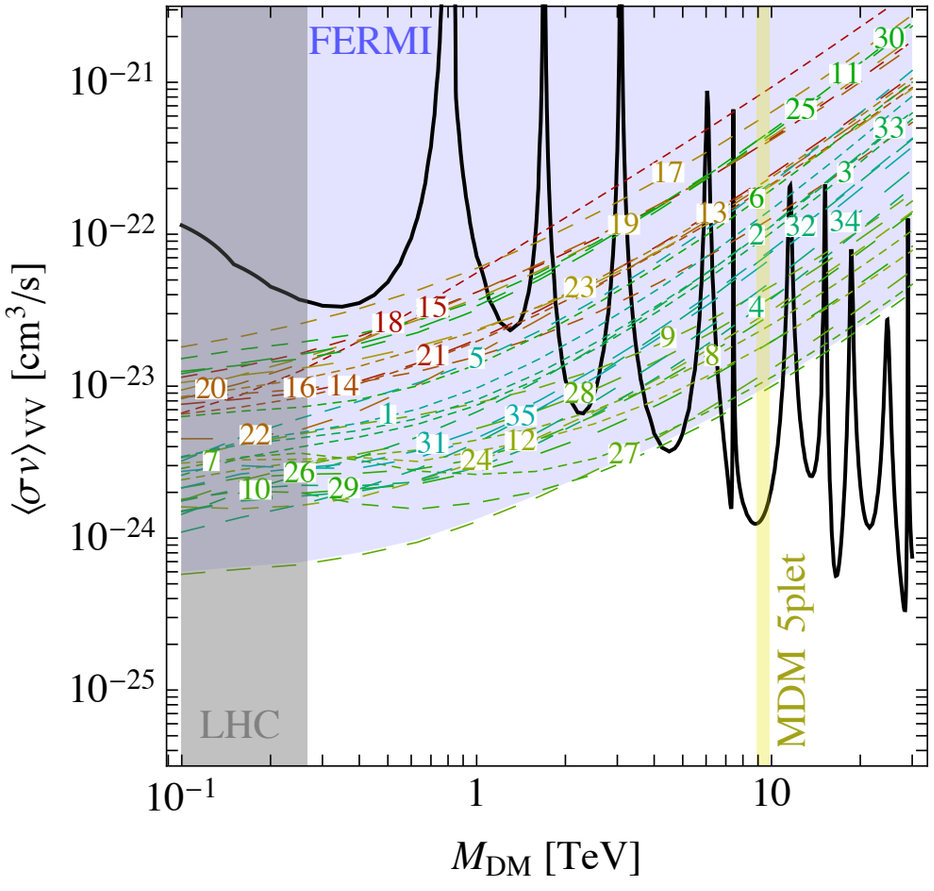
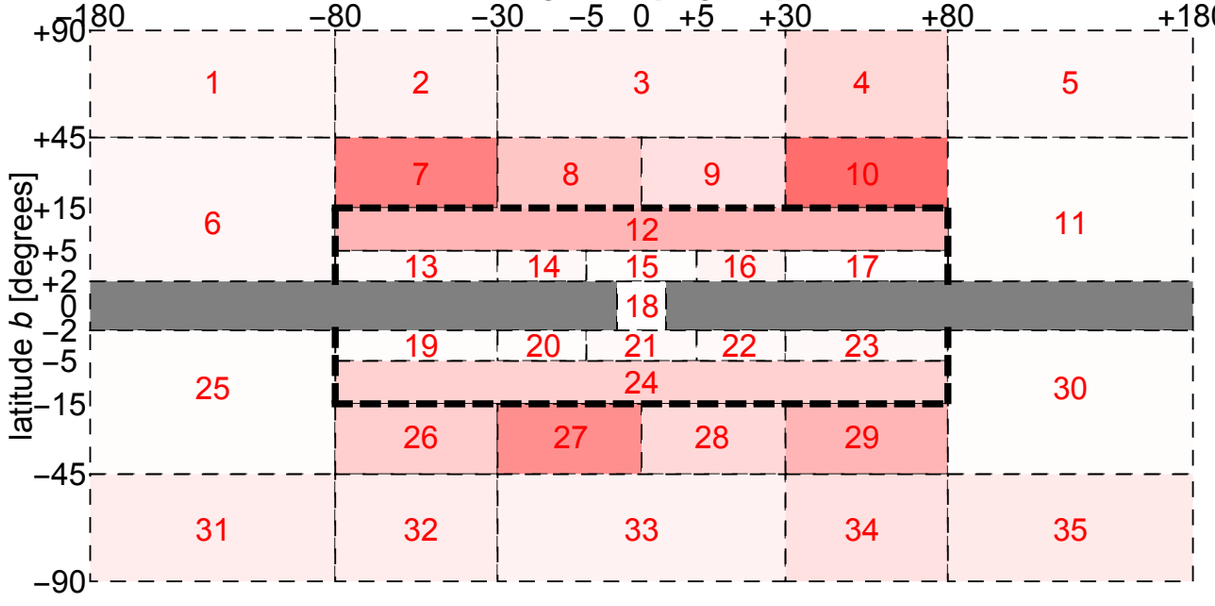
Burkert profile, including background

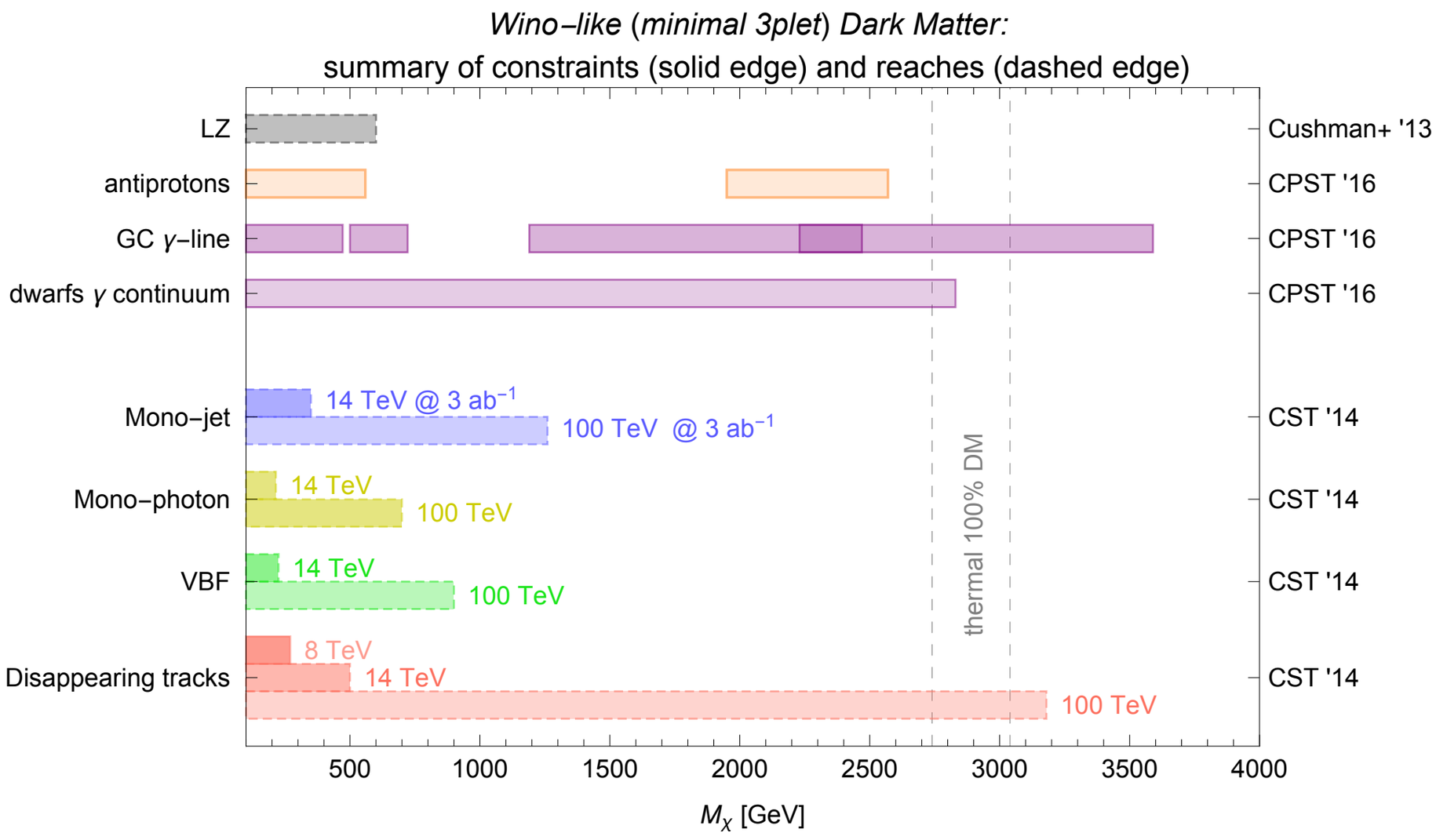


Burkert profile, bounds including background



Comparing WIMP searches with benchmark models

Example: EW fermion **3plet** (Minimal Dark Matter, Wino of split-Supersymmetry,…)



Astrophysical inputs could help set the strategy of telescopes, and of colliders too!