

Open talk “Beyond the Standard Model”

Filippo Sala

LPTHE Univ. Paris 6 and CNRS



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

Constraints + rules of the game + creativity =

The Standard Model has no DM candidate



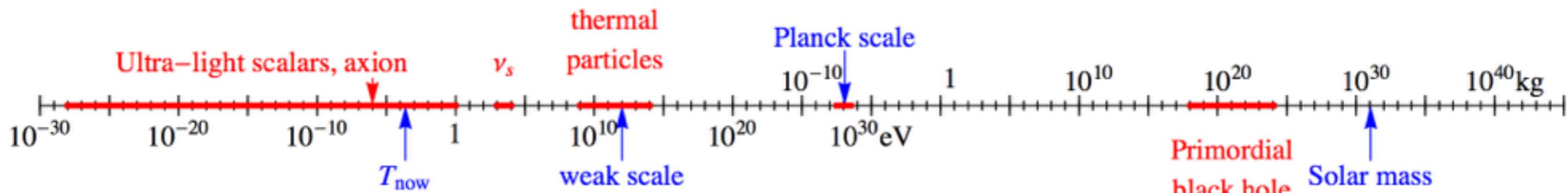
Beyond the Standard Model!

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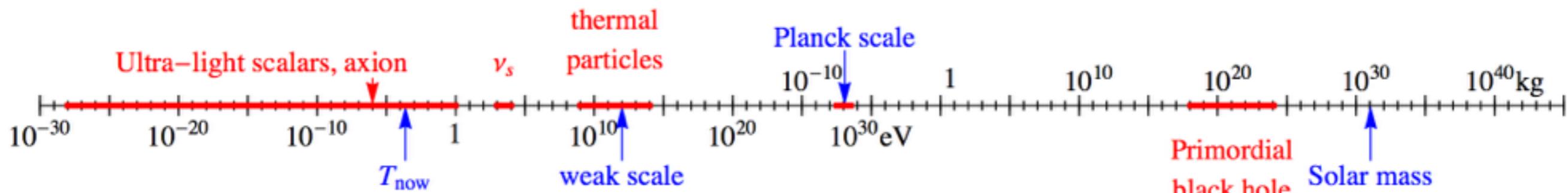
(courtesy of Marco Cirelli)

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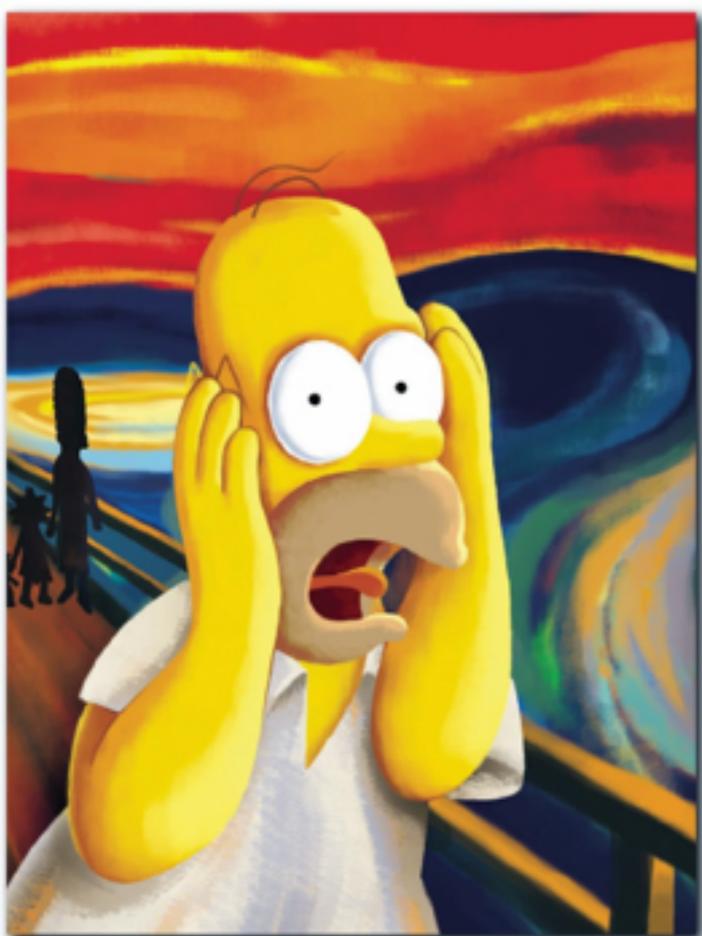
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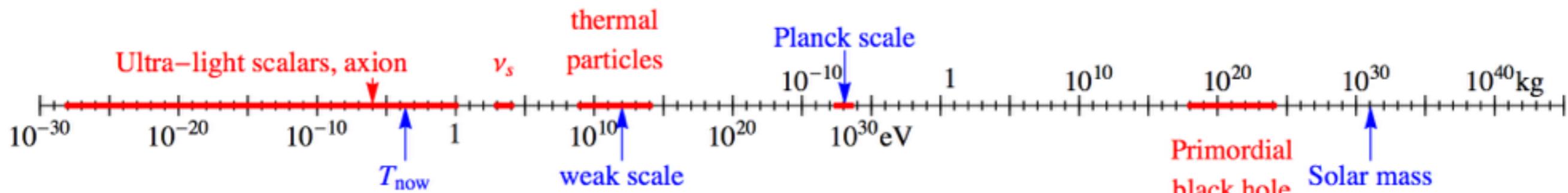


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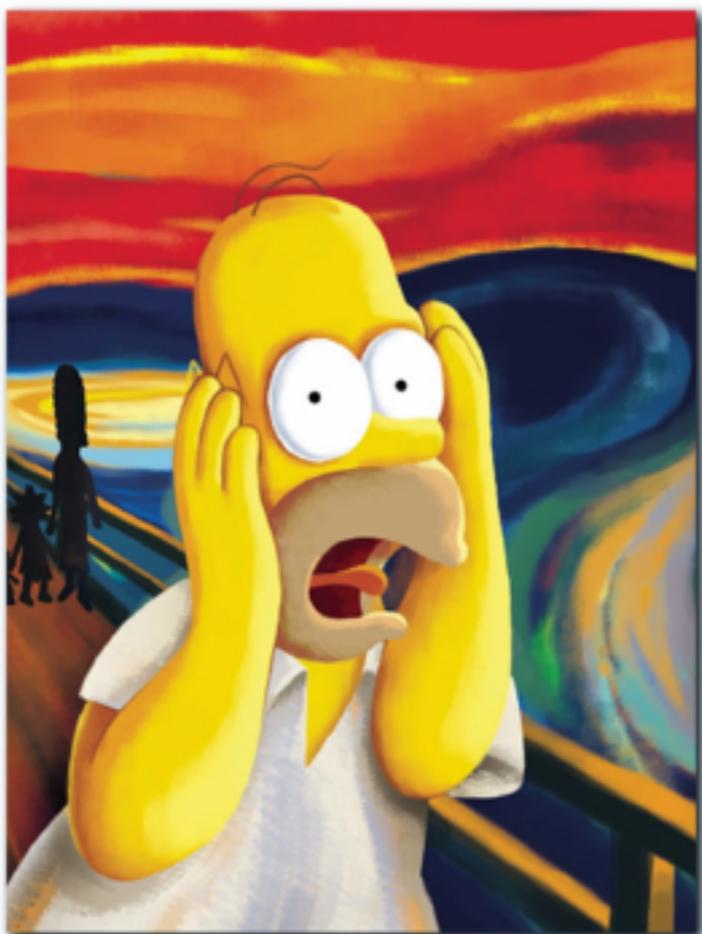
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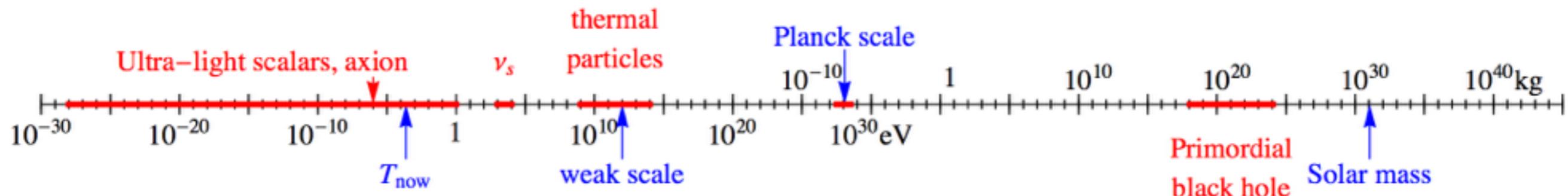
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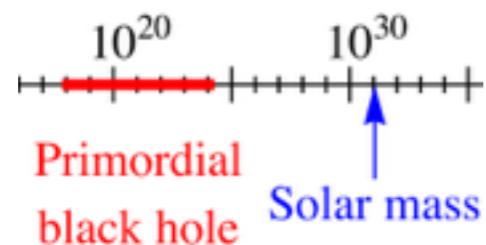
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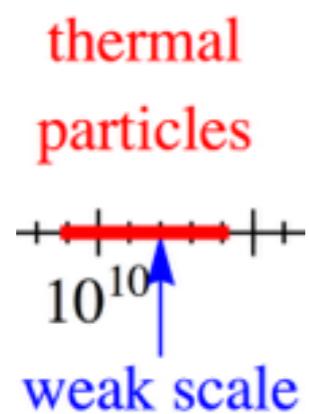
Outline



(courtesy of Marco Cirelli)



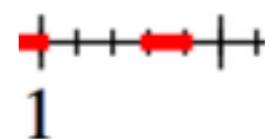
Possibly the “least conventional” candidate



Possibly the “most conventional” candidate

Apologies for not mentioning all the rest....but see next talk for

Mark Lovell & Francesc Ferrer
 ν_s

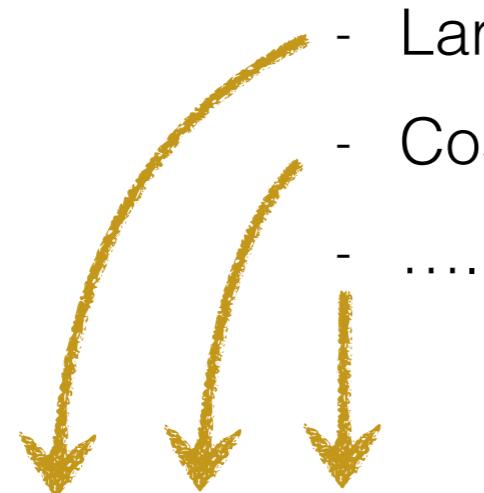


Primordial black holes (?)

- 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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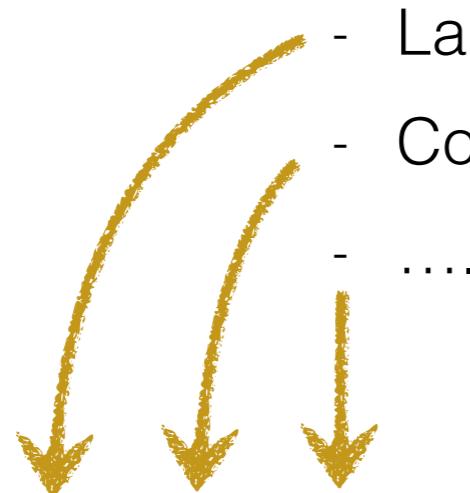
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They all require **BSM** physics, but likely at scales out of any experimental reach!

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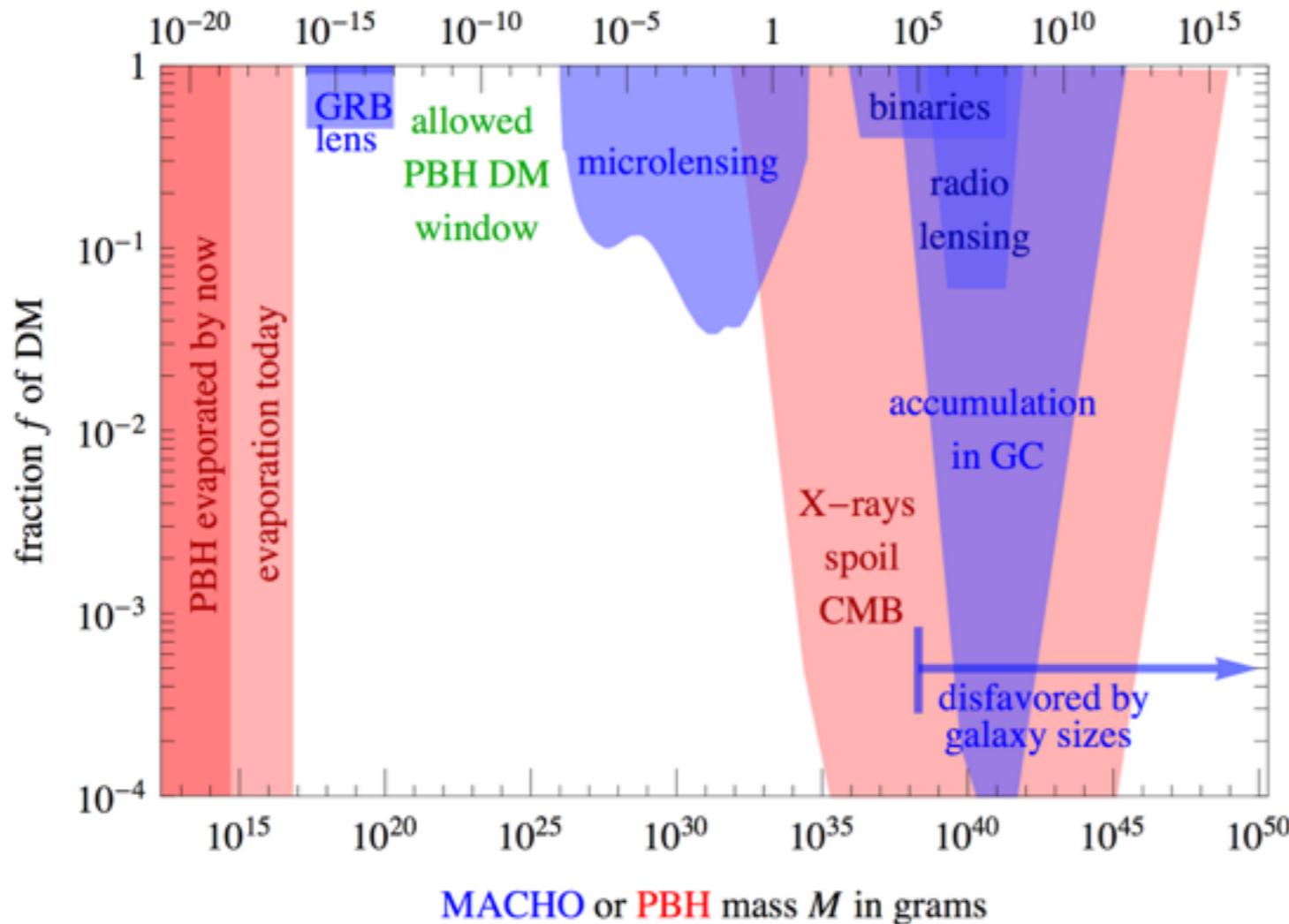
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Still we have gravity to probe them!

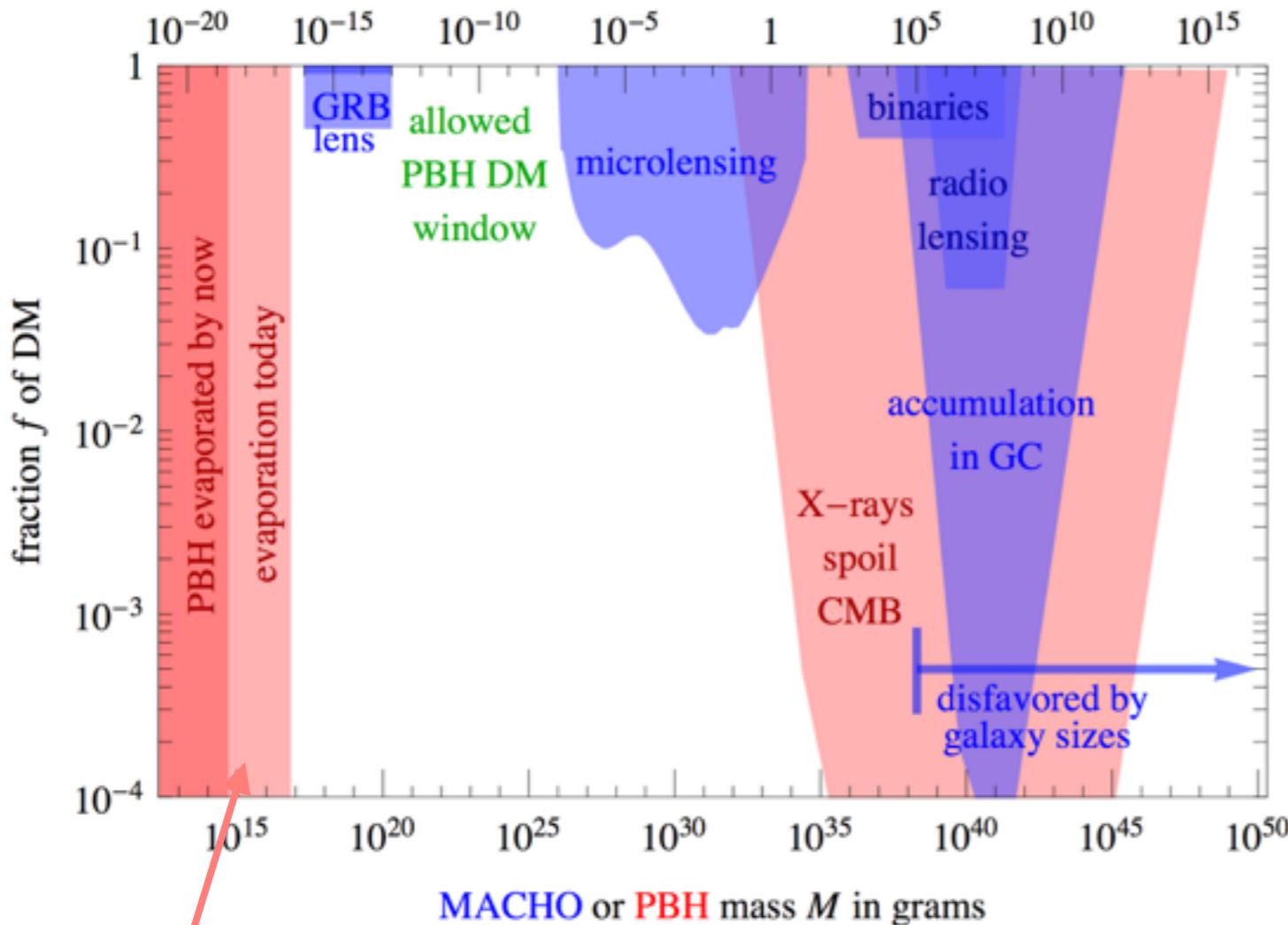
Dark Matter detection I: PBH

See e.g. review Jacob Starkman 1410.2236



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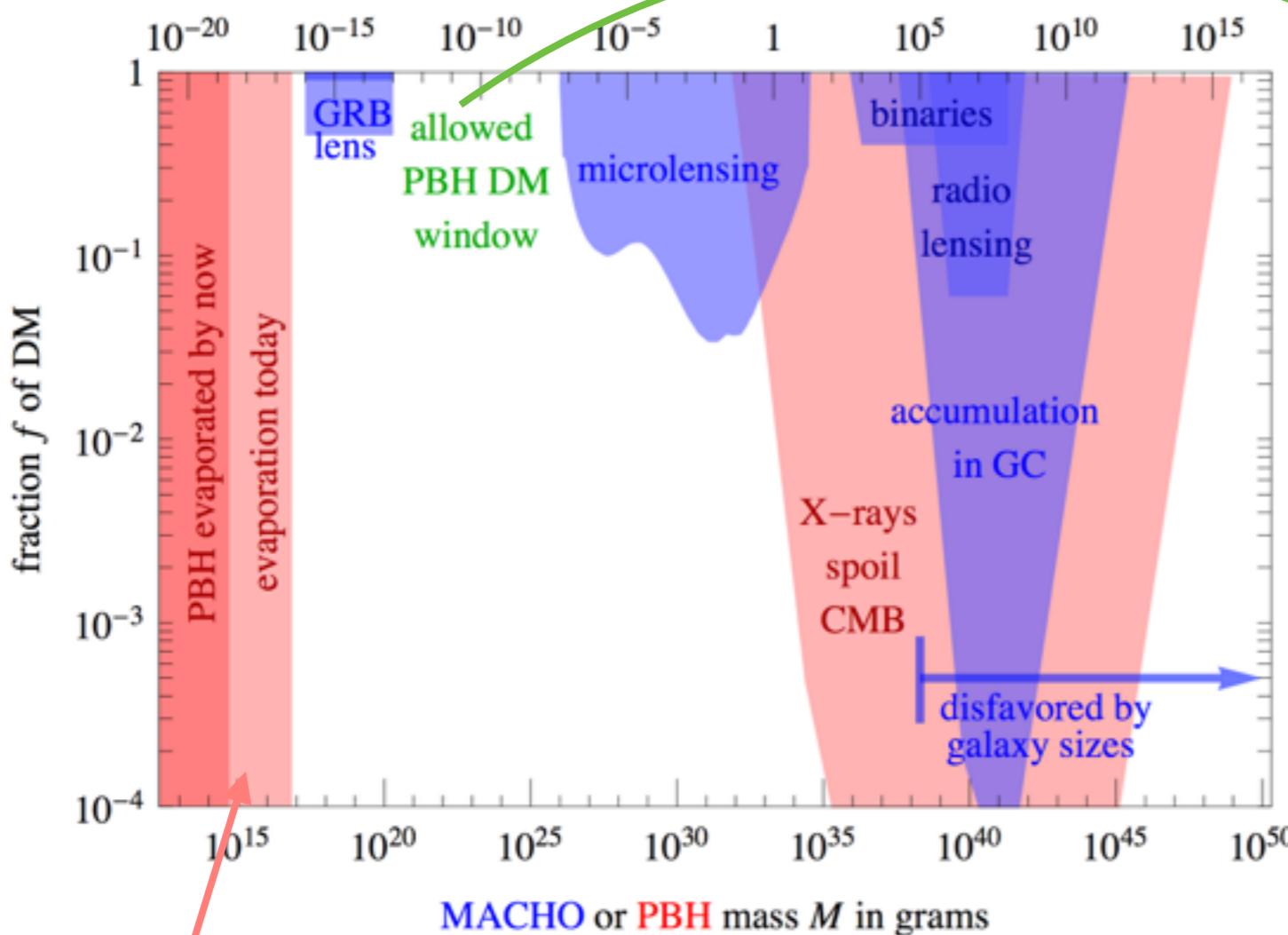


See e.g. Carr et al. 1604.05349

NB: Evaporation peculiar of BH

Dark Matter detection I: PBH

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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

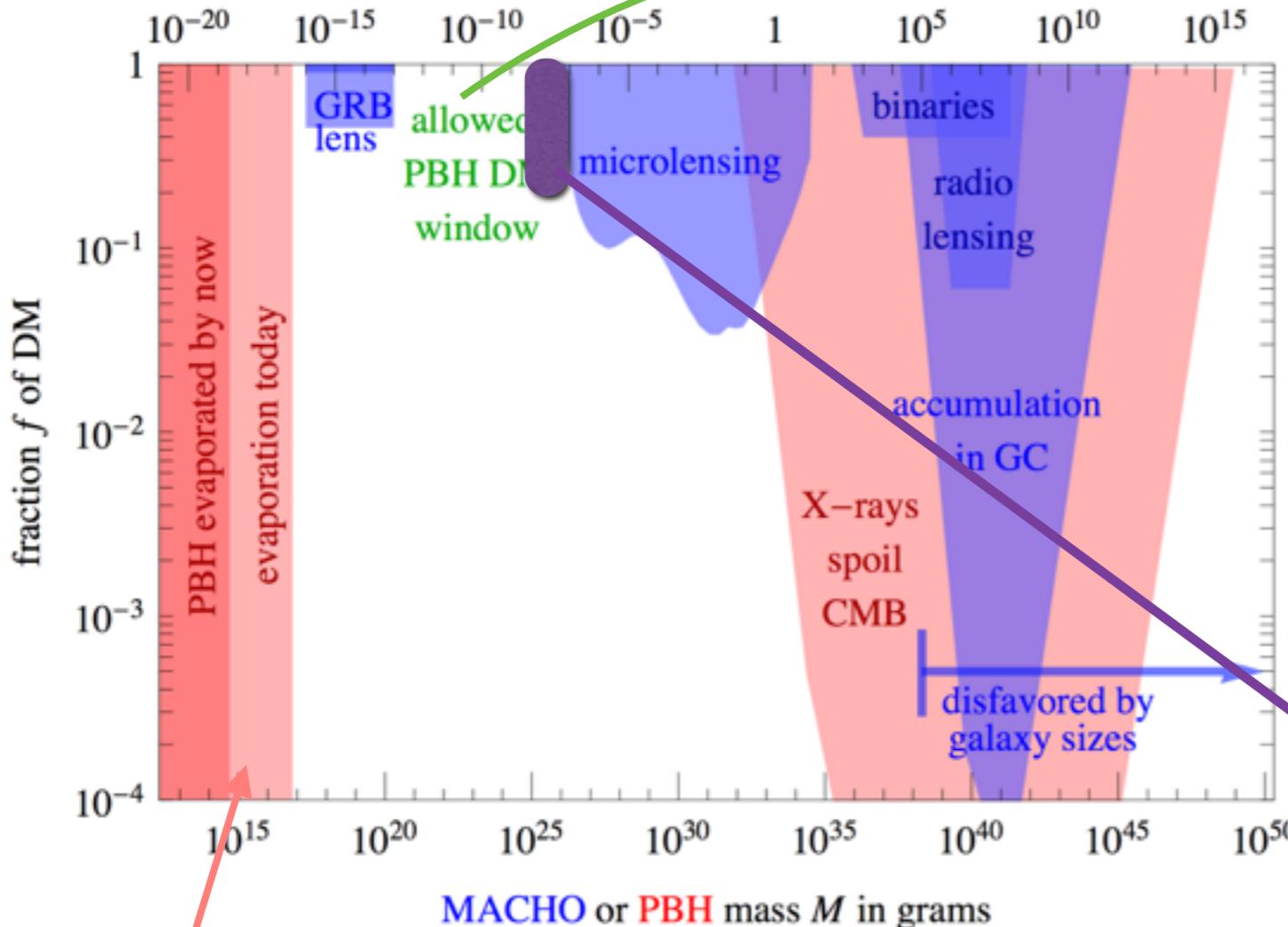
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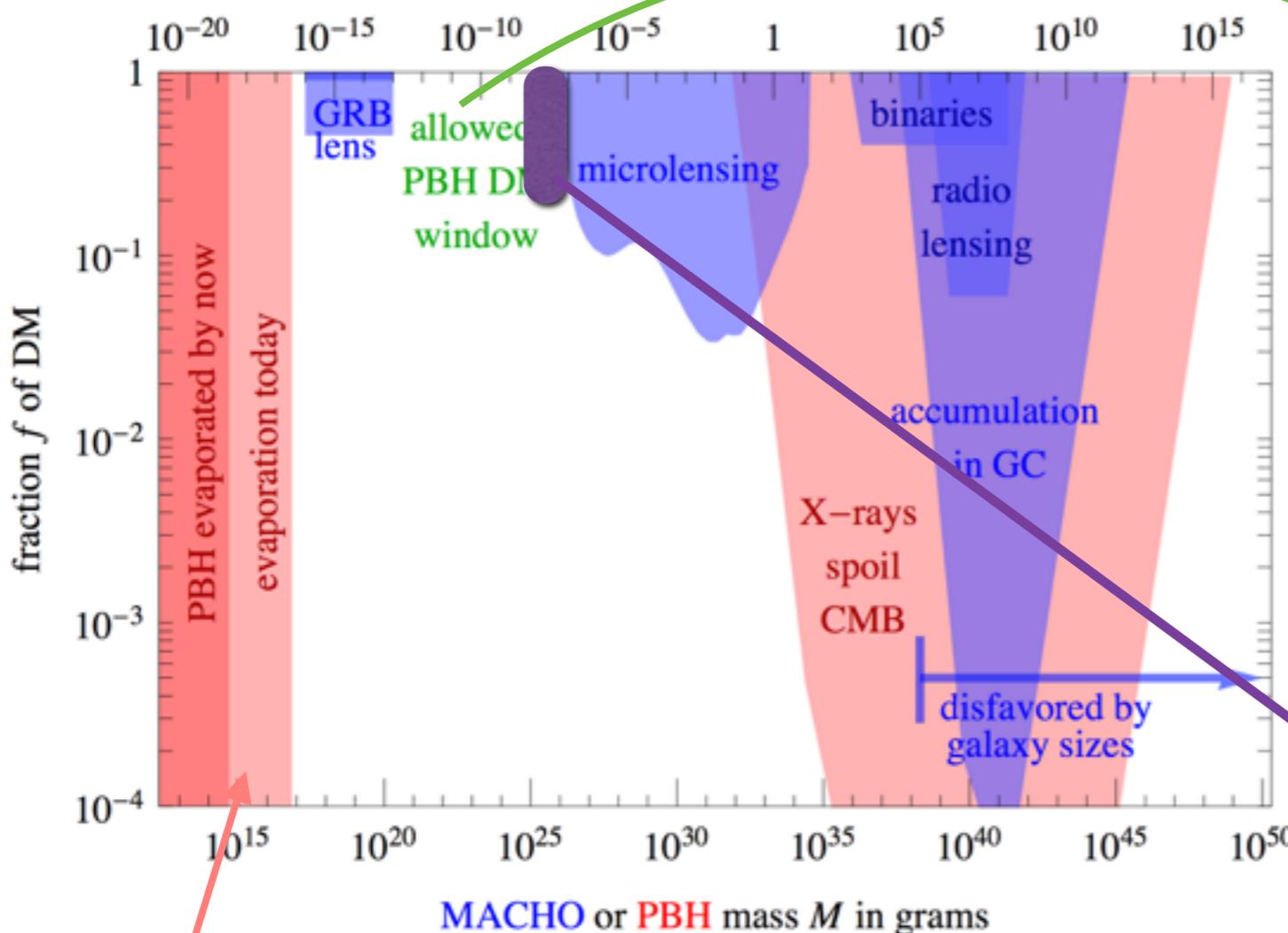
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Kepler satellite exoplanet searches
gives photometry of ~ 150000 stars
bounds on PBHs via microlensing!

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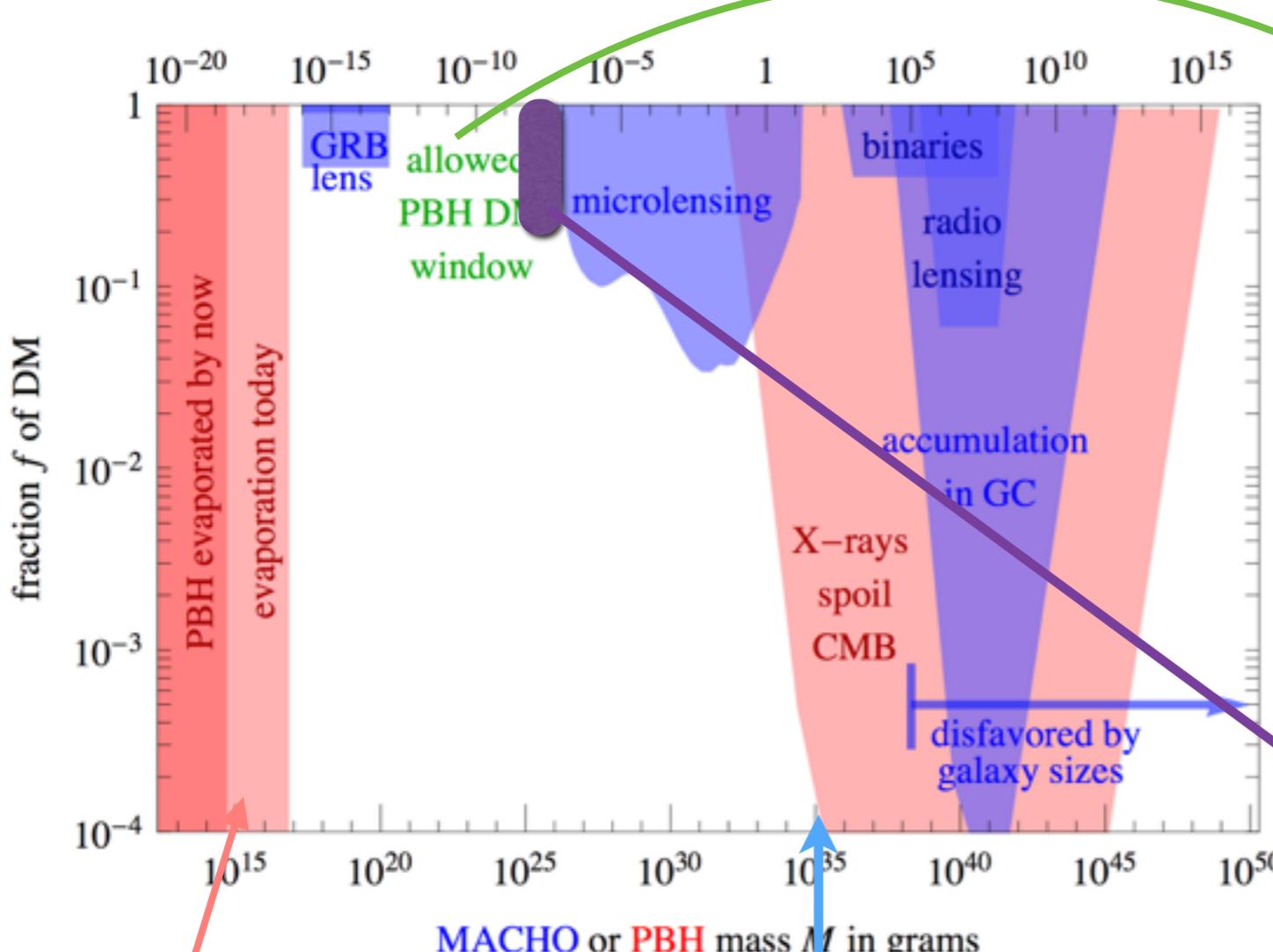
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PBH seed explosion of white dwarves
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IF you do not believe CMB constraints on PBH
can LIGO have observed Dark Matter?

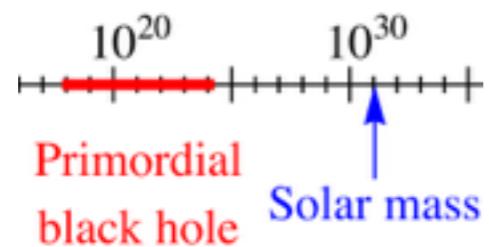
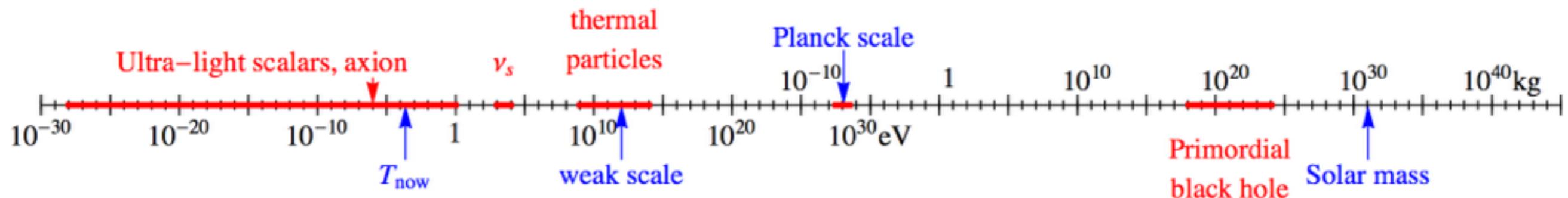
YES Bird+7 et al. 1603.00464

NO Sasaki et al. 1603.08338

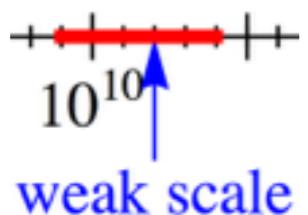
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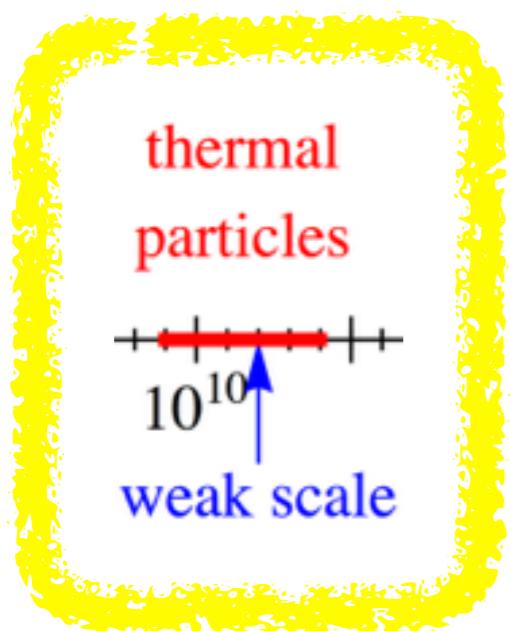
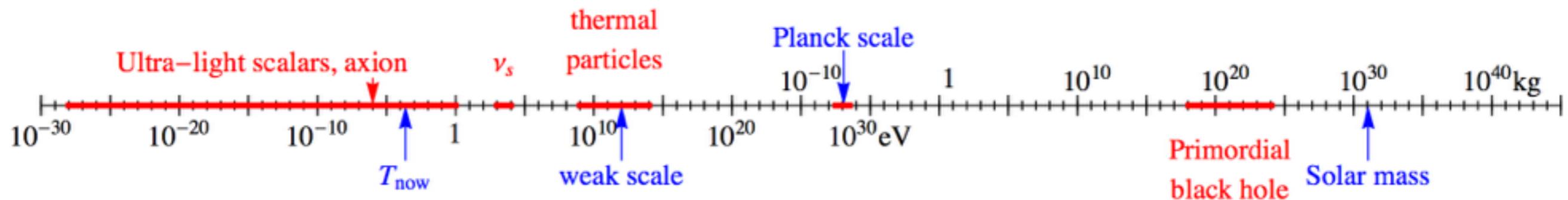
Outline



thermal
particles



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Weakly Interacting Massive Particles

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

Weak =

Or: = whatever interaction with the SM, provided $\alpha = 10^{-3} - 10^{-1}$

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But could be stable by accident (see later on), or long-lived enough (not in this talk)..

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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

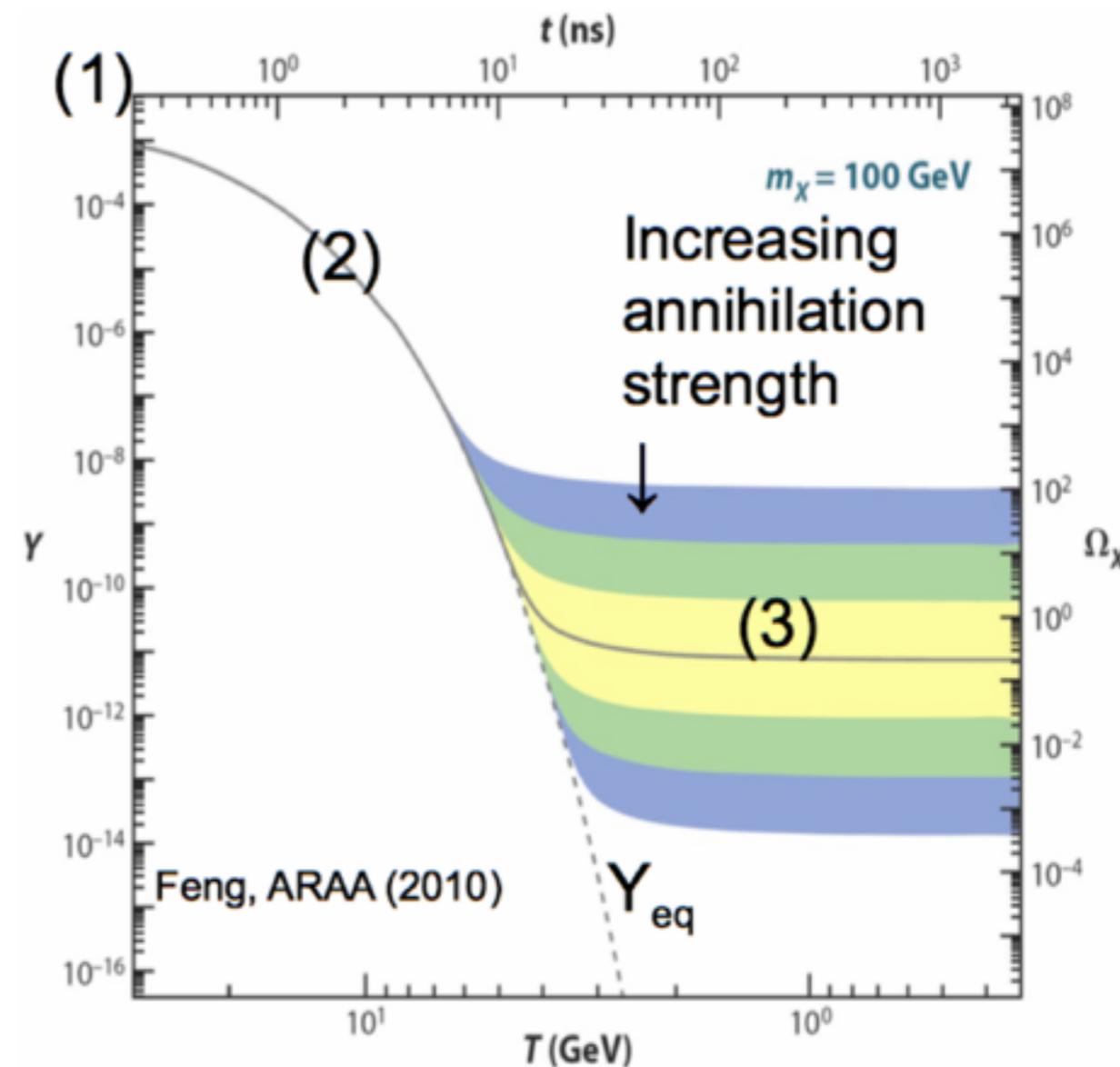
Already reviewed by Tim on Monday...operative recap:

(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!



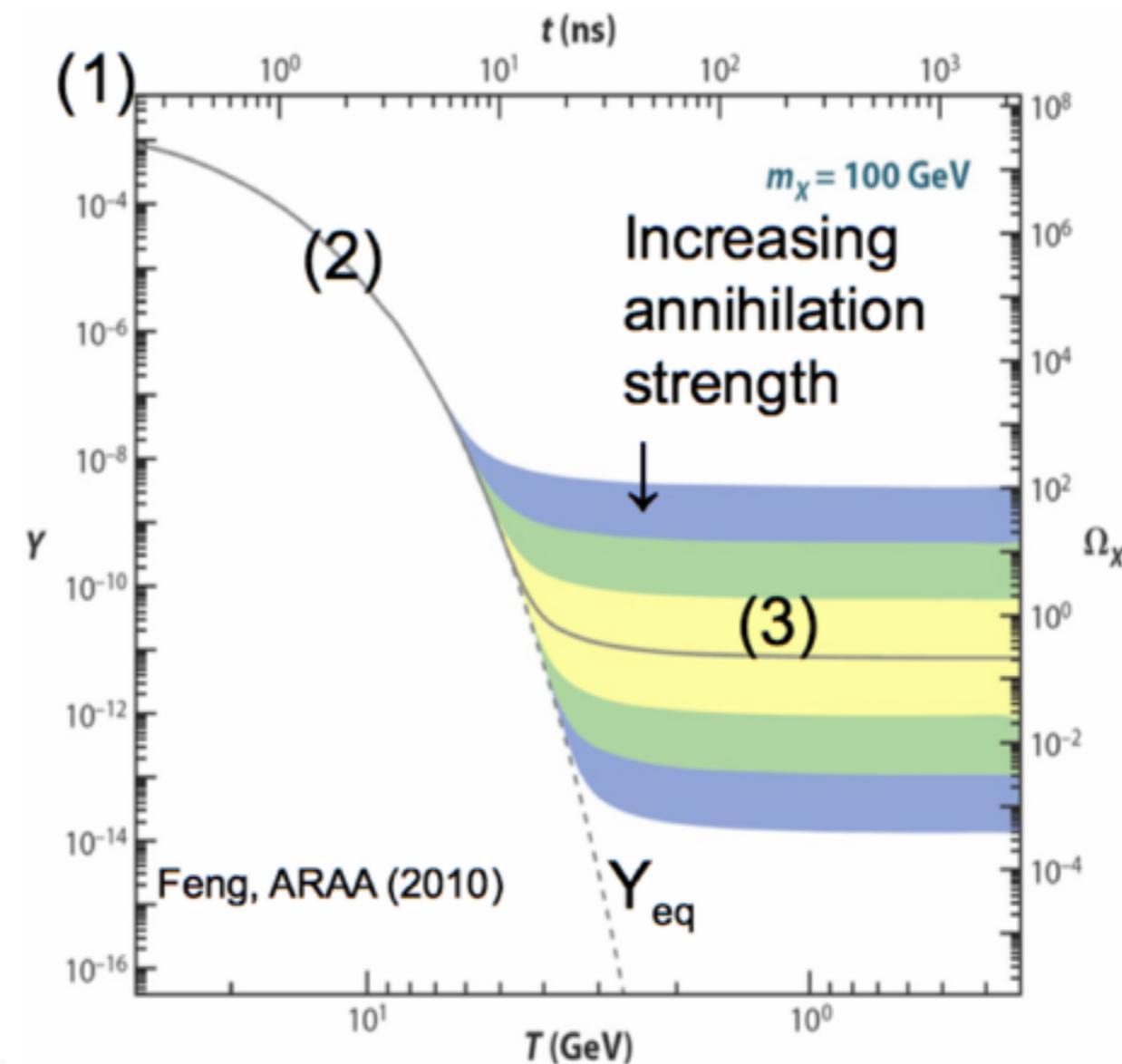
"Stolen" from Kai-Schmidt DM@LHC 2016 Amsterdam

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"WIMP miracle"

$$\alpha = 10^{-3} - 10^{-1} + M_{\text{DM}} \sim 10 - 10^3 \text{ GeV} =$$

the cross section we need! $\sigma v \sim 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$

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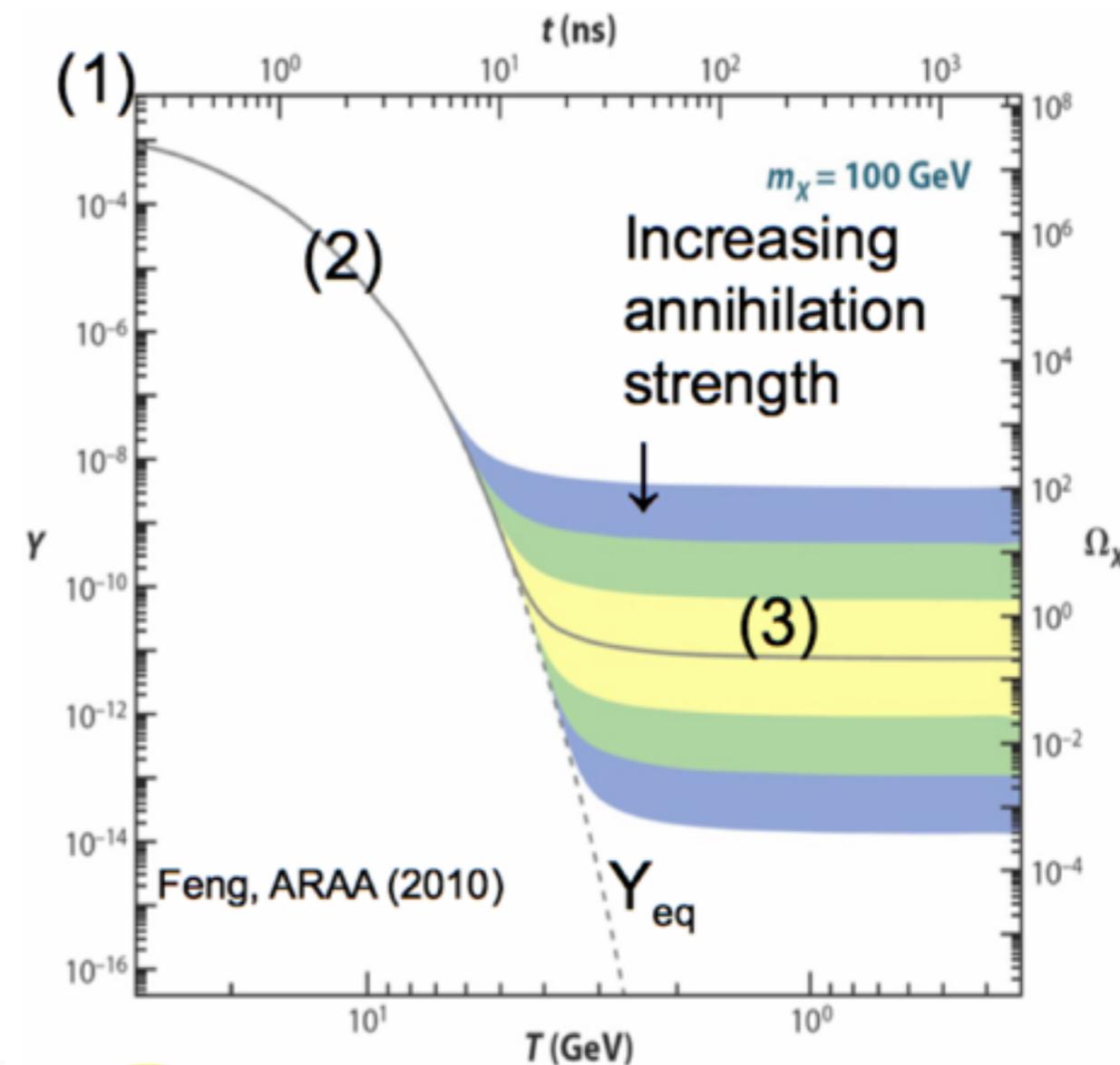
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WIMP miracle motivates
BSM at the weak scale!

WIMPs and theory: 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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The hierarchy problem

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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!



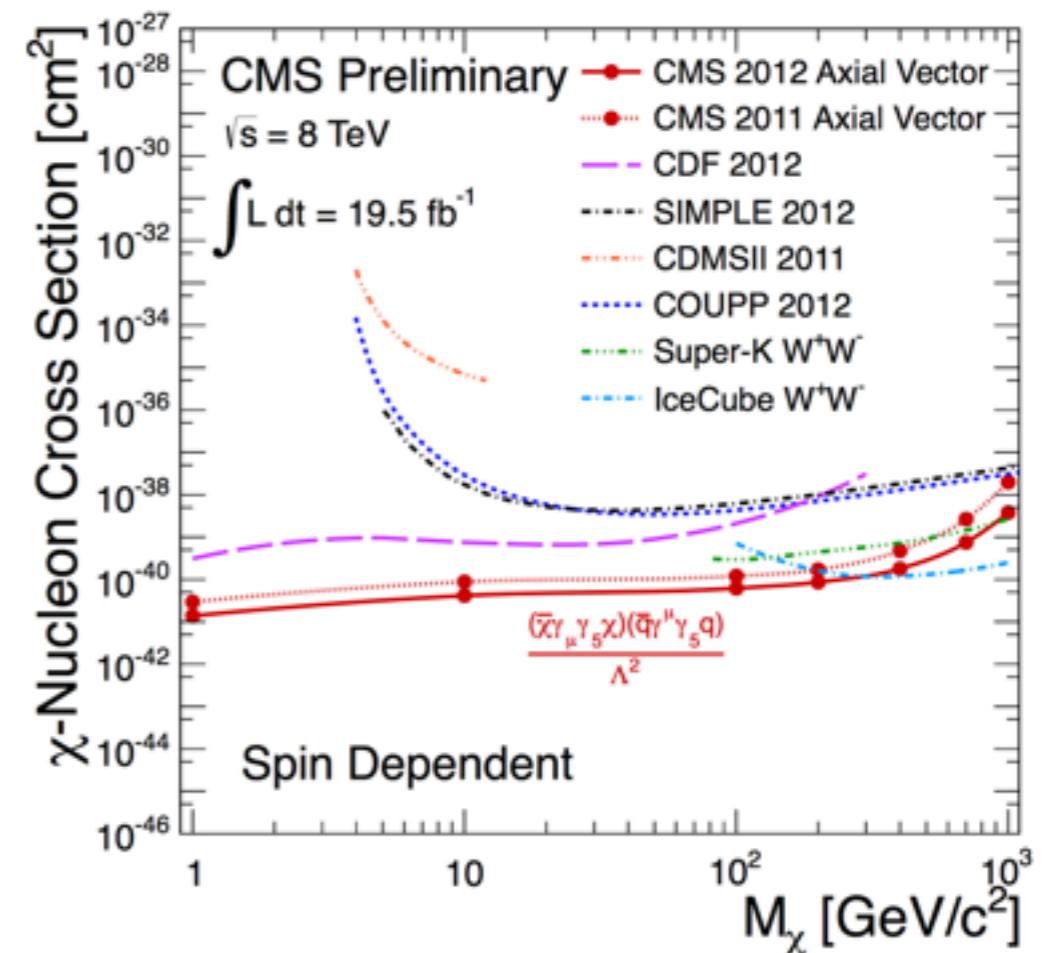
OK, how can we probe WIMPs?

More ambitious: can we probe thermal WIMP paradigm?

General strategy: effective field theories?

The EFT approach, scorecard:

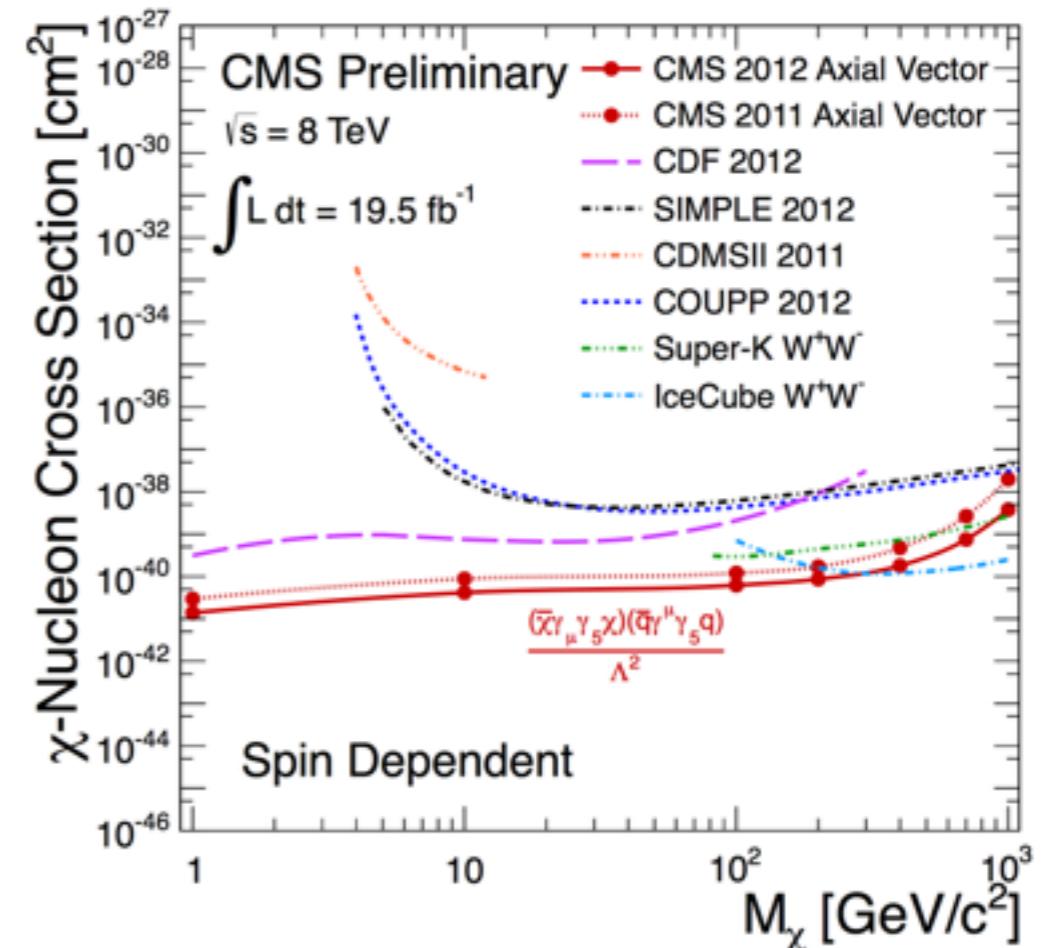
- 😊 Model-independent
- 😊 easy comparison collider - direct detection



General strategy: effective field theories?

The EFT approach, scorecard:

- 😊 Model-independent
 - 😊 easy comparison collider - direct detection
 - 😢 wrong for the LHC (especially 13-14 TeV!)
- often momentum transfer > suppression scale Λ



Lots of recent activity: Busoni et al 1307.2253 and 1402.1275,
Buchmuller et al 1308.6799,...
Abdallah et al 1409.2893,
Racco Wulzer Zwirner 1502.04701,...

Need to 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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helps with gauge coupling unification

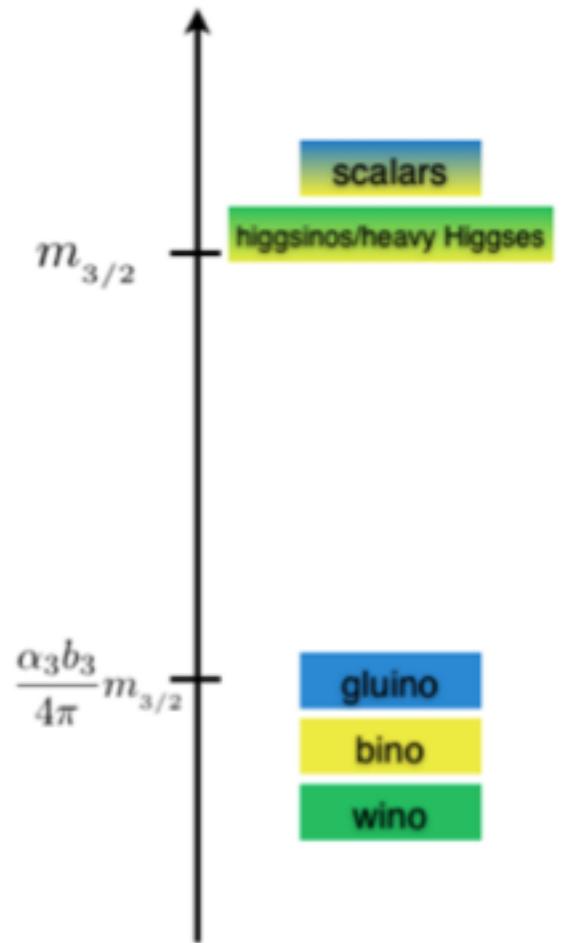
Frigerio Hambye 0912.1545

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Supersymmetry with heavy scalars James Wells hep-ph/0306127

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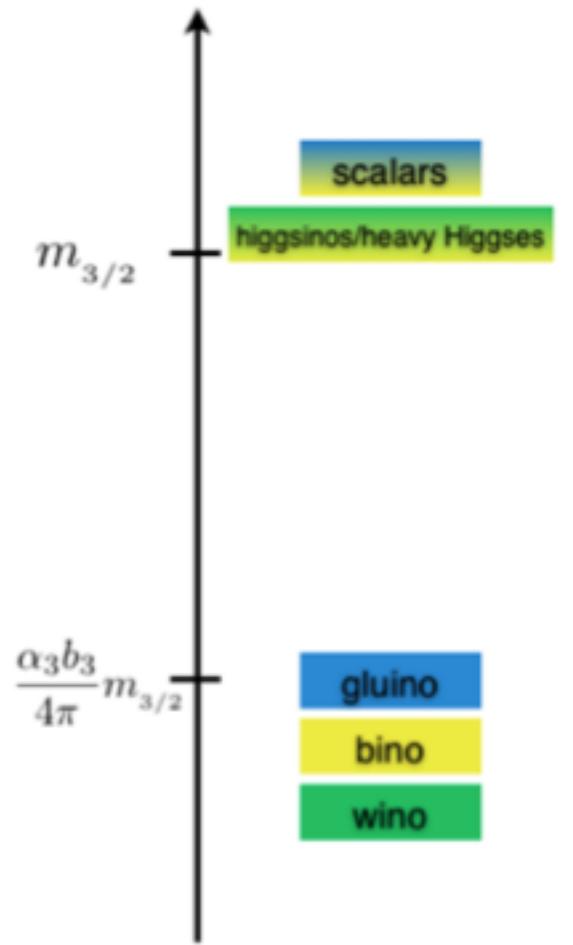


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All good SUSY features (DM, unification of gauge couplings,...)

Hierarchy problem? Go anthropic

See also

Arkani-Hamed Dimopoulos hep-th/0405159
Giudice Romanino hep-ph/0406088

Wino LSP candidate for Dark Matter!

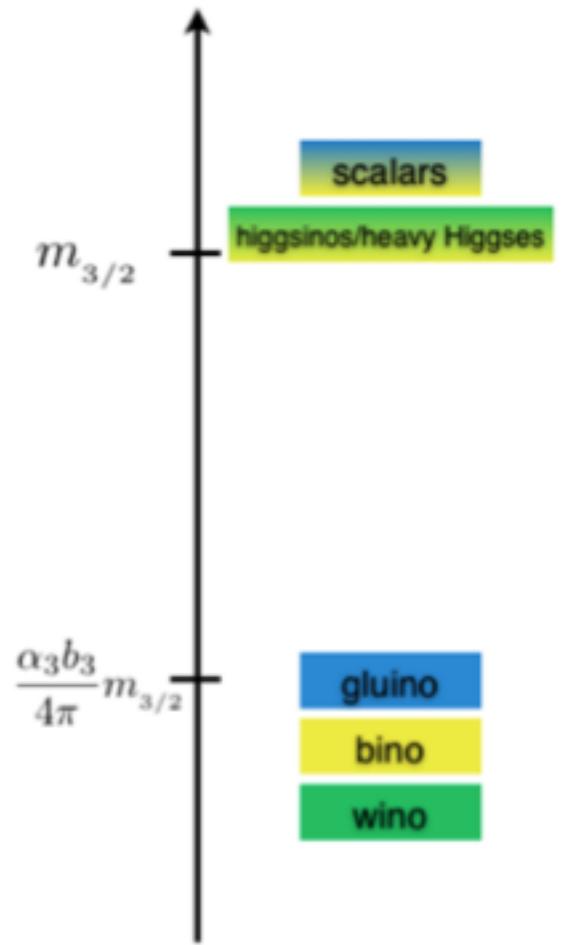
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D'Eramo Hall Pappadopulo 1409.5123

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Phenomenology

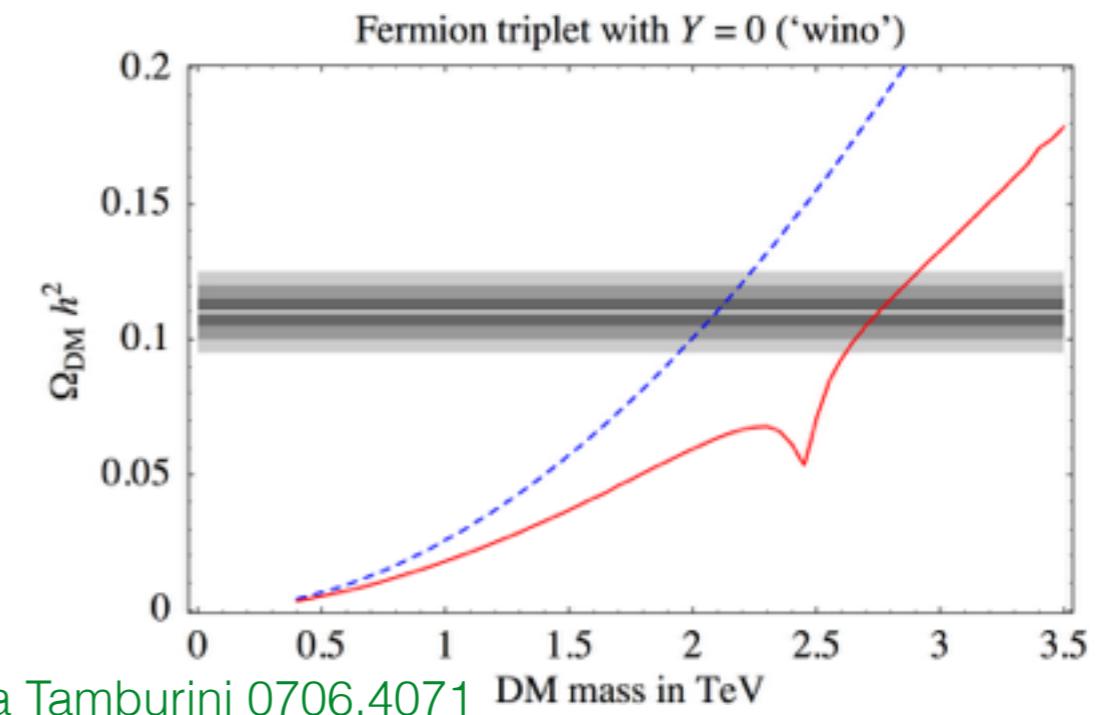
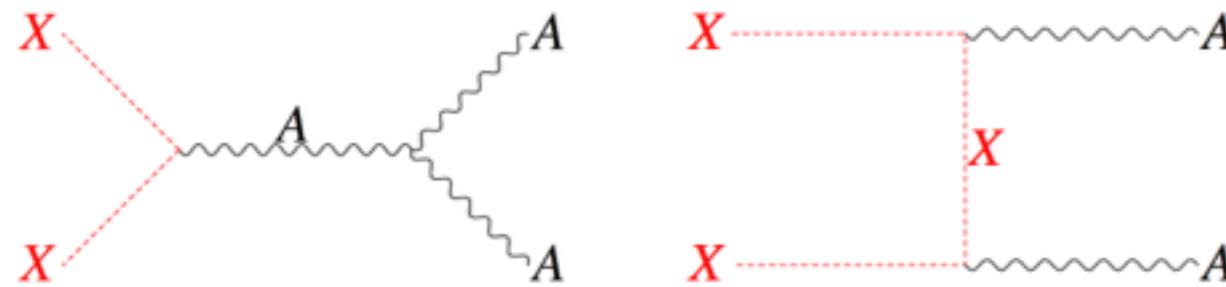
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\chi} (i \hat{D} - M_\chi) \chi$$

M_χ is **the only free parameter**, fixed if we impose thermal relic abundance

Thermal relic WIMPs

(we'll keep an open mind on DM mass)

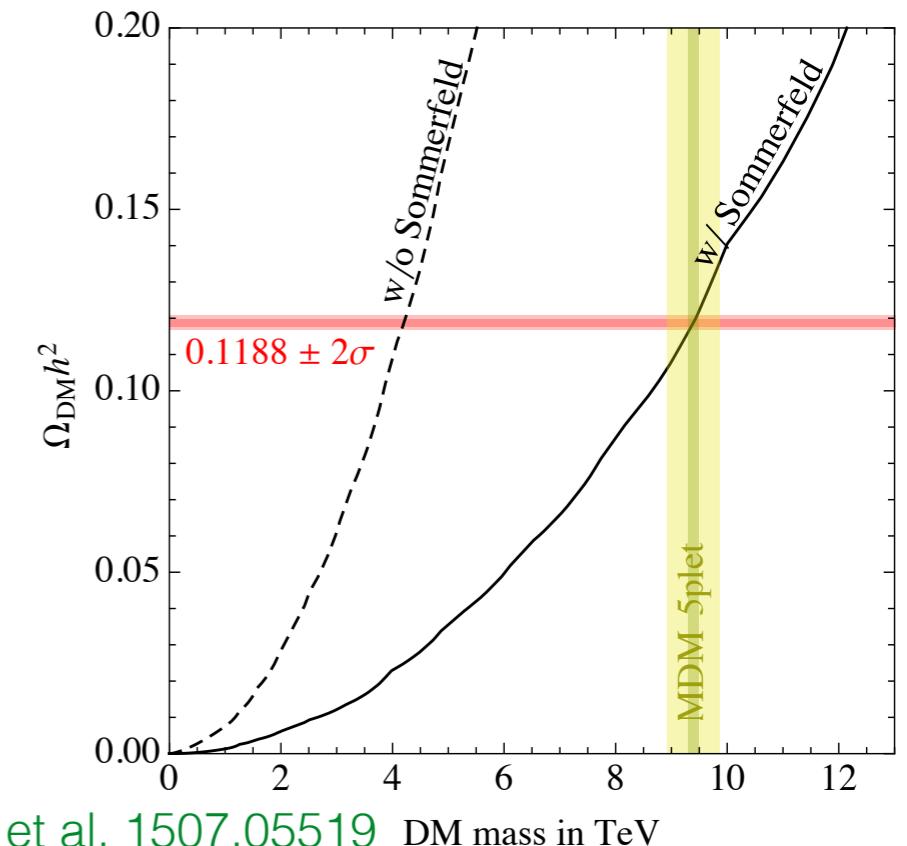
Prototypical WIMP candidate $\longrightarrow M_{\text{DM}} \sim \text{TeV}$



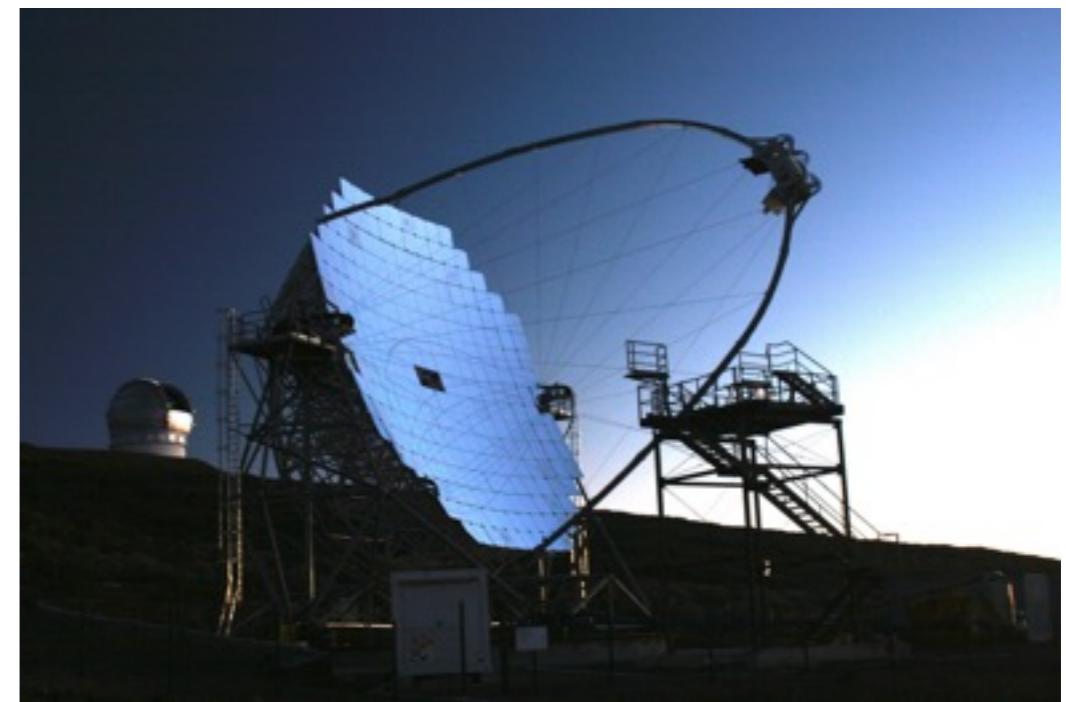
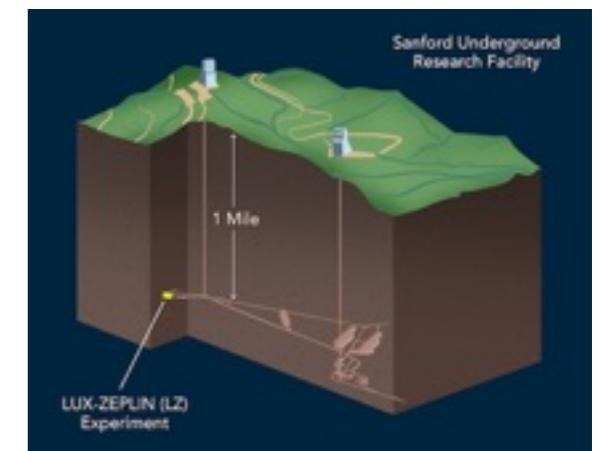
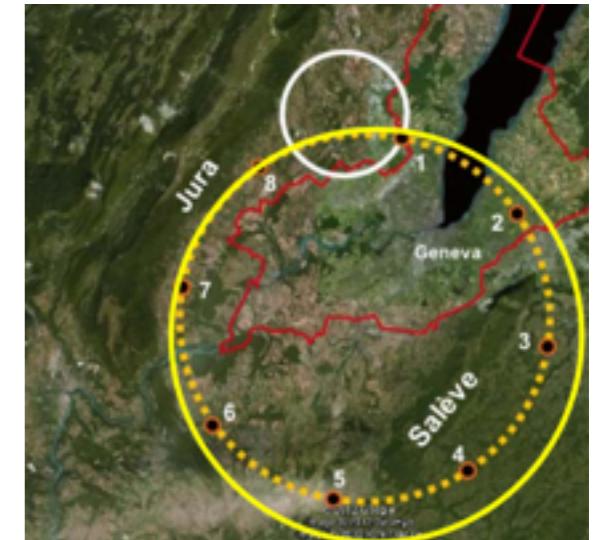
Important to include:

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

$$M_{\text{thermal}}^{\text{3plet}} \simeq 3 \text{ TeV} \quad M_{\text{thermal}}^{\text{5plet}} \simeq 9.5 \text{ TeV}$$



Phenomenology

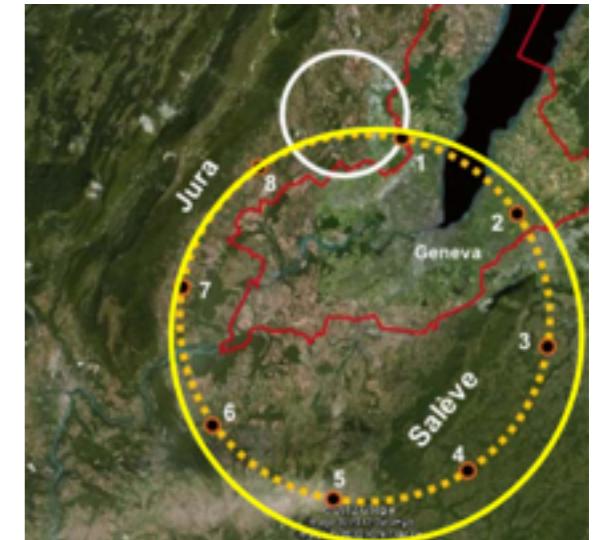


5plet: no hopes to reach thermal mass

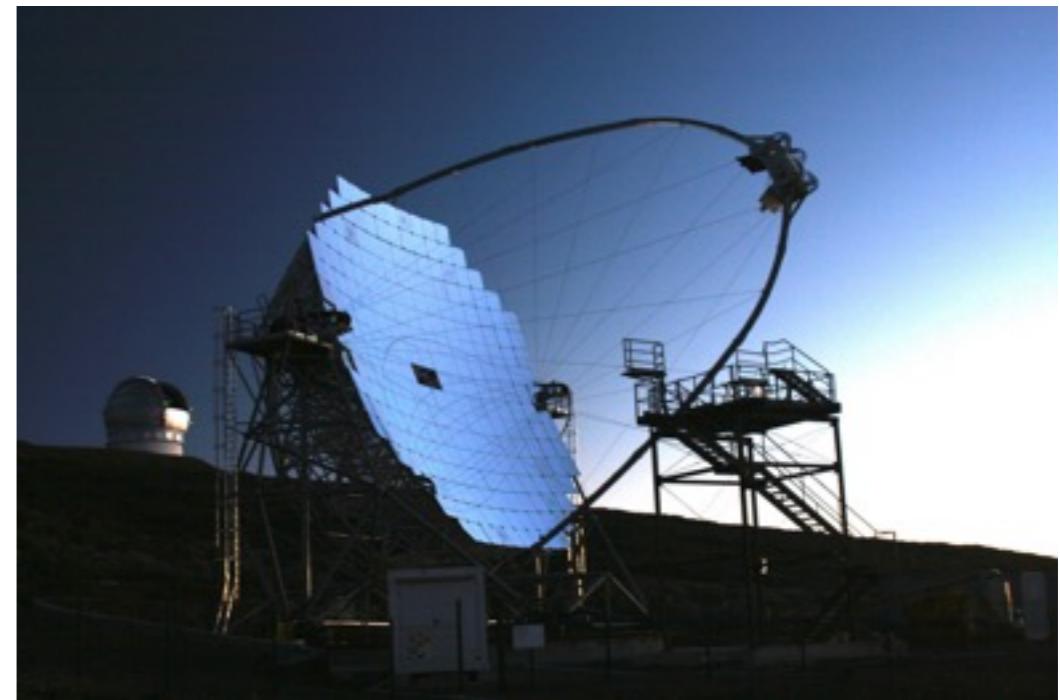
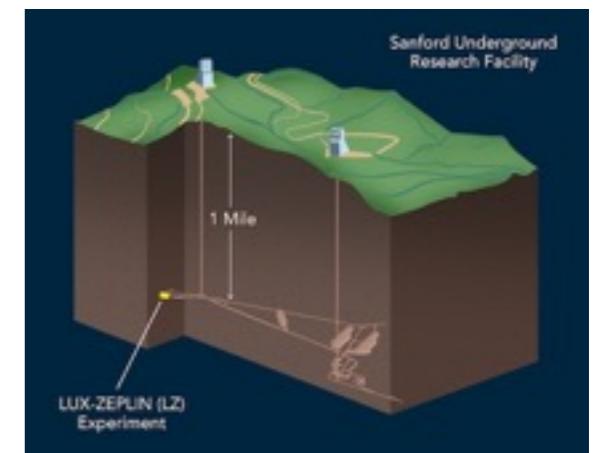
Ostdiek 1506.03445, FCC-hh CERN report (to appear soon...)

3plet: no hopes before a 100 TeV collider (i.e. 2040?)

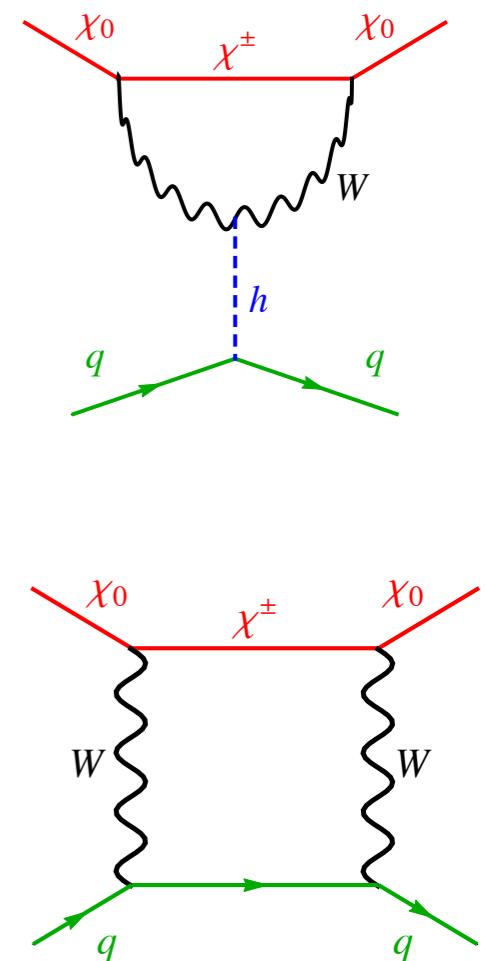
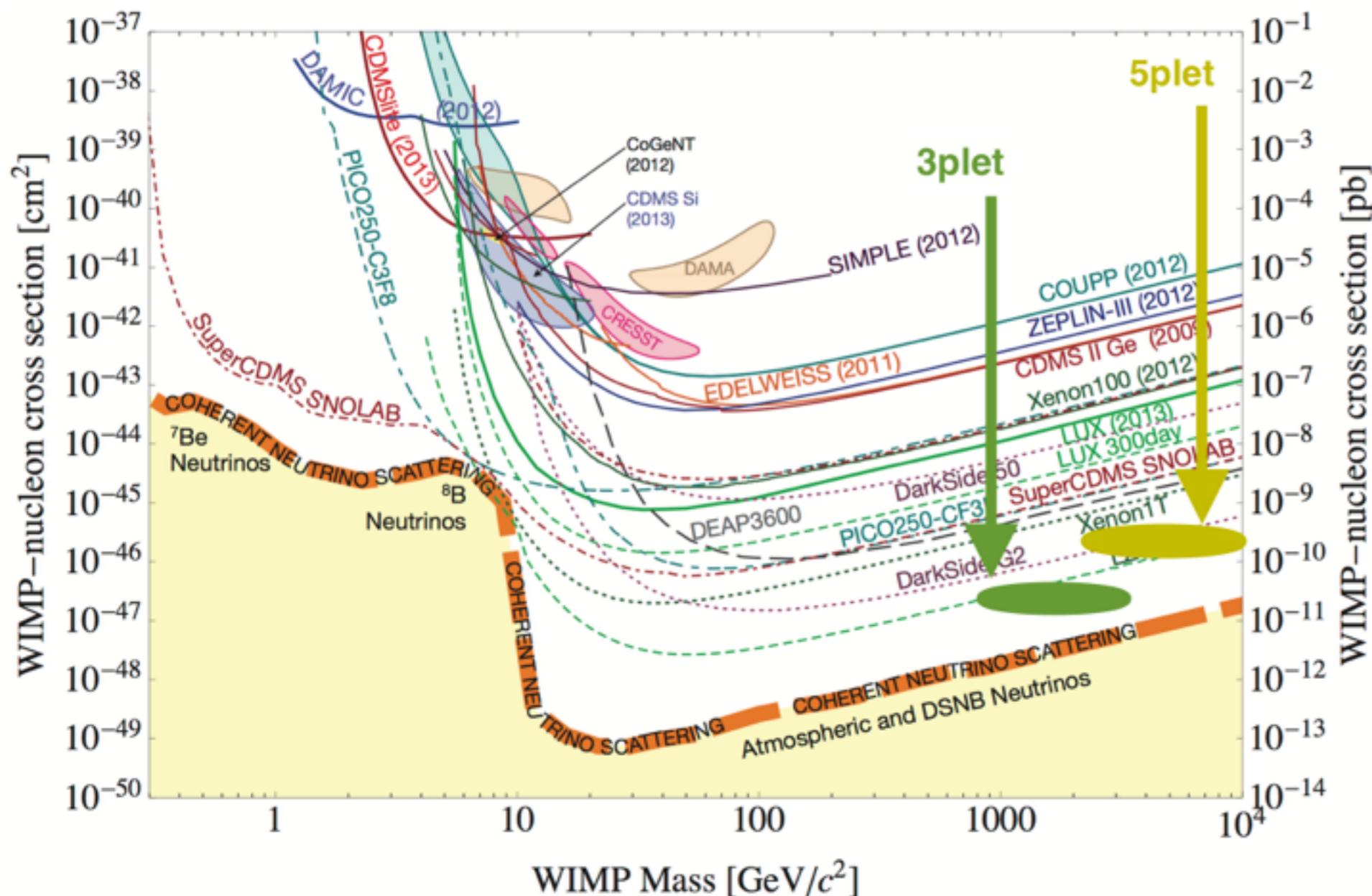
Low Wang 1404.0682, Cirelli FS Taoso 1407.7058, Berlin et al. 1502.05044



Phenomenology



Direct detection



Hisano et al. 1504.00915:

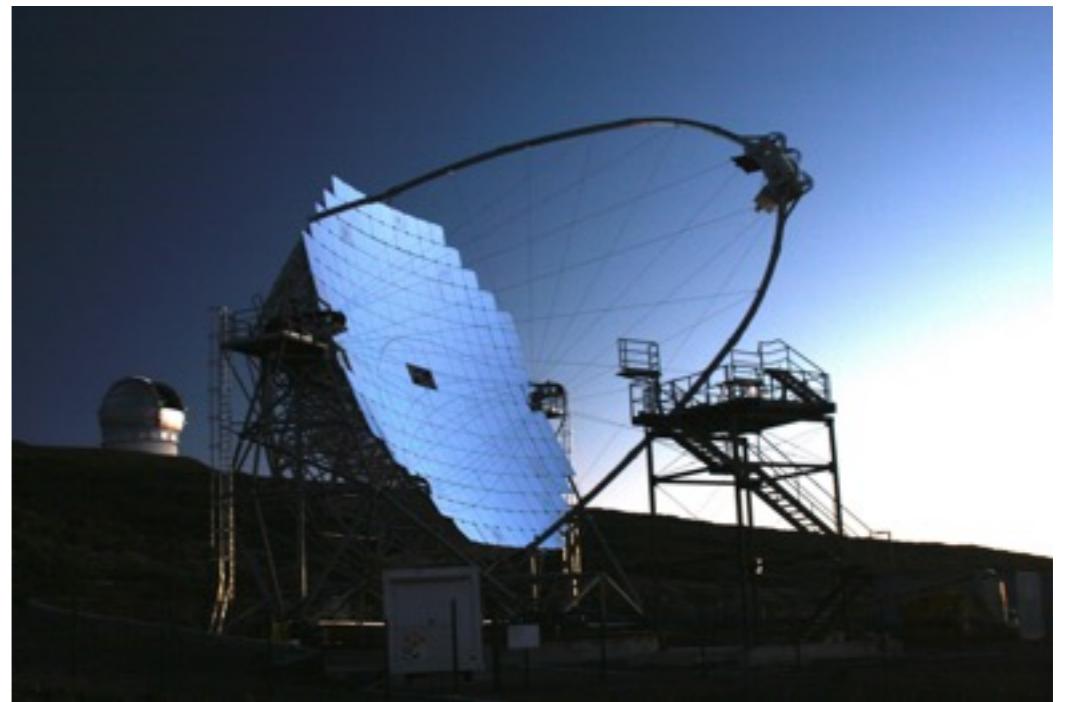
$$\sigma_{\text{SI}}^{\text{5plet}} = 1.9 \times 10^{-46} \text{ cm}^2$$

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

Full NLO in α_S , O(50%) uncertainties

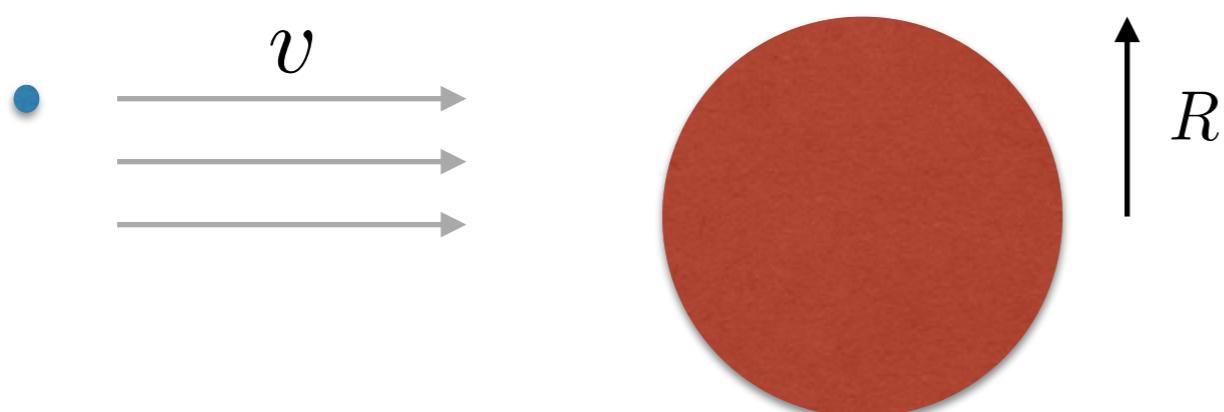
Phenomenology

- ➊ Sommerfeld enhancement
- ➋ Galactic Center vs Dwarf Spheroidals



Sommerfeld enhancement

Classical analogous



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

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

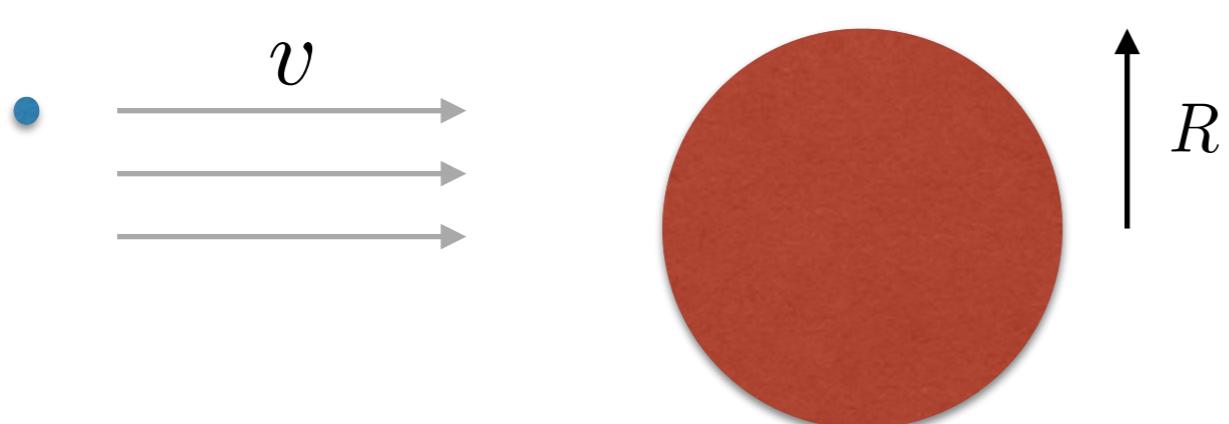
If slow, gravity becomes important:

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

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Arkani-Hamed et al. 0810.0713 for nice explanation

Classical analogous



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

If slow, gravity becomes important:

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

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

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

DM mass for SM weak force? $\alpha_w \sim 1/30$

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

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 Schrödinger eq.**

EW multiples in the gamma sky

Sommerfeld enhancement

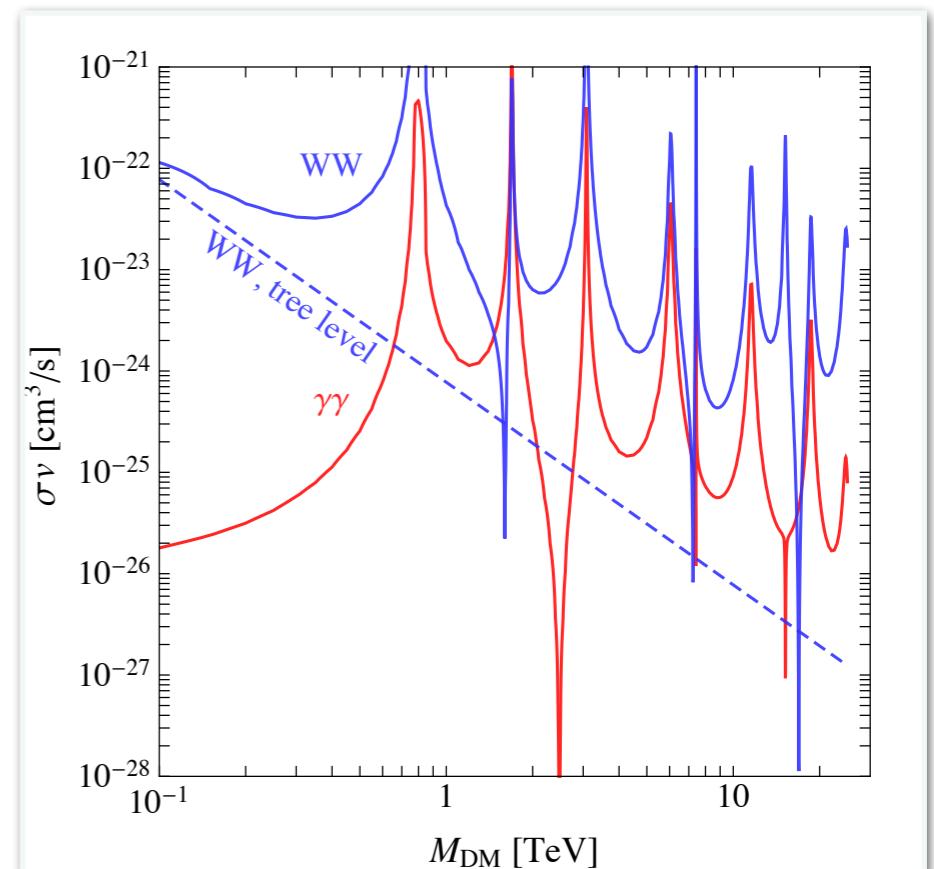
at low velocities non-relativistic attractive potential

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, $\chi_0\chi_0 \rightarrow WW, \gamma\gamma$



EW multiples in the gamma sky

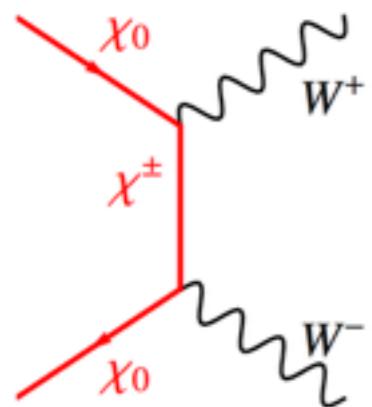
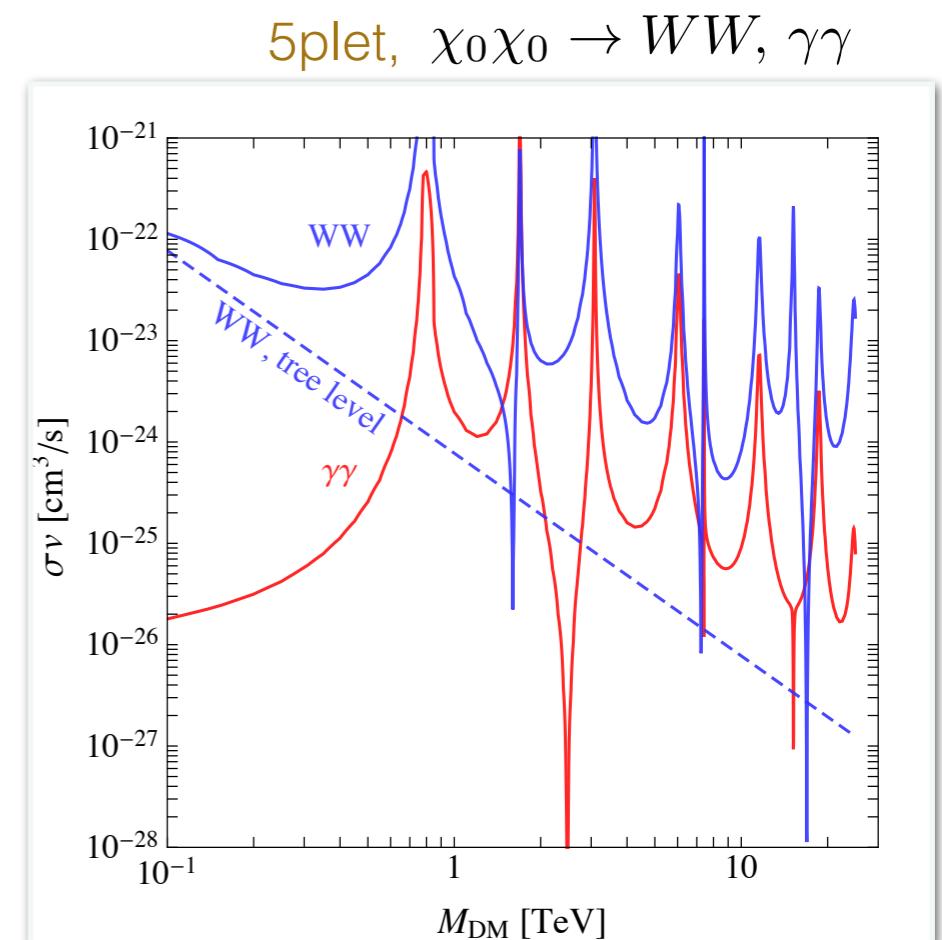
Sommerfeld enhancement

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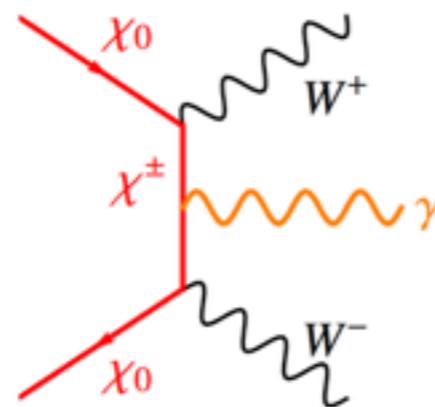
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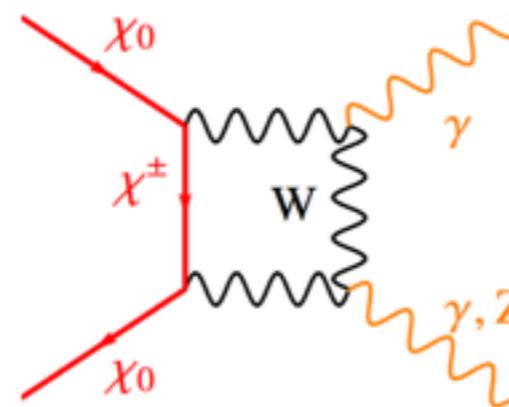
σv saturates at $v \sim 10^{-2} c$



$\bar{p}, e^+, \nu, \gamma, \dots$
“continuum”



γ -ray lines: smaller cross sections
but features in γ -spectrum enhance sensitivities!



Gamma-ray lines from the GC

Cirelli Hambye Panci FS Taoso 1507.05519 + in progress

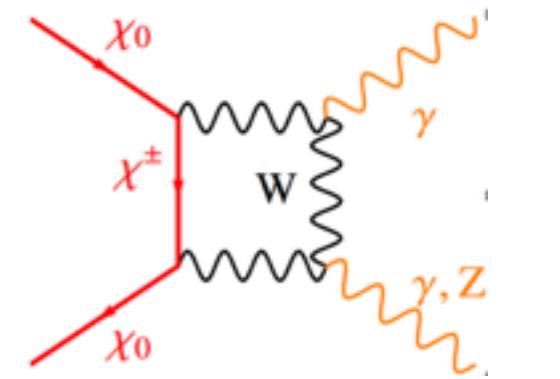
$$E_\gamma = M_{\text{DM}}$$

FERMI

up to a few x 100 GeV
space-based
covers all sky

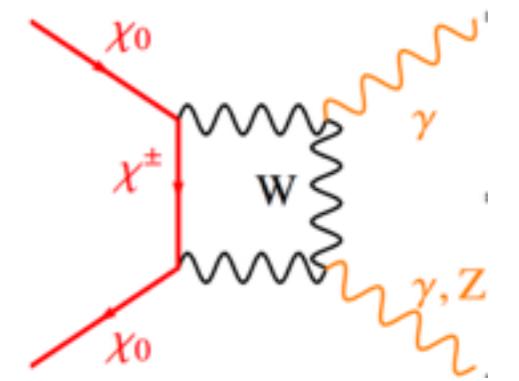
HESS

up to a few x 10 TeV,
ground based (Namibia, only southern sky!)
need to choose target (Galactic Center)



Gamma-ray lines from the GC

Cirelli Hambye Panci FS Taoso 1507.05519 + in progress

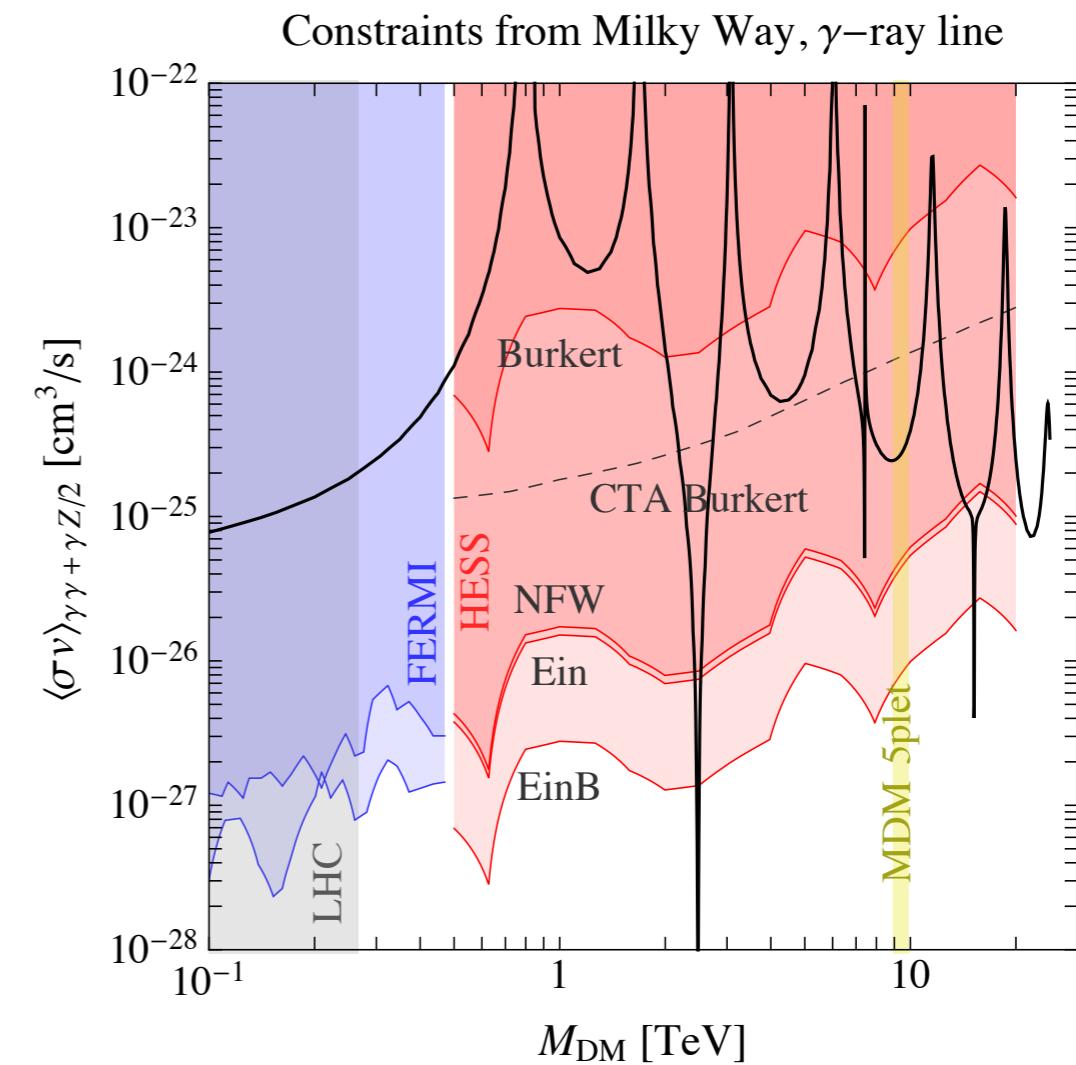
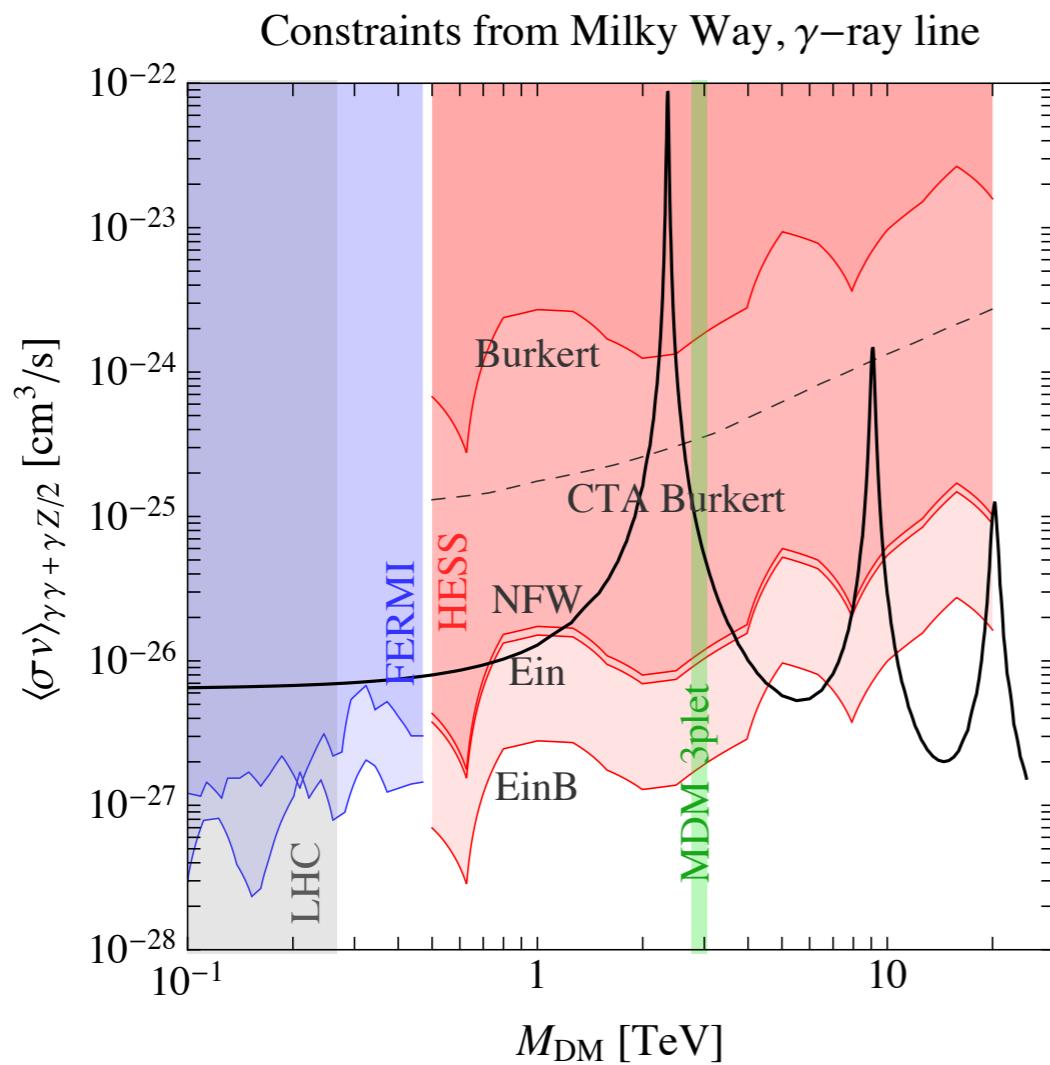


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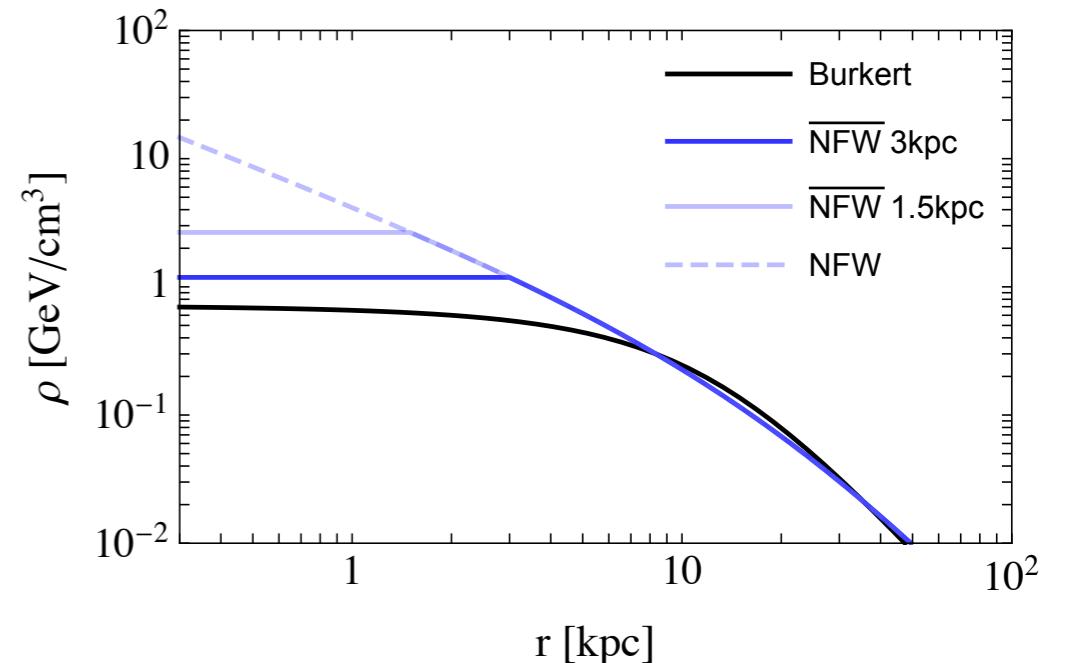


[CTA 5 hours prospects from Ovanesyan et al 1409.8294 and Bergstrom et al 1207.6773]

Astrophysical uncertainties & the GC

This is why I was bothering you!

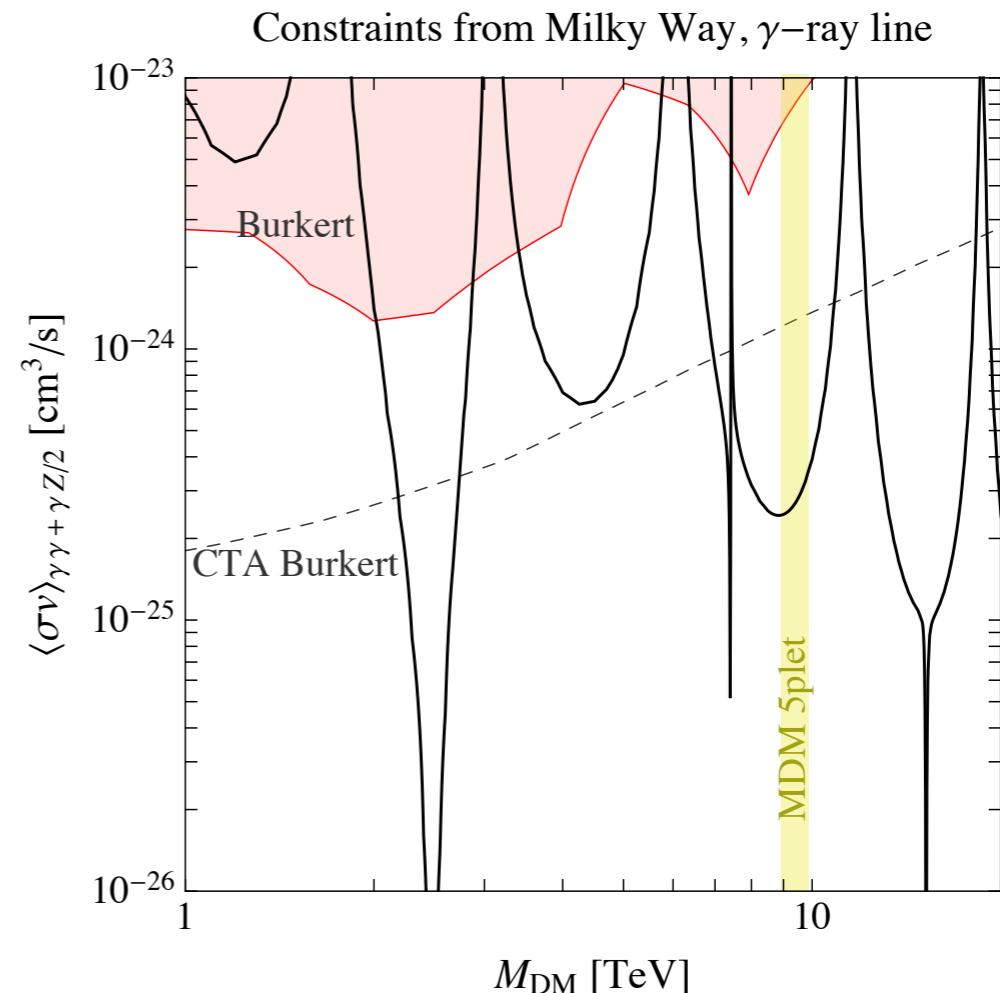
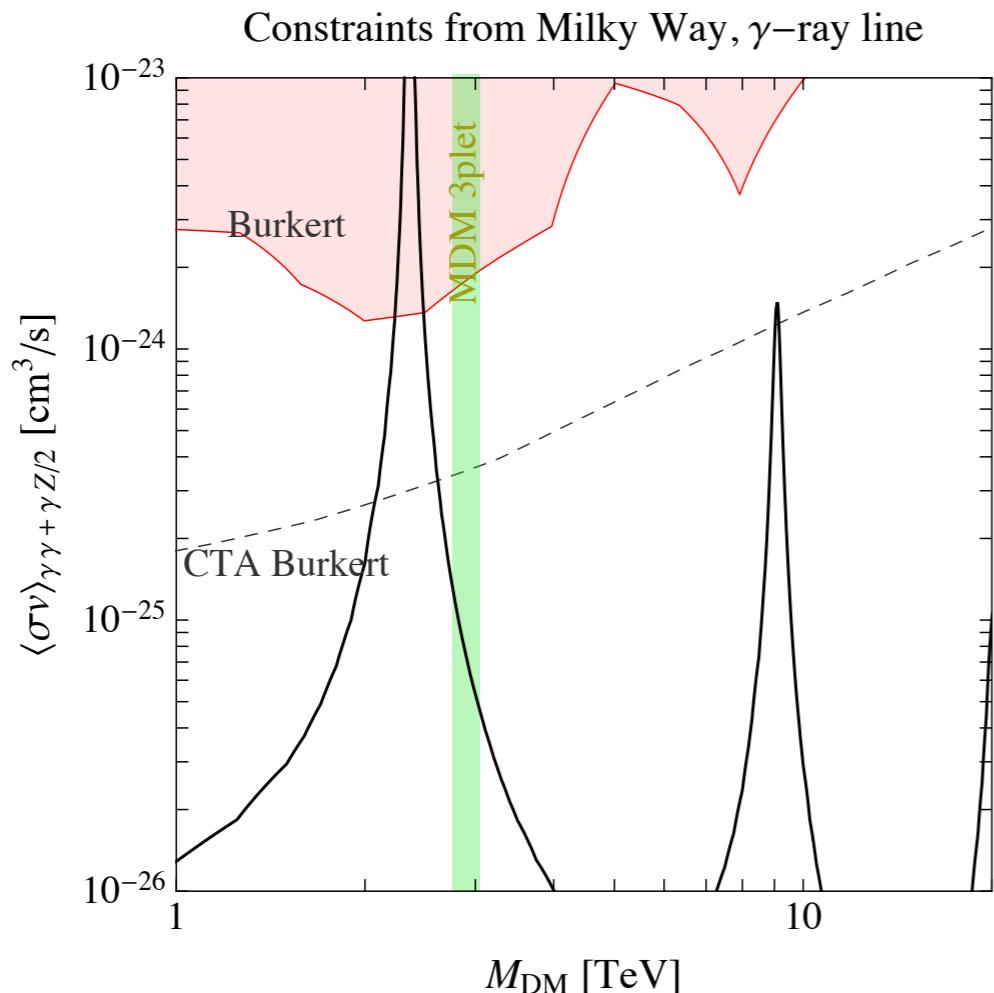
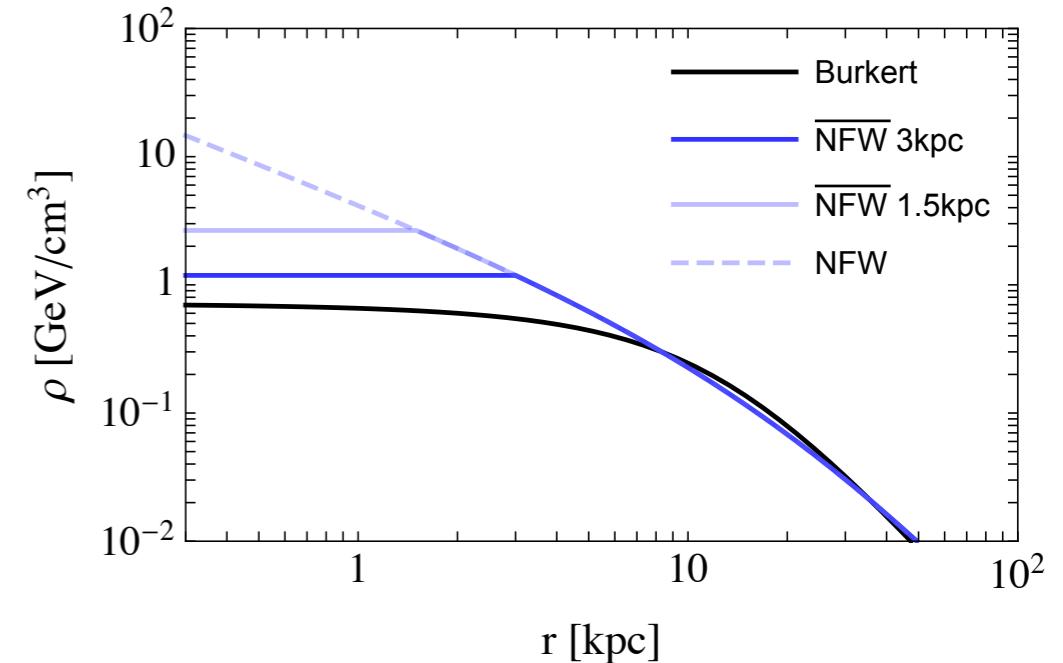
Feedback encouraged



Astrophysical uncertainties & the GC

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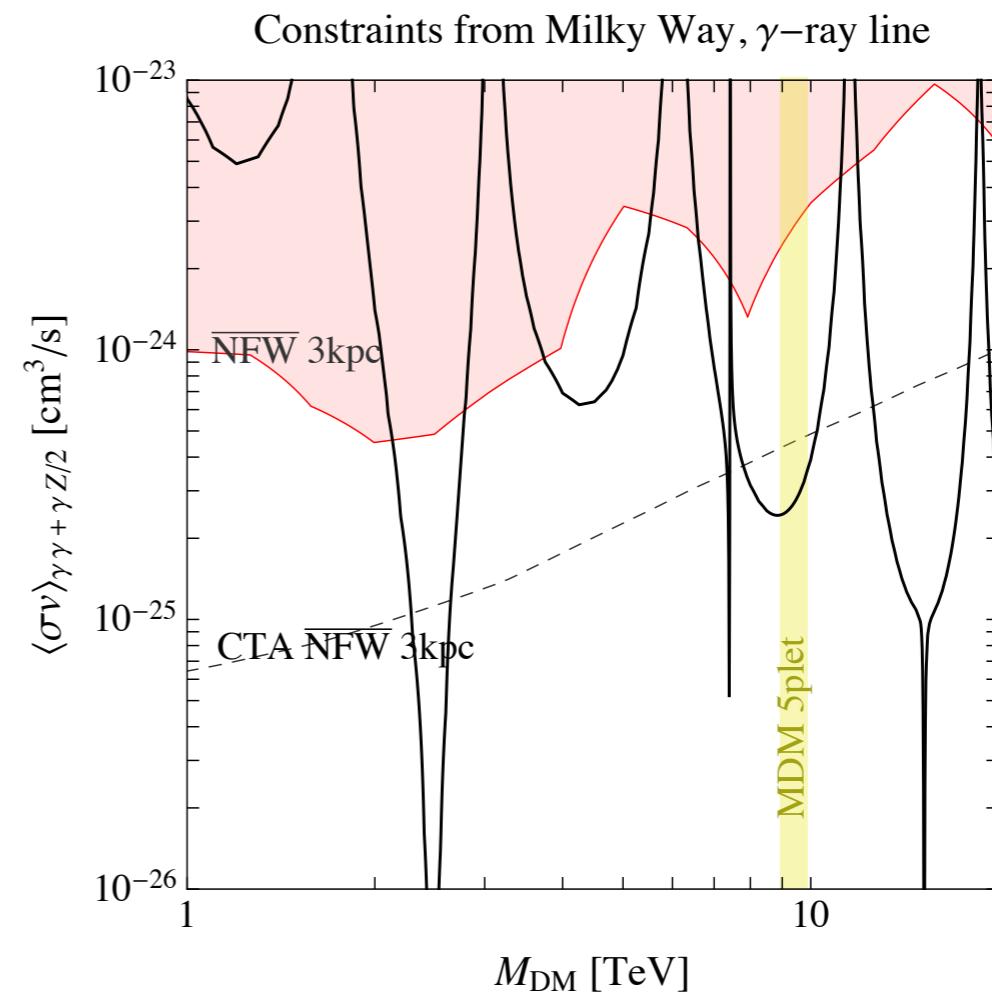
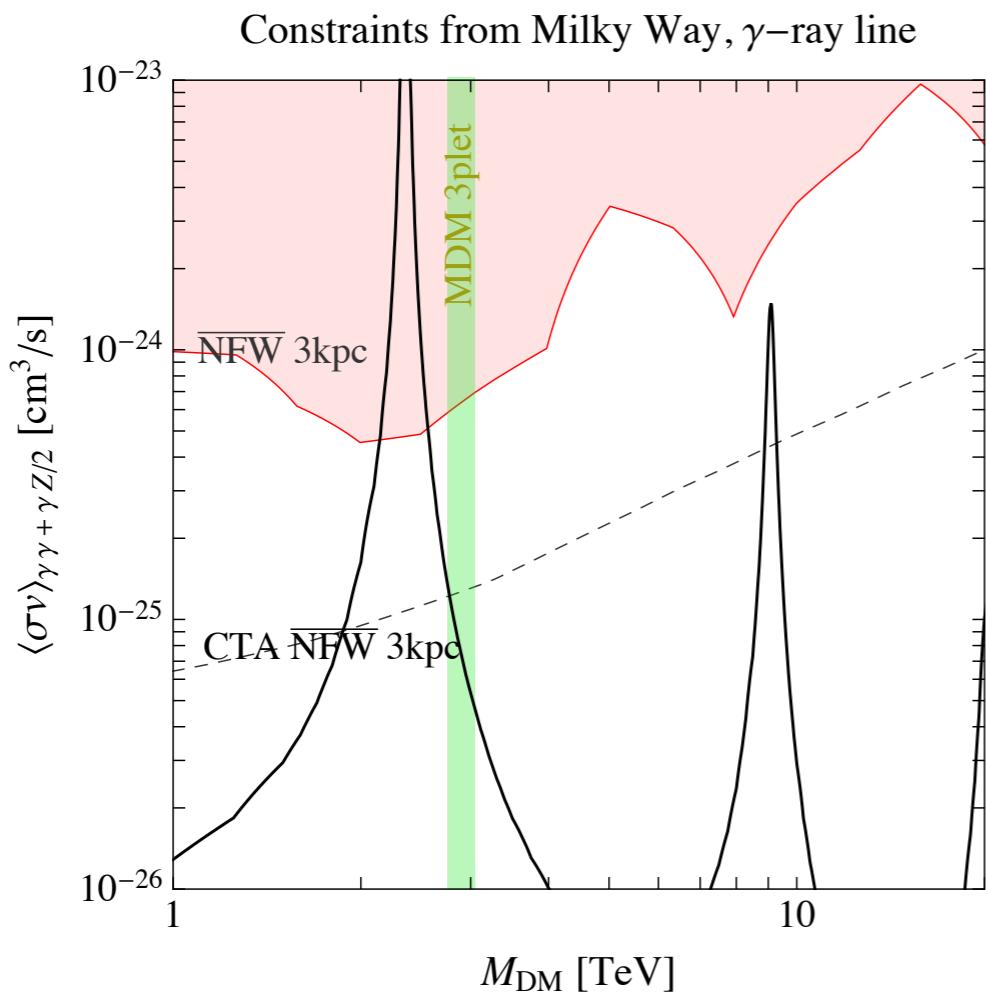
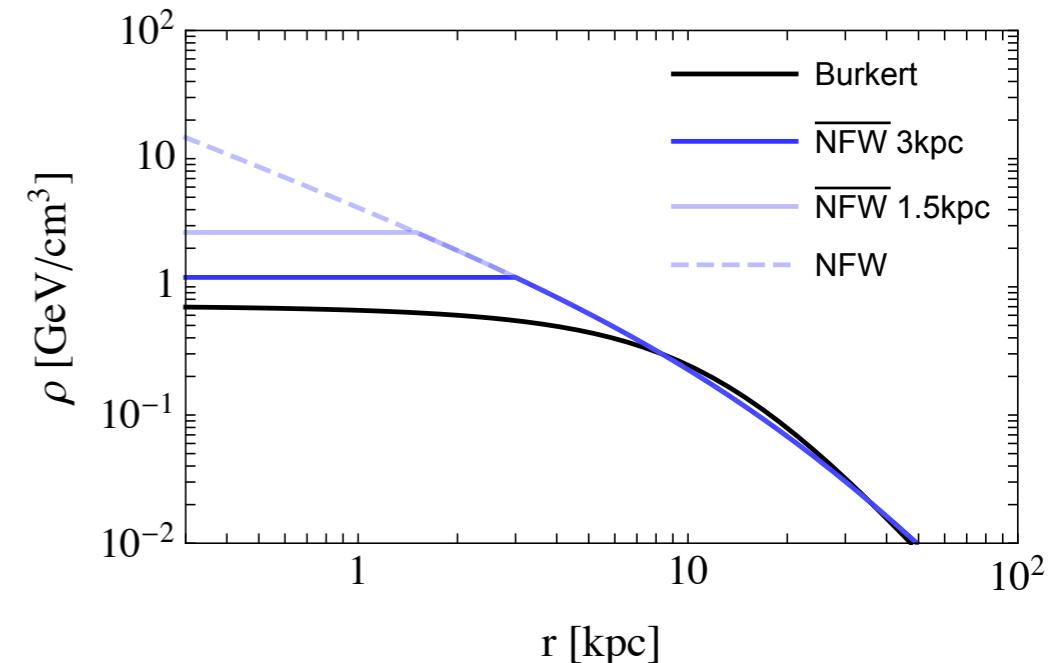
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Astrophysical uncertainties & the GC

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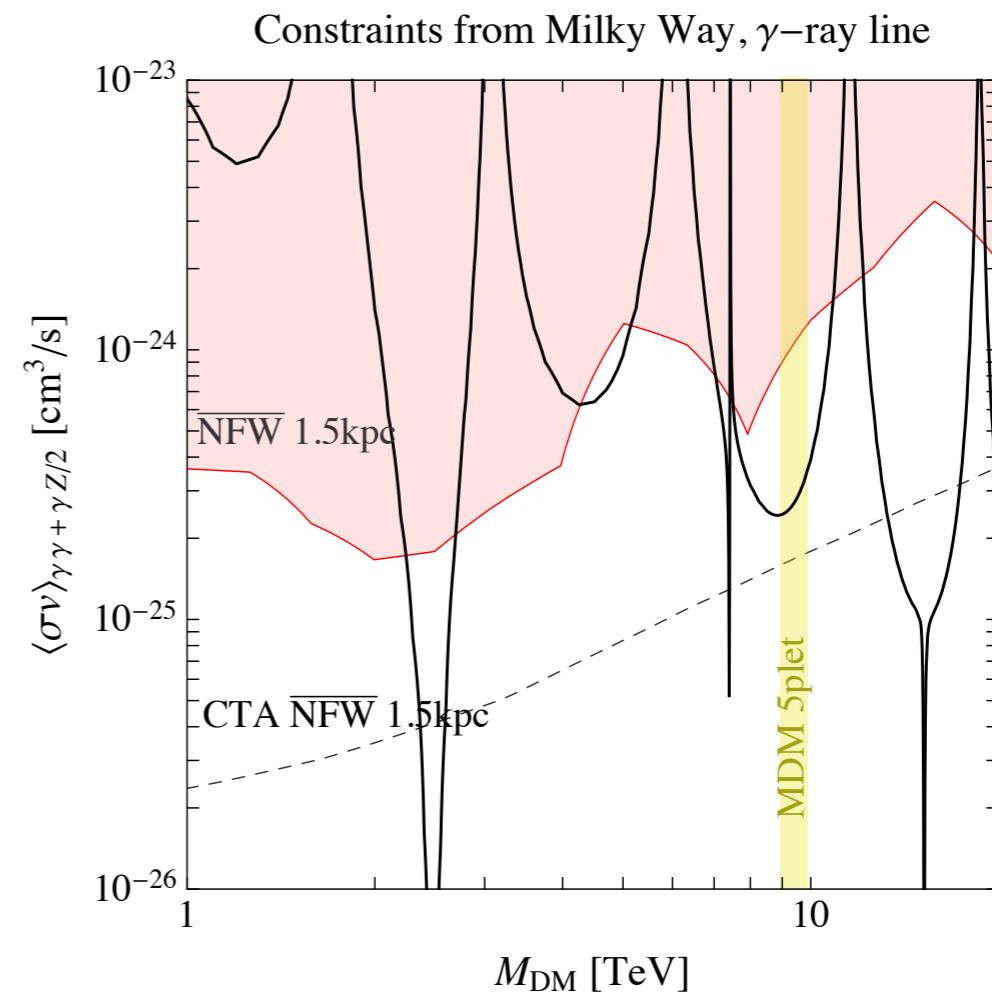
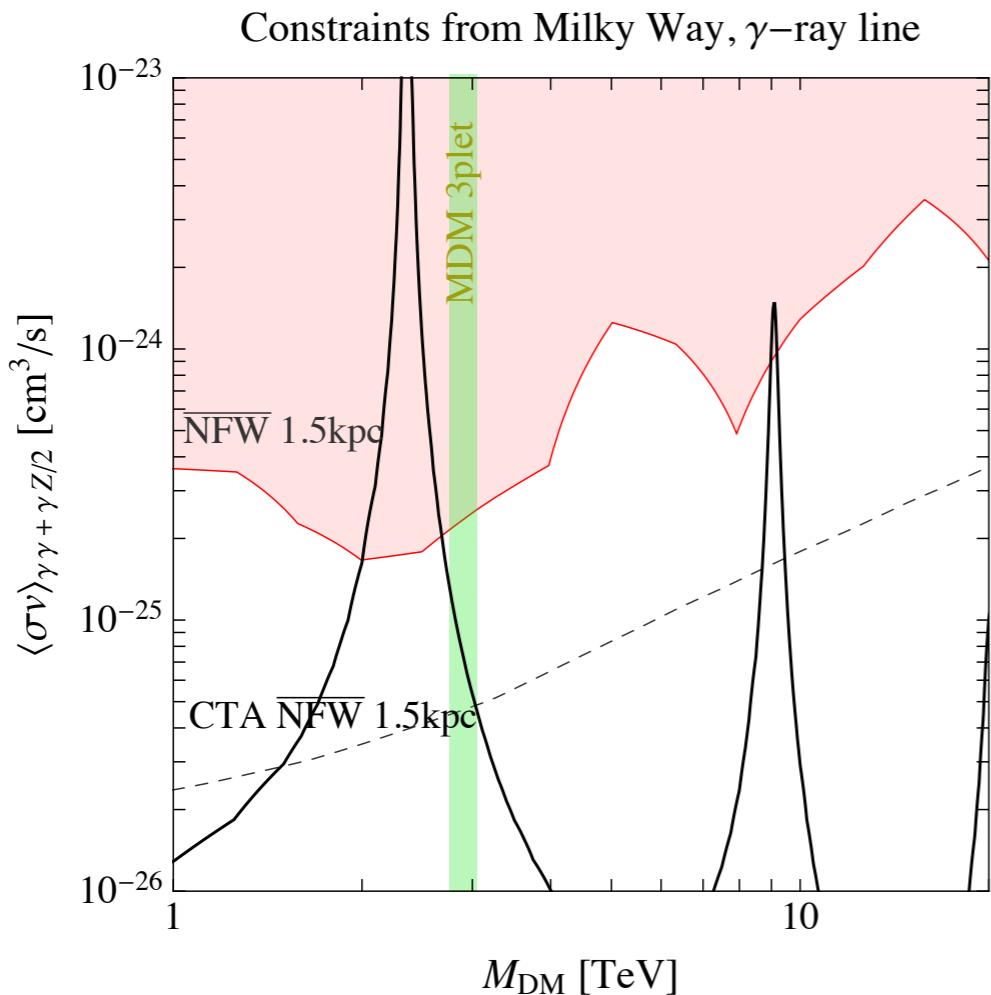
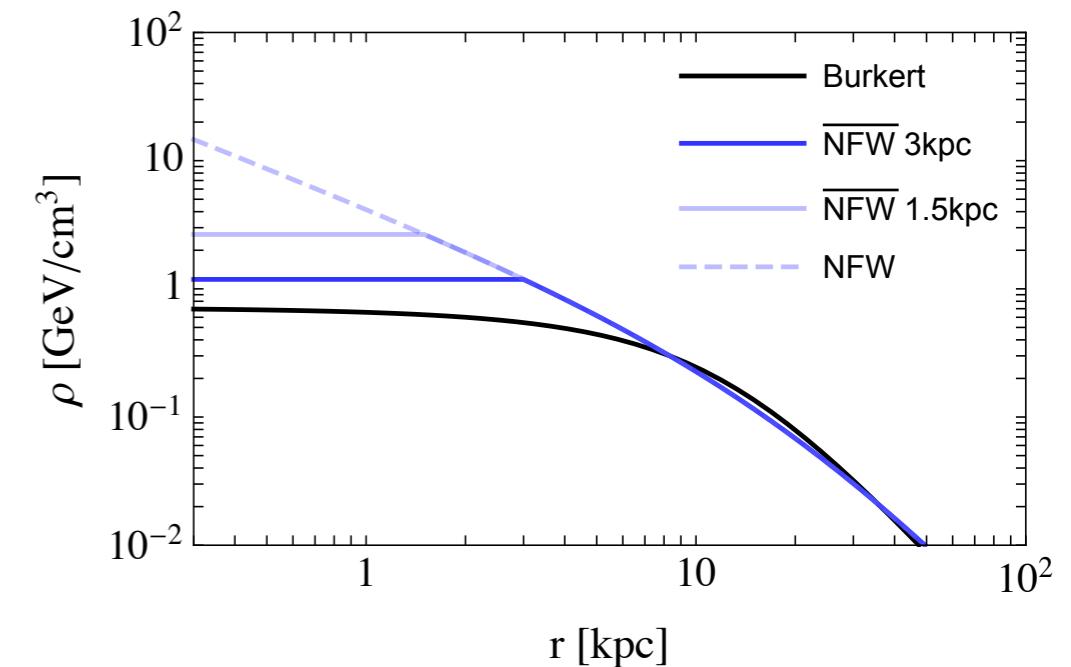
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Astrophysical uncertainties & the GC

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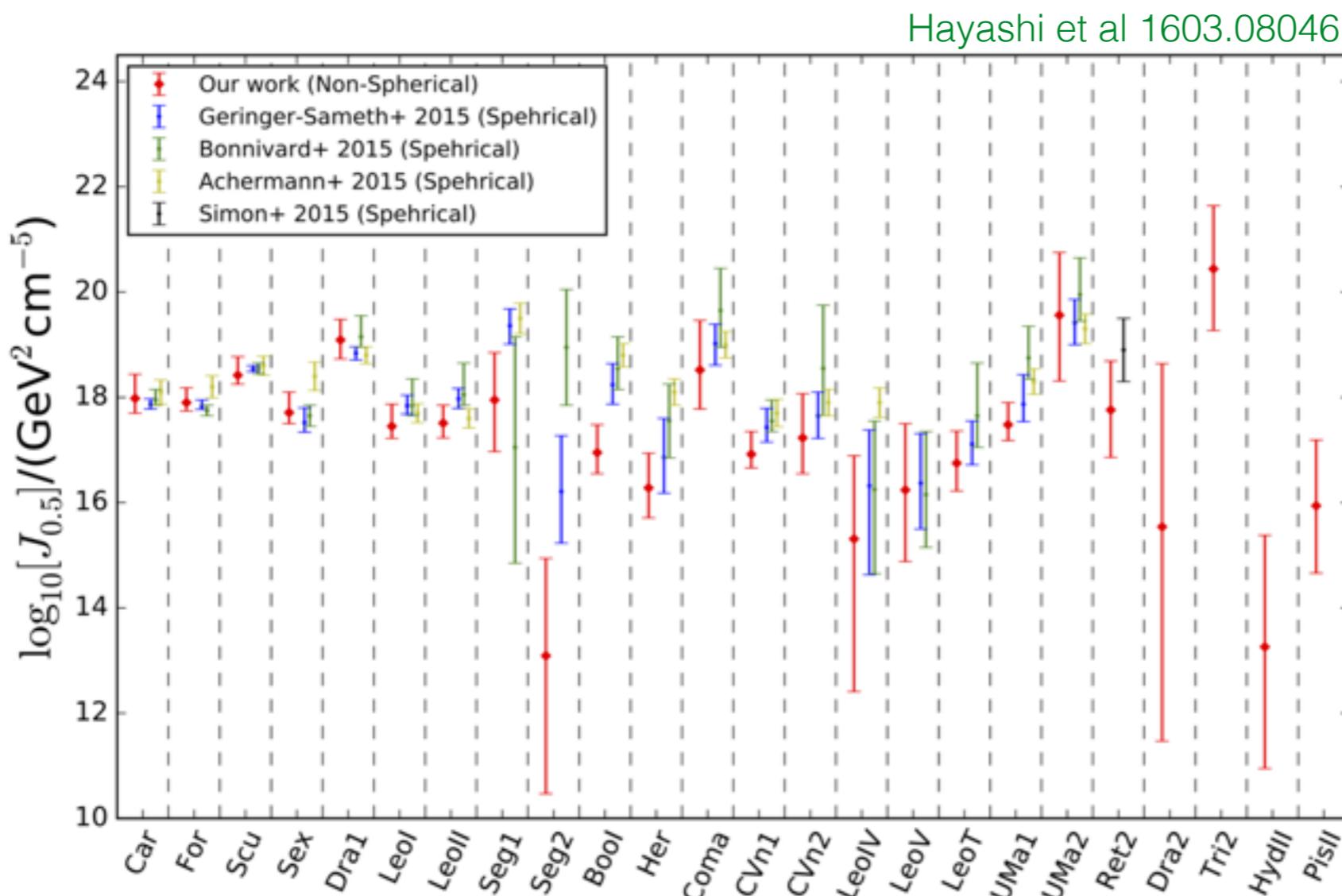
DM signals from dSphs

Dark Matter annihilation signals \propto "J"-factor

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

- 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,
-

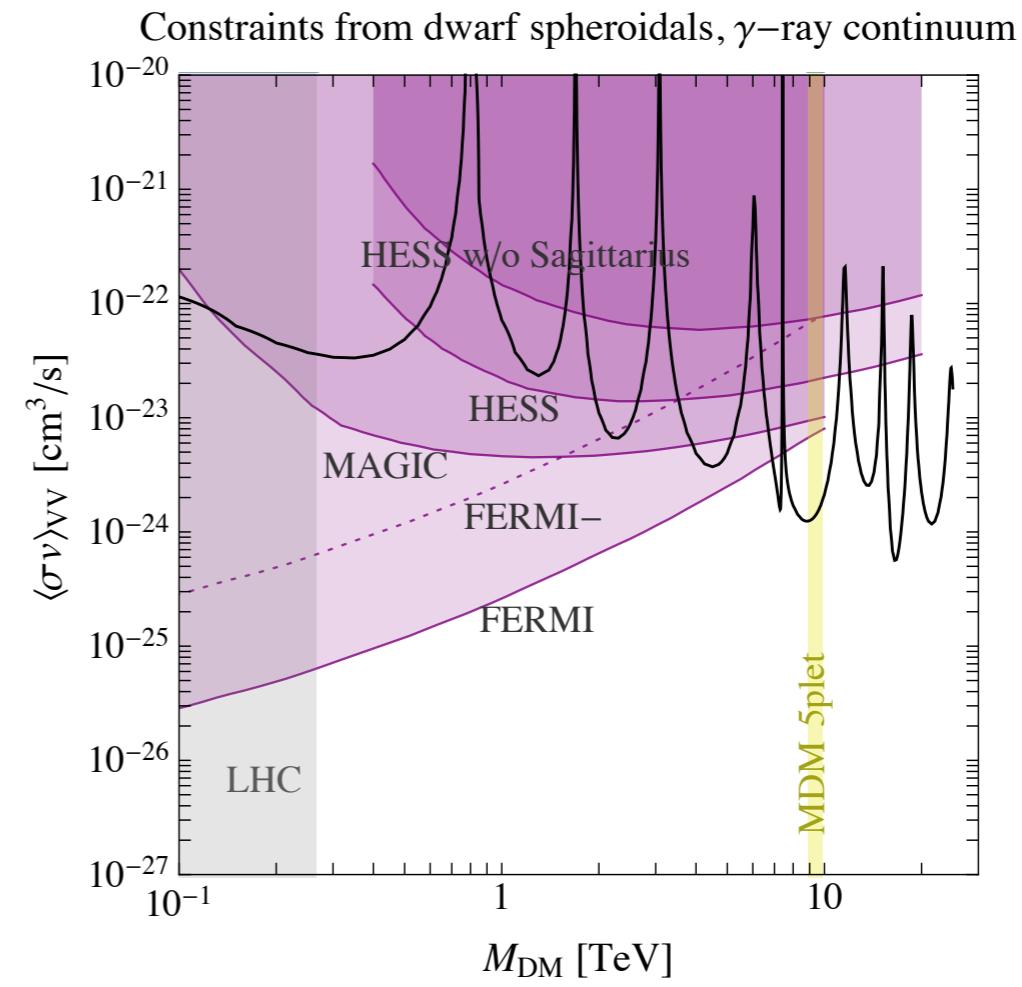
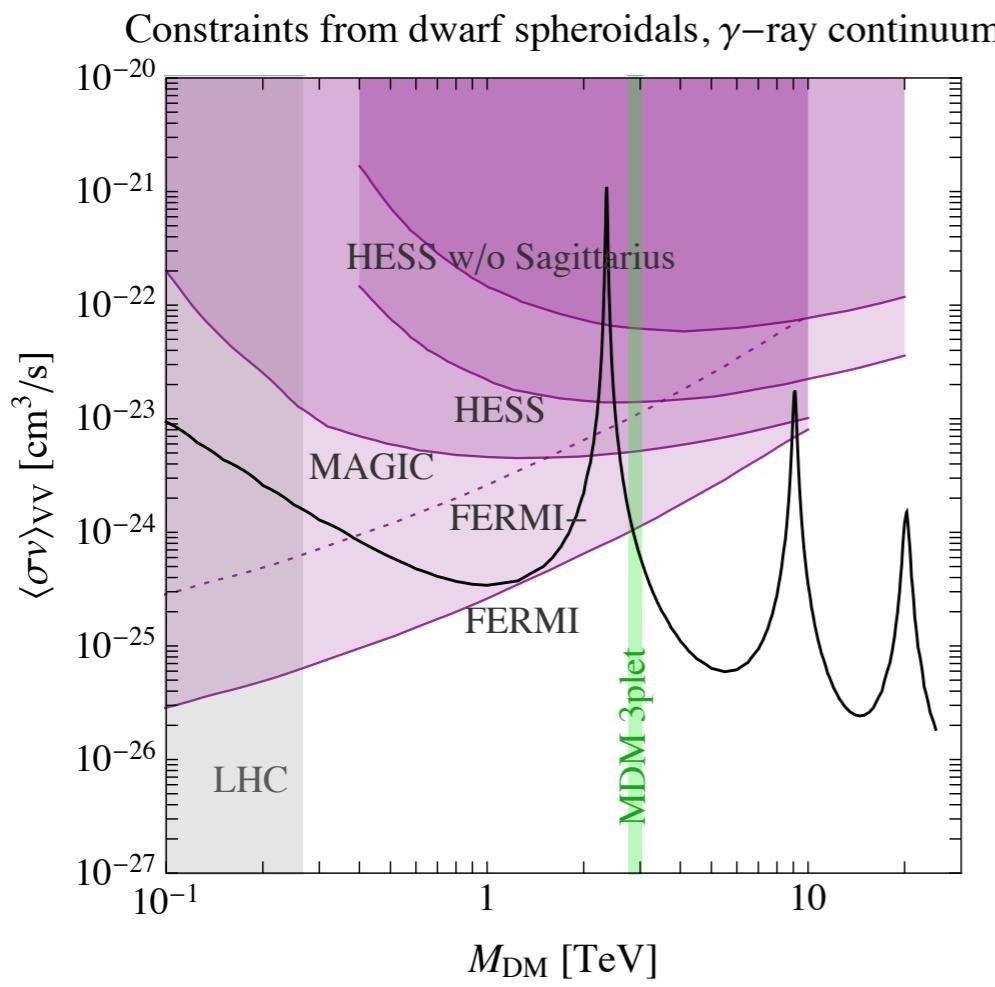
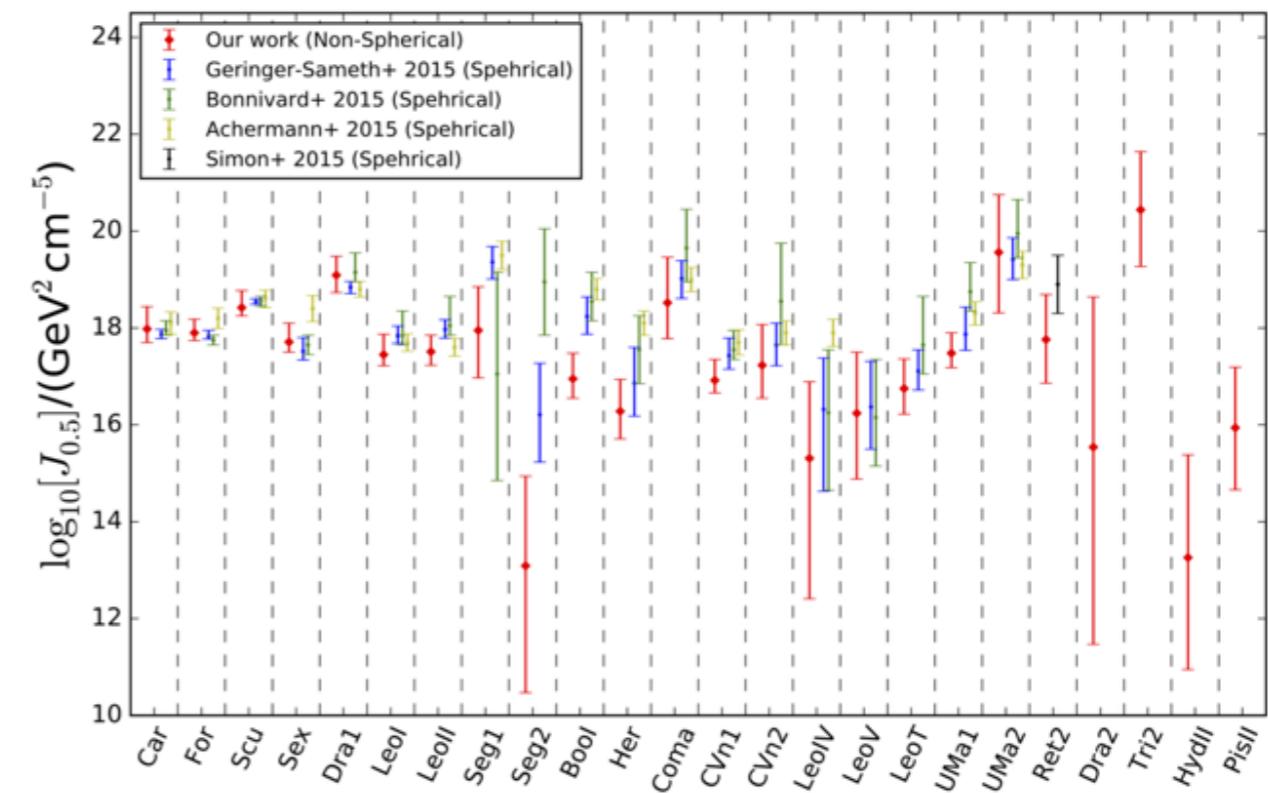
Continuum from dSphs

Hayashi et al 1603.08046

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

HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)



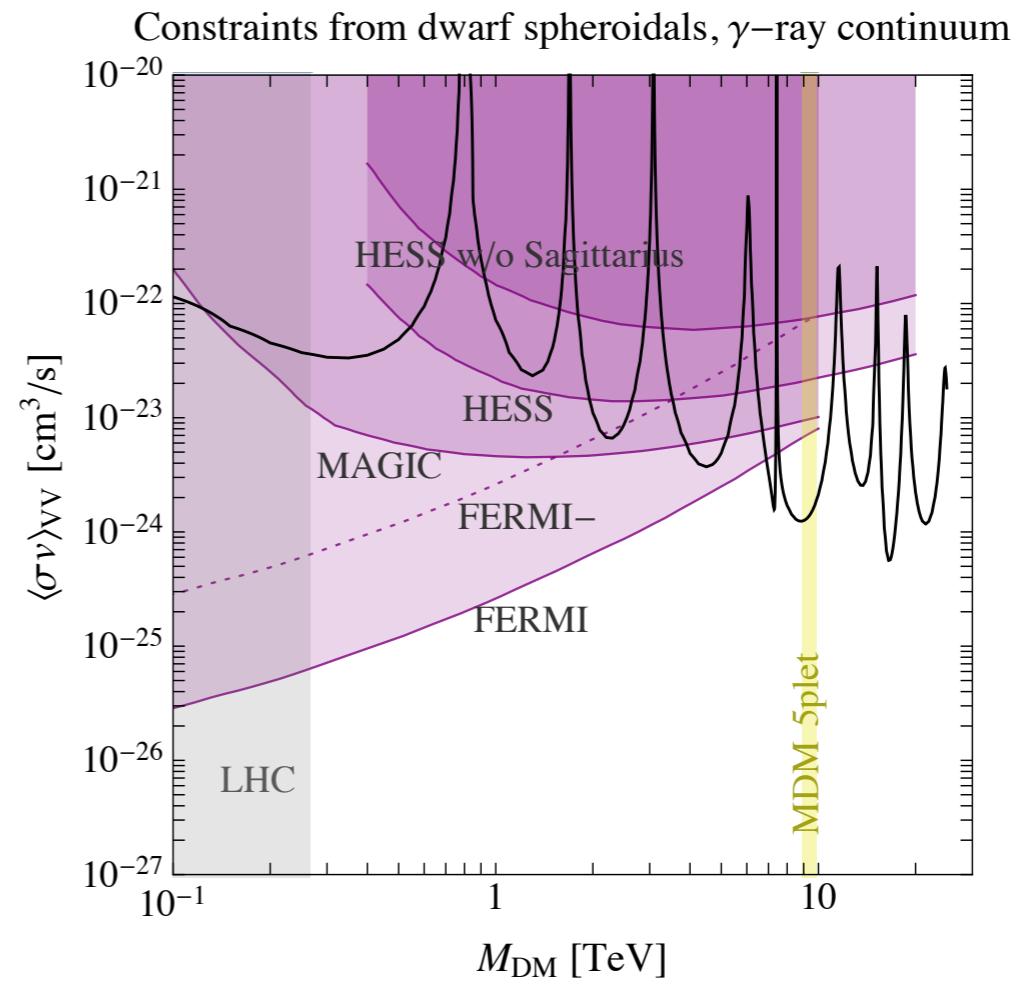
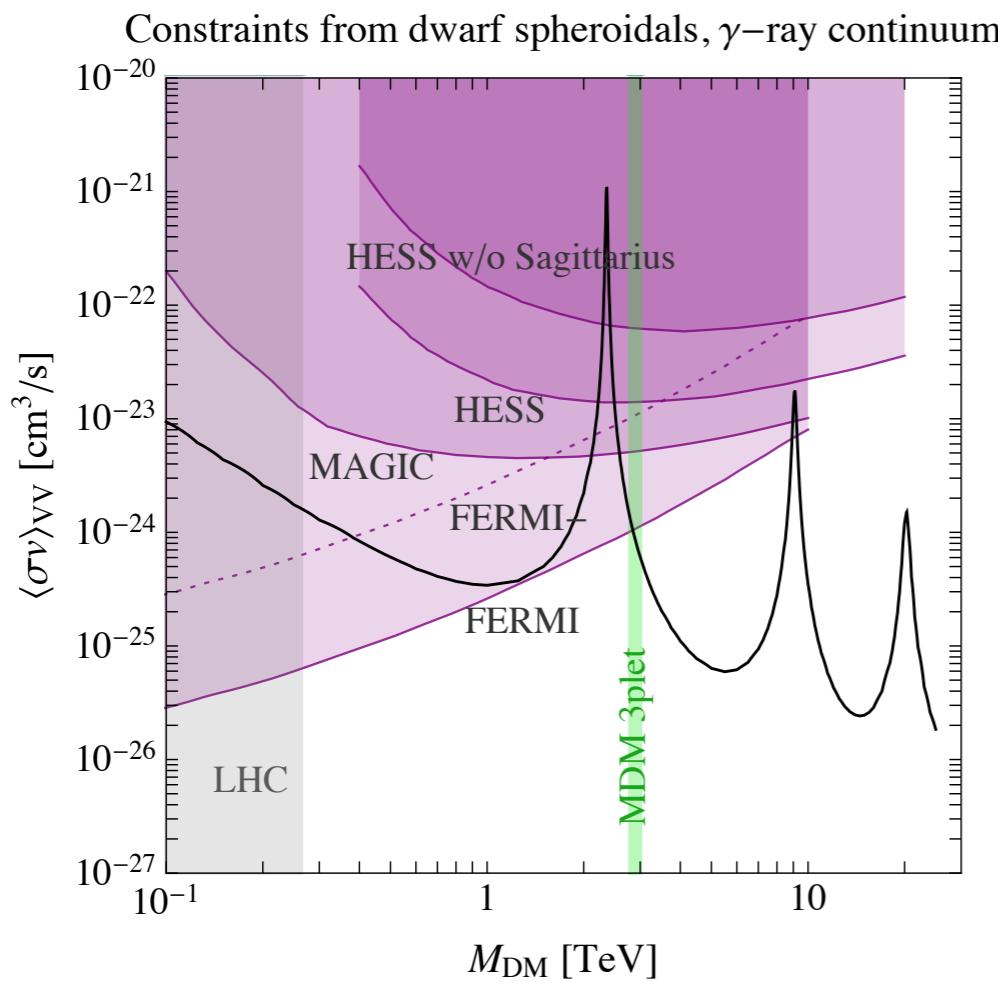
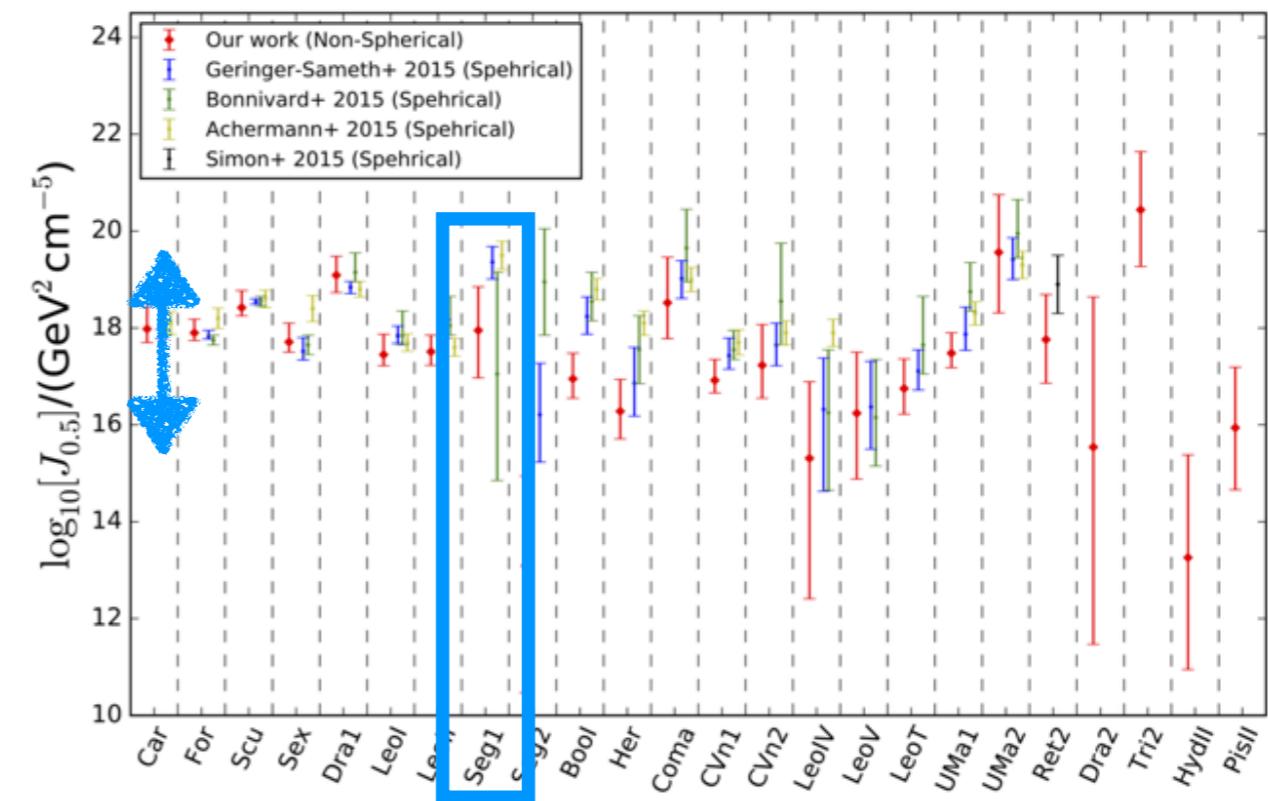
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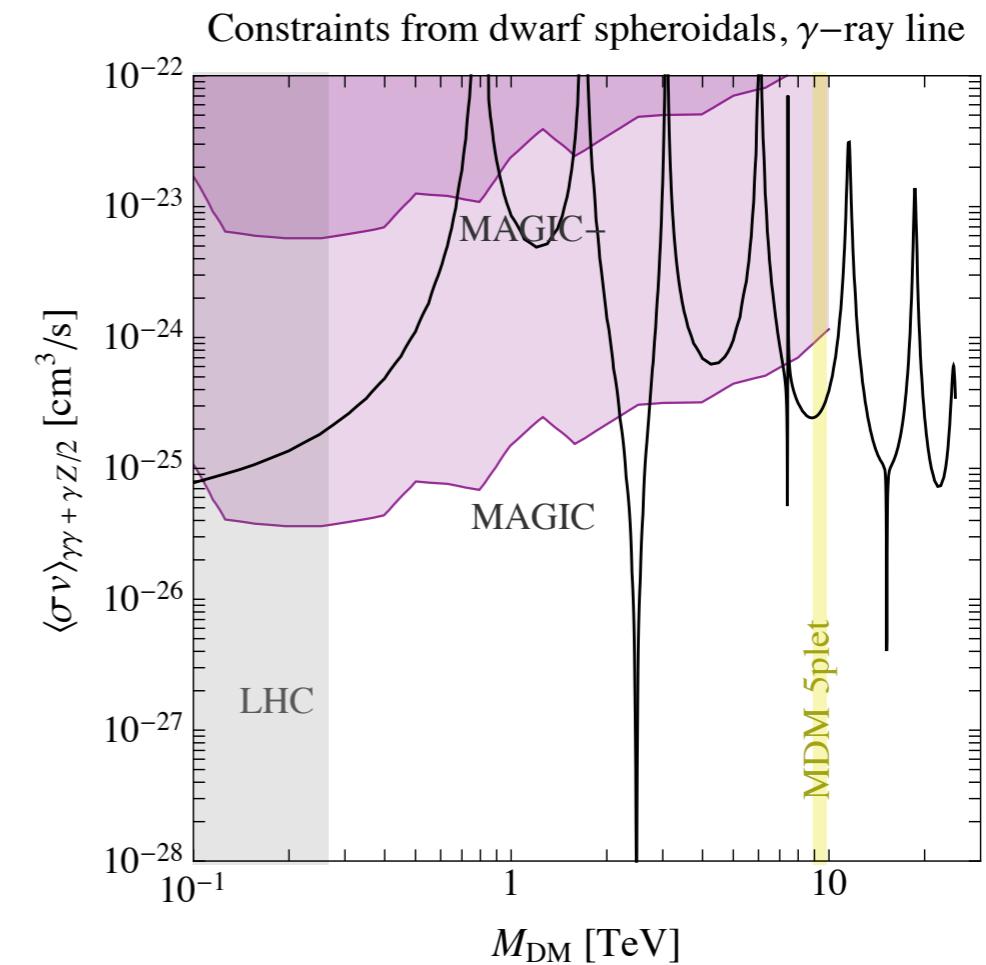
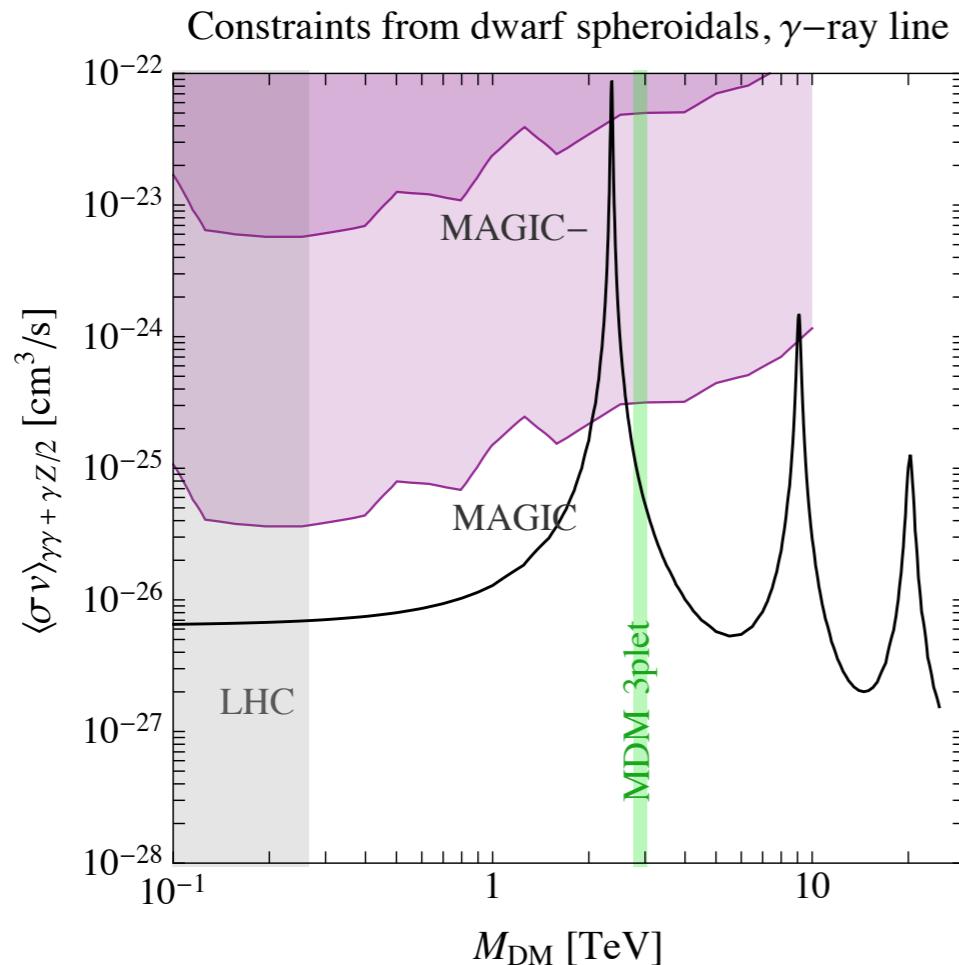
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Gamma-ray lines from dSphs

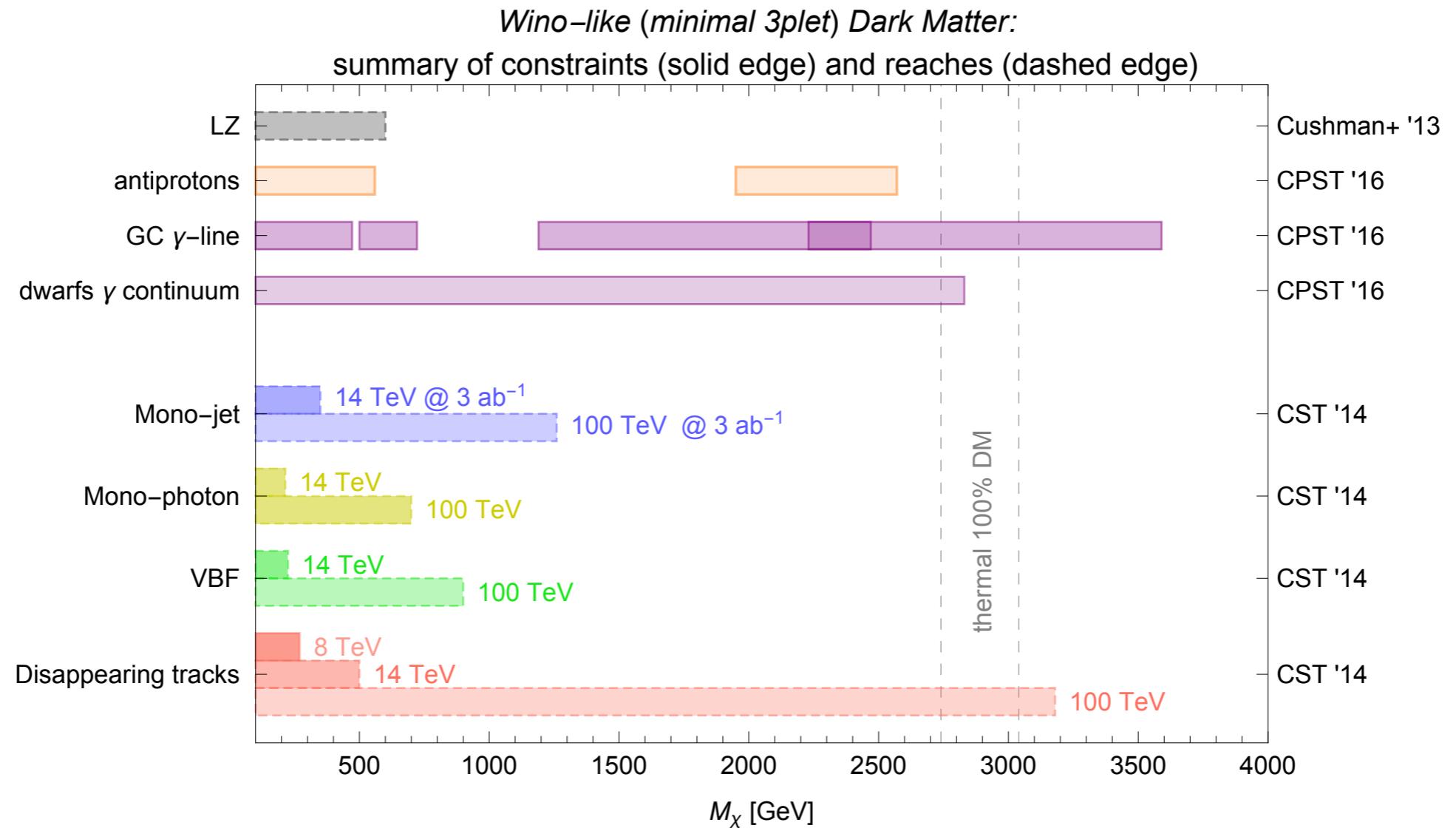
Only **MAGIC** performed this analysis, and was unlucky...



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

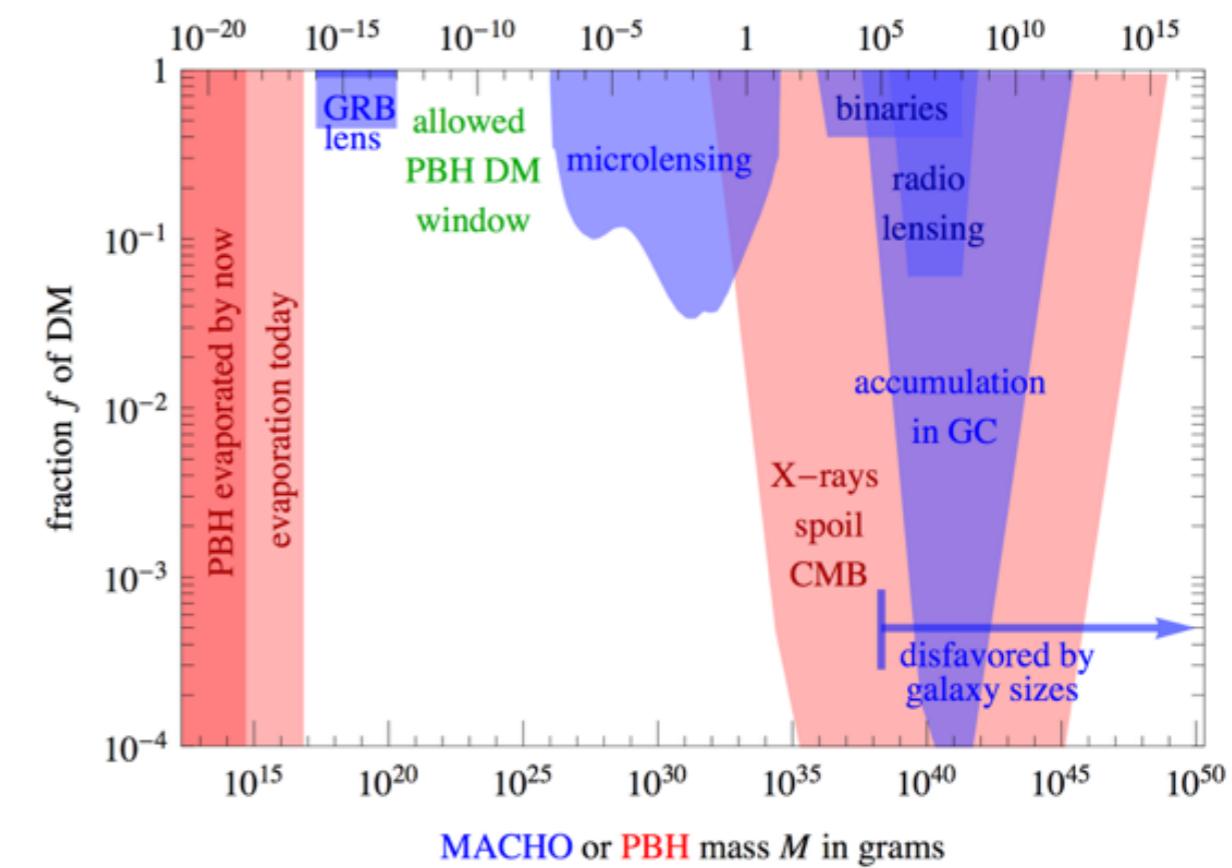
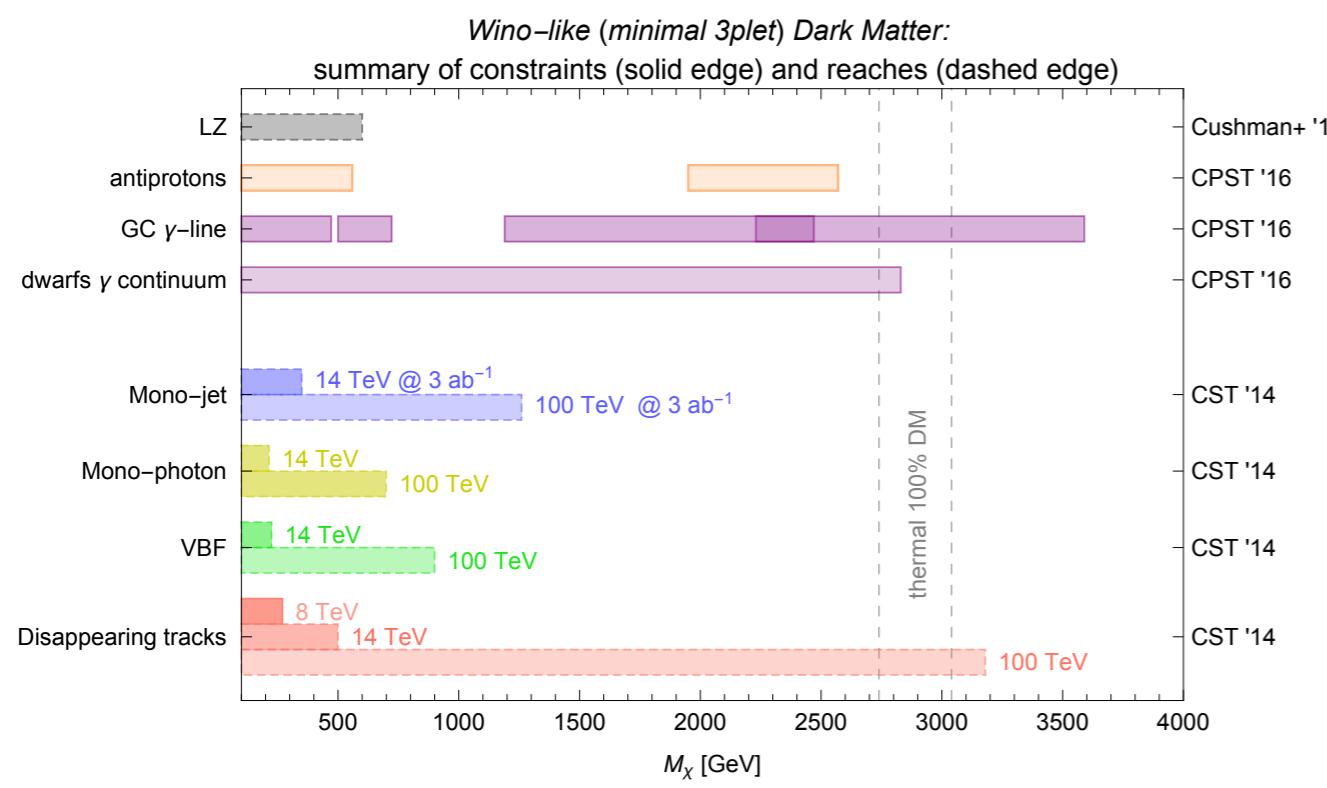
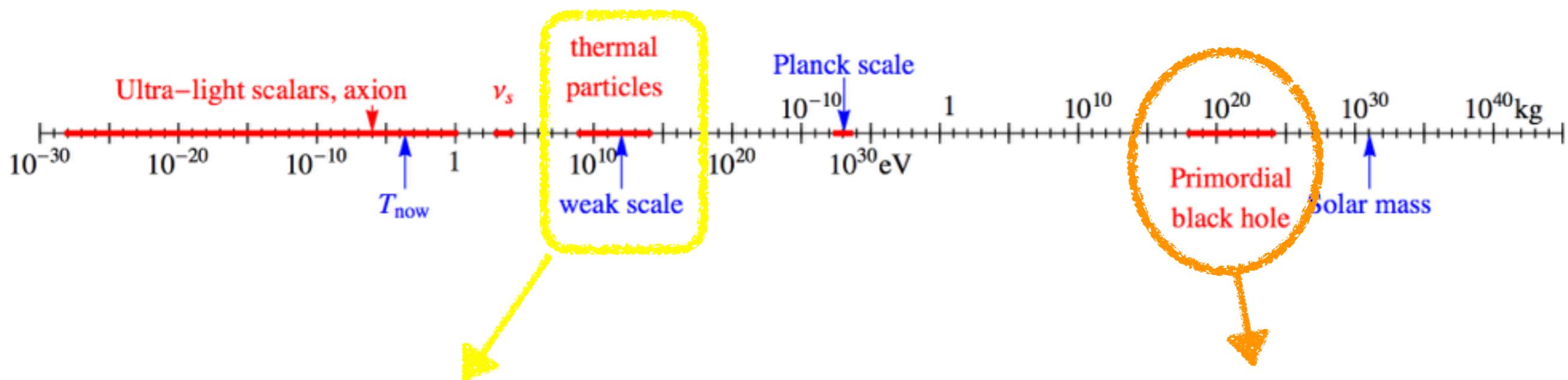
Comparing WIMP searches with benchmark models

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



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

Keep exploring!



Back-up slides

Why an EW fermion multiplet?

Minimal Dark Matter

Cirelli Fornengo Strumia hep-ph/0512090

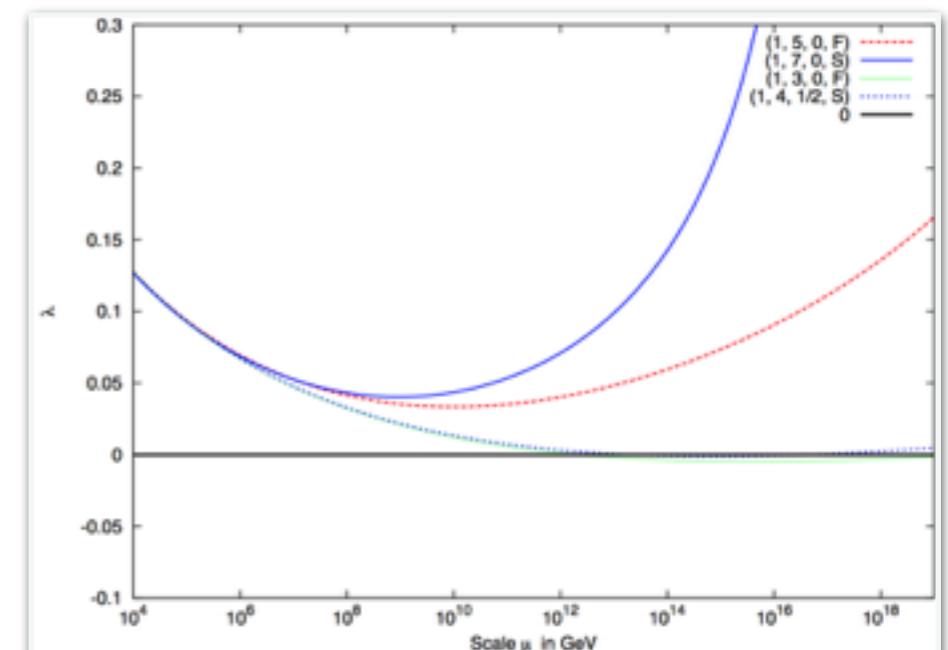
Philosophy: focus on DM, and try to preserve SM successes (flavour & CP,...)
+ DM stability, adding the least possible ingredients to the theory

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]
- ☺ ...



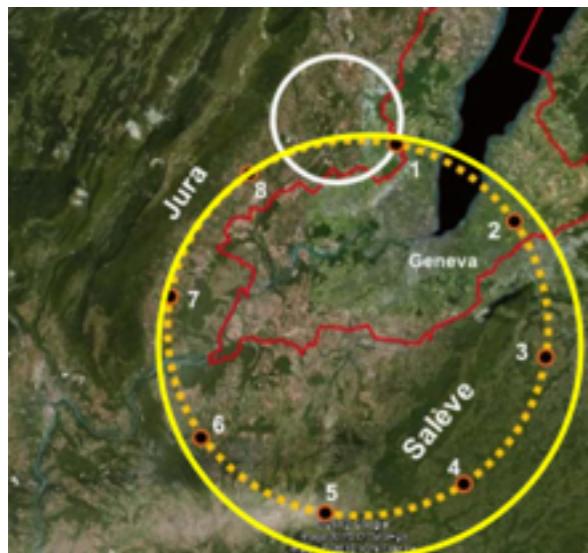
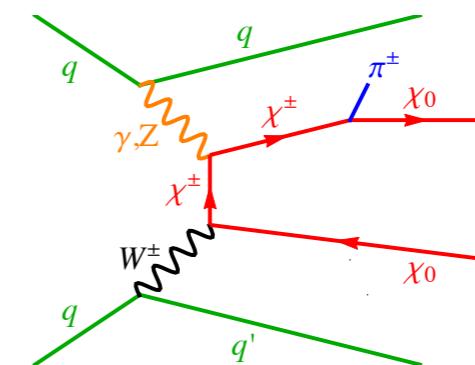
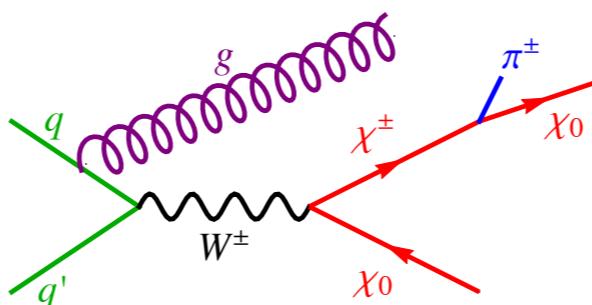
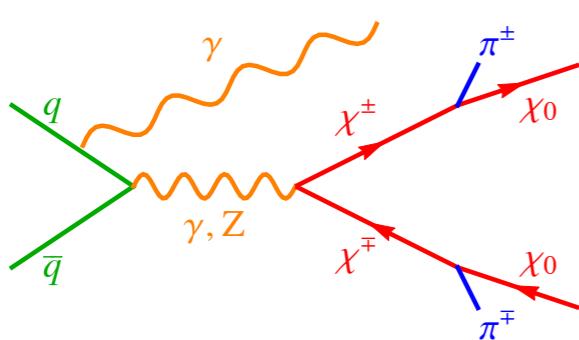
EW multiples at colliders - I

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

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

In fact $M_{\chi^\pm, \pm\pm} - M_{\chi_0} \gtrsim m_\pi \rightarrow$ lifetime $\tau \simeq 6 \text{ cm} \simeq 0.2 \text{ ns}$

\rightarrow almost all χ^\pm & $\chi^{\pm\pm}$ decay to χ_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

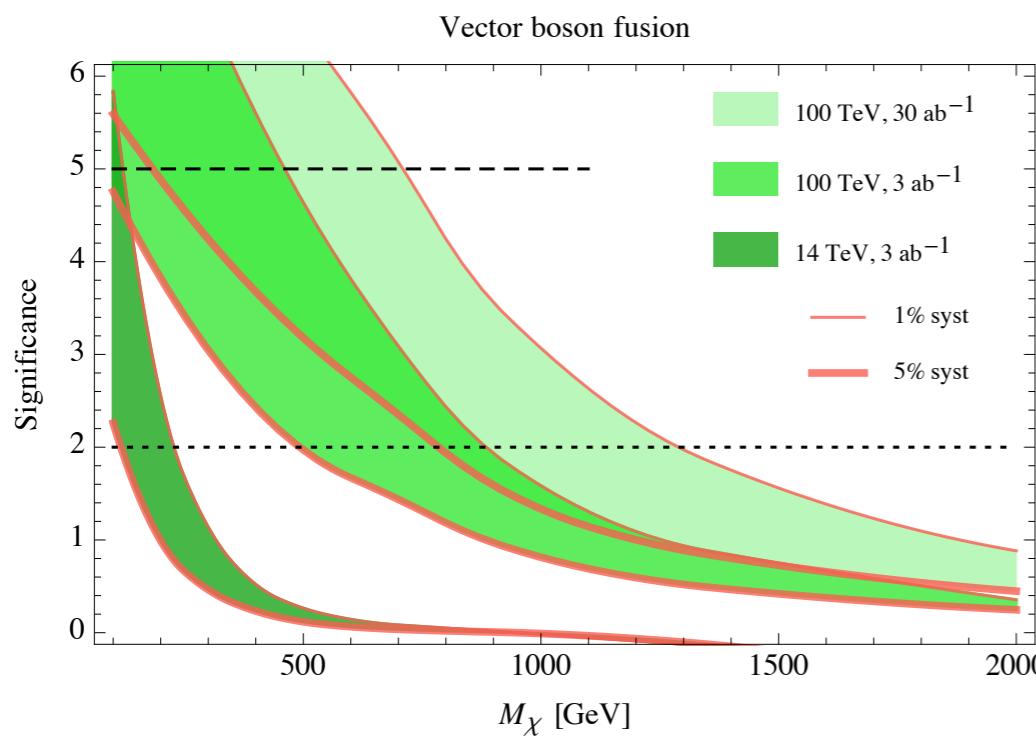
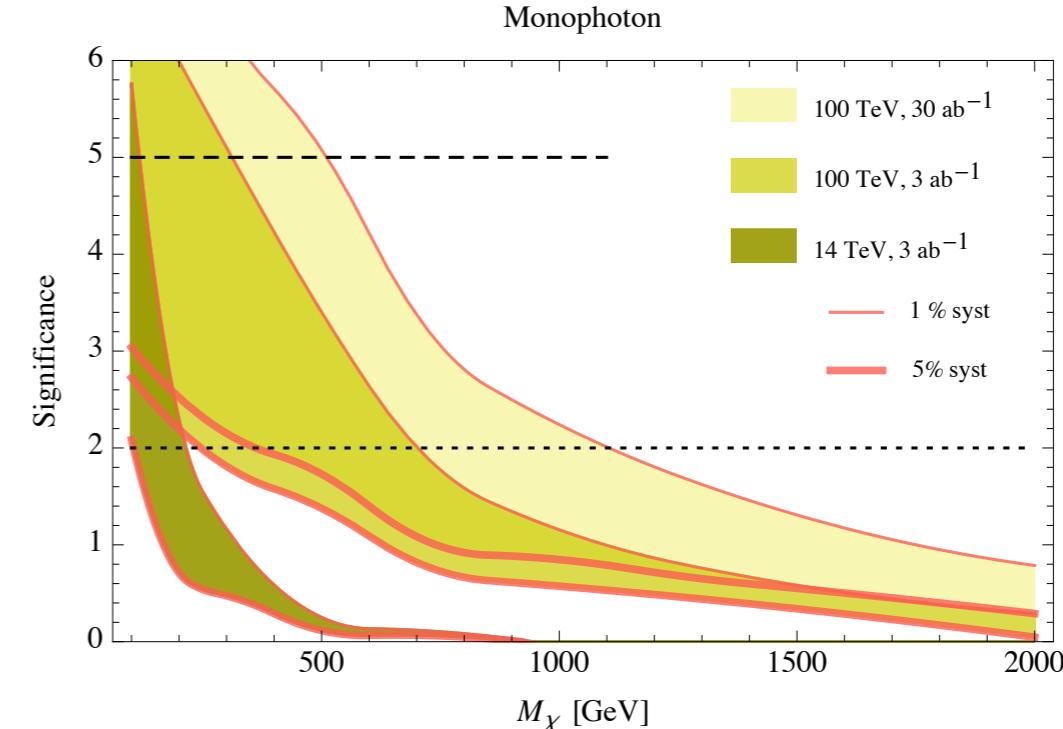
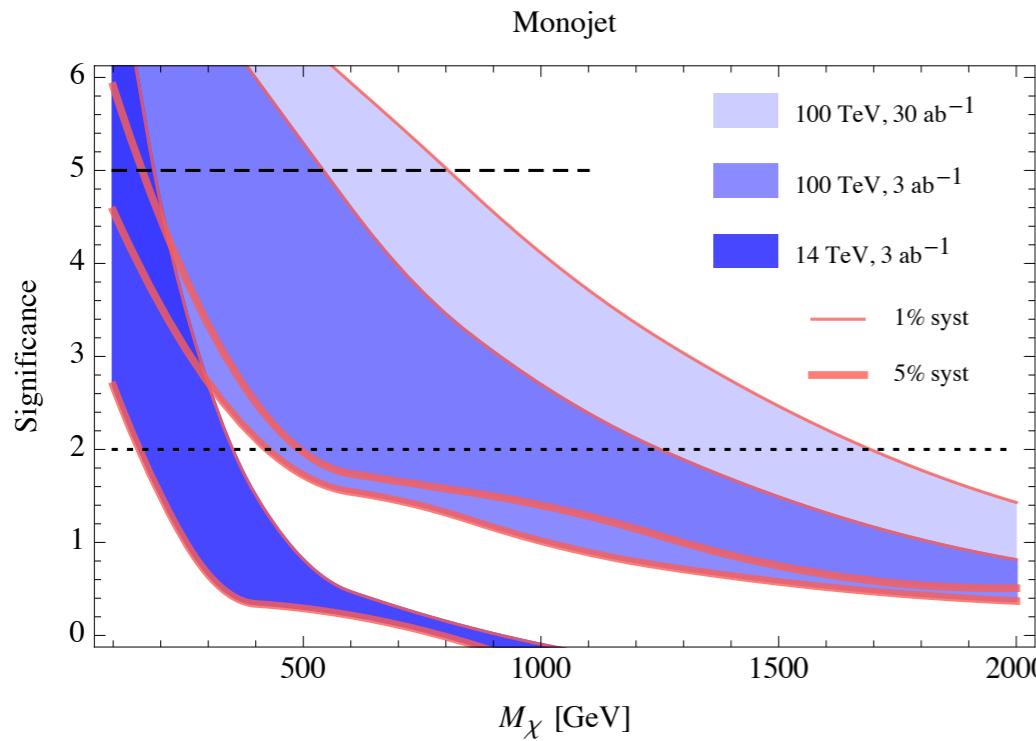
Need higher energies

\rightarrow **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 $\sim 5\%$, not 1% !)
- going from 14 to 100 TeV will increase mass reach by a factor of 3 - 4

Same conclusions for 5plet

EW multiples at colliders: disappearing tracks

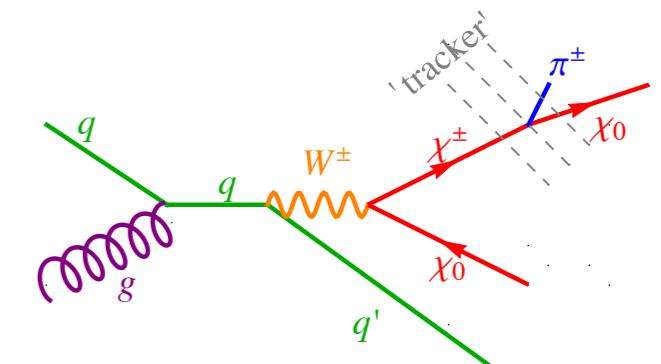
Feng et al 1999, ...

$$M_{\chi^{\pm}, \pm\pm} - M_{\chi_0} \gtrsim m_\pi \longrightarrow \text{lifetime } \tau \simeq 6 \text{ cm} \simeq 0.2 \text{ ns}$$

almost all χ^\pm & $\chi^{\pm\pm}$ decay to $\chi_0 + \text{soft pions}$ before reaching the detector

Both ATLAS and CMS performed this analysis

current strongest limits on EWmultiplets $M_{\chi_0} \gtrsim 270 \text{ GeV}$



EW multiples at colliders: disappearing tracks

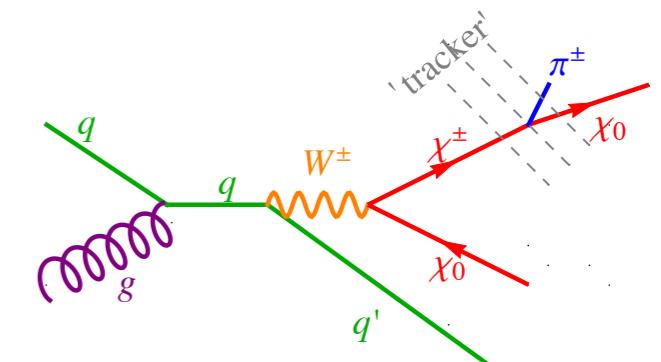
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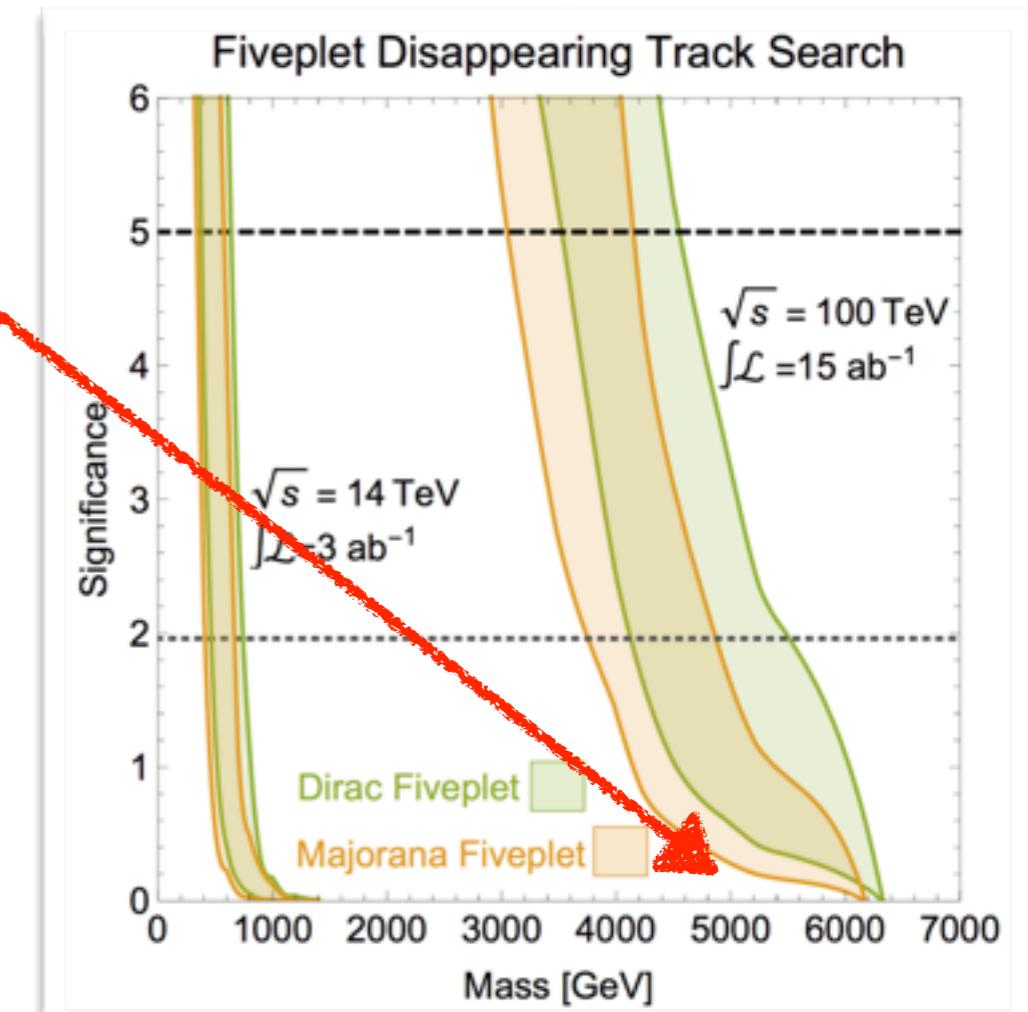
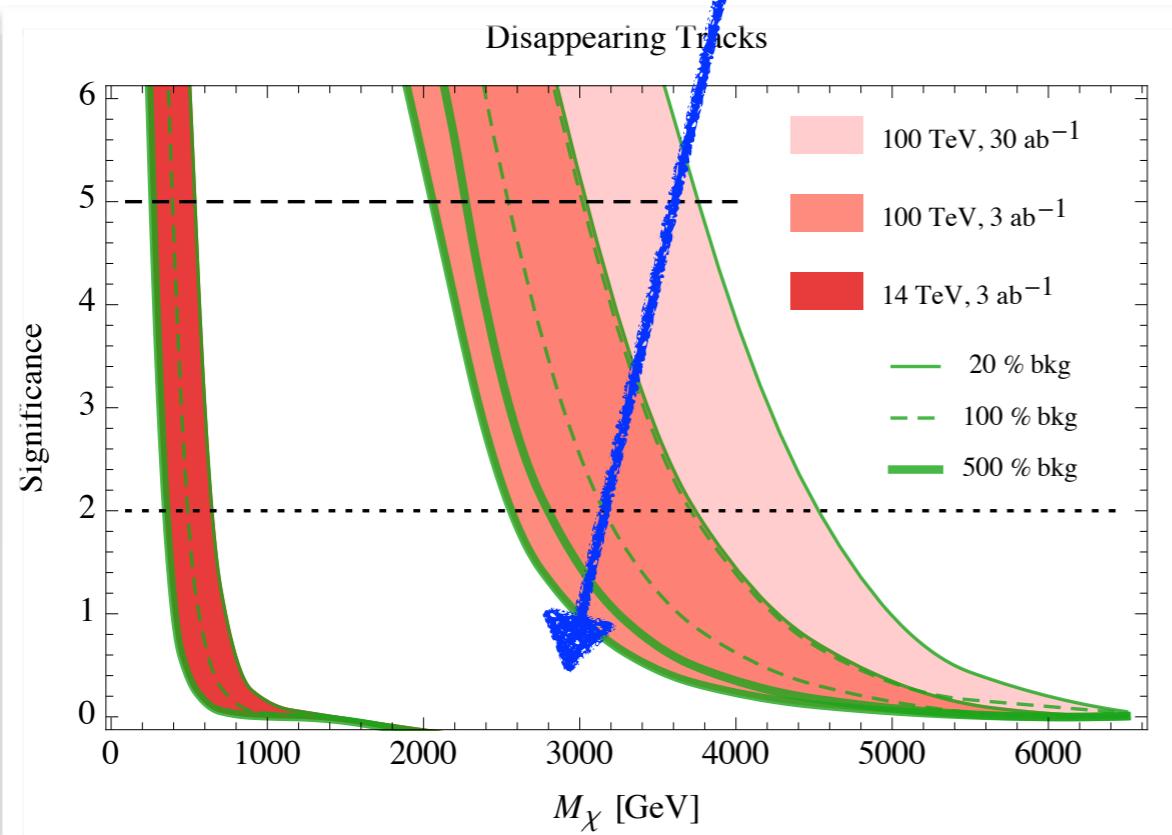
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FCC-hh will likely probe the **3plet**, not the **5plet**

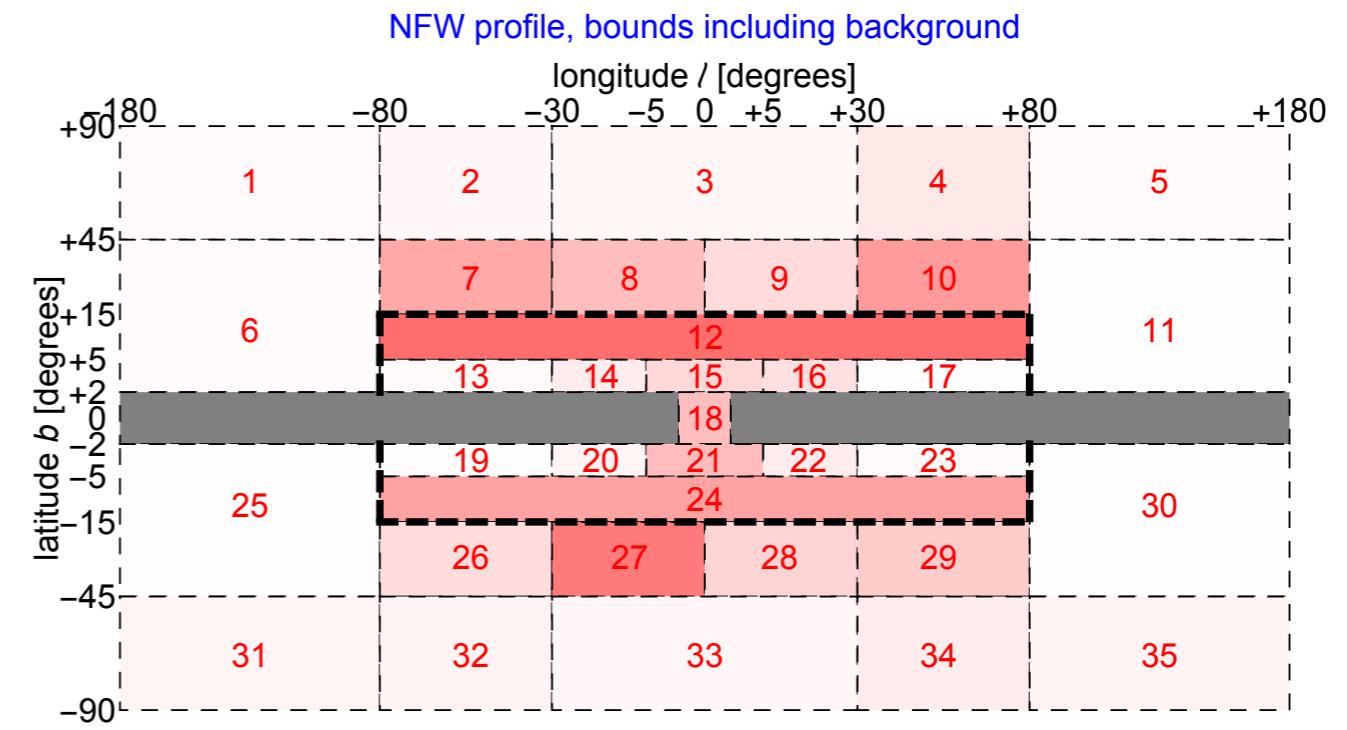
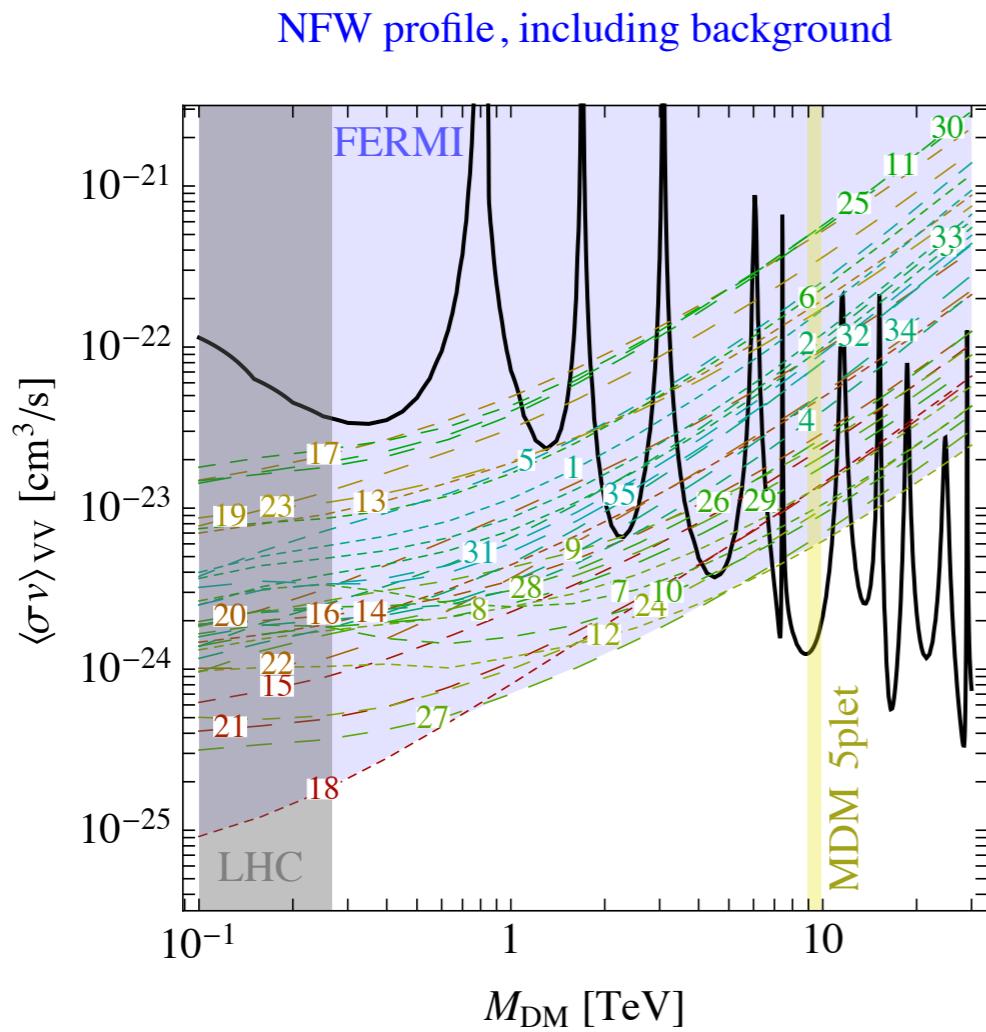


Continuum with FERMI

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

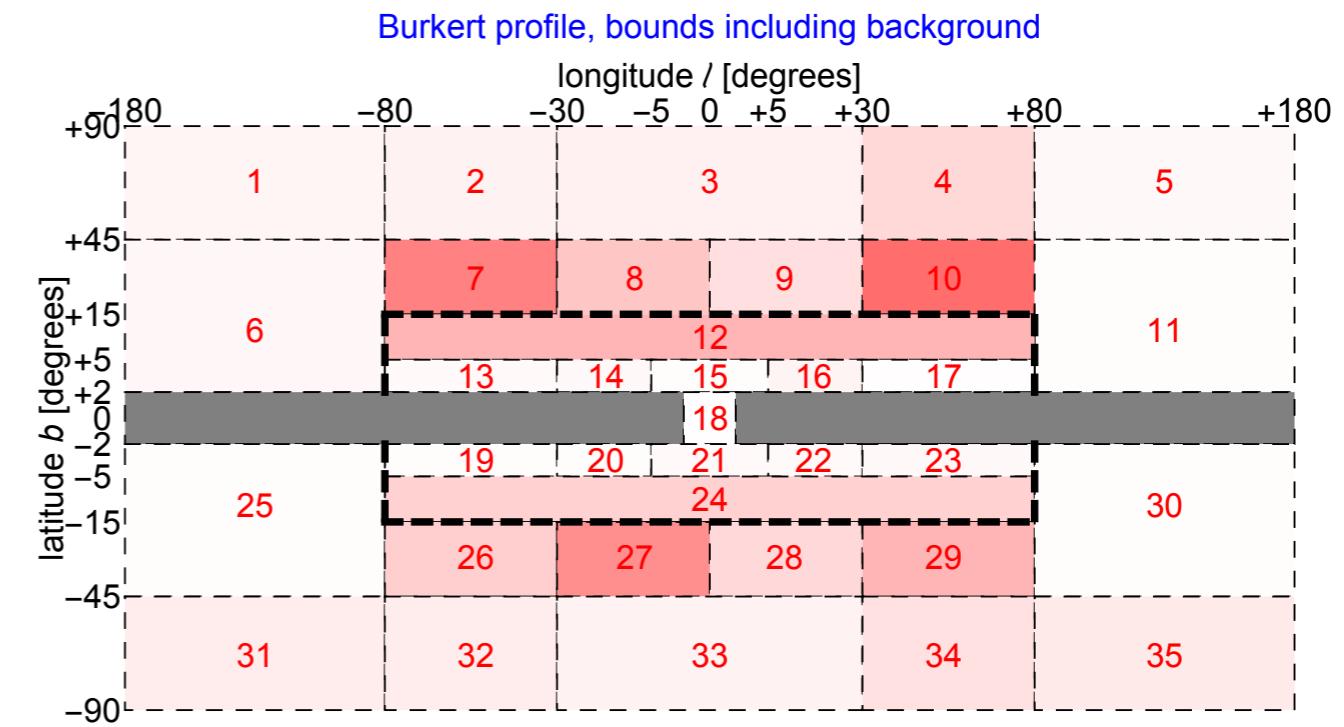
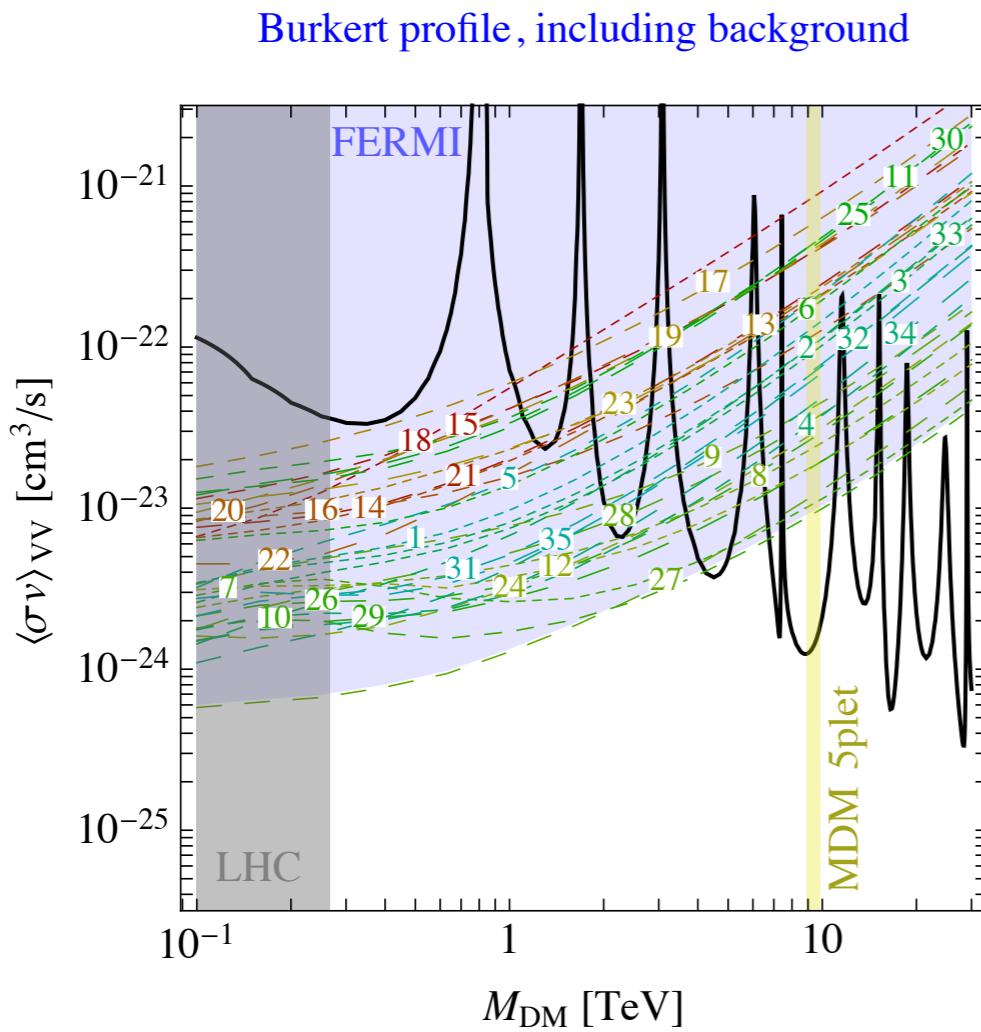
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Summary: EW fermion 5plet

Why interesting?

Prototype of a WIMP, and moreover

Minimal Dark Matter

Phenomenology

