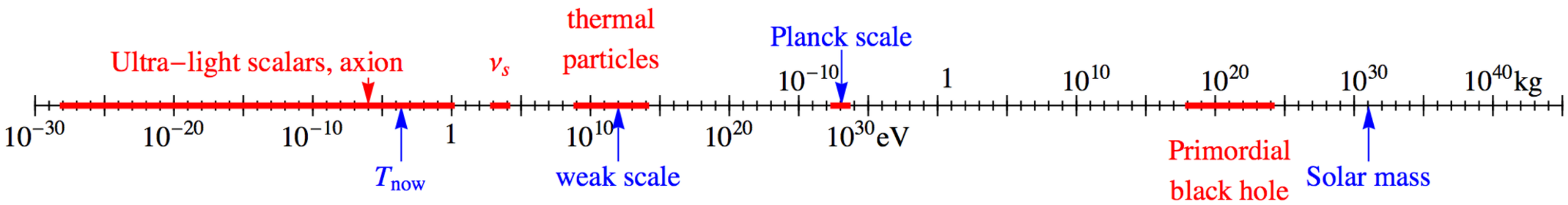
WIMP Dark Matter at γ-ray telescopes

Filippo Sala

LPTHE Univ. Paris 6 and CNRS

New frontiers in theoretical physics, GGI Firenze, 20 May 2016

Where is Dark Matter?



(courtesy of Marco Cirelli)

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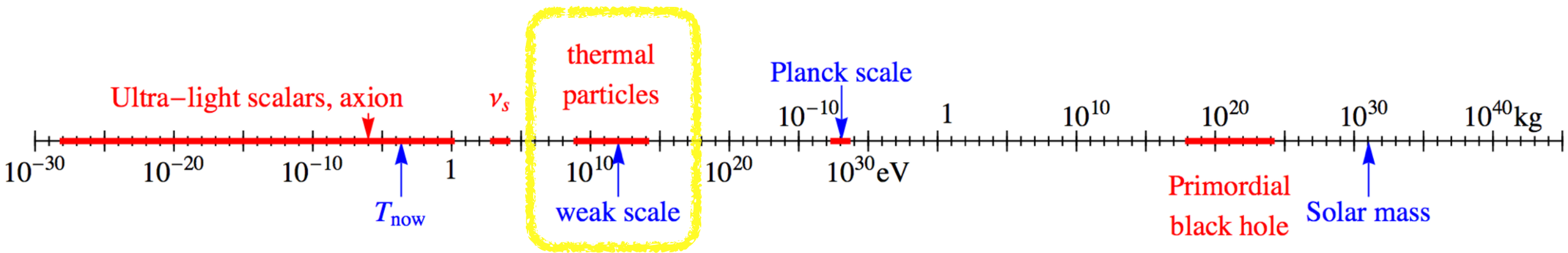


(courtesy of Marco Cirelli)

Still an ambitious question:

How far can we probe the WIMP paradigm?

WIMP = weakly interacting massive particle

- Mass ~ GeV-100 TeV
- Interacts with Standard Model
  (necessary to produce Dark Matter)

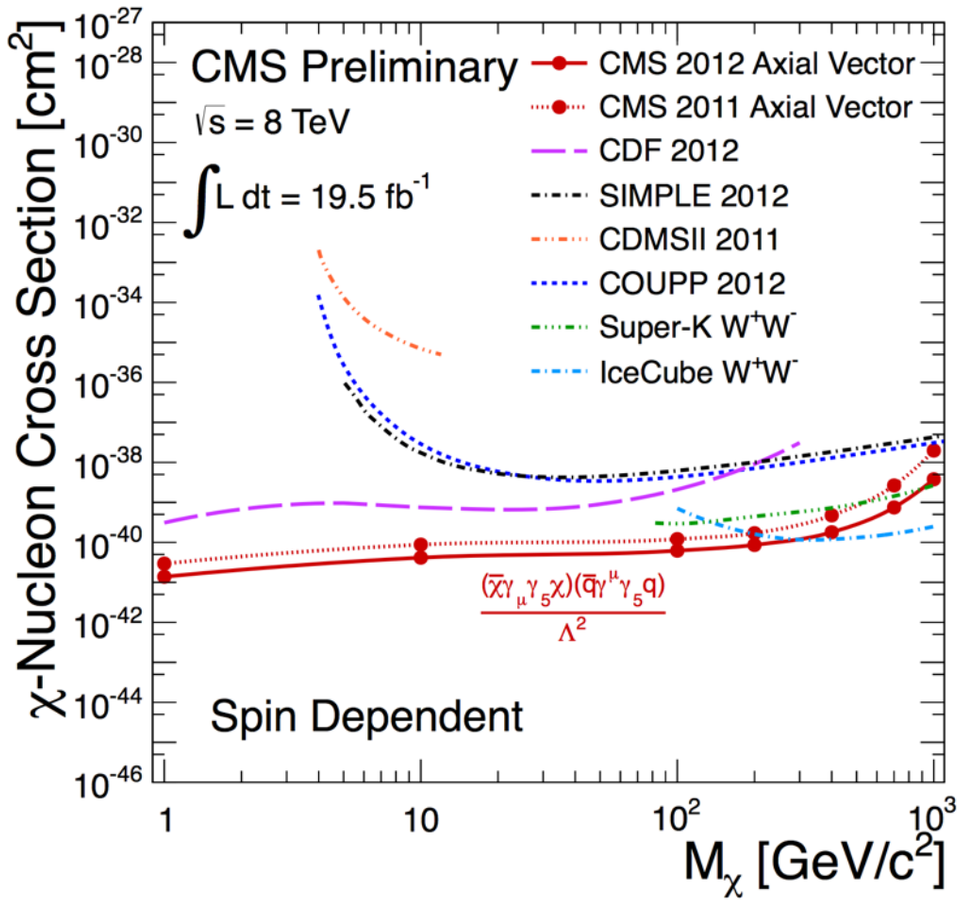
The “WIMP miracle" motivates the TeV scale, independently of Naturalness!

General strategy: effective field theories?

The EFT approach, scorecard:

☺ Model-independent

☺ easy comparison collider - direct detection



General strategy: effective field theories?

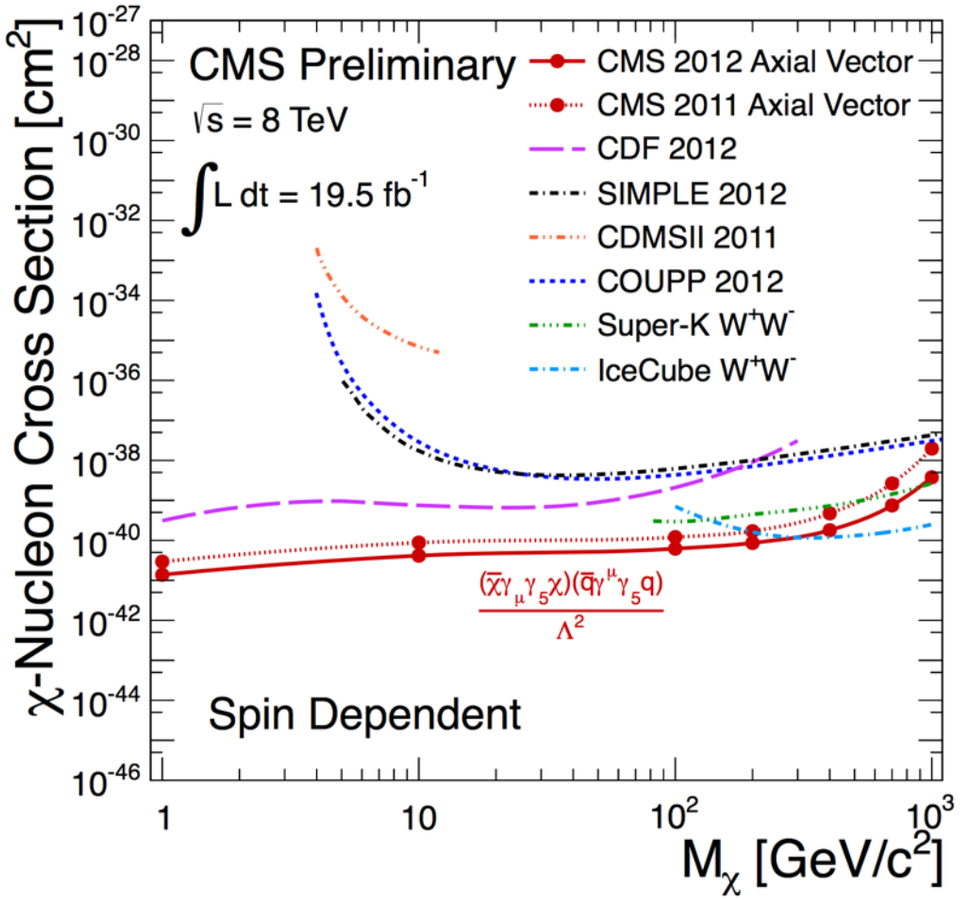
The EFT approach, scorecard:

☺ Model-independent

☺ easy comparison collider - direct detection

☹ too naive 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,…

Either you select only events with mom. transfer < Λ ⟶ but you lose NP reach

Or you go to benchmark/simplified models!

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

An EW fermion multiplet

Possibly the “simplest" simplified model

Why an EW fermion multiplet? (besides simplicity)

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Minimal Dark Matter
Cirelli Fornengo Strumia hep-ph/0512090

Approach: add to the SM one extra particle, and determine its “good" quantum numbers

“good" = i) automatically stable
ii) lightest component neutral
iii) allowed by DM searches

Result: 5plet, [3plet if you add B-L or L or subgroup…]

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Frigerio Hambye 0912.1545

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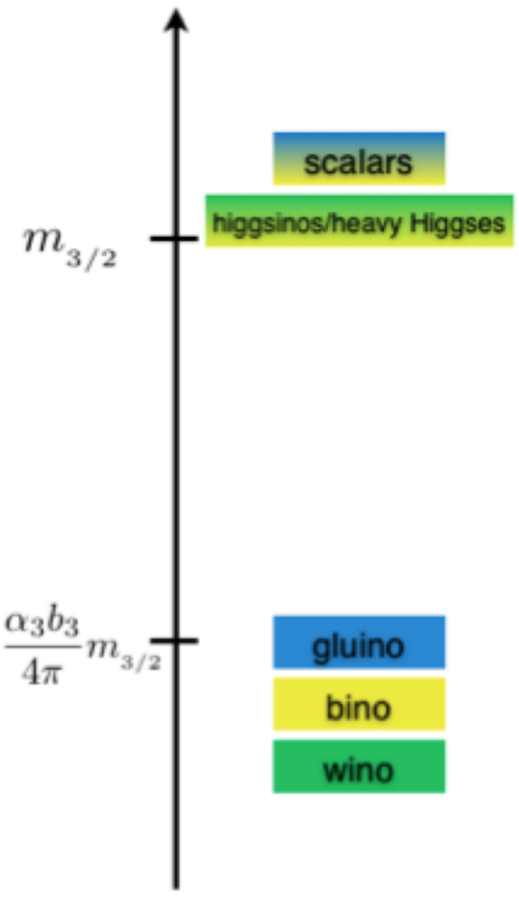

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Supersymmetry with heavy scalars
James Wells hep-ph/0306127

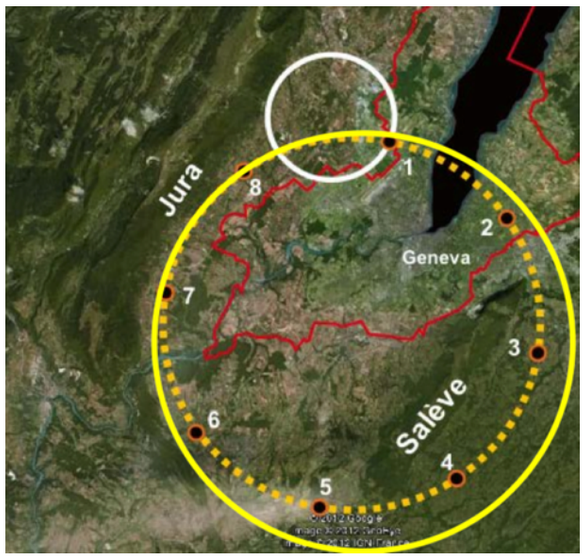
All good SUSY features (DM, unification of gauge couplings,…)

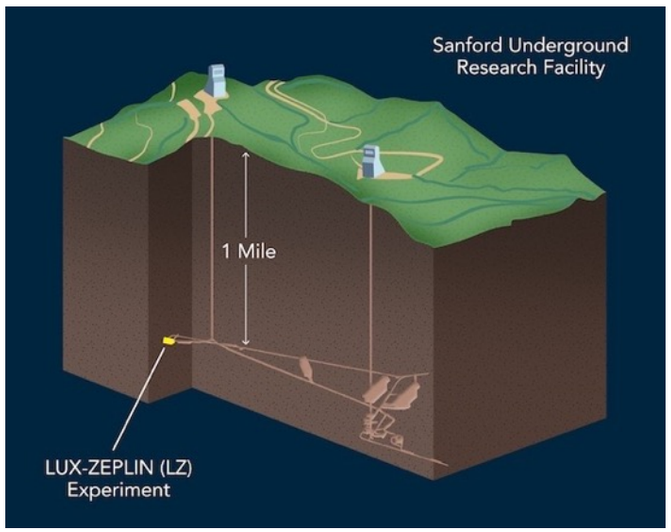
Hierarchy problem? Go anthropic

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





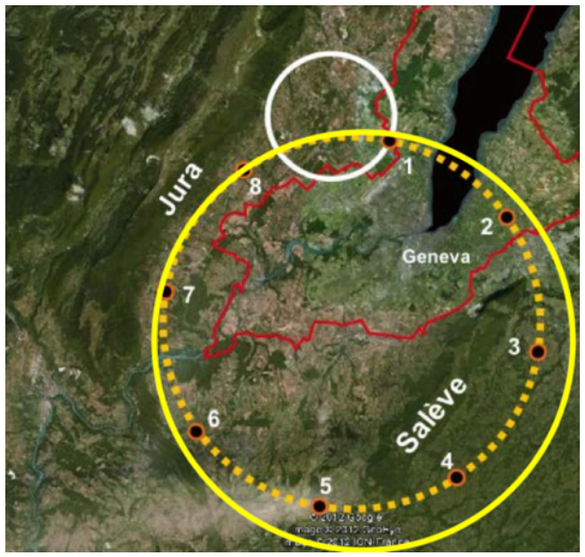
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \tfrac{1}{2}\,\bar{\chi}\big(i\hat{D} - M_\chi\big)\chi$$

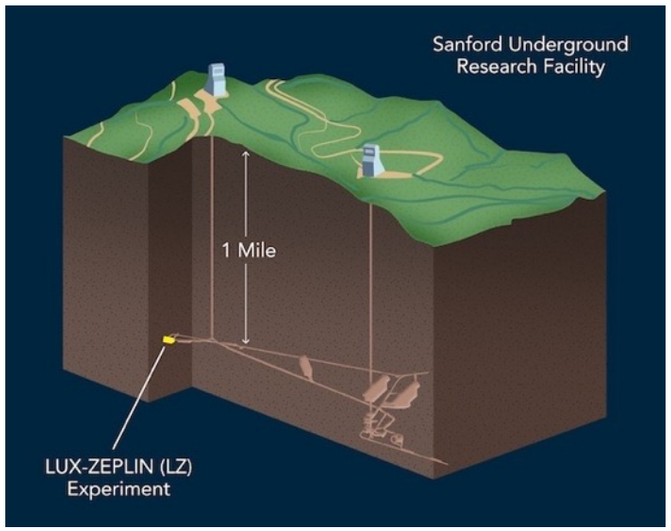
M_χ is **the only free parameter**

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

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

Phenomenology





EW multiples at colliders: disappearing tracks

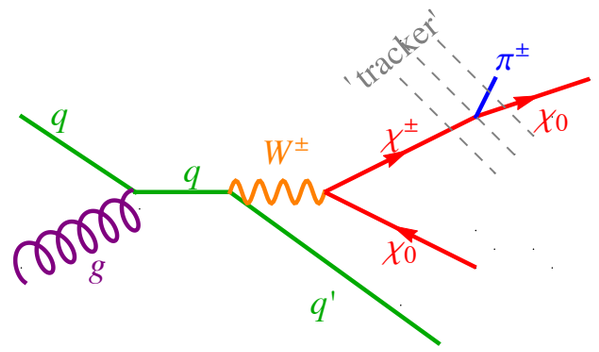
Feng et al 1999,…

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

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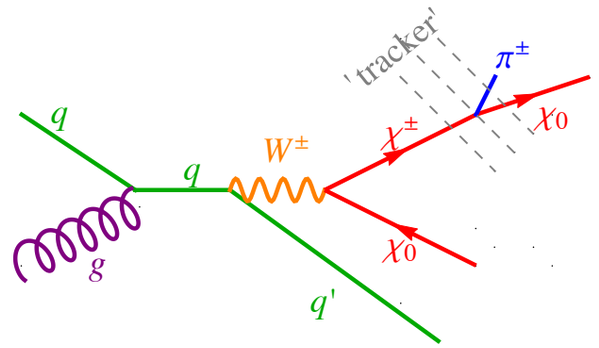
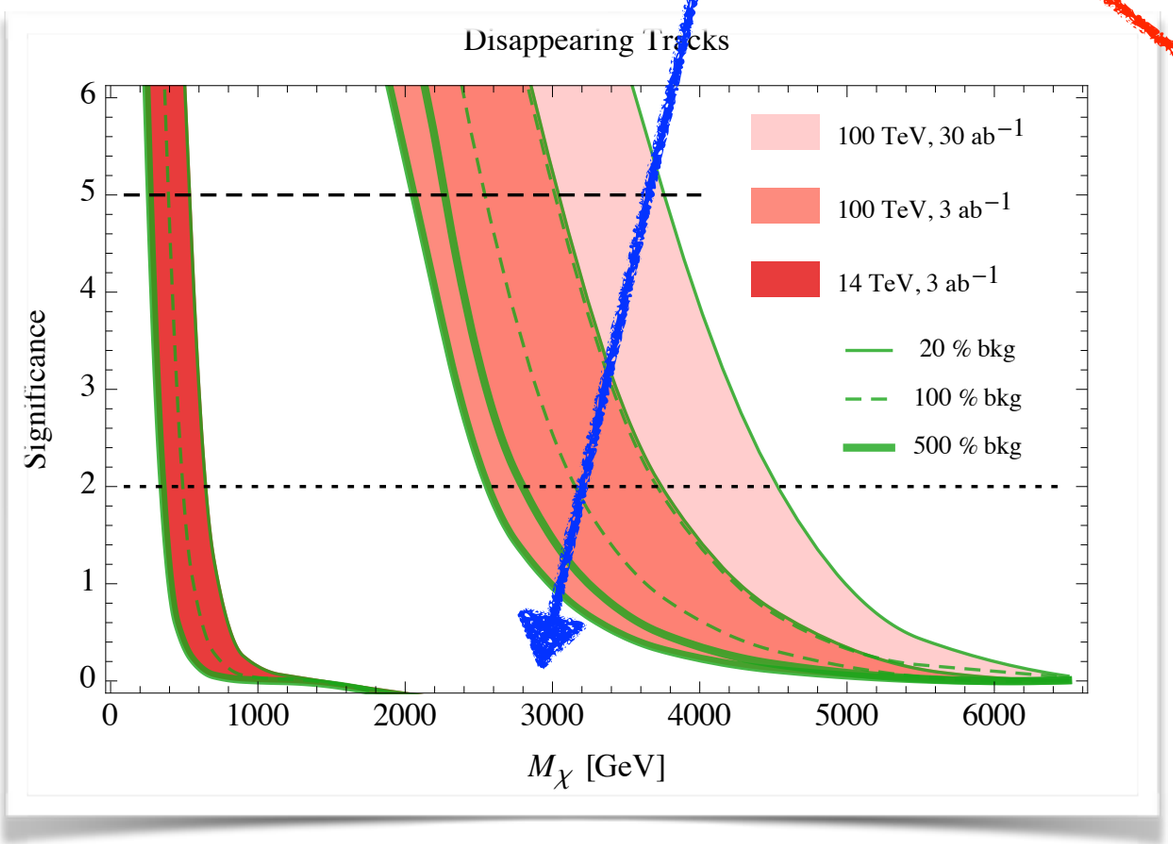
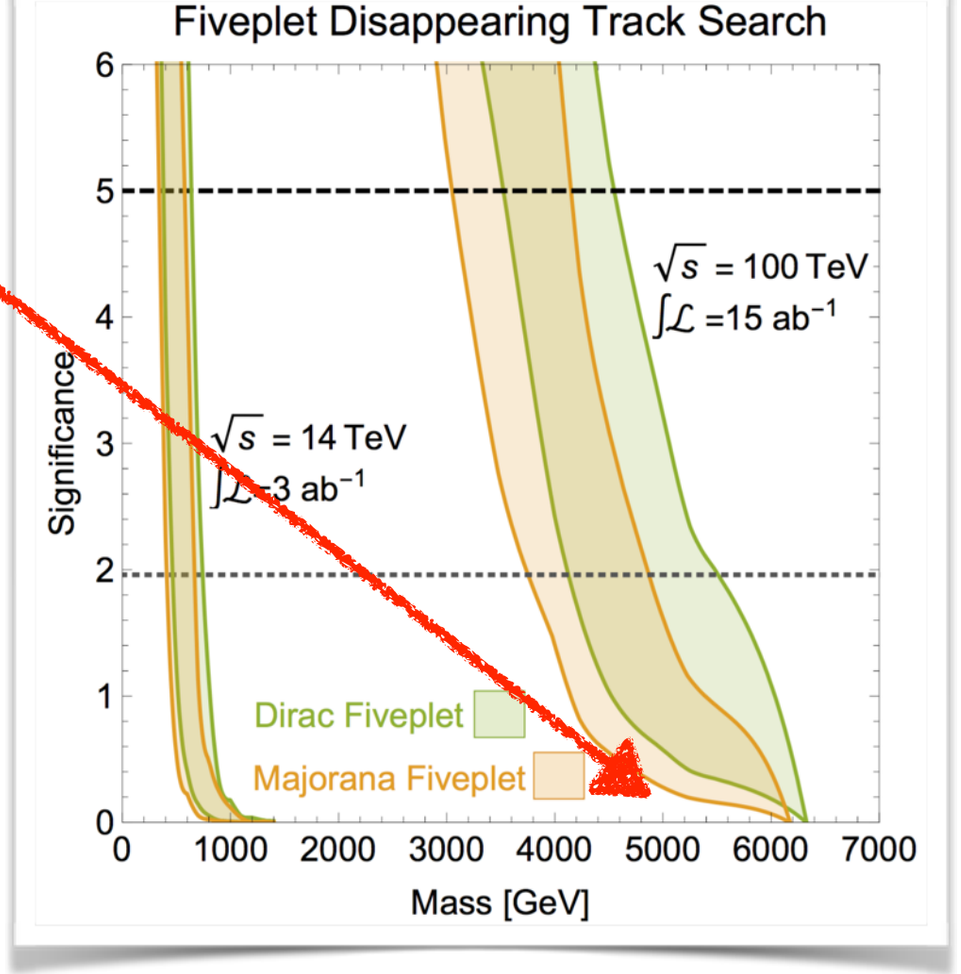


FCC-hh will likely probe the 3plet, not the 5plet

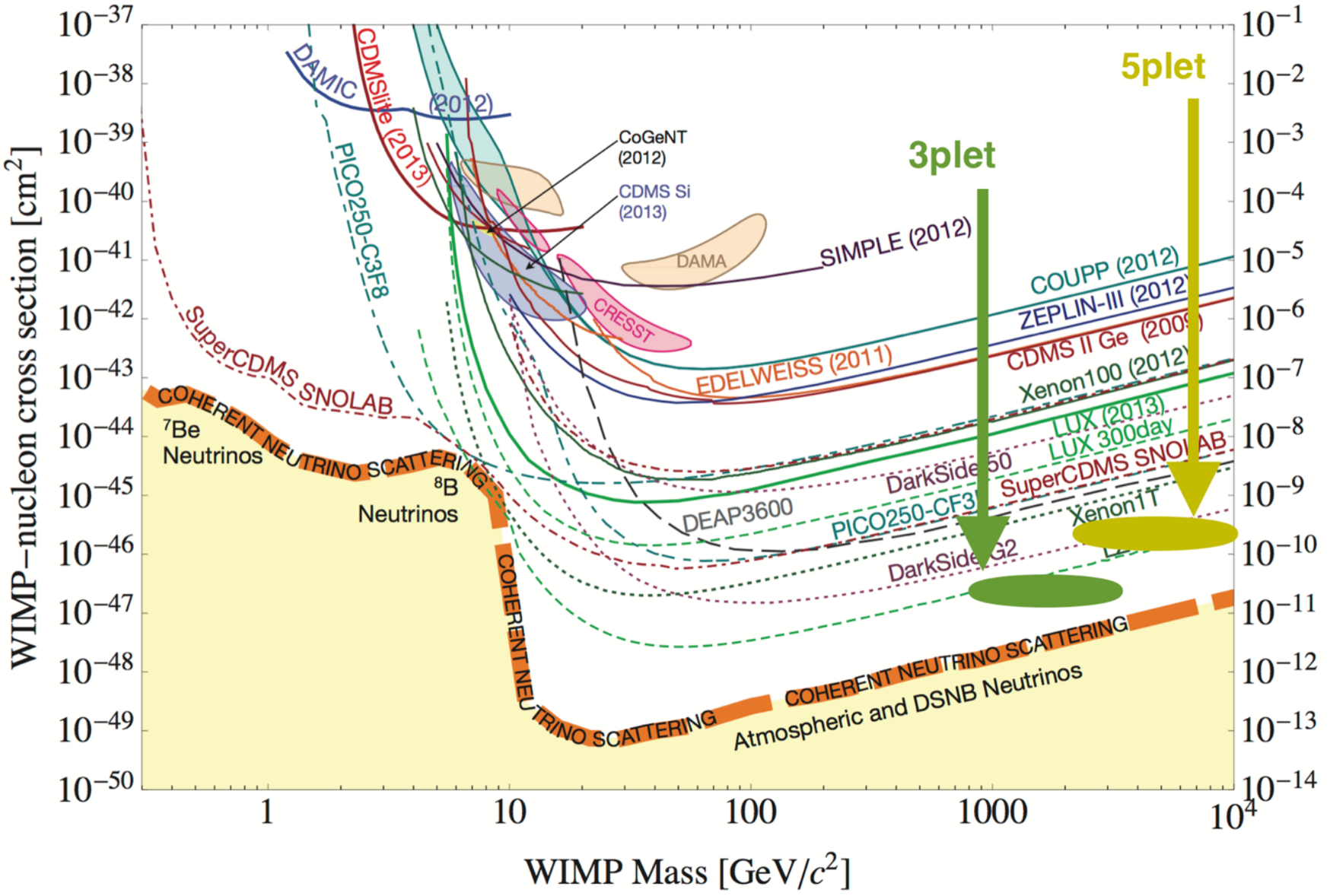


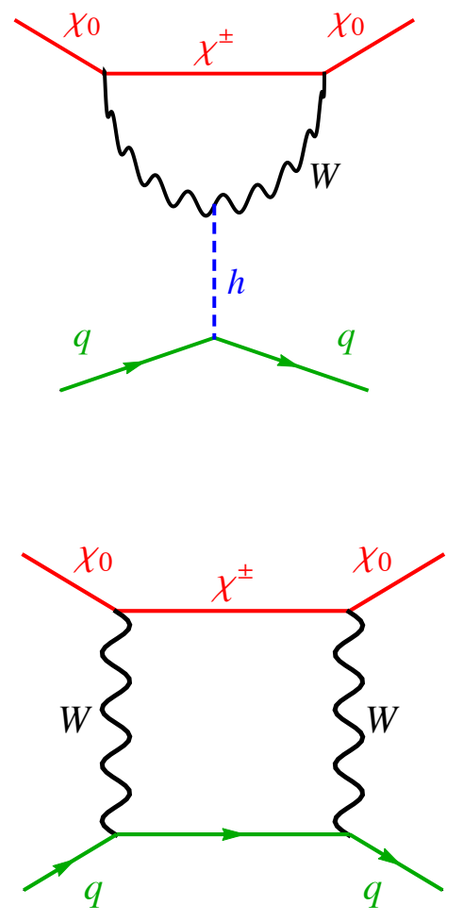
Cirelli Sala Taoso 1407.7058 [Madgraph+Pythia+Delphes]



BSM chapter of CERN FCC-hh report, to appear

Direct detection





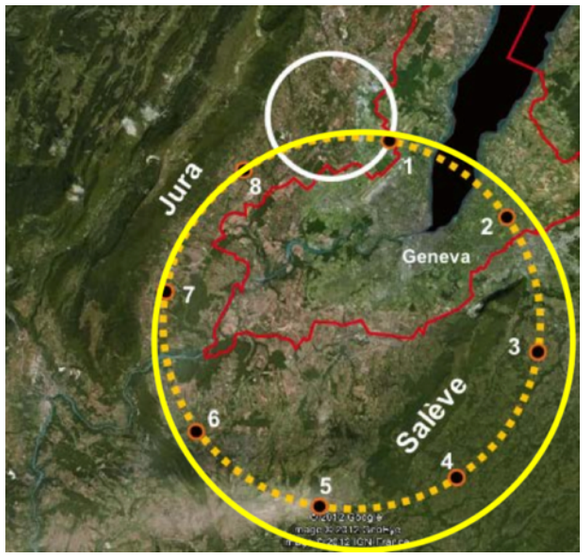
Hisano et al. 1504.00915:

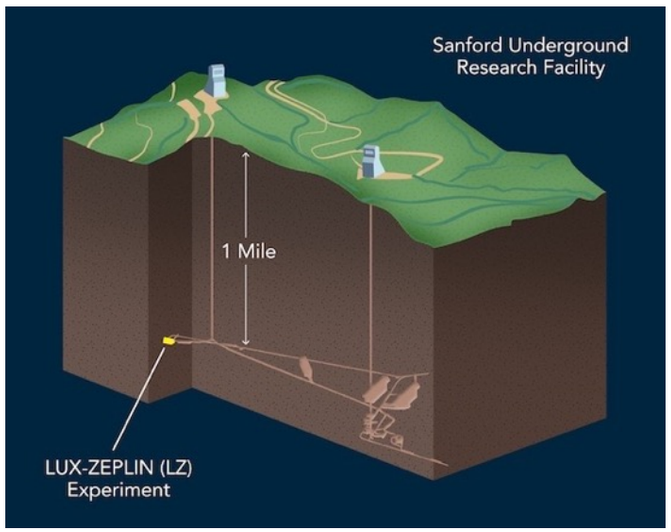
$$\sigma_{\rm SI}^{\rm 5plet} = 1.9 \times 10^{-46}\ {\rm cm}^2$$

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

Full NLO in α_S, O(50%) uncertainties

Phenomenology





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

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

Phenomenology

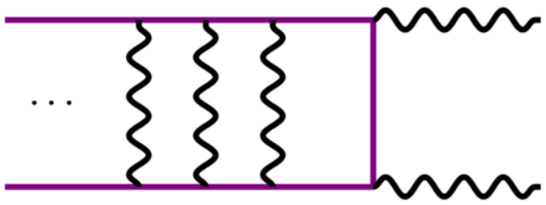
- Galactic Center
- Dwarf spheroidal galaxies

based on Cirelli Hambye Panci FS Taoso 1507.05519 + works & thoughts in progress

EW multiples in the gamma sky

Sommerfeld enhancement

at low velocities non-relativistic attractive potential

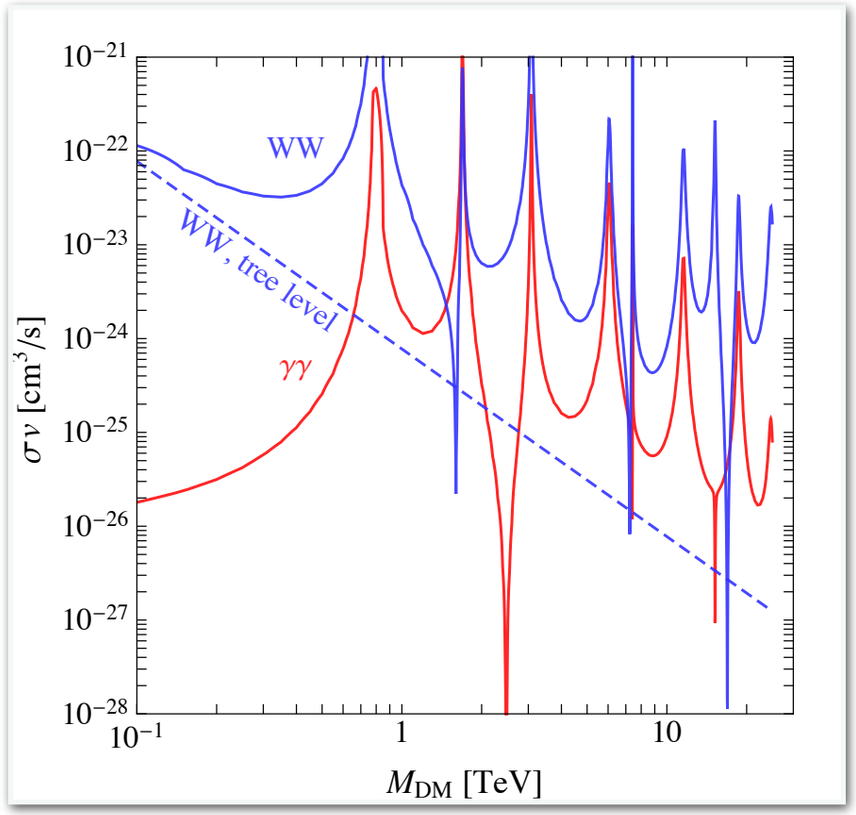


Milky Way $v \sim 10^{-3}$ c

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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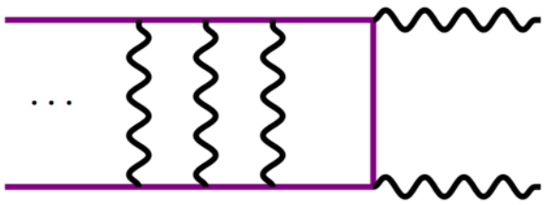

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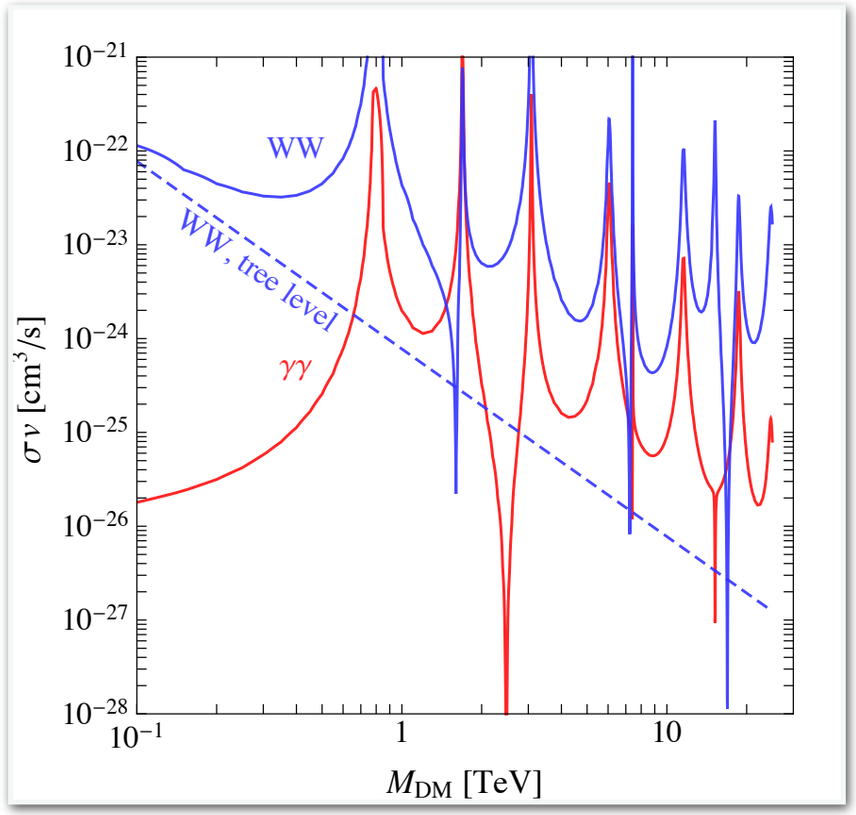
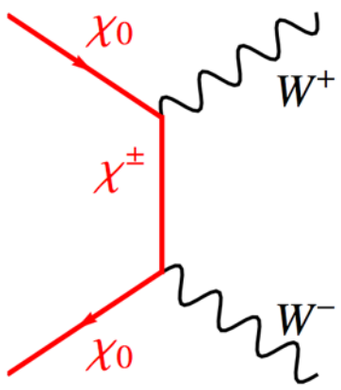
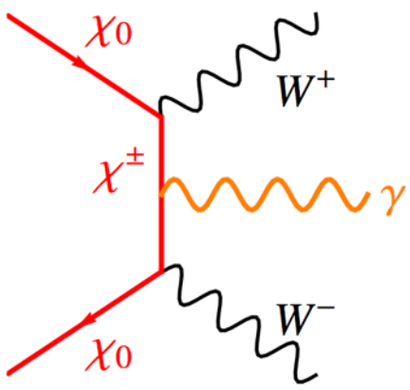
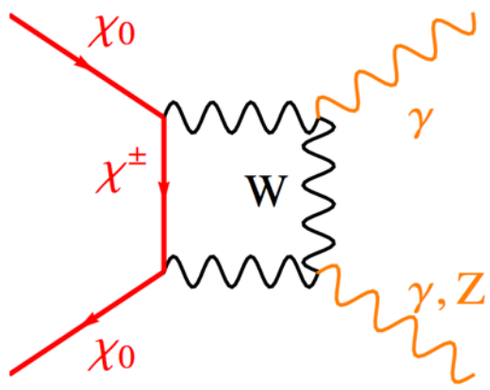








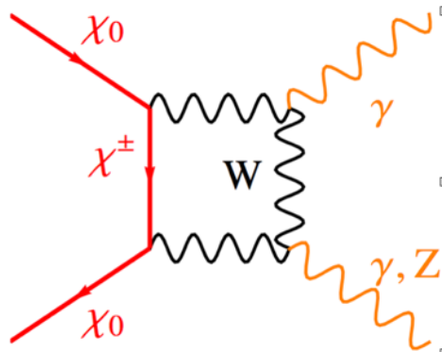
$\bar{p},\ e^+,\ \nu,\ \gamma, \ldots$

"continuum"

γ-ray lines: smaller cross sections

but features in γ-spectrum enhance sensitivities!

Lines from the Galactic Center



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

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)

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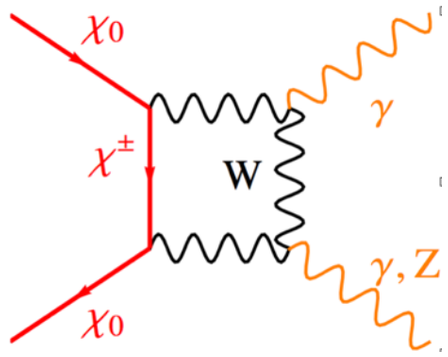

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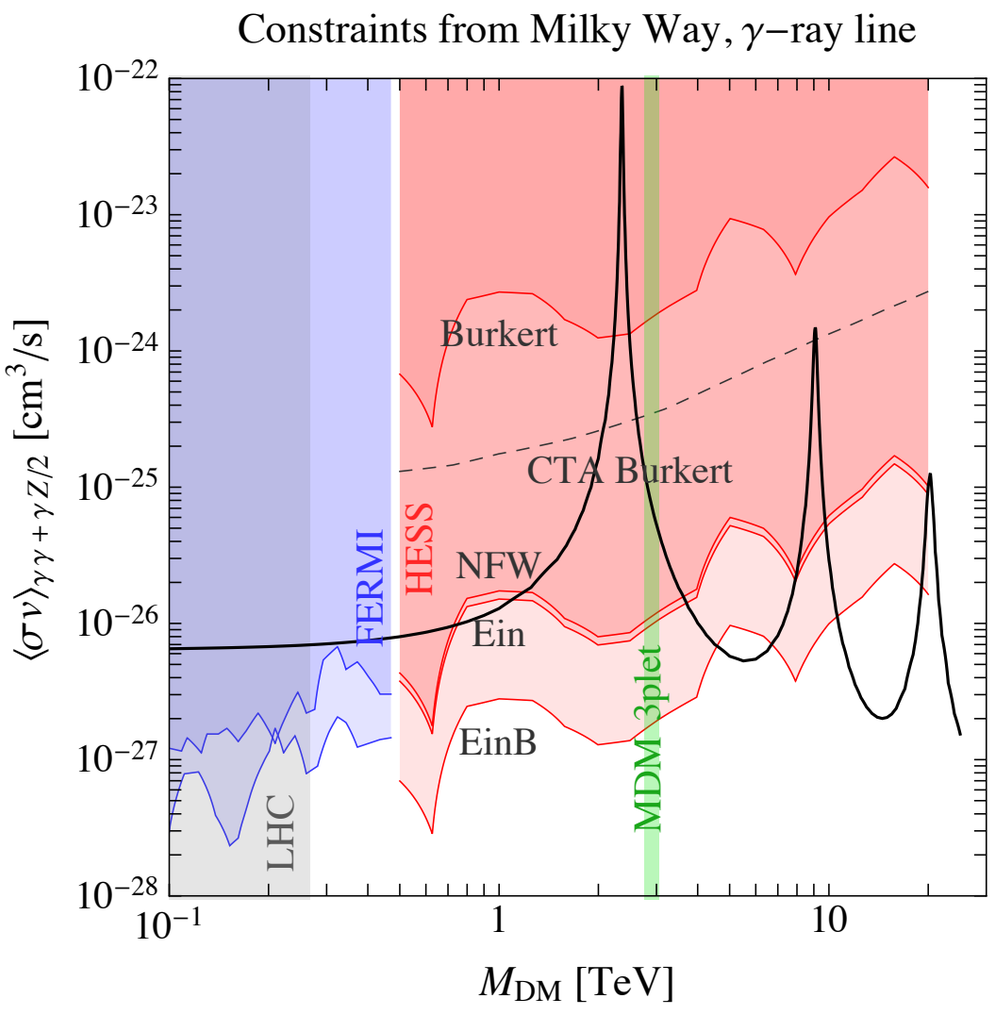
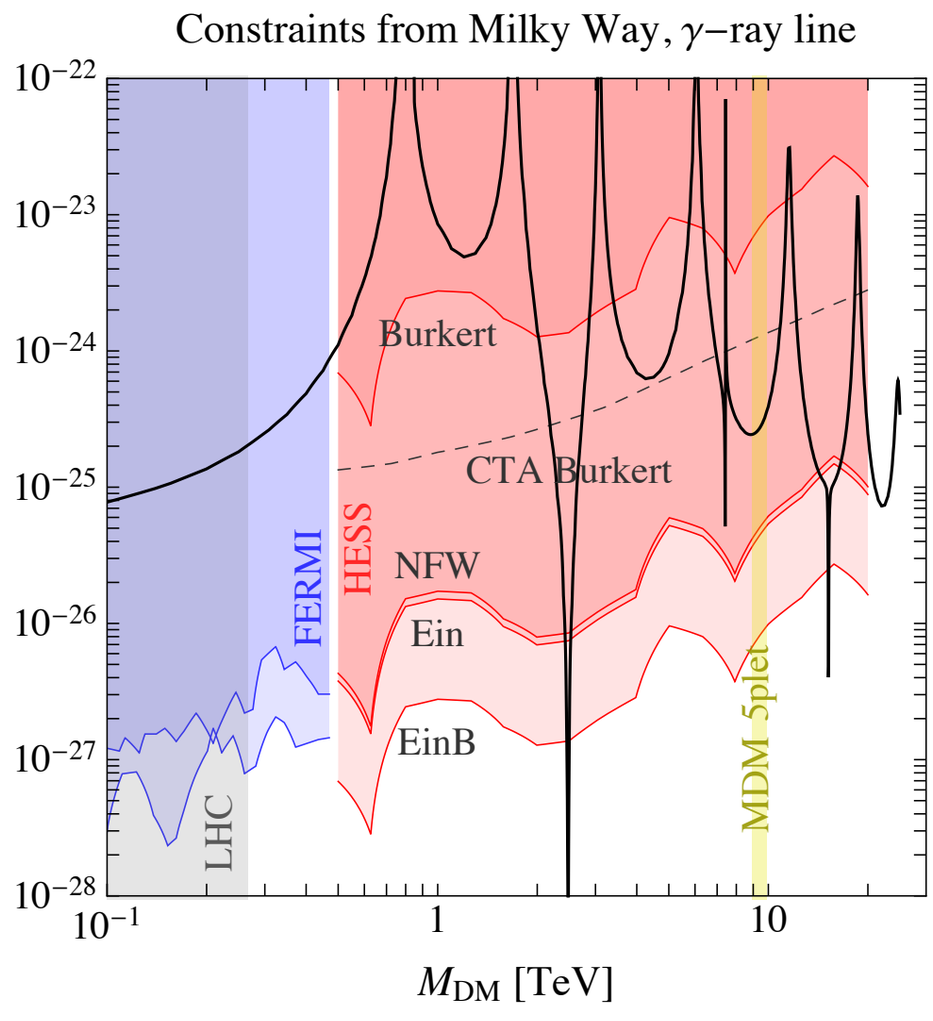




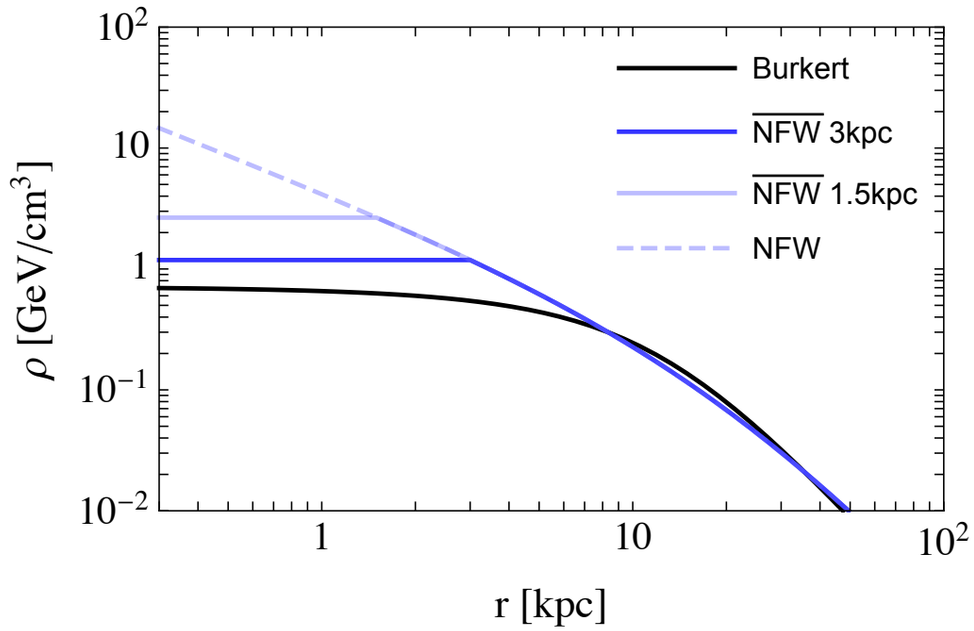
[CTA 5 hours prospects from Ovanesyan et al 1409.8294 and Bergstrom et al 1207.6773]

Astrophysical uncertainties & the GC

DM density ρ in the Milky Way:

N-body simulations “resolve" ~ 1-2 kpc
Marinacci et al. 1305.5360,…

Observations do not probe below ~ 5 kpc
Pato Iocco 1511.05571,…



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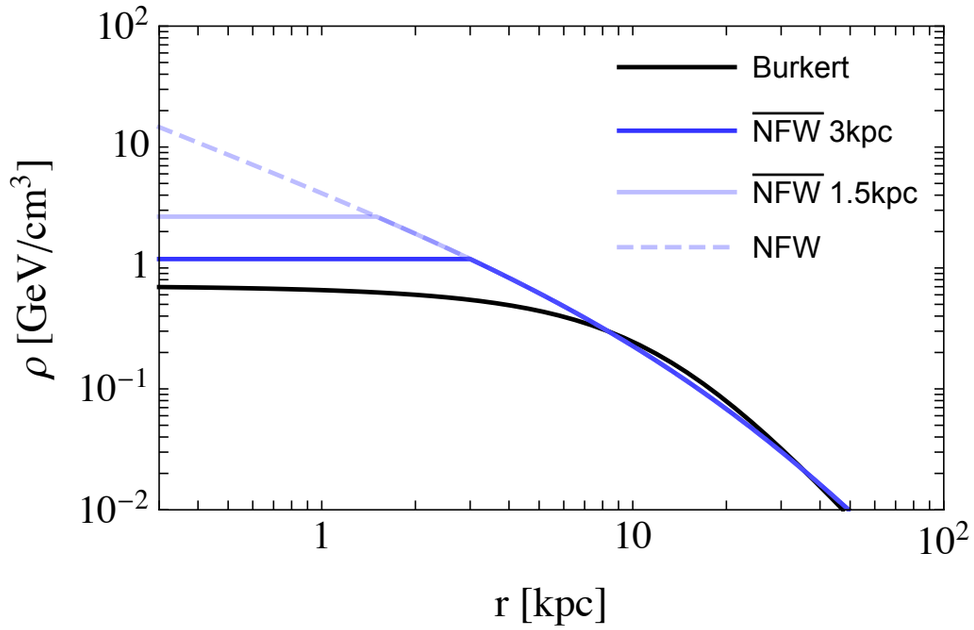

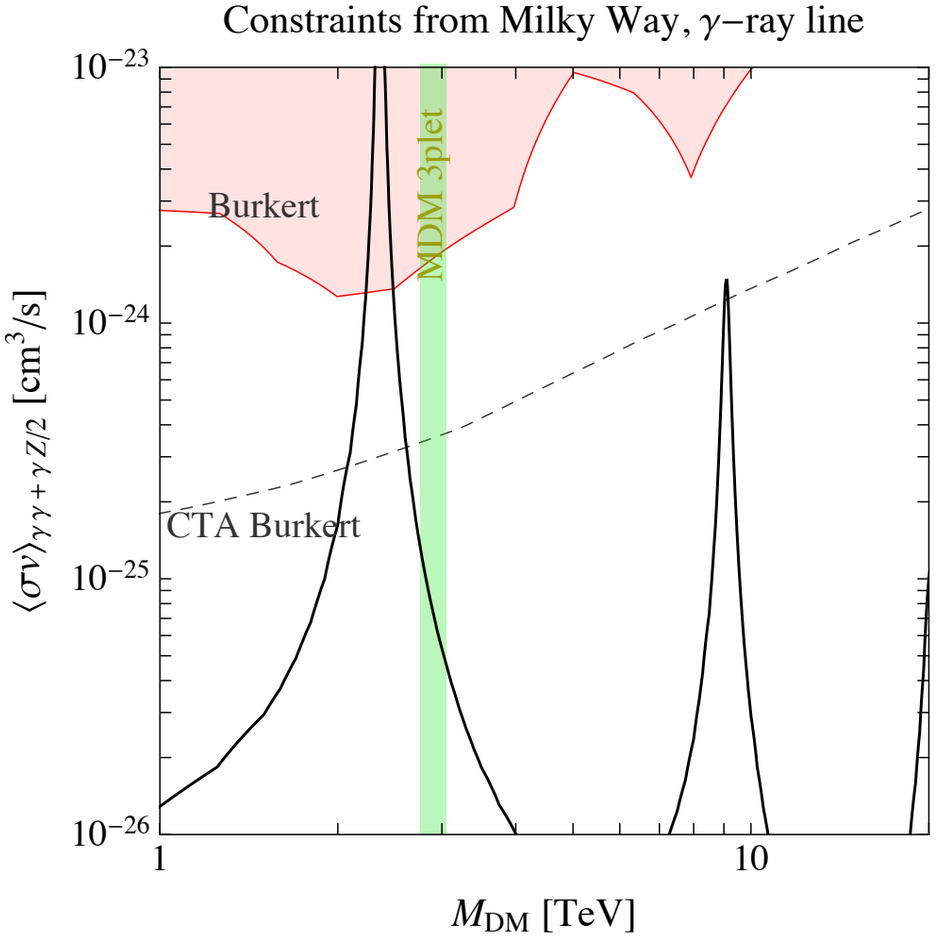

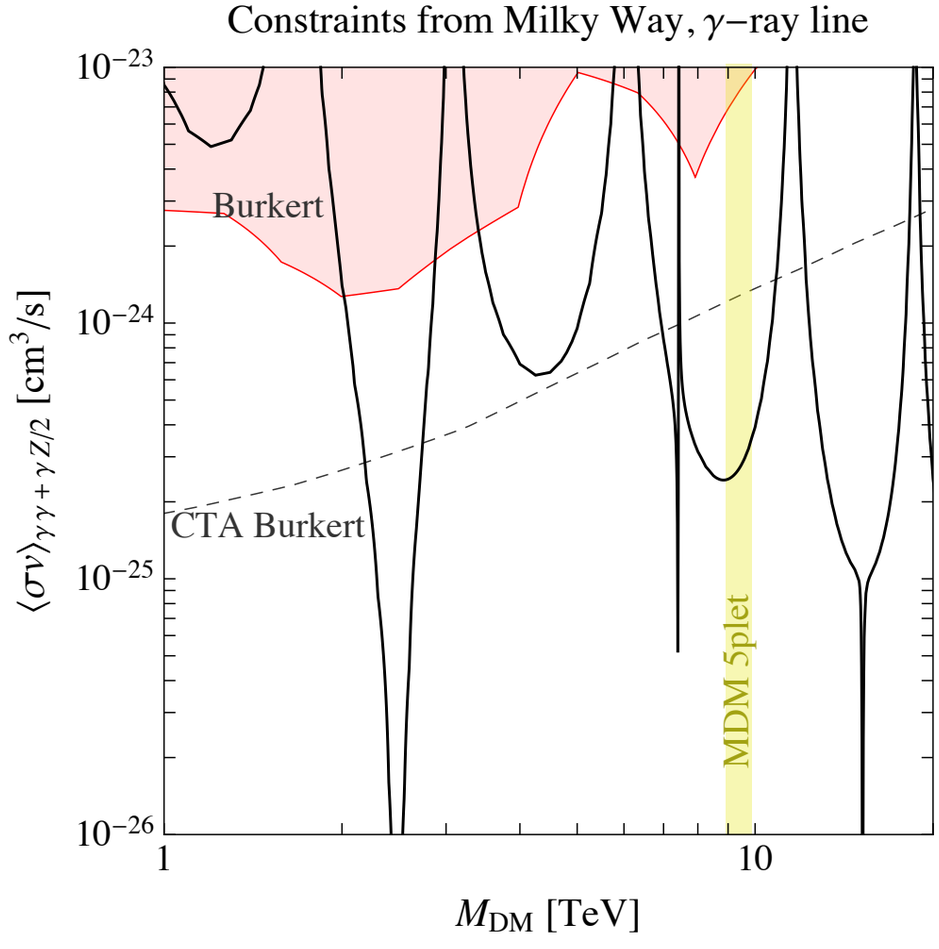

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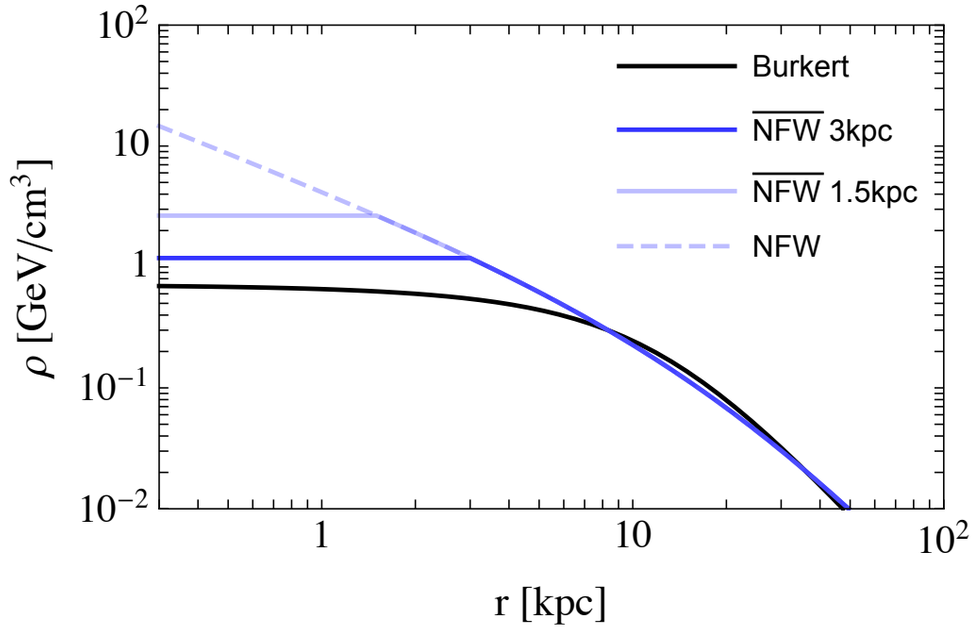

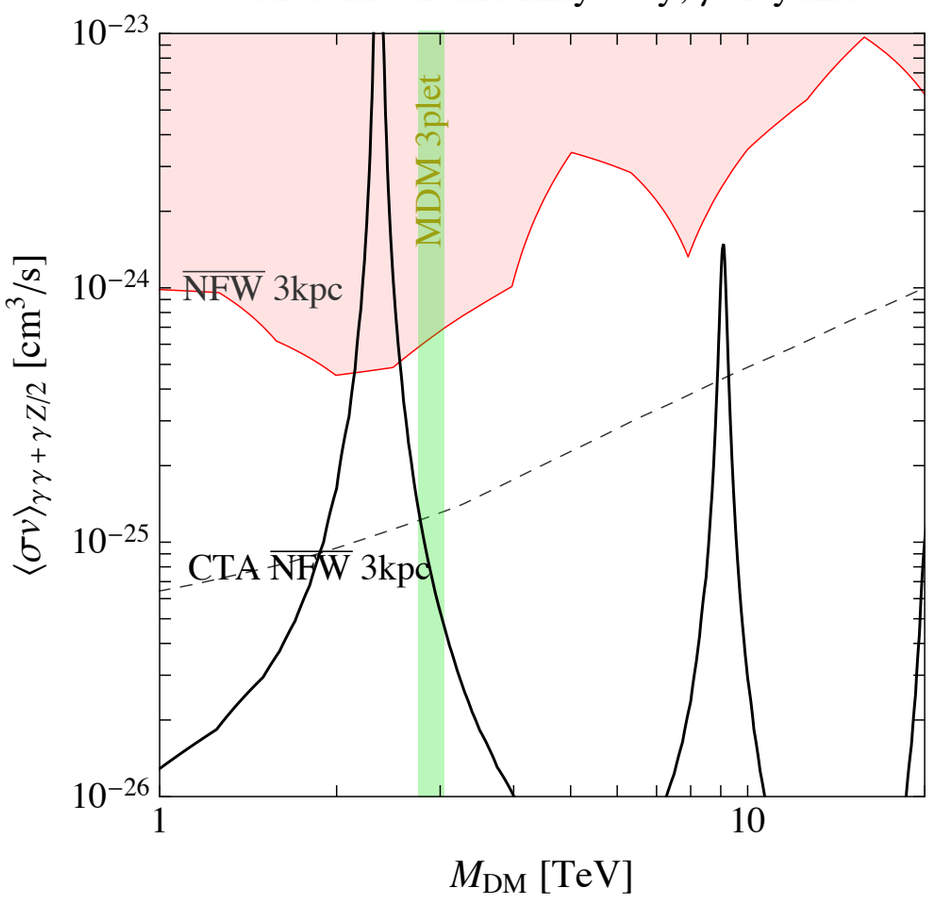

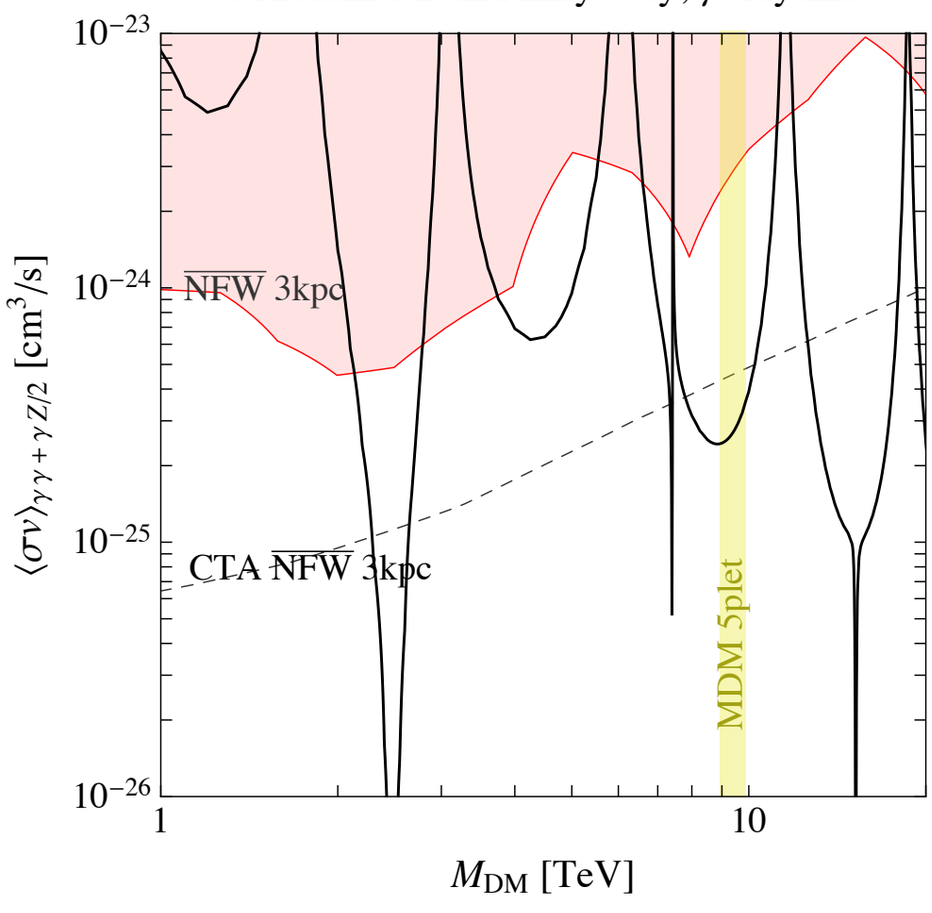

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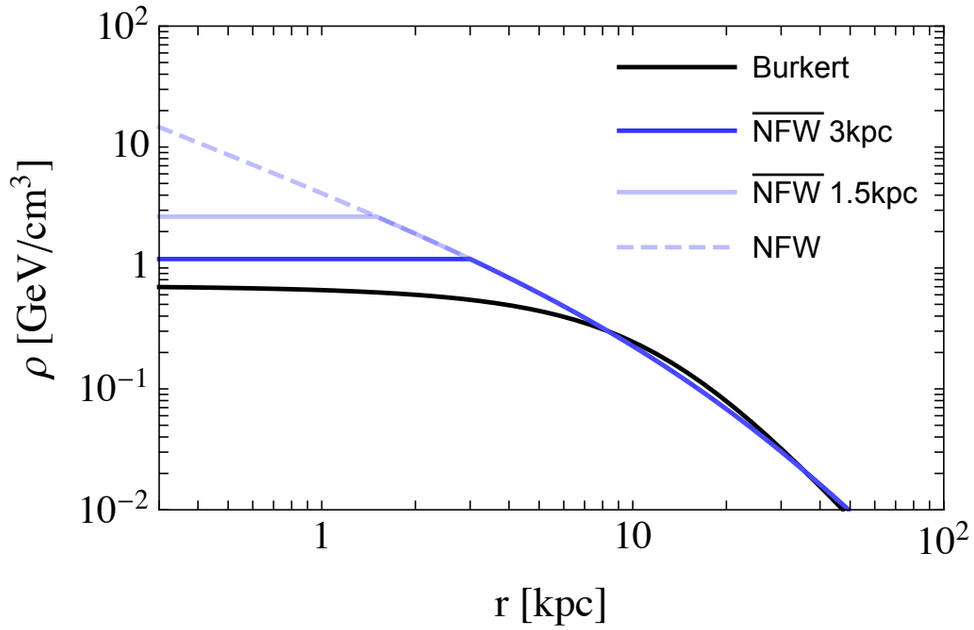

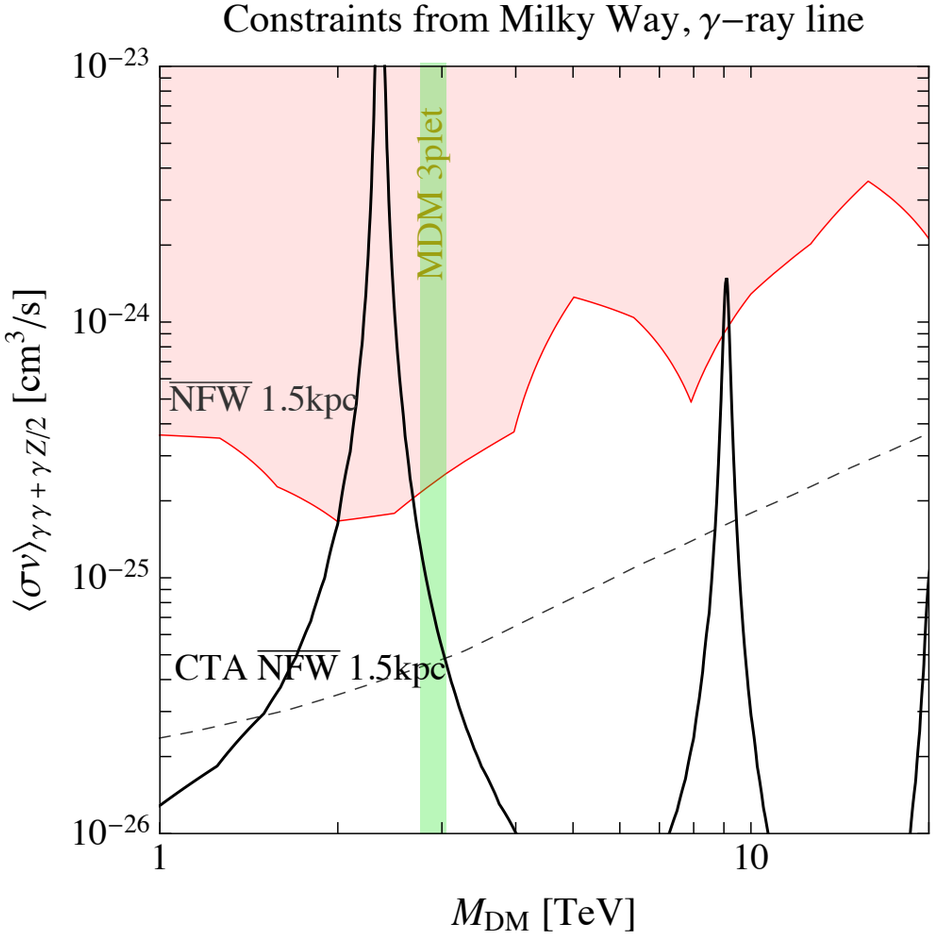

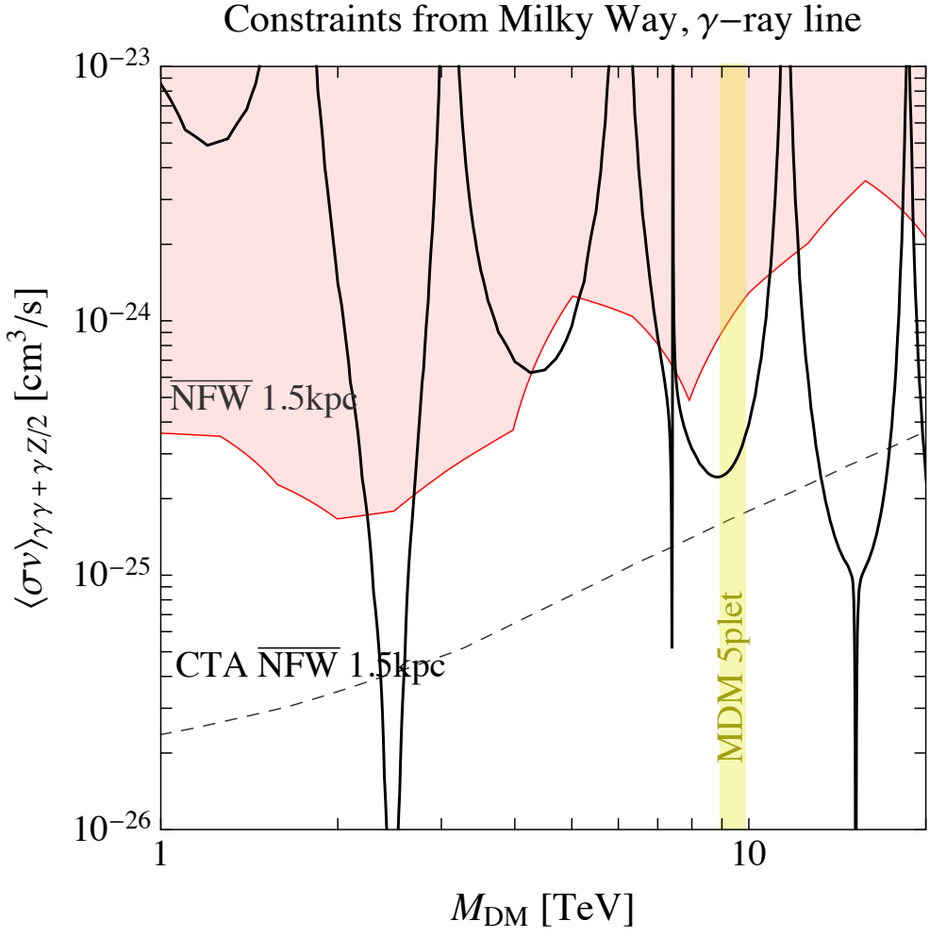

A primer on Dwarf Spheroidal Galaxies (dSph)

- 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…)

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Dark Matter annihilation from dSph

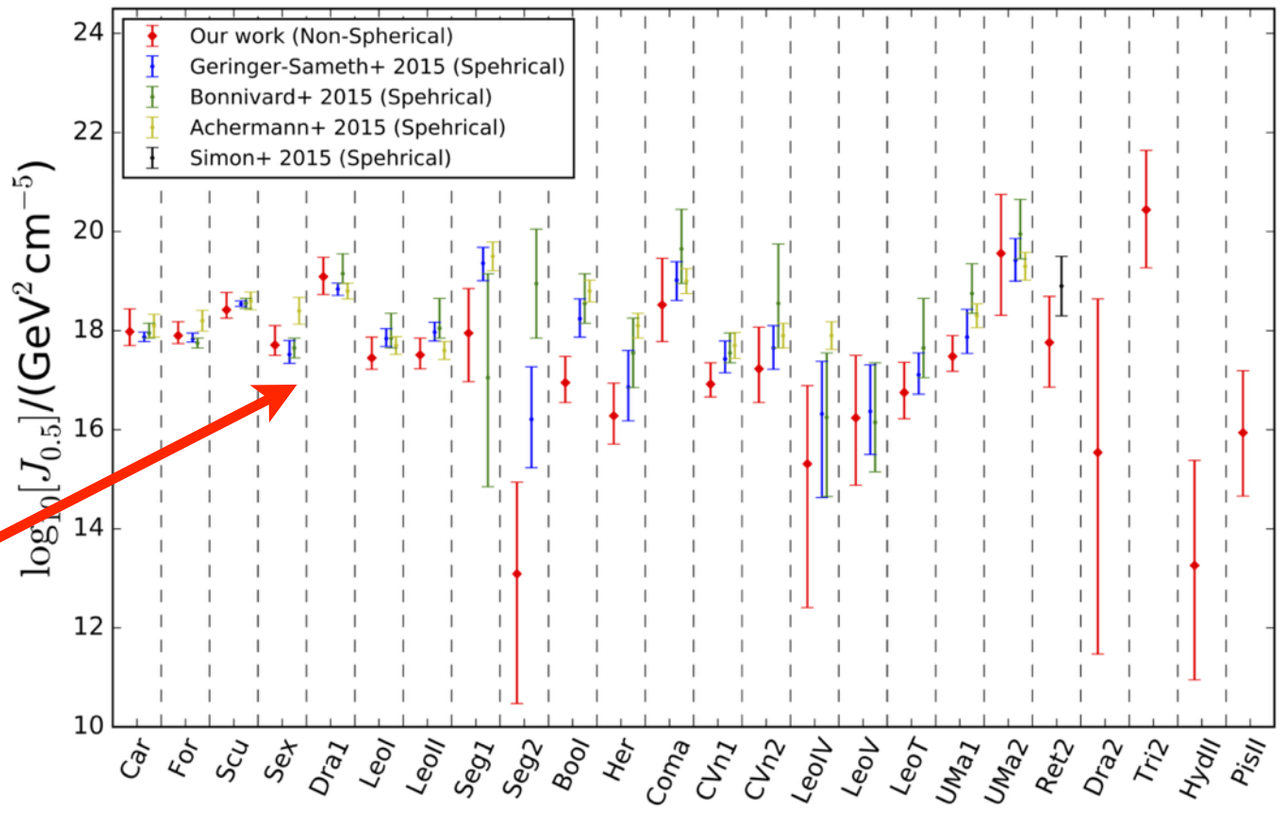
$$\text{Signal} \propto J = \int_{\Delta\Omega} \int_{\text{l.o.s.}} d\ell \, d\Omega \; \rho^2(\ell, \Omega)$$

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



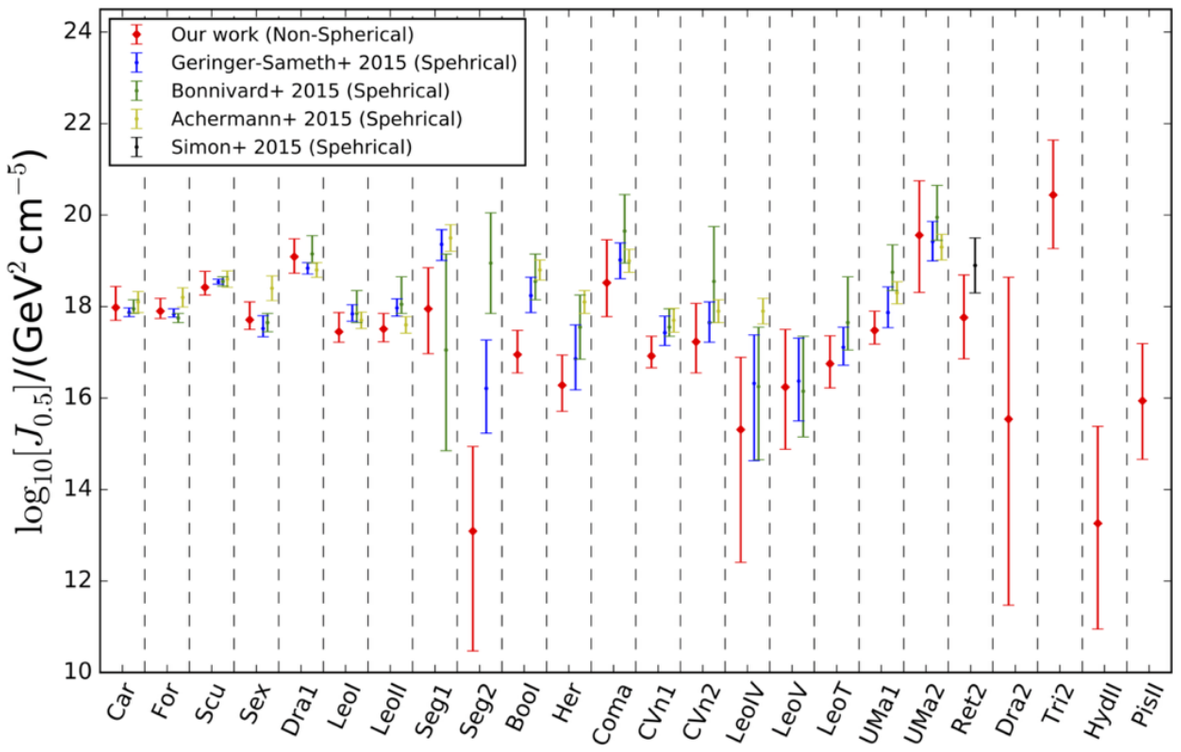
Continuum from dSphs

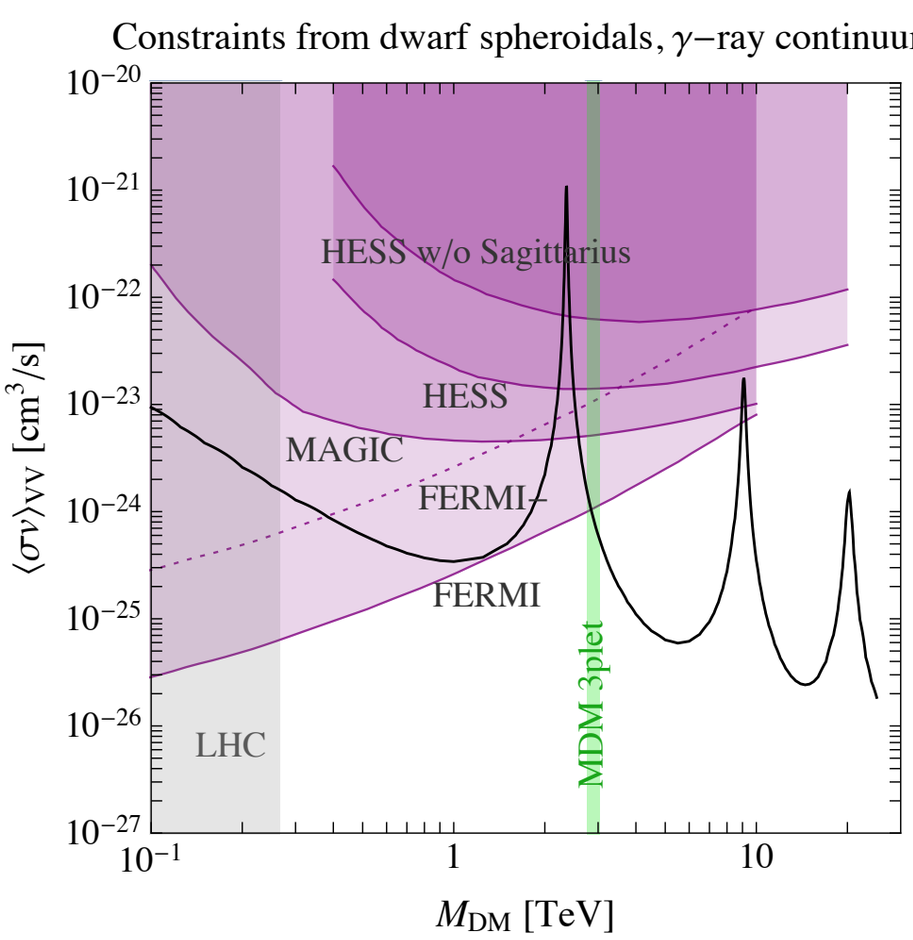
FERMI: 15 dwarves, assumes $\Delta J < 40\%$

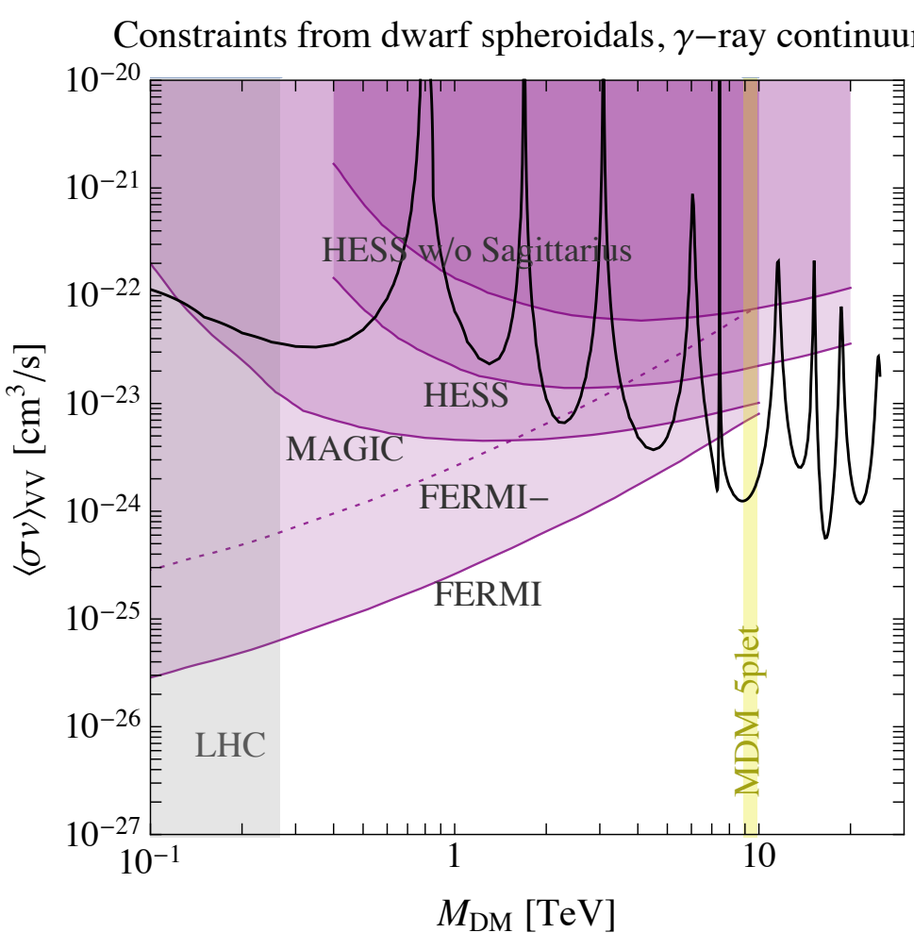
HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)

Hayashi et al 1603.08046







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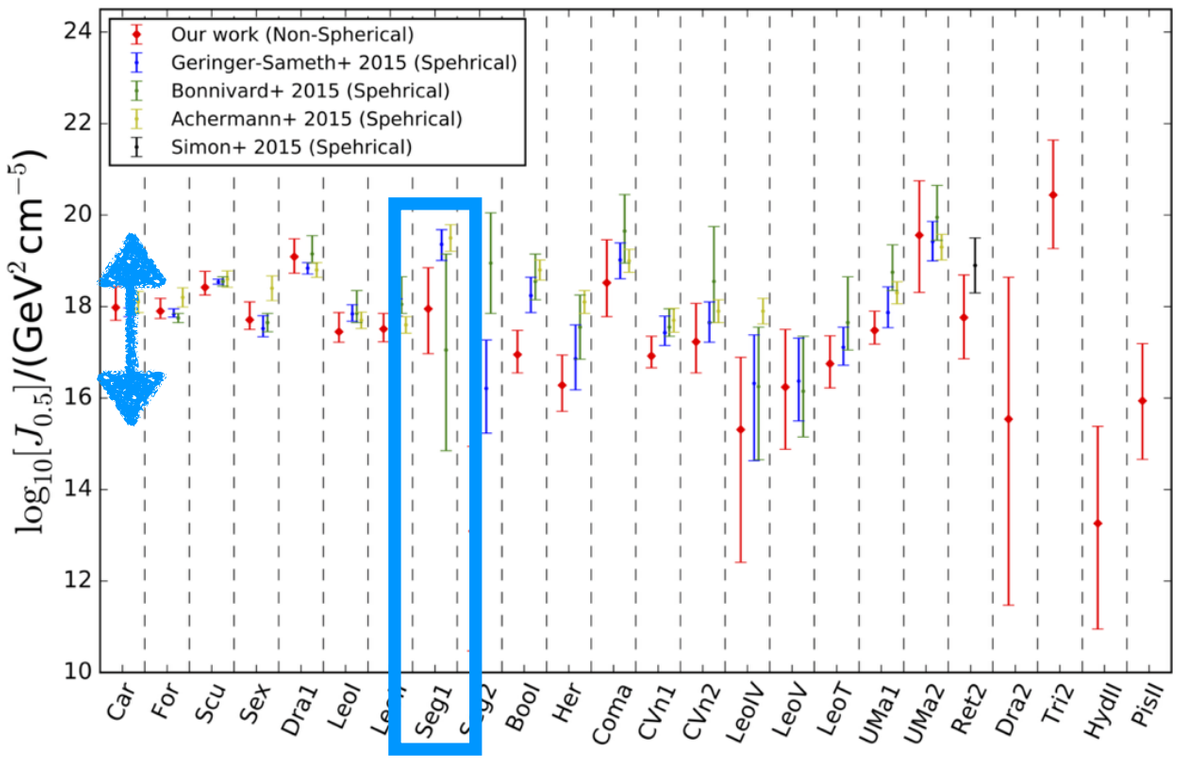
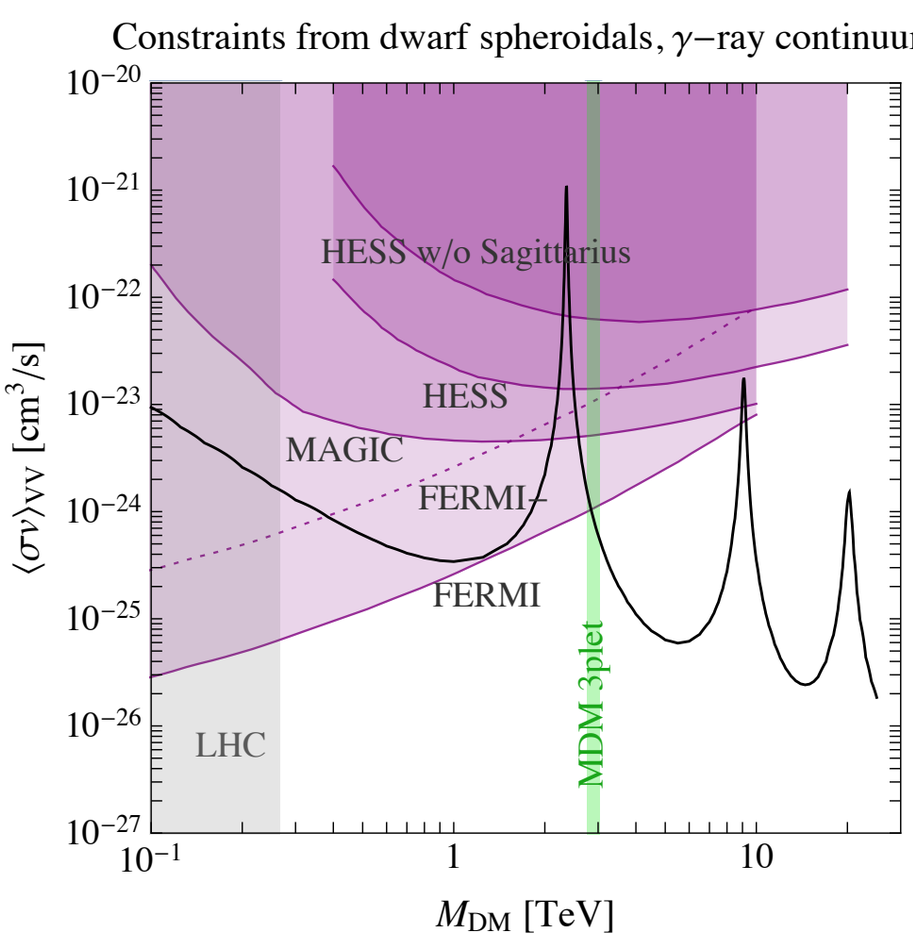
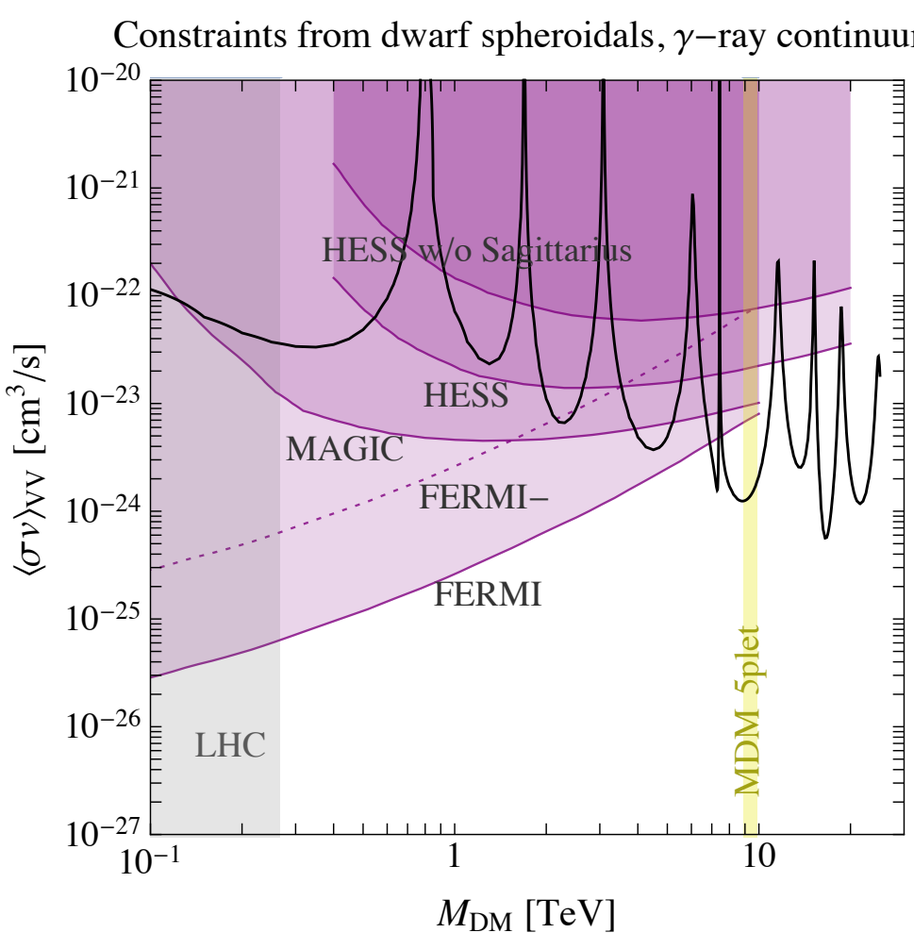
HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)

Hayashi et al 1603.08046

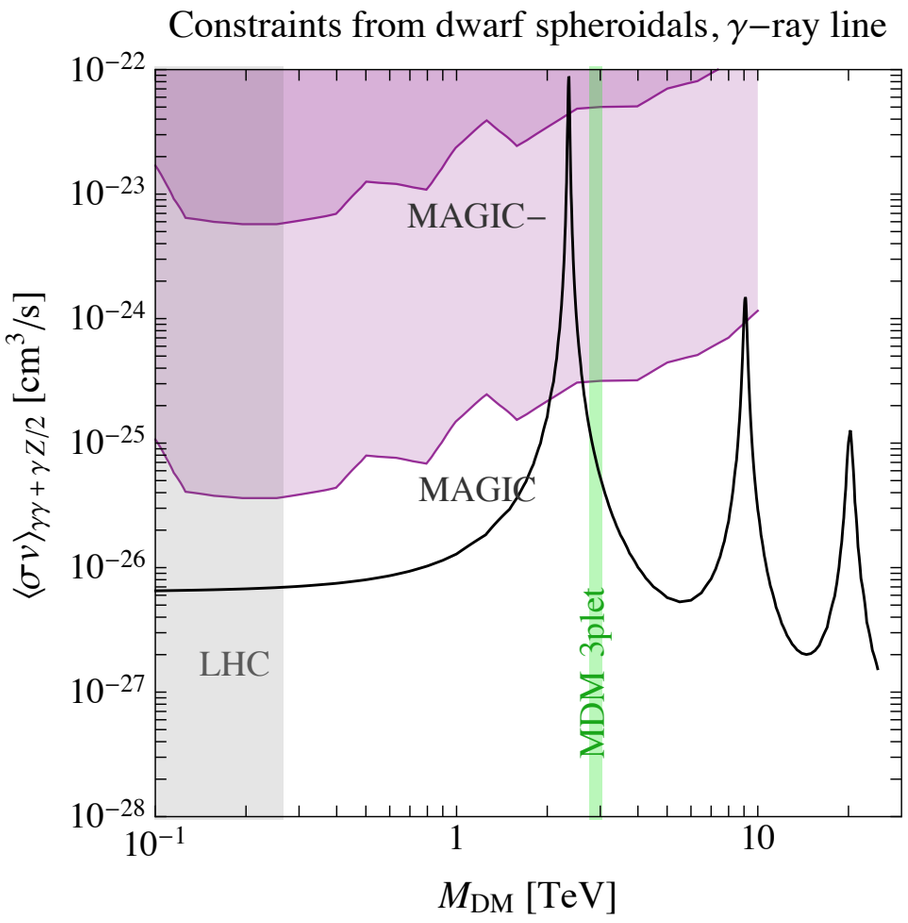


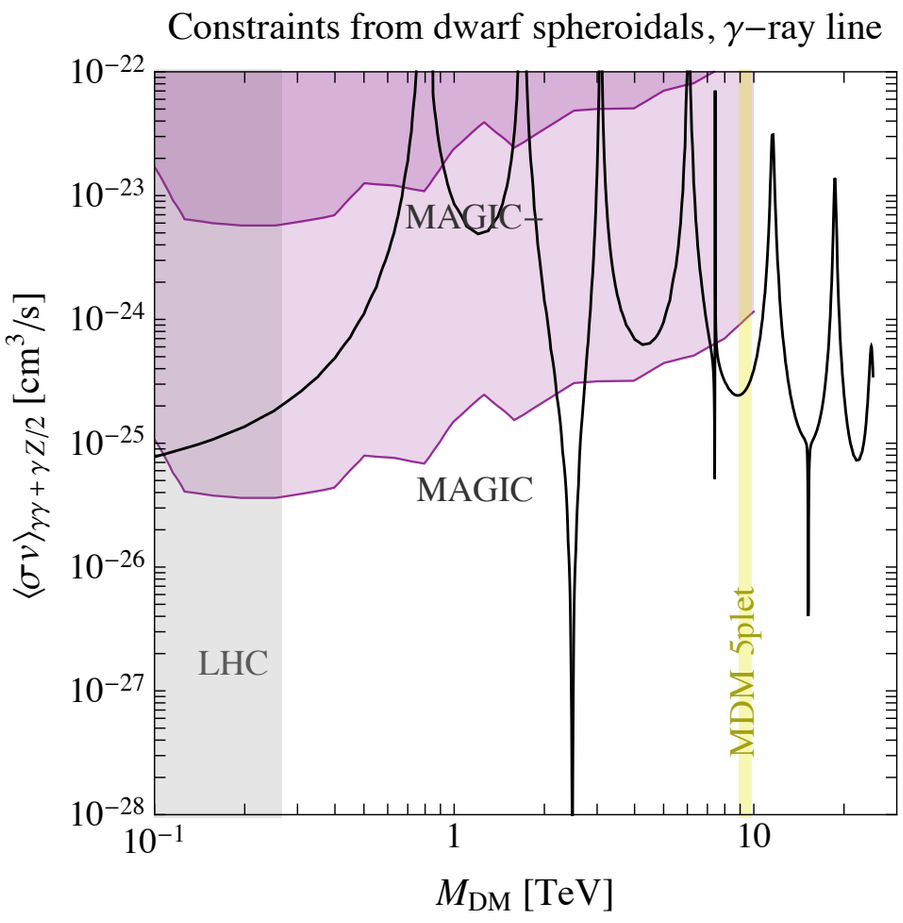




Gamma-ray lines from dSphs

Only MAGIC performed this analysis…





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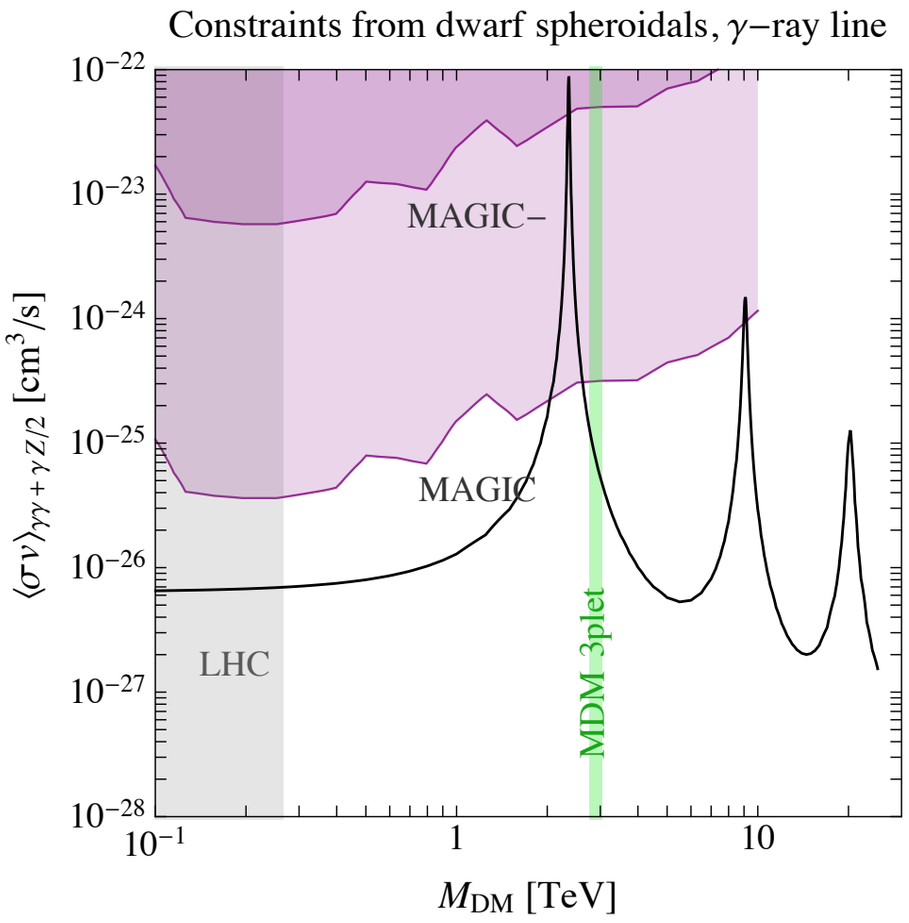
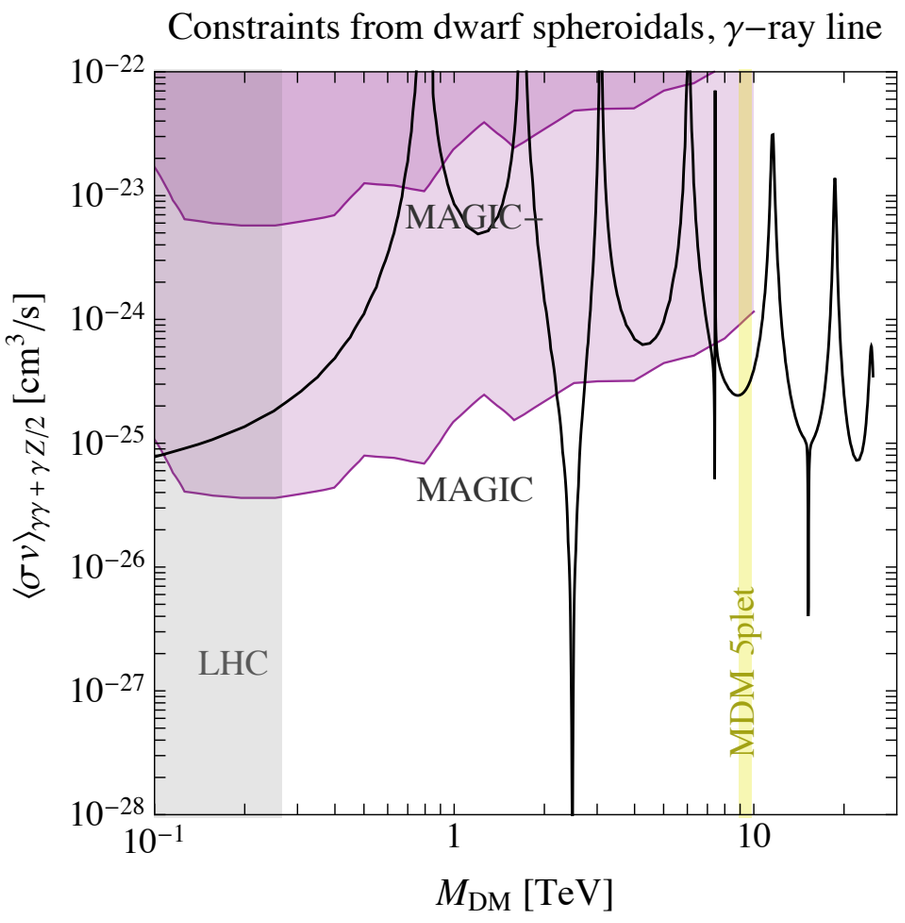
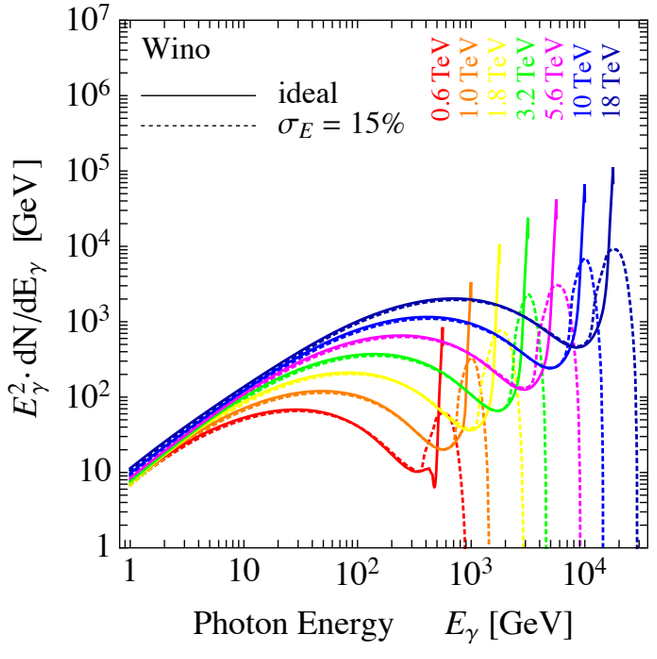




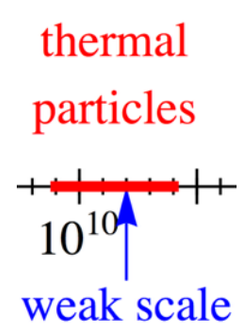
But HESS has already taken the data for the continuum!

Analysis should be out in “a few” months

HESS collaboration + Cirelli, Panci, FS, Silk, Taoso, in progress



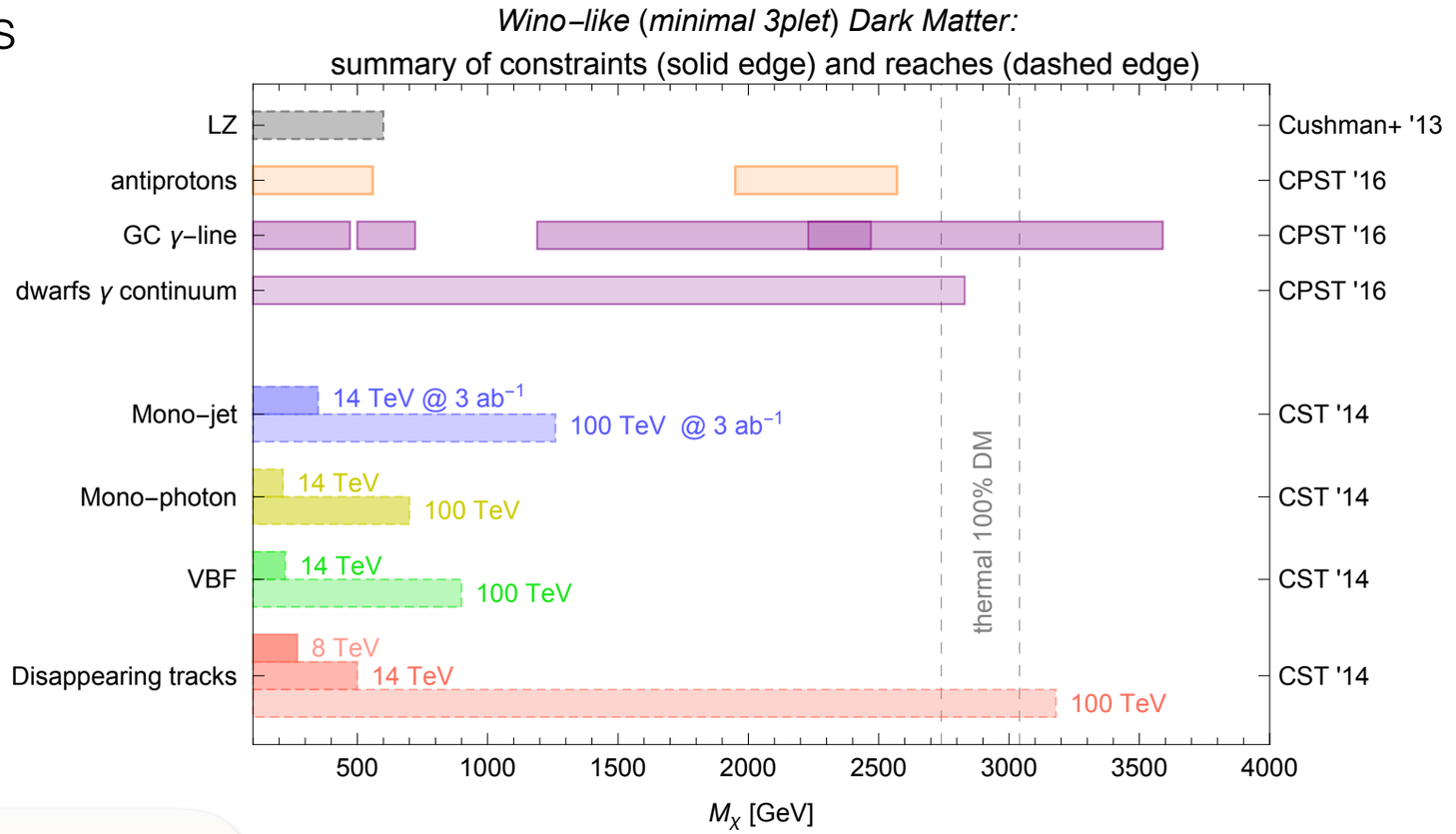
Conclusions: how far can we probe WIMPs?



Approach: benchmark/simplified models

EW multiplet are "the" WIMP prototypes

(+ Minimal Dark Matter, SUSY,…)



Present and Future of exploration

Collider ~ clear, need 100 TeV

Direct Detection ~ clear, need next generation

Telescopes: unclear, need to know more astro!

CTA (~ 2018) prospects for γ lines?

Lefranc, Moulin, Panci, FS, Silk in progress

Inputs from N-body simulations?

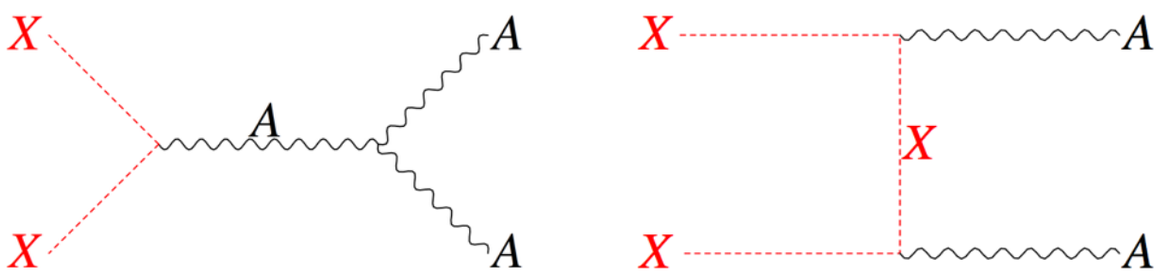
ongoing discussions…

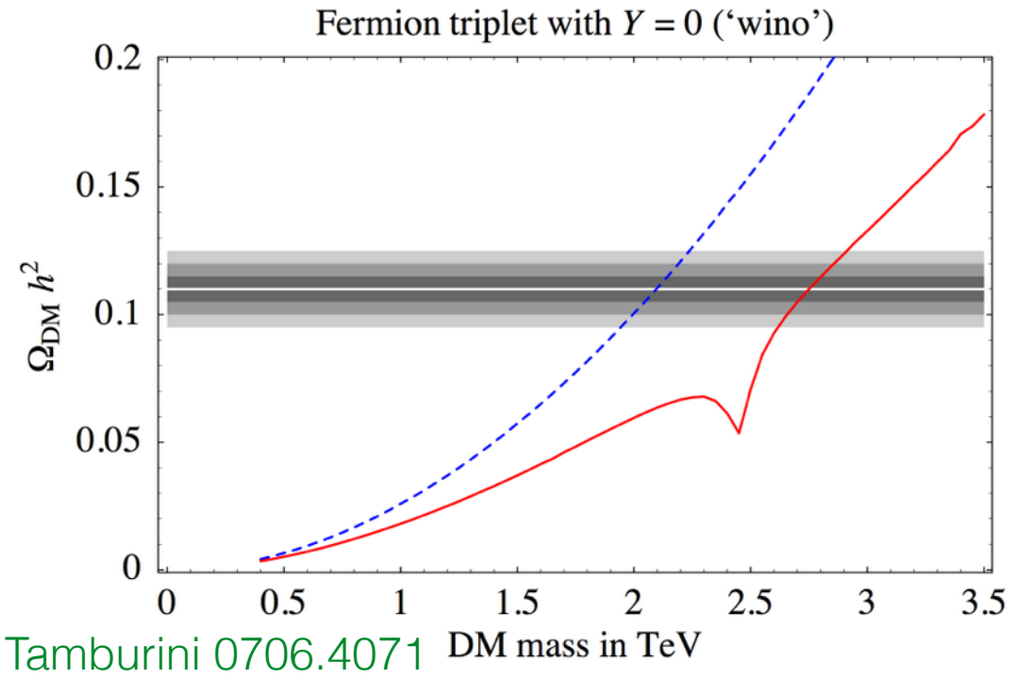
Inputs from observations (GAIA)?

Back-up slides

Thermal relic WIMPs

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



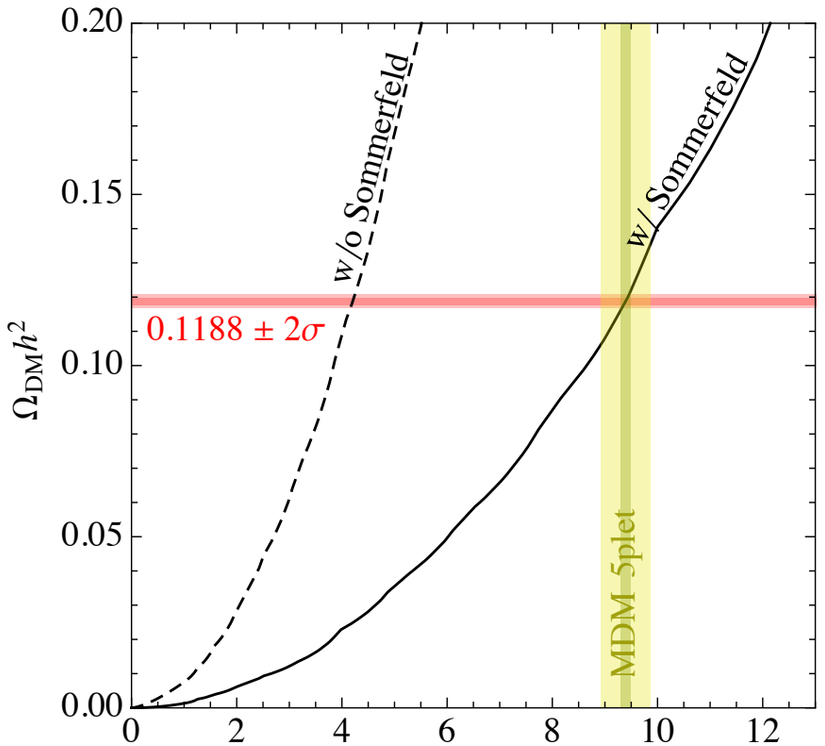


Cirelli Strumia Tamburini 0706.4071

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

Thermal relic WIMPs

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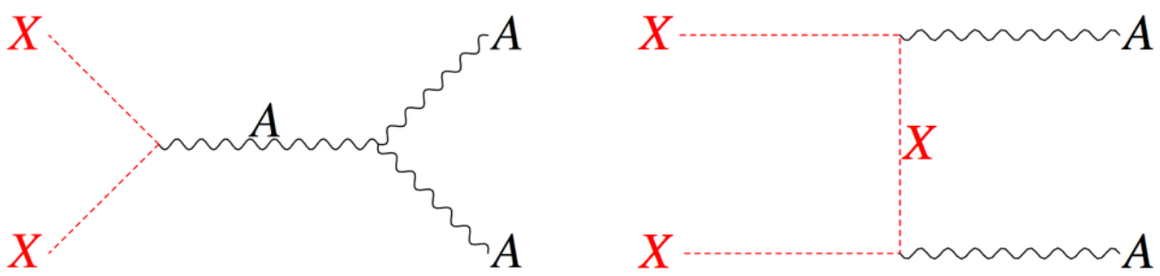
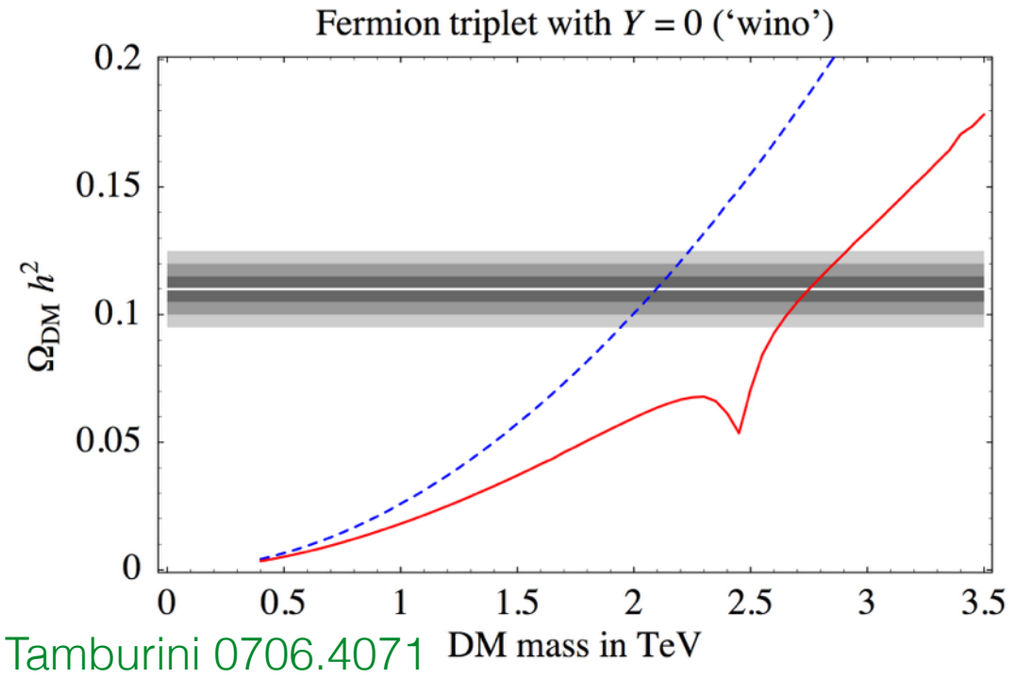




Cirelli Strumia Tamburini 0706.4071

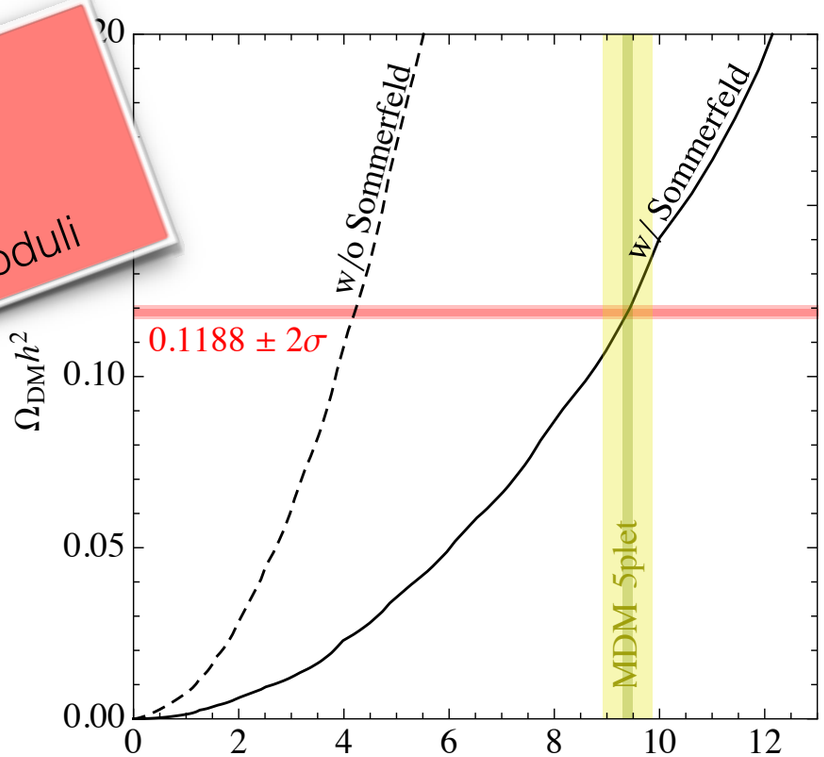
Important to include:

- ☑ 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

$M^{\rm 3plet}_{\rm thermal} \simeq 3$ [illegible] $M^{\rm 5plet}_{\rm thermal} \simeq 9.5$ TeV



Cirelli et al. 1507.05519

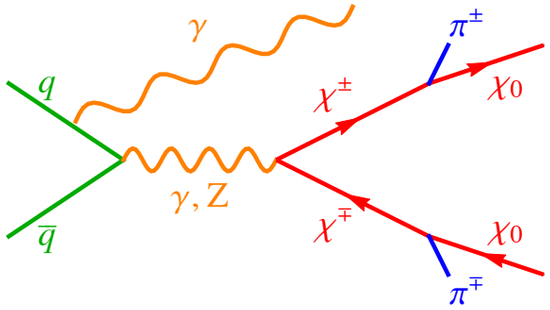
EW multiples at colliders - I

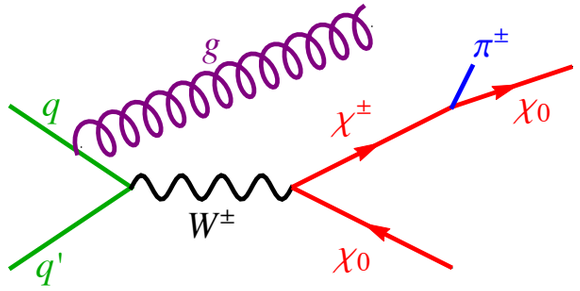
DM does not interact with detectors: look for missing energy + SM radiation

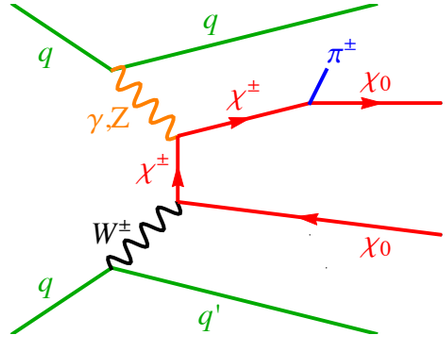
Pure EW multiplets: $\chi^{\pm}$ & $\chi^{\pm\pm}$ add to the signal!

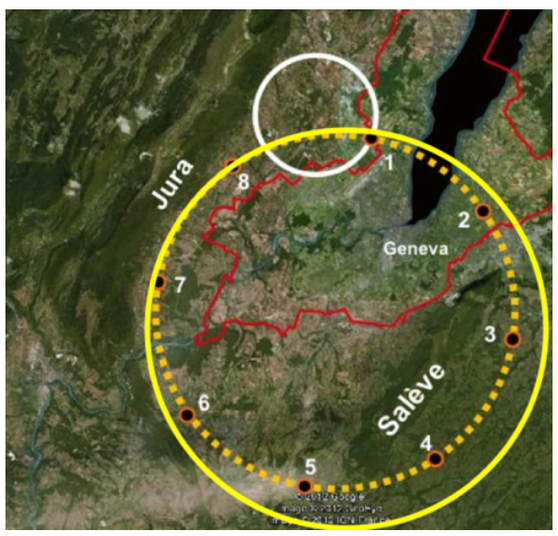
In fact $M_{\chi^{\pm,\pm\pm}} - M_{\chi 0} \gtrsim m_\pi$ ⟶ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

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









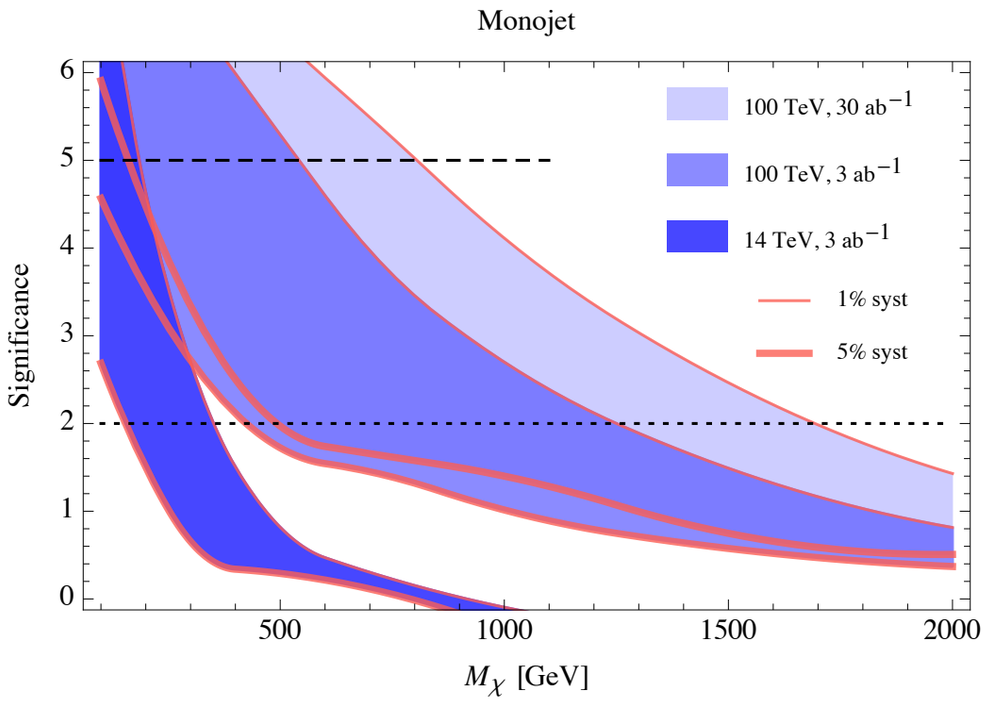
SM radiation: - monojet
- monophoton
- (forward) dijets - aka "Vector Boson Fusion"

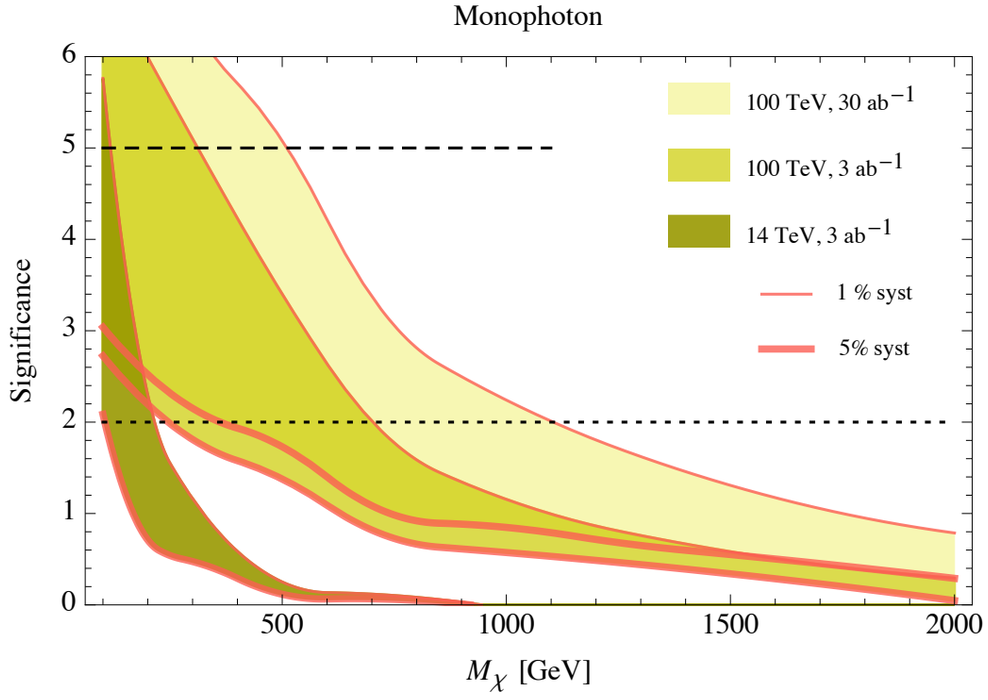
LHC8: hopeless to get even close to multi-TeV thermal masses

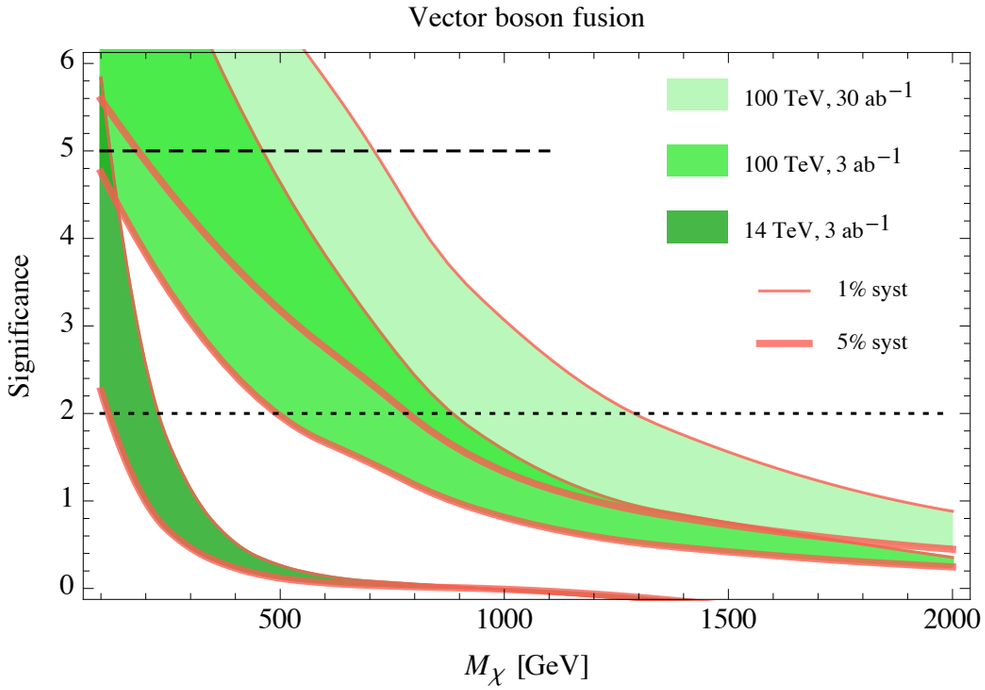
Need higher energies ⟶ **HL-LHC** (14 TeV) & **FCC-hh** (100 TeV)

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

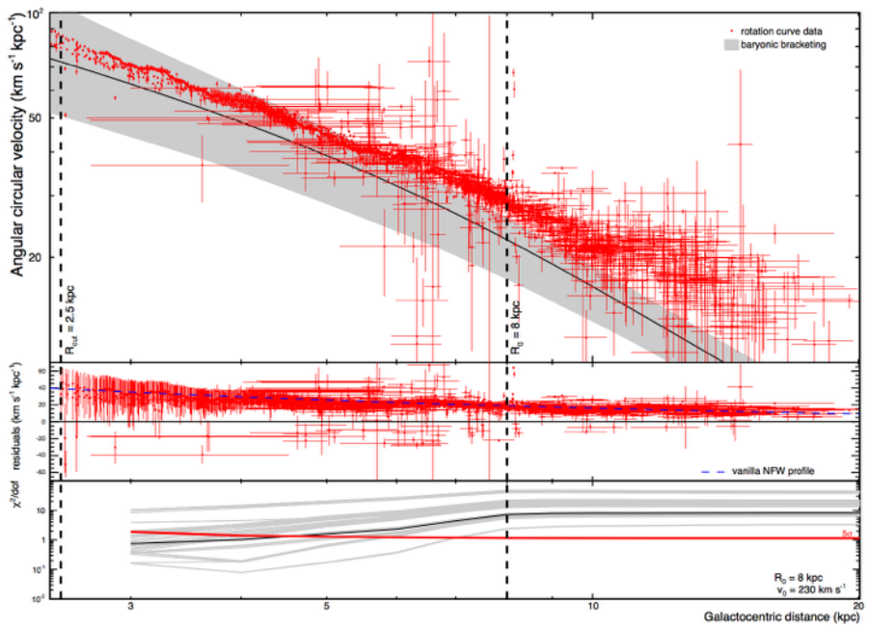
Same conclusions for 5plet

Dark Matter in the Milky Way

Observations

We *know* there is DM only down to ~ 5 kpc

Bertone Iocco Pato 1502.03821

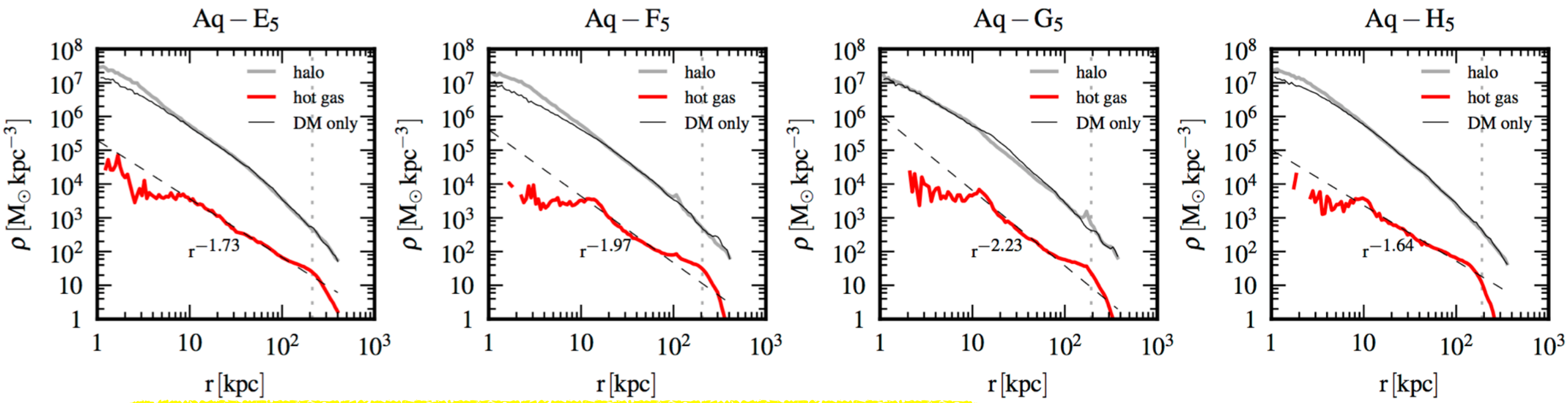


N-body simulations

With cold DM only: no core in density profile

With some baryon modelling:

"outflows" (e.g. supernovae) could drive DM to "exit" the Galactic Center…but:

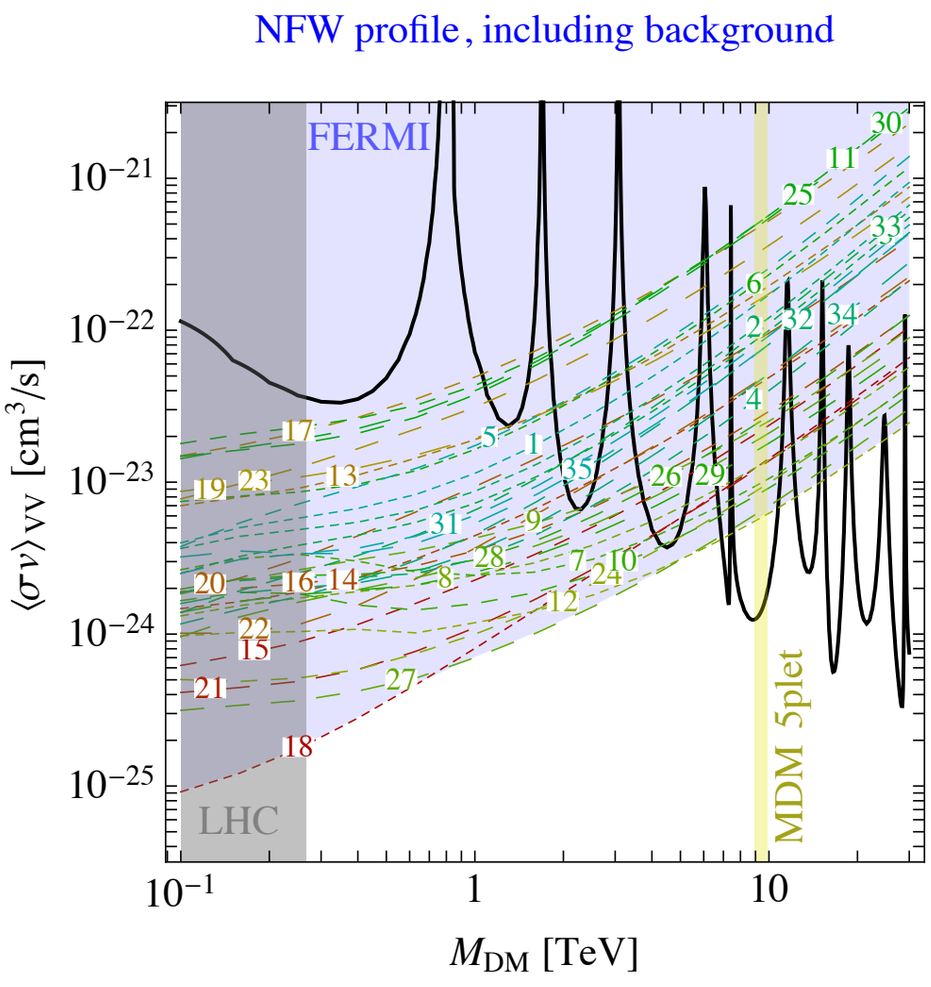


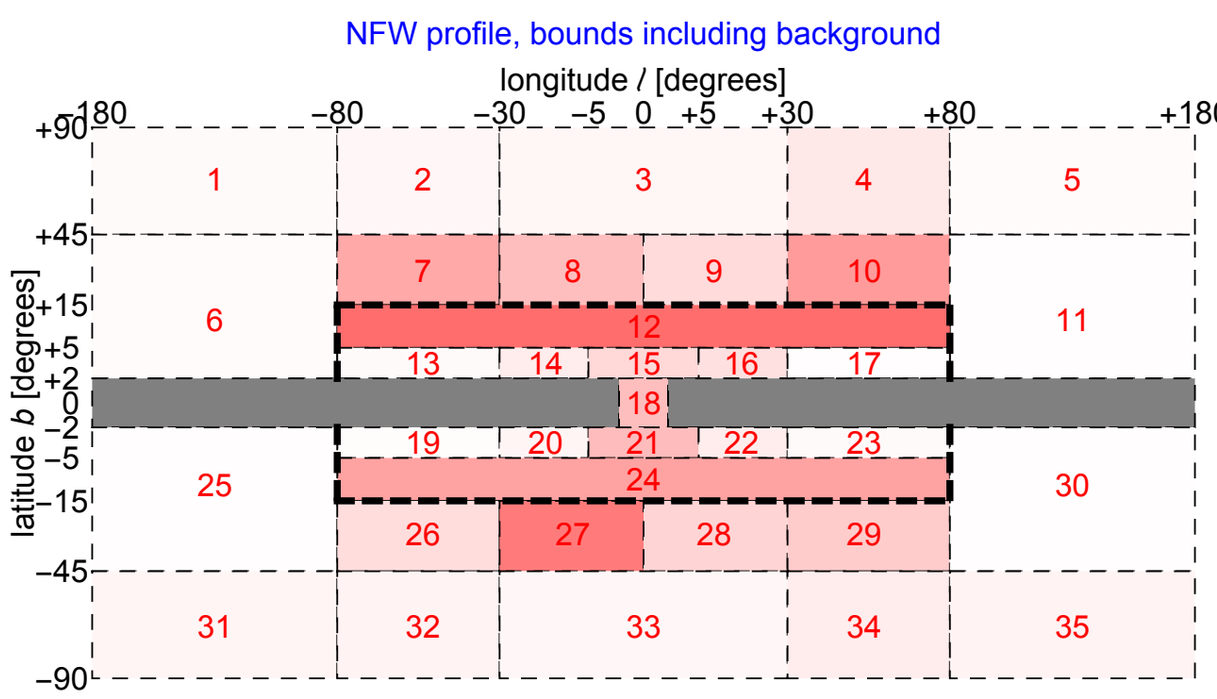
Limit: simulations today not trustable below ~ 1 kpc…

Marinacci et al. 1305.5360

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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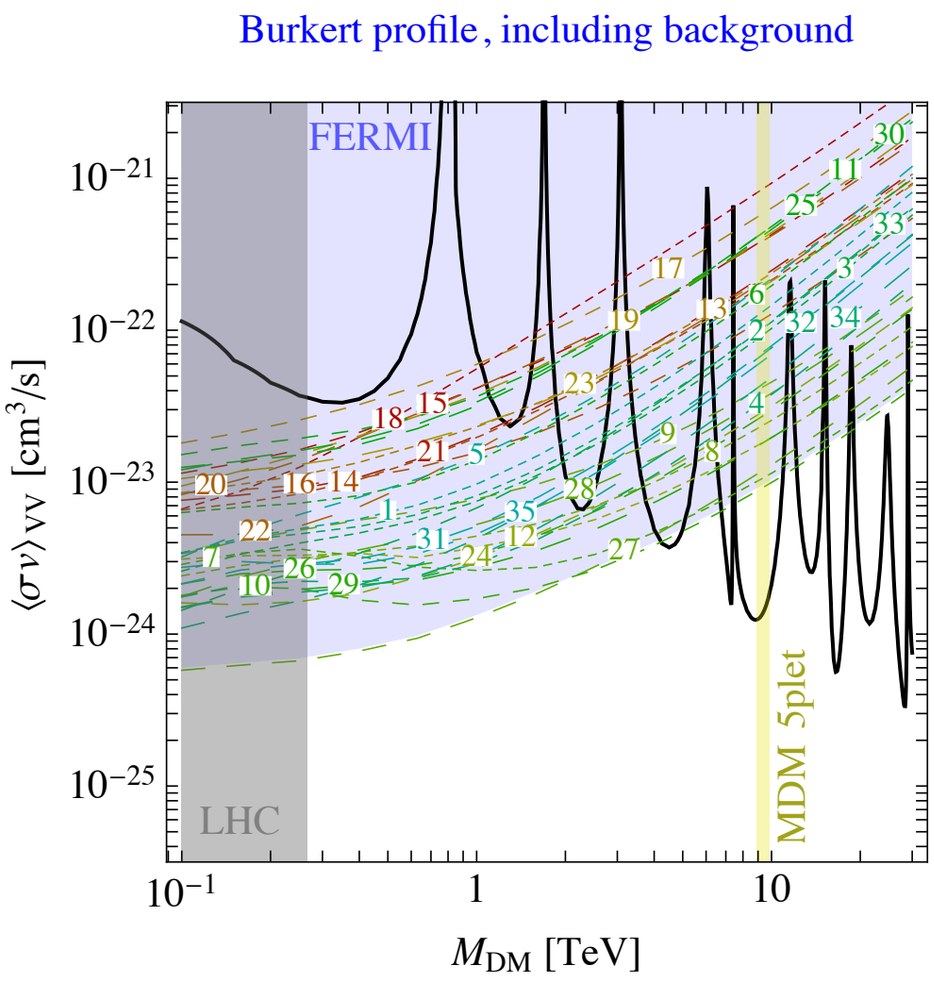

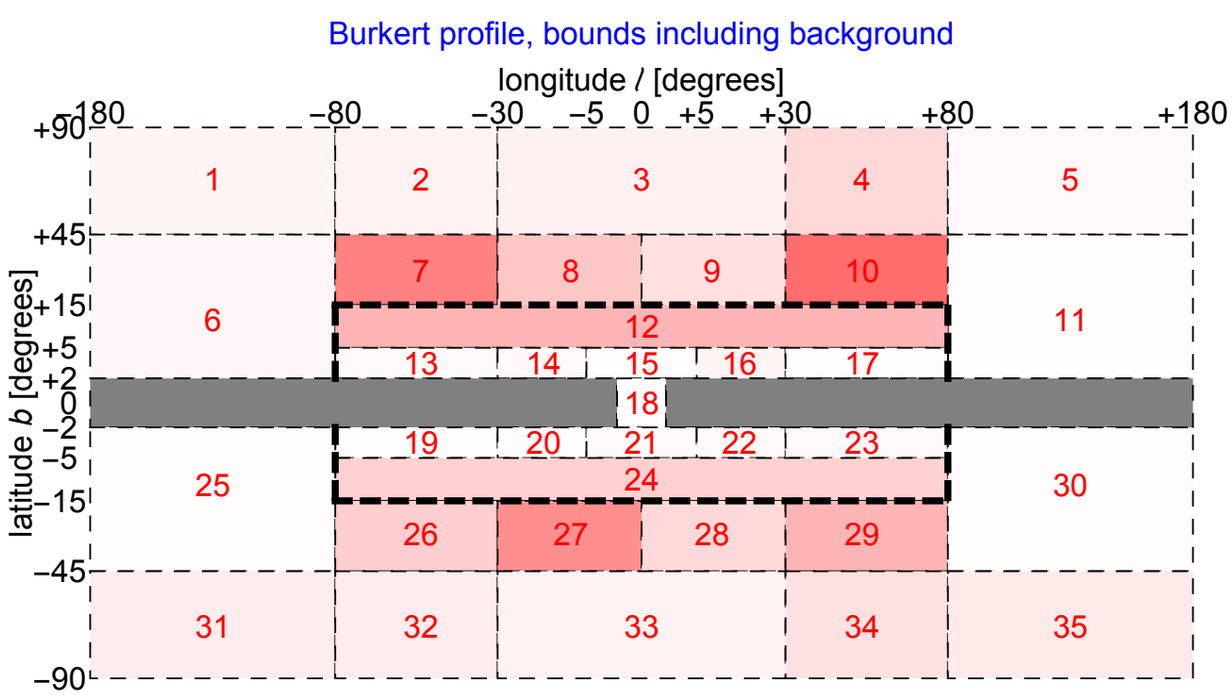

A primer on Dwarf Spheroidal Galaxies (dSph)

- 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…)

Hayashi et al 1603.08046

Object	$N_{\rm sample}$	RA(J2000) [hh:mm:ss]	DEC(J2000) [dd:mm:ss]	M_V	$D_\odot$ [kpc]
Classical dwarfs					
Carina	776	06:41:36.7	−50:57:58	-9.1 ± 0.5	106 ± 6
Fornax	2523	02:39:59.3	−34:26:57	-13.4 ± 0.3	147 ± 12
Sculptor	1360	01:00:09.4	−33:42:33	-11.1 ± 0.5	86 ± 6
Sextans	445	10:13:03.0	−01:36:53	-9.3 ± 0.5	86 ± 4
Draco	468	17:20:12.4	+57:54:55	-8.8 ± 0.3	76 ± 6
Leo I	328	10:08:28.1	+12:18:23	-12.0 ± 0.3	254 ± 15
Leo II	200	11:13:28.8	+22:09:06	-9.8 ± 0.3	233 ± 14
Ultra faint dwarfs					
Segue 1	73	10:07:04.0	+16:04:55	-1.5 ± 0.8	32 ± 6
Segue 2	24	02:19:16.0	+20:10:31	-2.5 ± 0.3	35 ± 2
Boötes I	37	14:00:06.0	+14:30:00	-6.3 ± 0.2	66 ± 2
Hercules	18	16:31:02.0	+12:47:30	-6.6 ± 0.4	132 ± 12
Coma Berenices	59	12:26:59.0	+23:54:15	-3.7 ± 0.6	44 ± 4

~ the more the tracers, the better (dSph more "solid" for DM)

~ the closer the dwarf, the better (stronger DM signal)

Summary: EW fermion 5plet

Why interesting?

Simple benchmark of a WIMP, and moreover

Minimal Dark Matter

Summary of constraints (solid edge) and reaches (dashed edge)

Phenomenology