‘We have no idea…’ - status of a search for dark matter signals in astrophysical data

Gabrijela Zaharijas

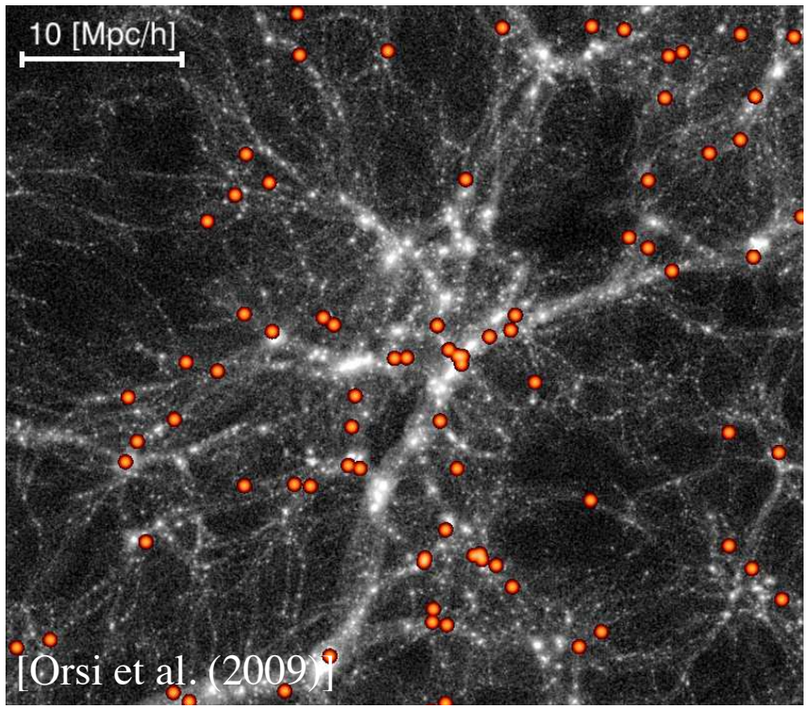
University of Nova Gorica, Slovenia and INFN, Trieste

on behalf of the Fermi LAT Collaboration

Dark matter is out there!

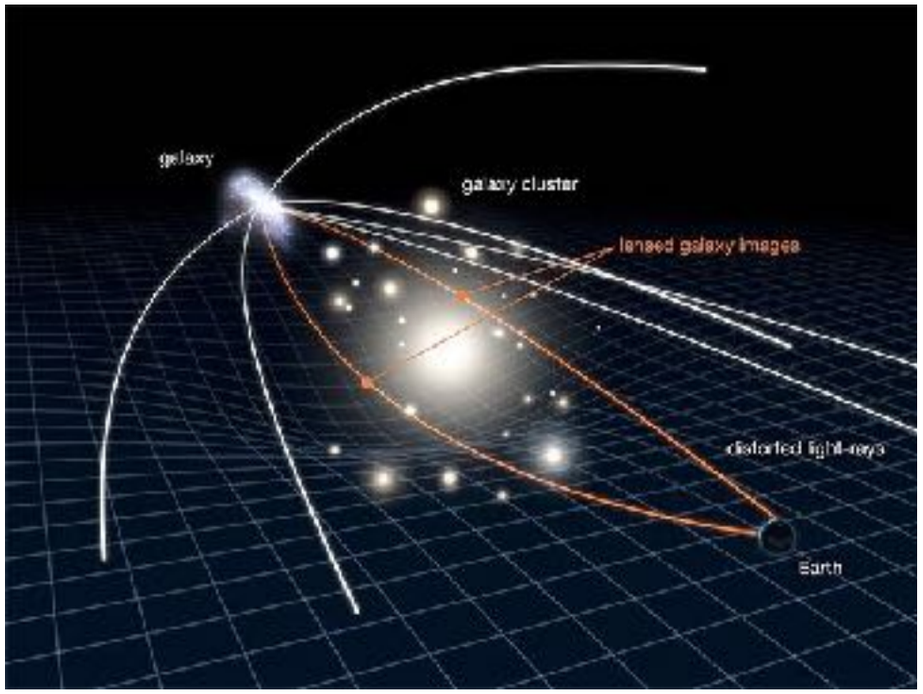
an essential building block of the Standard Model of Cosmology

large scale structures



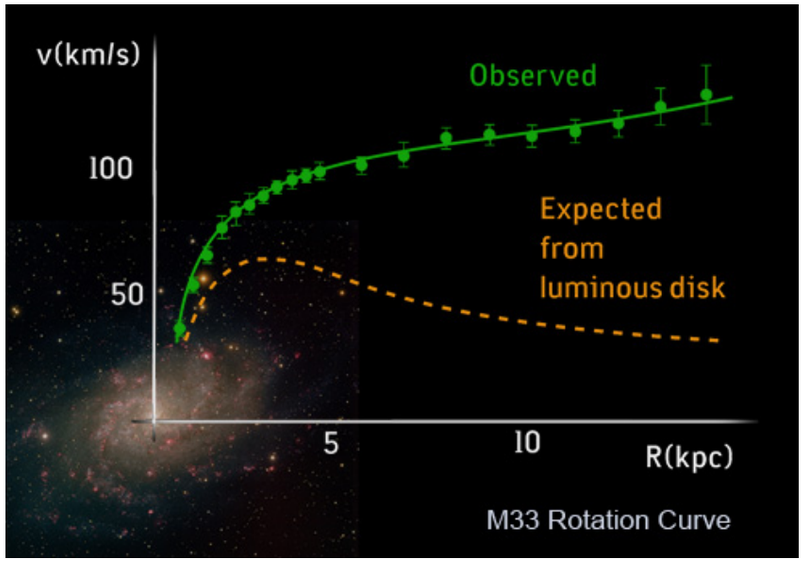
10s Mpc

clusters of galaxies



Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies

<~ kpc

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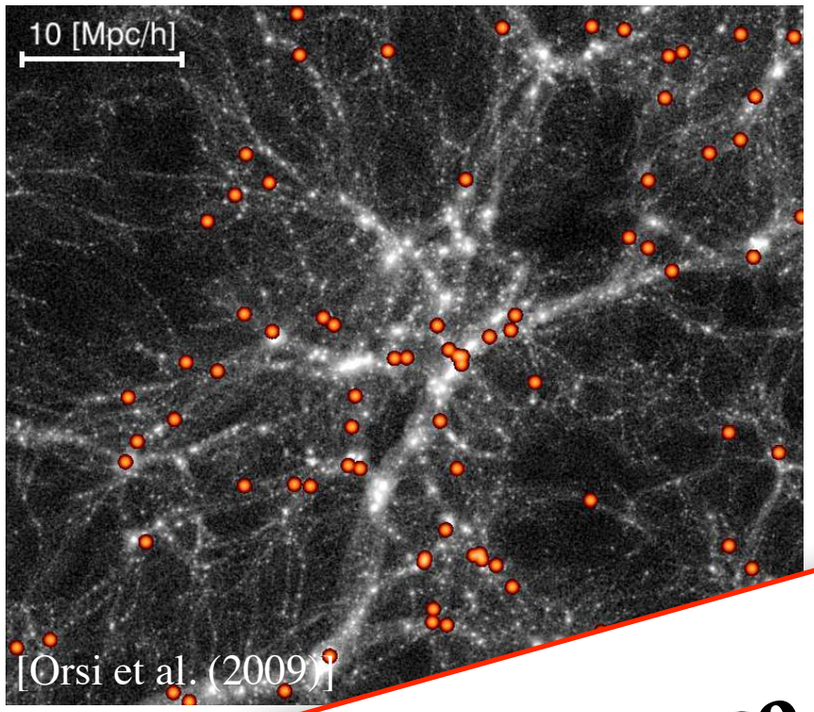

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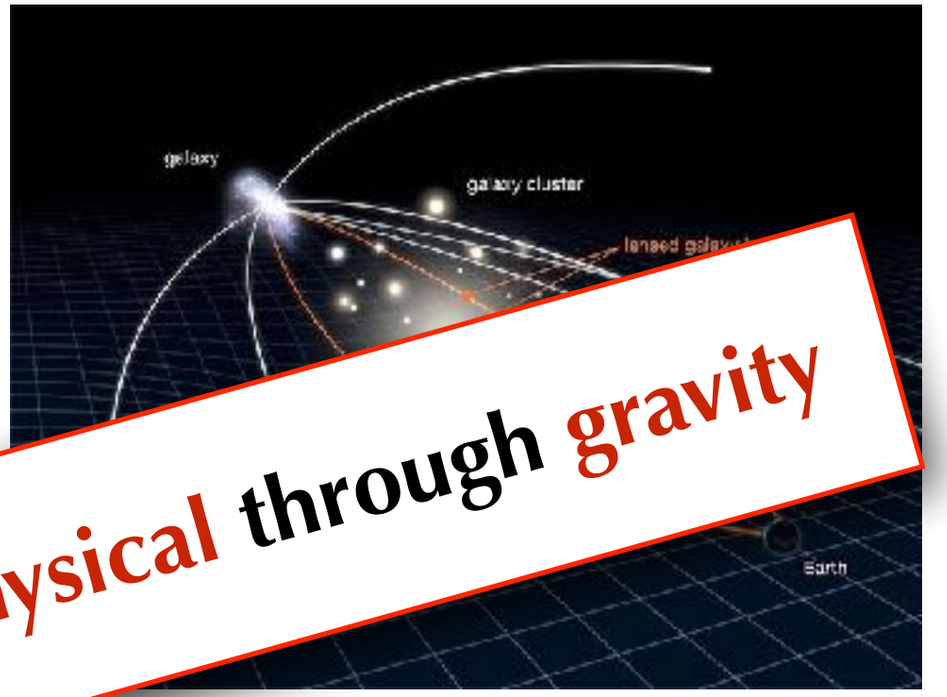
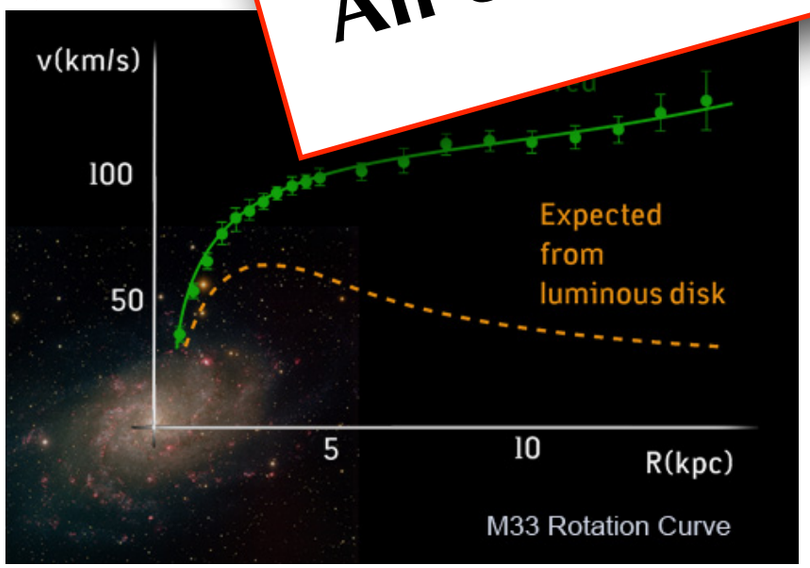


Mpc

All evidence is astrophysical through gravity

Milky W



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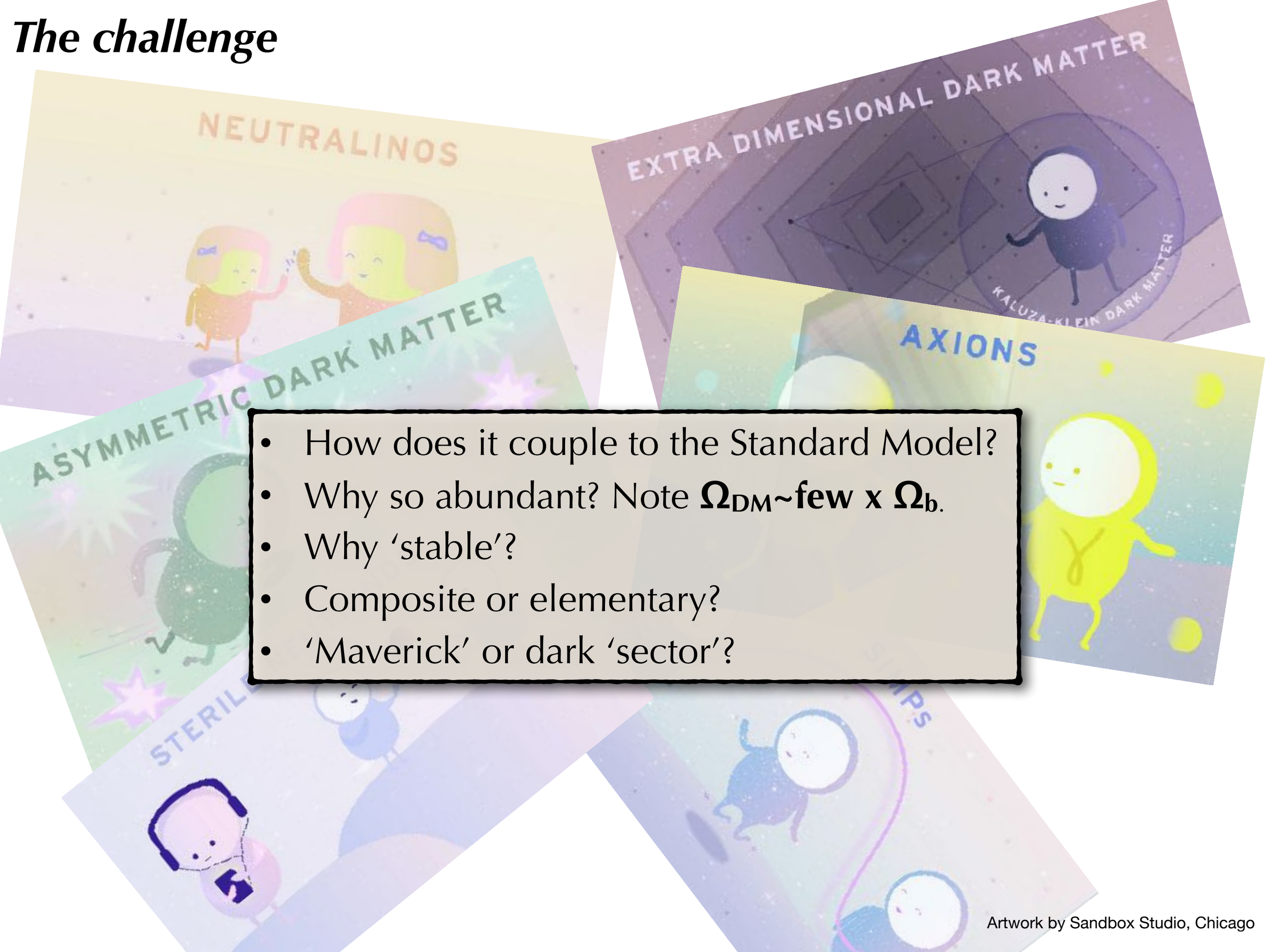
<~ kpc

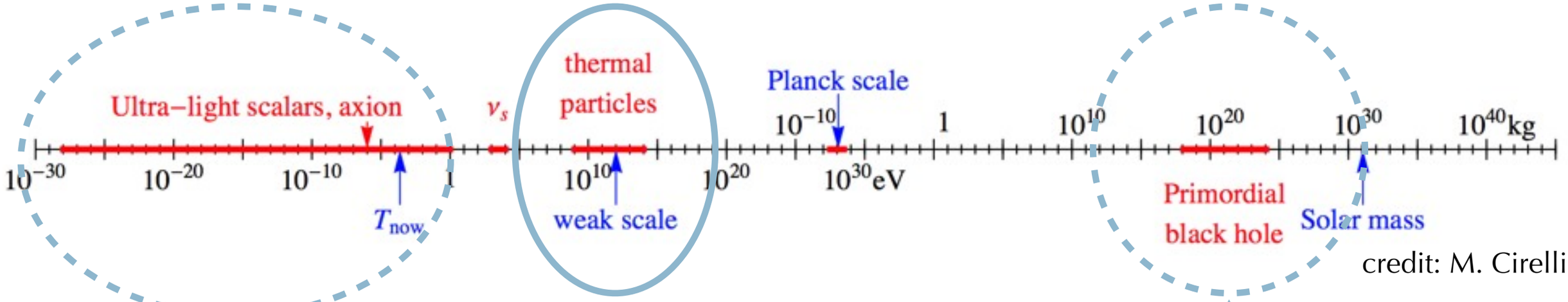
The challenge



- How does it couple to the Standard Model?
- Why so abundant? Note $\mathbf{\Omega_{DM}}$**~few x** $\mathbf{\Omega_b}$.
- Why 'stable'?
- Composite or elementary?
- 'Maverick' or dark 'sector'?

Artwork by Sandbox Studio, Chicago

What can it be? — the WIMP miracle



credit: M. Cirelli

usual barons, 'hidden' in dark objects/black holes

motivated by the strong CP problem in QCD

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

Thermal decoupling from primordial plasma singles out the Weak Scale - WIMP miracle suggestive & predictive!

$$\Omega_{\rm DM} \approx \frac{2 \times 10^{-37} {\rm cm}^2}{\langle \sigma_{\rm annih} v \rangle} \approx 0.23$$

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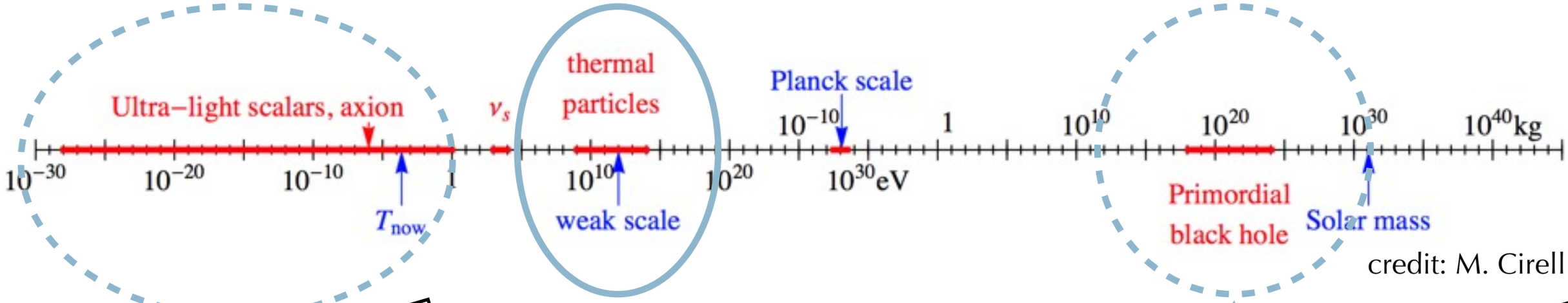

credit: M. Cirelli

I. Garcia Irastorza's talk

P. Serpico's talk

motivated by the strong CP problem in QCD

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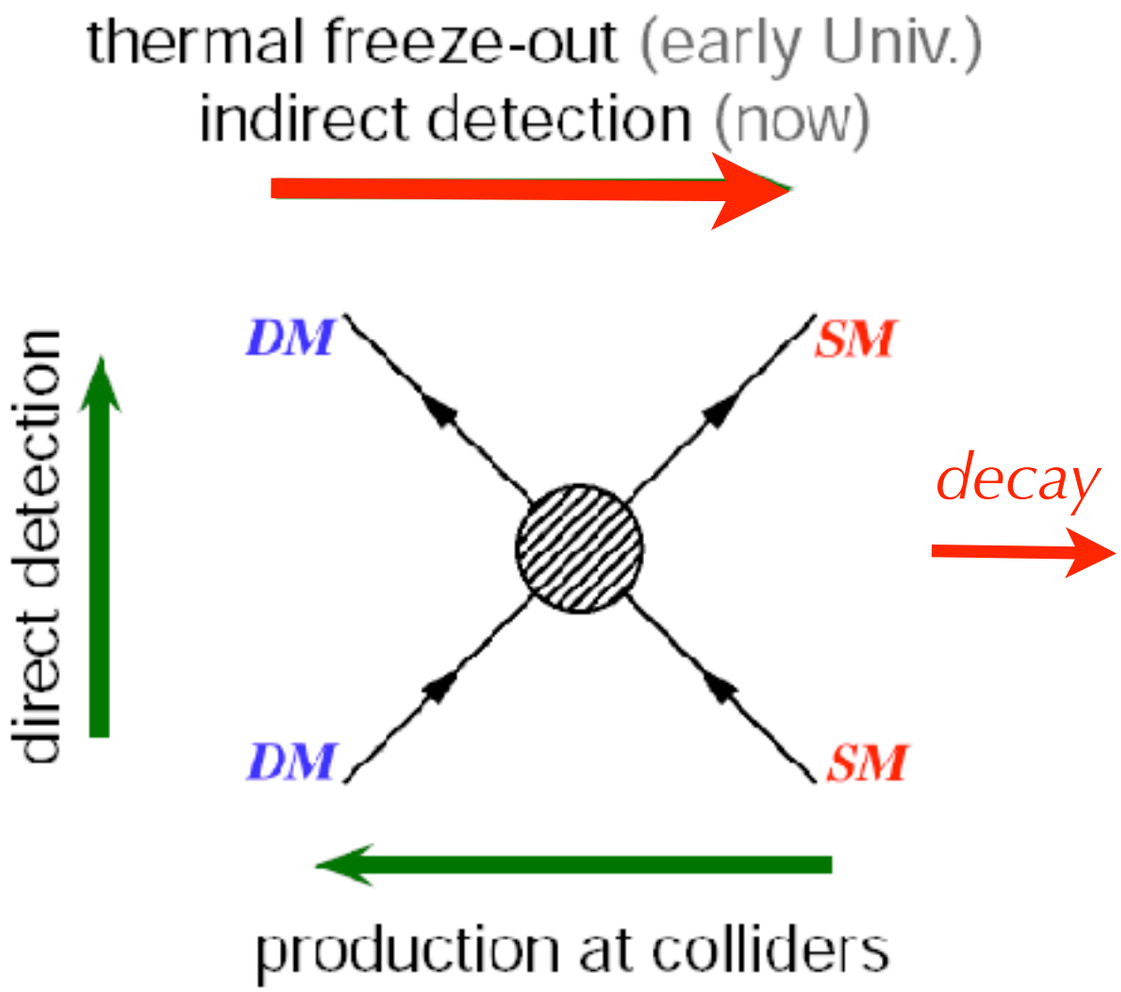
focus on WIMPs (+comment on axions)

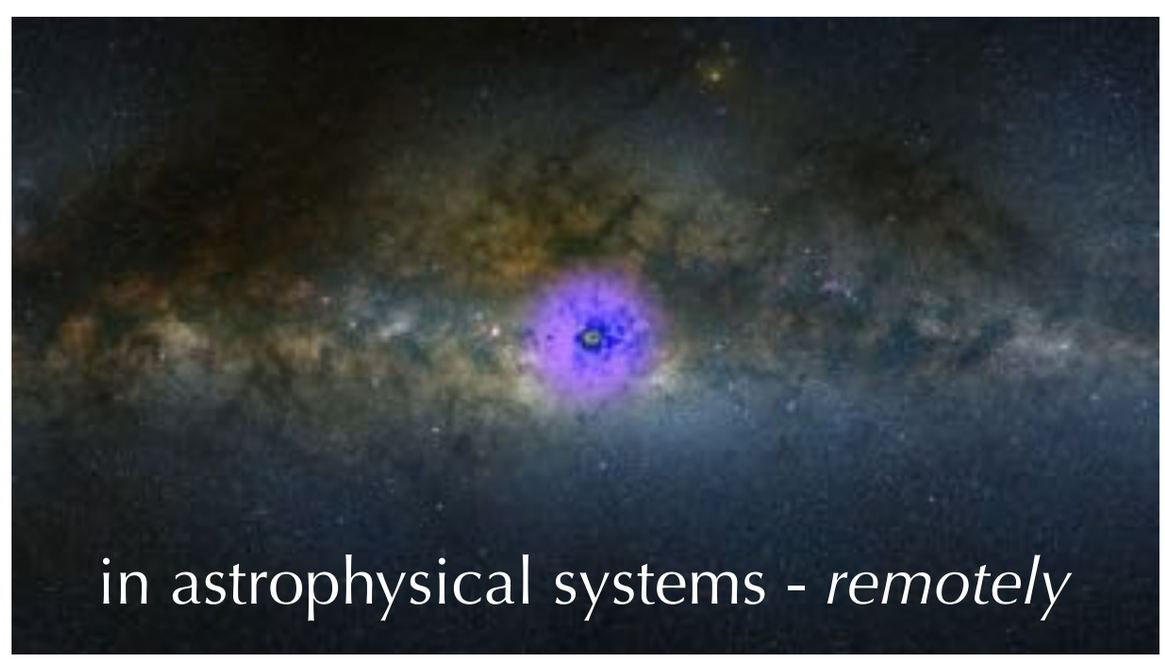
How to find it?



γ,
ν,
$e^{\pm}$,
$p^{\pm}$
D^{-}

@ $\mathcal{O}(M_Z)$ for standard WIMPs

For thermal dark matter:
— indirect searches provide insight into the **early Universe** decoupling
— we know 'where' to look



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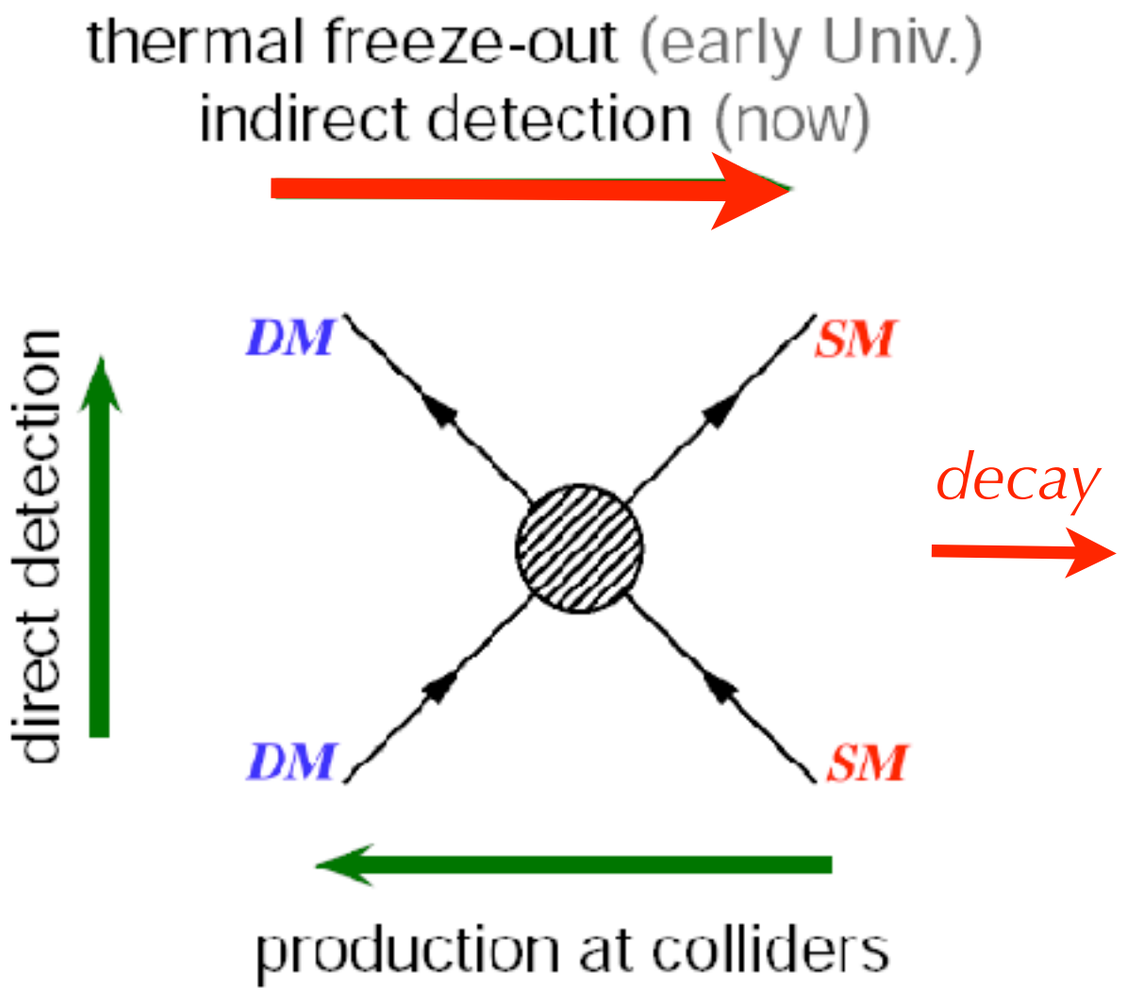

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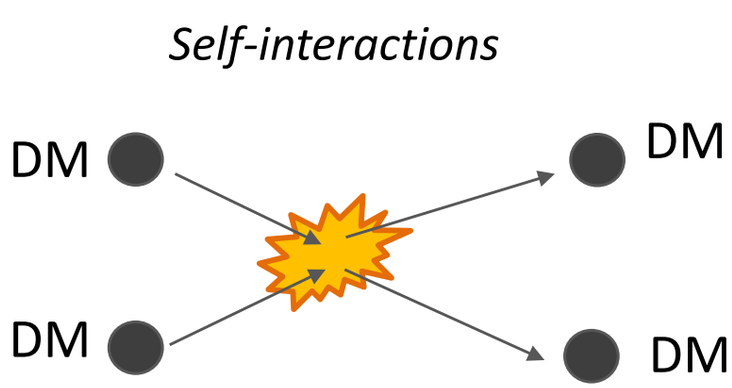
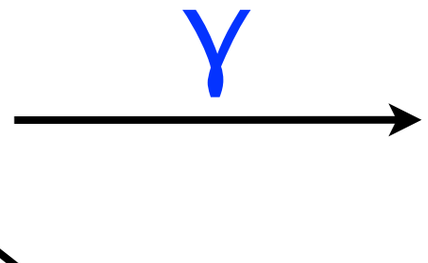


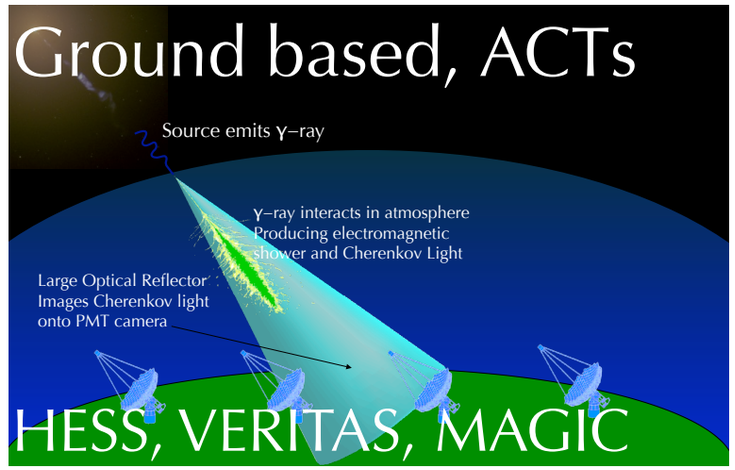
through cosmological clustering probes: we know DM interacts gravitationally… look at small scales — could probe dark matter self-interactions, its de-Broglie wave length (fuzzy DM) etc

[see e.g. Murgia+ 1704.07838]

‘The Golden Age’

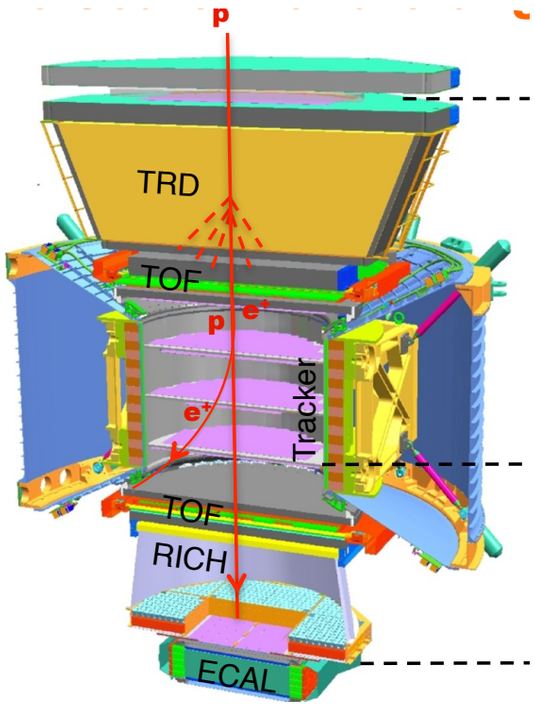
@ $\mathcal{O}(M_Z)$

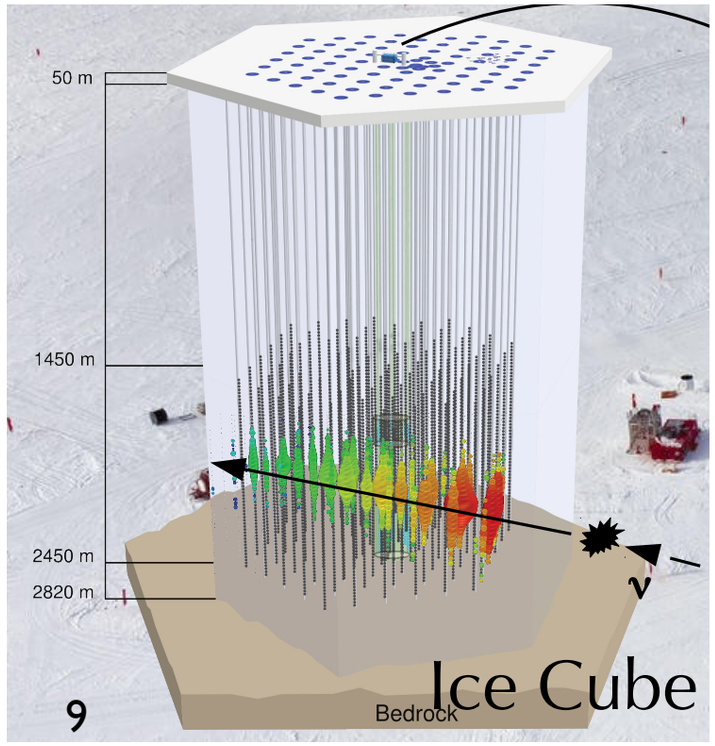


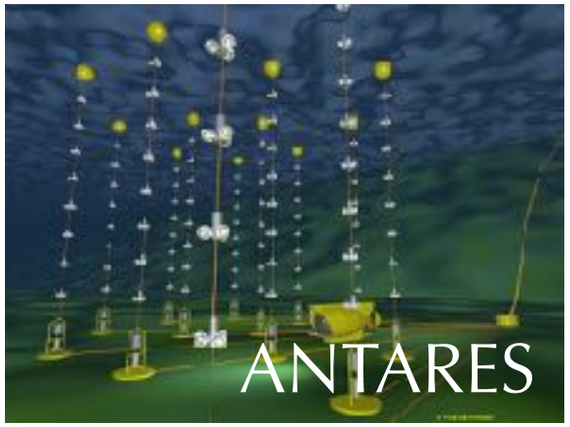


$e^{\pm}$, $p^{\pm}$, D^{-}

PAMELA, AMS02



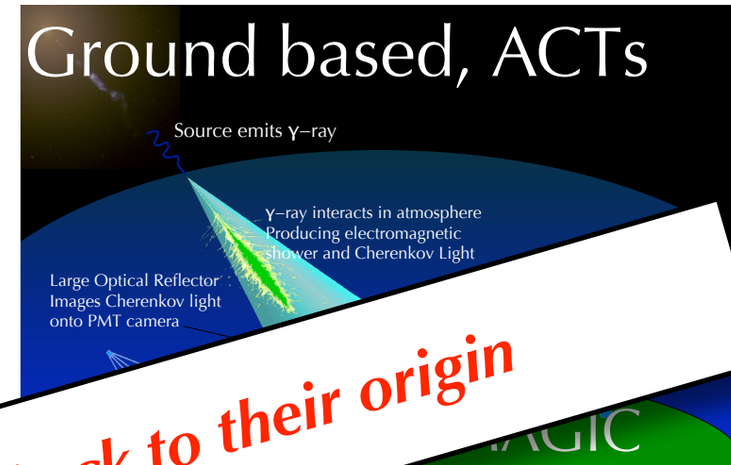




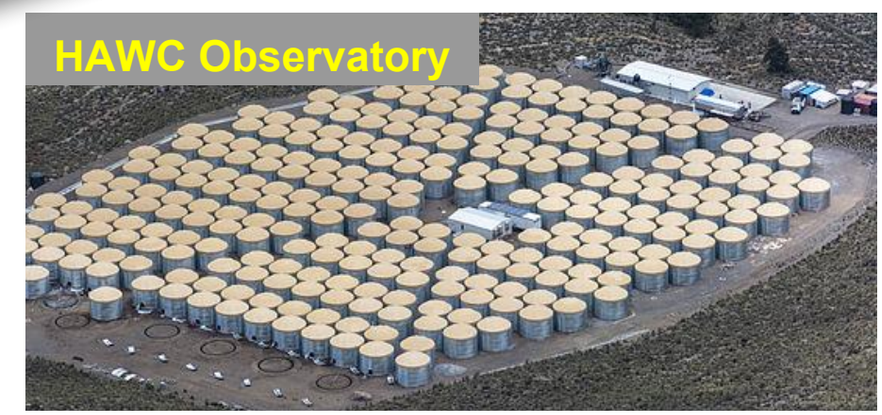
'The Golden Age'

@ $\mathcal{O}(M_Z)$

γ



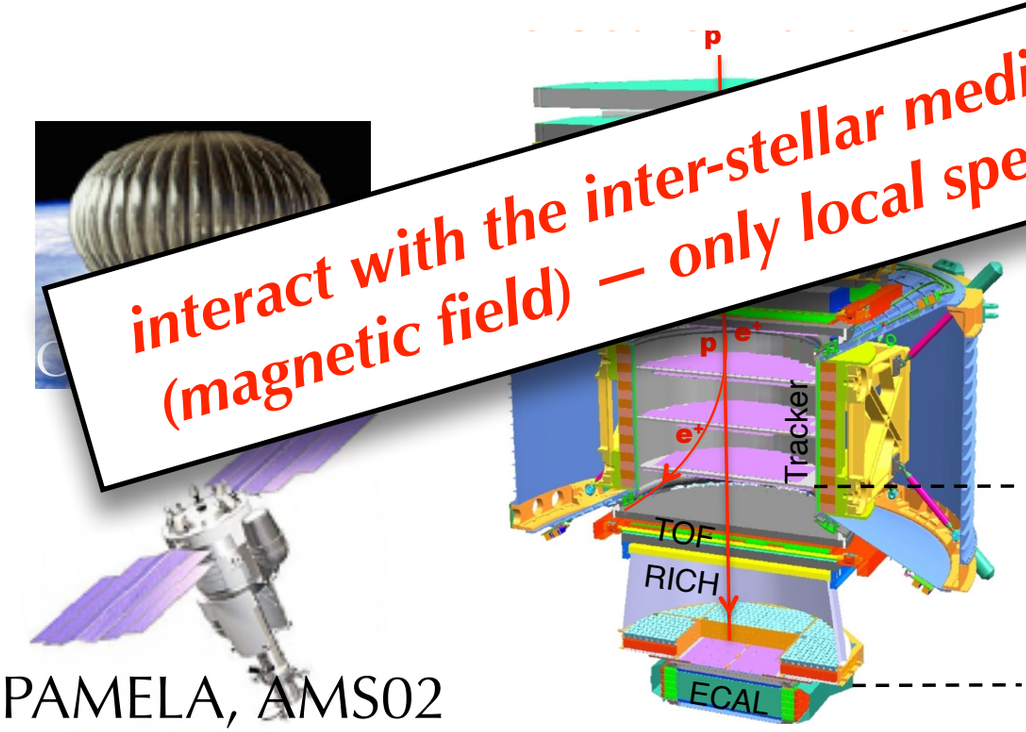
point back to their origin

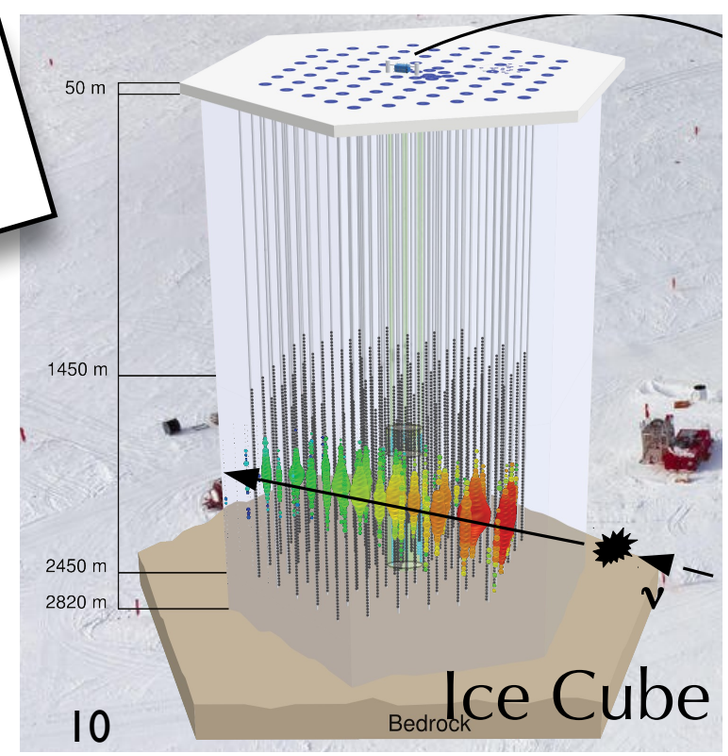


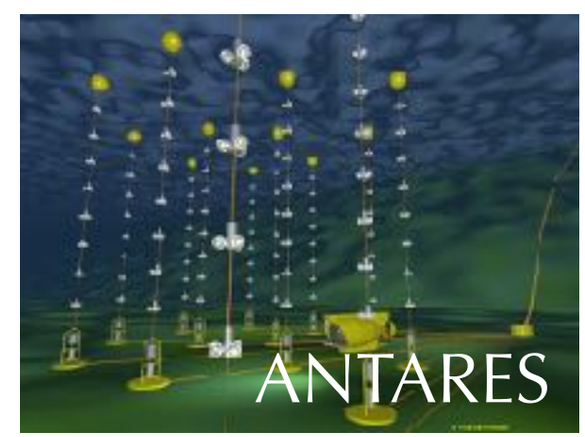
$e^{\pm}$, $p^{\pm}$, D^{-}

ν

interact with the inter-stellar medium (magnetic field) — only local spectra



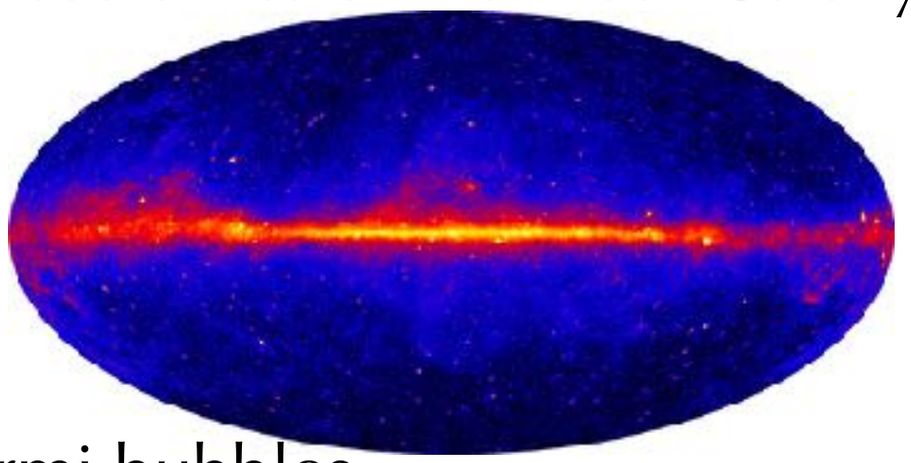




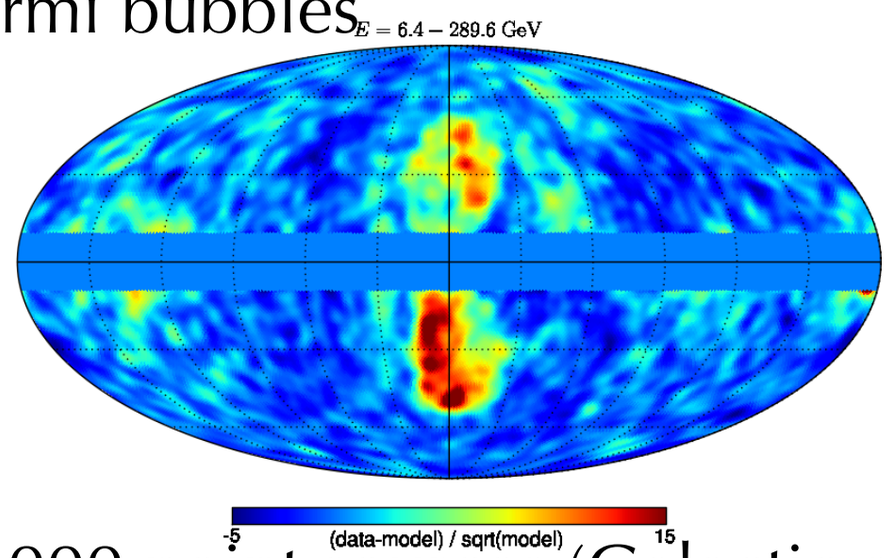
Astrophysical experiments: multipurpose experiments w rich scientific program --> discovering the sky @>~Mz energies

γ

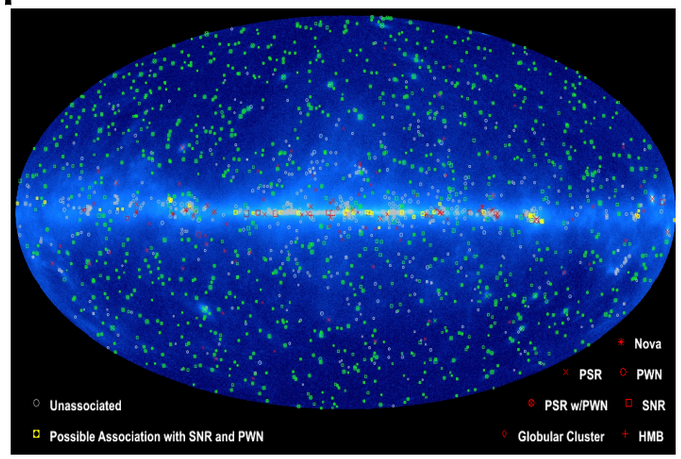
diffuse emission from our Galaxy:



Fermi bubbles

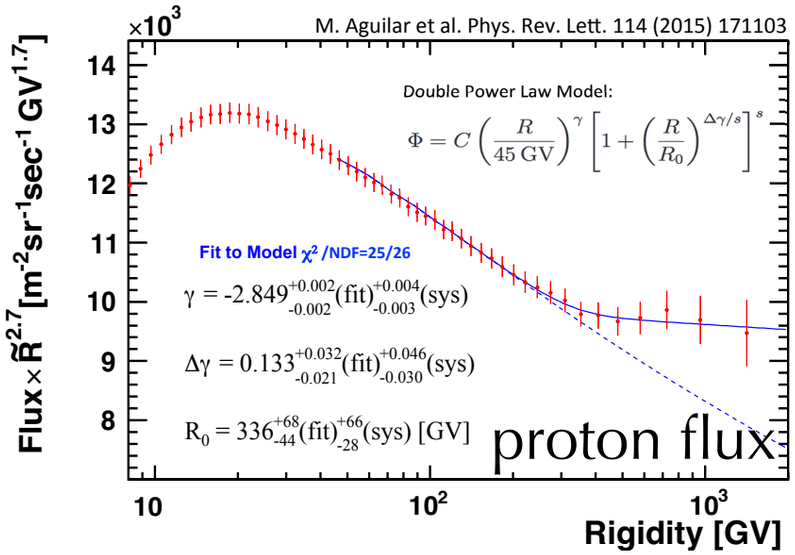


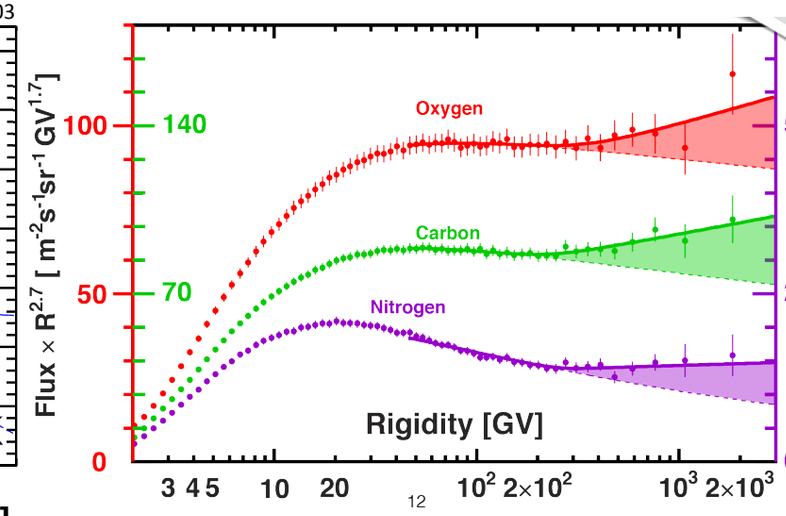
~3000 point sources (Galactic and extraGal):



charged cosmic rays

AMS results:

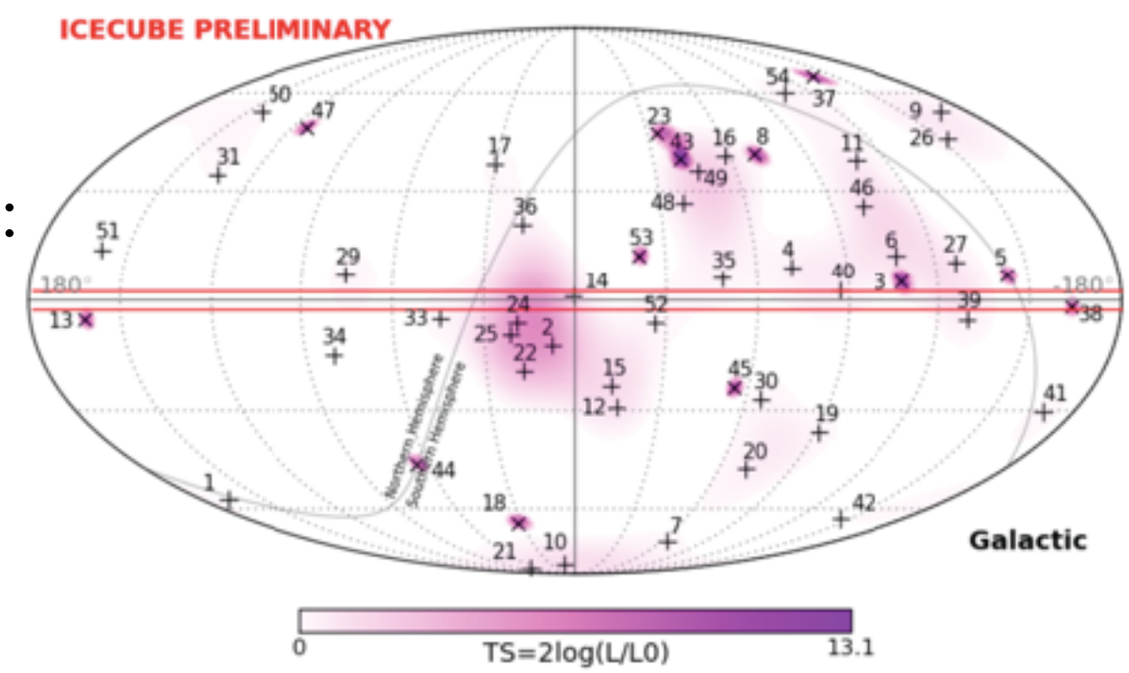




[V. Formato talk @ EPS17]

ν

First detection of astrophysical neutrinos!

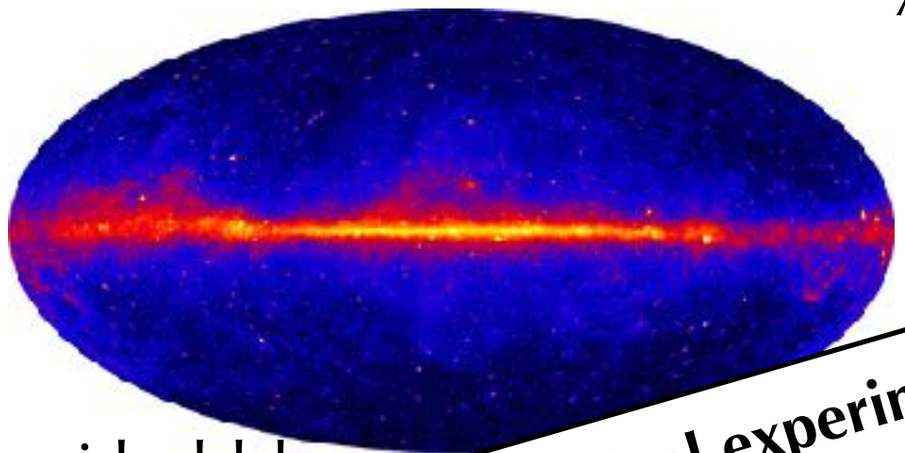


[T. Montaruli, 1512.07978]

Astrophysical experiments: multipurpose experiments w rich scientific program --> discovering the sky @>~Mz energies

γ

diffuse emission from our Galaxy:



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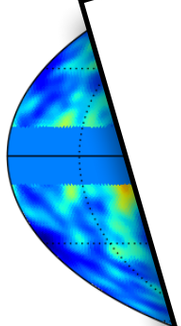
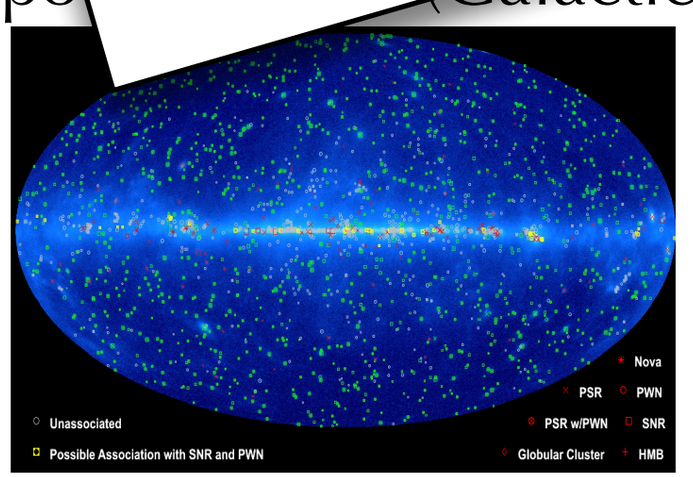


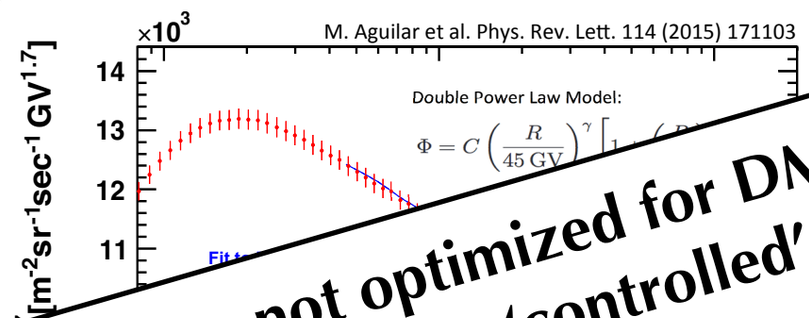
~3000 po

Galactic and extraGal



charged cosmic rays

New AMS results:

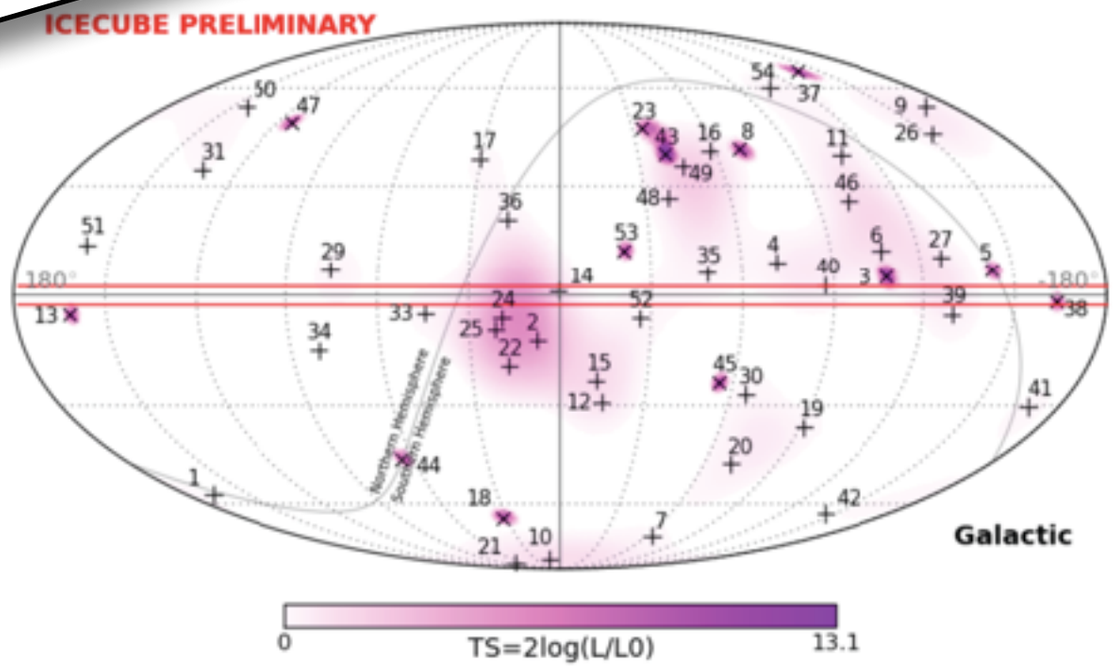


talk @ EPS17]

Astrophysical experiments are not optimized for DM searches
& 'backgrounds' are astrophysics, not a 'controlled'/lab system

Strategy — in case of a signal 'hint'
look at different targets within a single experiment
confirm w different experiments/messengers

of astrophysical neutrinos!



[T. Montaruli, 1512.07978]

Strategy 01: cross-check with different targets

gamma rays:

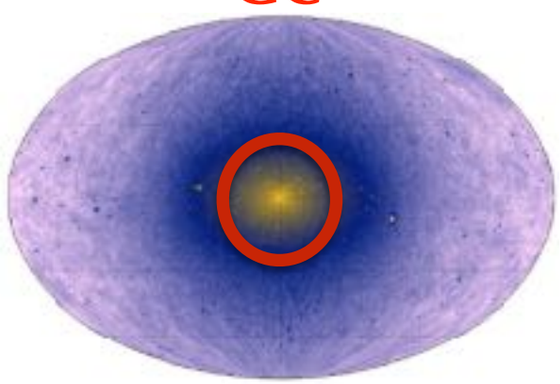
$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2} \times \sum_i {\rm BR}_i \frac{dN_\gamma^i}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)$$

gamma ray spectrum per interaction

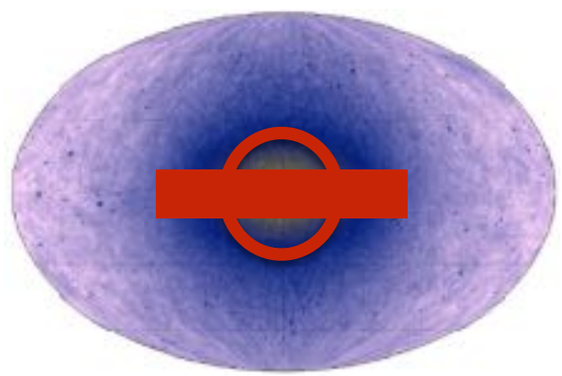
probability of interaction

signal strength

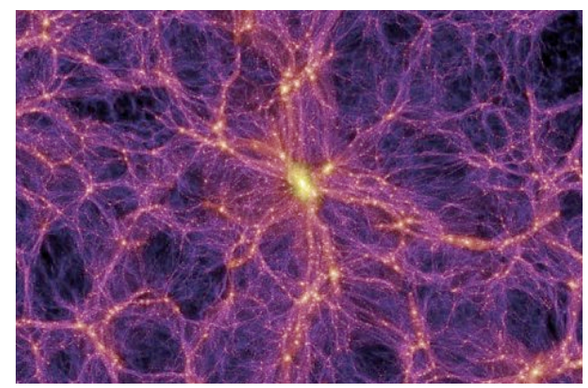
GC



GC halo

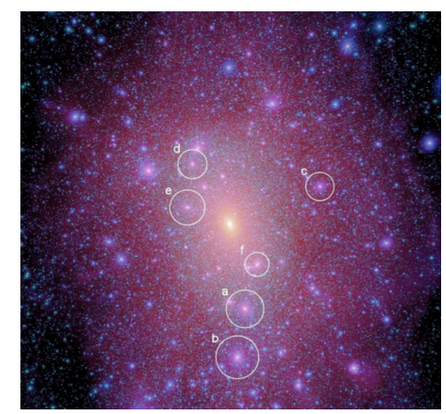


cumulative extragalactic signal

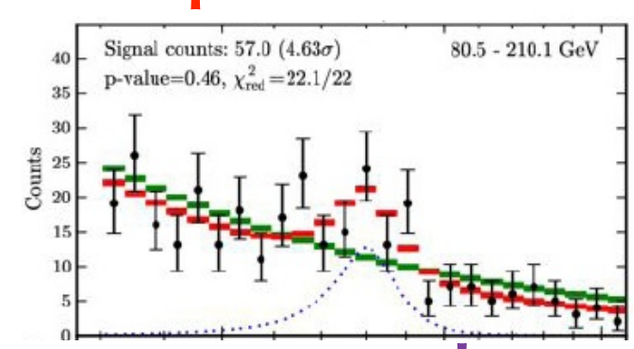


clusters of galaxies

dwarf satellites



spectral line



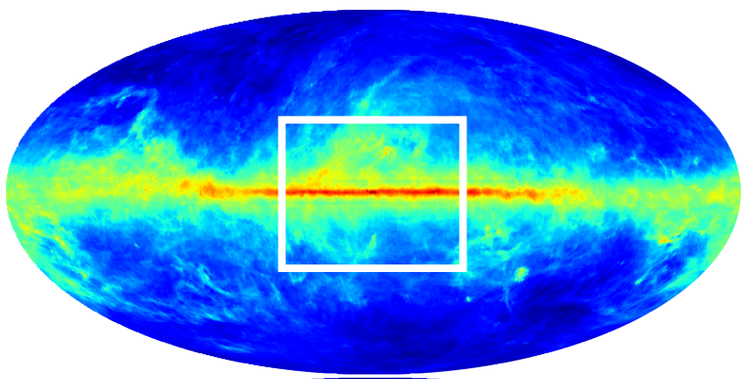
robustness

[adapted from: H.-S. Zechlin]

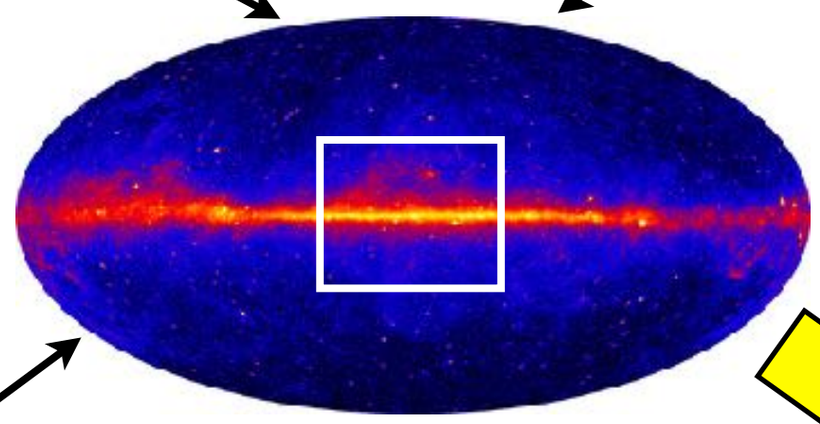
DM search in the inner Galaxy with Fermi LAT

prime example of a search strategy in practice:

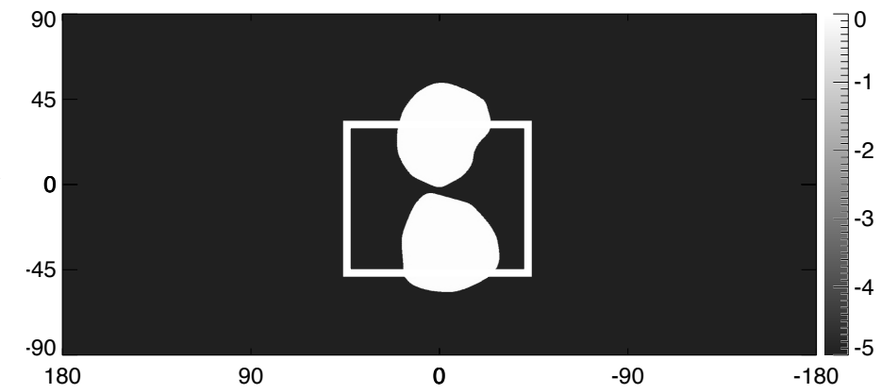
- look in high-signal/high background region
- in case of a detection hint — cross check the signal with different targets and experiments



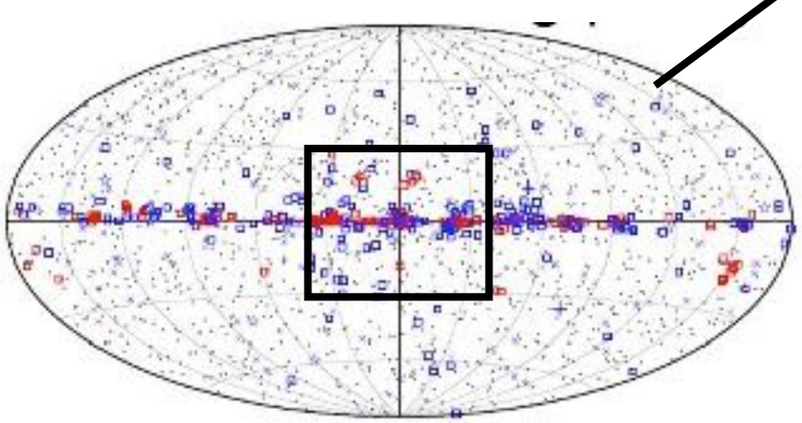
model(s) of the diffuse emission



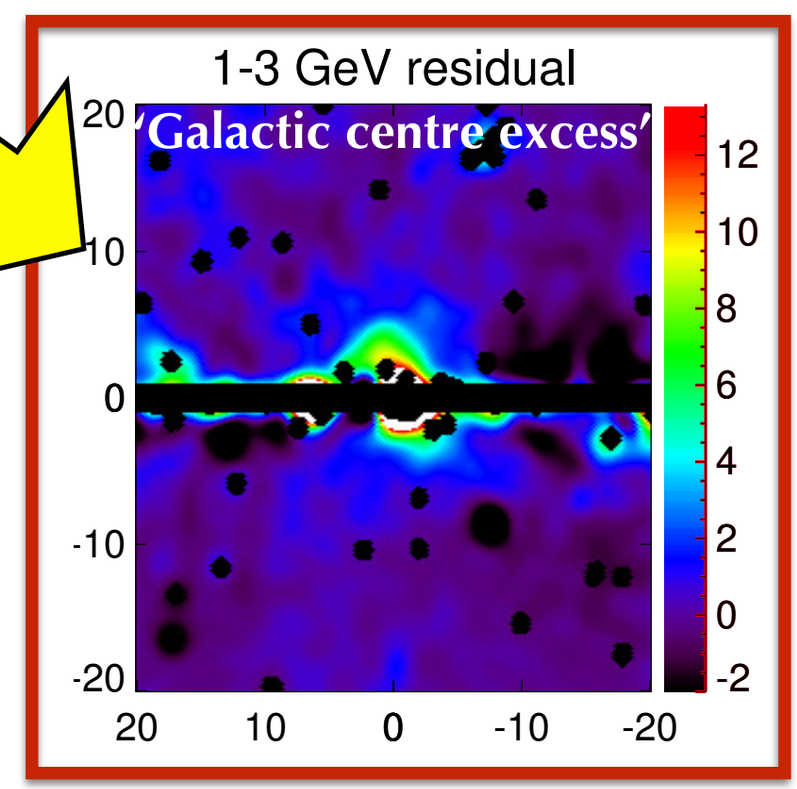
LAT data



uniform-brightness template for the Fermi Bubbles

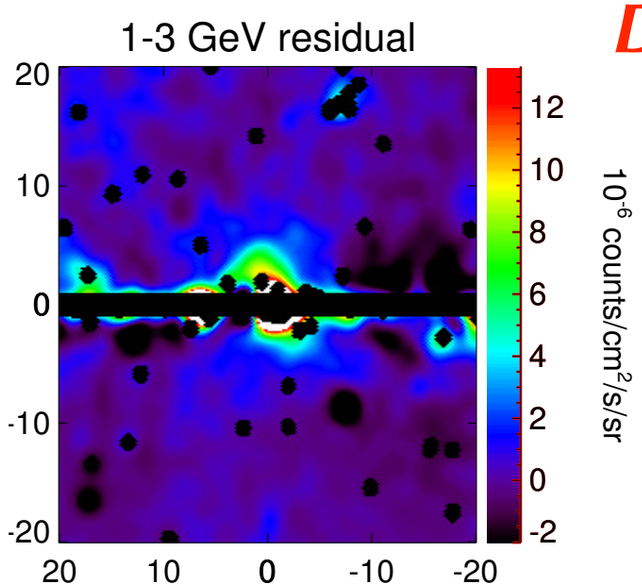


point sources from the catalog

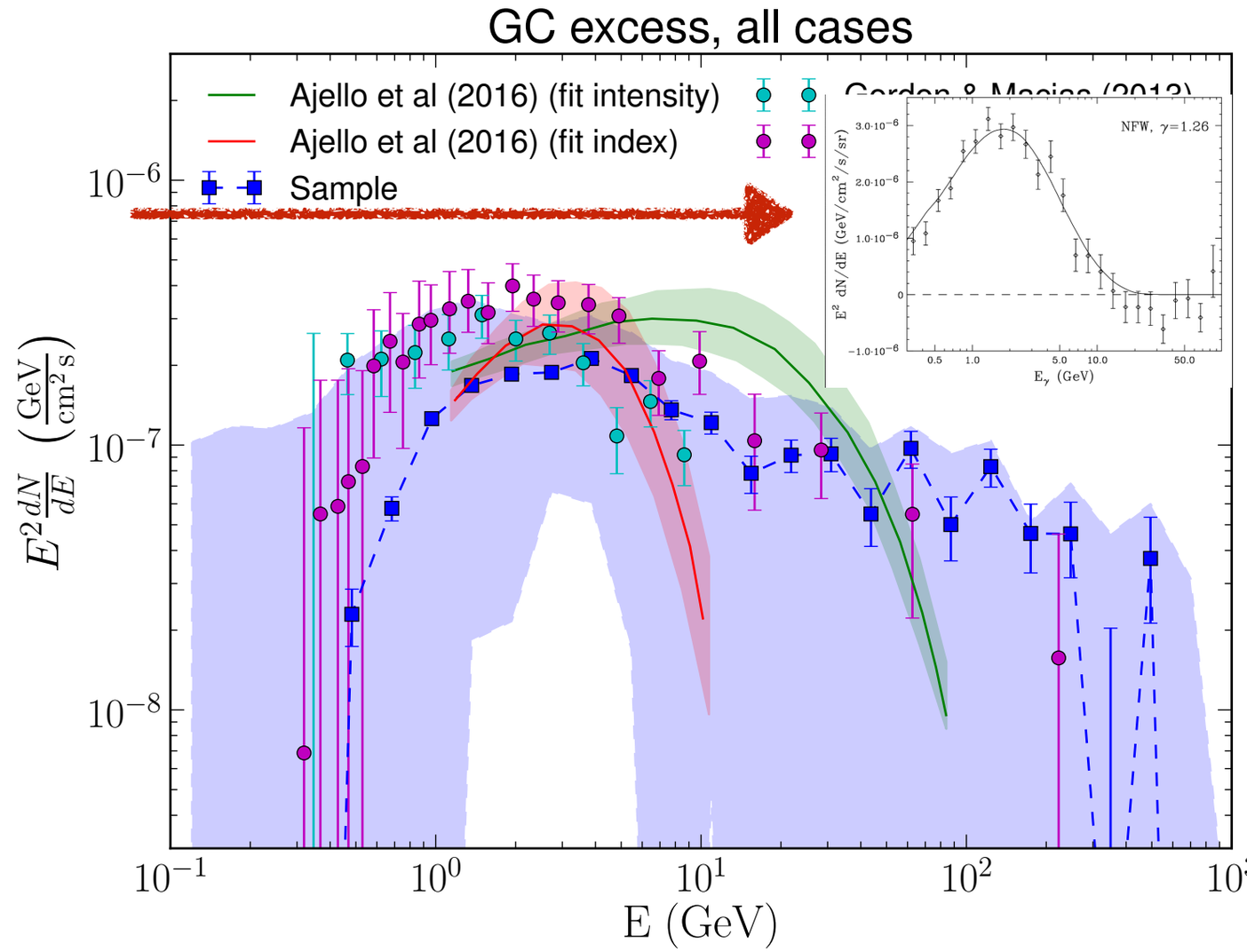


Pass 8 Fermi LAT analysis

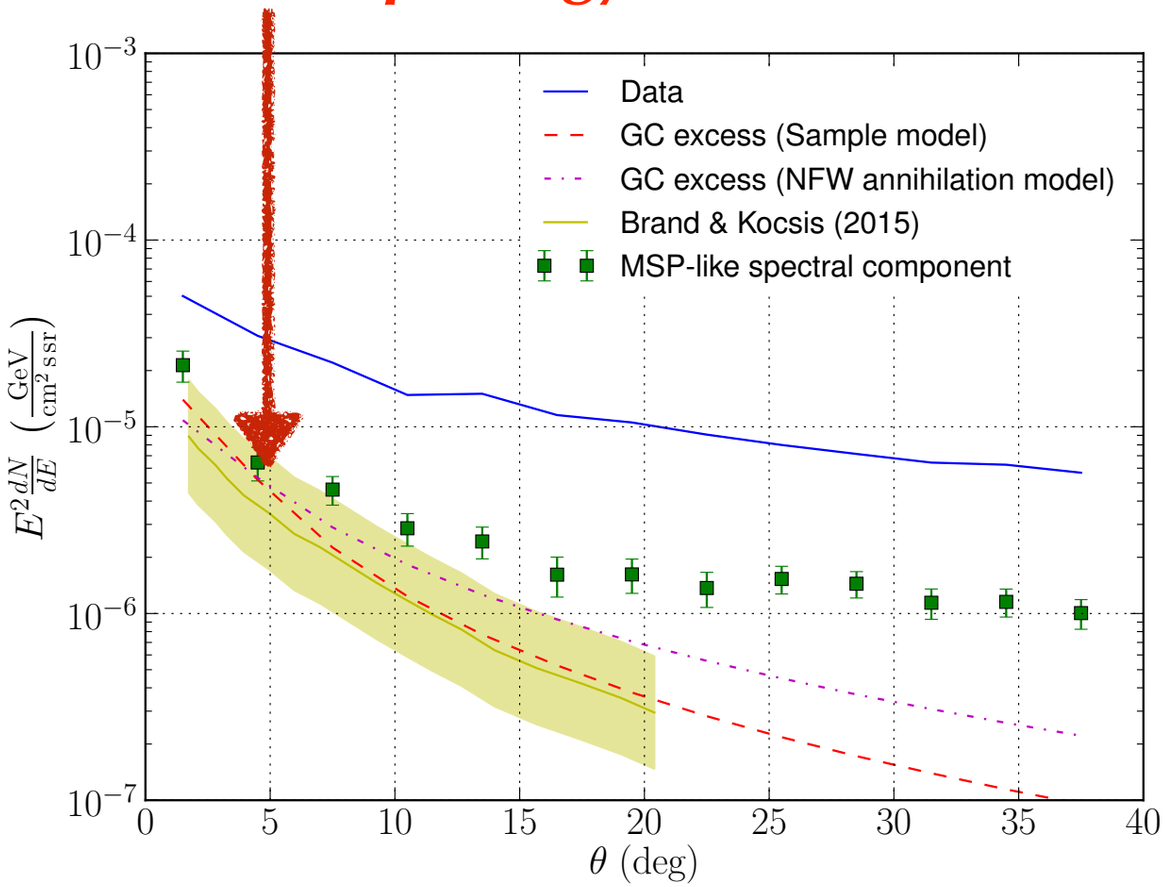
[Ackermann+, ApJ 2017]



DM spectral fits



DM morphology

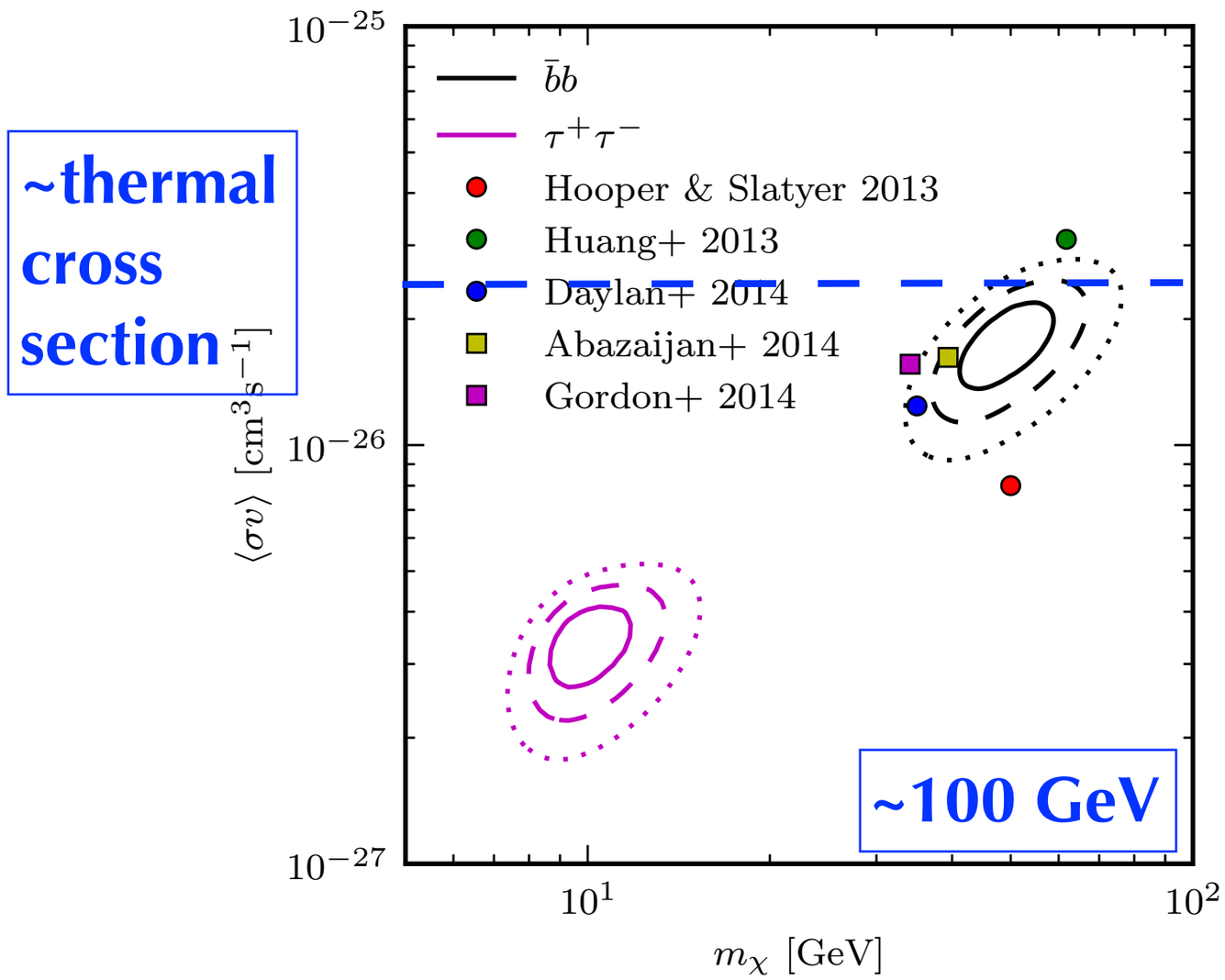


Many works reaching similar results:

Vitale & Morselli (**2009**), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 Macias & Gordon (2014, PRD 89 6) 1312.6671, Abazajian et al. (2014, PRD 90 2) 1402.4090, Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527

Could it be dark matter?

Right on the spot where WIMP DM is supposed to be!



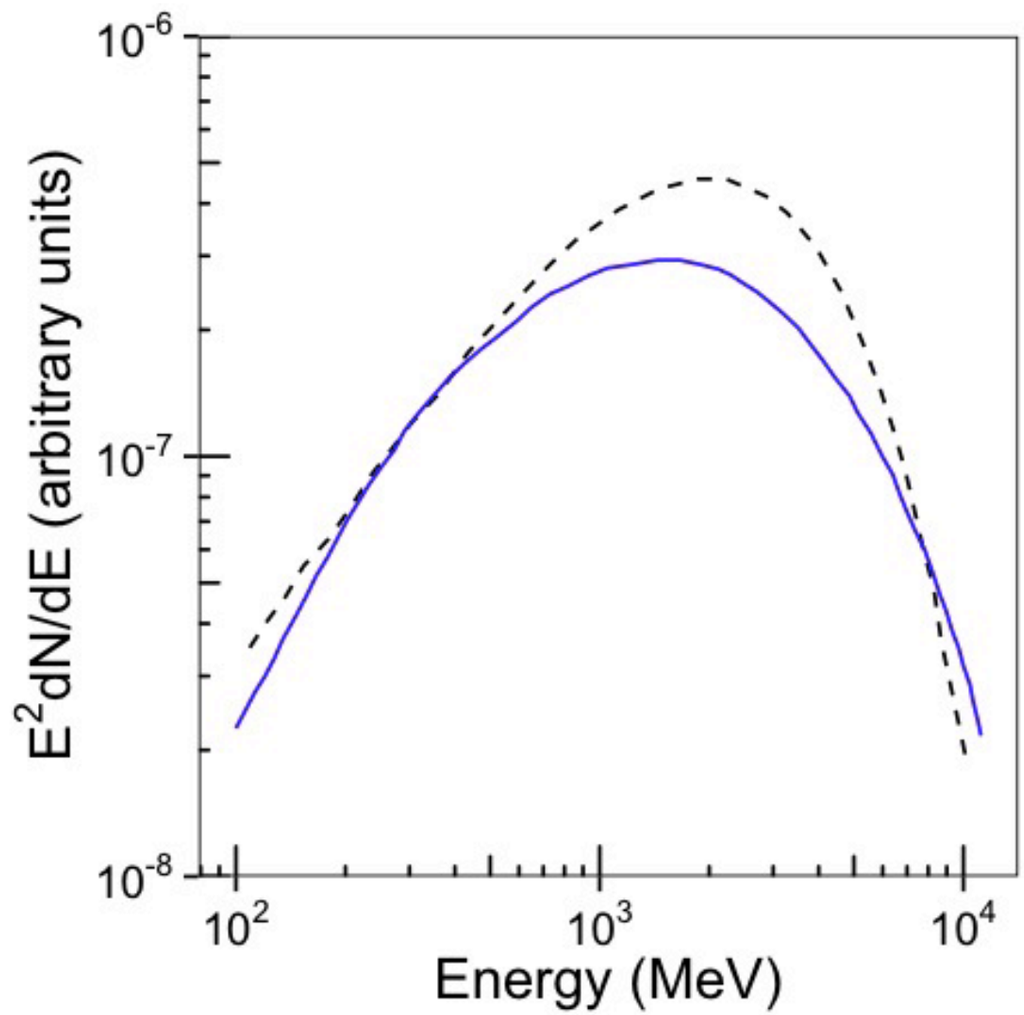
γ

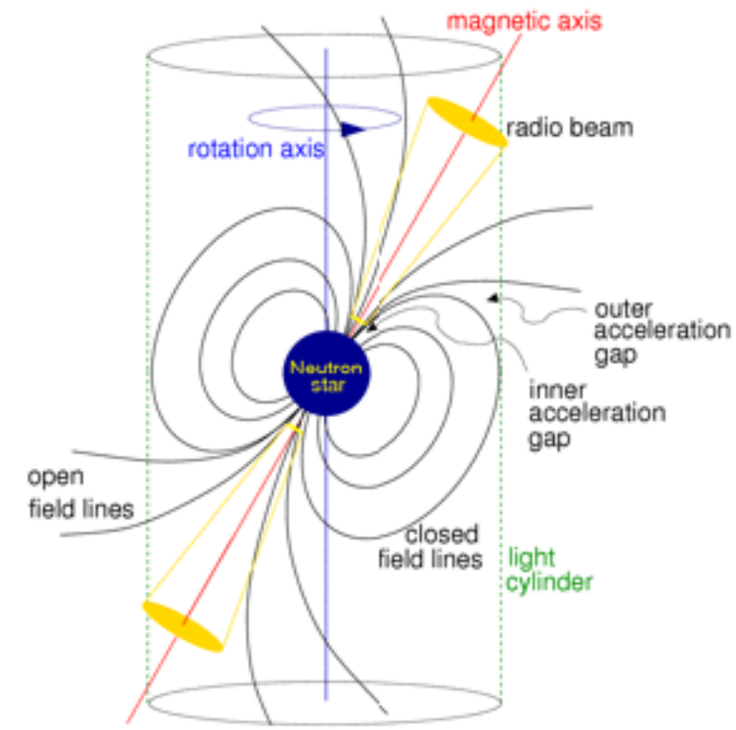
Thermal cross section & <~100 GeV & at the Galactic center

Spatial distribution close to the predicted NFW profiles.

Or…

Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)



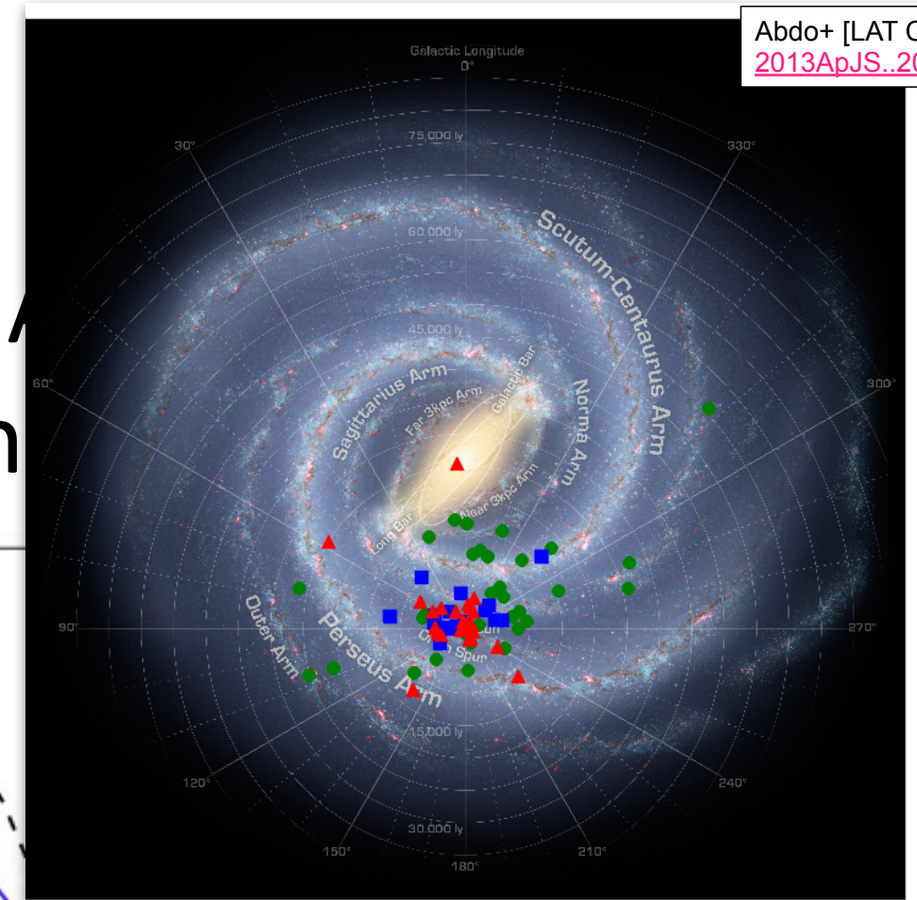


Baltz et al (2007)

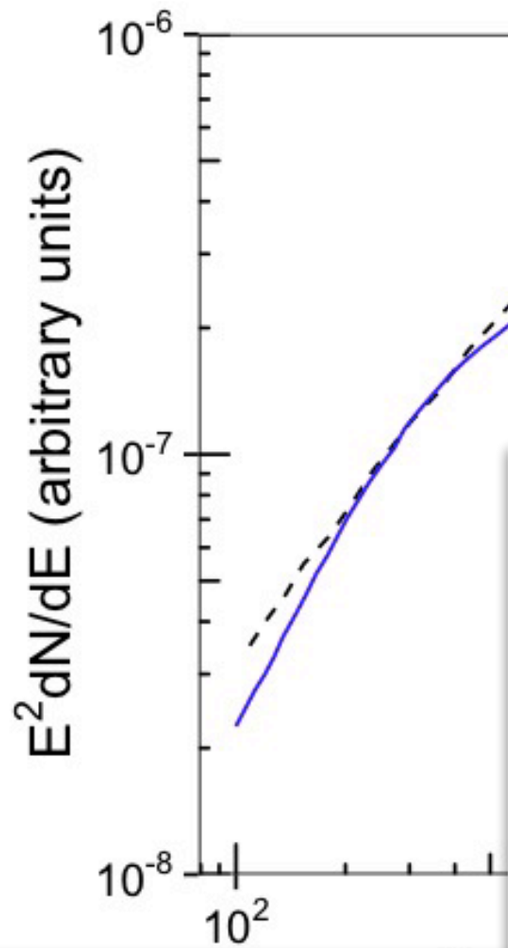
But, only a handful gamma-ray pulsars known pre-Fermi LAT.

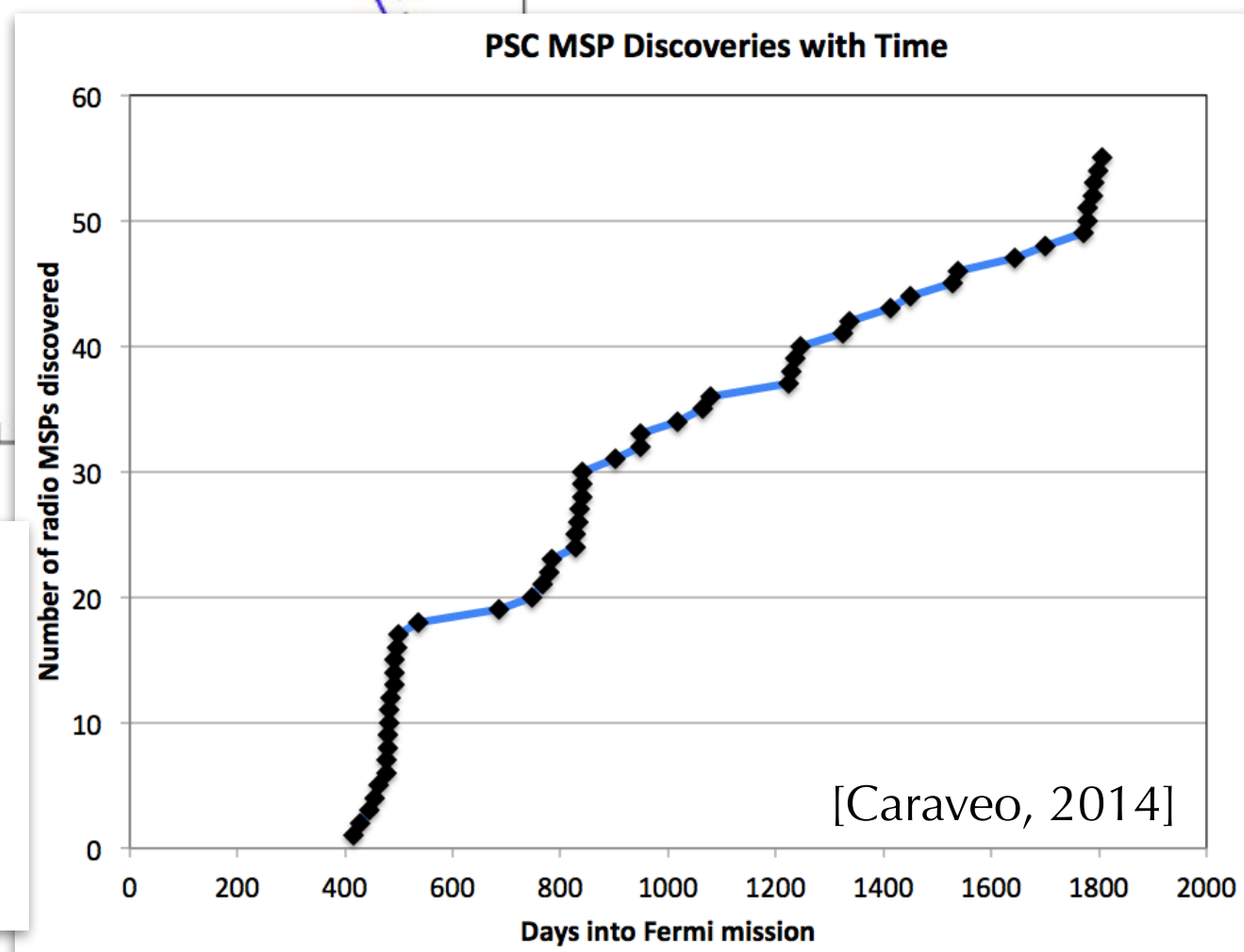
Or…

Spectral twins: Pulsar/DM A
(30 GeV bb chann



- M
p

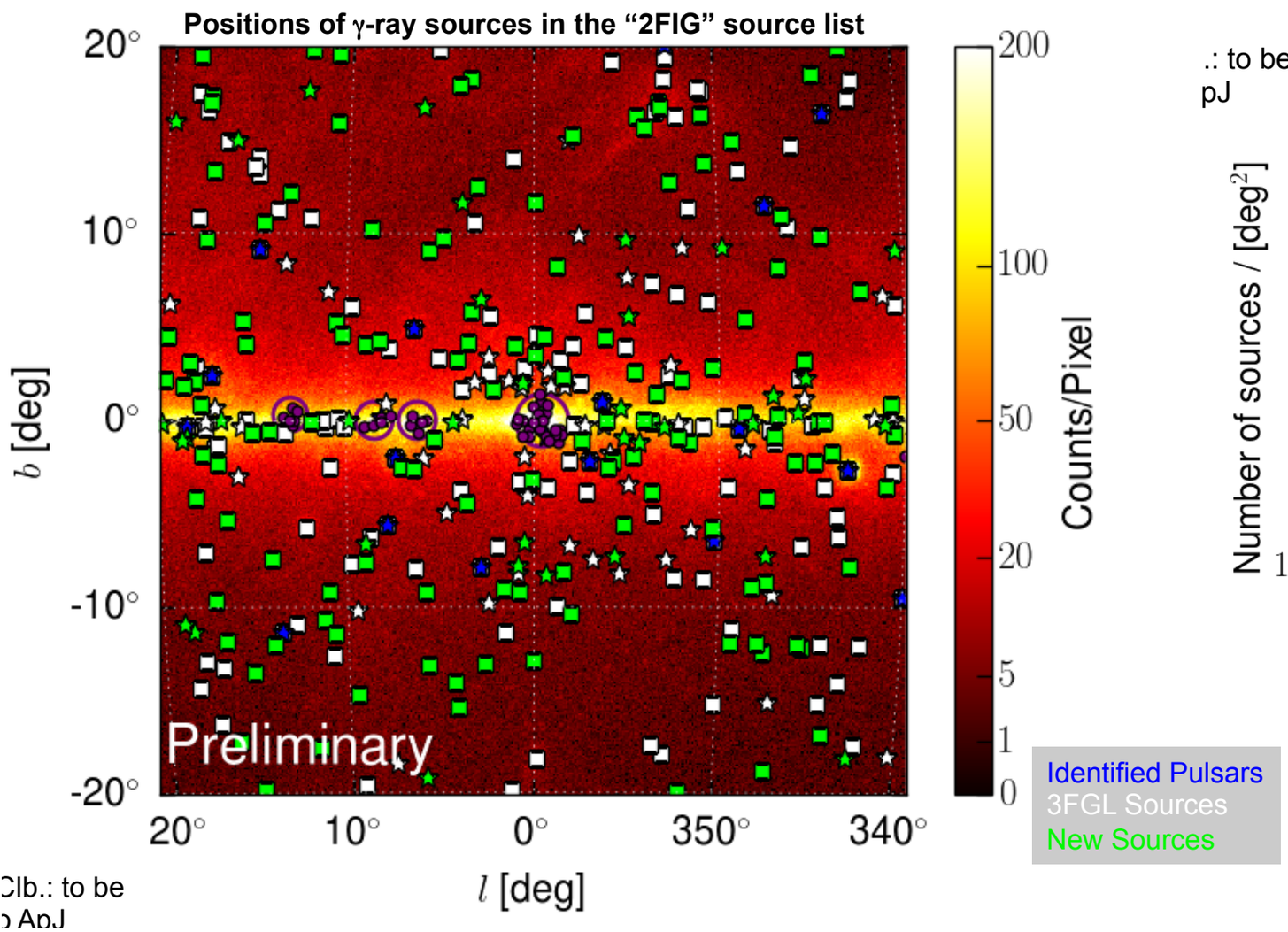


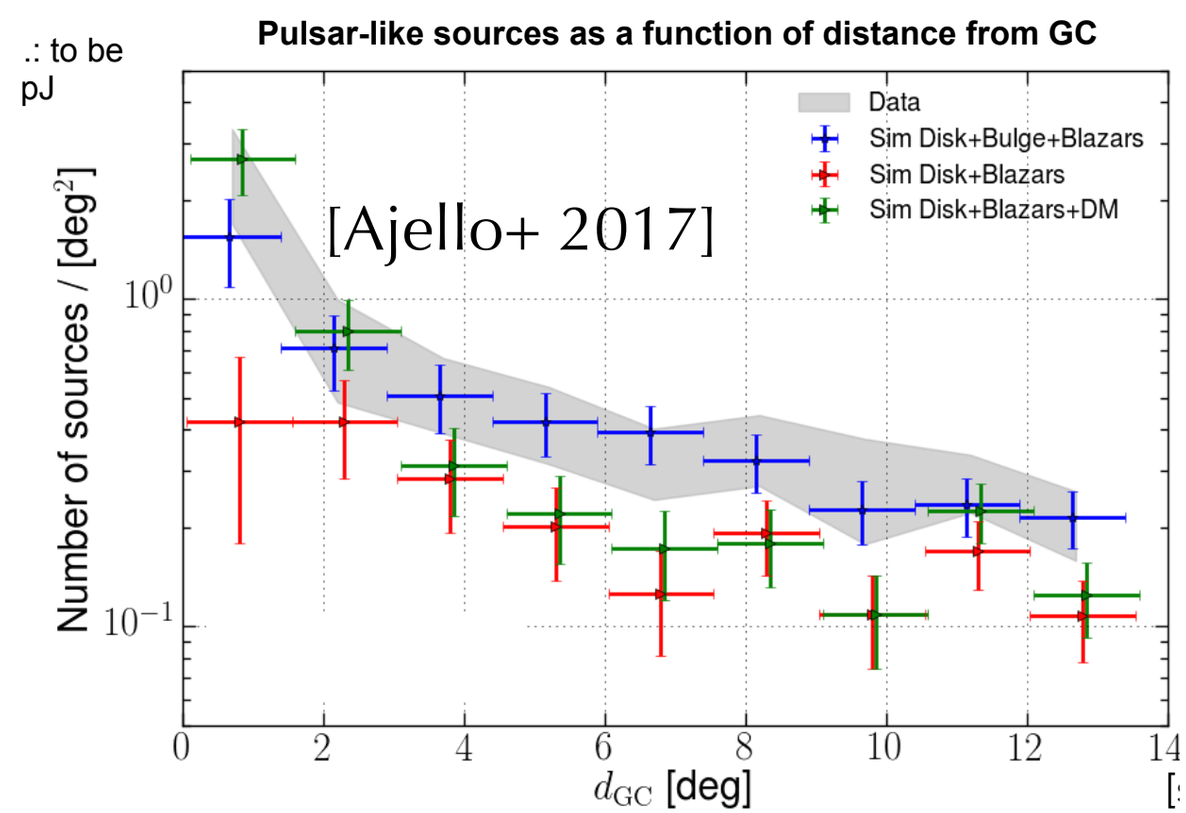


Since, >100 pulsars and milli-second pulsars observed in the MW
most of them local — possible that many faint ones contribute to the Galactic centre excess

Bulge MSP population?

Individual pulsars hard to detect at the distance of the GC.
What if we account for **unassociated sources** (1/3 of all sources)?
— Identify **candidate pulsar sources** among the unassociated ones,
— use the 'local' γ-ray pulsar luminosity function from known pulsars to estimated efficiency of the pulsar selection
— use maximum likelihood analysis to extract the **morphology of the Galactic pulsar population**





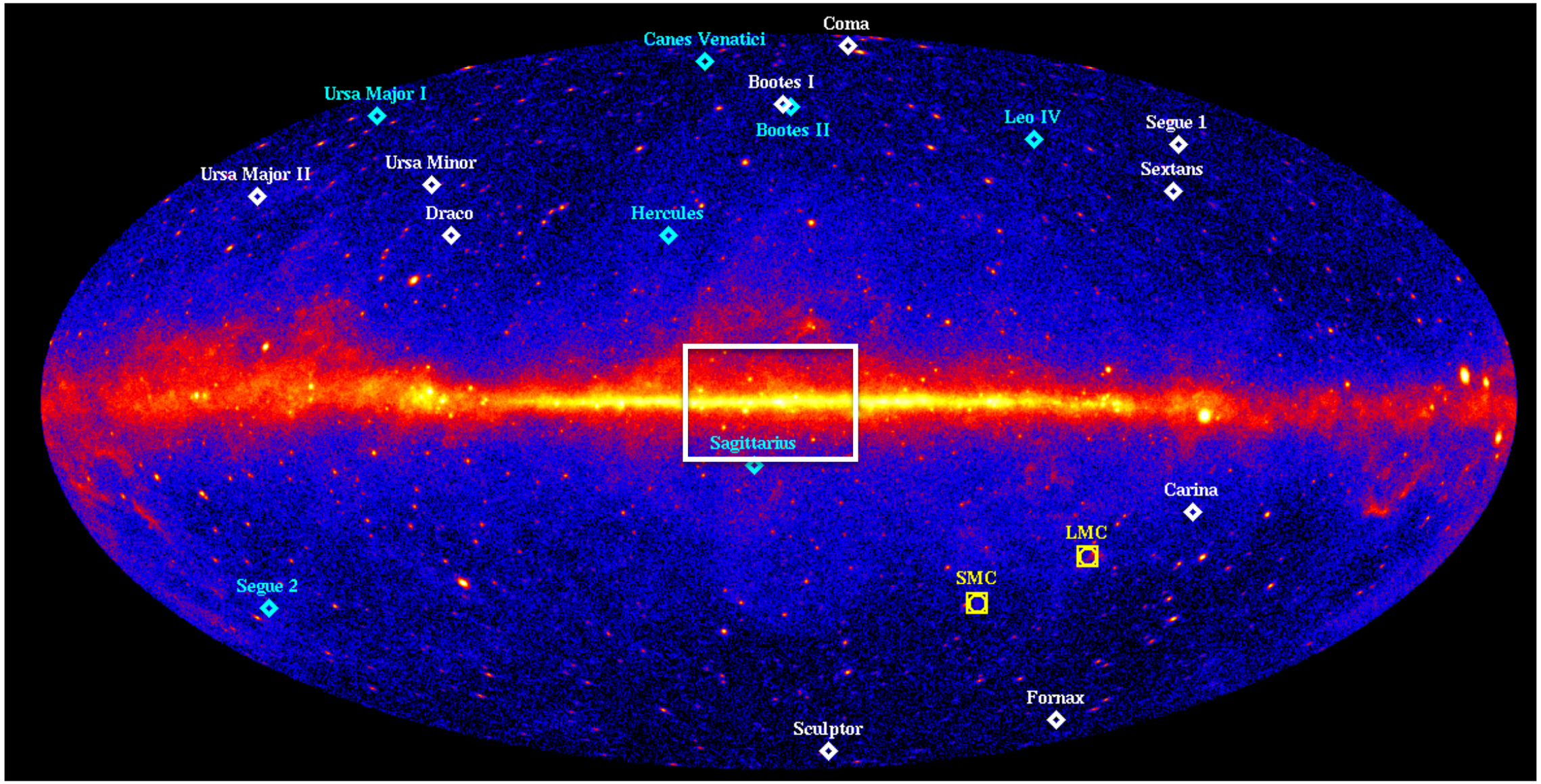
consensus is building up that **(milli-second) pulsar population in the Galactic bulge** is responsible for the excess

[see also Bartels+ and Lee+, 2016]

How can we test the GCE origin?

For DM interpretation, **multi-target tests** are essential
—> dwarf spheroidal galaxies!

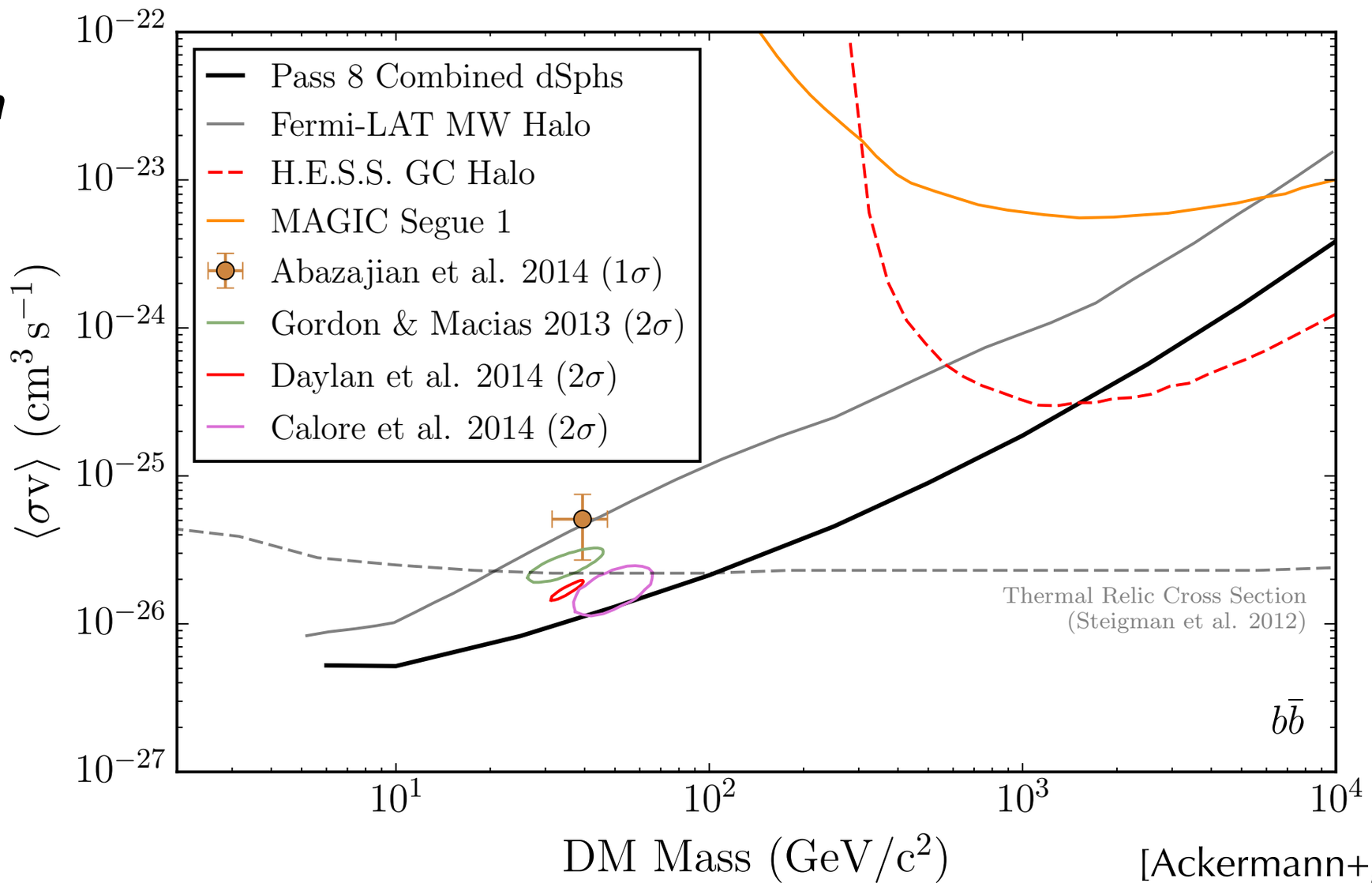
M. Valli's talk



DM search in dwarf galaxies with Fermi LAT

Using the joint likelihood to combine info from **15 dSphs, taking into account the uncertainties in their DM content —> one of the strongest DM limits to date**

annihilation cross section



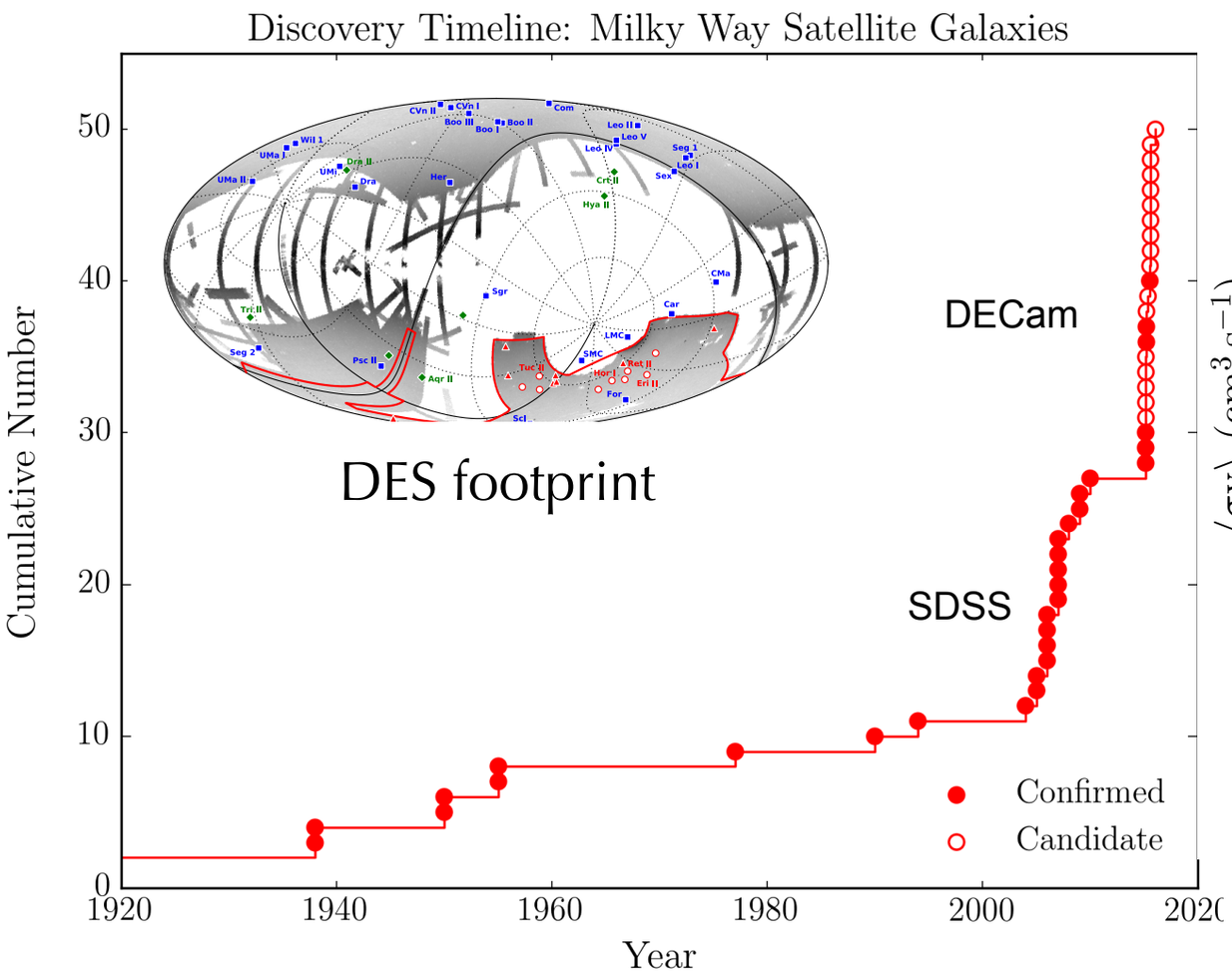
[Ackermann+, 1503.02641]

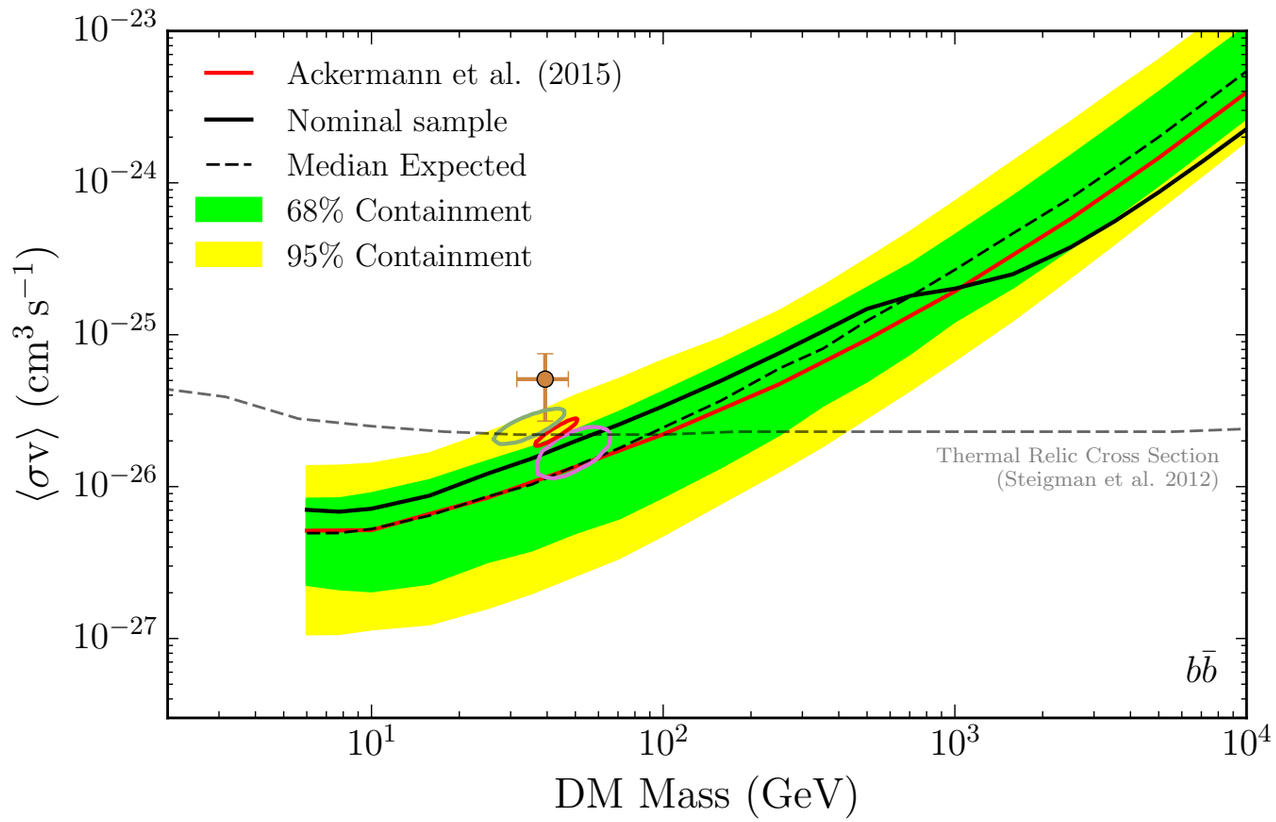
GCE dark matter origin in tension with complementary gamma ray observations

DM search in dwarf galaxies with Fermi LAT

More targets coming up!

>45 dSphs, 28 kinematically confirmed + 17 candidates since 2015 (DES, PANSTARSS)





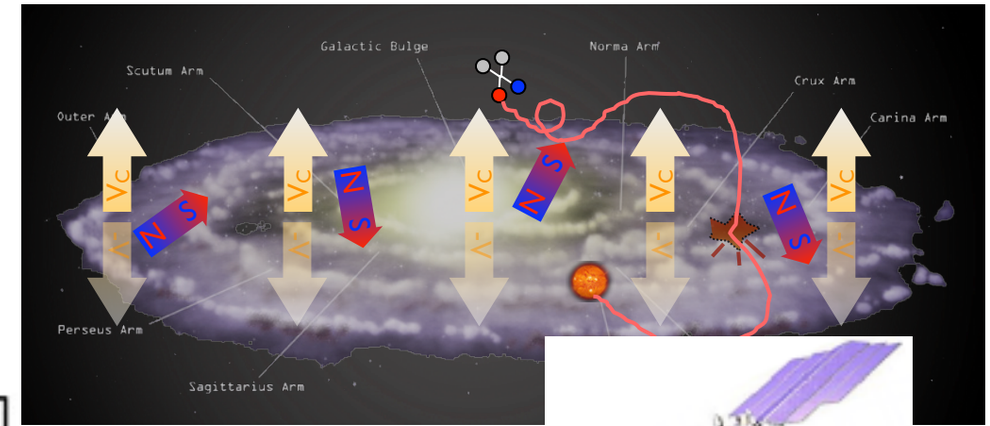
[A. Albert+, (2016)]

LAT data coincident with **four** of the newly discovered targets show a ~**2σ (local) γ-ray emission in excess of the background**, weakening the limits by 1.5x at low masses.

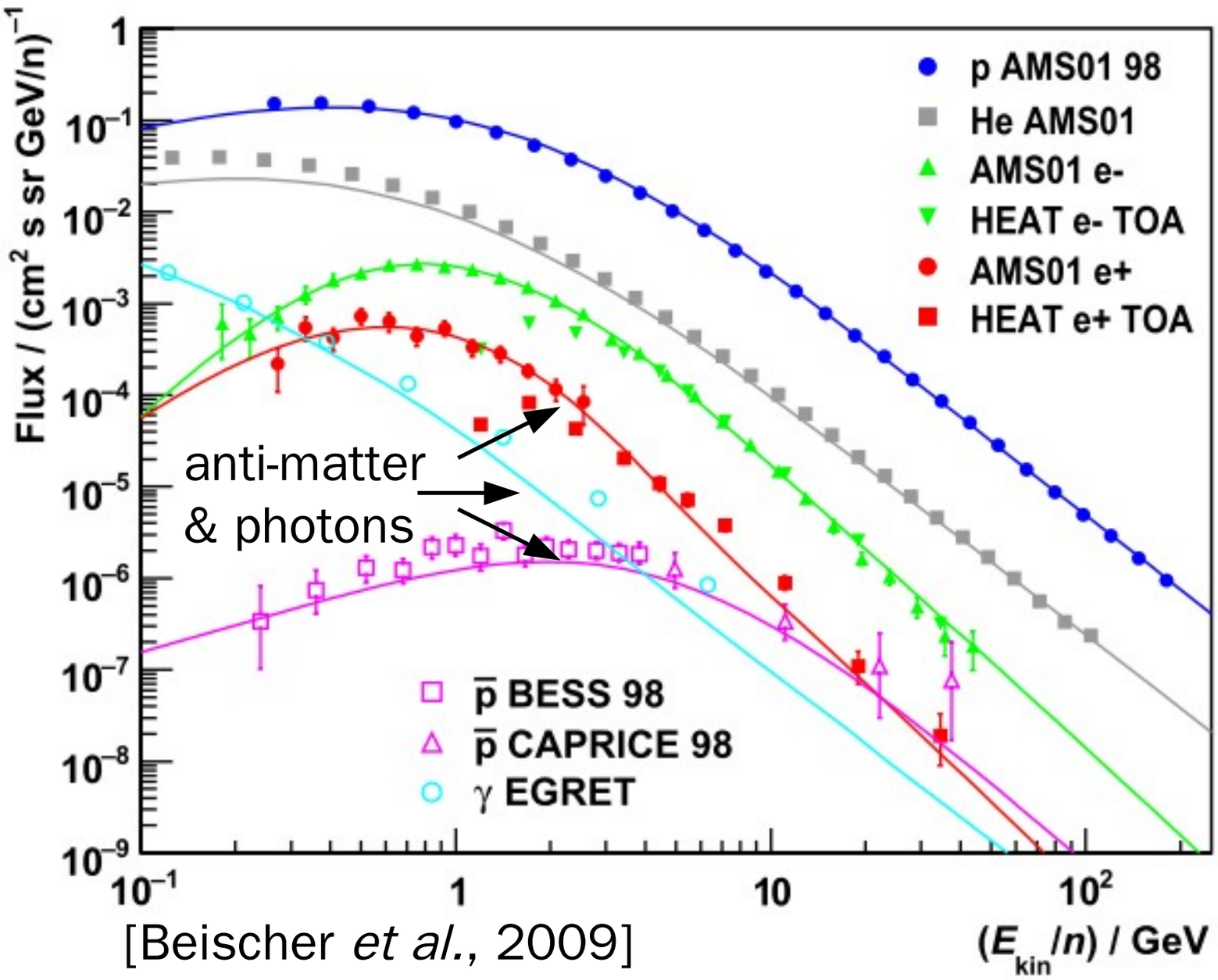
[Bechtol+ 1503.02584, Belokurov+, 1403.3406, Laevens+, 1503.05554]
[Gerringer-Sameth et al. 2015, Hooper & Linden 2015, Li et al. 2016]

Strategy 02: cross-check with different messengers

-> charged cosmic rays:



PAMELA, AMS02



[Beischer *et al.*, 2009]

matter

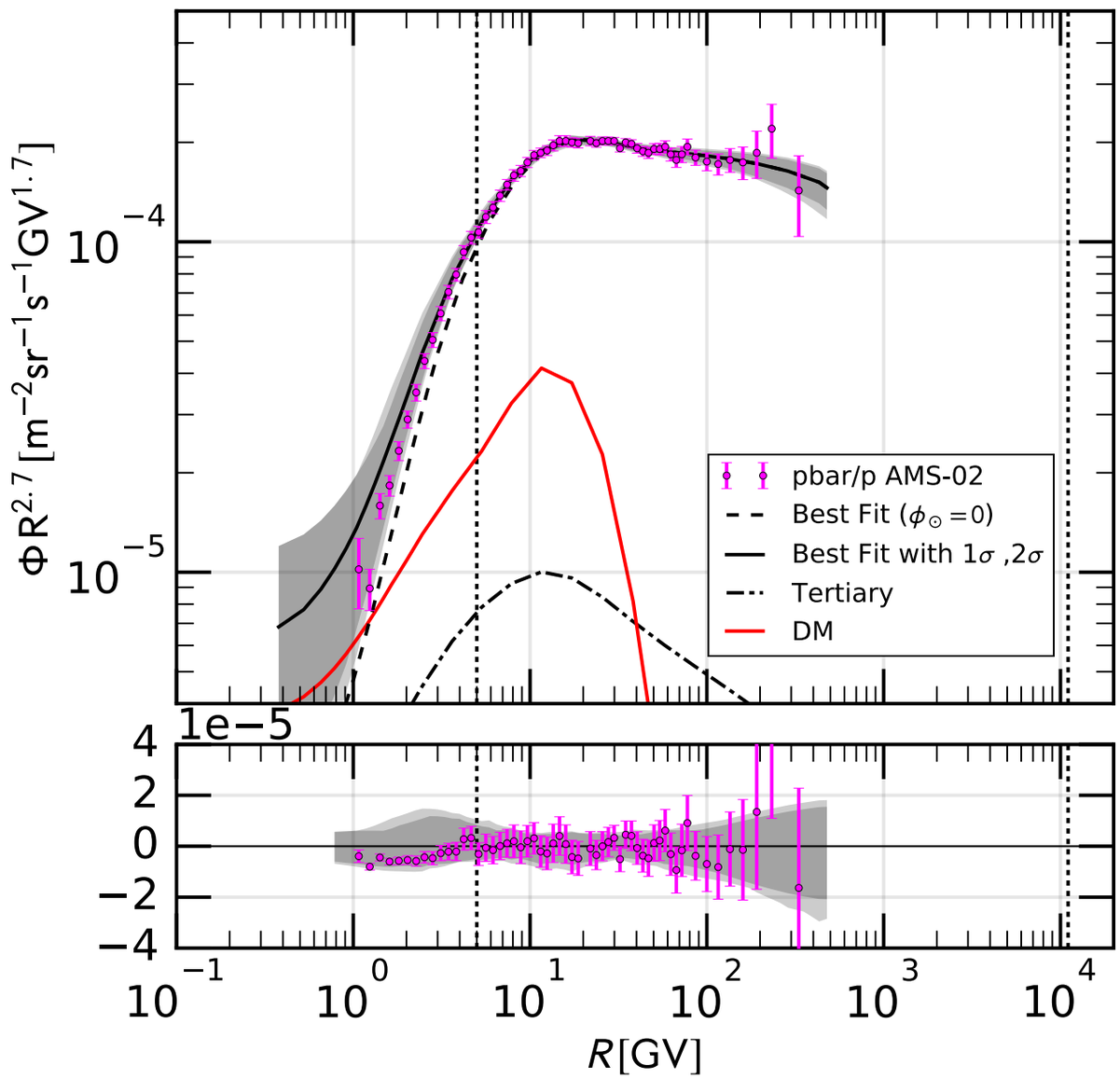
anti-particles

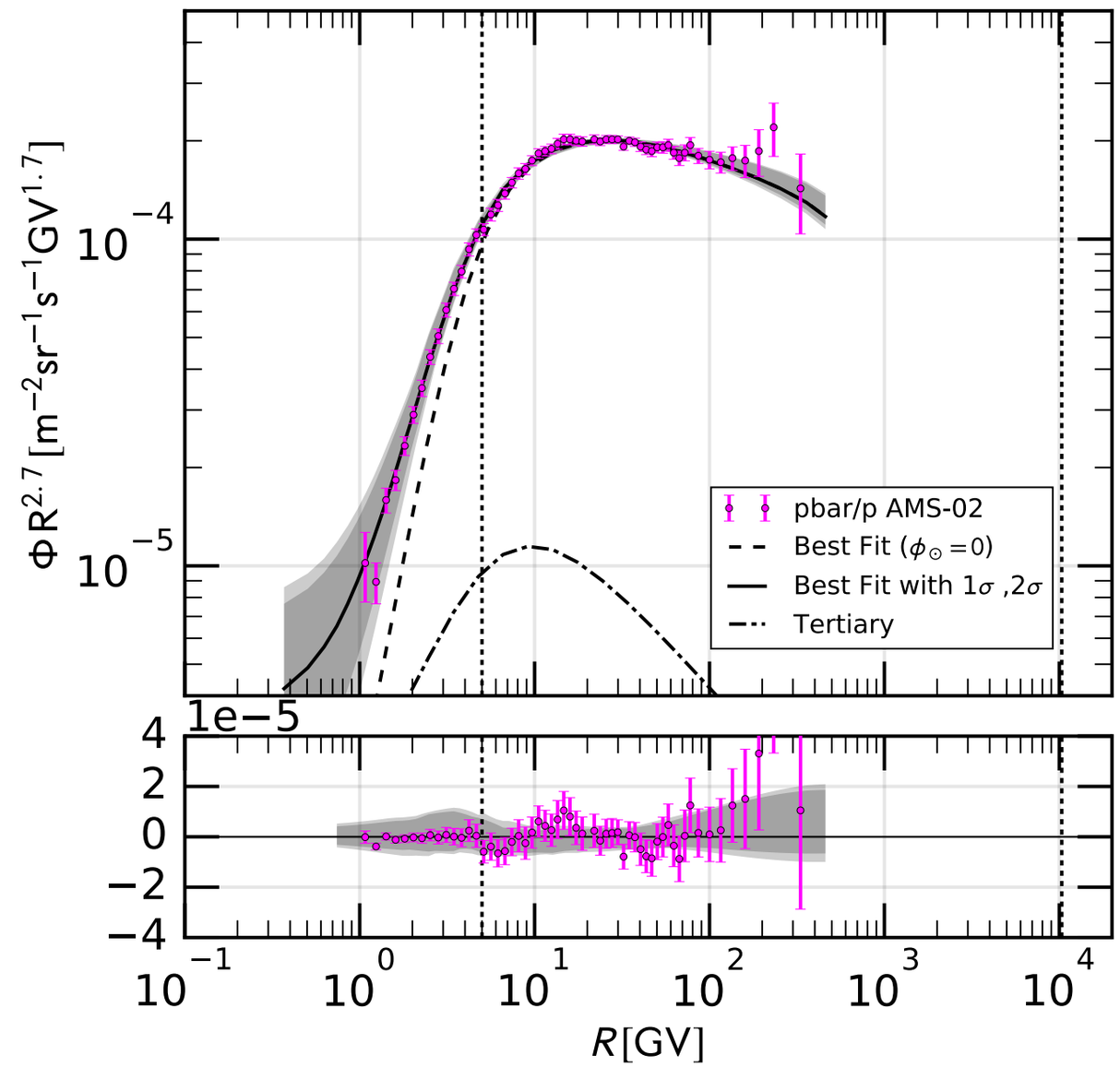
- golden channels

GCE origin test?

Use high precision **AMS-02** data!

J. Heisig's talk





[Cuoco+, PRL 2017]

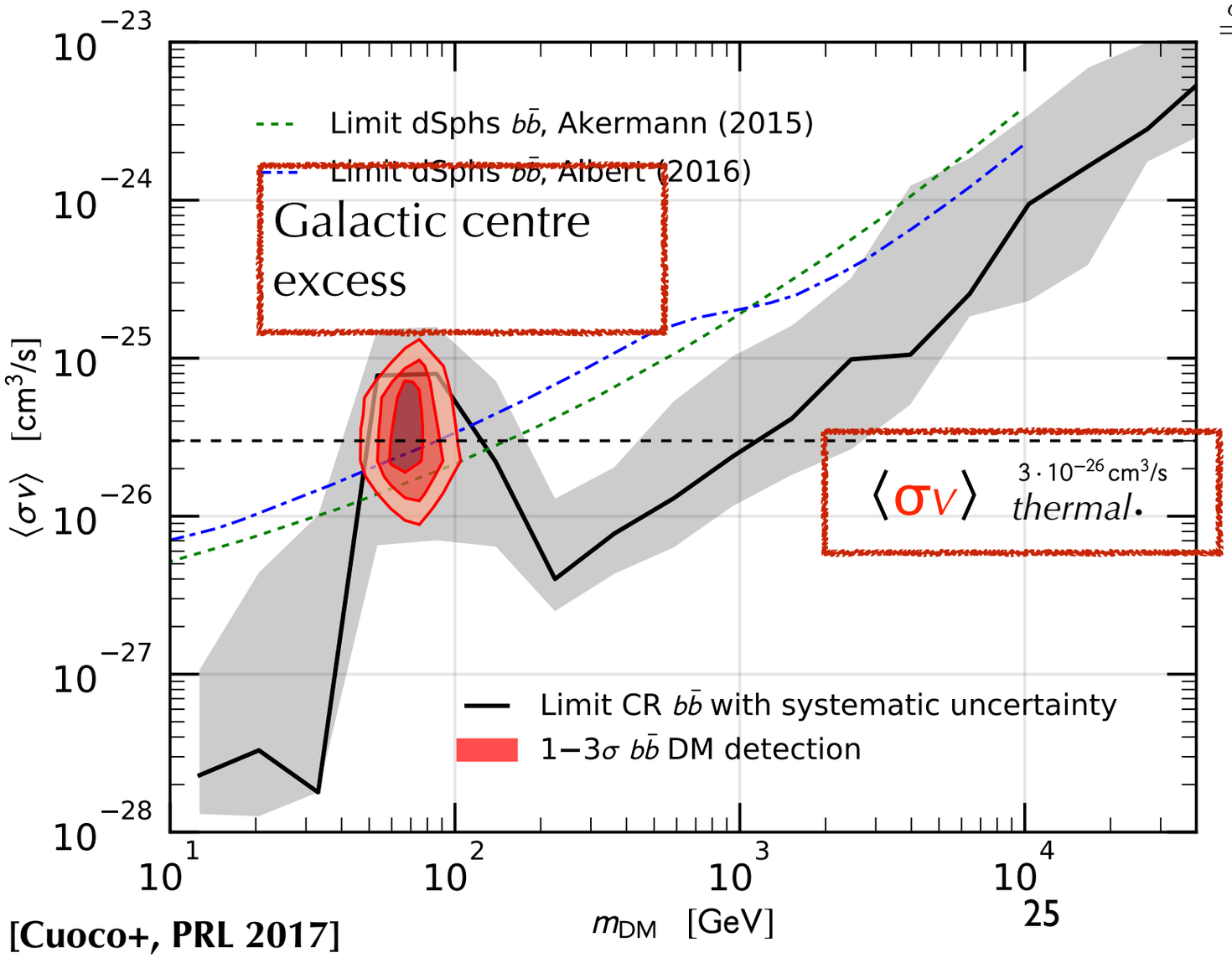
Remember:

propagation of charged cosmic rays determined by many free parameters

—> significant uncertainties!

— **strong limits, in tension but not excluding the GCE**

Propagation parameters		Fit without DM	Standard fit with DM	Fit range
$\gamma_{1,p}$		$1.54^{+0.04}_{-0.18}$	$1.41^{+0.19}_{-0.01}$	1.2 - 1.8
$\gamma_{2,p}$		$2.425^{+0.023}_{-0.002}$	$2.531^{+0.008}_{-0.010}$	2.3 - 2.6
γ_1		$1.56^{+0.03}_{-0.18}$	$1.21^{+0.22}_{-0.02}$	1.2 - 1.8
γ_2		$2.388^{+0.021}_{-0.003}$	$2.480^{+0.005}_{-0.005}$	2.3 - 2.6
R_0	$[GV]$	$8.43^{+0.27}_{-1.93}$	$5.01^{+1.30}_{-0.12}$	1.0 - 10
s		$0.38^{+0.11}_{-0.01}$	$0.46^{+0.01}_{-0.06}$	0.05 - 0.9
δ		$0.361^{+0.005}_{-0.043}$	$0.245^{+0.015}_{-0.007}$	0.2 - 0.5
D_0	$[10^{28}\ \mathrm{cm}^2/\mathrm{s}]$	$7.48^{+1.52}_{-1.88}$	$9.84^{+0.26}_{-2.85}$	0.5 - 10.0
v_A	[km/s]	$23.8^{+3.09}_{-0.91}$	$28.5^{+1.5}_{-0.64}$	0 - 30
$v_{0,\mathrm{c}}$	[km/s]	$26.9^{+34.7}_{-3.33}$	$45.3^{+5.69}_{-19.2}$	0 - 100
z_h	[kpc]	$6.78^{+0.22}_{-2.70}$	$5.35^{+1.65}_{-1.27}$	2 - 7
ϕ_AMS	[GV]	580^{+65}_{-50}	520^{+35}_{-35}	0 - 1.8



[Cuoco+, PRL 2017]

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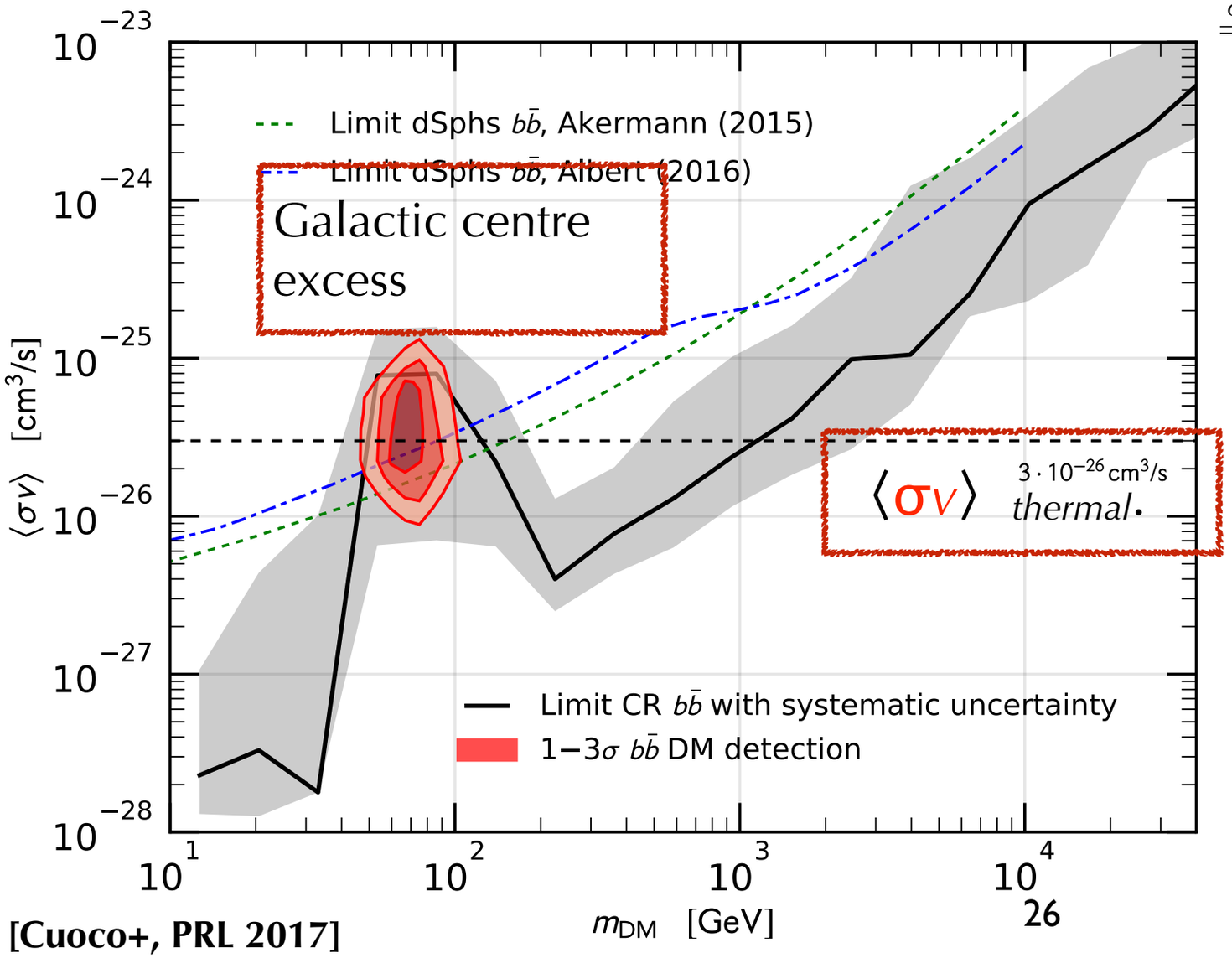


[Cuoco+, PRL 2017]

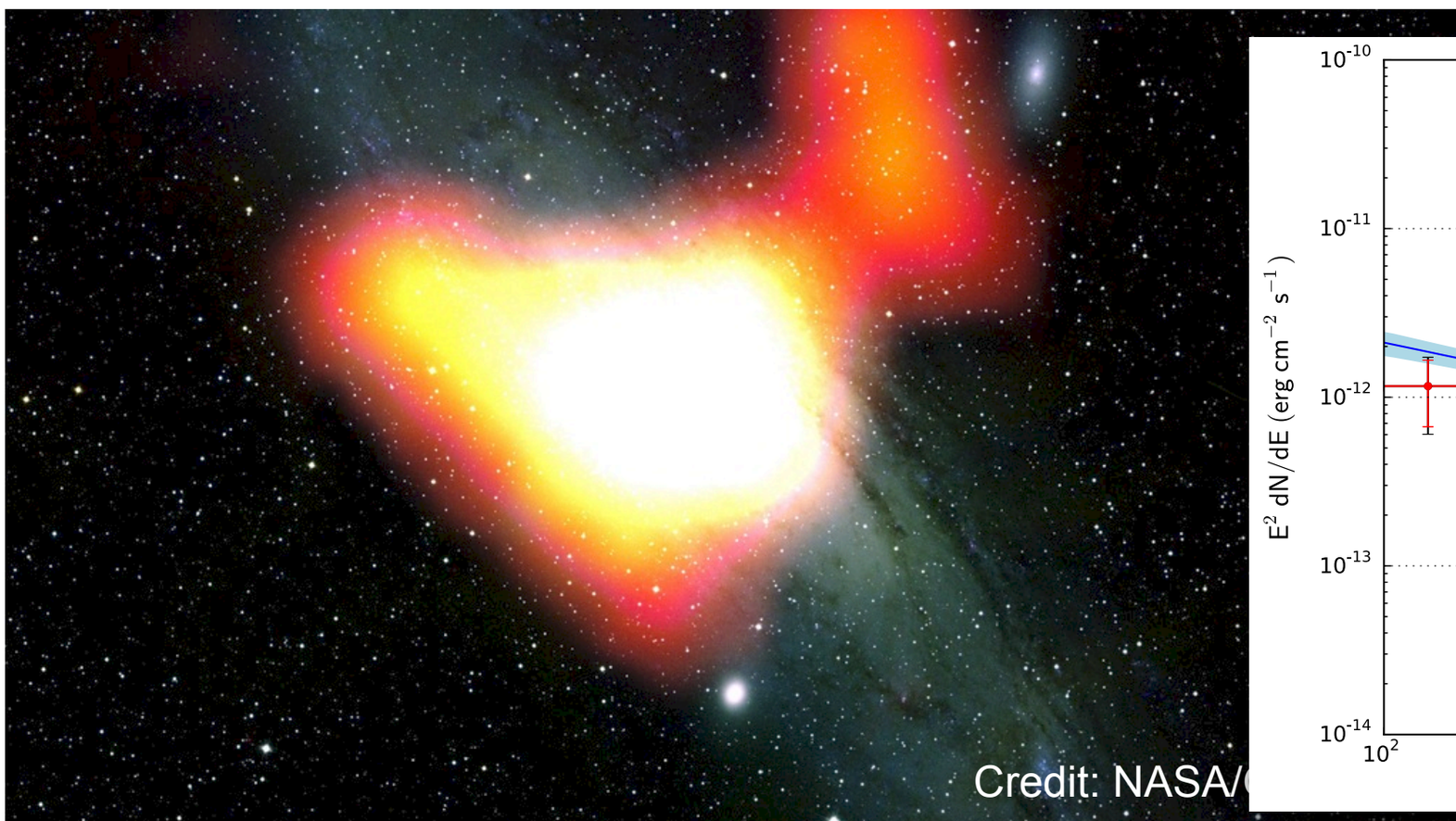
—> Several probes are reaching the thermal cross section limits and are in tension with the GCE DM interpretation.

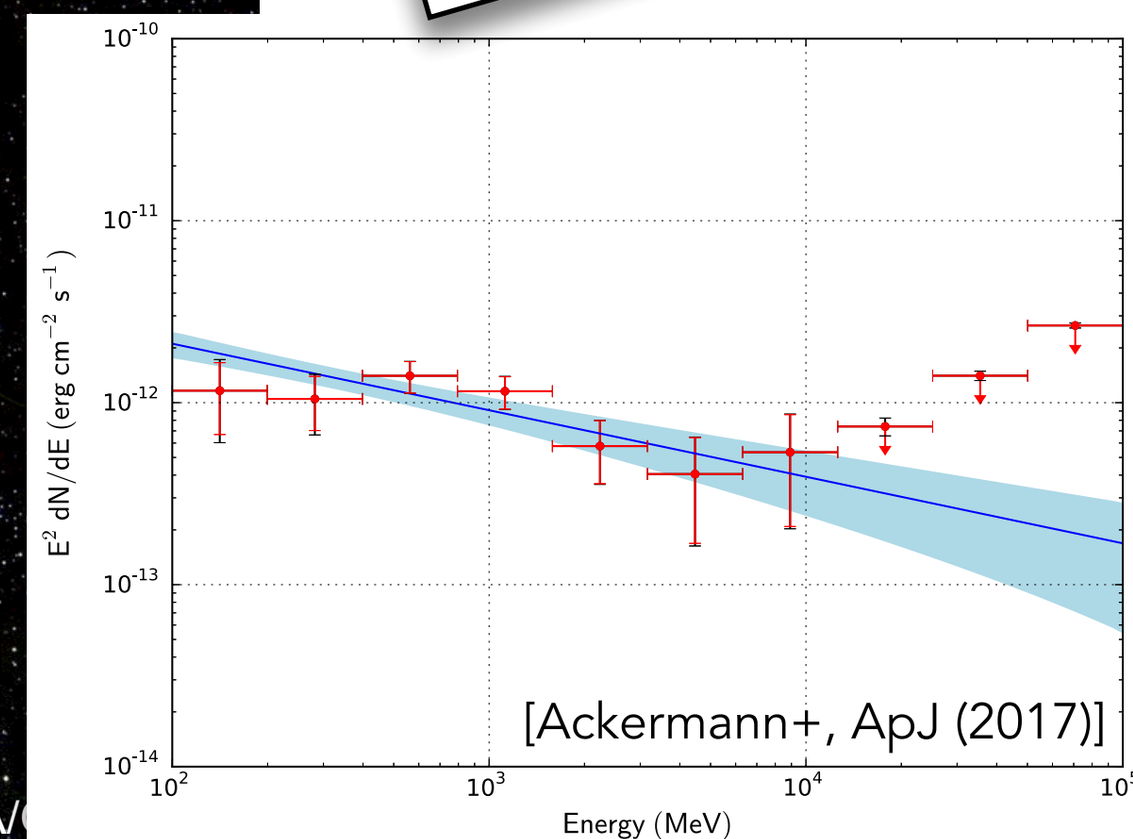
Things are getting more interesting…

The gamma-ray emission from M31

- Main facts
  - Emission confined to inner regions (R<5kpc)
  - Not correlated with interstellar gas and star formation sites
  - Galactic disk not detected

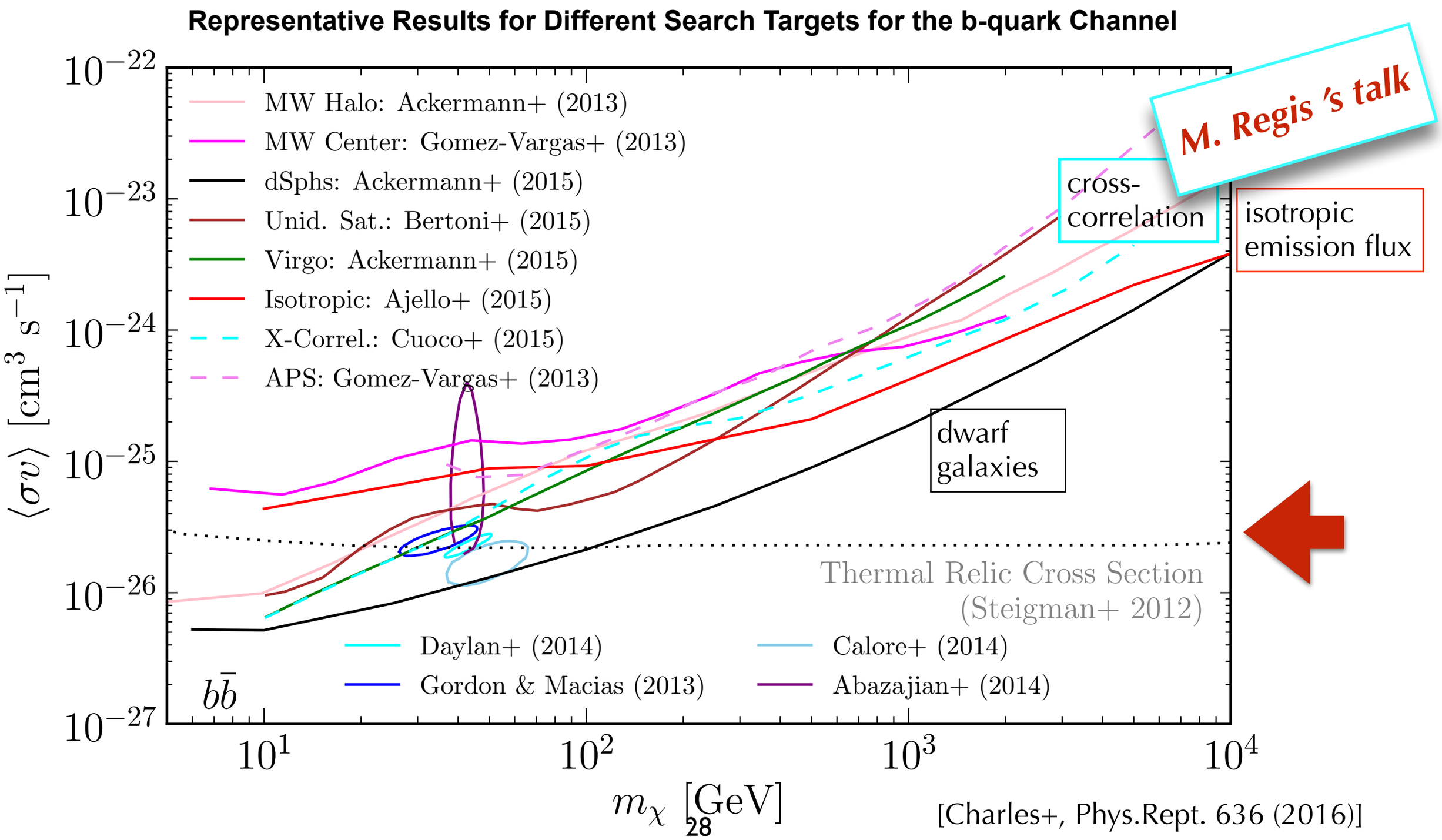
C. Eckner's talk





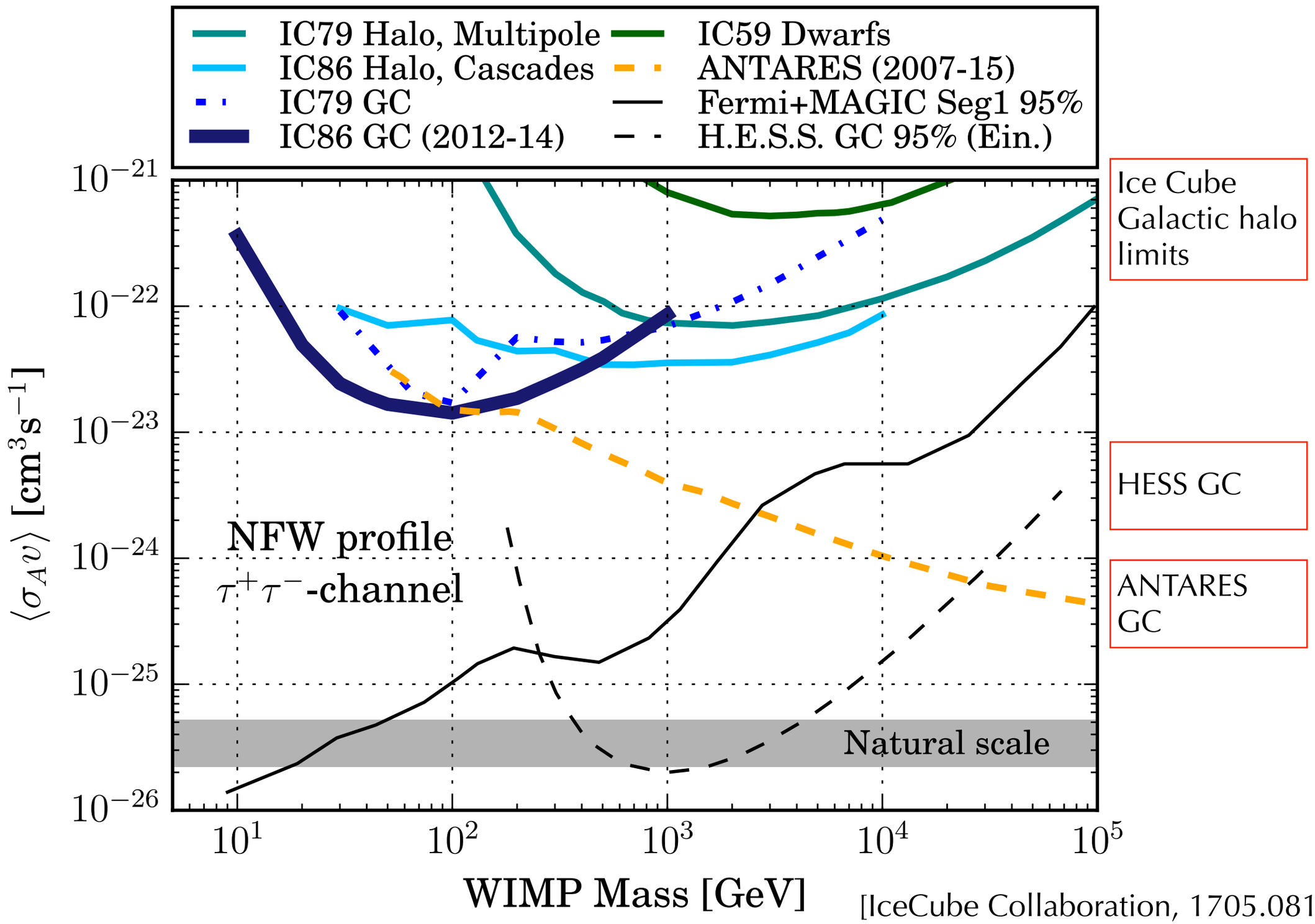
Outlook - gamma ray limits come from many targets!

Many interesting analysis approaches, increasingly competitive constraints



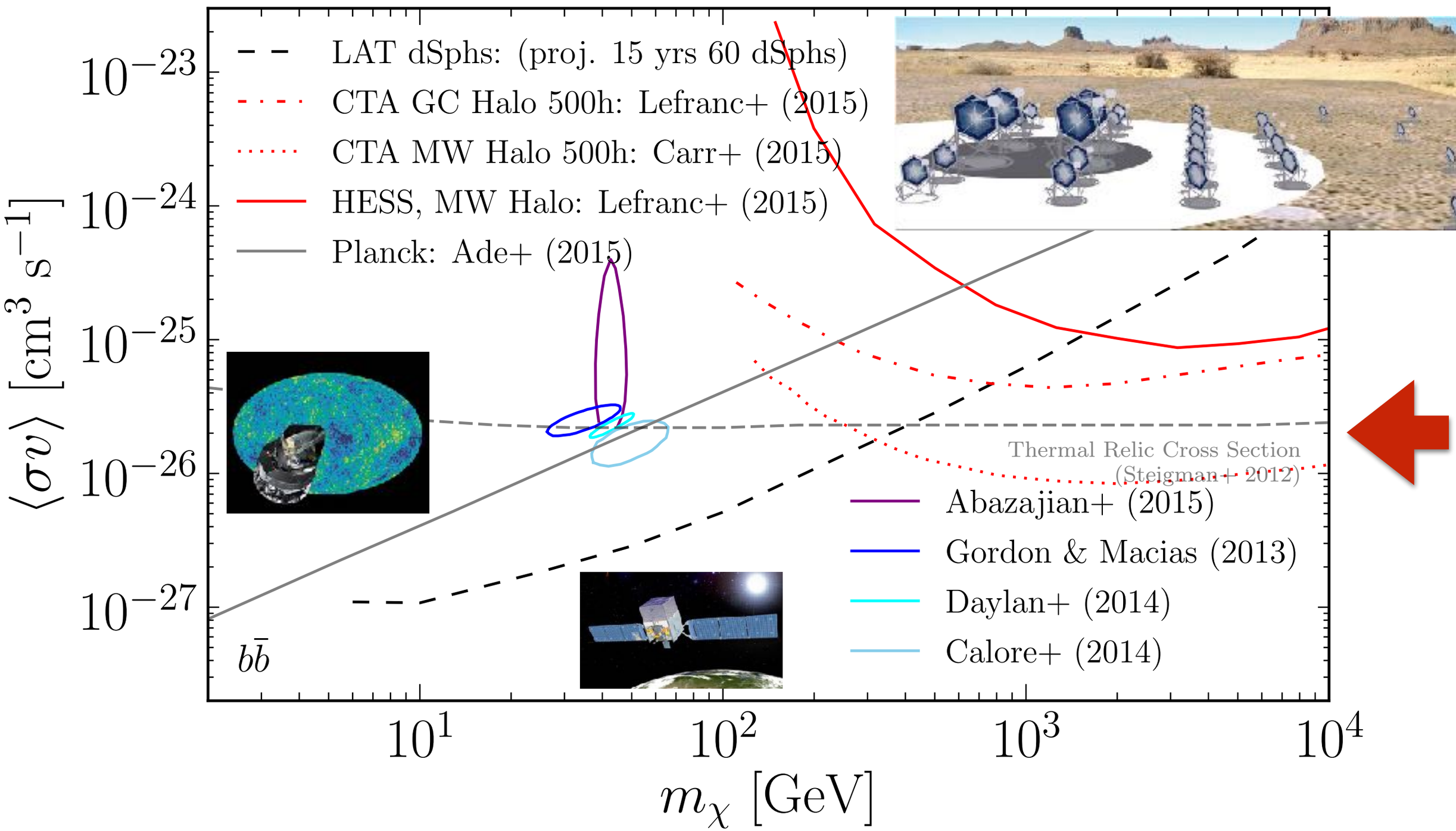
[Charles+, Phys.Rept. 636 (2016)]

Outlook - many experiments contribute to the effort!

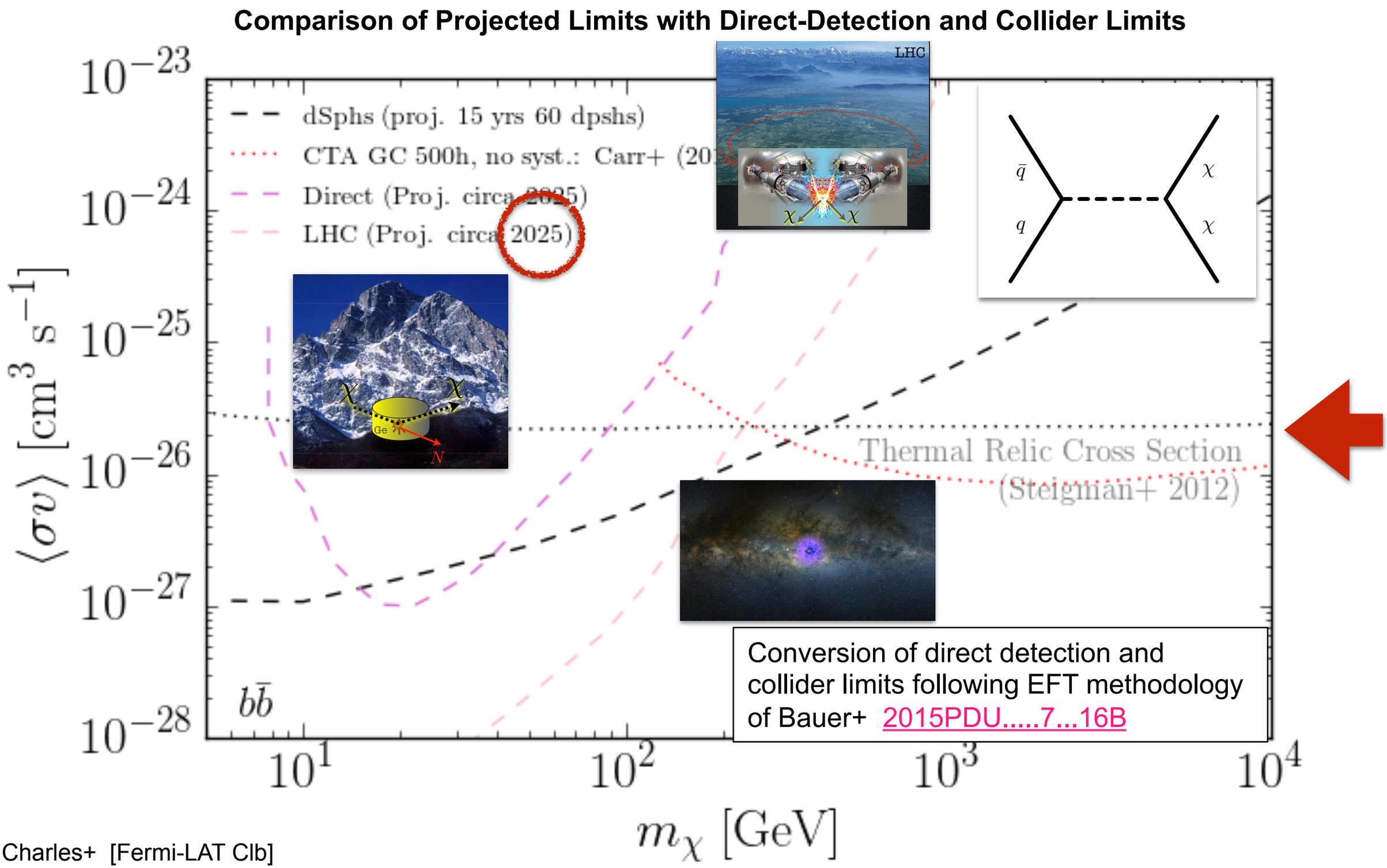


[IceCube Collaboration, 1705.08103]

Outlook - future WIMP searches



Outlook— cornering the WIMPs

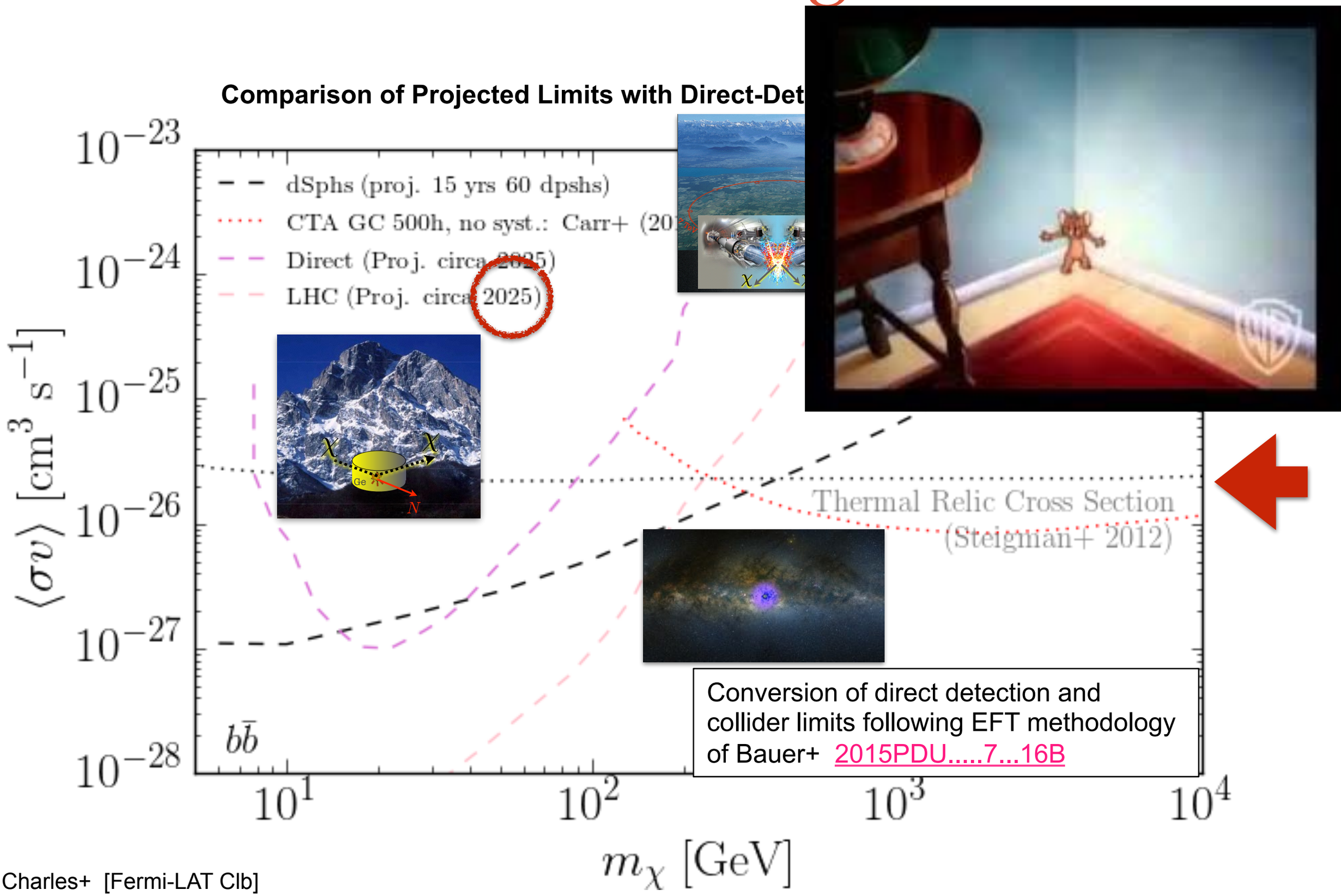


Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

Charles+ [Fermi-LAT Clb]
2016PhR...636....1C

Caution: model dependent! EFT assumed here.

Outlook— cornering the WIMPs



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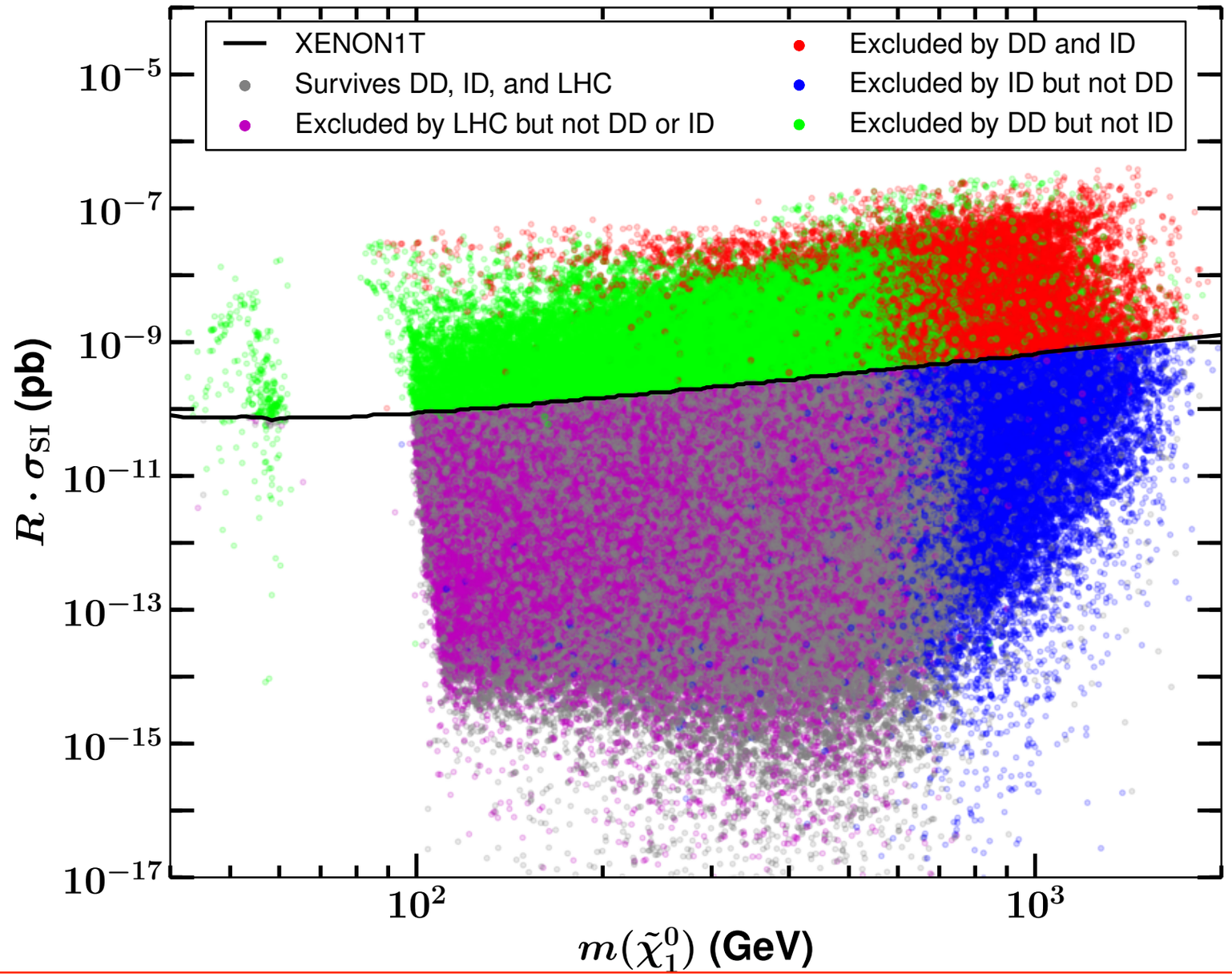


or for MSSM

[Cahill-Rowley et al. arXiv:1305.6921]

The community (theorists & experimentalists from many fields) came together over the past ~40 years and **executed a complex strategy** to test the WIMP models.

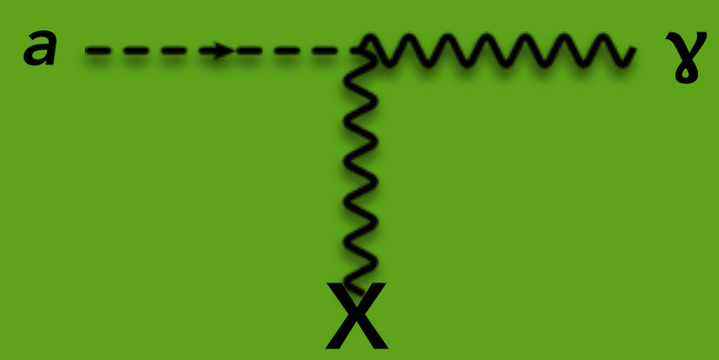
By **~2025**+ n-ton scale direct detection + upgraded LHC + indirect detection should have delivered (bulk of) the message.

Not 'only' WIMPs…

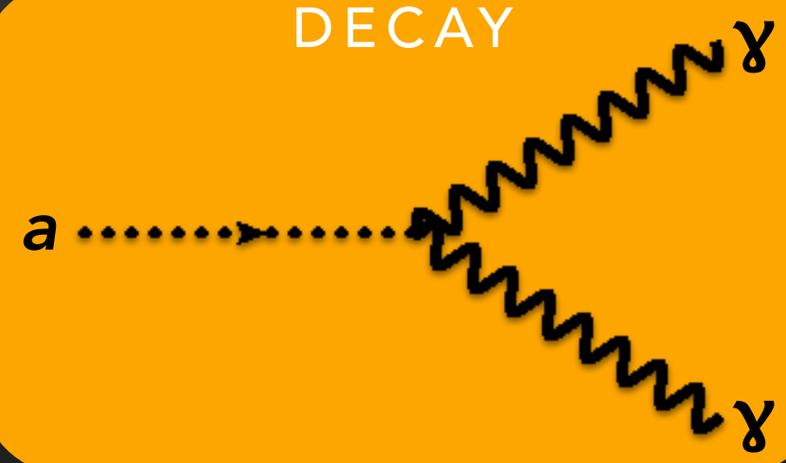
DETECTING AXIONS/ALPs WITH PHOTONS

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\,\mathbf{B} a$$

PRIMAKOFF EFFECT



DECAY



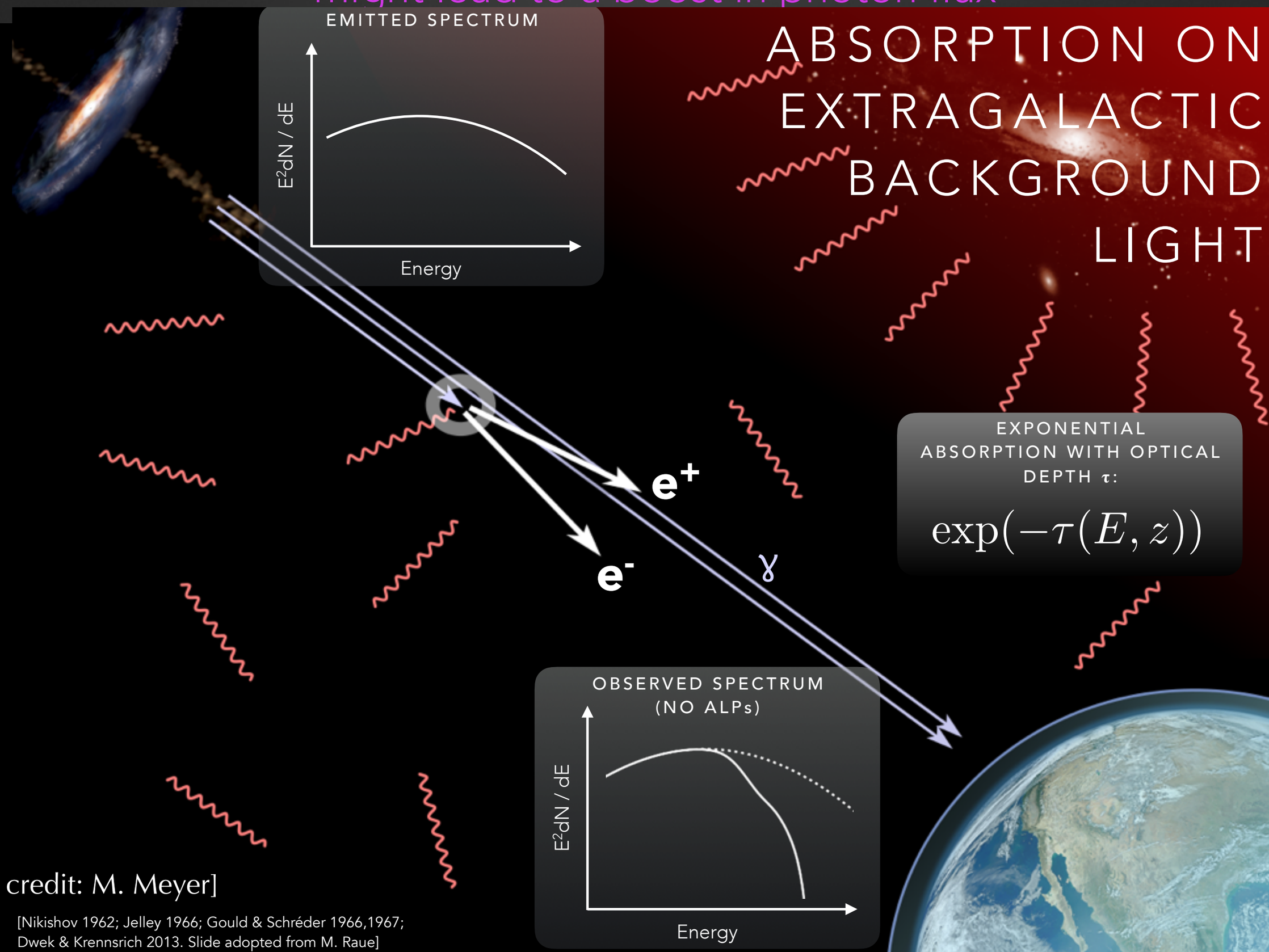
$$\tau_{a\gamma\gamma} \sim 10^{25}\,\mathrm{s} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_a}{\mathrm{eV}}\right)^{-3}$$

QCD Axion: $m_a \approx 0.3\,\mathrm{eV} \frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} = 0.3\,\mathrm{eV}\, g_{10}$

[slide credit: M. Meyer]

[Birenji, Gaskins, Meyer 2016]

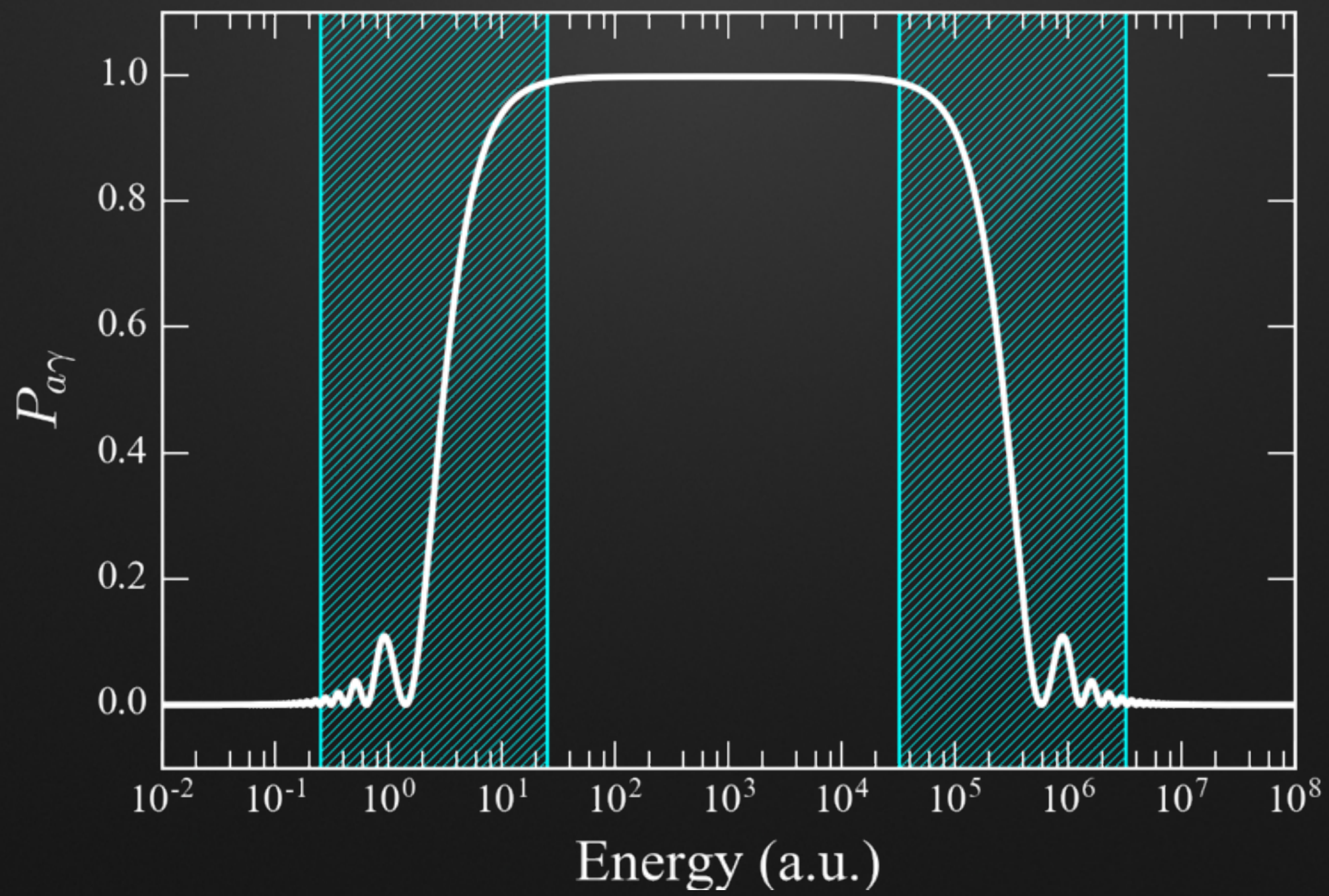
1st Observable: axions/ALPs do not get absorbed during propagation, might lead to a boost in photon flux



[slide credit: M. Meyer]

[Nikishov 1962; Jelley 1966; Gould & Schréder 1966,1967; Dwek & Krennsrich 2013. Slide adopted from M. Raue]

2nd Observable: irregularities in energy spectrum around E_{crit} and E_{max}

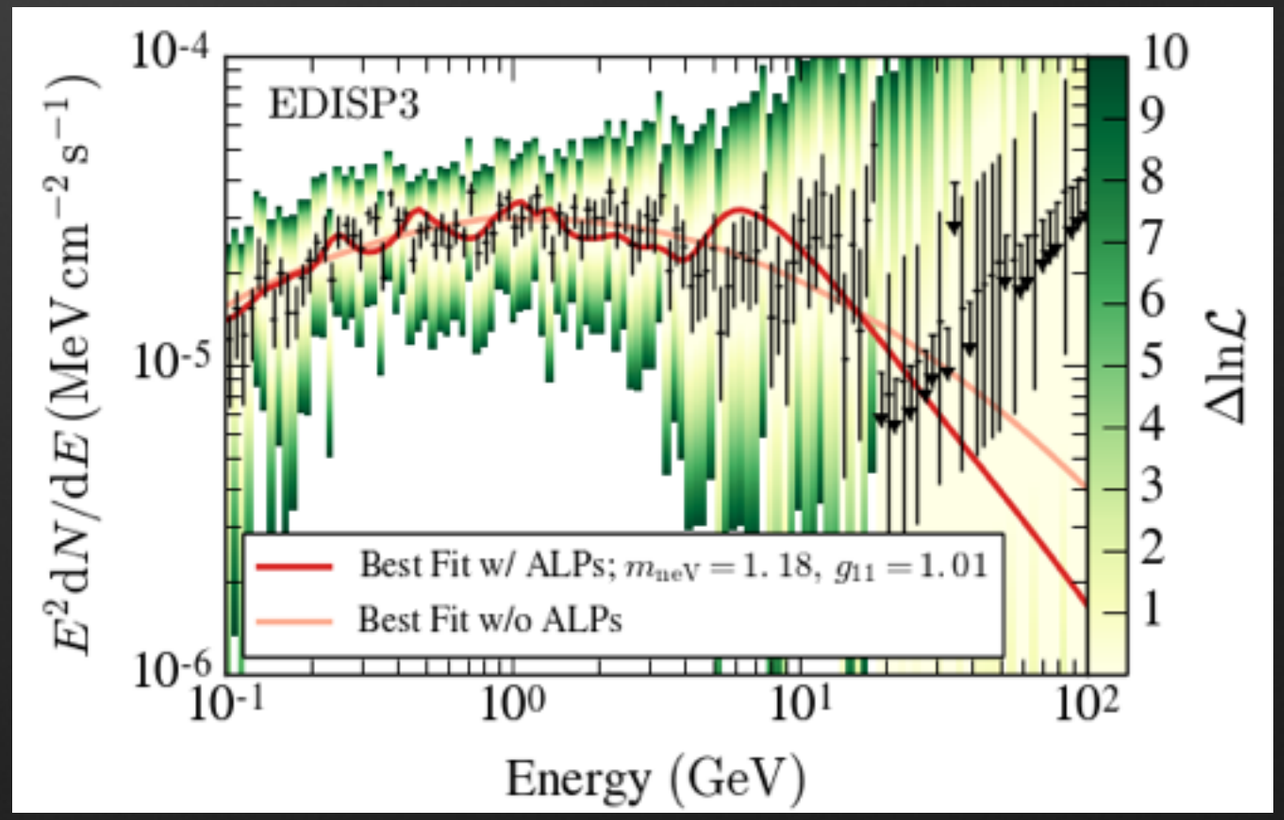


[slide credit: M. Meyer]

[Östman & Mörtsell 2005; Hooper & Serpico 2007; Mirizzi et al 2007; Hochmuth & Sigl 2007; De Angelis et al. 2008; Wouters & Brun 2012,2013; Abramowski et al. 2013; Ajello et al. 2016]

SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

- **Radio galaxy NGC 1275, bright *Fermi* source** [e.g. Abdo et al. 2009]
- In the center of **cool-core** Perseus cluster



ALP HYPOTHESIS: $P_{\gamma\gamma}(E, m_a, g_{a\gamma}, \mathbf{B}) F(E)$

Photon. surv. prob.; incl. EBL — Intrinsic spectrum

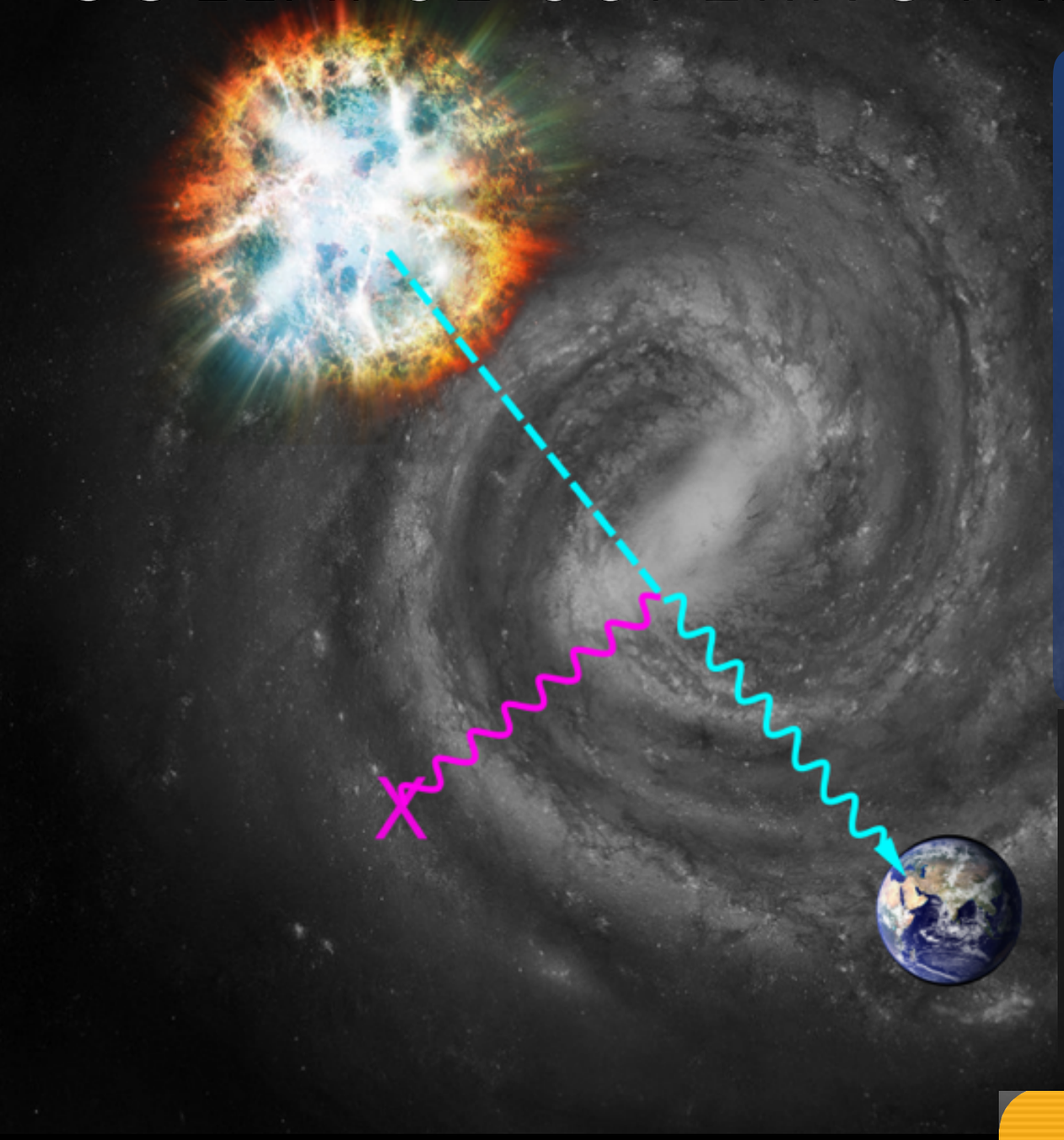
NO-ALP HYPOTHESIS: $\exp(-\tau) F(E)$

EBL attenuation only — Intrinsic spectrum

[slide credit: M. Meyer]

[Ajello et al. (*Fermi*-LAT Collaboration) 2016]

AXIONLIKE PARTICLES FROM CORE COLLAPSE SUPERNOVAE



- ALPs would be **produced in a core-collapse SN** explosion via Primakoff process
- Could **convert into gamma-rays in Galactic magnetic field**
- **Gamma rays would arrive co-incident with SN neutrinos** (provides time tag)

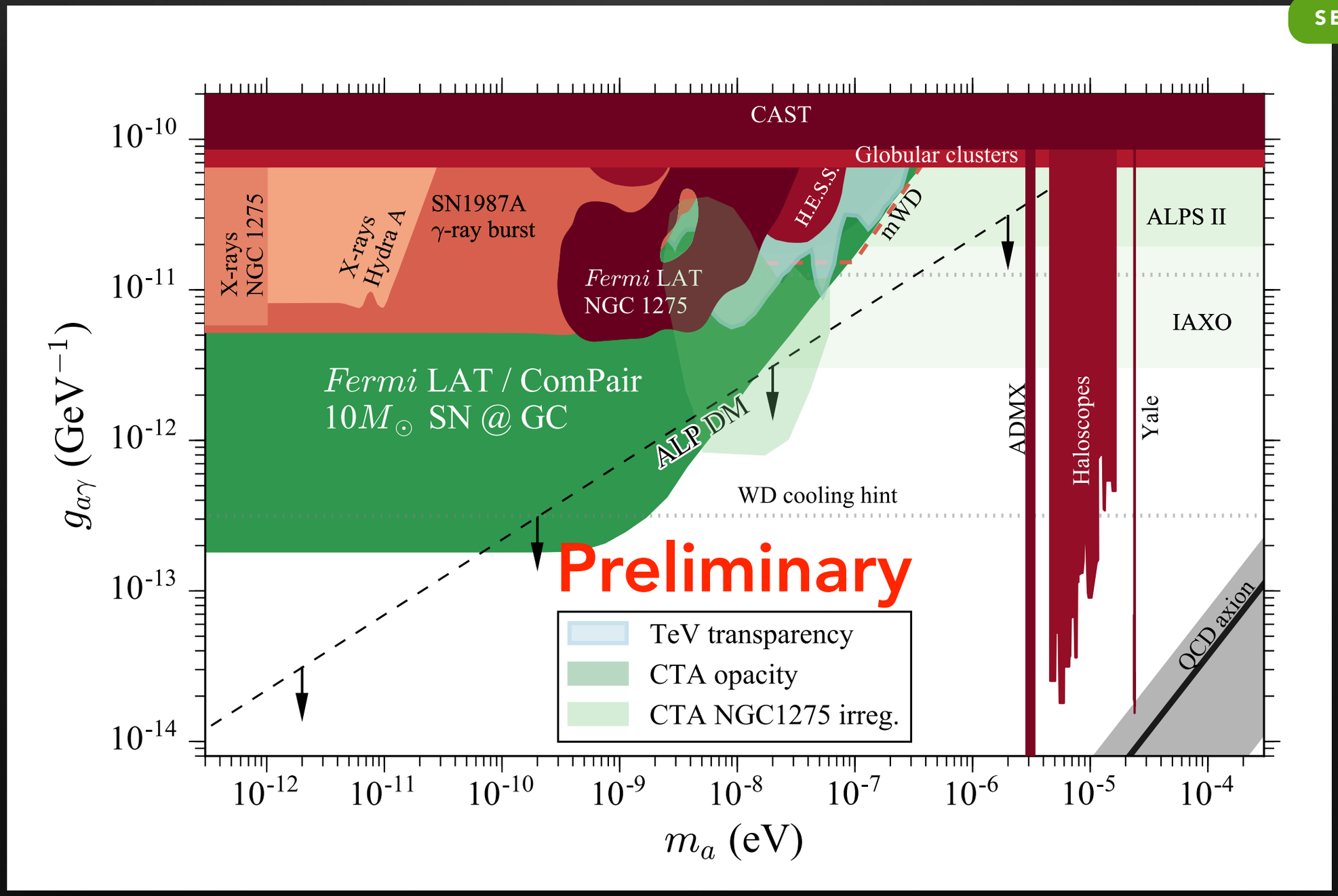
Assuming 4 background counts in one 20s time bin:
Exclude ALP models predicting more than 6.4 counts at 95% confidence

[slide credit: M. Meyer]

CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES

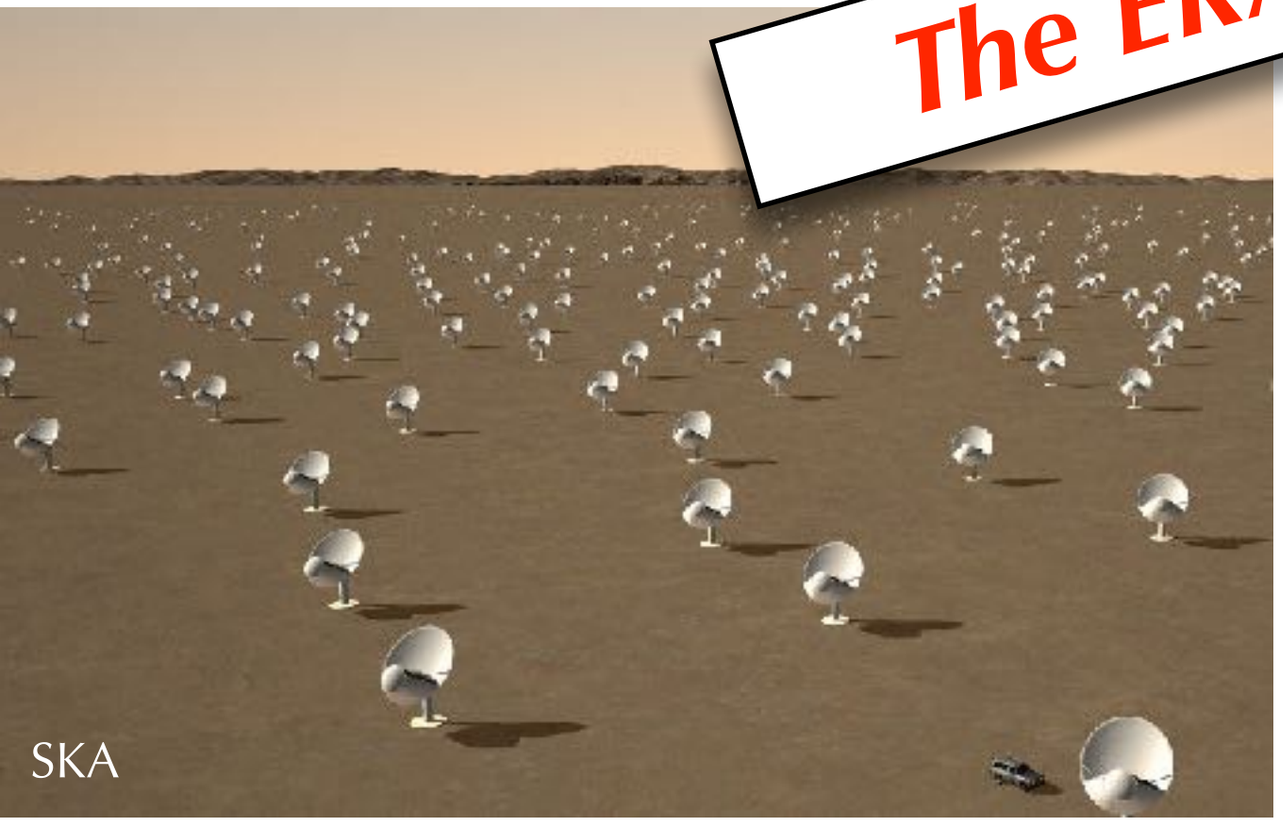


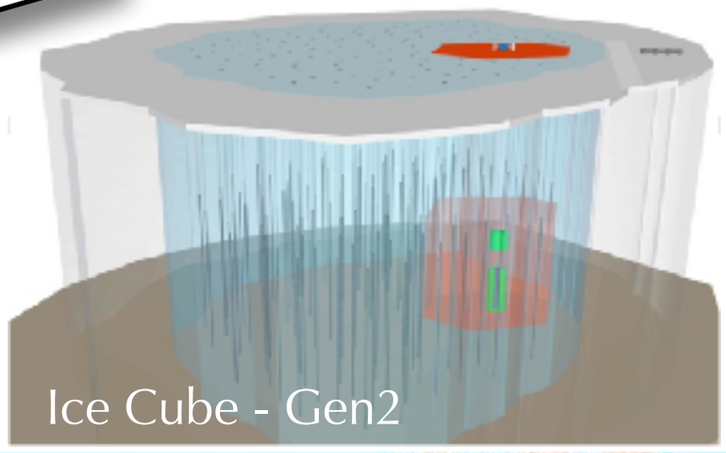
[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde, [redacted] PRL. ArXiv:1609.02350]

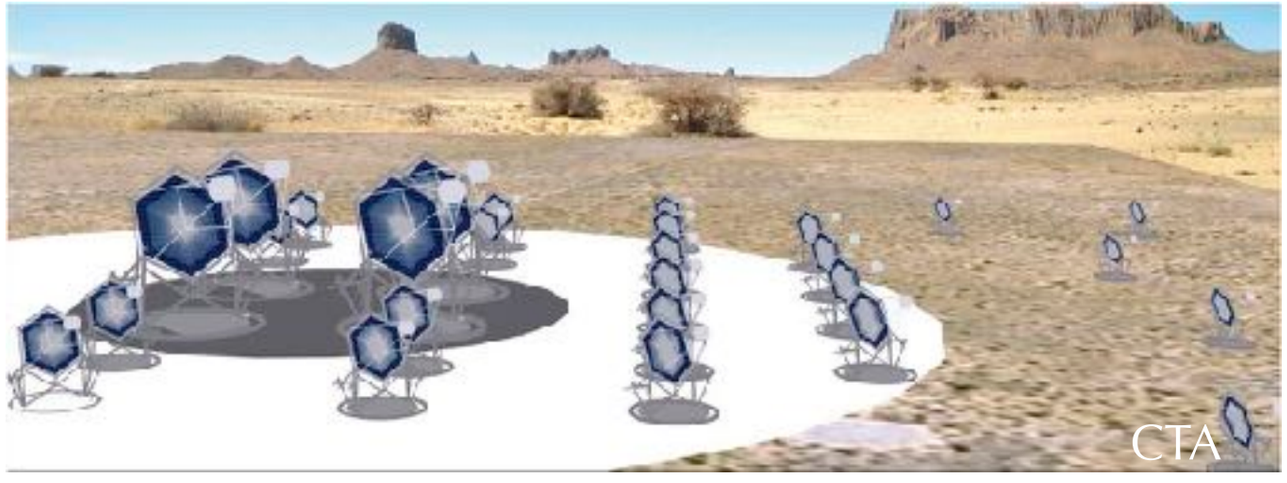
[slide credit: M. Meyer]

Summary

The ERA of data!







Extra Slides

the DM signal:

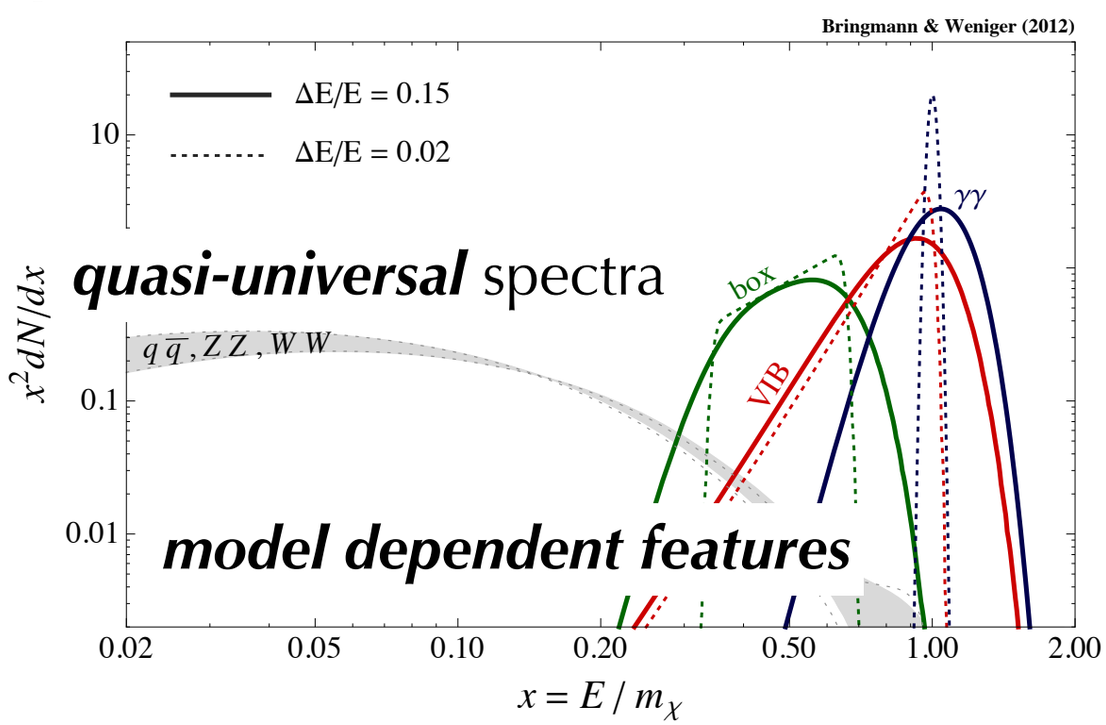
particle physics — cosmology

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2} \times \sum_i {\rm BR}_i \frac{dN_\gamma^i}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)$$

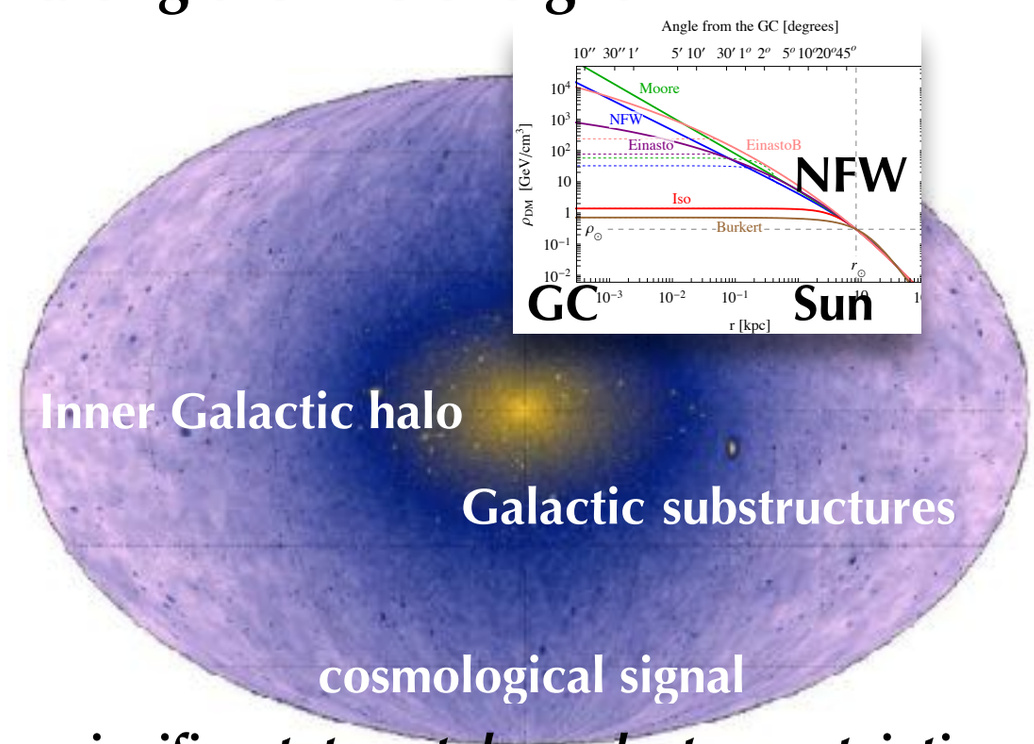
this is what we are after!

genuinely multi-disciplinary field!

flux of SM particles per DM annihilation

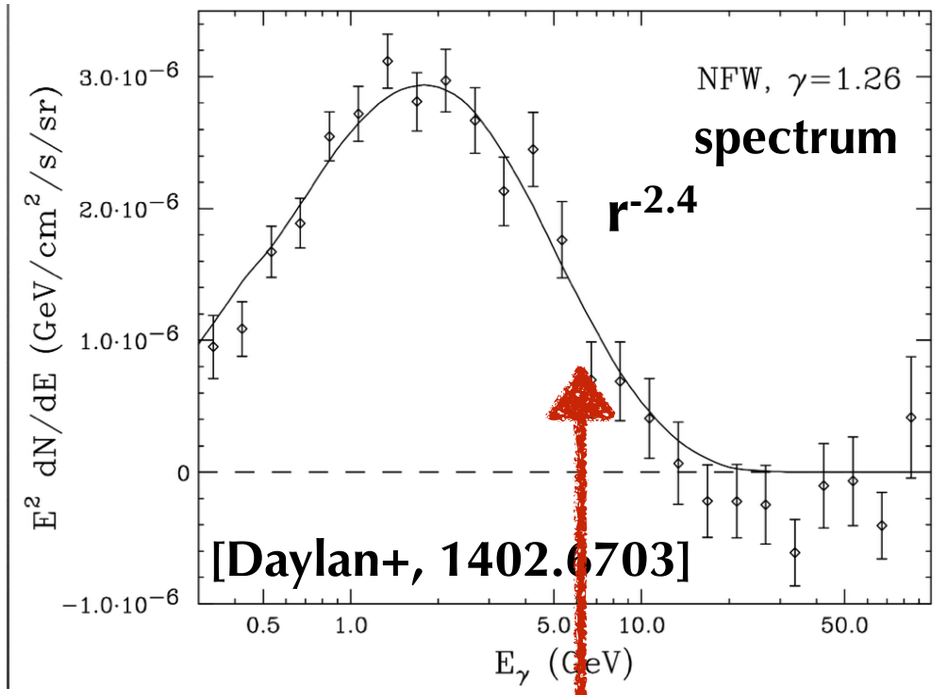


integrated DM density squared along the line of sight

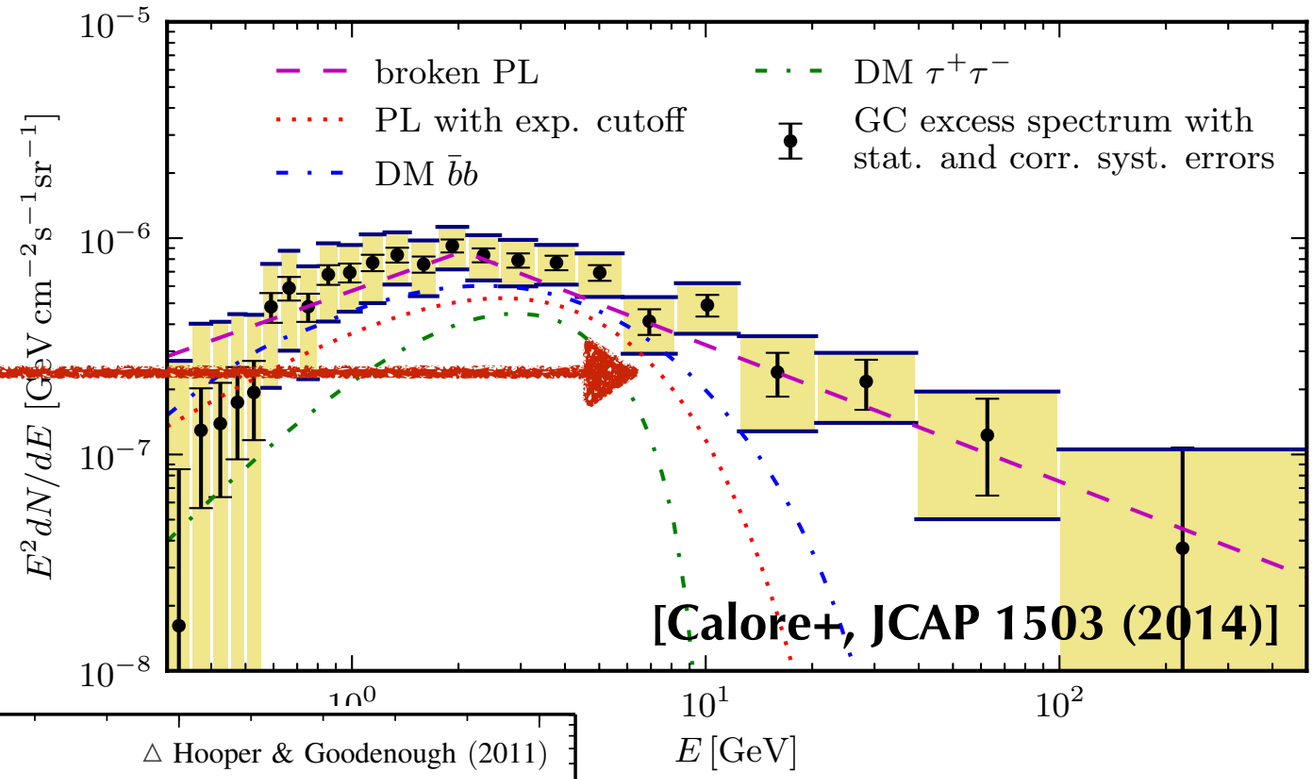


significant, target dependent uncertainties

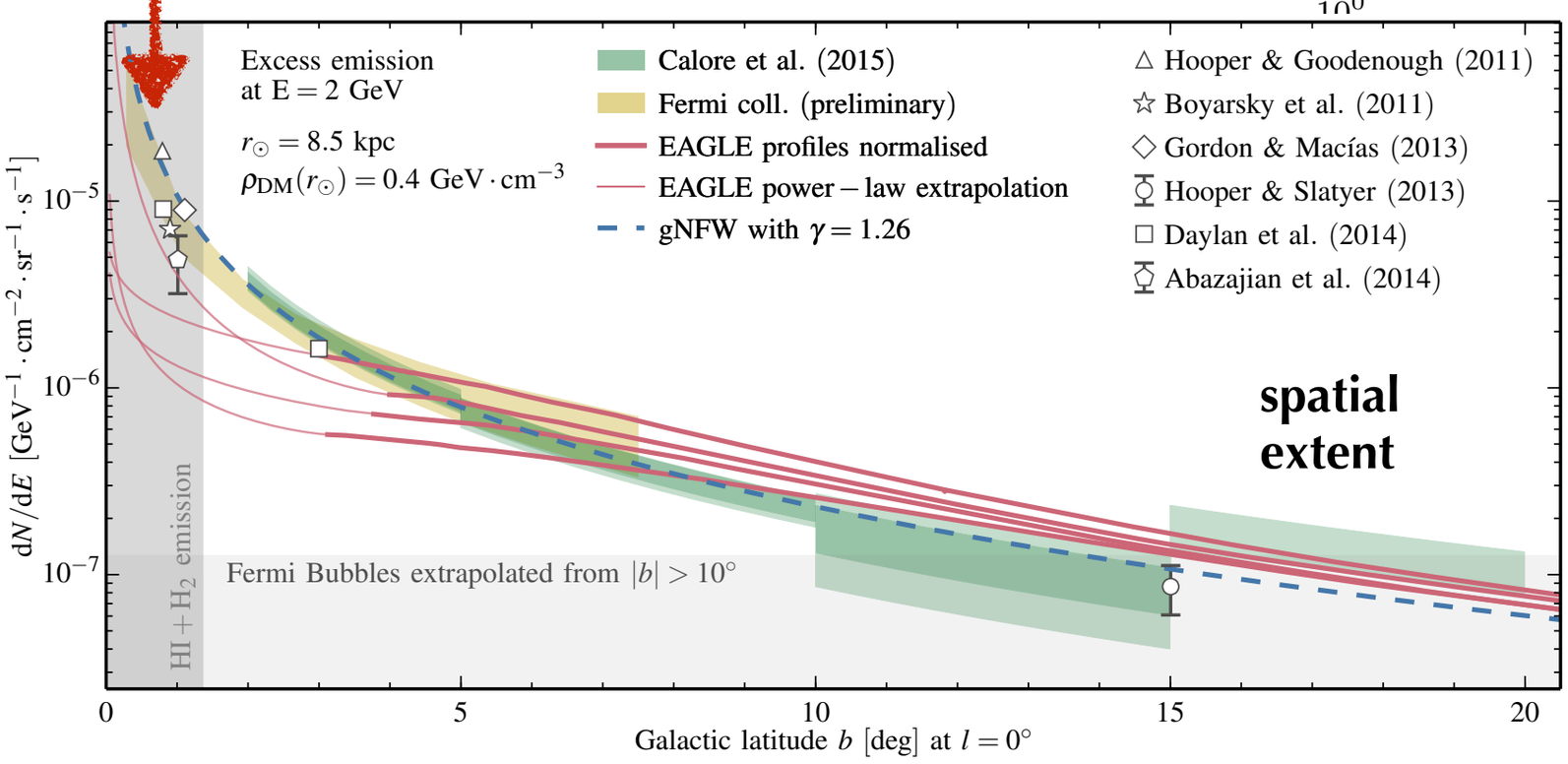
Many works reaching similar results: Vitale & Morselli (**2009**), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 Macias & Gordon (2014, PRD 89 6) 1312.6671, Abazajian et al. (2014, PRD 90 2) 1402.4090, Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527

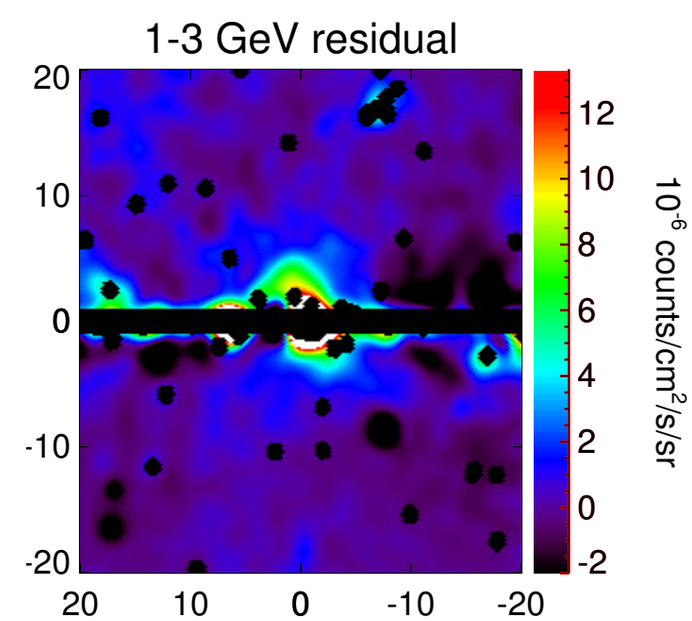


DM spectral fits



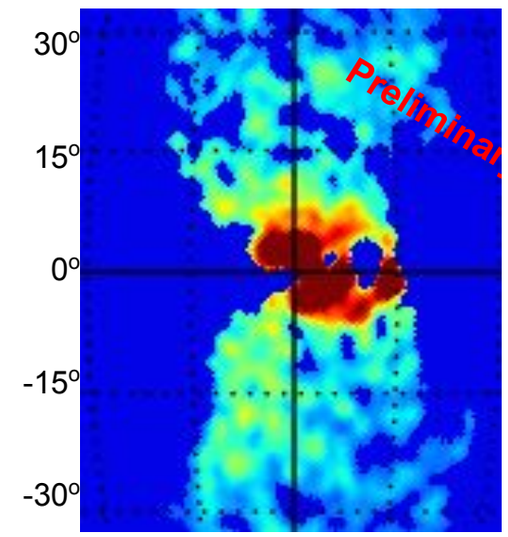
DM morphology

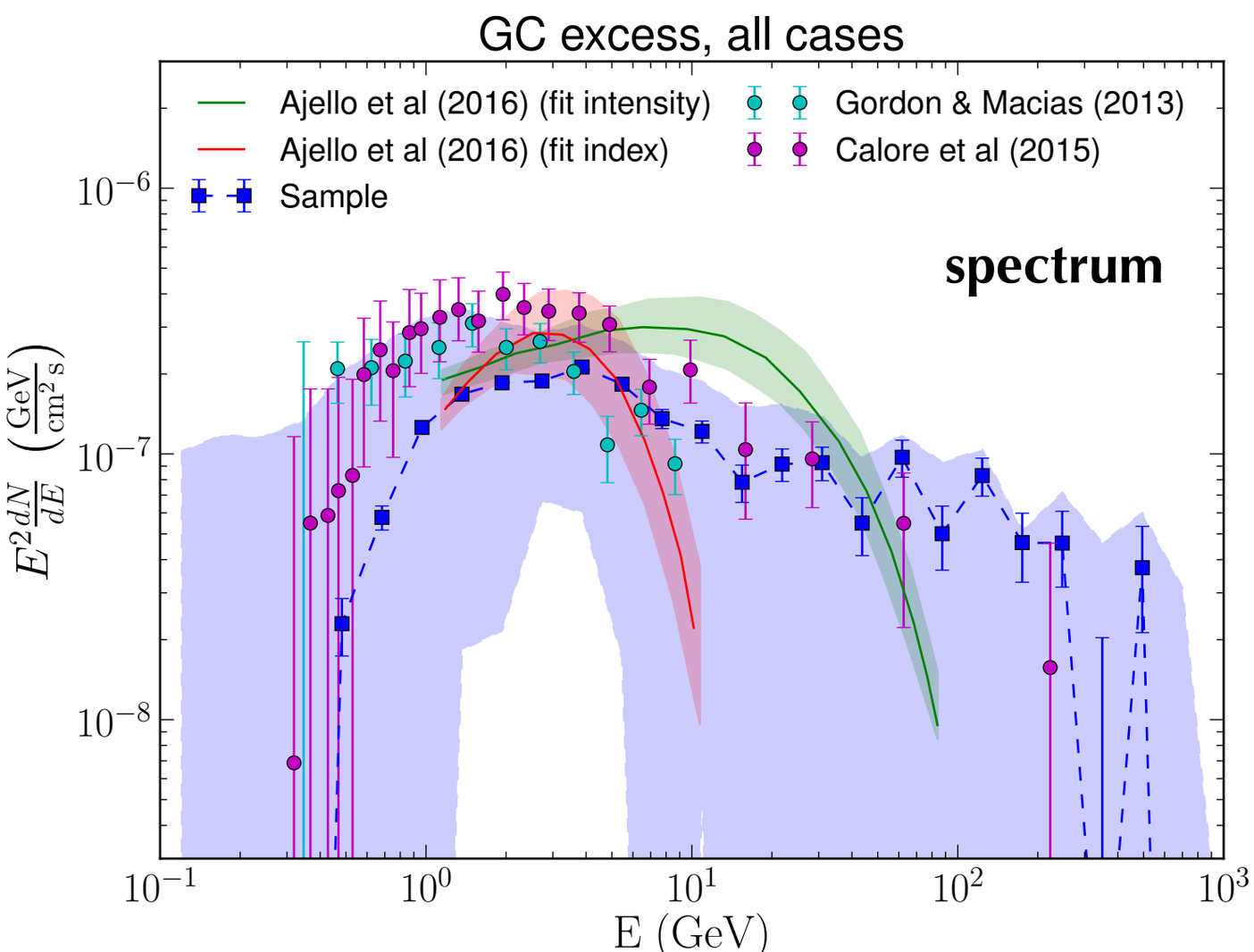




Pass 8 Fermi LAT analysis

- uses more data (**80m)**
- uses improved event selection: **pass 8 (**improved angular and energy resolution, increased effective area at the high- and low-energy ends)
- checks additional systematic uncertainties:
  - GALPROP model parameters variations
  - **Alternative gas maps** (softer GCE spectrum < 1GeV)
  - Include additional sources of **CR electrons near the GC** (Gaggero+2015, Carlson+2015 ; GCE reduced)
  - add **data driven template of the Fermi Bubbles** (excess >10 GeV gone)





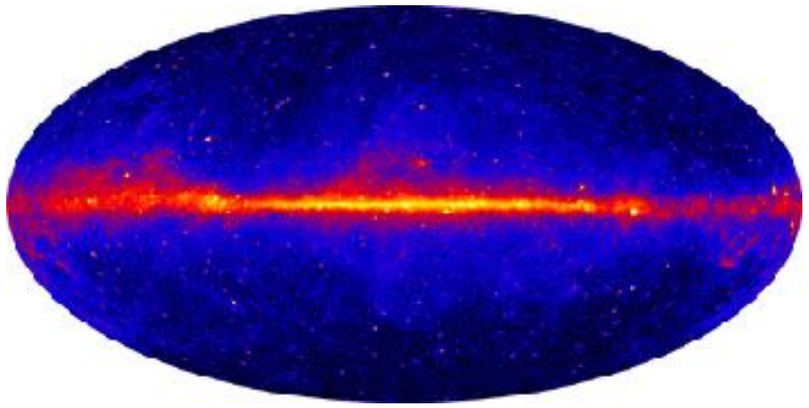
New emission component in the Galactic centre appears robust to various checks of the systematic uncertainty

its exact spectral features are model dependent

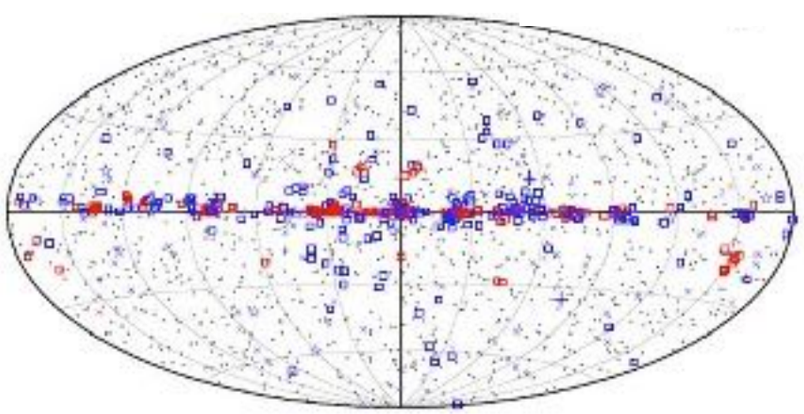
[Ackermann+, ApJ 2017]

The Fermi sky

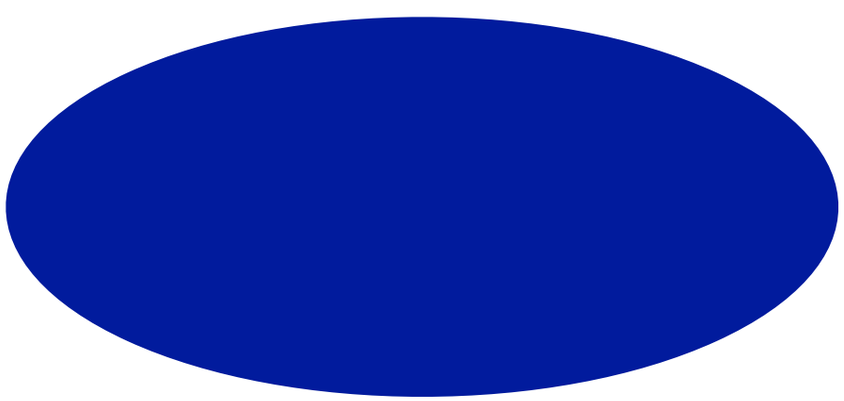
Diffuse emission from our Galaxy



Point sources



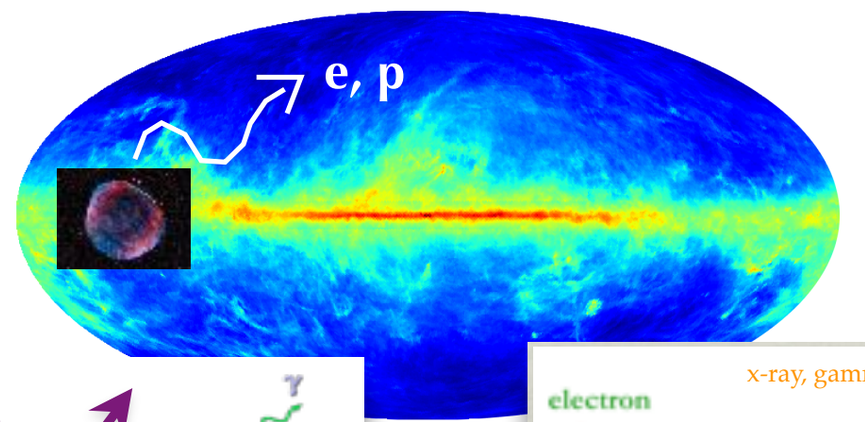
Isotropic emission

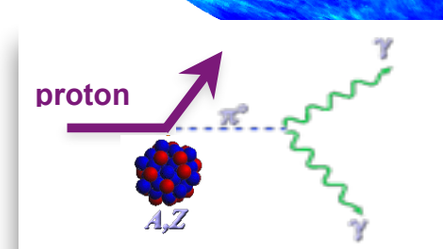


90% of the LAT photons!

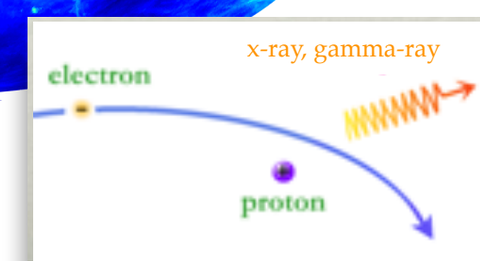
cosmic rays+**interstellar medium**

→**gamma rays parameters:** distribution of sources, magnetic fields, gas, injection spectra...



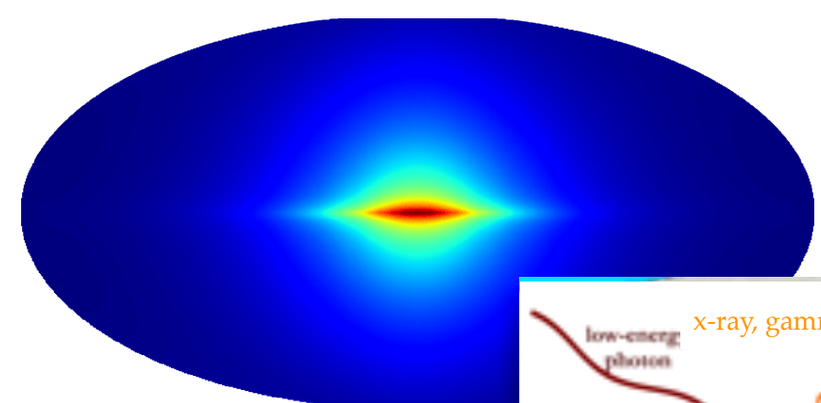


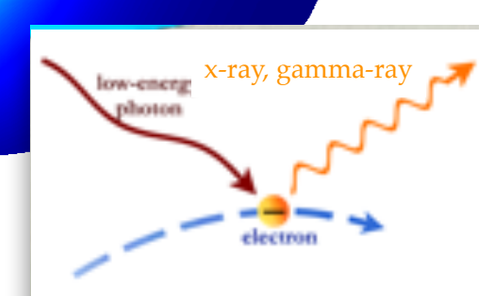
π^0 decay



bremsstrahlung

+

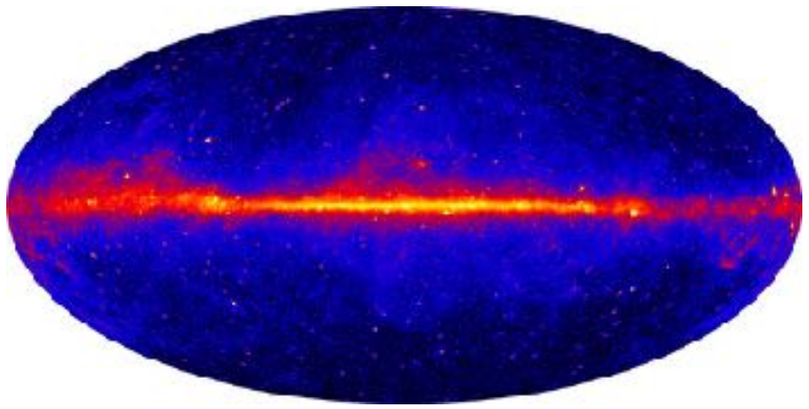




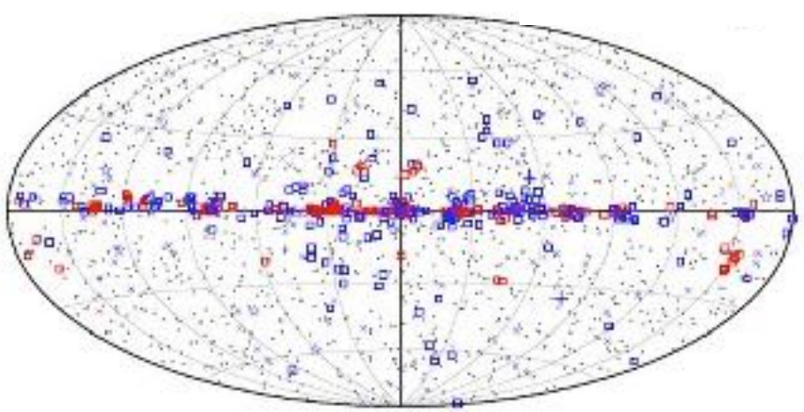
inverse Compton

The Fermi sky

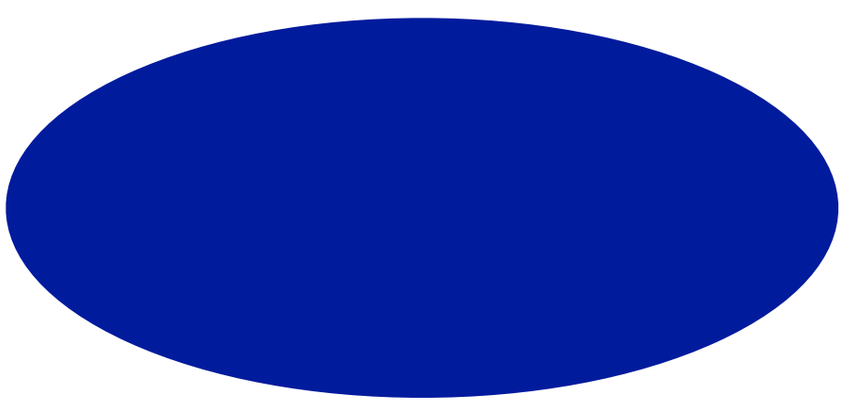
Diffuse emission from our Galaxy



Point sources



Isotropic emission



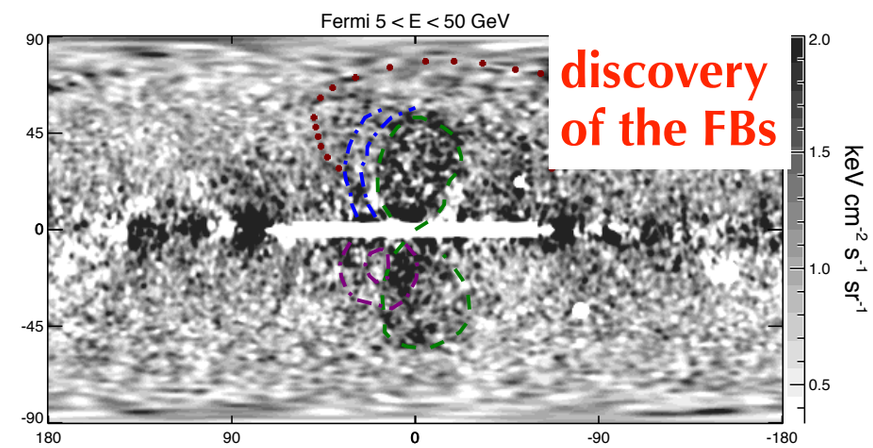
The Fermi bubbles

8 kpc tall structures entered at the Galactic Centre

revealed after subtraction of the diffuse emission

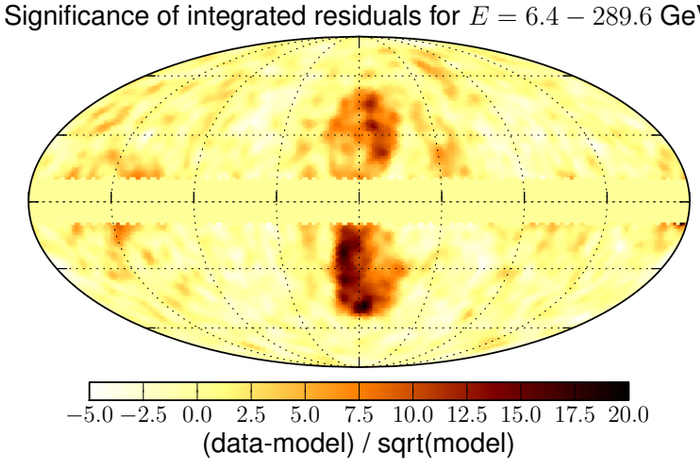
apparent uniform brightness

hard power law spectrum



[Su+., ApJ, 2010, 1005.5480]

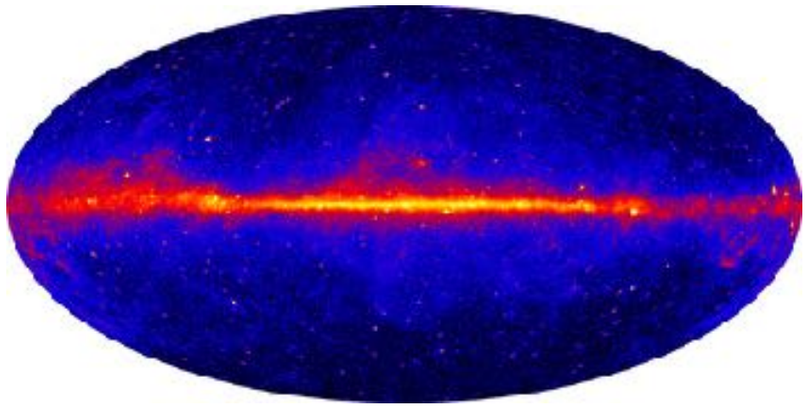
Significance of integrated residuals for $E = 6.4 - 289.6$ GeV



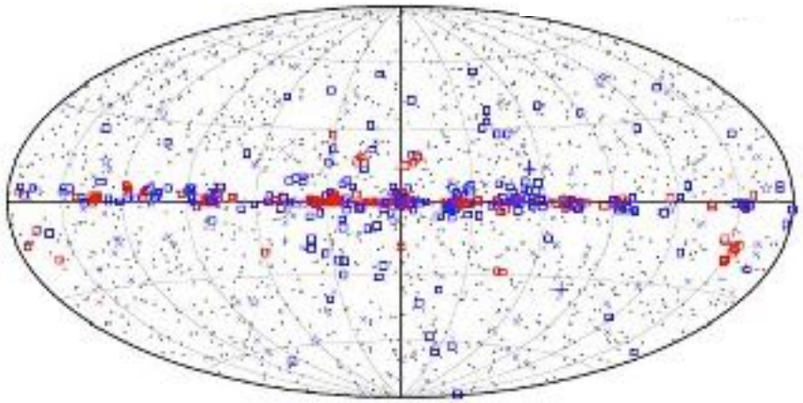
[Fermi LAT coll., ApJ, 2014,1407.7905]

The Fermi sky

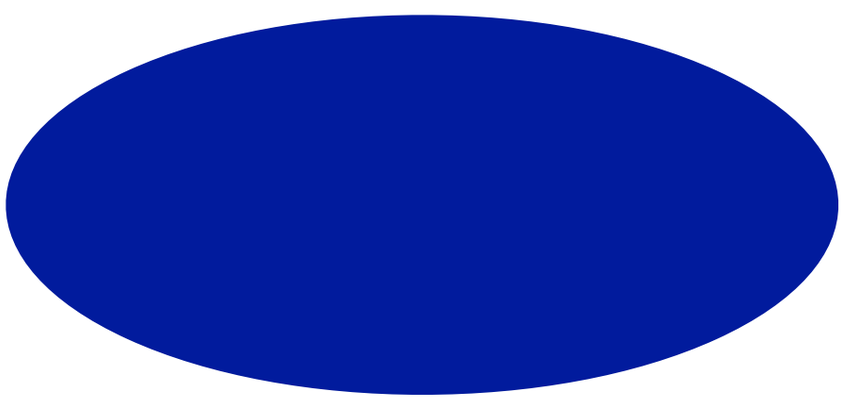
Diffuse emission from our Galaxy

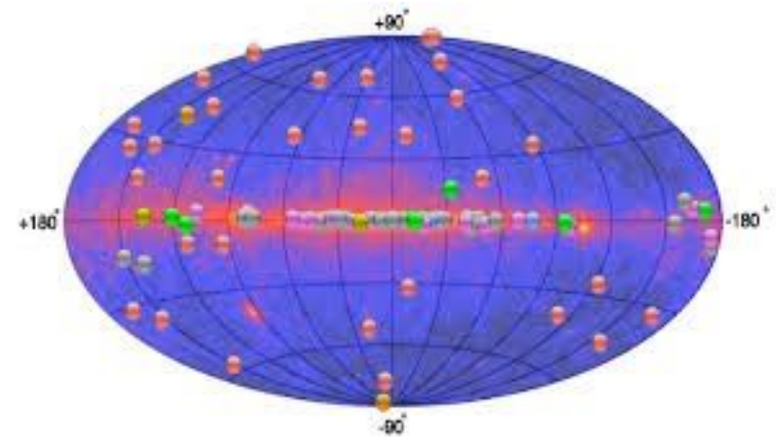


Point sources



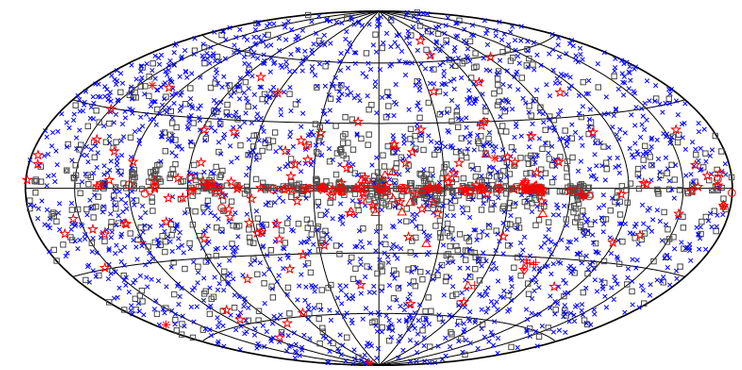
Isotropic emission



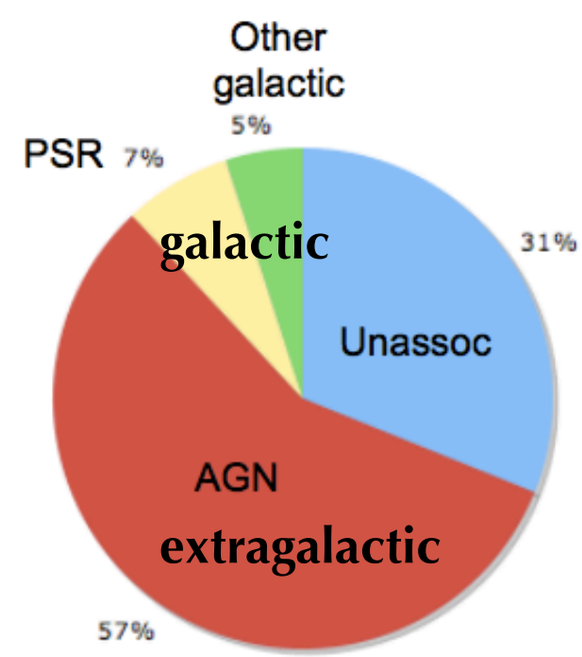


High-energy (ground-based observations)

Fermi catalog 3000 sources!

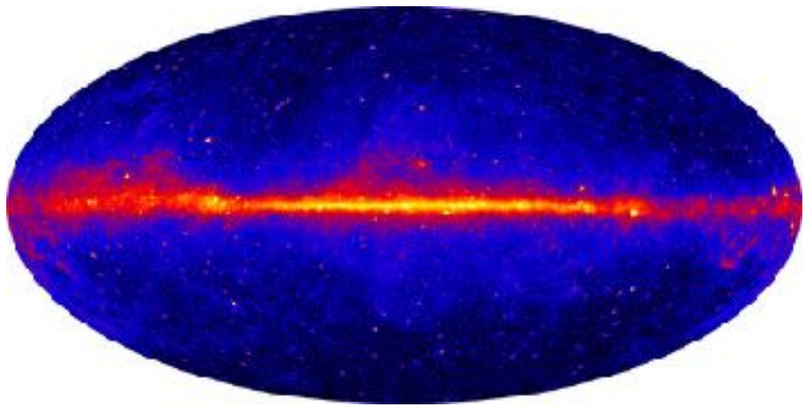


3FGL [Fermi LAT coll. 1501.02003]

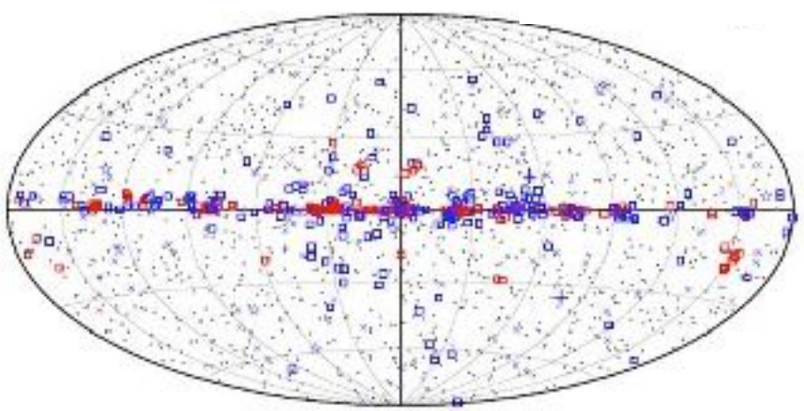


The Fermi sky

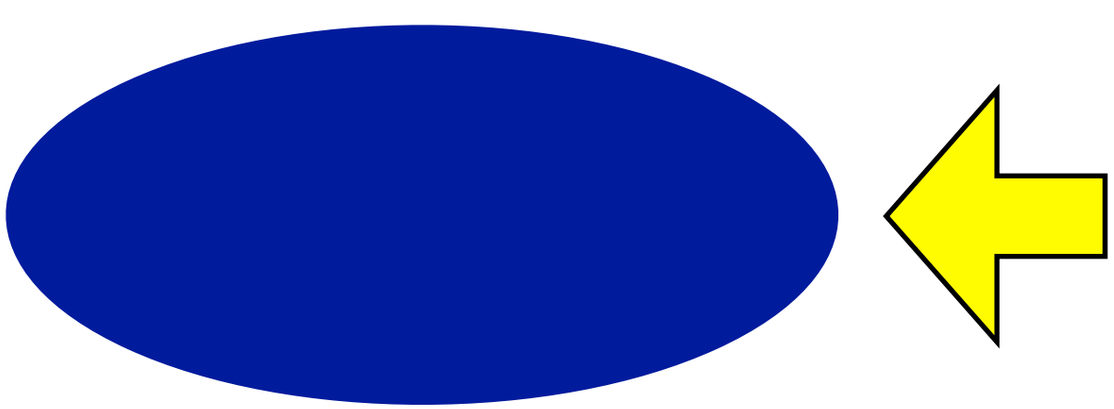
Diffuse emission from our Galaxy



Point sources

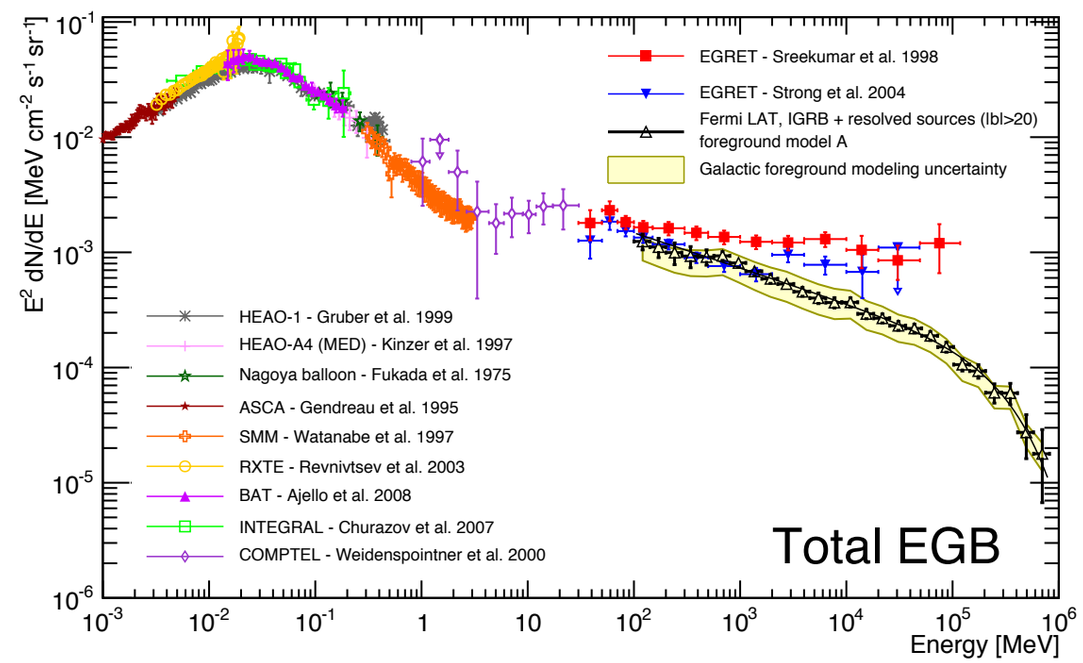


Isotropic emission



dominates at high latitudes

origin not yet fully understood

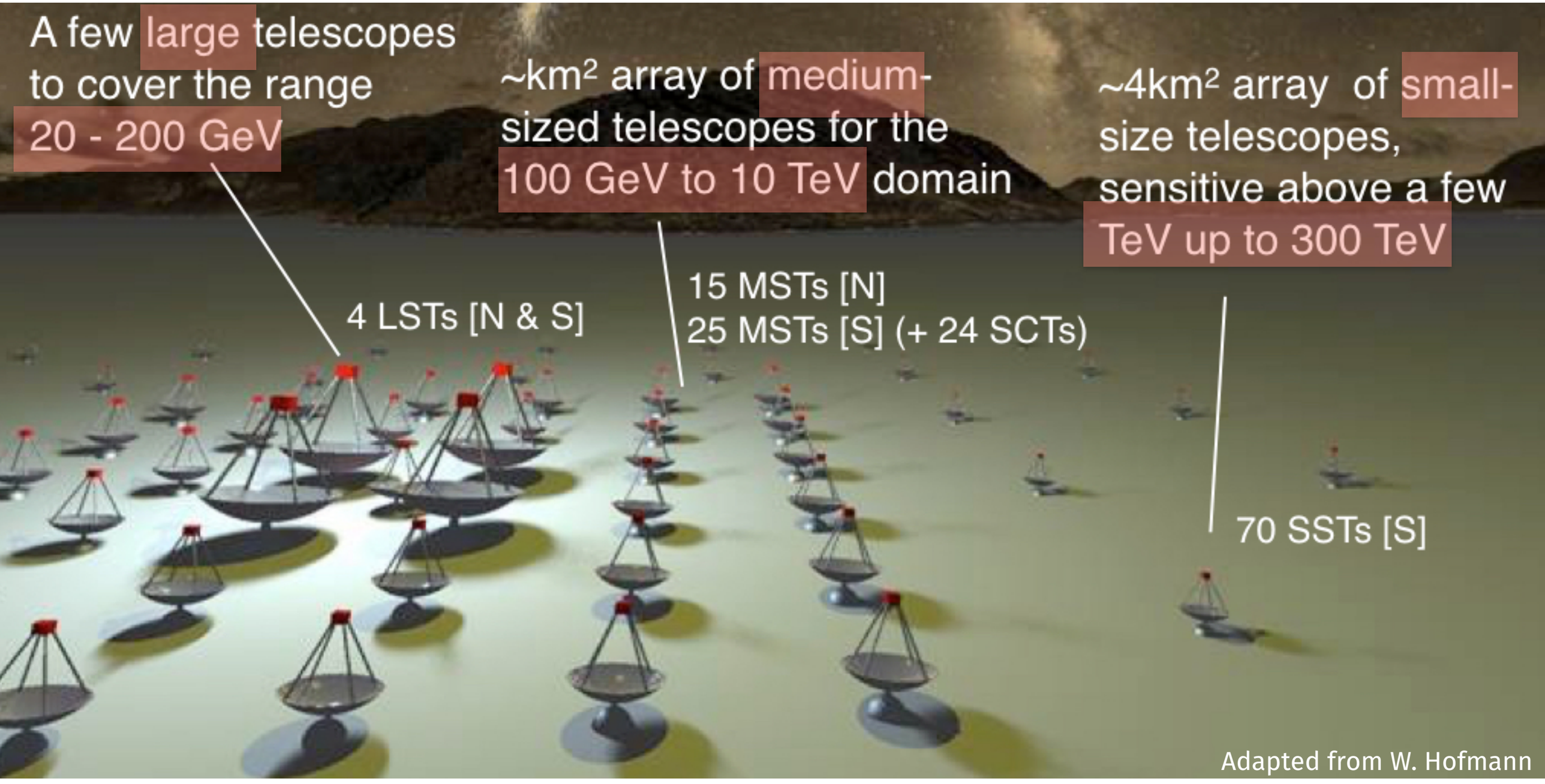


guaranteed contribution: faint (not individually resolved) extragalactic sources

[Ackermann+, ApJ799, 2015)]

CTA - Cherenkov Telescope Array

Three types of telescopes:



Adapted from W. Hofmann