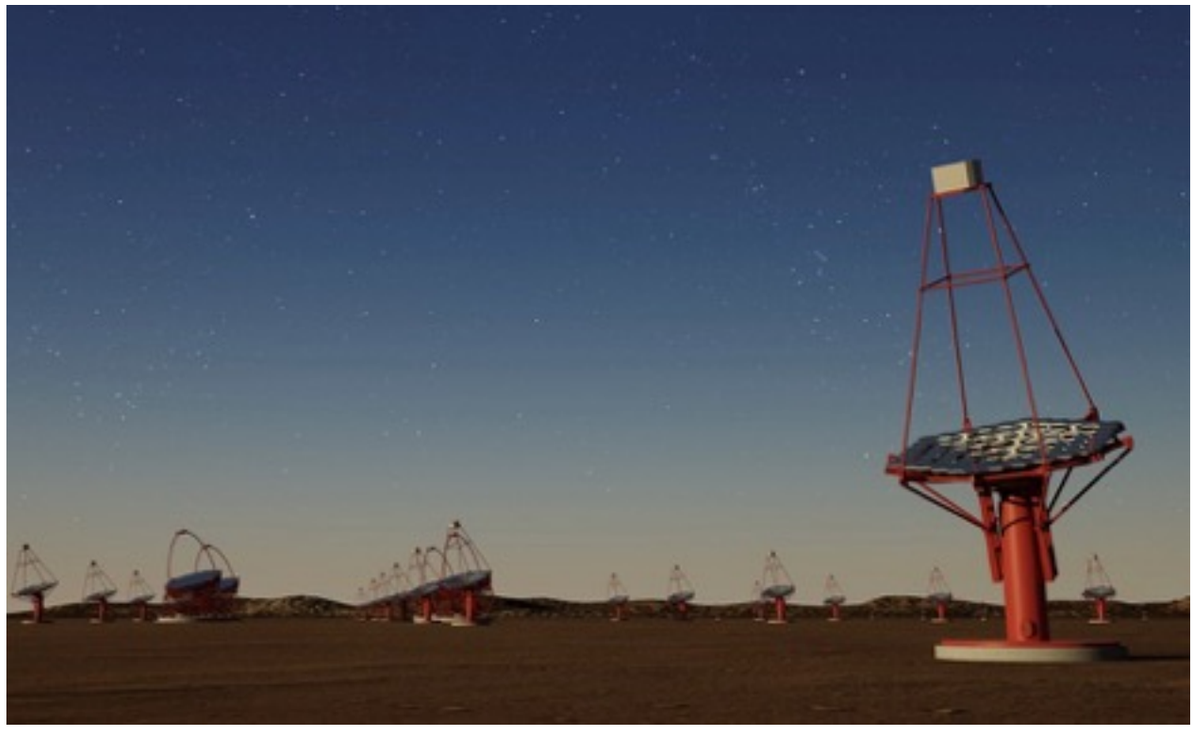
Everything you always wanted to know on … dark matter with gamma rays

(status of the Fermi LAT searches and prospects for the CTA)



Gabrijela Zaharijas

University of Nova Gorica, Slovenia

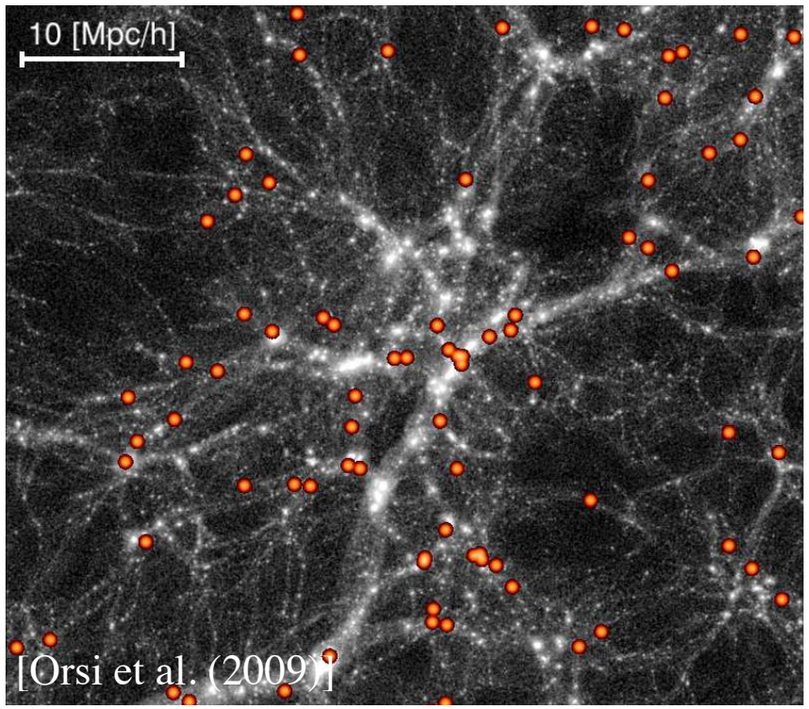
on behalf of the Fermi LAT Collaboration and the CTA consortium

Dark matter is out there!

an essential building block of the Standard Model of Cosmology

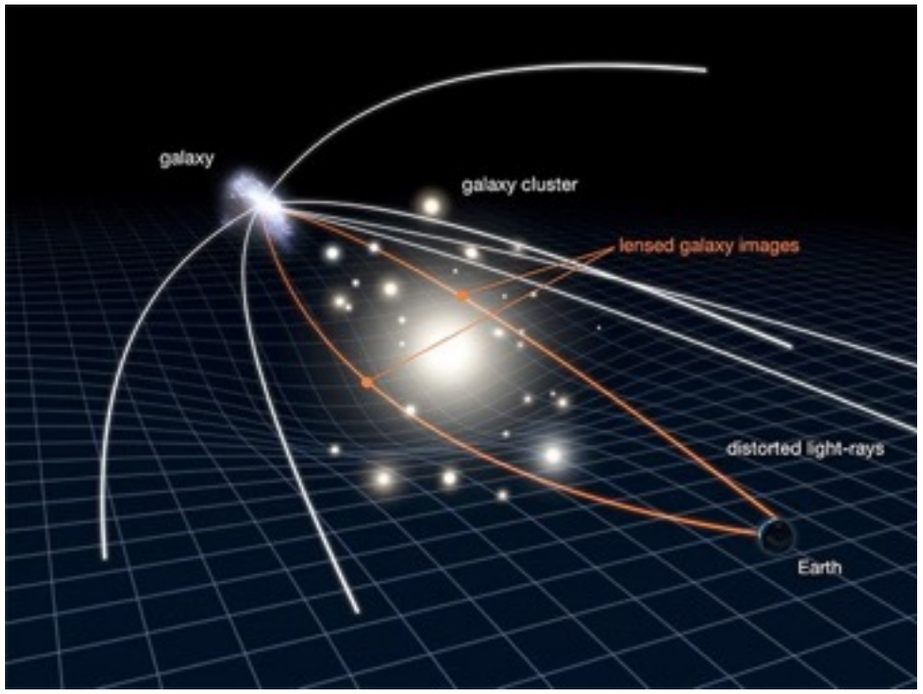
D. Clowe's talk

large scale structures



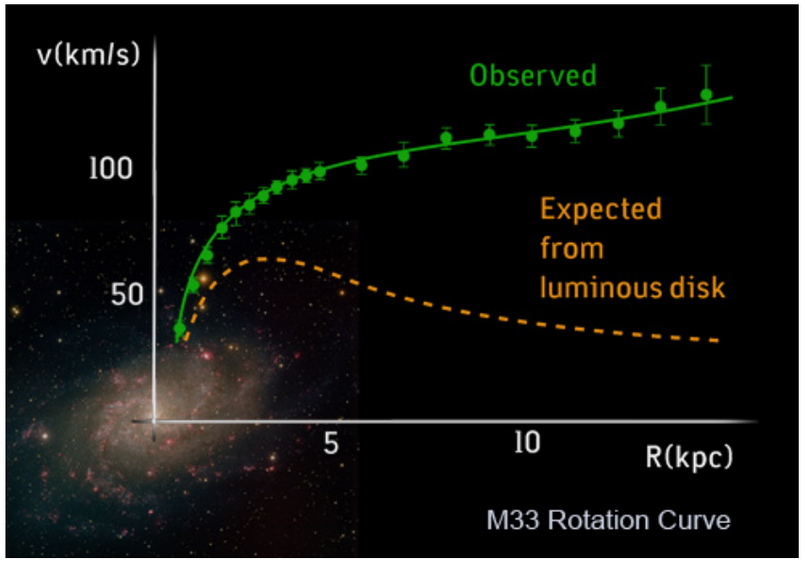
10s Mpc

clusters of galaxies



Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies

<~ kpc

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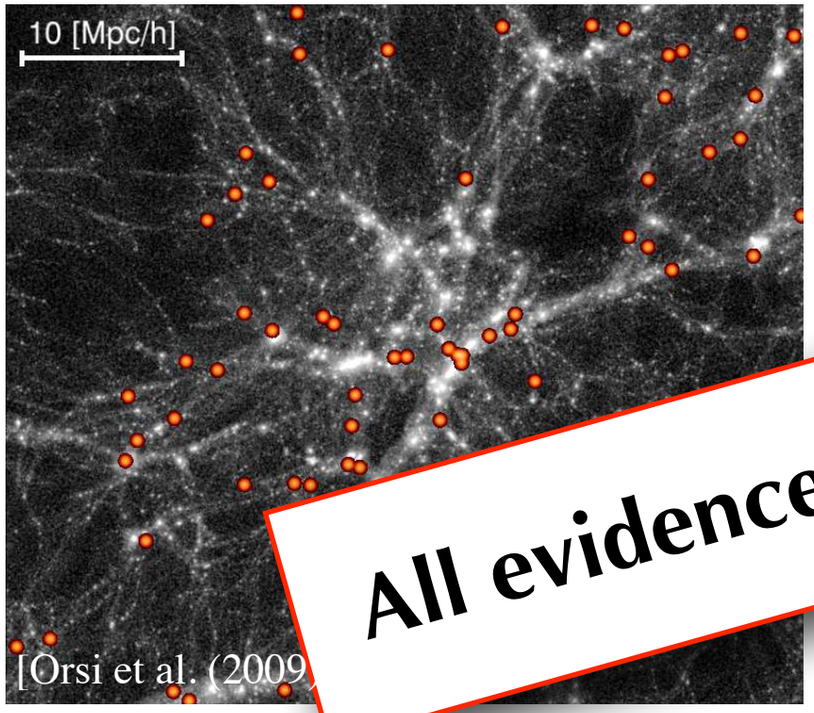
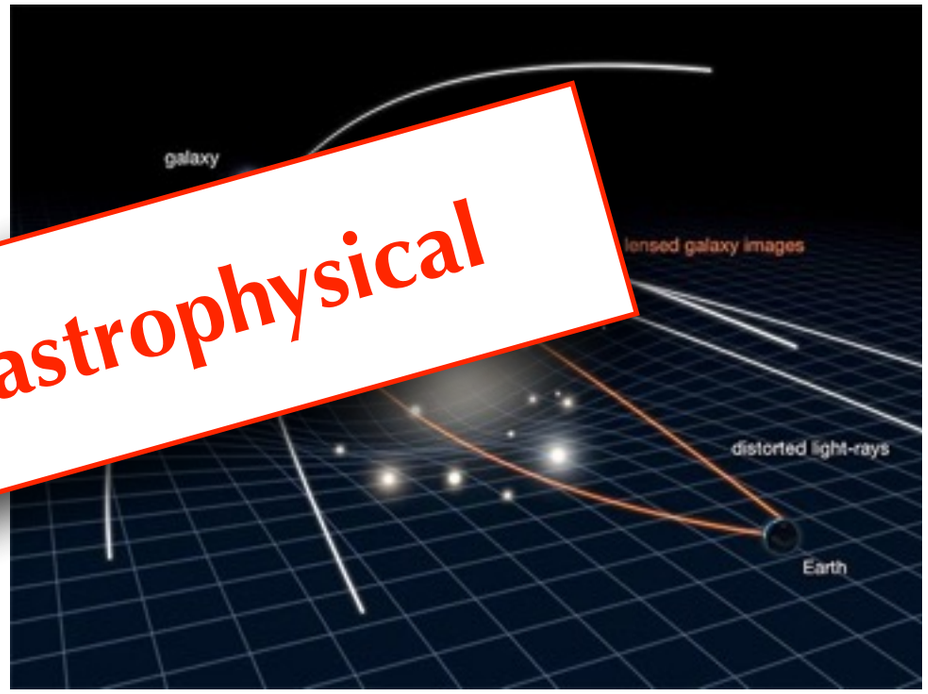


clusters of galaxies

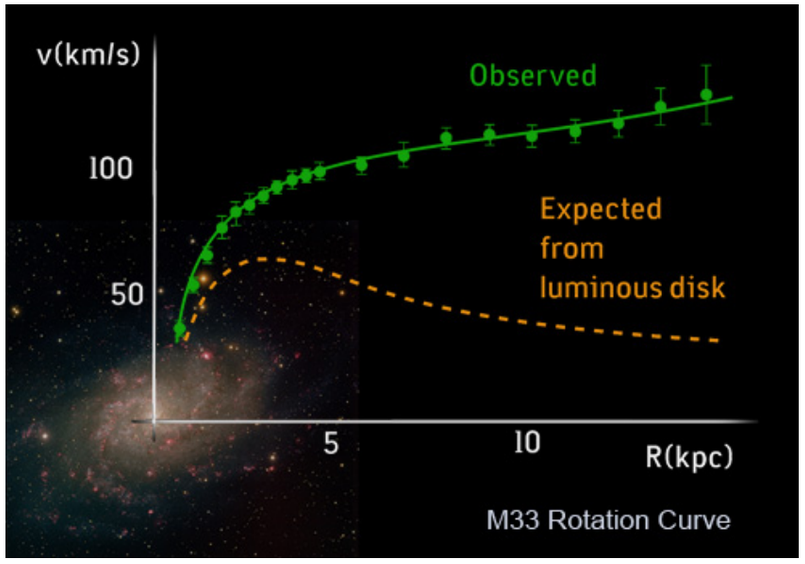
Mpc



All evidence so far is astrophysical

Milky Way-sized galaxies

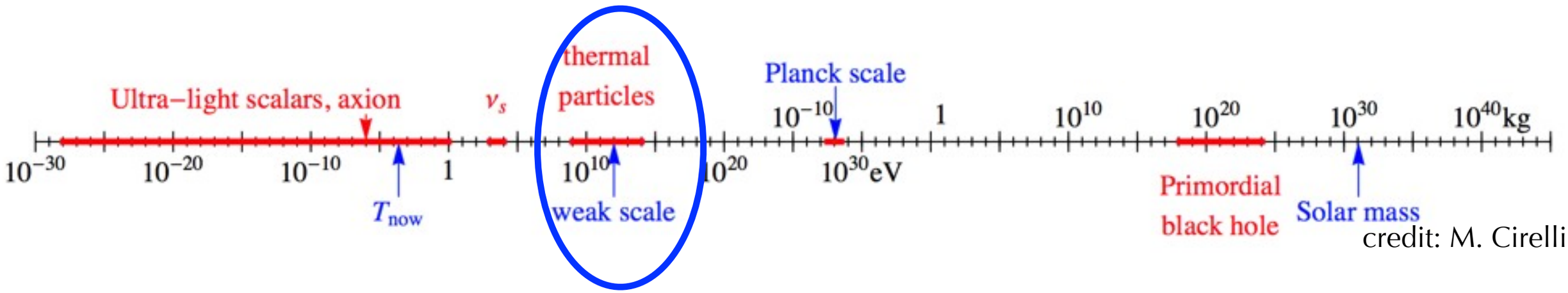
10s kpc



dwarf galaxies

<~ kpc

Focus on WIMPs



credit: M. Cirelli

weak-scale mass (~M_Z) + weak interactions (~G_F)

→ cold

→ many candidates in theories which attempt to explain the origin of EW mass

→ predictive!

Dark Matter Abundance from Thermal Production

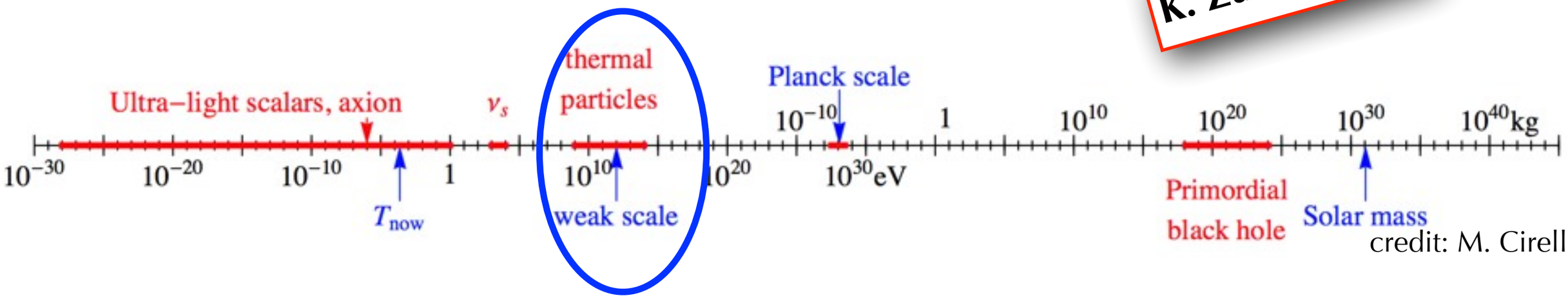
$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

Cosmological Measurement

Weak Scale Physics

Focus on WIMPs

K. Zurek's talk



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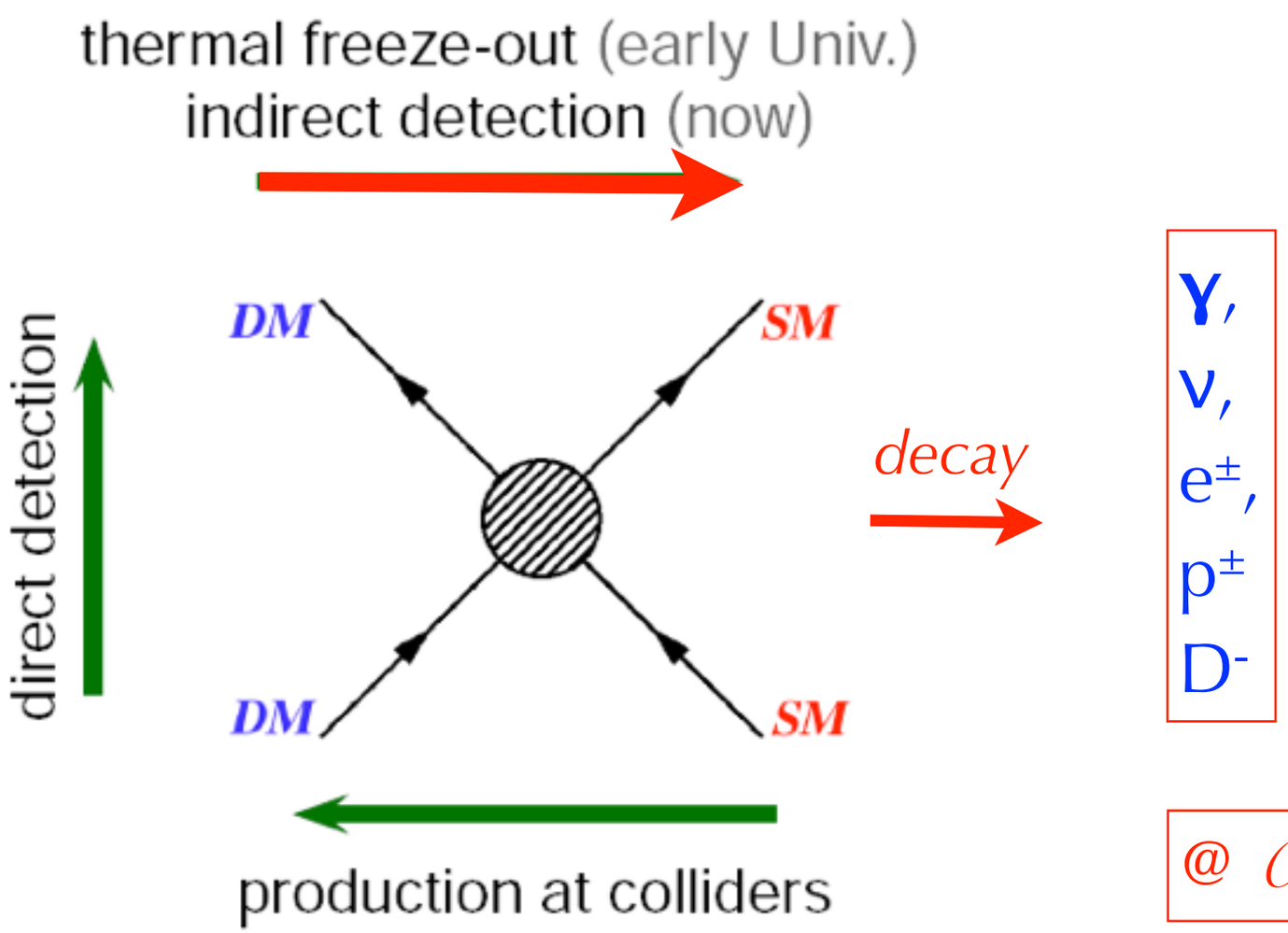
Cosmological Measurement

Weak Scale Physics

postmodern view *"Like all tyrannies, there is a single yoke of control: the one thing we know about WIMPs is their relic abundance. We've lived with this tyranny for a long time. It's provided all of us with jobs... and some of us with tenure."*
– Neal Weiner, **on the 'tyranny' of the WIMP Miracle paradigm** *(F. Tanedo, DMNotes)*

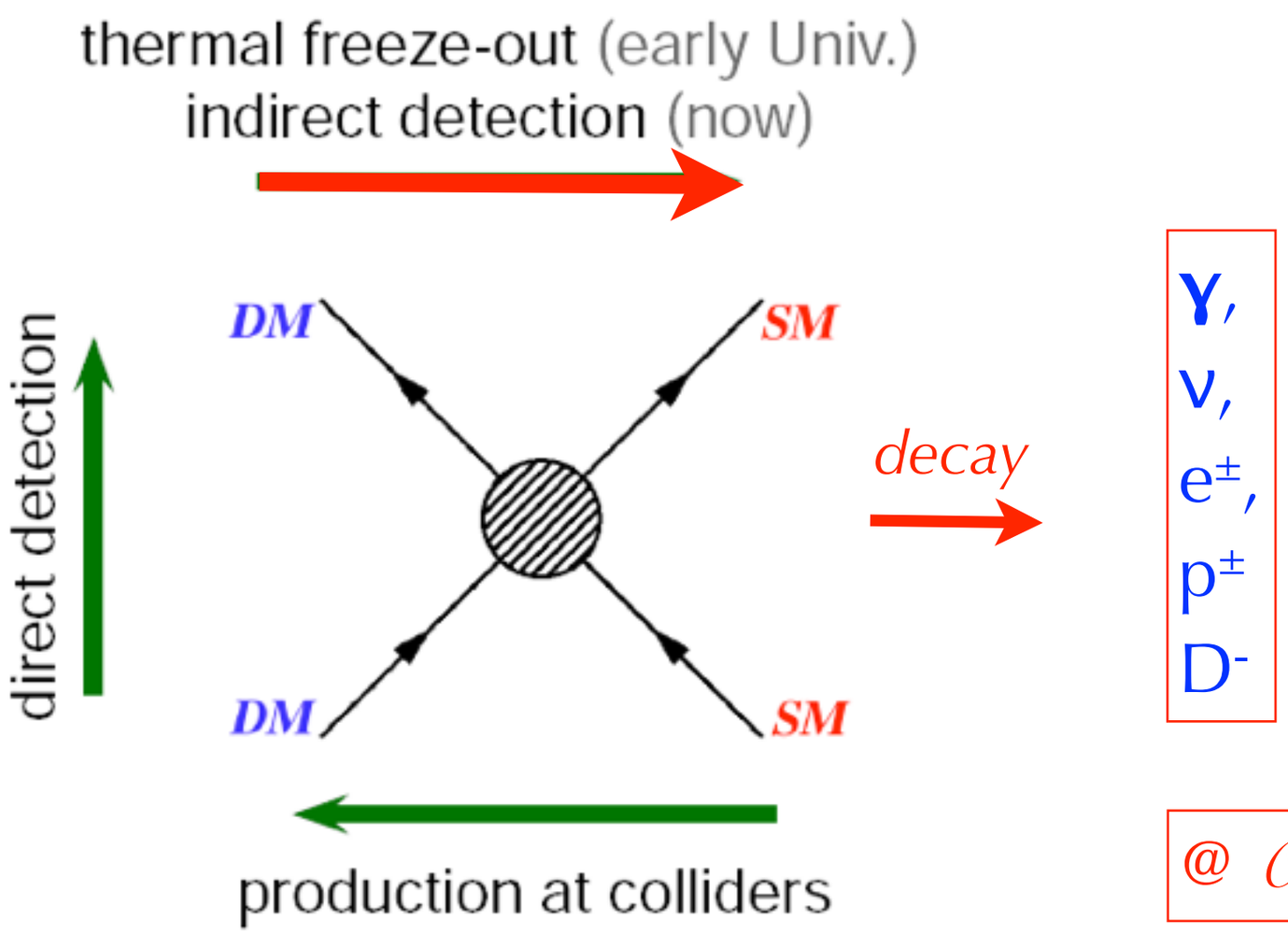


In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its* **density is enhanced**!

@ $\mathcal{O}(M_Z)$

in astrophysical systems - *remotely*



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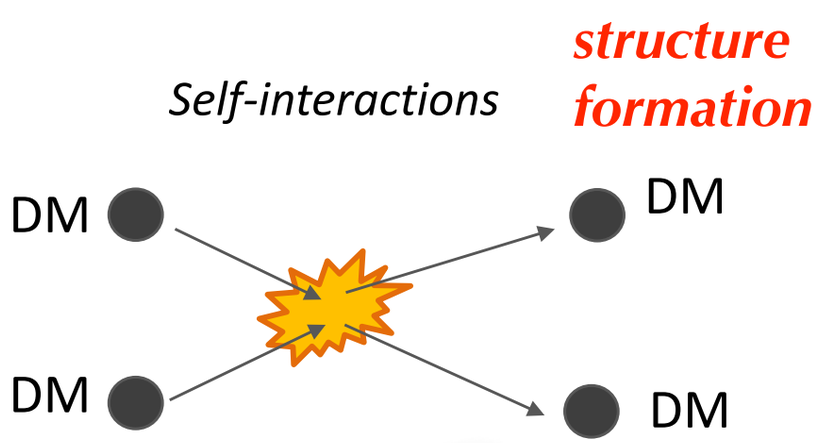


Credit: S. Tulin

J. Zavala's talk

in astrophysical systems - *remotely*

the DM signal:

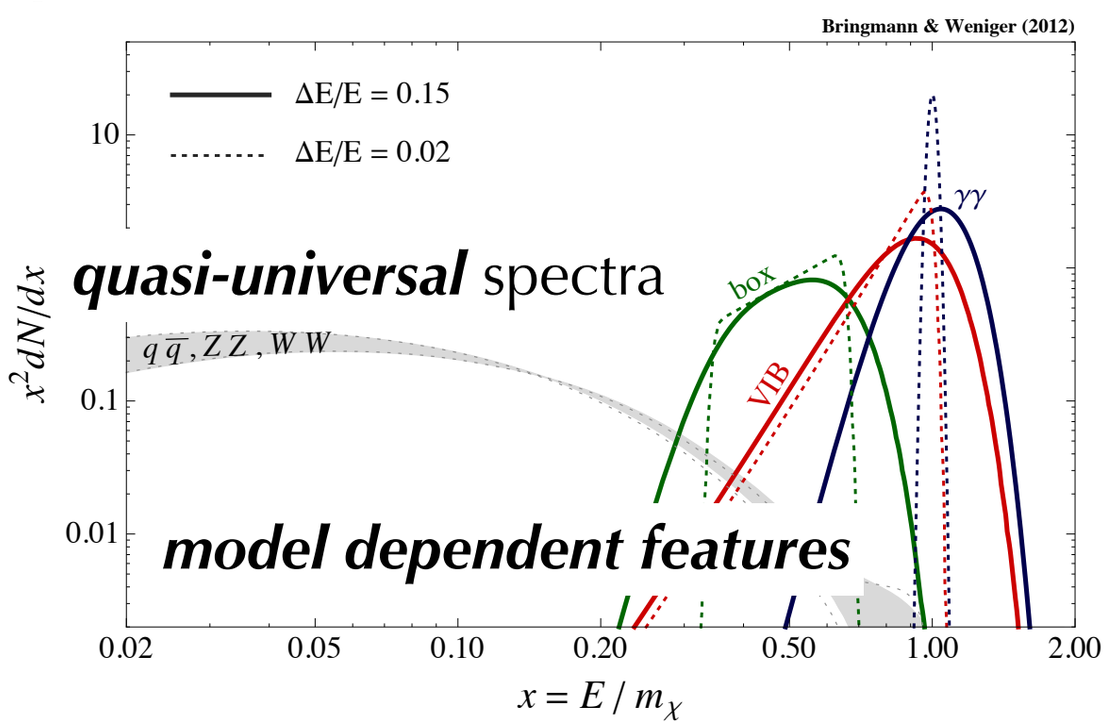
particle physics — cosmology

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

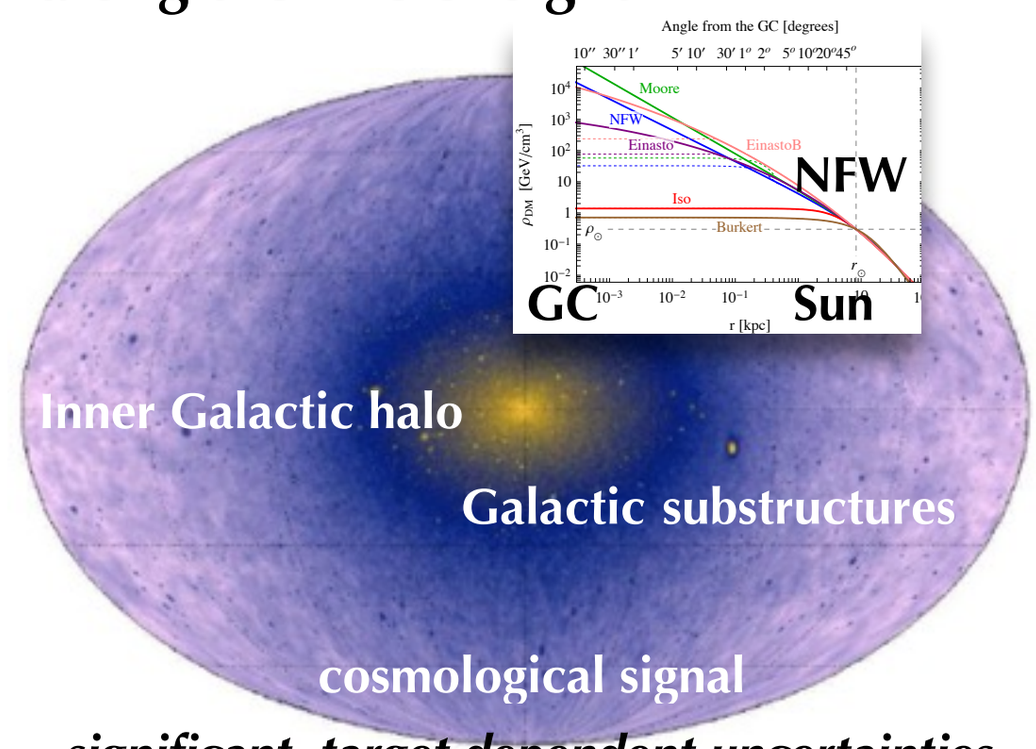
P. Serpico's talk

this is what we are after!

flux of SM particles per DM annihilation



integrated DM density squared along the line of sight



significant, target dependent uncertainties

the DM signal:

particle physics — cosmology

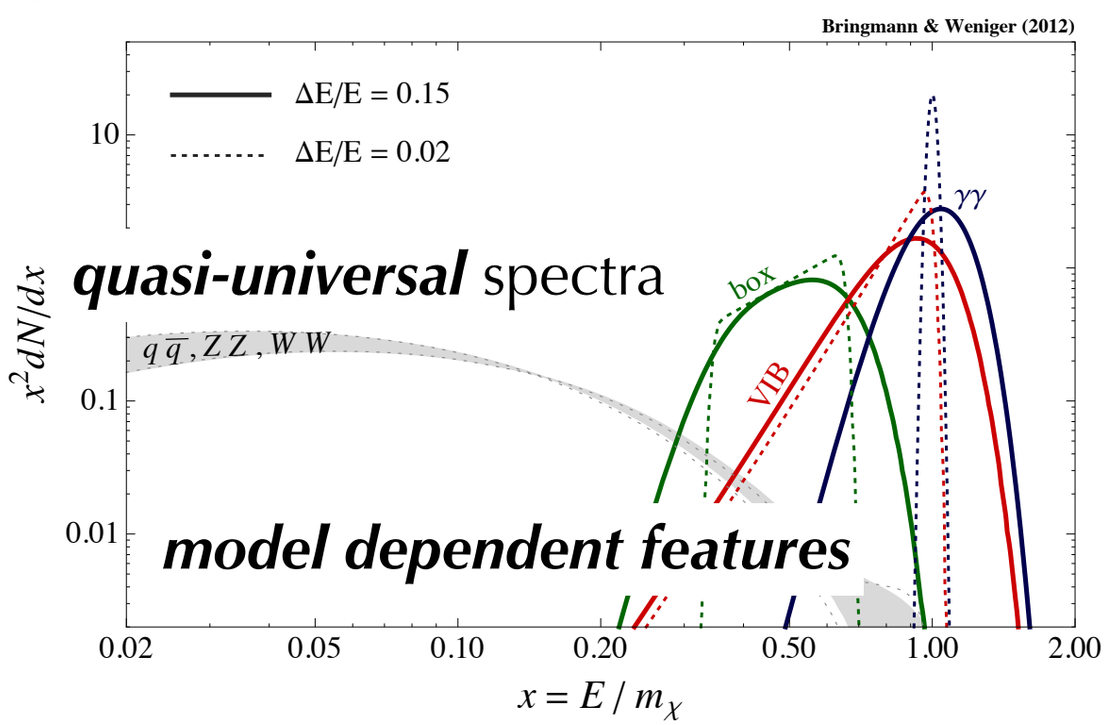
$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2} \times \sum_i {\rm BR}_i \frac{dN_\gamma^i}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)$$

P. Serpico's talk

this is what we are after!

genuinely multi-disciplinary field!

flux of SM particles per DM annihilation



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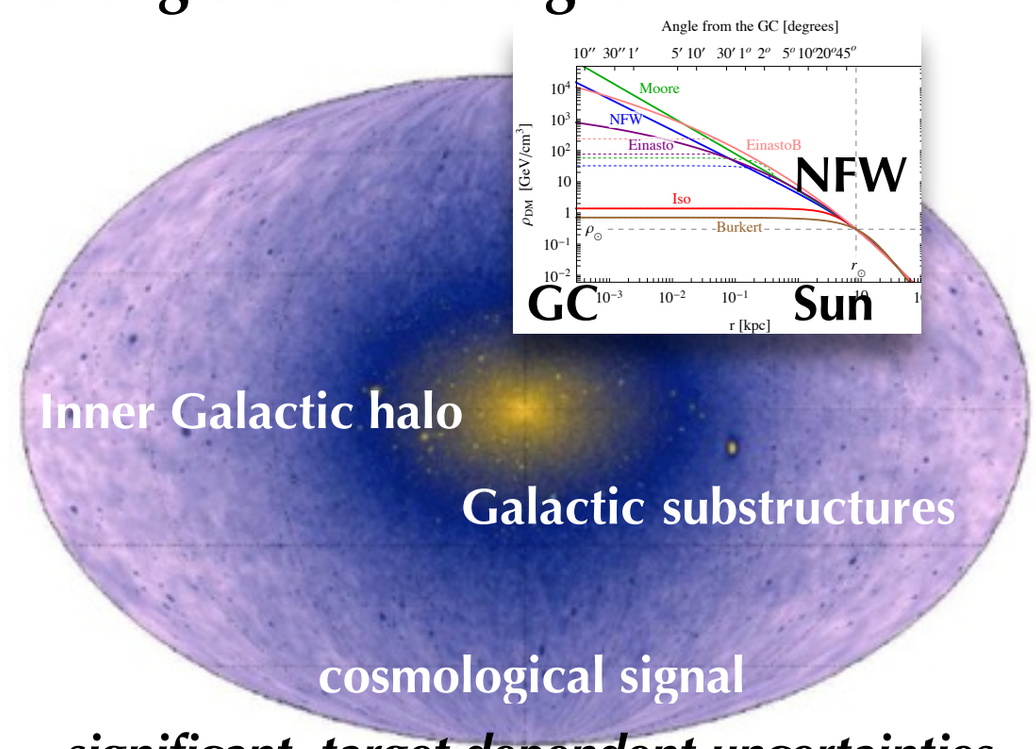
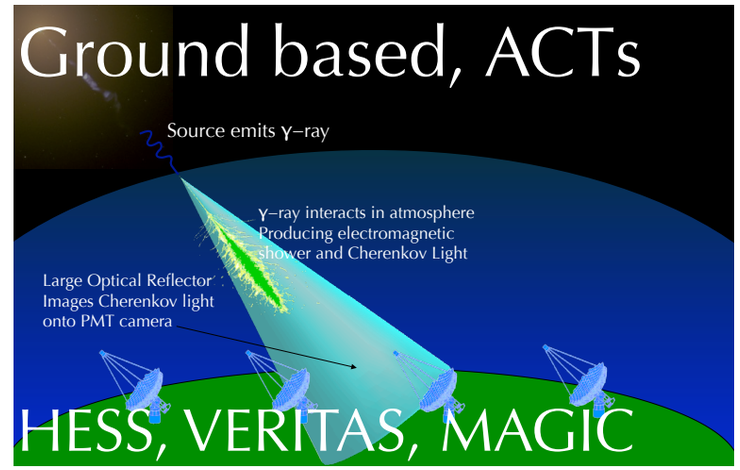
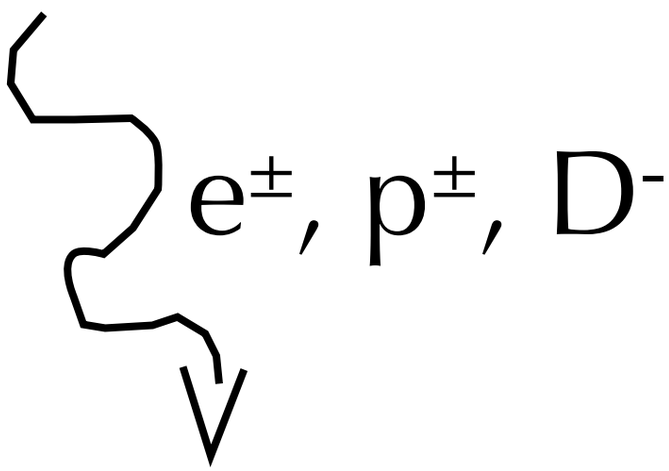


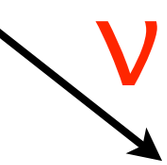
significant, target dependent uncertainties

and now we have powerful tools

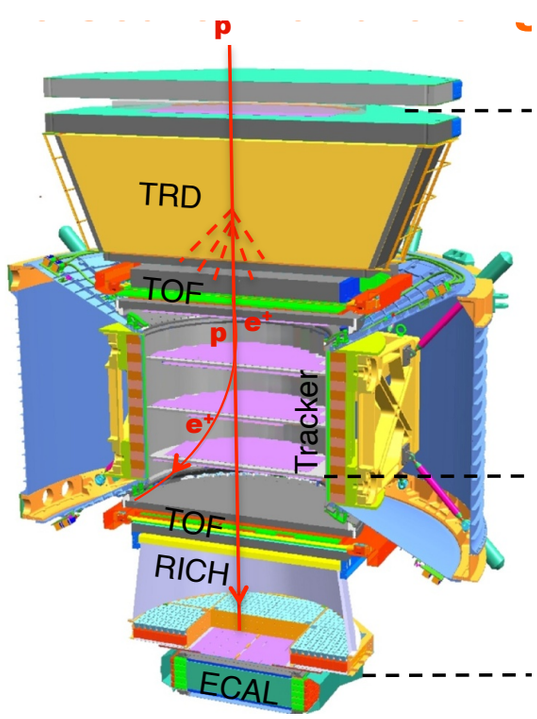
@ $\mathcal{O}(M_Z)$

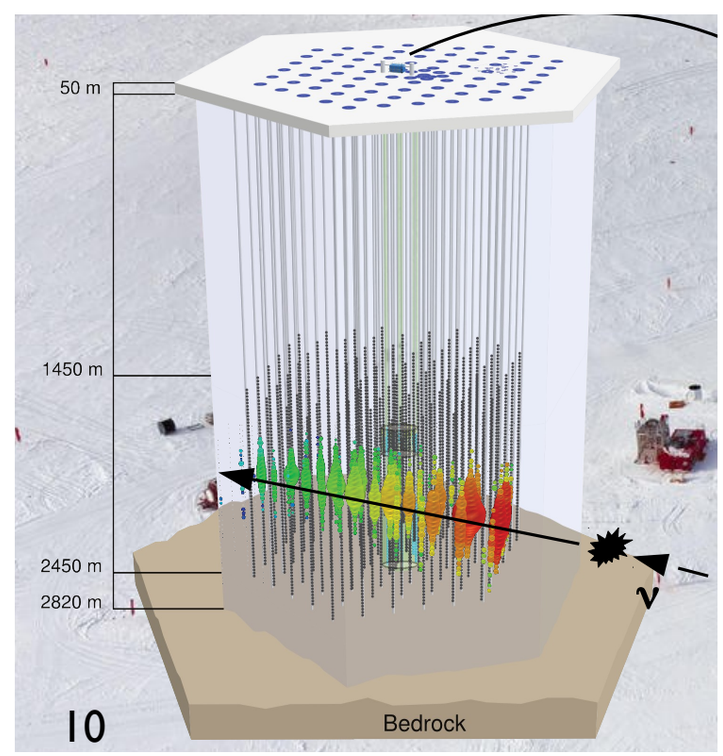






PAMELA, AMS02



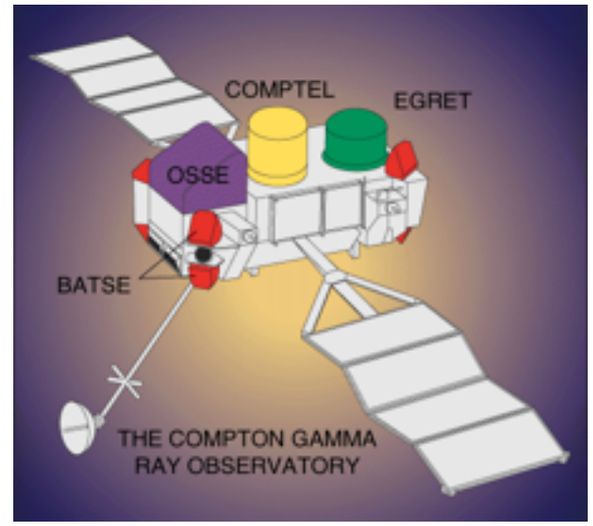


Ice Cube, ANTARES

Gamma rays

atmosphere is not transparent to gamma rays → ***satellites***

EGRET ***1991-2001***



Fermi LAT ***2008-***

(AGILE ***2007-)***

→ ***or ground based:***

i) Imaging Atmospheric Cherenkov Telescopes

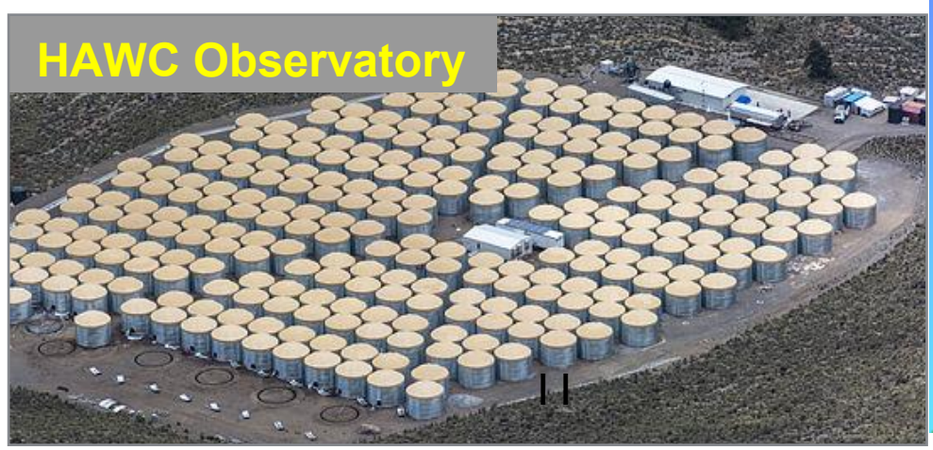
WHIPPLE 10m (1968-2013) - the beginning of gamma ray astronomy

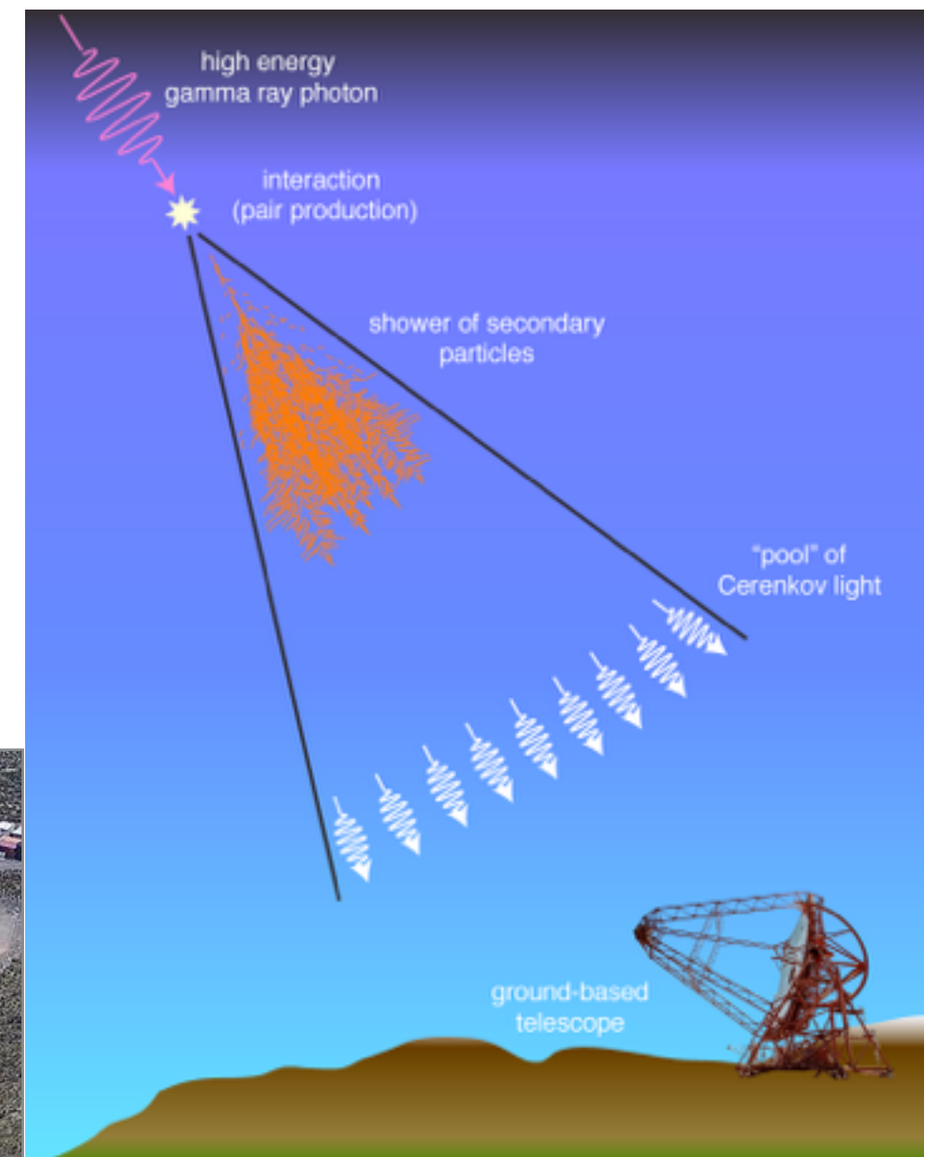
H.E.S.S. (2002 -), ***MAGIC*** (2004 -), ***VERITAS*** (2007 -)

ii) Air shower arrays ('with buckets of water')

MILAGRO (2001-2008)

HAWC (2010 -)

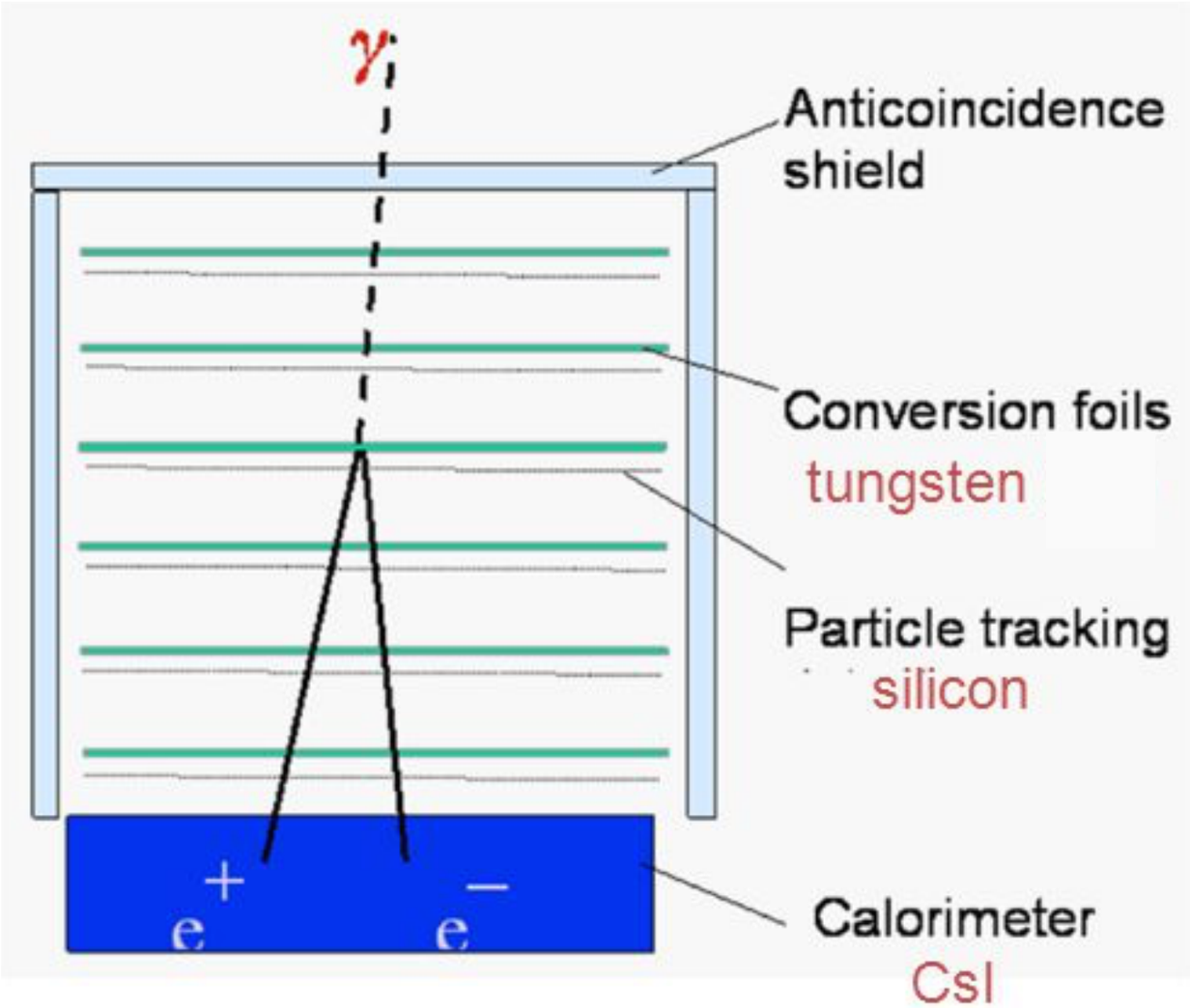


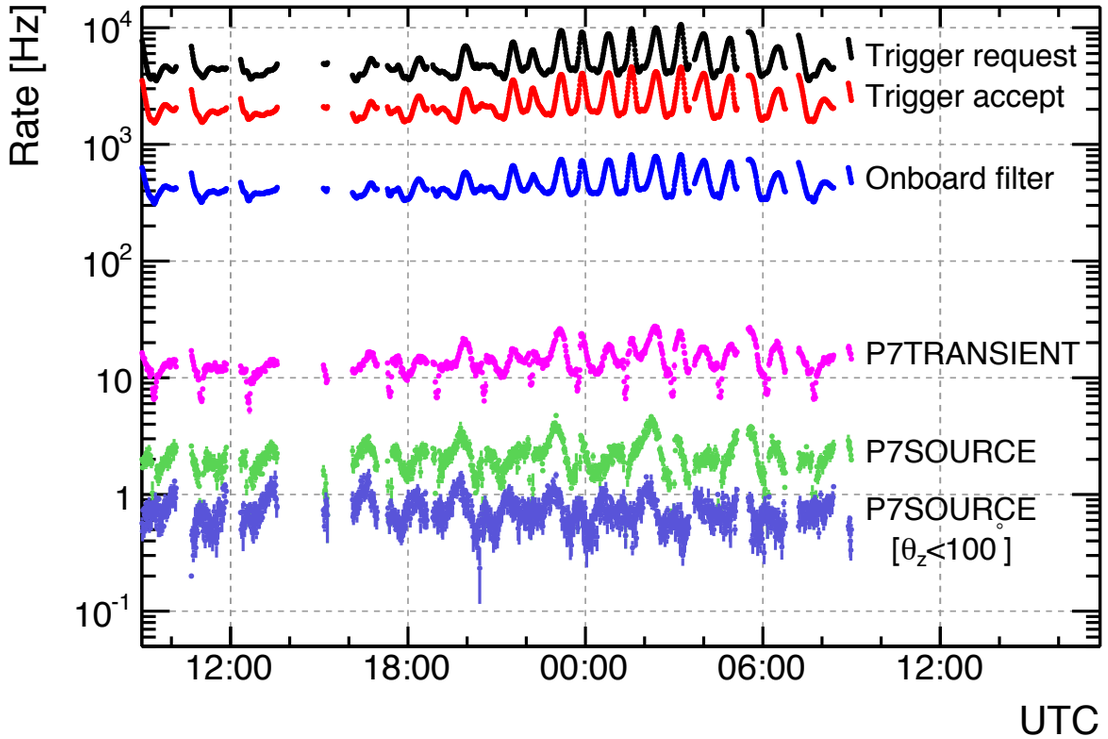


Fermi LAT

Launched 11 June 2008 - a ~month since its 8th birthday!

Data public within 24h and actively used by the community



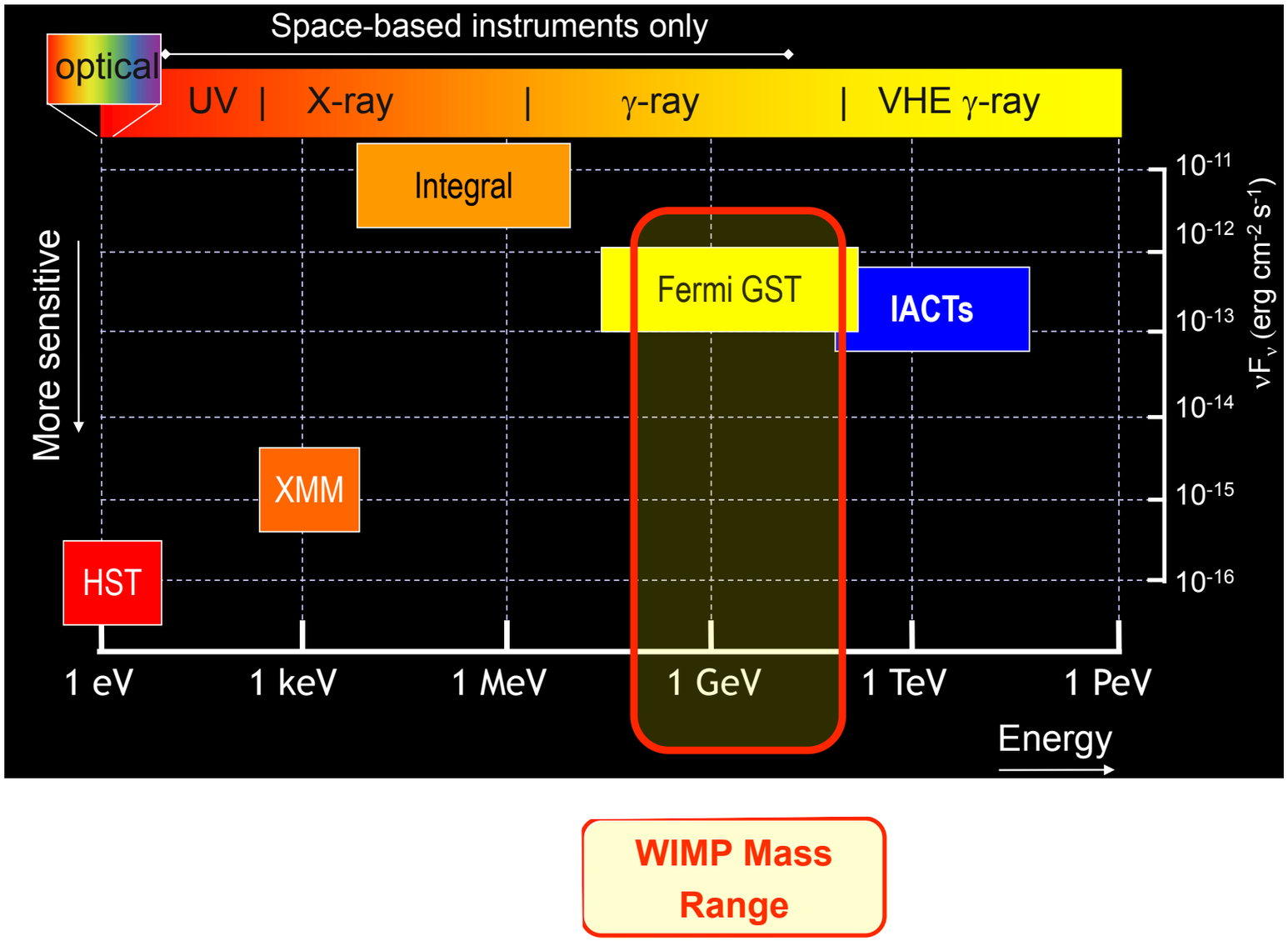


Challenge: flux of charged CRs is ~ thousand times larger than the γ-ray flux.

Fermi LAT

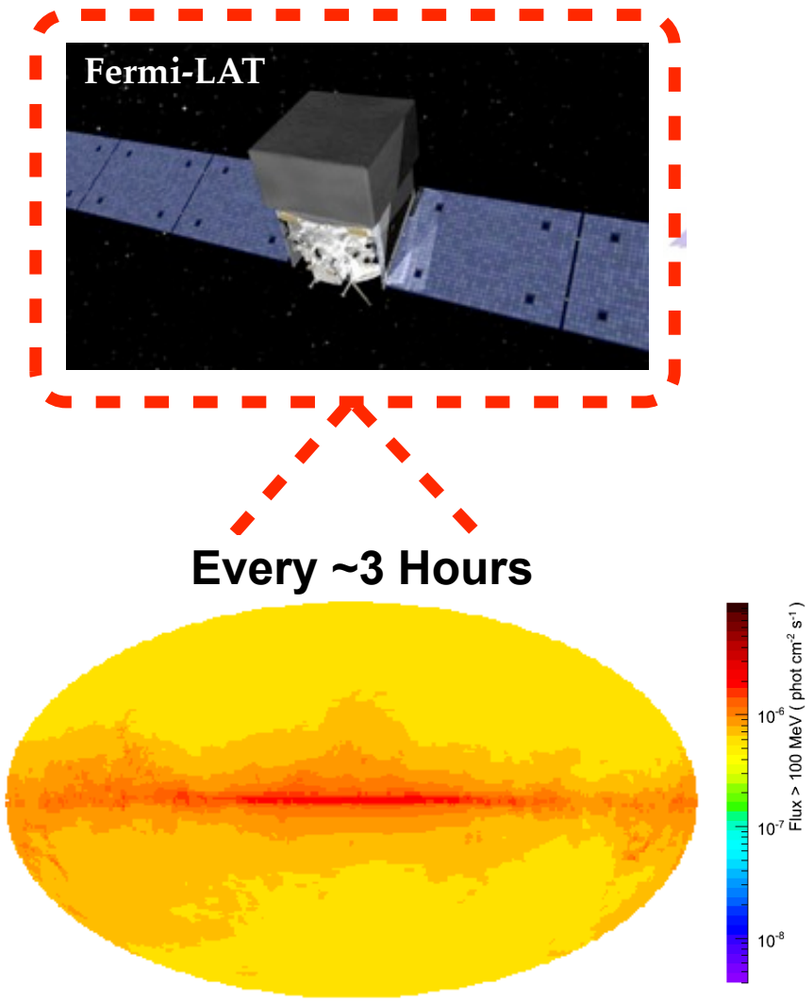
anticipated as a *'dark matter discovery tool'*

i) Energy range: 20 MeV to >300 GeV @ $\mathcal{O}(M_Z)$



ii) Large field of view:

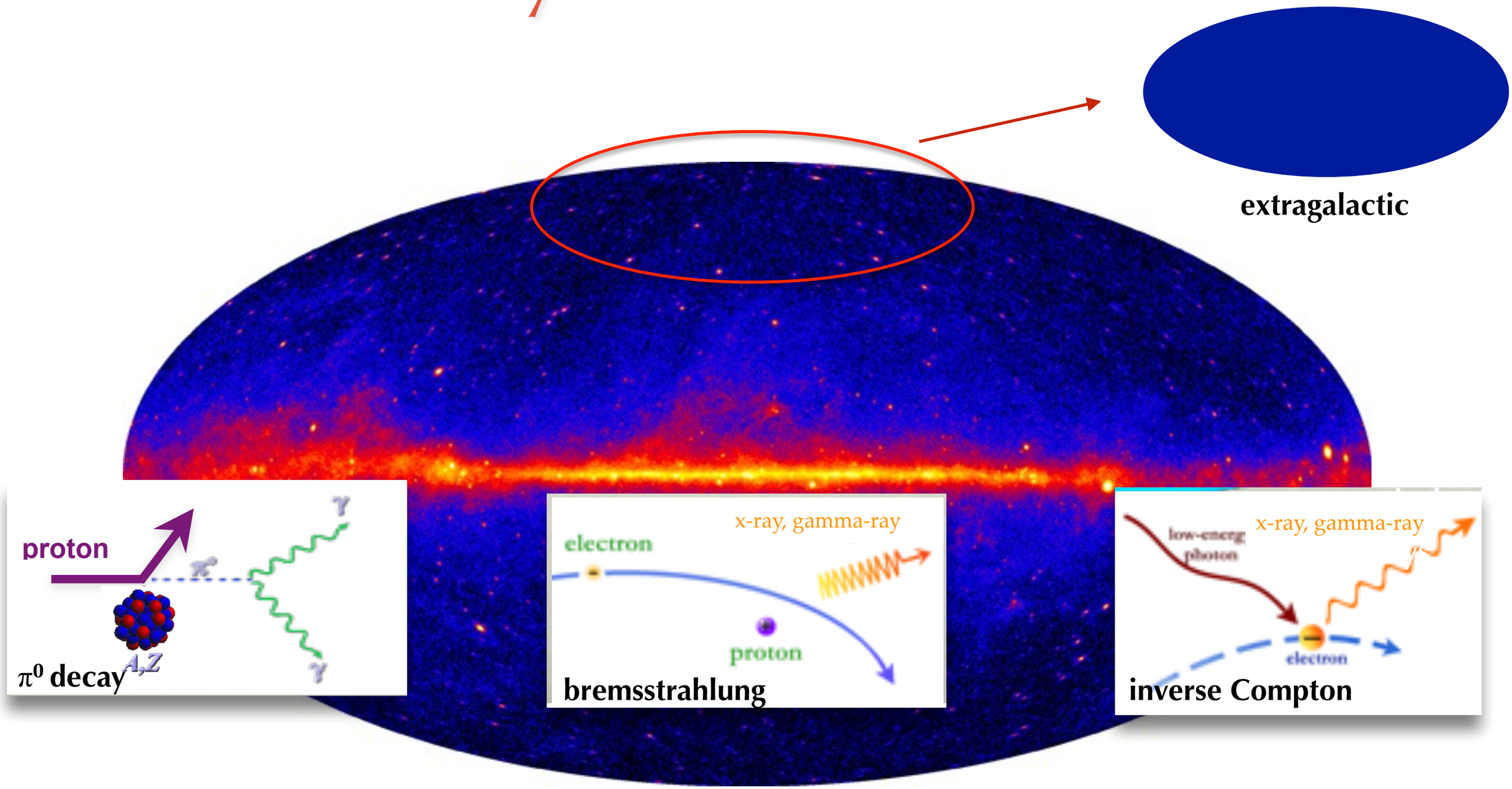
20% of the sky at any instant!



iii) Limited charged CR contamination:

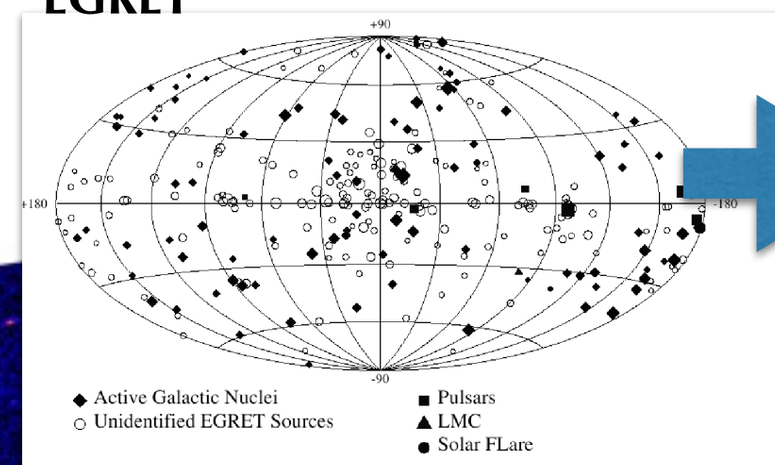
(anti-coincidence detector) — good for measuring extended signals!

The Fermi sky

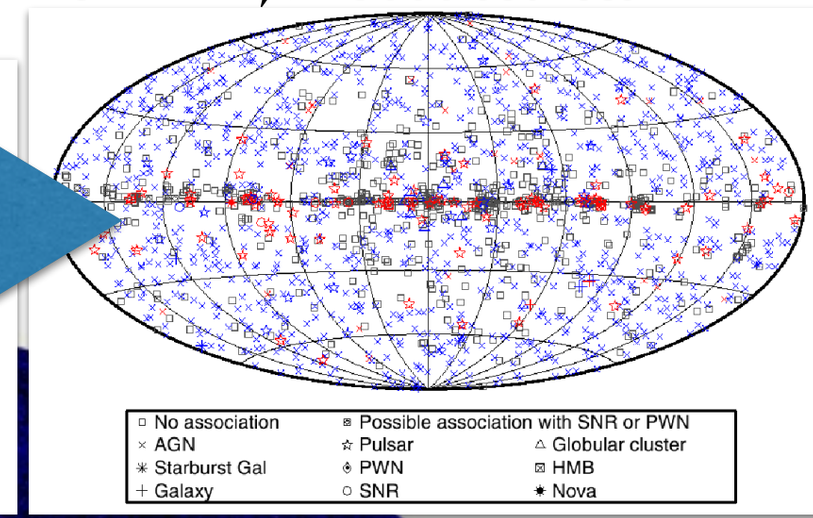


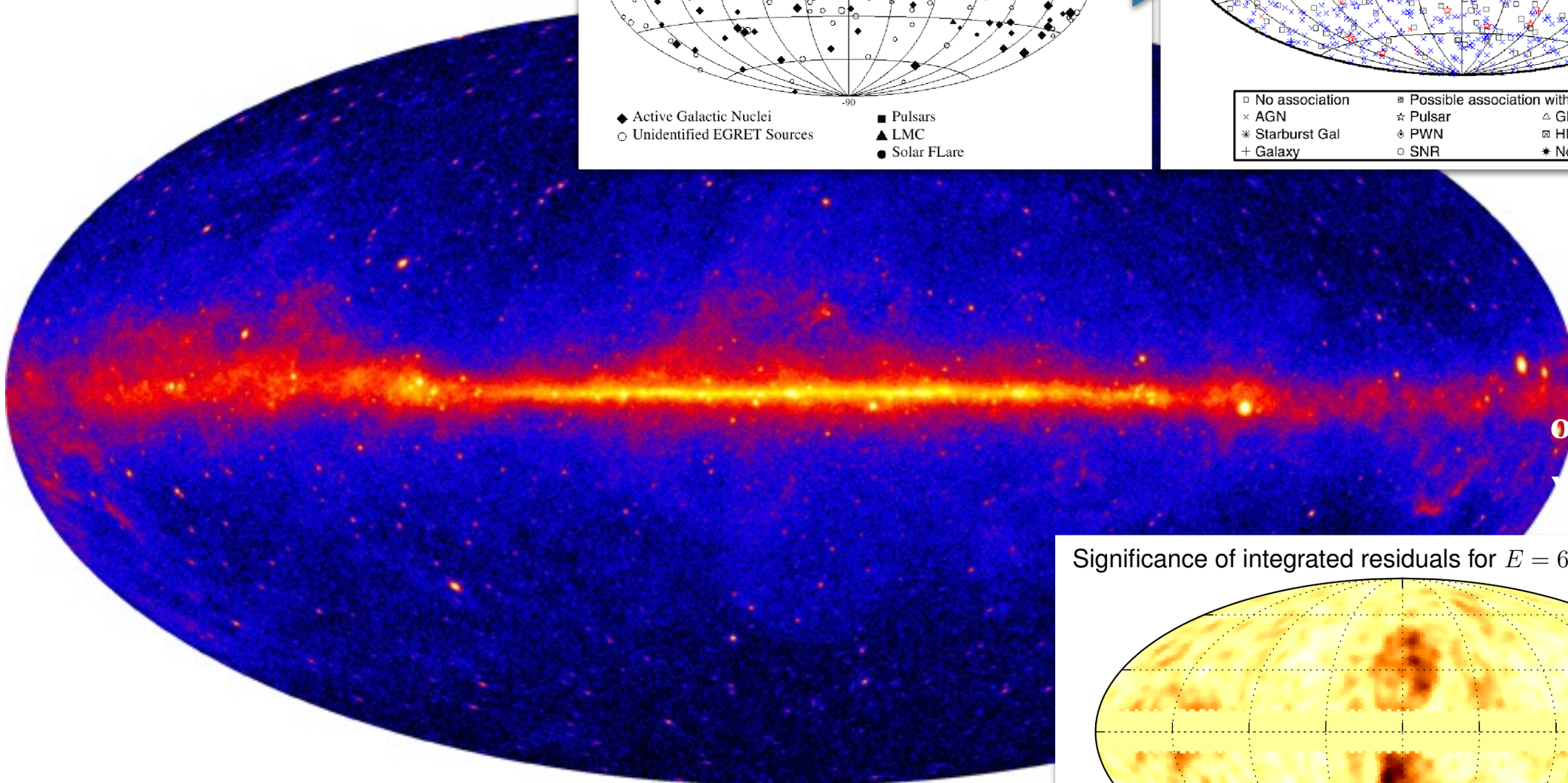
The Fermi sky

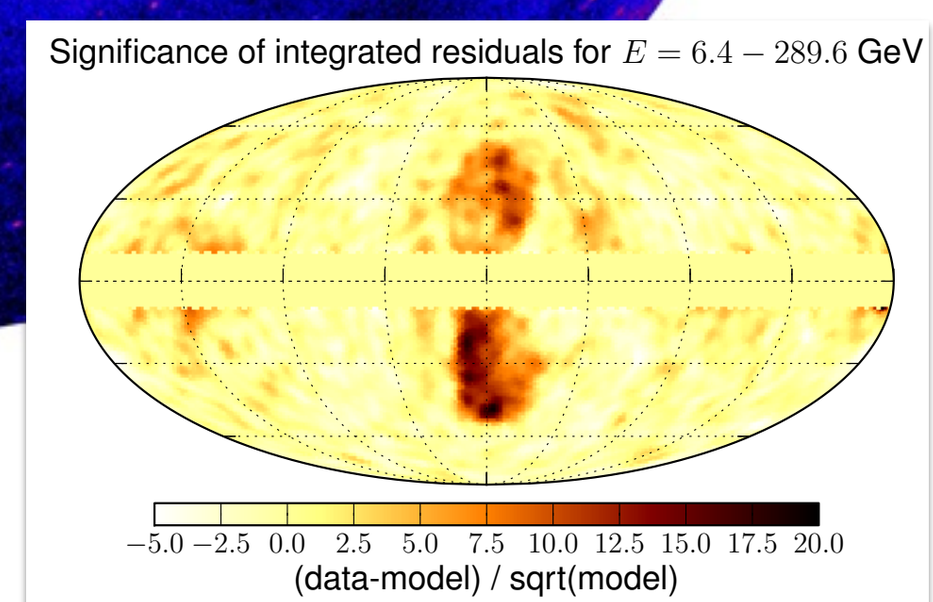
point sources
EGRET



Fermi LAT, >~3000 sources



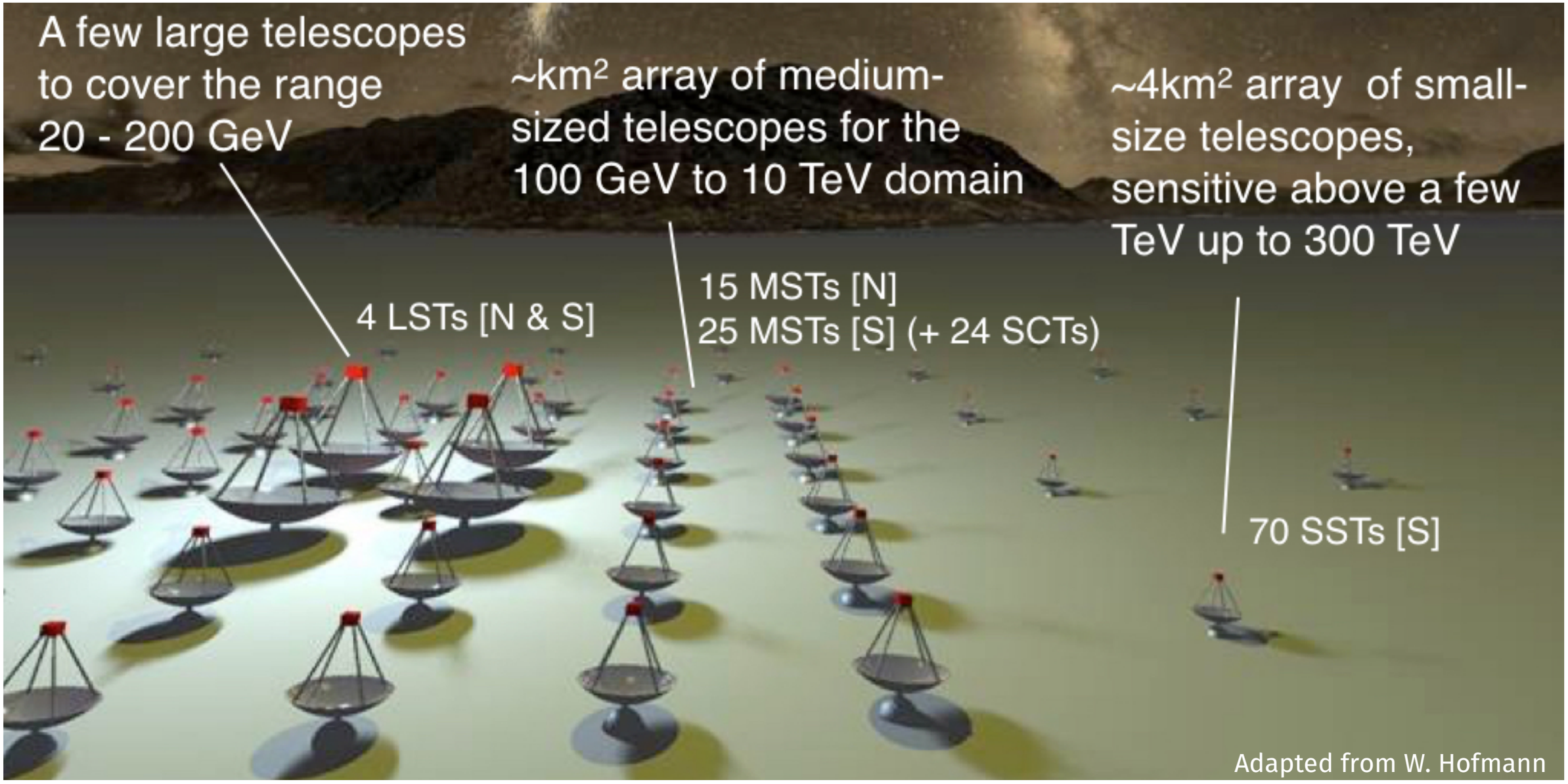




[Fermi LAT coll., ApJ, 2014,1407.7905]

CTA

one of the biggest projects in high energy astrophysics



CTA

one of the biggest projects in high energy astrophysics

32 countries
88 parties
202 institutes
1308 members (438 FTE)

June 14, 2016:

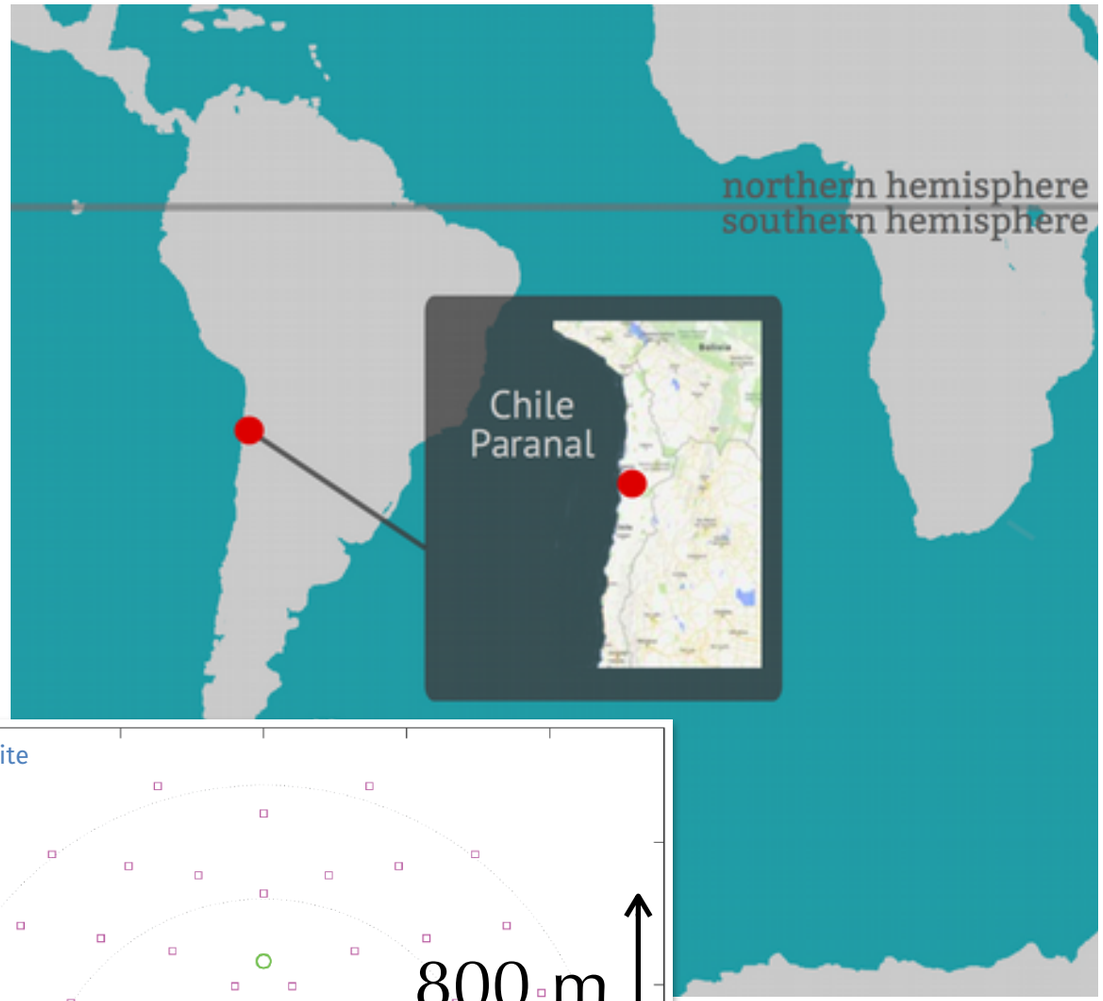
CTA Headquarters: Bologna
Science Data Management Centre: Zeuthen

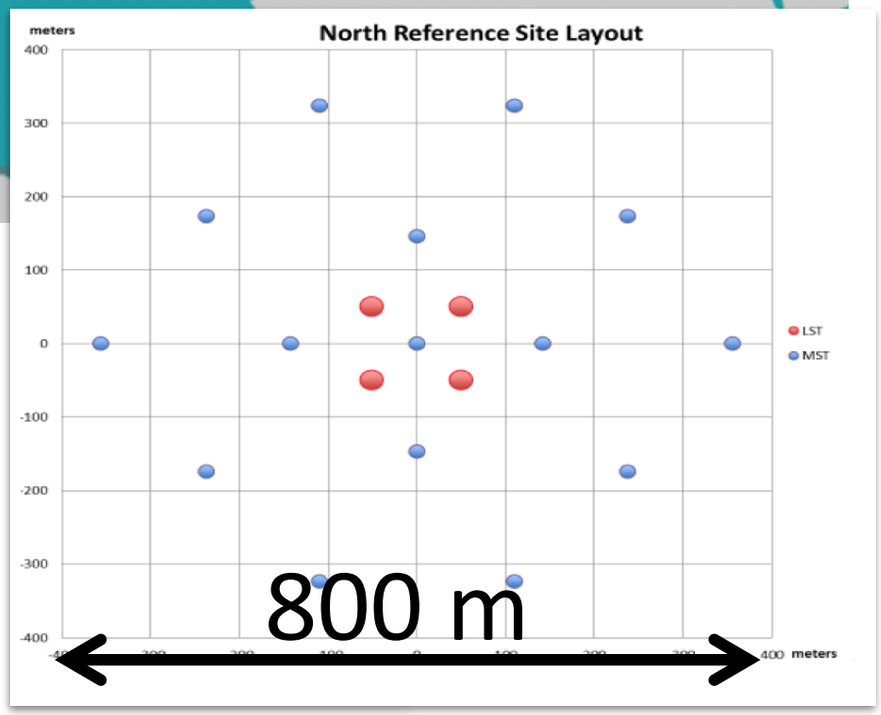
Credits: W. Hofmann and The CTA Consortium

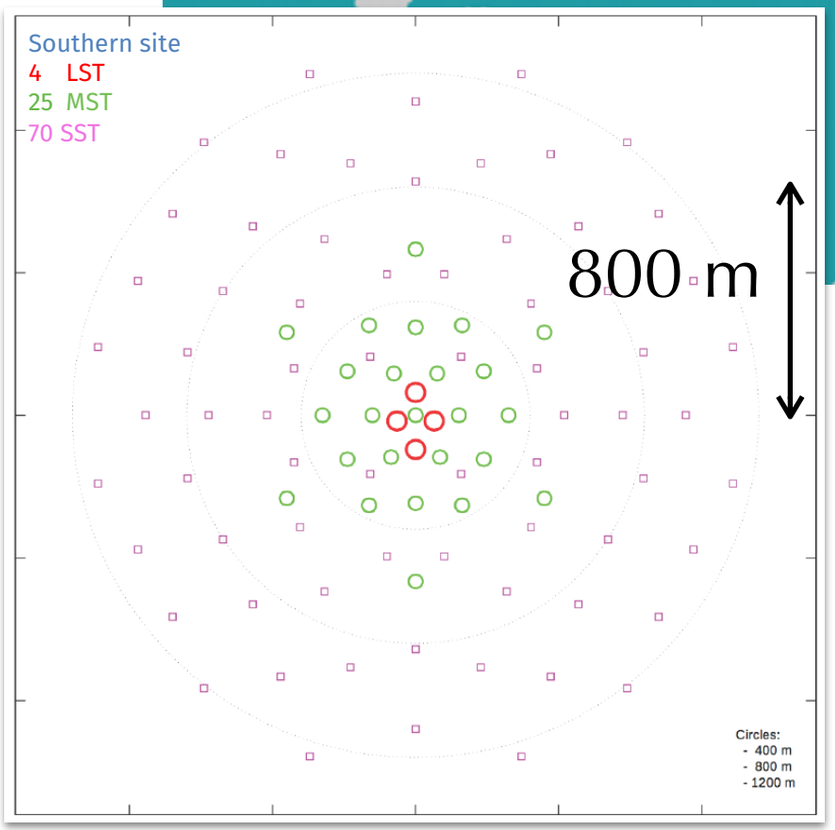
CTA

sites and example telescope layouts

different deployment strategies







23-m LST

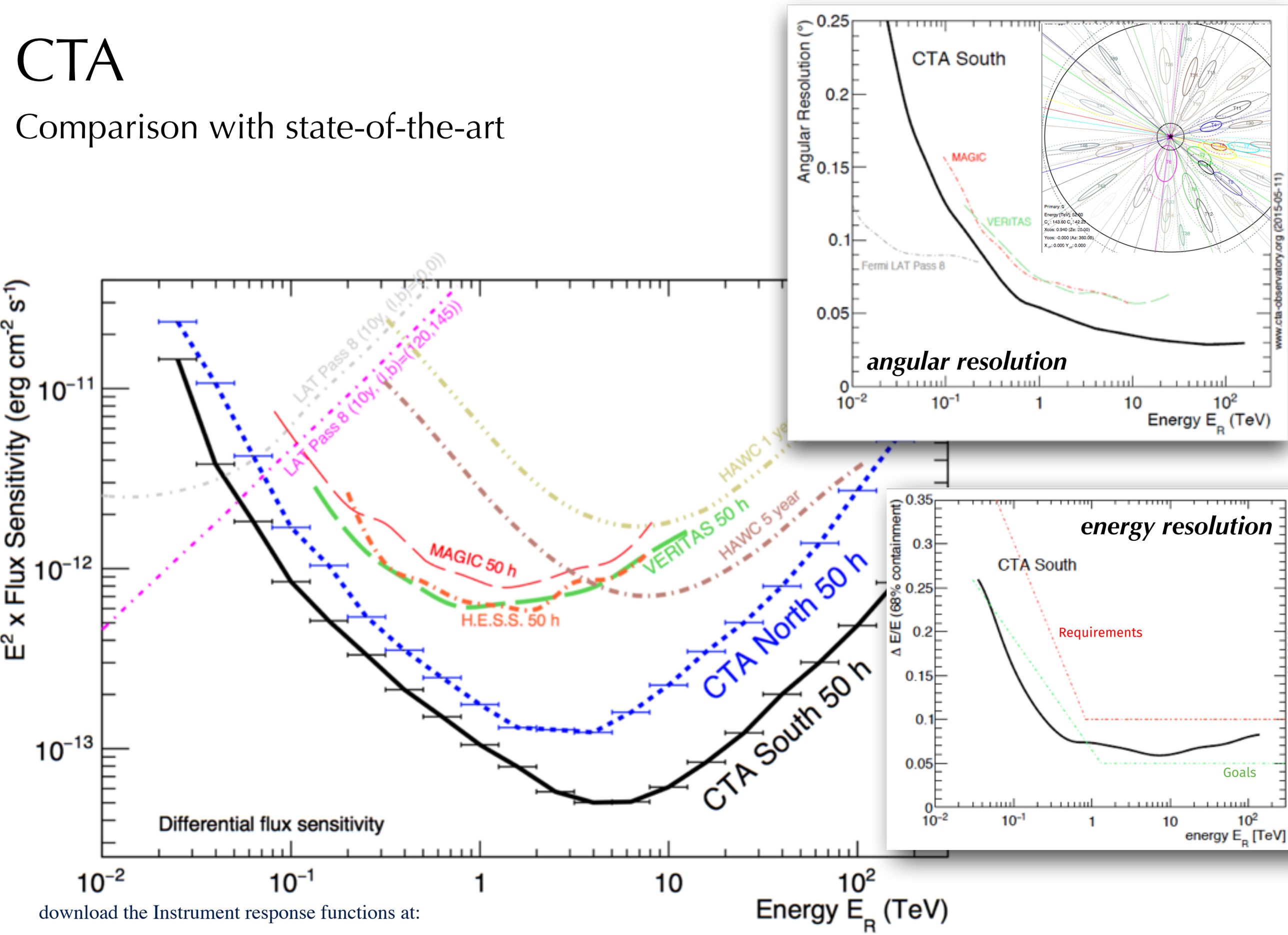
12-m MST

4-m SST

[credit: T. Hassan, CTA consortium]

CTA

Comparison with state-of-the-art



download the Instrument response functions at:

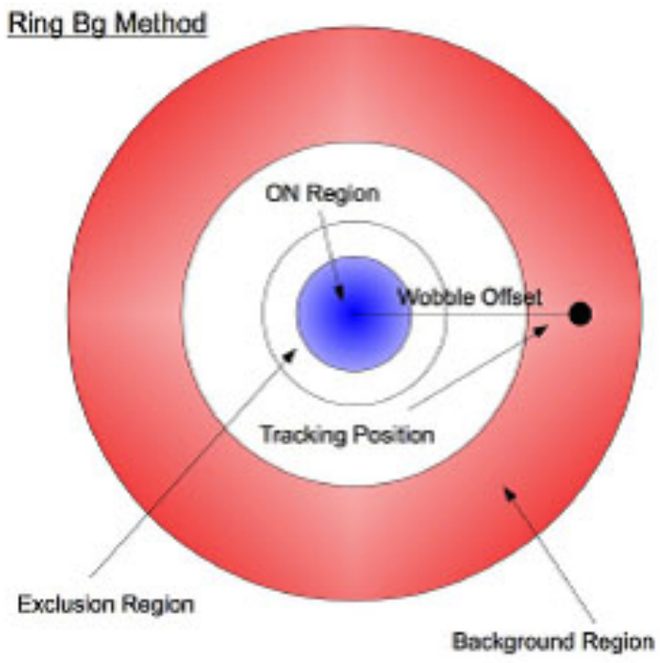
https://portal.cta-observatory.org/Pages/CTA-Performance.aspx

Credits: W. Hofmann and The CTA Consortium

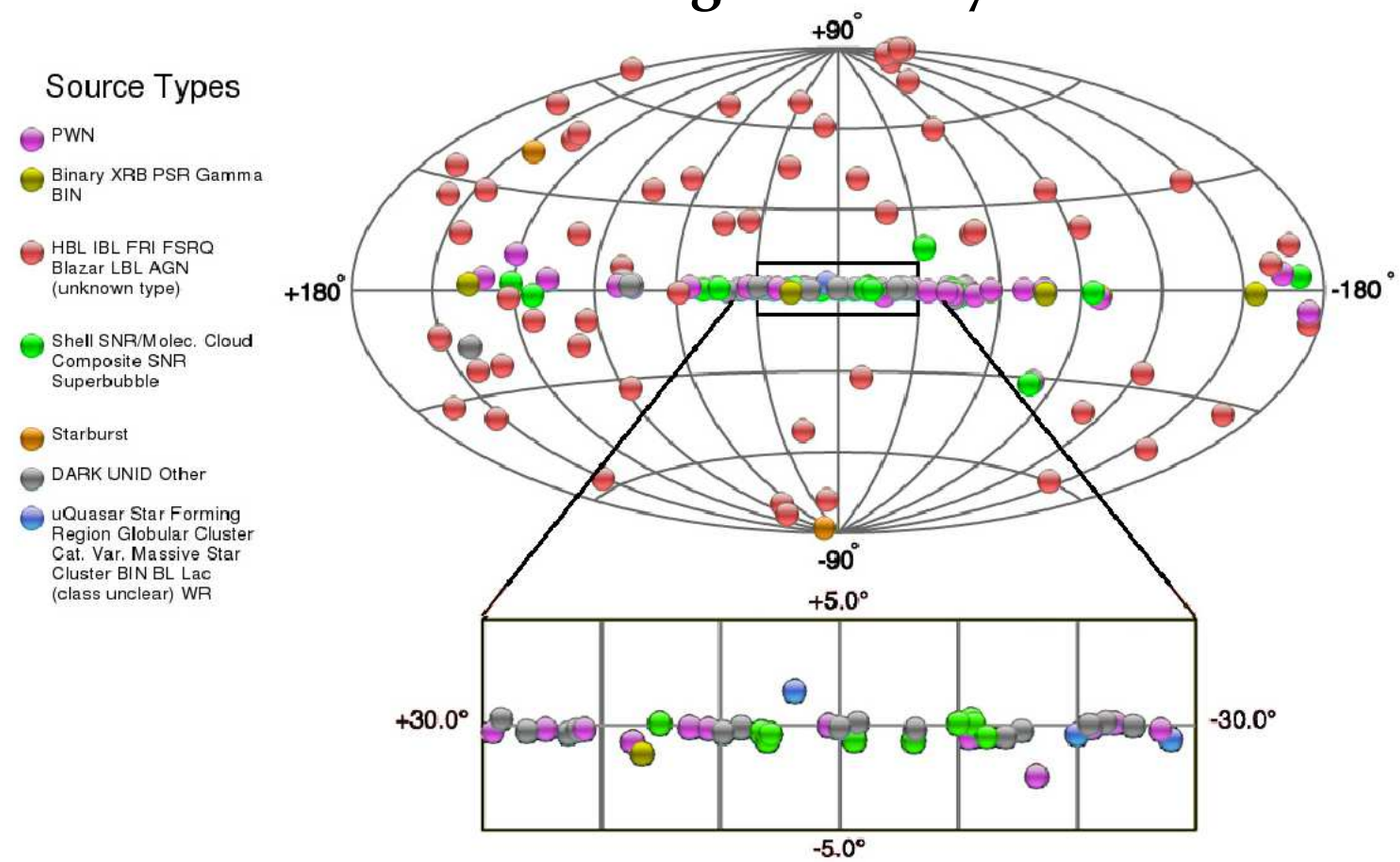
The TeV sky

i) IACTs are pointing telescopes!

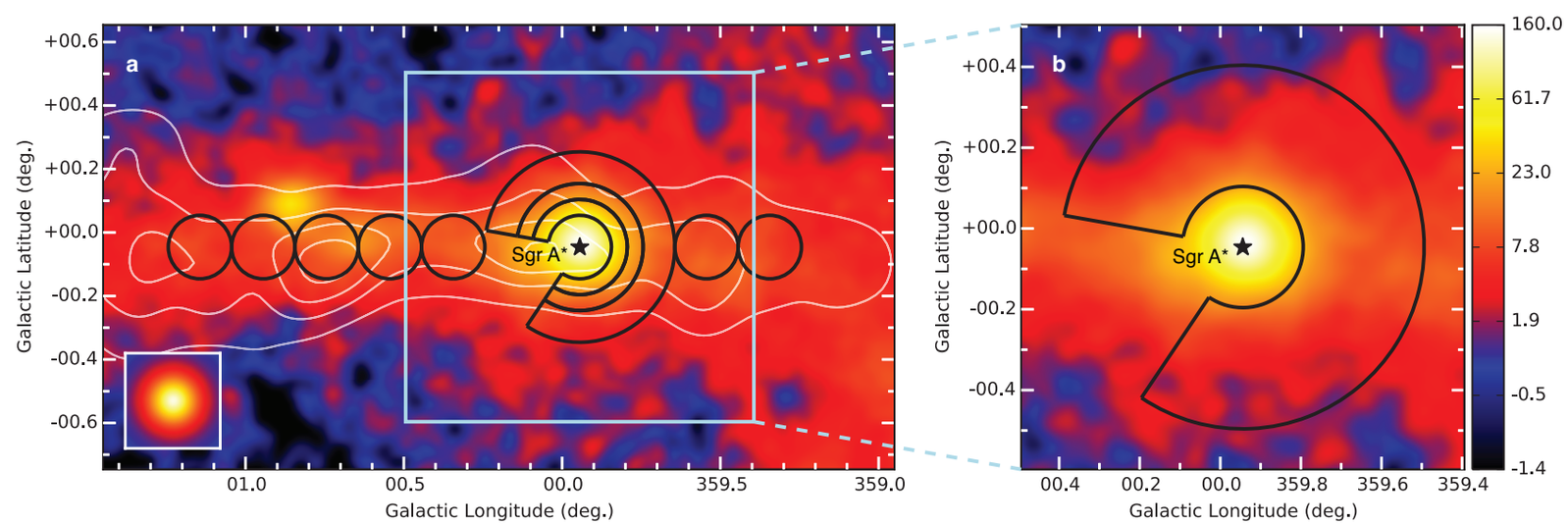
ii) Significant CR backgrounds
(no anti-coincidence detector), challenge to detect extended emission



170 VHE gamma-ray sources



Extended emission from the Galactic centre ridge

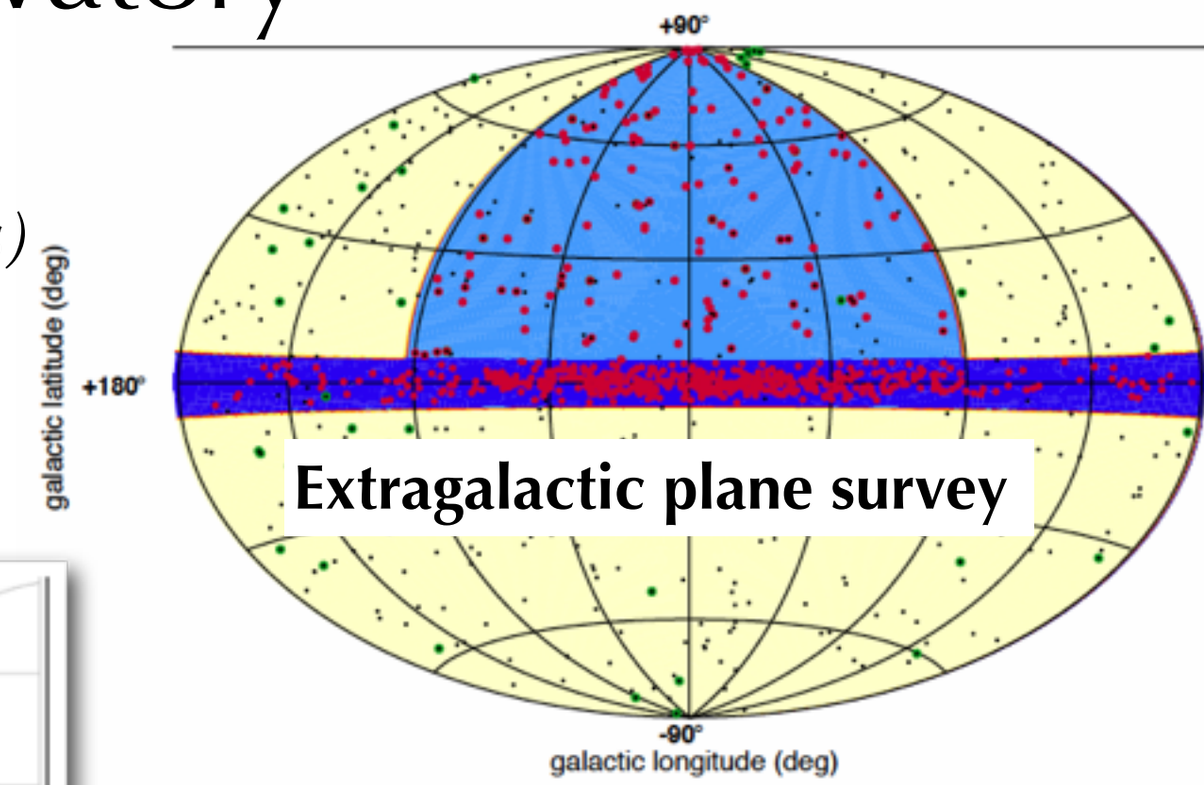


H.E.S.S. Collaboration, Nature, 2016

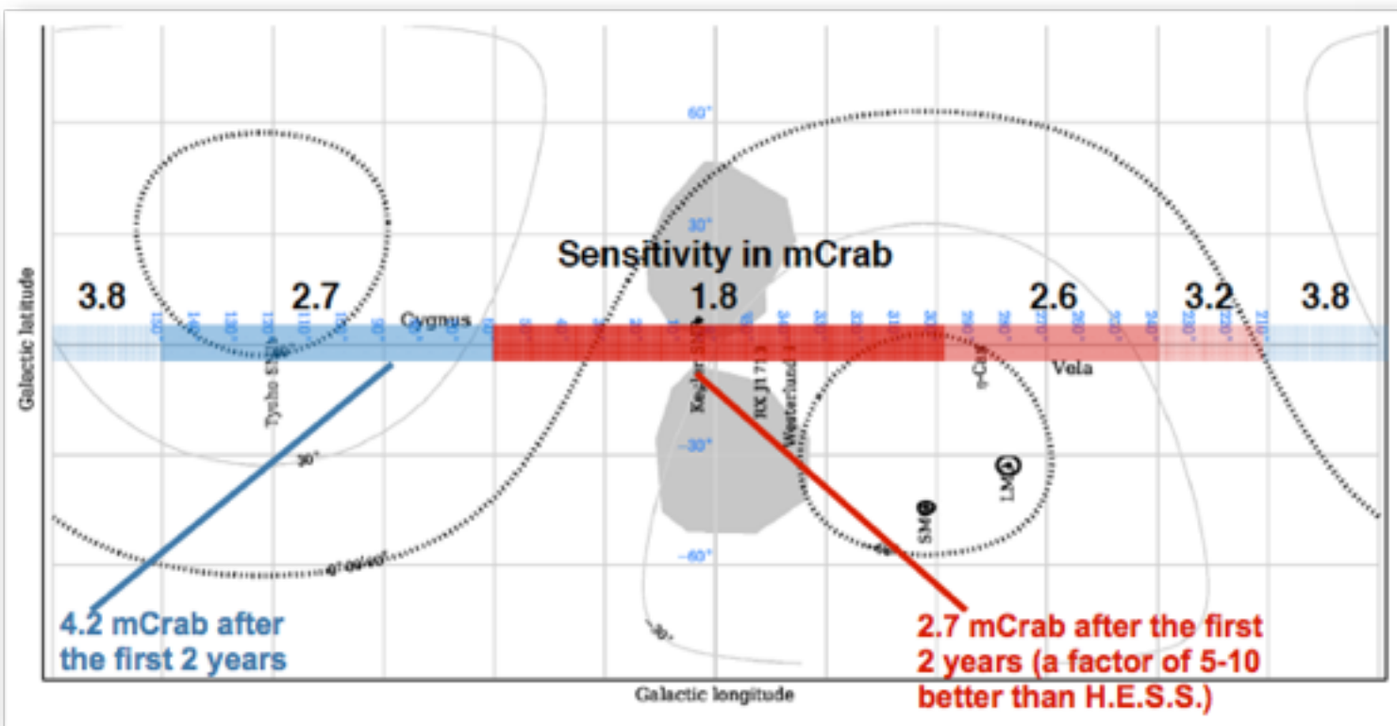
CTA as a whole-sky observatory

Planned sky surveys

(thanks to a large number of CTA telescopes)



Galactic plane survey

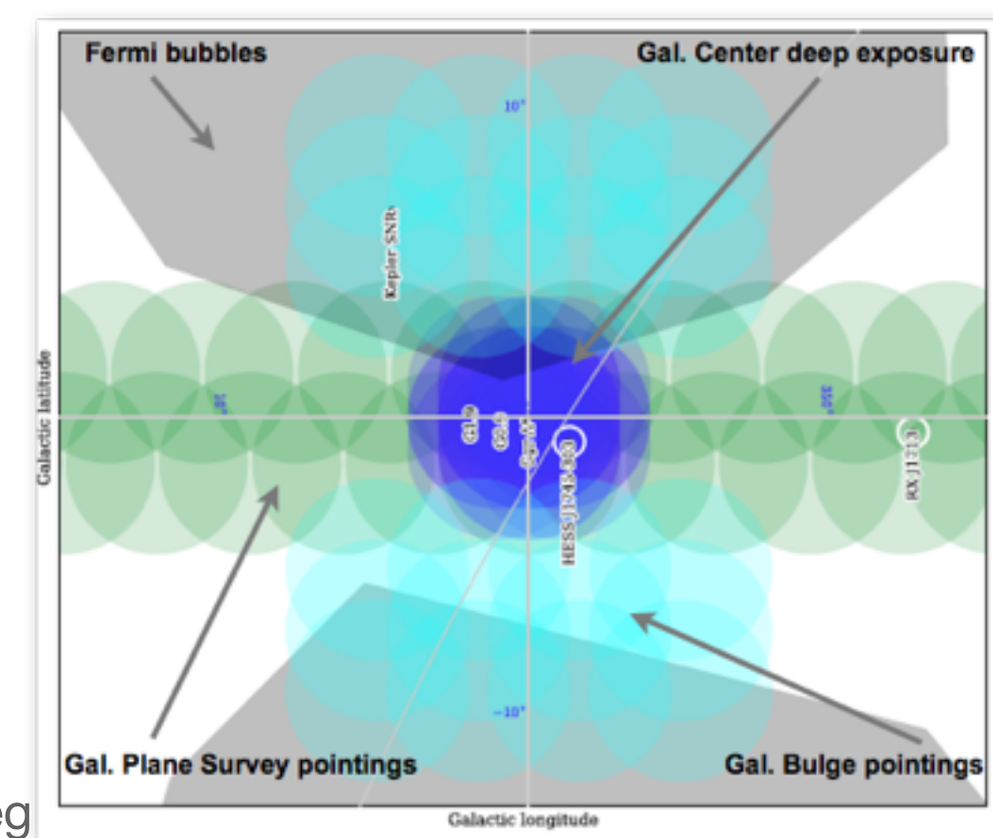


1/4 of the sky (~10^4 deg^2) Limiting flux ~ 5 mCrab

Galactic centre

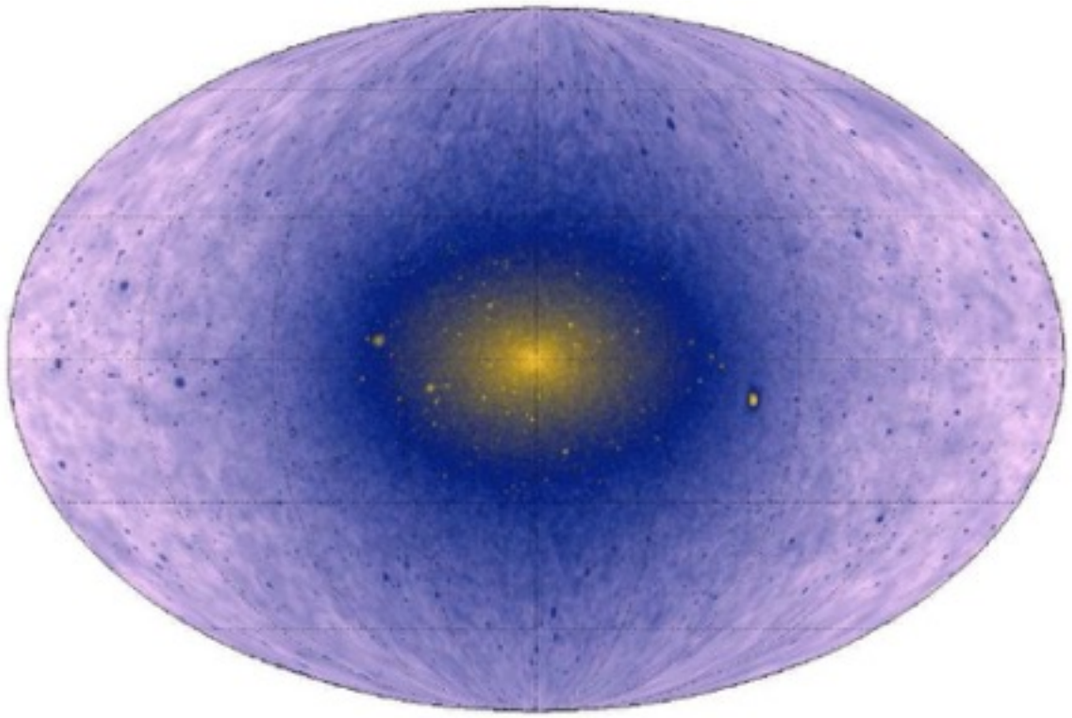
525 h deep exposure to uniformly cover the central 5 deg

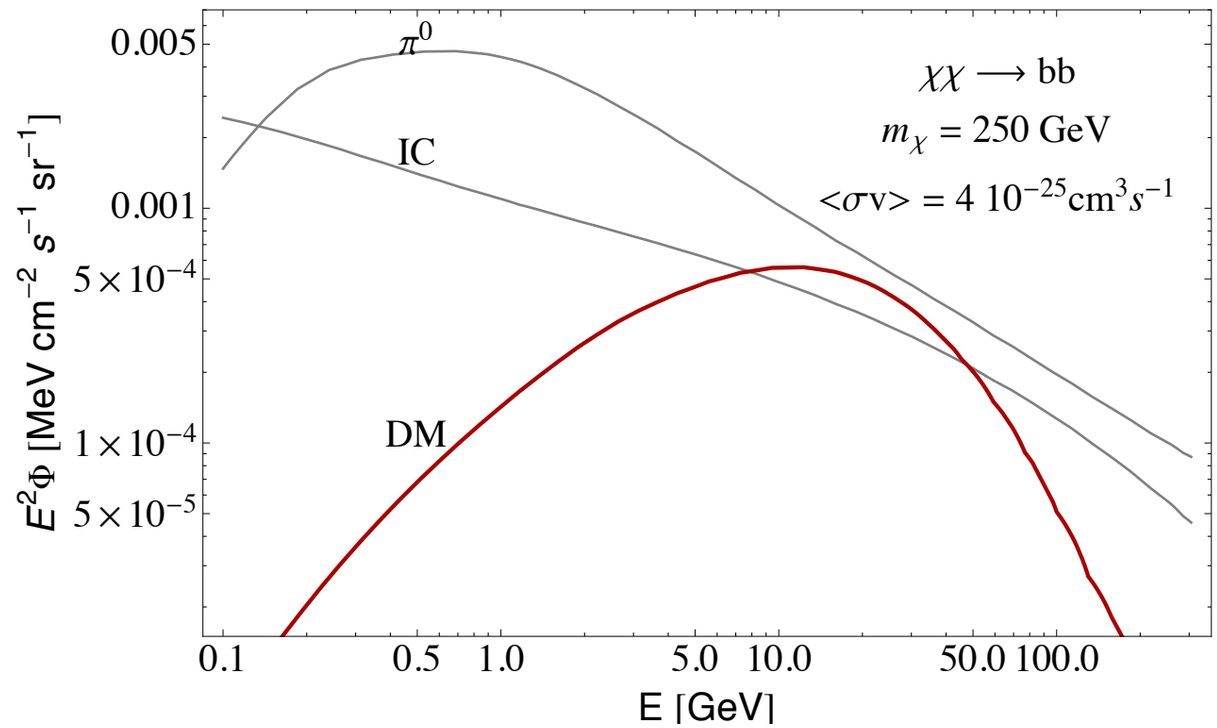
+ 300 h extended survey,10x10 deg



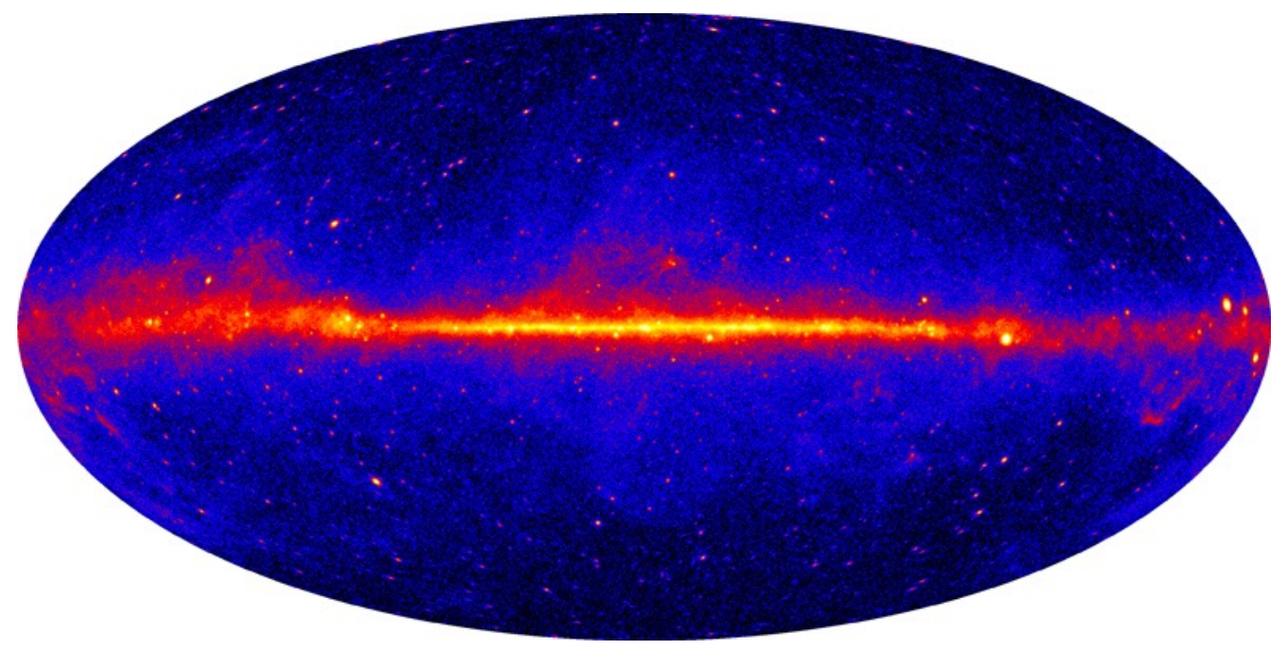
DM search - the challenge

look for an uncertain signal hidden in uncertain backgrounds



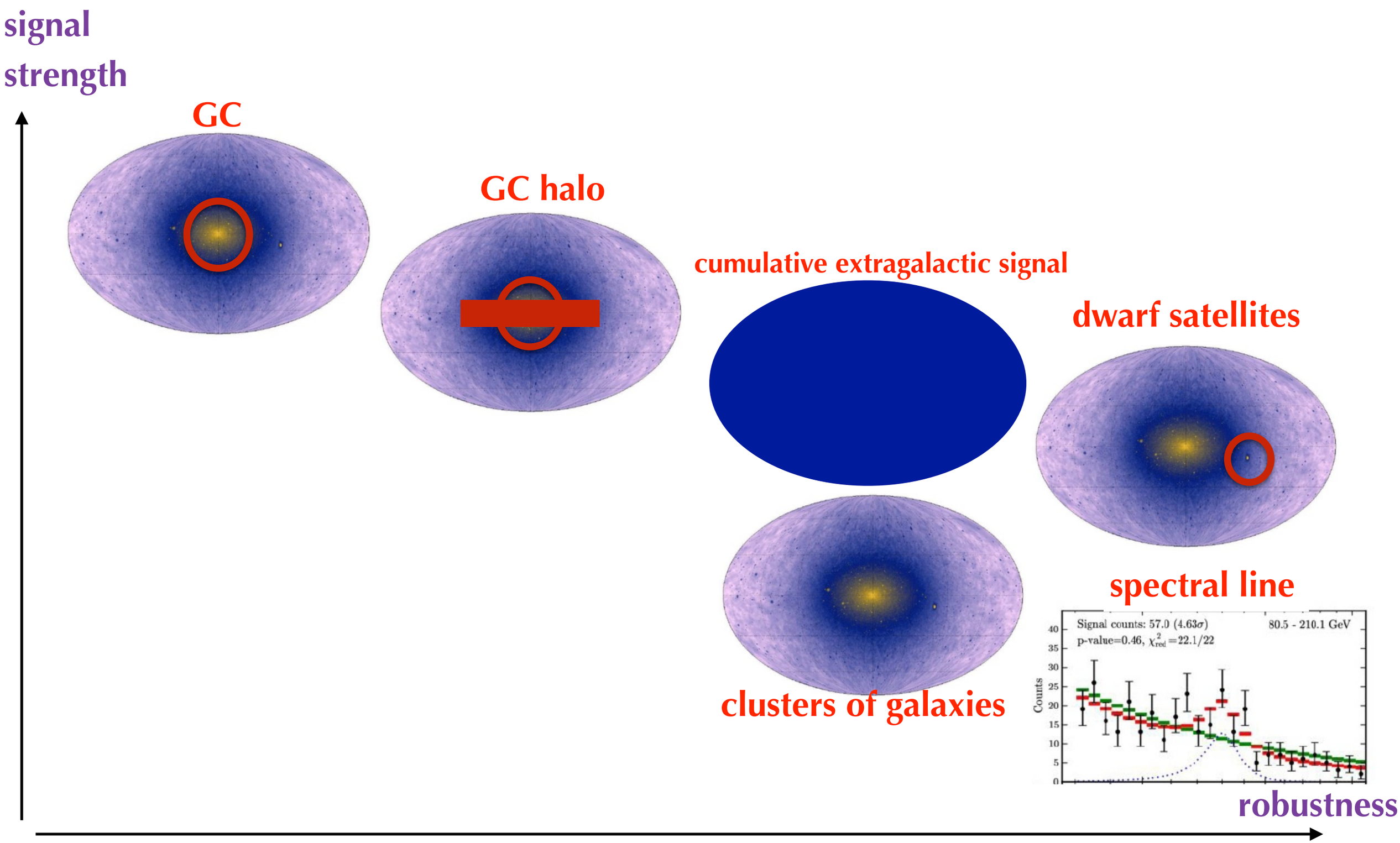


WIMPs gamma ray signals, as (expected to be) seen from the Earth



gamma ray sky, >1 GeV, 5yr Fermi LAT

Strategies

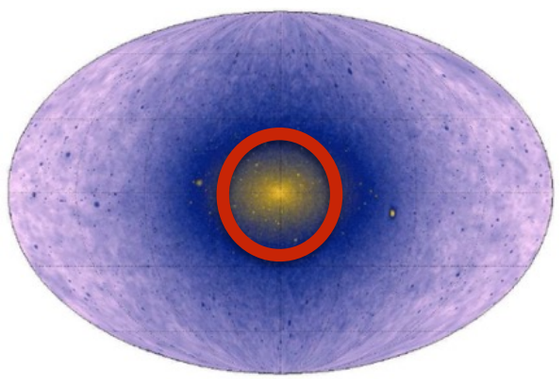


[adapted from: H.-S. Zechlin]

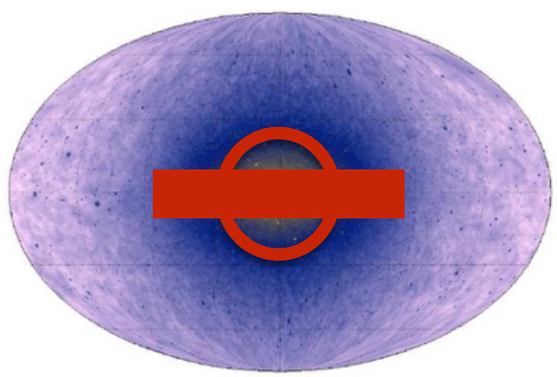
Strategies

signal strength

GC



GC halo



search for generic WIMP signatures
and use rich astrophysical data to model (or measure) the backgrounds

current experimental sensitivity in the right ballpark for vanilla models
due to confusion with astro backgrounds possible hints **NEED**
confirmation across the range of wavelengths/messengers/targets

robustness

[adapted from: H.-S. Zechlin]

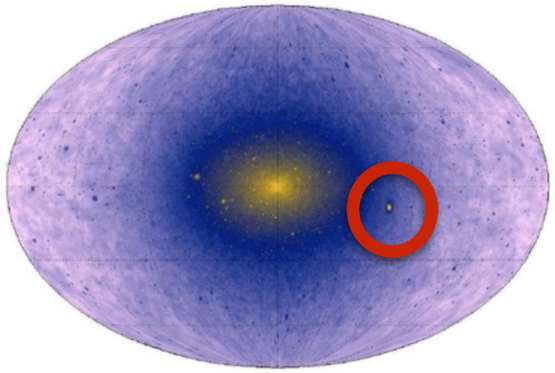
Strategies

signal strength

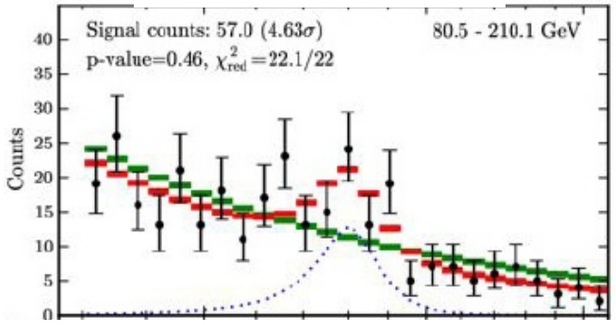
or, look for the ‘smoking guns’

‘zero’ astro backgrounds, but expected signals (for vanilla DM) low
need luck, or optimised analysis techniques

dwarf satellites



spectral line



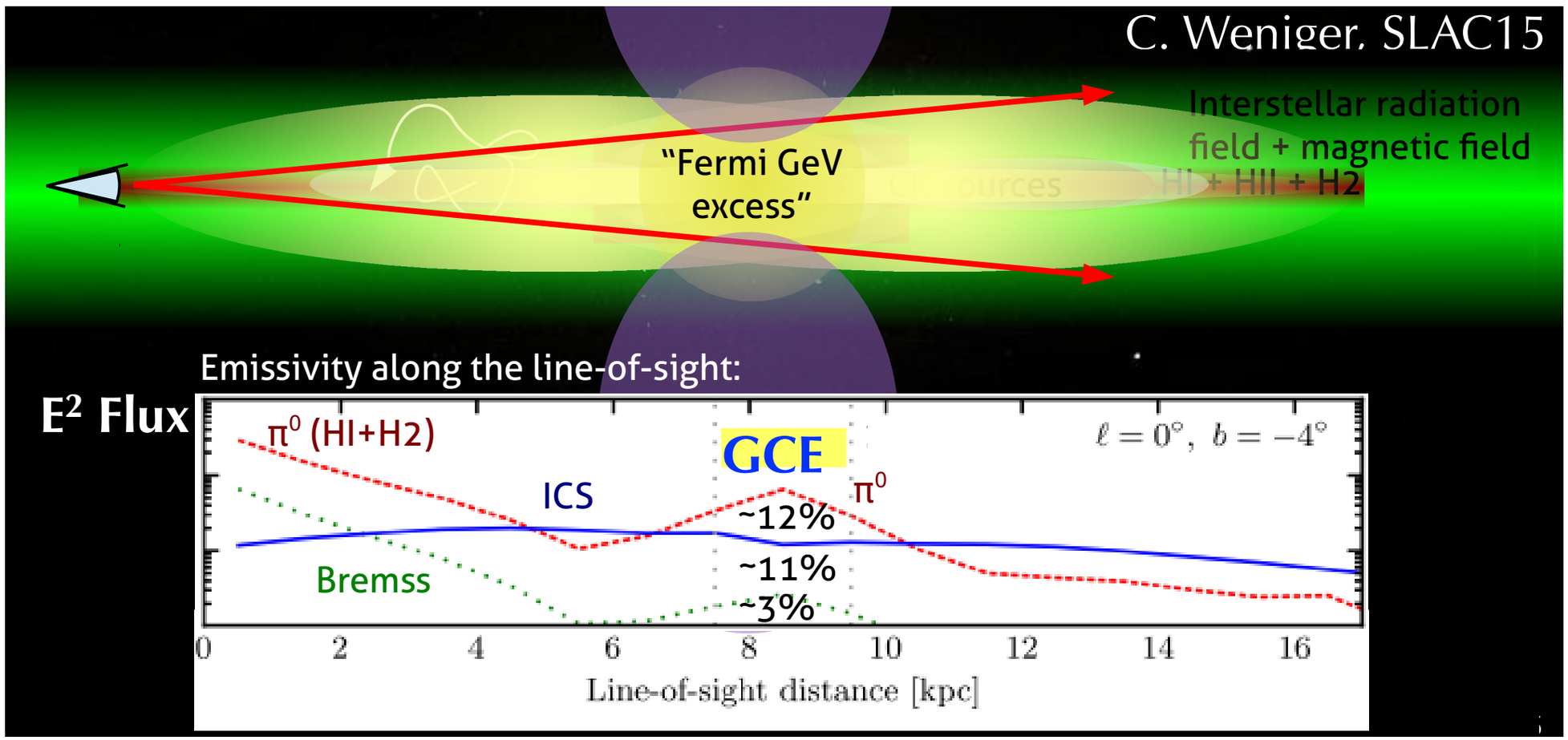
robustness

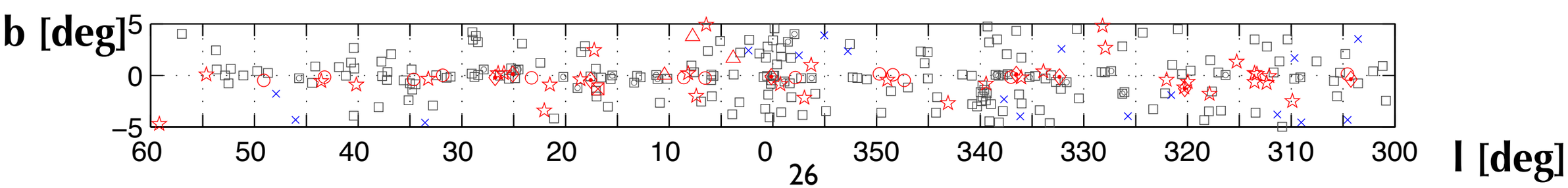
[adapted from: H.-S. Zechlin]

DM search in the inner Galaxy

closer to the plane astrophysical backgrounds especially challenging

- have to model the ***diffuse emission*** along the line of sight
- and numerous ***point sources*** in that region



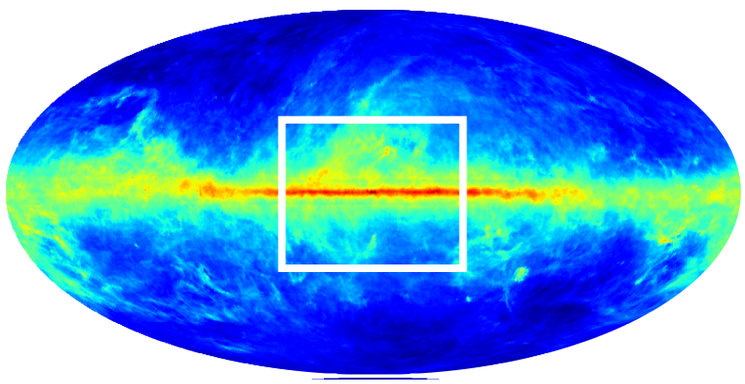


DM search in the inner Galaxy

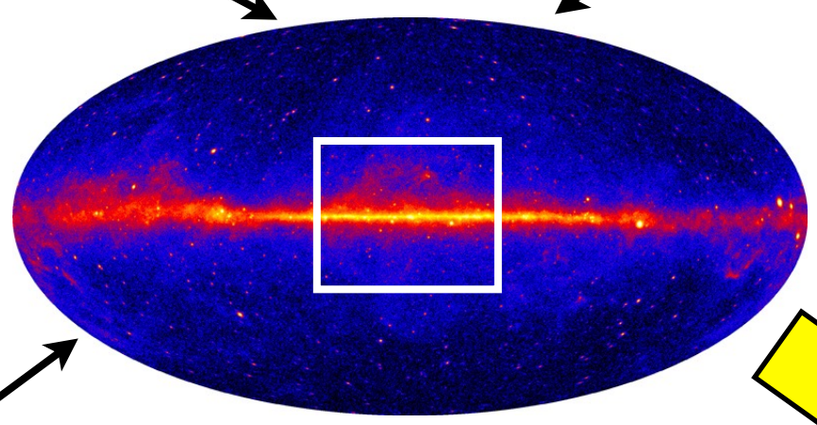
general approach

apply ***template fitting*** procedure to the inner ~<20 deg with addition of the FBs

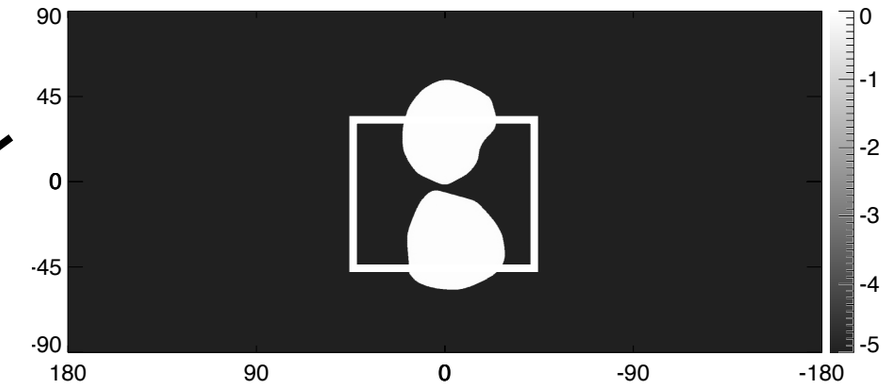
C. Weniger's **talk**



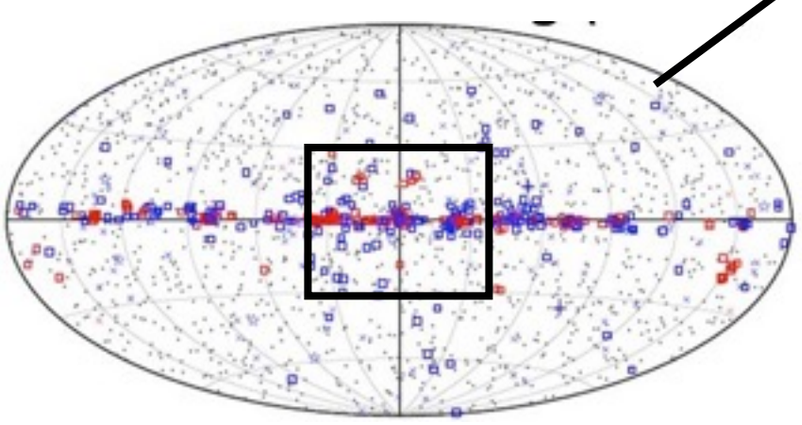
model(s) of the diffuse emission



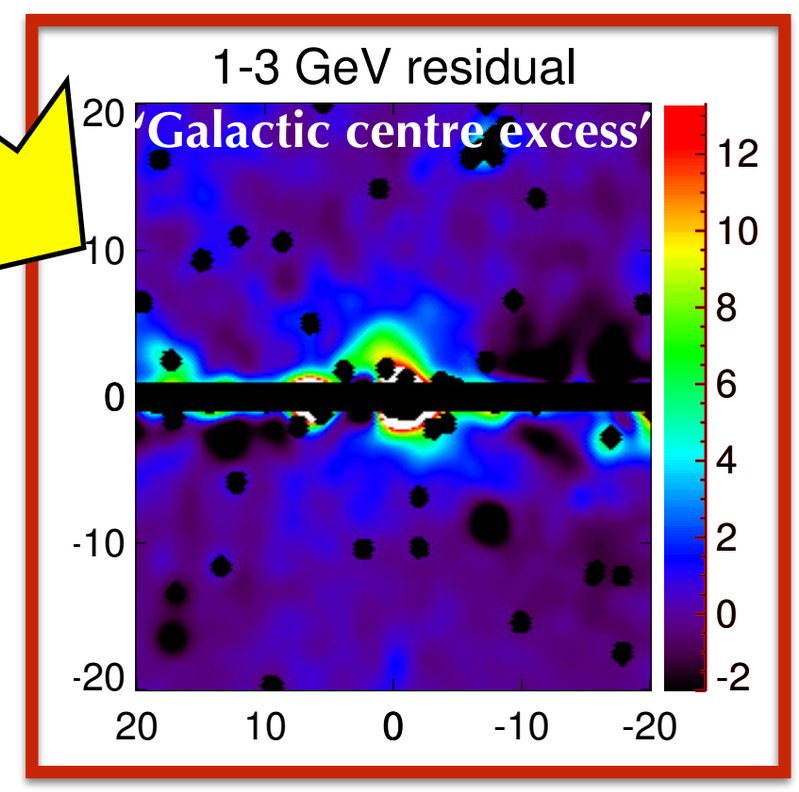
LAT data



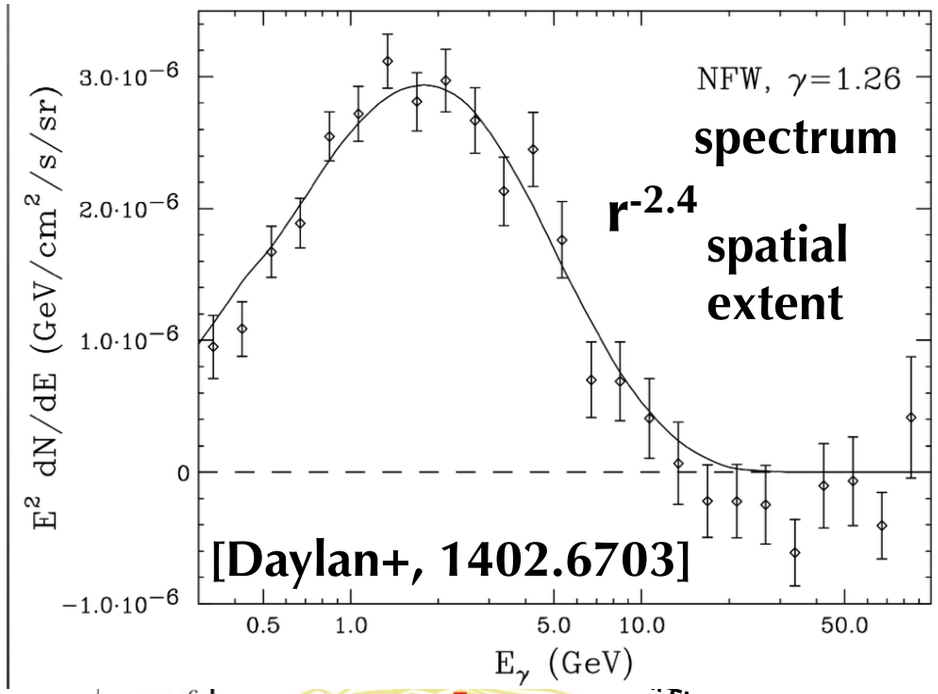
uniform-brightness template for the Fermi Bubbles

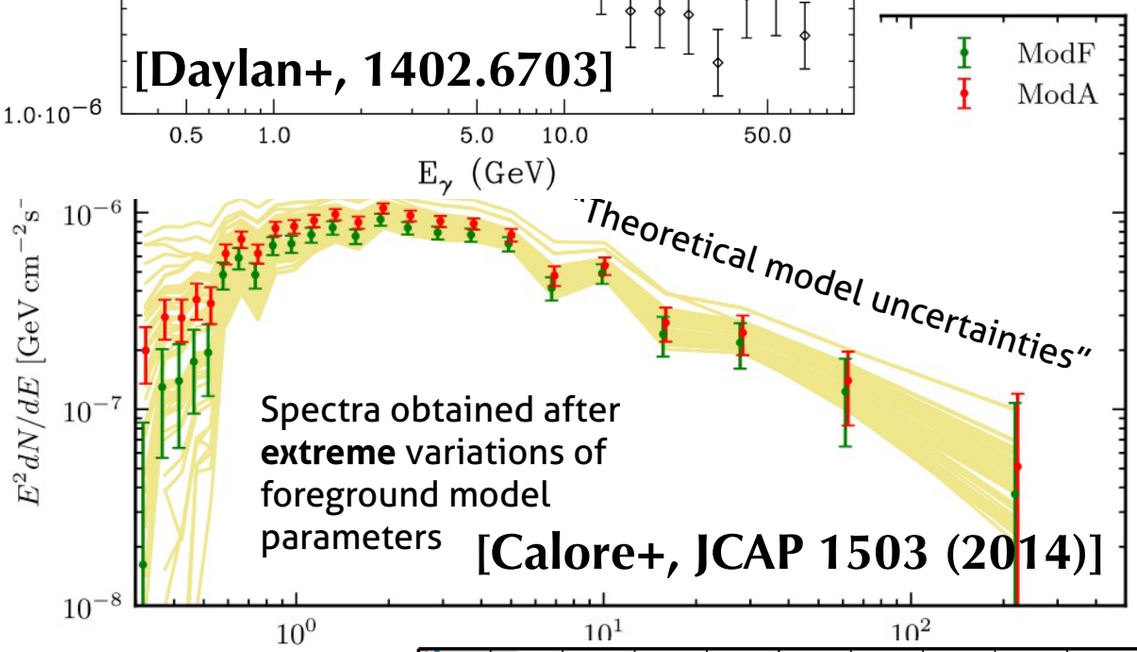


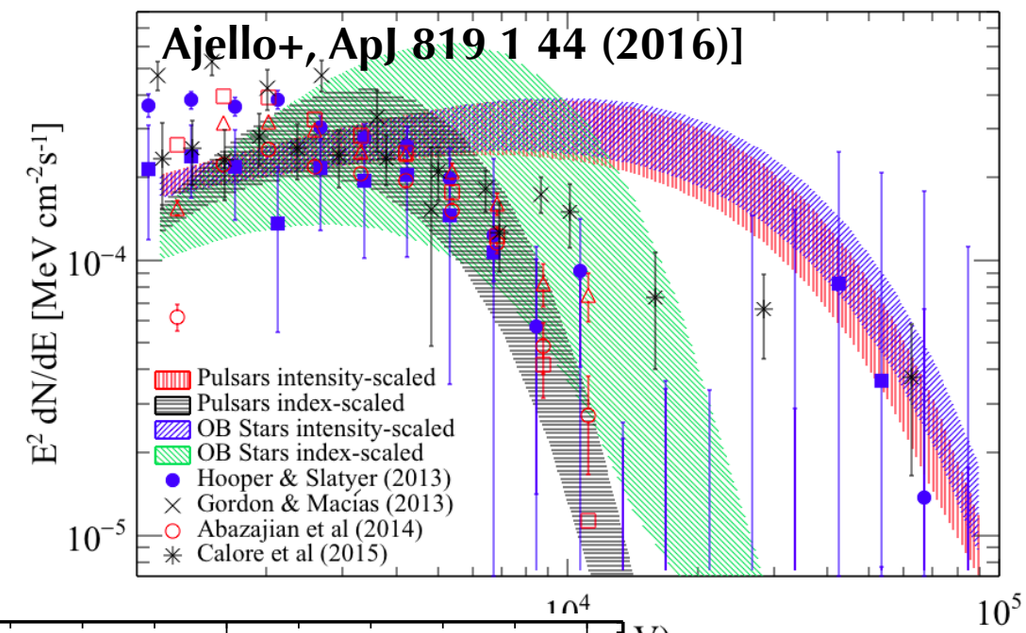
point sources from the catalog

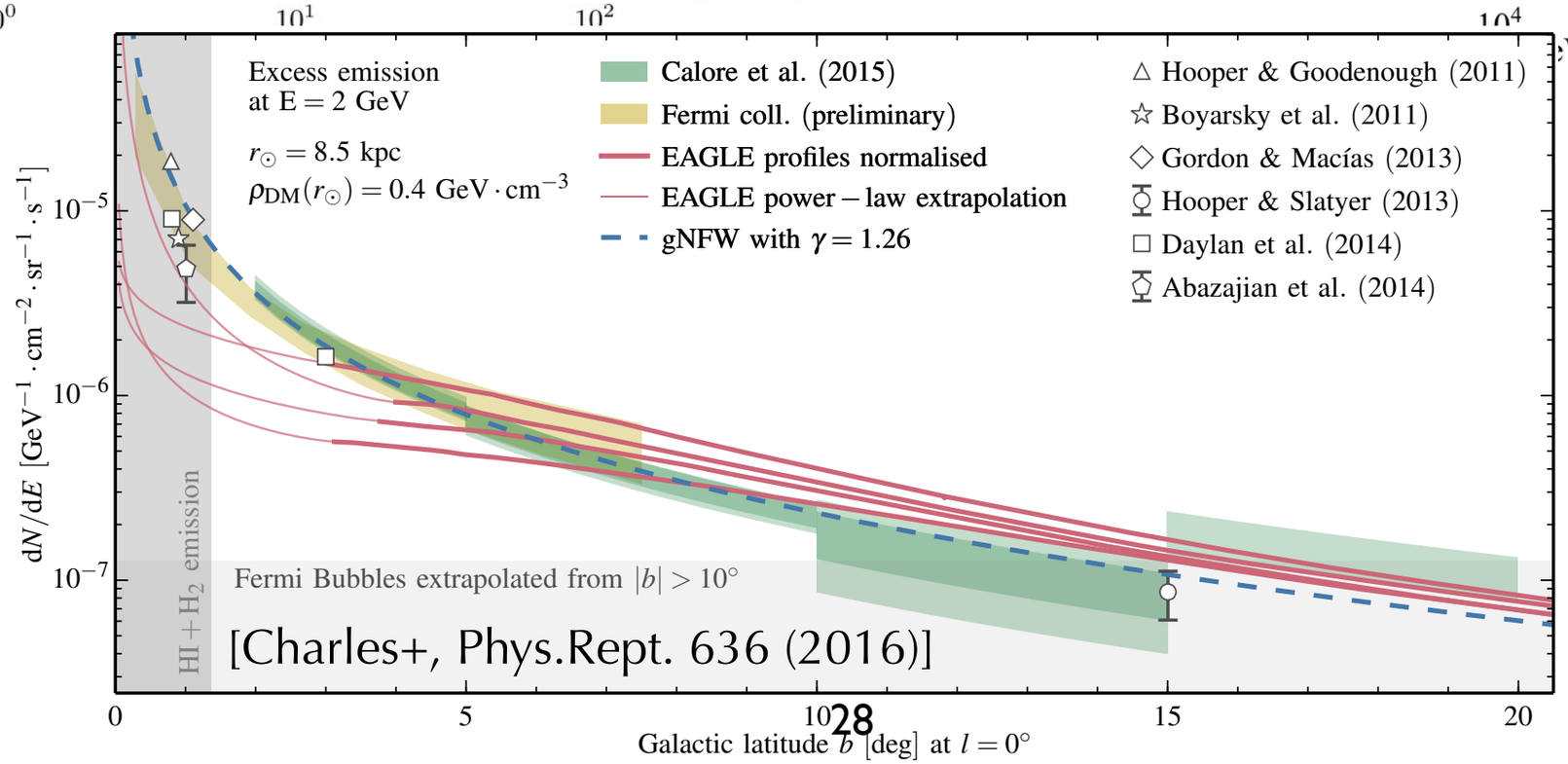


Many works reaching similar results: Vitale & Morseli (**2009**), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 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



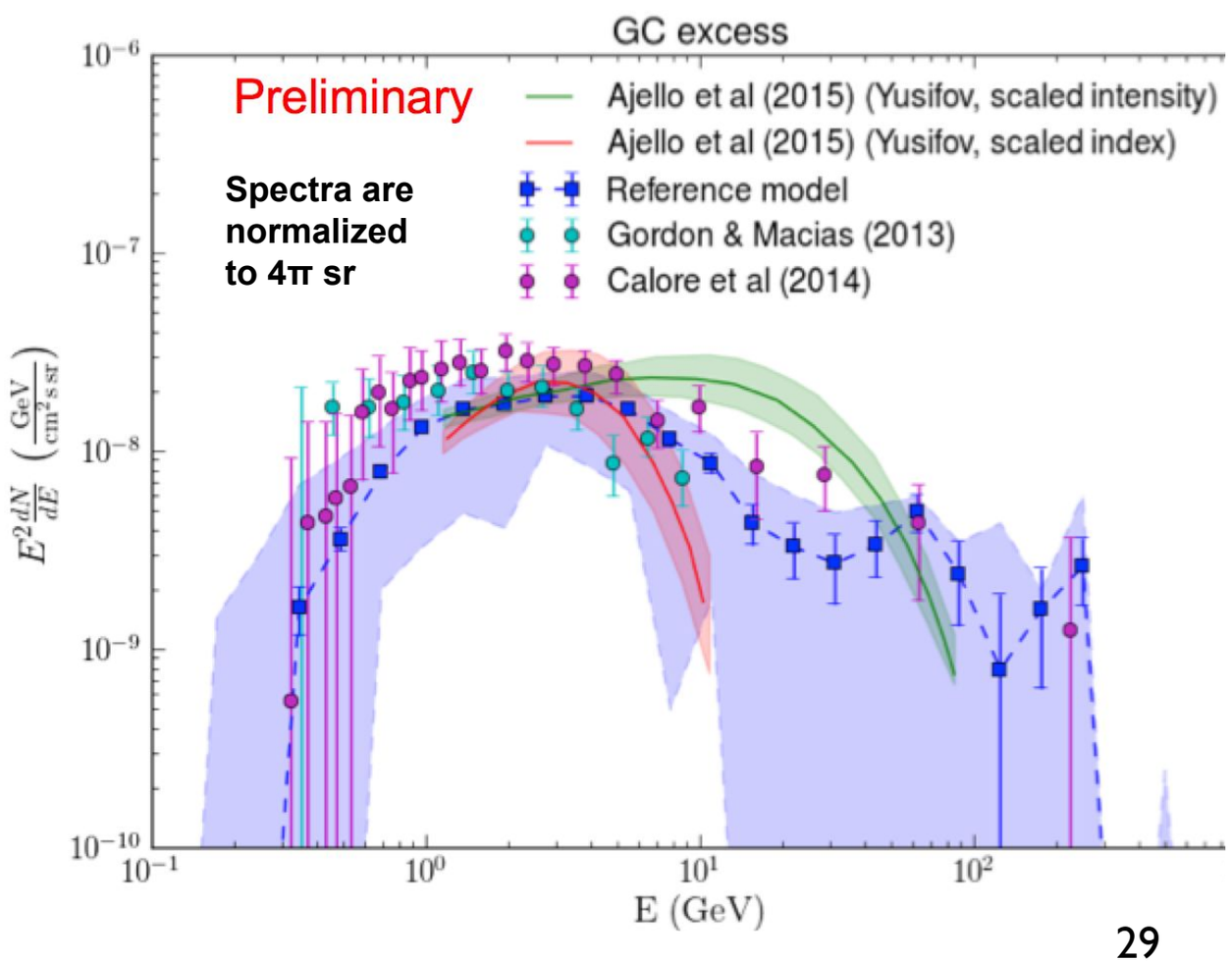






Updated Fermi LAT analysis (preliminary)

- 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)

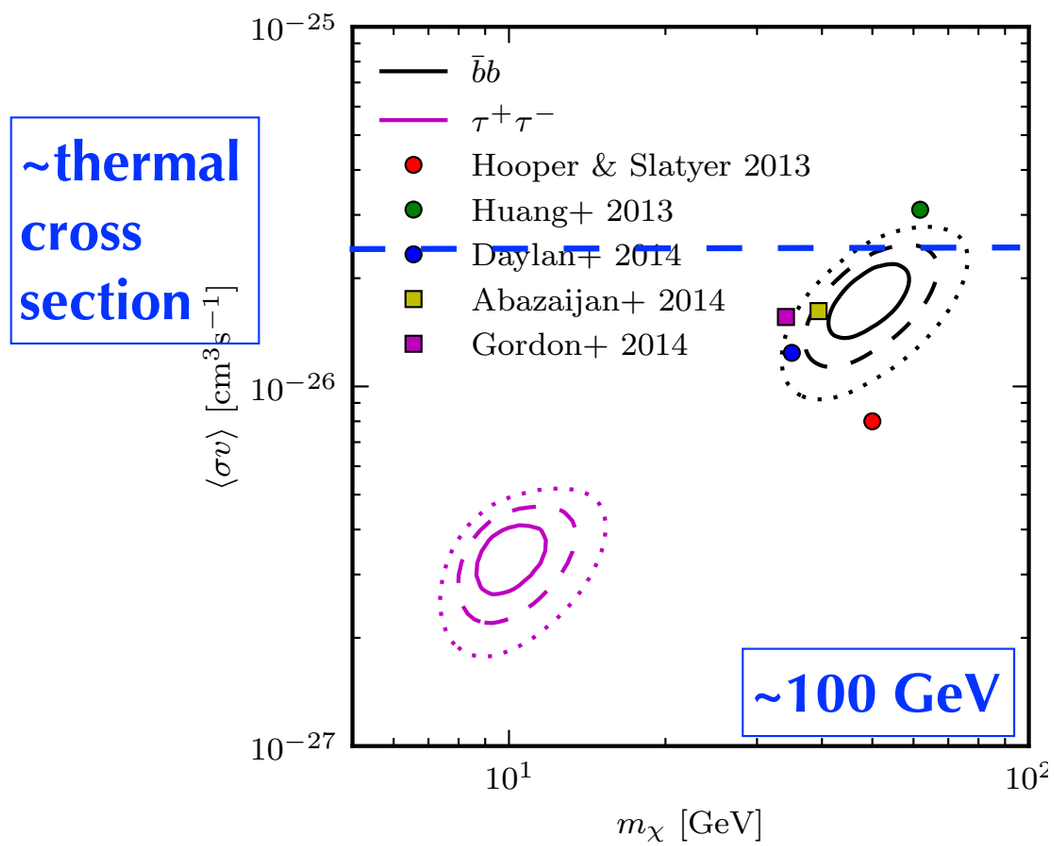


New emission component in the Galactic centre appears robust to various checks of the systematic uncertainty
its exact spectral features are model dependent

[A. Albert, APS 2016 meeting]

Origin of the excess?

C. Weniger's **talk**

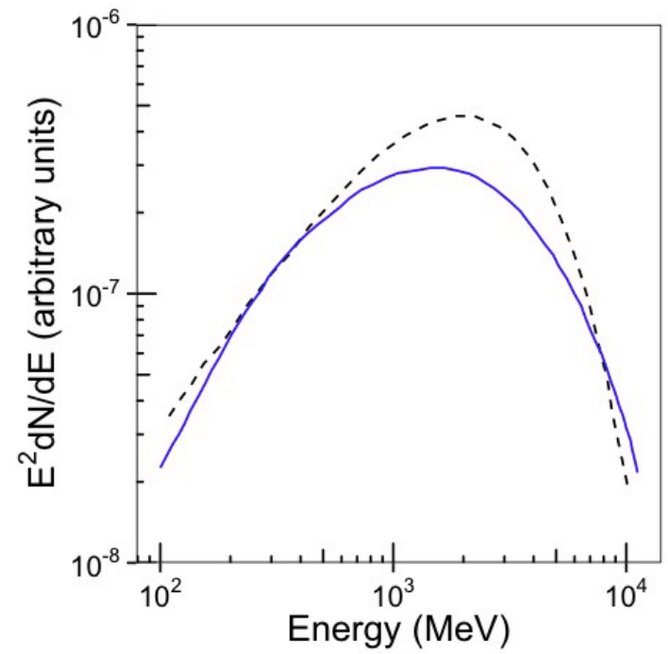


Right on the spot where WIMP DM is supposed to be!

i) Individually unresolved point sources?

pulsars?

- spectral twins of ~50 GeV DM



Baltz et al (2007)

[Abazajian, 2012, Mirabal, 2014; Macias, 2014, Petrovic +, 2015, Brandt+2015, Lee+, 2015, Bartels+, 2015…]

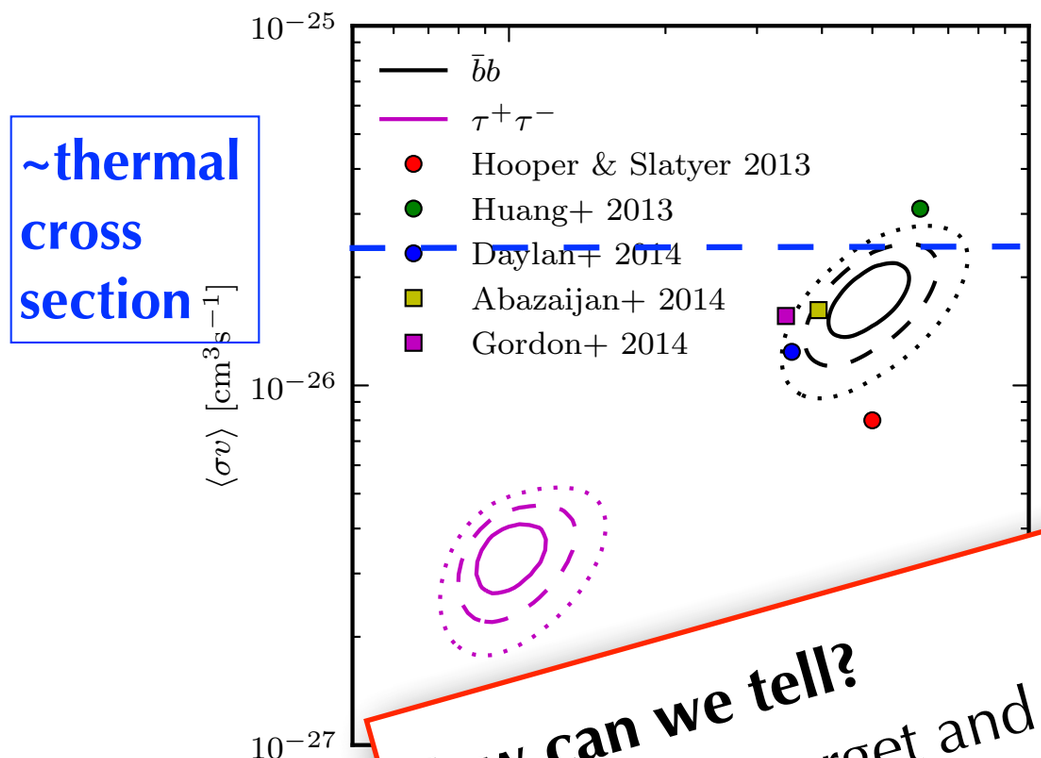
ii) Transient at the GC: inverse Compton emission from electrons injected during an energetic burst event ~Myr ago

[Petrovic+, 2015; Carlson+, 2015, Cholis+, 2016]

iii) steady-state electron source at the GC

[Carlson+, 2016; Gaggero+, 2015]]

Origin of the excess?



How can we tell?

DM — multi-target and -messenger tests

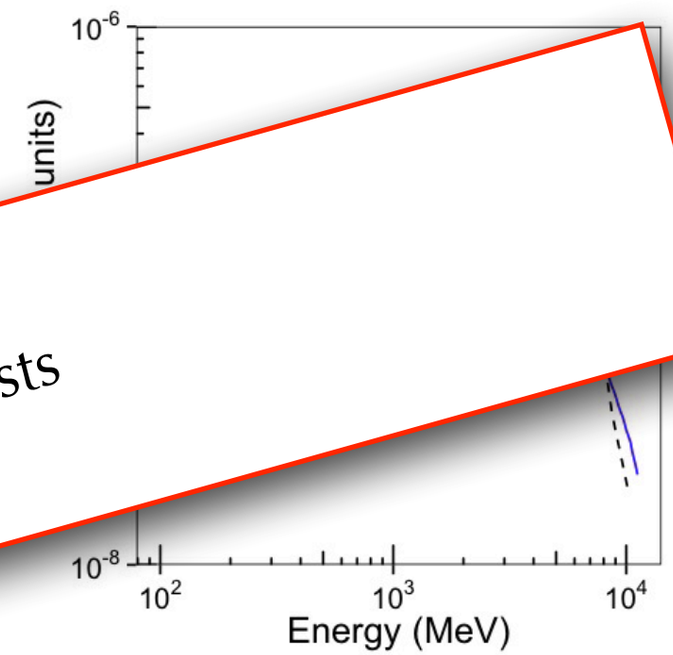
astro — radio pulsar searches, …

Right on the [illegible] where WIMP DM is supposed to be!

i) Individually unresolved point sources?

pulsars?

- spectral twins of ~50 GeV DM



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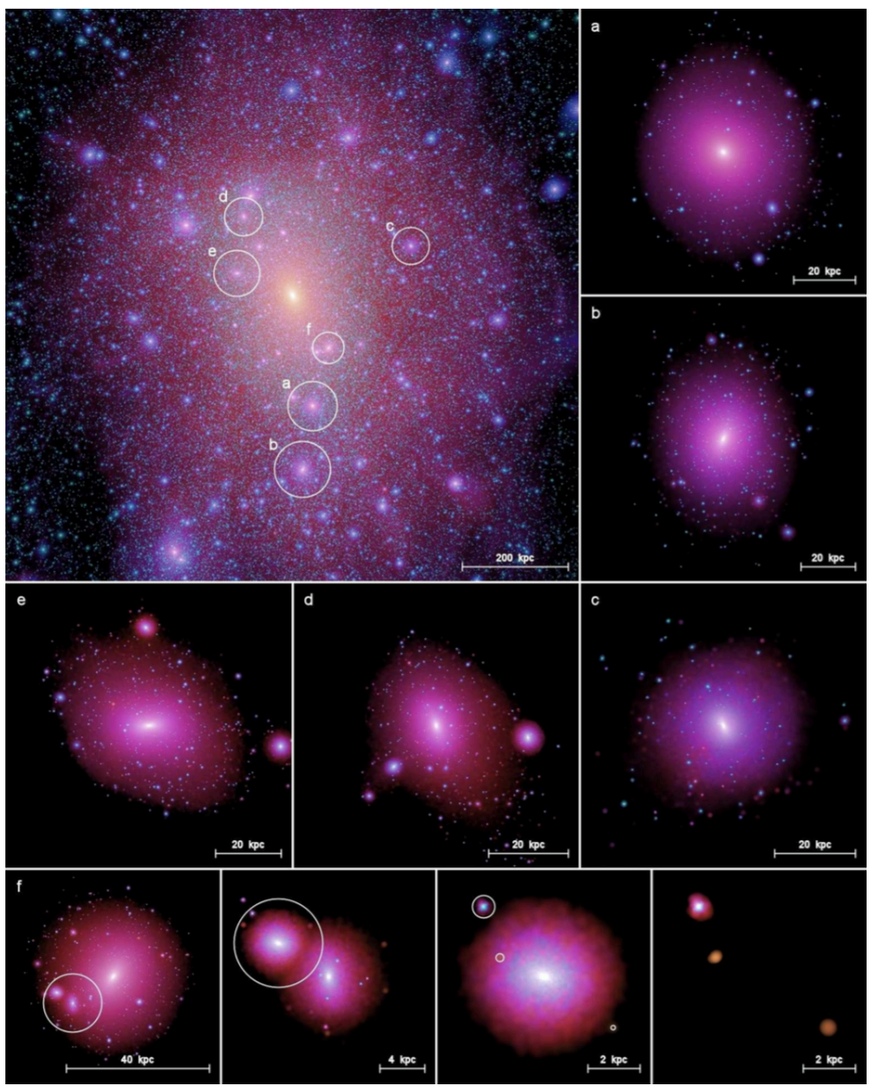
[Carlson+, 2016; Gaggero+, 2015]]

DM search in dwarf galaxies

Milky Way like halo and several sub-halos



Dwarf spheroidal galaxies are ***the cleanest targets*** for DM search

- old stars - expect no high energy astrophysical emission

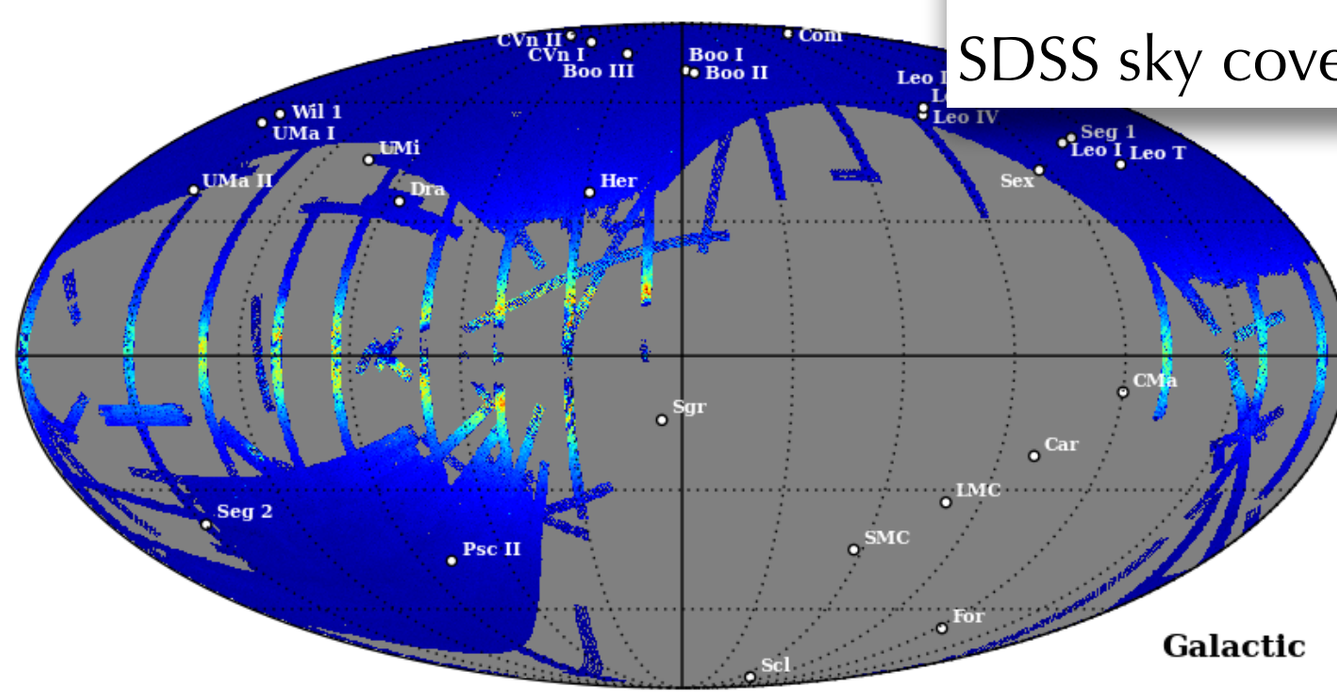
- 100 - 1000 times more dark than visible matter

- located in quiet regions of the sky

Sample of 15 dSphs with well-determined DM content (J-factors)

- not yet detected in gamma rays

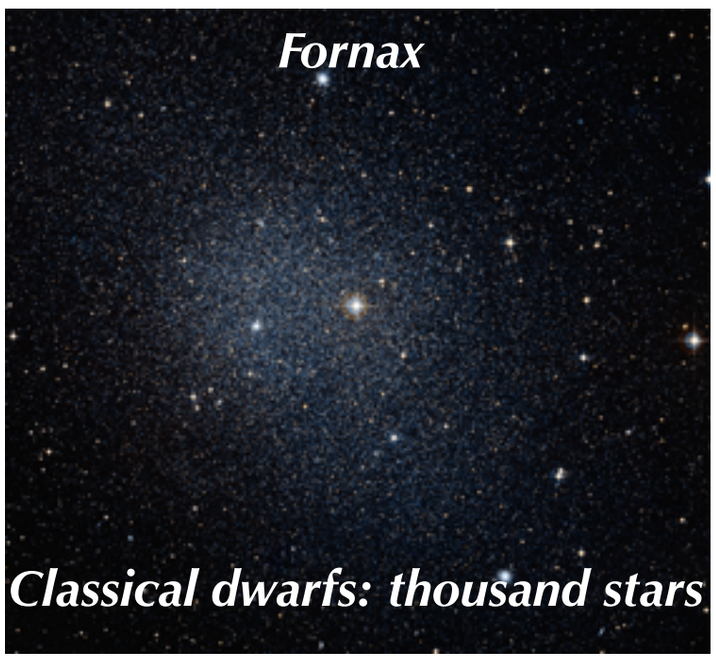
LAT data within SDSS sky coverage

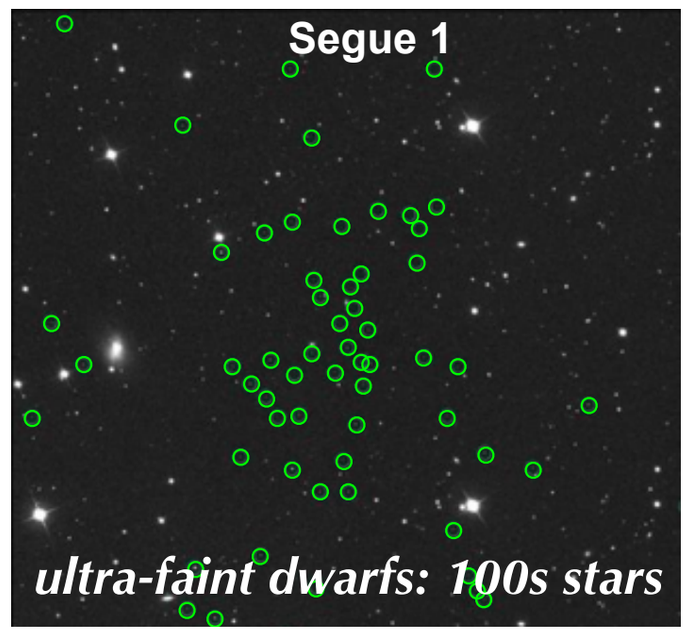


DM search in dwarf galaxies

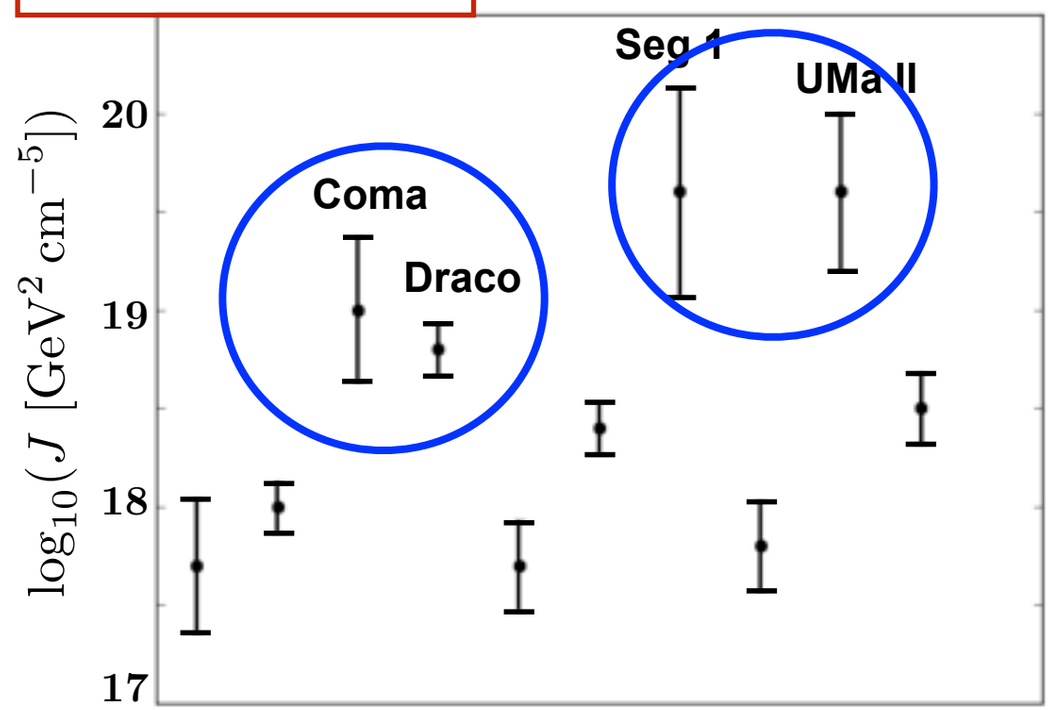
The biggest uncertainty: dark matter content!

Determined from stellar velocity dispersion





$$\int_{\Delta\Omega} d\Omega \int_{\rm los} {\rm d}s\, \rho^2(s,\Omega)$$



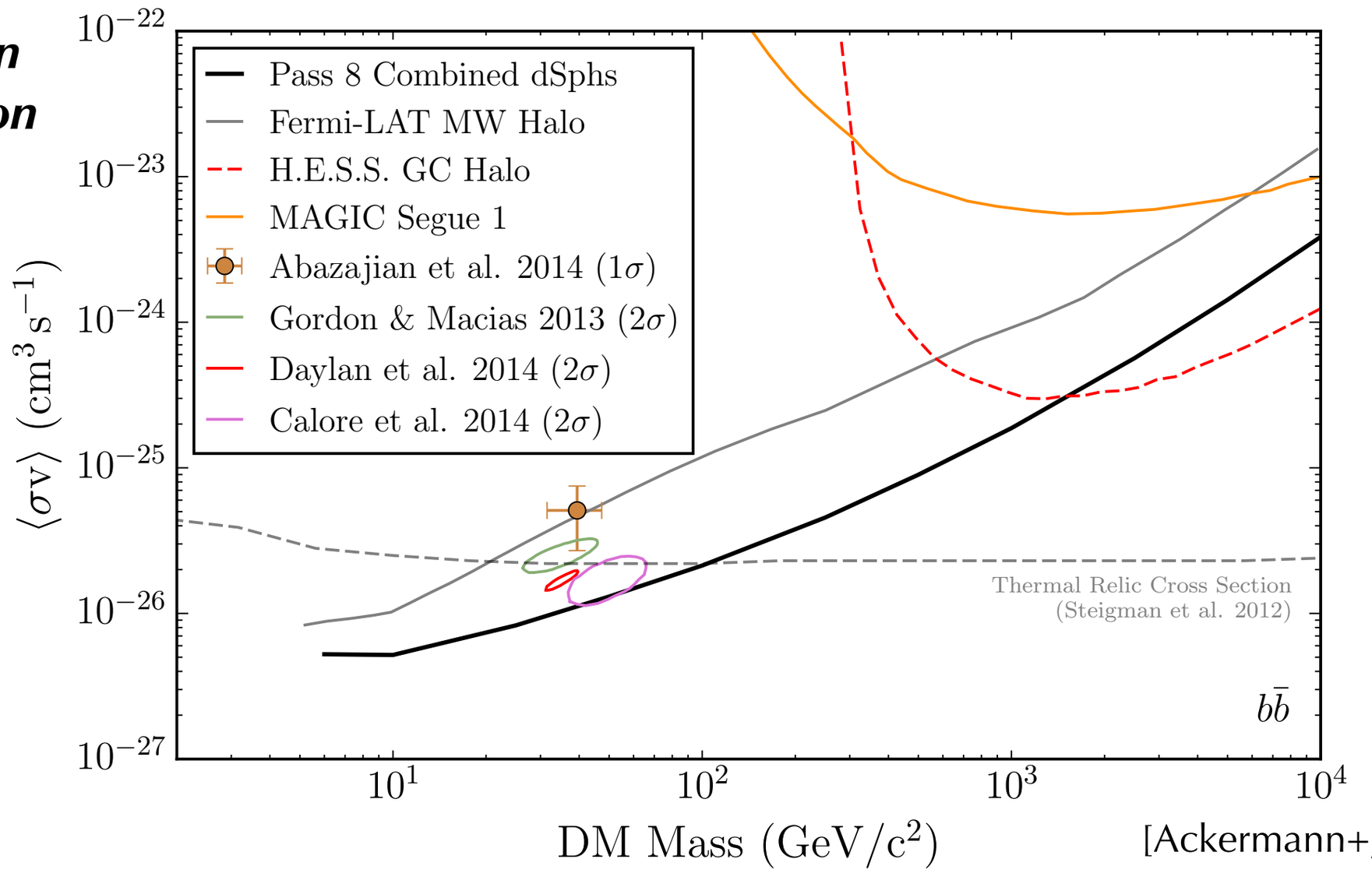
Fermi LAT analysis method:

- construct the **joint likelihood**, combining info from:
  - *15 dSphs*
  - *all photon angular resolution information*
  - *line-of-sight uncertainties ('J factor')*

    (caveat Ullio+, 1603.07721)

DM search in dwarf galaxies

annihilation cross section



[Ackermann+, 1503.02641]

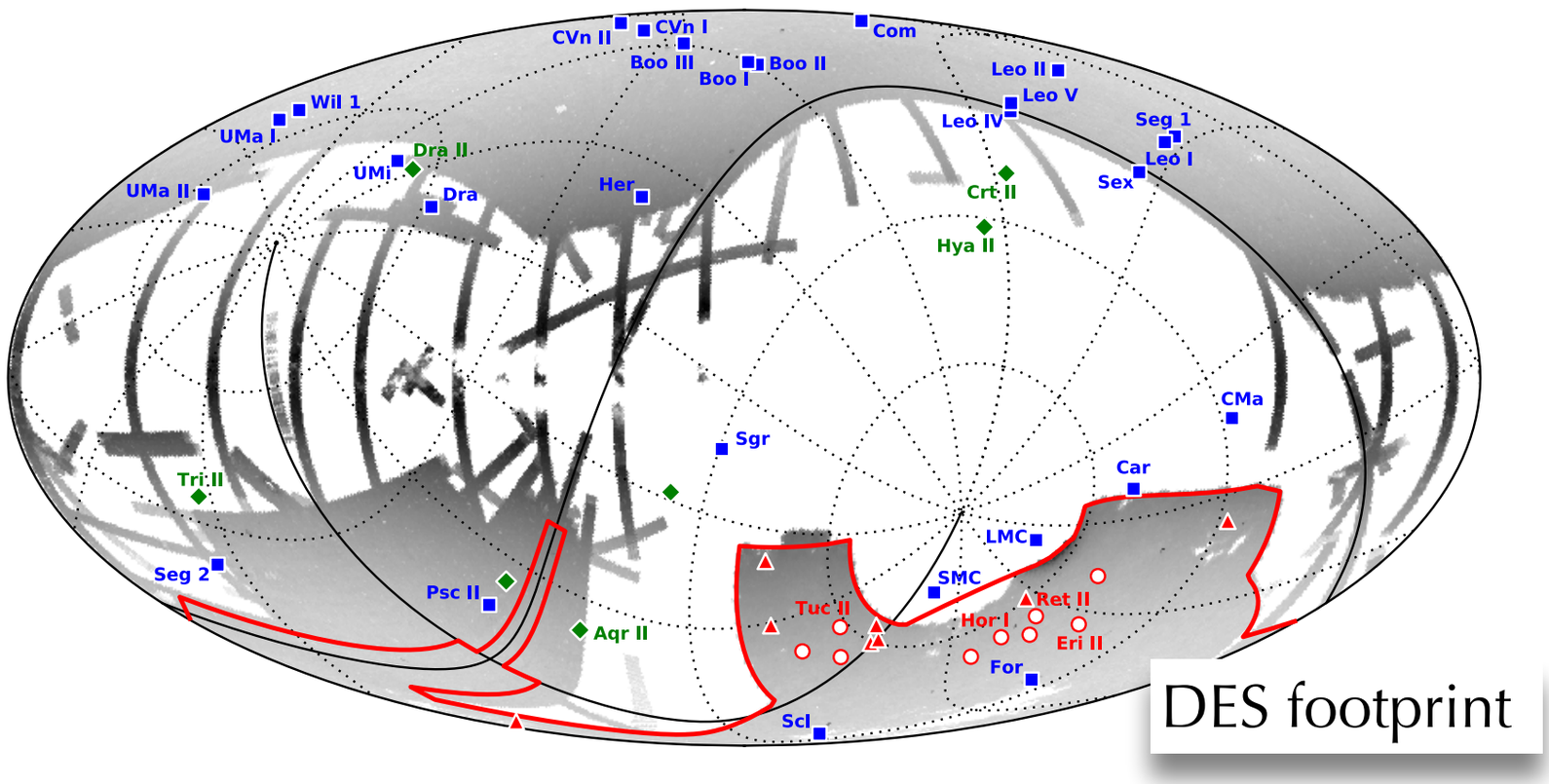
One of the strongest DM limits to date

GCE dark matter origin in tension with complementary gamma ray observations

DM search in dwarf galaxies

More targets coming up!

>20 new dSph candidates reported since 2015 (DES, PANSTARSS)

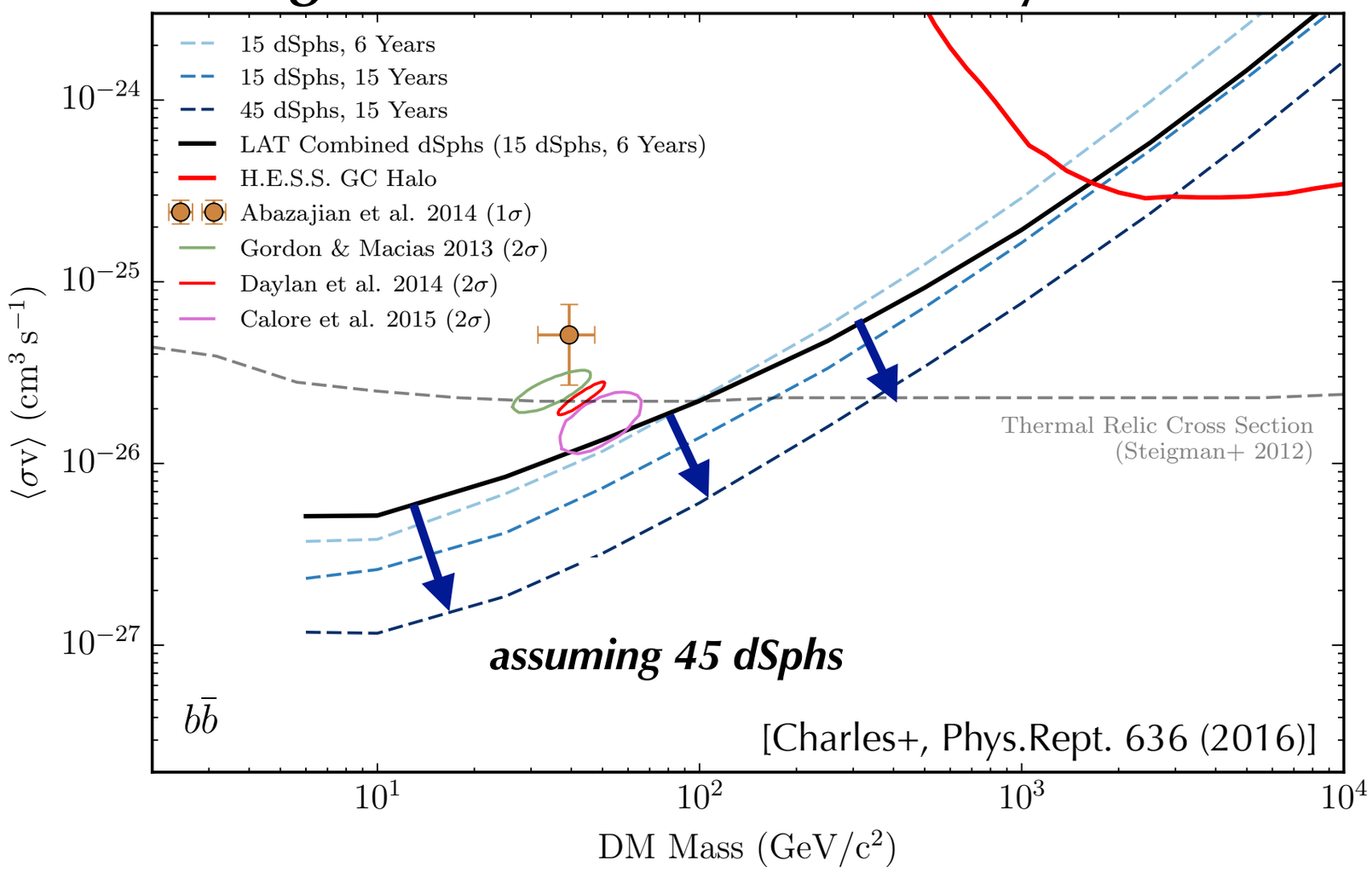


- 1st year of DES: No significant gamma ray emission in the direction of the 8 new dSphs (local significance of 2.4σ for Reticulum II dSph, [Drlica-Wagner, 1503.02632])

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

DM search in dwarf galaxies

The situation should get clearer within several years



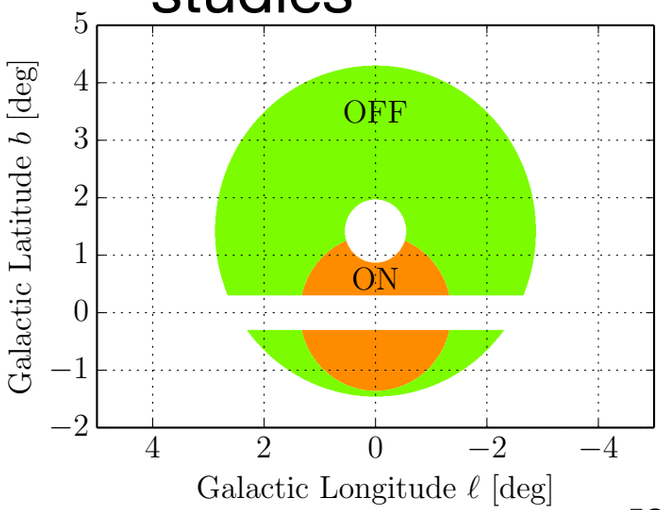
- 2nd year DES/LAT paper (submitted): 28 confirmed and 17 dSph candidates, ***stay tuned!***

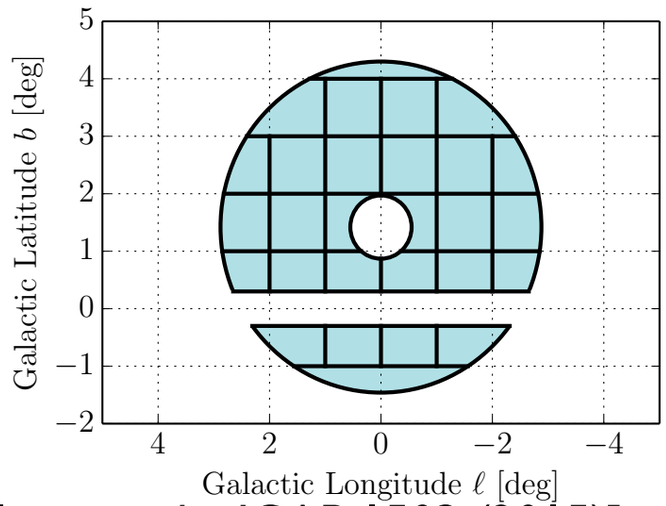
[Bechtol+ 1503.02584, Belokurov+, 1403.3406, Laevens+, 1503.05554]
[Gerringer-Sameth et al. 2015, Hooper & Linden 2015, Li et al. 2016]

CTA @ the Galactic centre

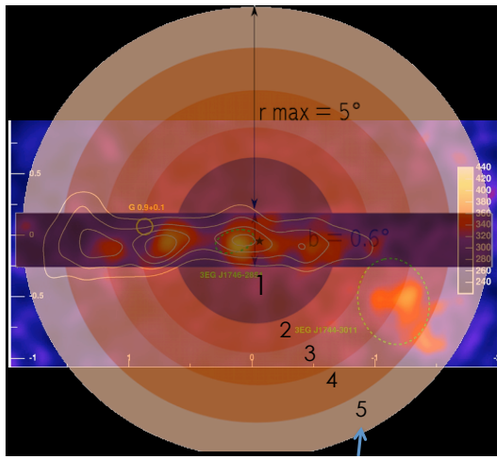
Exploration of the most promising techniques and strategies ongoing:

- CR backgrounds: traditional 'ring background' method vs 2D likelihood morphology studies





[Silverwood+, JCAP 1503 (2015)]



[Lefranc+, Phys.Rev. D91 (2015)]

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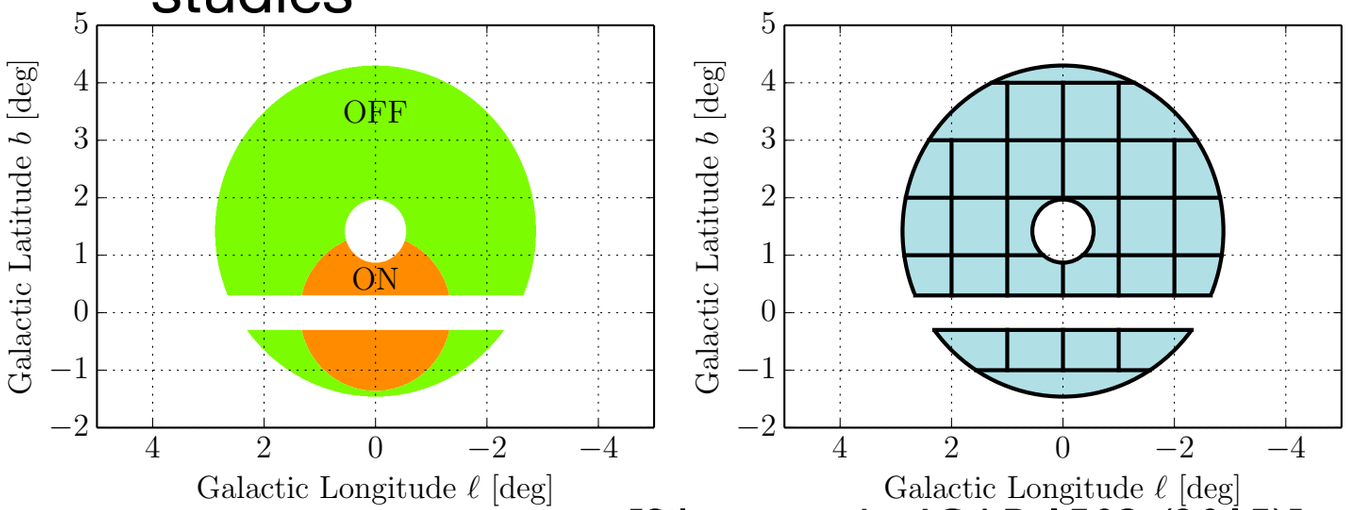
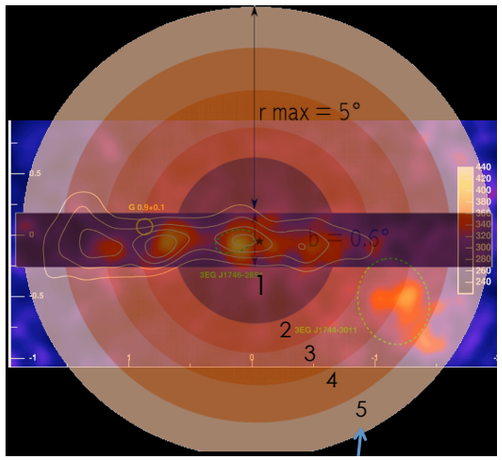
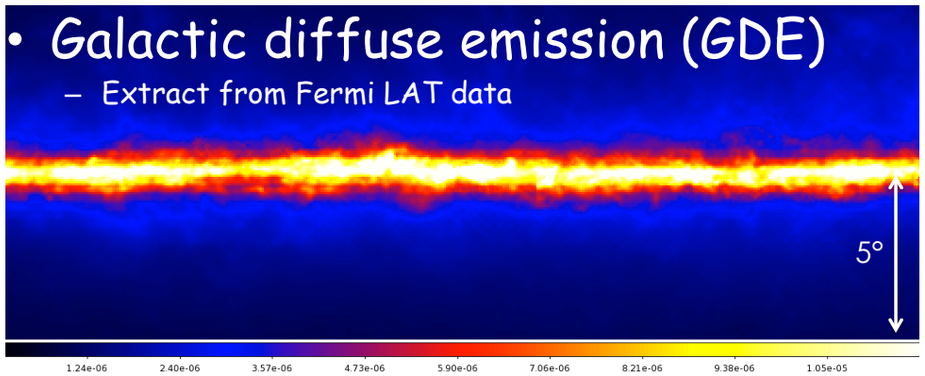


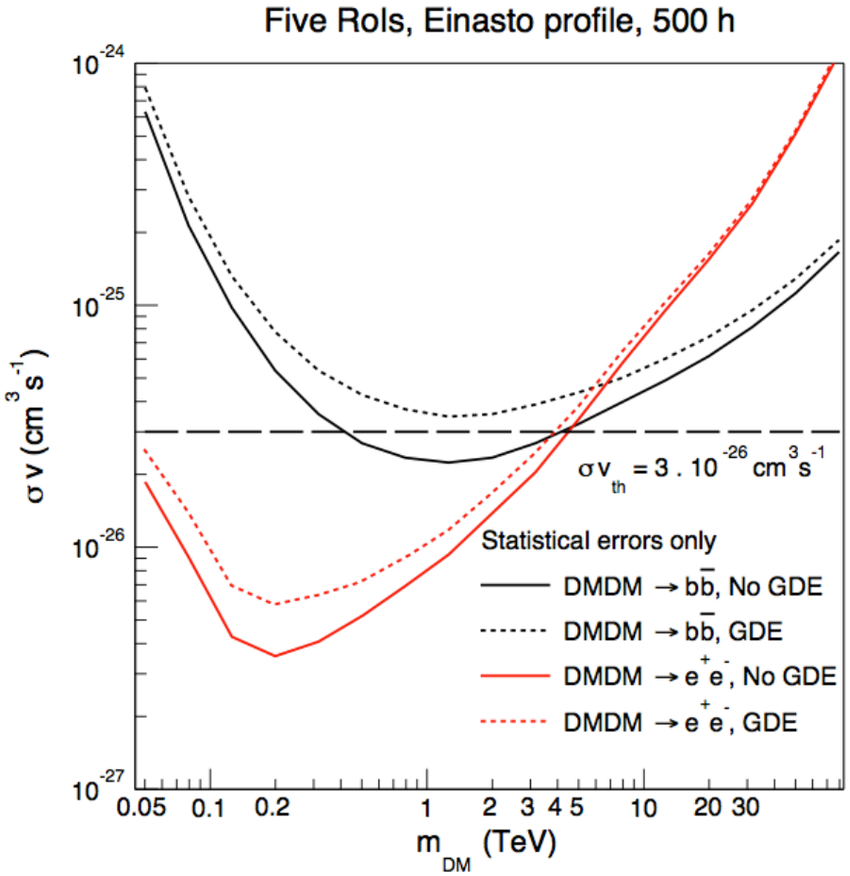
[Silverwood+, JCAP 1503 (2015)]



[Lefranc+, Phys.Rev. D91 (2015)]

- impact of Galactic diffuse emission





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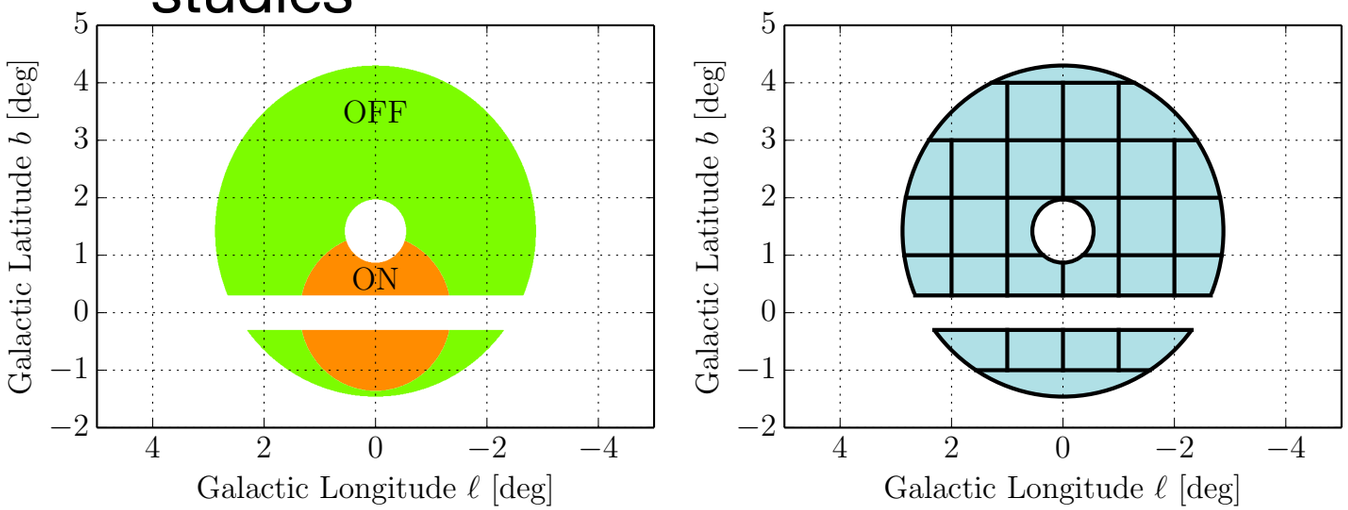
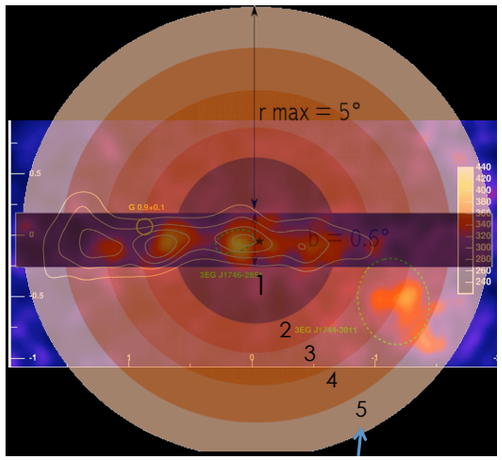
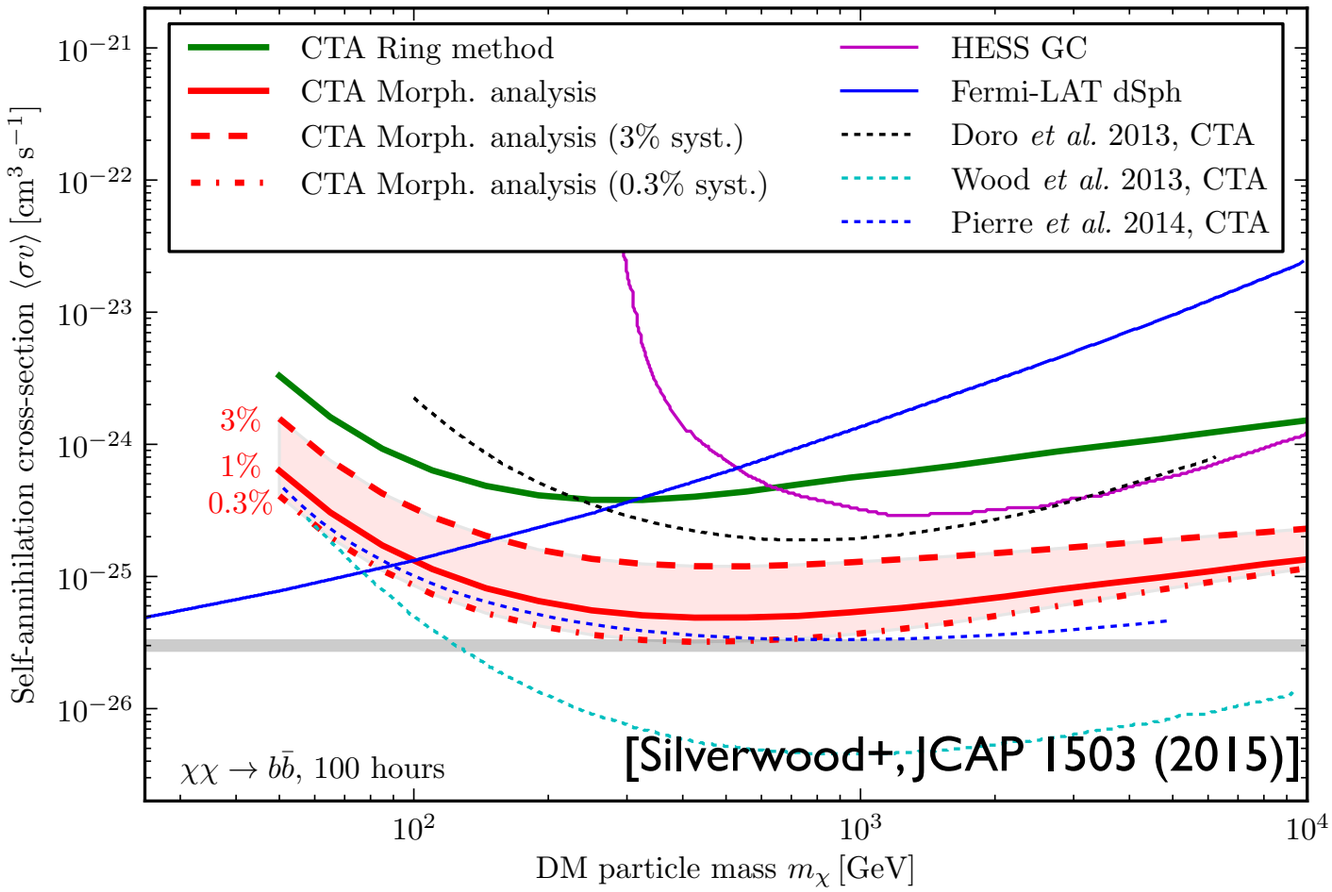




[Lefranc+, Phys.Rev. D91 (2015)]

- impact of Galactic diffuse emission
- instrumental systematics



[Silverwood+, JCAP 1503 (2015)]

CTA @ the Galactic centre

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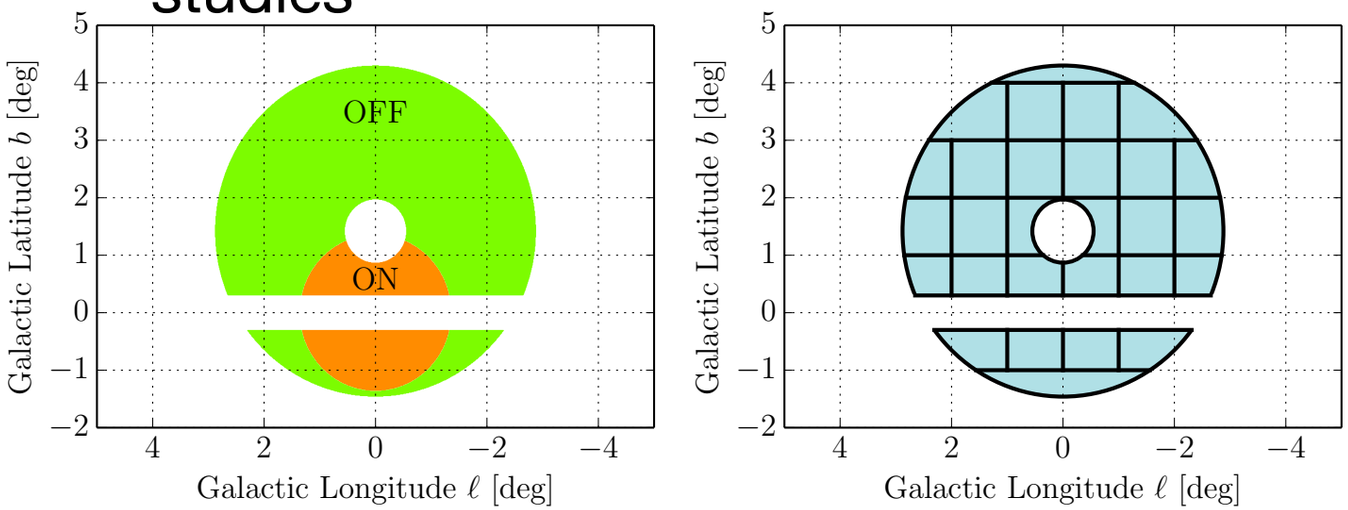

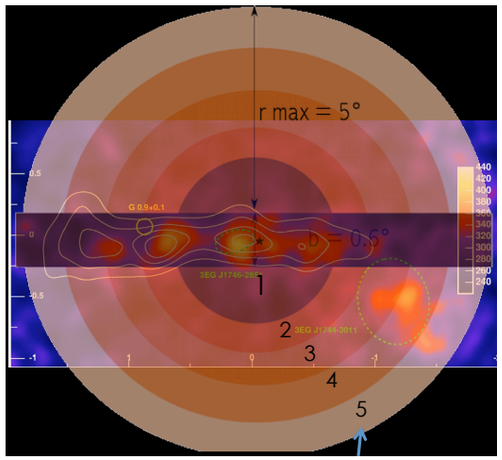

[Lefranc+, Phys.Rev. D91 (2015)]

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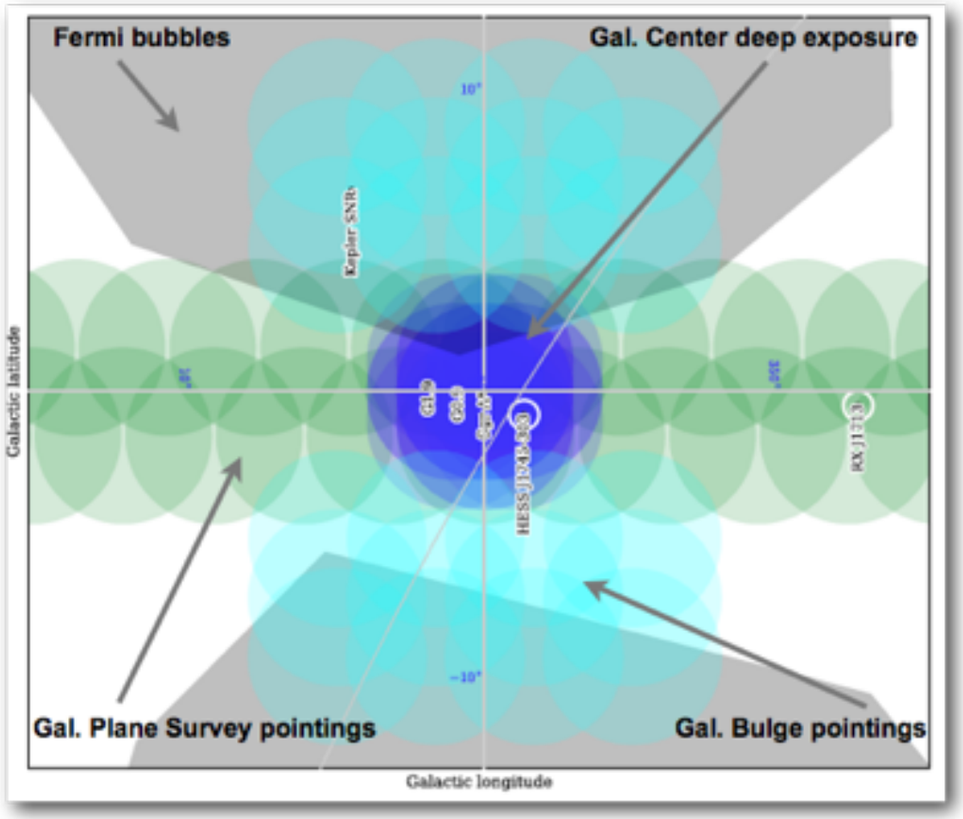
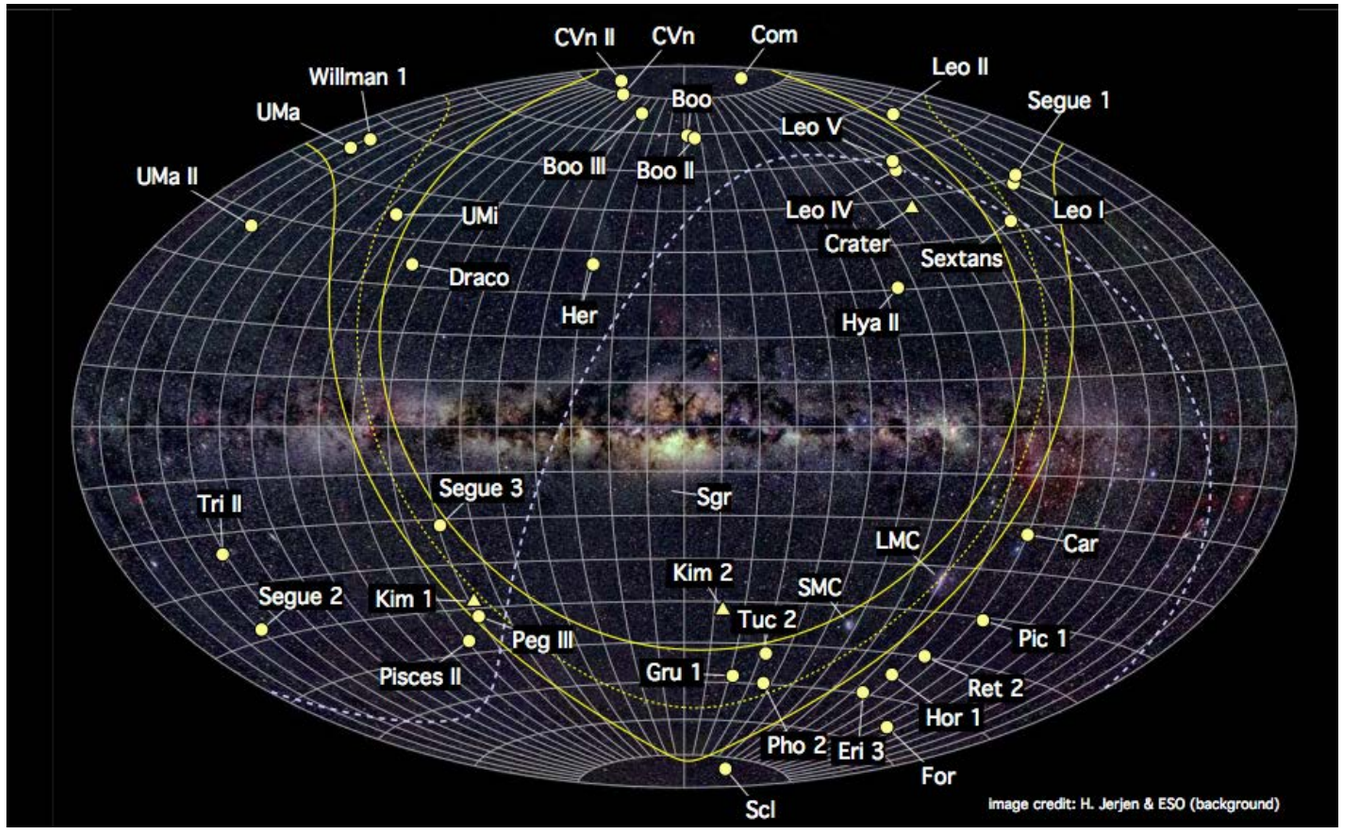
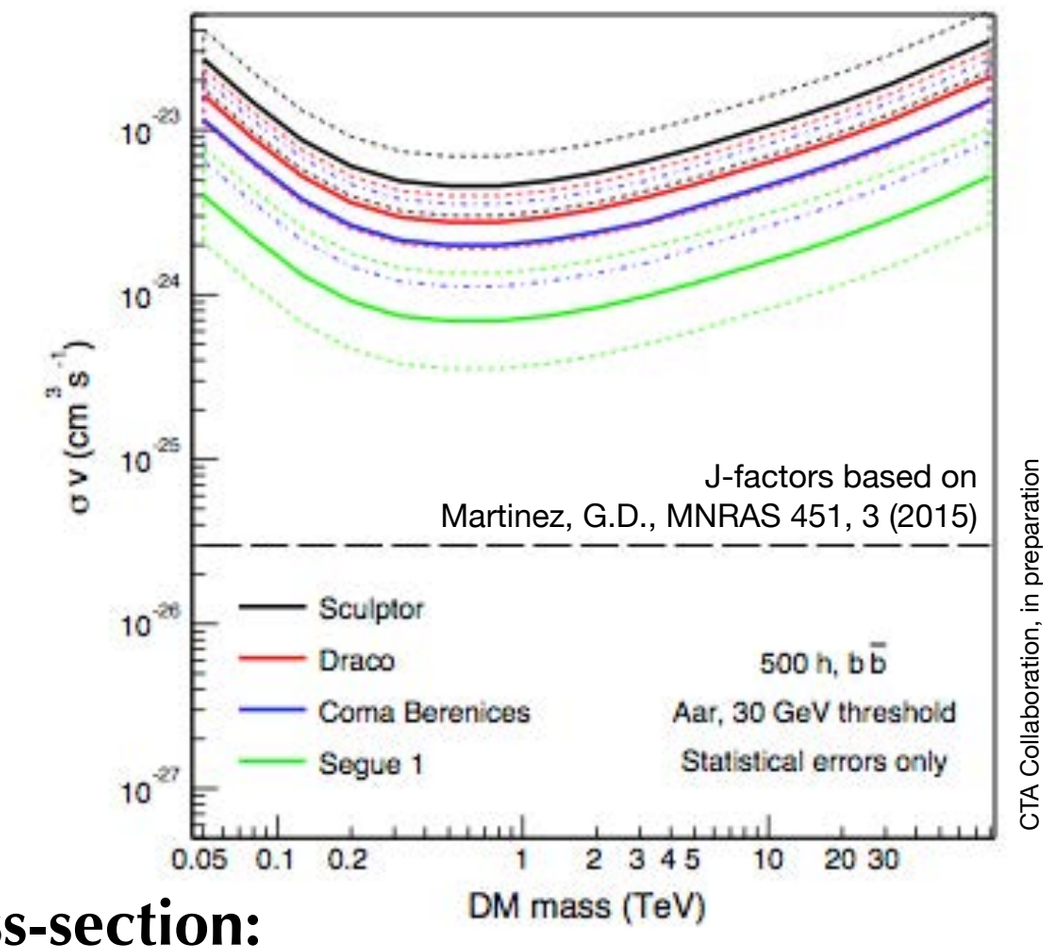


Work within the collaboration to quantify these effects and devise the best observational strategies, for the latest telescope configurations ongoing

CTA @ the dSphs

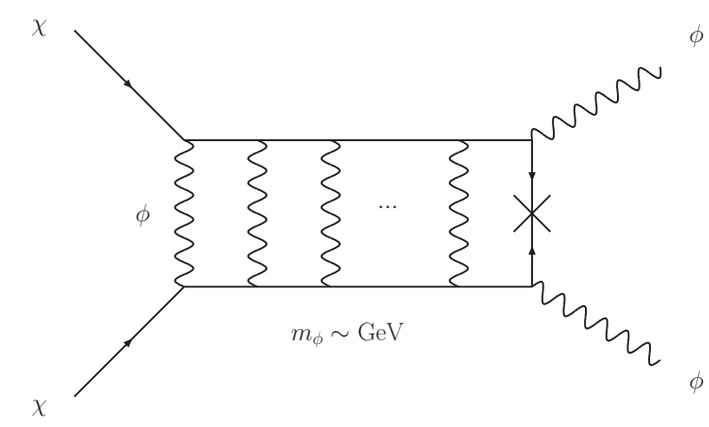




Expected sensitivity does not reach the thermal cross-section:

- sensitive to models with significant Sommerfeld enhancement (TeV dark matter) [e.g. Hisano+, 2008; Abazajian+ 2012; Bringmann+, 2014; Garcia-Cely+, 2016; …] α/v

Current plan: focus on the most promising dSph target



CTA @ spectral lines

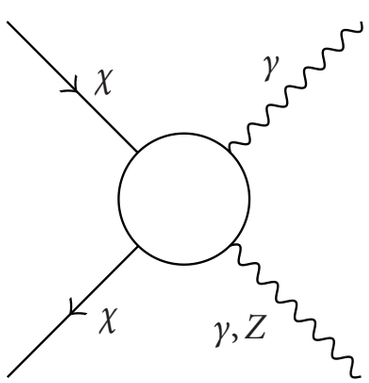
CTA excellent energy resolution — high sensitivity to spectral line search!

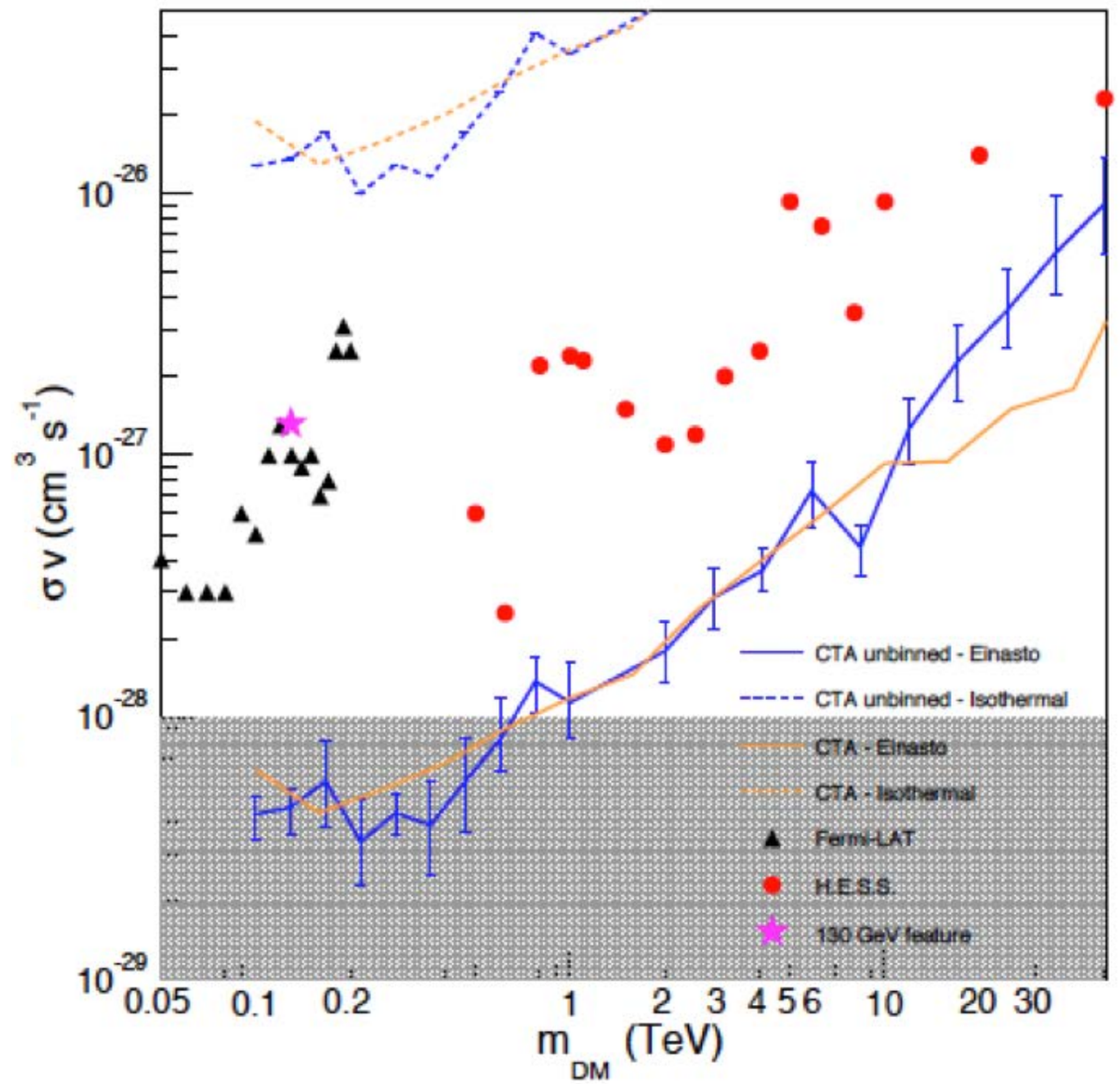
- data within a circle of 1 deg radius around the center

- standard astrophysical emission taken into account as background

- sensitivity improvement by a factor of ~10 expected

Line signal (loop level $\mathcal{O}(\alpha^2)$)

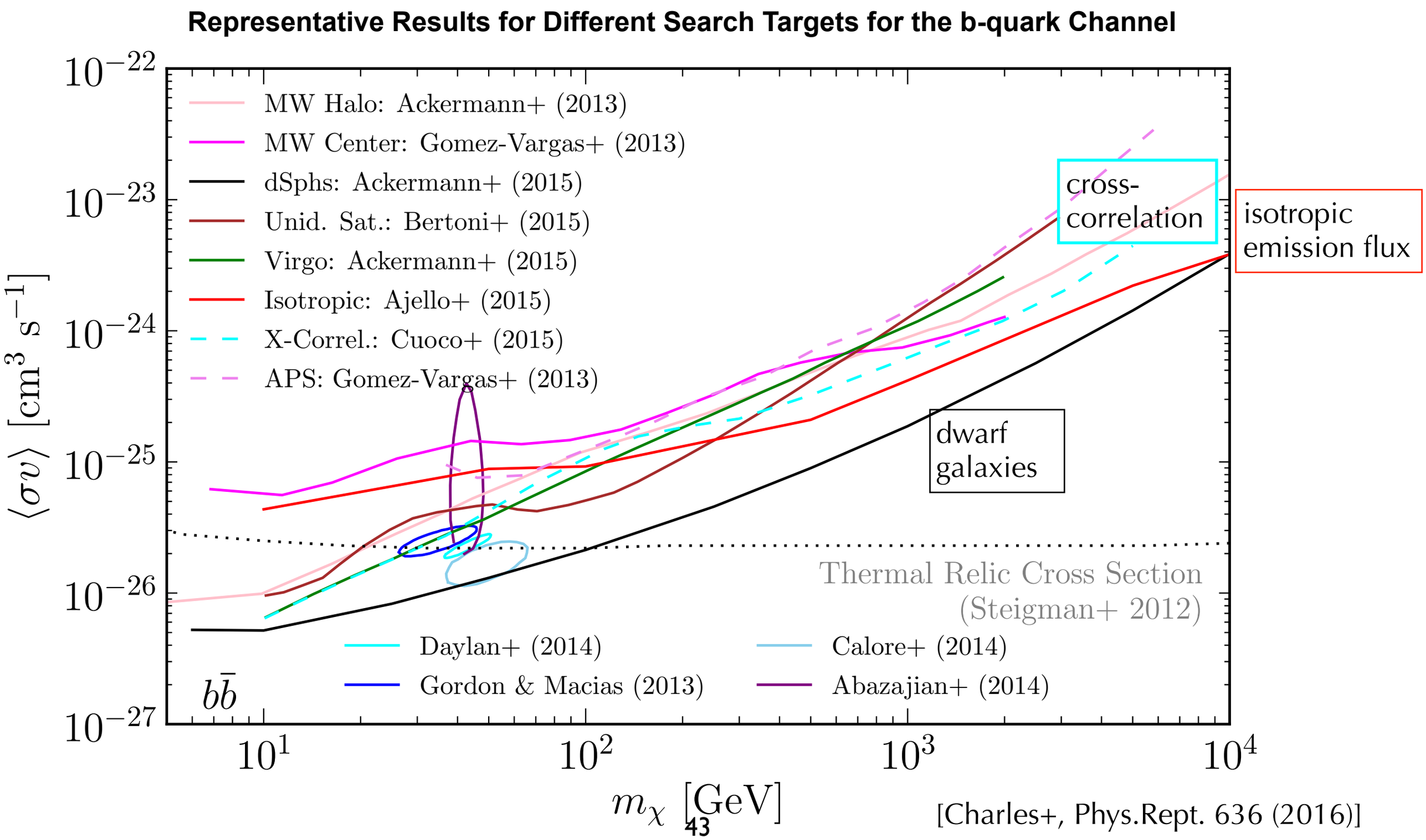




CTA Collaboration, in preparation

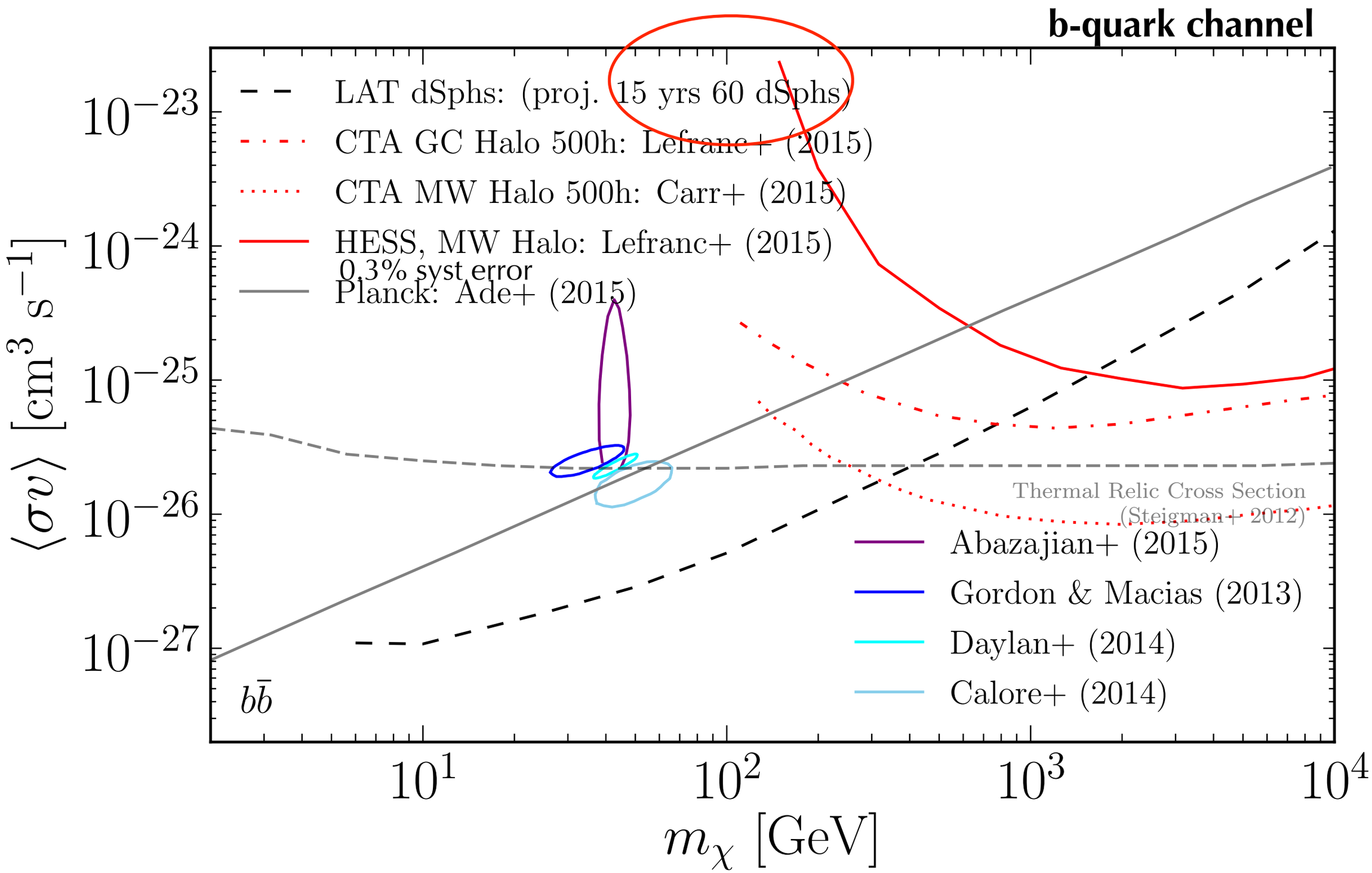
Outlook - LAT looks at many DM targets!

Many interesting analysis approaches, increasingly competitive constraints



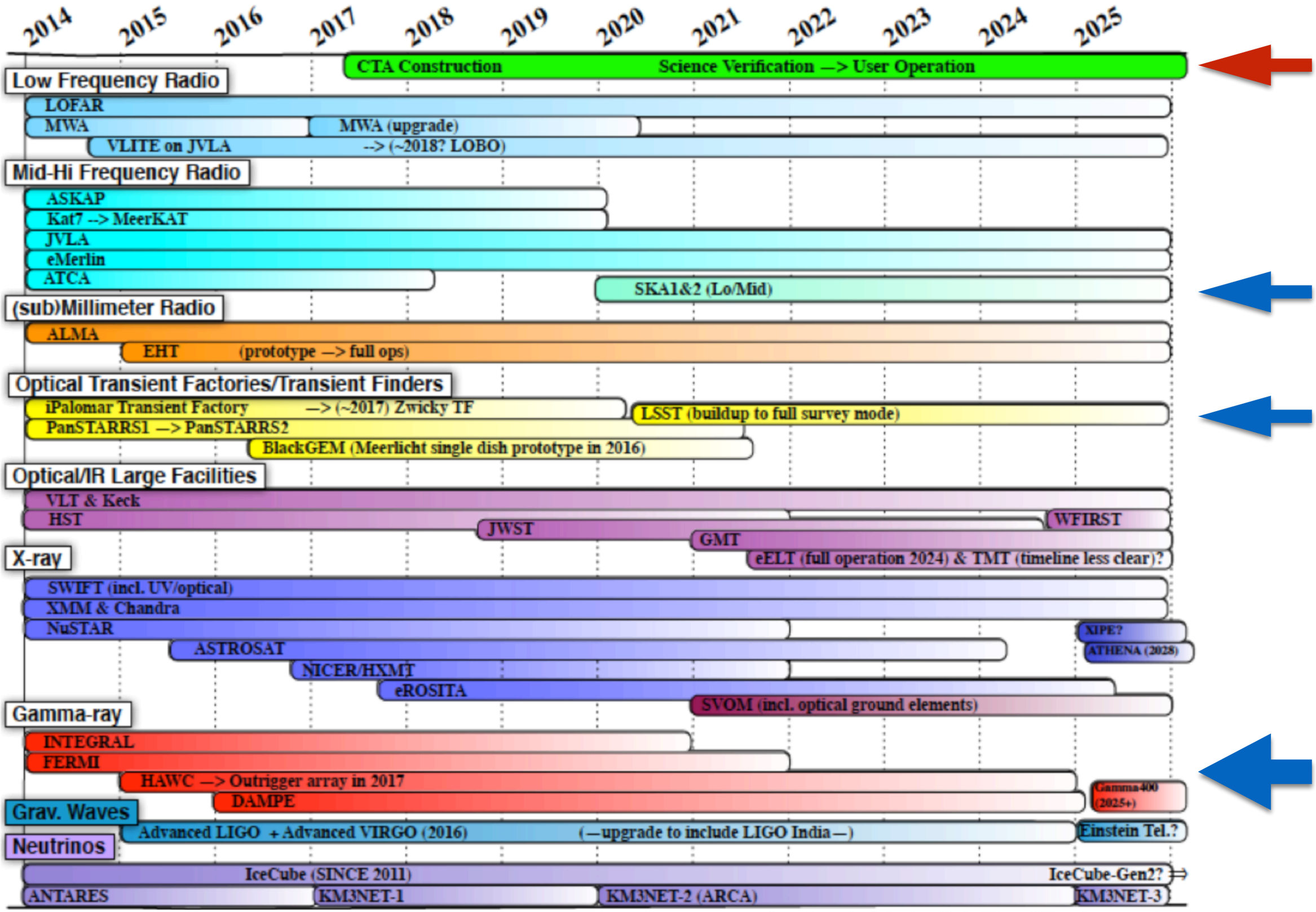
[Charles+, Phys.Rept. 636 (2016)]

Outlook - LAT & CTA



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

Future?



Credits: S. Markoff & The CTA Consortium

Future?

CTA as an open observatory — fun for all!

Key Science Programmes

- Ensure that important science questions for CTA are addressed in a coherent fashion and with a well-defined strategy,
- Conceived to provide legacy data sets for the entire community

Example: galactic and extragalactic surveys

- Deep investigation of known sources
- Follow-up of KSP discovered sources
- Multiwavelength campaigns
- Follow-up of ToOs from other wavebands / messengers
- Search for new sources
- ...

Proposal-Driven User Programme

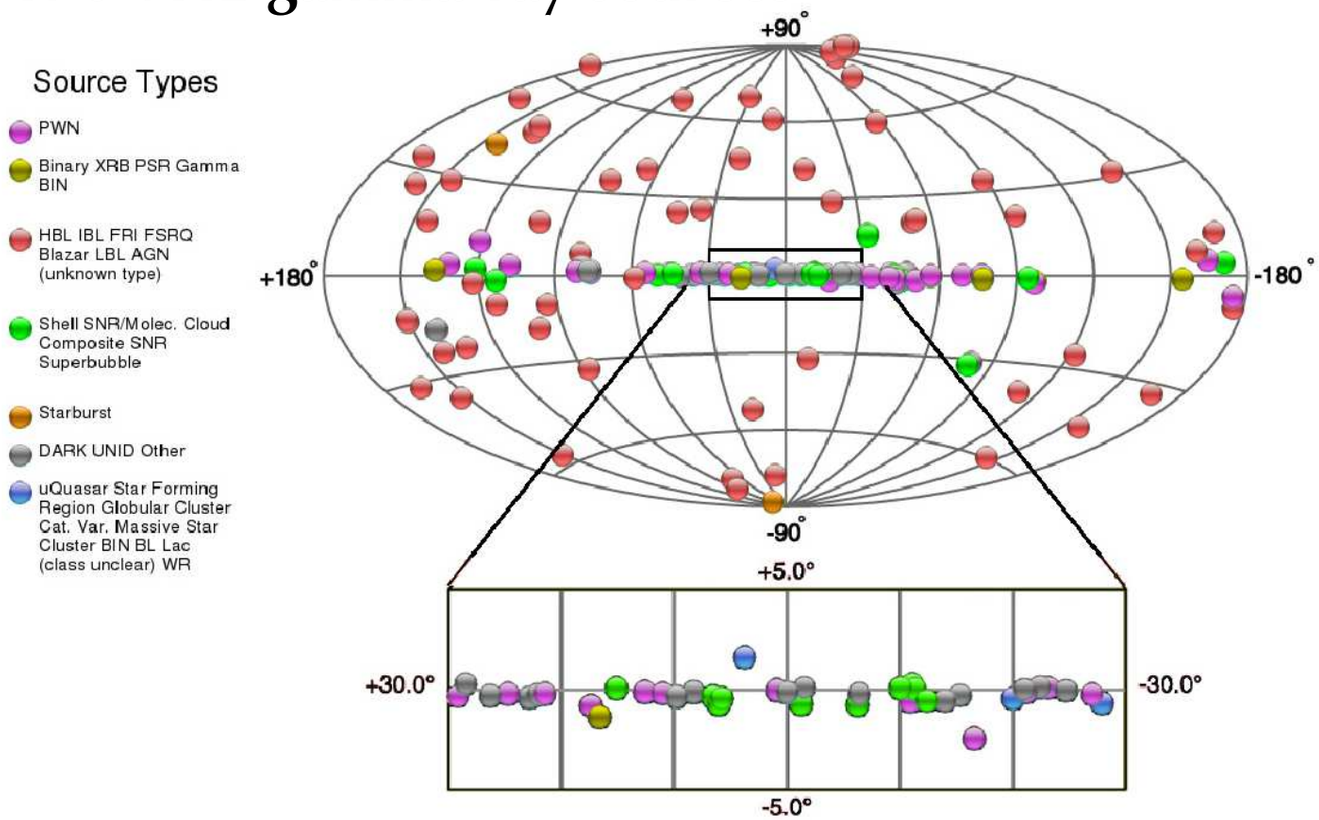
Credits: W. Hofmann and The CTA Consortium

Extra Slides

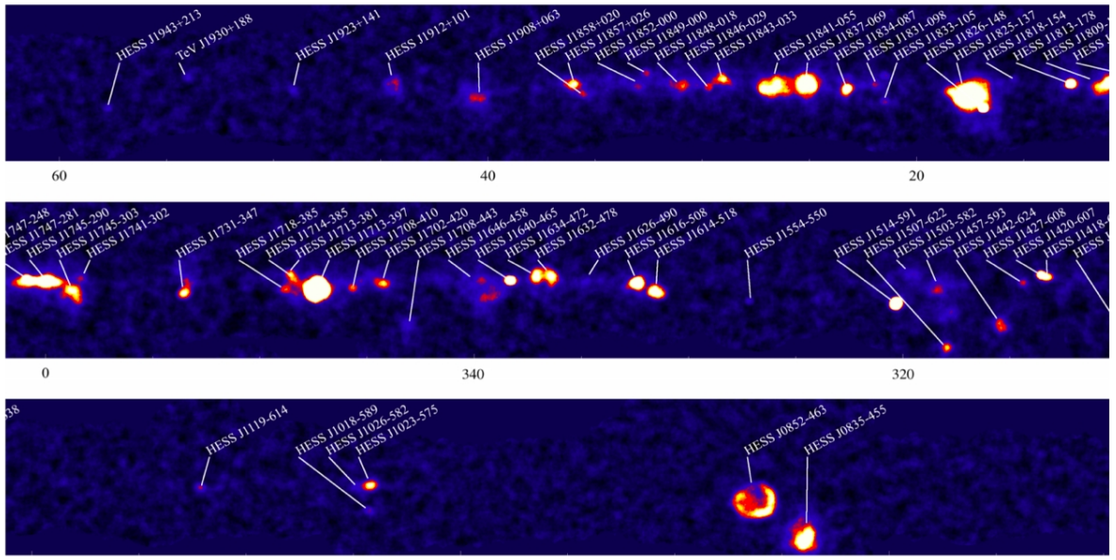
The TeV sky

IACTs are pointing telescopes!

170 VHE gamma-ray sources

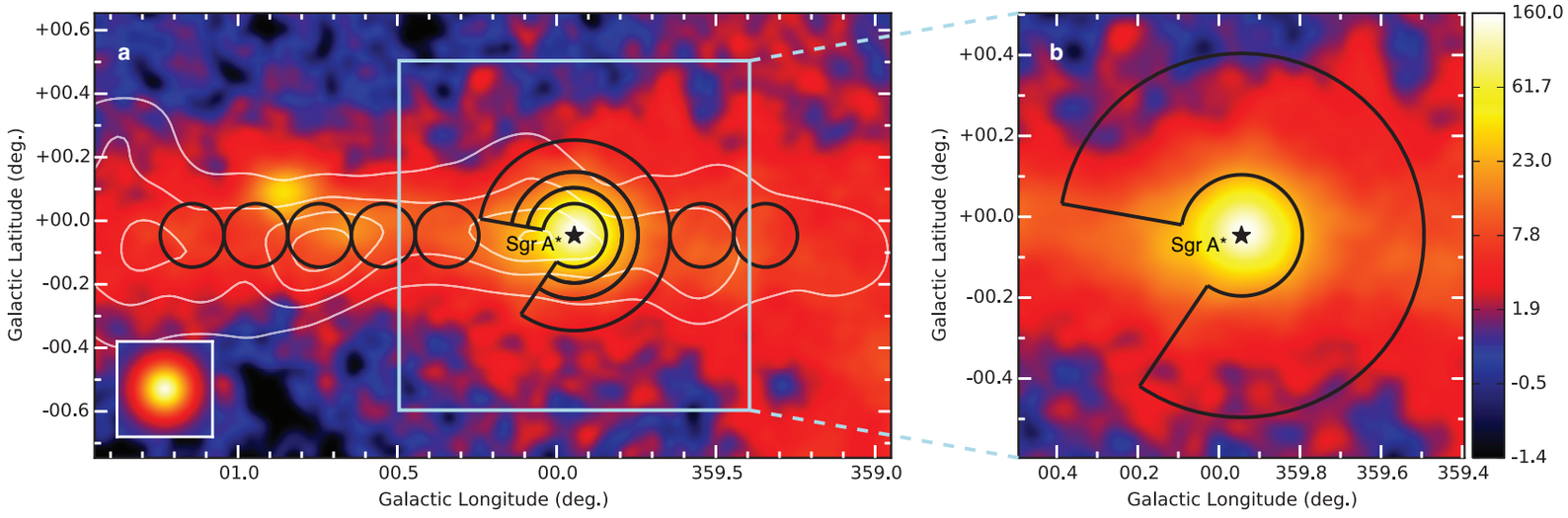


2nd Galactic plane survey, H.E.S.S.

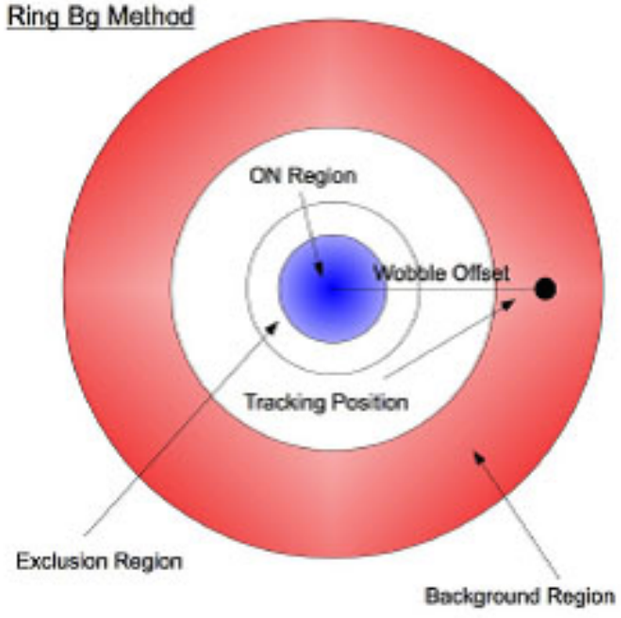


H.E.S.S. Collaboration, 2016

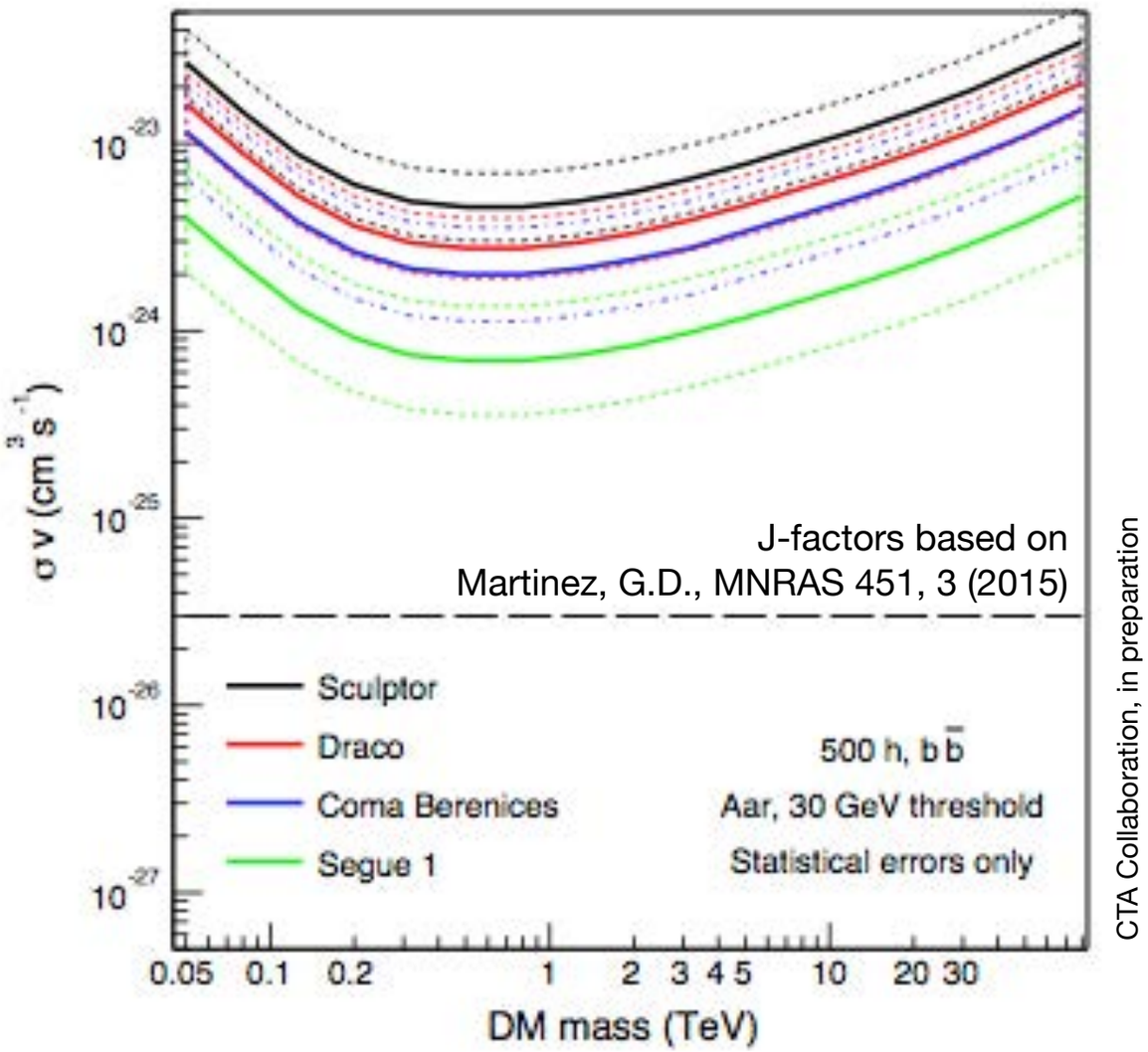
Extended emission from the Galactic centre ridge



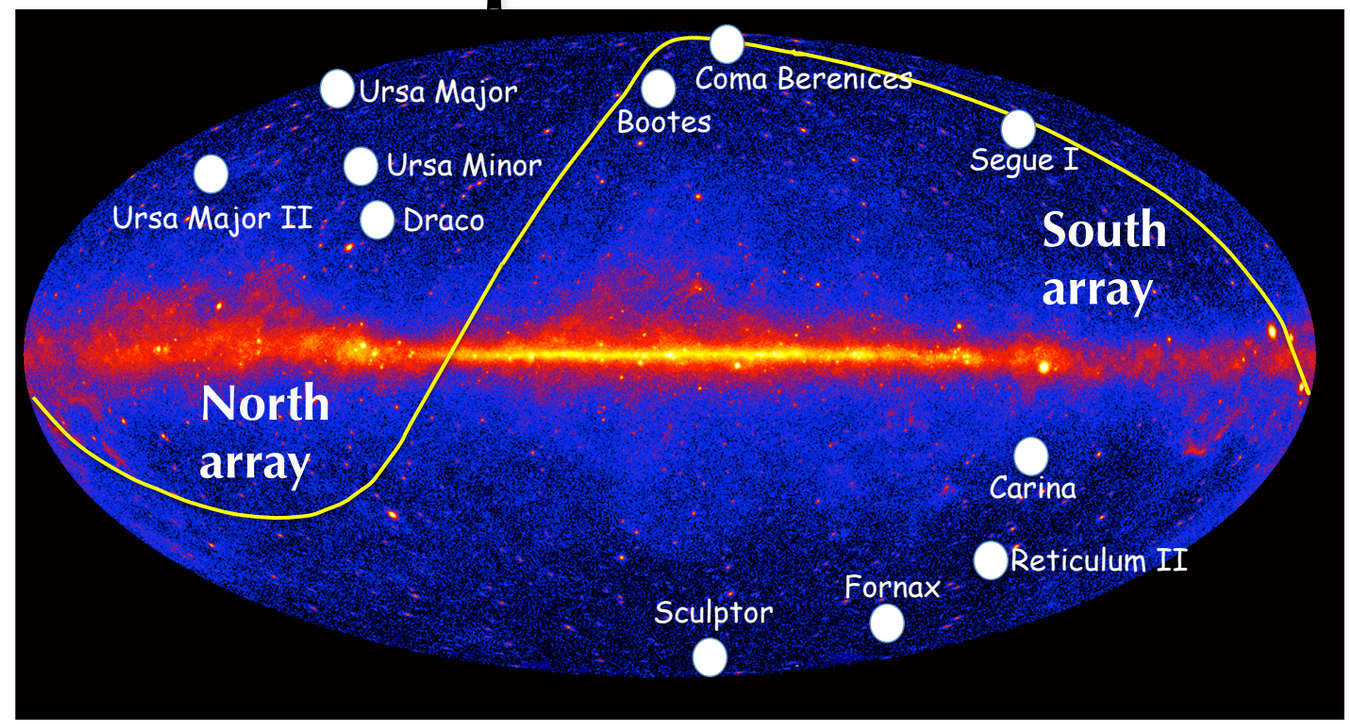
H.E.S.S. Collaboration, Nature, 2016

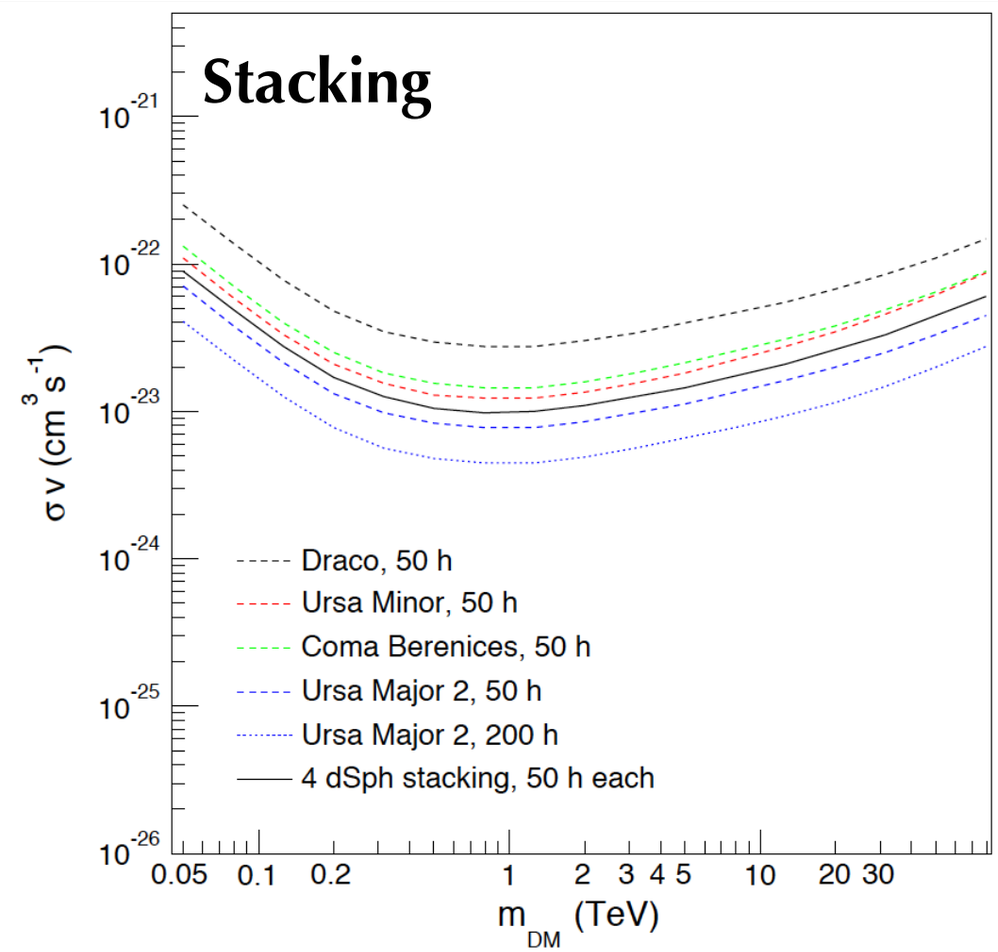


CTA @ the dSphs



CTA Collaboration, in preparation

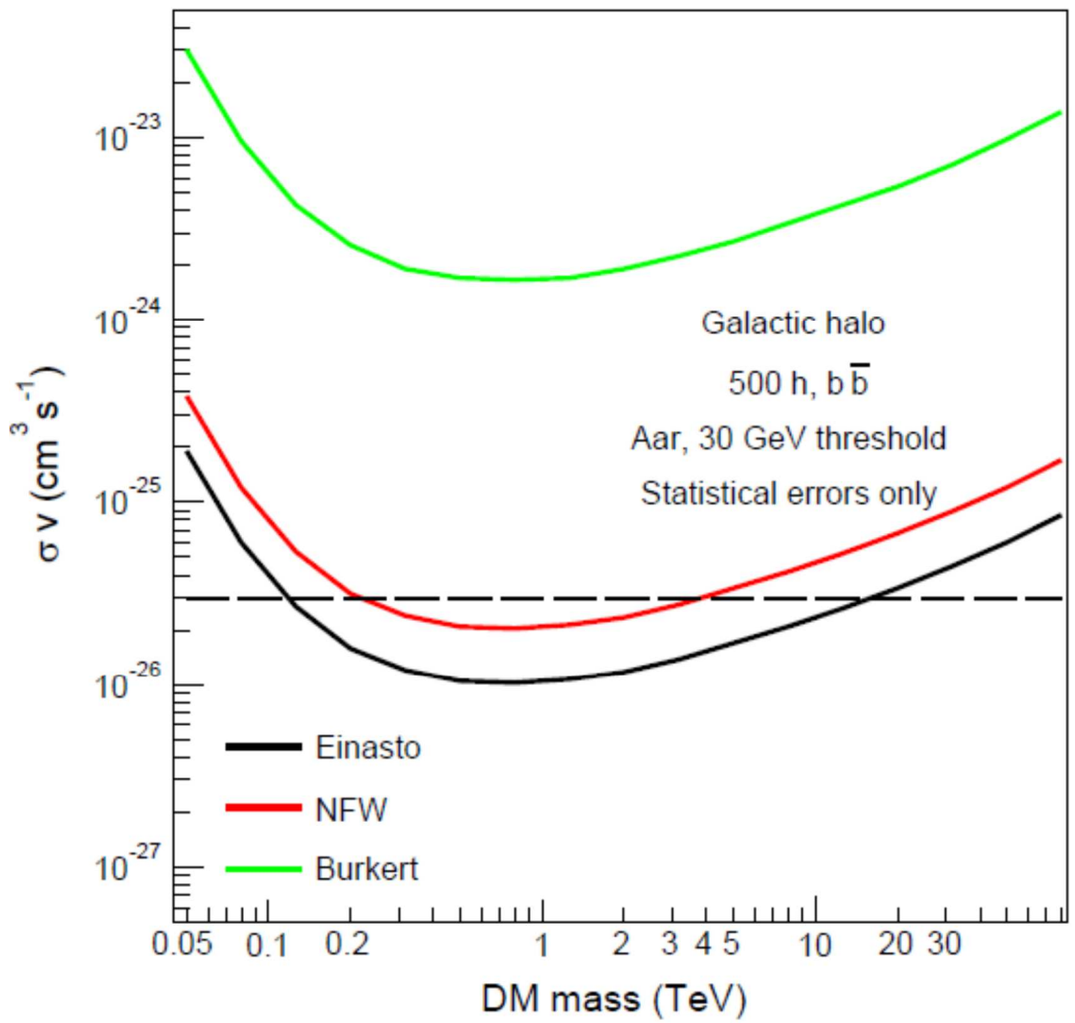




arxiv:1605.02793

Current plan: focus on the most promising target

CTA @ GC


Galactic halo
500 h, b b̄
Aar, 30 GeV threshold
Statistical errors only
Einasto
NFW
Burkert
σ v (cm³ s⁻¹)
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷
0.05
0.1
0.2
1
2
3
4
5
10
20
30
DM mass (TeV)

the DM signal:

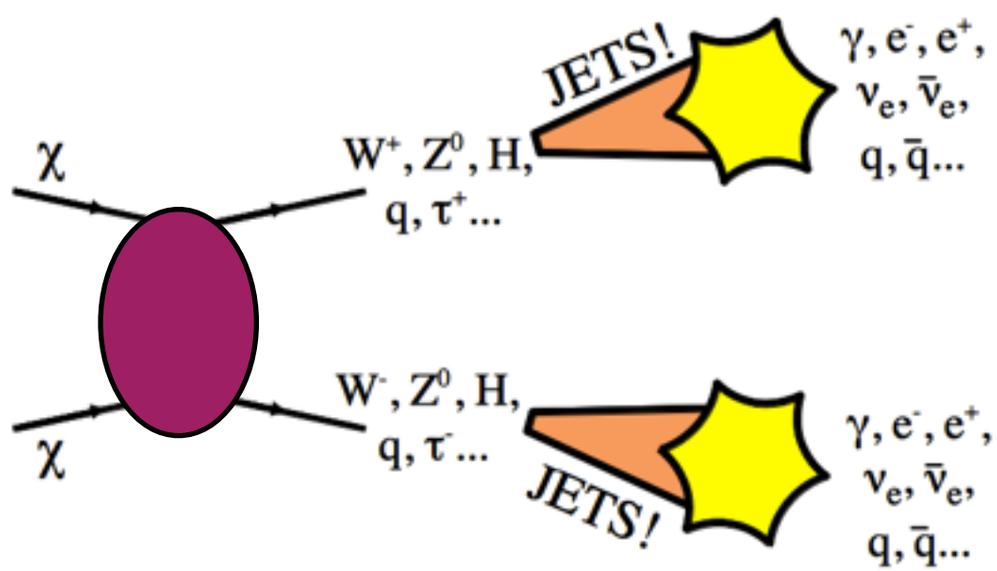
particle physics

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!

flux of SM particles per DM annihilation



simulation of hadronic showers (e.g. PYTHIA)

the DM signal:

particle physics

cosmology

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

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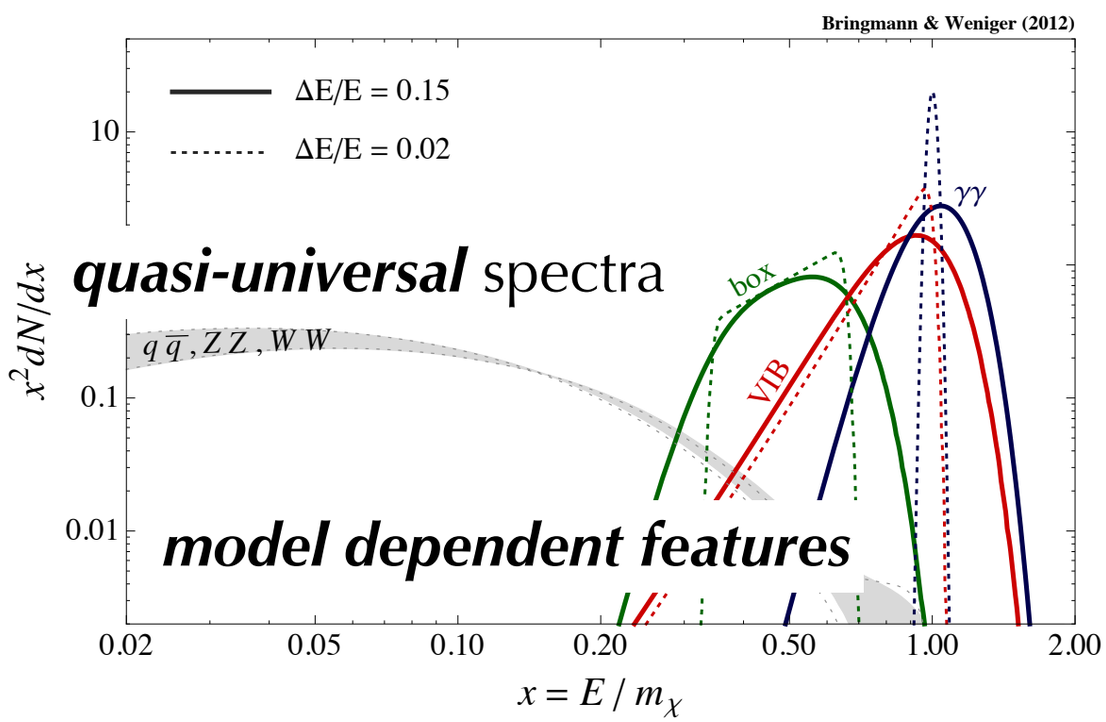
flux of SM particles per DM annihilation



quasi-universal spectra

model dependent features

the DM signal:

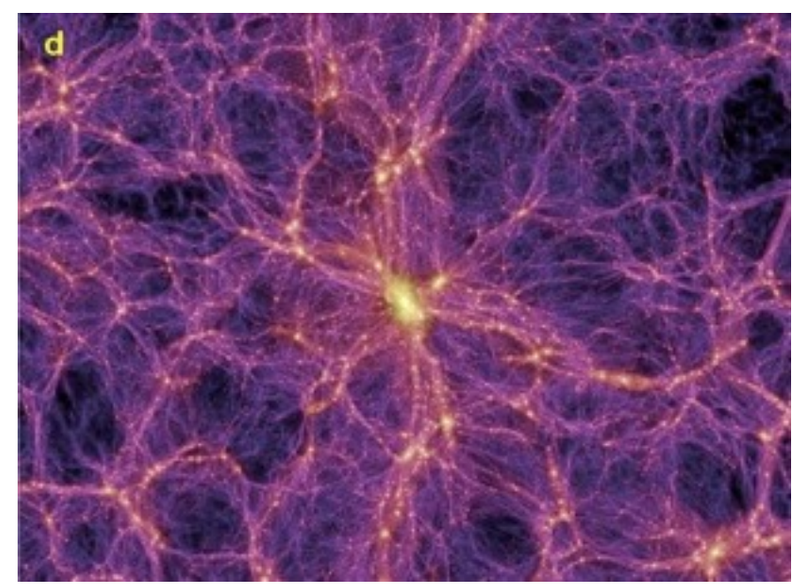
particle physics

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!

integrated DM density squared along the line of sight



from N-body simulations of matter clustering (e.g. Millenium simulation)

the DM signal:

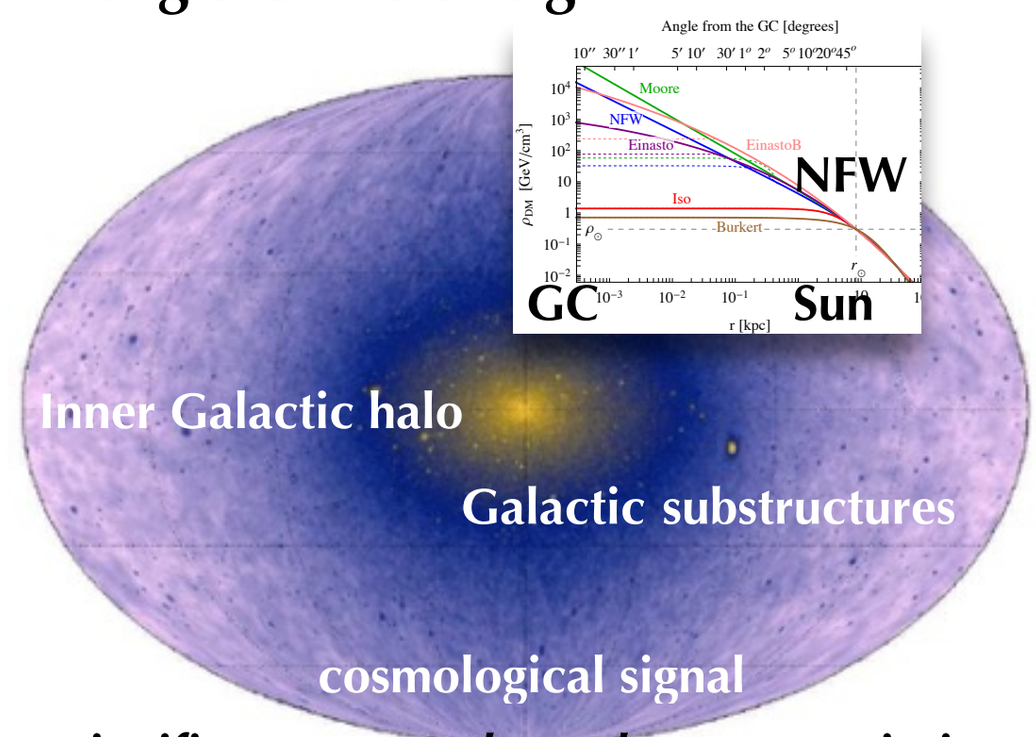
particle physics

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!

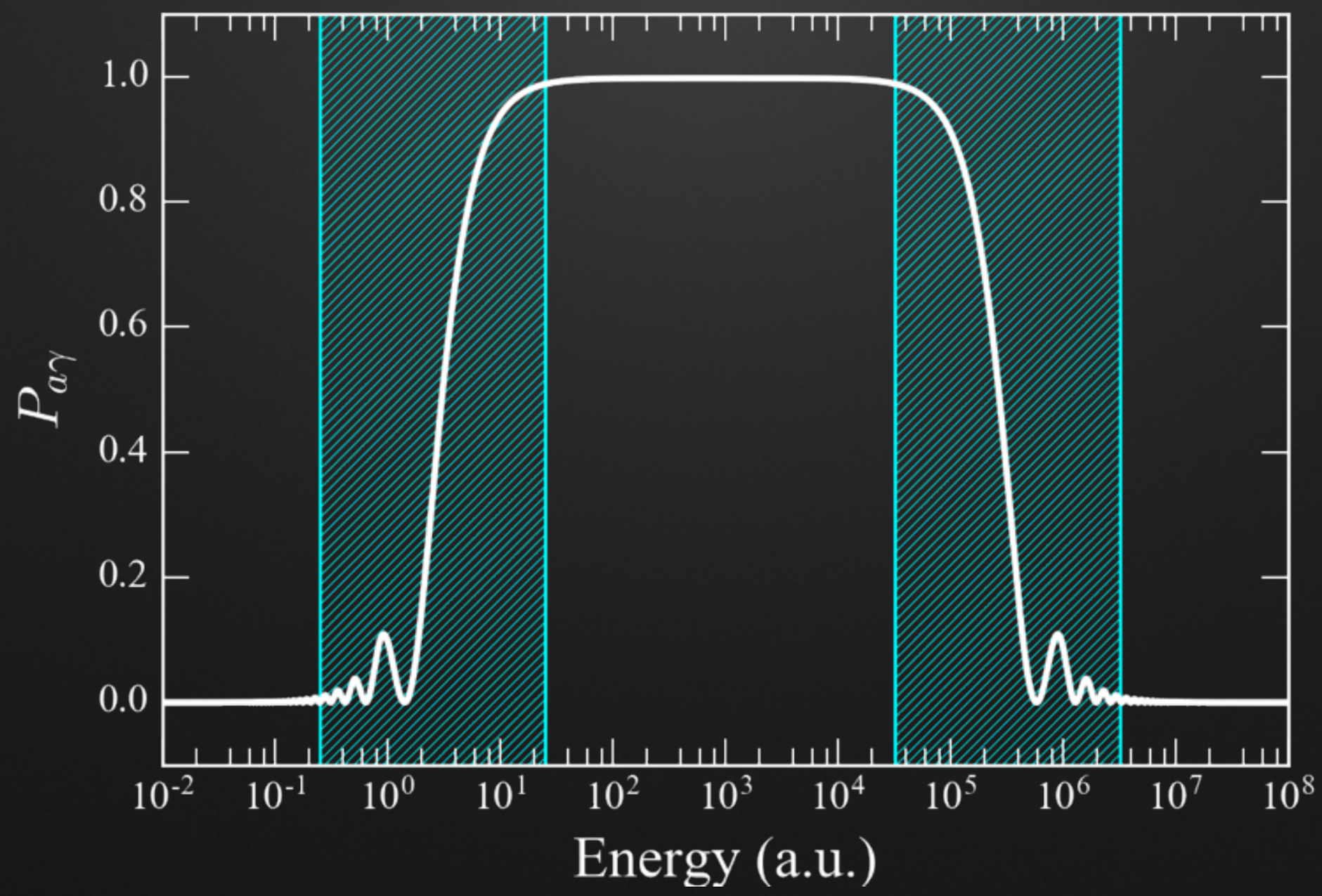
integrated DM density squared along the line of sight



significant, target dependent uncertainties

PHOTON-AXION/ALP MIXING

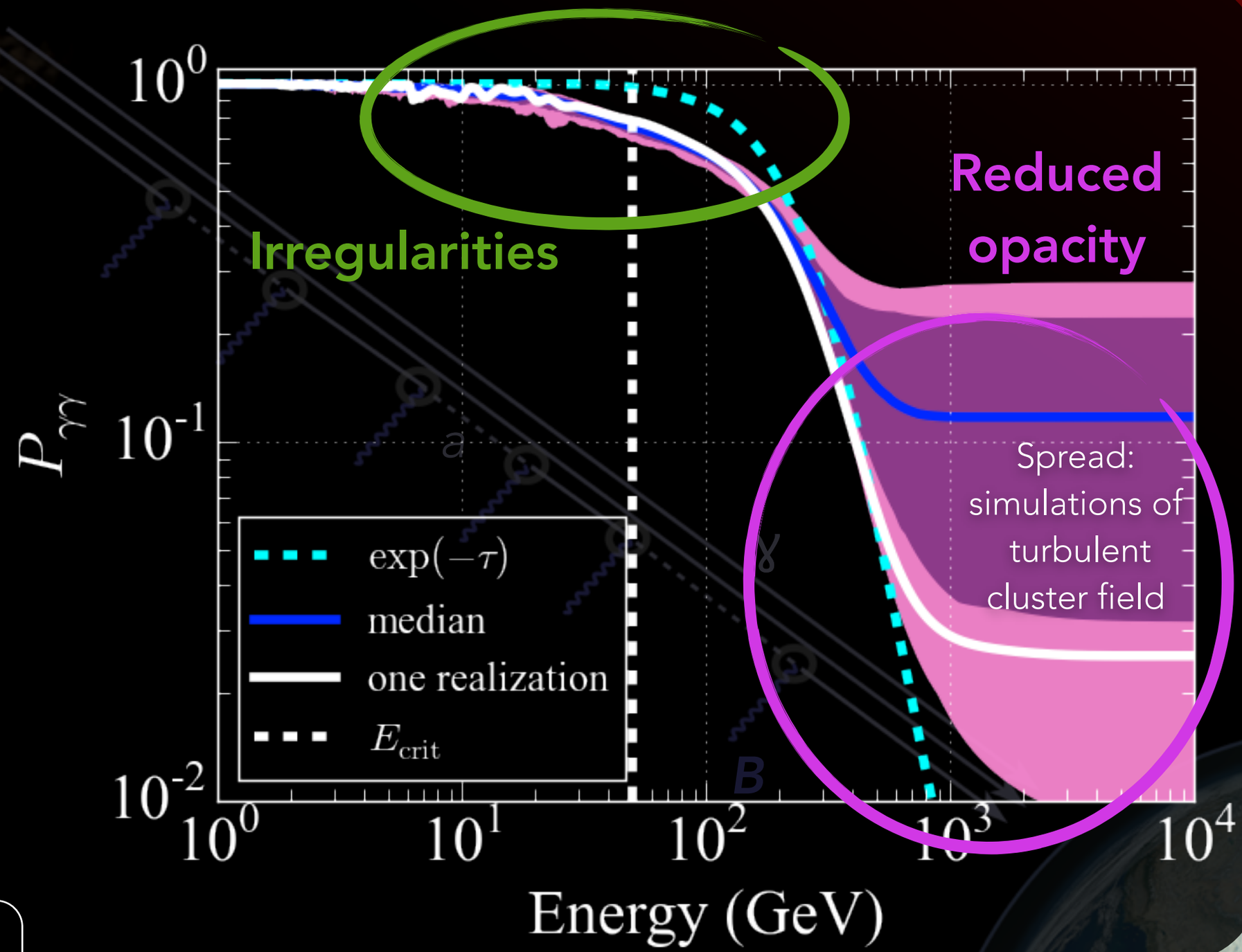
2nd Observable: irregularities in energy spectrum around E_{crit} and E_{max}



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]

EXAMPLE: MIXING IN GALAXY CLUSTER & MILKY WAY



$z = 0.4$
$g_{11} = 5$
$m_{\rm neV} = 10$

Credit: M. Meyer

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
- Rotation measures: **central** B field ~**25μG** [Taylor+ 2006]
- **B ≳ 2 μG from non-observation of γ rays** [Aleksic et al. 2012]

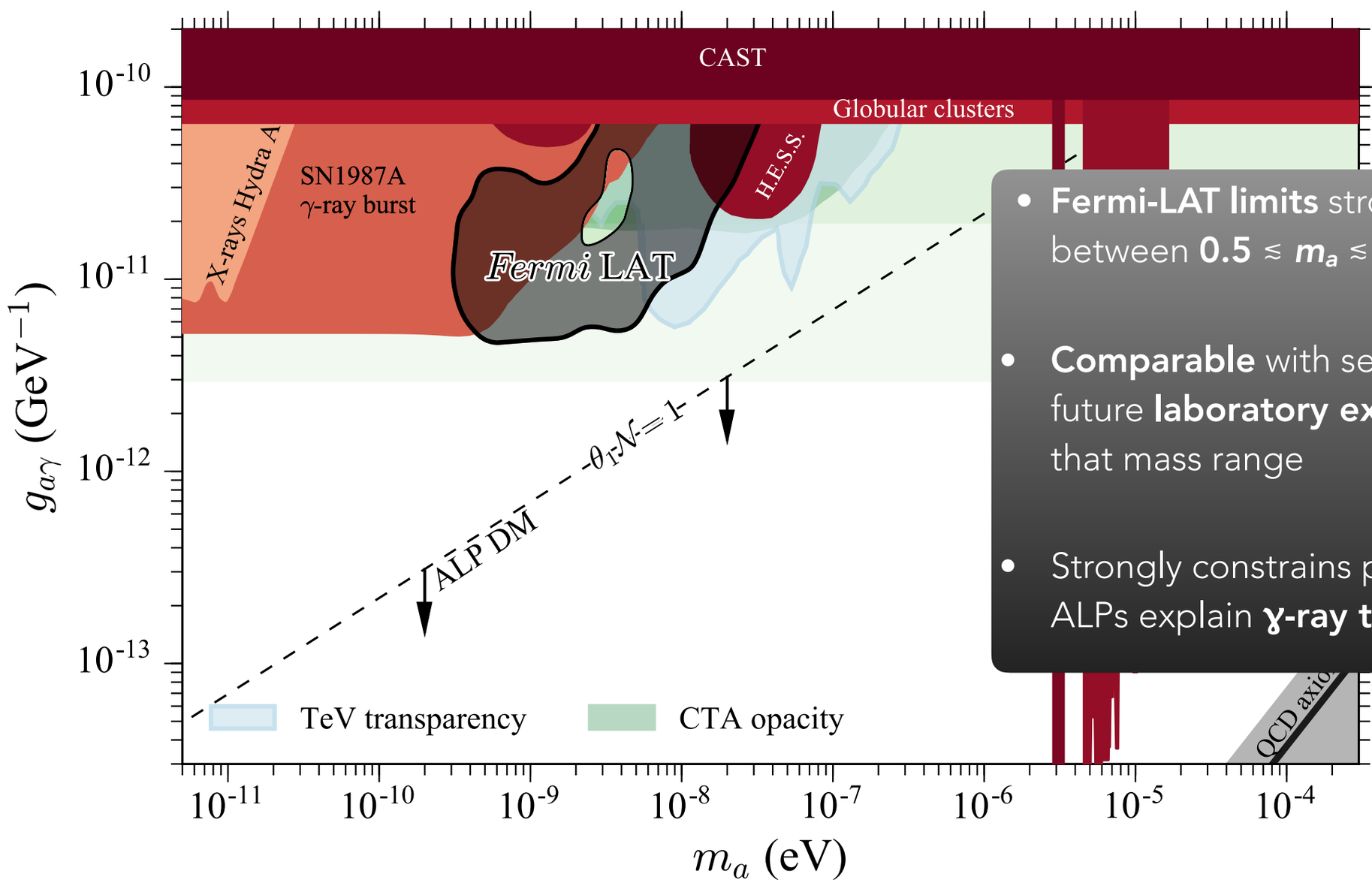

Credit: M. Meyer

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

Credit: M. Meyer

LIMITS

SENSITIVITIES



- **Fermi-LAT limits** strongest to date between **0.5 ≲ m_a ≲ 20 neV**
- **Comparable** with sensitivity of future **laboratory experiments** in that mass range
- Strongly constrains possibility that ALPs explain **γ-ray transparency**

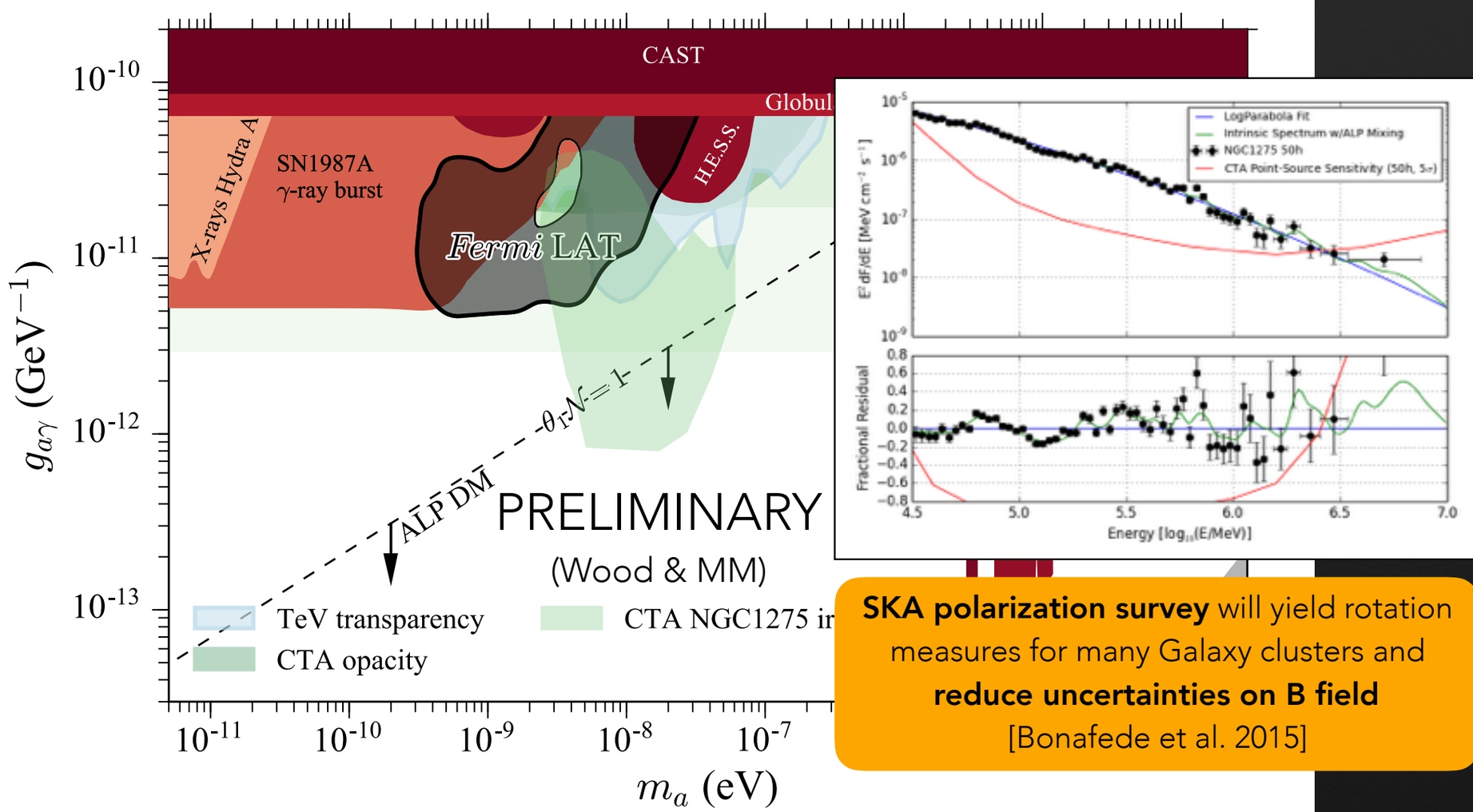
QCD Axion: $m_a \approx 0.3\,\mathrm{eV}\,\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} = 0.3\,\mathrm{eV}\,g_{10}$

Credit: M. Meyer

CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES



SKA polarization survey will yield rotation measures for many Galaxy clusters and **reduce uncertainties on B field** [Bonafede et al. 2015]