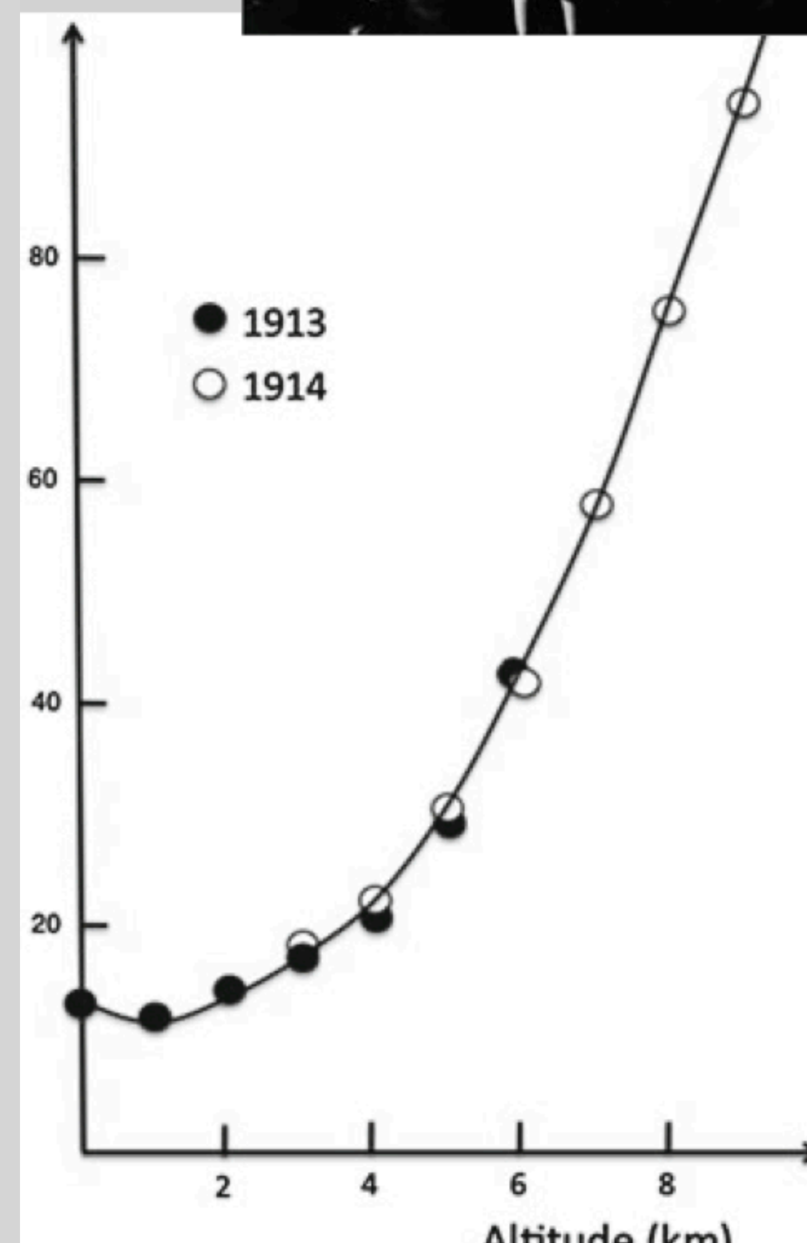
The gamma-ray sky
- surprises and insights

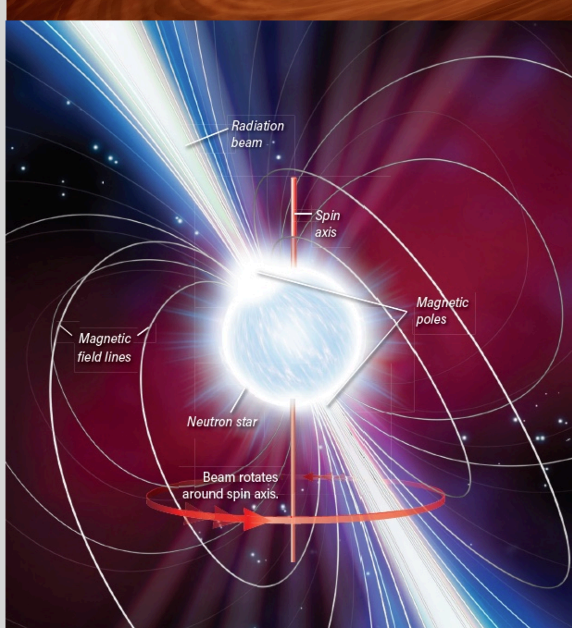
Gabrijela Zaharijas

Centre for Astrophysics and Cosmology, University of Nova Gorica

‘Cosmic’ messengers - the big questions

- Sources? - mechanism of acceleration of CRs
- Propagation? - insights about (inter-) Galactic medium and fields



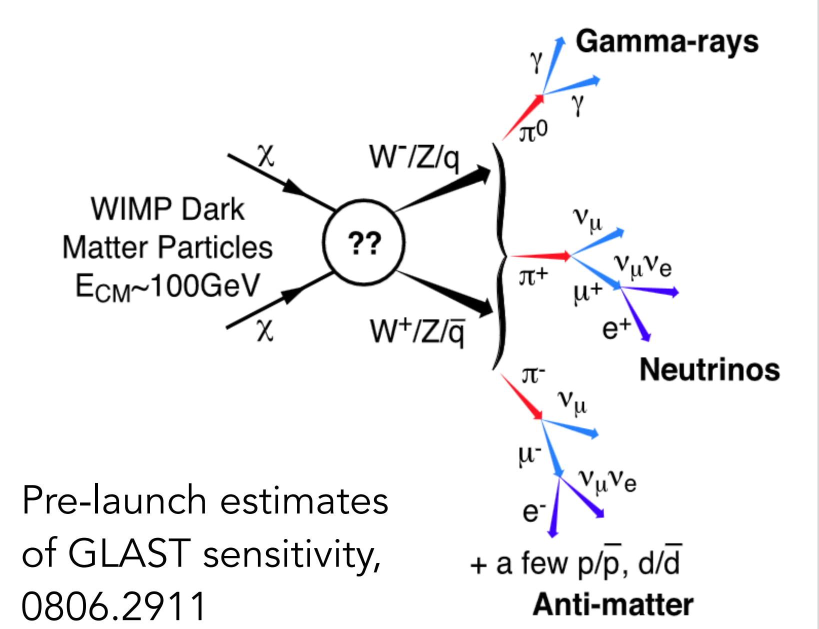


'Cosmic' messengers – the big questions

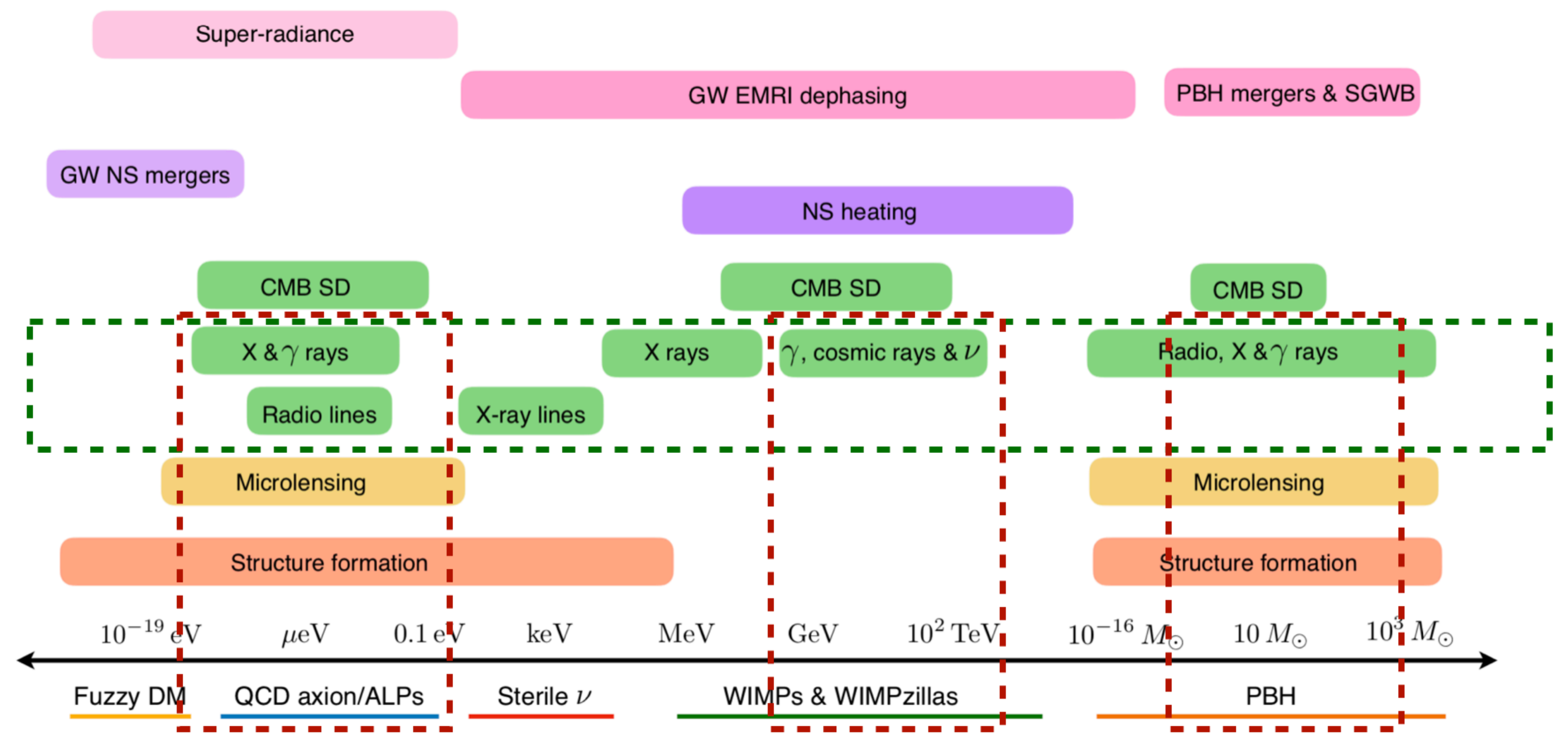
- The nature of Dark Matter

Coupling with SM?

Have evidence that DM is present in astrophysical systems —> **look for its '*other than gravitational*' signals in its natural habitat**



Pre-launch estimates of GLAST sensitivity, 0806.2911

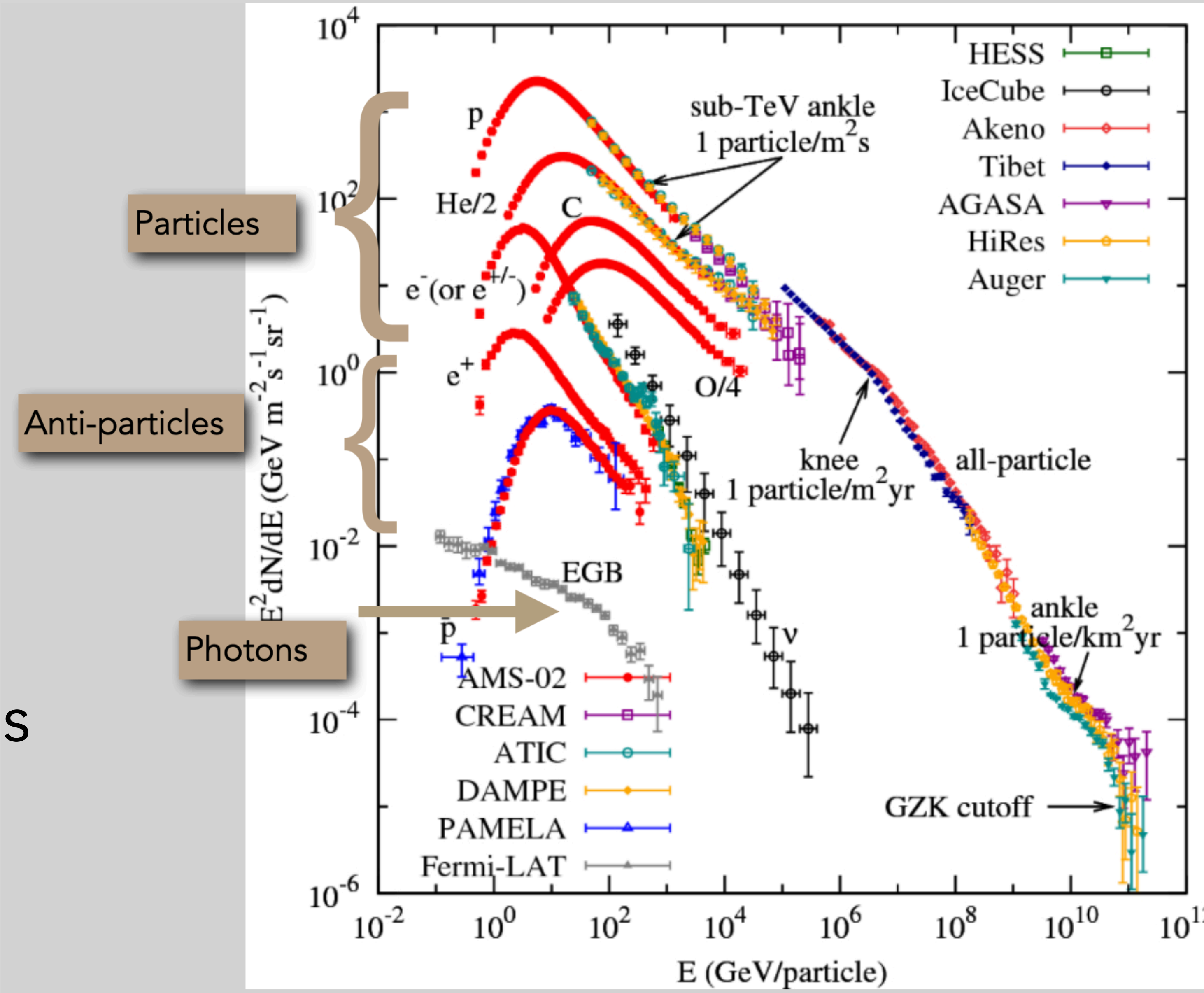


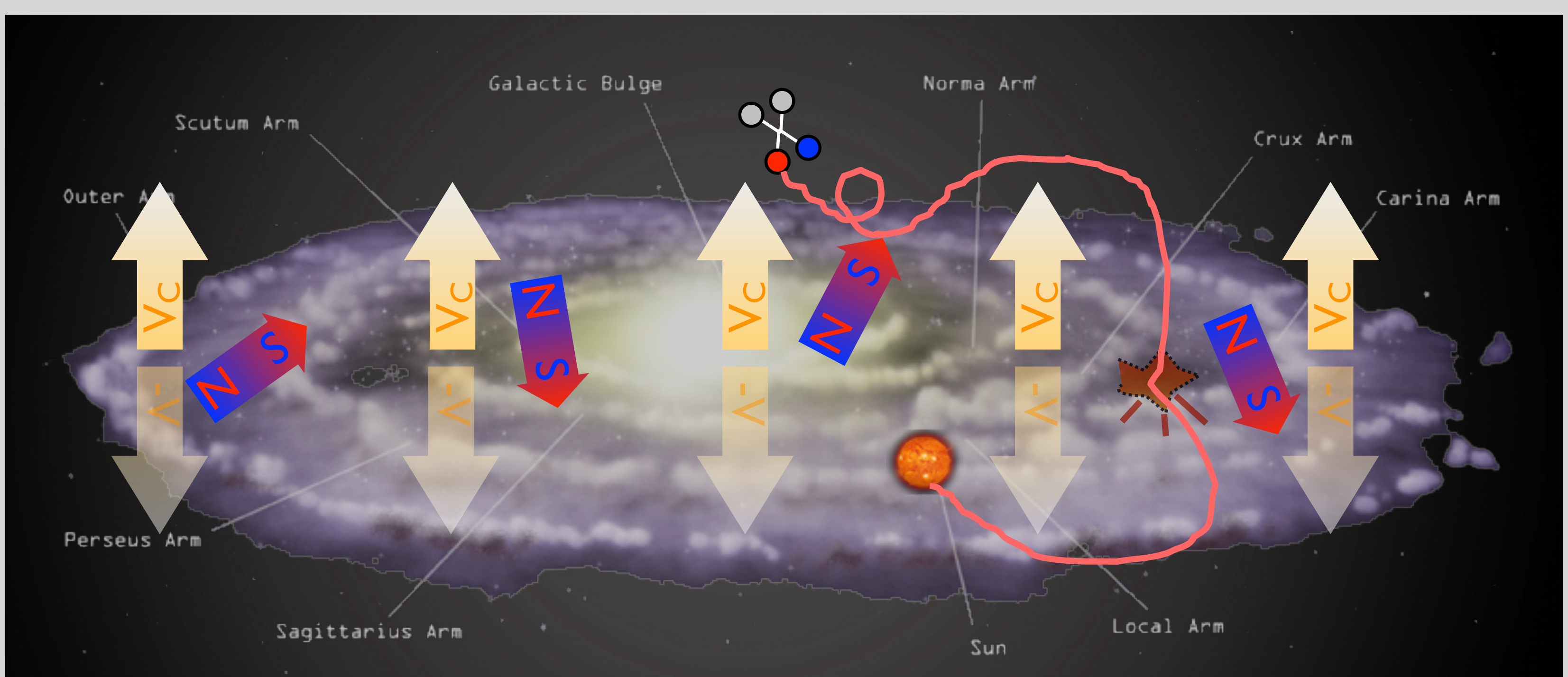
EuCAPT white paper, arXiv: 2110.10074

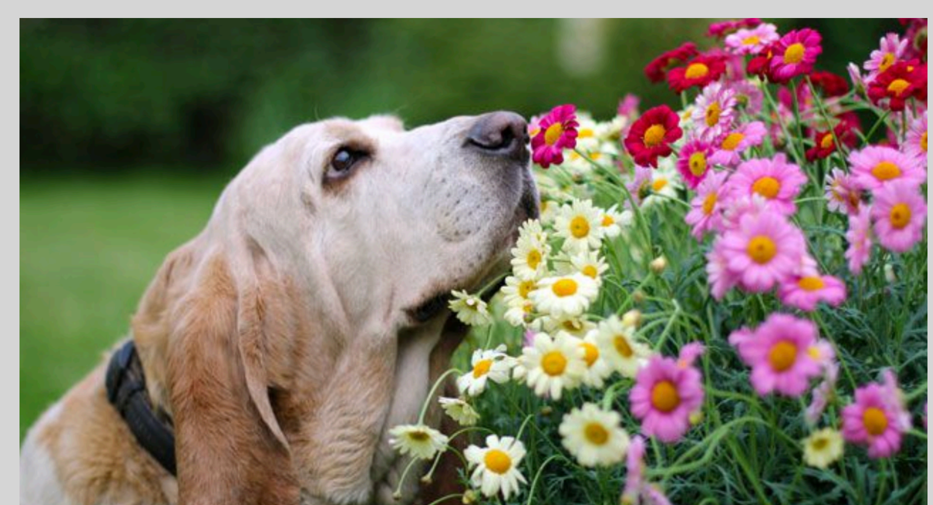
Cosmic messengers

Charged Cosmic Rays

- Charged particles make up a large majority of ‘cosmic’ rays
- Reach energies >> LHC
- Path affected by magnetic fields

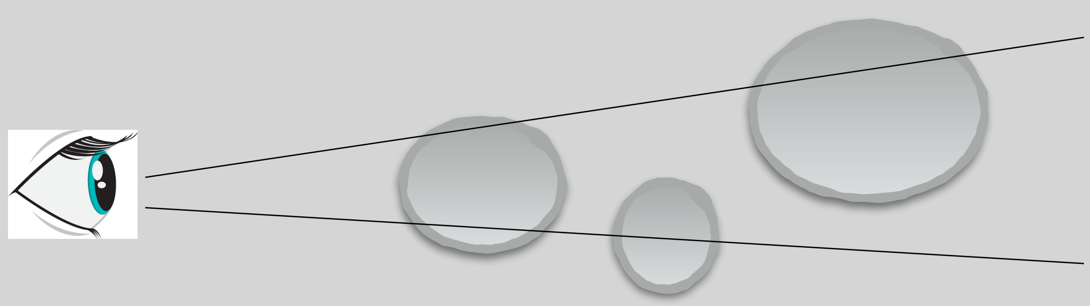


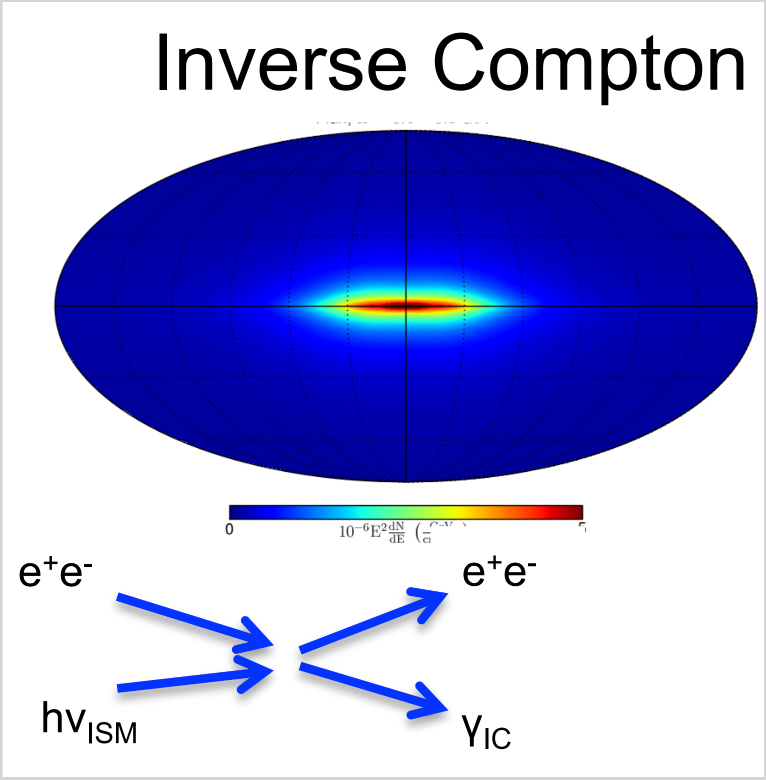


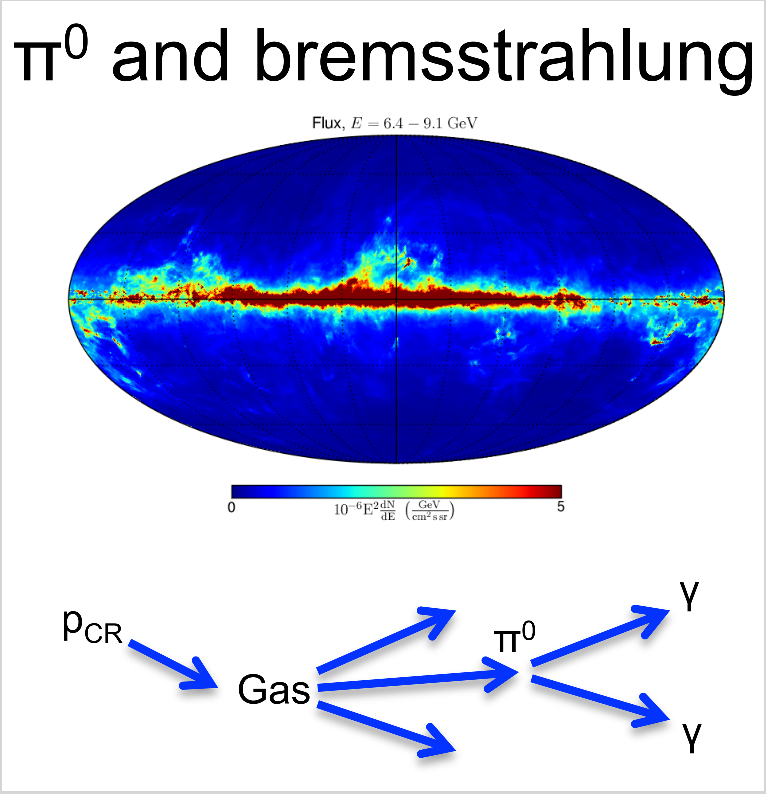


γ's (and ν's)

- **produced in interactions of charged CRs with the medium (gas…) and fields (B, low energy photons…)**
- travel in straight lines!
- Allow us to pierce in the regions of CR production and resolve shape







Gamma rays

γ's 'blocked' by the atmosphere → ***satellites***

(EGRET (1991- 2001), AGILE (2007-), Fermi LAT (2008-))

or ground based

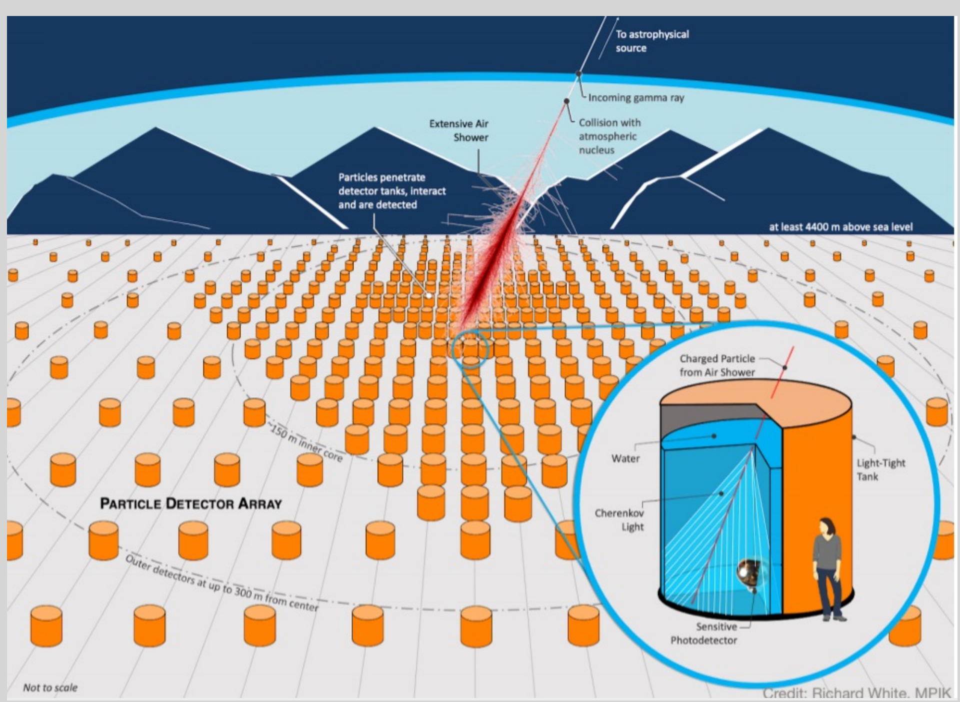
Imaging Atmospheric Cherenkov Telescopes

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

Water Cherenkov detectors

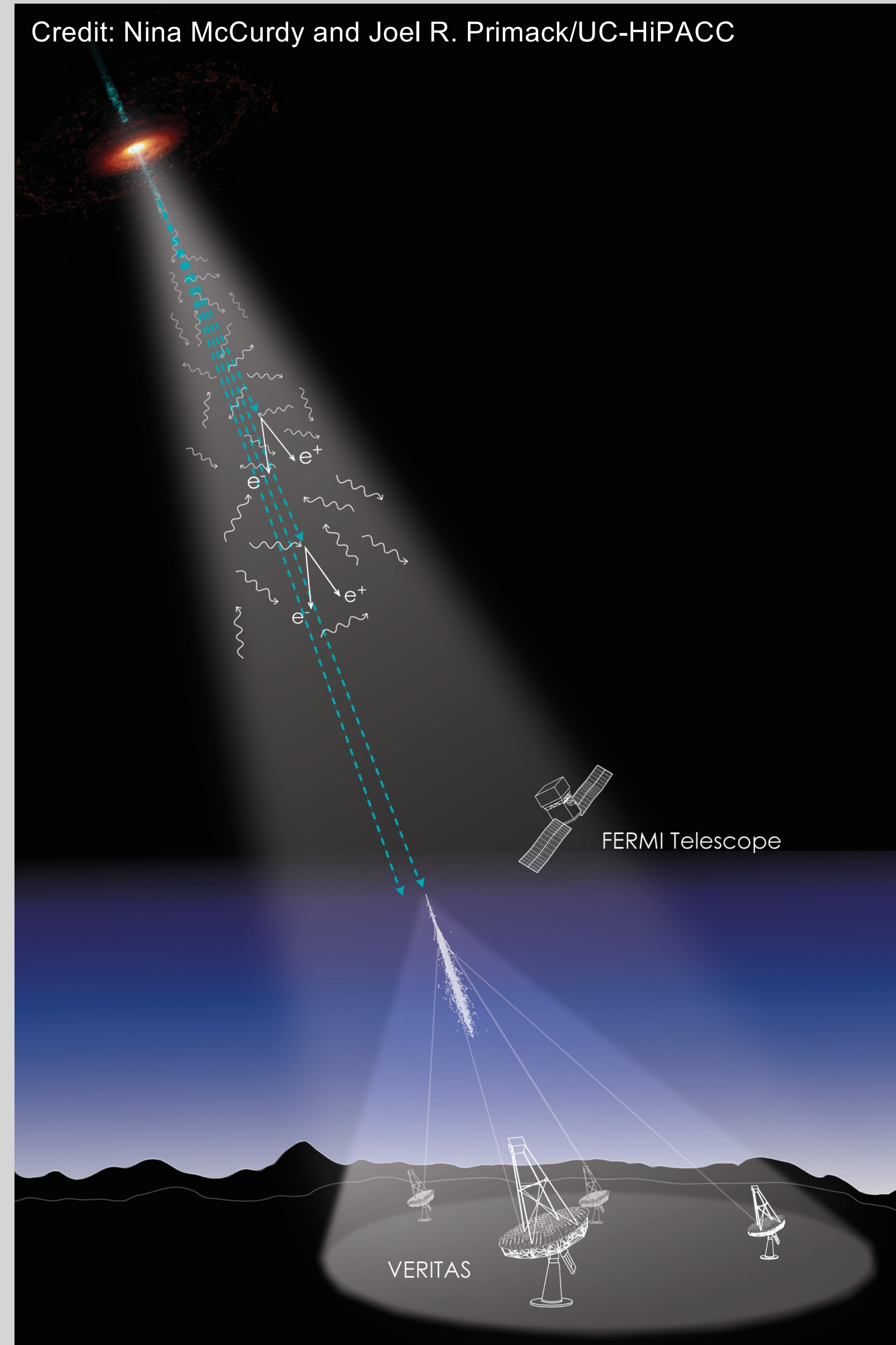
('observing Universe with a bucket of water')

(…, HAWC (2011 -))

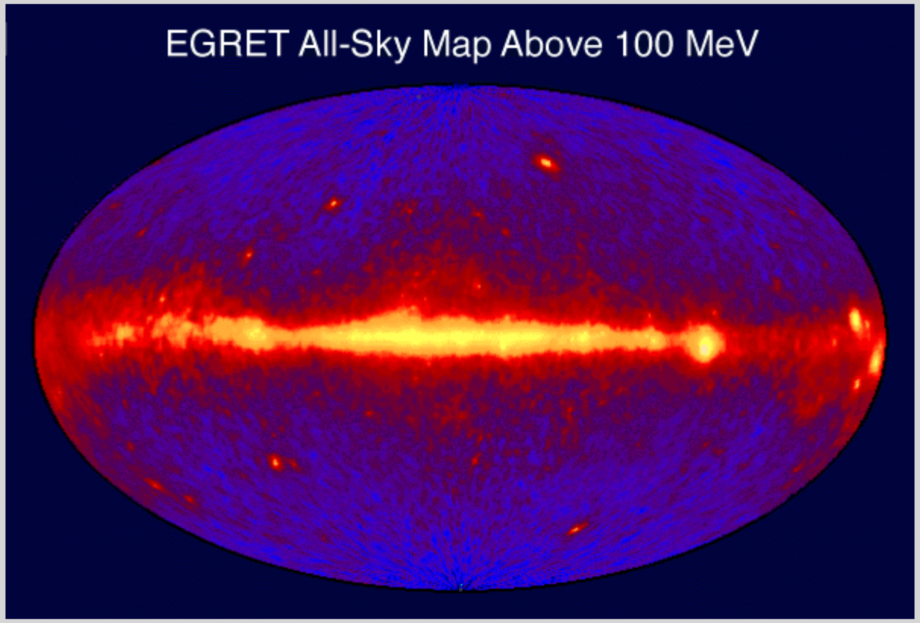


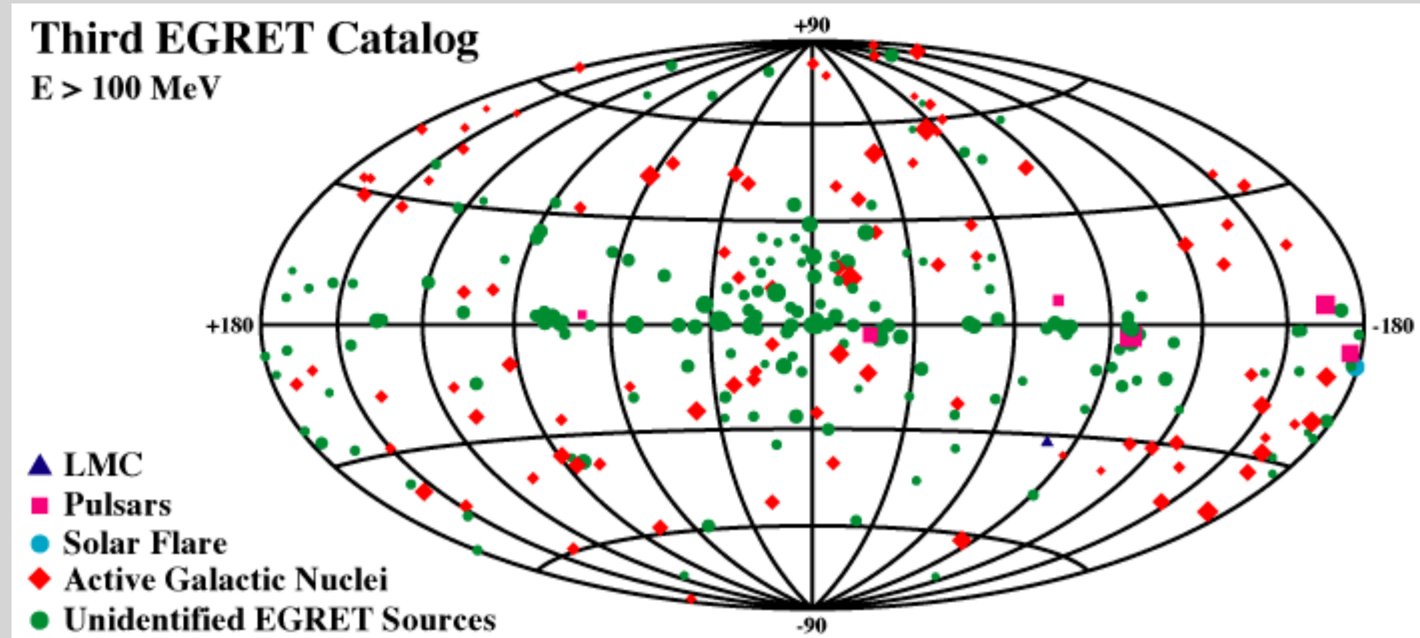
Other techniques (scintilators) + combinations

(Tibet ASγ (1990-), LHASSO (2021 -))



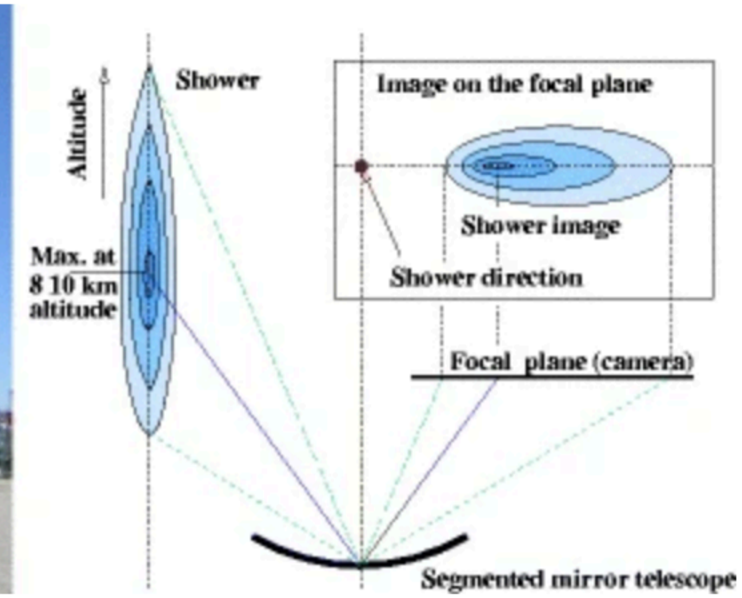
'Pre-' history - satellites





EGRET (1991-2000):
energy range: 30 MeV to 30 GeV
And resolution: 0.5 deg

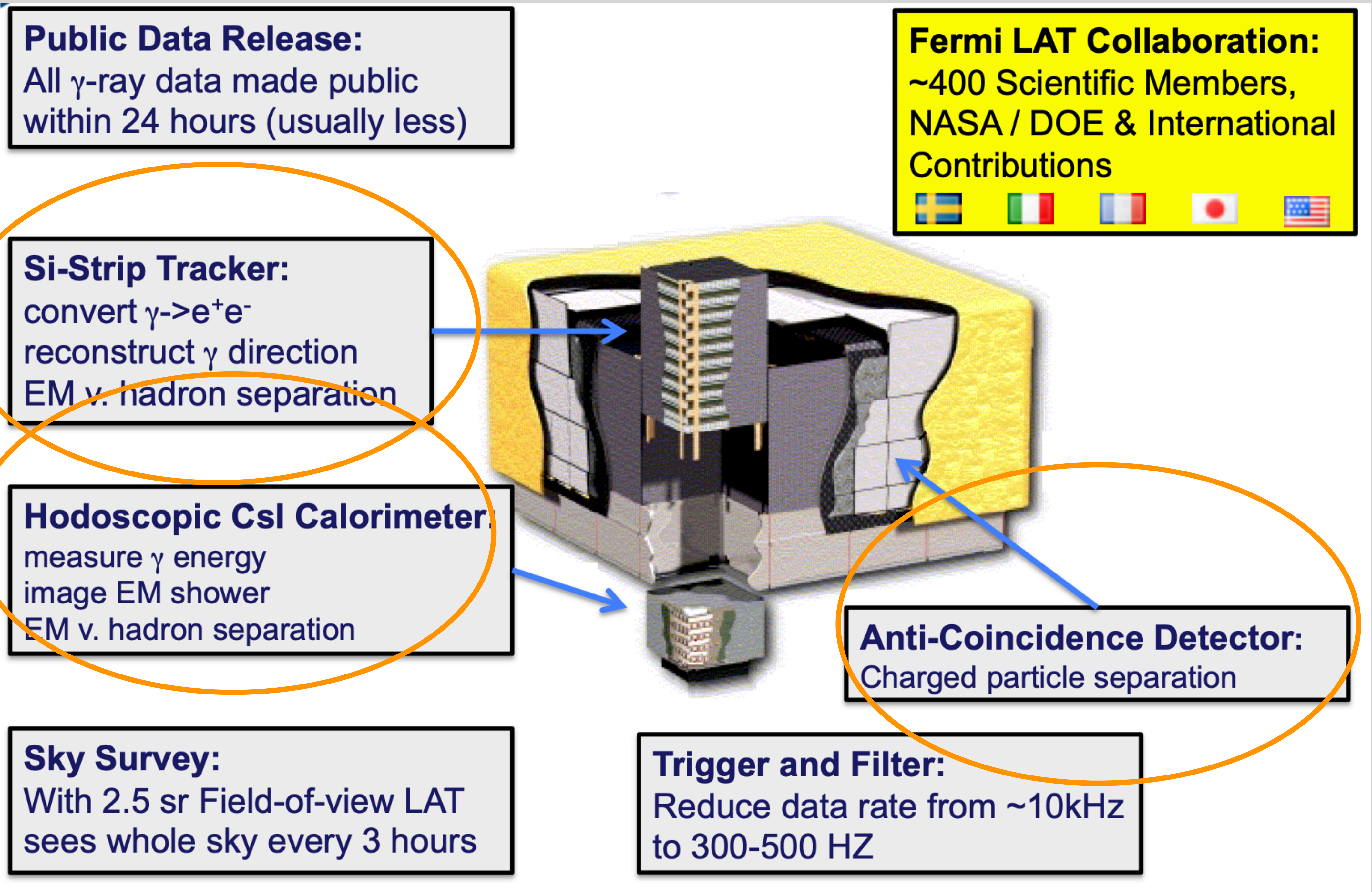
6 pulsars
~300 AGNs



The Whipple 10 m telescope is situated at the Fred Lawrence Whipple Observatory on Mount Hopkins, Arizona 1997–2006

MILAGRO, water Cherenkov, Los Alamos, NM,1999

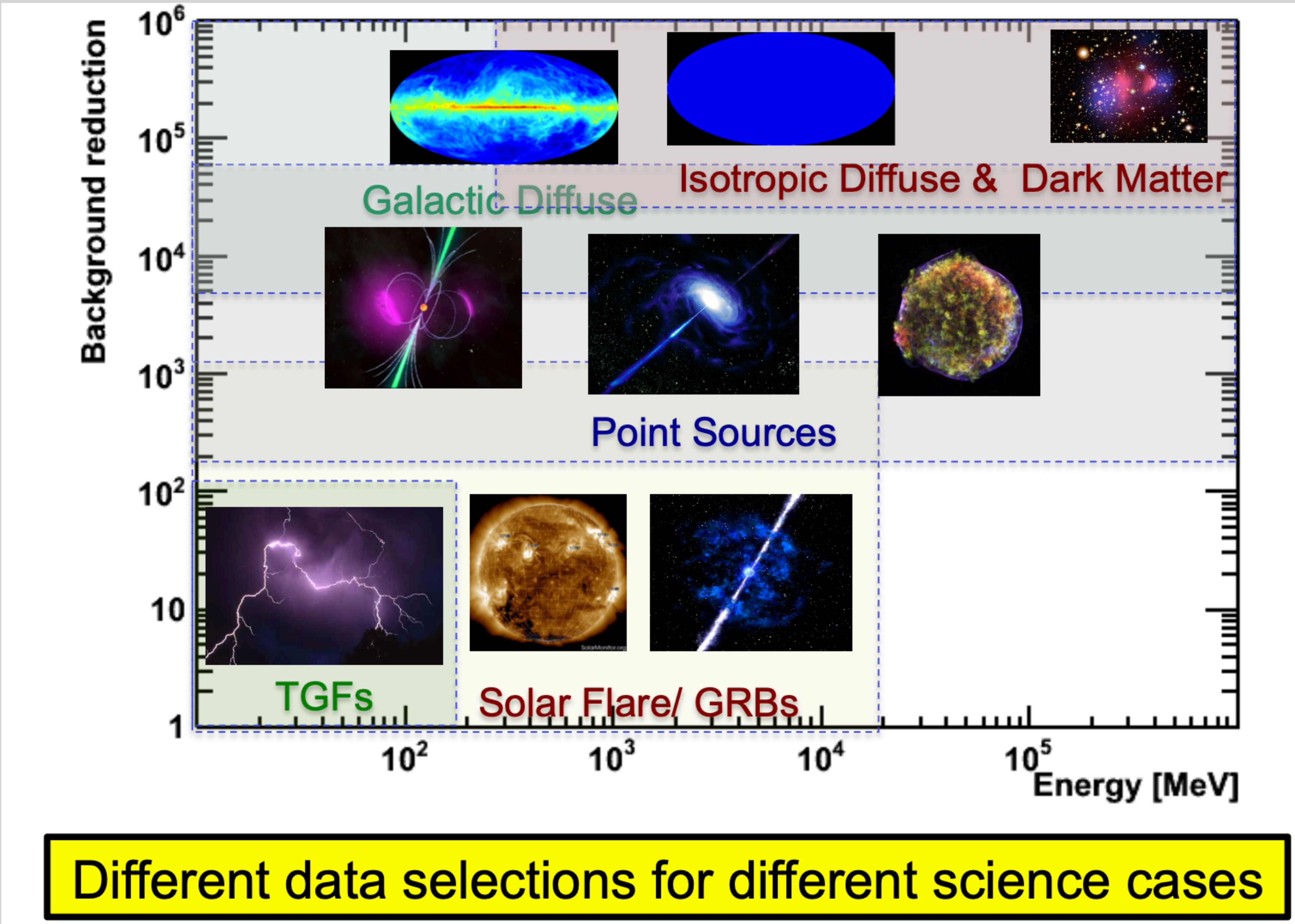
Enter the Fermi LAT (GLAST)



"The LAT is a particle physics detector we've shot into space" (Eric Charles)

Superior angular and energy resolution and excellent charged CR background rejection.

Enter Fermi LAT (GLAST)



"The LAT is a particle physics detector we've shot into space" (Eric Charles)

Note funded by DOE - "**Dark matter discovery machine**"

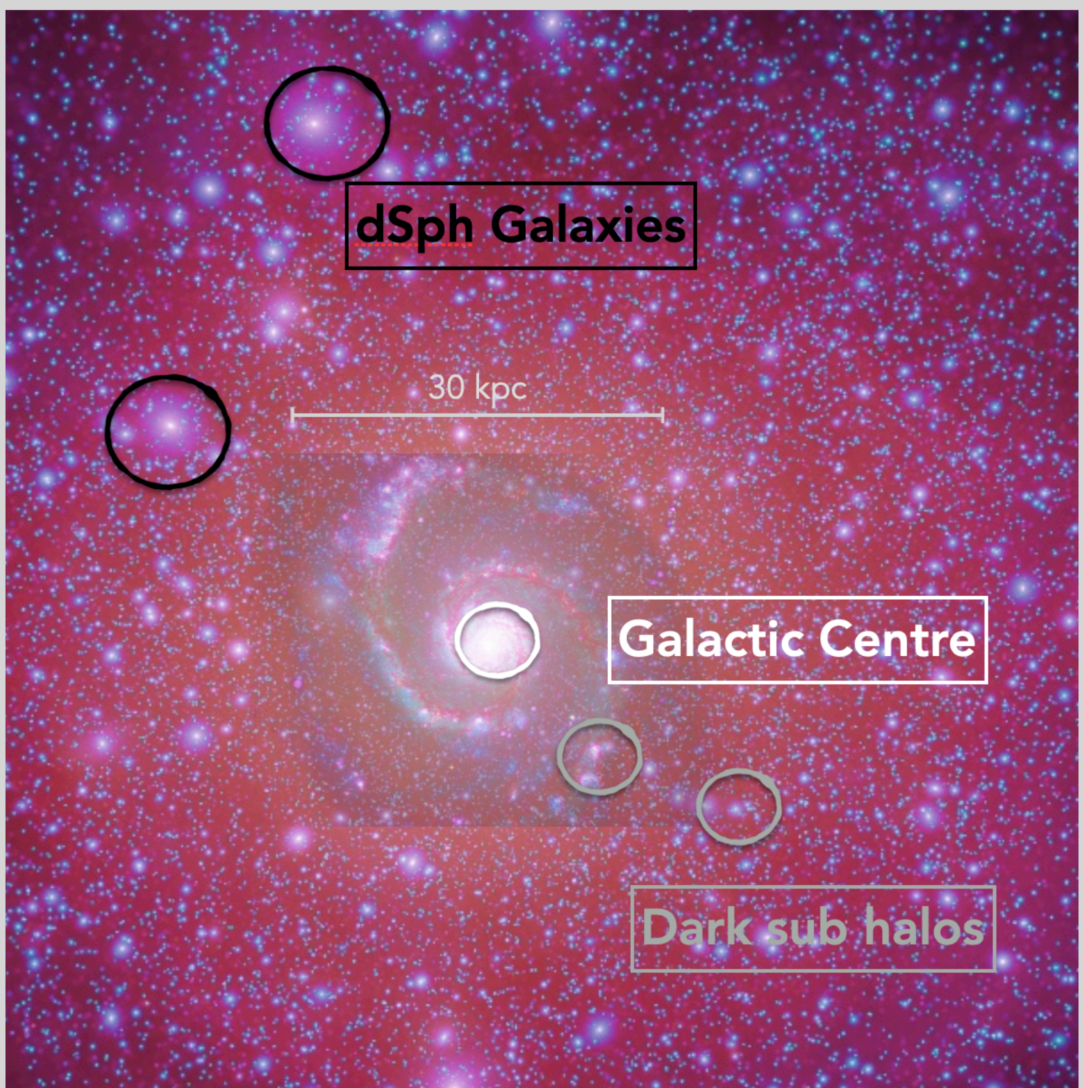
Precision + sensitivity + the 'right' energy range

Enter Fermi LAT (GLAST)

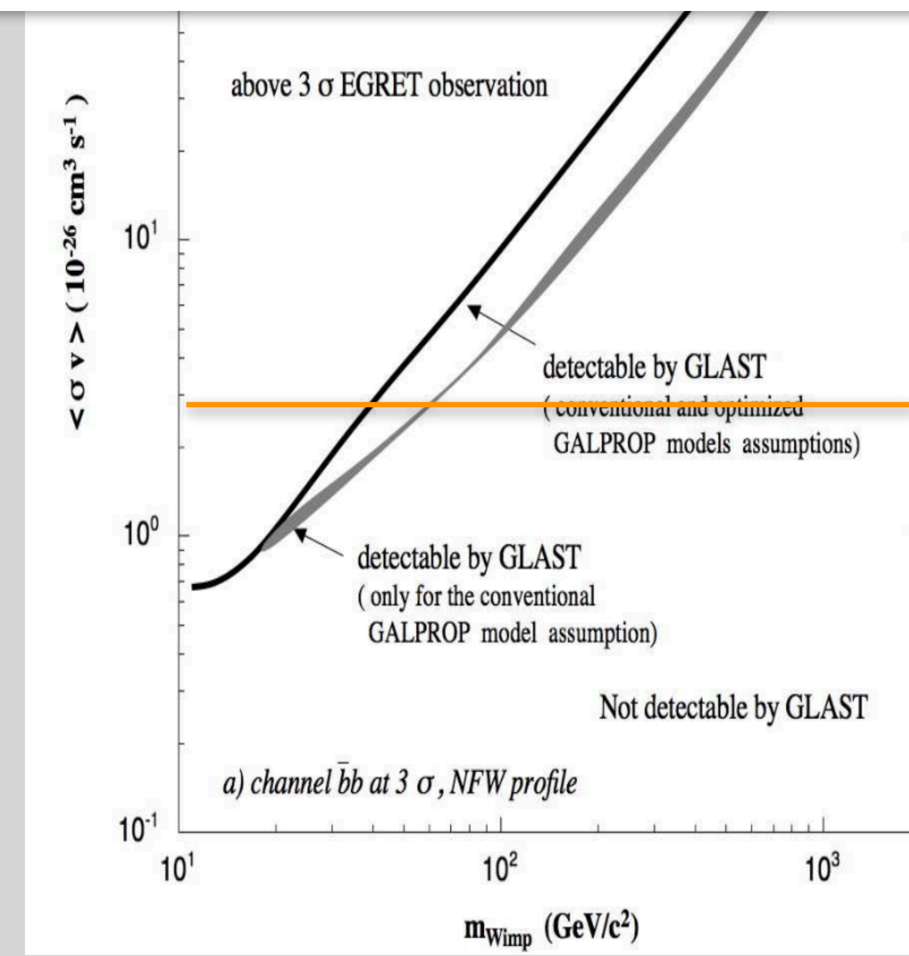
Pre-launch estimates for GLAST sensitivity to Dark Matter annihilation signals

E.A. Baltz (KIPAC, Menlo Park and SLAC), B. Berenji (KIPAC, Menlo Park and SLAC), G. Bertone (Paris, Inst. Astrophys.), L. Bergstrom (Stockholm U.), E. Bloom (KIPAC, Menlo Park and SLAC) et al. (Jun, 2008)

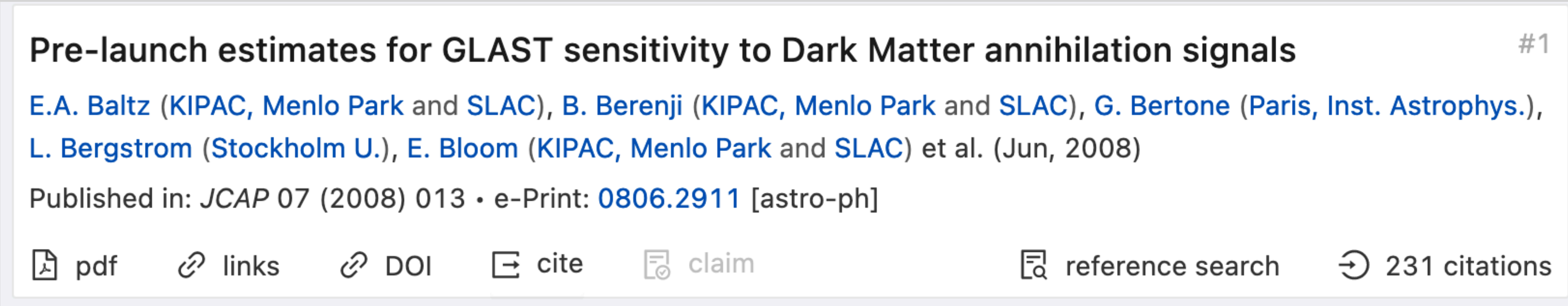
Published in: *JCAP* 07 (2008) 013 • e-Print: 0806.2911 [astro-ph]



Sensitivity at the Galactic center



Enter Fermi LAT (GLAST)


Pre-launch estimates for GLAST sensitivity to Dark Matter annihilation signals

#1

E.A. Baltz (KIPAC, Menlo Park and SLAC), B. Berenji (KIPAC, Menlo Park and SLAC), G. Bertone (Paris, Inst. Astrophys.), L. Bergstrom (Stockholm U.), E. Bloom (KIPAC, Menlo Park and SLAC) et al. (Jun, 2008)

Published in: *JCAP* 07 (2008) 013 • e-Print: 0806.2911 [astro-ph]

pdf links DOI cite claim reference search 231 citations

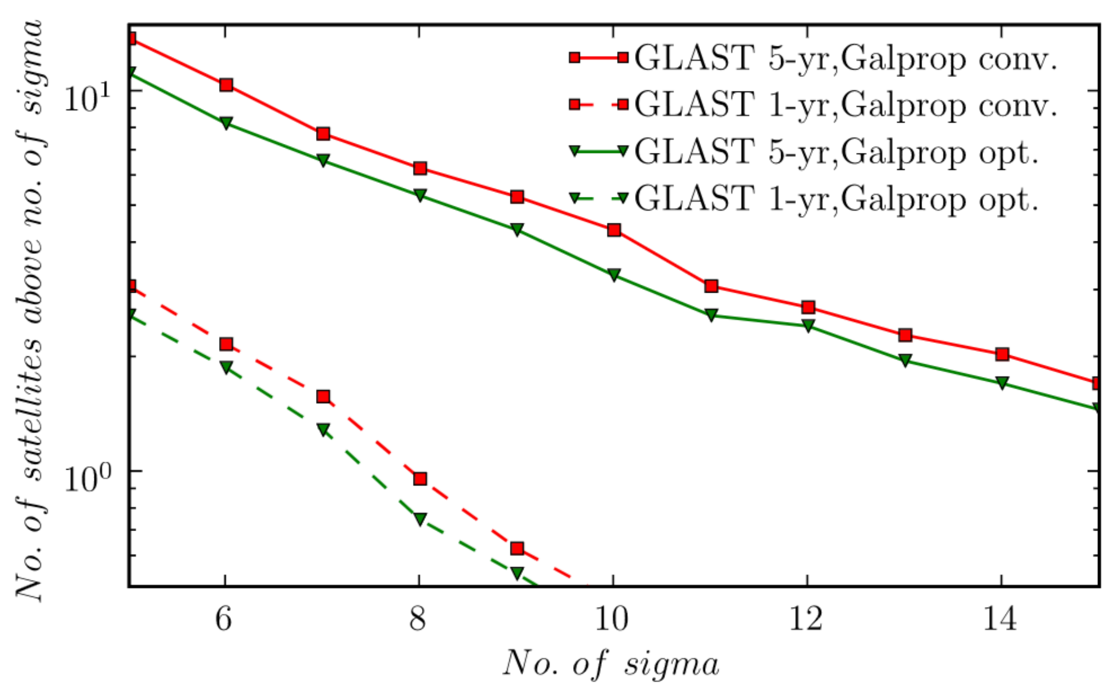


Figure 11. Estimated number of observable DM satellites for tl Milky Way for **1 and 5 year of GLAST operation**. The backį

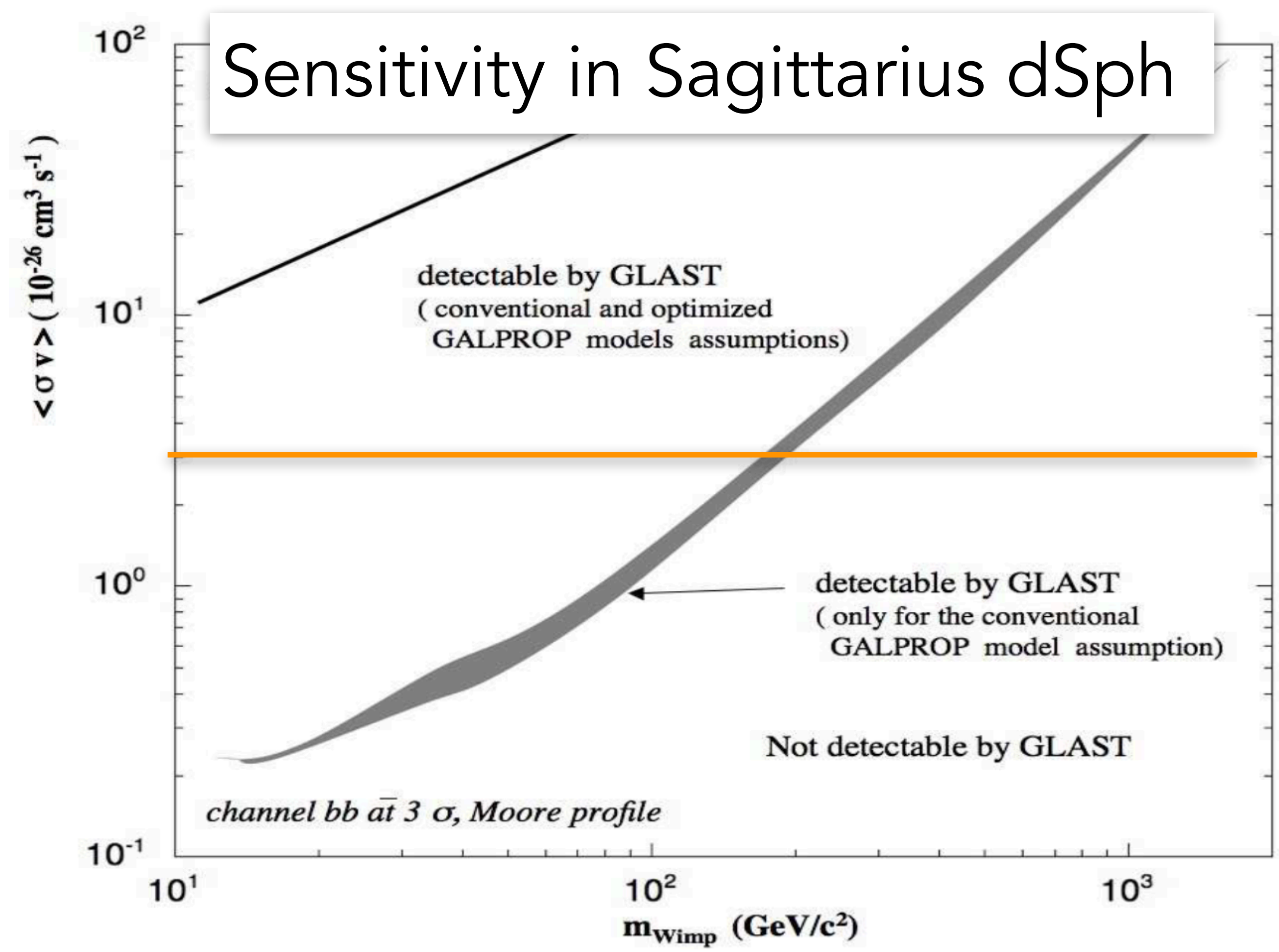


Figure 15. Sensitivity to a Sagittarius Dwarf DM signal for **5 years of GLAST operation** assuming Moore profile as described in [88]. The region labeled "above

Enter Fermi LAT (GLAST)

ASTROPHYSICS AND COSMOLOGY | FEATURE

Fermi Gamma-ray Space Telescope sees first light

20 October 2008

New window opens on high-energy universe

Enter Fermi LAT (GLAST)

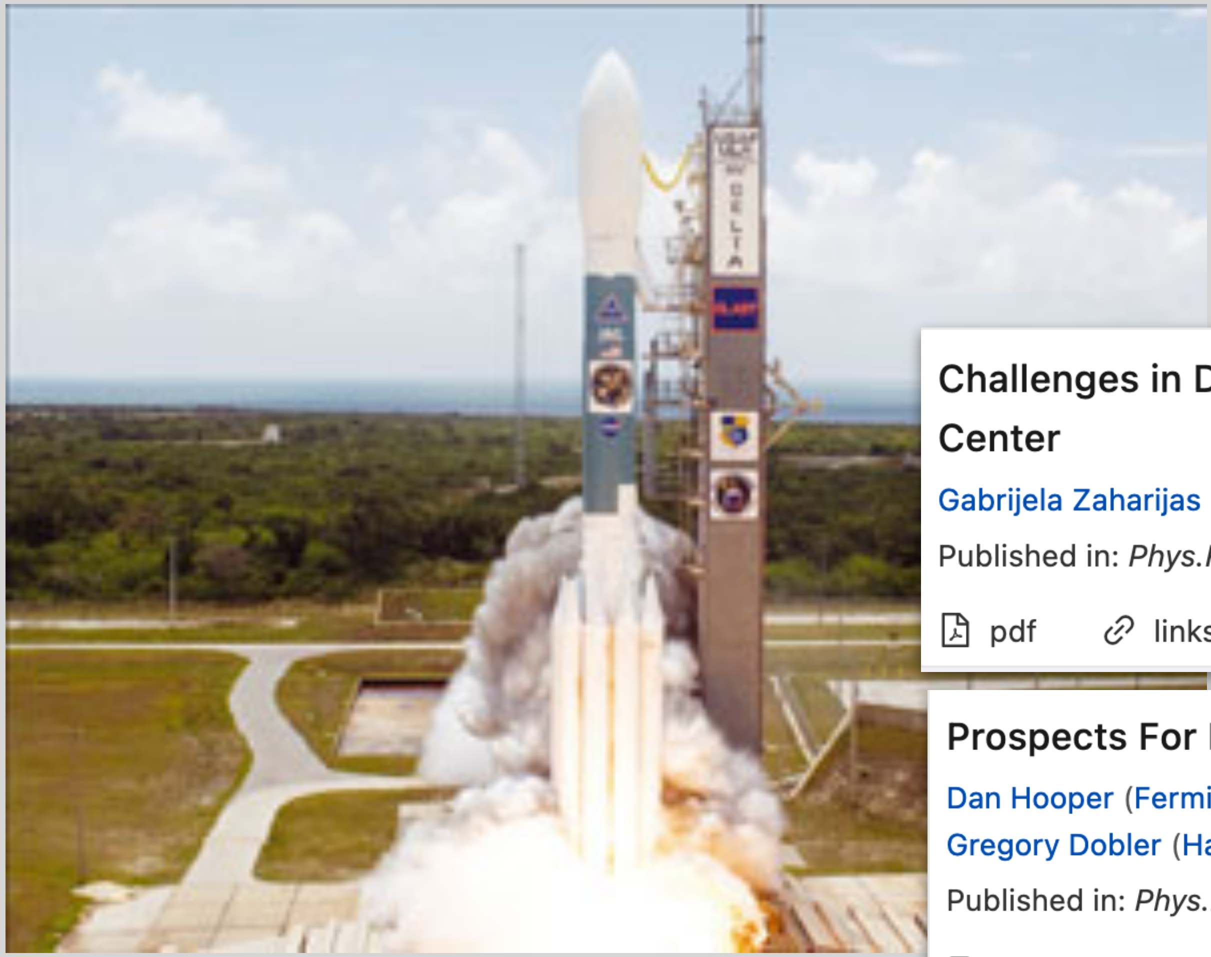
ASTROPHYSICS AND COSMOLOGY | FEATURE

Fermi Gamma-ray Space Telescope sees firs[t] light

20 October 2008

New window opens on high-energy universe

An eventful year, OKC + Fermi
And more or less **the time I started my postdoc at OKC :)**
(was a 'teaser' OKC fellow)



Challenges in Detecting Gamma-Rays From Dark Matter Annihilations in the Galactic Center #6

Gabrijela Zaharijas (Fermilab), Dan Hooper (Fermilab) (Mar, 2006)

Published in: *Phys.Rev.D* 73 (2006) 103501 • e-Print: astro-ph/0603540 [astro-ph]

pdf | links | DOI | cite | claim | reference search | 90 citations

Prospects For Detecting Dark Matter With GLAST In Light Of The WMAP Haze #4

Dan Hooper (Fermilab), Gabrijela Zaharijas (Argonne), Douglas P. Finkbeiner (Harvard-Smithsonian Ctr. Astrophys.), Gregory Dobler (Harvard-Smithsonian Ctr. Astrophys.) (Sep, 2007)

Published in: *Phys.Rev.D* 77 (2008) 043511 • e-Print: 0709.3114 [astro-ph]

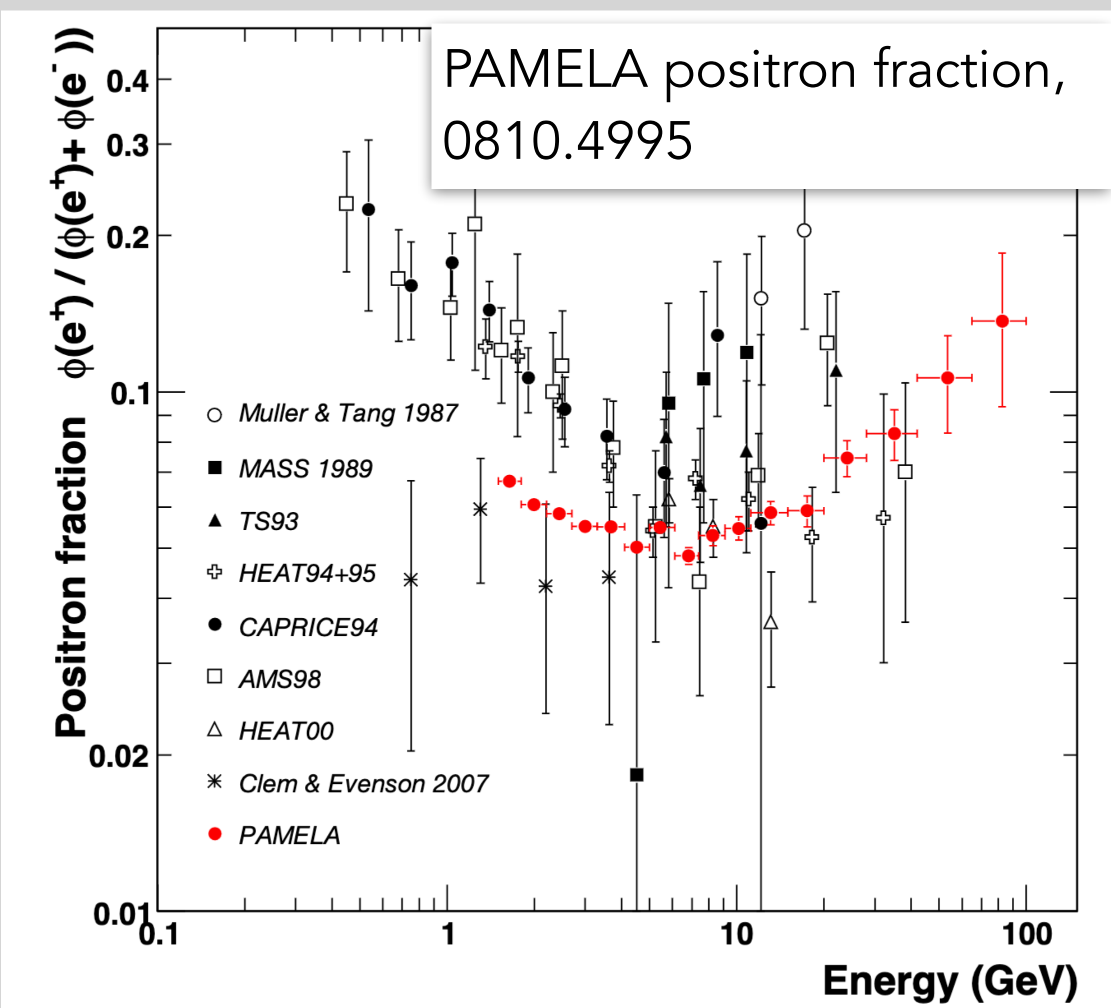
pdf | links | DOI | cite | claim | reference search | 45 citations

Early LAT results

- Puzzling electron/positron spectrum

PAMELA presented for the first time its measurement at the iDM 2008, in Stockholm

Oskar Klein centre



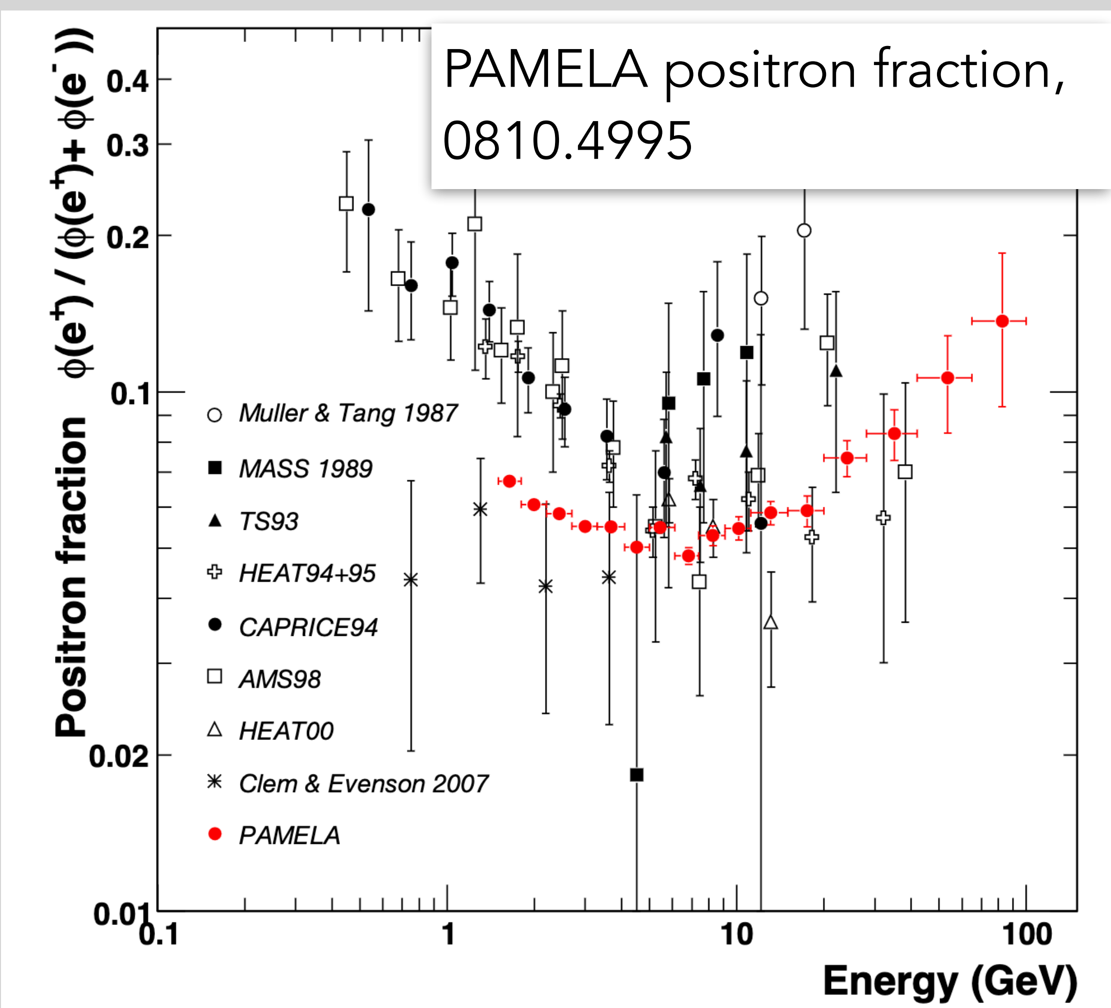
PAMELA positron fraction, 0810.4995

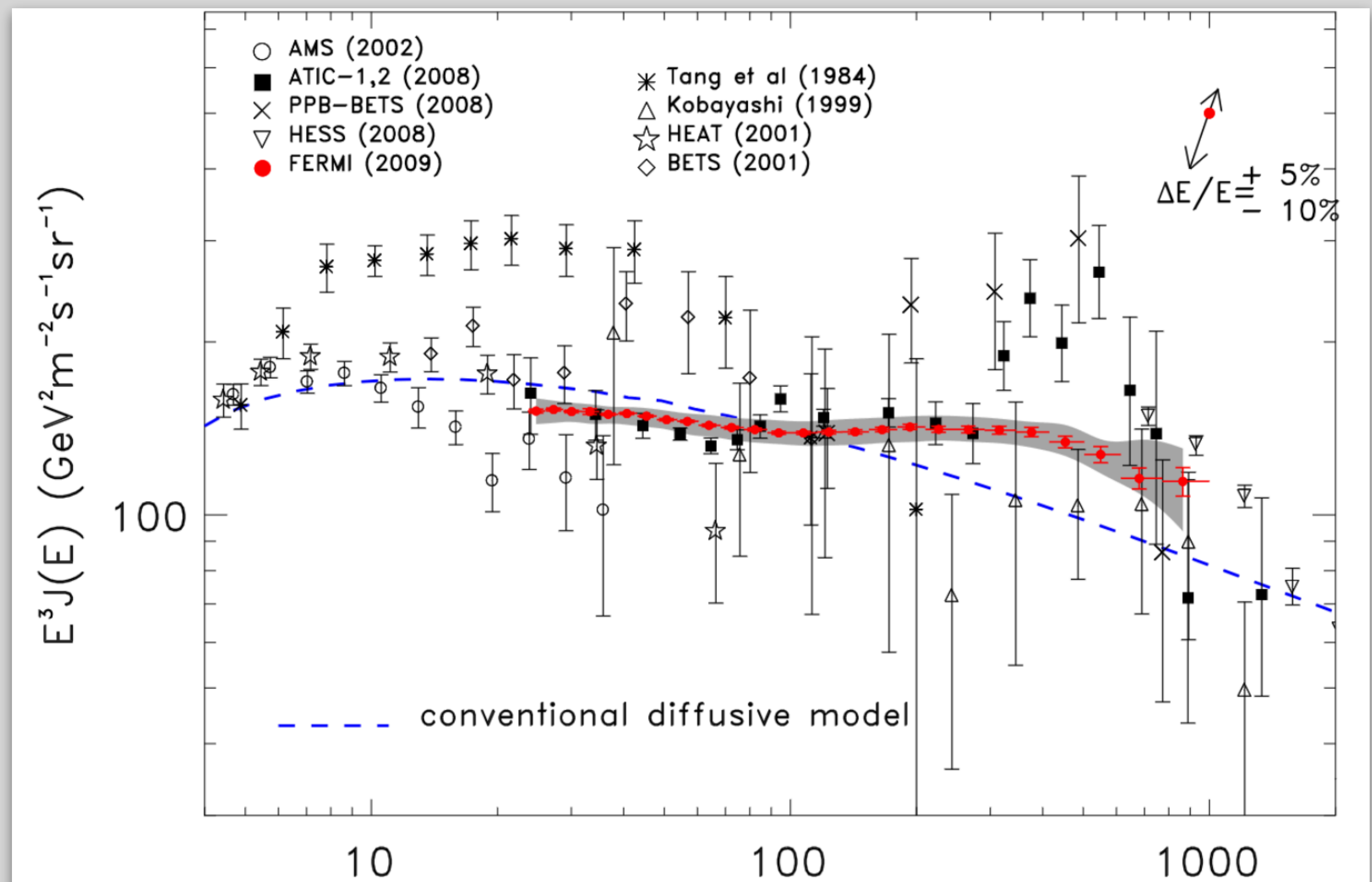
Early LAT results

- Puzzling electron/positron spectrum

PAMELA presented for the first time its measurement at the iDM 2008, in Stockholm

Early 2009, Fermi LAT measurement of the electron spectrum, confirming the excess!





[Fermi LAT, 0905.0025]

Early LAT results

- Puzzling electron/positron spe...

Excess of electrons/positrons
with no excess in anti-p/p
⇒ not may options

PAMELA presented for the first
time its measurement at the
iD...

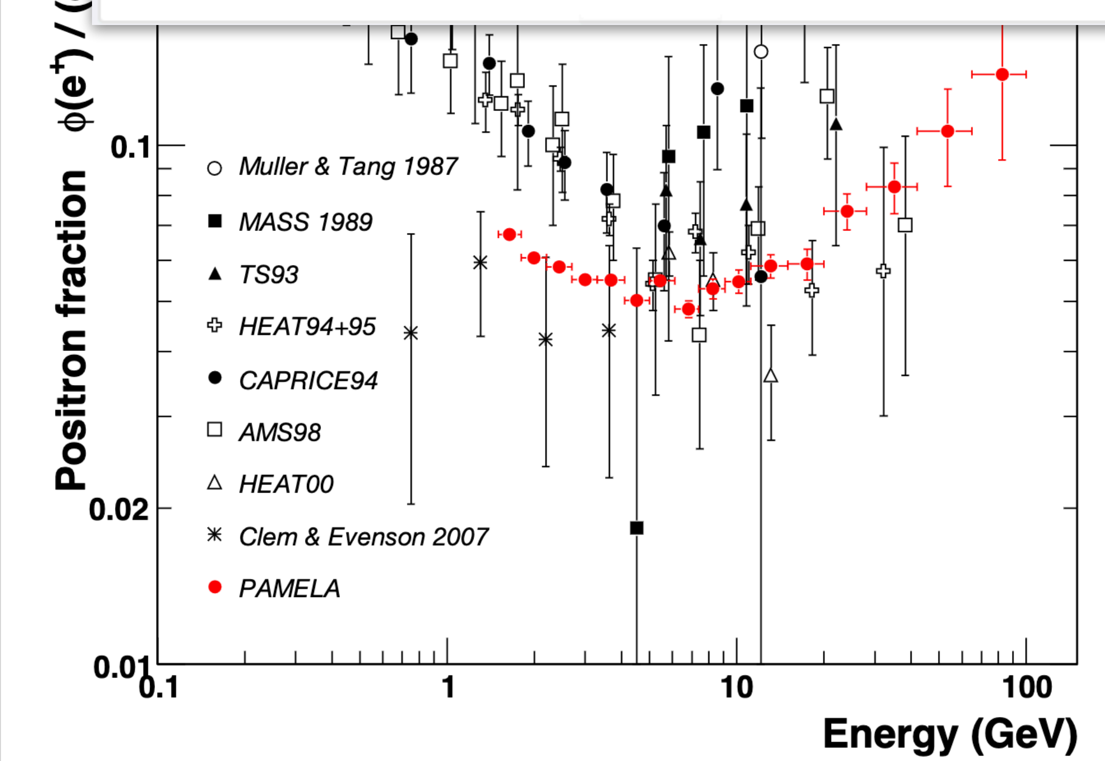
Early 2009, Fermi LAT measurement of the ... s!

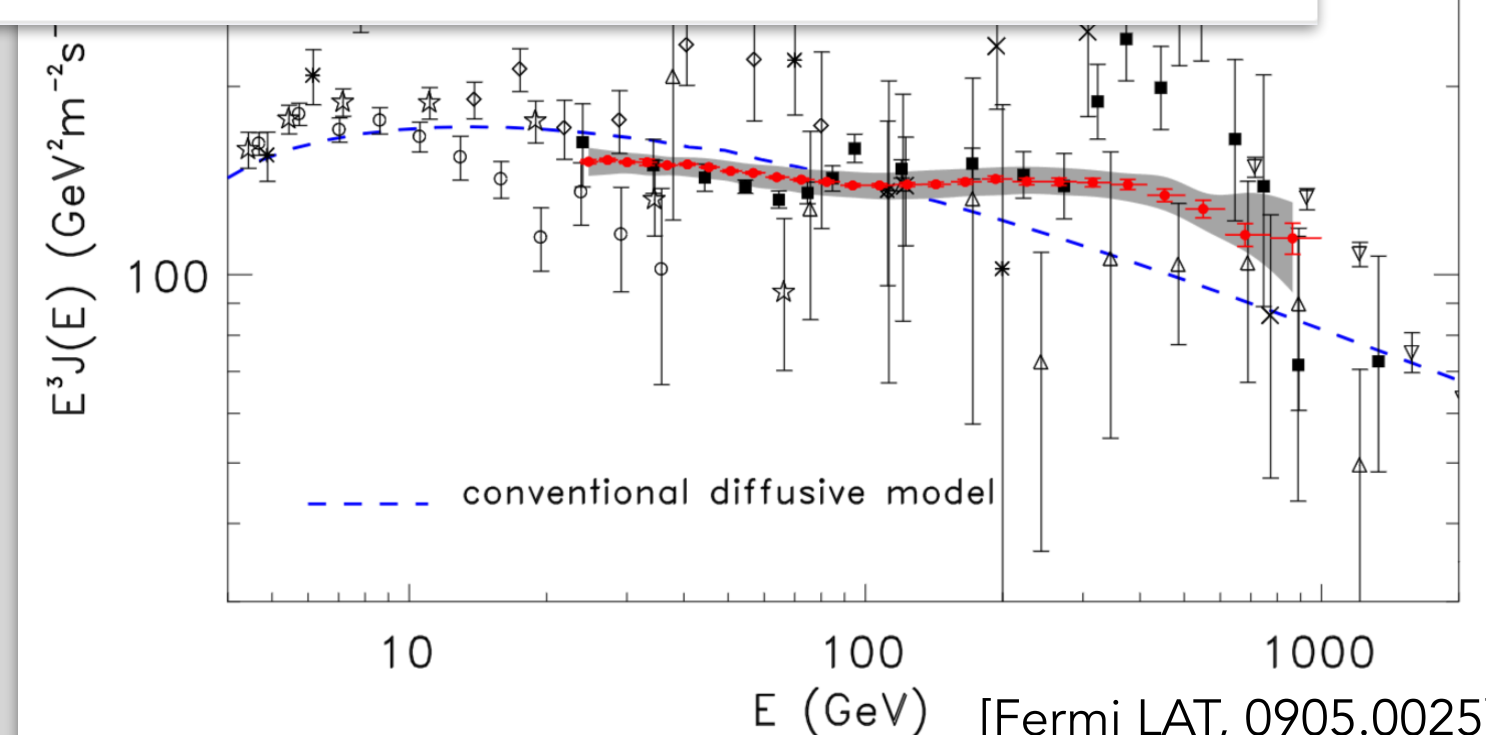
A Theory of Dark Matter #1

Nima Arkani-Hamed (Princeton, Inst. Advanced Study), Douglas P. Finkbeiner (Harvard-Smithsonian Ctr. Astrophys.), Tracy R. Slatyer (Harvard U., Phys. Dept.), Neal Weiner (New York U., CCPP) (Oct, 2008)

Published in: *Phys.Rev.D* 79 (2009) 015014 • e-Print: 0810.0713 [hep-ph]

pdf DOI cite claim reference search 1,836 citations





[Fermi LAT, 0905.0025]

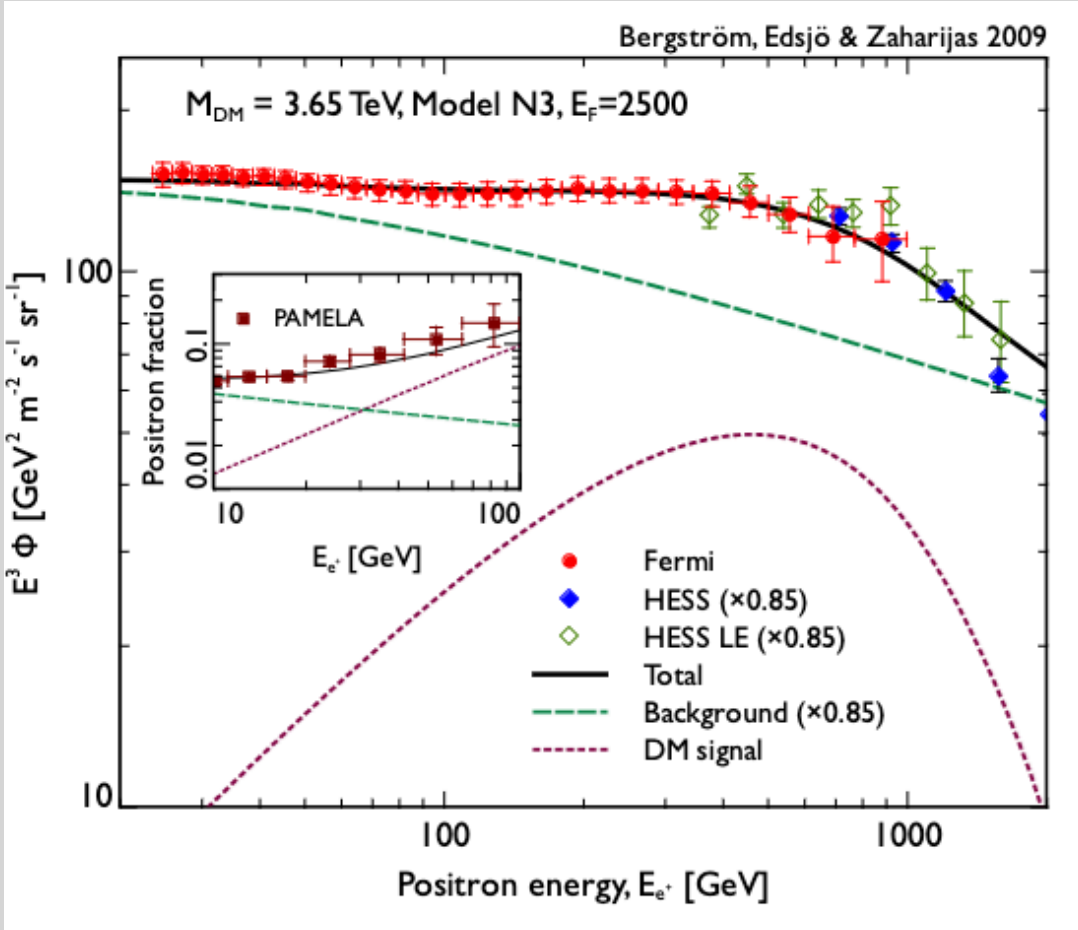
Early LAT results

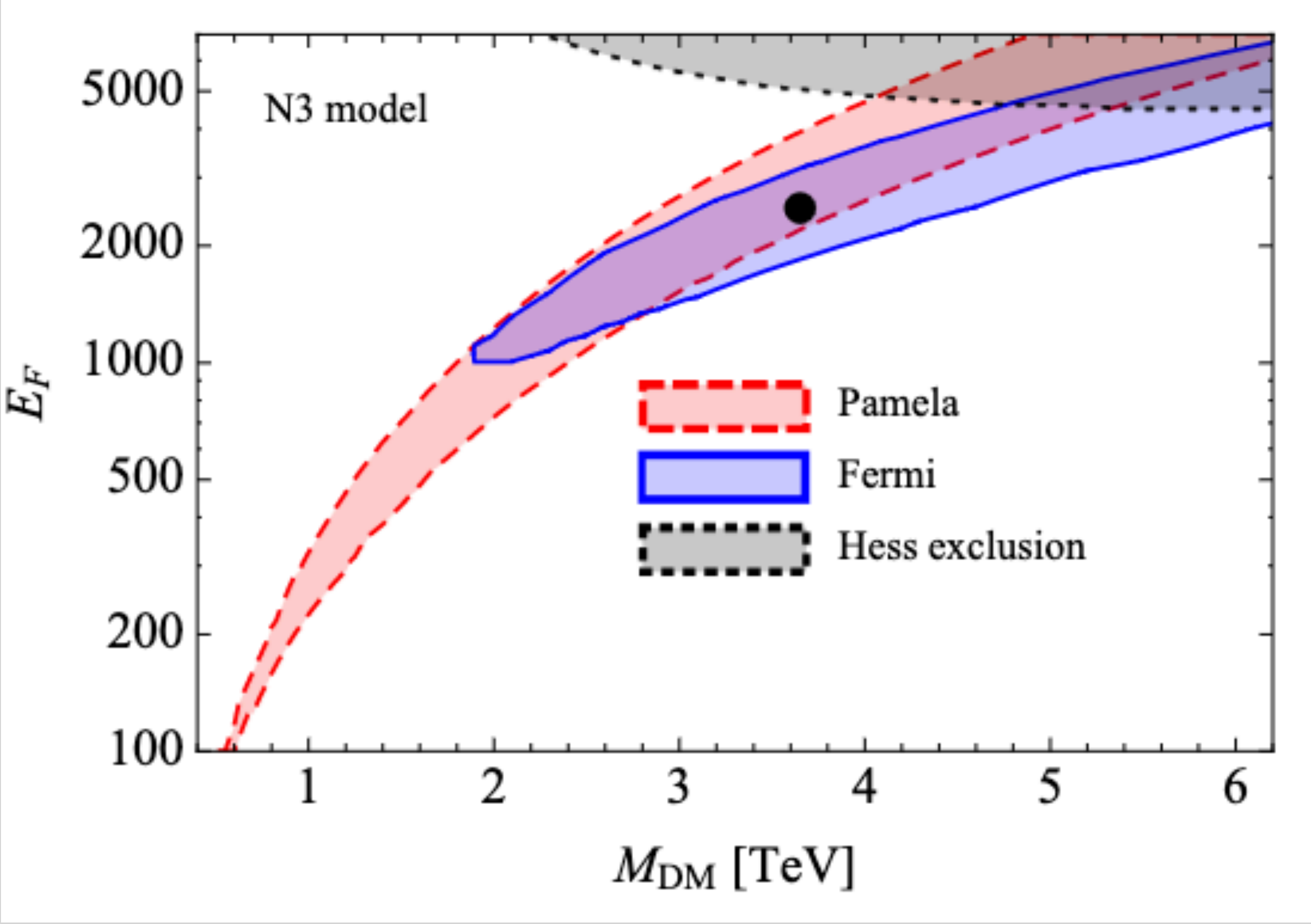
- Puzzling electron/positron spectrum

Dark matter interpretation of recent electron and positron data

Lars Bergstrom (Stockholm U.), Joakim Edsjo (Stockholm U.), Gabrijela Zaharijas (Stockholm U.) (May, 2009)

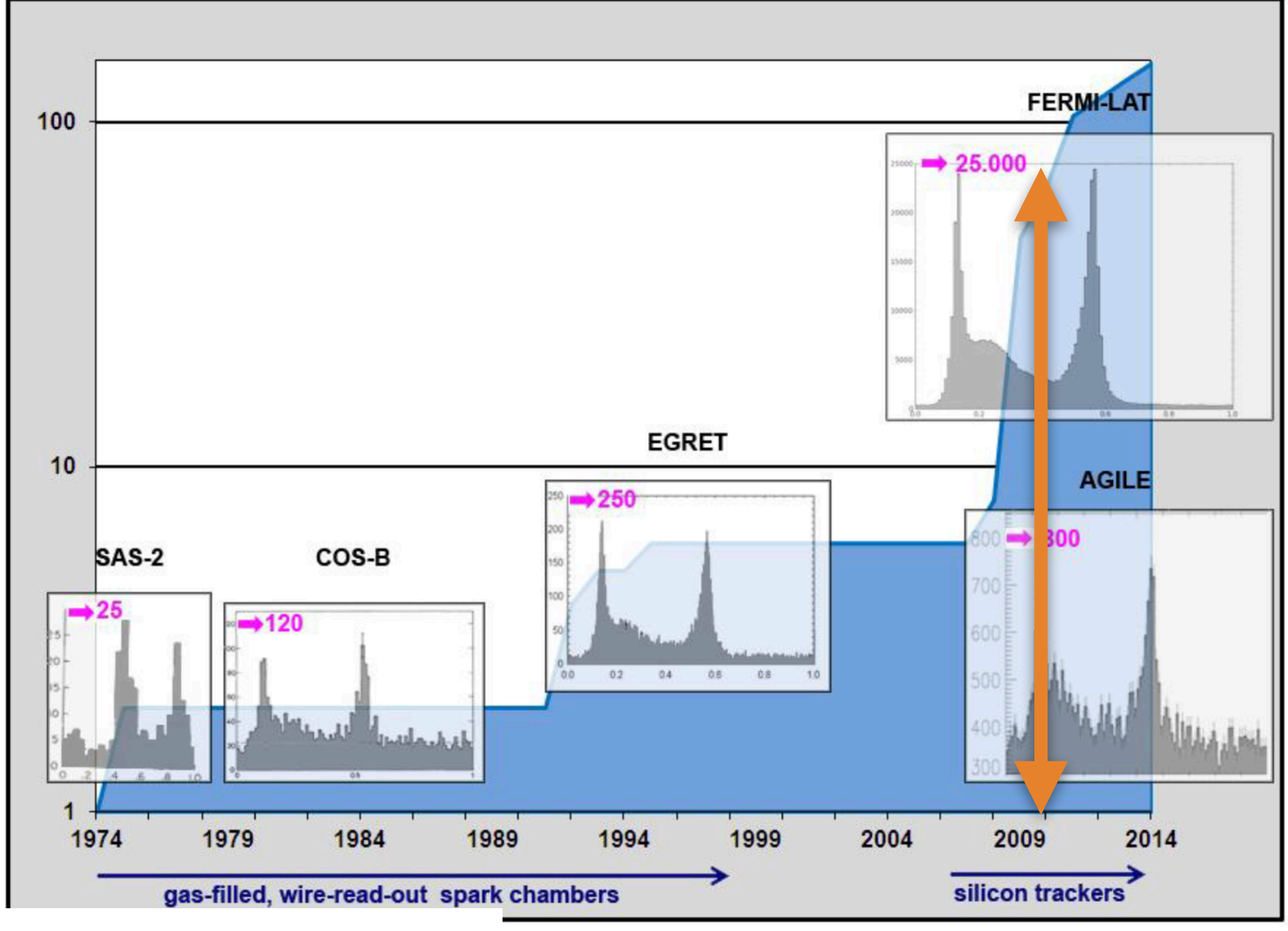
Published in: *Phys.Rev.Lett.* 103 (2009) 031103 • e-Print: 0905.0333 [astro-ph.HE]

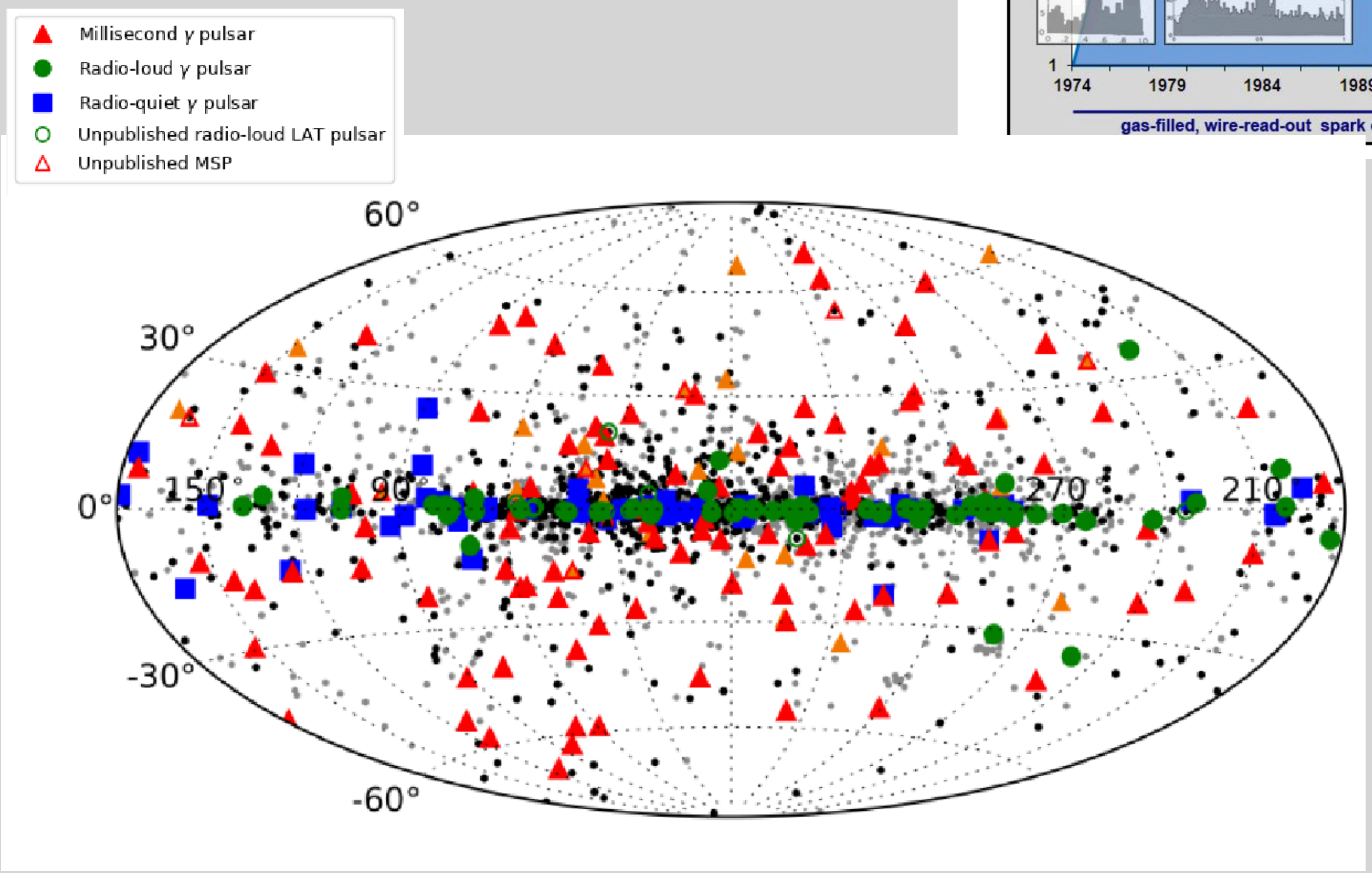




Early LAT results

- pulsar revolution





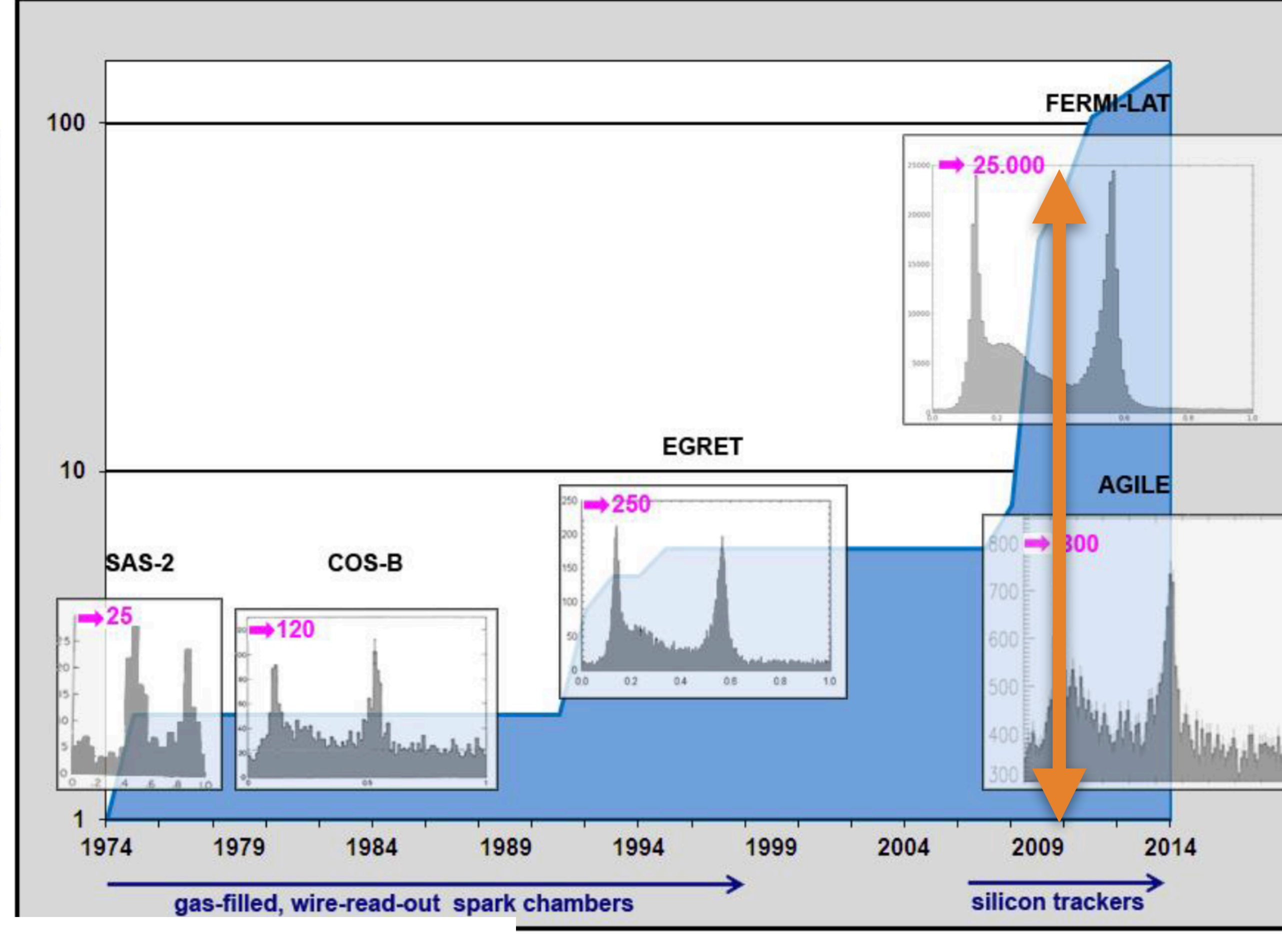
Pulsars are everywhere:

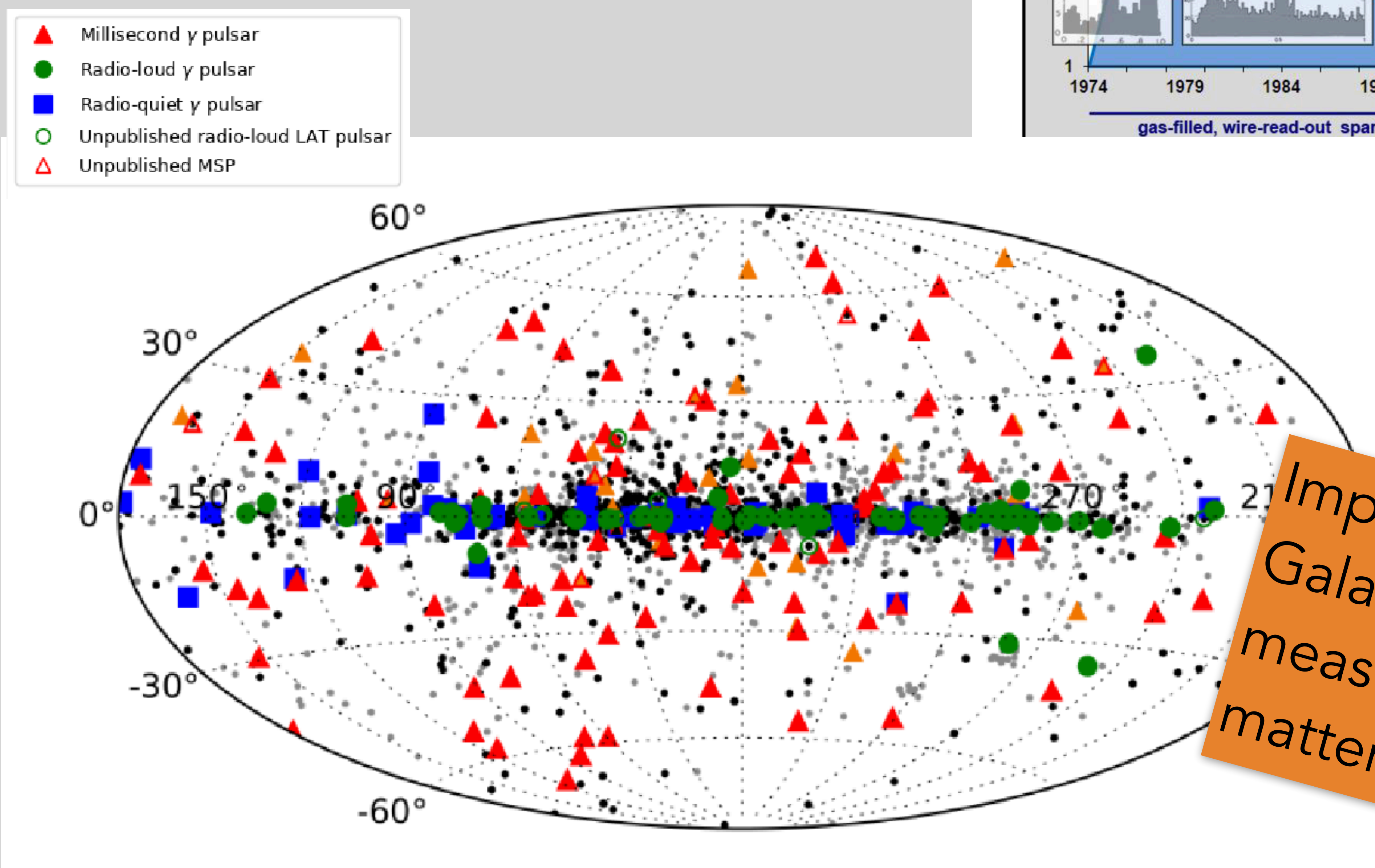
Going from a handful (pre LAT) to 300 pulsars in 3PC

Including radio quiet and MSPs

Early LAT results

- pulsar revolution





Pulsars are everywhere:

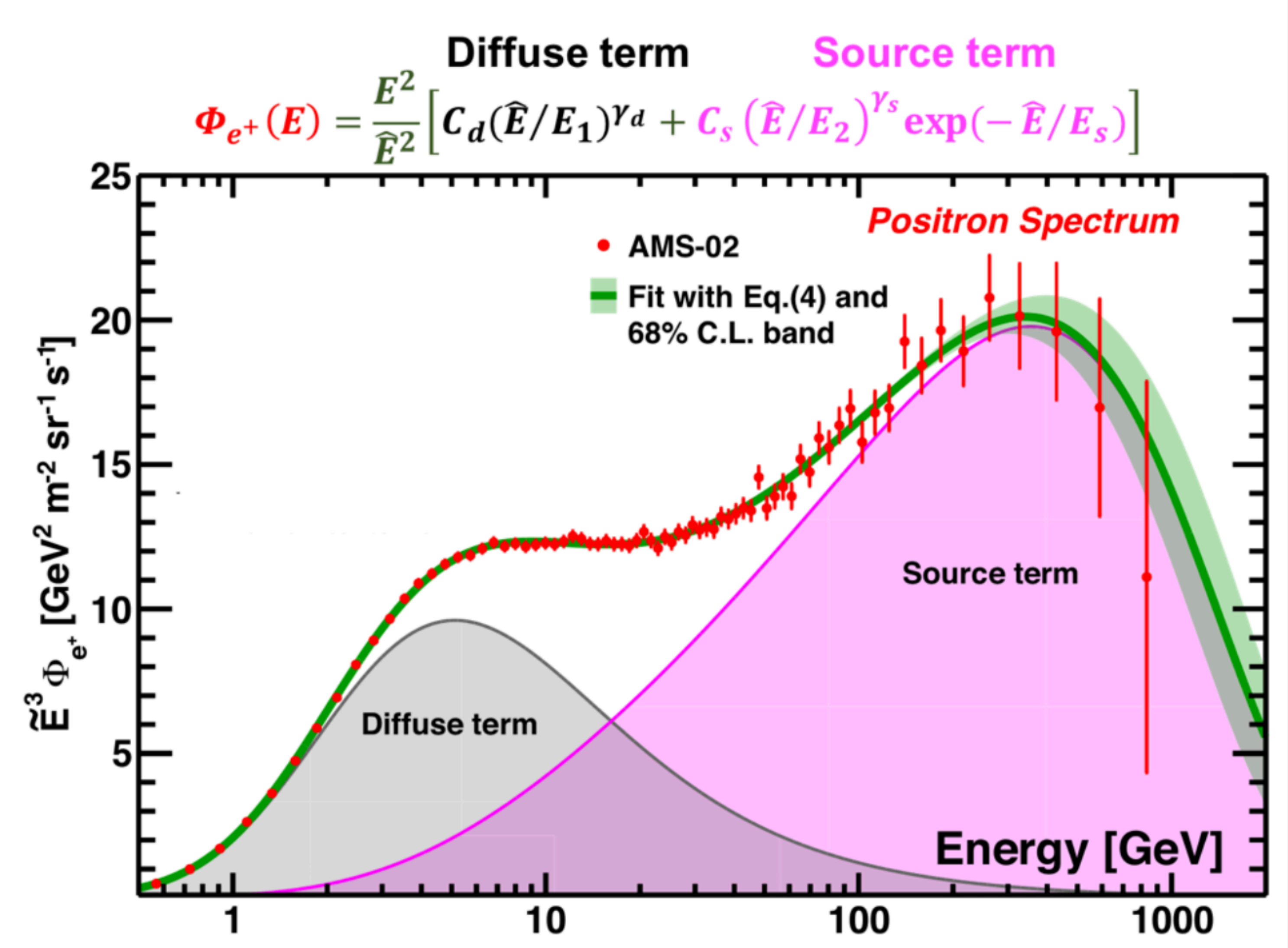
Going from a handful (pre LAT) to 300 pulsars

Implications for all Galactic science: el/pos measurement, dark matter searches…

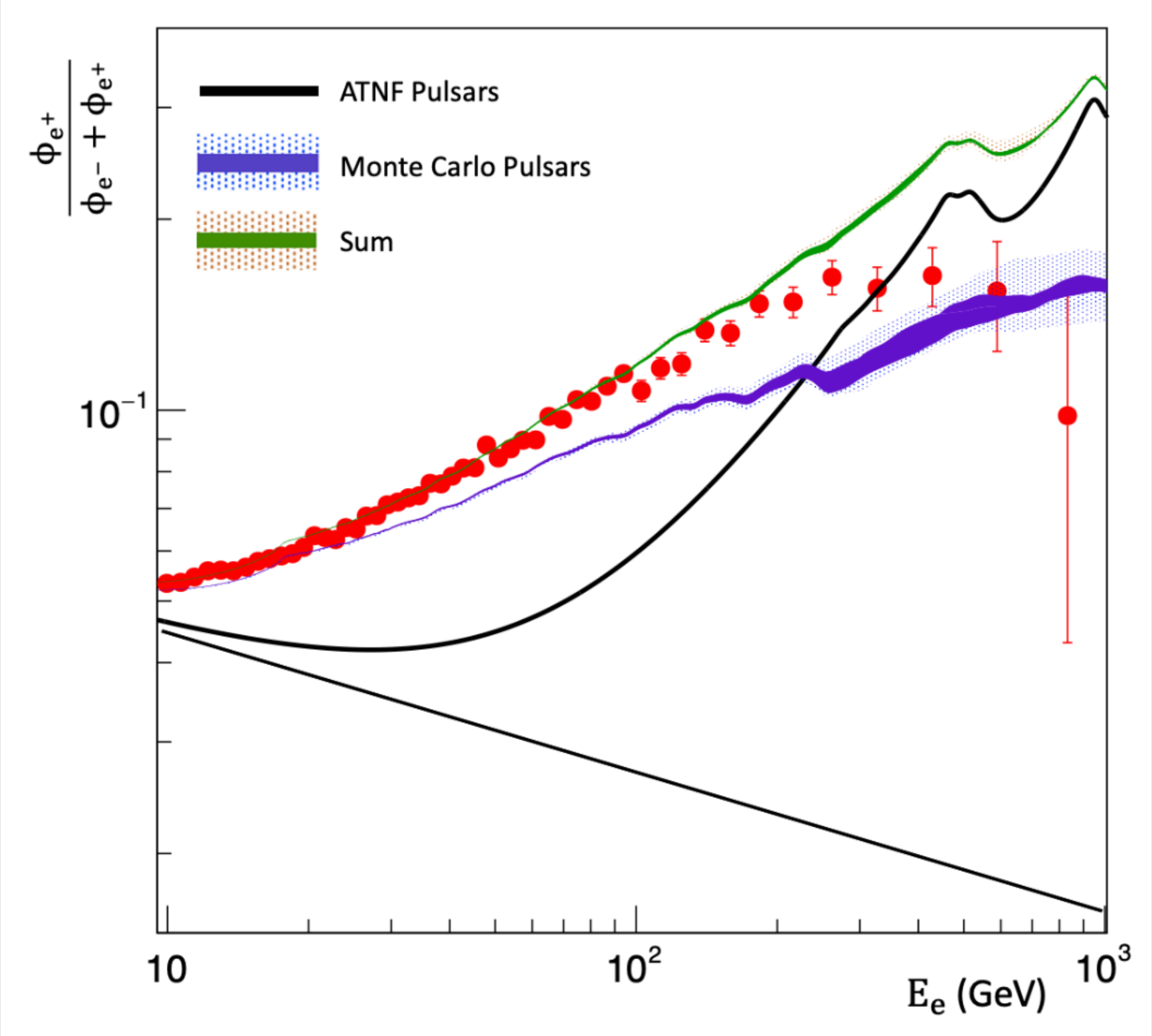
Fast forward

- pulsar revolution and positron fraction

AMS02 measurement 2019



Bitter&Hopper, 2023



Early LAT results - Galactic center excess

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope #5

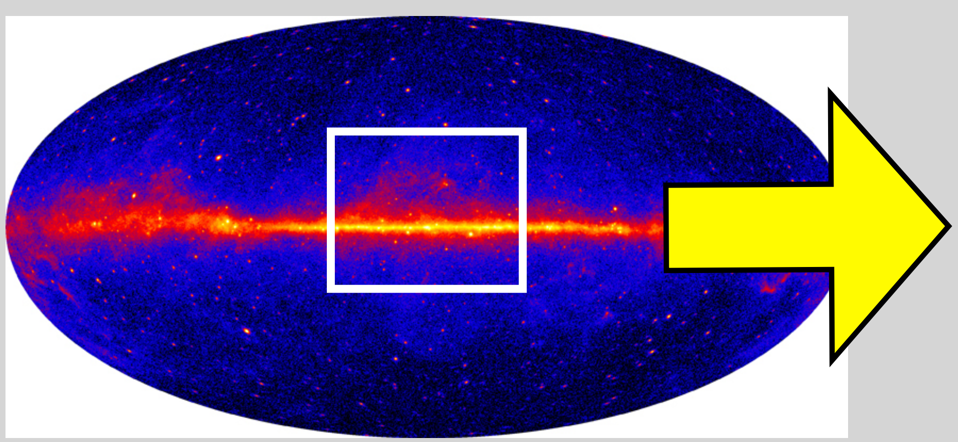
Lisa Goodenough (New York U., CCPP), Dan Hooper (Fermilab and Chicago U., Astron. Astrophys. Ctr.) (Oct, 2009)

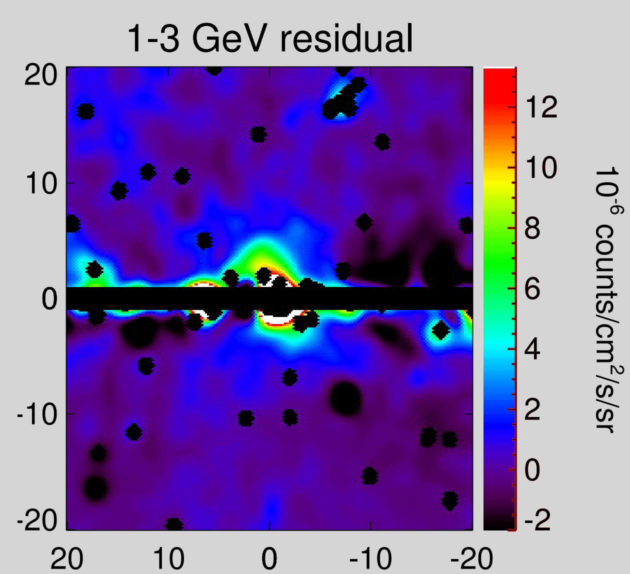
e-Print: 0910.2998 [hep-ph]

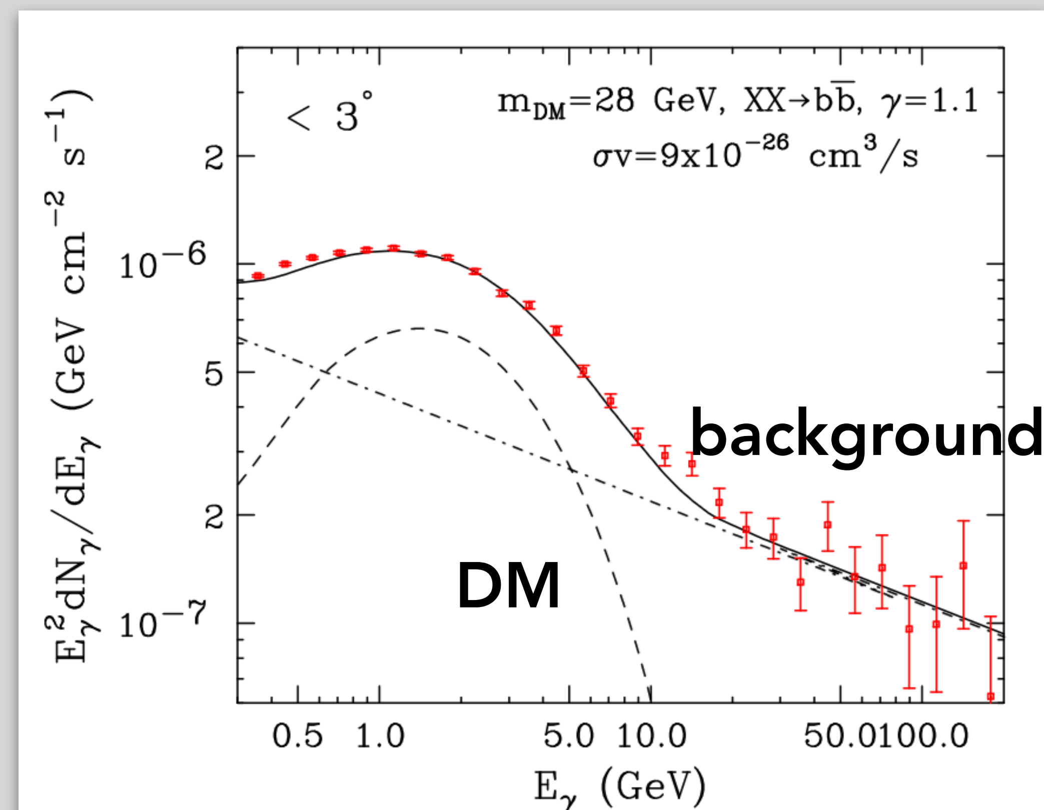
2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

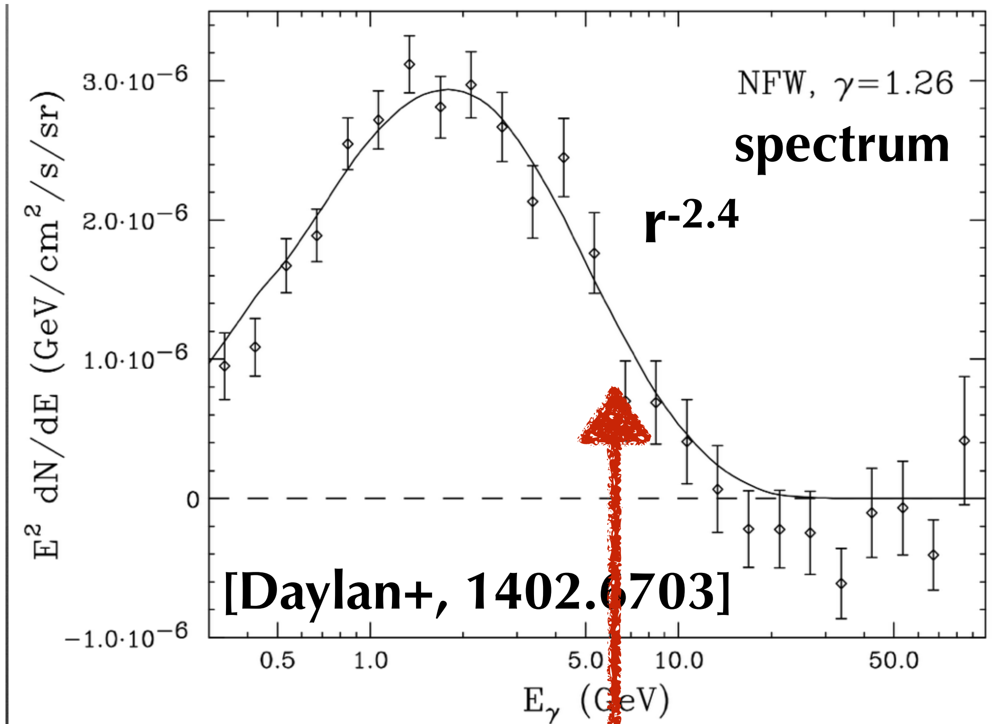
Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy



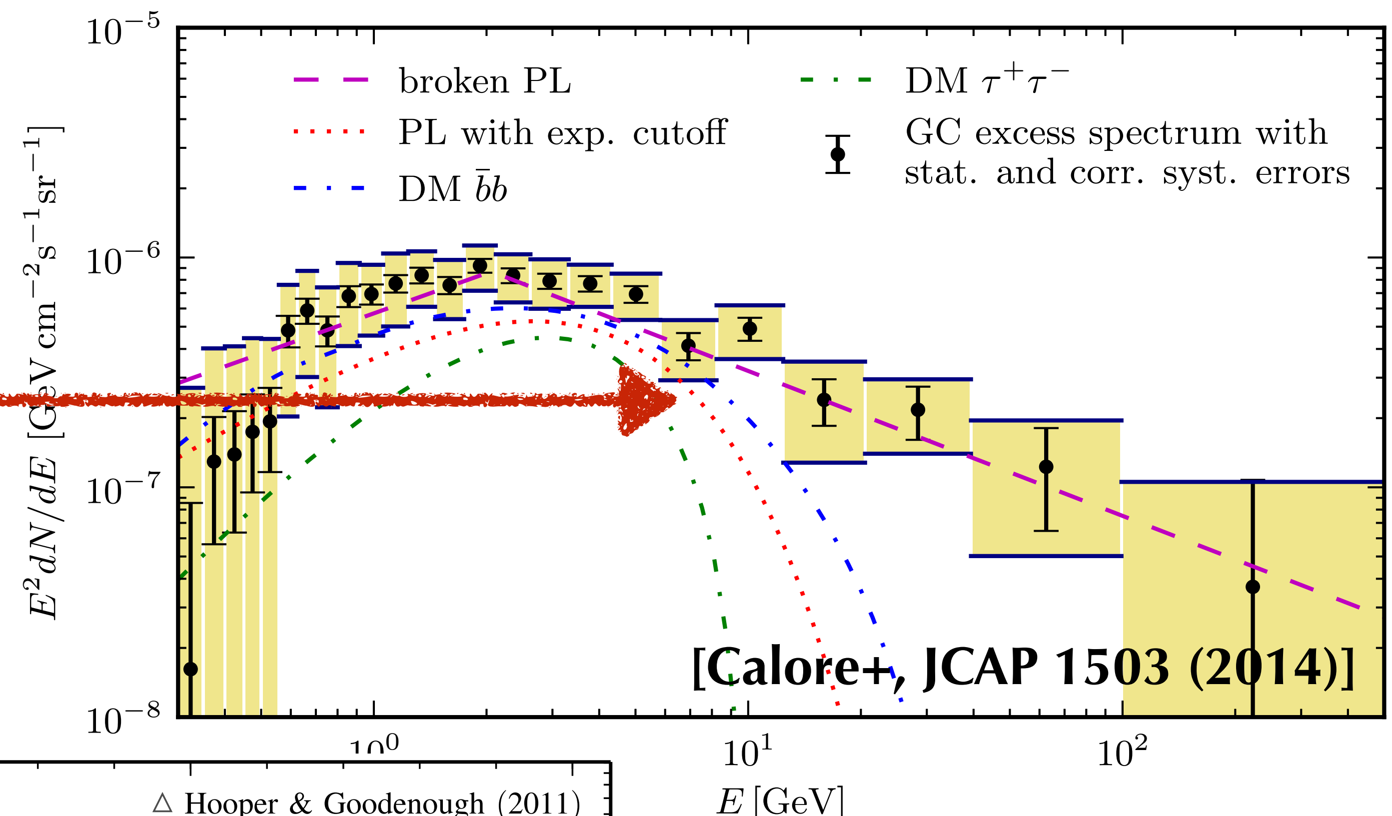




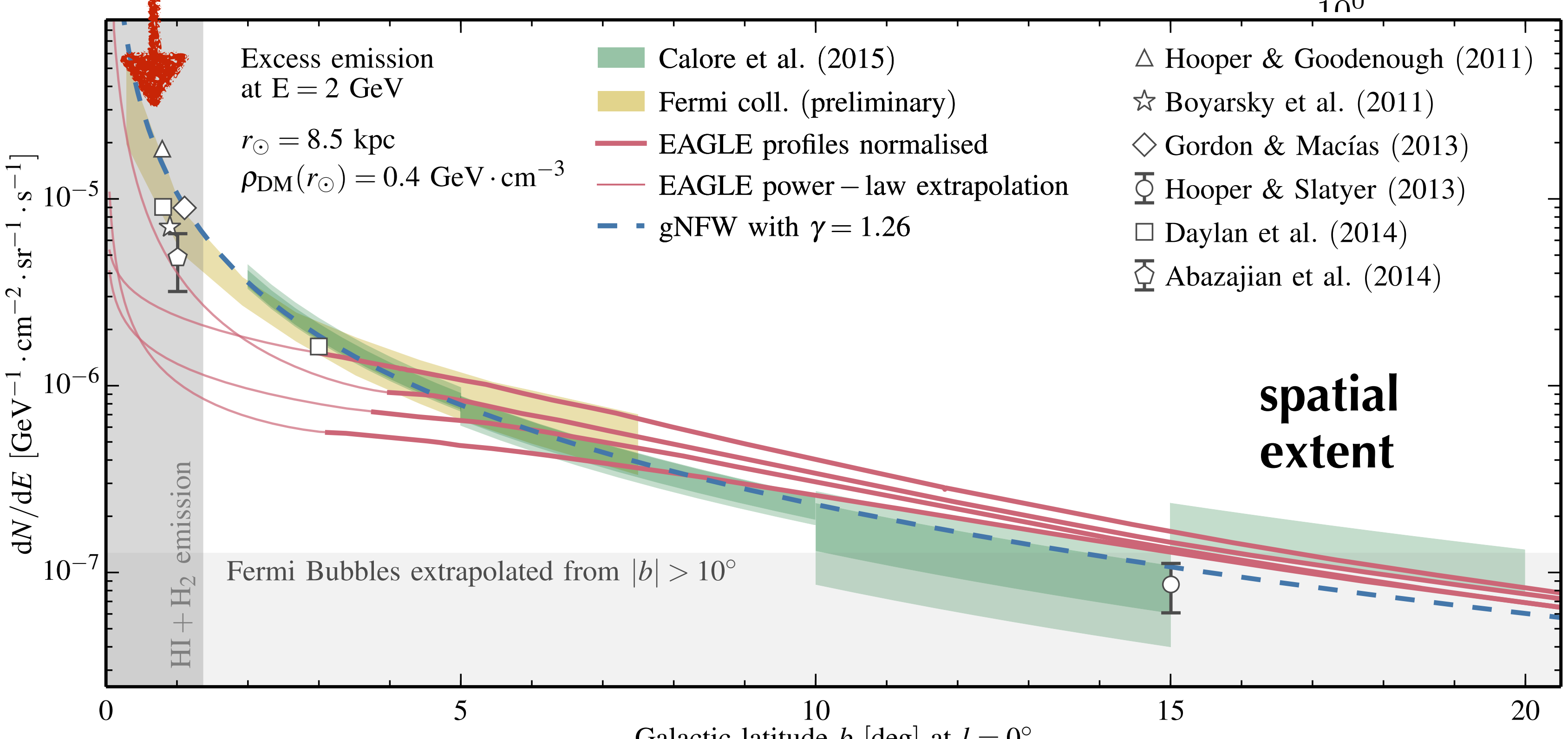
Many works reaching similar results: Vitale & Morseli (2009), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 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

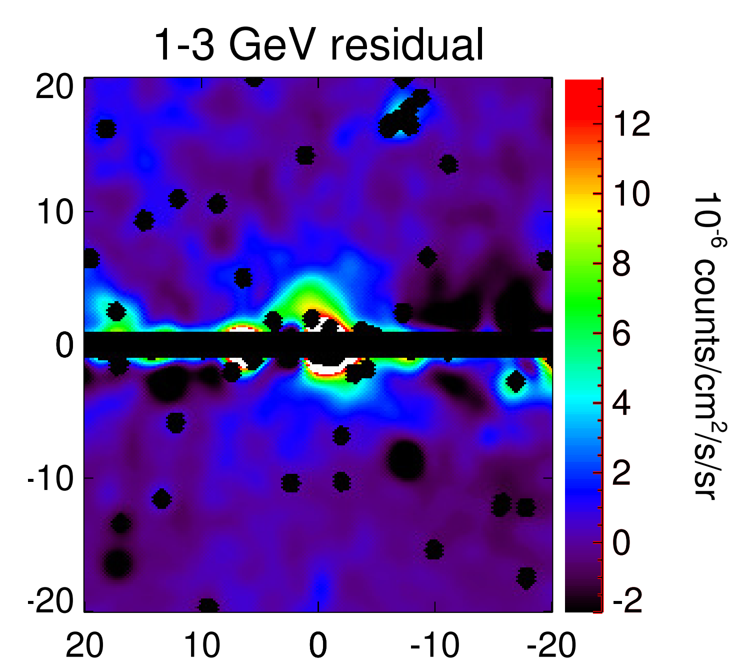


DM spectral fits



DM morphology



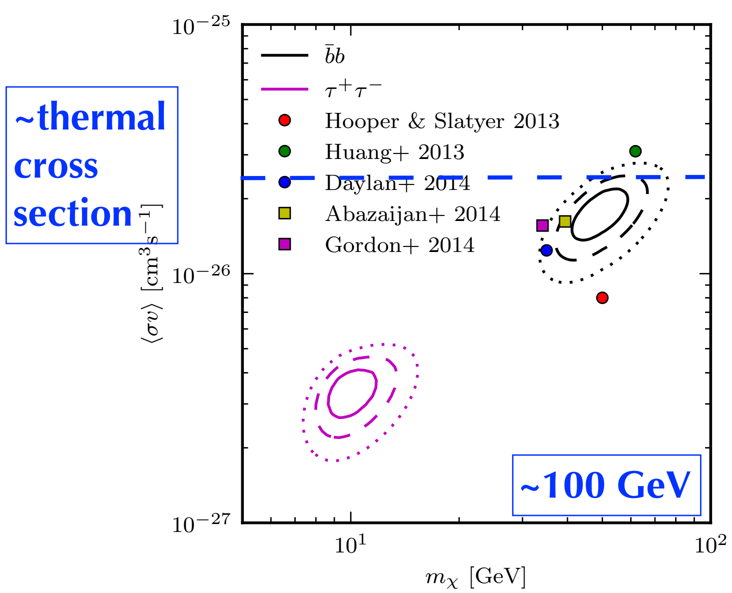


Nature of the GCE

DM vs pulsars: spectral twins

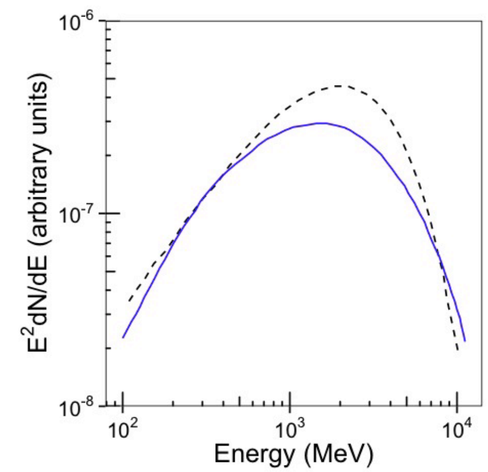
Your vanilla DM

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

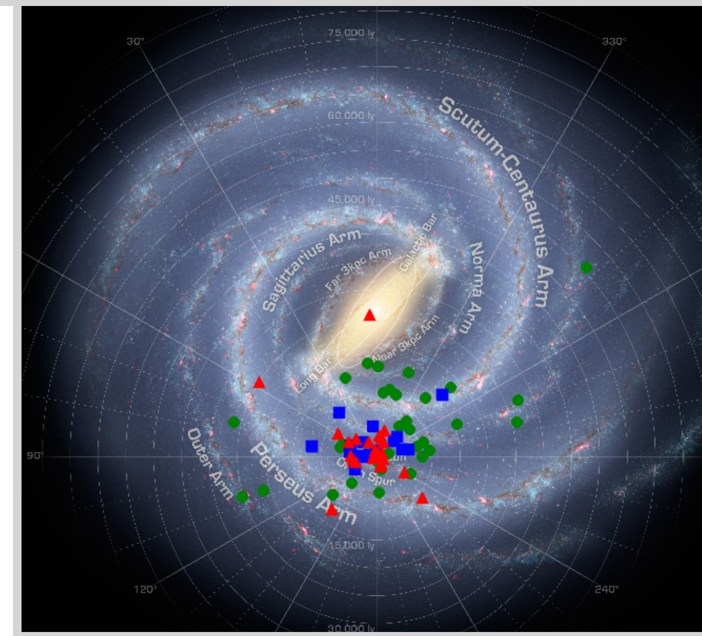


Or (milli second) pulsars

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

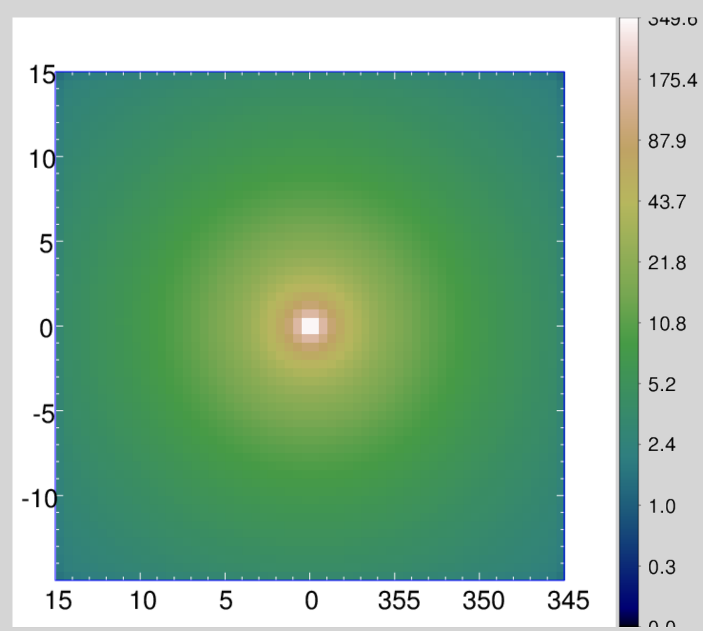


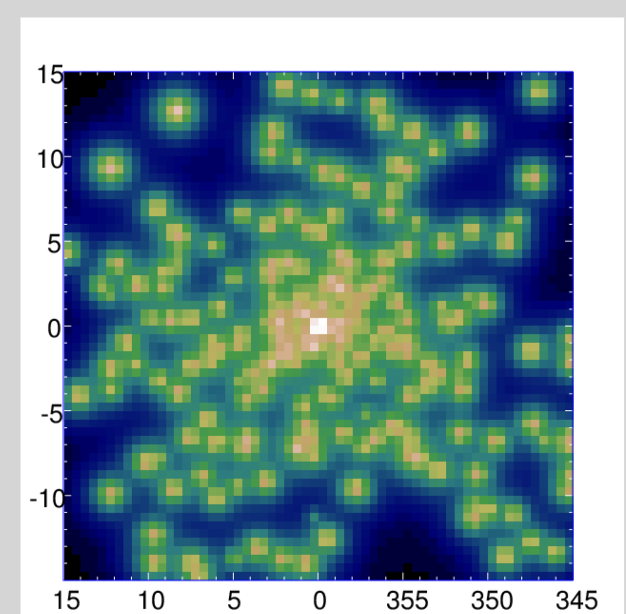
Baltz et al (2007)



Question boils down to: is excess smooth or ‘point source-like’

Advanced analysis techniques including machine learning inconclusive





Fast forward

Mind the gap!

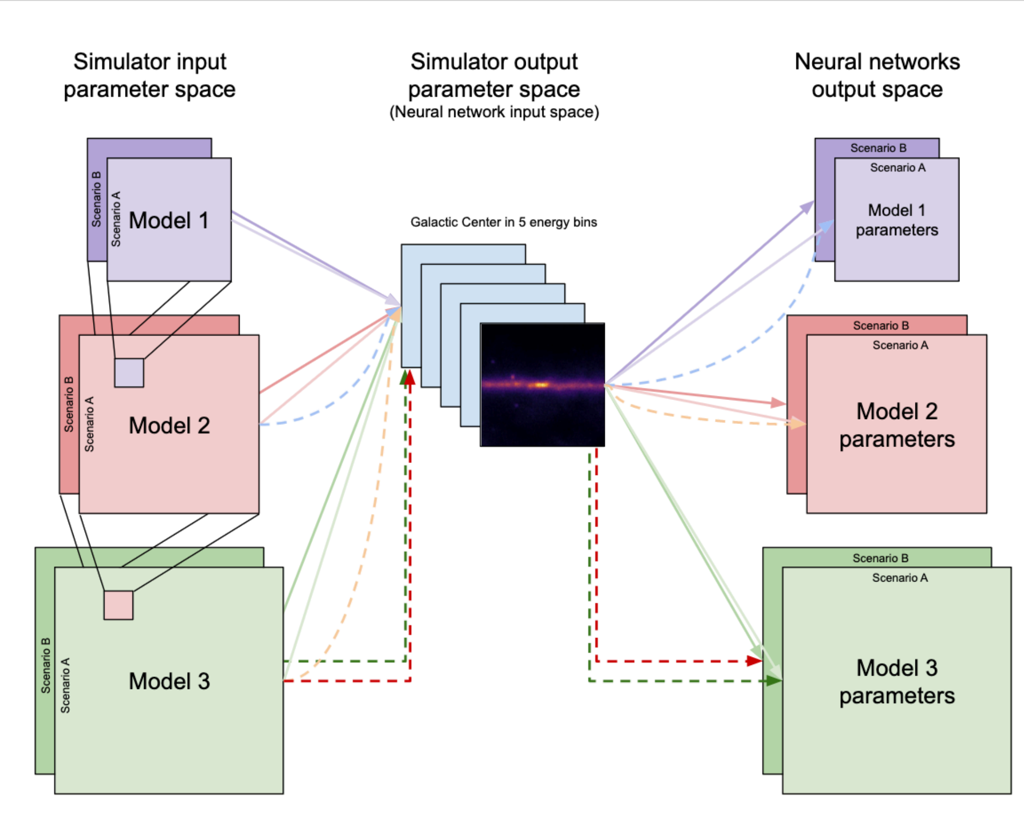
Is any of models realistic 'enough'?

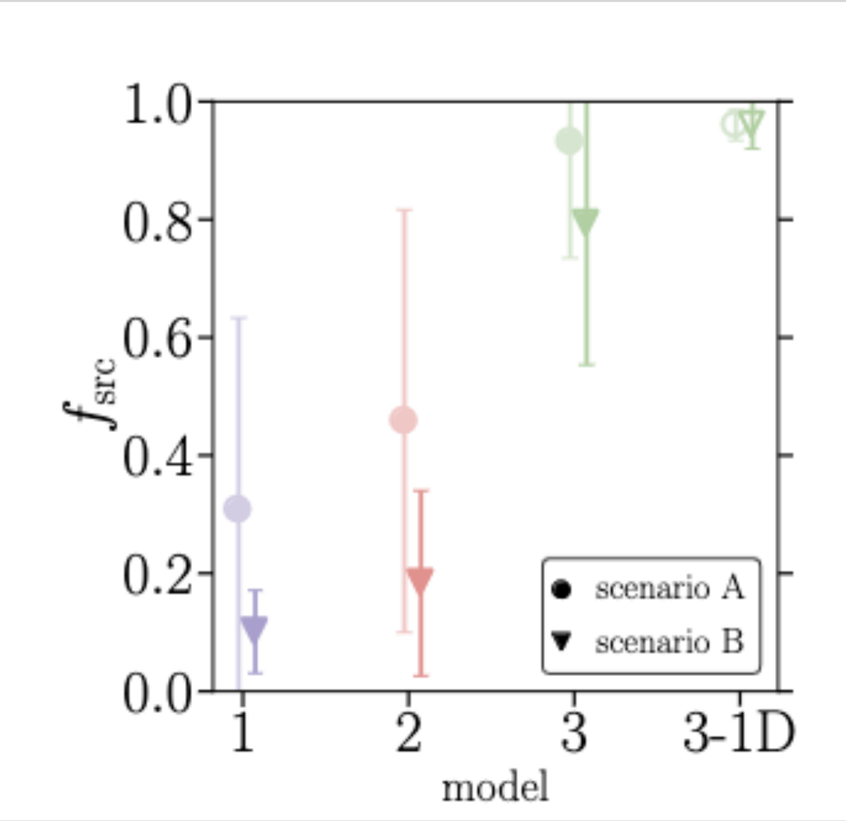
Possible to study with ML techniques (a 'reality gap' problem)

Mind the gap: The discrepancy between simulation and reality drives interpretations of the Galactic Center Excess #2

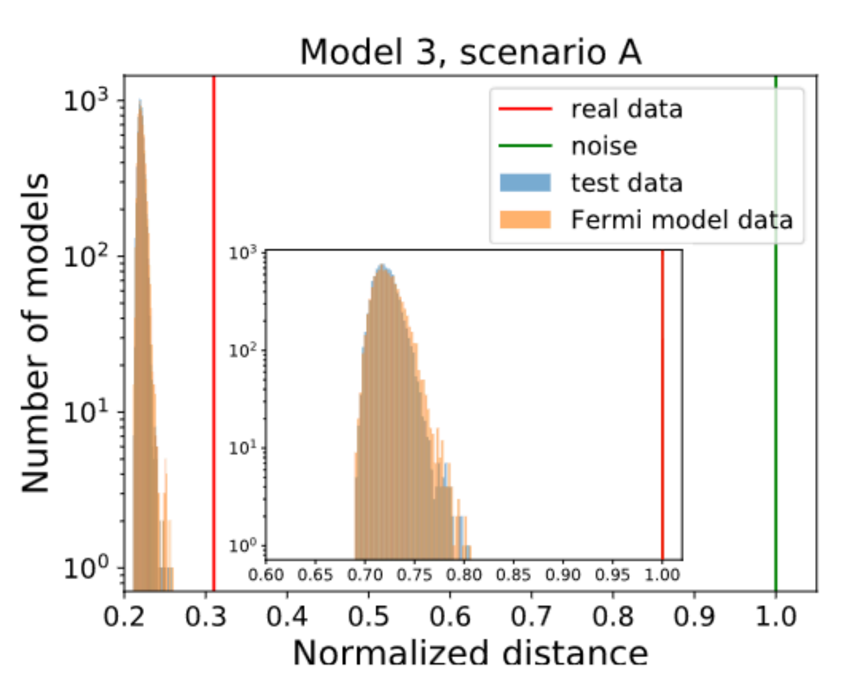
Sascha Caron (Nijmegen U. and NIKHEF, Amsterdam), Christopher Eckner (Annecy, LAPTH and Annecy, LAPP), Luc Hendriks (Nijmegen U. and NIKHEF, Amsterdam), Guðlaugur Jóhannesson (Iceland U. and Nordita), Roberto Ruiz de Austri (Valencia U., IFIC) et al. (Nov 17, 2022)

e-Print: 2211.09796 [astro-ph.HE]





SVDD approach - how far is the real data from the models

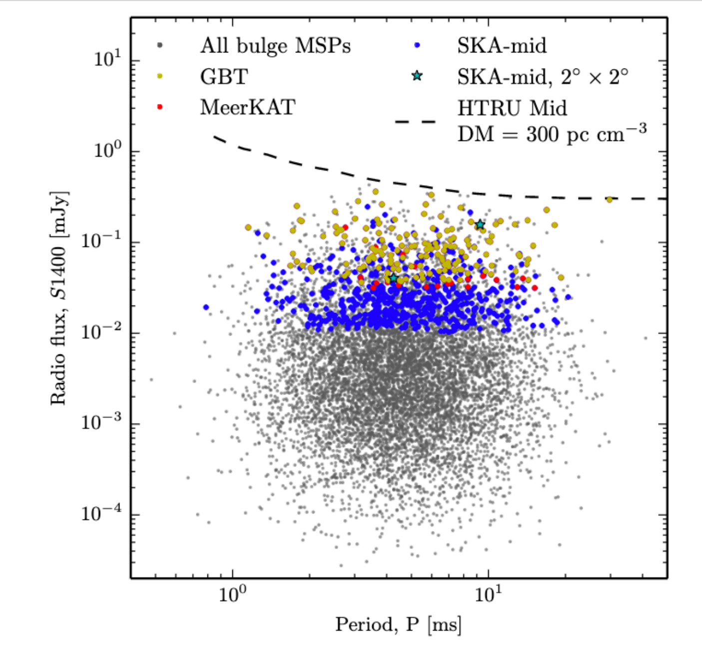


Future - GCE

Radio detection prospects for a bulge population of millisecond pulsars as suggested by Fermi LAT observations of the inner Galaxy #1

Francesca Calore (U. Amsterdam, GRAPPA), Mattia Di Mauro (SLAC and Stanford U., Phys. Dept.), Fiorenza Donato (INFN, Turin and Turin U.), Jason W. T. Hessels (ASTRON, Dwingeloo and Amsterdam U., Astron. Inst.), Christoph Weniger (U. Amsterdam, GRAPPA) (Dec 21, 2015)

Published in: *Astrophys.J.* 827 (2016) 2, 143 • e-Print: 1512.06825 [astro-ph.HE]



Probing the Fermi-LAT GeV excess with gravitational waves #1

Francesca Calore (Annecy, LAPTH), Tania Regimbau (Annecy, LAPP), Pasquale Dario Serpico (Annecy, LAPTH) (Dec 12, 2018)

Published in: *Phys.Rev.Lett.* 122 (2019) 8, 081103 • e-Print: 1812.05094 [astro-ph.HE]

Neutron star high rotation velocities make any irregularity in their shape a quadrupolar source of GWs. This “monochromatic”, continuous, emission is often considered the leading GW signal associated to pulsars.

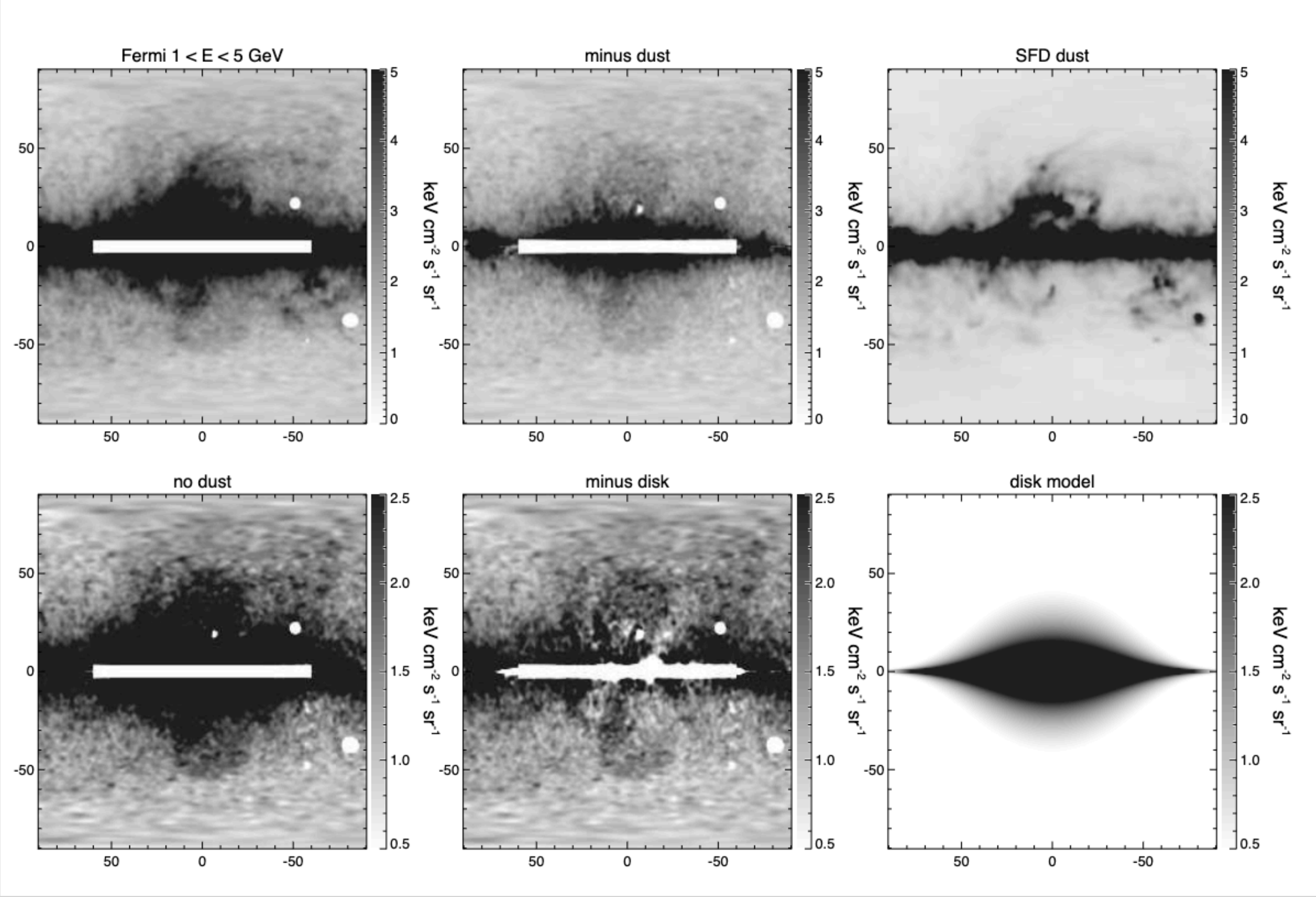
The population of rotating neutron stars can contribute to the so-called **stochastic GW background** (SGWB). MSP population in the Galactic bulge to be the strongest Galactic SGWB component in the LIGO/Virgo sensitivity band. **If the first individual MSPs will be identified in GW in the current 2G run, hence around ε ~ 10^{-8}, there are good perspectives that the 3G may detect the unresolved bulge contribution as well.**

Early results - Fermi bubbles

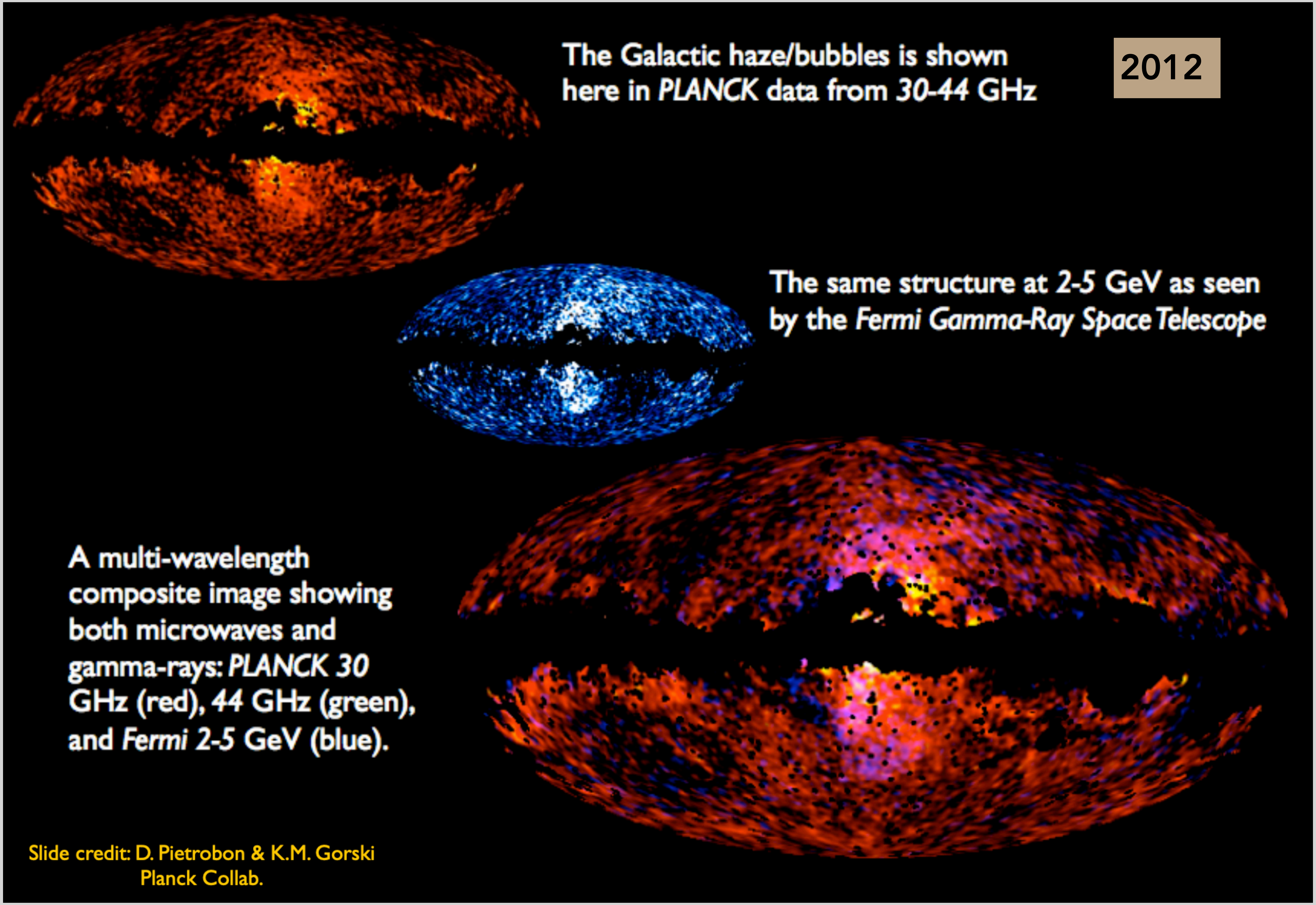
Giant Gamma-ray Bubbles from Fermi-LAT: AGN Activity or Bipolar Galactic Wind? #1

Meng Su (Harvard-Smithsonian Ctr. Astrophys.), Tracy R. Slatyer (Harvard U. and Harvard-Smithsonian Ctr. Astrophys.), Douglas P. Finkbeiner (Harvard U. and Harvard-Smithsonian Ctr. Astrophys.) (May, 2010)

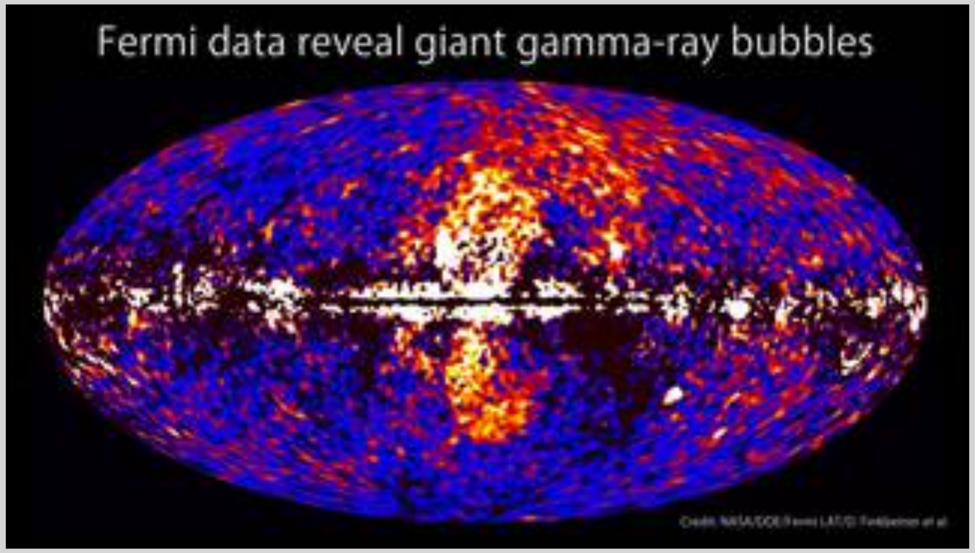
Published in: *Astrophys.J.* 724 (2010) 1044-1082 • e-Print: 1005.5480 [astro-ph.HE]



Fermi bubbles

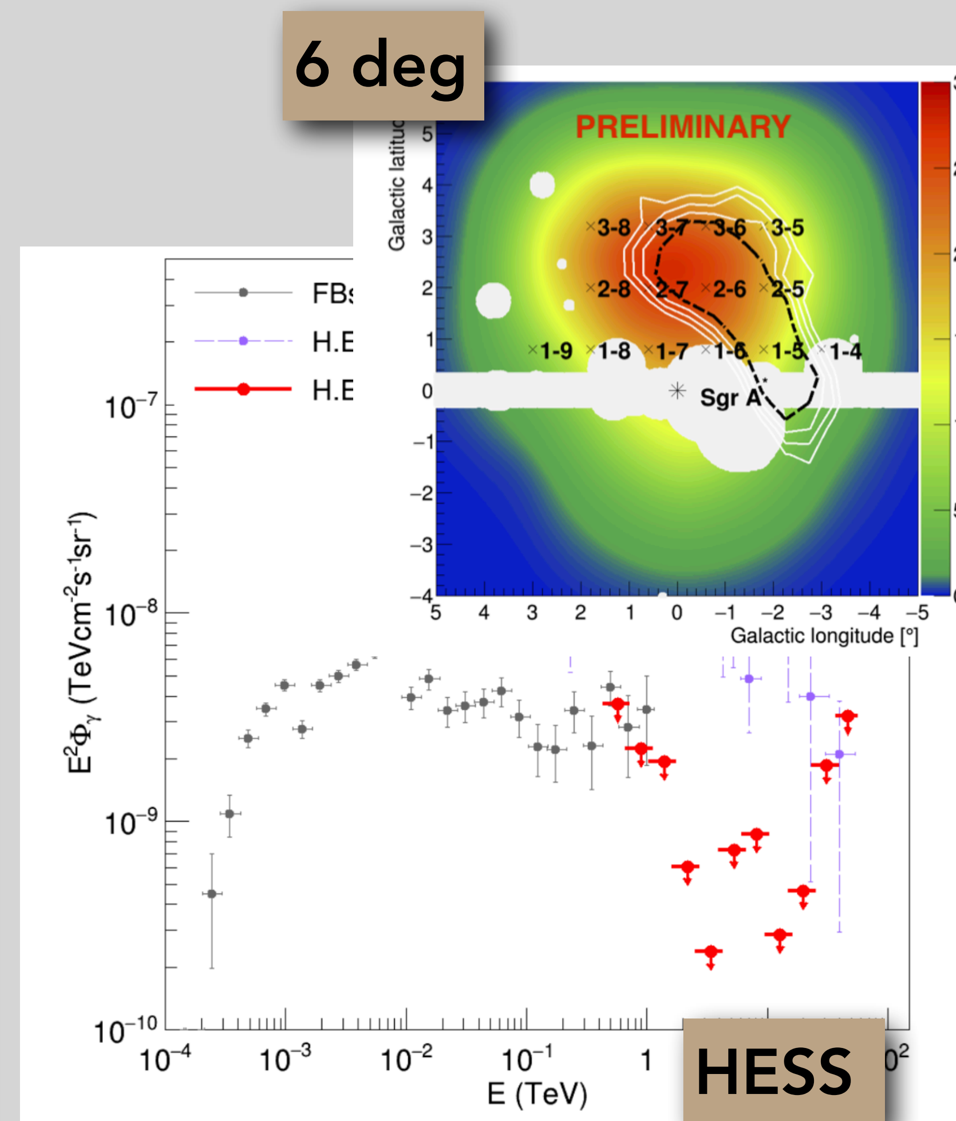


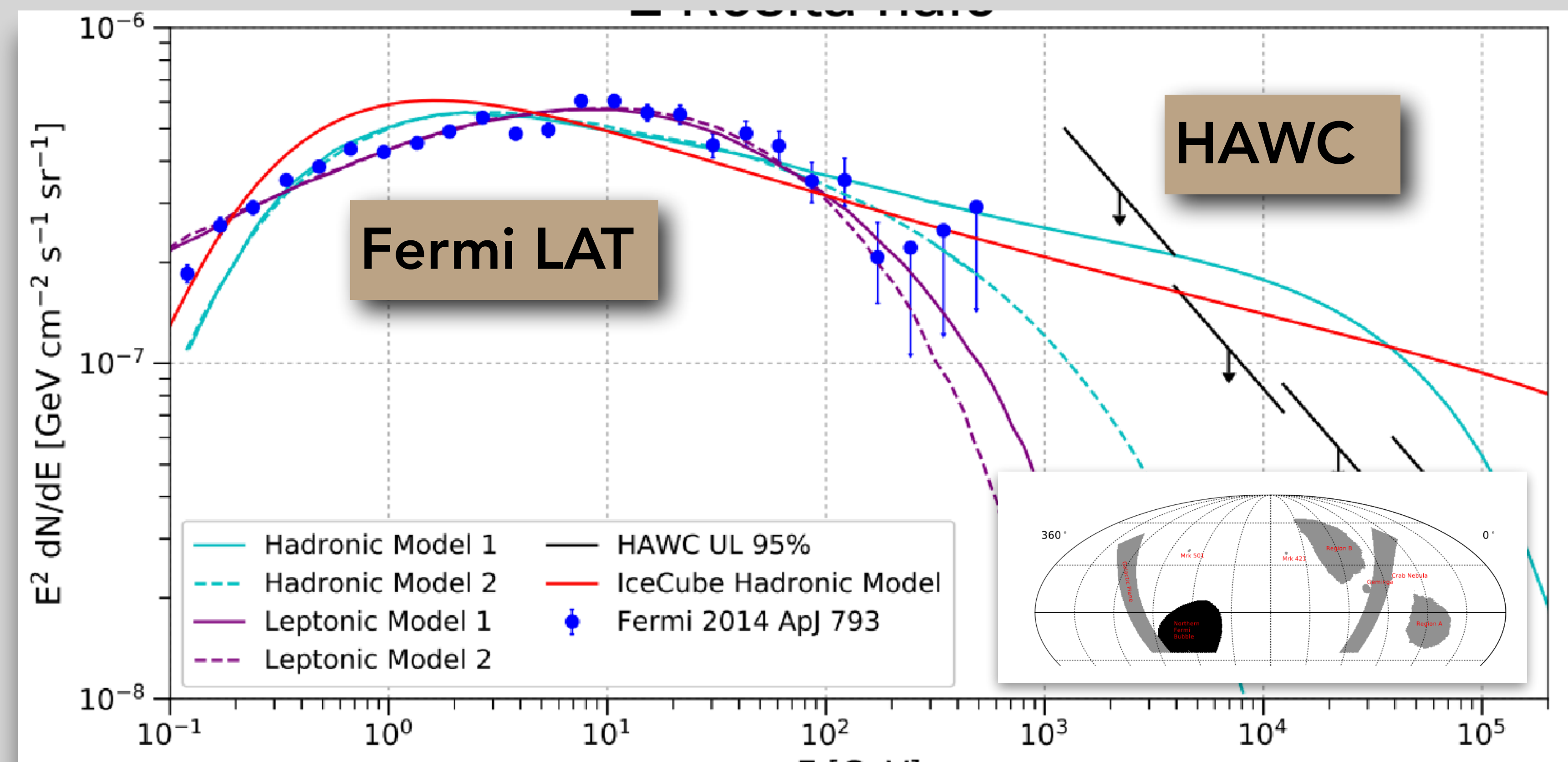
Current status - Fermi bubbles



Telling us something about the past activity at the Galactic center

- black hole jet
- Or a starburst activity?





Early LAT results

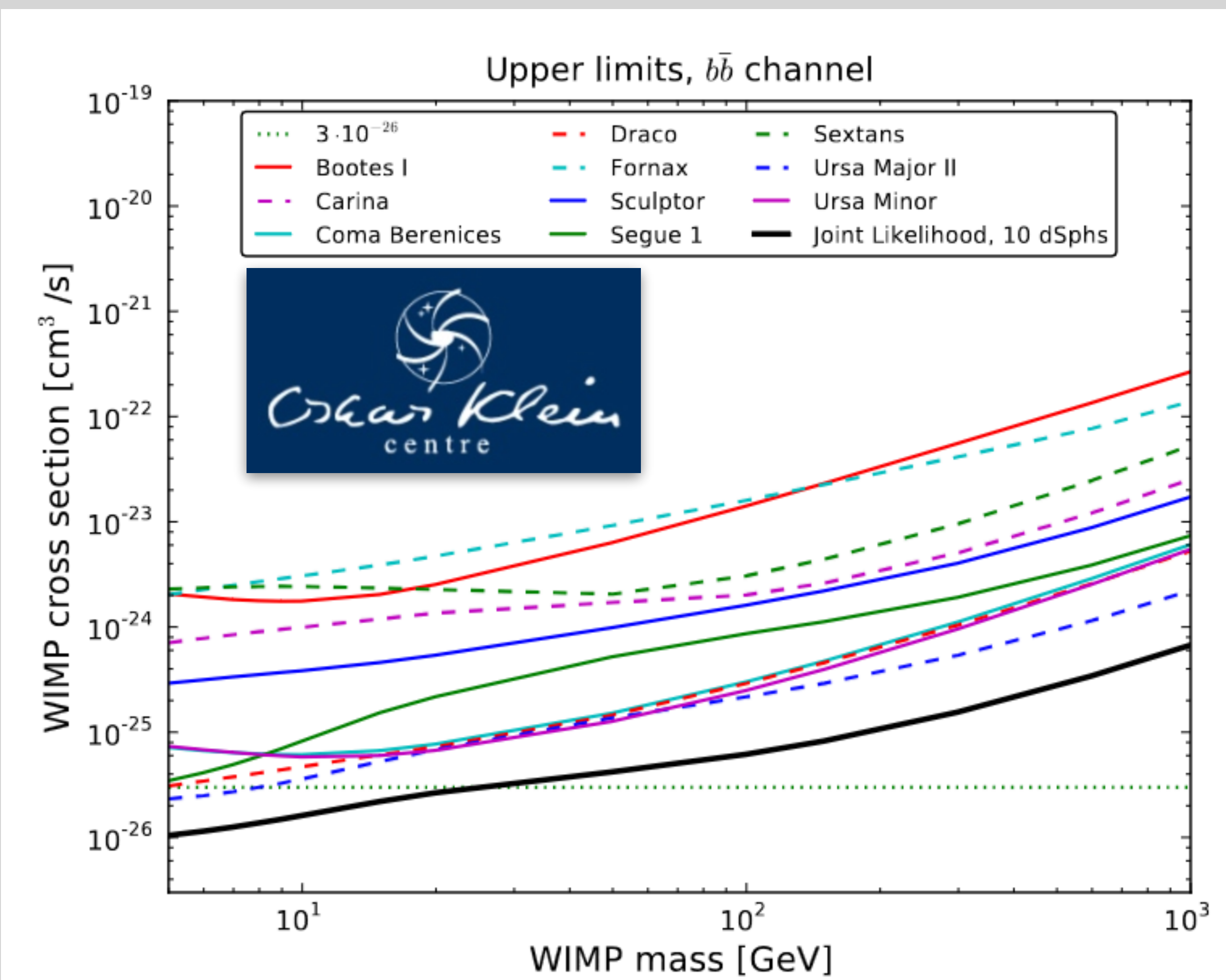
– thermal dark matter limits

Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope #1

Fermi-LAT Collaboration • M. Ackermann (Stanford U., HEPL and Taiwan, Natl. Taiwan U. and SLAC) et al. (Aug, 2011)

Published in: *Phys.Rev.Lett.* 107 (2011) 241302 • e-Print: 1108.3546 [astro-ph.HE]

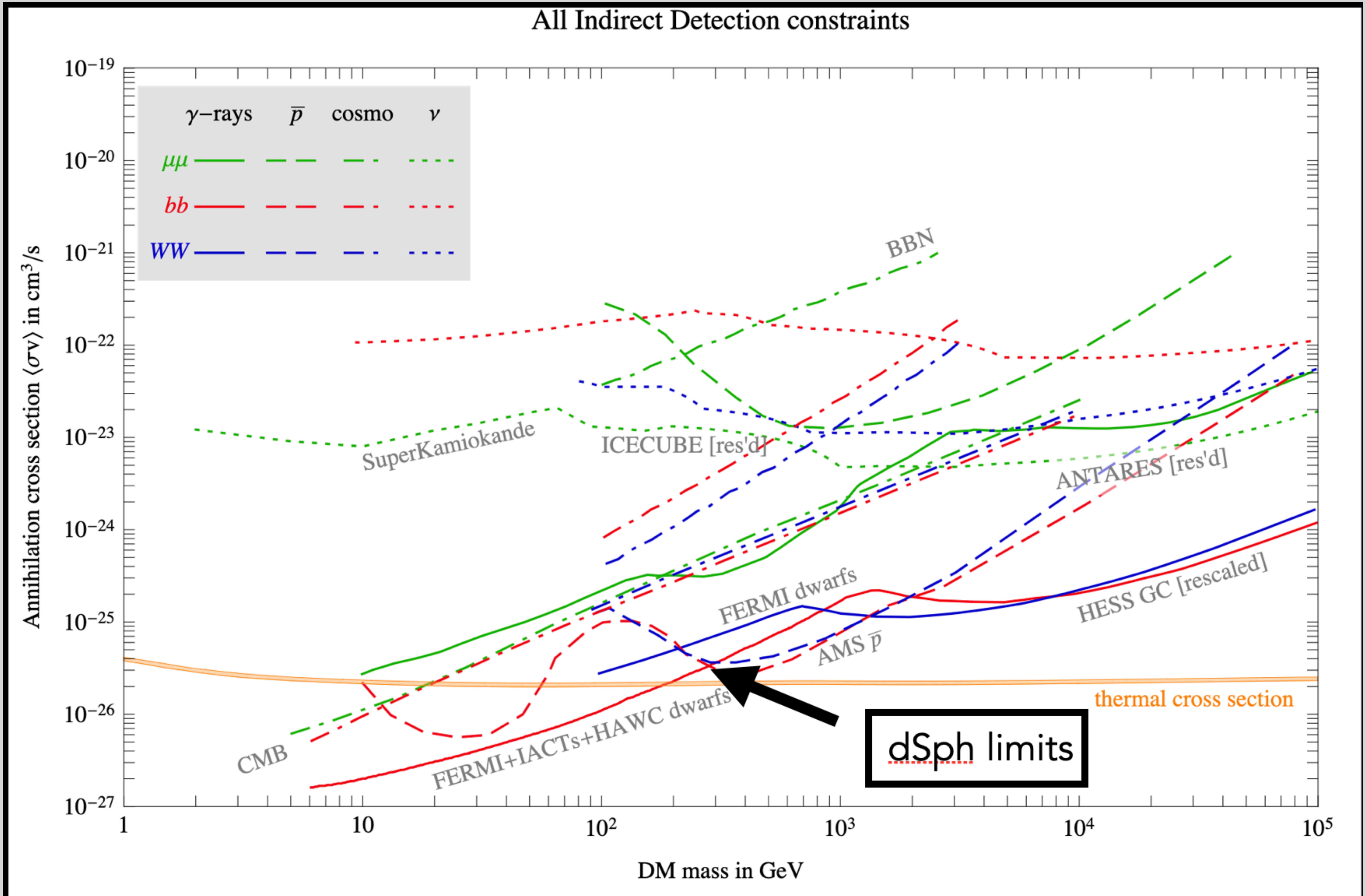
pdf   links   DOI   cite   claim   reference search   640 citations



Novel DM analysis technique that combines uncertainty from all dSPh galaxies

- Crossed the thermal cross -section with a robust probe!

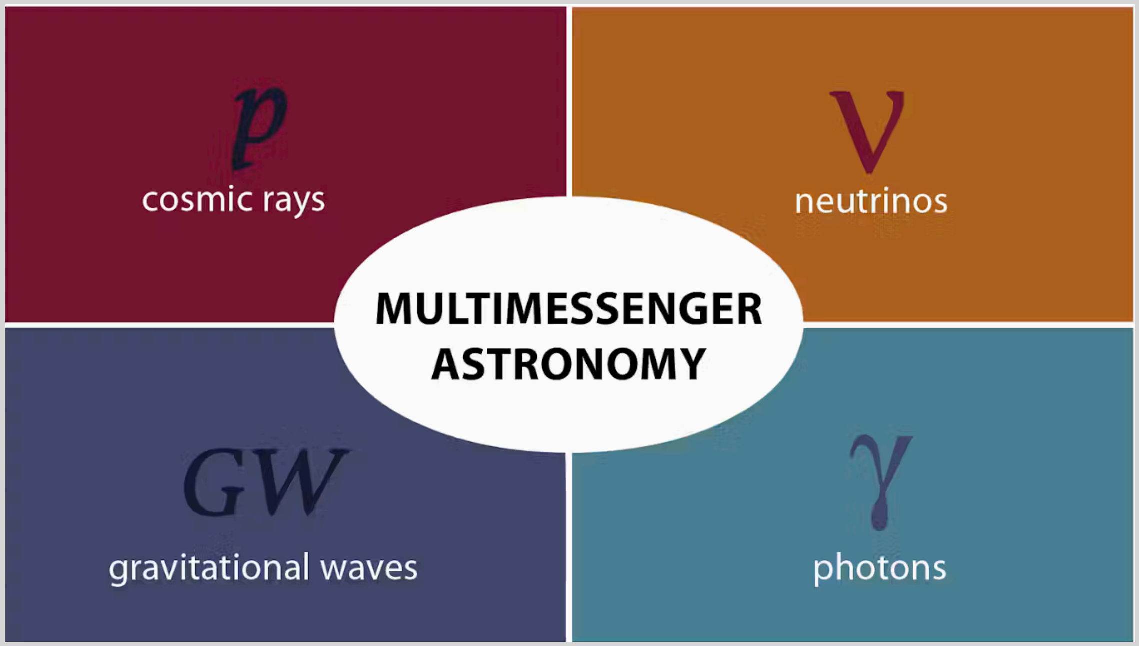
Nowadays - thermal DM constraints



M. Cirelli, A. Strumia, J. Zupan to appear

Fermi LAT Legacy

Fundamental player in modern day MW astrophysics



Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A #35

IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations • M.G. Aartsen (Canterbury U.) et al. (Jul 12, 2018)

Published in: *Science* 361 (2018) 6398, eaat1378 • e-Print: 1807.08816 [astro-ph.HE]

pdf links DOI cite claim reference search 796 citations

Fermi-LAT Observations of LIGO/Virgo Event GW170817 #36

M. Ajello (Clemson U.), A. Allafort (KIPAC, Menlo Park and SLAC), M. Axelsson (Royal Inst. Tech., Stockholm and Tokyo Metropolitan U.), L. Baldini (INFN, Pisa and Pisa U.), G. Barbiellini (INFN, Trieste and Trieste U.) et al. (Jul 6, 2018)

Published in: *Astrophys.J.* 861 (2018) 2, 85

pdf DOI cite claim reference search 40 citations

Some extraordinary results

A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background #1

Fermi-LAT Collaboration • M. Ajello (Clemson U.) et al. (Apr

Published in: *Science* 376 (2022) 6592, abm3231 • e-Print

pdf DOI cite claim

Evidence for a New Component of High-Energy Solar Gamma-Ray Production #13

Tim Linden (Ohio State U., CCAPP), Bei Zhou (Ohio State U., CCAPP and Ohio State U.), John F. Beacom (Ohio State U., CCAPP and Ohio State U. and Ohio State U., Dept. Astron.), Annika H.G. Peter (Ohio State U., CCAPP and Ohio State U. and Ohio State U., Dept. Astron.), Kenny C.Y. Ng (Weizmann Inst.) et al. (Mar 14, 2018)

Published in: *Phys.Rev.Lett.* 121 (2018) 13, 131103 • e-Print: 1803.05436 [astro-ph.HE]

pdf DOI cite claim reference search 38 citations

A gamma-ray determination of the Universe's star formation history #34

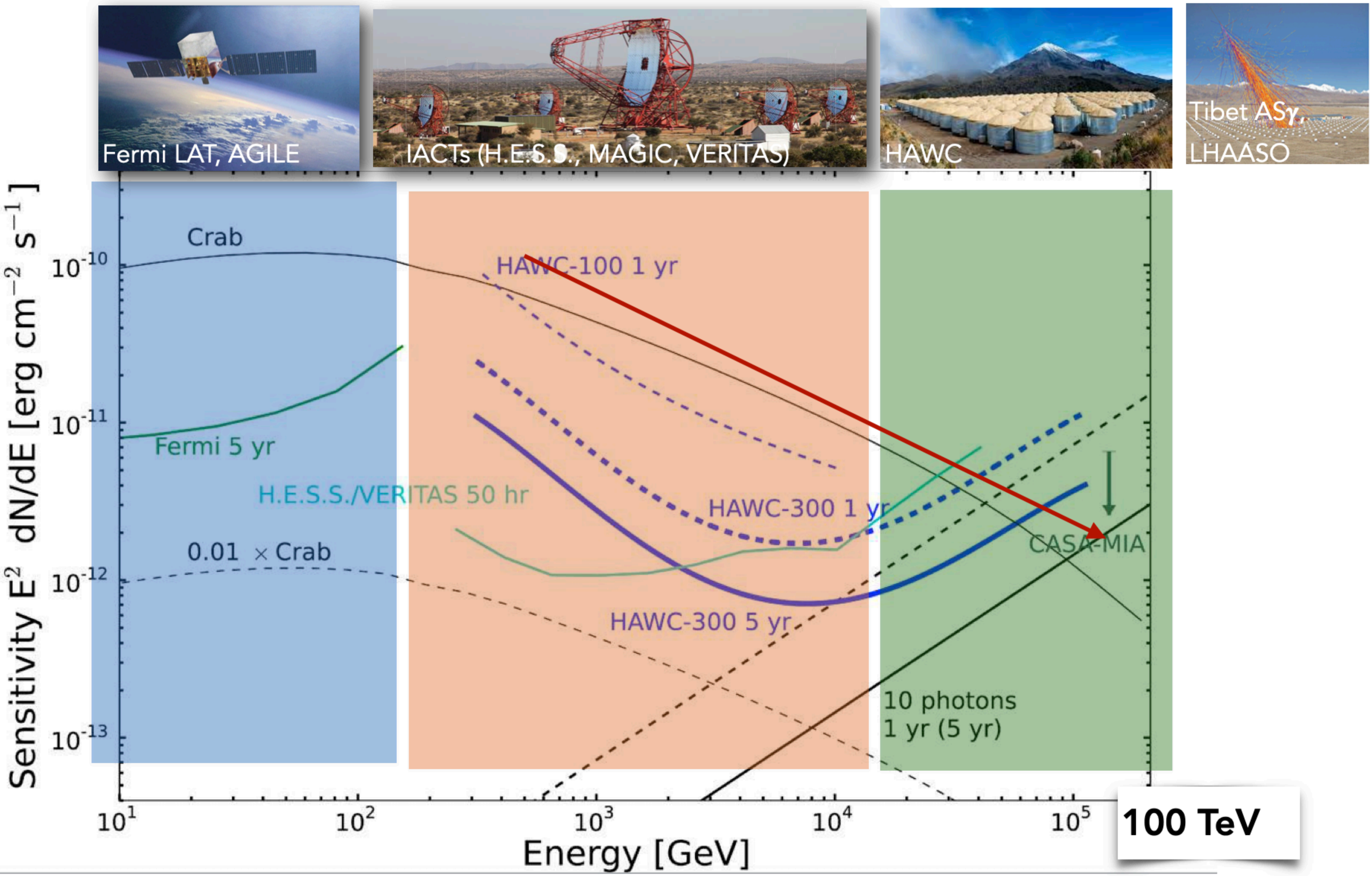
Fermi-LAT Collaboration • S. Abdollahi (Hiroshima U.) et al. (Dec 3, 2018)

Published in: *Science* 362 (2018) 6418, 1031-1034 • e-Print: 1812.01031 [astro-ph.HE]

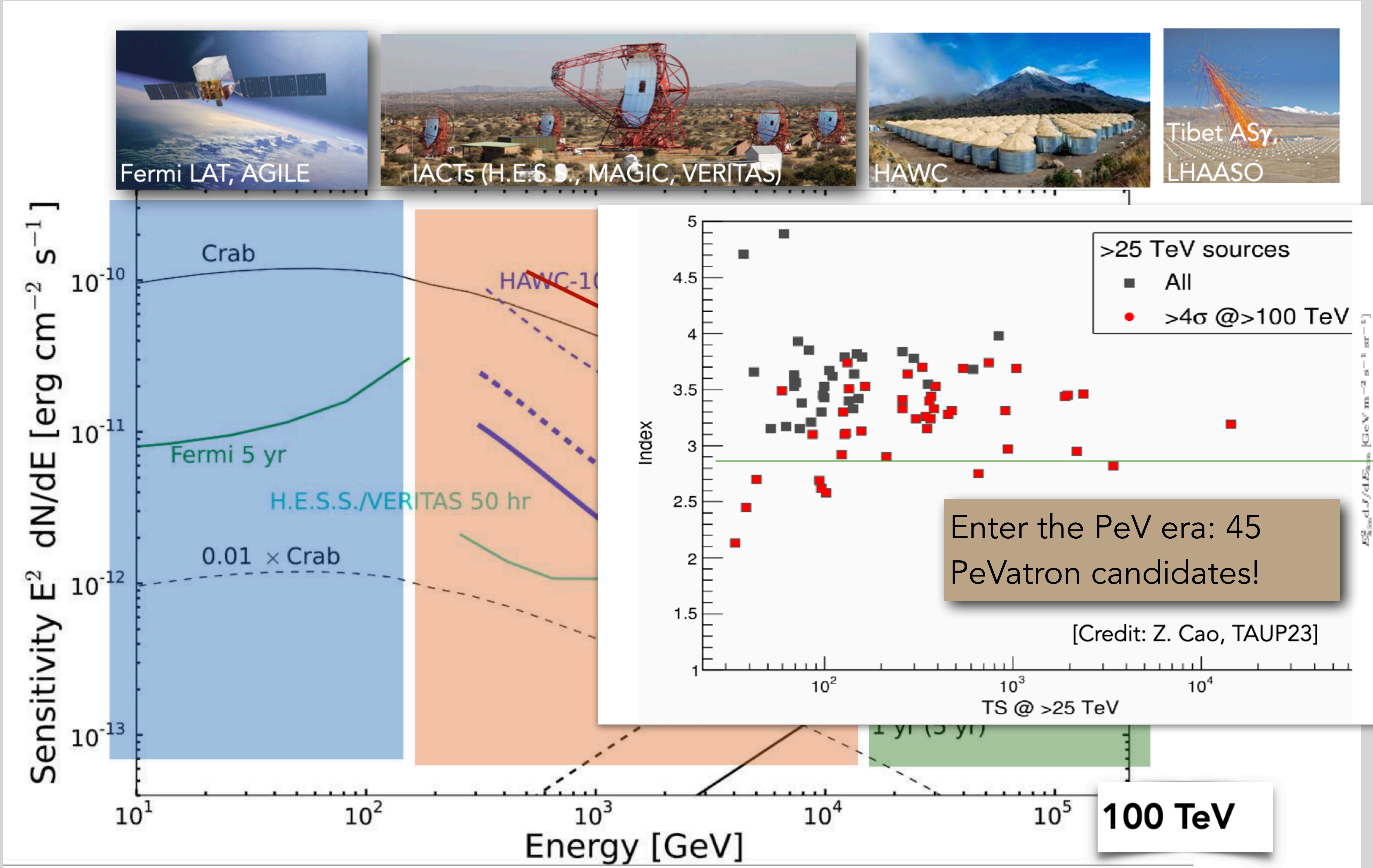
pdf DOI cite claim reference search 121 citations

+ many more

Gamma ray astrophysics nowadays

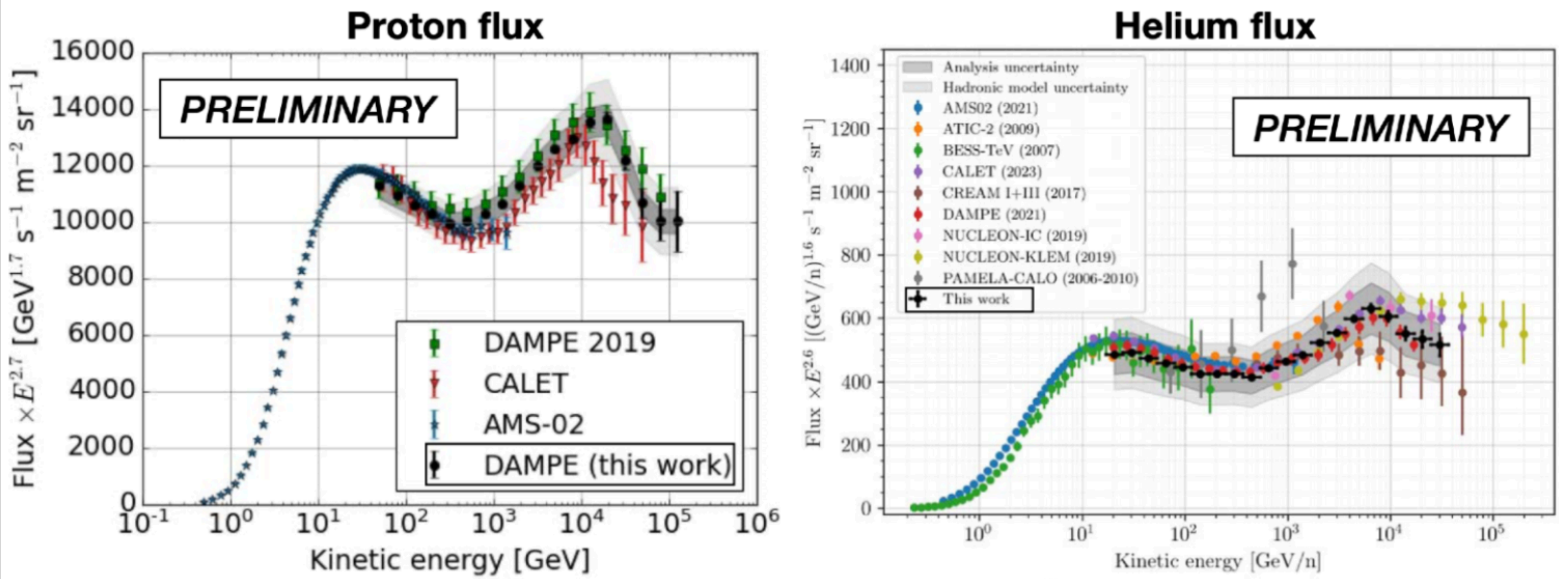


Gamma ray astrophysics nowadays

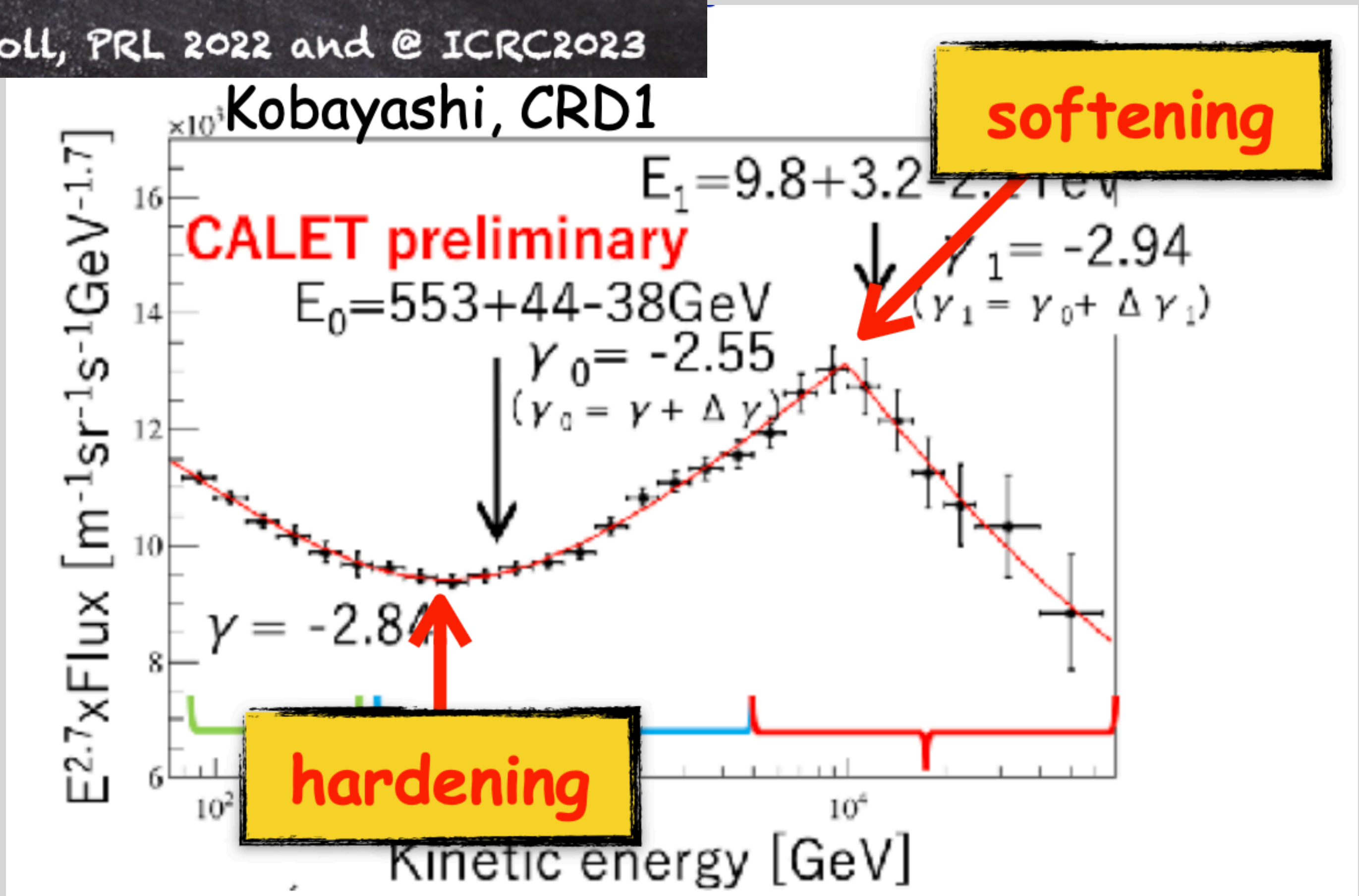


High energy astrophysics nowadays

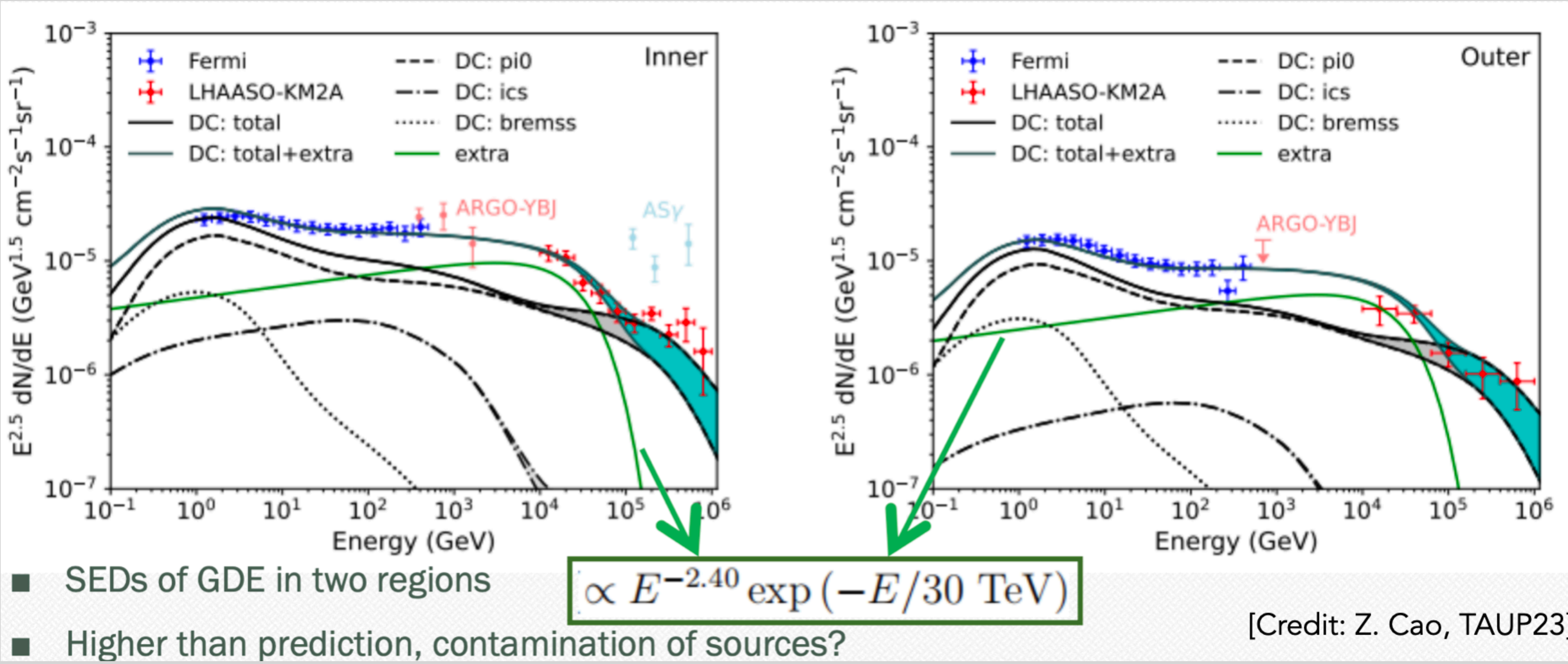
P and He spectra: shifts, breaks and bumps



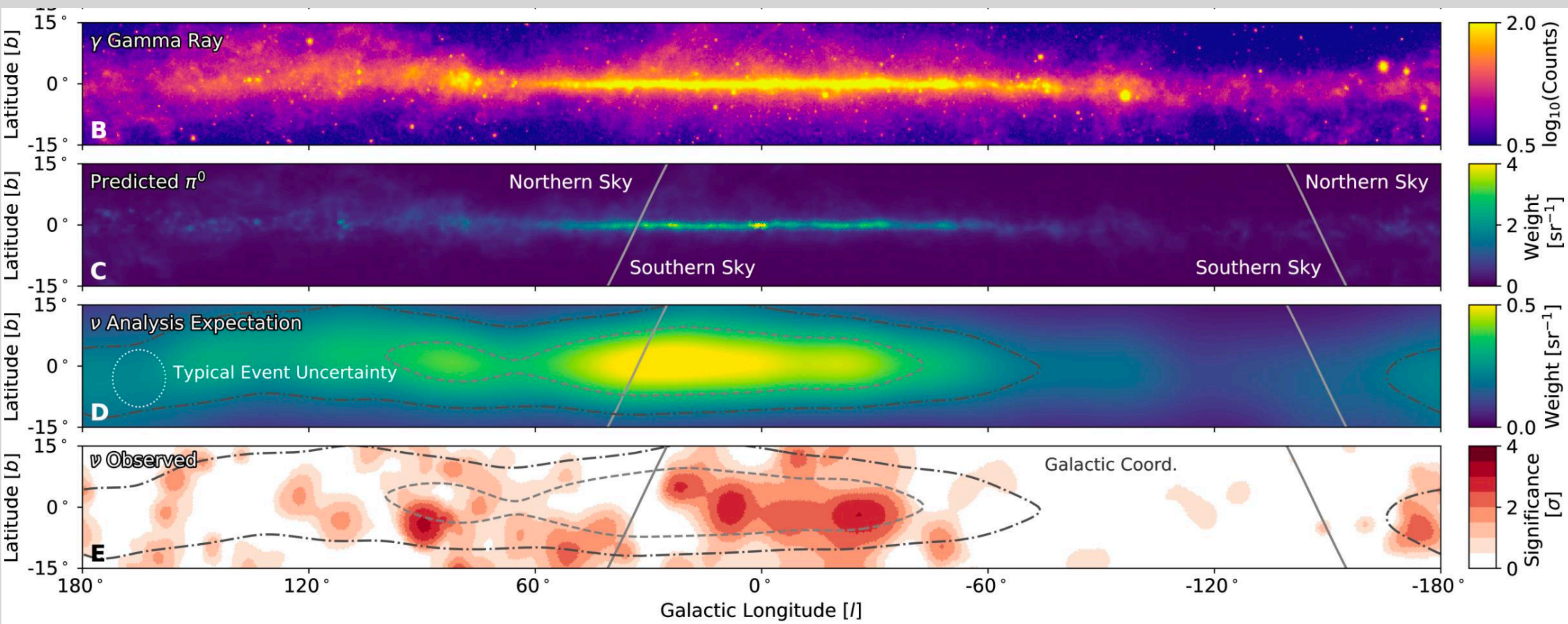
Dampe Coll See also CALET Coll, PRL 2022 and @ ICRC2023



High energy astrophysics nowadays

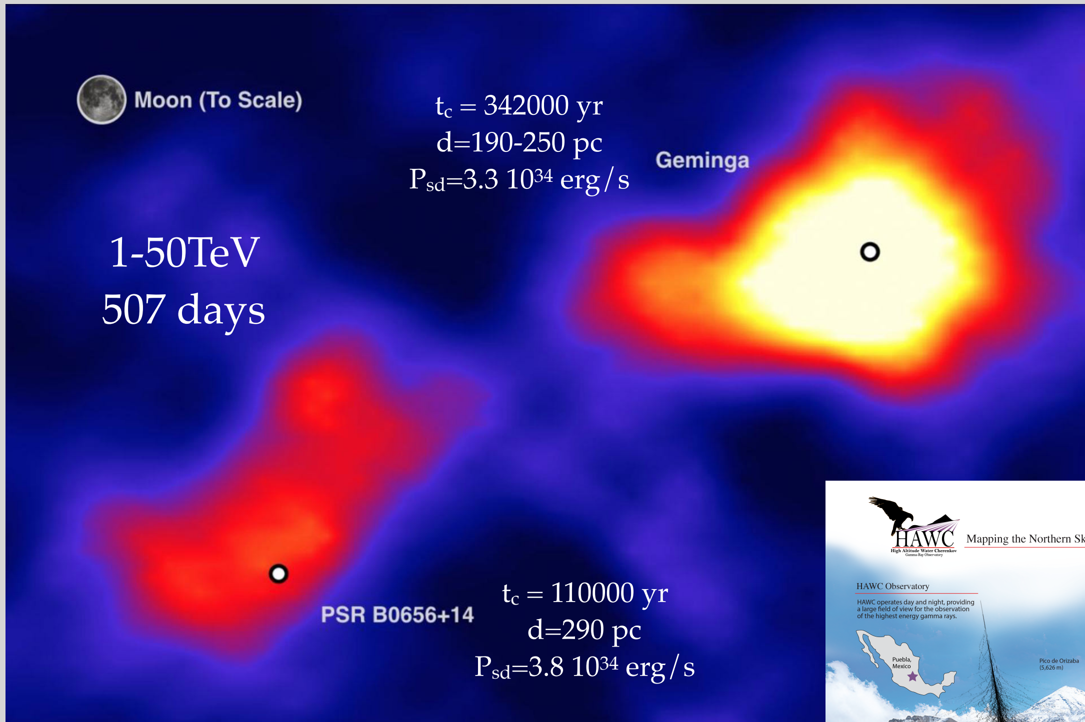


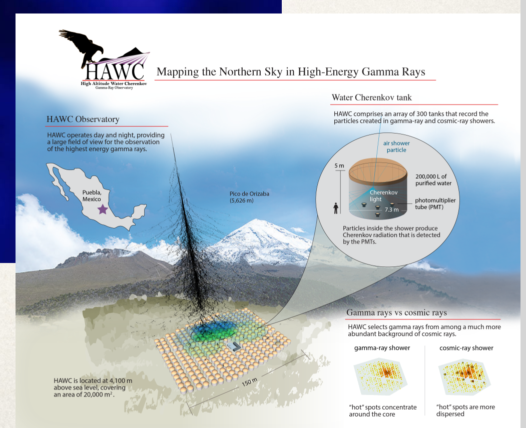
Galactic diffuse emission with LHAASO



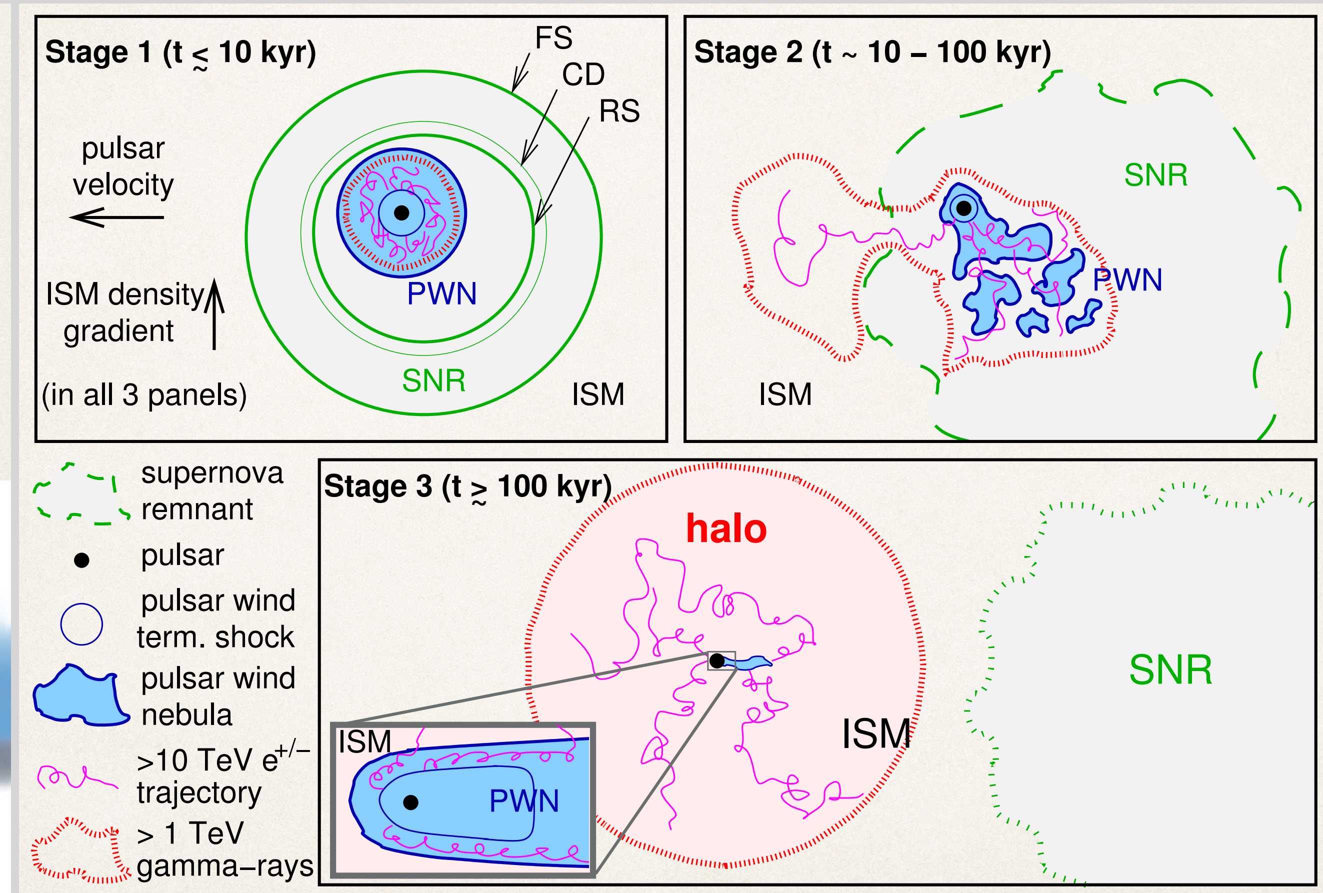
And Ice Cube

High energy astrophysics nowadays
TeV halos - pulsars keep on surprising...





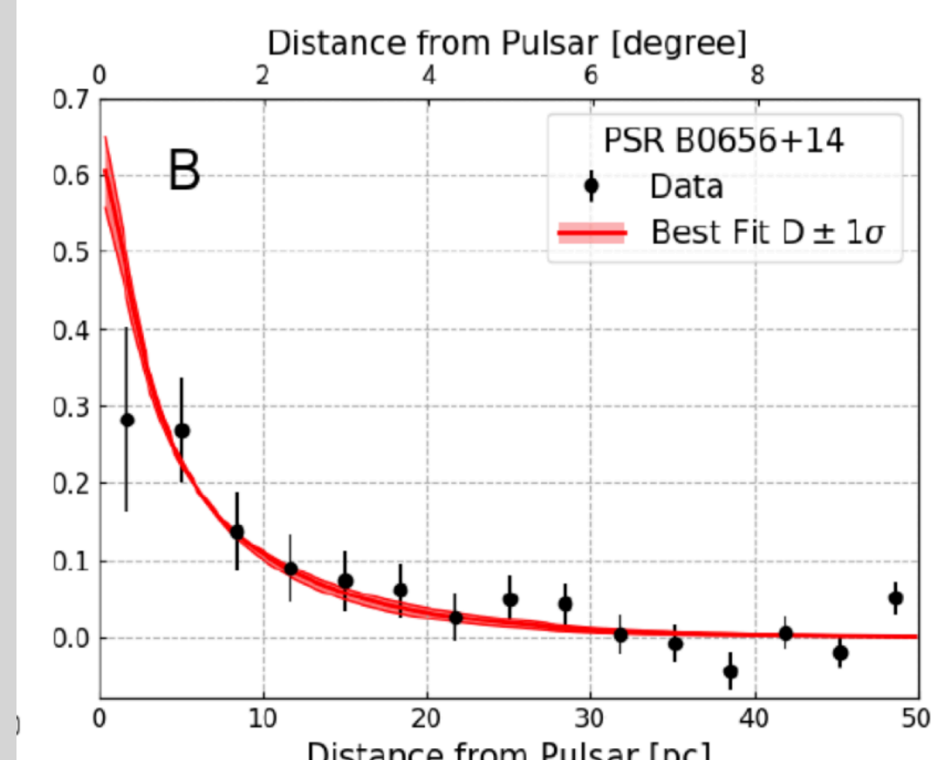
Abeysekara et al. 2017, Science, 358
Abdo et al. 2009



- **Pulsars surrounded by a spatially extended region (~25 pc) emitting multi- TeV gamma-rays**

- **Diffusion coefficient 2-3 orders of magnitude smaller** than the standard value in the regions surrounding pulsars

The HAWC Collaboration, *Science* 358, 911 (2017)



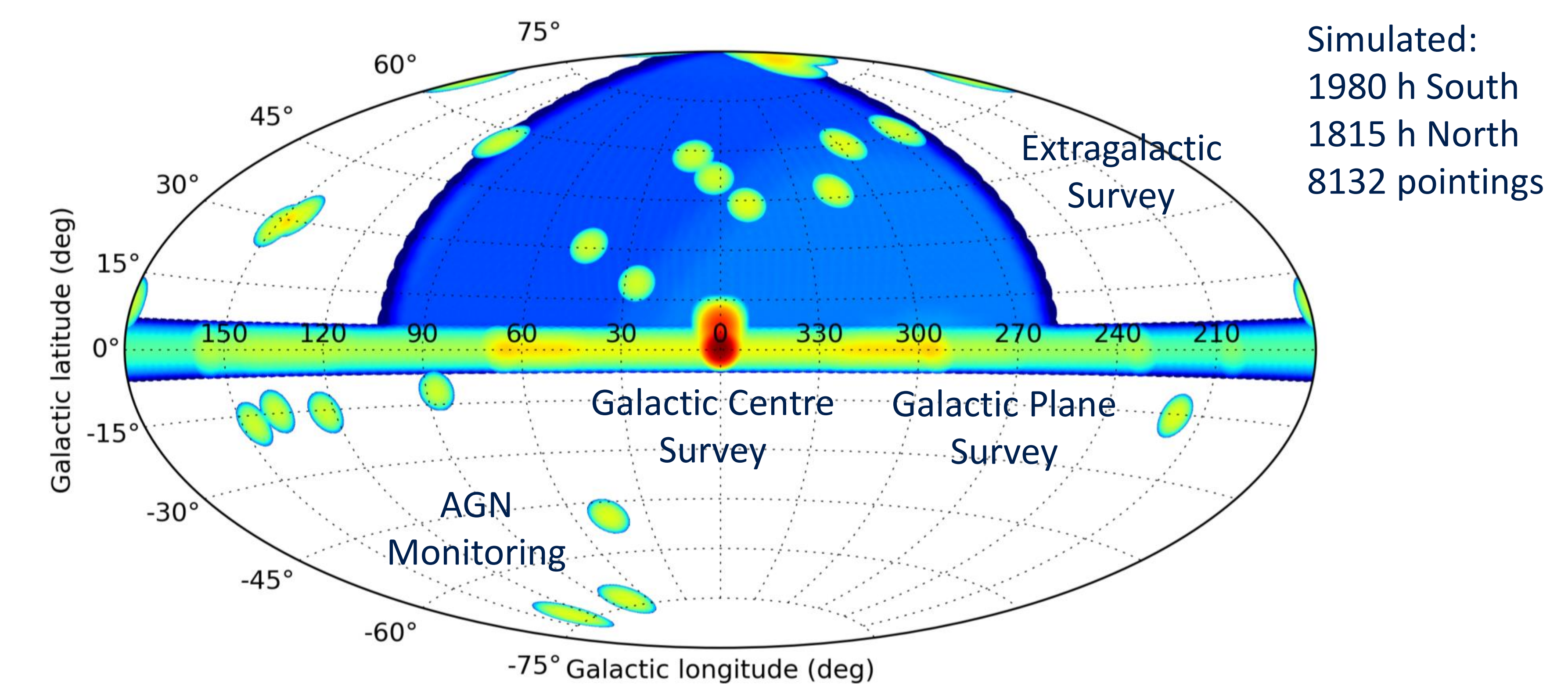
Coming up next - the CTA

Next generation gamma-ray observatory

~**70 telescopes of three sizes (wide en coverage), located in N and S hemispheres**

Dedicated observational strategy: **sky surveys**

- **Unbiased view** of the sky
- Bridging the differences with **satellite data**



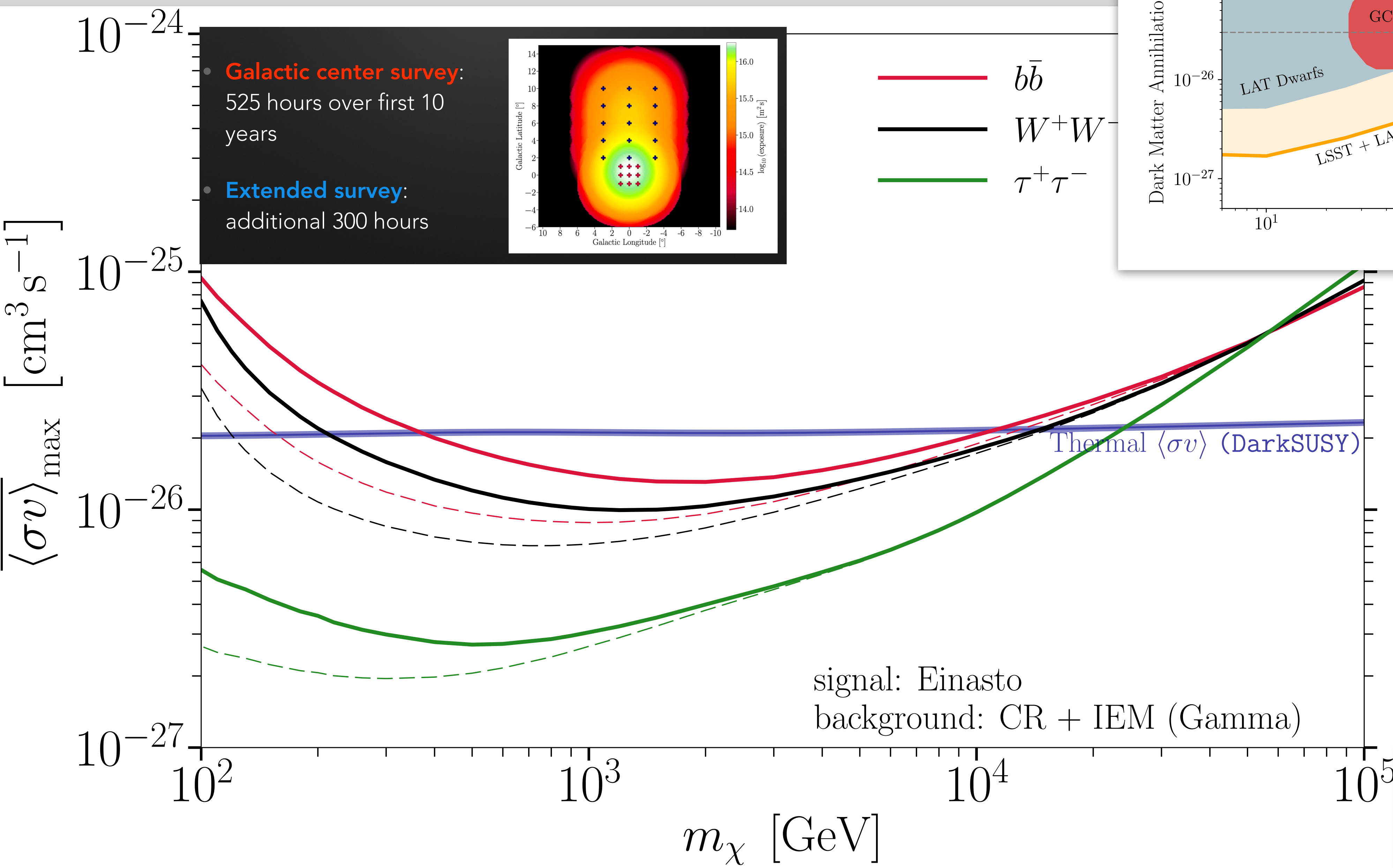
Galactic Plane survey

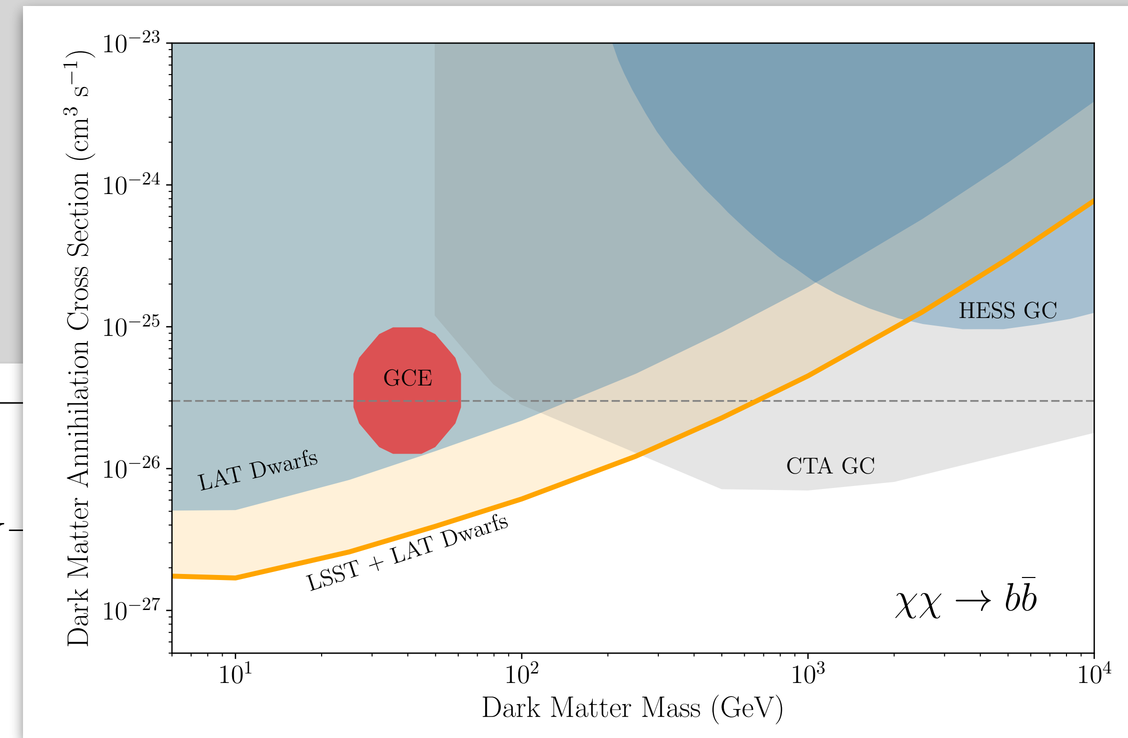
Extragalactic survey

Galactic center survey

CTA and thermal dark matter

Closing the TeV gap



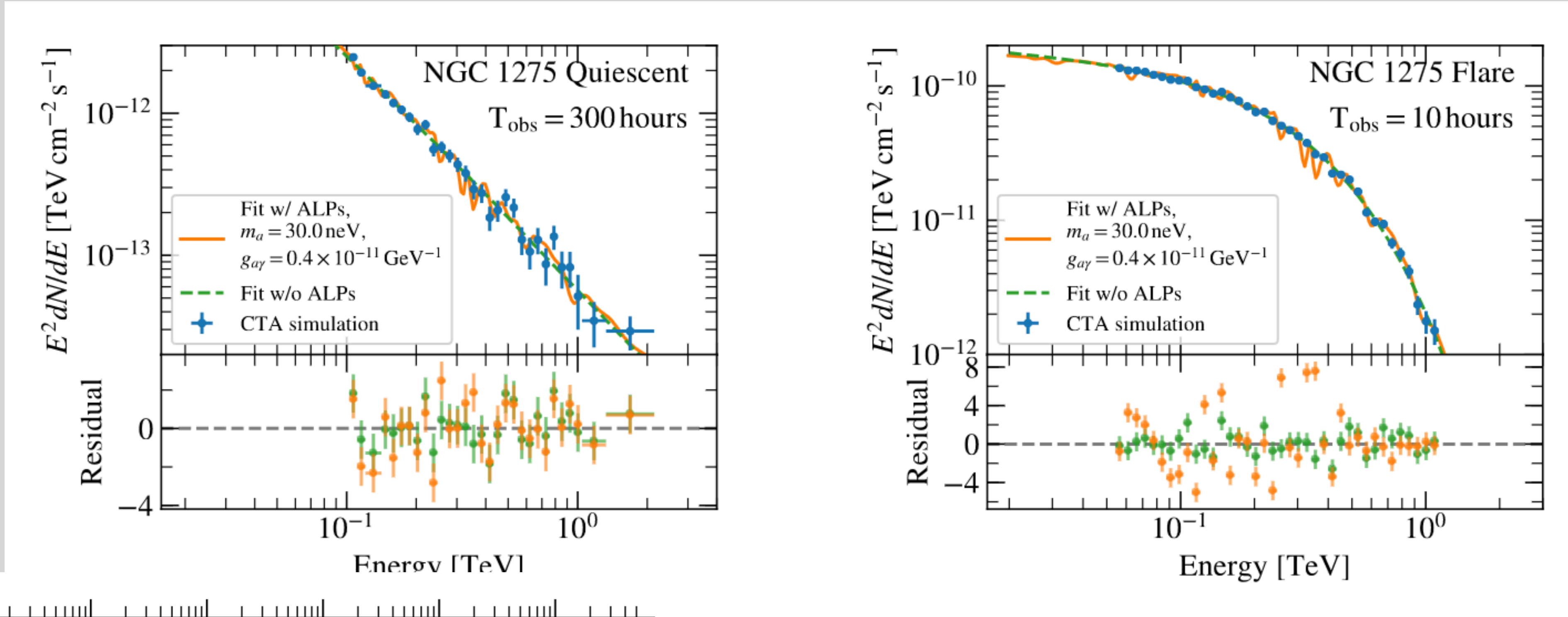


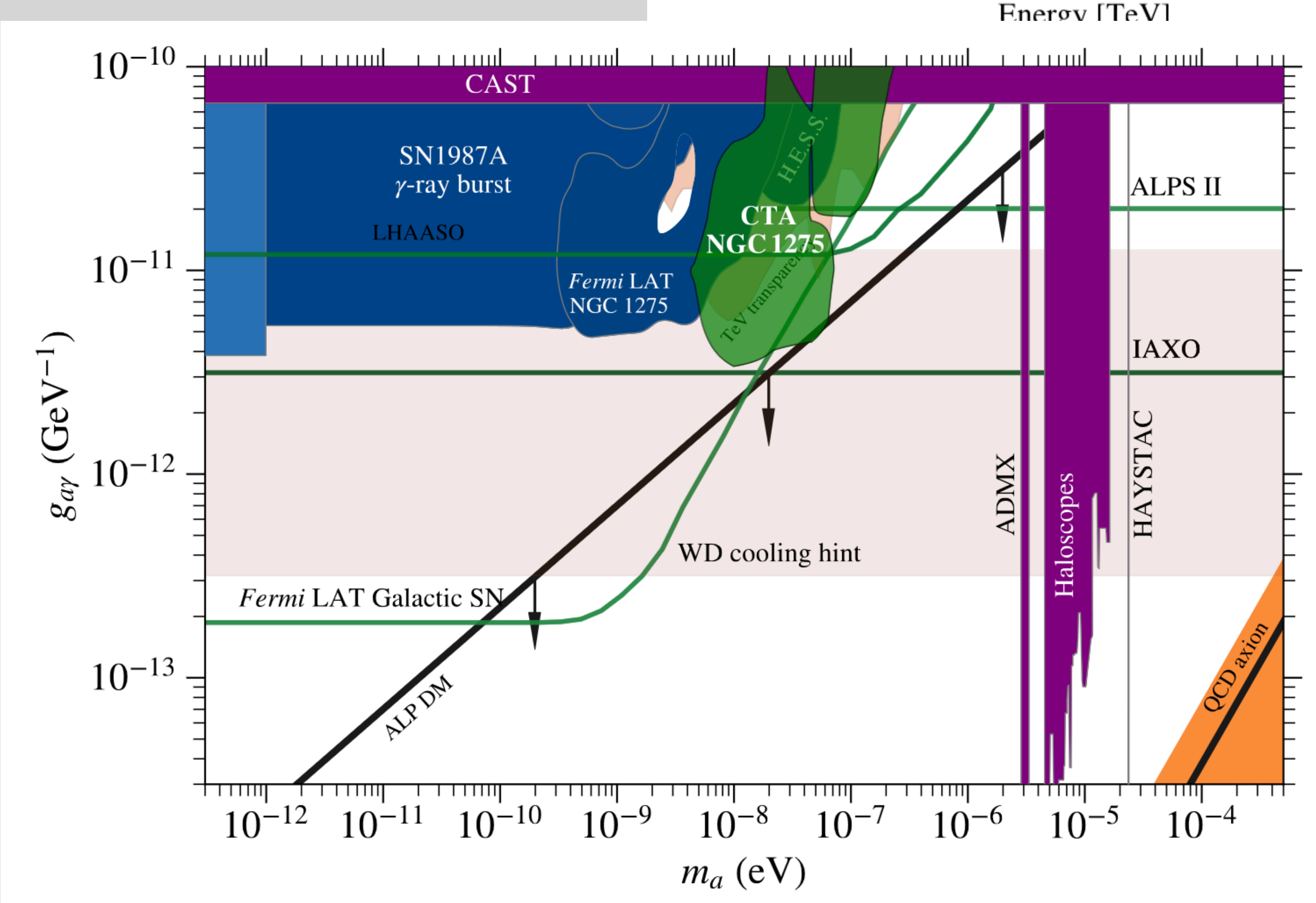
[CTA Collaboration (Eckner, GZ+), JCAP 2021]

CTA and ALPs as dark matter

ALPs induce spectral wiggles

Radio galaxy NGC1275 in the heart of Perseus cluster (strong B)

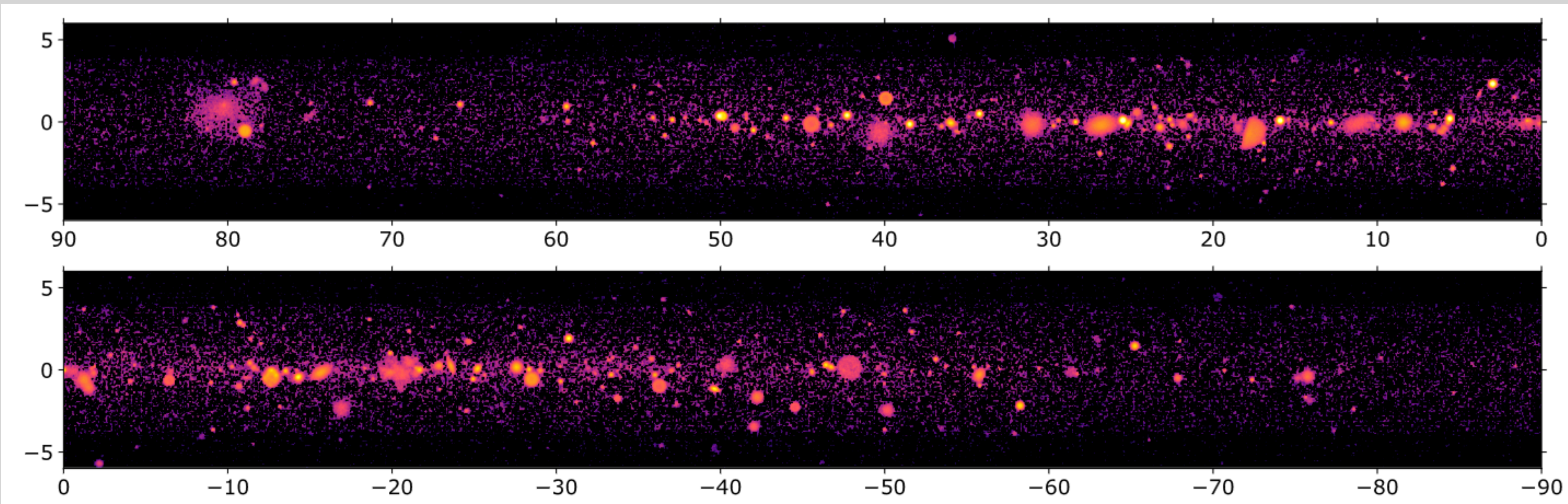


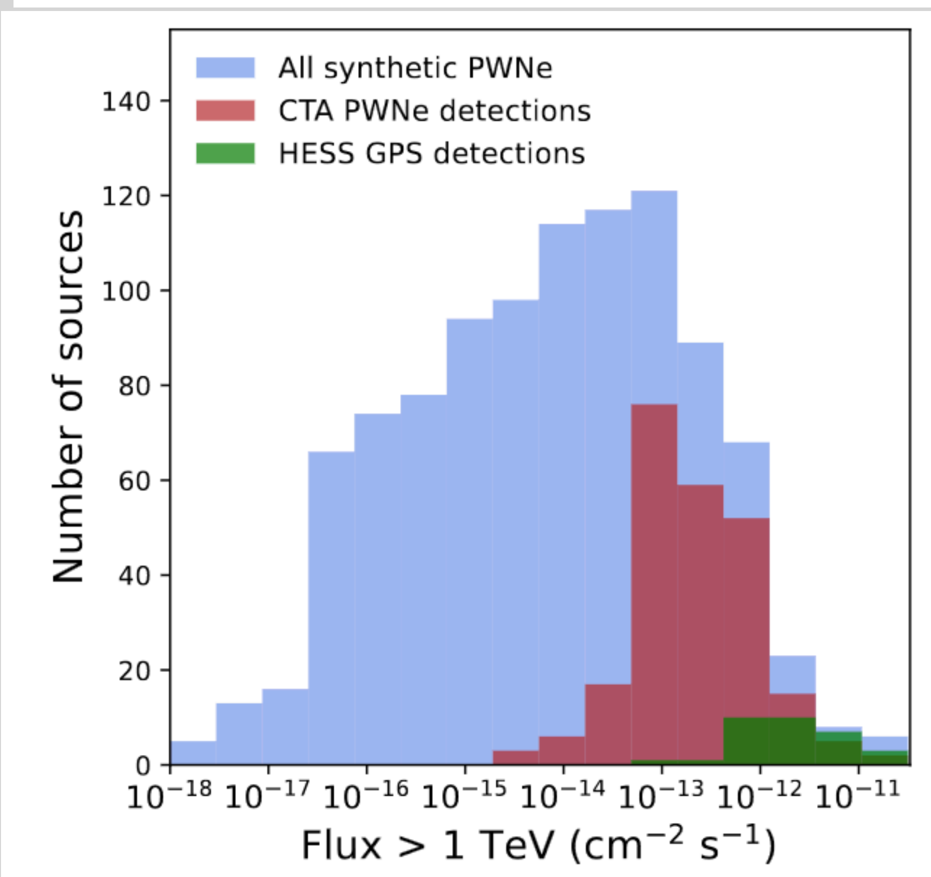


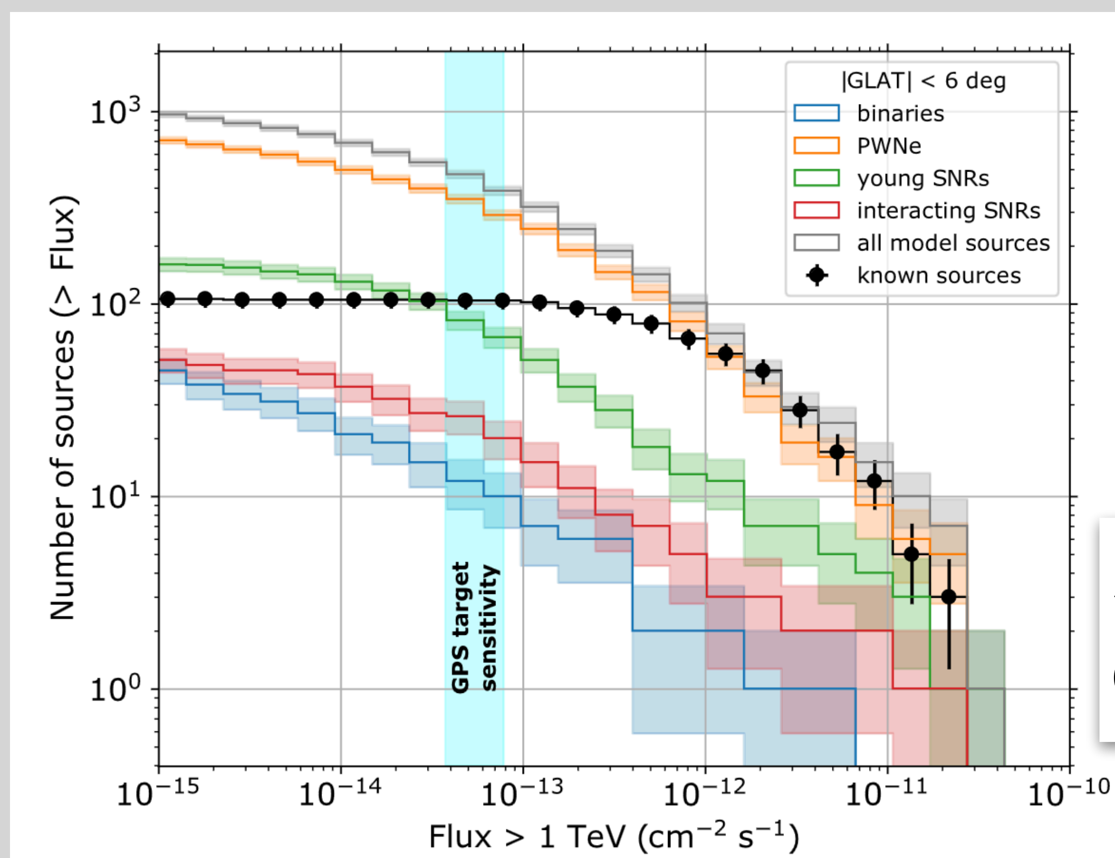
[CTA Collaboration, JCAP 2021]

CTA and GP survey

~300 TeV halos might be detected by the CTAs GP survey with ~30 candidates allowing for spectral and radial decomposition







Sensitivity at the Galactic center

CTA and TeV halos

~300 TeV halos might be detected by the CTAs GP survey
with ~30 candidates allowing for spectral and radial decomposition

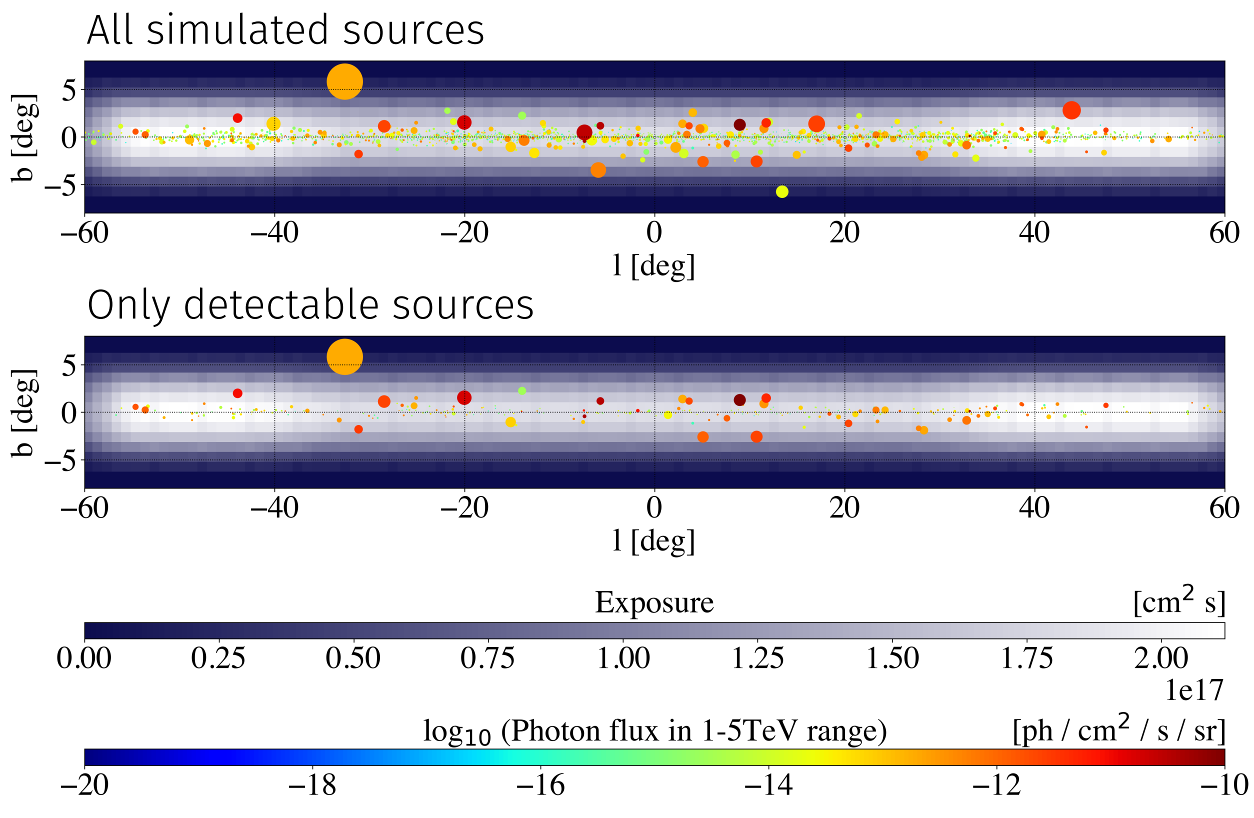
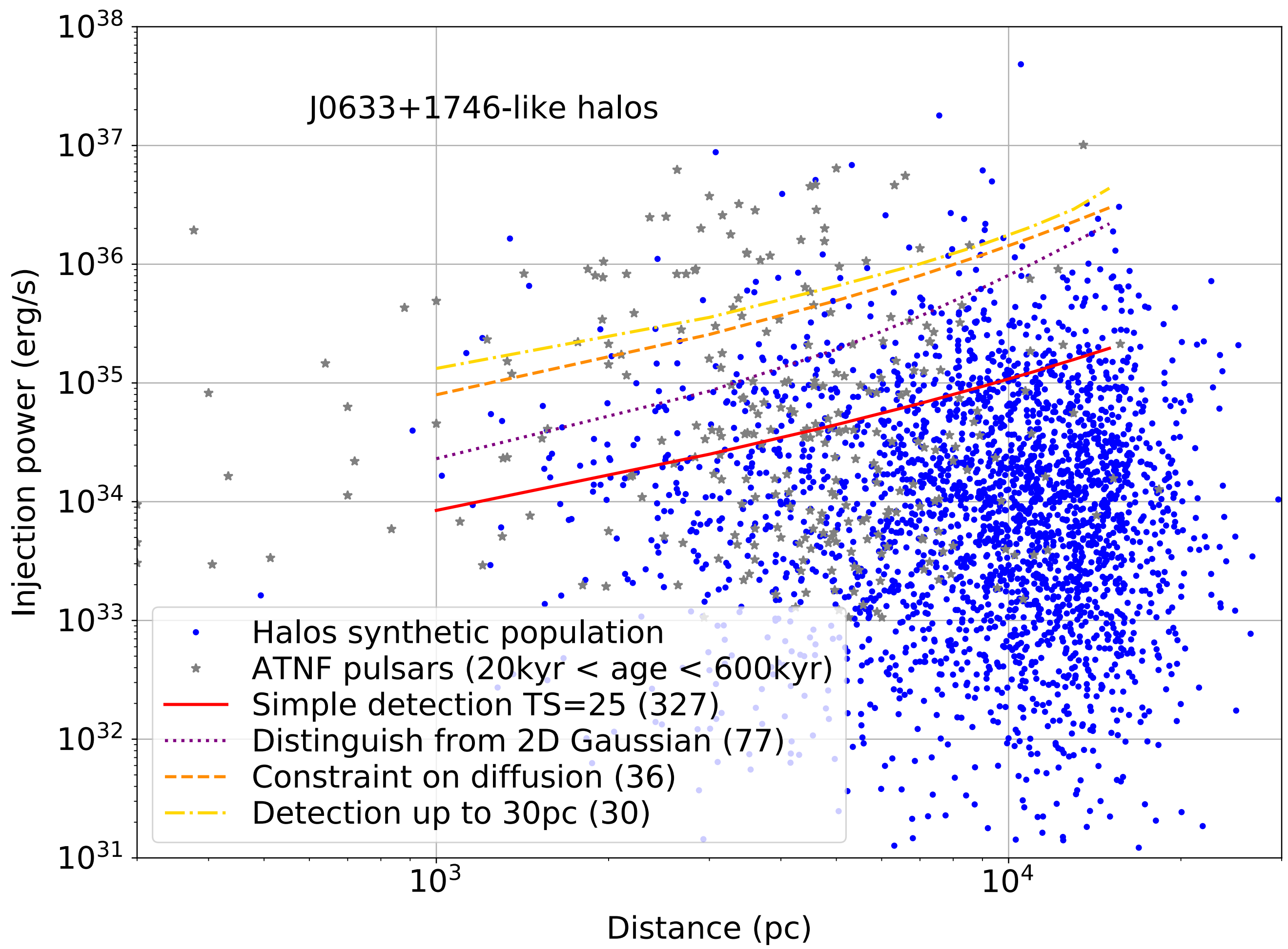


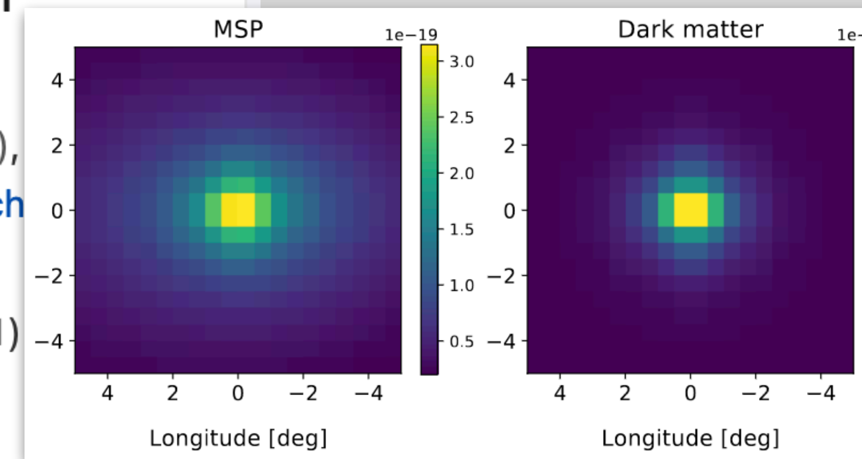
Figure 1: A synthetic pulsar halo population overlaid on an exposure map for the central regions surveyed in the GPS.



[Eckner, Vodeb et al.(+GZ), MNRAS 2023]

Future

Cherenkov Telescope Array sensitivity to the putative millisecond pulsar population responsible for the Galactic Centre excess #4



Oscar Macias (Tokyo U., IPMU and U. Amsterdam, GRAPPA), Harm van Leijen (U. Amsterdam, GRAPPA), Song (Virginia Tech.), Shin'ichiro Ando (U. Amsterdam, GRAPPA and Tokyo U., IPMU), Shunsaku Horiuch Tech.) et al. (Feb 10, 2021)

Published in: *Mon.Not.Roy.Astron.Soc.* 506 (2021) 2, 1741-1760, *Mon.Not.Roy.Astron.Soc.* 506 (2021) 1741-1760 • e-Print: 2102.05648 [astro-ph.HE]

pdf DOI cite claim reference search 13 citations

MSP population in the bulge, if responsible for GCE would also inject large quantities of $e\pm$ into the interstellar medium. These $e\pm$ could potentially IC scatter ambient photons into γ rays that fall within the sensitivity range of the upcoming Cherenkov Telescope Array (CTA).

Millisecond Pulsars, TeV Halos, and Implications For The Galactic Center Gamma-Ray Excess #1

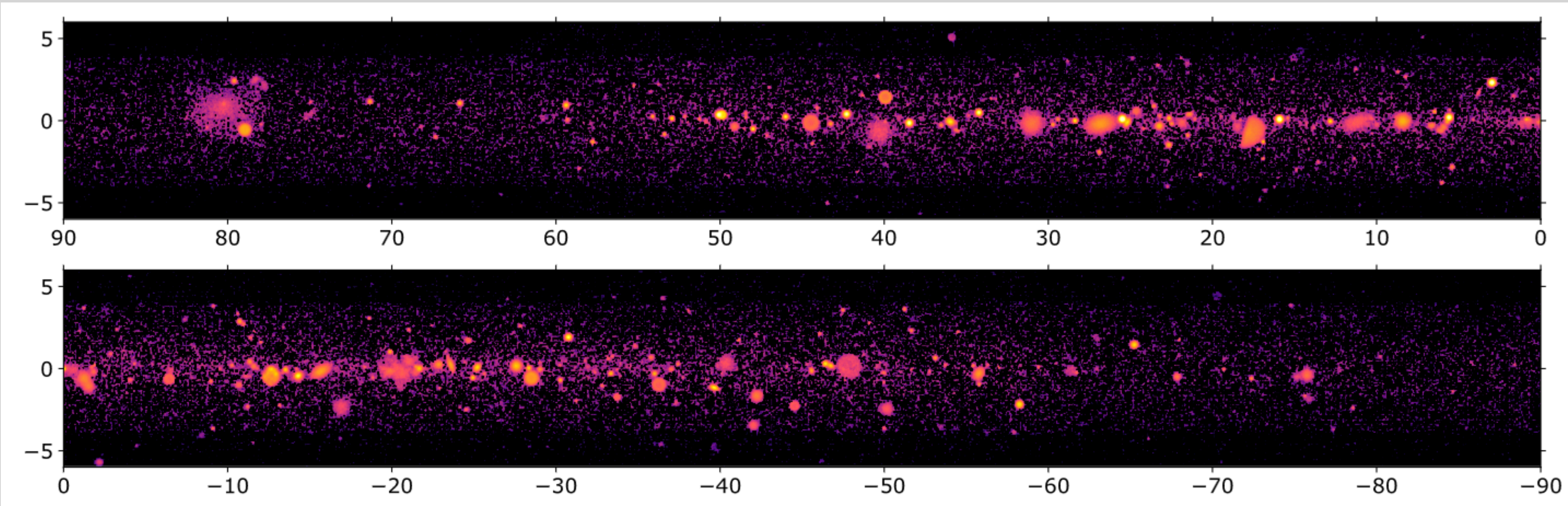
Dan Hooper (Chicago U., Astron. Astrophys. Ctr. and Chicago U., KICP and Fermilab), Tim Linden (Ohio State U. and UC, Santa Cruz and UC, Santa Cruz, Inst. Part. Phys.) (Mar 21, 2018)

Published in: *Phys.Rev.D* 98 (2018) 4, 043005 • e-Print: 1803.08046 [astro-ph.HE]

pdf links DOI cite claim reference search 37 citations

At multi-TeV energies, most extragalactic sources are masked by gamma-ray attenuation, implying that the **TeV halos** surrounding MSPs could dominate the very high-energy diffuse emission observed at high-**latitudes**.

Machine learning?

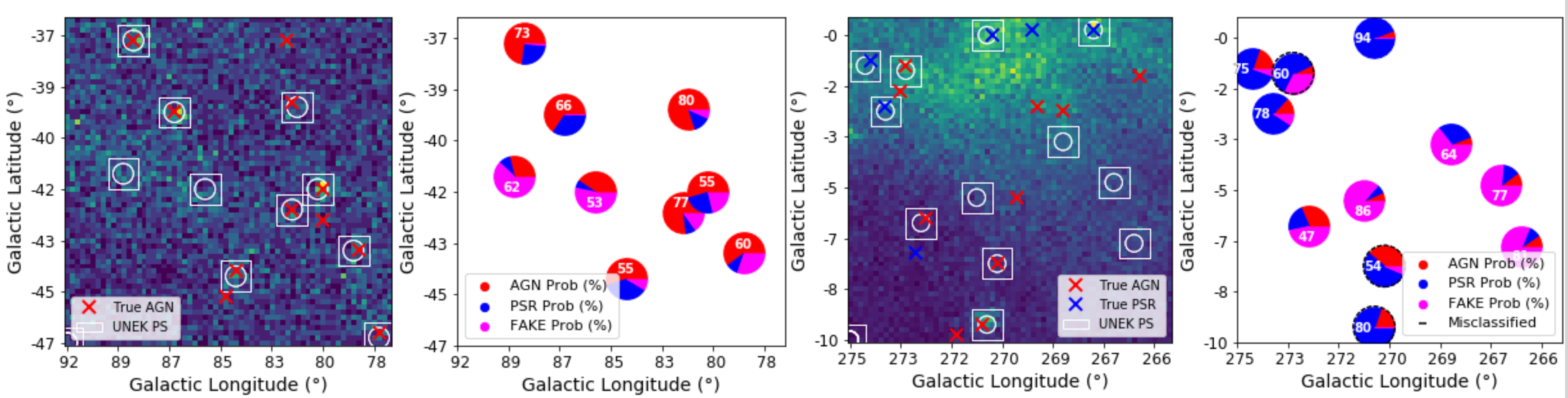


Numerous extended and overlapping sources - could computer vision be useful?

AutoSourceID (**ASID**, A&A, 2103.11068) — proof of principle

Results for High Latitude: $|b| > 20°$

Results for Low Latitude: $|b| < 20°$



Low background emission. Higher accuracy in localization.

Better classification.

Regions closer to galactic plane. Background emission dominates.

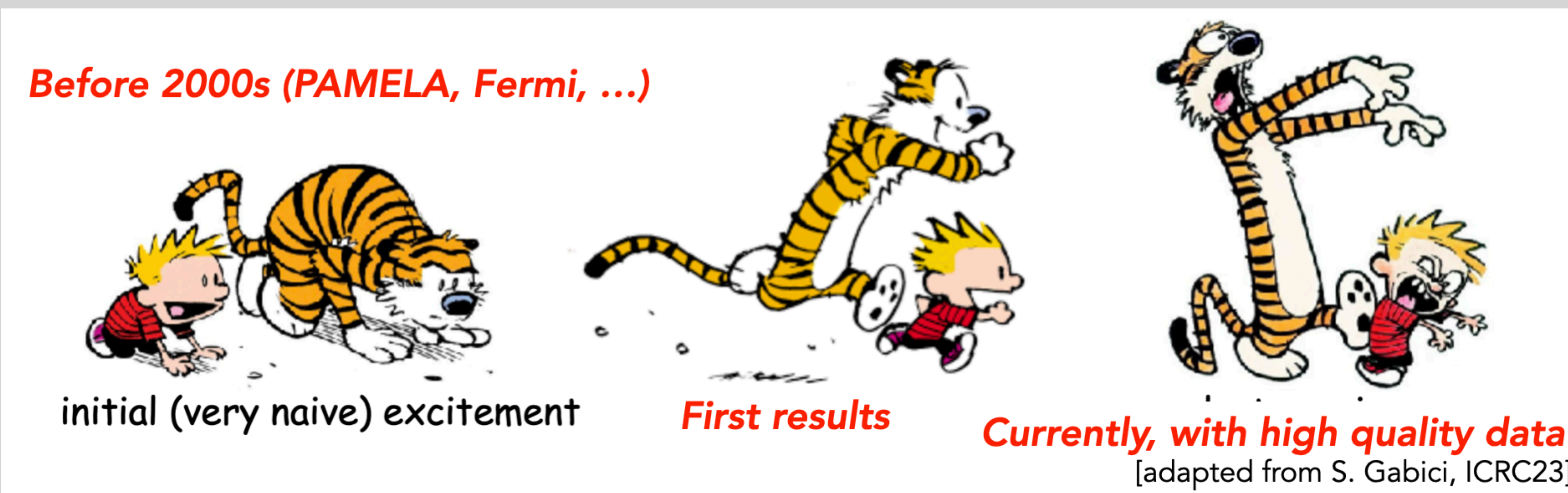
Algorithm performance deteriorates.

[*credit: Saptashwa Bhattacharyya, TeVPA 2021*]

Summary

New data continuously force us to further theoretical efforts —>
Exciting multi-disciplinary field & lots of data to play with !

Entering the TeV/PeV region — theoretical progress and dialog with experimentalists needed



Summary

New data continuously force us to further theoretical efforts —>
Exciting multi-disciplinary field & lots of data to play with !

Entering the TeV/PeV region — theoretical progress and dialog with experimentalists needed

Machine learning? - Algorithms perfected for a range of tasks in modern day life. ***Is it just a hammer in search of a nail, or can it facilitate the real scientific progress?***

SMASH

machine learning for science and humanities **postdoctoral program**

Univerza *v Ljubljani*

Institut "Jožef Stefan" Ljubljana, Slovenija

IZUM Institut informacijskih znanosti, Maribor

REPUBLIKA SLOVENIJA
MINISTRSTVO ZA OKOLJE IN PROSTOR
AGENCIJA REPUBLIKE SLOVENIJE ZA OKOLJE

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 101081355.

Co-funded by
The European Union

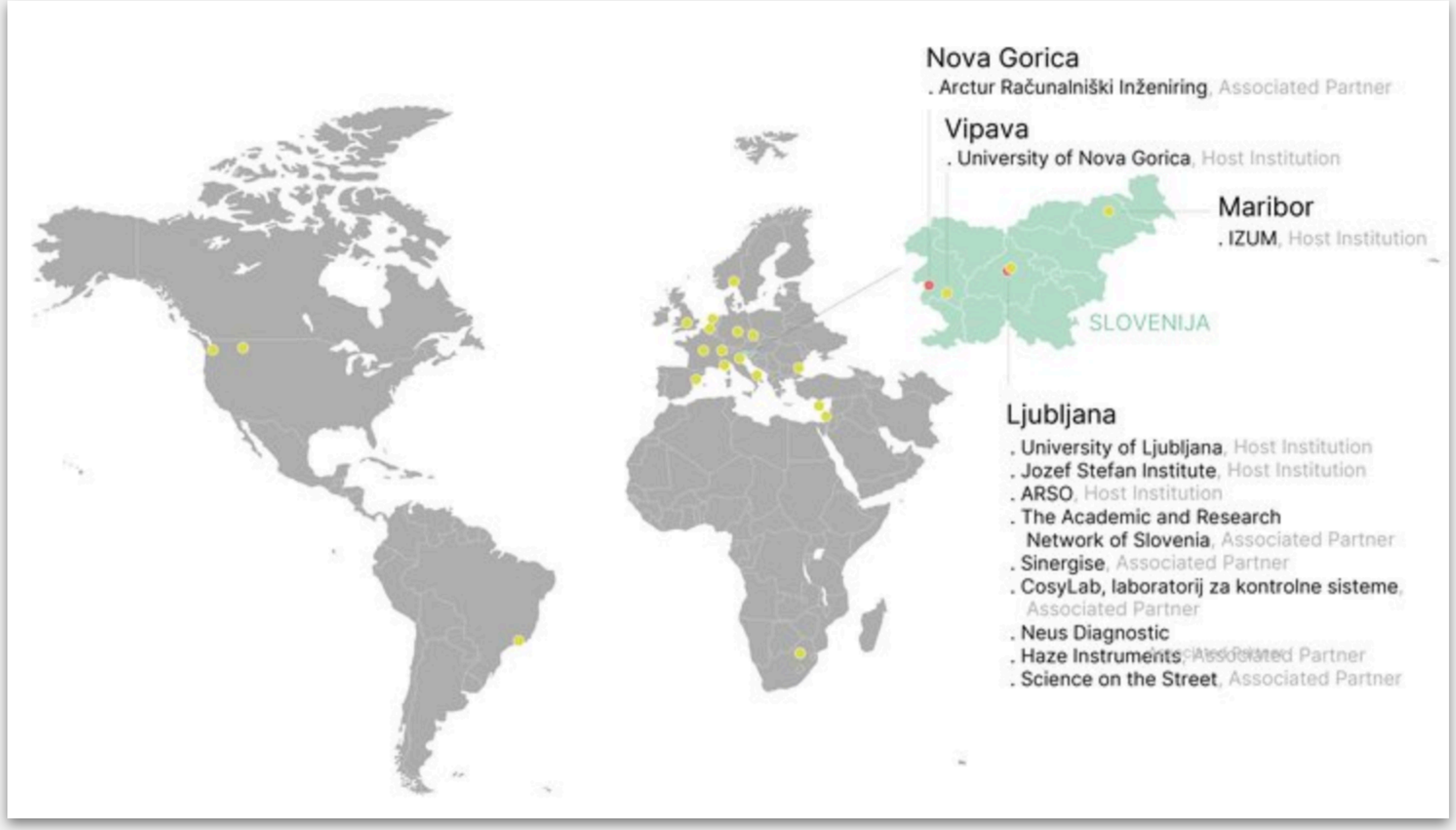
What is SMASH

SMASH is a career-development training program co-funded by the Marie Skłodowska-Curie COFUND Actions for the 2023-2028 period, budget 10MEU. Funds to hire postdoctoral researchers (50 postdocs, 2 year contracts)

Postodcs will be hosted in five Slovenian institutions ('implementing partners').

Can spend up to 8 months total in at least two of ('associate partner') institutions. **Including SMEs!**

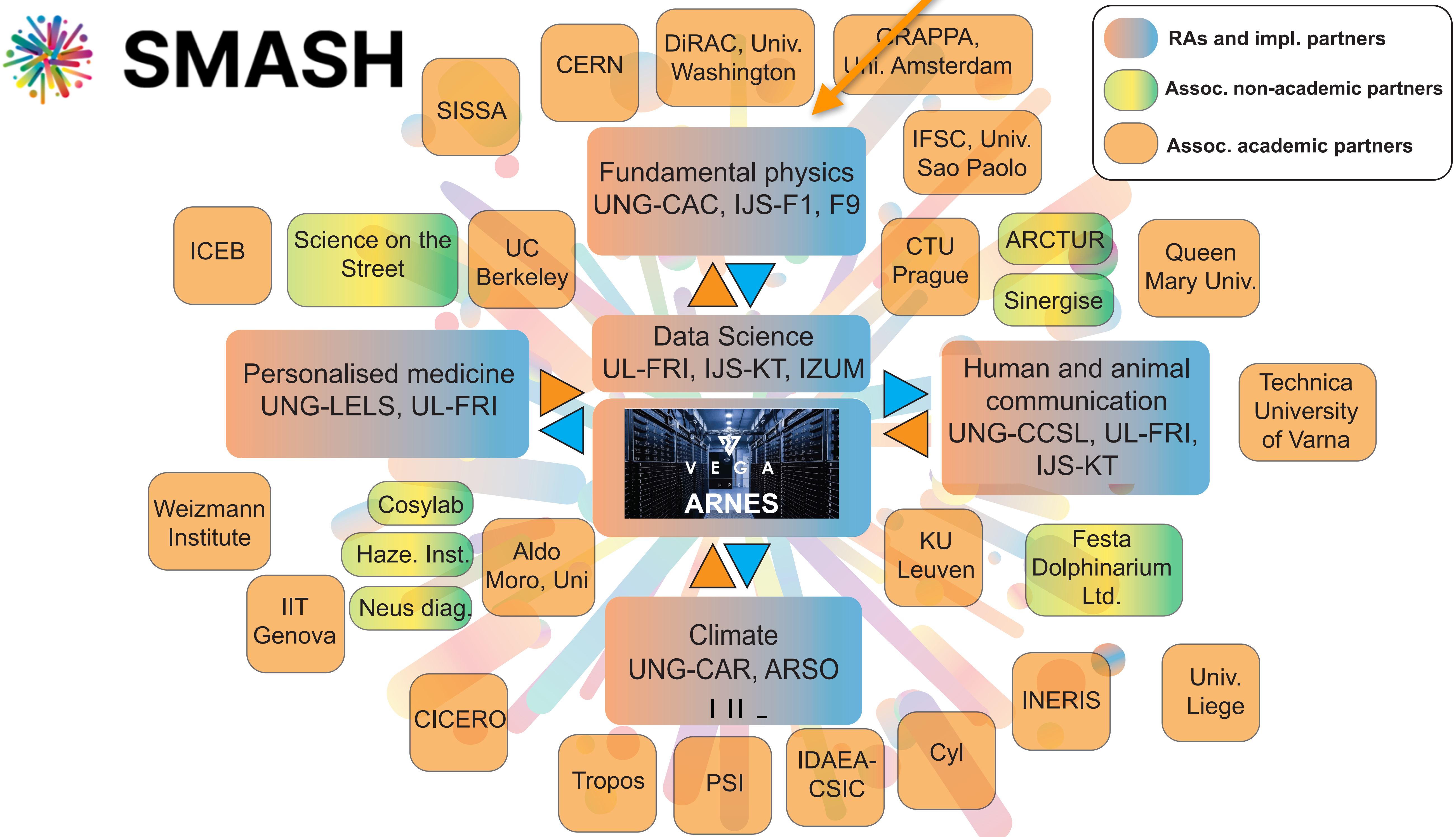
https://smash.ung.si/



SMASH

Research areas

CTA, Vera Rubin and LHC related science



Where are we now

SMASH officially started (contract with EC) on July 1st.

8 postdocs hired in Call-1 finalised, first just started!

Call-2 open, deadline Oct 27. Aim to hire 20 fellows in this call.

Call-3 expected to open July 2024.

Stay tuned!

SMASH