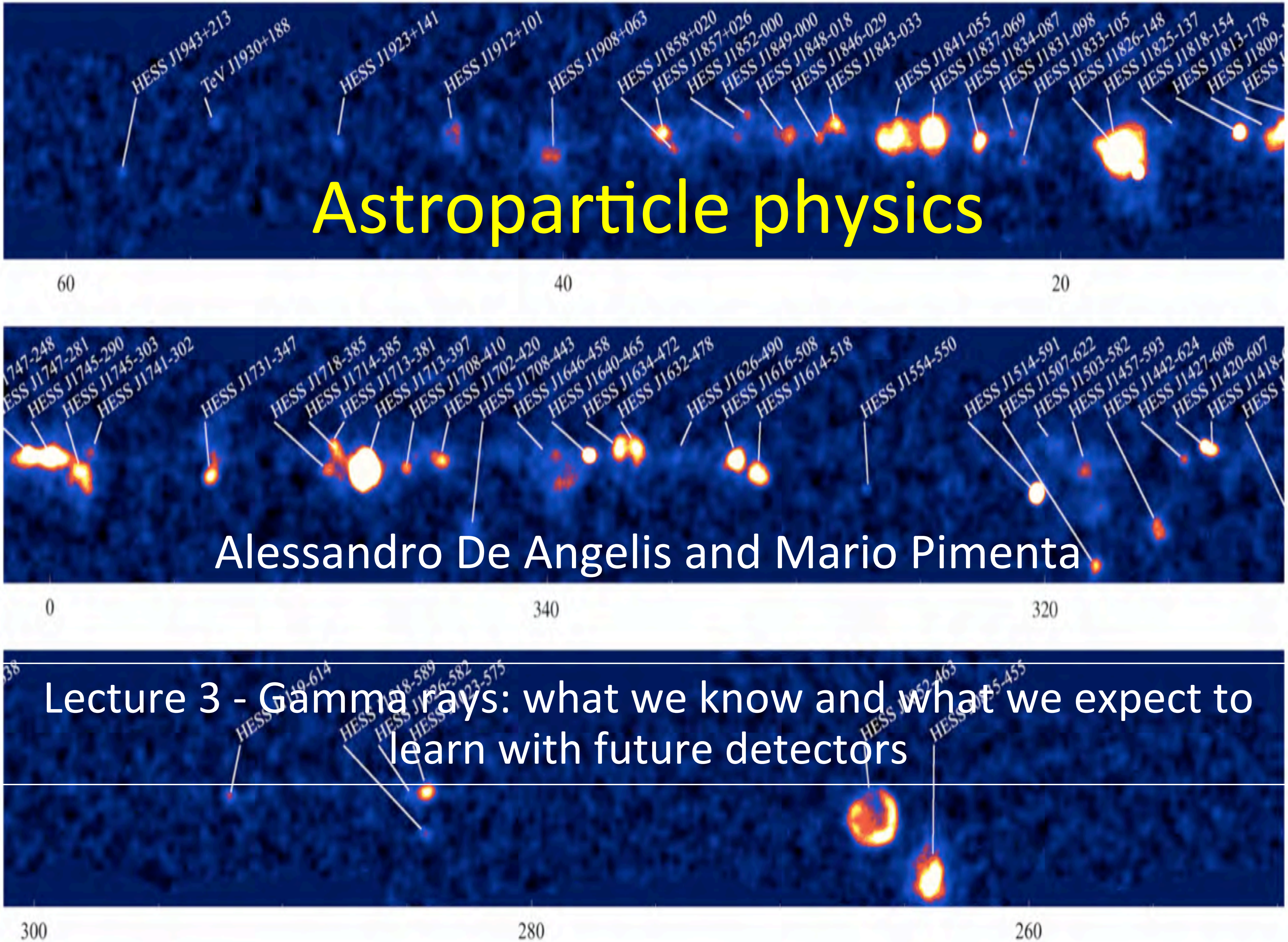
Astroparticle physics

Alessandro De Angelis and Mario Pimenta

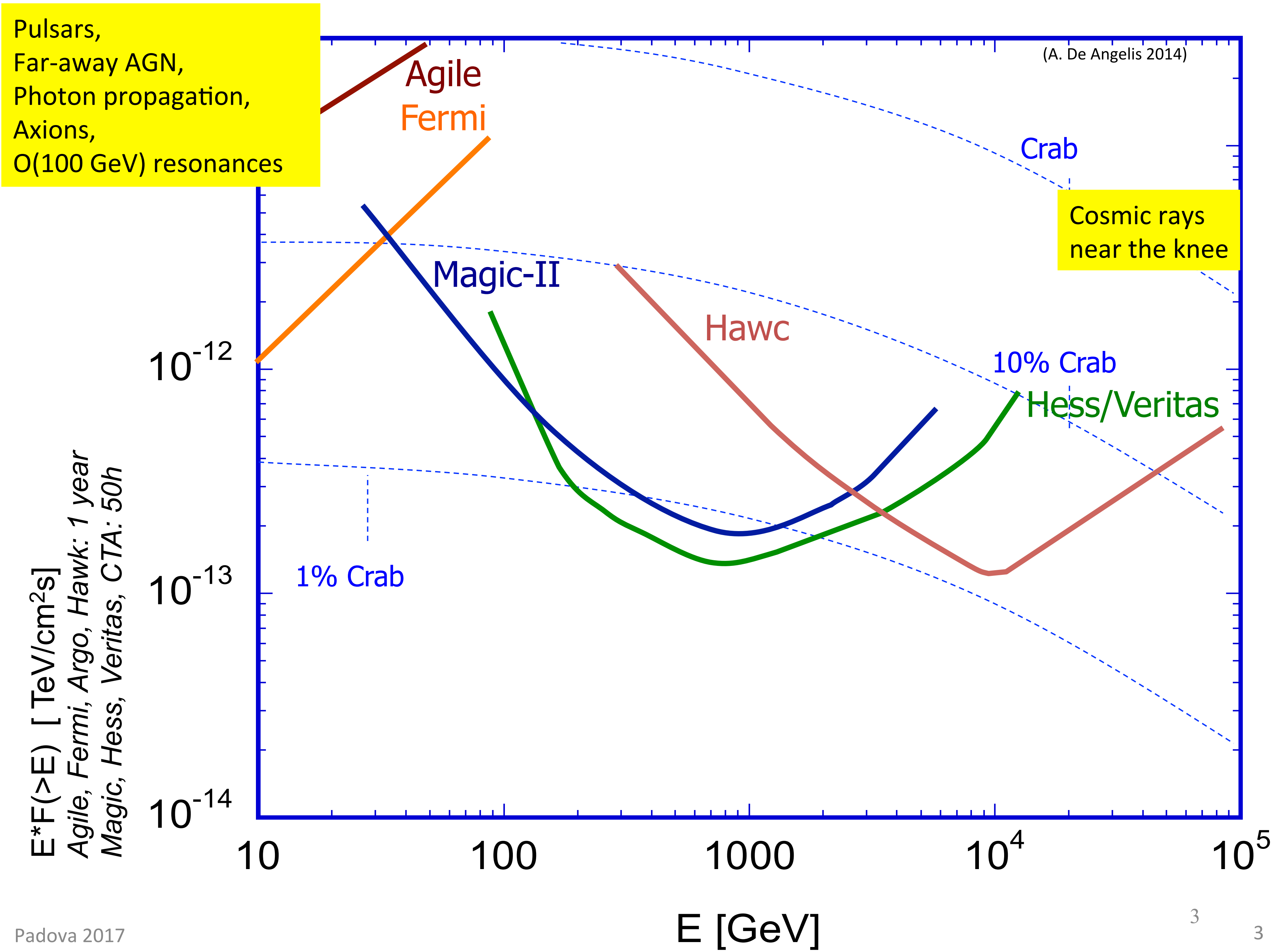
Lecture 3 - Gamma rays: what we know and what we expect to learn with future detectors



Performance of different types of HE gamma detectors

Table 4.5 A comparison of the characteristics of Fermi, the IACTs and of the EAS particle detector arrays. Sensitivity computed over one year for Fermi and the EAS, and over 50 h for the IACTs

Quantity	Fermi	IACTs	EAS
Energy range	20 MeV – 200 GeV	100 GeV – 50 TeV	400 GeV – 100 TeV
Energy res.	5–10 %	15–20 %	$\sim 50\,\%$
Duty cycle	80 %	15 %	$> 90\,\%$
FoV	$4\pi/5$	5 deg × 5 deg	$4\pi/6$
PSF (deg)	0.1	0.07	0.5
Sensitivity	1 % Crab (1 GeV)	1 % Crab (0.5 TeV)	0.5 Crab (5 TeV)



Pulsars,
Far-away AGN,
Photon propagation,
Axions,
O(100 GeV) resonances
(A. De Angelis 2014)
Agile
Fermi
Crab
Cosmic rays near the knee
Magic-II
Hawc
10% Crab
Hess/Veritas
1% Crab
10^{-12}
10^{-13}
10^{-14}
10
100
1000
10^4
10^5
E [GeV]
E*F(>E) [TeV/cm^{2}s]
Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h

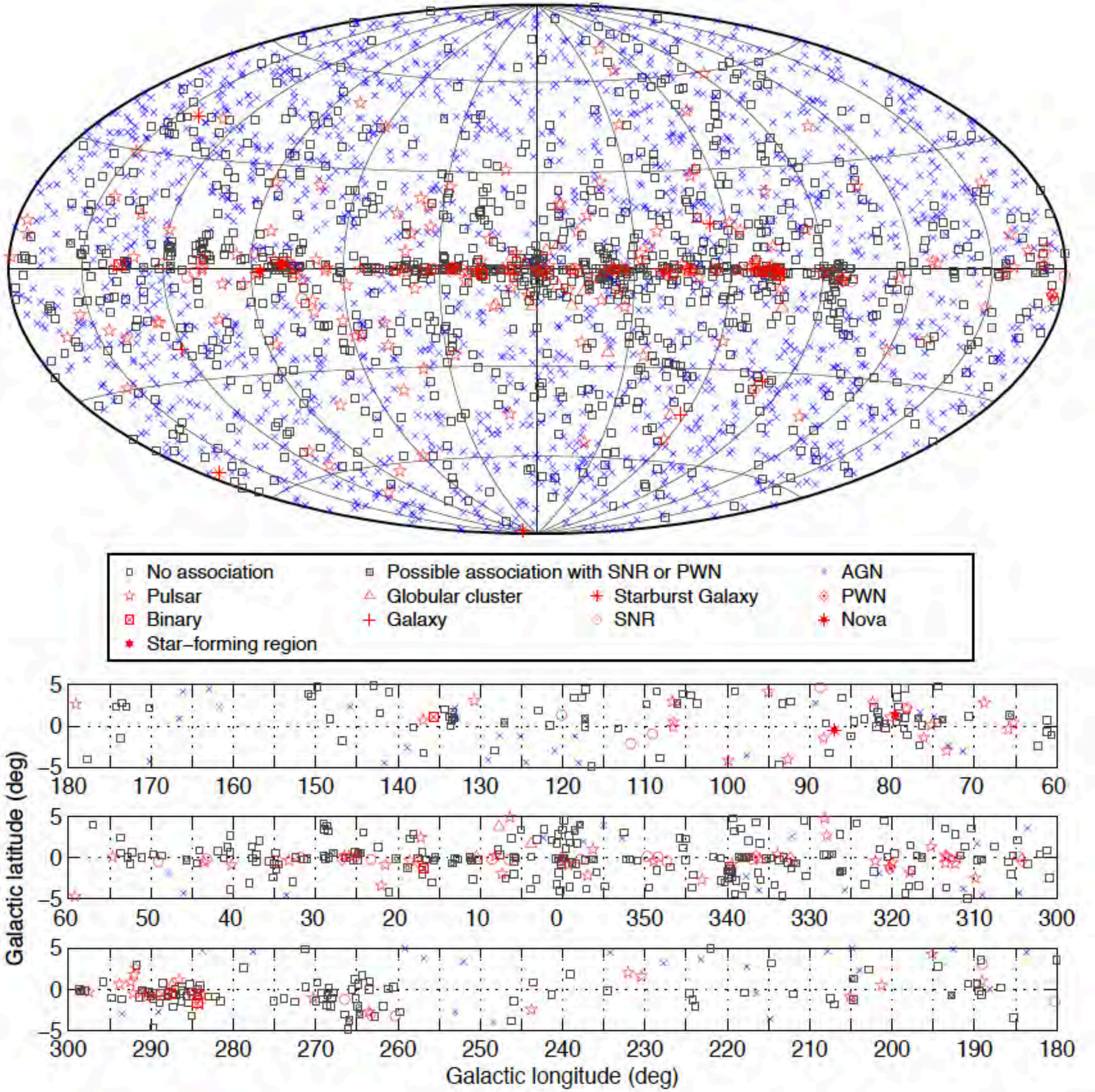
3

SOURCES OF GAMMA RAYS
RELATION WITH EXTREME ACCELERATORS

LAT 4-year Point Source Catalog (3FGL)

Fermi-LAT Third Source Catalog (4y) arXiv:1501.02003v3

3033 sources above 100 MeV



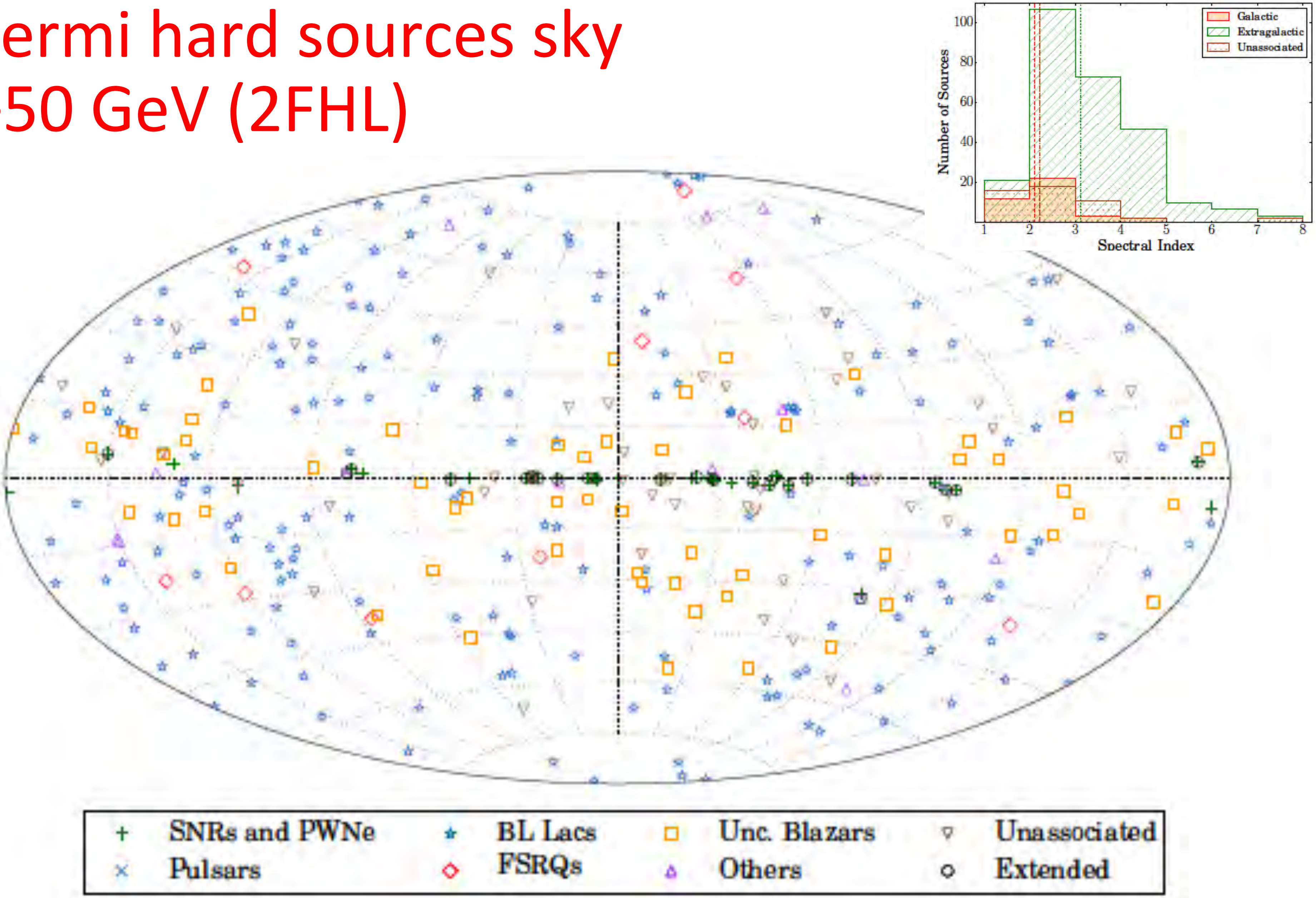
Emission models

- Leptonic model (needs B field to generate synchrotron radiation)
- Also hadronic mechanism (needs matter as a target with density > ISM (1p/cm^3), or radiation fields)

In both cases, for a apower-law energy distribution,

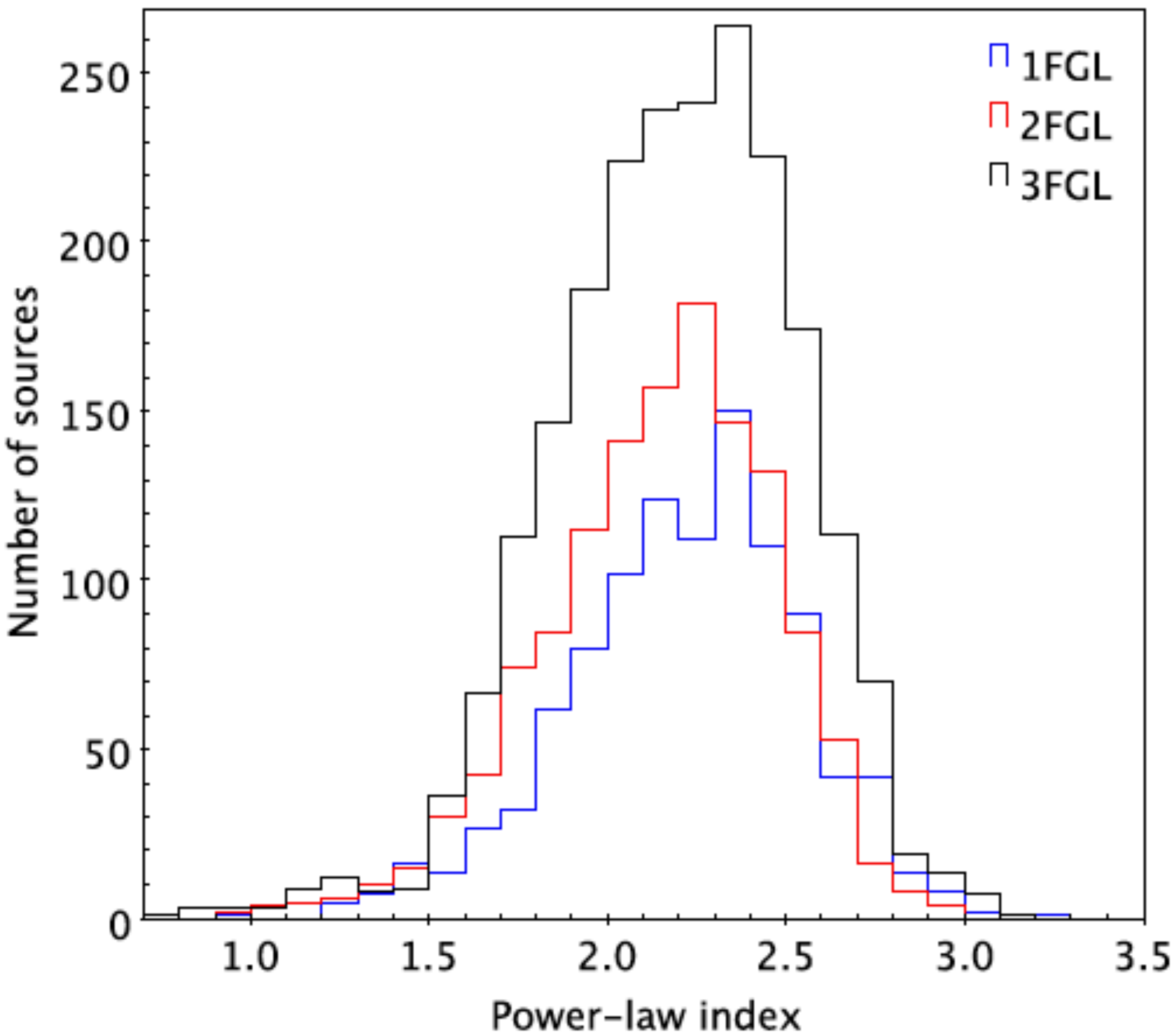
$$\frac{dN_\gamma}{dE_\gamma} \propto \frac{dN_{p,e}}{dE_{p,e}}$$

Fermi hard sources sky >50 GeV (2FHL)

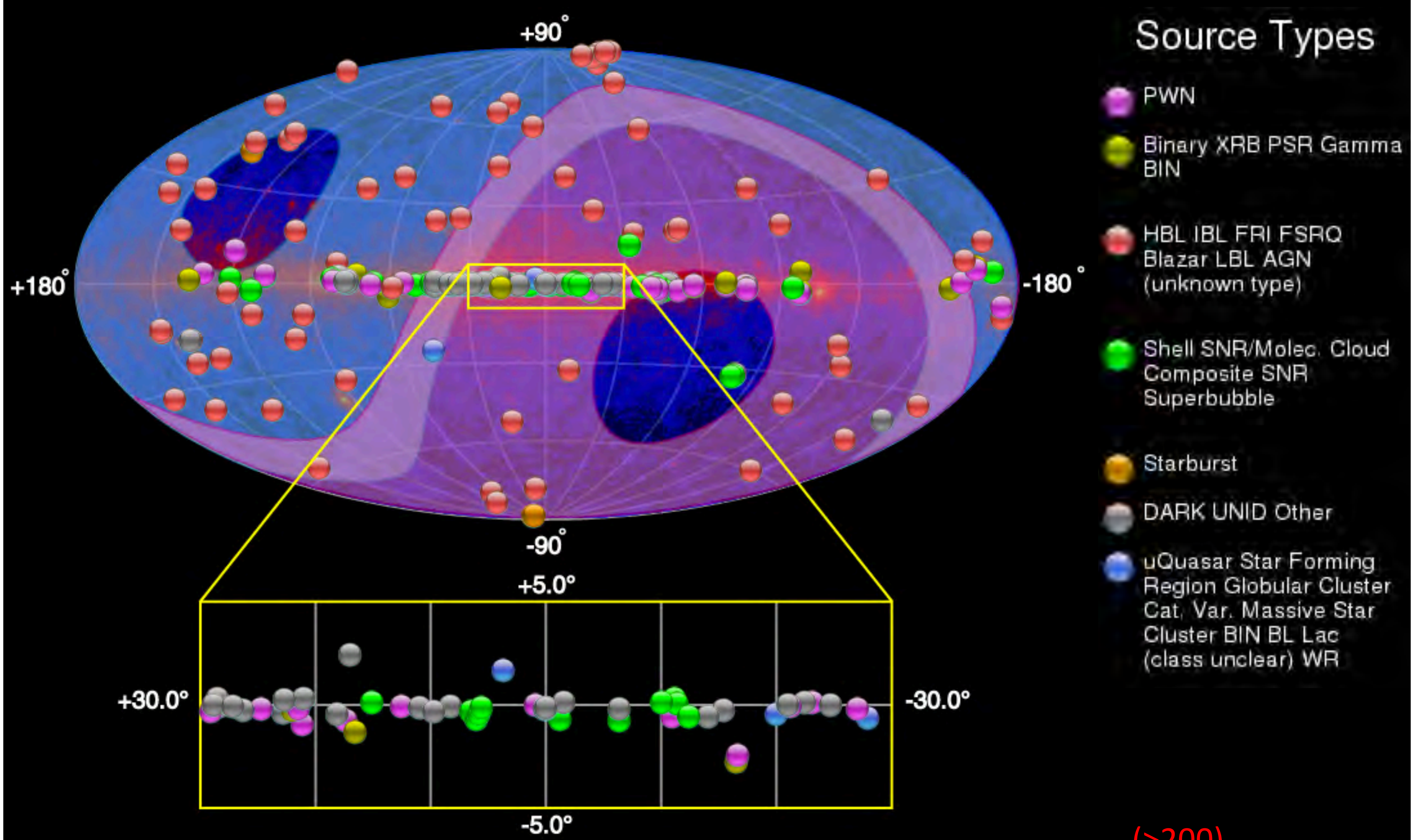


360 sources in 80 months, arXiv :1508.04449v1

Energy spectral index



TeV sources tevcat.uchicago.edu

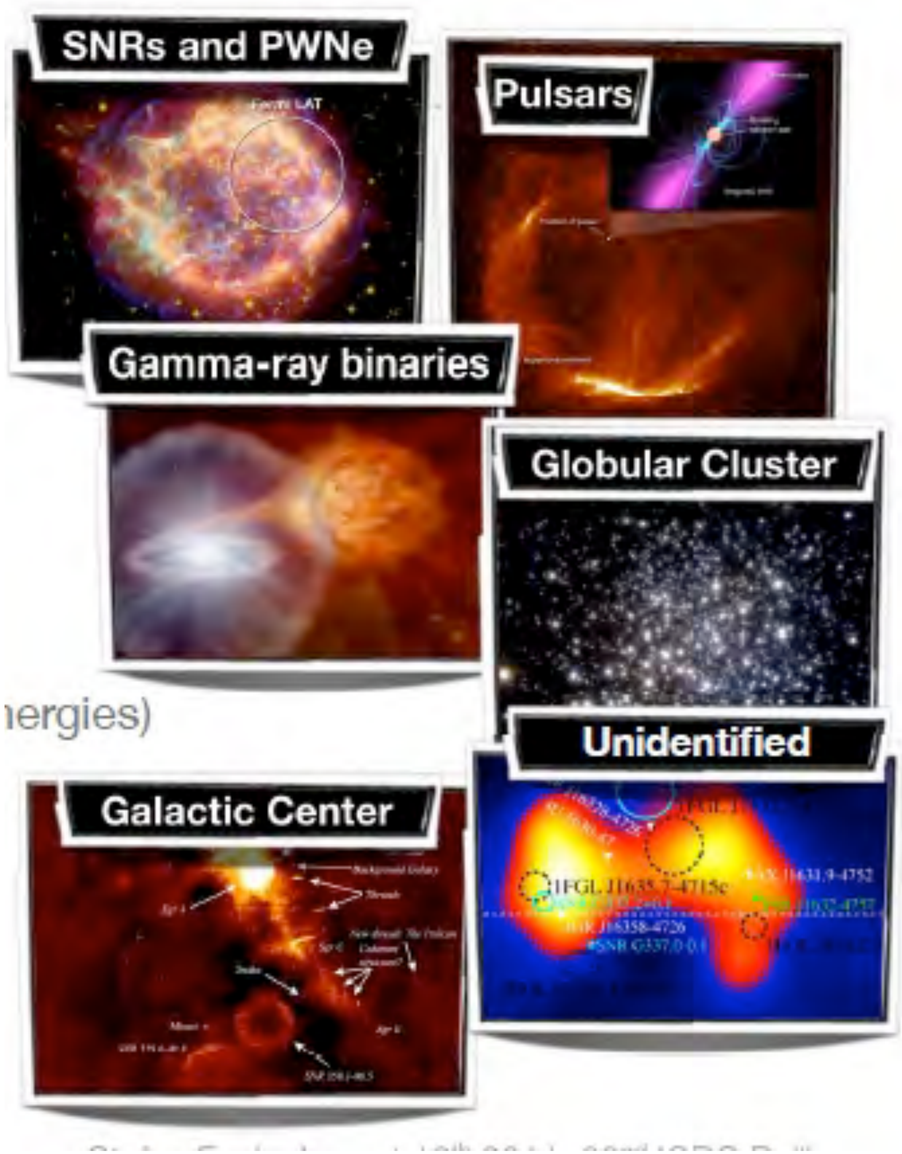


(>200)

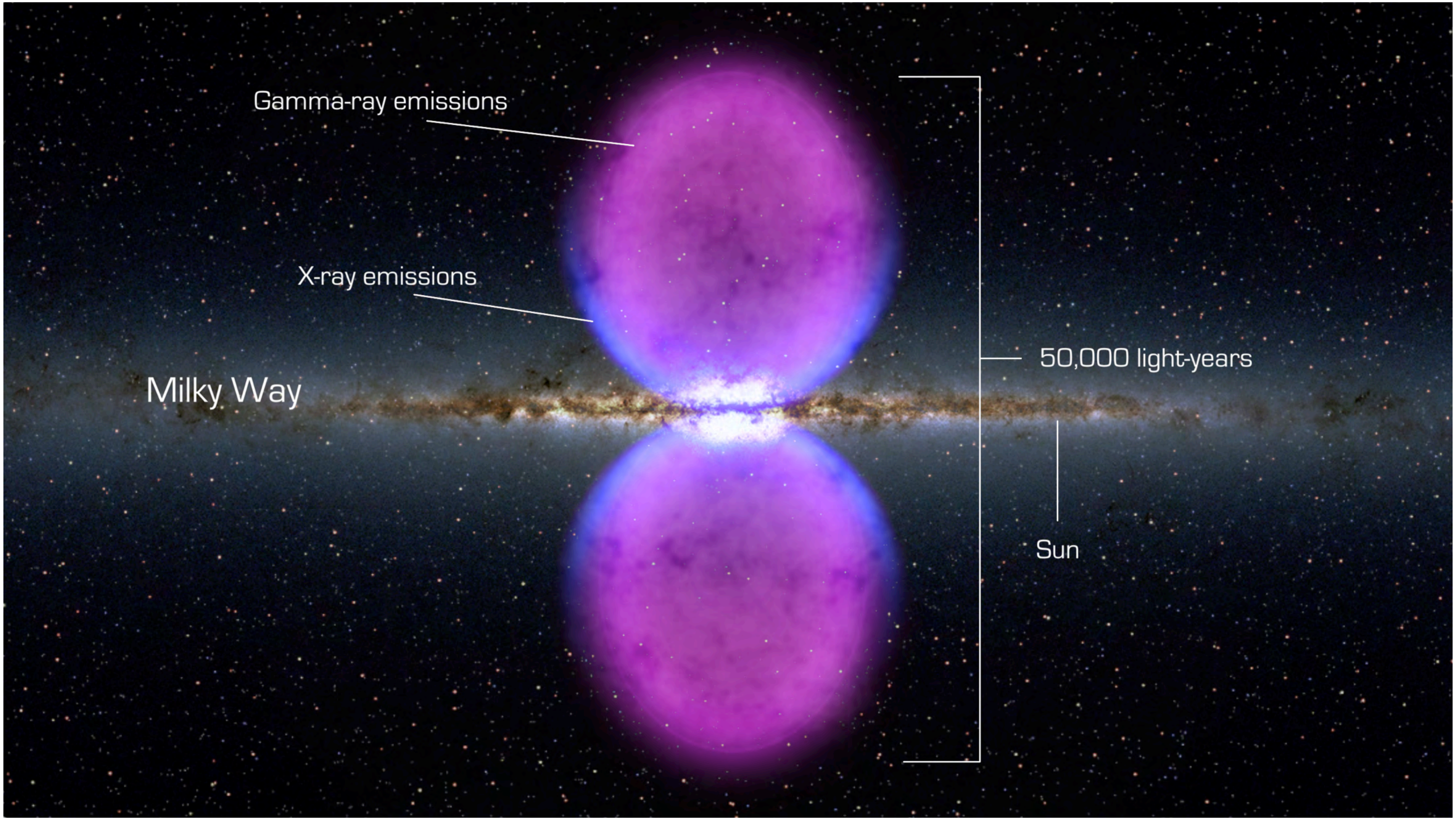
Galactic sources

- Remnants of SN explosions (shells, pulsar wind nebulae, pulsars themselves)
- Gamma-rays binaries
- The Galactic Center

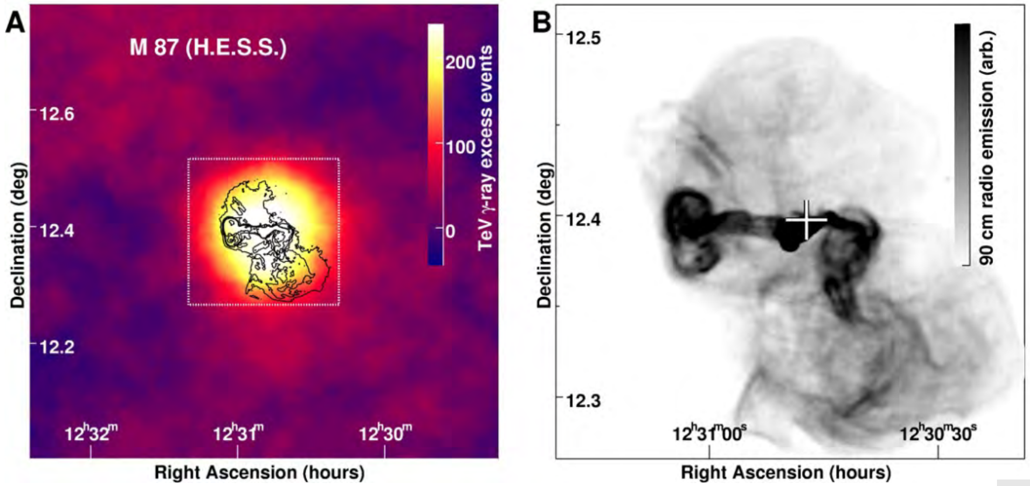
- **And a lot of unassociated sources**



Something special: the Fermi bubbles

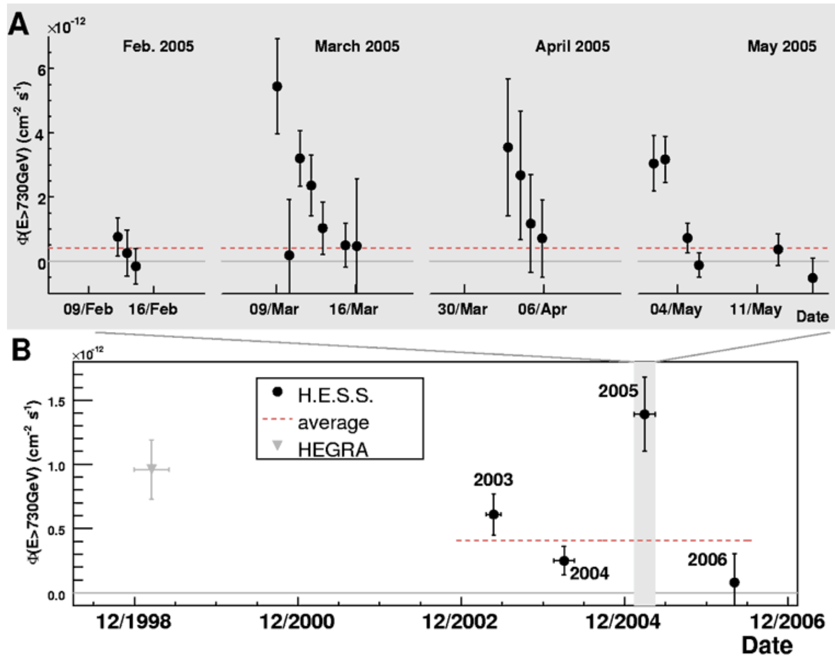


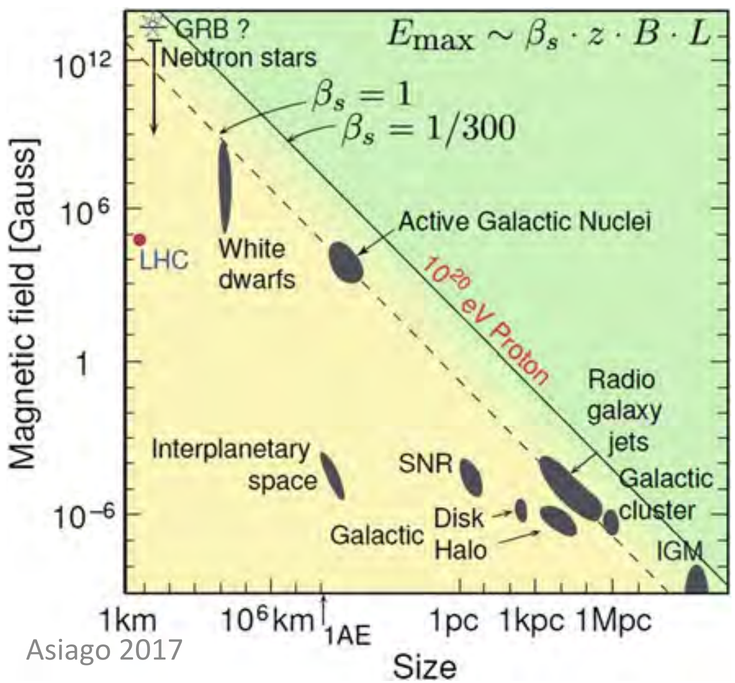
Extragalactic emitters: AGN
(we don't have the resolution to see structures in HE)



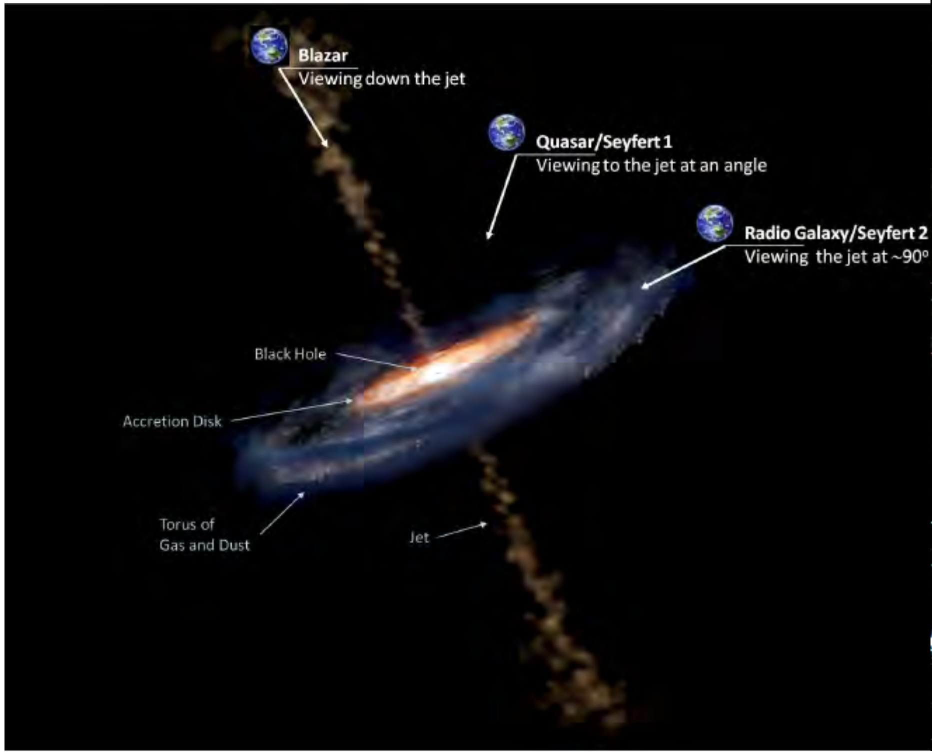
M87: Image from HESS and radio image

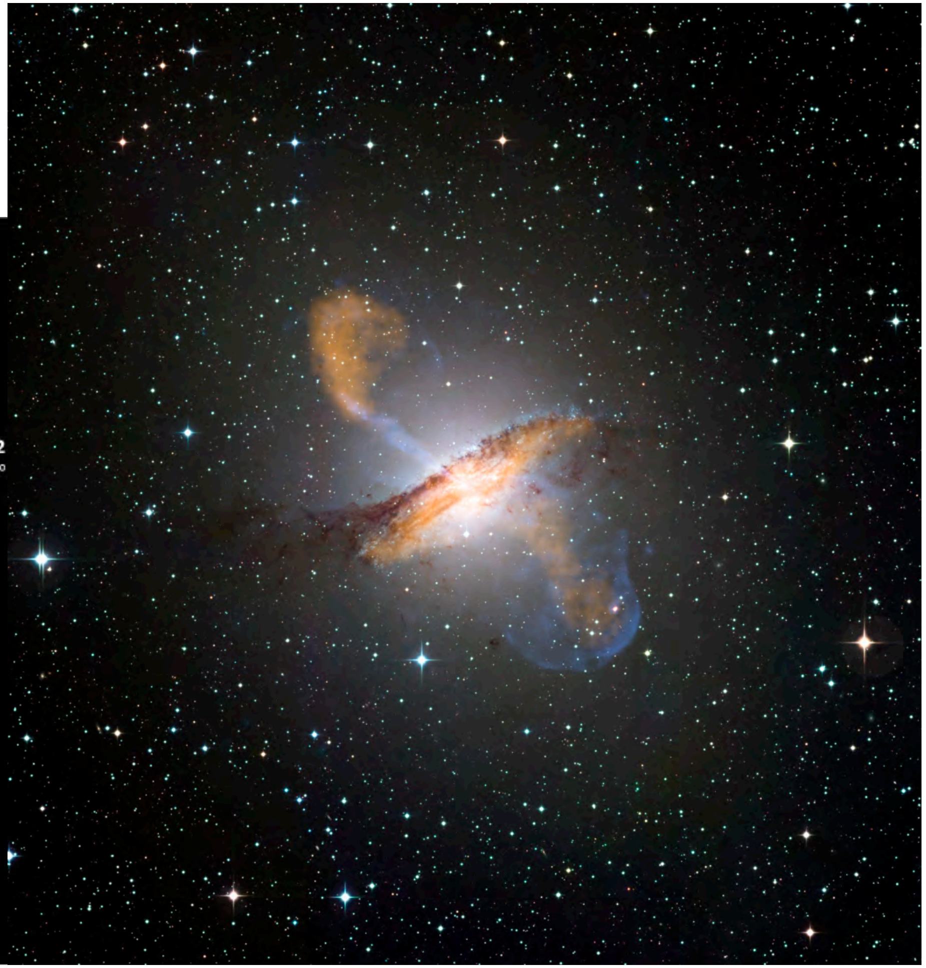
M87 variability in the TeV





Classification of AGN

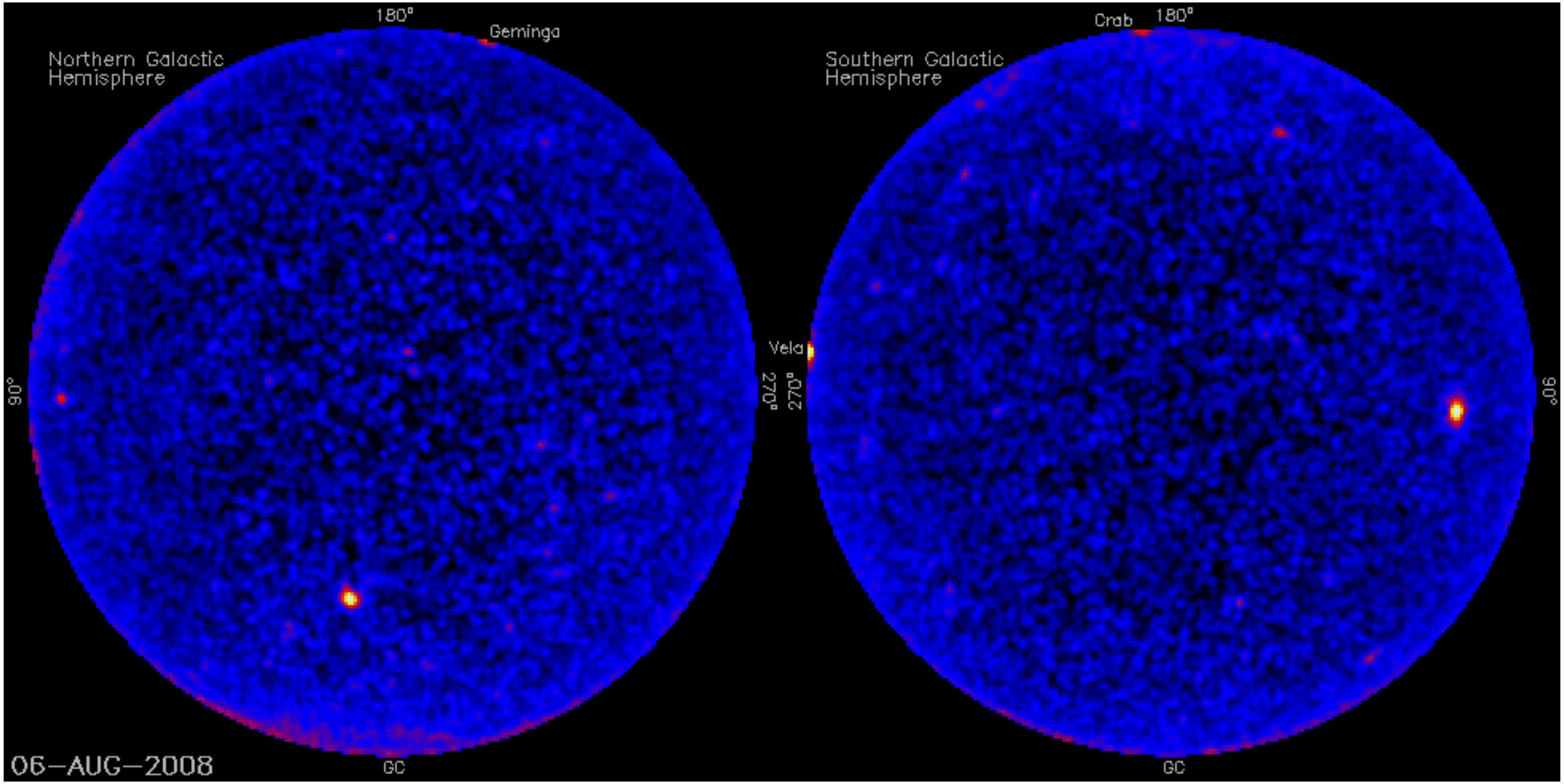




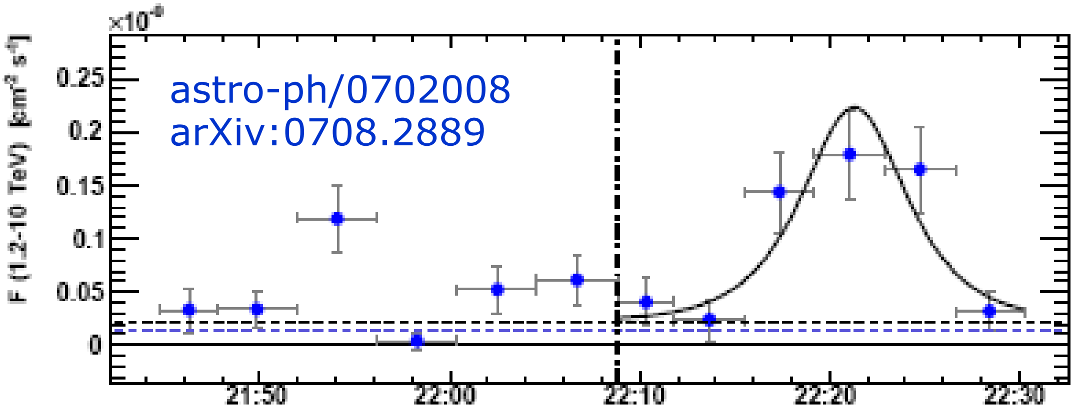
Centaurus A

Observational bias: most of the observed AGN are blazars

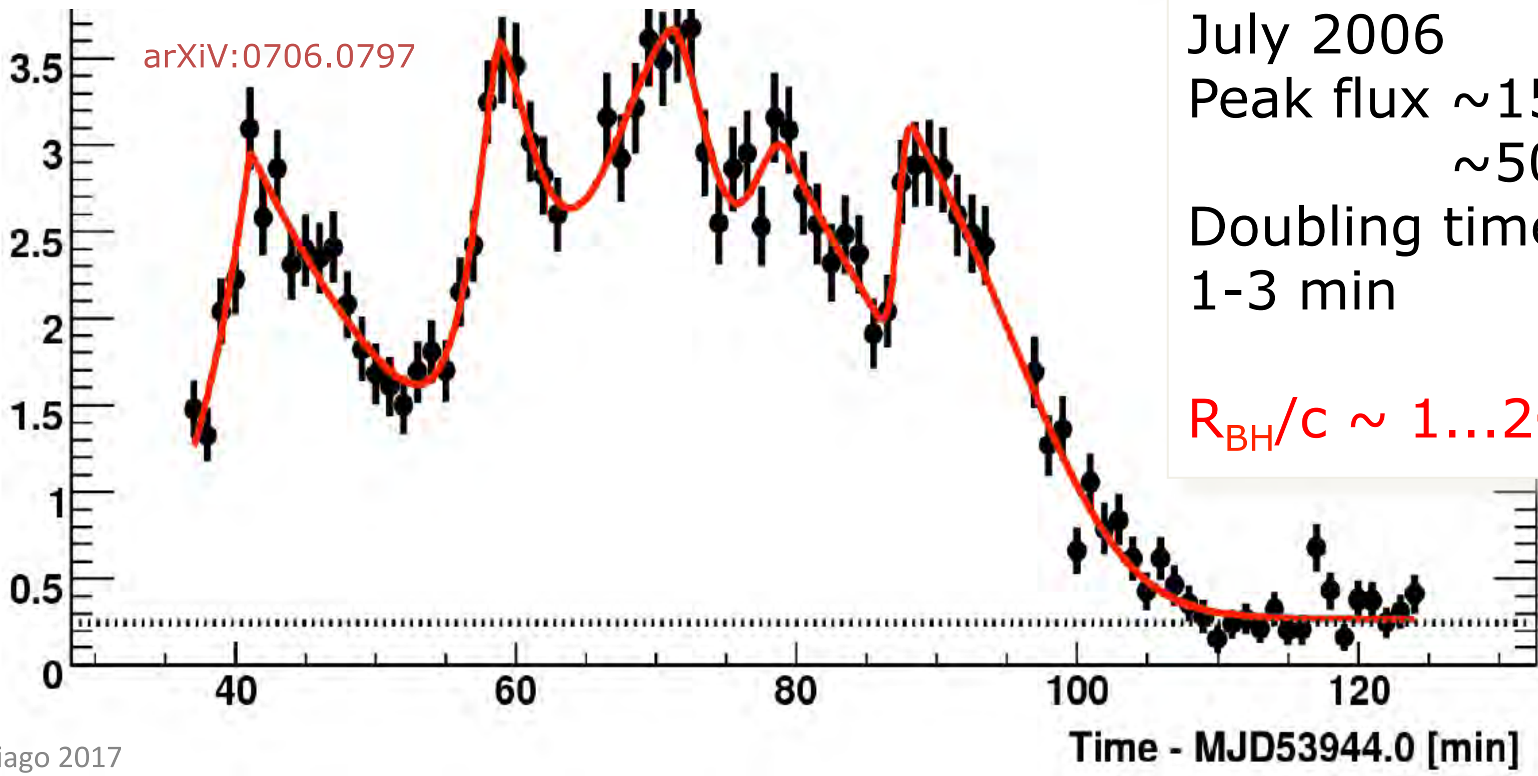
Variability



Rapid variability



MAGIC, Mkn 501
Doubling time ~ 2 min



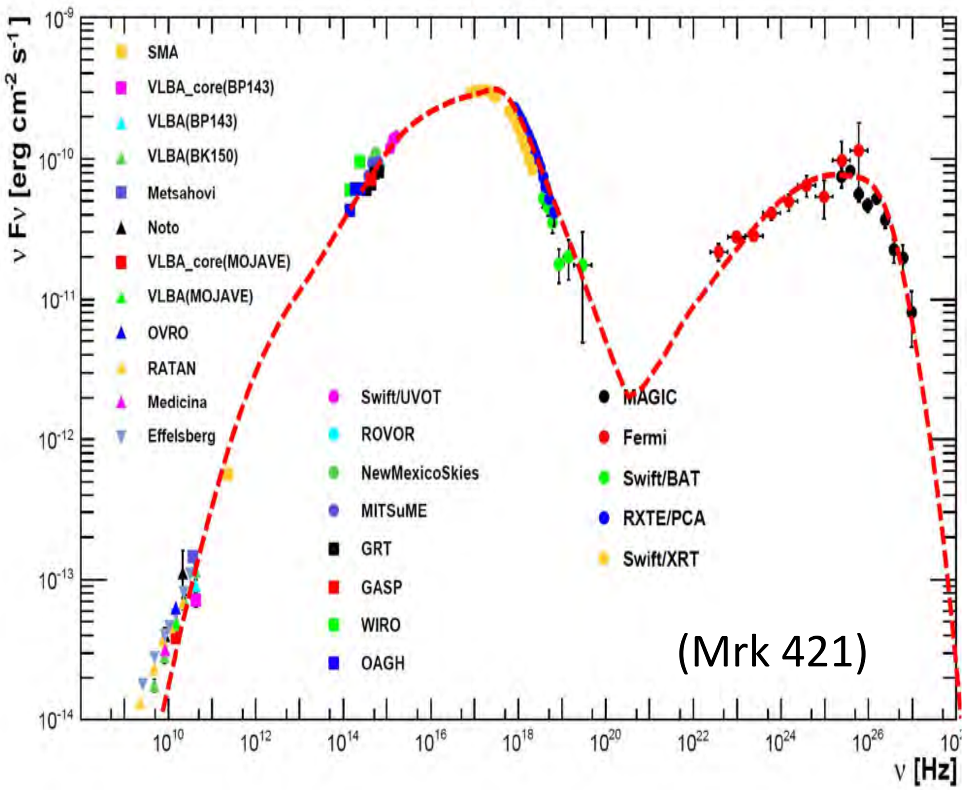
HESS PKS 2155
z = 0.116

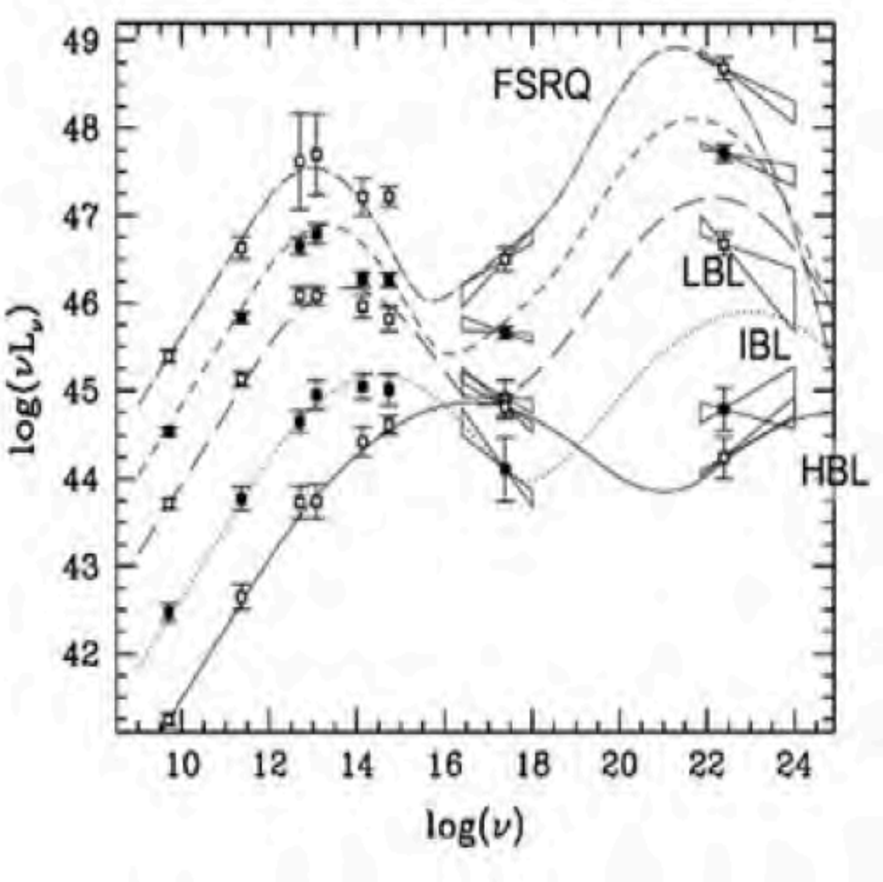
July 2006
Peak flux ~15 x Crab
~50 x average
Doubling times
1-3 min

$R_{BH}/c \sim 1...2 \cdot 10^4$ s

The spectral energy distributions of blazars

The "blazar sequence"



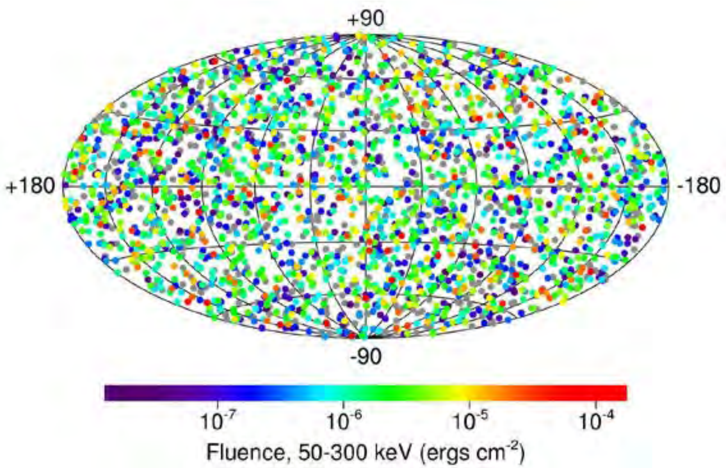


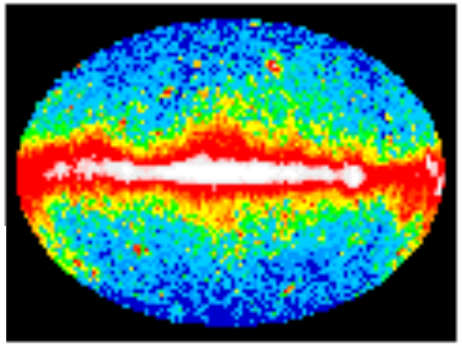
But: some indications of "orphan" flares

Gamma Ray Bursts (GRBs)

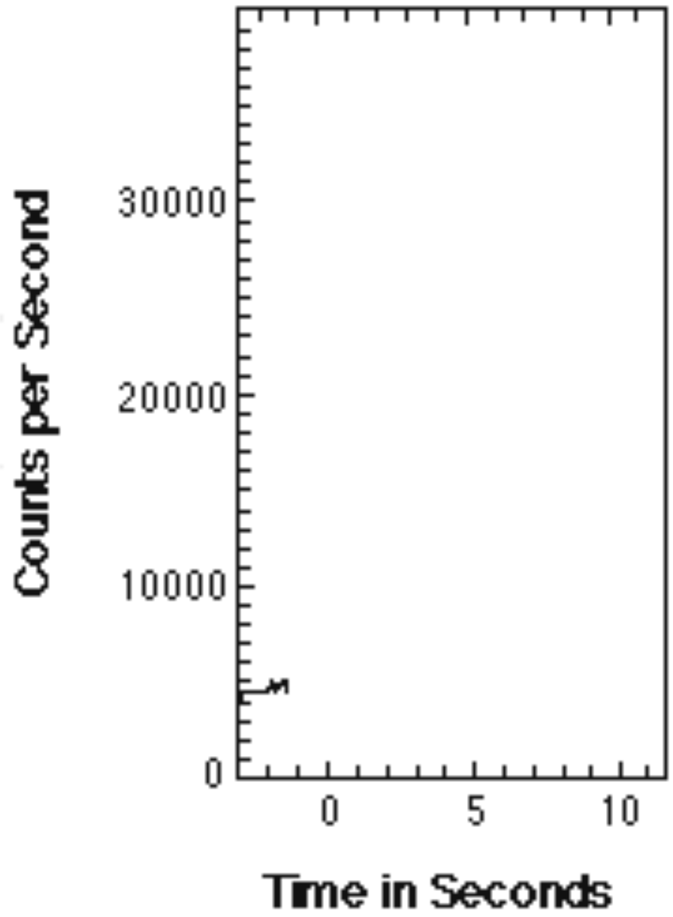
Transient Sources

- Frequently they have a delayed high-energy emission (afterglow)

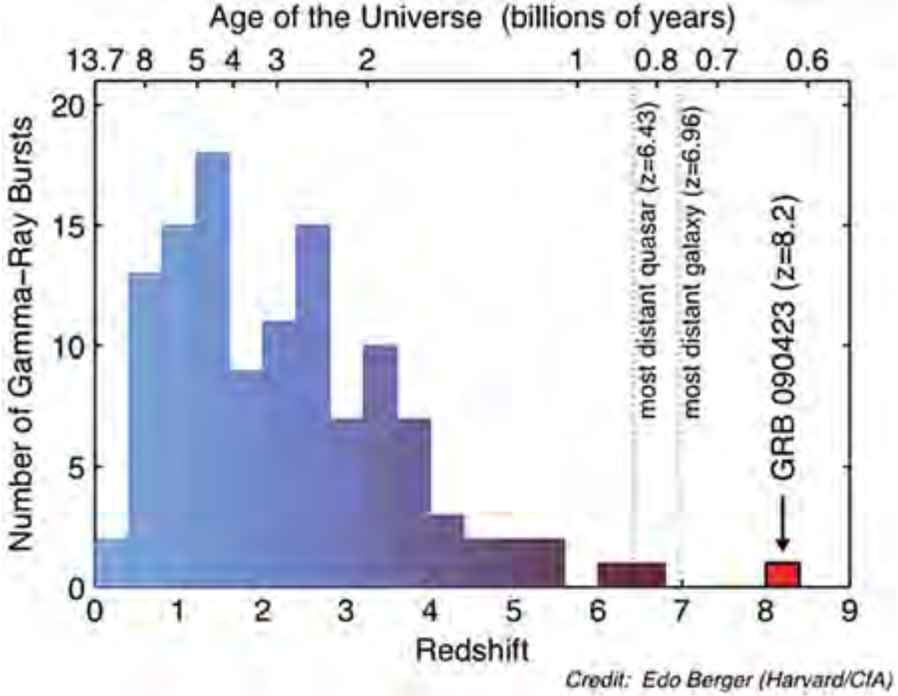


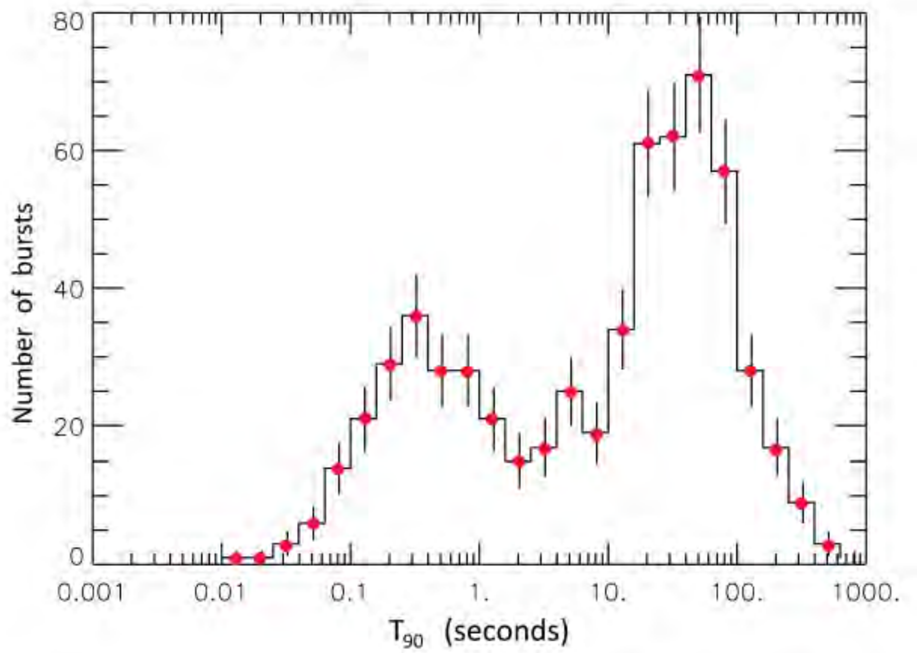


BATSE on CGRO



Isotropical => Extragalactic origin

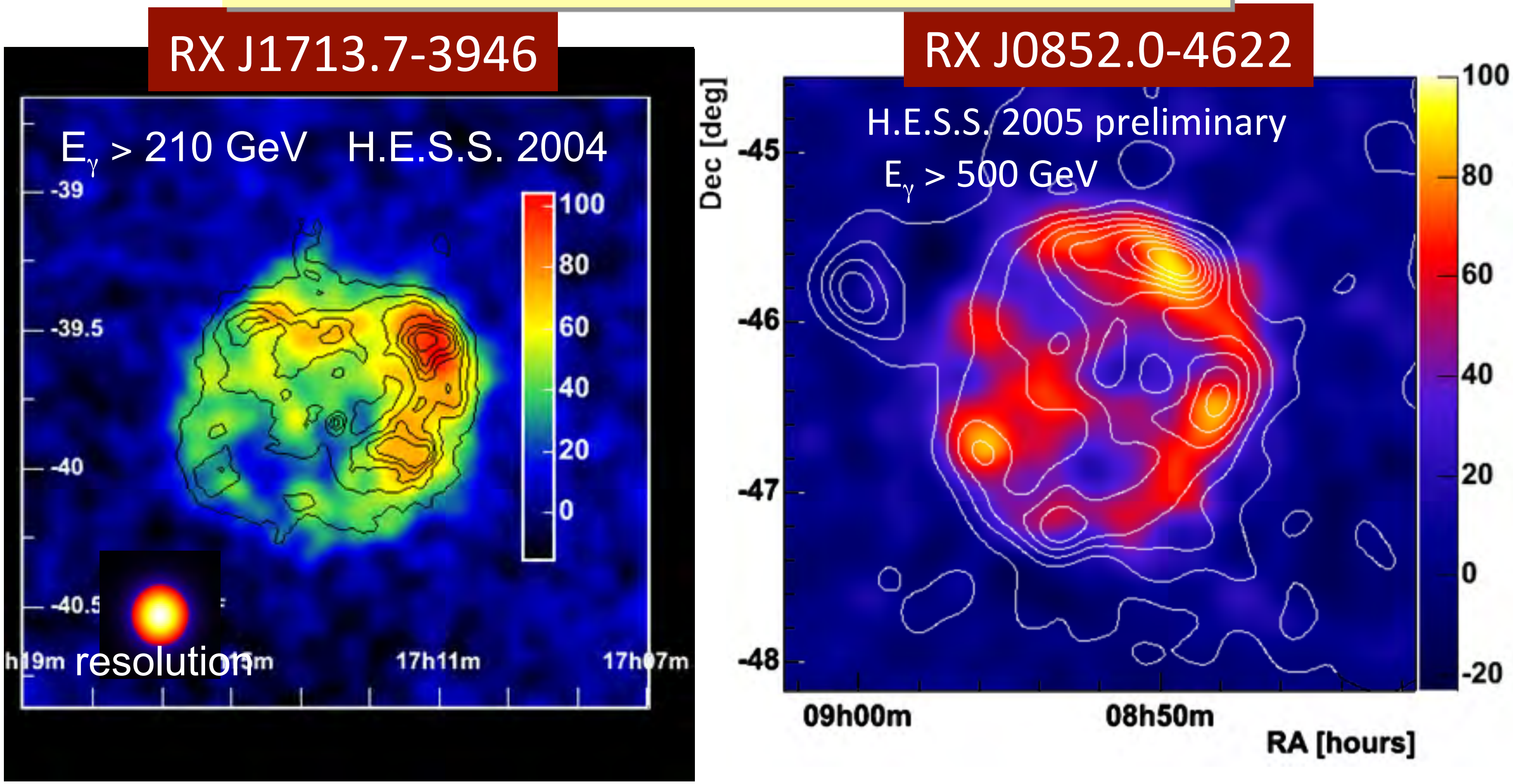




- GRBs are detected roughly once per day, from random directions in the sky by satellite experiments. They are typically far away
- Lasting anywhere from a few milliseconds to several minutes, GRBs shine hundreds of times brighter than a typical supernova, making them briefly the brightest source of cosmic gamma-ray photons in the observable Universe.
- GRBs are separated into two classes: long- and short-duration bursts.
  - Long duration last more than 2 seconds and short-duration less.
  - Short GRBs are difficult to associate

Supernova remnants: sources of galactic CRs

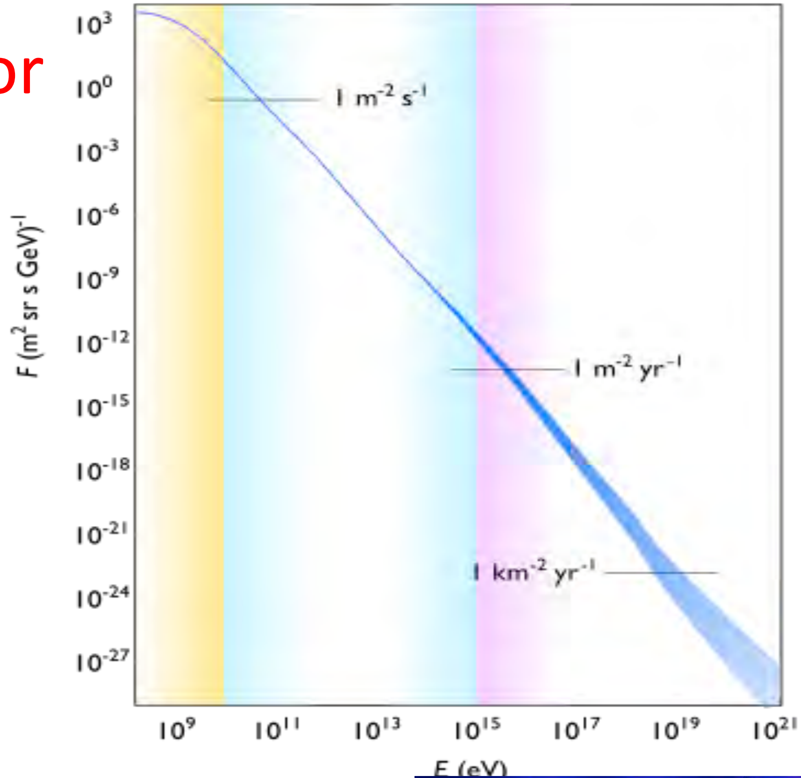
Strong Correlation with X-ray Intensities

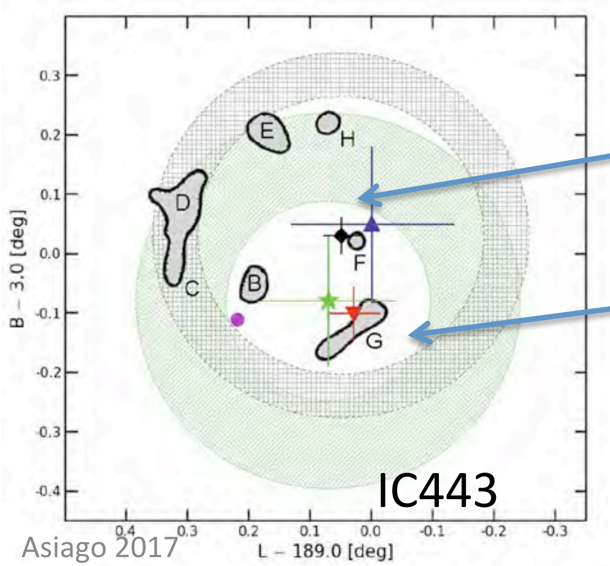


- SN-Shells accelerate particles up to 100 TeV at least
- Are the accelerated particles protons or electrons?

Interaction with molecular clouds or gammas in the ambient

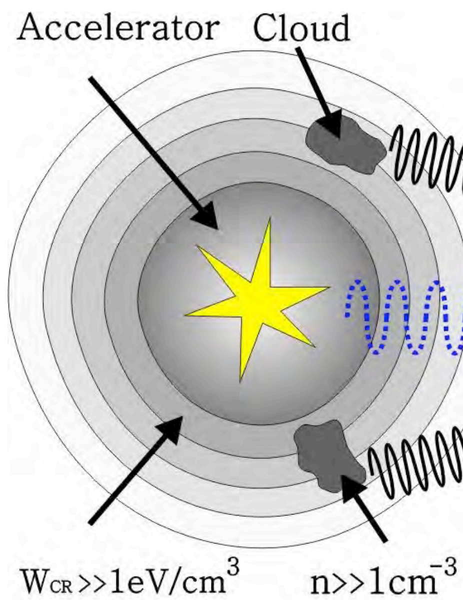
- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004) with photons
- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)

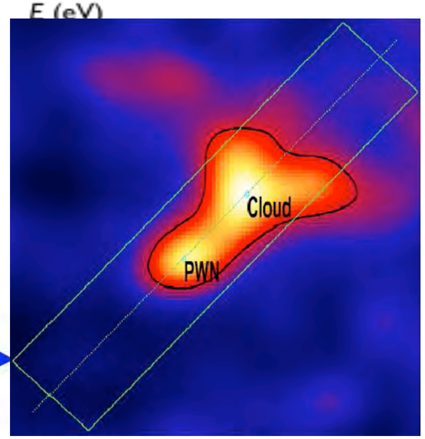




Fermi, Egret

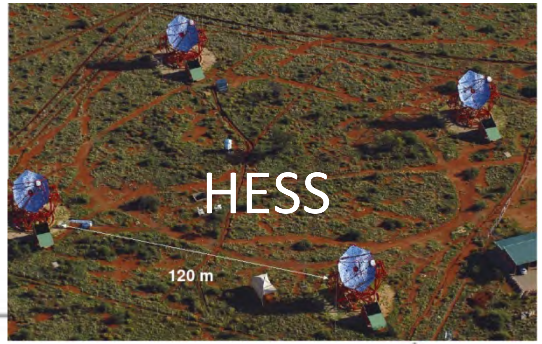
Magic, Veritas



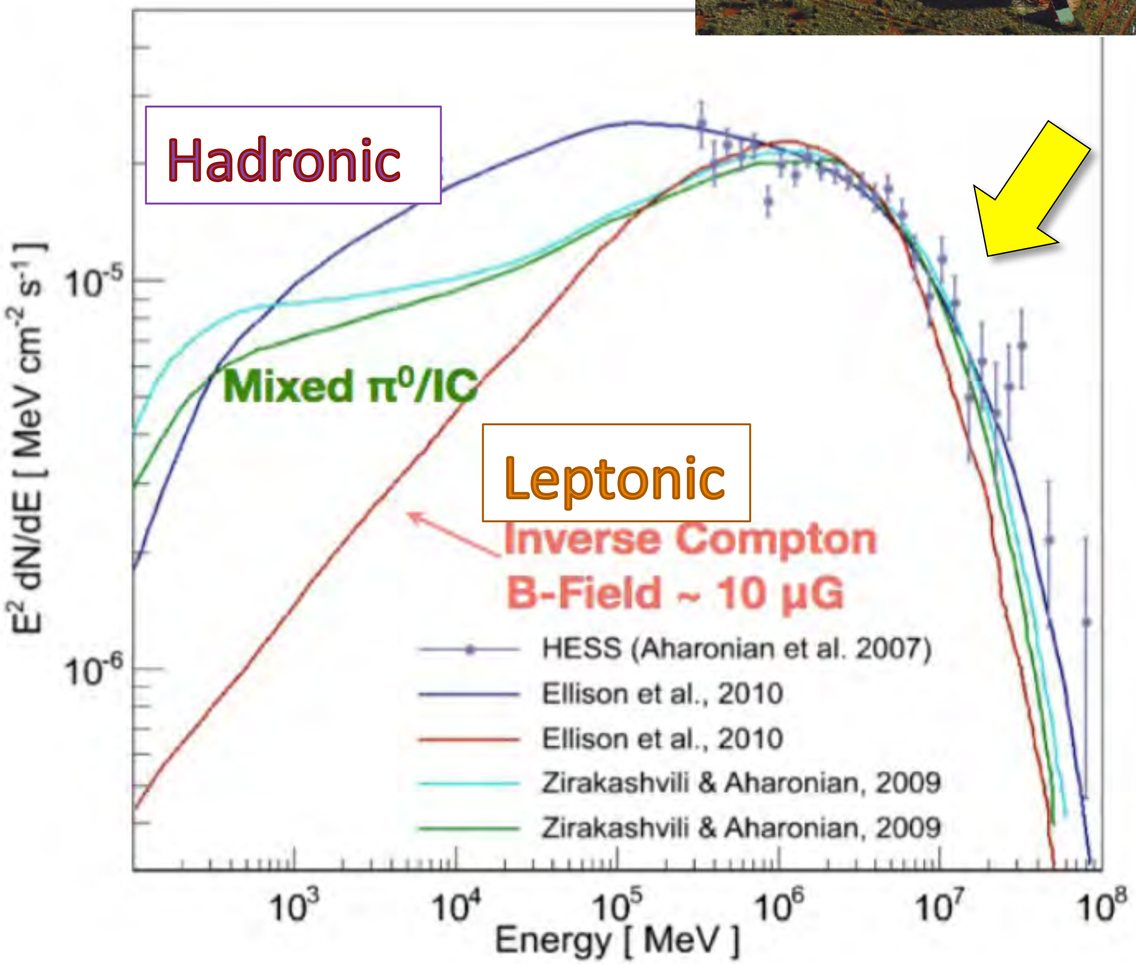


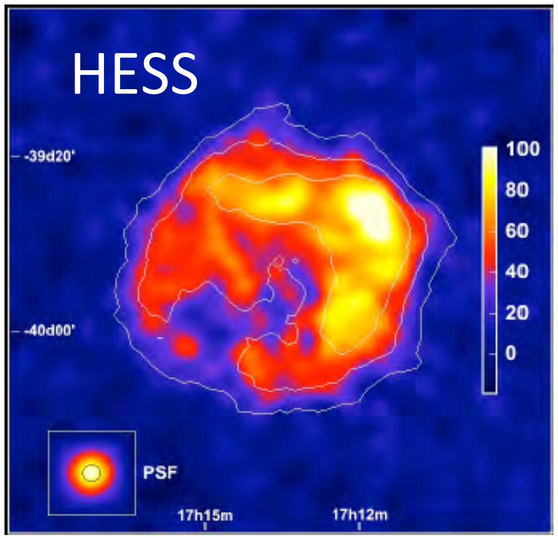
The SNR RX J1713.7-3946

SN remnant
RX J1713.7-3946
age: 1.6 kyr,
distance: 1 kpc

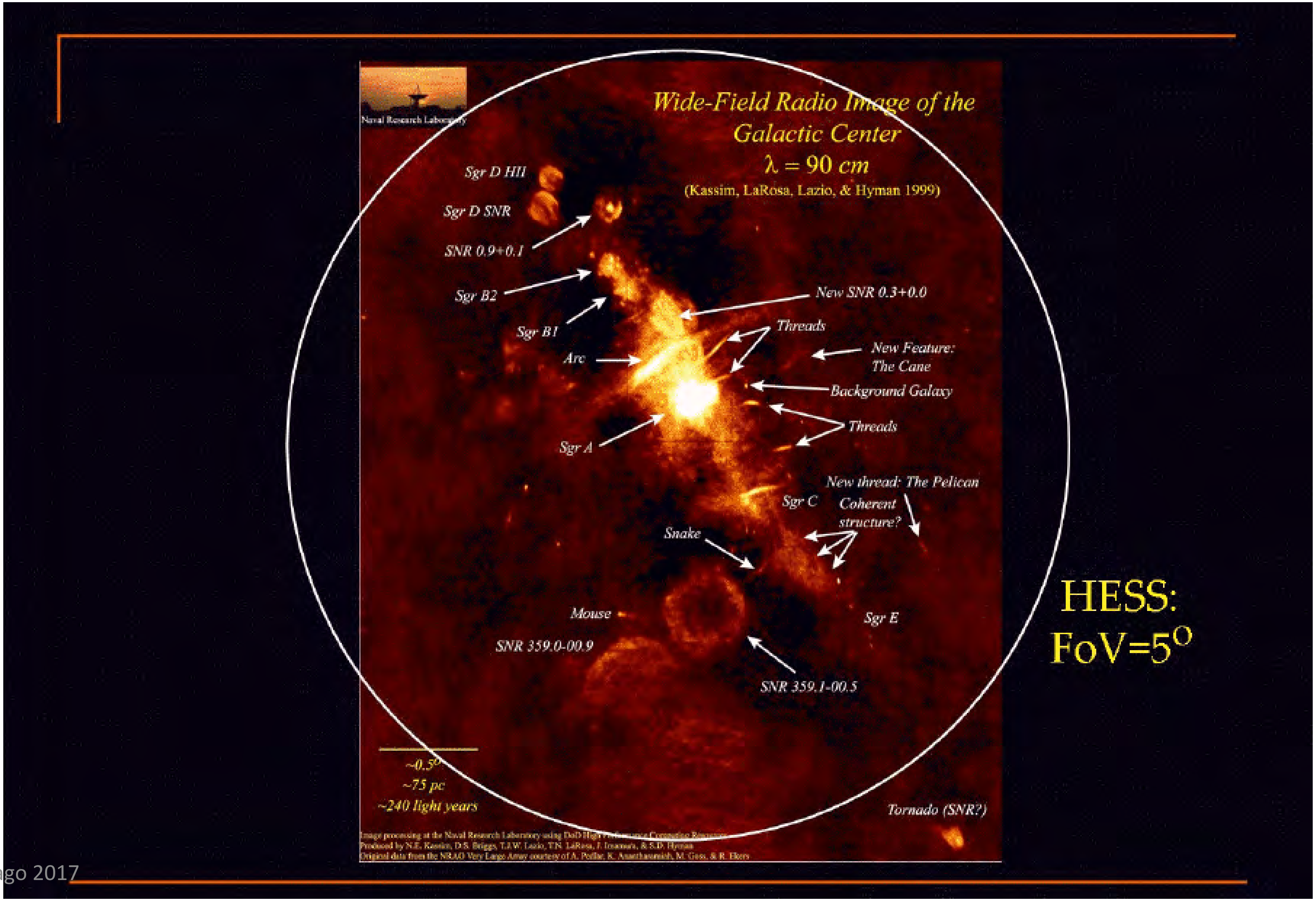


Funk, 2007- Pre FERMI era

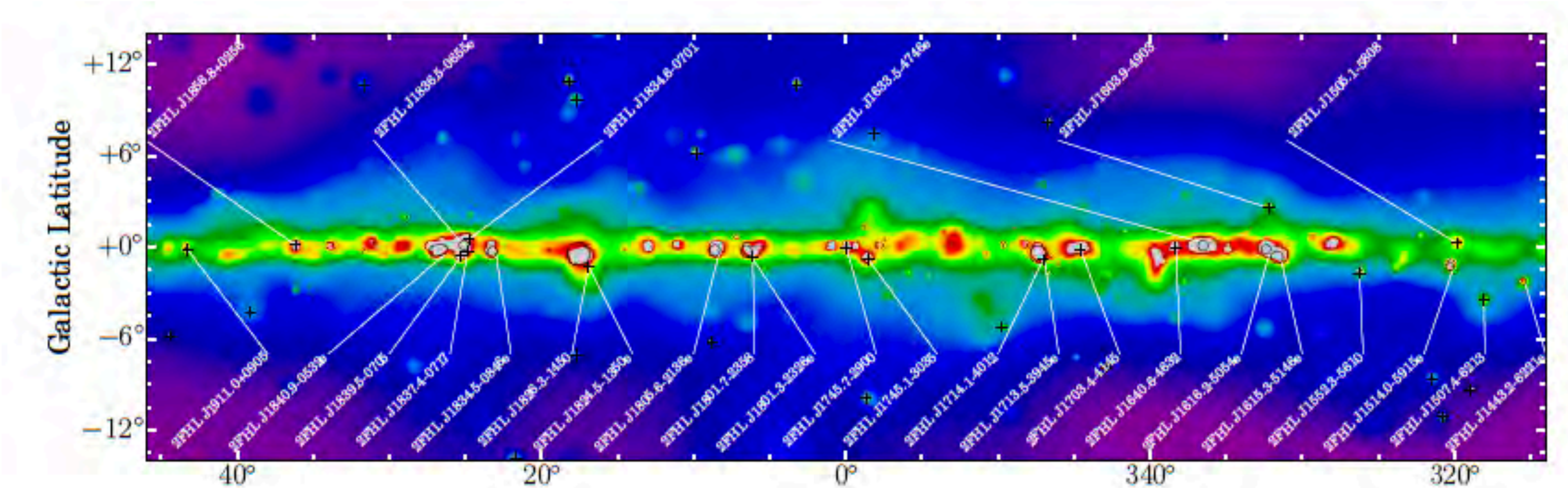


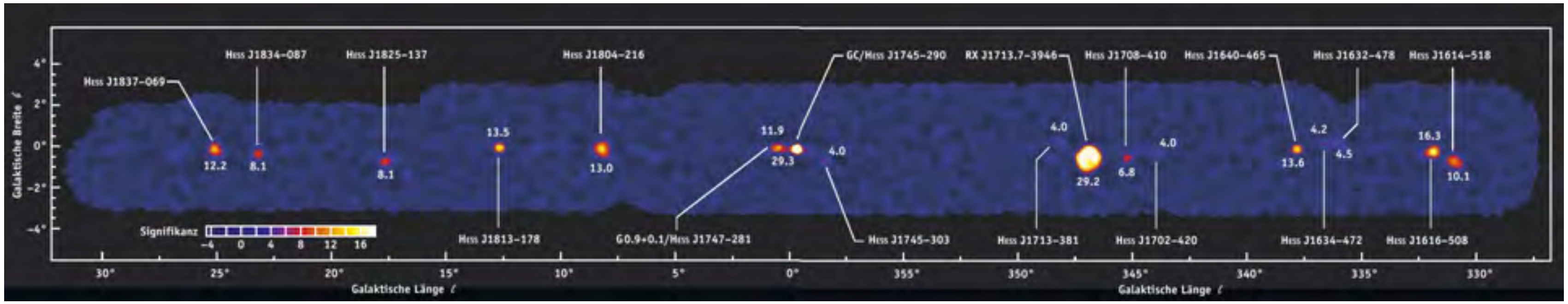


The Galactic Center

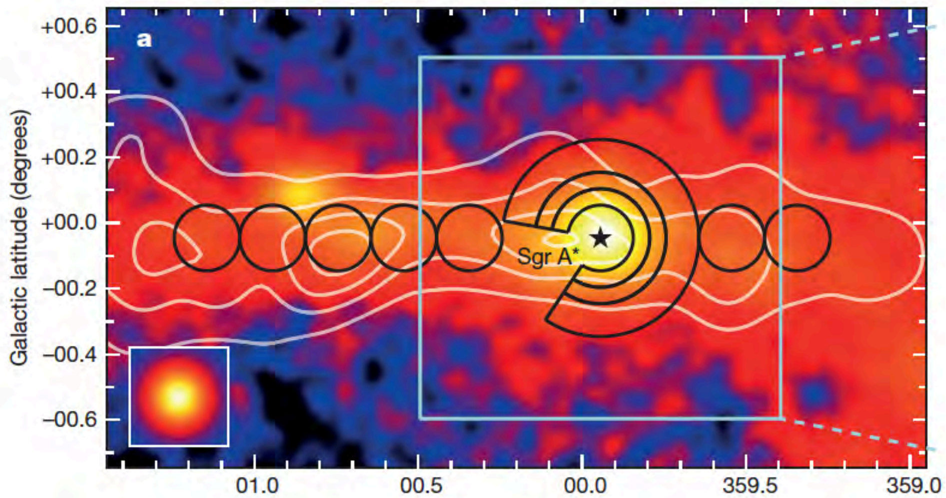


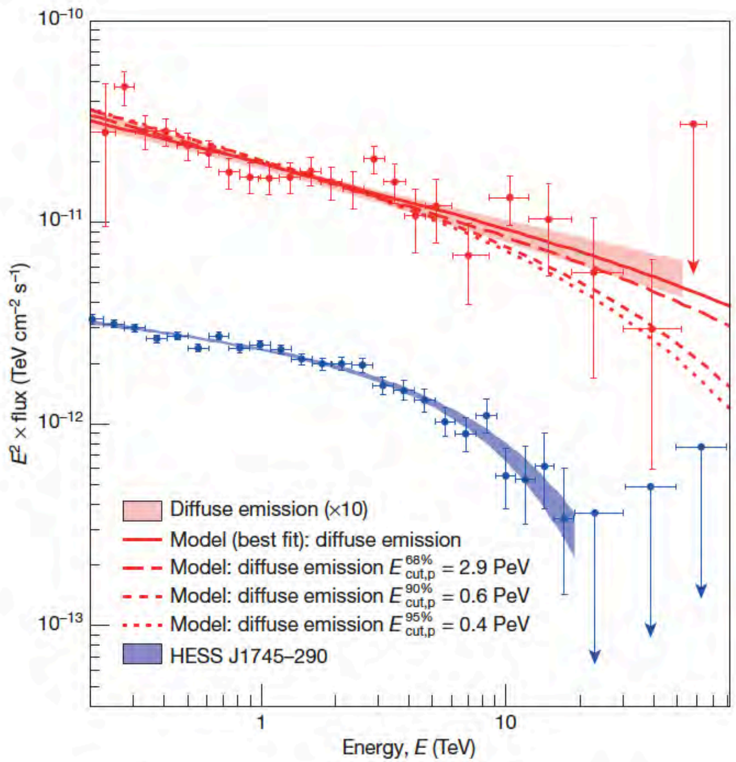
The Galactic center above 50 GeV (Fermi) and in TeV (HESS)





A PeVatron in the GC? (Nature 2016)





- Diffuse emission from the decay of π^0 produced in pp interactions can reach some 50 TeV => primary energy ~ 1 PeV

Summary on gamma-rays as CR

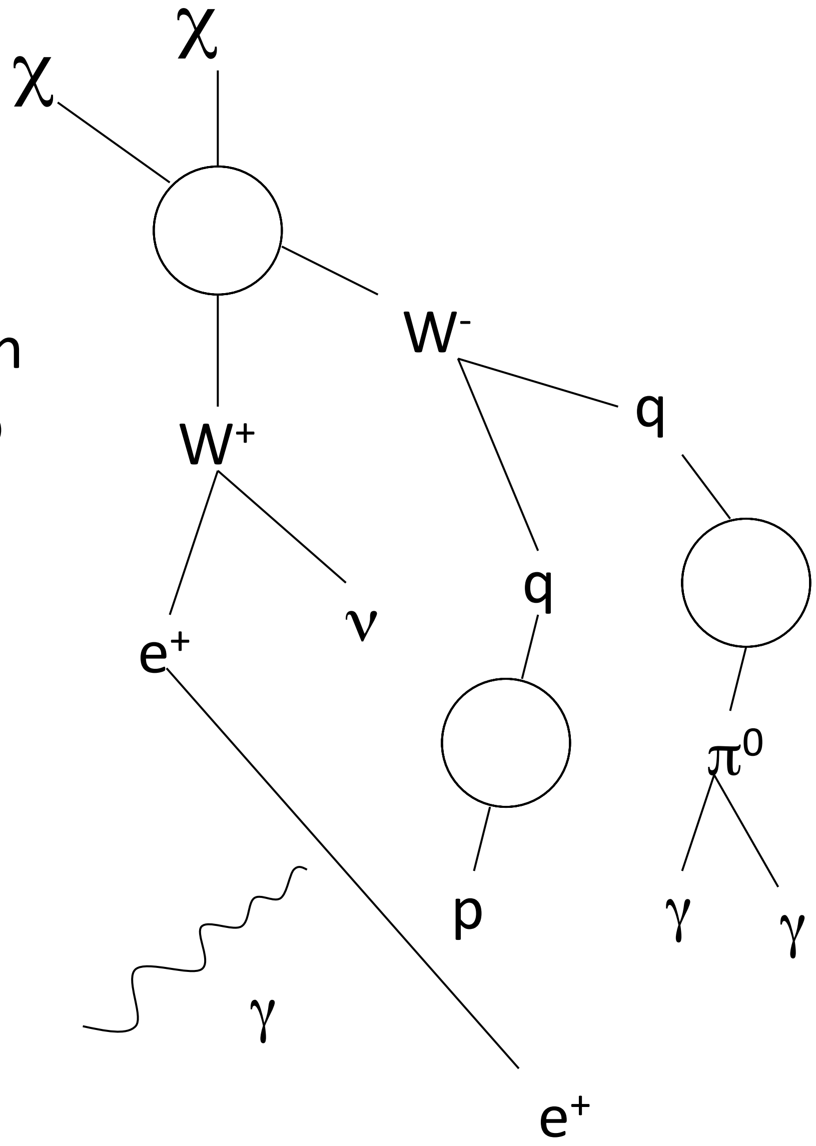
- We discovered many sources and source classes, galactic and extragalactic, of gamma rays up to ~50 TeV
- We saw the SSC at work in AGN and Galactic sources
- We established the presence of the hadronic acceleration mechanism in several SNR
- We observed several interactions of charged CRs with molecular clouds
- We discovered (at least) one PeVatron in the Galaxy, with position consistent with the GC
- We observed a large structure with cutoff ~10 GeV, possibly the remnant of the activity of our GC

DARK MATTER

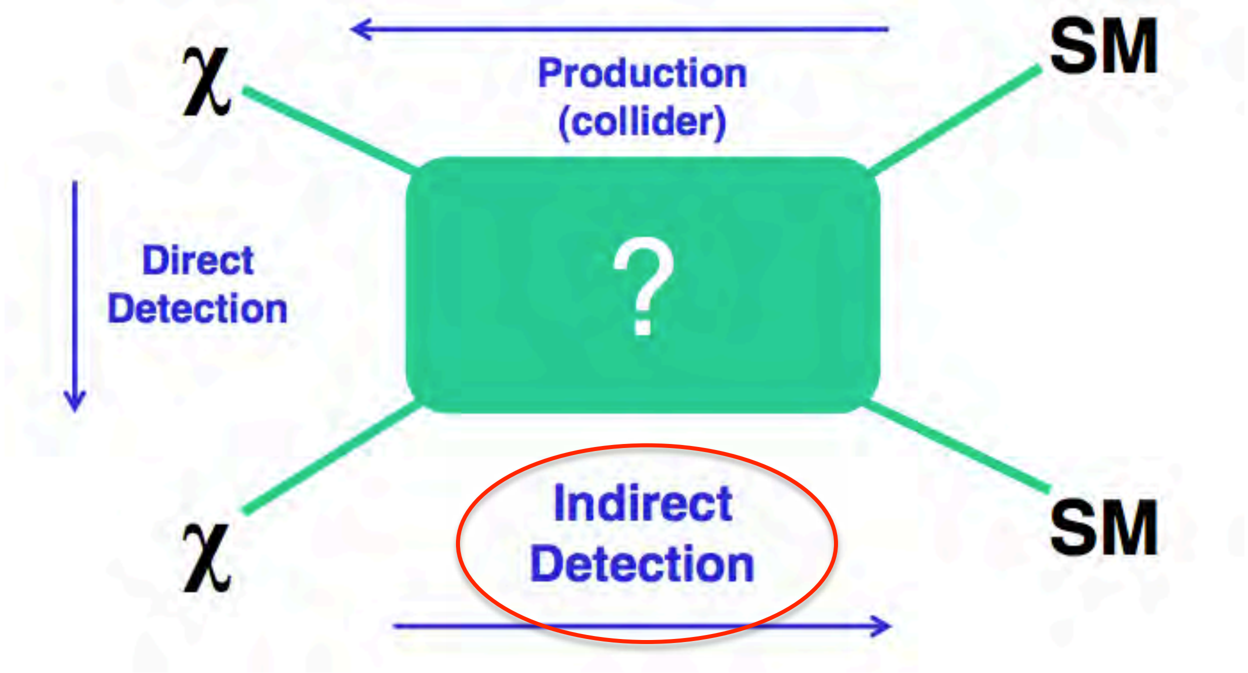
The indirect detection of DM

- ❑ **WIMP Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons

- ❑ **Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, (and their antiparticles), gamma-rays and neutrinos



Role of Indirect Detection Dark Matter Searches

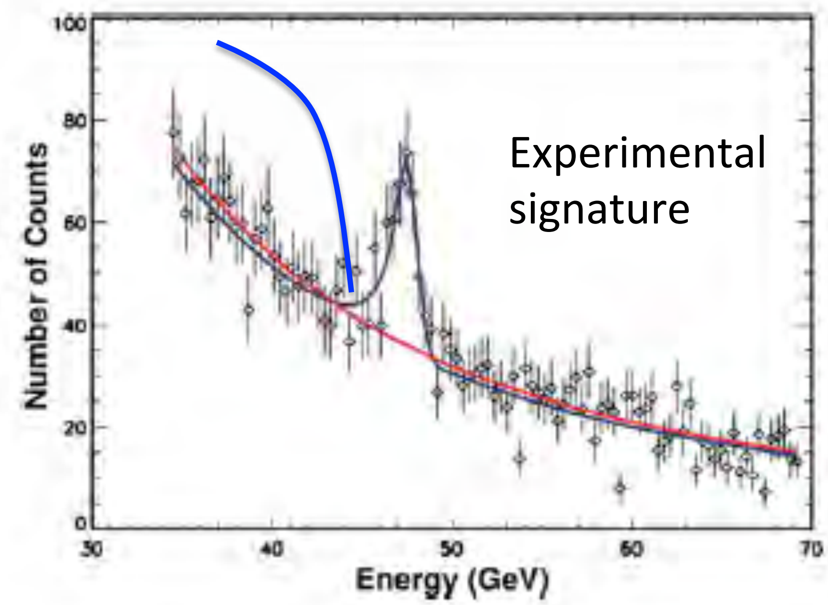


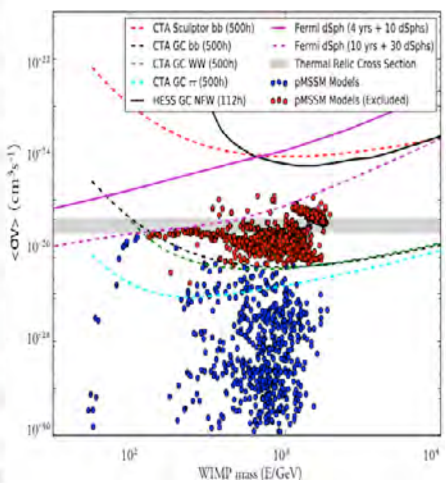
- *Compared to collider searches*: indirect detection is sensitive to high mass scales (particles already exist, stable final state particle spectrum peaks at ~10% of m_c)
- *Compared to direct detection*: indirect detection is sensitive to annihilation rather than scattering off of nuclei (i.e., more sensitive when c couples more to heavy quarks and vector bosons than to light quarks and gluons)

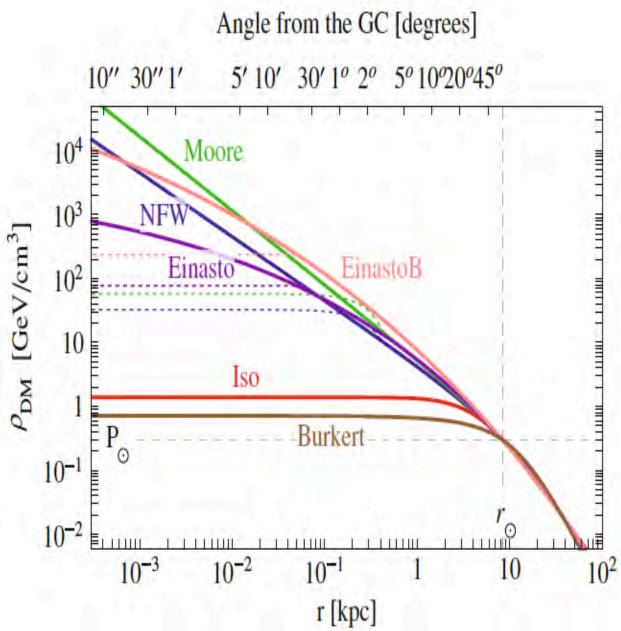
The Key Formula for WIMP Searches

Particle Physics **Astrophysics (*J*-Factor)**

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f} \; \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$







- *J*-factor includes distance, i.e., *J*-factor would decrease by four if a point-like source were twice as far away => look as close as possible
- The factor of $1/m_\chi^2$ is due to the fact we express the *J*-factor as a function of mass density (which we can measure), not number density
- We usually call χ the generic WIMP, like the SUSY neutralino, but it's more general

Search in the γ channel (waiting for neutrinos)

Satellites

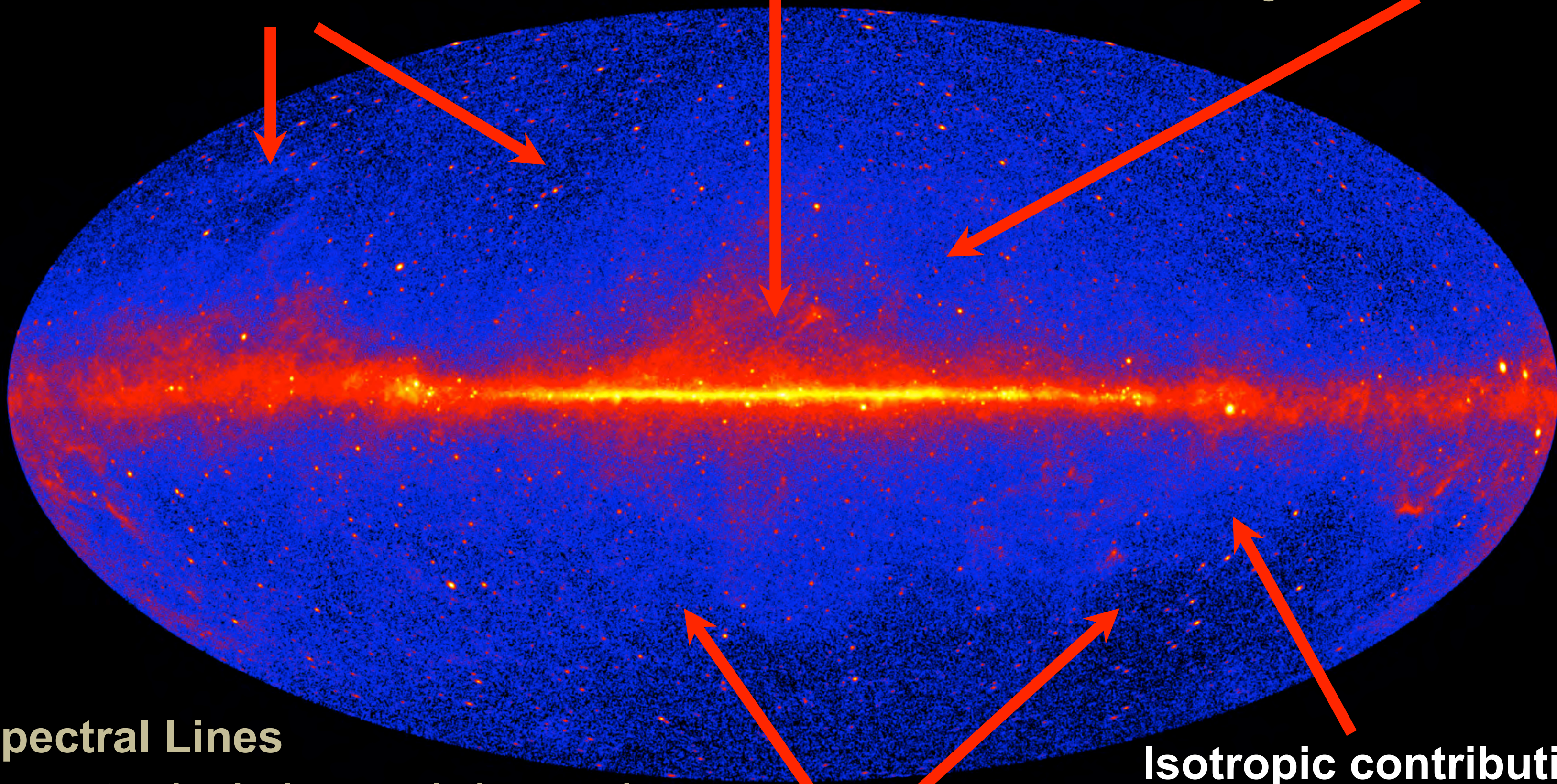
Low background and good source id, but low statistics

Galactic Center

Good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

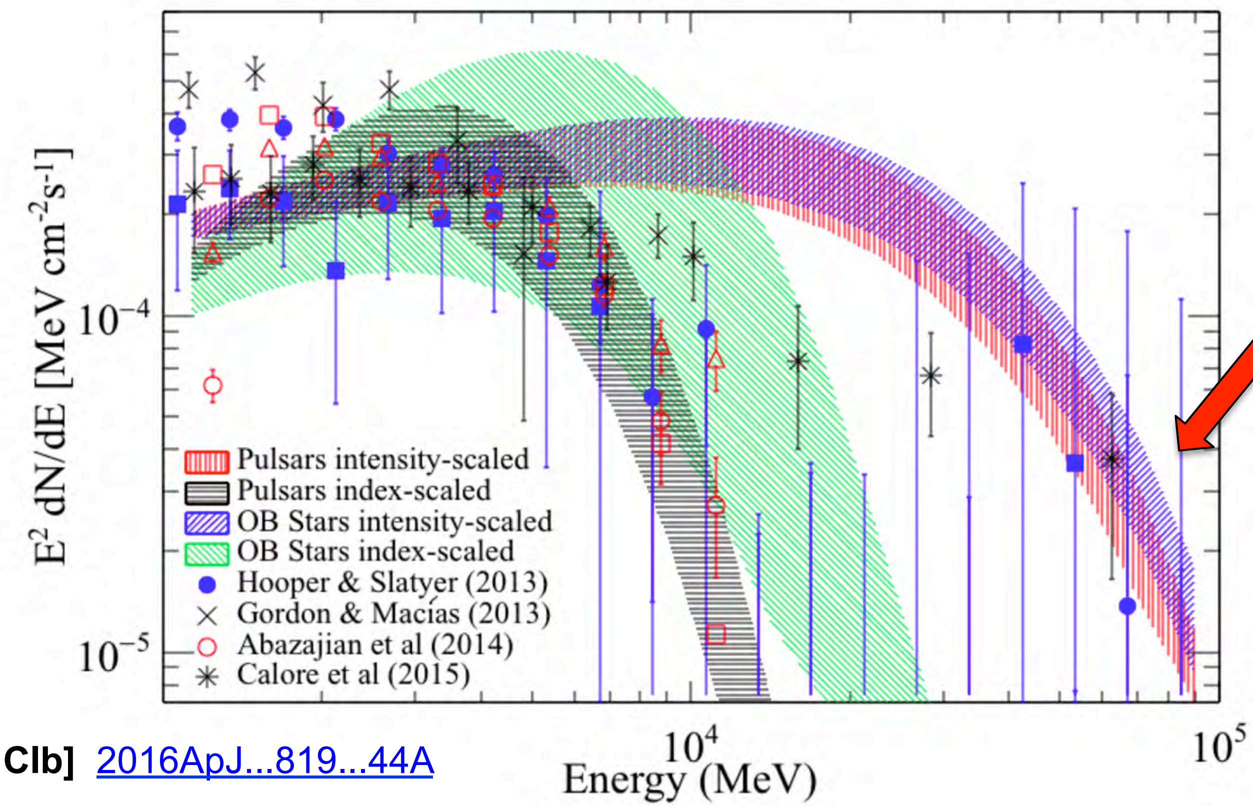
Isotropic contributions

Large statistics, but astrophysics, galactic diffuse background

LAT 7 Year Sky > 1 GeV

Spectrum of the Galactic Center Excess

Spectral Energy Density for Galactic Center Excess Compared to Several Models

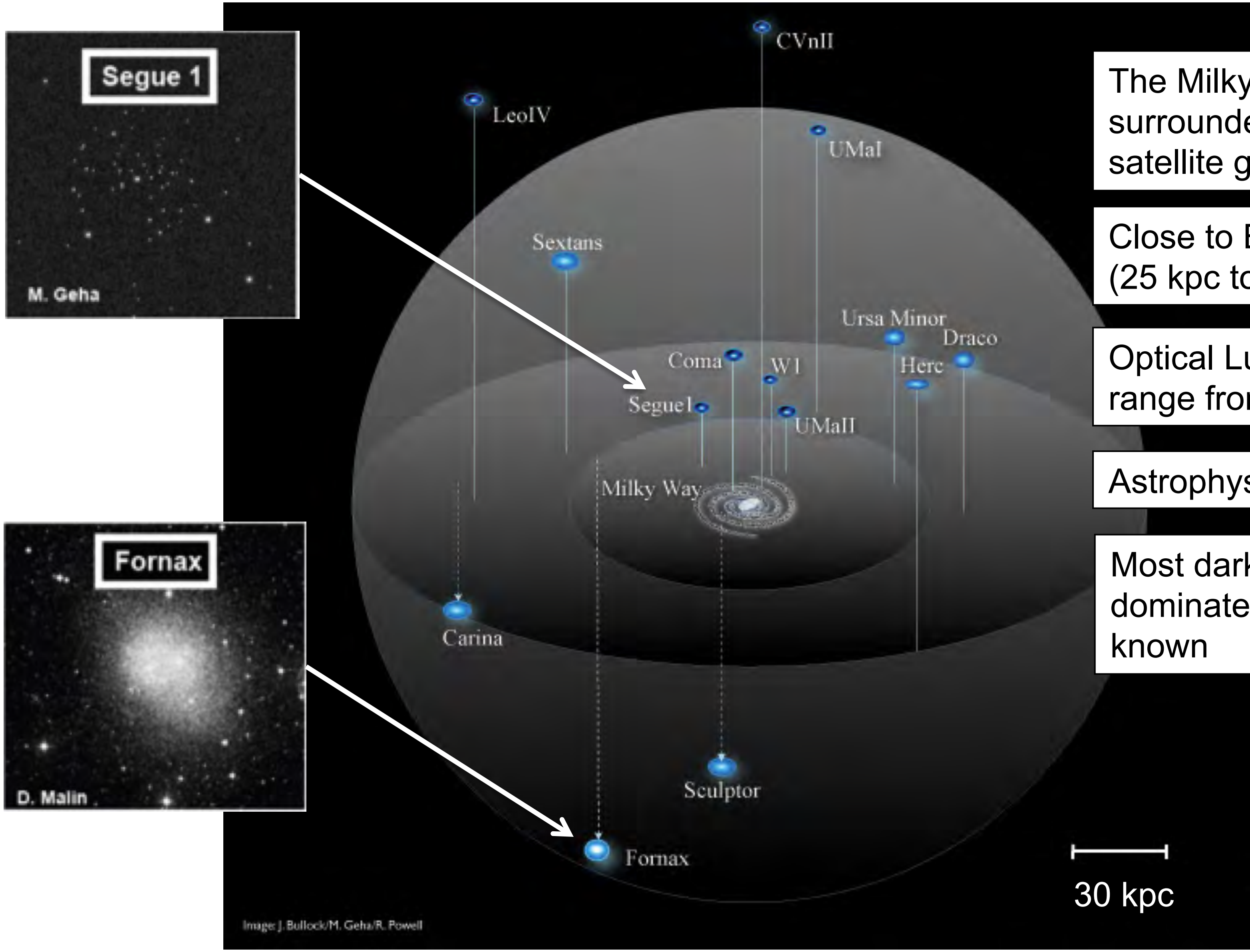


Emission above 50 GeV not from 50 GeV dark matter

Ajello+ [LAT Clb] 2016ApJ...819...44A

- The presence for an γ-ray excess with respect to the modeled diffuse emission at the Galactic center at a few GeV is well established
- However, the details (and the interpretation) of the excess depend on the modeling of the astrophysical fore/background

Dwarf Spheroidal Satellites of the Milky Way



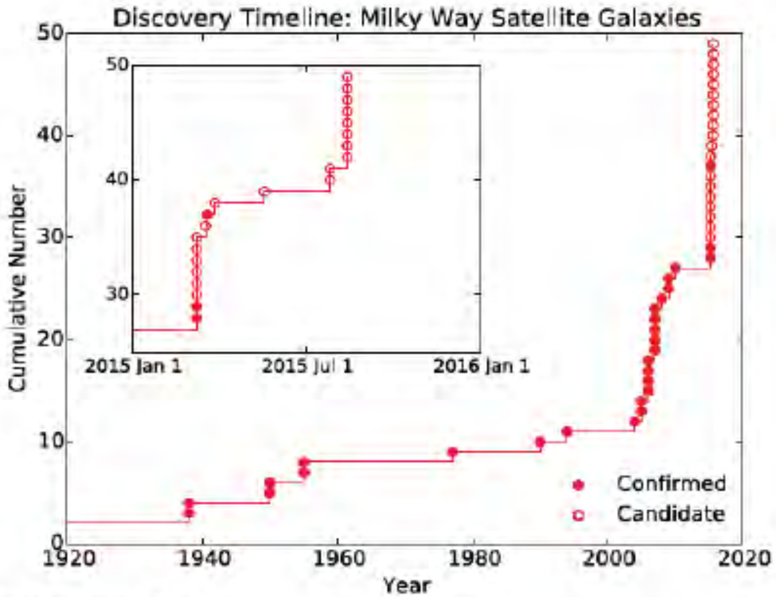
The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

Optical Luminosities range from 10^3 to 10^7 $L_\odot$

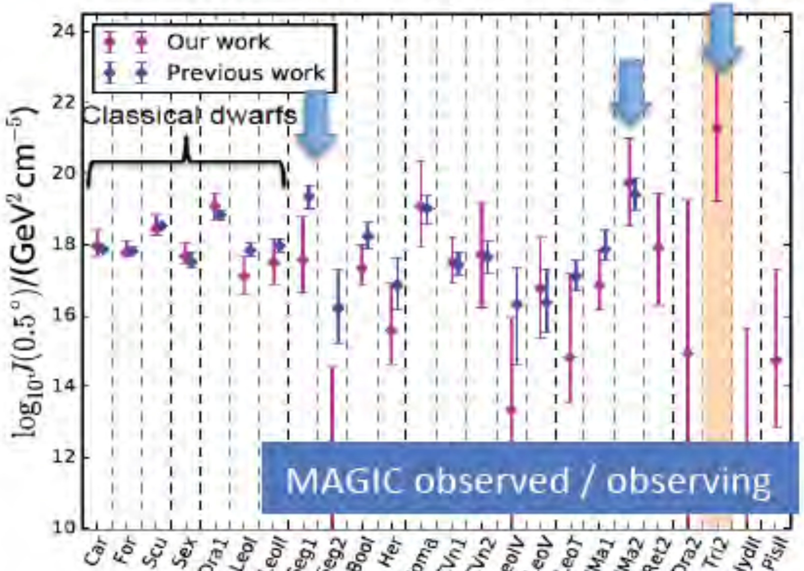
Astrophysically inactive

Most dark matter dominated objects known

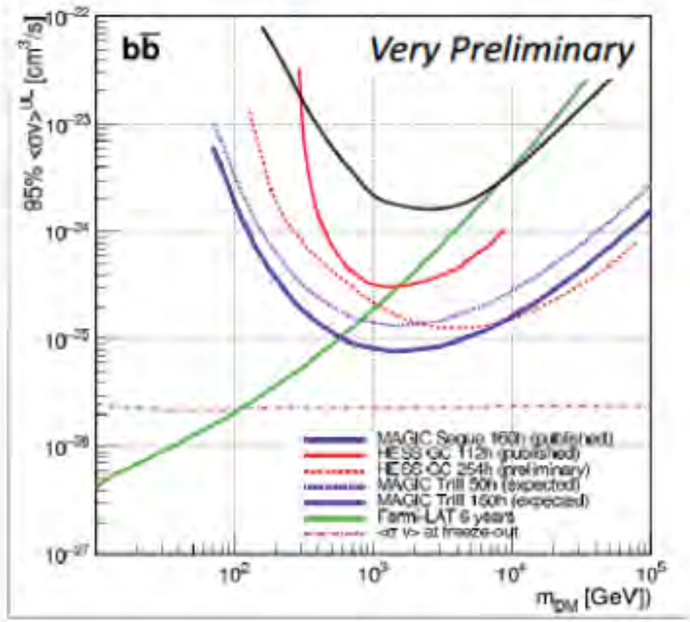


k. bechtol 2015

J-factors – K. Hayashi et al 2015

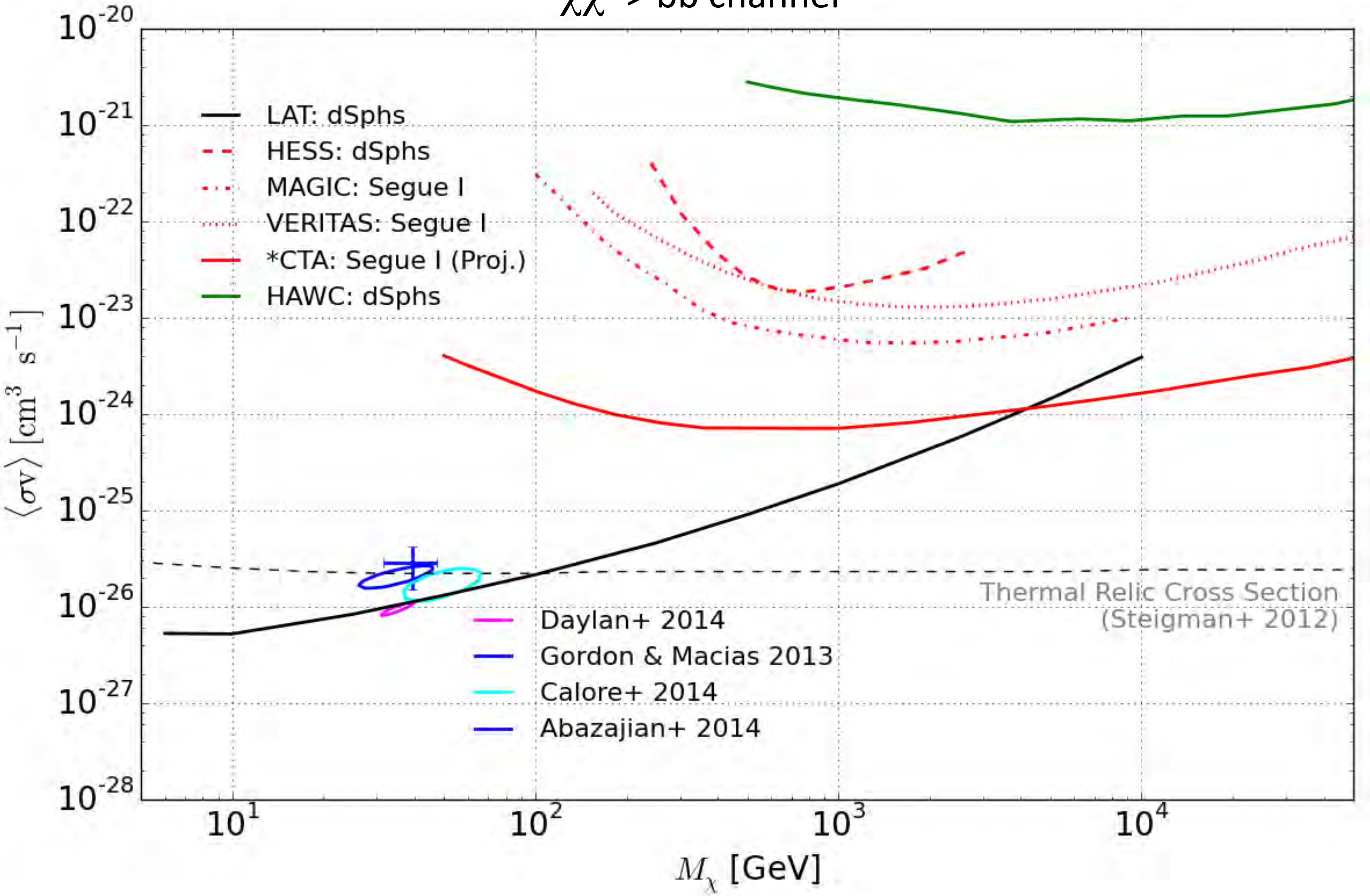


- The framework for particle dark matter particles is still very open, given the scarce guidelines from cosmology or accelerator physics
- Plans to observe Triangulum II
  Distance = 30 kparsec
  Mass/light = 3600
- Caveat: big uncertainties
  in J-factor estimations



Upper Limits from Dwarf Galaxies

χχ -> bb channel



Summary on DM

- Motion of stars cannot be explained by the luminous matter in the current theory of gravity
- Simplest solution consistent with experimental data (direct searches, accelerators, indirect searches) is just one "dark" particle, "weakly" interacting: a WIMP of mass > 40 GeV (better if < 2 TeV)
- No indirect detection yet; if any, a "miracle" particle of mass 40-80 GeV is consistent with marginal anomalies on gamma-rays from the GC, antimatter, some direct detection experiments (but other anomalies, one notable pointing at m ~ 800 GeV)

VERY EXOTIC PHYSICS
(VIOLATION OF THE LORENTZ INVARIANCE+)

Is Lorentz invariance exact?

- For longtime violating Lorentz invariance/Lorentz transformations/Einstein relativity was a heresy
  – Is there an aether? (Dirac 1951)
  – Many preprints, often unpublished (=refused) in the ’90s

- Then the discussion was open
  – Trans-GZK events? (AGASA collaboration 1997-8)
  – LIV => high energy threshold phenomena: photon decay, vacuum Cherenkov, GZK cutoff (Coleman & Glashow 1997-8)
  – GRB and photon dispersion (Amelino-Camelia et al. 1997)
  – Framework for the violation (Colladay & Kostelecky 1998)
  – LIV and gamma-ray horizon (Kifune 1999)
  – …

LIV? New form of relativity?

- Von Ignatowsky 1911: {relativity, omogeneity/isotropy, linearity, reciprocity} => Lorentz transformations with "some" invariant c (Galilei relativity is the limit $c \rightarrow \infty$)
- CMB is kind of an aether: give away isotropy?
- QG motivation: give away linearity? (A new relativity with 2 invariants: "c" and E_P)

- In any case, let's sketch an effective theory…
  - Let's take a purely phenomenological point of view and encode the general form of Lorentz invariance violation (LIV) as a perturbation of the Hamiltonian (Amelino-Camelia+)

A heuristic approach: modified dispersion relations (perturbation of the Hamiltonian)

- We expect the Planck mass to be the scale of the effect

$$E_P = \sqrt{hc/G} \cong 1.2 \times 10^{19}\,\mathrm{GeV}$$

$$H^2 = m^2 + p^2 \rightarrow H^2 = m^2 + p^2\left(1 + \xi \frac{E}{E_P} + \ldots\right)$$

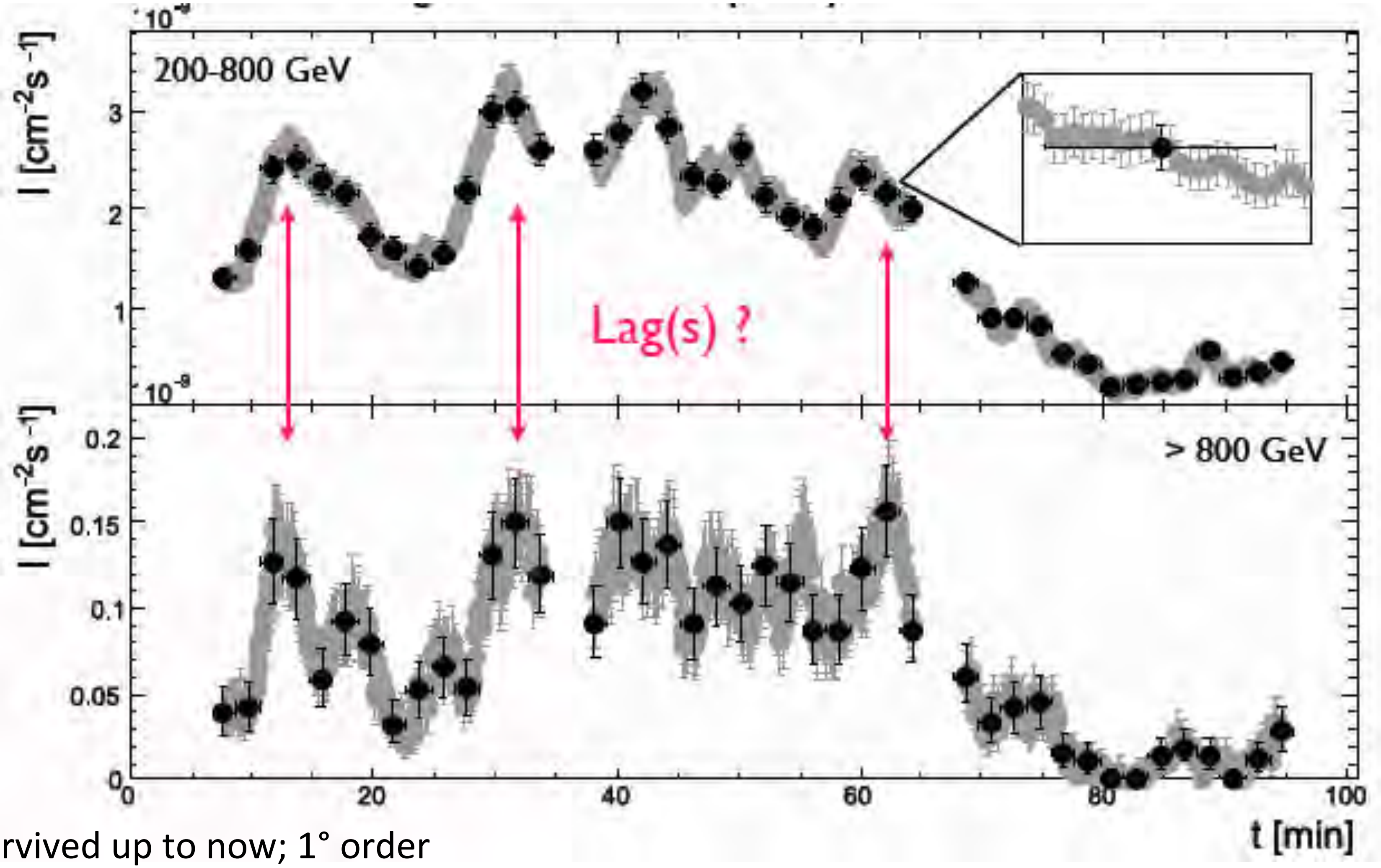
$$H \xrightarrow[p>>]{} p\left(1 + \frac{m^2}{2p^2} + \xi \frac{p}{2E_P} + \ldots\right)$$

$$v = \frac{\partial H}{\partial p} \cong 1 - \frac{m^2}{2p^2} + \xi \frac{p}{E_P} \Rightarrow v_\gamma \cong 1 + \xi \frac{E}{E_P}$$

=> effect of dispersion relations at cosmological distances can be important at energies well below Planck scale:

$$\Delta t_\gamma \cong T \Delta E \frac{\xi}{E_P}$$

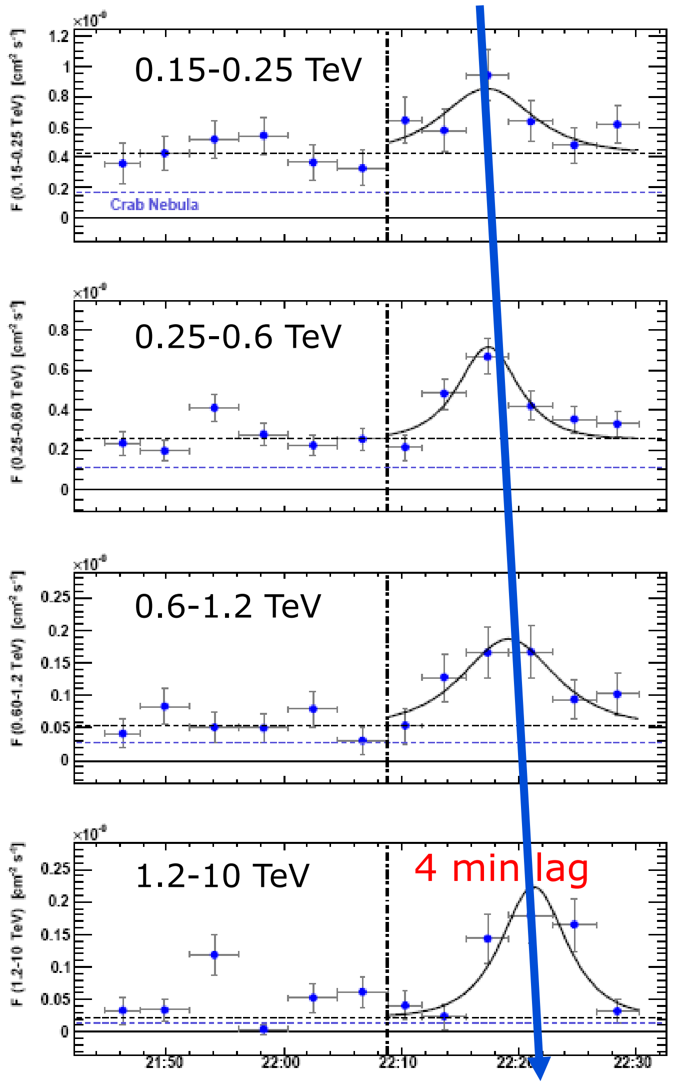
Rapid variability is the name of the game



No claim survived up to now; 1° order effects unlikely

HESS, PKS 2155

Apart from one positive claim
(MAGIC, Mkn 501 2007)
Finally interpreted as a source effect



$E_{QG,1} > 7.6\ E_P$

$E_{QG,2} > 1.3\text{x}10^{11}$ GeV

Mostly based on one GRB from Fermi

2^{nd} order? Cherenkov rules!

$$(\Delta t)_{obs} \cong \frac{3}{2}\left(\frac{\Delta E}{E_{s2}}\right)^2 H_0^{-1}\int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}}$$

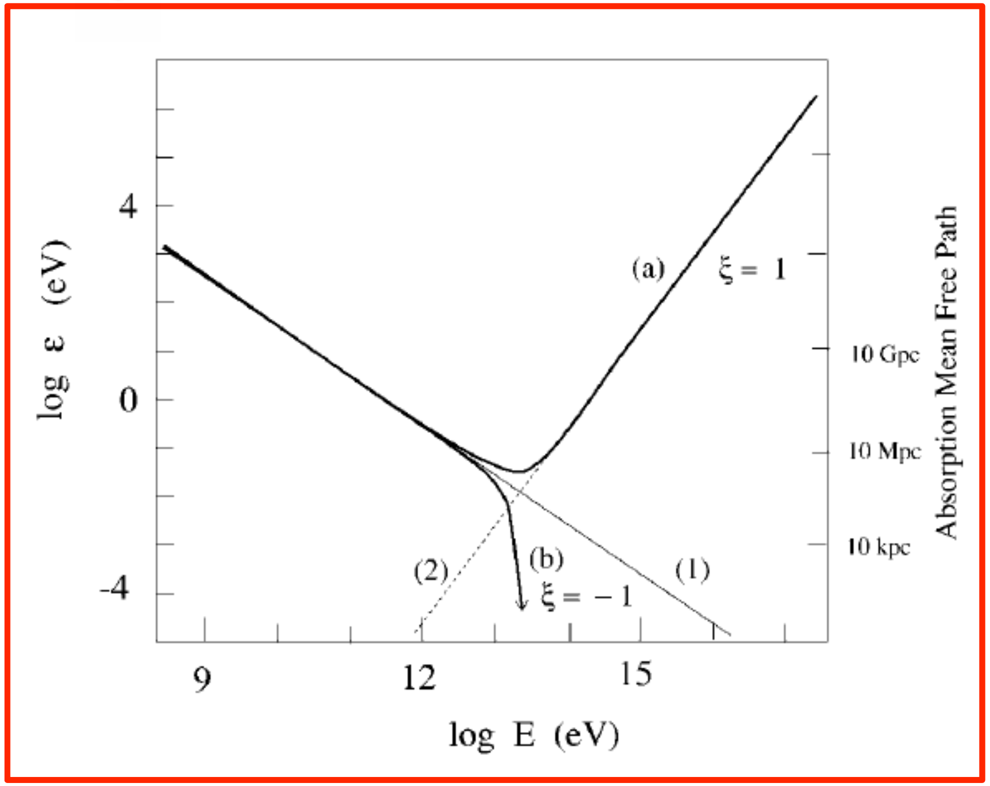
$E_{s2} > 10^{11}$ GeV (~10^{-9} M_P) (HESS, MAGIC, Fermi)

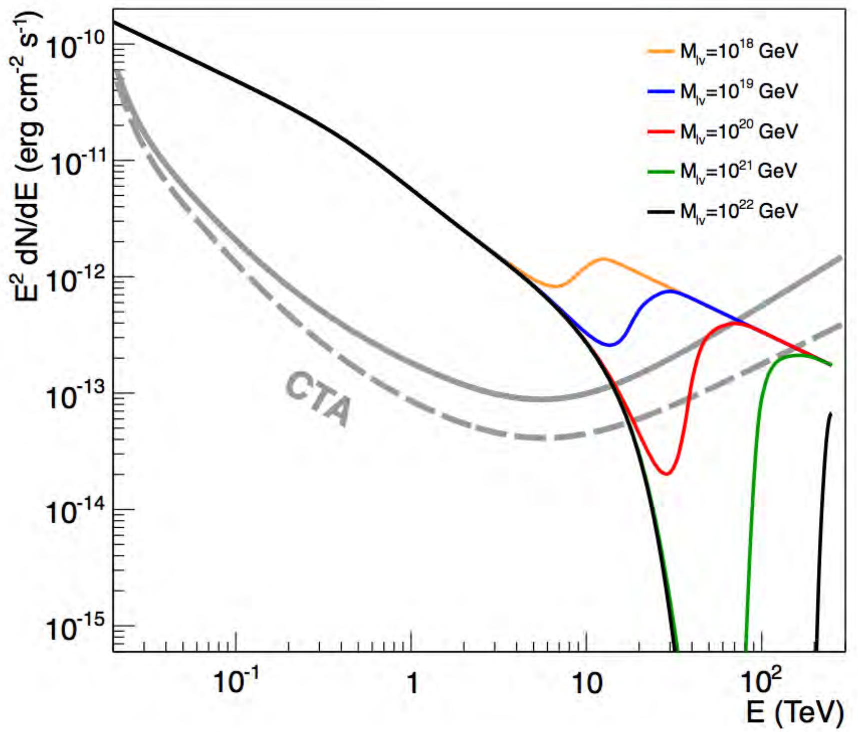
Kifune 1999: modified GRH due to LIV (increases or decreases depending on the sign of ξ)

LIV provides effective mass to photons →

$$m_\gamma^2 = \xi \frac{E_\gamma^{2+\alpha}}{E_{LIV}^{\alpha}}$$

Protheroe&Meyer, Phys.Lett.B 93 (2000)

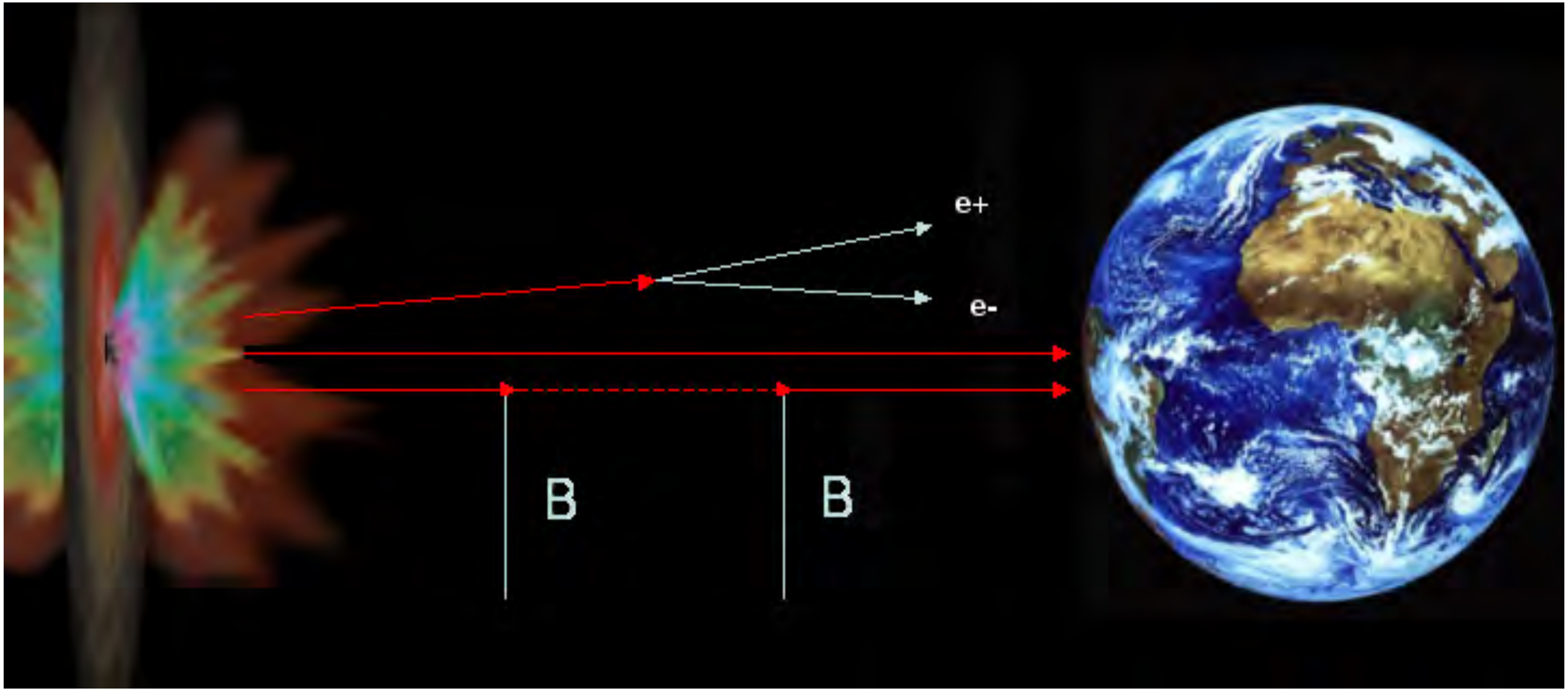




Fairbairn et al, arXiv:1401.8178 (2014)

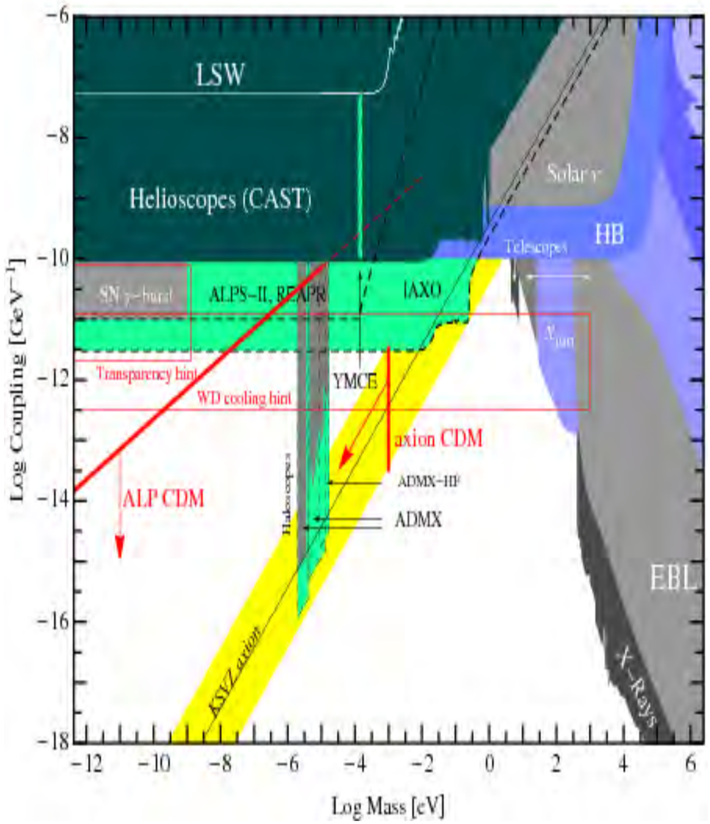
But: factorization questioned (Liberati, Sonego, …)

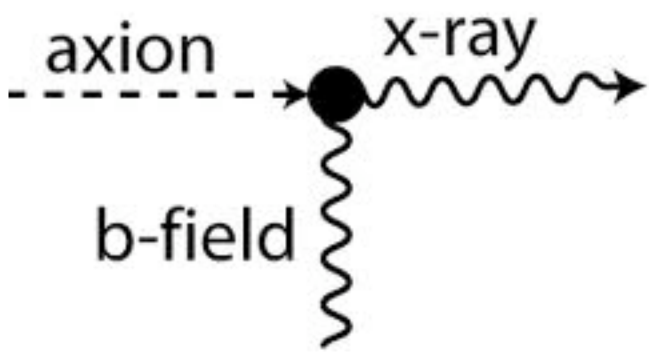
Interactions of photons with the "vacuum"



Axions and ALPs

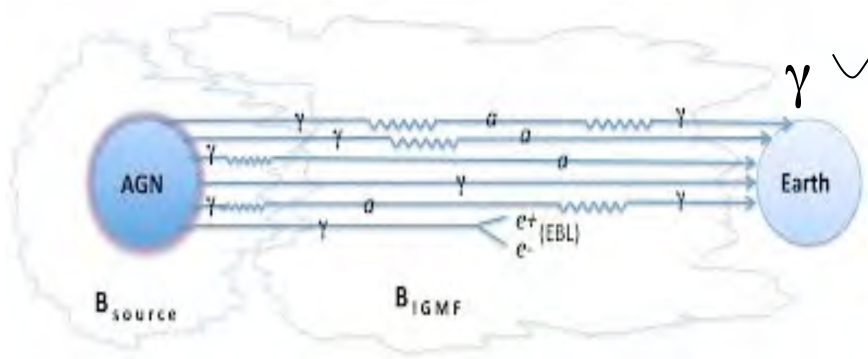
- The "strong CP problem": CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Called the "axion" from the name of a cleaning product
  - Pseudoscalar, neutral, stable on cosmological scales, feeble interaction, couples to the photon
    - Can make light shine through a wall
  - The minimal (standard) axion coupling g ∝ m; however, one can have an "ALP" in which g = 1/M is free from m
- m_a < 0.02 eV (direct searches)
- g < 10^{-10} GeV^{-1} from astrophysical bounds
- Production is not thermal, and it might be cold (ALPs can be a DM candidate)

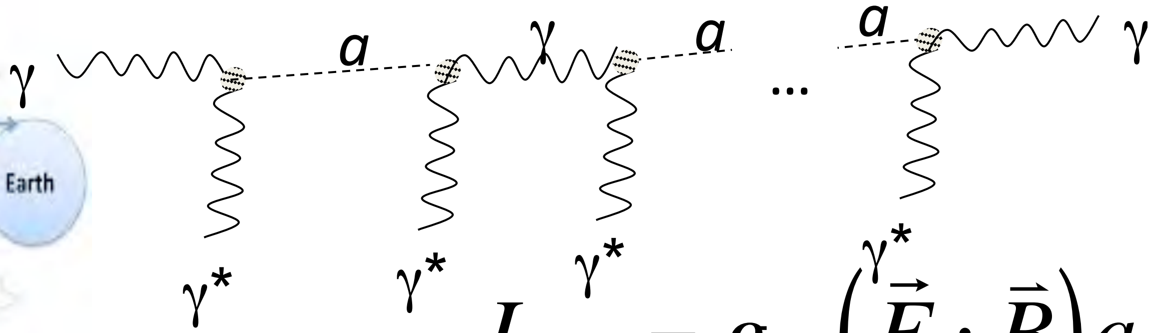




$$\frac{m}{1\,\text{eV}} \simeq \frac{1}{M/6\times 10^6\,\text{GeV}}$$

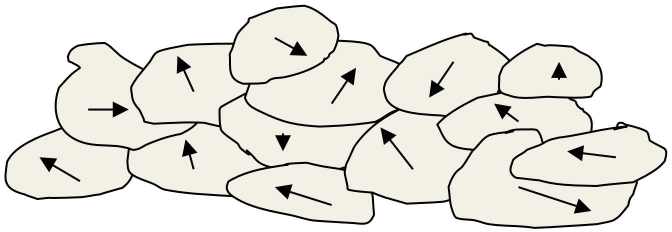
The photon-axion mixing mechanism





$$L_{a\gamma\gamma} = g_{a\gamma}\left(\vec{E}\cdot\vec{B}\right)a$$

- Magnetic field 1 nG < B < 1fG (AGN halos). Cells of ~ 1 Mpc

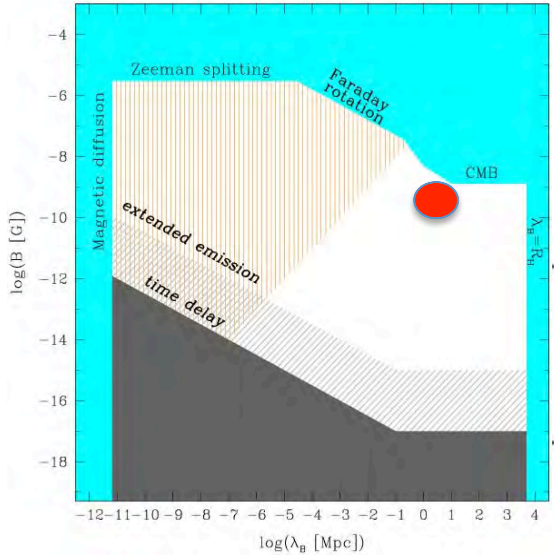


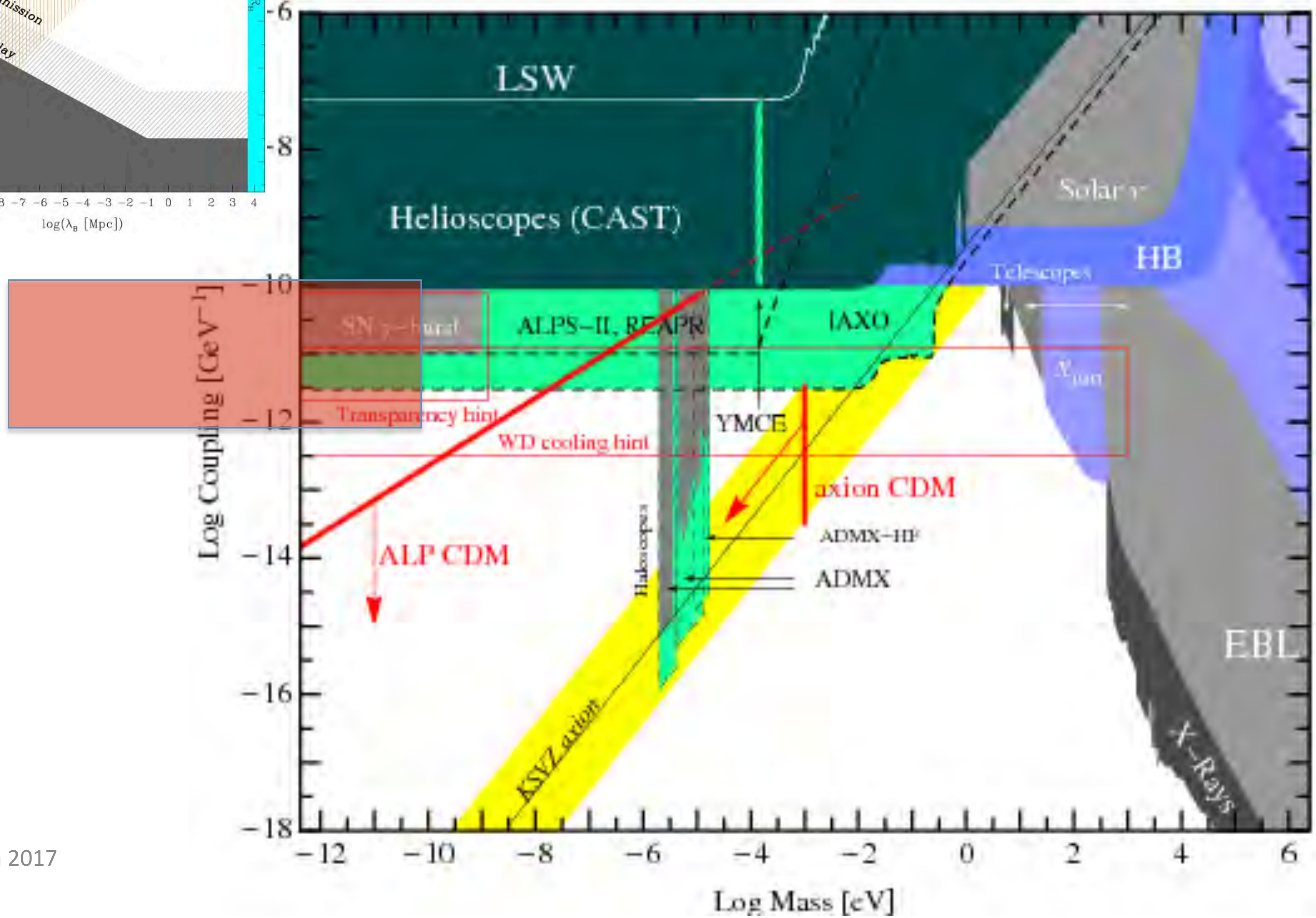
$$P_{\gamma\to a} \approx NP_1$$

$$P_1 \approx \frac{g_{a\gamma}^2 B_T^2 s^2}{4} \approx 2\times 10^{-3}\left(\frac{B_T}{\text{1nG}}\frac{s}{\text{1Mpc}}\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2$$

- Photons-ALP mixing could enhance the transparency of the Universe:
  - Photon/ALP mixing in the intergalactic space (DA, Roncadelli & MAnsutti [DARMA], PRD2007)
  - Conversion into axion at the source, reconversion in the Milky Way (Hooper, Simet, Serpico 2008)Axion emission (Simet+, PRD2008)
  - A combination of the above

Regions of sensitivity for HE astrophysical observations



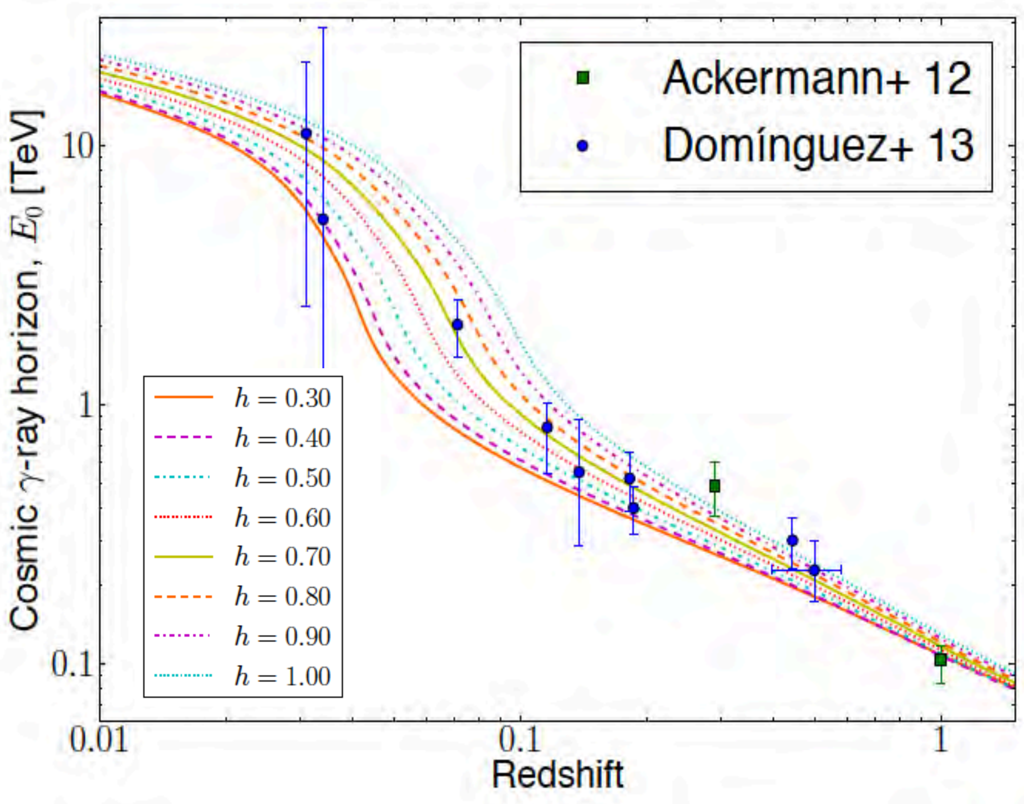


A win-win game: if no anomalous physics, determination of cosmological parameters

- Fluxes of VHE photons reaching the Earth have been attenuated due to the EBL density from observed spectra

⟹ Determine cosmological constants from observed HE spectra vs. fitted from lower energy

(Blanch & Martinez 2005; Dominguez & Prada 2013)



Cosmology

$$\tau(E,z) = \int_0^z \left(\frac{dl}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{th}}^{\infty} d\varepsilon' \; \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

$$\left|\frac{dt}{dz'}\right| = \frac{1}{H_0(1+z')E(z')}$$

$$E(z') \equiv \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$

Summary on exotic physics from photon propagation

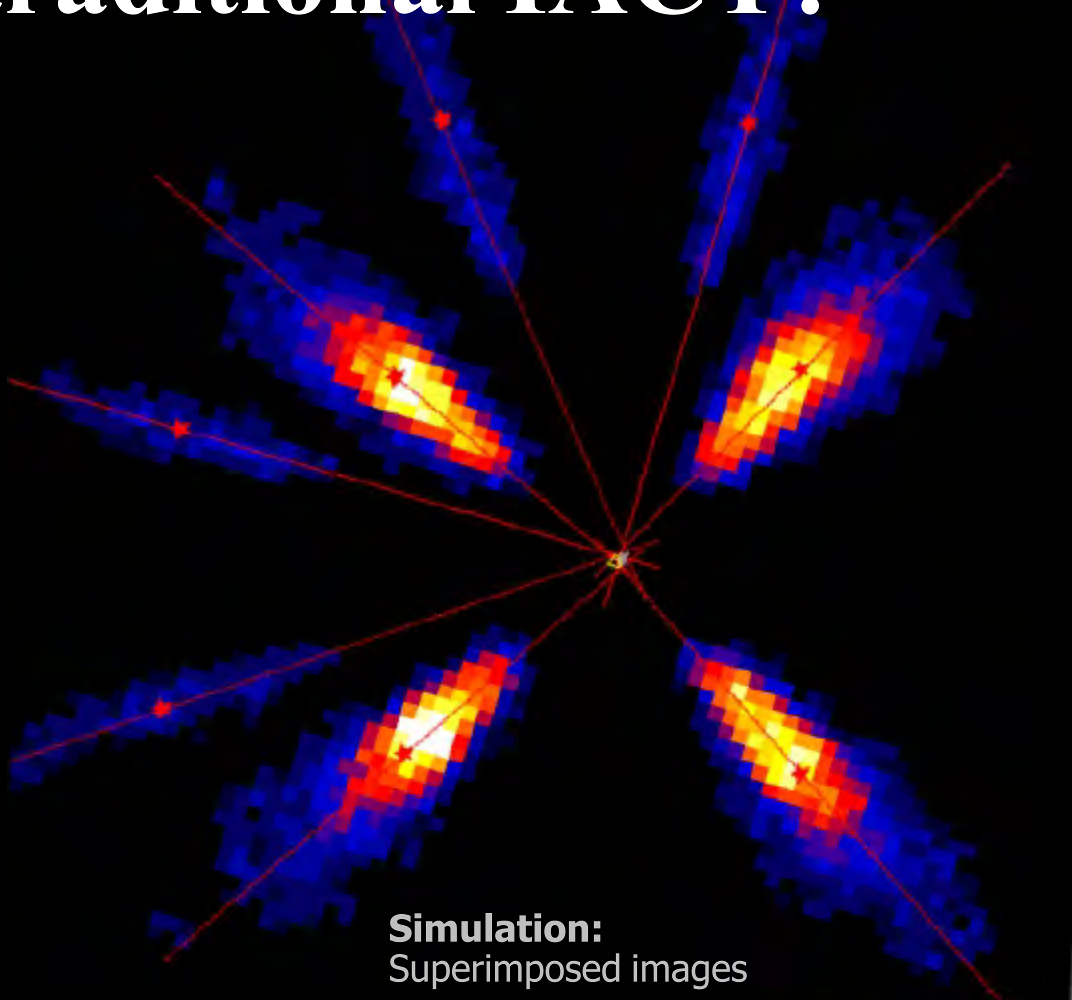
- We set significant limits on Lorentz invariance violation
- We set significant limits (and a hint of very low mass?) on axion-like particles

The FUTURE
The TeV gamma region: CTA

The 20 GeV- 100 TeV region: how to do better with traditional IACT?

- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power

☛ The CTA solution: More telescopes !



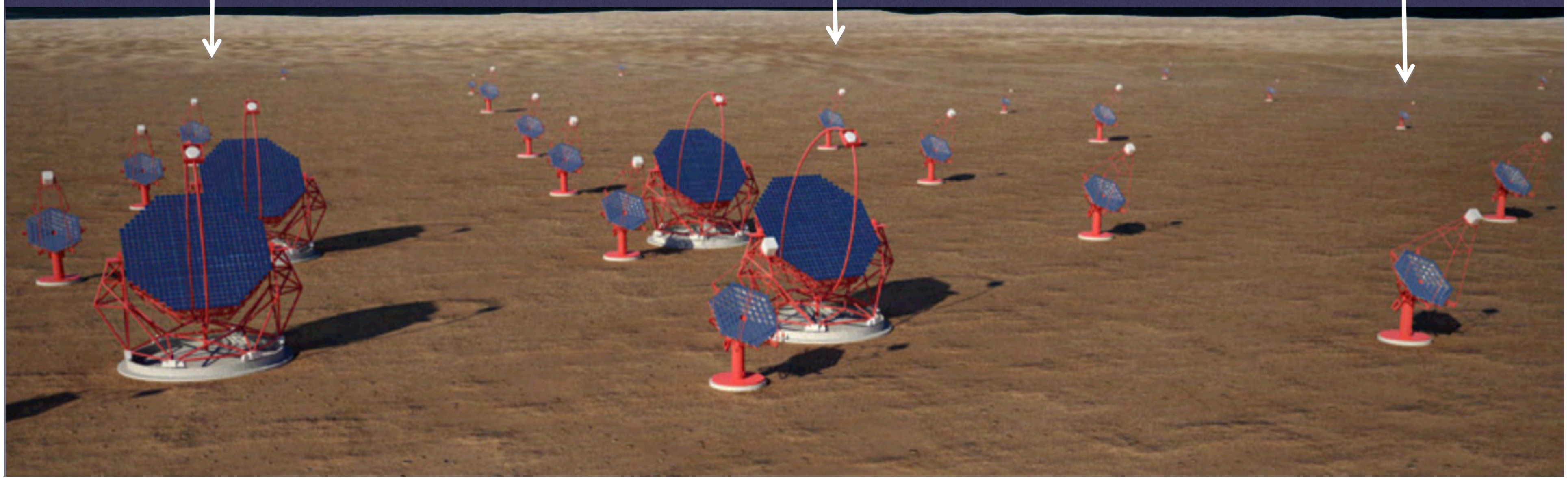
Simulation: Superimposed images from 8 cameras

What is CTA? A multi-telescope Cherenkov array

Low energies
Energy threshold 20 GeV
23 m diameter
4 telescopes
(LST)

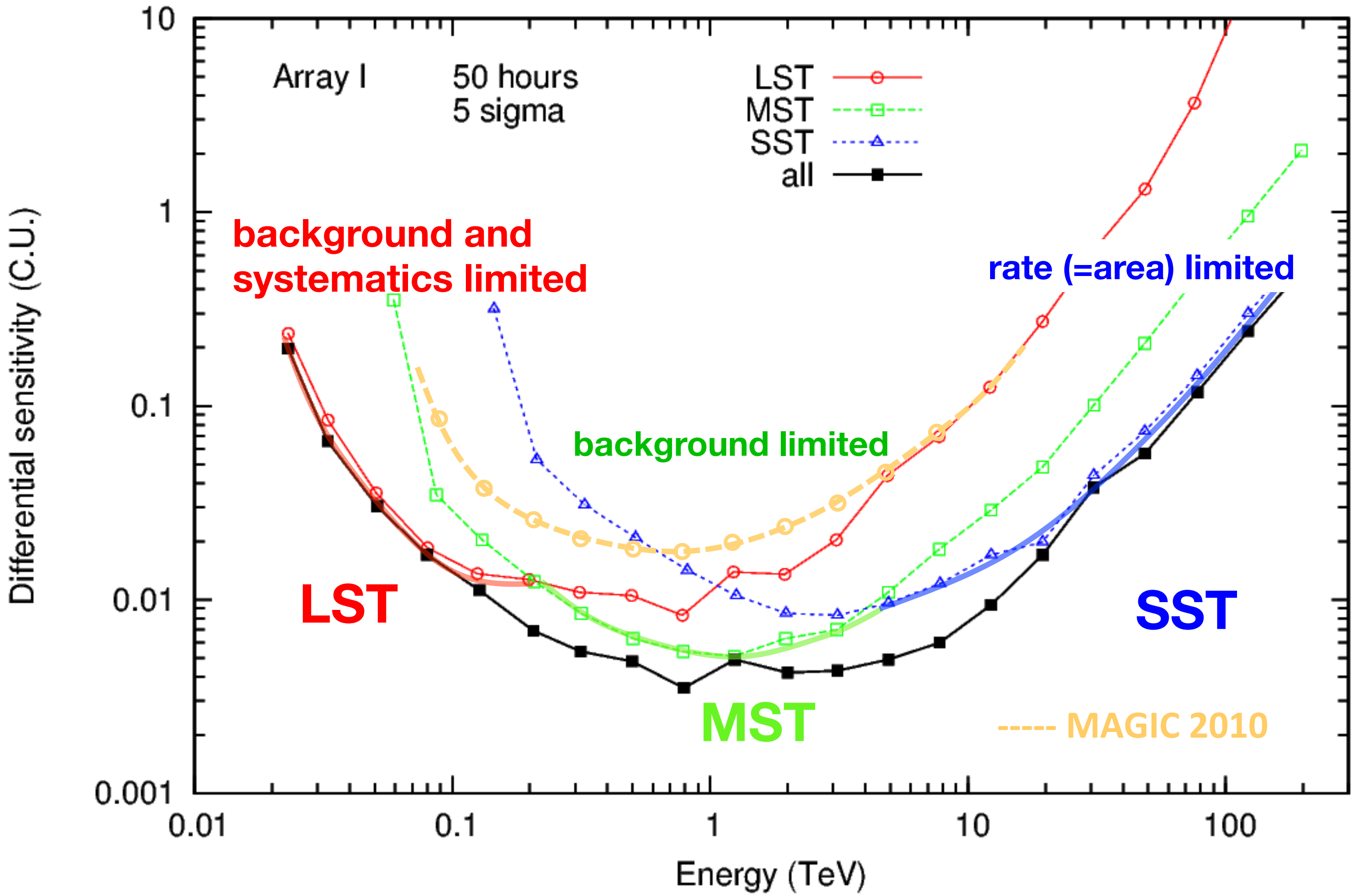
Medium energies (MST)
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
up to 24 dual-mirror telescopes
mCrab sensitivity in 50h at 0.1-10 TeV

High energies
10 km^2 area at few TeV
4 to 6 m diameter
70 telescopes
(SST)

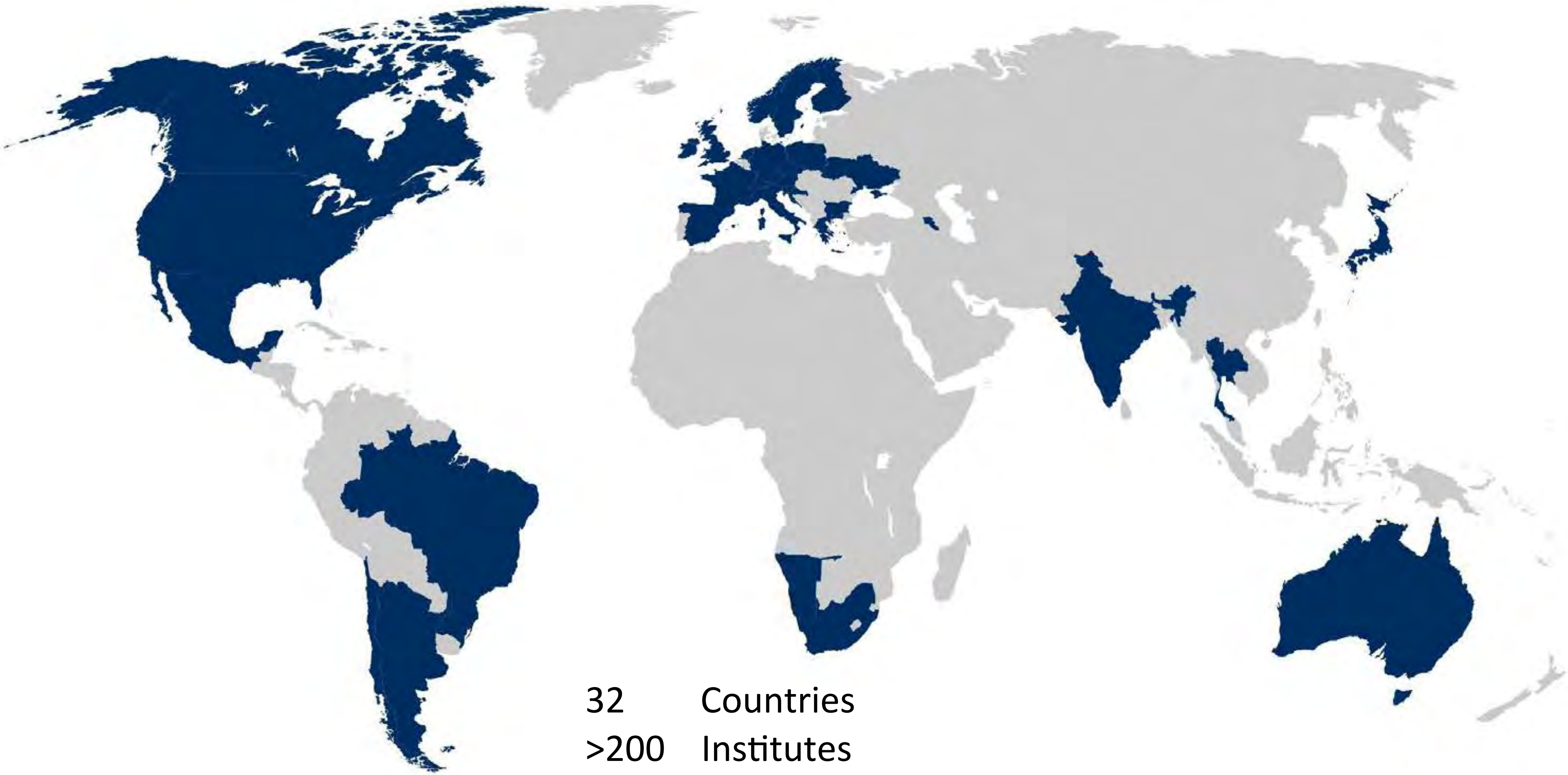


CTA sensitivity in units of Crab flux

for 5 σ detection & $N_\gamma > 10$ in each 0.2-dex bin in E, in 50 h



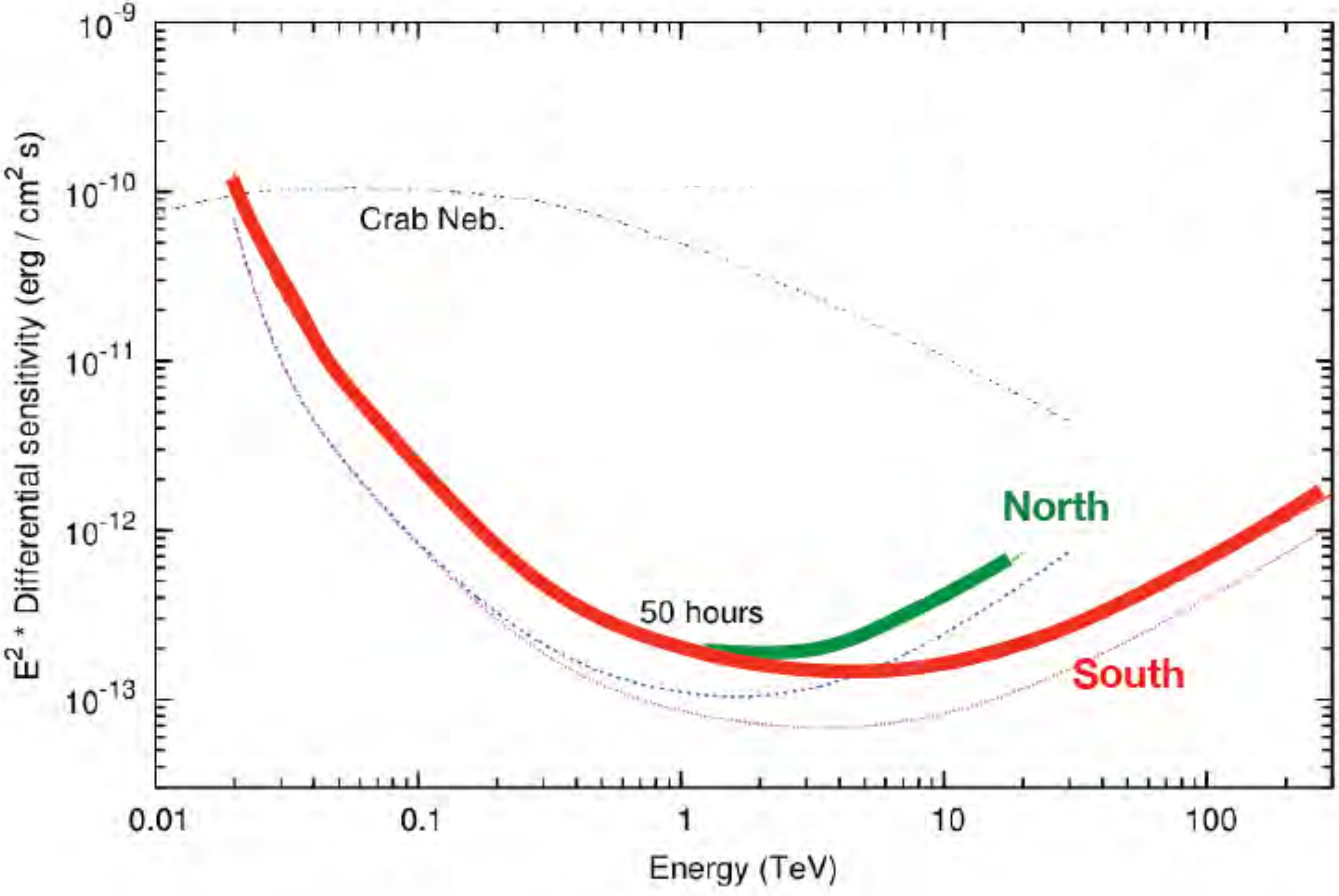
CTA consortium: a world-wide effort



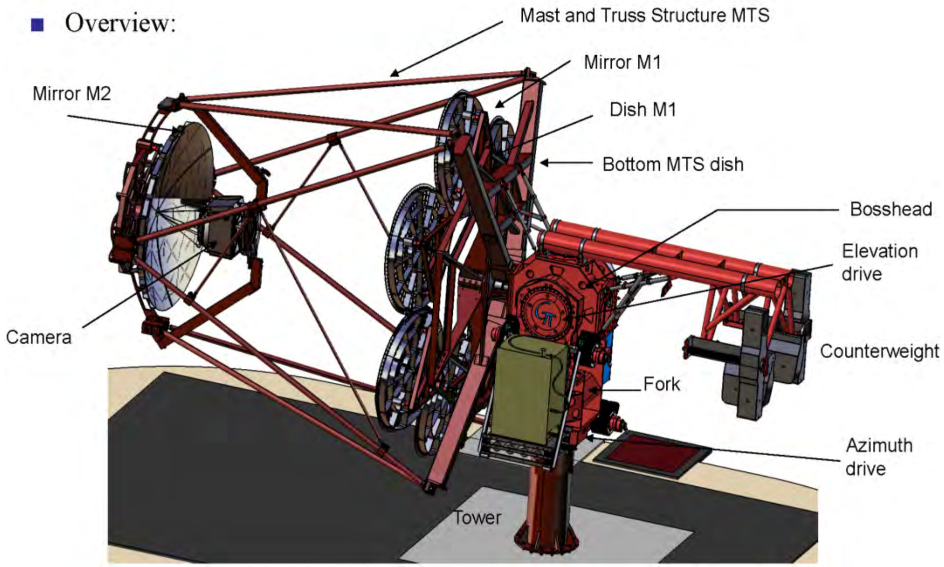
32 Countries
>200 Institutes
>1500 Members

All-sky coverage: two observatories

Sensitivity for North and South

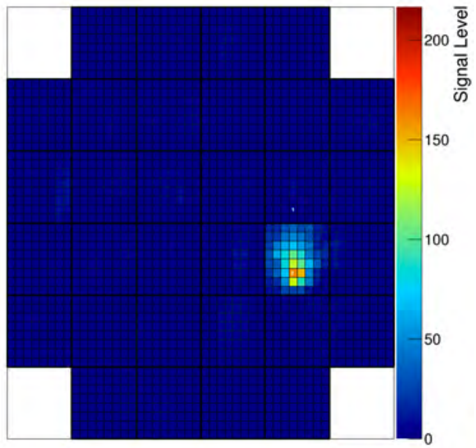


Small Telescope 2-mirror (SST-2M)



SST-2M –ASTRI MECHANICAL PROTOTYPE
INAUGURATION, 24 SEPT 2014
(SERRA LA NAVE, SICILY)

SST-2M-GCT (GATE TELESCOPE)
INAUGURATED IN JUNE 2016
SAW ALREADY 1ST LIGHT



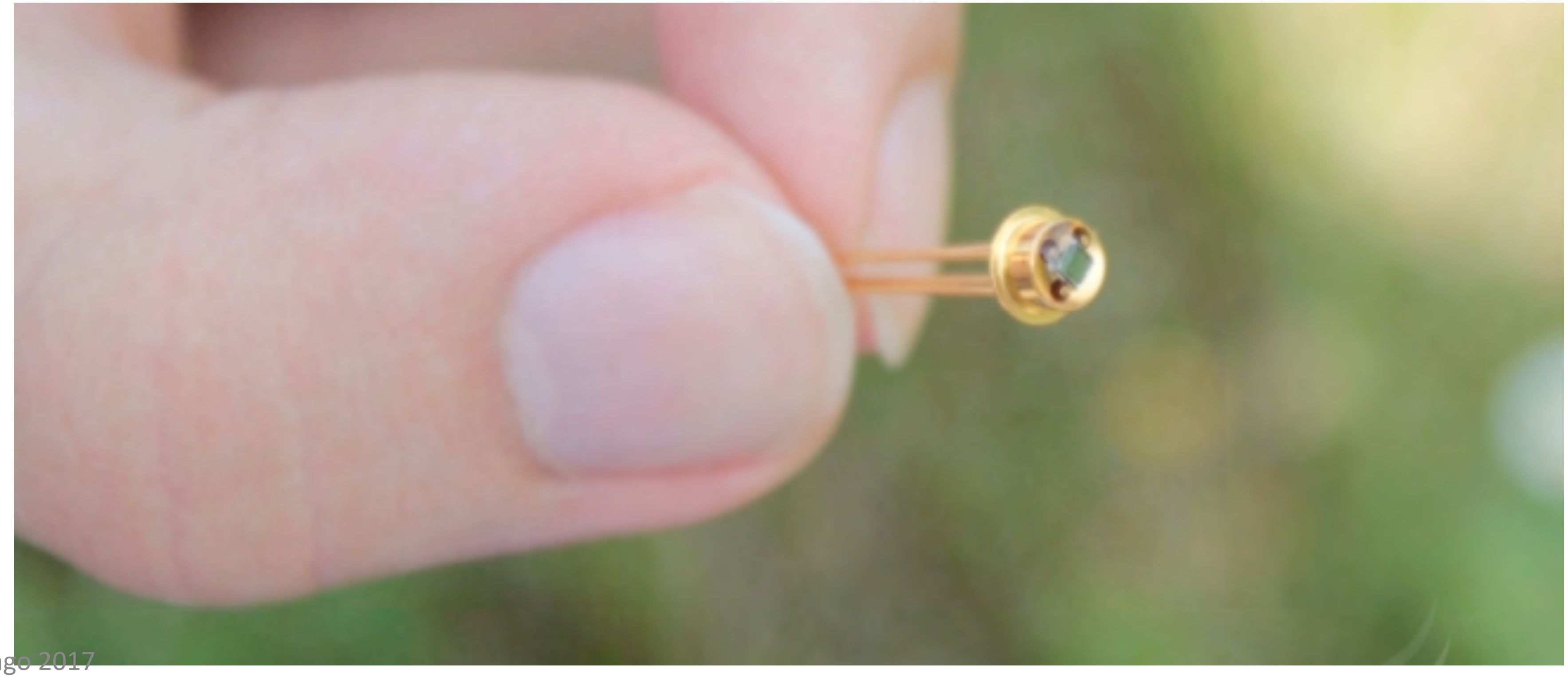
BOTH 2-MIRROR SST DESIGNS: COMPACT,
SILICON-PM CAMERAS

SiPM: the technological challenge for small cameras

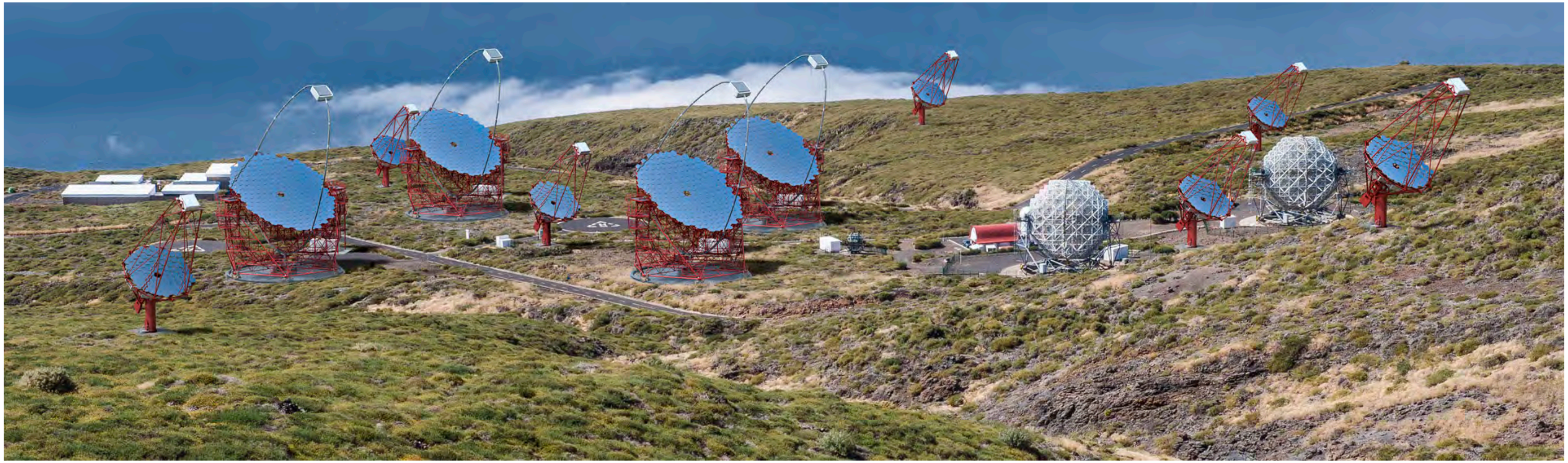
Cameras need high granularity, and typical PMT size of 5-6 mm

Difficult to do with standard PMT

New detectors (SiPM) under development

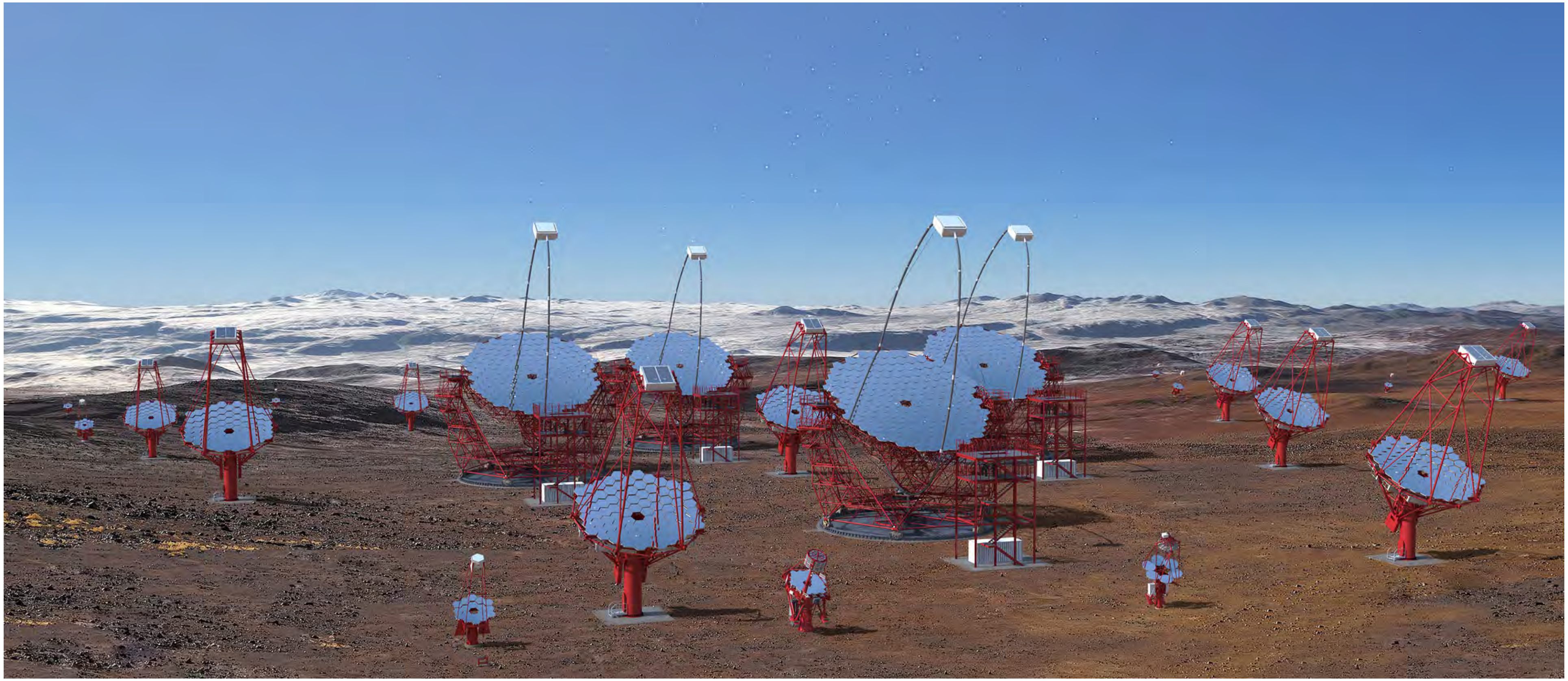


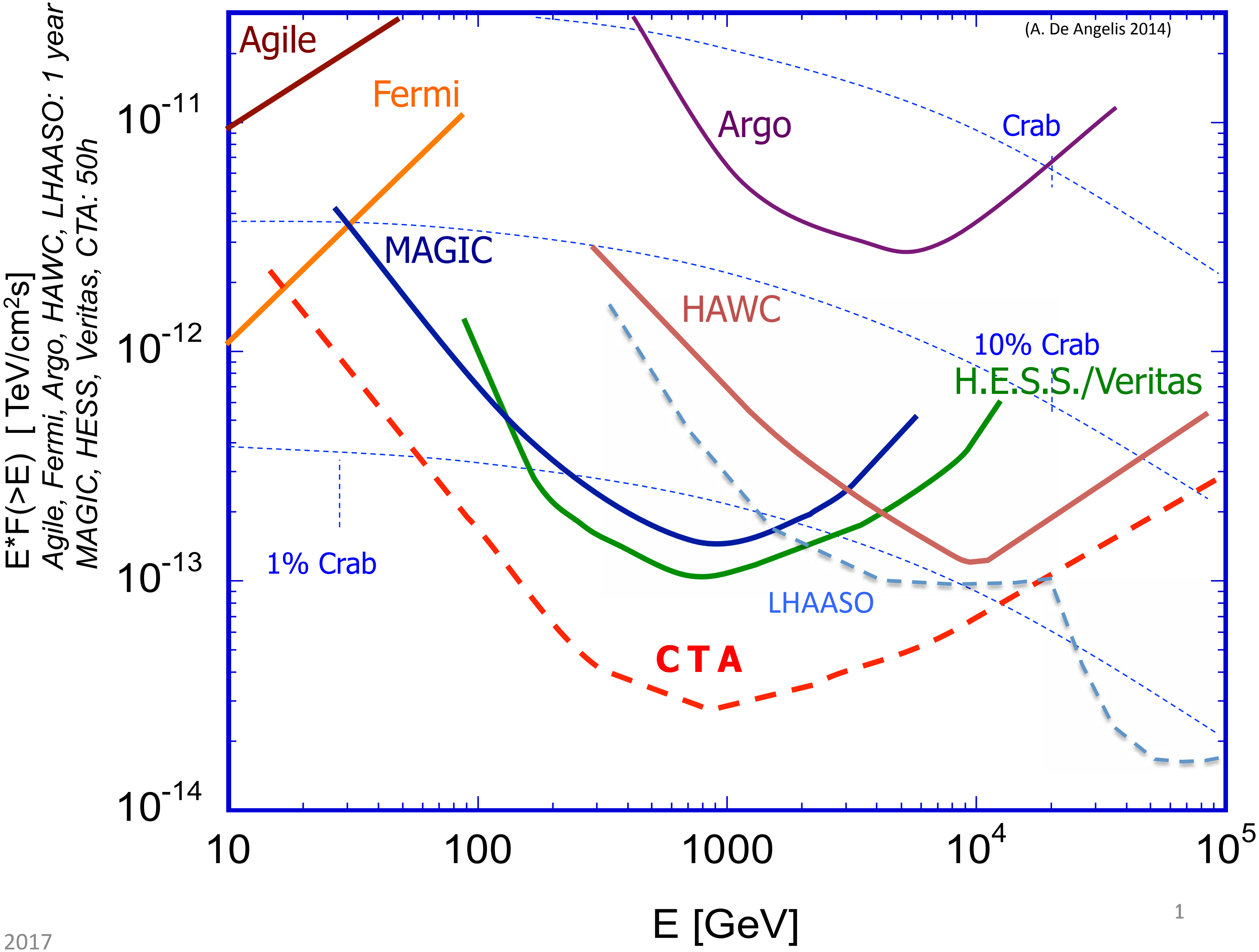
CTA-N: rendering

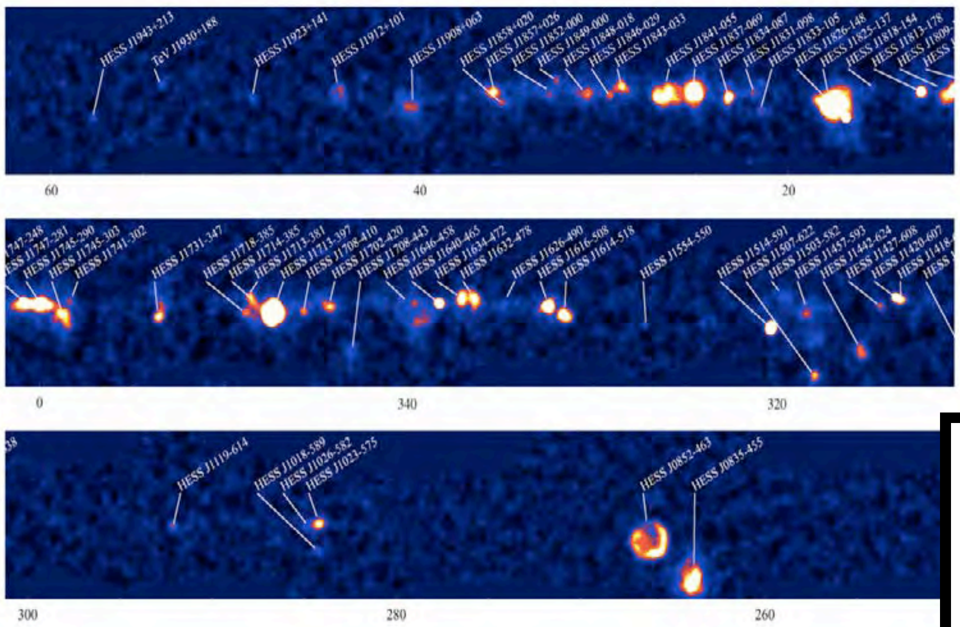


LST1 to be commissioned in 2018 (inauguration July 2018?)
LST2-4 commissioned in 2020?
First 5 MST commissioned in 2022?

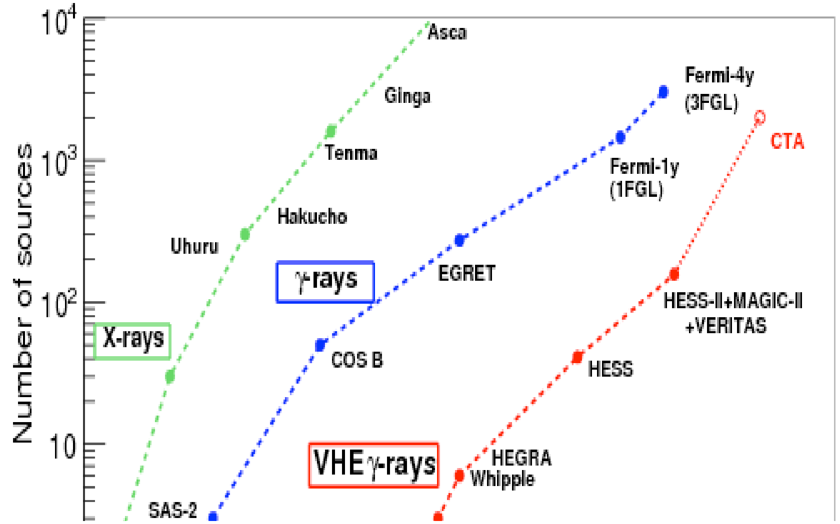
CTA-S in Paranal: rendering (works starting in 2018?)

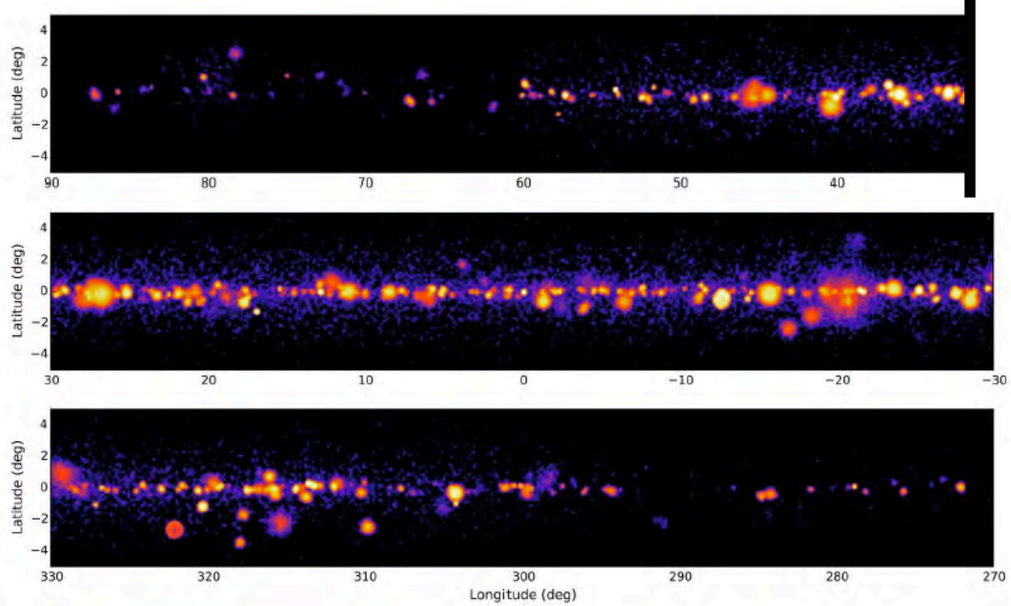



E*F(>E) [TeV/cm2s]
Agile, Fermi, Argo, HAWC, LHAASO: 1 year
MAGIC, HESS, Veritas, CTA: 50h
(A. De Angelis 2014)
Agile
Fermi
Argo
Crab
MAGIC
HAWC
10% Crab
H.E.S.S./Veritas
1% Crab
LHAASO
CTA
10-11
10-12
10-13
10-14
10
100
1000
104
105
E [GeV]



Huge physics case for CTA



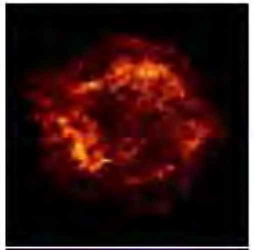


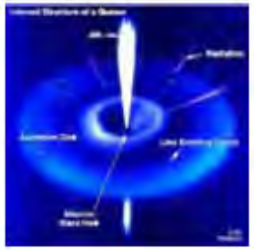
Guaranteed Science with CTA

An advanced Facility for ground-based gamma-ray Astronomy

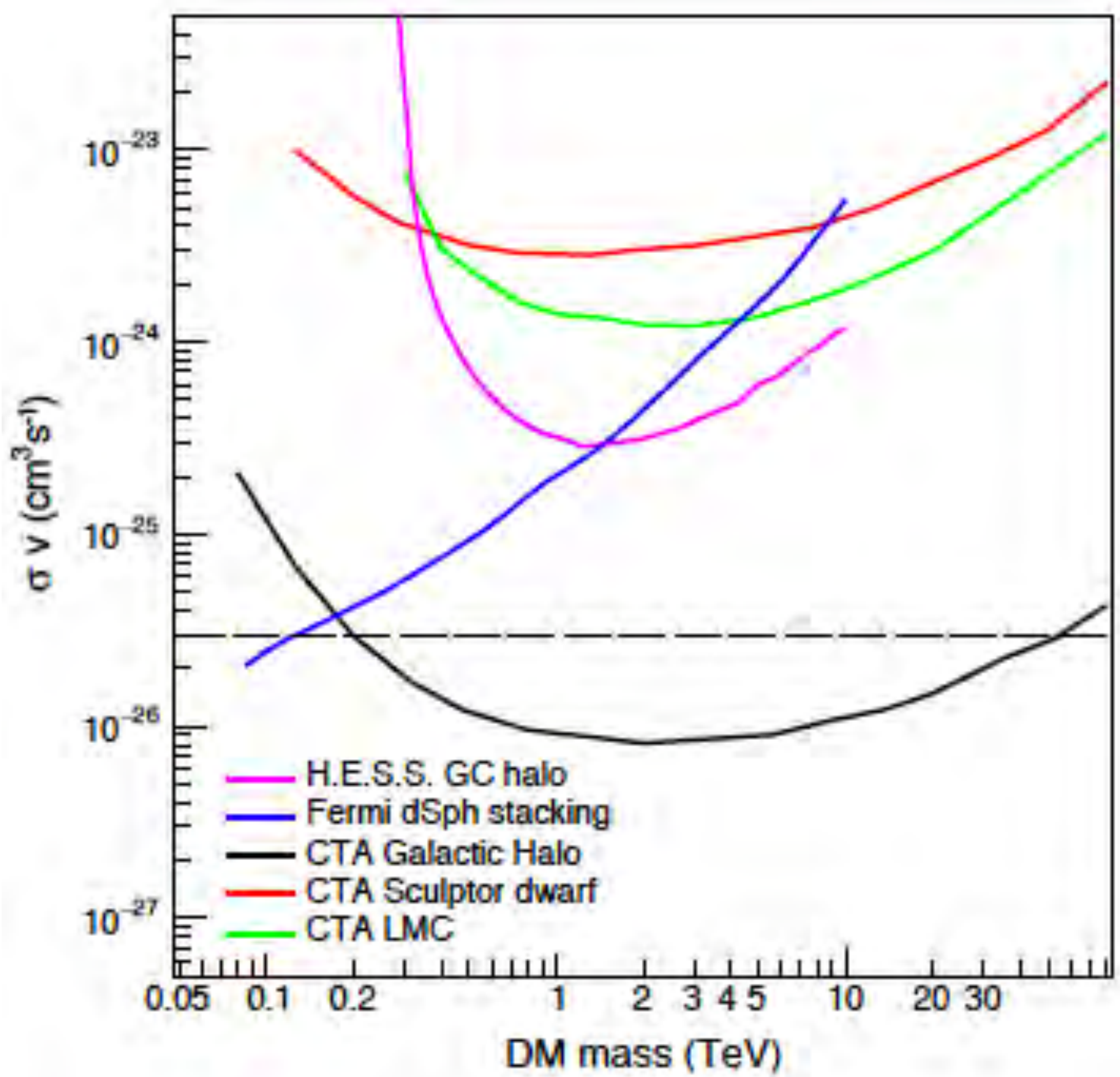
~200 -> ~2000 sources above 100 GeV

- Study of sources and propagation of high energy particles in the Cosmos, on scales ranging from compact objects to large scale structures
  - Pulsars
  - Pulsar wind nebulae
  - Stellar winds
  - Supernova remnants
  - Diffuse emission
  - Galactic center region
  - Starburst galaxies
  - Clusters of galaxies
- Black holes and their environment
  - Stellar-mass black holes
  - Supermassive black holes



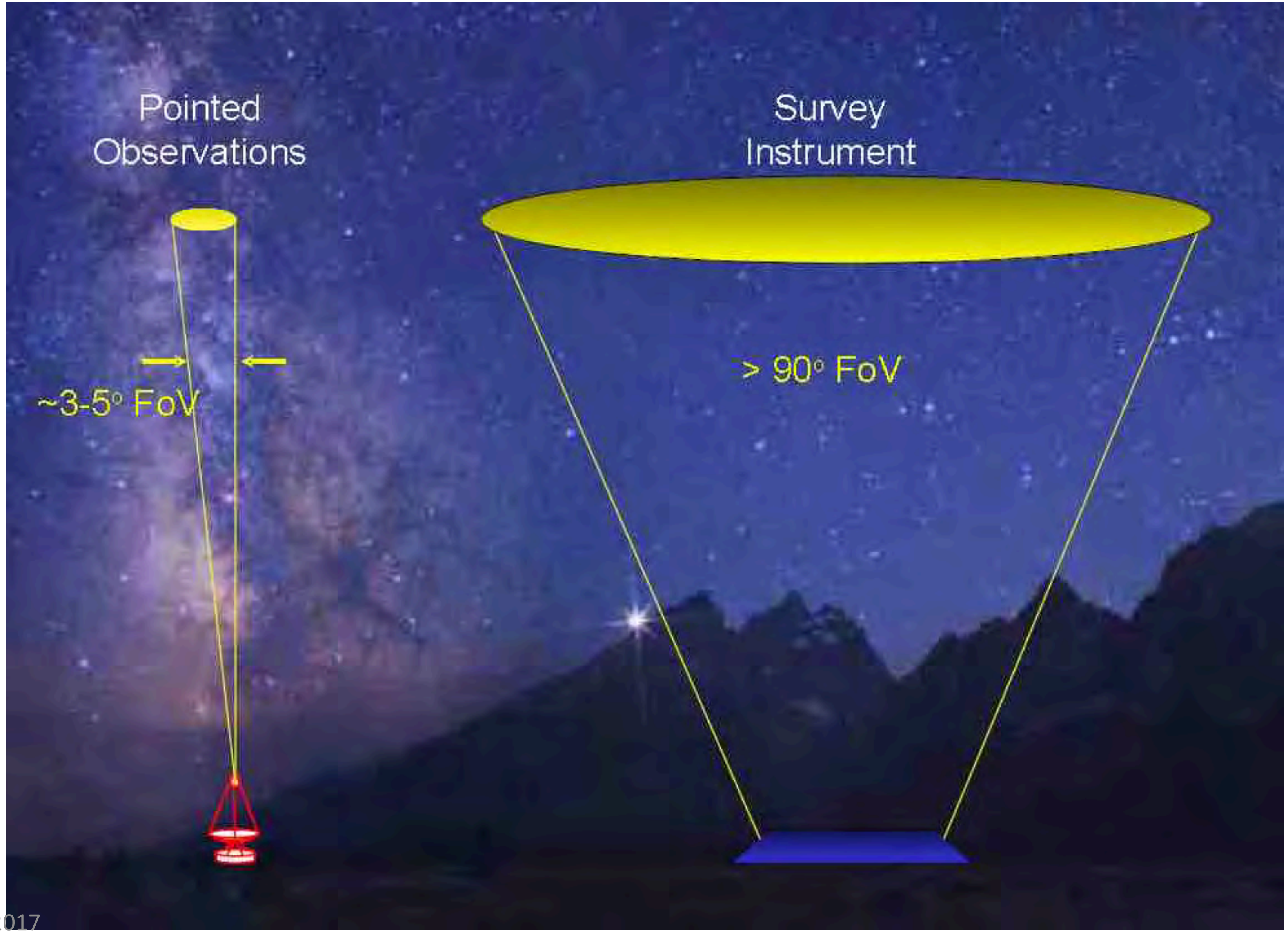



Dark matter



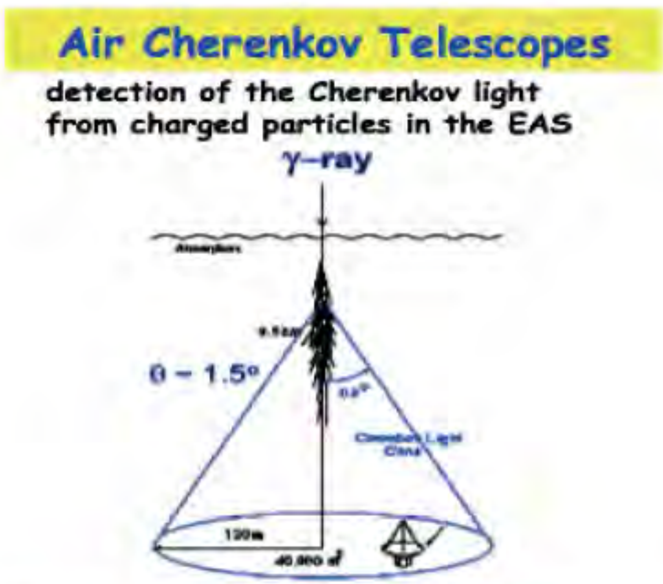
CTA Science Book,
To appear in IJMP

Cherenkov vs. EAS

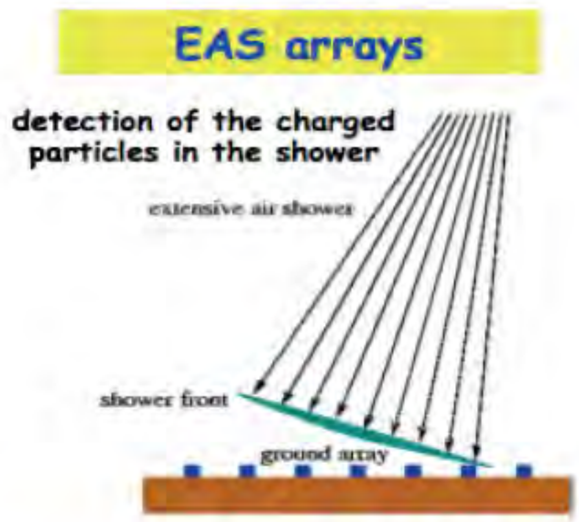


EAS-type designs (serendipity => GRB, unexpected…)

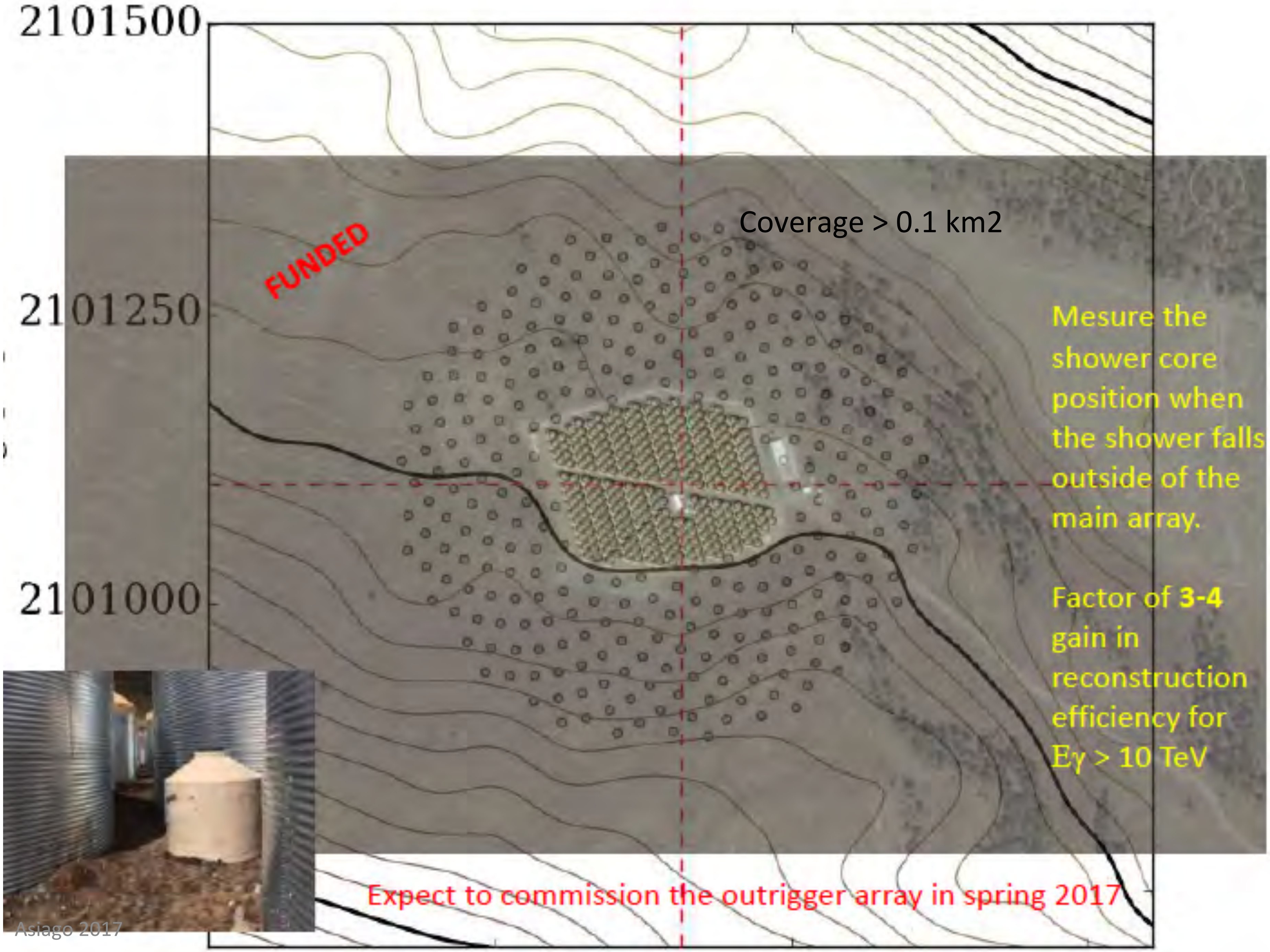
- CTA can be non optimal for PeV detection
- EAS can be the key for Pevatron studies



Very low energy threshold (≈50 GeV)
Excellent bkg rejection (>99%)
Excellent angular resolution (≈0.05 deg)
Good energy resolution (≈15%)
High Sensitivity (< % Crab flux)
Low duty-cycle (≈10%)
Small field of view (4-5 deg)



Higher energy threshold (≈300 GeV)
Good bkg rejection (>80%)
Good angular resolution (0.2-0.8 deg)
Modest energy resolution (≈50%)
Good Sensitivity (5-10% Crab flux)
High duty-cycle (≈100%)
Large field of view (≈2 sr)



2101500
2101250
2101000
FUNDED
Coverage > 0.1 km2
Mesure the shower core position when the shower falls outside of the main array.
Factor of **3-4** gain in reconstruction efficiency for Eγ > 10 TeV
Expect to commission the outrigger array in spring 2017
Asiago 2017

The LHAASO project

The Large High Altitude Air Shower Observatory (LHAASO) project is a new generation all-sky instrument to perform a combined study of cosmic rays and gamma-rays in the wide energy range 10^{11} -- 10^{17} eV.

The experiment will be located at 4300m asl (606 g/cm^2) in the Sichuan province

1 KM2A:
5635 EDs
1221 MDs

WFCTA:
24 telescopes
1024 pixels each

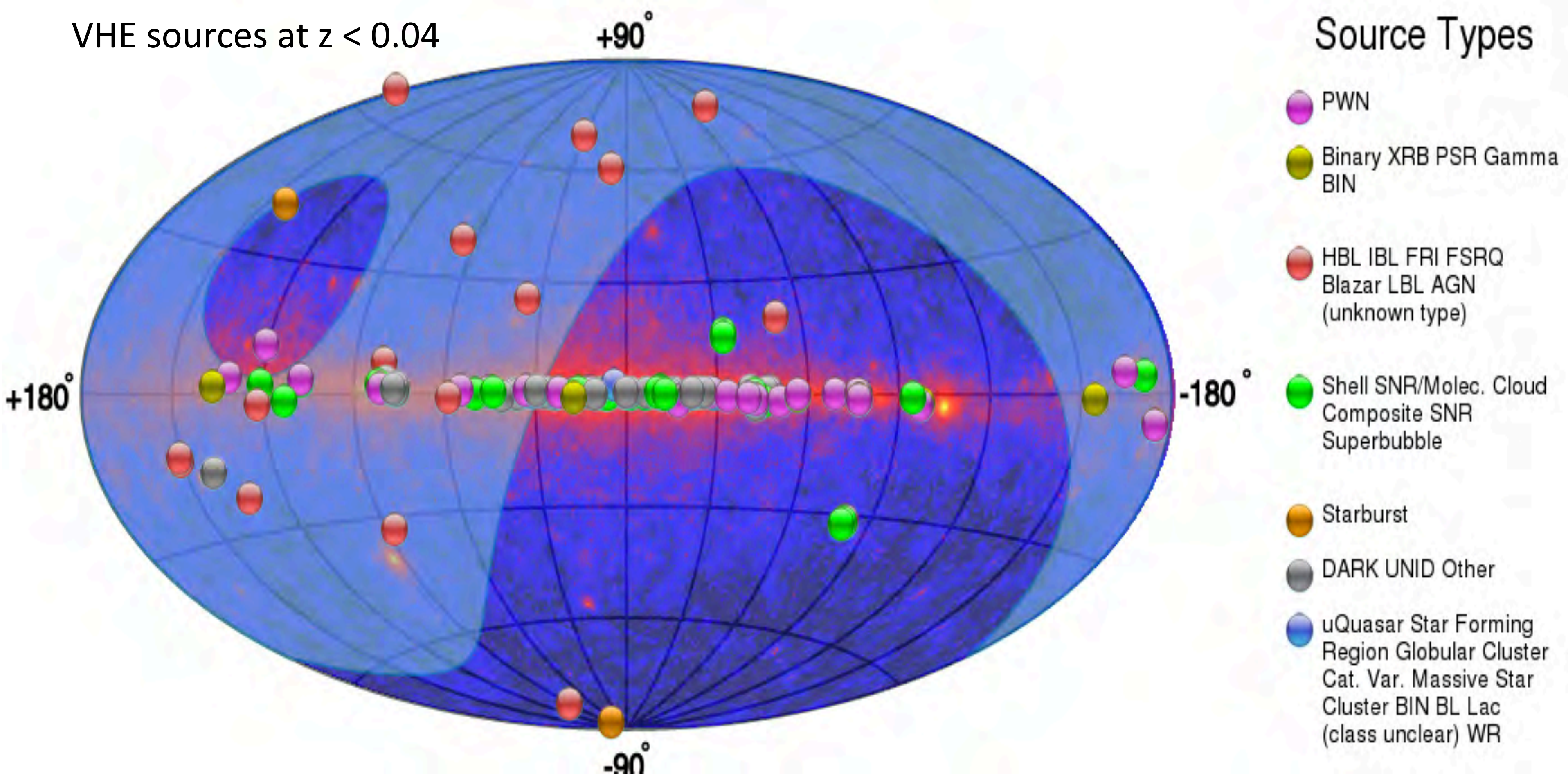
WCDA:
3600 cells
90,000 m^2

SCDA:
452 detectors

Coverage area: 1.3 km^2

HAWC+, LHAASO, HiSCORE ~ funded, but there is a strong case for a sub-PeV experiment in the Southern hemisphere

VHE sources at z < 0.04



HAWC South

- 3rd generation water Cherenkov detector
- higher altitude, more sensitive than HAWC
- for example at the Alma site at 5,000 masl

Large Array Telescope for Tracking Energetic Sources (LATTES)

- Instrument a large area with closed-loop RPCs
  - Under test (MARTA)
- and Cherenkov tanks
  - Cherenkov can be water or glass, under test (CESAR)

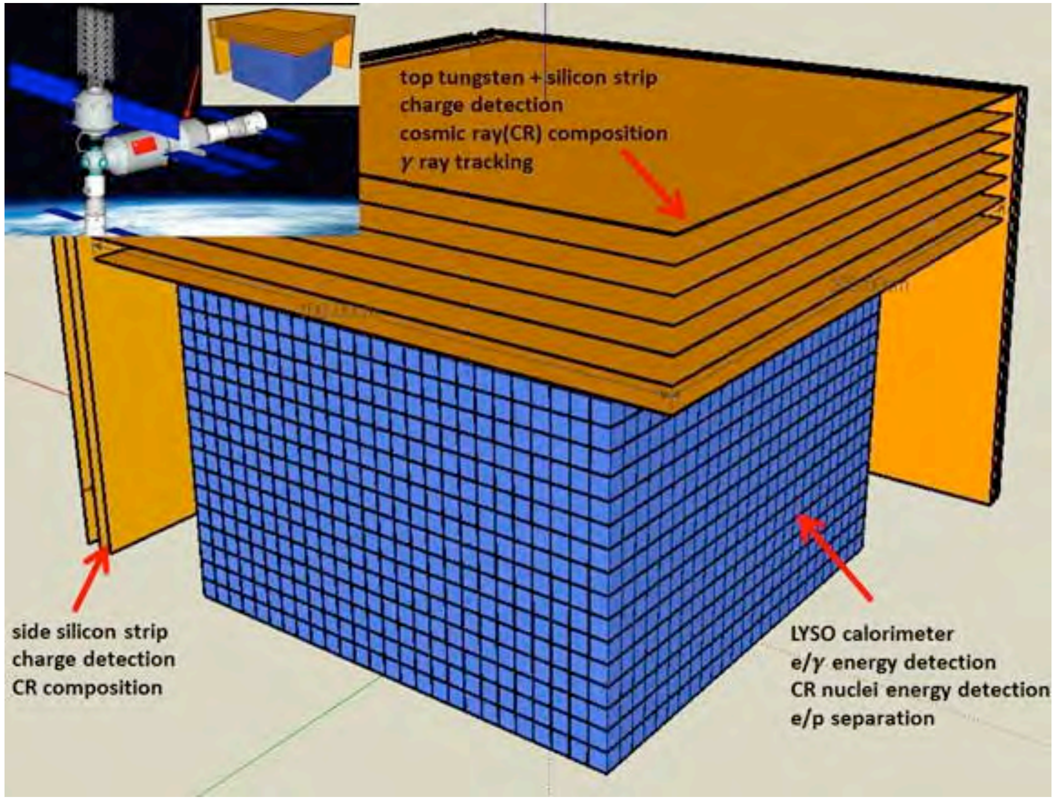
- Proposal by CBPF Rio, LIP Lisboa, Univ. Padova & Udine (2014; to be reiterated in 2017)

- Possible sites
  - Argentina
  - Bolivia (Chacaltaya site, latitude 16.3 S, altitude 5200 m asl)
  - Chile (Atacama destert, latitude 23.7 S, altitude 5060 m asl)

LOWER ENERGIES (GeV and MeV)

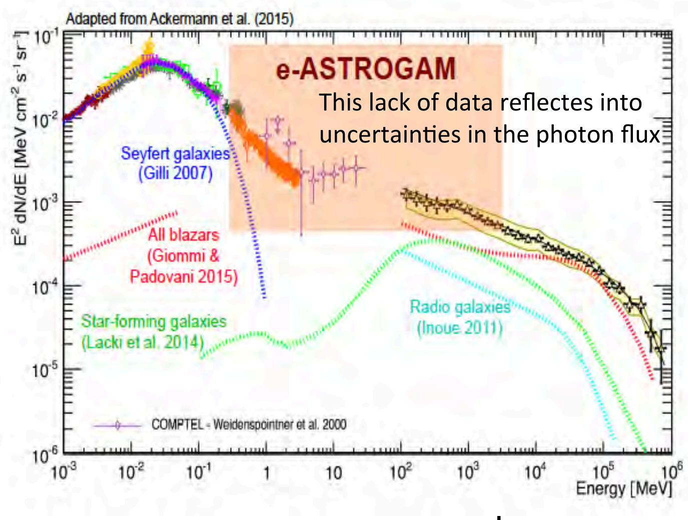
GeV region from space

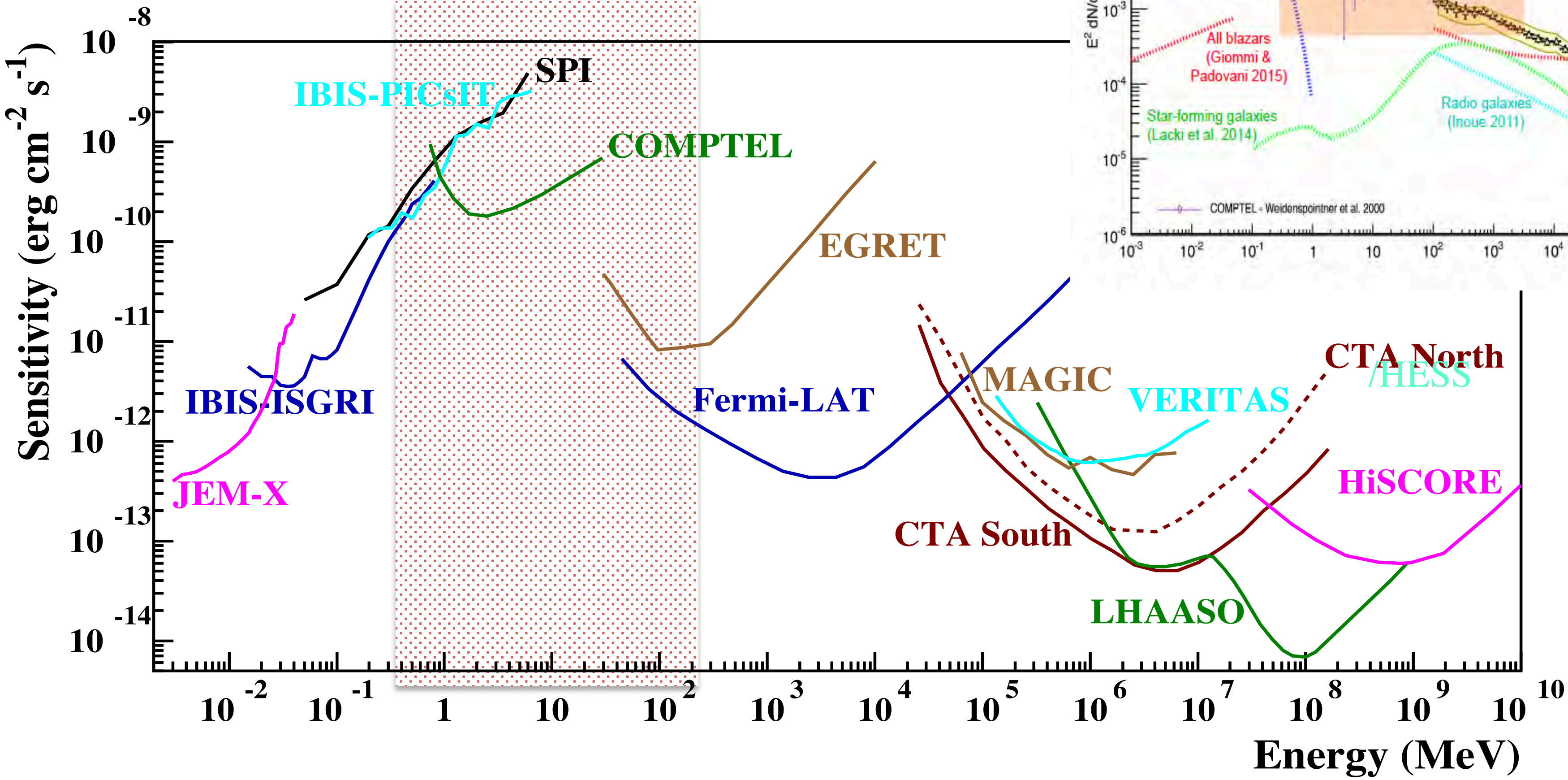
- Fermi can fly till 2028 (granted till 2020)
- Difficult to find a successor…
- Only one super-Fermi project on the field: the Chinese-Italian HERD
  - A Fermi with better calorimetry
  - A few years after the CSS
  - Approved in 2017



- Also useful for observing charged cosmic rays up to ~ the knee

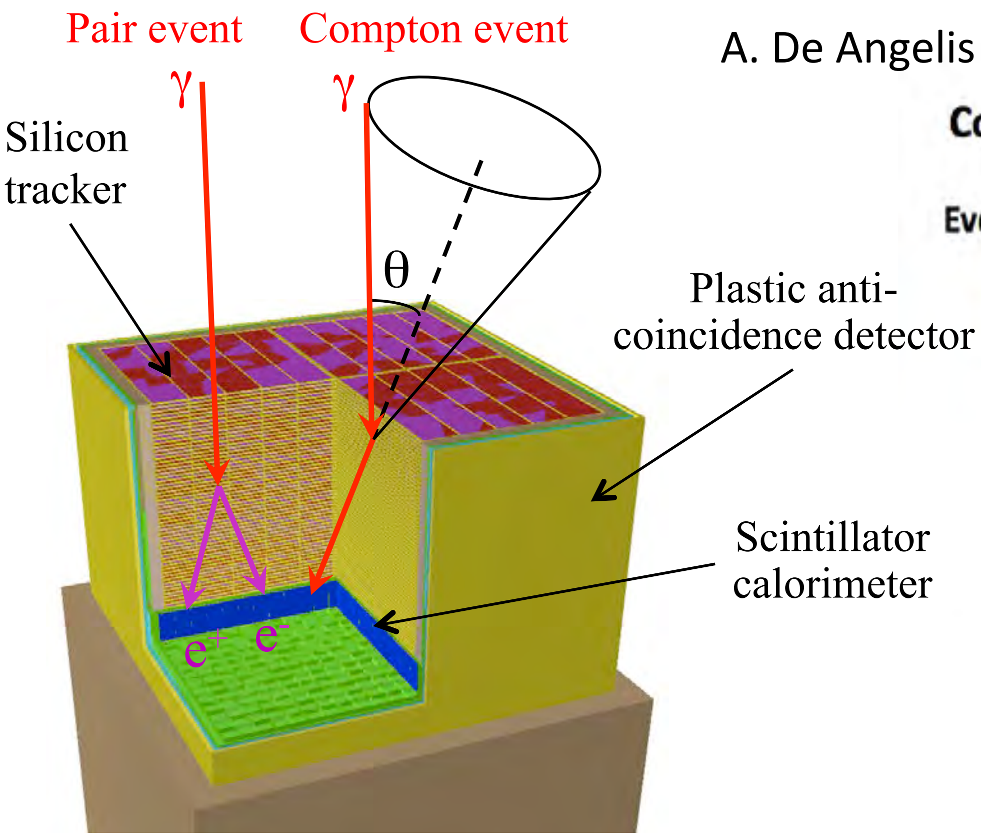
The MeV/GeV domain



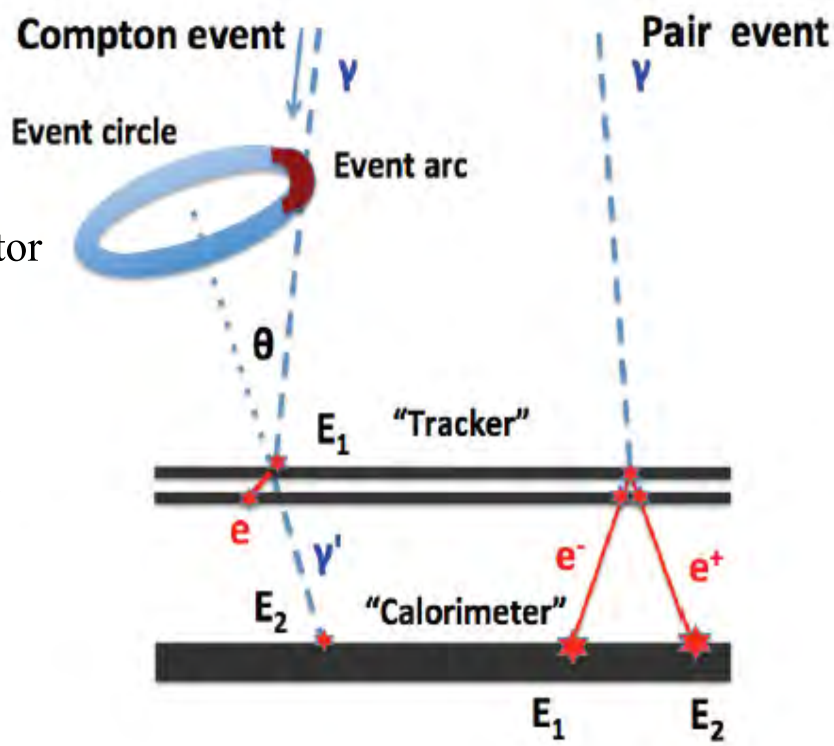


- Worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)
- Binding energies of atomic nuclei fall in this range, which therefore is as important for HE astronomy as visible light is for phenomena related to atomic physics

How to measure gamma rays in the MeV-GeV?

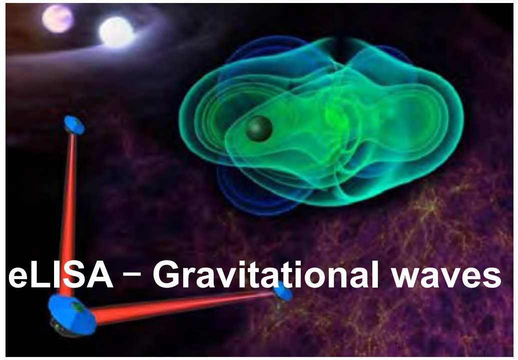


A. De Angelis et al., https://arxiv.org/abs/1611.02232



- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution (1m^2, 500 μm thick, 0.3 Xo in total)
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon ⇒ CsI(Tl) scintillation crystals readout by Si drift detectors or photomultipliers for best energy resolution. 8 cm (4.3 Xo)
- **Anticoincidence detector** to veto charged-particle induced background ⇒ plastic scintillators readout by Si photomultipliers

e-ASTROGAM (Europe) & AMEGO (US) – 2028/29

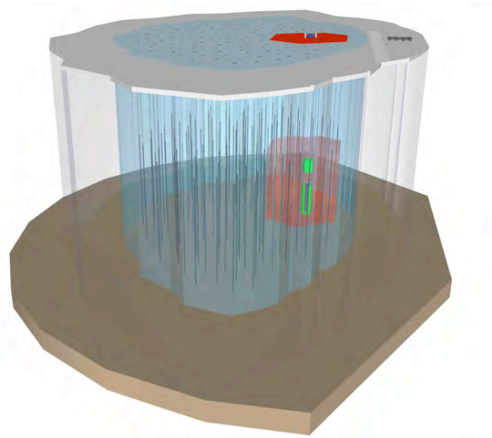


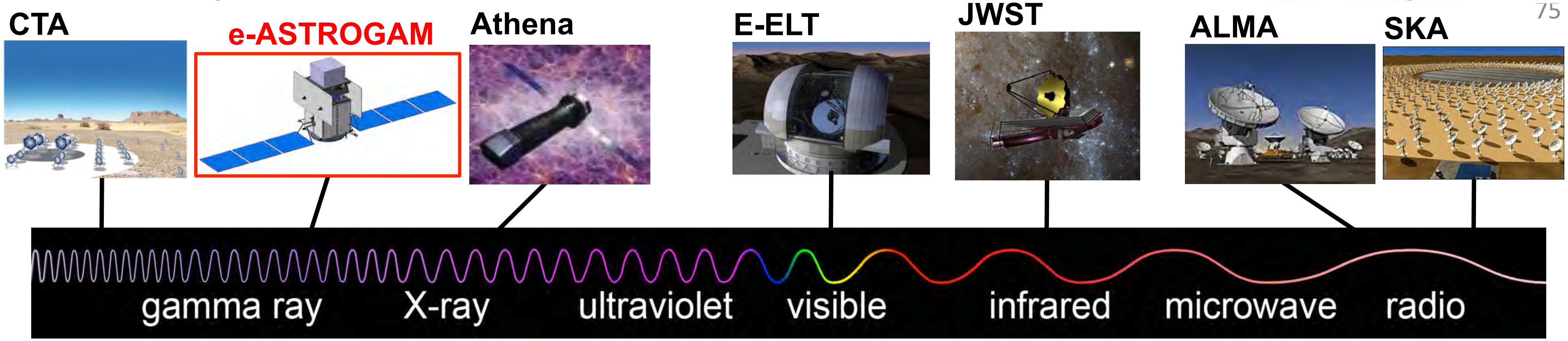
1. Processes at the heart of the extreme Universe (AGNs, GRBs, microquasars): prospects for the Astronomy of the 2030s
   - Multi-wavelength, multi-messenger coverage of the sky (with CTA, SKA, eLISA, ν detectors...), with special focus on transient phenomena

2. The origin of high-energy particles and impact on galaxy evolution, from cosmic rays to antimatter

3. Nucleosynthesis and the chemical enrichment of our Galaxy

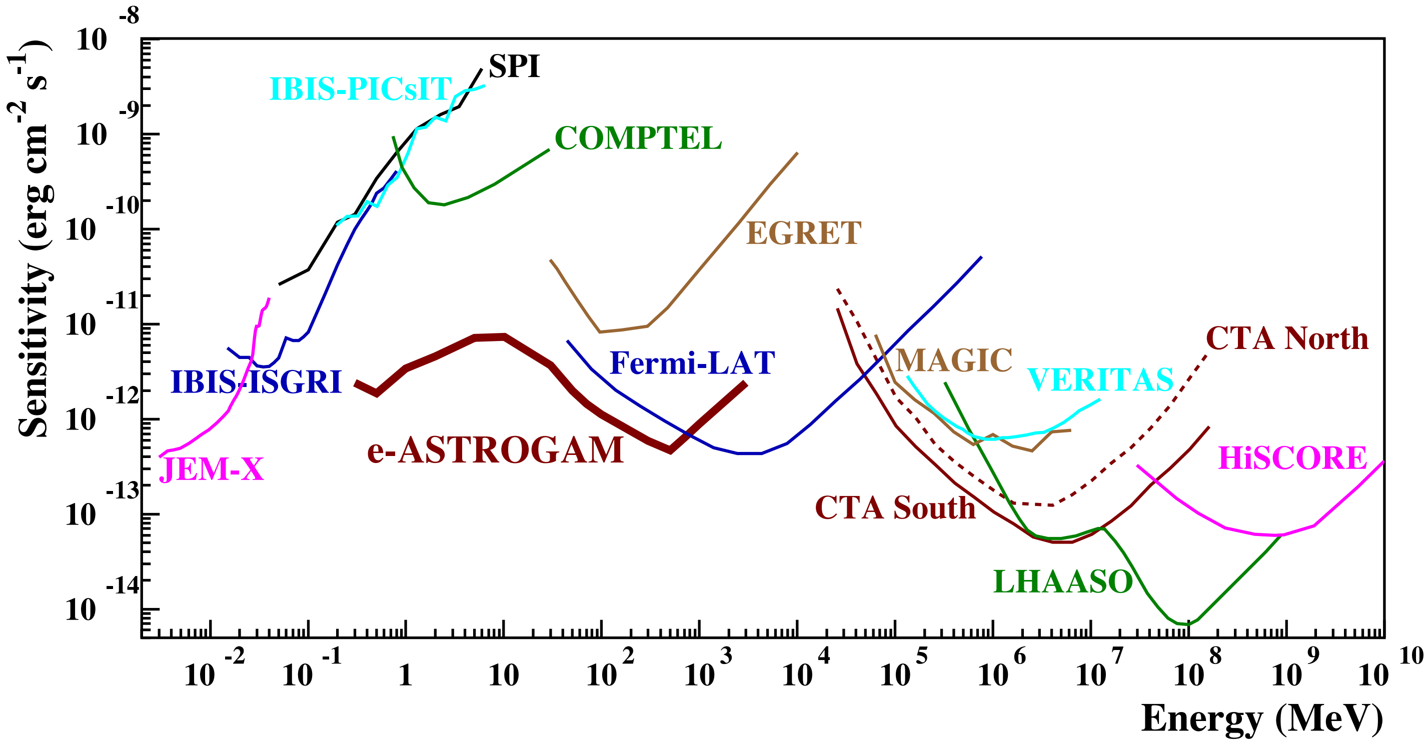
Km3Net/IceCube-Gen2 - ν





e-ASTROGAM, AMEGO performance

1. Achieve a sensitivity better than INTEGRAL/CGRO/COMPTEL by a factor of 20 - 50 – 100 in the range 0.2 – 30 MeV
2. Fully exploit gamma-ray polarization for both transient and steady sources
3. Improve significantly the angular resolution (to reach, e.g., ~ 10' at 1 GeV)
4. Achieve a very large field of view (~ 2.5 sr) ⇒ efficient monitoring of the γ-ray sky
5. Enable sub-millisecond trigger and alert capability for transients

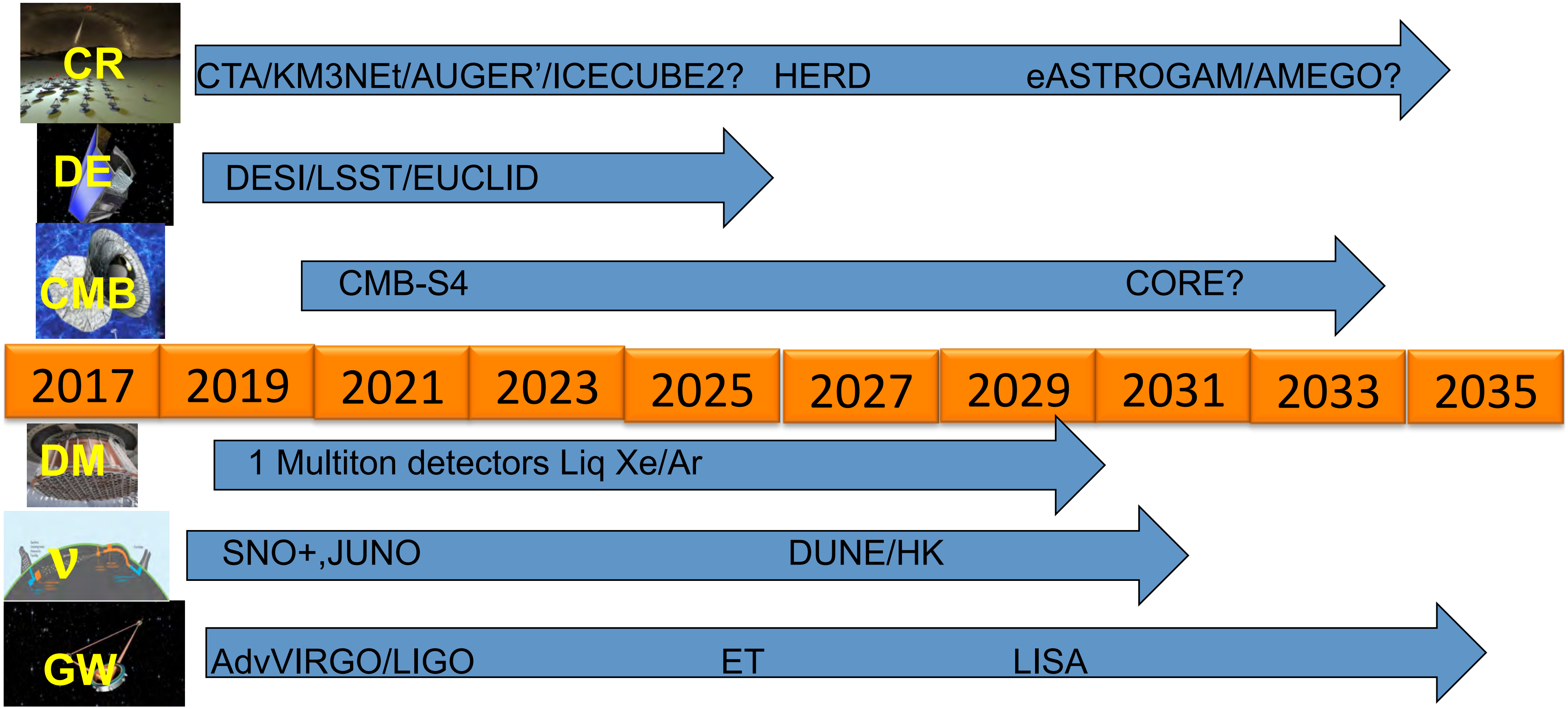


Summary on science from future detectors

- CTA will expand the panorama of known sources, by multiplying them by a factor 10
  - Possibly new source classes
- The sensitivity to DM will cover the full “miracle” region, apart from a small interval ~ 100 GeV
- Together with a large FoV detector in the Southern hemisphere, will study in detail the GC region (something unexpected?)
- A MeV detector (e-ASTROGAM? AMEGO?) will unveil the mechanism of chemical evolution of the Galaxy and of supernovae, and possibly measure axion emission from supernovae

FINAL CONSIDERATIONS

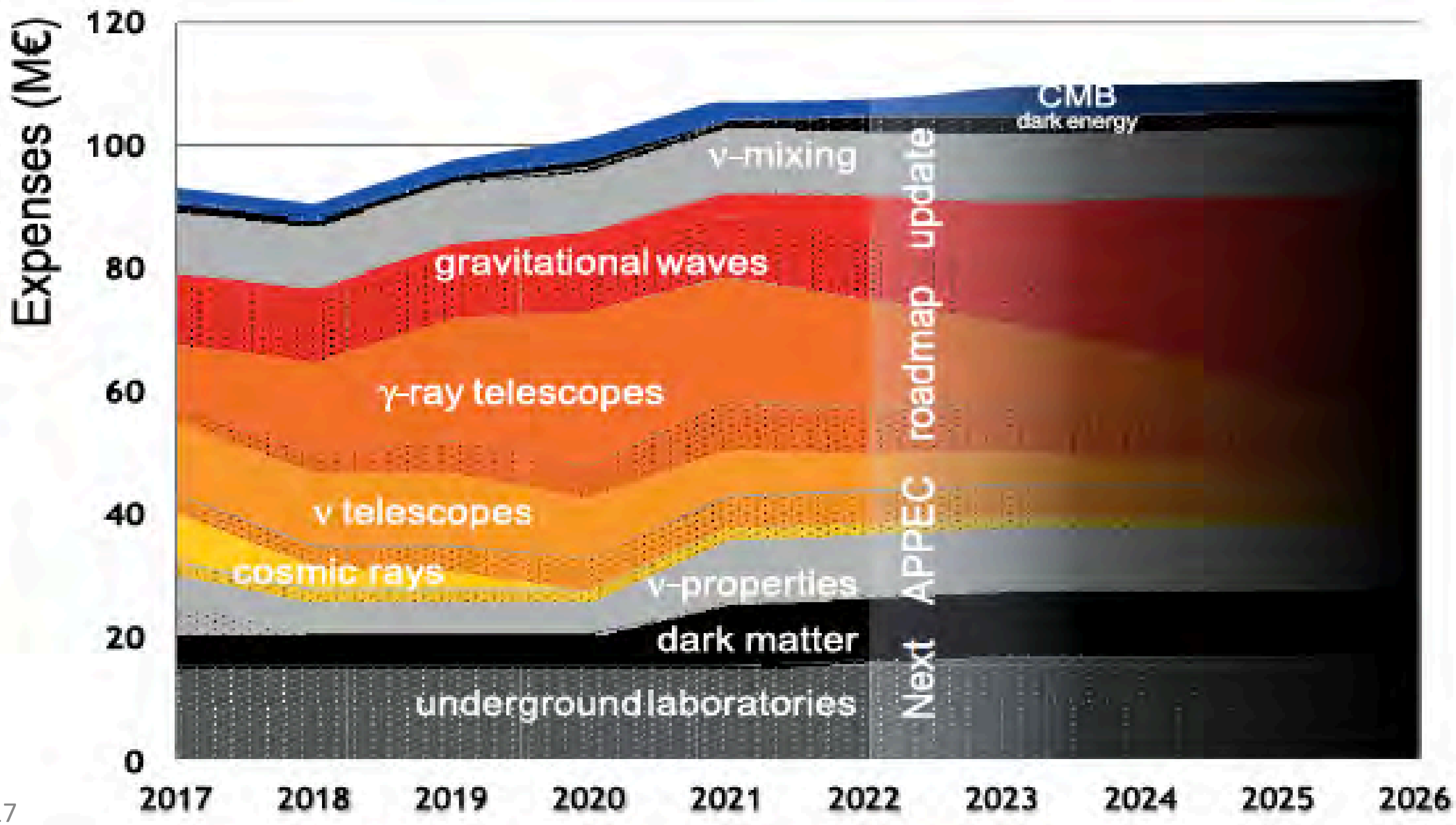
Agencies need (like?) to make plans…



…and to offer money in exchange of granted science

(budget excluding manpower, labs, regional funds, and competitive calls by NASA/ESA.)

(M/L space missions approved can be ~50 MEUR/year on top of this)



- Gamma rays:
  - A rich panorama of gamma experiments at VHE gamma proposed for the future. CTA will lead the field.
    - Besides CTA, new techniques. Exploration of the PeV region is fundamental – and feasible. Northern projects approved, will produce nice science. Need to converge to a Southern 100 GeV-100 TeV EAS array.
  - In the longer term, need taking care of multiwavelength aspects: priorities are
    - A MeV mission (room for smart improvement; 2 missions proposed)
    - A successor of Fermi
- Big science in gamma-ray astroparticle physics can grant many discoveries in the next 10-20 years
  - Localization of acceleration sites of cosmic rays
  - Origin of gravitational waves, and multiwavelength analysis
  - …

  and the preparation of experiments capable to clarify (if possible) the problem of the energy budget of the Universe
- Fortunately, Nature is largely independent of what we (and agencies) think, and detectors and scientists are somehow as well: we can have surprises like in recent years (neutrino mass, BH mergings, structure of the Milky Way, …)
  - And there are many unanswered questions…