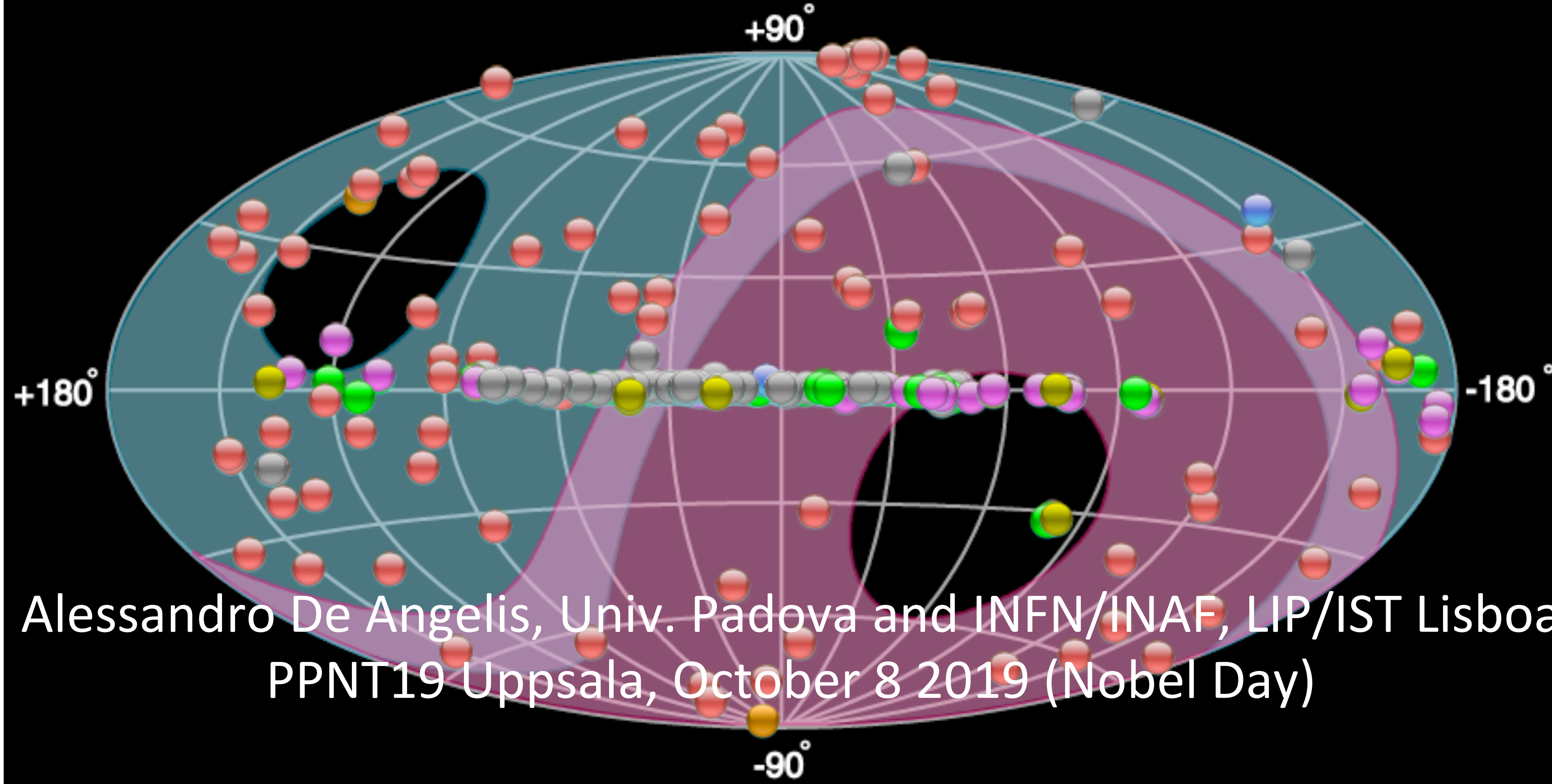
Searches for Physics Beyond the Standard Model using VHE cosmic photons



Alessandro De Angelis, Univ. Padova and INFN/INAF, LIP/IST Lisboa

PPNT19 Uppsala, October 8 2019 (Nobel Day)

1. Fundamental properties of spacetime BSM?
2. New Particles
   a. Axions and ALPs
   b. WIMPs

Physics within the SM assumes

- Basics spacetime continuum symmetries (homogenity, isotropy), CPT
- $SU(3) \times SU(2)_L \times U(1)$

=> Accidental symmetries (baryon number, lepton number, …)

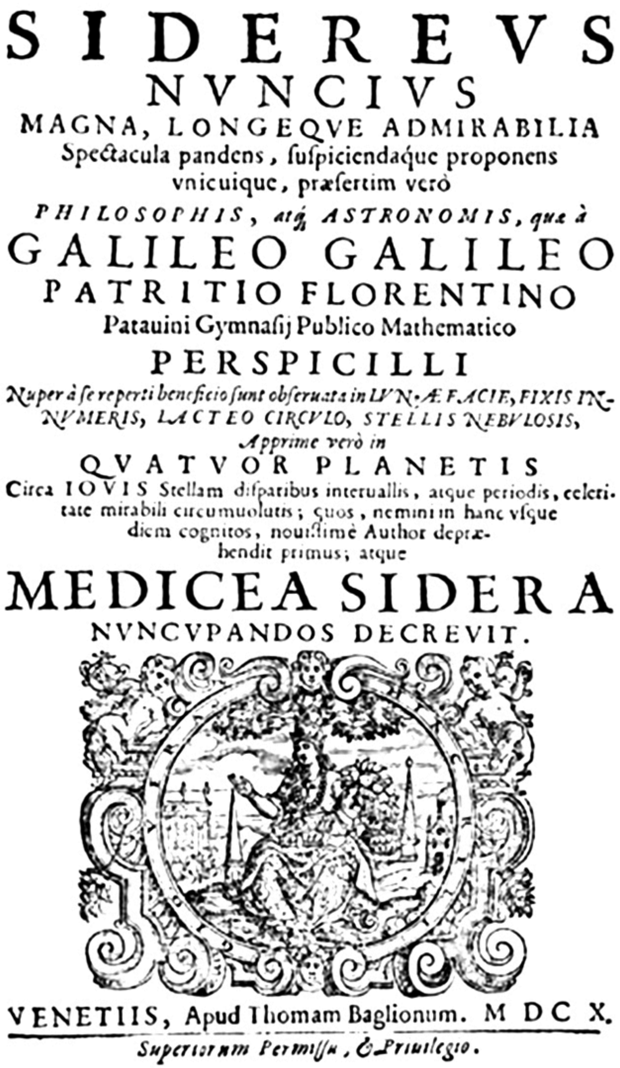
- Quarks and leptons, their masses and mixings (*)

Why/where to look BSM? (personal view)

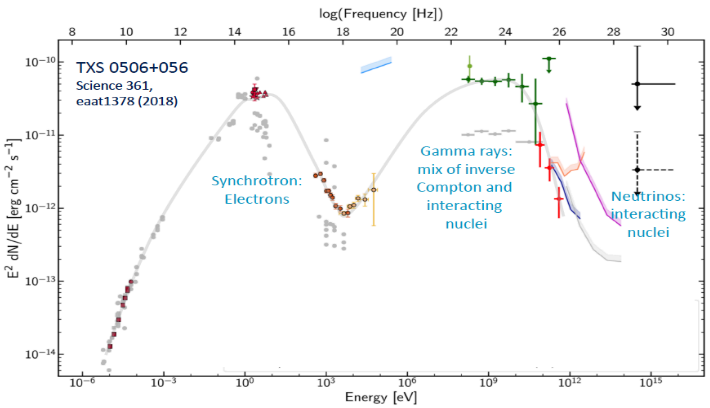
- It's a model
- "Not natural" (?)
- Does not include gravity (?)
- Dark Energy (?)
- Neutrino masses (?)
- Dark Matter (?)
- Baryon asymmetry (?)
- CP conservation in QCD (the strong CP problem) (?)

How?
Neutral messengers for astronomy & astrophysics

<u>Photons</u> have a long tradition in astronomy and astrophysics since millennia… They are the “starry messengers” by default since 1610 at latest (or the “message from the stars”)


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

But neutrinos are also important and complementary



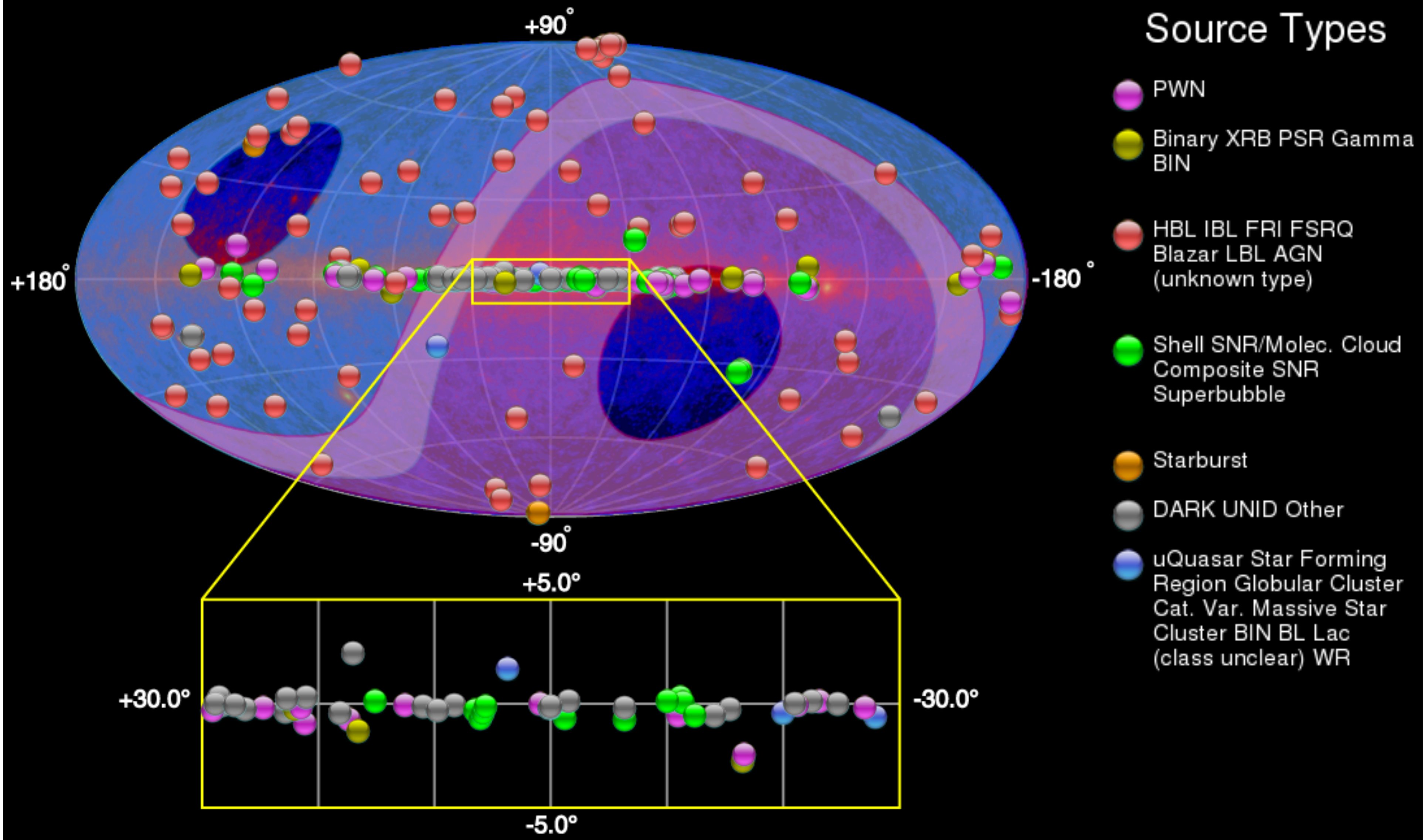
Photons above the thermal regions

- (LE) or MeV : 0.1 (0.03) -100 (30) MeV
- HE or GeV : 0.1 (0.03) -100 (30) GeV
- VHE or TeV : 0.1 (**0.03**) - 100 (**30**) TeV
- UHE or PeV : 0.1 (**0.03**) -100 (**30**) PeV

- An arbitrary classification, which however corresponds to differences on
  – Physical processes involved
  – Types of detectors involved (Cherenkov, EAS)

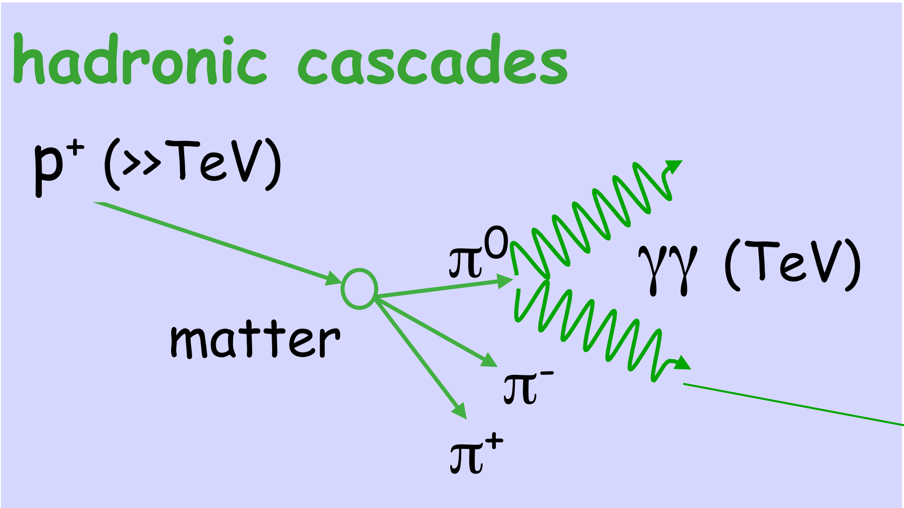
- When no ambiguity, we call "HE" all the HE, VHE+…

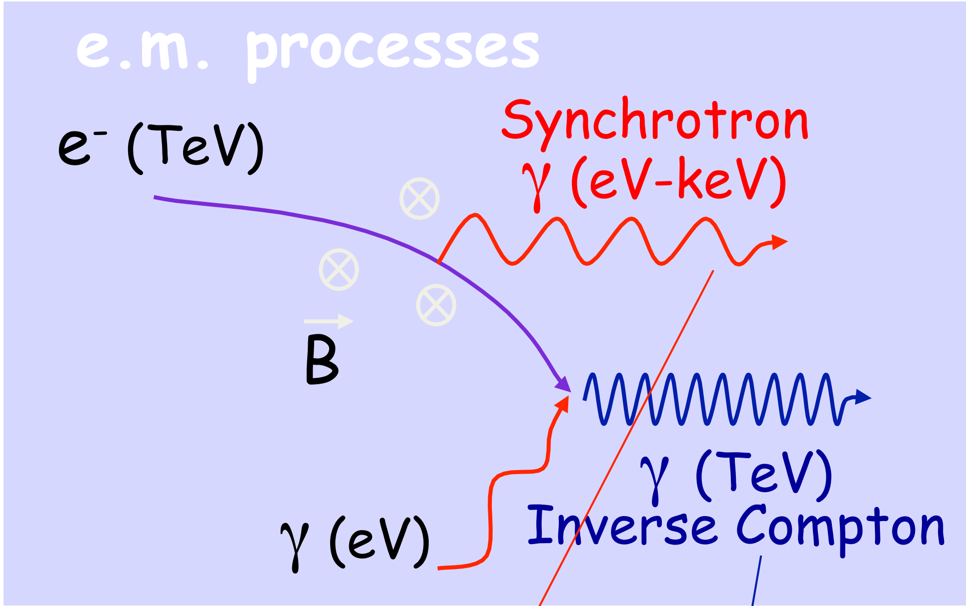
>3k HE and >200 VHE photon emitters

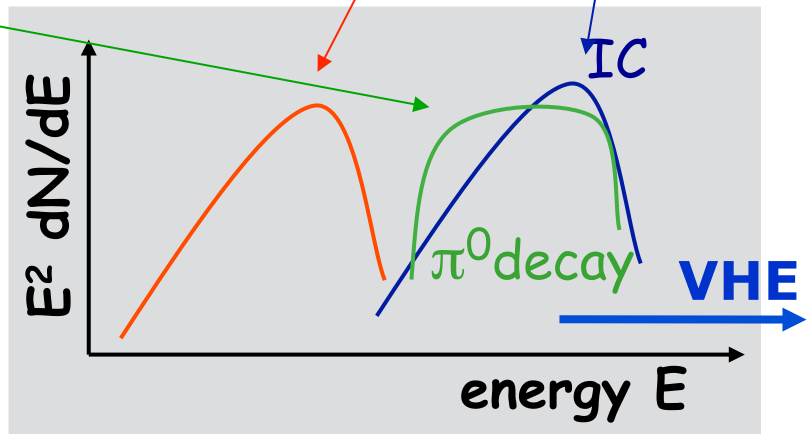


(1) Bottom-up mechanisms for HE photons: radiation from accelerated charged particles. Leptons (SSC) and hadrons

50 TeV gamma-rays hadronically produced track a population of protons of energy ~ 1 PeV





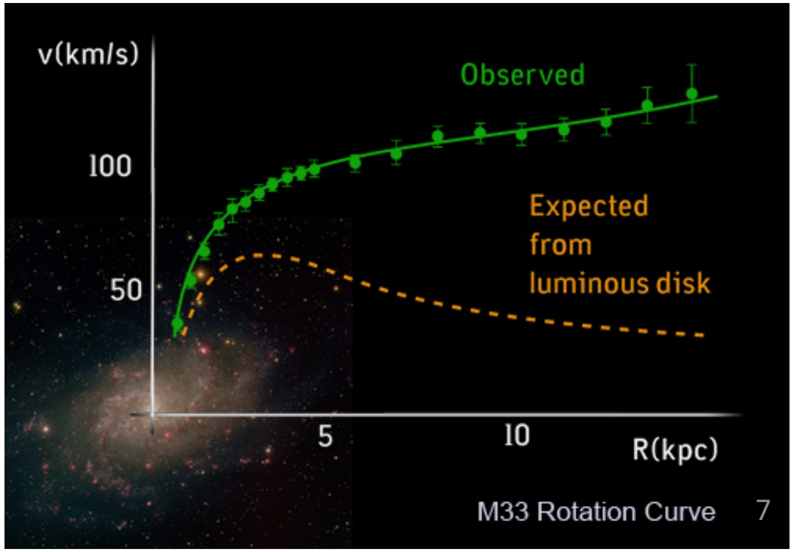


In the VHE region,
$dN/dE \sim E^{-\Gamma}$ (Γ: spectral index)

To distinguish between hadron/leptonic origin study Spectral Energy Distribution (SED):
(differential flux) · E^2

(2) Top-down mechanisms: are there new (heavy) particles which can produce HE photons?

- Hypothetical DM particles are a good candidate…
  - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system, given the visible mass
  - Observed for many galaxies, including the Milky Way
- But any new hypothetical heavy particle (relics?) can play the game

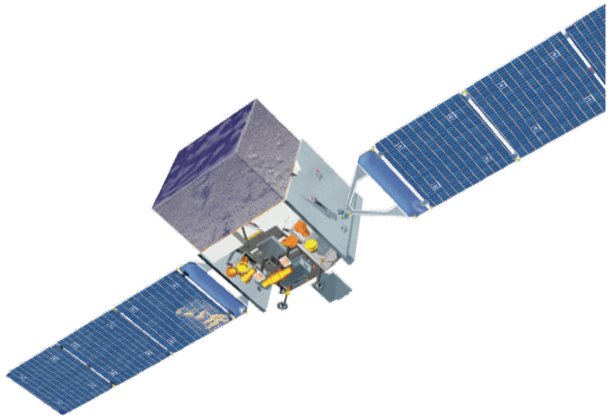


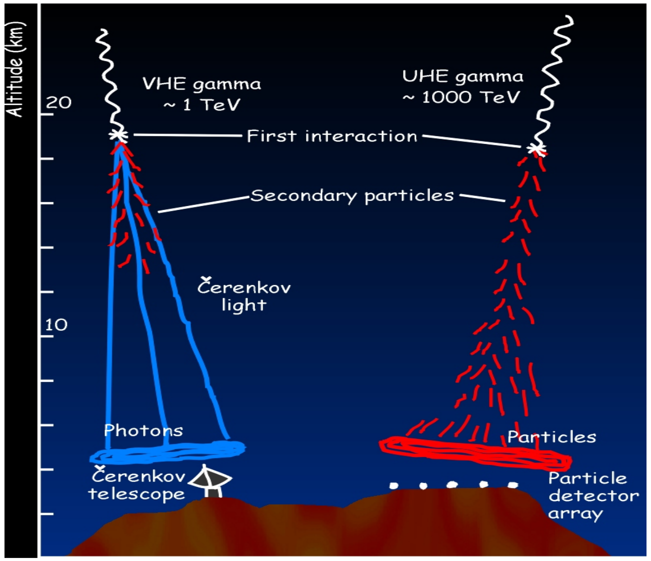
0. Detectors of VHE gamma rays

Why detection at ground?

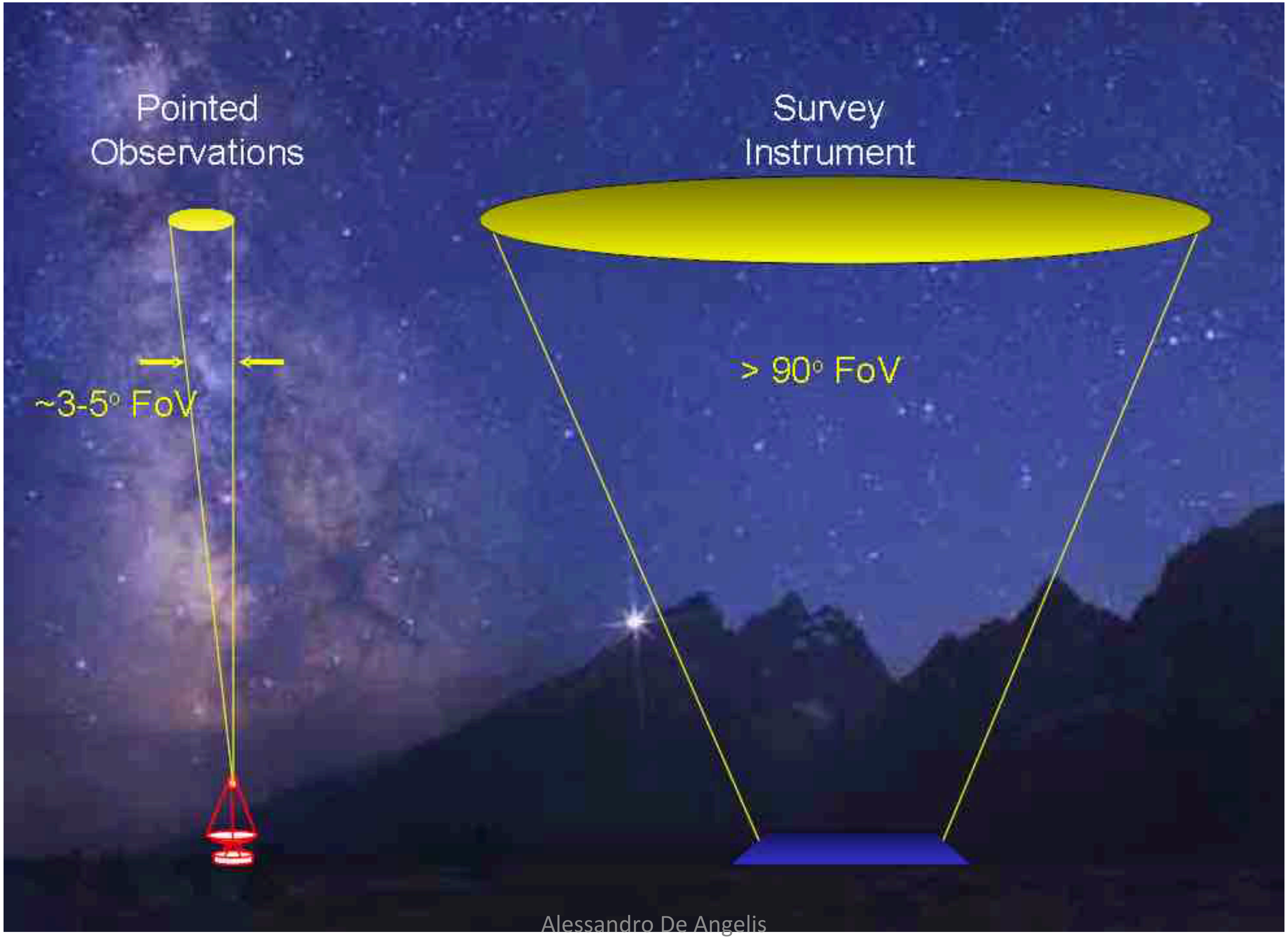
- High energies
  - Only way to build sensitive >TeV instruments
    - Maximum flux < 1 photon/h/m^2 above 200 GeV in Fermi
- High statistics /short timescales
  - Large collection areas O(km^2)
- Precision (Imaging Air Cherenkov telescopes, IACTs)
  - Superior angular resolution
- Limitations?
  - IACTs
    - Smaller duty cycle
    - Smaller field of view
  - EAS ground particle detectors
    - Modest resolution and background rejection power

=> Complementary approaches





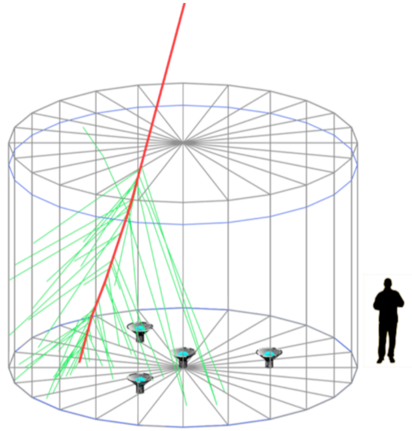
Cherenkov vs. EAS

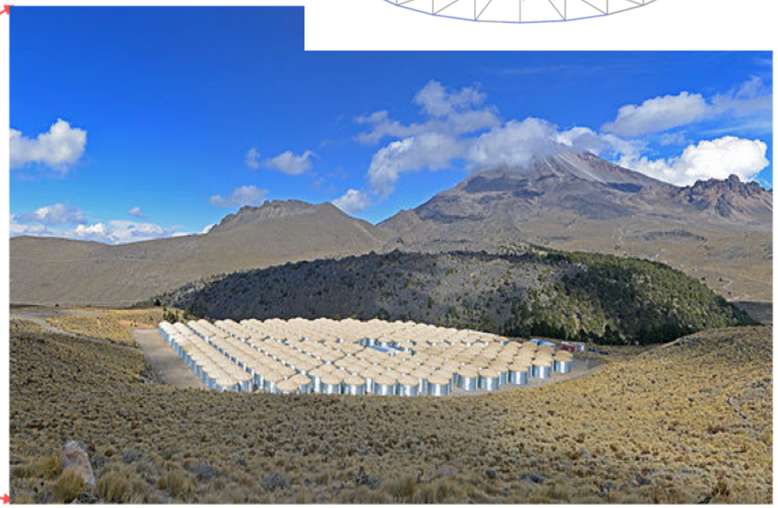



MAGIC + LST1 (CTA-N)
VERITAS
TAIGA
TIBET
LHAASO
HAWC
CTA/S
SWGO
HESS

EAS detectors

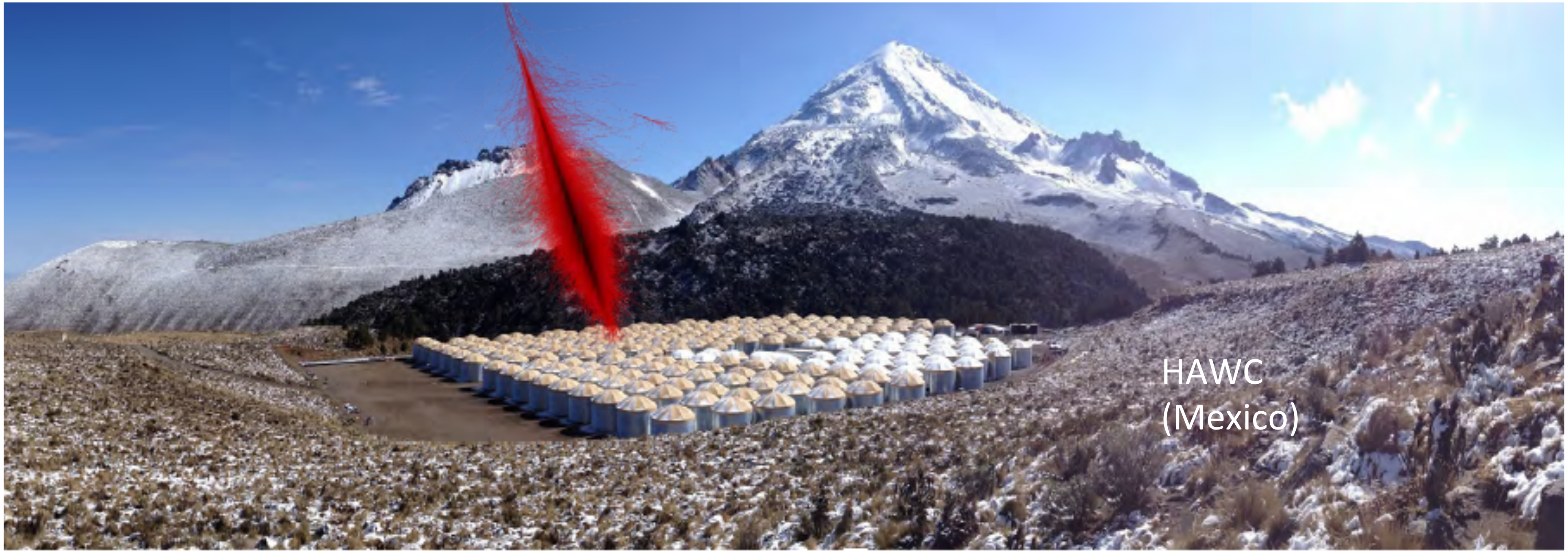
The HAWC Observatory





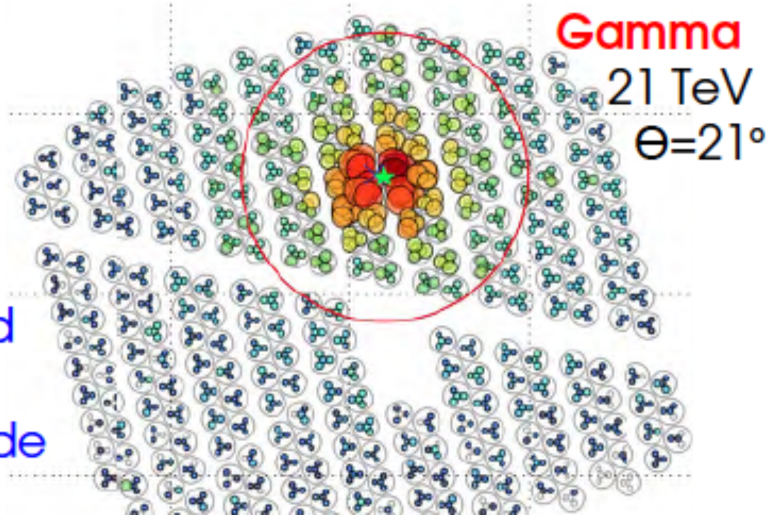
- Located at **4100 m** a.s.l. in Mexico near Pico de Orizaba at 19ºN
- Effective Area: **~22,000 m²**
- Instantaneous field of view **2 sr**; daily coverage of **2/3** of the sky.
- 300 Water Cherenkov Detectors (WCDs)
- Declinations from **-26º to 64º** (***Part of Northern Fermi Bubble visible***)
- Inaugurated in **March 2015**, taking science data since **2013**.

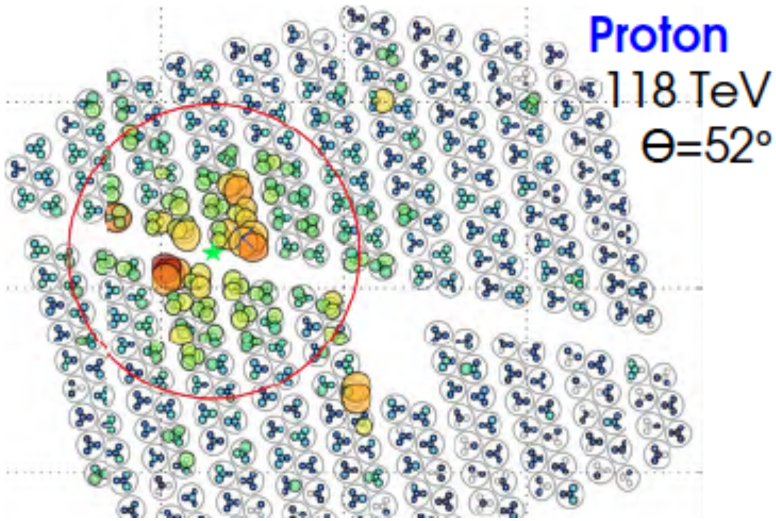
Very-high-energies (above 400 GeV)

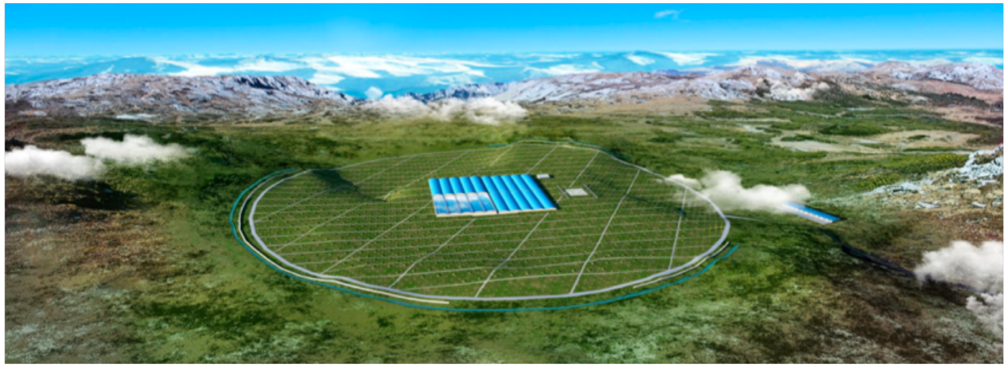


Reconstruct air showers based on PMT hit times and charges

Reject charged primaries via bright hits outside the core

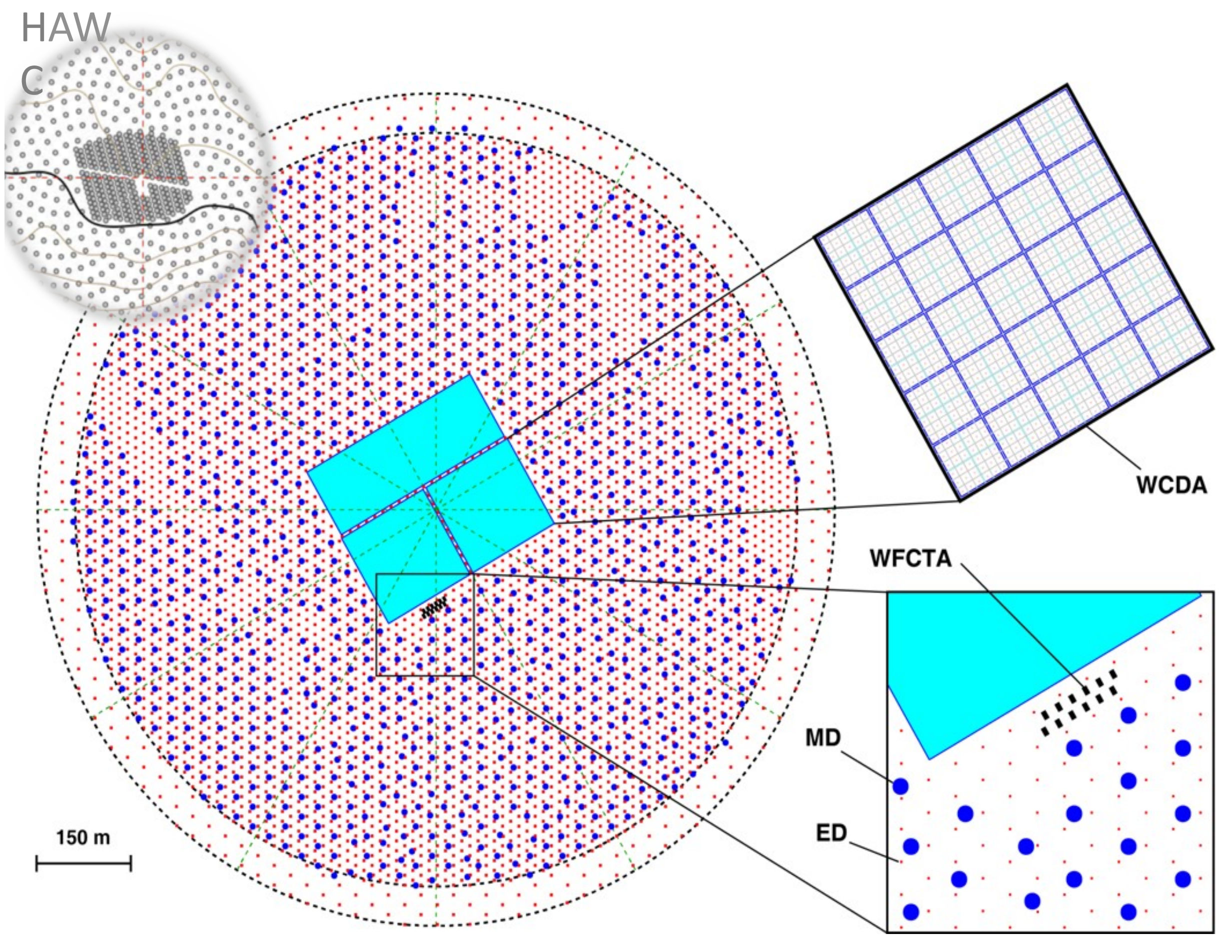






LHAASO

Sichuan, China, 4410 m asl
25% ready



5195 Scintillators
- 1 m^2 each
- 15 m spacing

1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

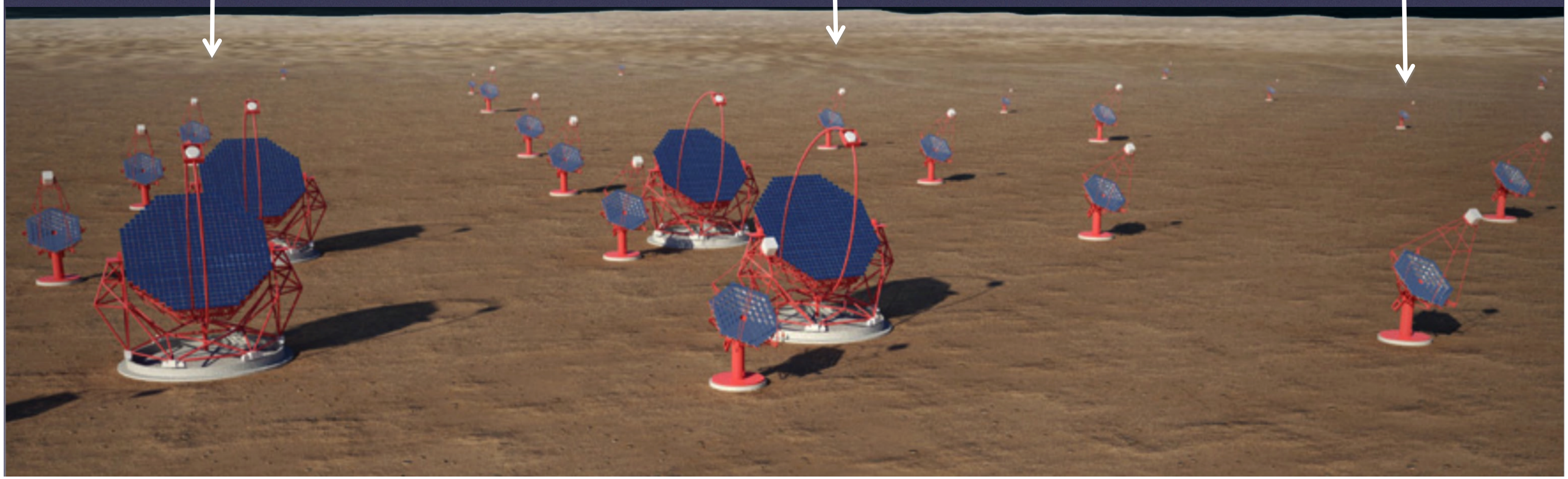
12 Wide Field Cherenkov Telescopes

Next: CTA, A multi-telescope Cherenkov array ~2000 scientists from all around the world

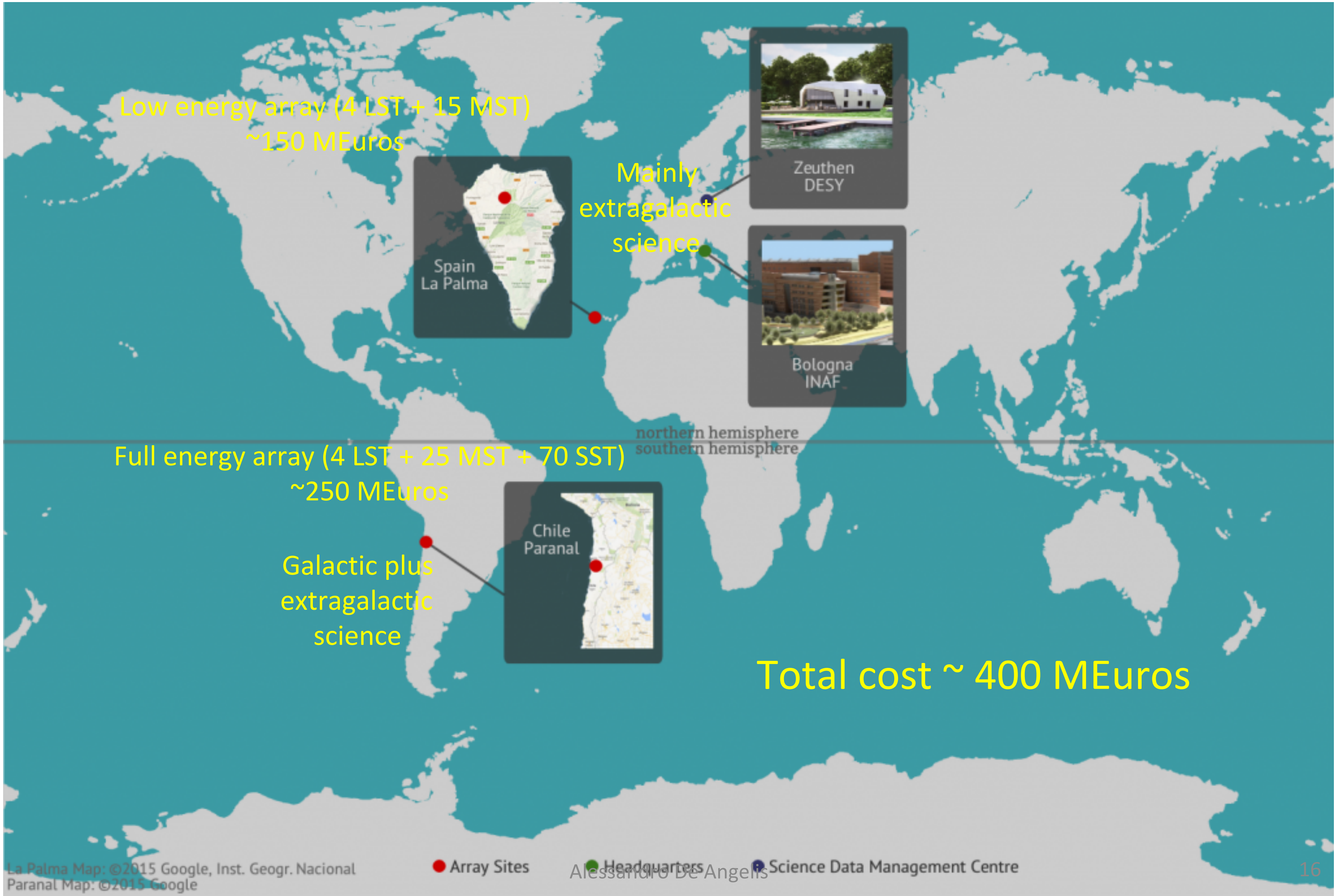
Low energies
Energy threshold 20 GeV
23 m diameter
4 telescopes
(LST)

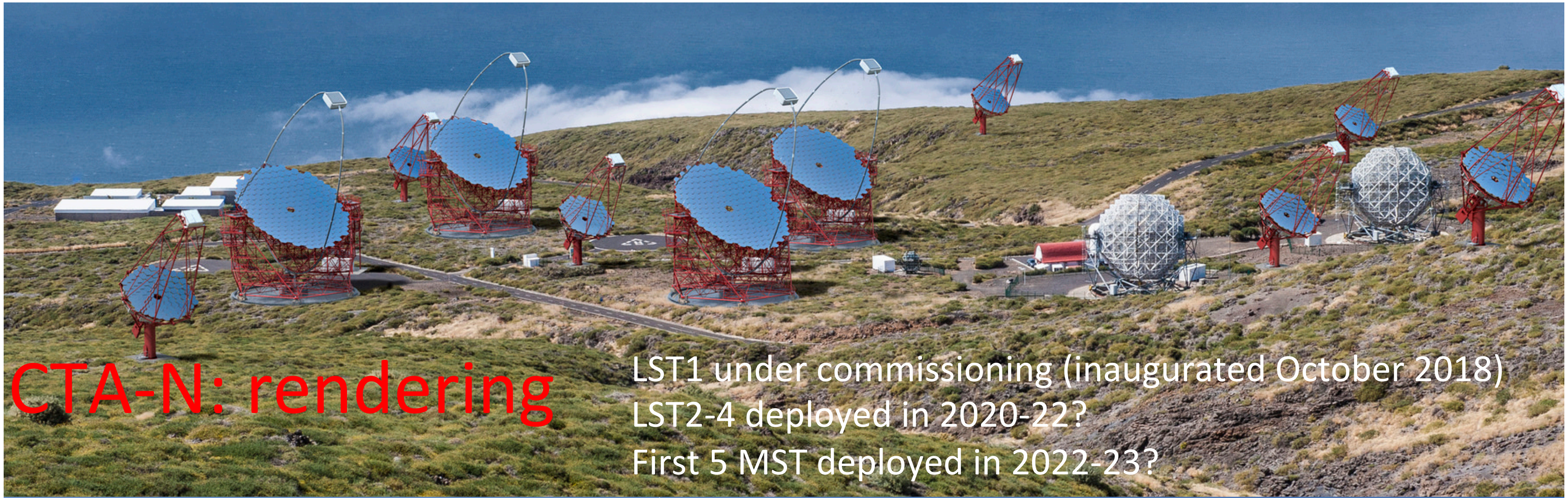
Medium energies (MST)
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
up to 24 dual-mirror telescopes
mCrab sensitivity in 50h at 0.1-10 TeV

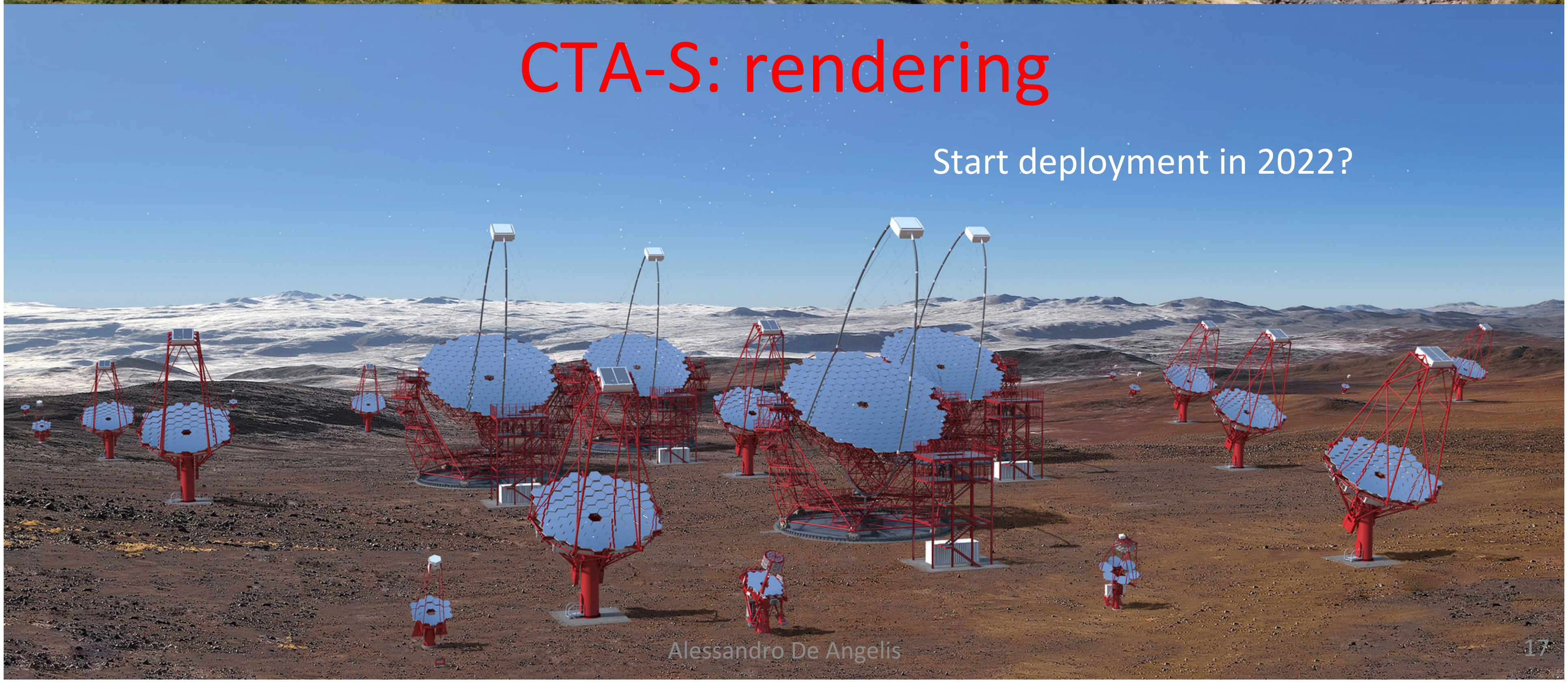
High energies
10 km^2 area at few TeV
4 to 6 m diameter
70 telescopes
(SST)



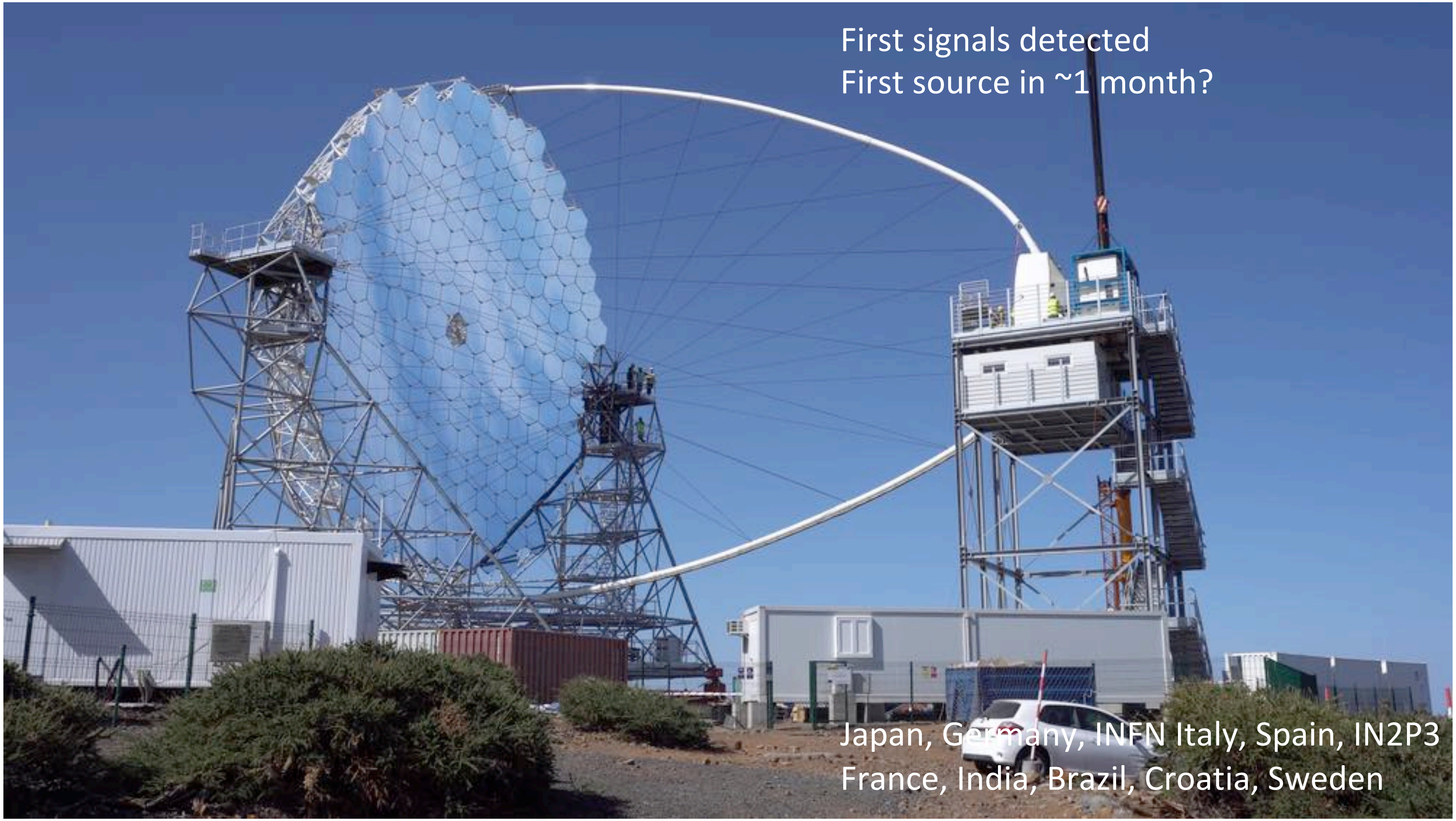
All-sky coverage: two observatories




CTA-N: rendering
LST1 under commissioning (inaugurated October 2018)
LST2-4 deployed in 2020-22?
First 5 MST deployed in 2022-23?

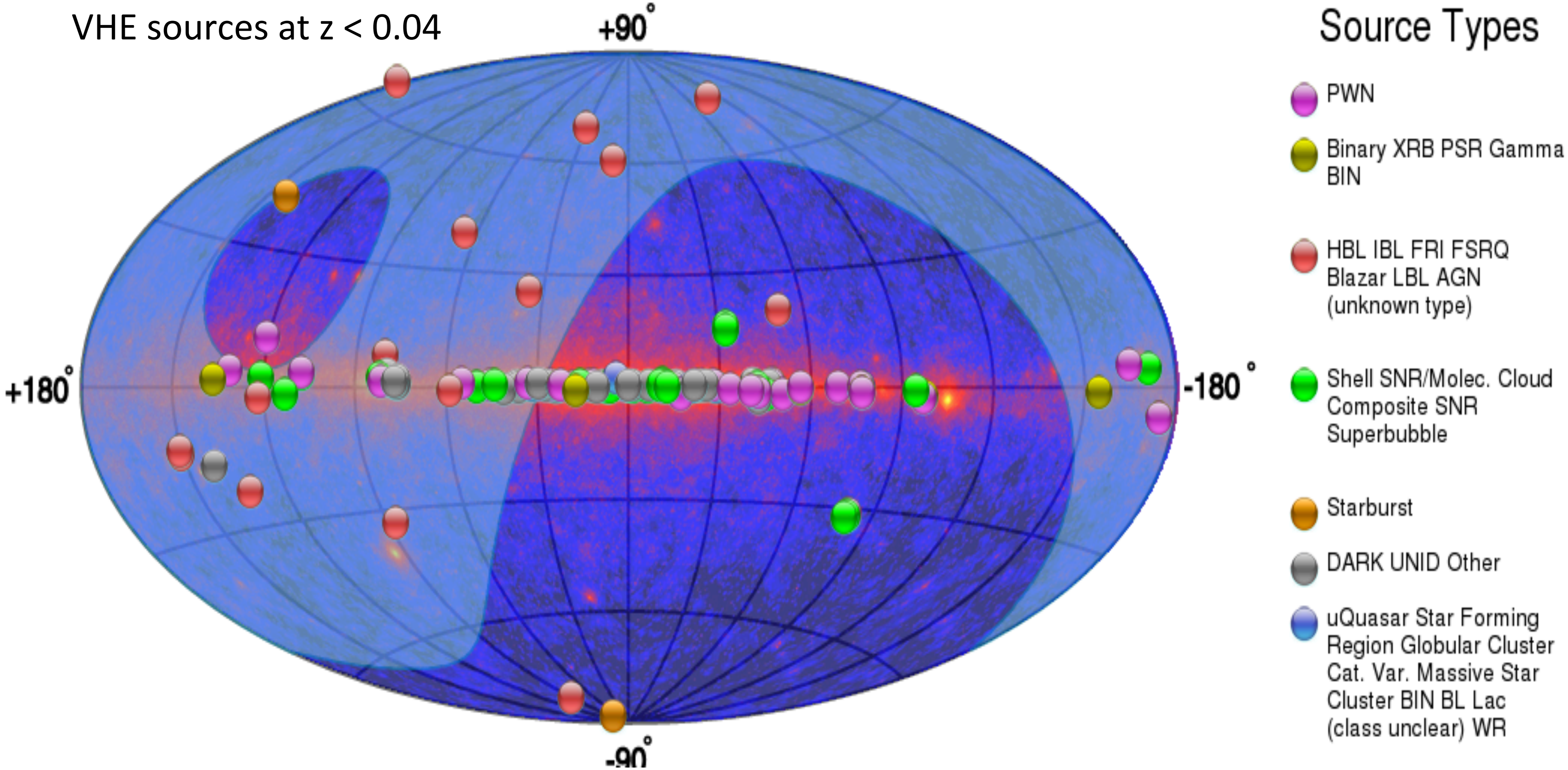

CTA-S: rendering
Start deployment in 2022?

LST1 at La Palma (near MAGIC)



HAWC+, LHAASO funded, but there is a strong case for a **wide-field experiment in the Southern hemisphere**

VHE sources at z < 0.04

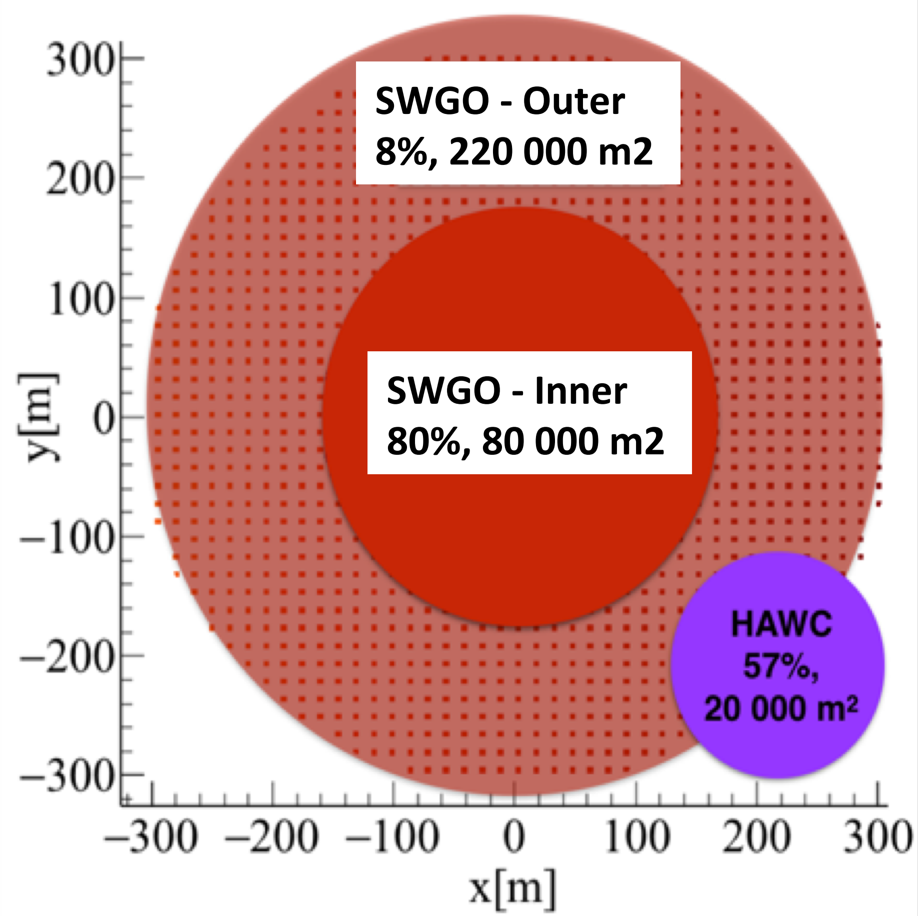


Sites > 4.6 km asl in Argentina, Chile, Peru

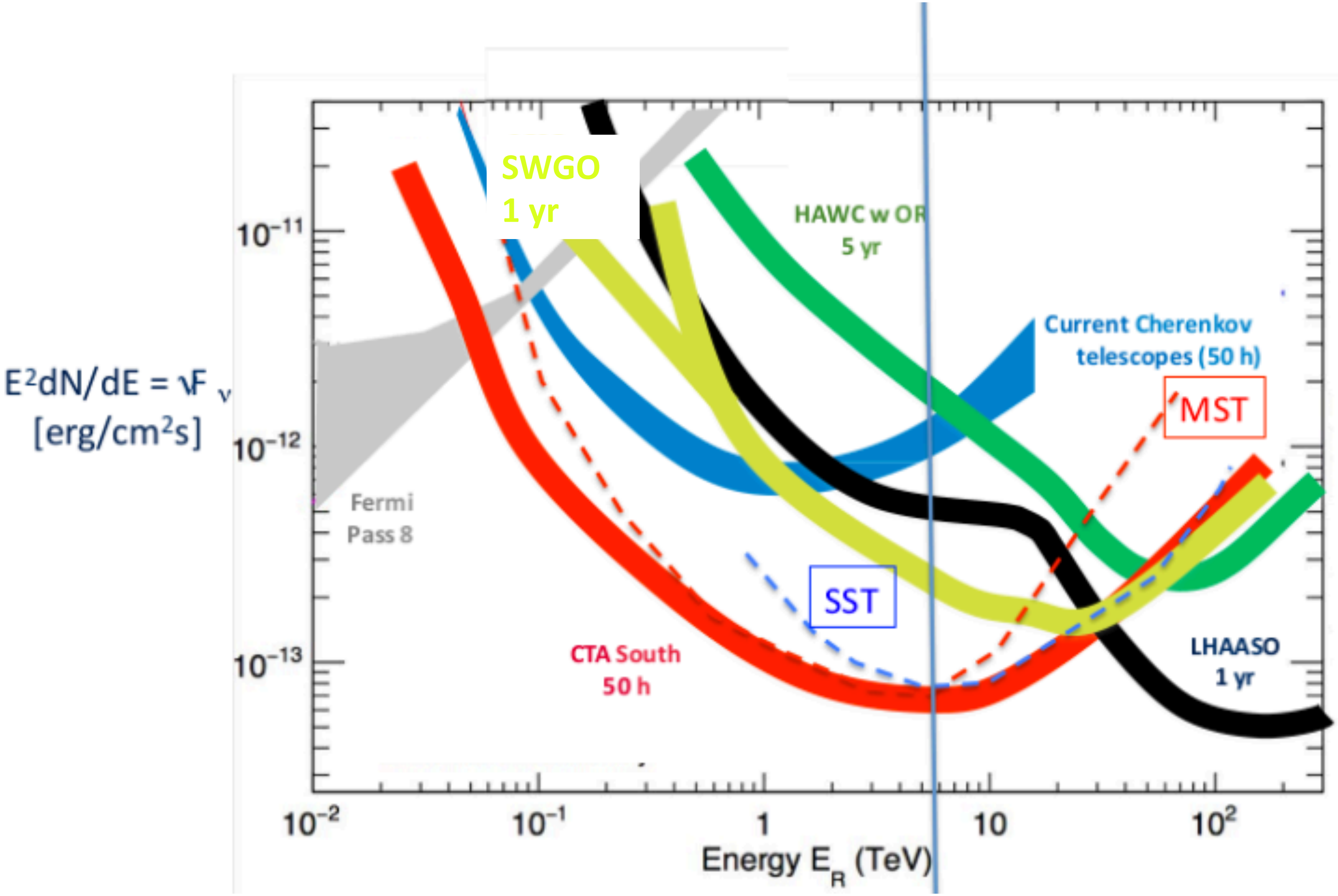
SWGO: a world-based project for the R&D of the Southern Wide-field Gamma-ray Observatory

- A 3-year project starting on July 1st, 2019

- Signed by Parties from Argentina, Brazil, Czech Republic, Germany, Italy, Mexico, Portugal, UK, US (groups interested and negotiations ongoing with Chile, China, France, Japan, Spain, Sweden, Peru)



Sensitivity of present & near future detectors



1. Violation of Lorentz Symmetry (LIV)

Is Lorentz invariance exact?

- For longtime violating Lorentz invariance/Lorentz transformations/Einstein relativity was a heresy
  - Von Ignatowsky 1911: {relativity, omogeneity/isotropy, linearity, reciprocity} => Lorentz transformations with "some" invariant c (Galilei relativity is the limit $c \to \infty$)
  - 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)
  - QG motivation: give away linearity? (A new relativity with 2 invariants: "c" and E_P)
  - Give away reciprocity? Isotropy?
- Framework for the violation (Colladay & Kostelecky 1998)
- Let's sketch an effective theory (Amelino-Camelia+ 1999)

Perturbation of the Hamiltonian => dispersion relation

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

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

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

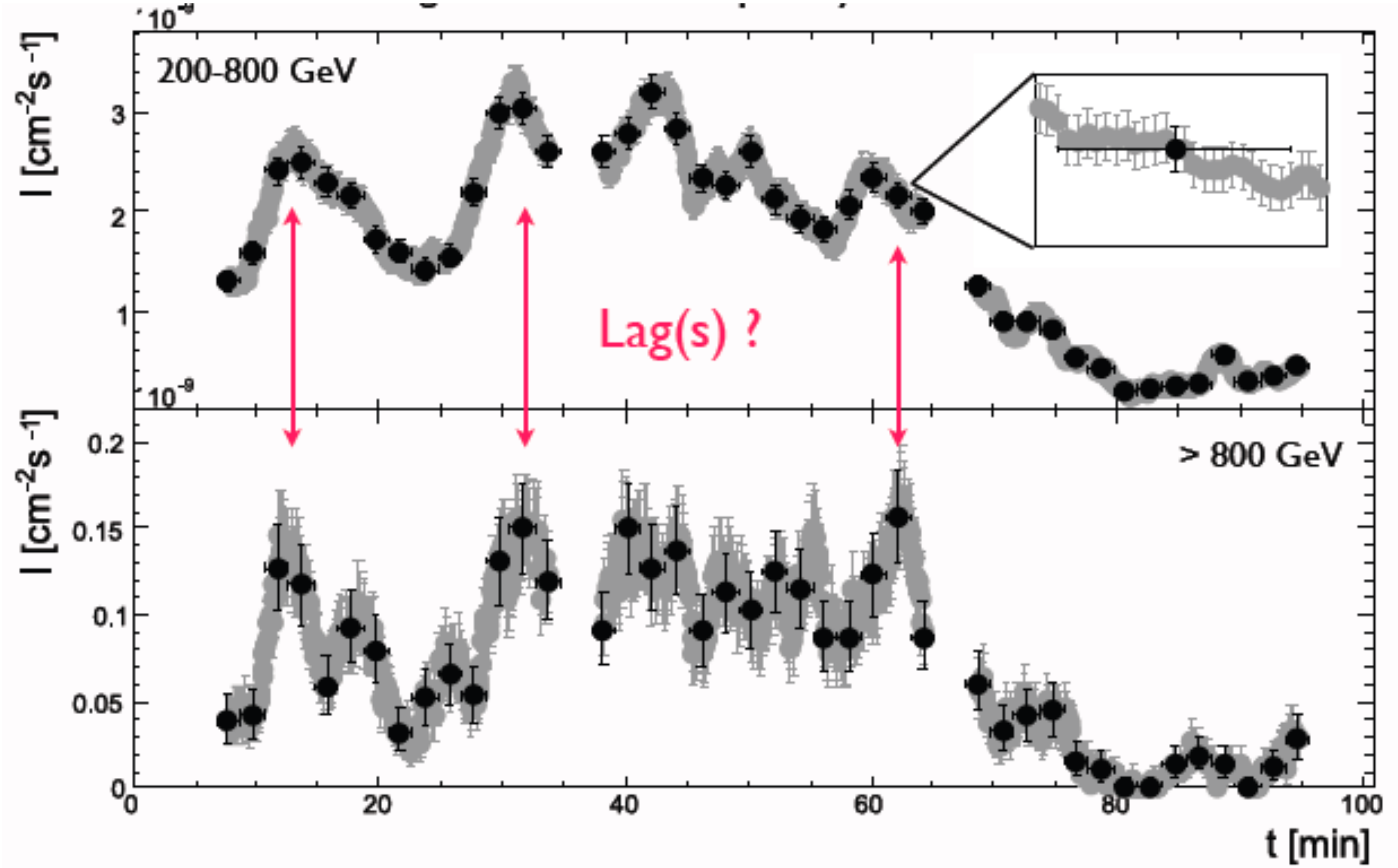
$$H \xrightarrow[p>>]{} p\left(1 + \frac{m^2}{2p^2} + \xi \frac{p}{2E_P} + \ldots\right)$$

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

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

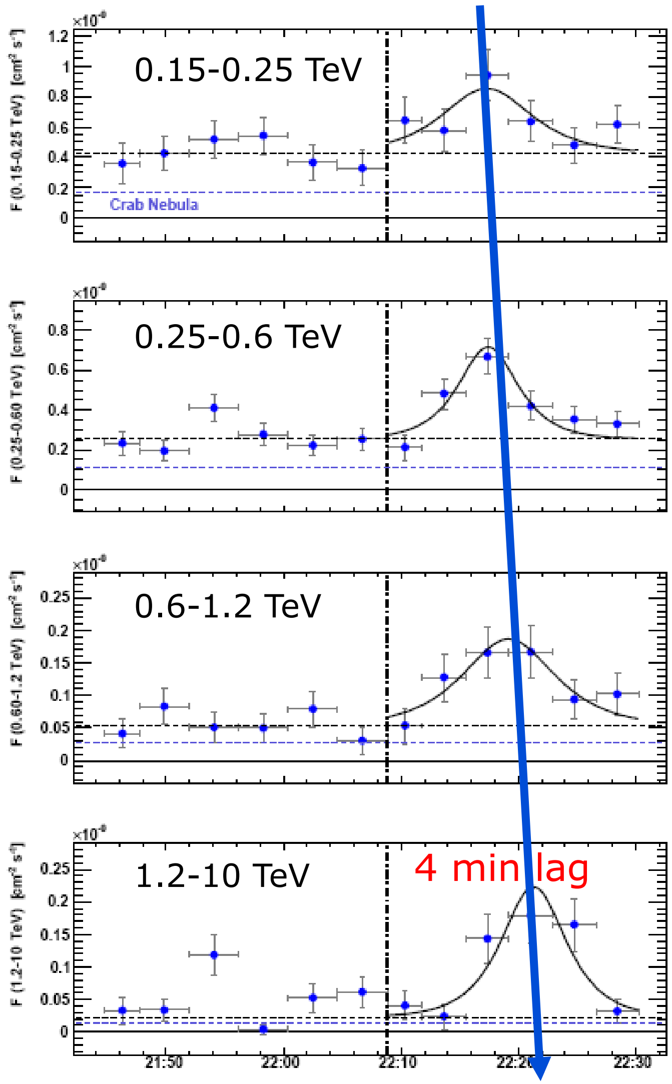
$$\boxed{\Delta t_\gamma \cong T \Delta E \frac{\xi}{E_P}}$$

Rapid variability is the name of the game



HESS, PKS 2155

Apart from one positive claim
(MAGIC, Mkn 501 2007)
Finally interpreted as a source effect,
no evidence



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

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

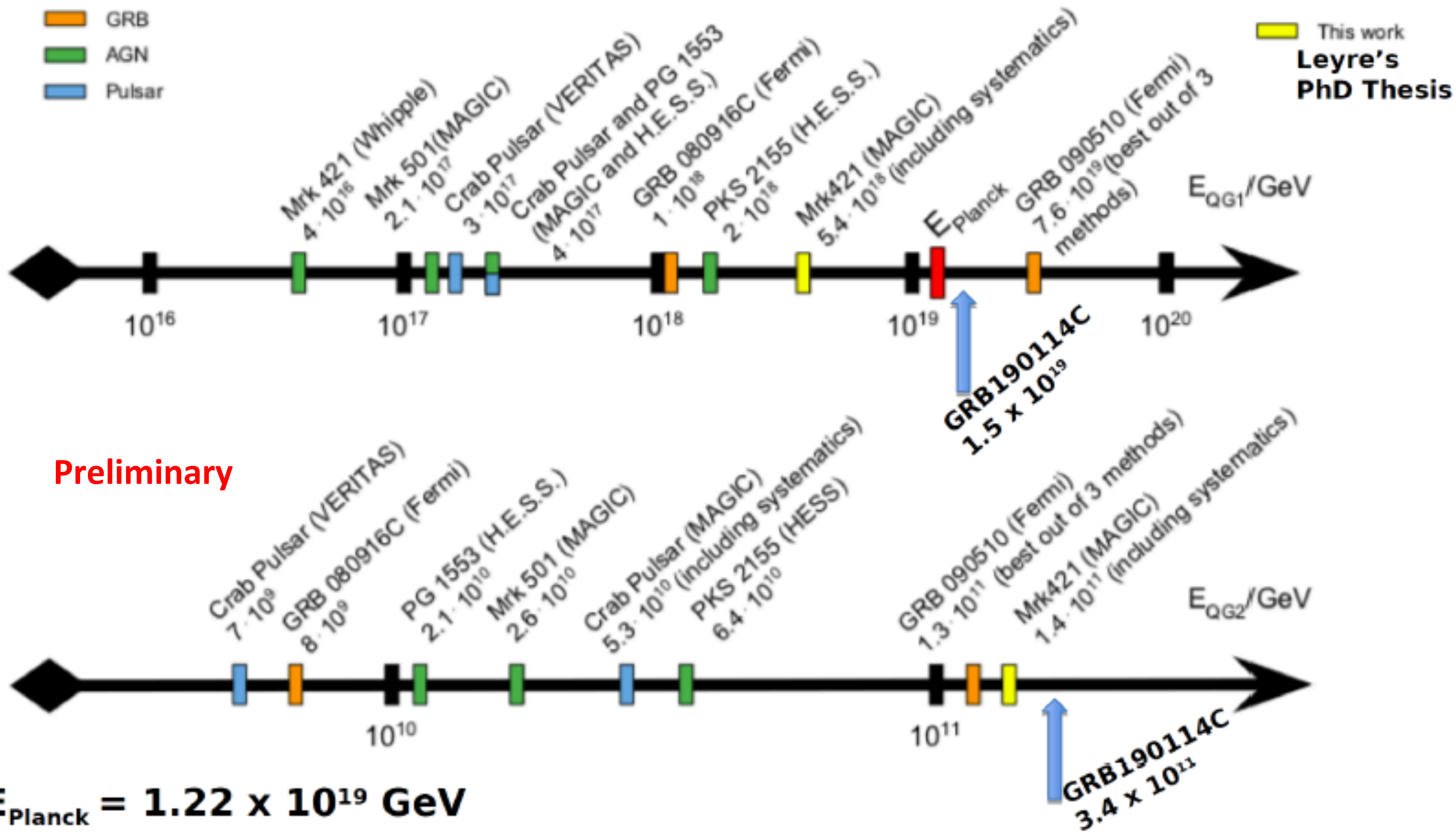
1st order mostly based on one GRB from Fermi

2nd order? Cherenkov rules!

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

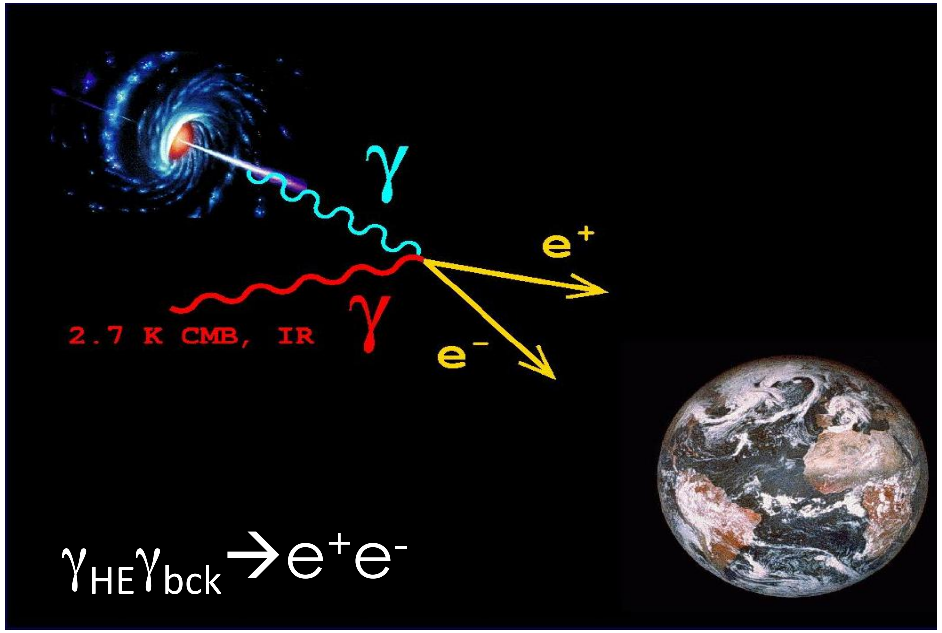
$E_{s2} > 10^{11}$ GeV (~10^{-9} M_P) (HESS, MAGIC, Fermi)

First GRB detected at TeV energies: GRB19014C (MAGIC). Stay tuned…



$E_{Planck} = 1.22 \times 10^{19}$ GeV

2a. Gamma-ray propagation and Axion-Like Particles (and LIV, again)

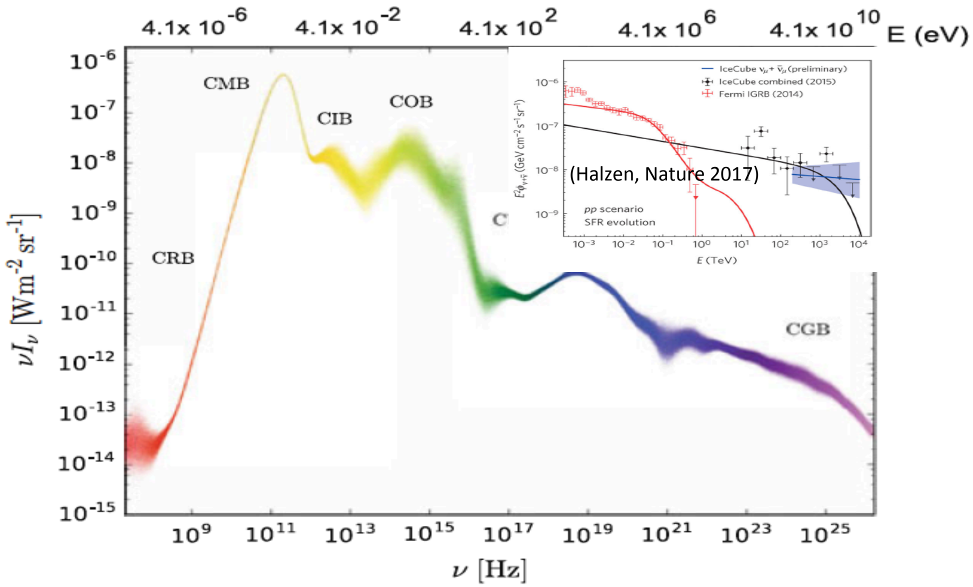


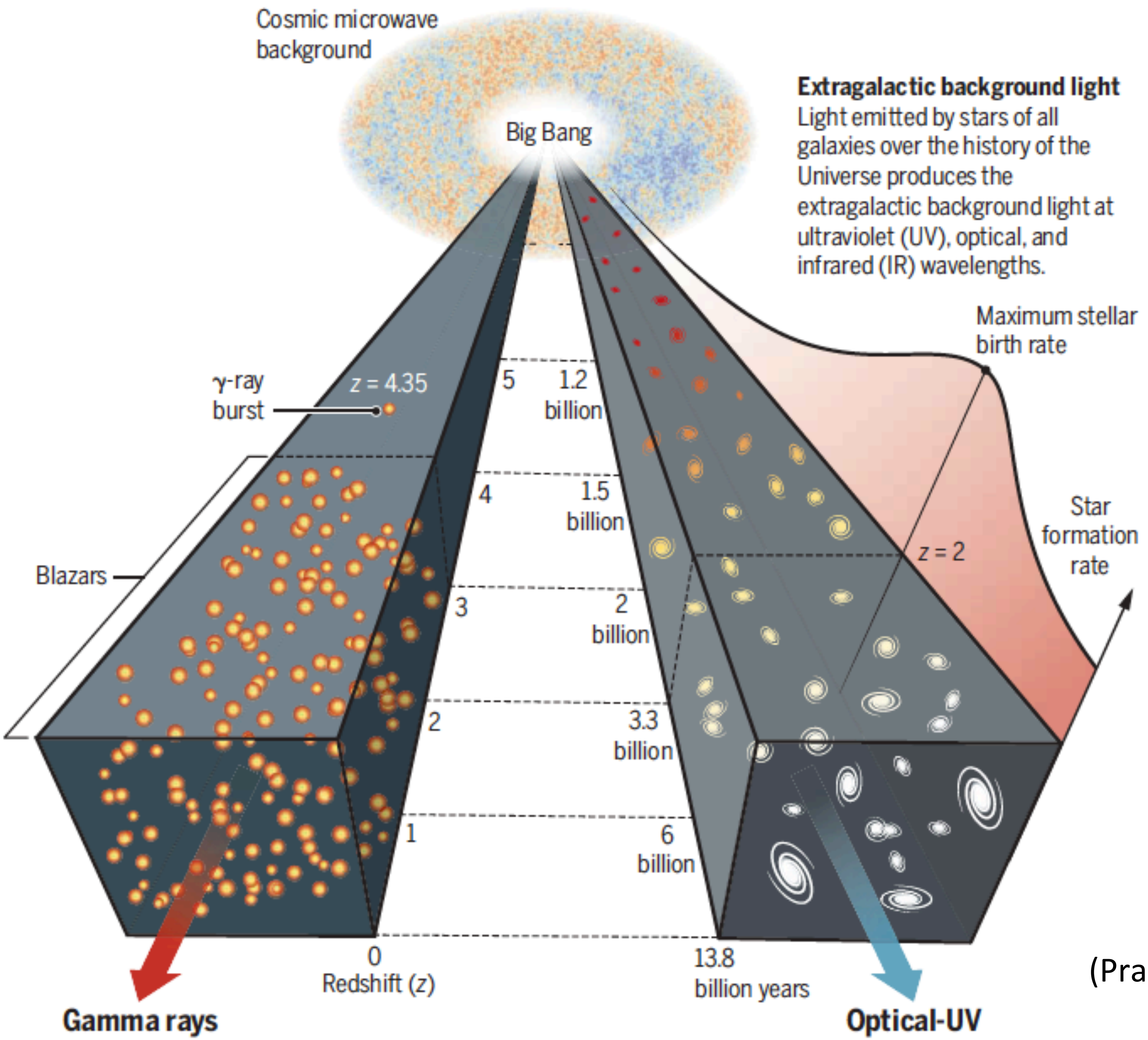
Attenuation of γ−rays

- γ-rays are effectively produced in EM and hadronic interactions
  - Energy spectrum at sources ~E^{-2}
- are effectively detected by space- and ground-based instruments
- effectively interact with matter, radiation ($\gamma\gamma \rightarrow e^+e^-$) and B-fields

The interaction with background photons in the Universe attenuates the flux of gamma rays

The "enemies" of VHE photons are photons near the optical region (Extragalactic Background Light, EBL)





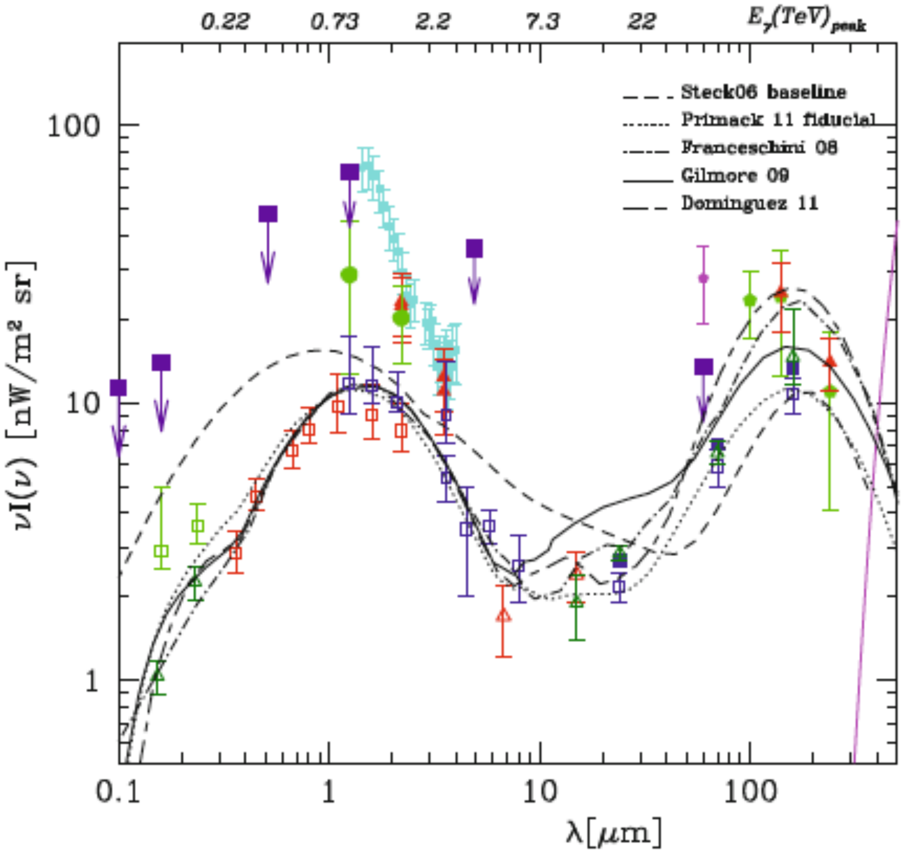
(Prandini 2018)

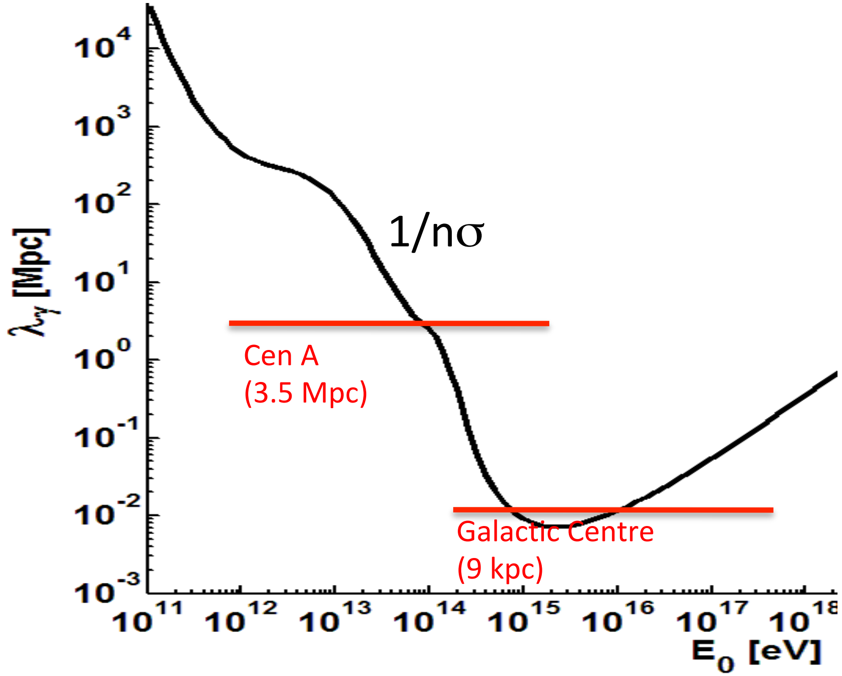
$$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$$

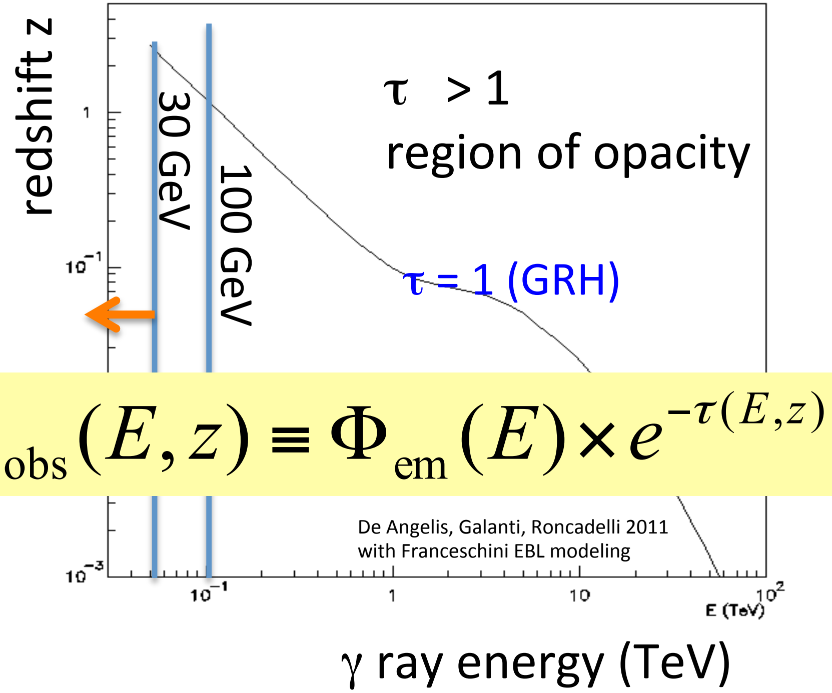
$$\sigma(\beta) \sim \frac{2\pi\alpha^2}{3m_e^2} W(\beta) \simeq 1.25 \cdot 10^{-25}\, W(\beta)\ \mathrm{cm}^2$$

$$W(\beta) = (1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ \ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

Max for: $\epsilon(E) \simeq \left(\frac{900\ \mathrm{GeV}}{E}\right)\ \mathrm{eV}$

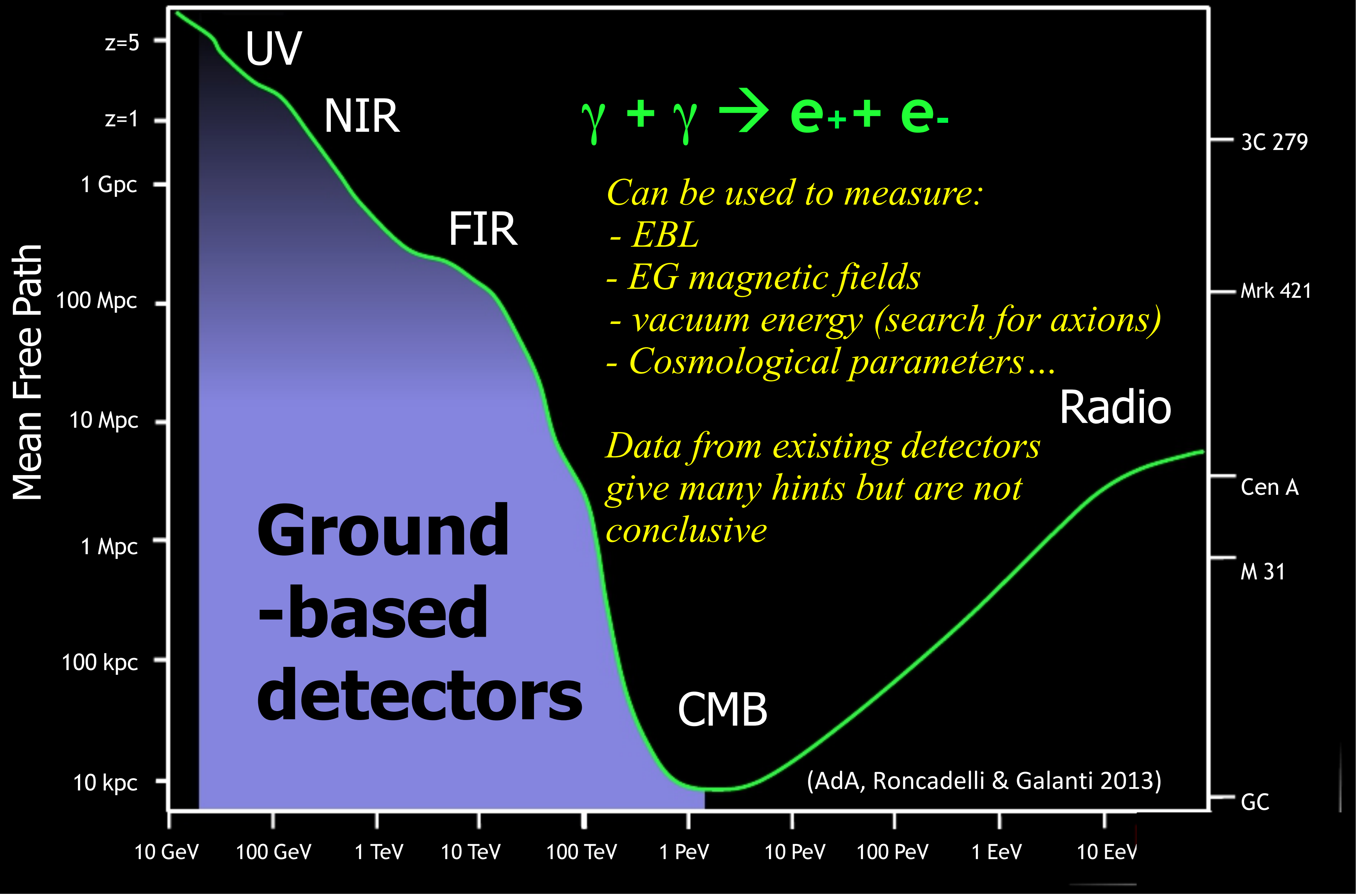




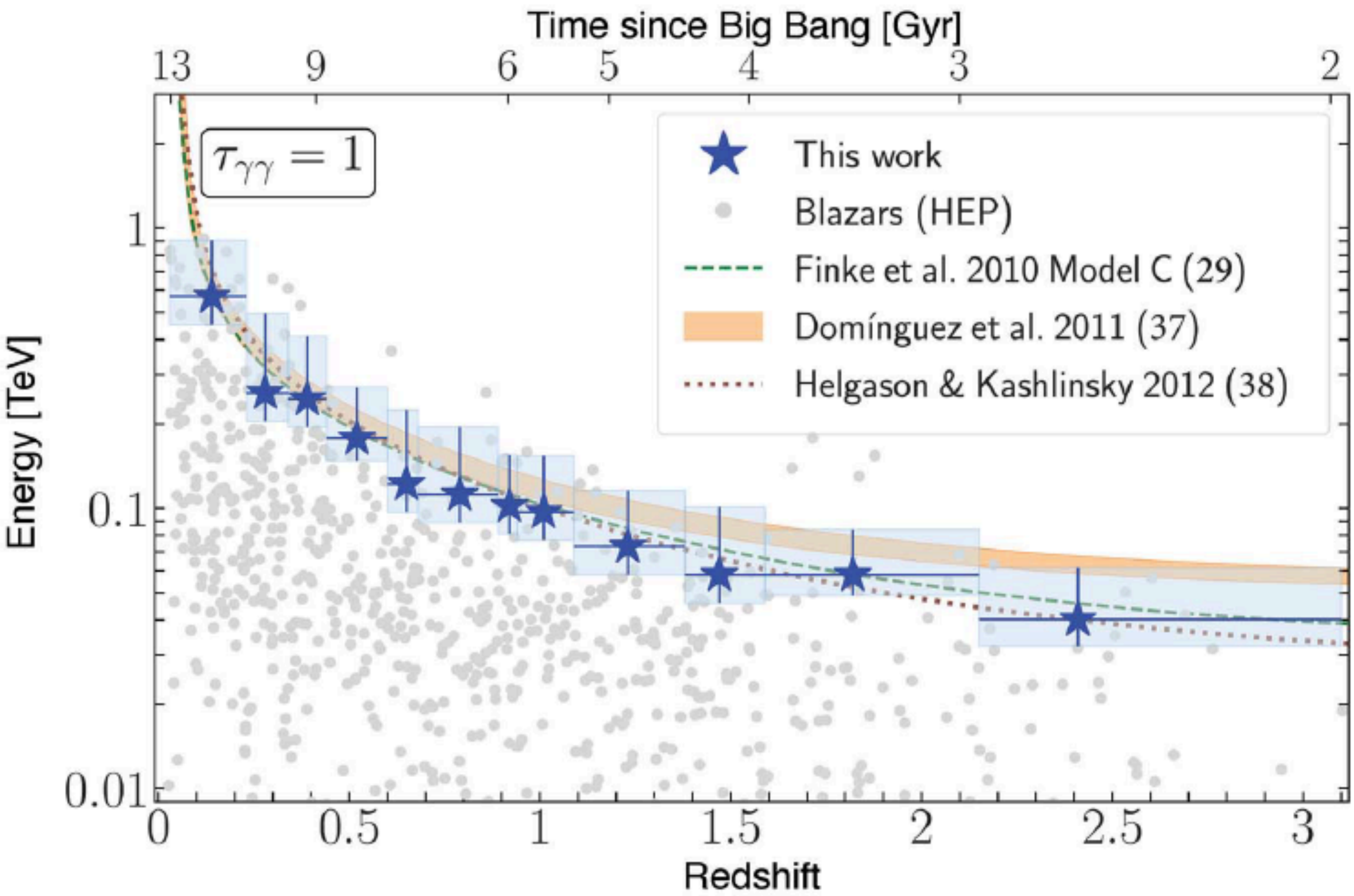


$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

The γ horizon: nuisance and resource

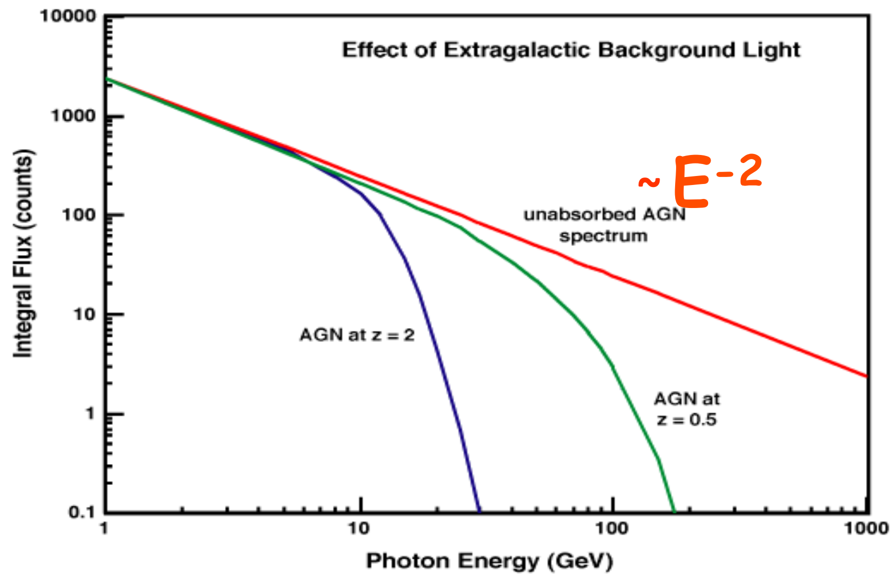


739 VHE sources by Fermi and gamma horizon



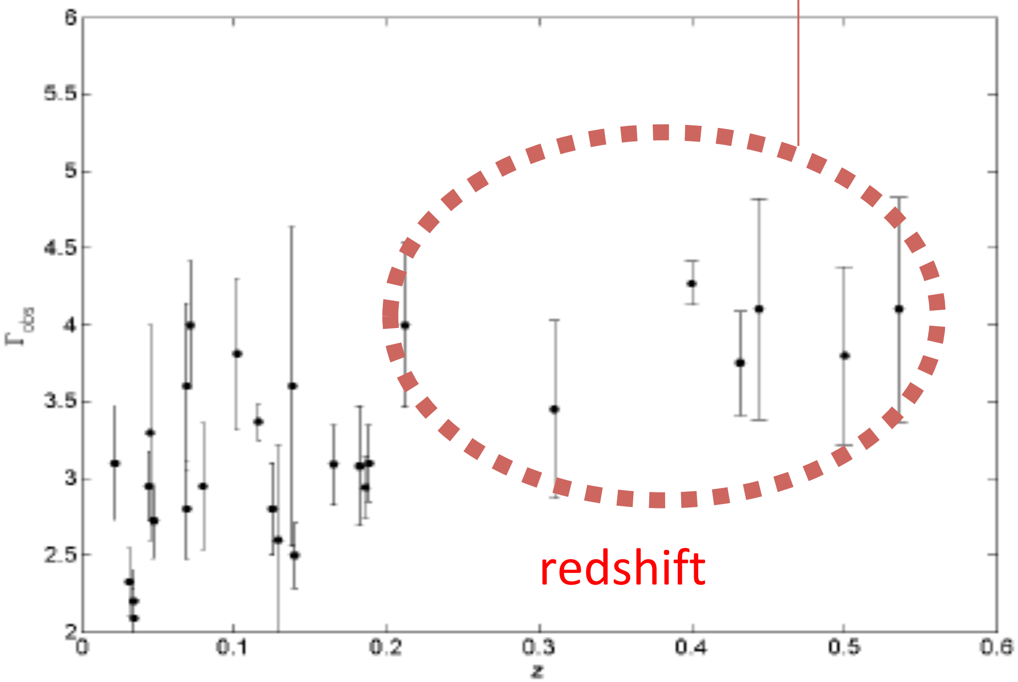
Some tension between AGN observations and theory

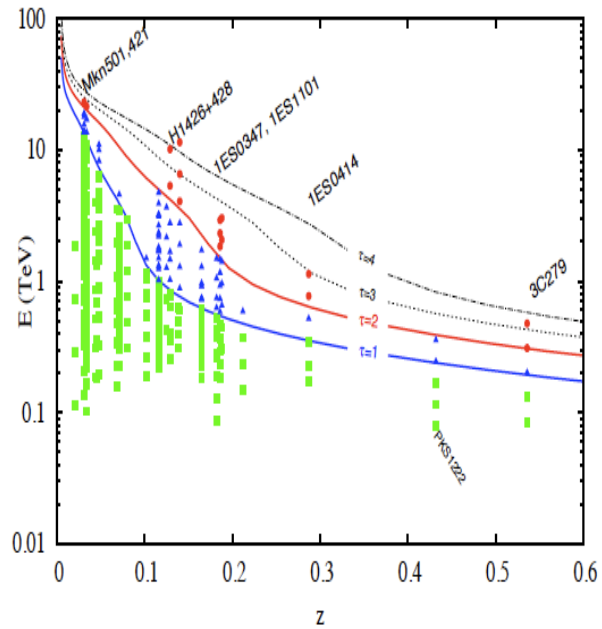
Measured spectra affected by attenuation in the EBL:



Selection bias?
New physics ?

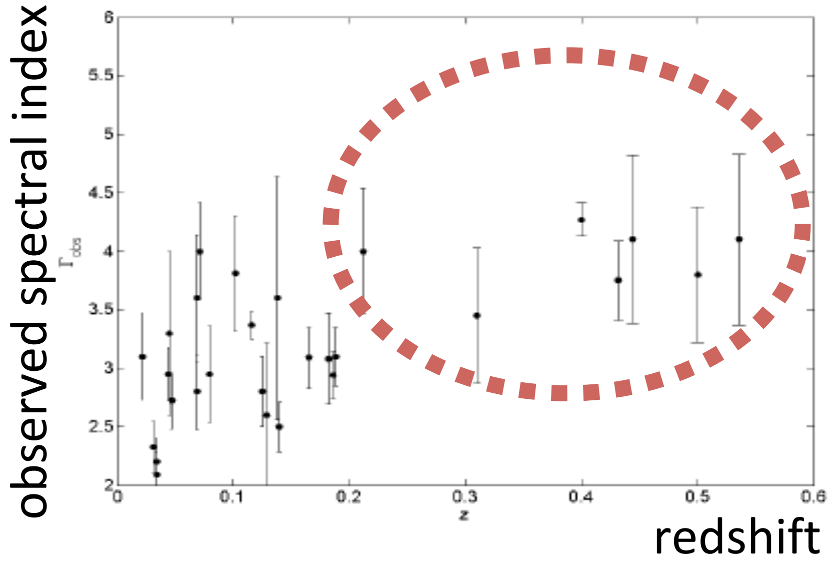
observed spectral index

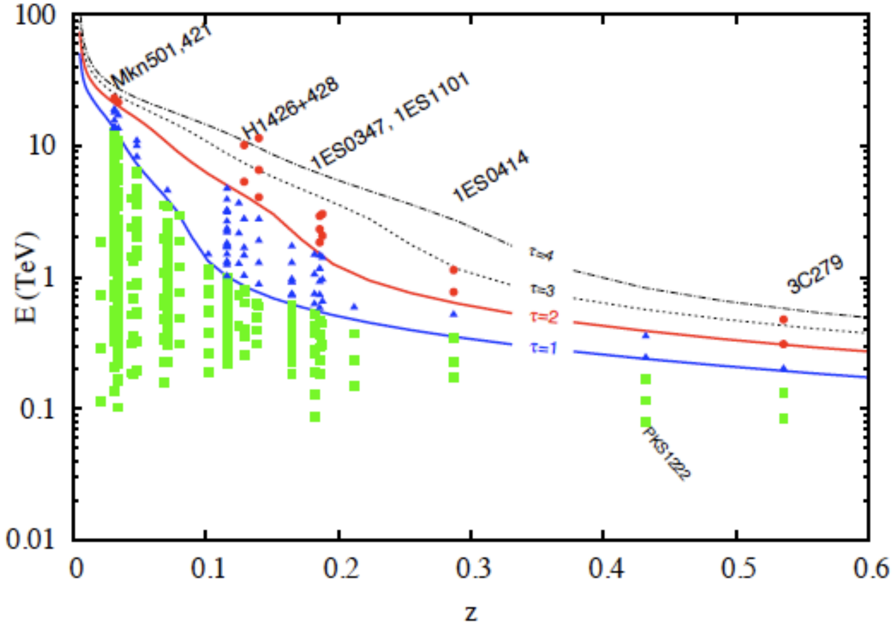




(DA, Galanti, Roncadelli; PRD 2011; PRD2007; Hooper&Serpico, PRL 2008; …)

If there is a problem





Explanations from the standard ones

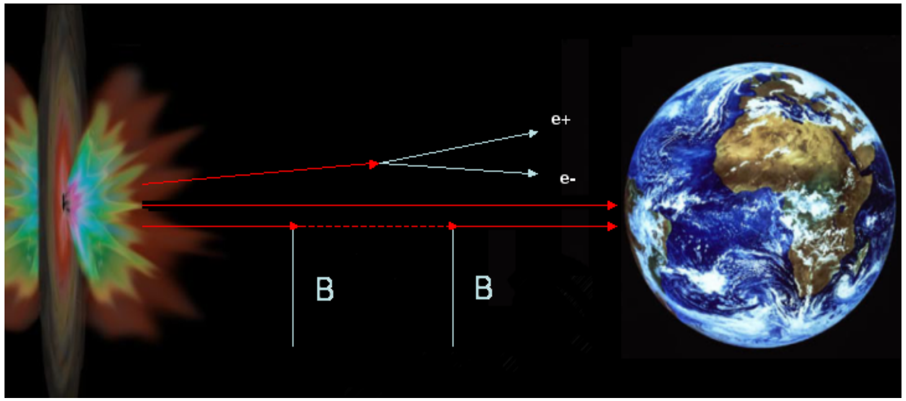
- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of “wrong” outliers

to almost standard

- γ-ray fluxes enhanced by relatively nearby production by interactions of primary cosmic rays or ν from the same source

to possible evidence for new physics

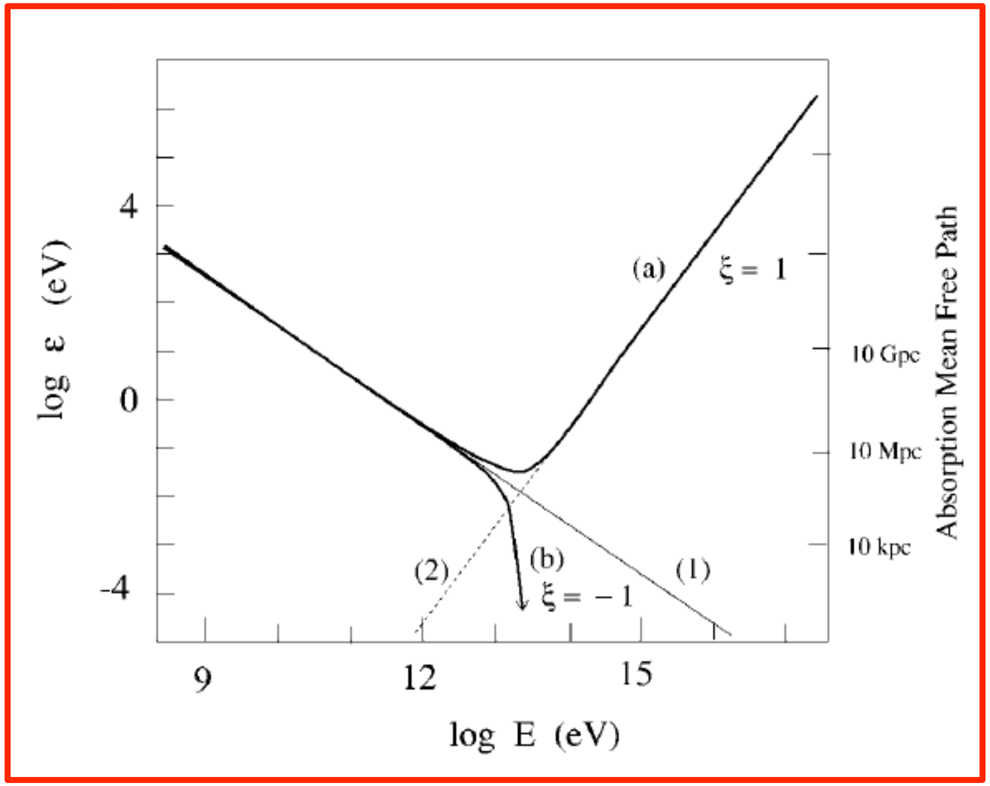
- LIV?
- Oscillation to a light particle coupled to the photon?



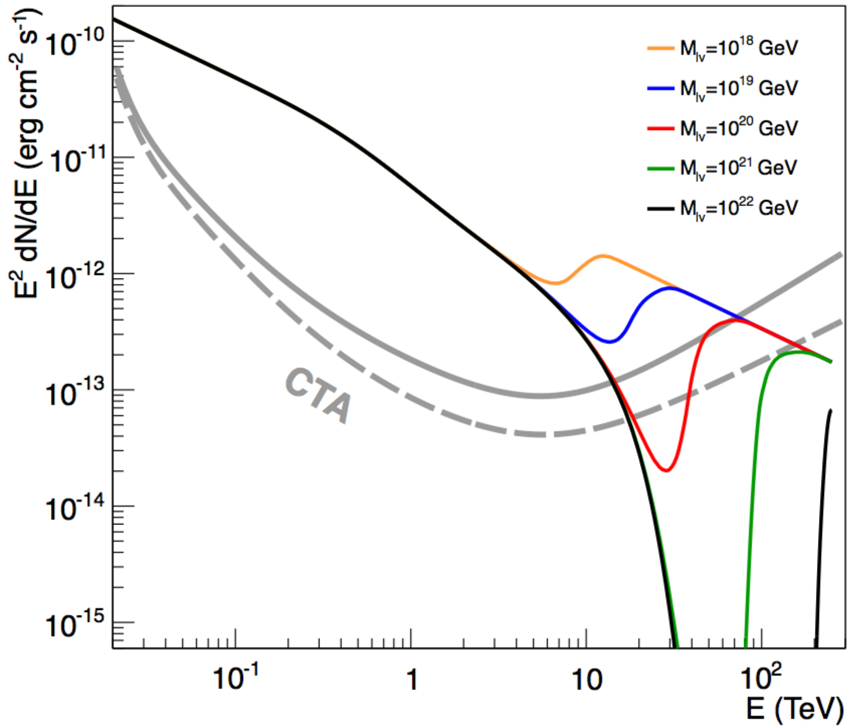
Kifune 1999: modified GRH due to LIV (increases or decreases depending on the sign of ξ)

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)



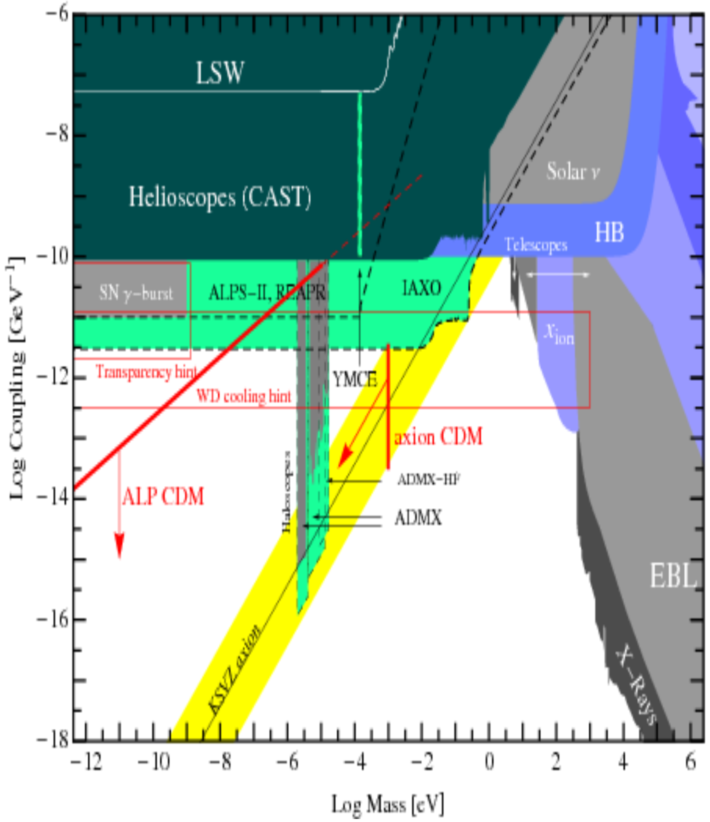
But: factorization questioned (Liberati, Sonego, ...)

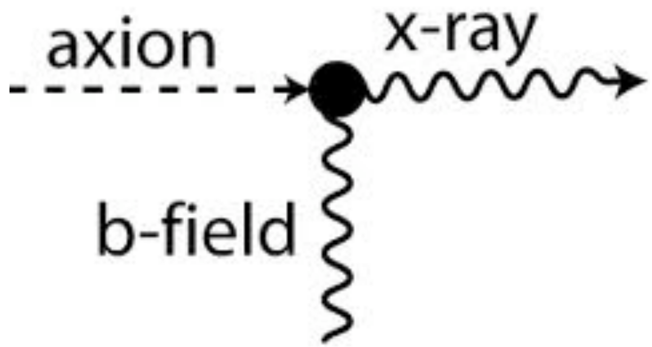


Fairbairn et al, arXiv:1401.8178 (2014)

Axions and ALPs

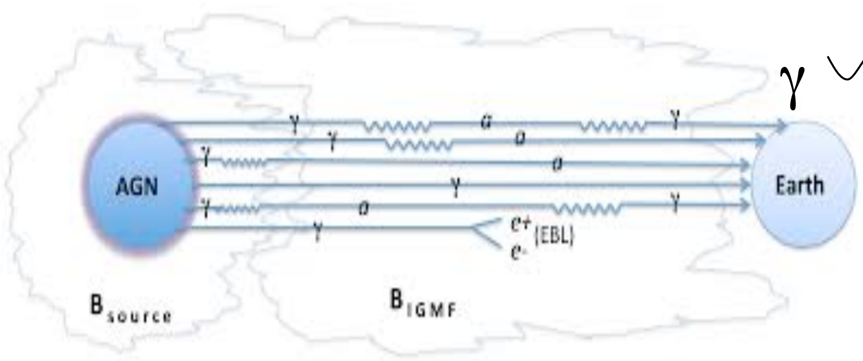
- The "strong CP problem": CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Called the "axion" from the name of a cleaning product
  - Pseudoscalar, neutral,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

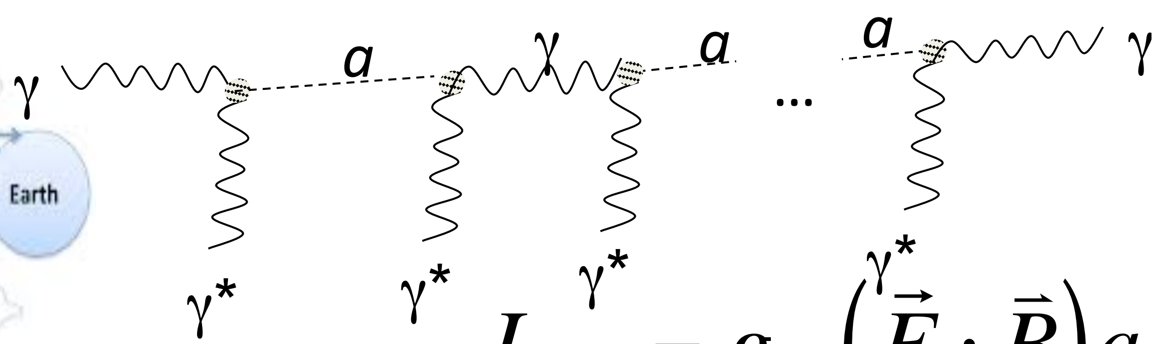




$$\frac{m}{1\,\mathrm{eV}} \simeq \frac{1}{M/6 \times 10^6\,\mathrm{GeV}}$$

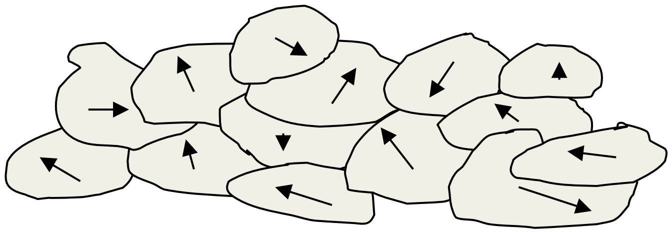
The photon-axion mixing mechanism





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

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

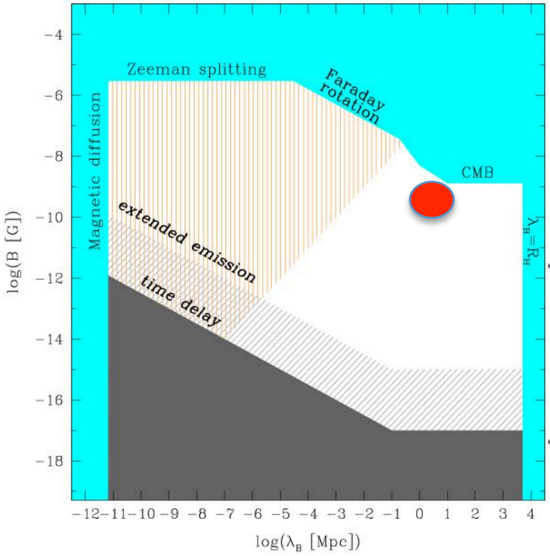


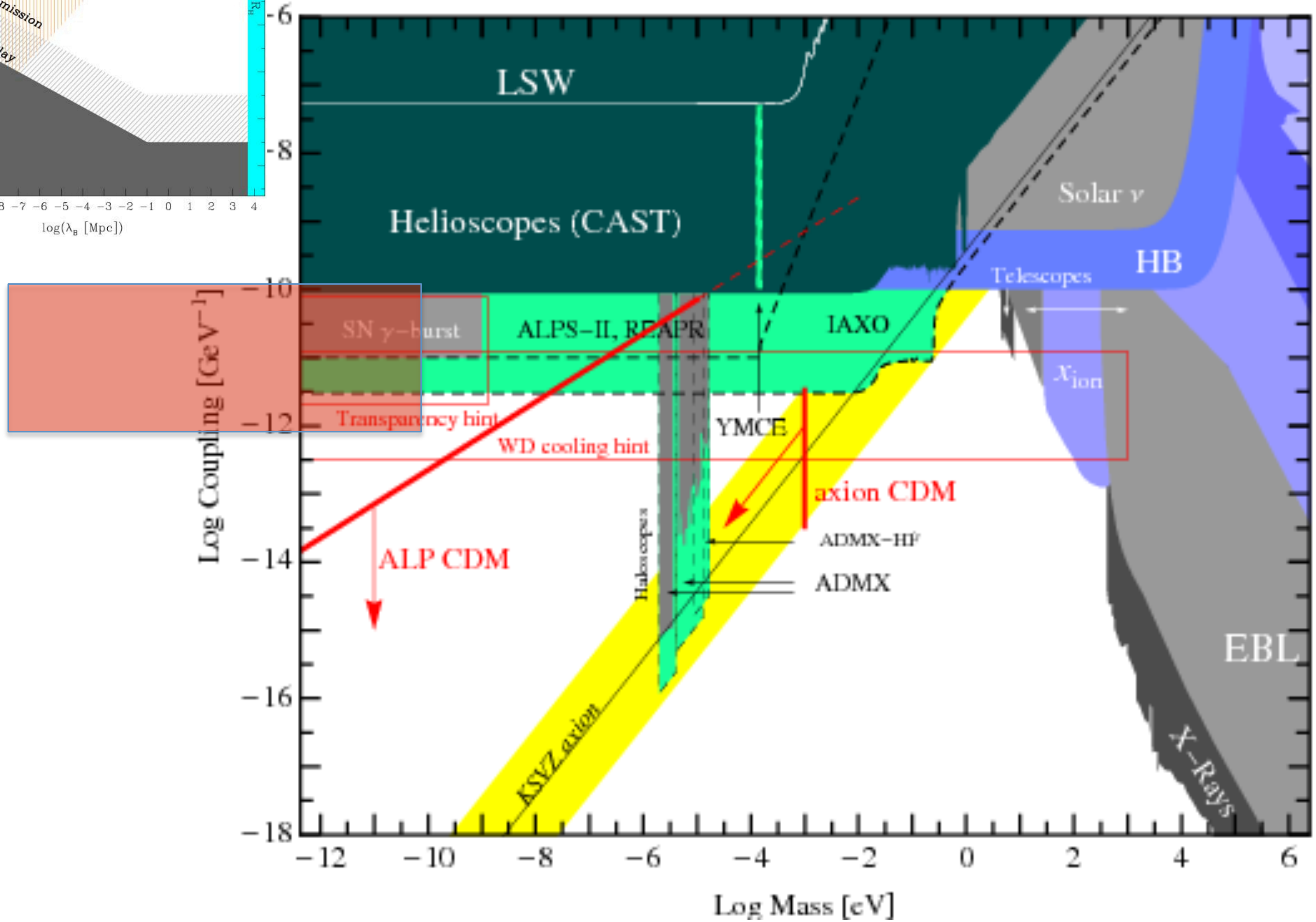
$$P_{\gamma\to a} \approx NP_1$$

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

- 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

Preferred values for m, g (DARMA)





2b. DARK MATTER

Evidence for Dark Matter

- We have solid astrophysical evidence that the dynamics of some astrophysical objects cannot be explained on the basis of the current gravitational theory unless yet undiscovered sources of gravity exist
  - Stars in the halos of galaxies (including the Milky Way)
  - Dwarf SPHeroidal galaxies
  - Clusters of galaxies (the first evidence)
- The most economical solution is to assume that new nonluminous, "weakly" interacting (=> neutral), long-lived on the Hubble scale ($\tau >> 10^{18}$ s; $\tau > 10^{23.5}$ s?), particles exist
- Should be ~5x the visible matter, and
  - Accumulate where standard matter accumulates (centers of galaxies, DSPHs)
  - Be dominant in halos of galaxies
  - Have, maybe, its own cusps
- The SM does not provide candidates for such particles

The WIMP paradigm (miracle)

- No sound proposal of modifications of the theory of gravity explained all observations
- It is then natural to assume that the missing gravity is due to new neutral, and “weakly” (could be also only gravitationally) interacting particle(s)
- Total energy density required for these particles is ~1.5 GeV/m^3 in average

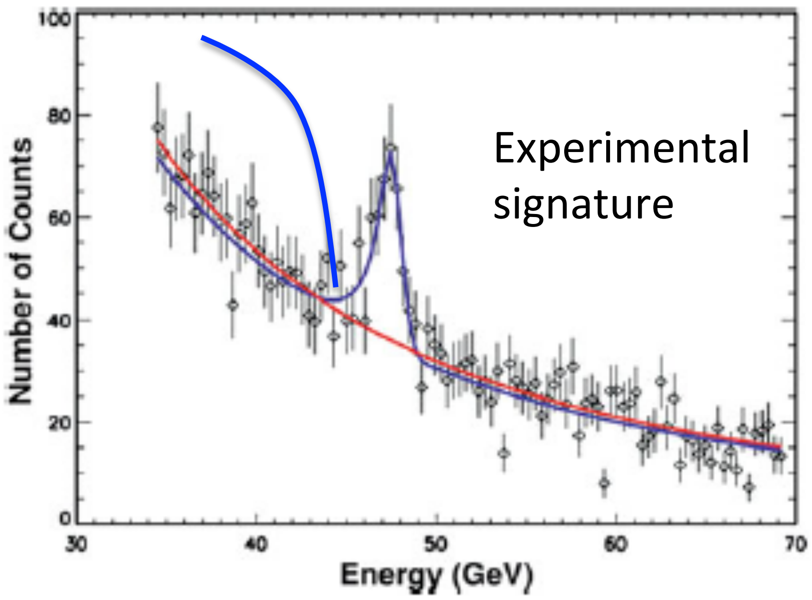
- If there is just one kind of particle, weakly interacting, a miracle occurs
  - For a mass between 45 GeV and O(10 TeV) this hypothetical particle explains the whole “missing mass” and is consistent with the current cosmological paradigm
  - It could not have been detected by accelerators
  - We can compute σ ($\chi\chi$ -> anything), $\langle\sigma v\rangle \sim 3\ 10^{-26}\ cm^3/s$ (“benchmark” x-section)

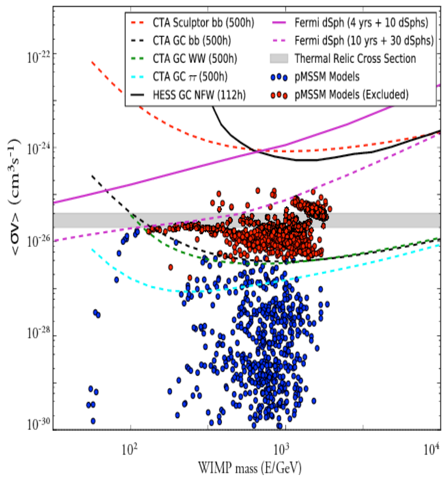
- This hypothetical particle is dubbed WIMP, and (extra miracles):
  - Can be observed into photons, neutrinos, antimatter
  - One such candidate is predicted by SUSY: the neutralino

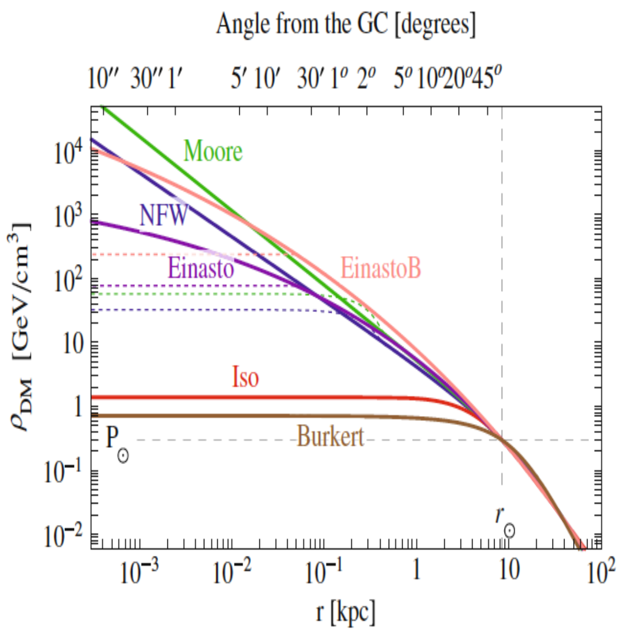
WIMP Dark Matter: production of SM partices

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

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



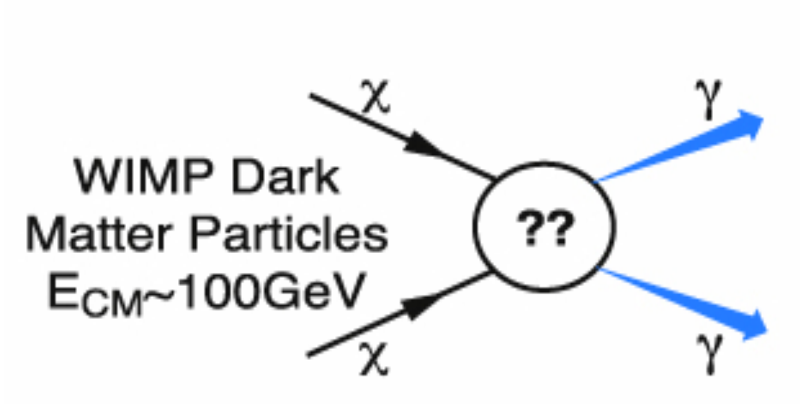


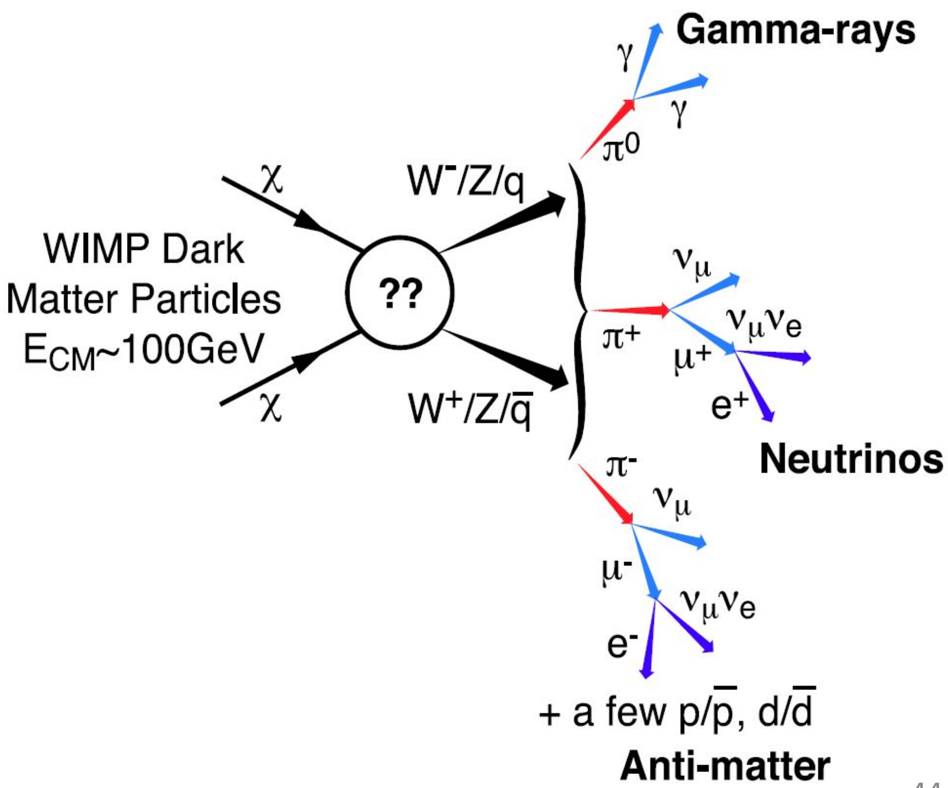


- *J*-factor includes distance, i.e., *J*-factor would decrease by four if a point-like source were twice as far away => look as close as possible
- The factor of $1/m_\chi^2$ is due to the fact we express the *J*-factor as a function of mass density (which we can measure), not number density
- We usually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

How do WIMPs produce photons?

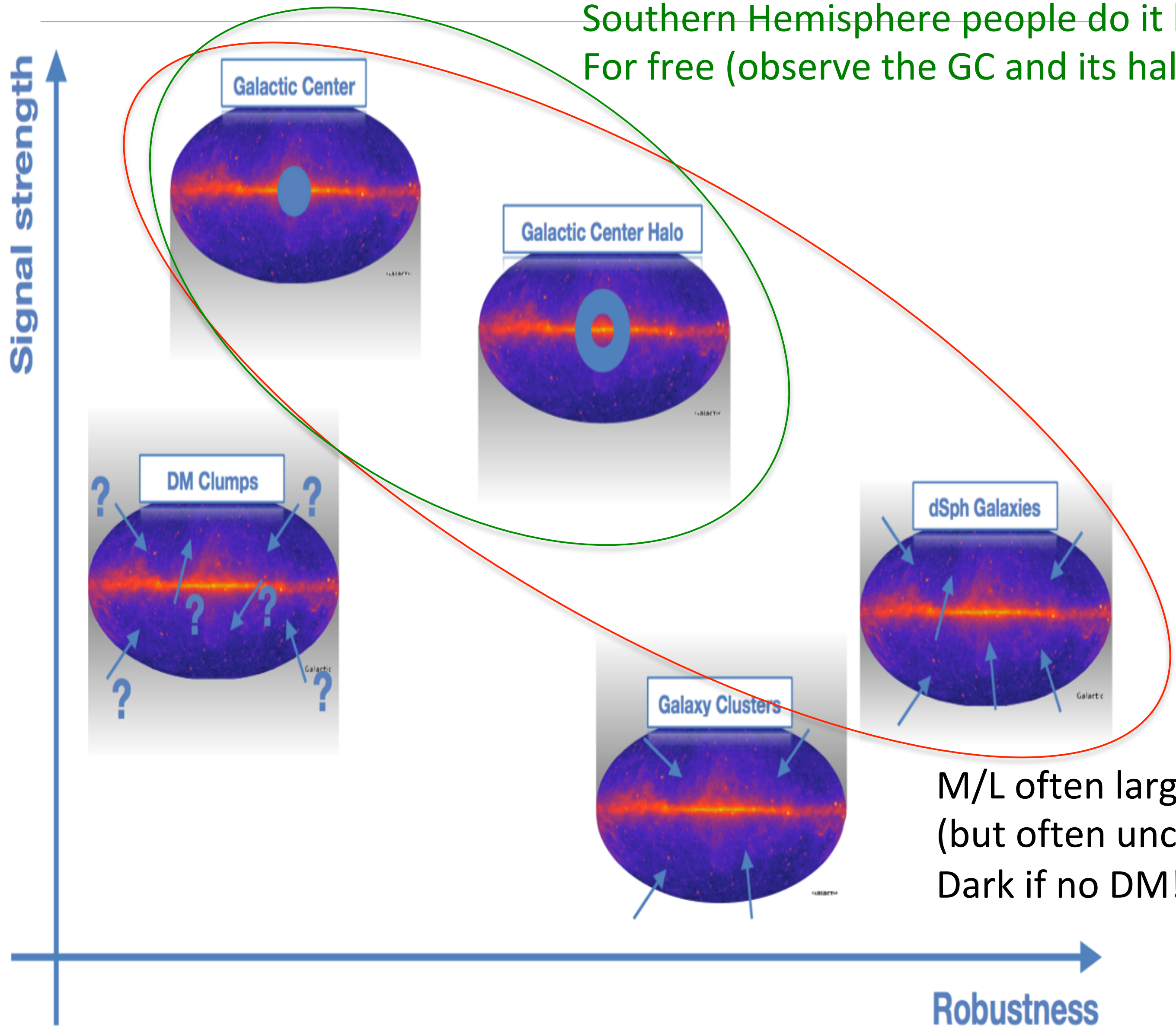
- The energy “blob” from χχ annihilation (thermal eq., neutralino) might decay:
  - Directly into 2γ, or into Zγ if kinematically allowed. Clear experimental signature (photon line), but not very likely (requires one loop). In SUSY, BR depends on the lightest neutralino composition.
  - Into a generic f-fbar pair, then generating a hadronic cascade with π^0 decaying into photons in the final state.
    - Relation with neutrinos





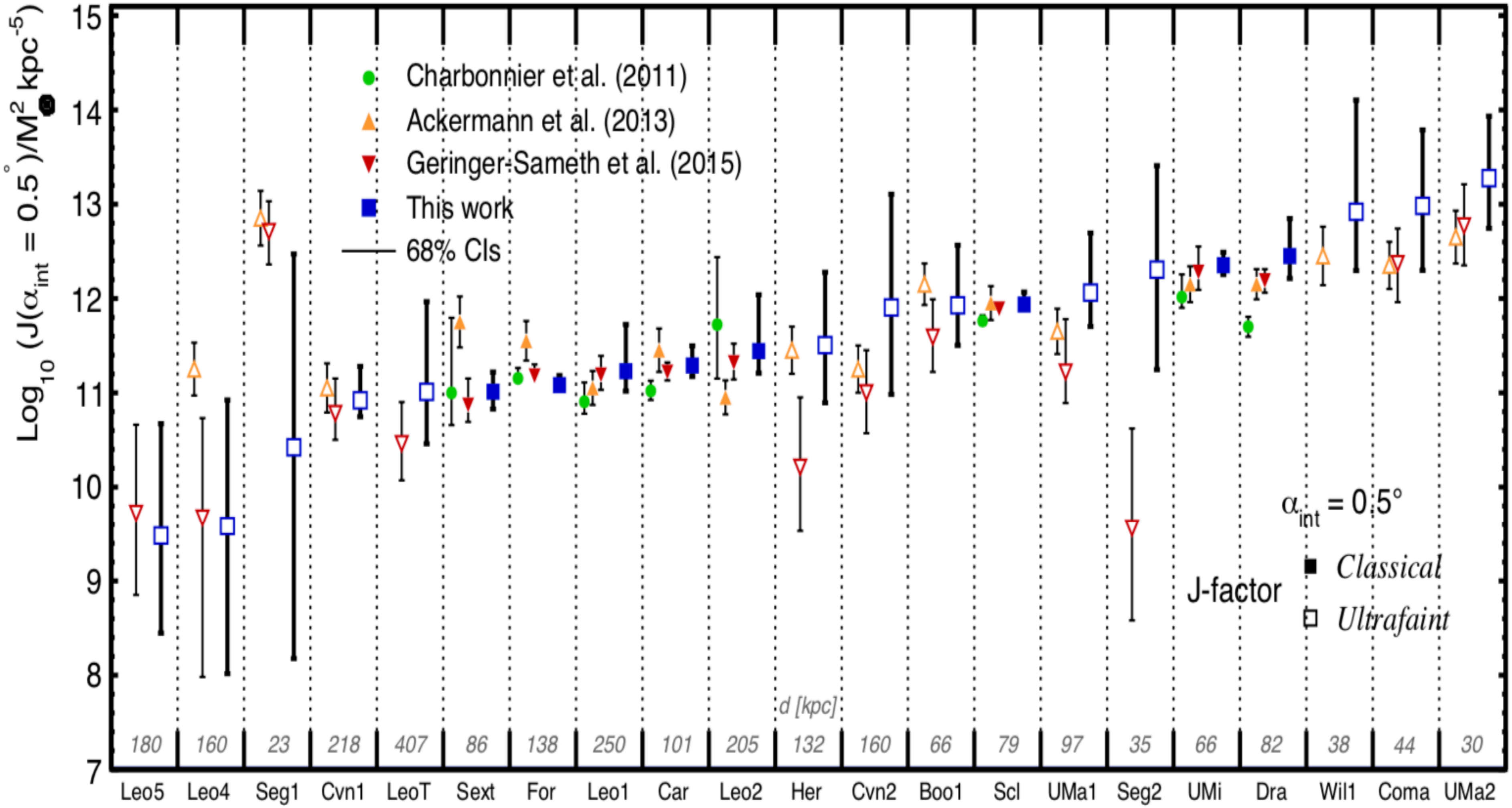
Cherenkov Telescopes: where to point?

Southern Hemisphere people do it better
For free (observe the GC and its halo anyway)



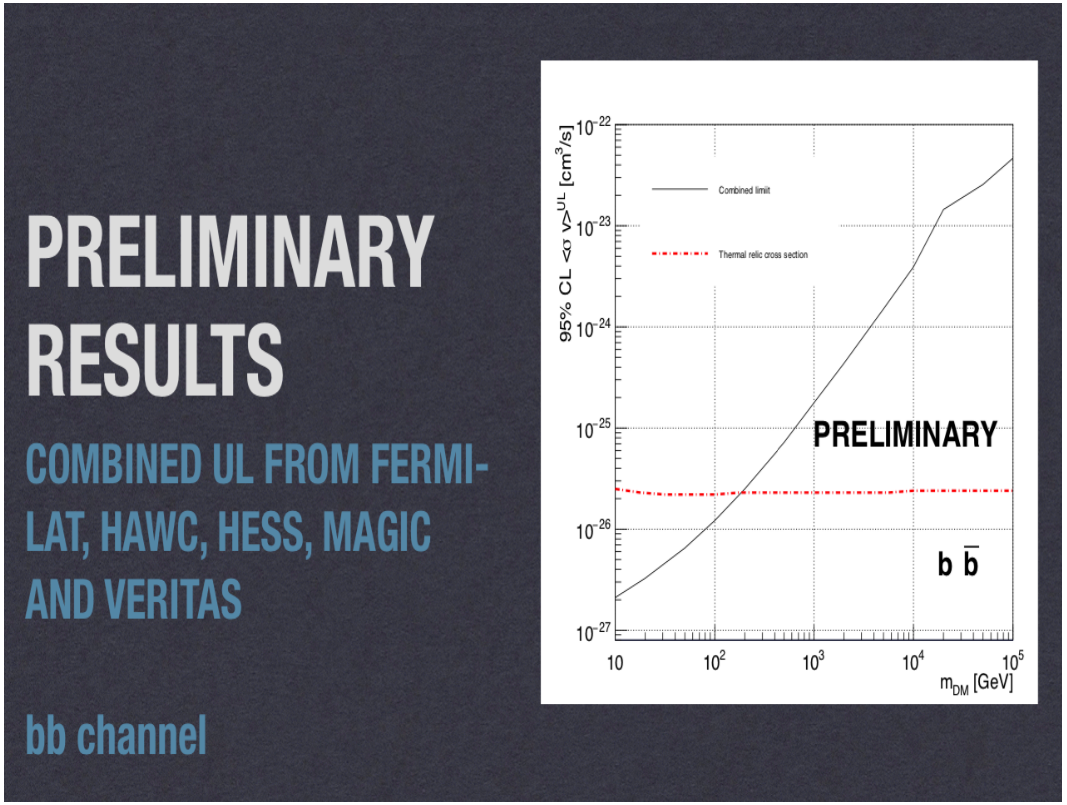
M/L often large
(but often uncertain)
Dark if no DM!

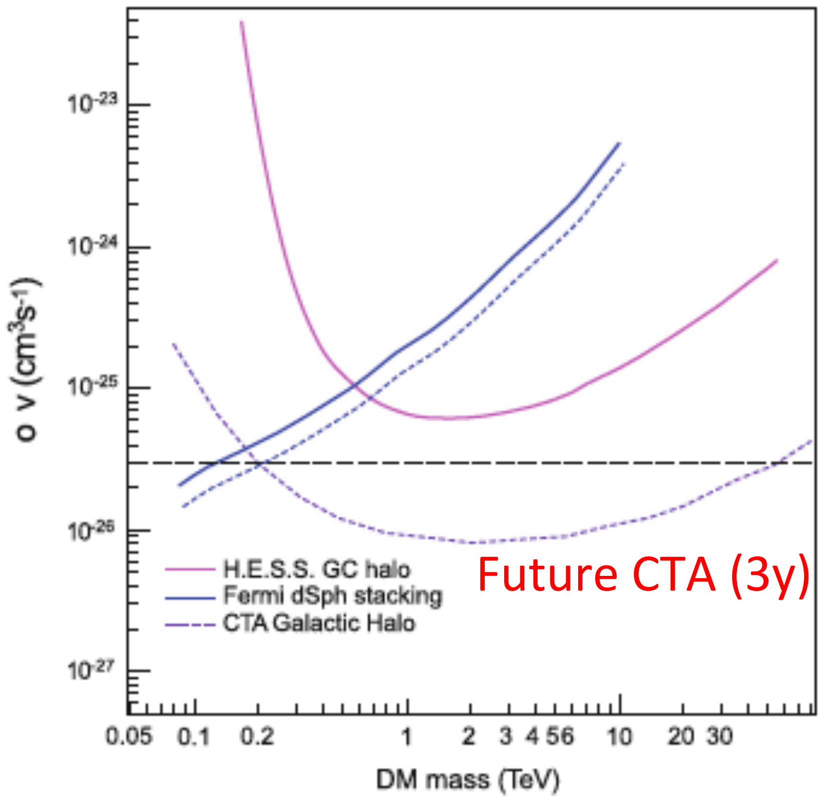
DSPHs: a large effort, often "useless" (large uncertainties on M/L)



Now, a common DSPH project: MAGIC (300h), VERITAS (300h), HESS (100h), Fermi & HAWC.

ICRC19: Fermi dominates DSPHs till ~25 TeV, full spectrum till ~800 GeV





- Conclusion:present instruments close to exhausting their potential. Fermi + EAS continue taking data anyway…
- Next generation instruments will conclude the exploration of the explorable (reach the benchmark x-section, but don't forget the strong hypotheses behind)

Summary

- Notable results on physics BSM during the last years thanks mostly to IACTs:
  - ALPs
  - WIMPs (or new heavy particles decaying into final channels involving photons)
  - Violation of Lorentz Invariance

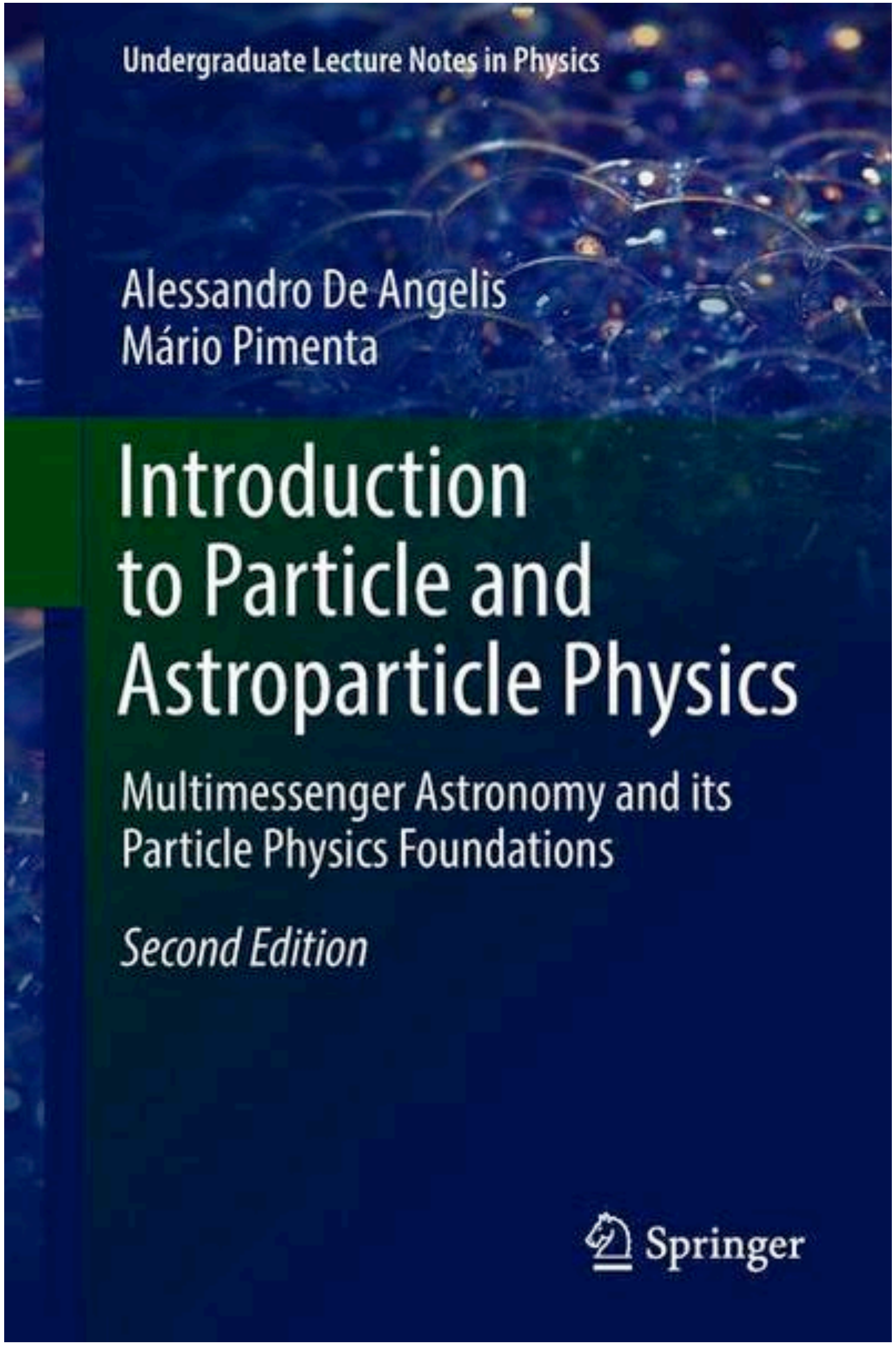
  But unfortunately just limits (apart from hint on ALPs)
- In the future, CTA and LHAASO/SWGO will explore the remaining space accessible to the VHE photon channels
- Let's hope we find new physics… Unfortunately if we don't find it, we cannot say much…

A reference for this talk (2018)

Download

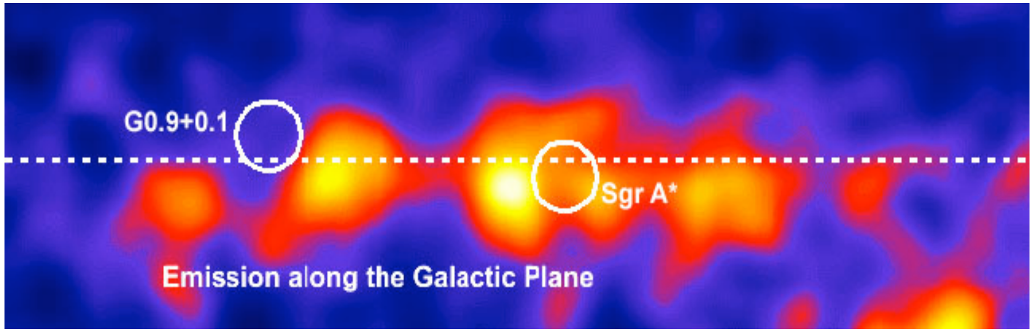
*** FOR FREE ***

at SpringerLink from CERN, Max-Planck, Padova, GSSI, …

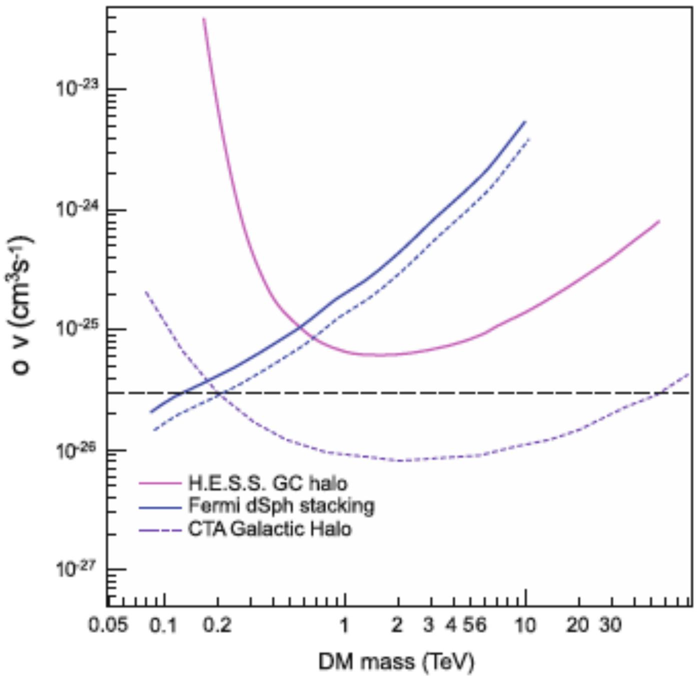


BACKUP

Searches for DM

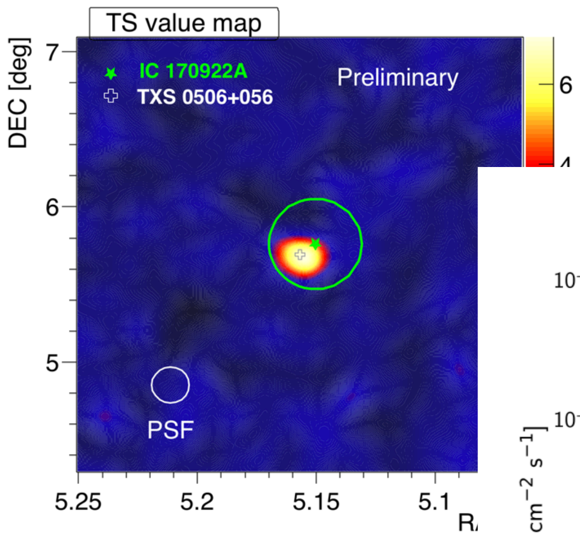


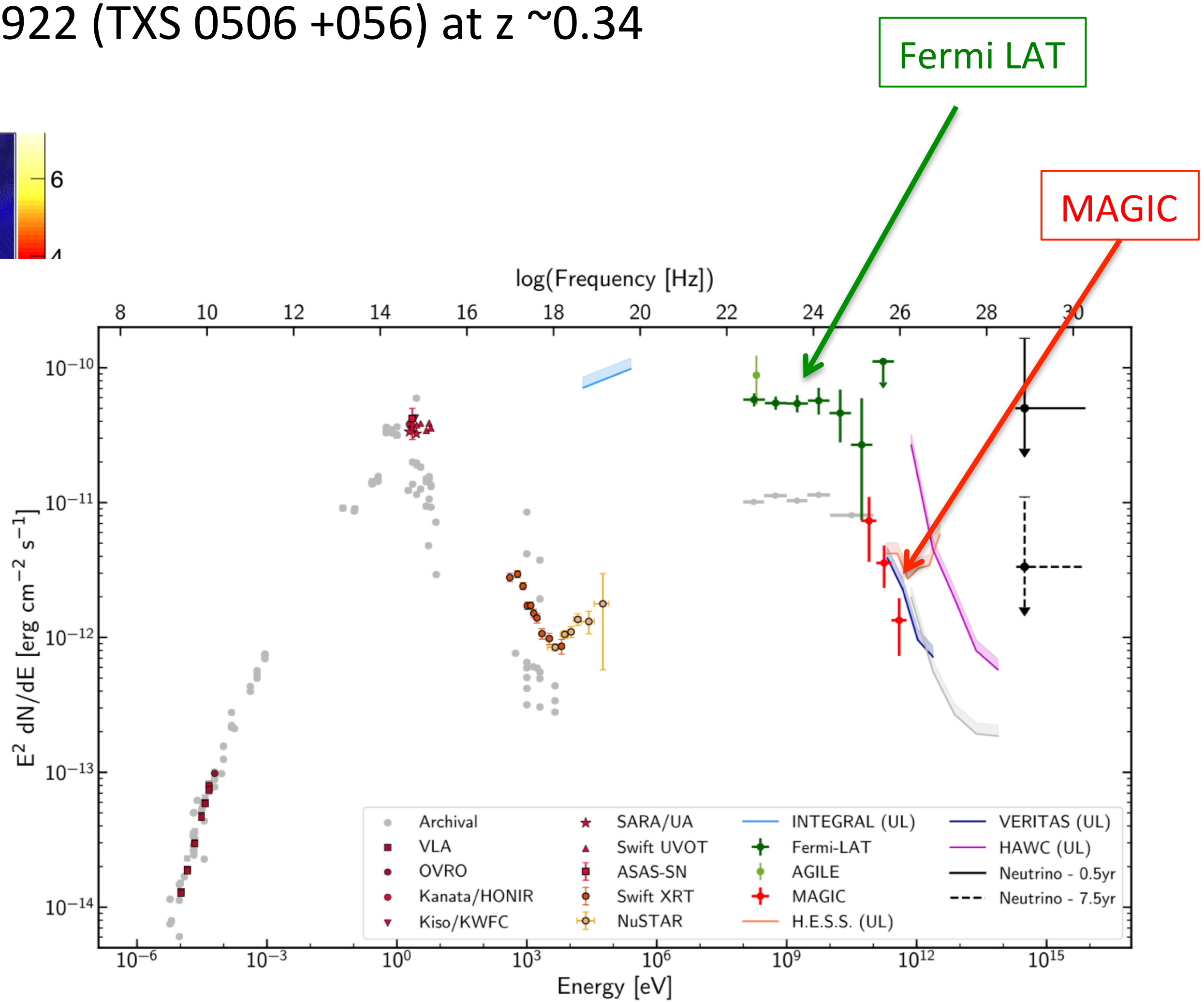
- Something marginal (maybe 0) from the GC at ~ 40 GeV (but very confuse region)
- No signal from dwarf satellites
- Room for sensitivity improvement



September 2017: the first identified AGN

- Are AGN sources of VHE neutrinos and thus of UHECR?
- The case of EHE 170922 (TXS 0506 +056) at z ~0.34





Neutrinos in an AGN

- Although $\sigma_{\gamma p}$ ~ 0.3 mb ~ $\sigma_{pp}/100$, photoproduction is favored in jets because the photon density is expected to be larger

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+\nu_\mu \rightarrow n\,e^+\nu_e\bar{\nu}_\mu\nu_\mu \end{cases}$$

- This process has obviously a threshold, and is dominated by the Δ pole:

$$E_p \sim 350\ \text{PeV} / (\varepsilon/\text{eV})$$

=> The creation of a neutrino (or gamma ray) from a photon gas at 5-10 eV requires protons at E_p > ~50 PeV

- E^{-p} in protons => E^{-p} in photons and neutrinos, rescaled by a factor ~10 – 20
  - By the way, a factor of ~20 also in hadroproduction around the PeV

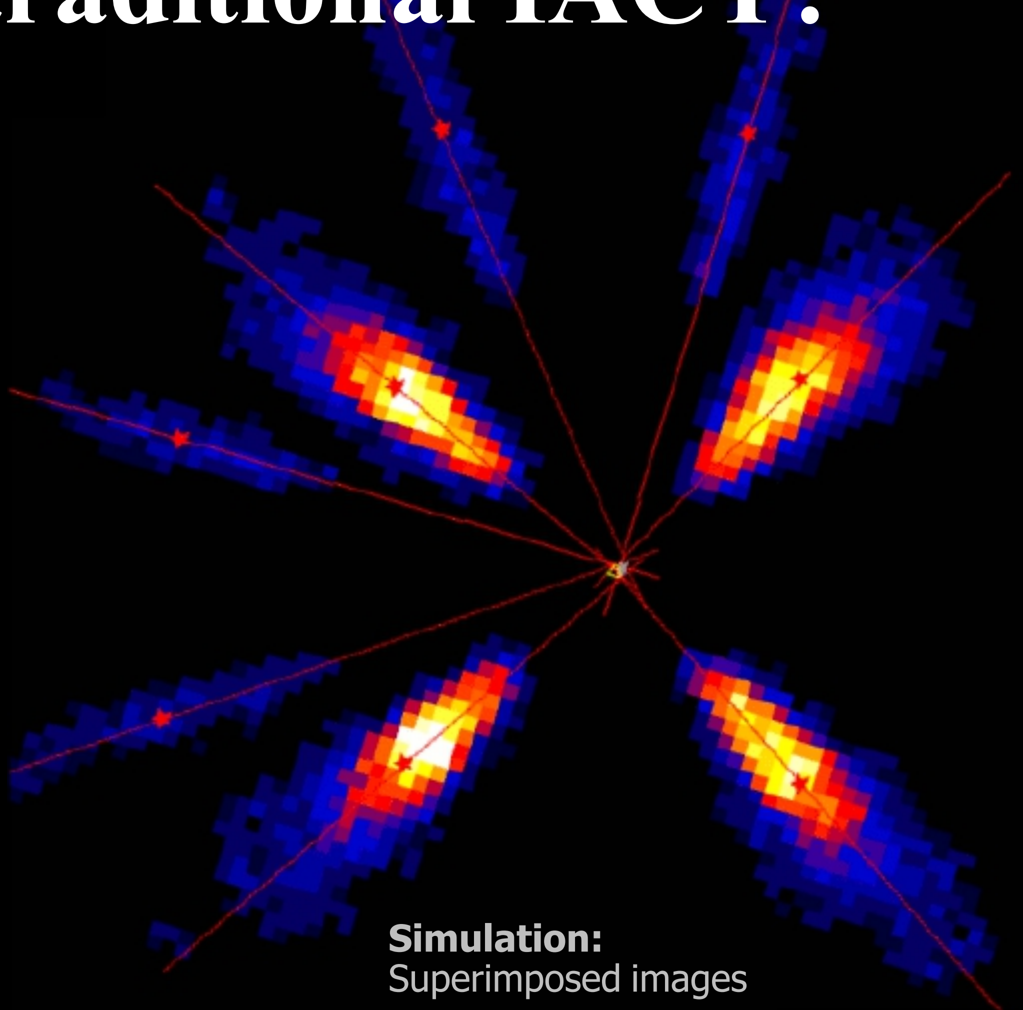
Why bigger and bigger?

Figures of merit of a Cherenkov telescope

- Sensitivity: effective area (effective area covered,
  => ~ number of telescopes)
- Angular resolution: number N of telescopes
  - Still we use small N (cost: 1-10 MEUR/telescope)
- Serendipity: FoV, Duty Cycle
- Threshold: Area, Efficiency $E_{threshold} \propto \sqrt{\frac{\phi \Omega \tau}{\epsilon A}}$

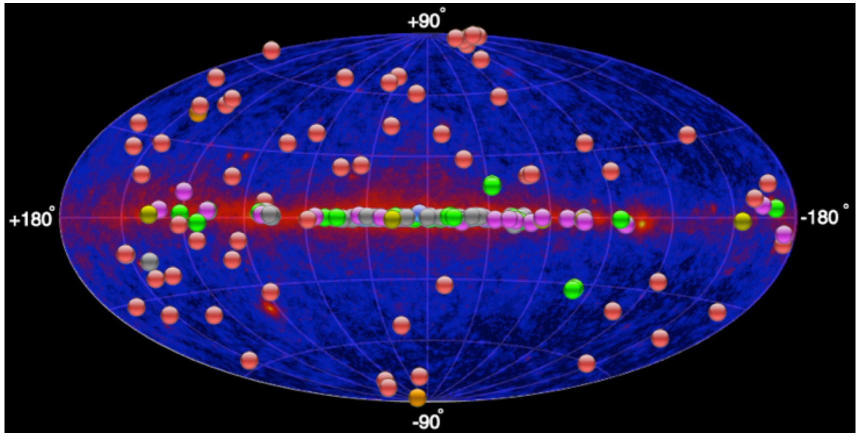
The 20 GeV- 100 TeV region: how to do better with traditional IACT?

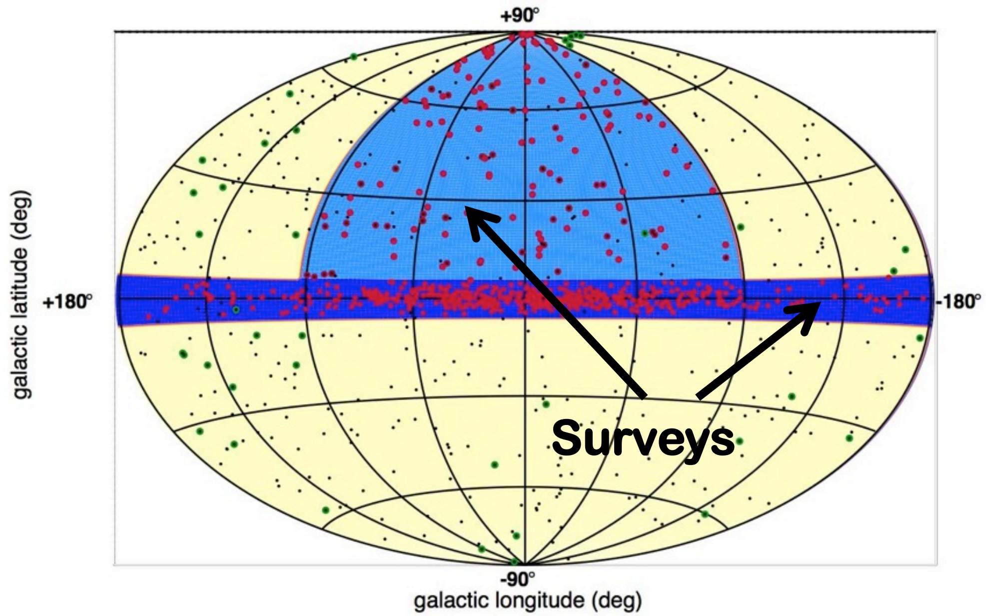
- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power

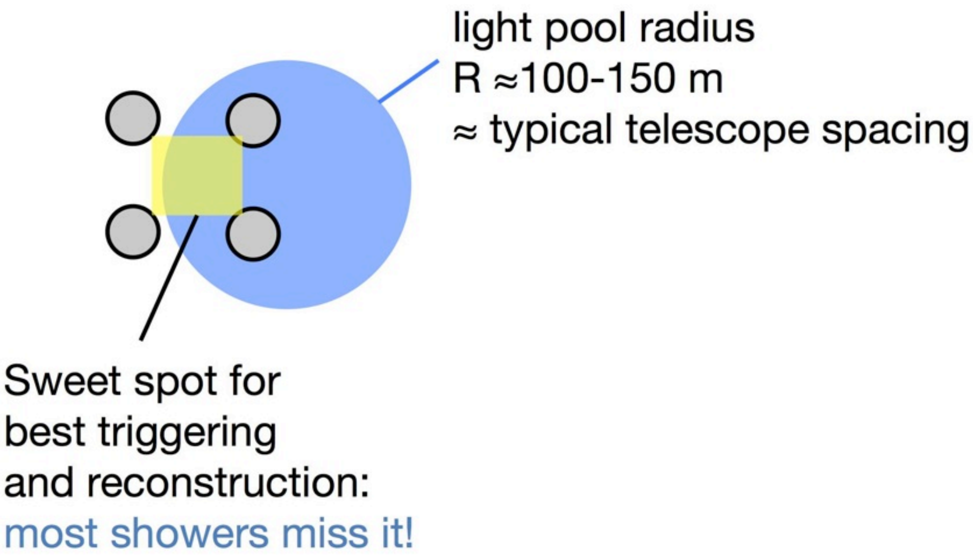


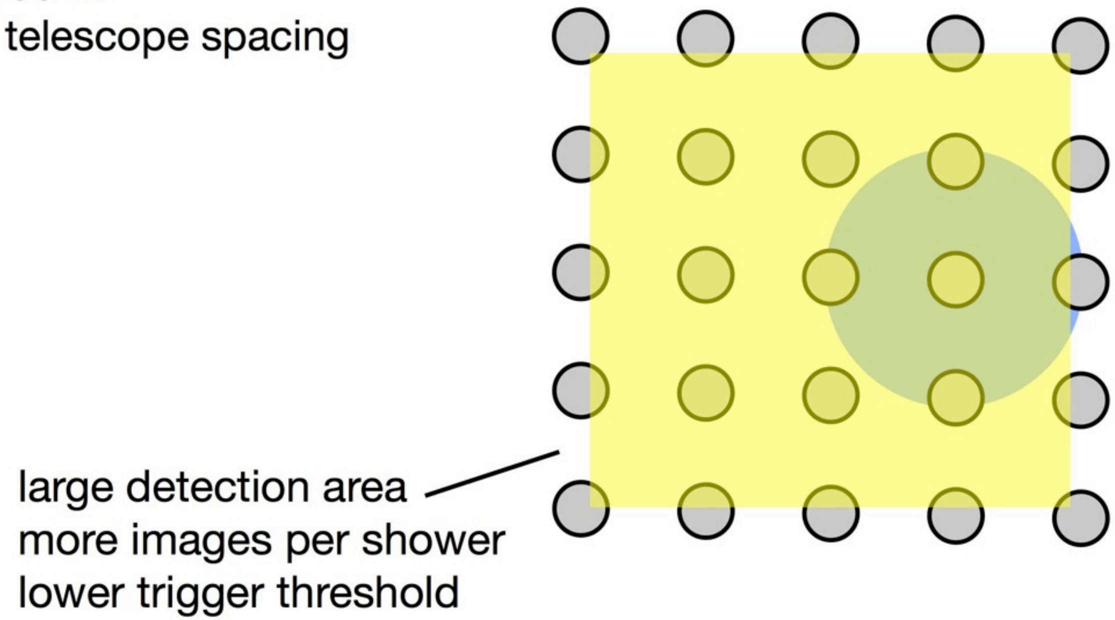
☛ The CTA solution: More telescopes !

From current arrays to CTA

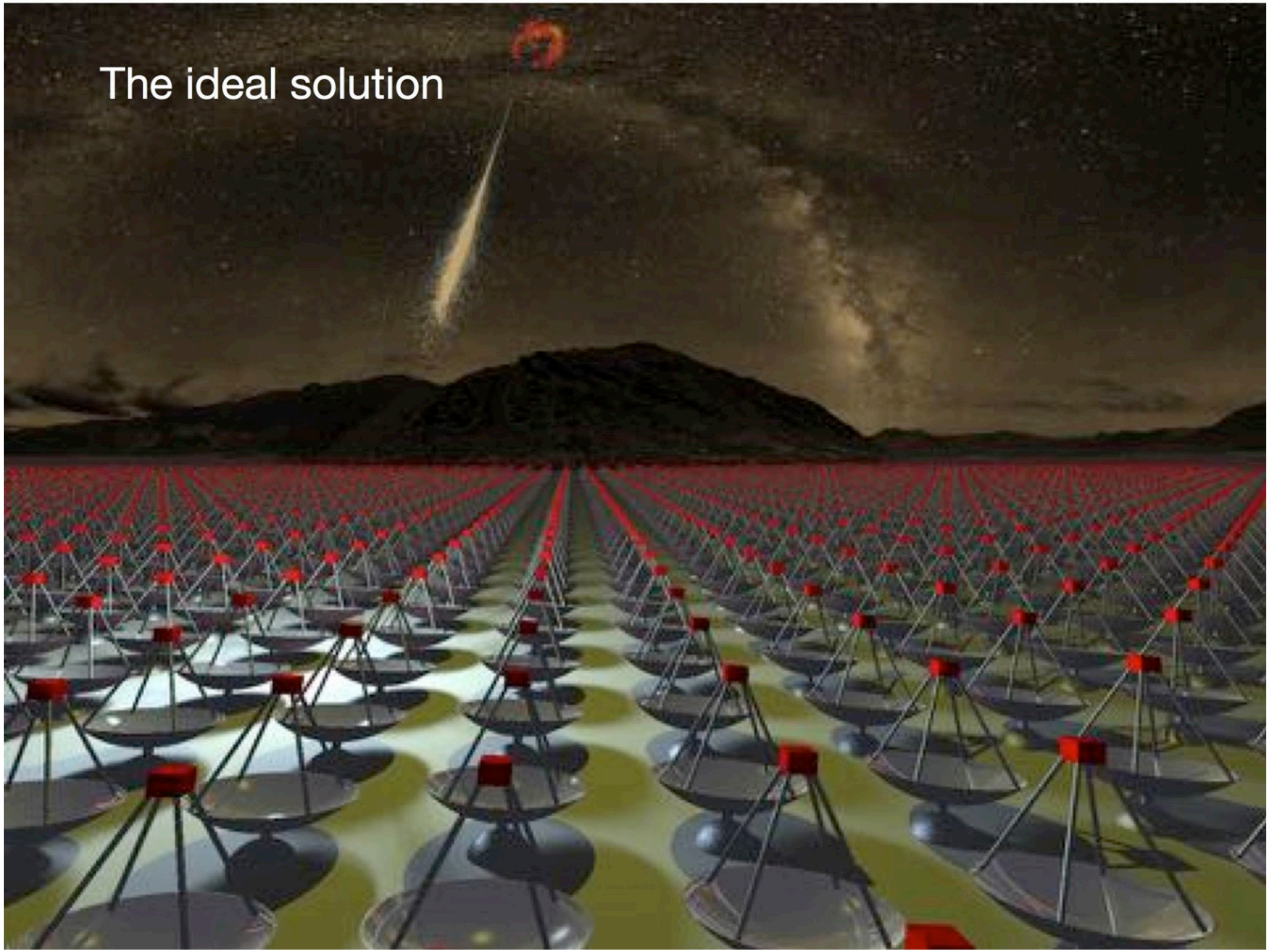






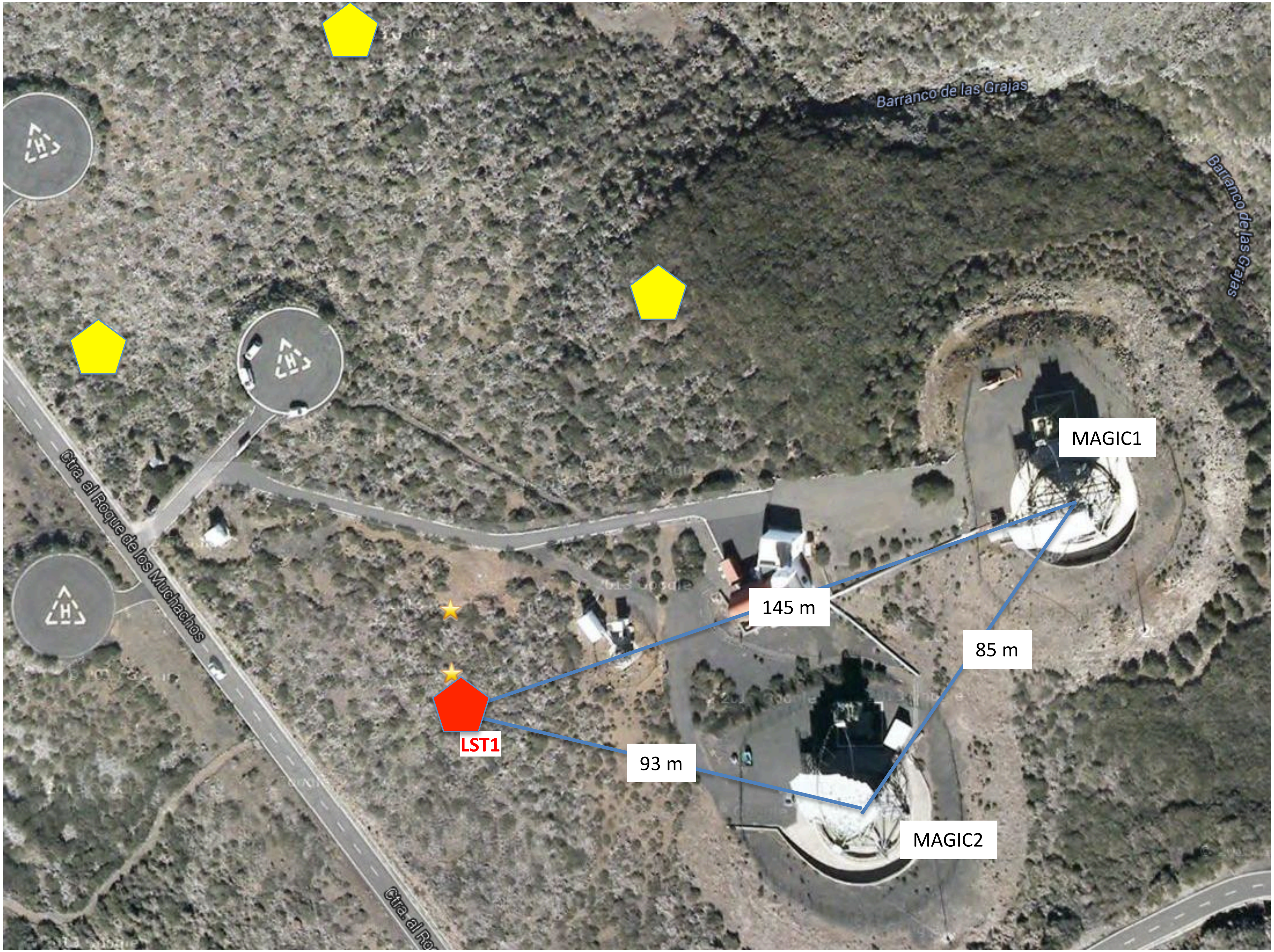


A next generation VHE facility



W. Hofmann

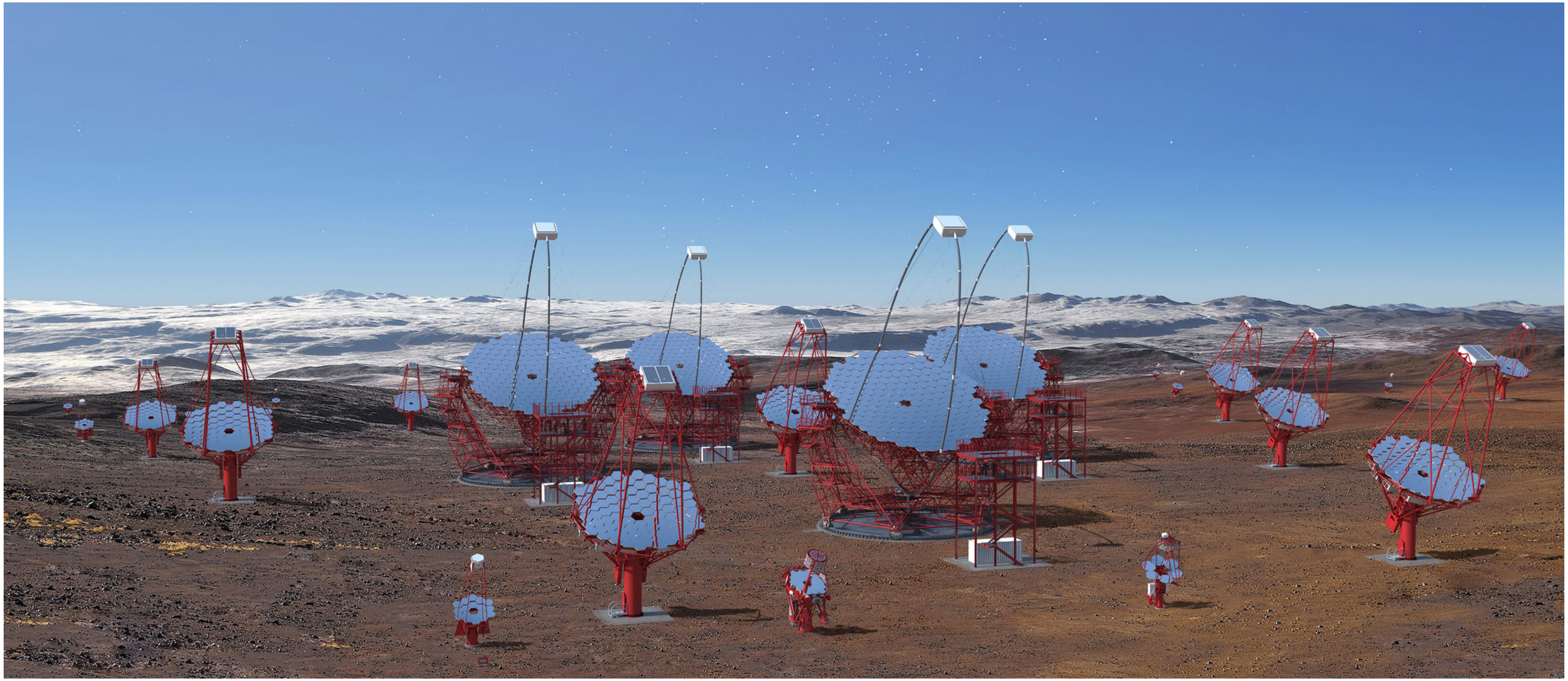
Commissioning in progress, ~20 people in the field


Barranco de las Grajas
Barranco de las Grajas
MAGIC1
MAGIC2
LST1
145 m
85 m
93 m
Ctra. al Roque de los Muchachos
Ctra. al Ro

MST: 2 designs

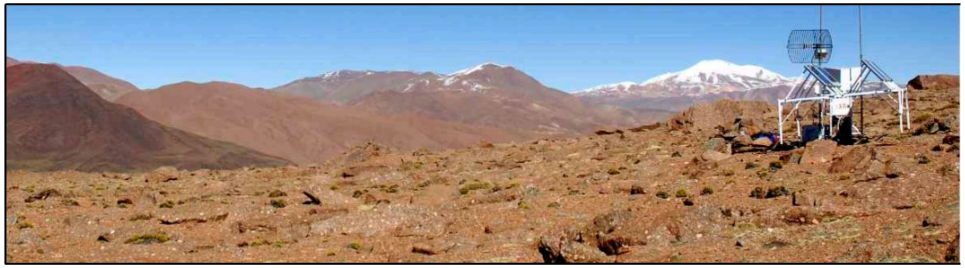
SST: 3 designs

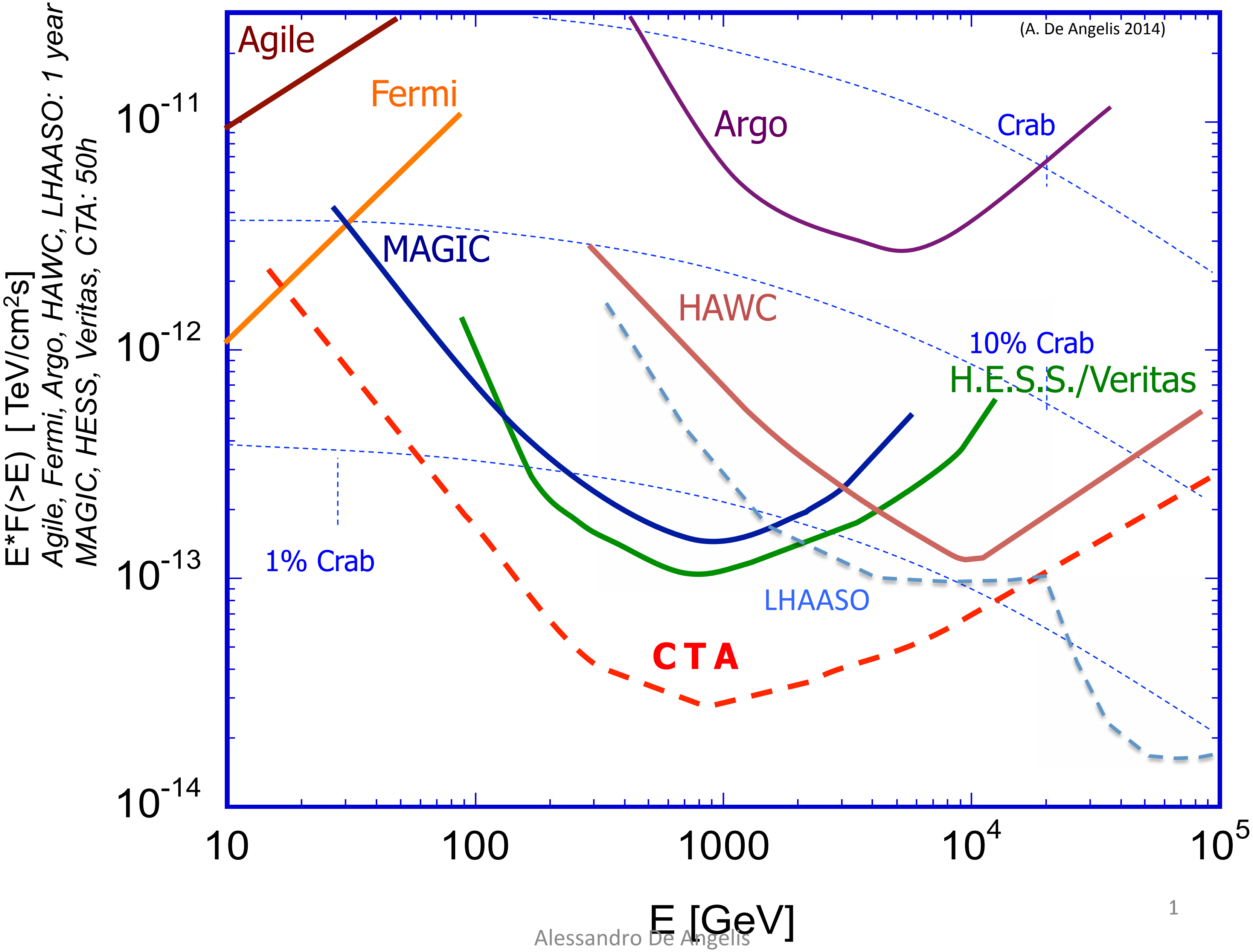
CTA-S in Paranal: rendering (deployment starting in 2022?)



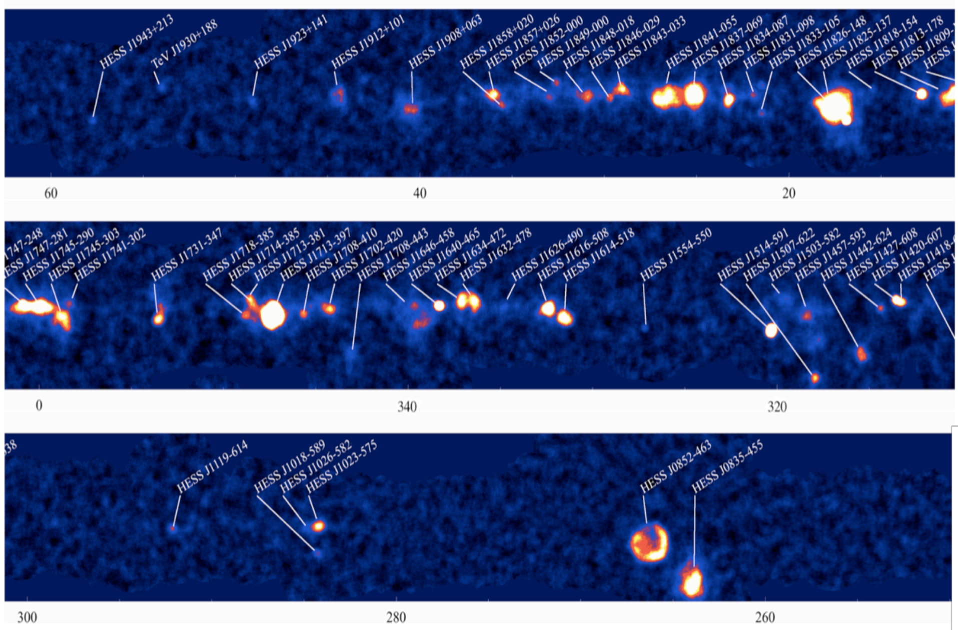
Where? Site Considerations

- Host country
  - Legal, political, economic, security, …
  - Local partners
- Local Infrastructure
  - Road access, water access, power, network
- Altitude
  - >4.5 km
- Longitude
  - Not much choice given high altitude
- Latitude

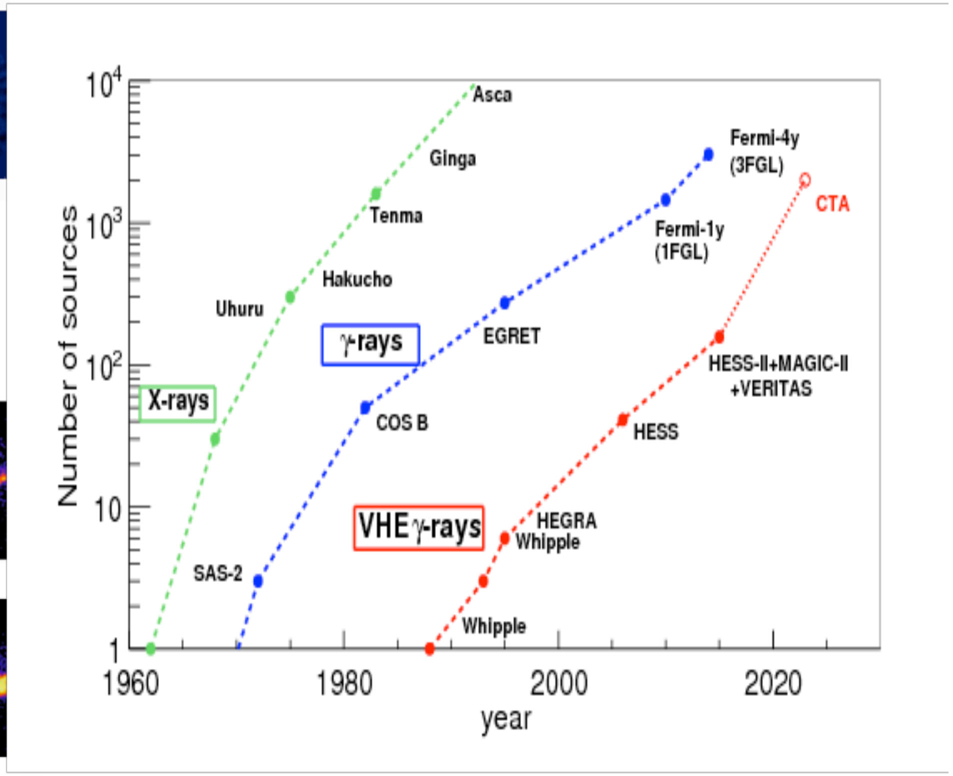


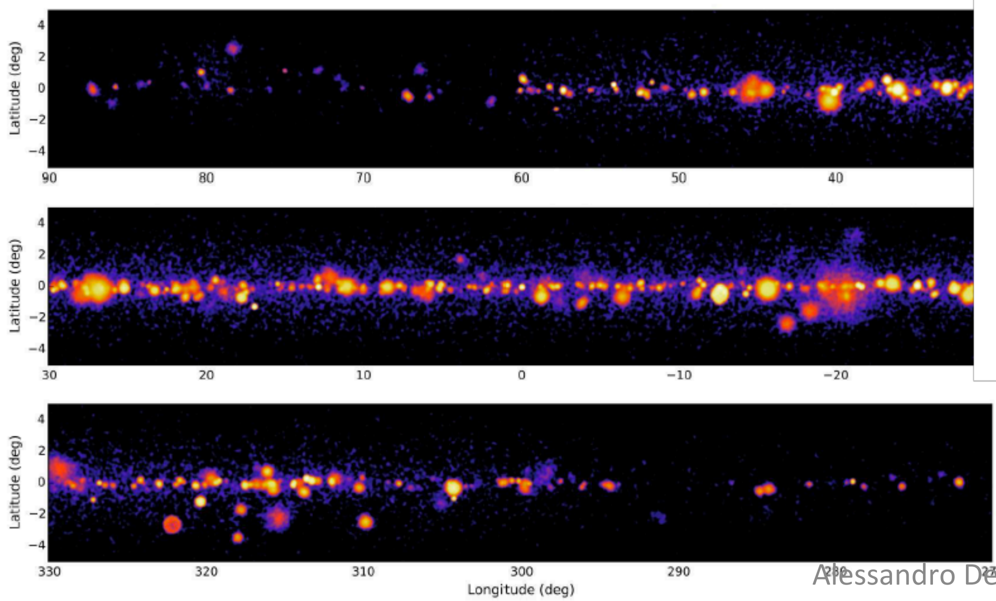


(A. De Angelis 2014)
Agile
Fermi
Argo
Crab
MAGIC
HAWC
10% Crab
H.E.S.S./Veritas
1% Crab
LHAASO
CTA
E*F(>E) [TeV/cm2s]
Agile, Fermi, Argo, HAWC, LHAASO: 1 year
MAGIC, HESS, Veritas, CTA: 50h
10-11
10-12
10-13
10-14
10
100
1000
104
105
E [GeV]



Huge physics case for CTA



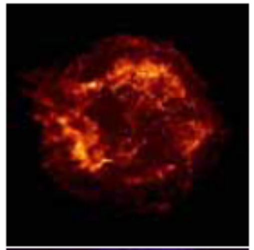


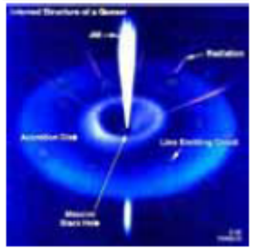
Guaranteed Science with CTA

An advanced Facility for ground-based gamma-ray Astronomy

~200 -> ~2000 sources above 100 GeV

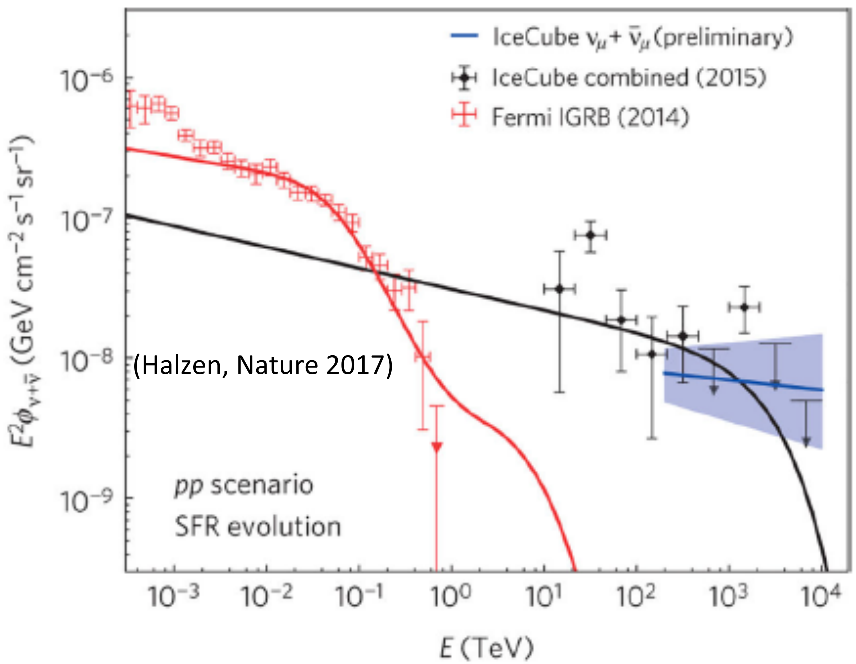
- Study of sources and propagation of high energy particles in the Cosmos, on scales ranging from compact objects to large scale structures
  - Pulsars
  - Pulsar wind nebulae
  - Stellar winds
  - Supernova remnants
  - Diffuse emission
  - Galactic center region
  - Starburst galaxies
  - Clusters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



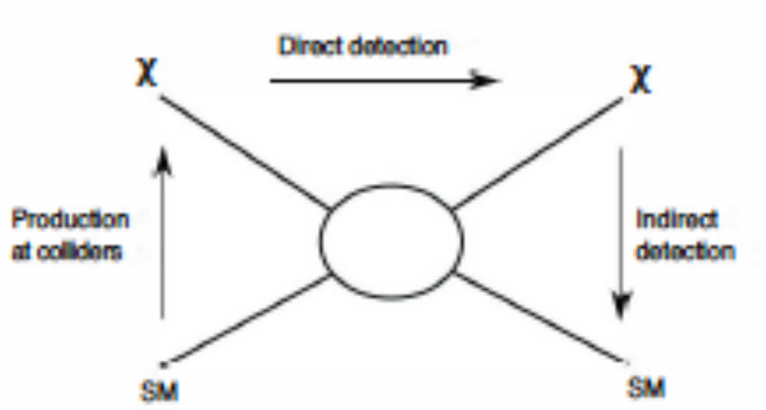


Gravity near compact objects (in particular through multimessenger astronomy)

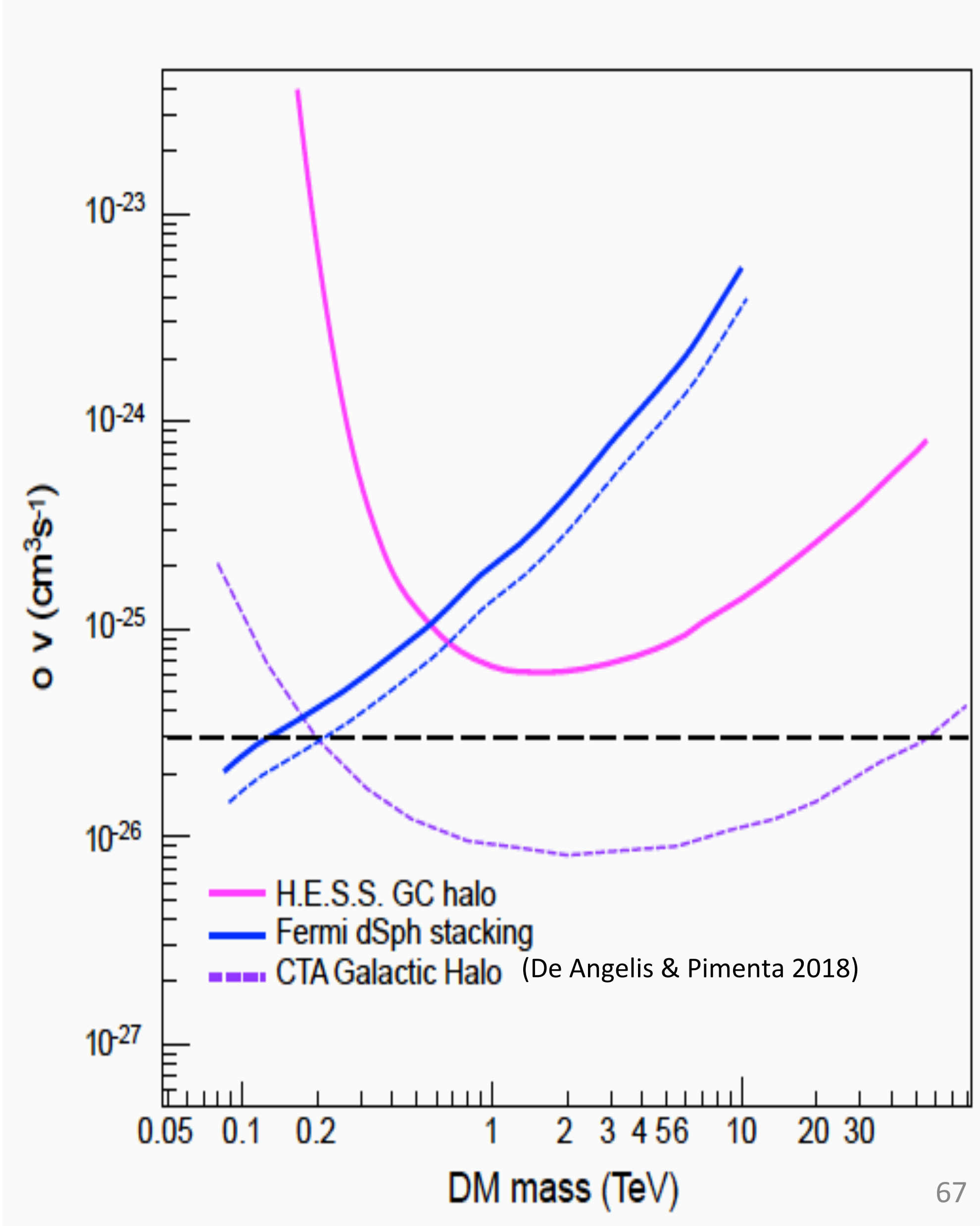
- Astrophysics has recently became multimessenger thanks to the simultaneous observations of GW/gamma rays and of neutrino/gamma ray events
- While the counterparts of GW events seem out of reach for IACTs (~MeV), IACTs are perfect for the counterparts of neutrino events



Dark Matter and New Particles



- Indirect detection of DM: CTA will reach the "thermal cross section" in 3 years
- Photon propagation: explore new regions in the axion m/coupling plane

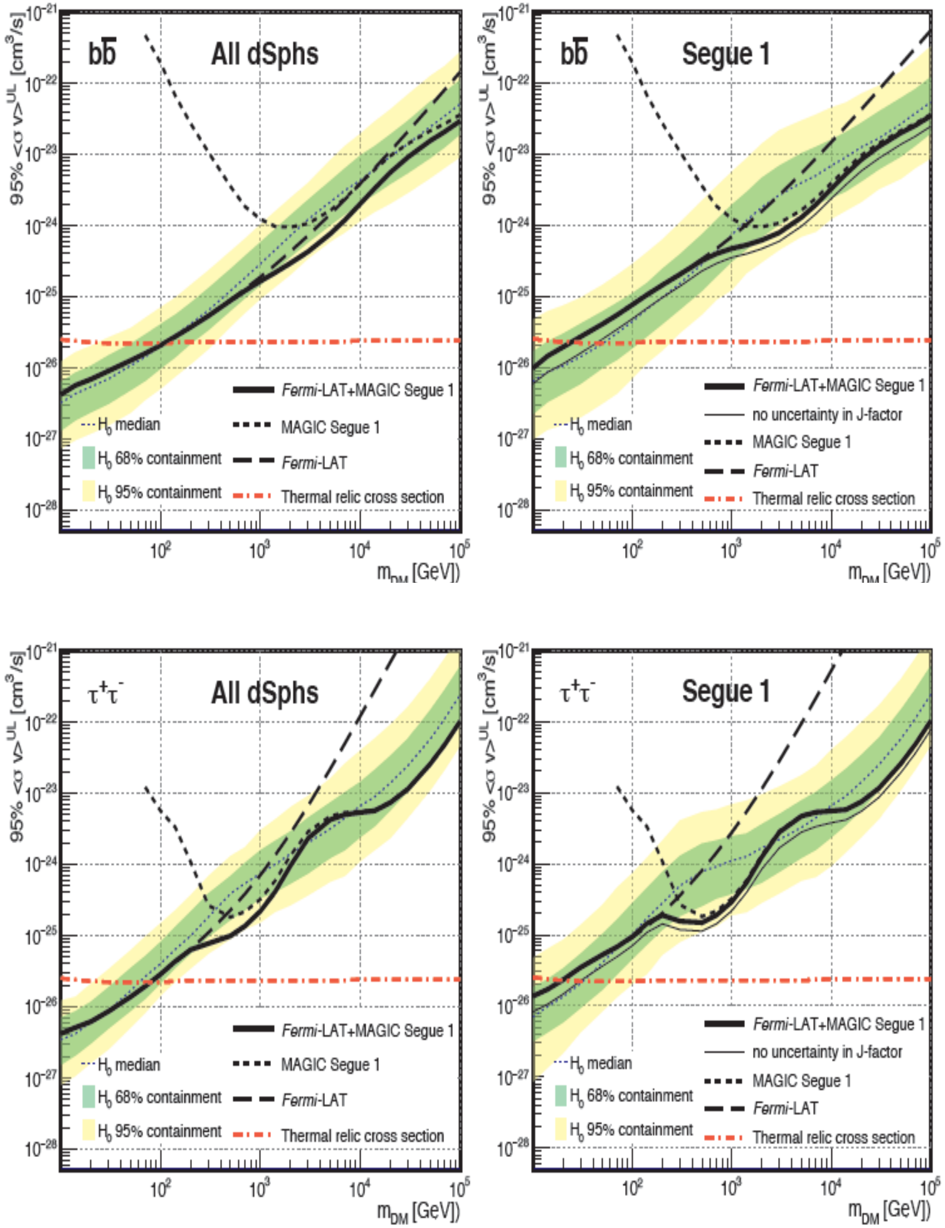


MAGIC + Fermi (2016)

- MAGIC: Segue 1 (158 h) and Fermi-LAT: 15 dwarfs (6 years, Pass8)
- **Coherent limits** between 10 GeV and 100 TeV (widest range so far explored)
  - Annihilation limits for DM particle masses below O(1) TeV dominated by Fermi-LAT, above O(1) TeV by MAGIC (and IACTs, in general)

Now, a common project between MAGIC (300h), VERITAS (300h), HESS (100h), Fermi & HAWC. Waiting for the 3 CTA years

JCAP 02 (2016) 039



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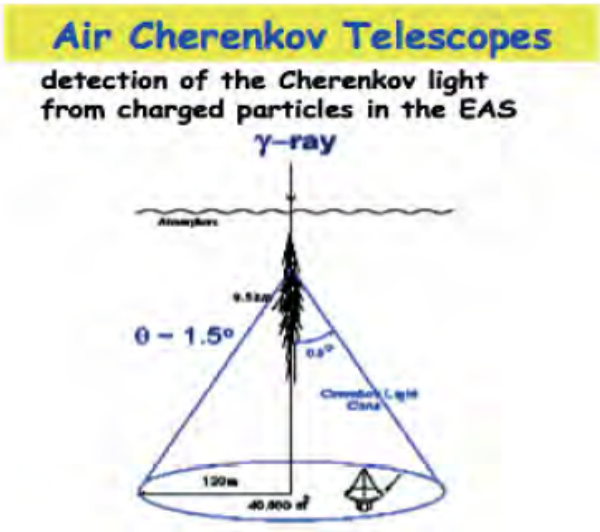
The unexpected

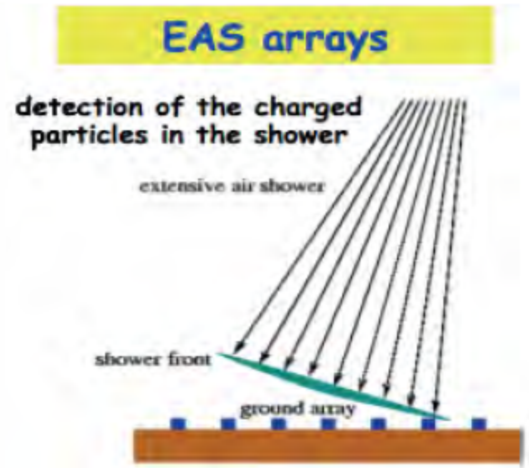
- A number 10x of sources detected
- Access to unexpected science (fast transients, new compact objects, etc.)
- Tests of fundamental symmetries of Nature in an unexplored regime

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

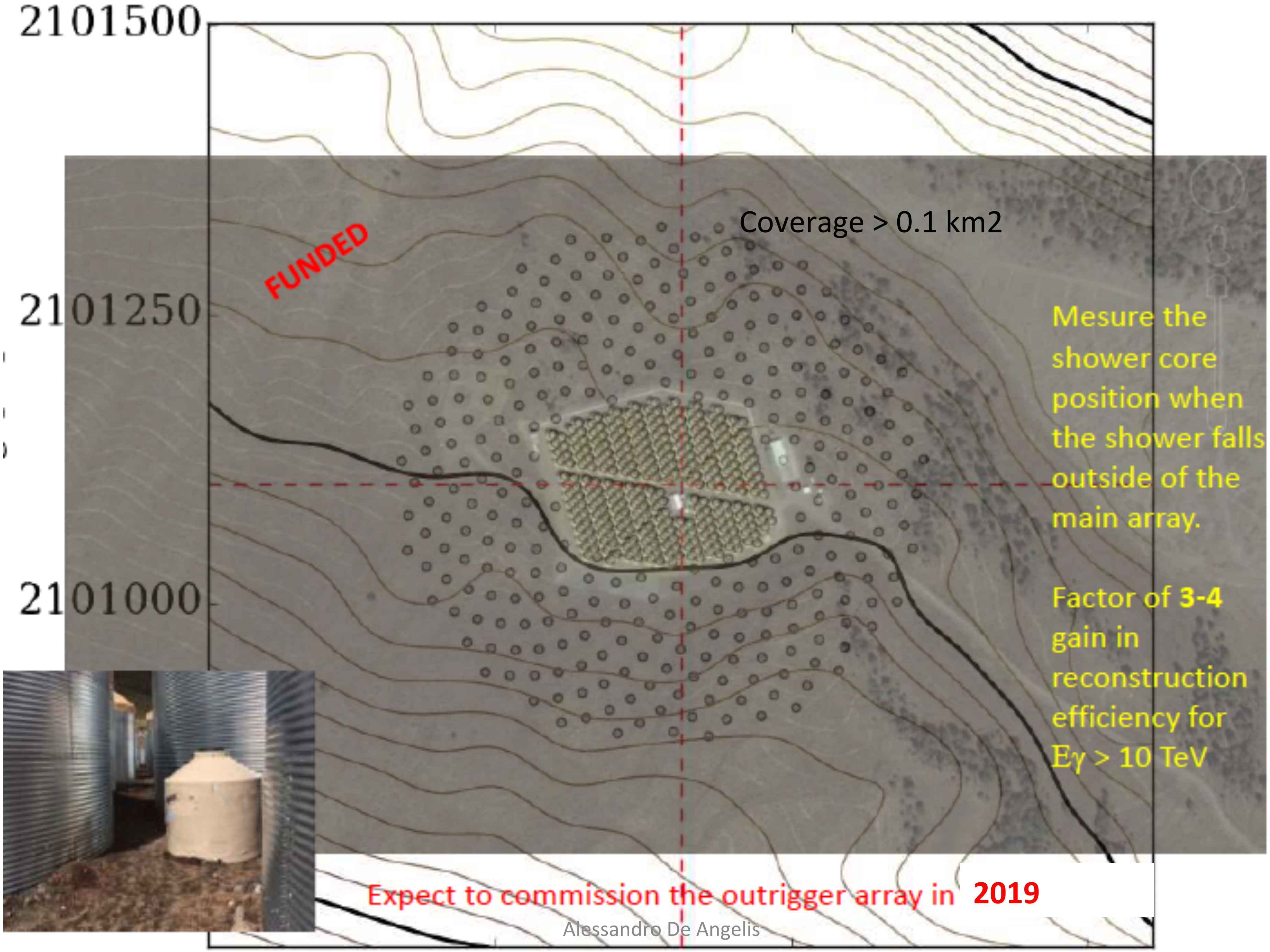
- CTA can be non optimal for PeV detection
  - EAS can be the key for Pevatron studies
- CTA not optimal for VHE transients



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)



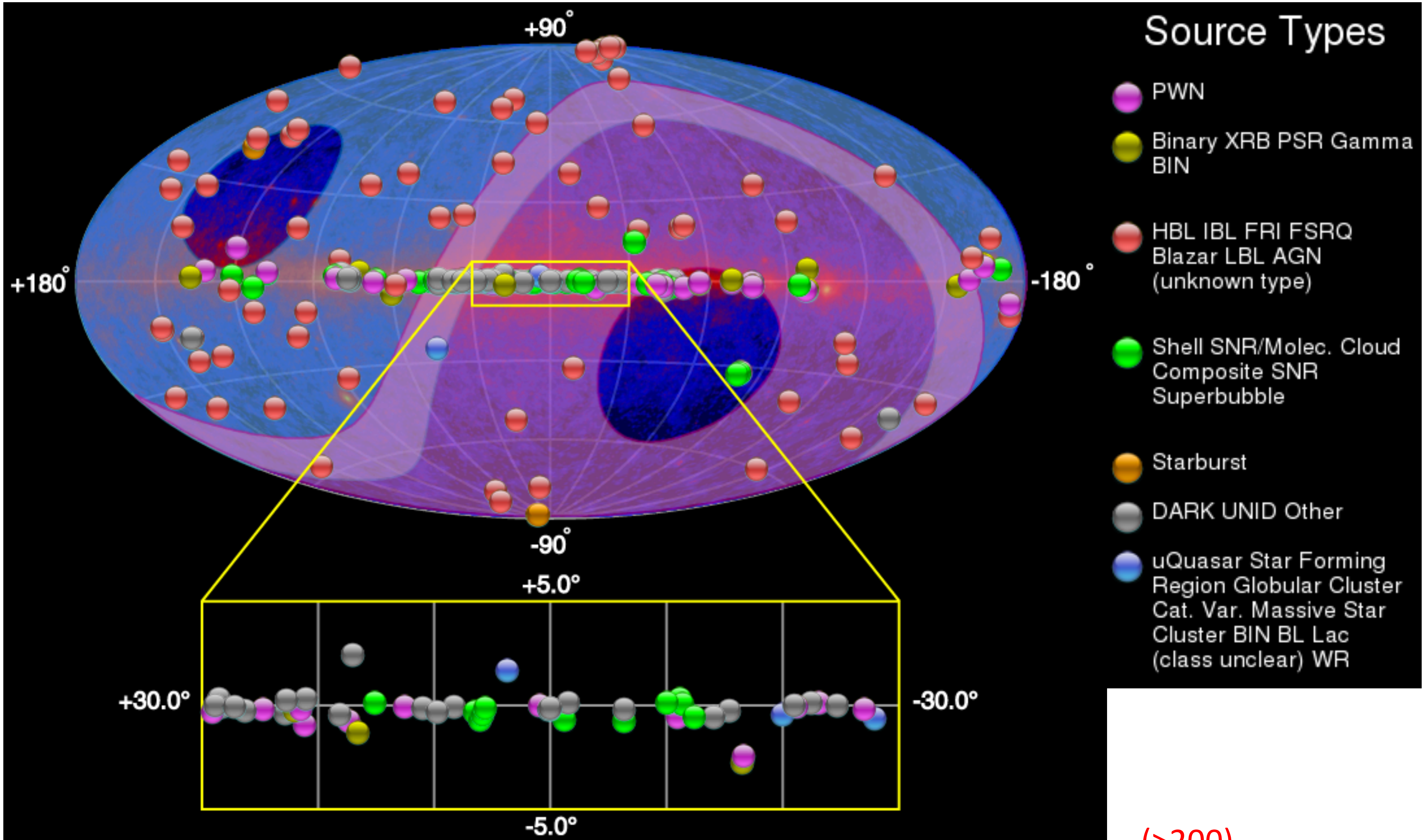
Mesure the shower core position when the shower falls outside of the main array.

Factor of **3-4** gain in reconstruction efficiency for Eγ > 10 TeV

Expect to commission the outrigger array in **2019**

GAMMA RAYS
the right tool to locate sources, up to now
(with at least one very important exception)

TeV sources tevcat.uchicago.edu

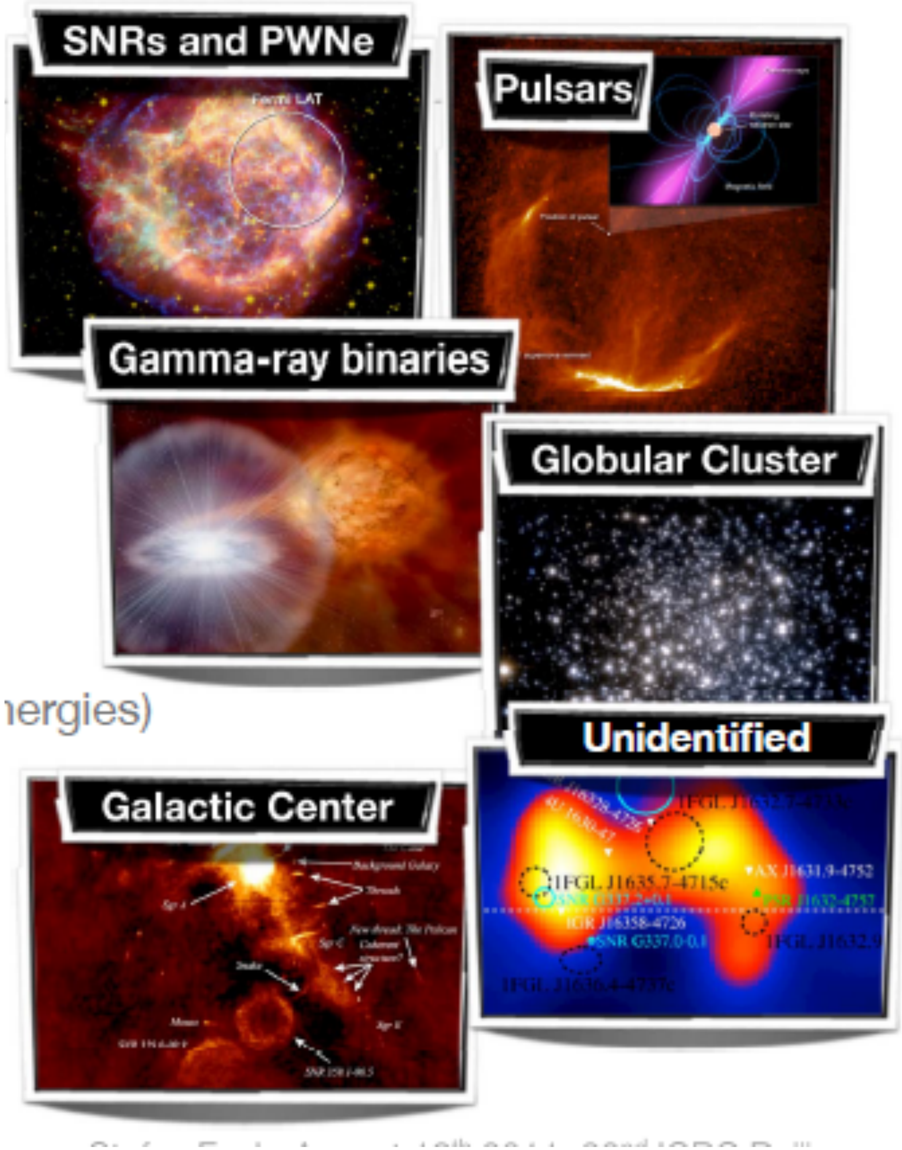


(>200)

Galactic sources of gamma rays

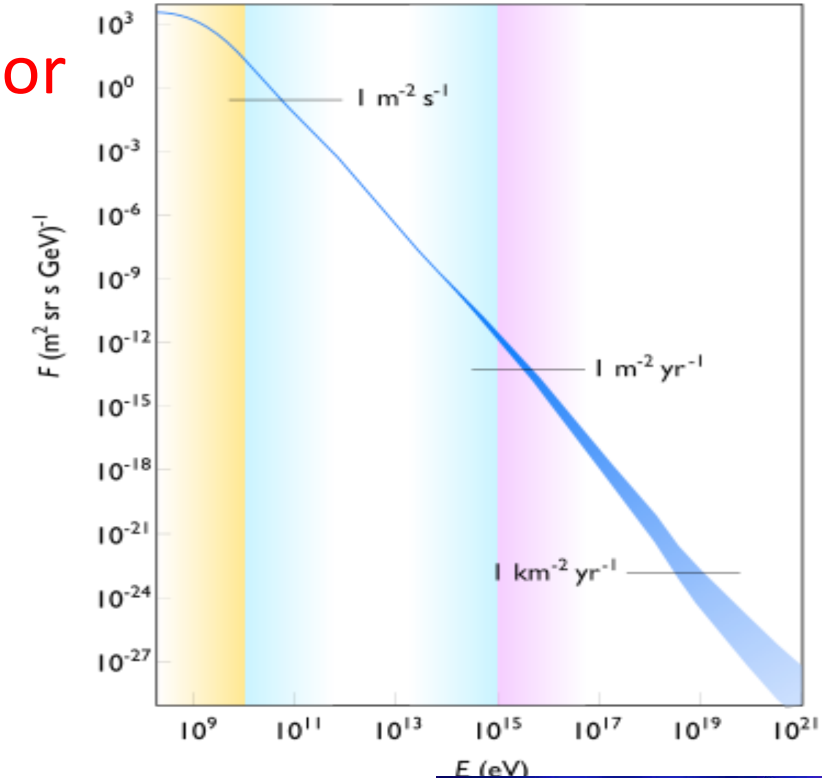
- Remnants of SN explosions (shells, pulsar wind nebulae, pulsars themselves)
- Gamma-rays binaries
- The Galactic Center

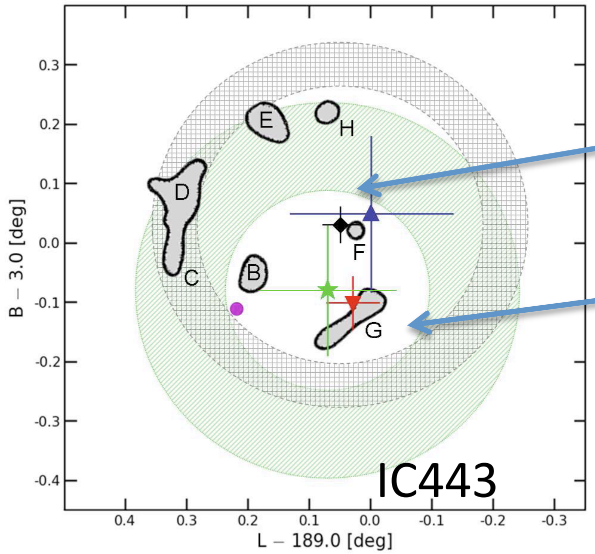
- Many unassociated sources



Interaction with molecular clouds or gammas in the ambient

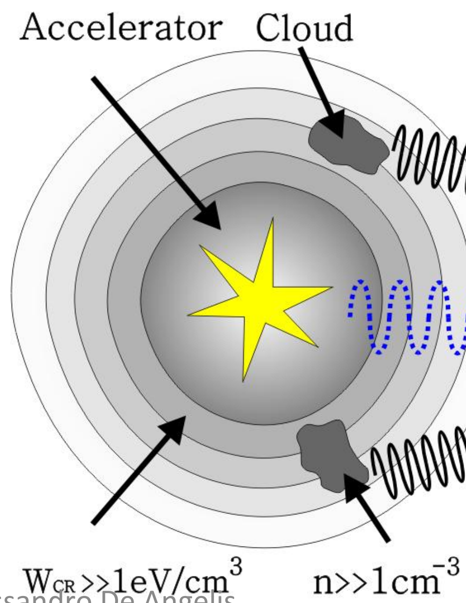
- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004) with photons
- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)

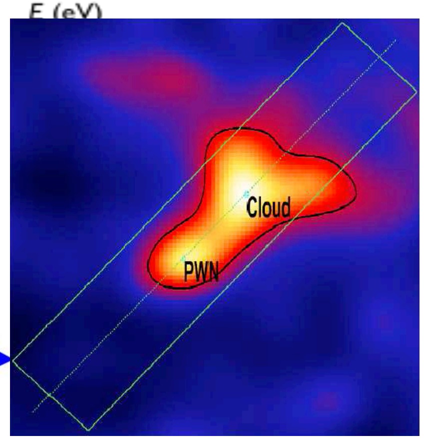




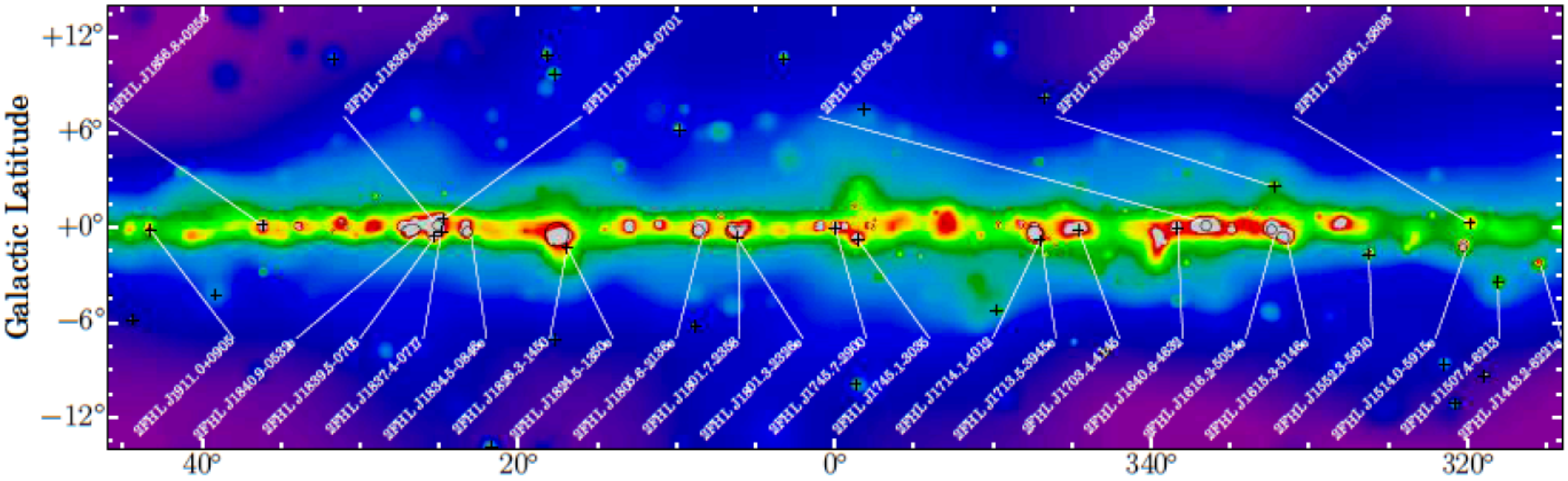
Fermi, Egret

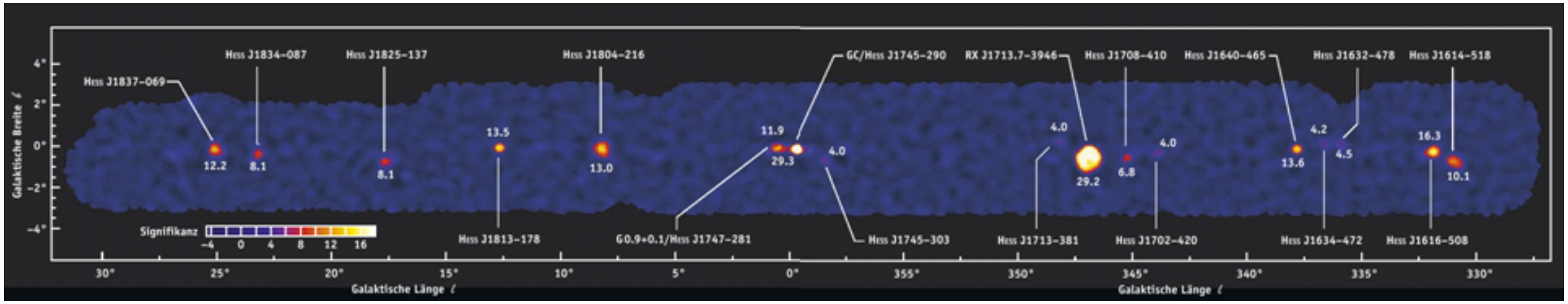
Magic, Veritas



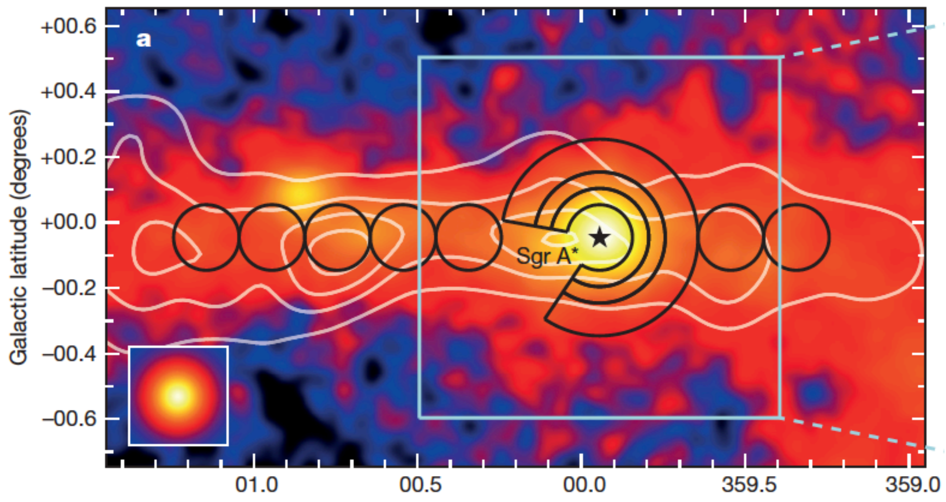


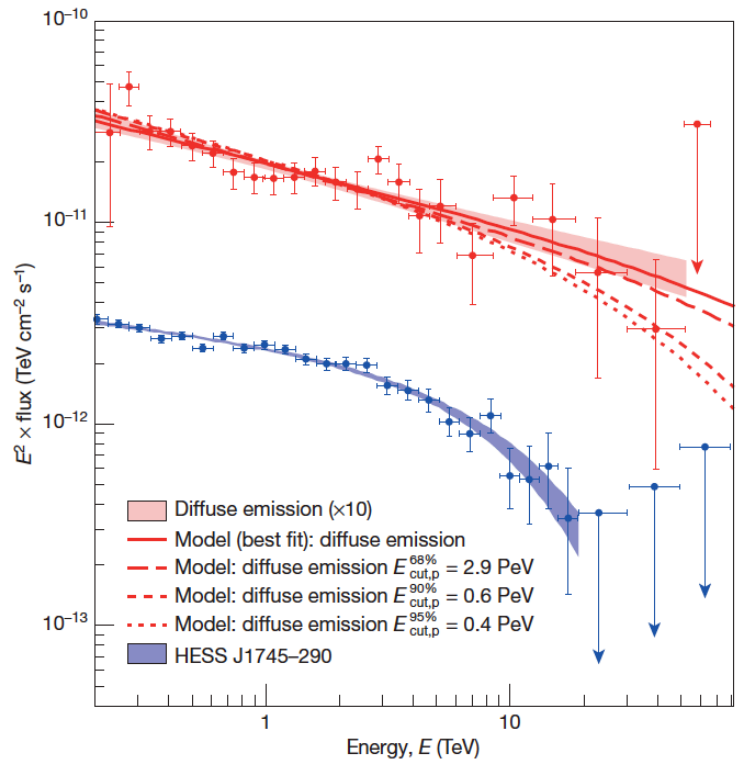
The Galactic center above 50 GeV (Fermi) and in TeV (HESS)





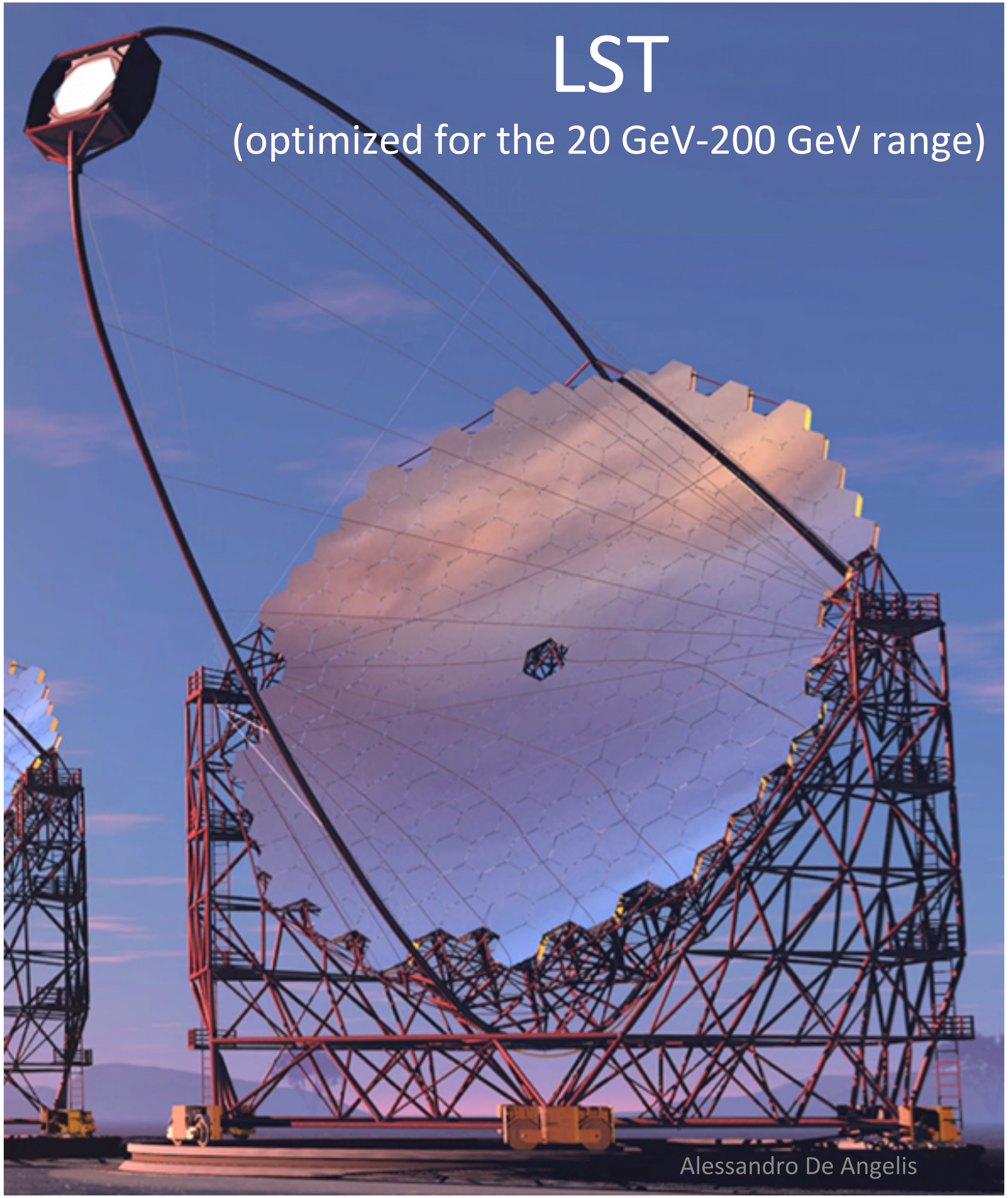
A PeVatron in the GC? (HESS, Nature 2016)





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

A PeVatron in Crab? (MAGIC, HAWC 2019)



- 23 m diameter (400 m^2 dish area)
- 28 m focal length
- 200x2m^2 hexagonal mirrors
- 4.5 deg FoV
- 0.1° pixels, camera diam. 2m
- Light structure for 20 s positioning
- AMC
- 4 LSTs on North site, 4 LSTs on South site
- Prototype = 1st telescope at La Palma.
- Foundations end 2016
- Inaugurated Oct 10, 2018
- First signals detected
- First source in ~1 month?
- Japan, Germany, INFN Italy, Spain, IN2P3 France, India, Brazil, Croatia, Sweden