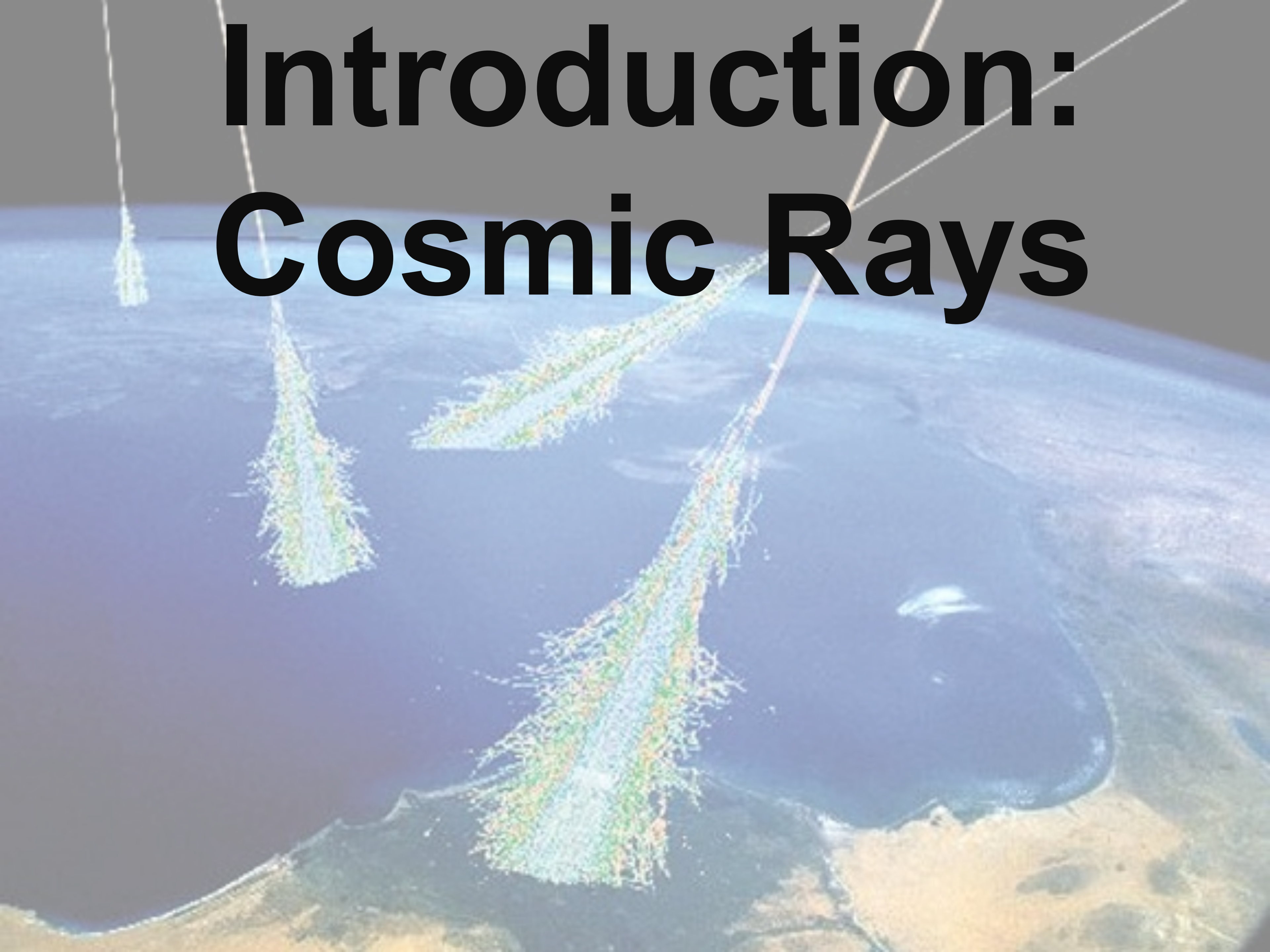
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

AstroPARTICLE Physics

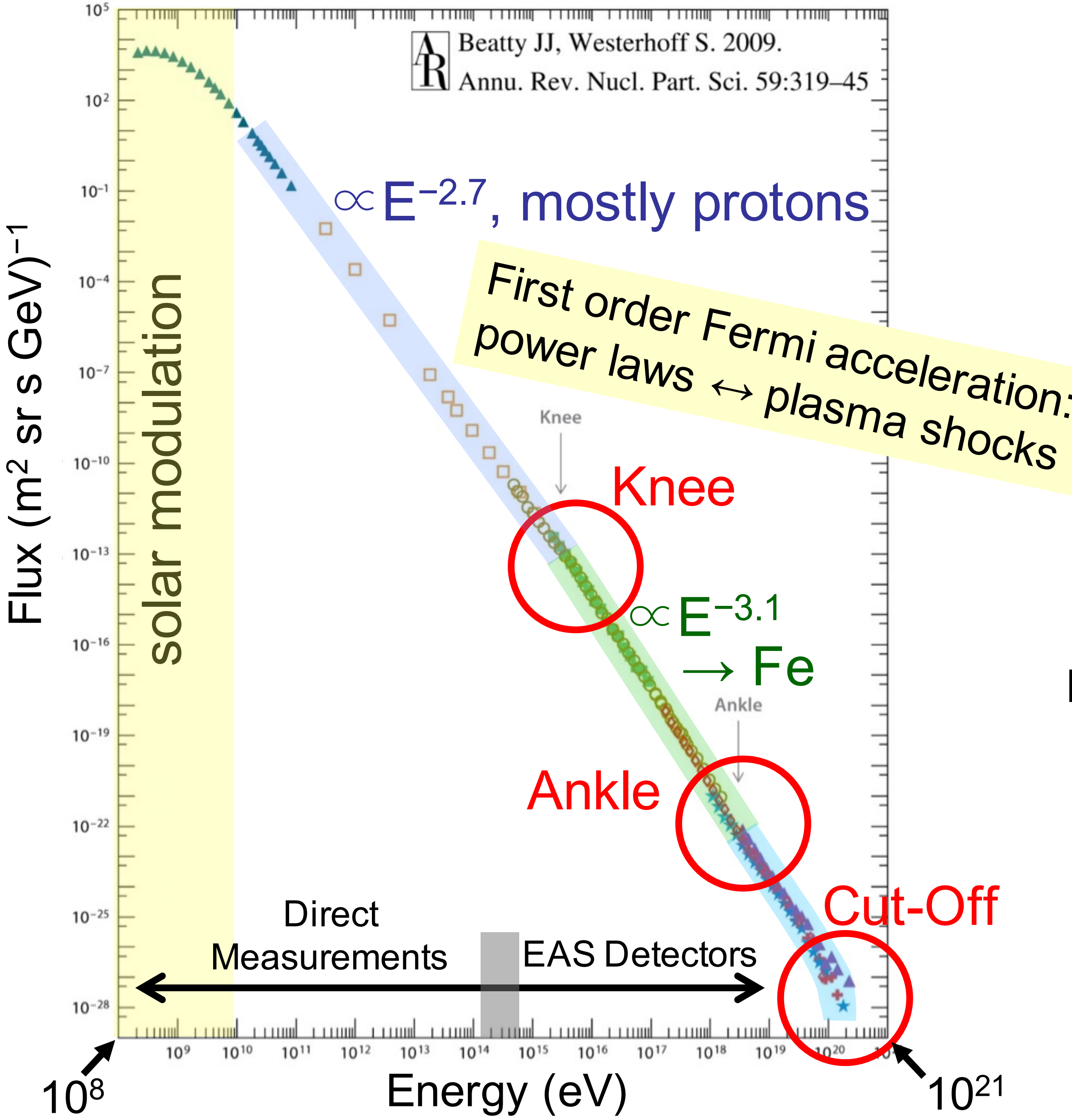
Thomas Lohse
Humboldt-Universität zu Berlin

CTEQ & Mcnet QCD School on QCD and EW Phenomenology
09 July 2016

Introduction: Cosmic Rays



Cosmic Rays



Beatty JJ, Westerhoff S. 2009. Annu. Rev. Nucl. Part. Sci. 59:319–45

$\propto E^{-2.7}$, mostly protons

First order Fermi acceleration: power laws ↔ plasma shocks

Knee

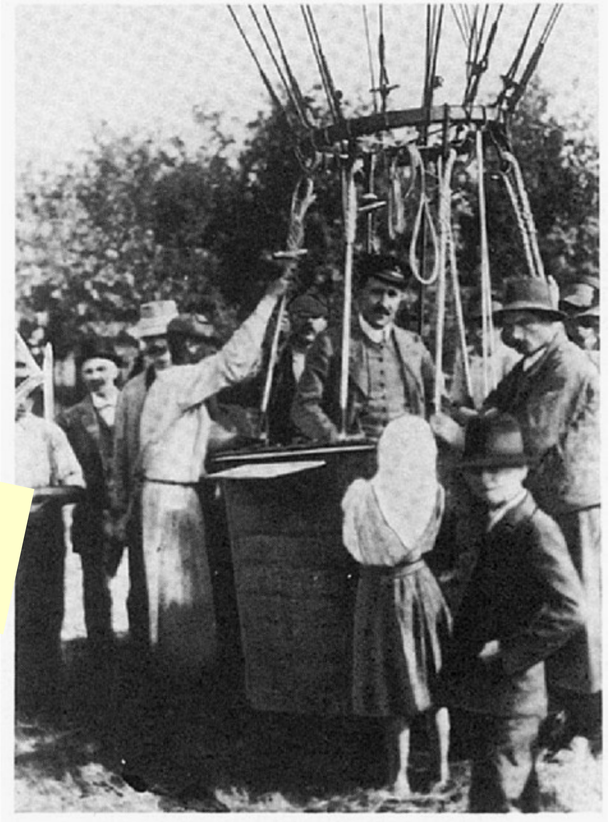
$\propto E^{-3.1}$ → Fe

Ankle

Cut-Off

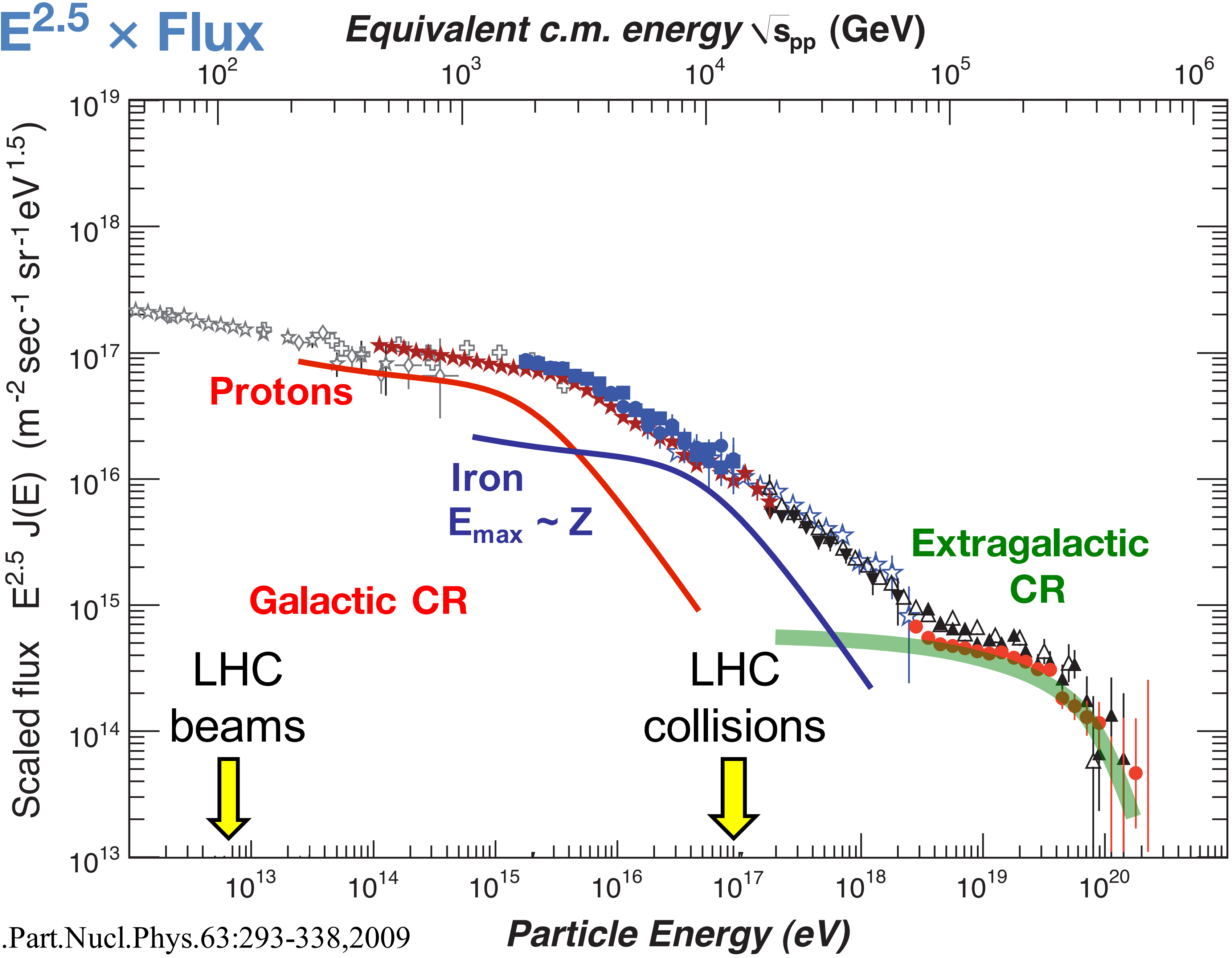
Direct Measurements

EAS Detectors



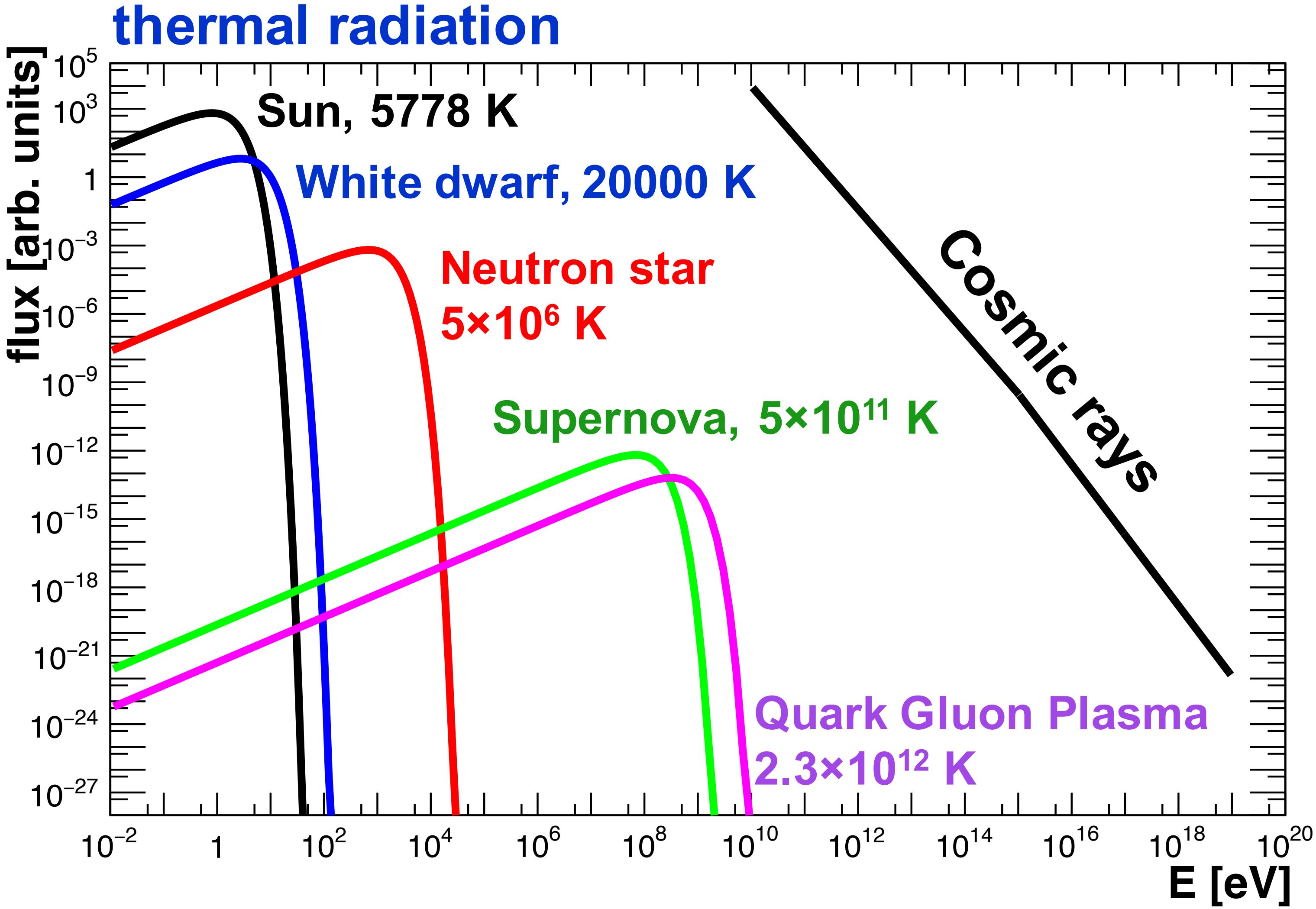
Discovery Balloon Flight
Victor Hess, 1912

$E^{2.5} \times$ Flux



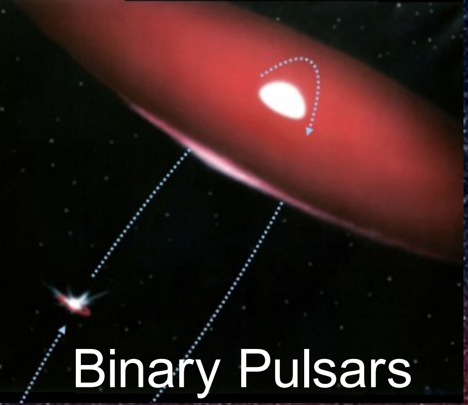
Prog.Part.Nucl.Phys.63:293-338,2009

The relevance of power laws



Cosmic rays ↔ the **non-thermal** Universe

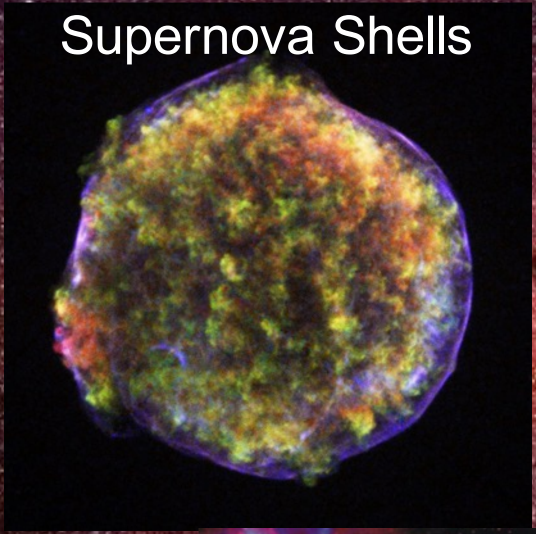
Origin of Galactic Cosmic Radiation



Binary Pulsars

Neutron Stars

Pulsar Wind Nebulae



Supernova Shells

Galactic Centre

Molecular Clouds

Stellar Winds

Black Holes

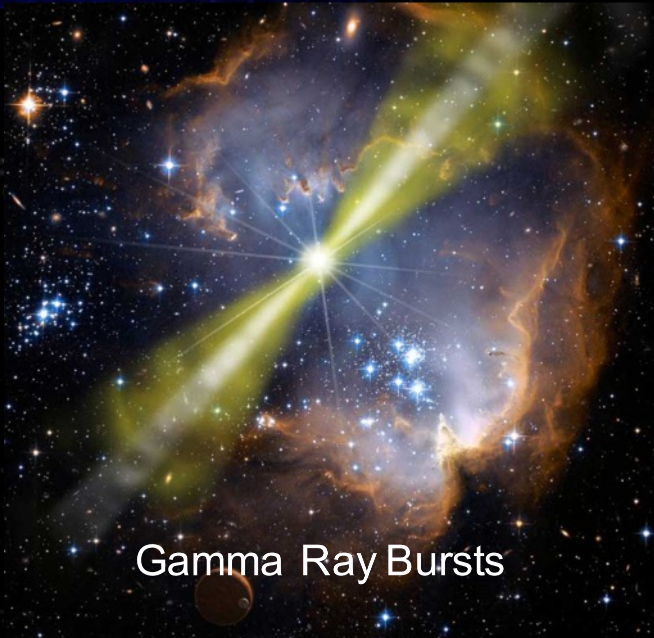
Spitzer, NASA

Origin of Extragalactic Cosmic Radiation


Active Galactic Nuclei


Galaxy Clusters

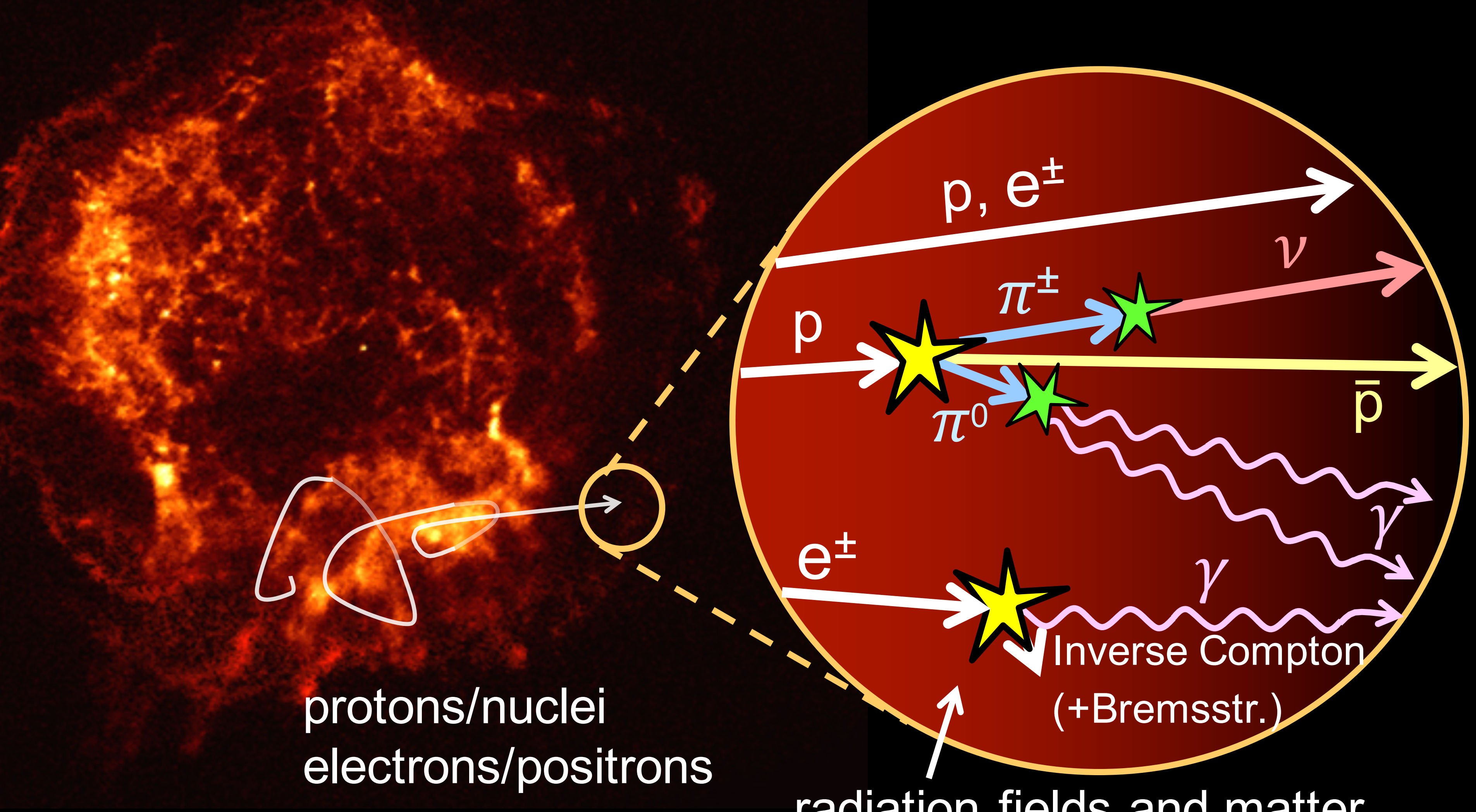

Starburst Galaxies

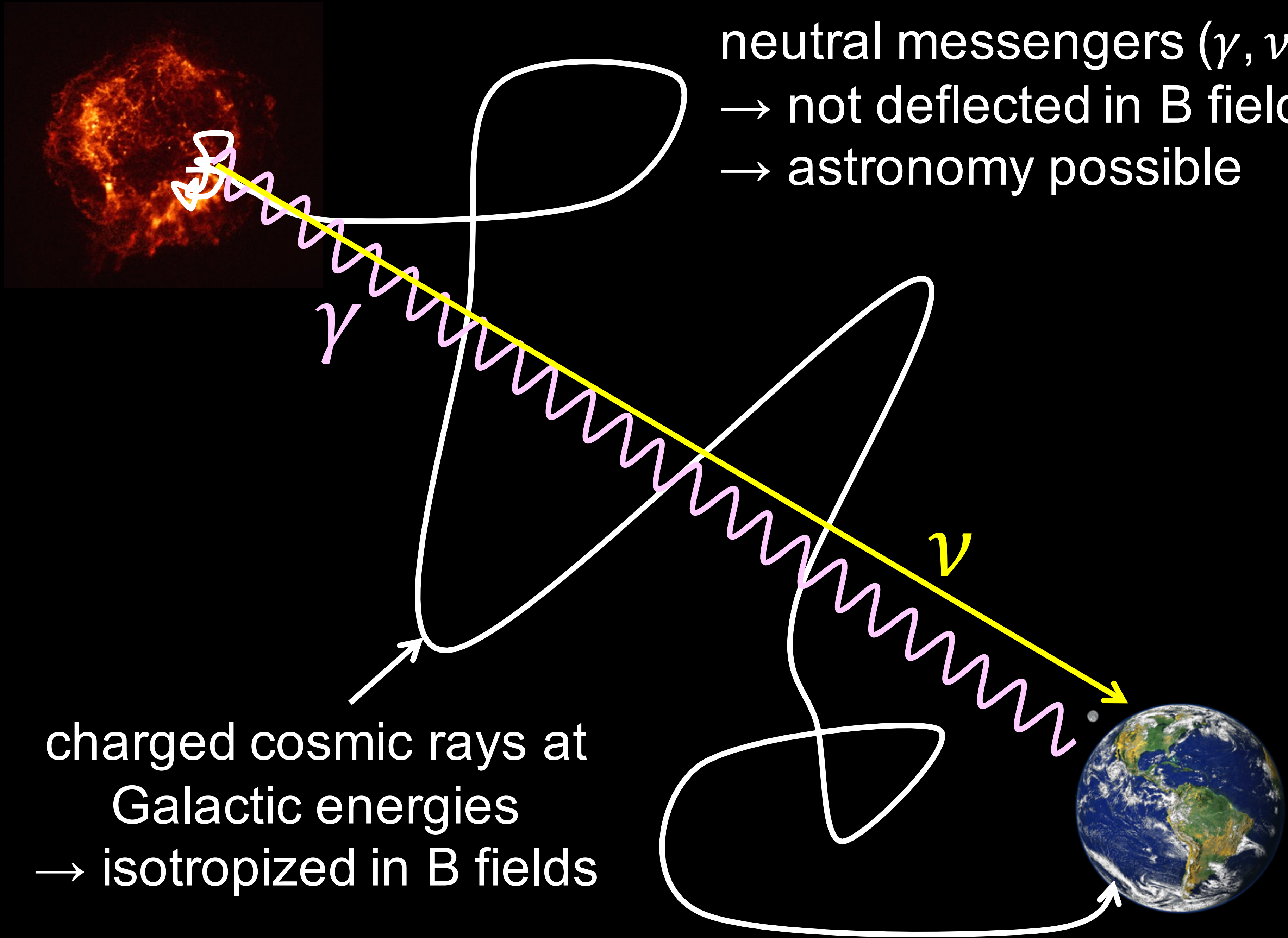

Gamma Ray Bursts

Large Magellanic Cloud

NASA

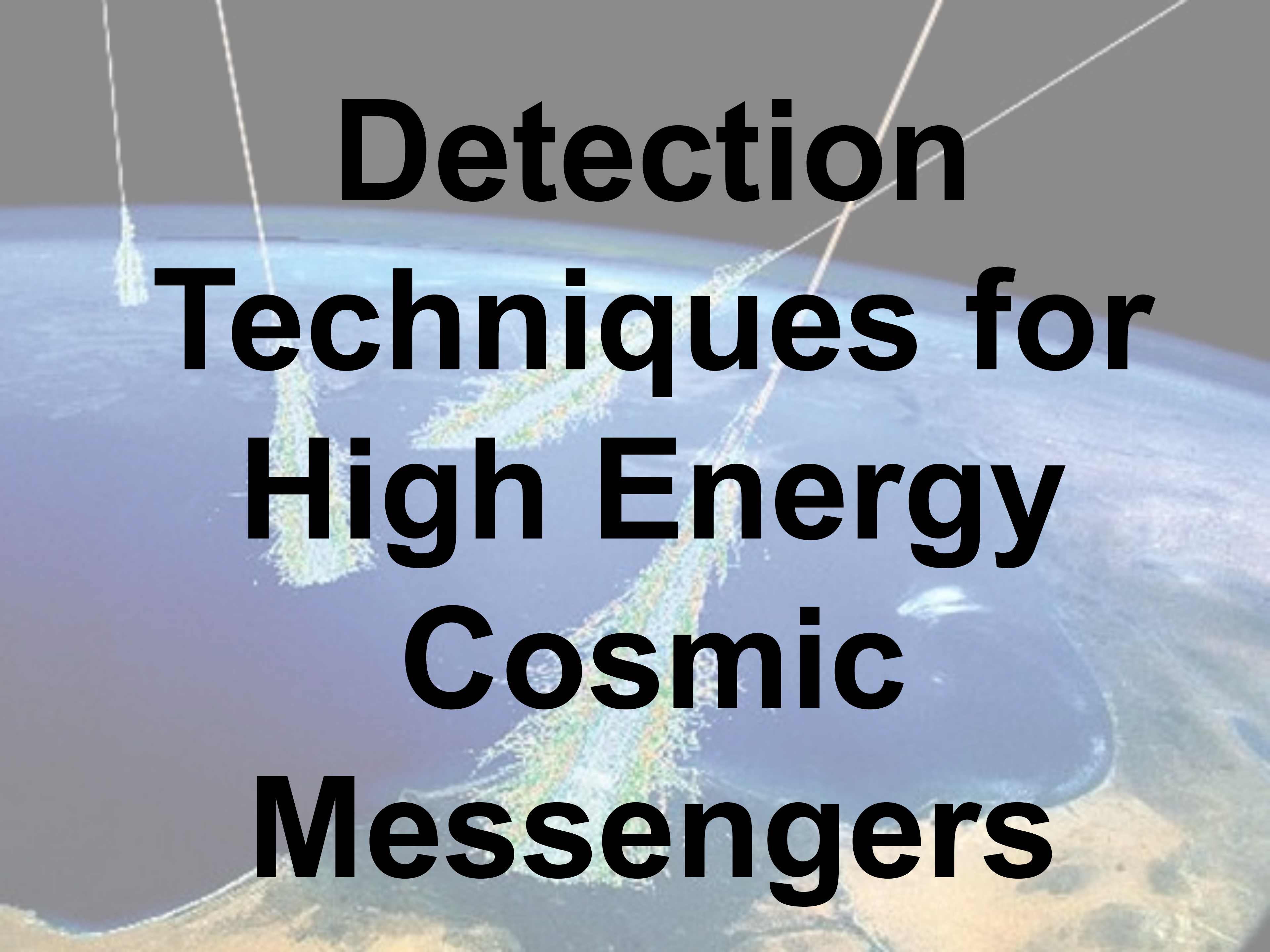
Production in Cosmic Accelerators



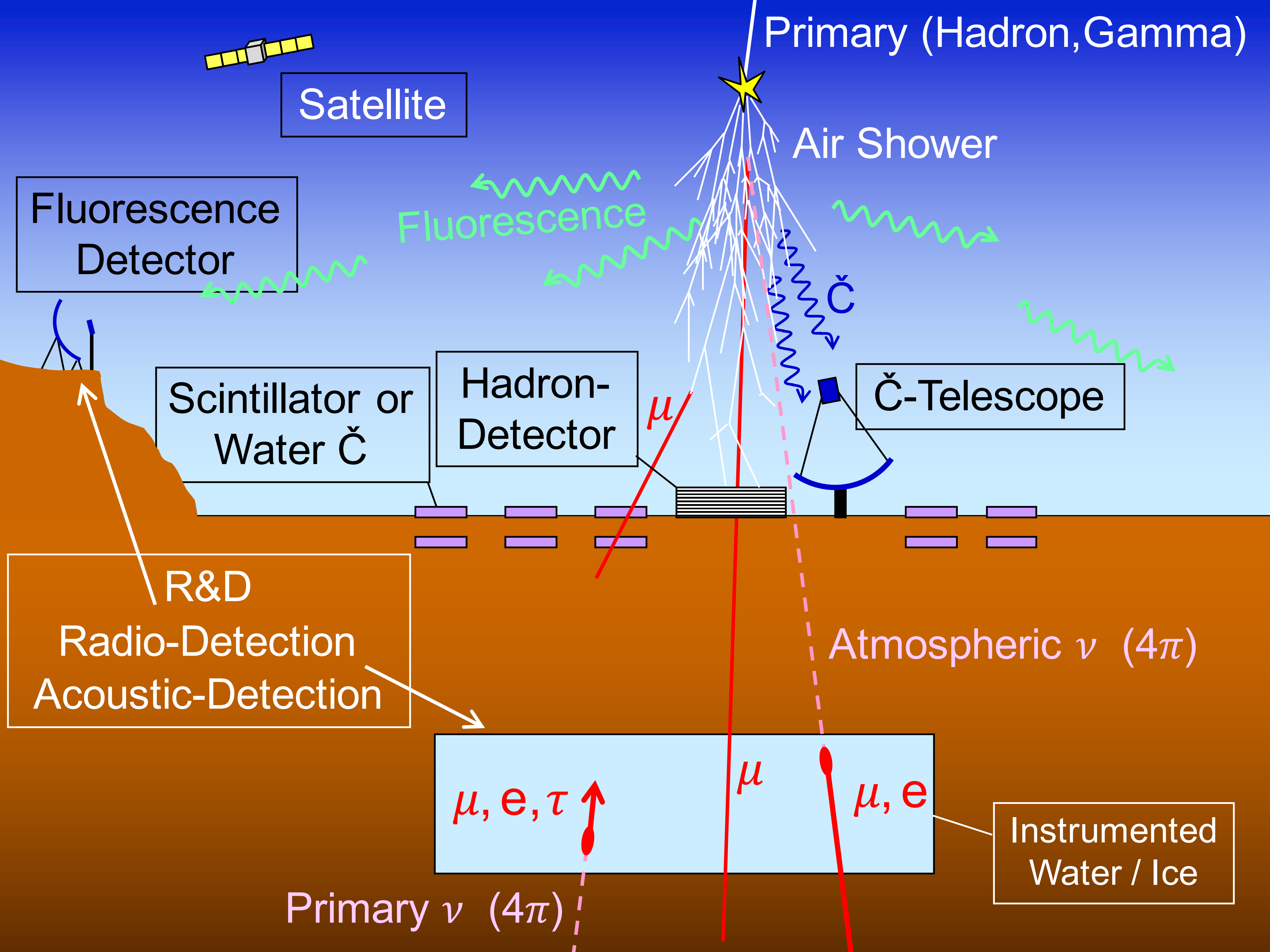


neutral messengers (γ, ν)
→ not deflected in B fields
→ astronomy possible

charged cosmic rays at
Galactic energies
→ isotropized in B fields



Detection Techniques for High Energy Cosmic Messengers



Primary (Hadron, Gamma)

Satellite

Air Shower

Fluorescence Detector

Fluorescence

Č

Č-Telescope

Scintillator or Water Č

Hadron-Detector

μ

R&D

Radio-Detection

Acoustic-Detection

Atmospheric ν (4π)

μ, e, τ

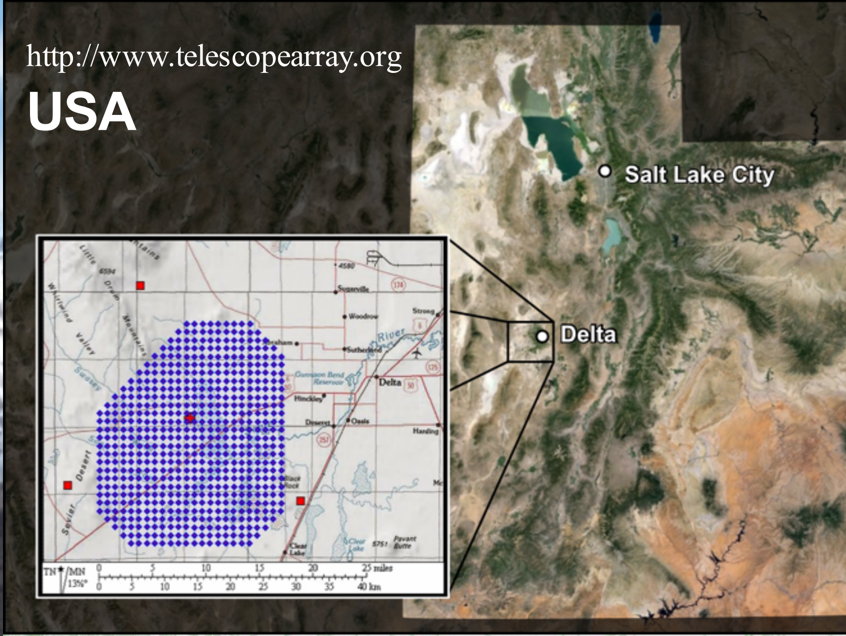
μ

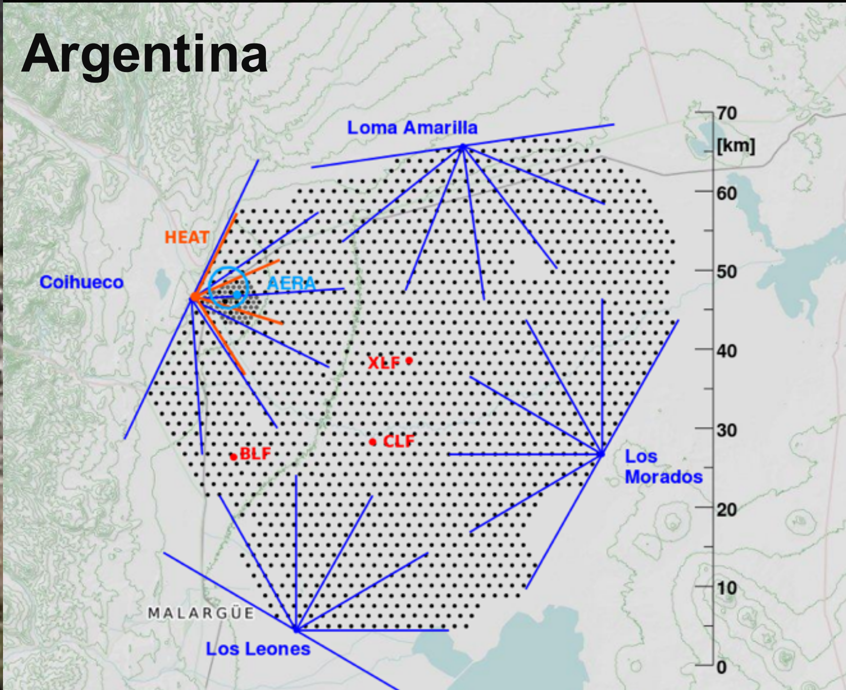
μ, e

Instrumented Water / Ice

Primary ν (4π)

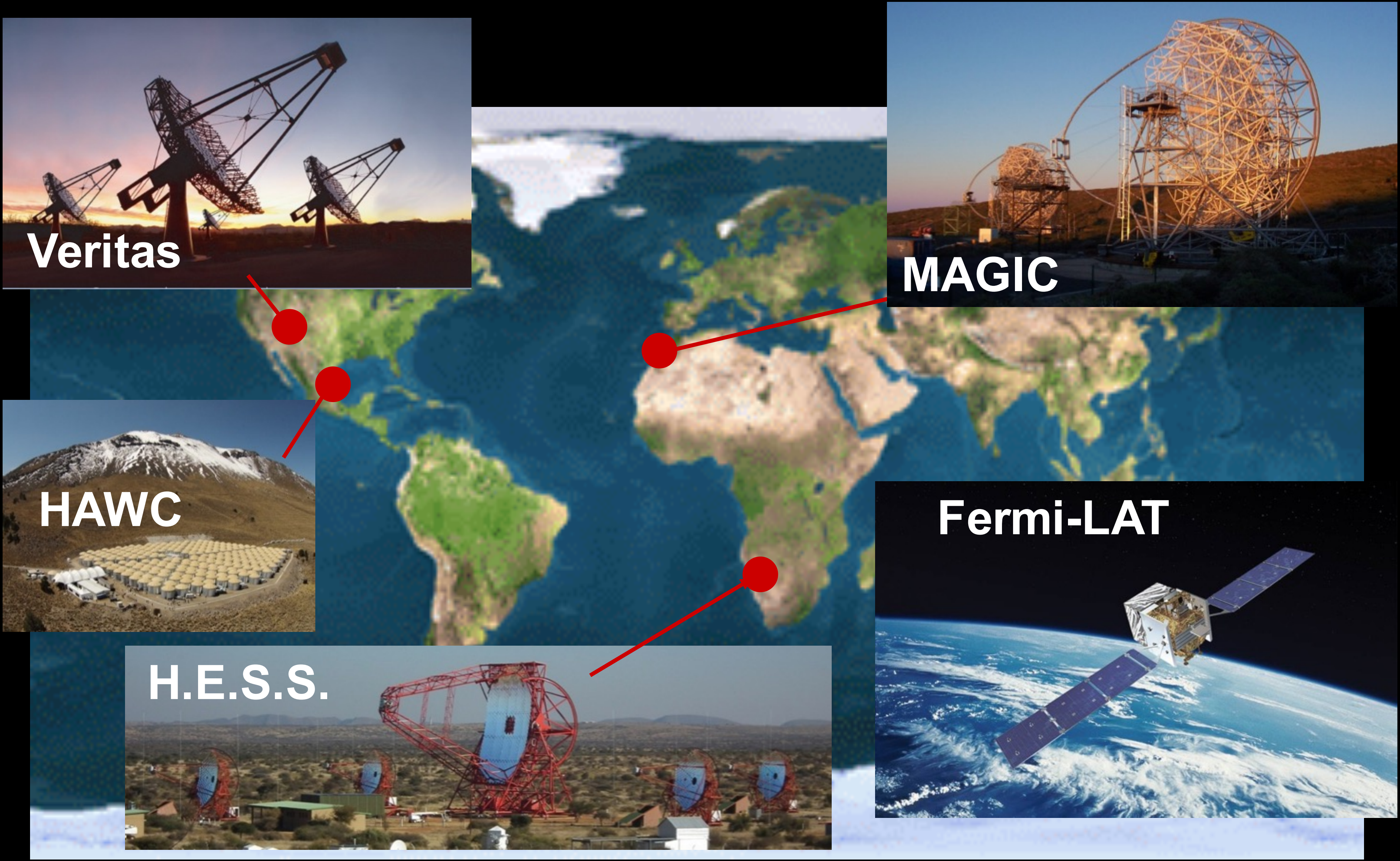
Cosmic Ray Detector Arrays



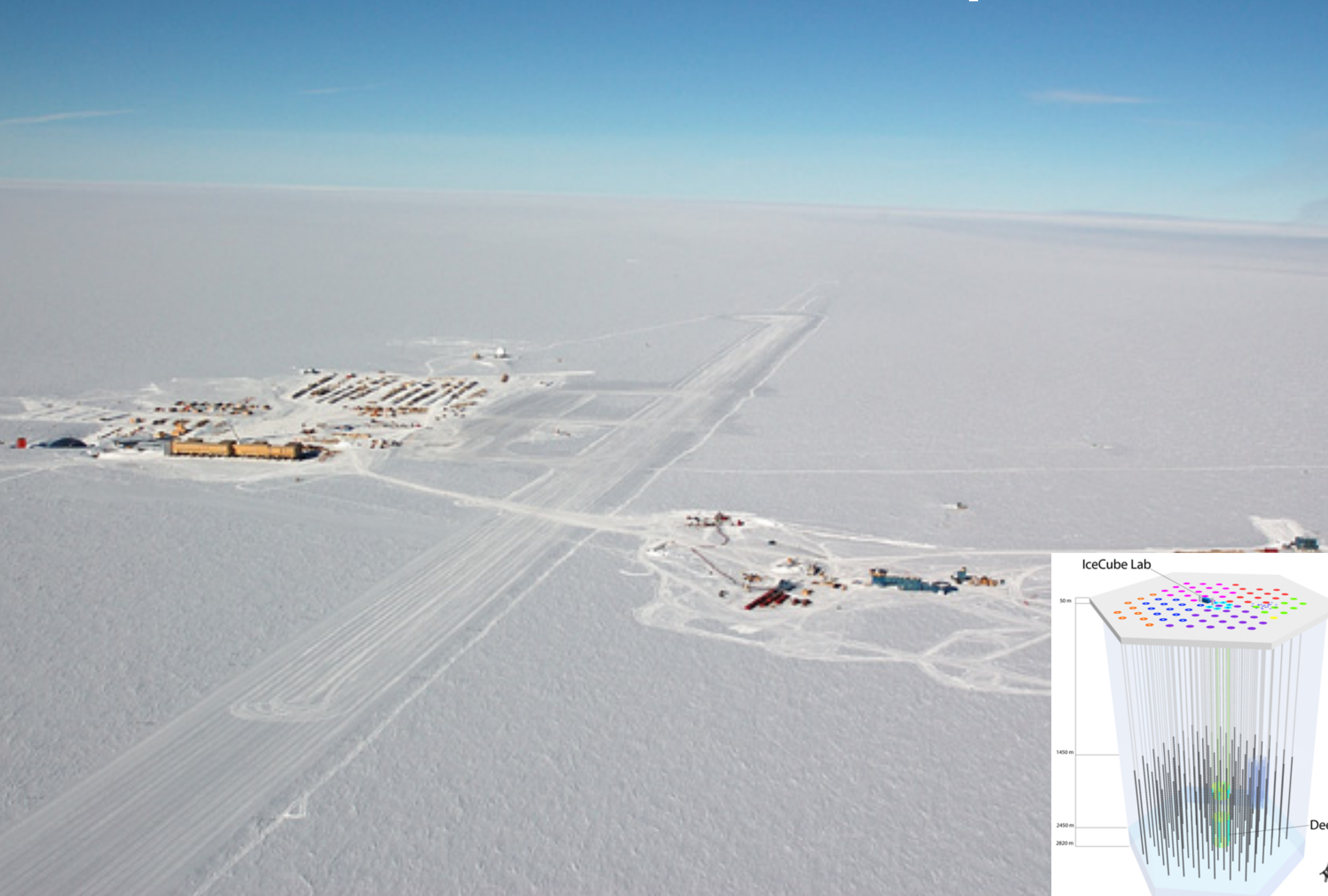


By Darko.veberic - gimp, inkscape, root, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=25179096

Gamma Ray Telescopes

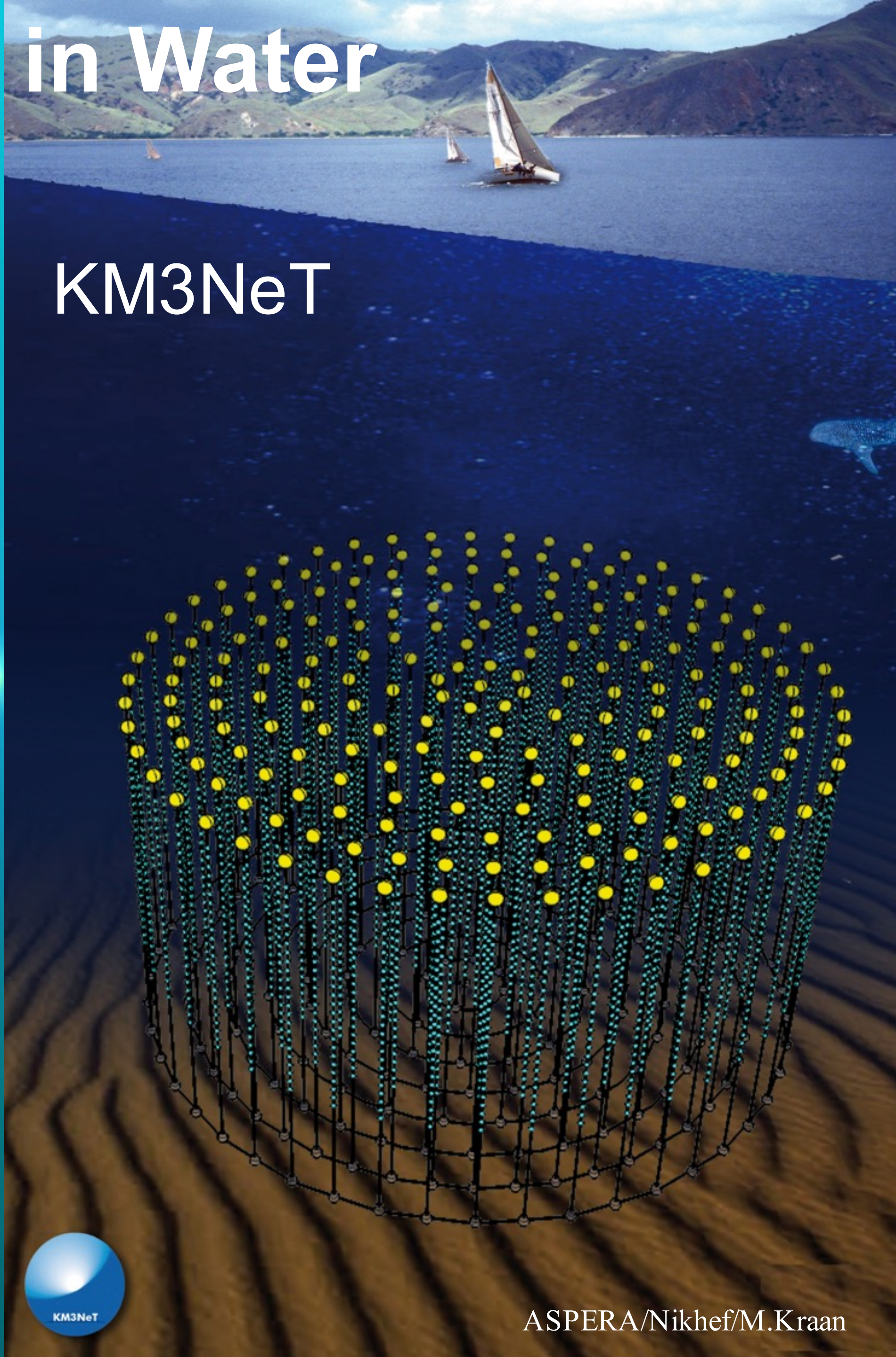


IceCube: Neutrino Telescope in Ice



Neutrino Telescopes in Water

ANTARES



KM3NeT

ASPERA/Nikhef/M.Kraan

Anti-matter from the Universe

Alpha Magnetic Spectrometer on ISS

Outline

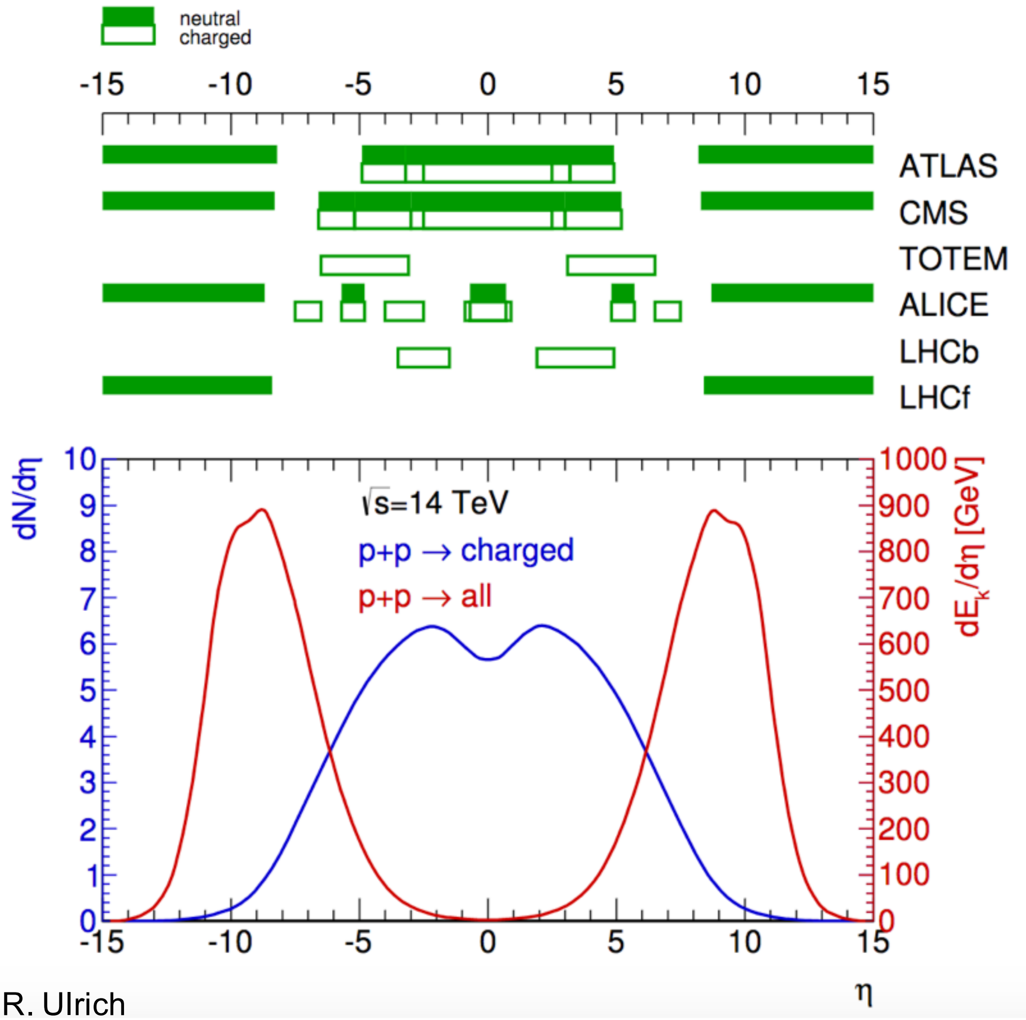
- Cosmic Rays and Air Showers
- Dark Matter: WIMPs and ALPs
- Quantum Gravity

Outline

- **Cosmic Rays and Air Showers**
- Dark Matter: WIMPs and ALPs
- Quantum Gravity

Air Shower Simulation

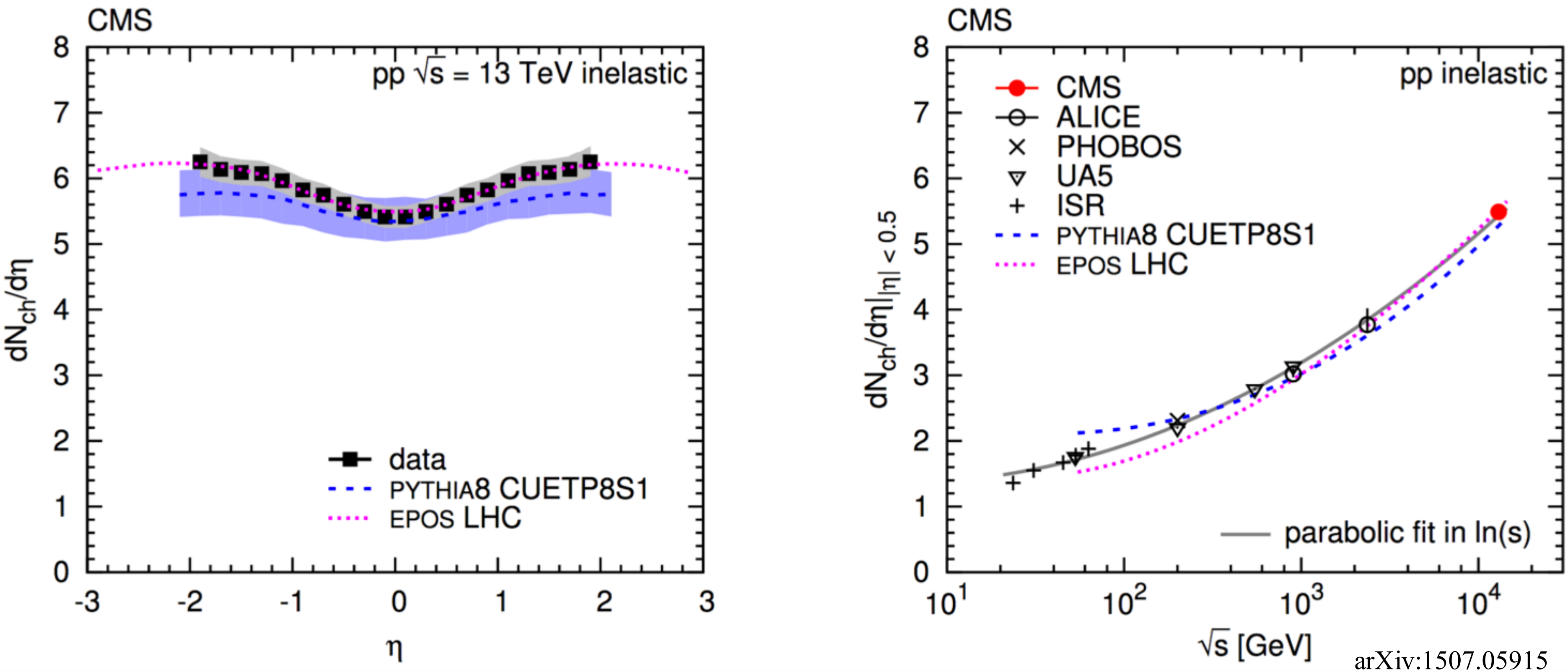
and tuning of interaction models



R. Ulrich

- most energy goes very forward
- LHC data extremely important to assess ultra high energy regime

CMS (magnet off) multiplicity spectra at $\sqrt{s} = 13\,\mathrm{TeV}$



arXiv:1507.05915

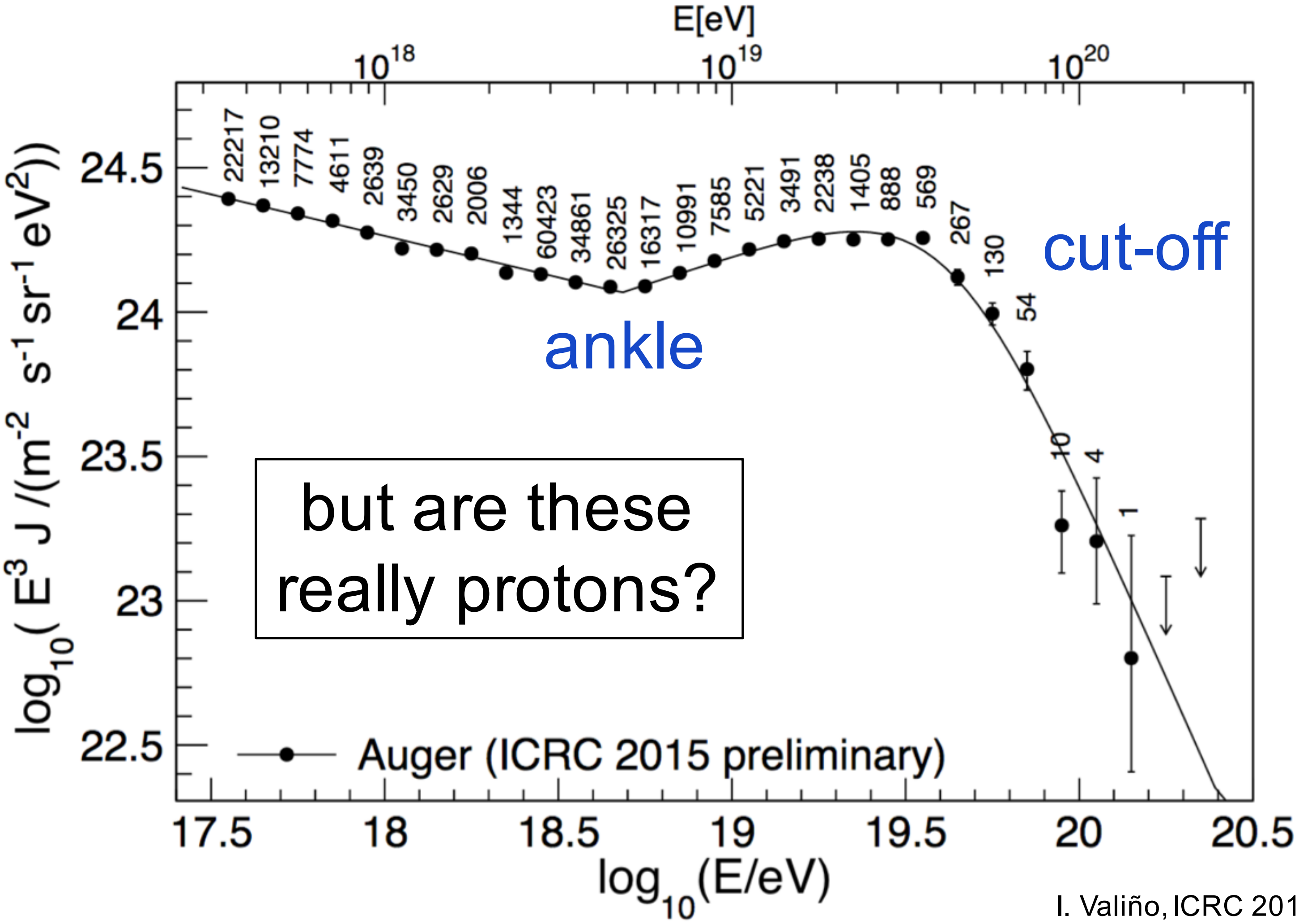
Air shower interaction models

EPOS-LHC QGSJet Sibyll

tend to perform better than particle physics generators for multi-particle spectra

Mass Composition

golden key to understand spectral features

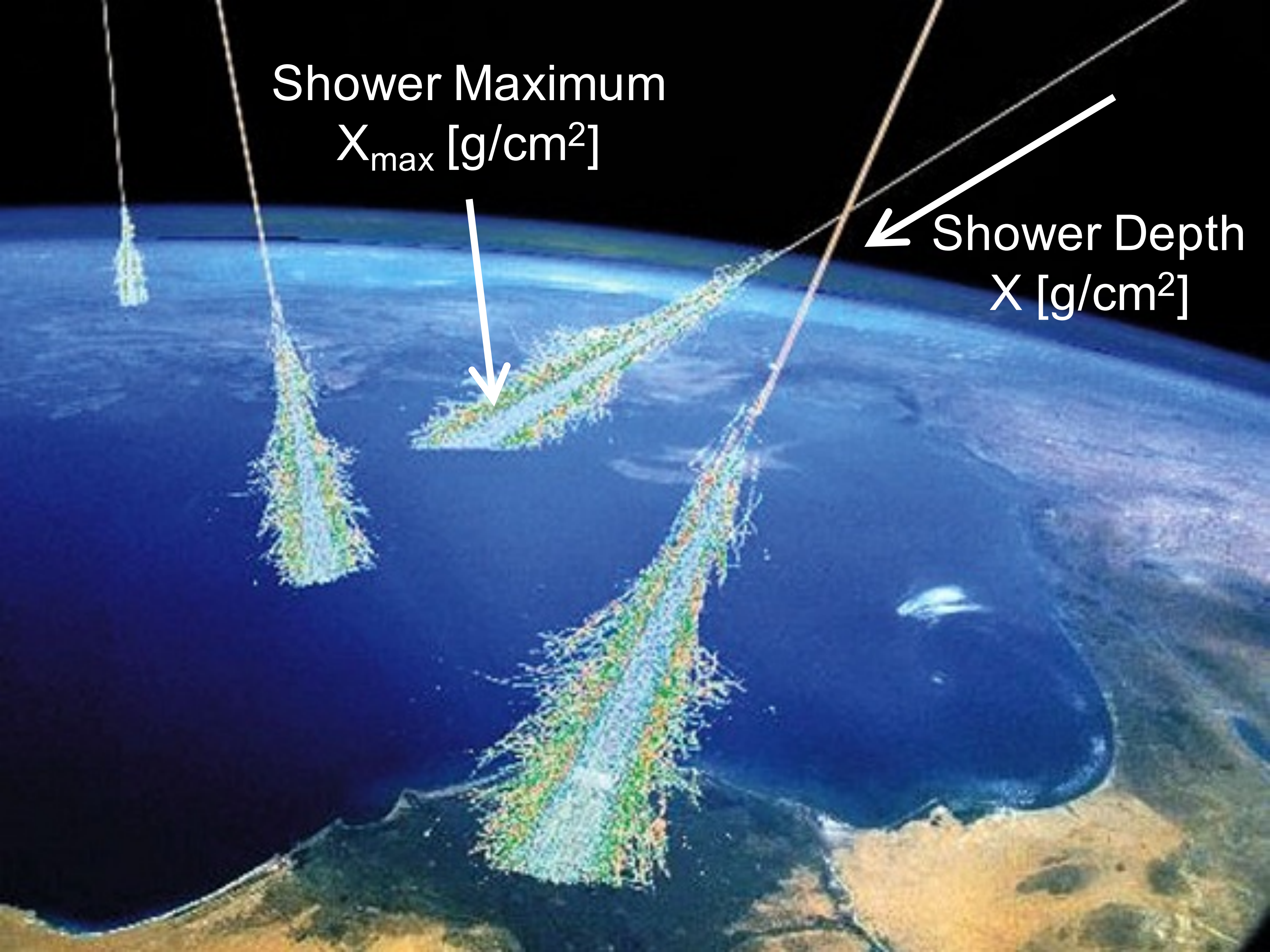


cut-off

ankle

but are these really protons?

I. Valiño, ICRC 2015



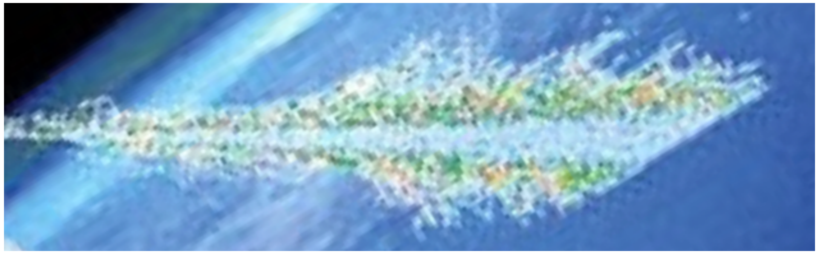
Shower Maximum

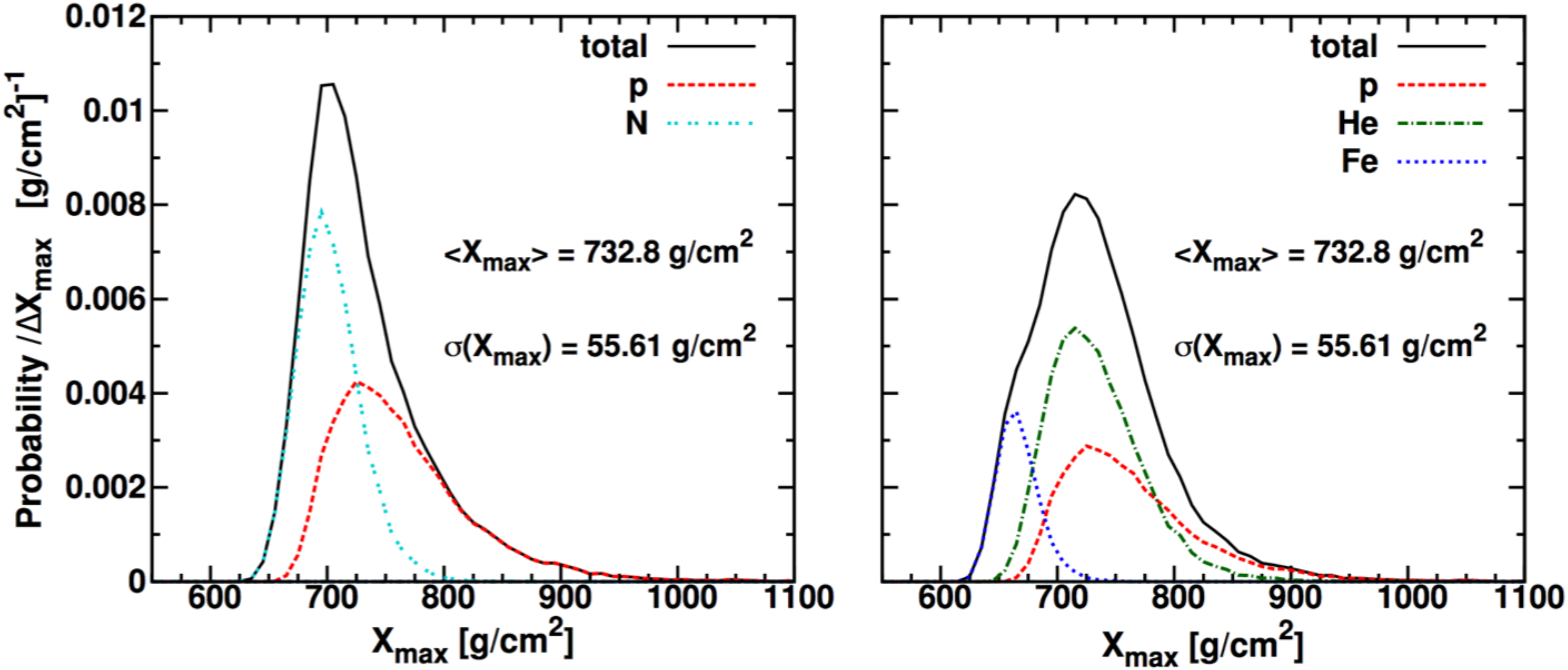
X_{max} [g/cm^2]

Shower Depth

X [g/cm^2]

Mean and width of X_{max} distribution $\Rightarrow$ mass mix

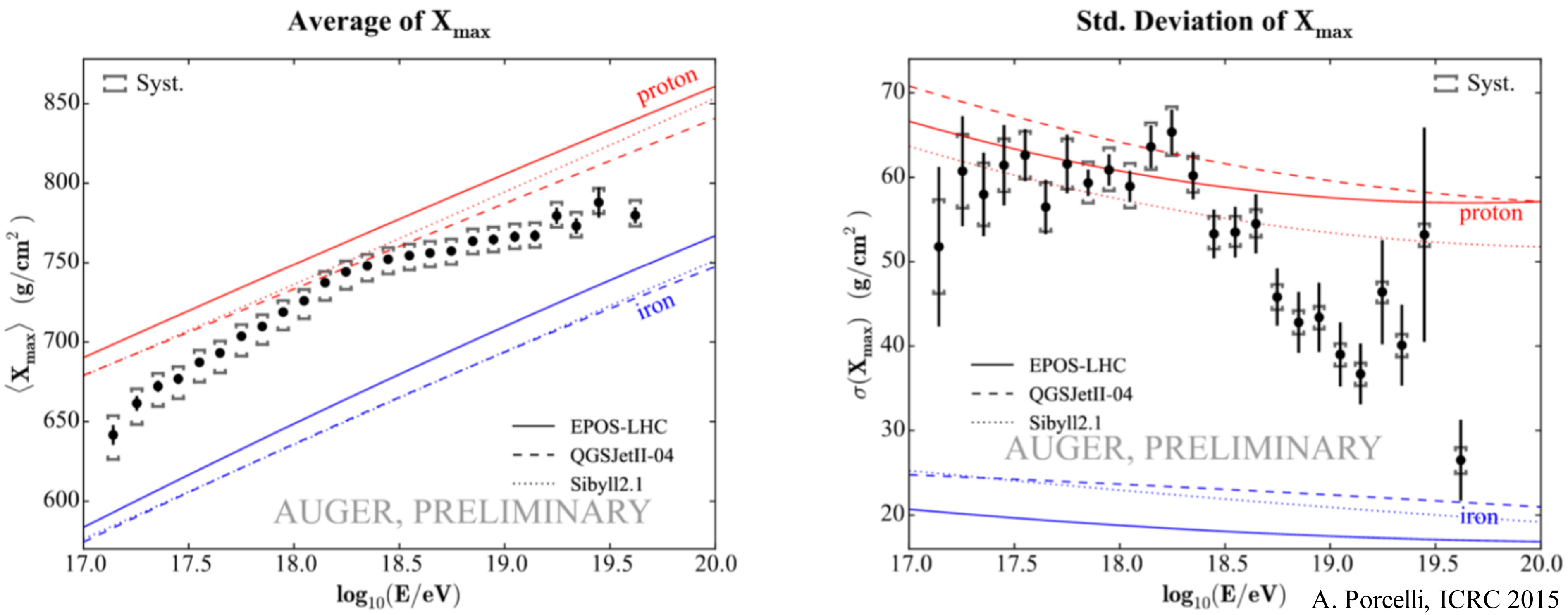




EPOS-LHC

$E = 10^{18.2-18.3}\,\mathrm{eV}$

Pierre Auger Collab., arXiv:1409.5083v1 [astro-ph.HE]

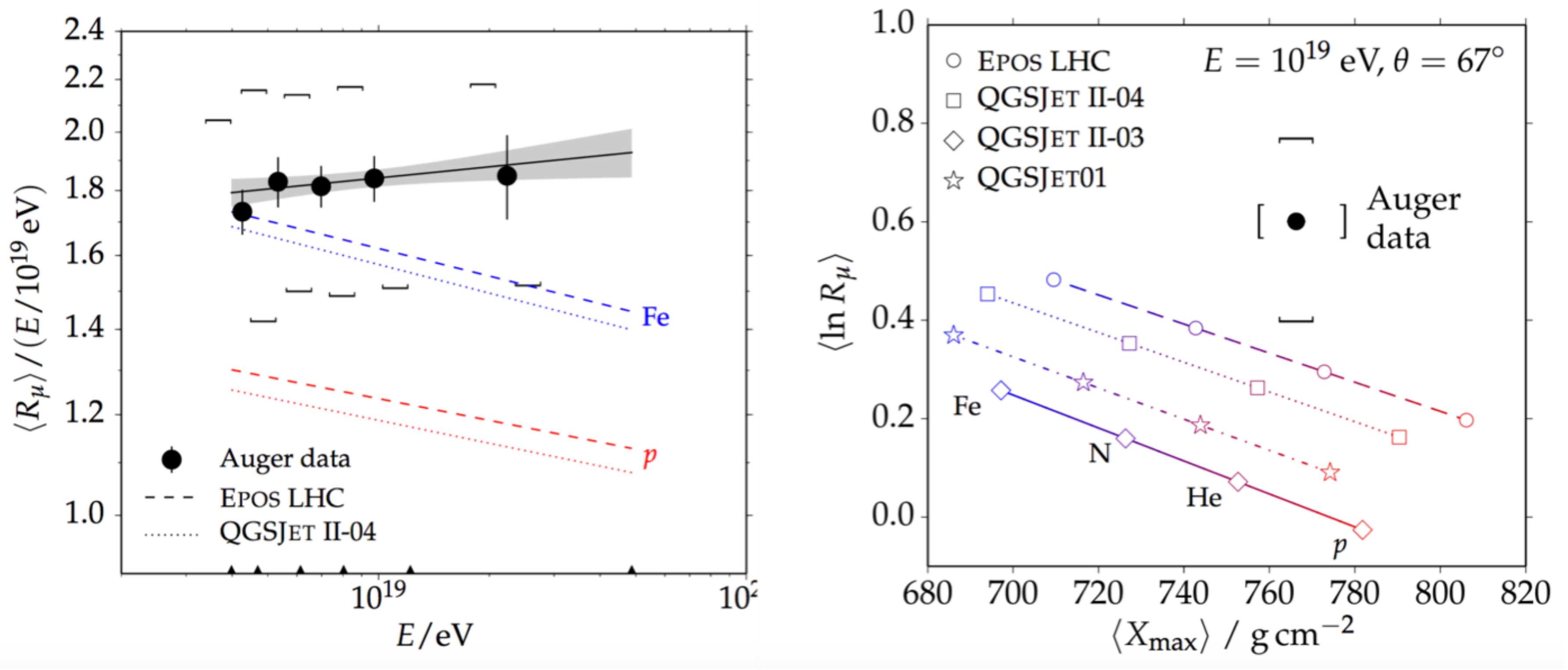


A. Porcelli, ICRC 2015

- above knee: heavy
- ankle: again light; dip due to $p\,\gamma_{\rm CMB} \rightarrow p\,e^+e^-$
- cut-off: mixture; NOT pure GZK cut-off

$$p\,\gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow p\pi^0\,, \quad n\pi^+$$

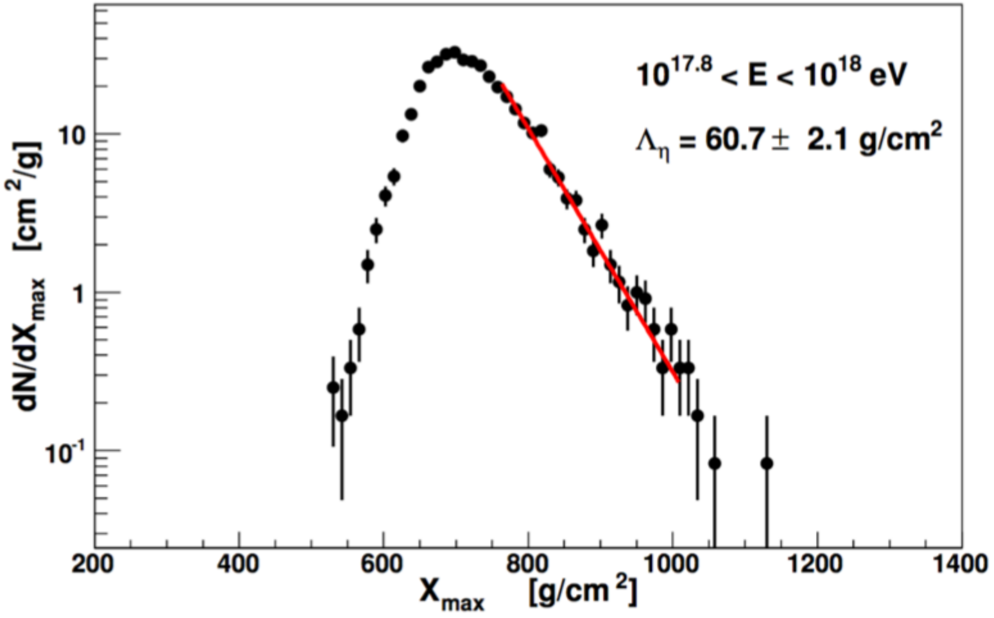
Mystery: Overproduction of myons at highest energies



L. Collica, ICRC 2015

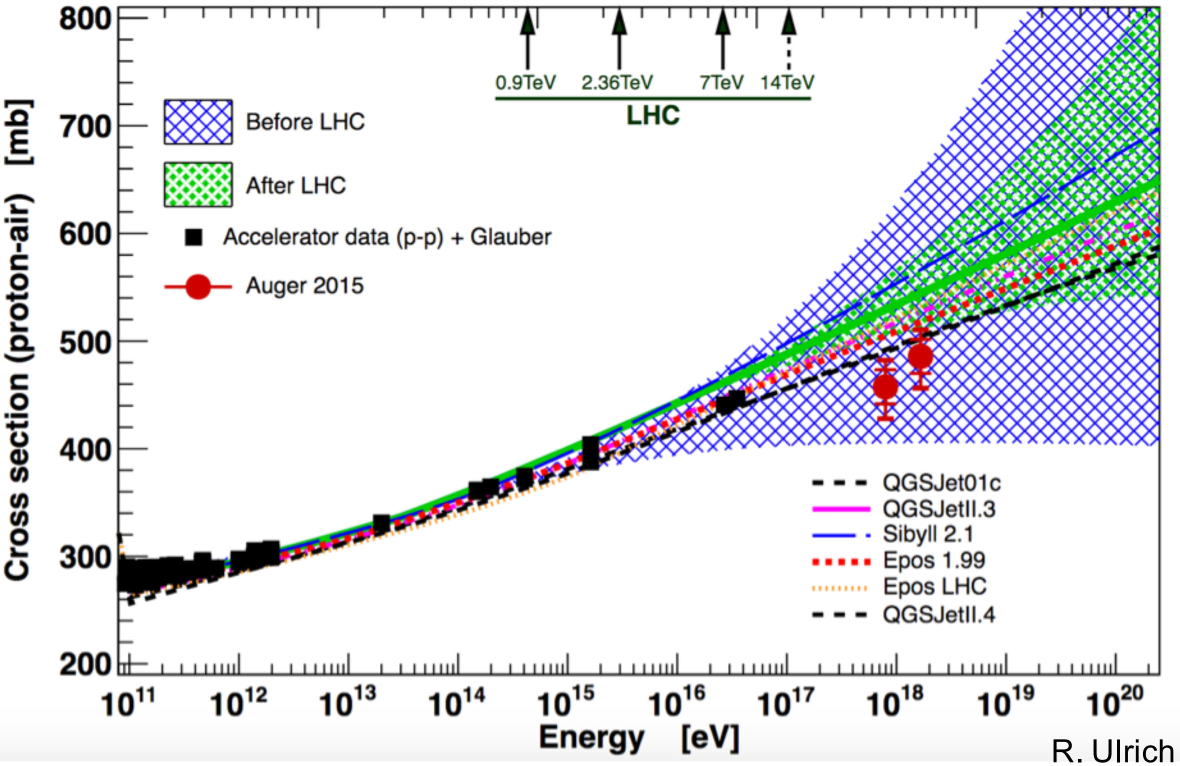
- Problem with interaction models? Very hard to solve!
- New particle physics at highest energies?

p-air Cross section



measure slope in X_{max} distr.

translation with interaction models



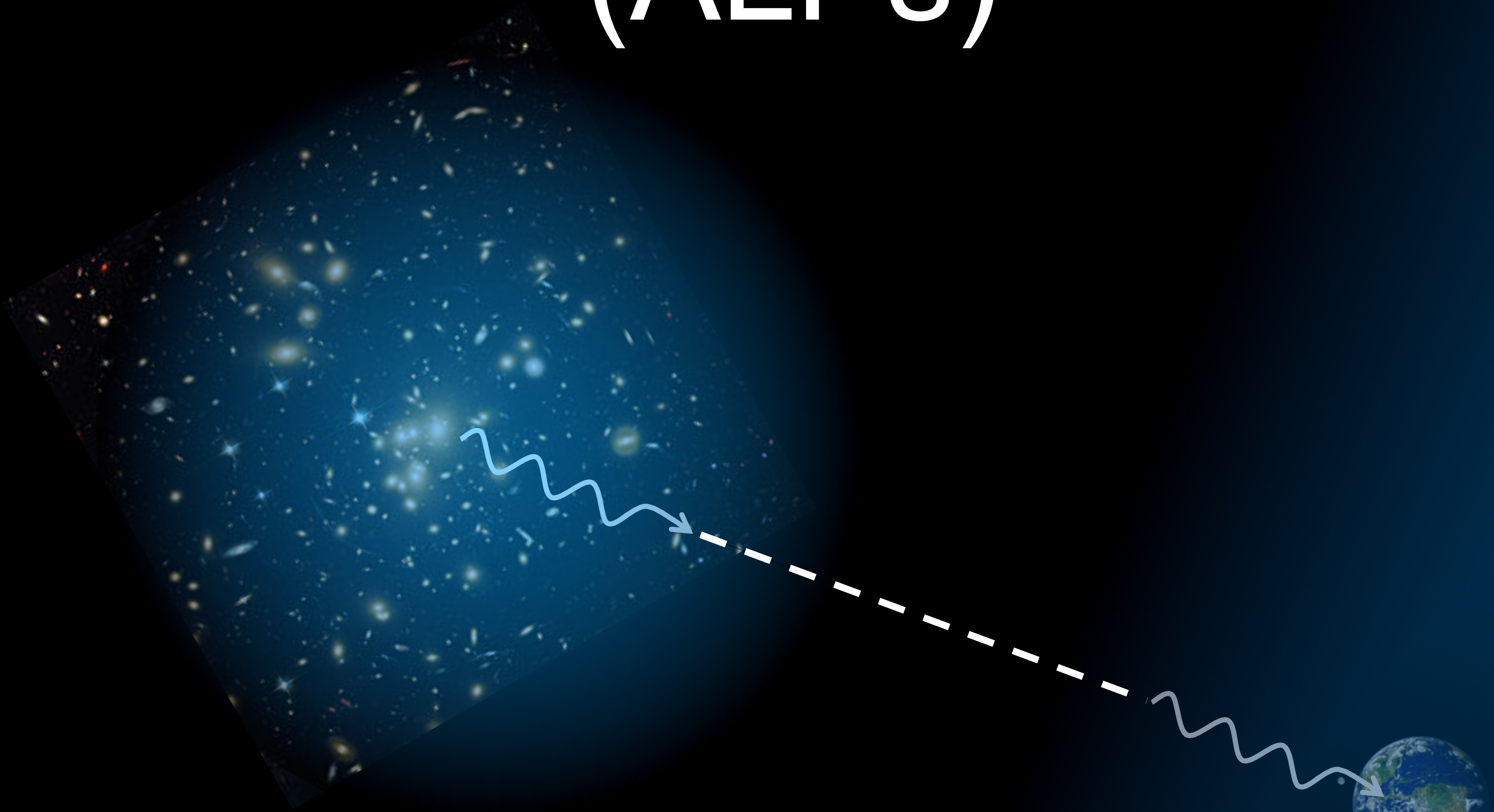
accelerator data:
σ_{inel}(p-p) to σ(p-air)
using Glauber model

R. Ulrich

Outline

- Cosmic Rays and Air Showers
- **Dark Matter: WIMPs and ALPs**
- Quantum Gravity

Axion-Like-Particles
(ALPs)



Axion-Like-Particles (ALPs)

non-thermally produced light DM candidates

Pseudo-Nambu-Goldstone Bosons

- U(1) symmetries arising in string theory (Alps)
- global U(1) Peccei-Quinn symmetry (QCD-Axion)

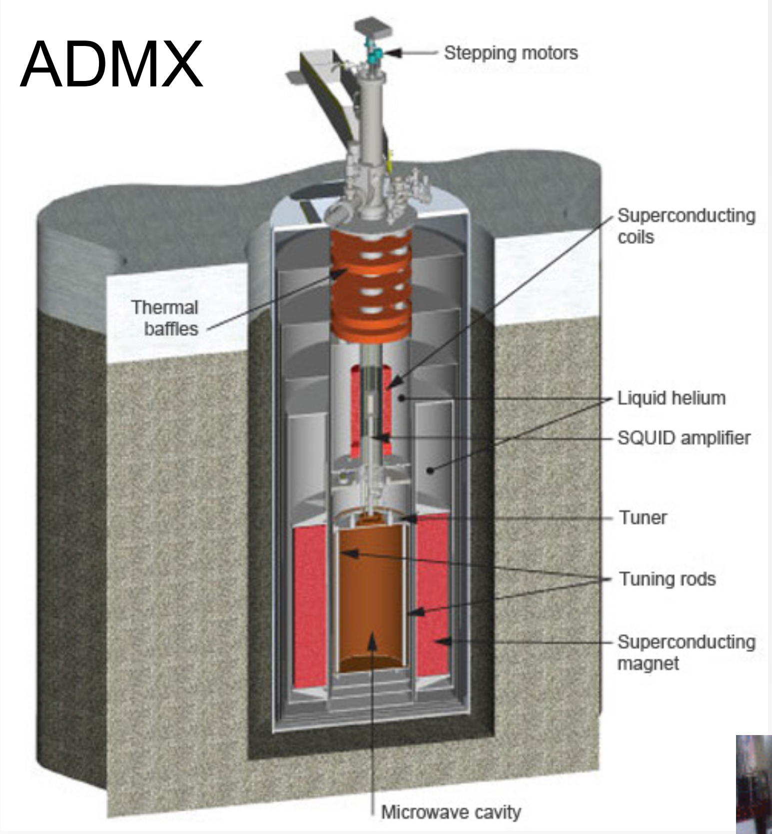
Coupling to photons:

Photon external B-field

$$\mathcal{L}_{a\gamma} = g_{a\gamma} \vec{E} \cdot \vec{B} \, a$$

ALPs field

Rich experimental program

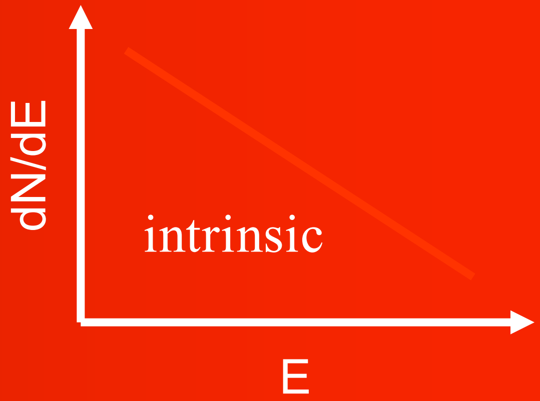


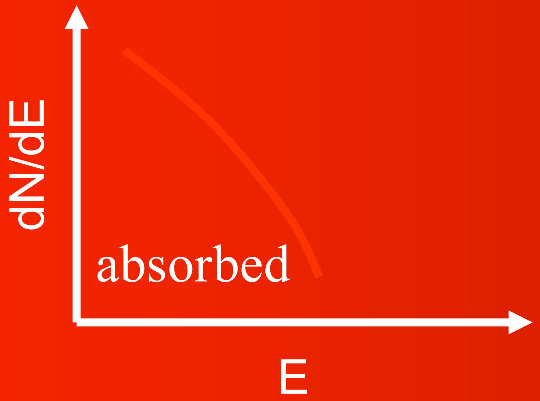
tunable high Q microwave cavity

LHC magnet pointing at the sun

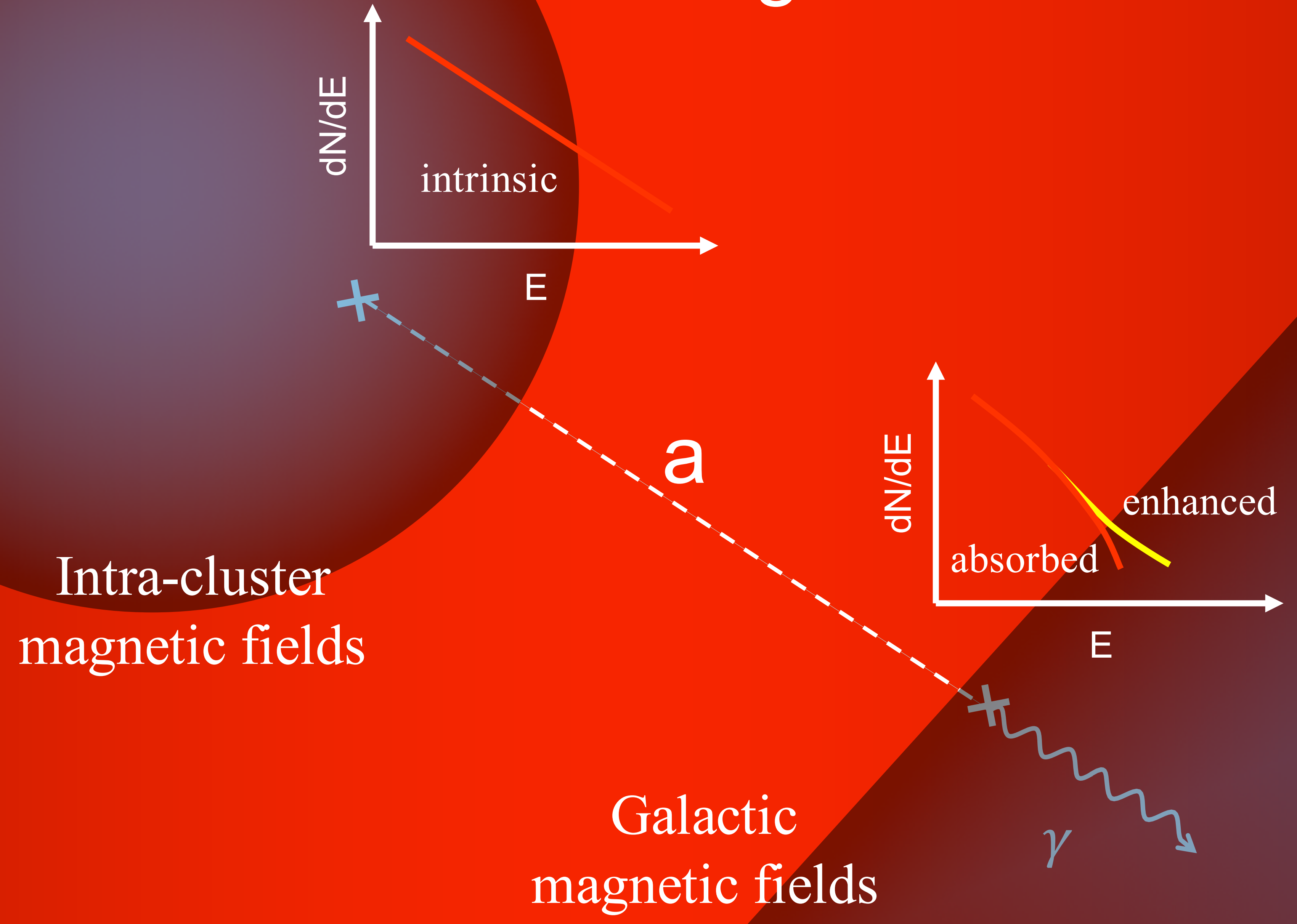
laser shining through a wall in a magnet

Cosmological ”Walls“



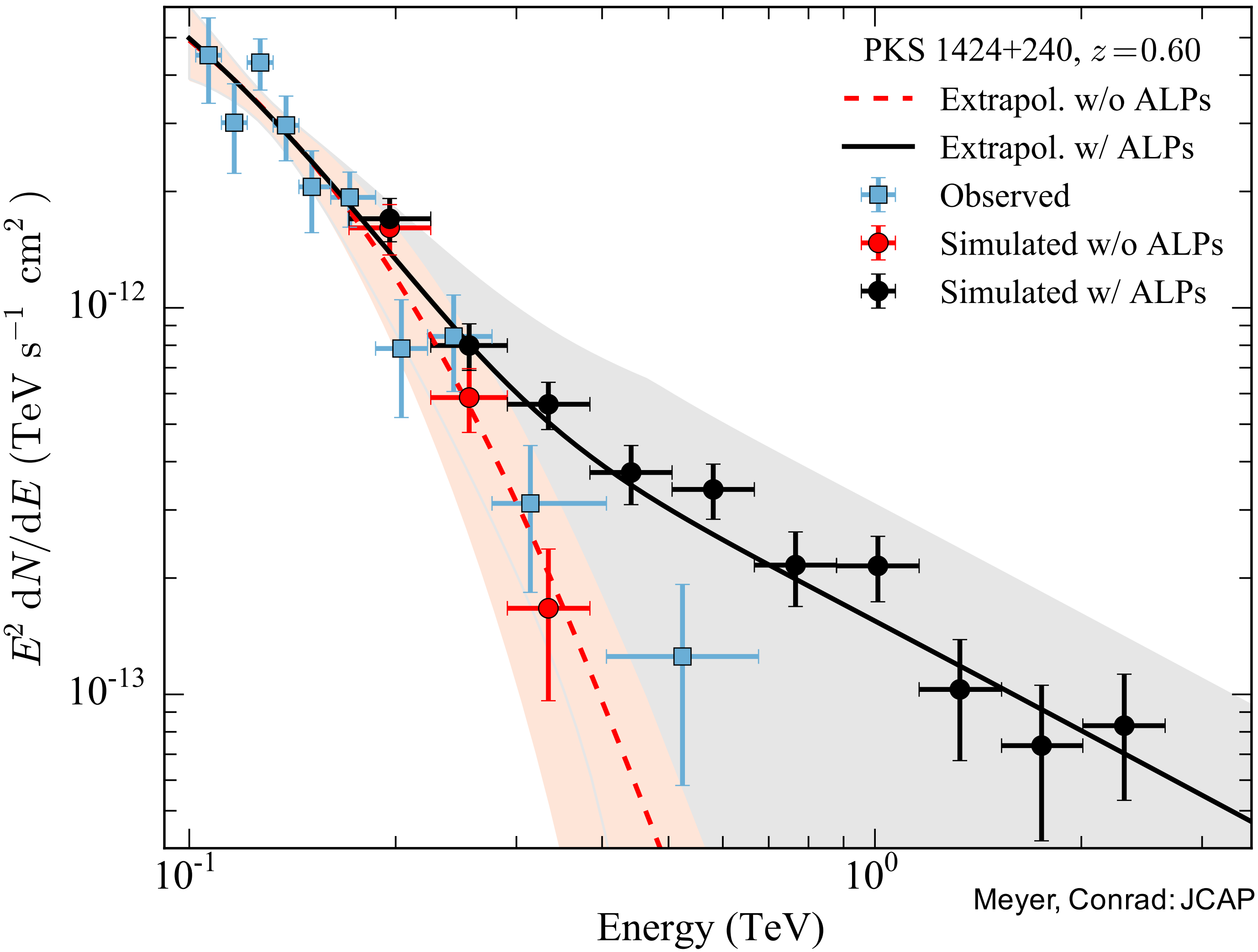


Cosmological ”Walls“



Simulation of ALPs enhancements:

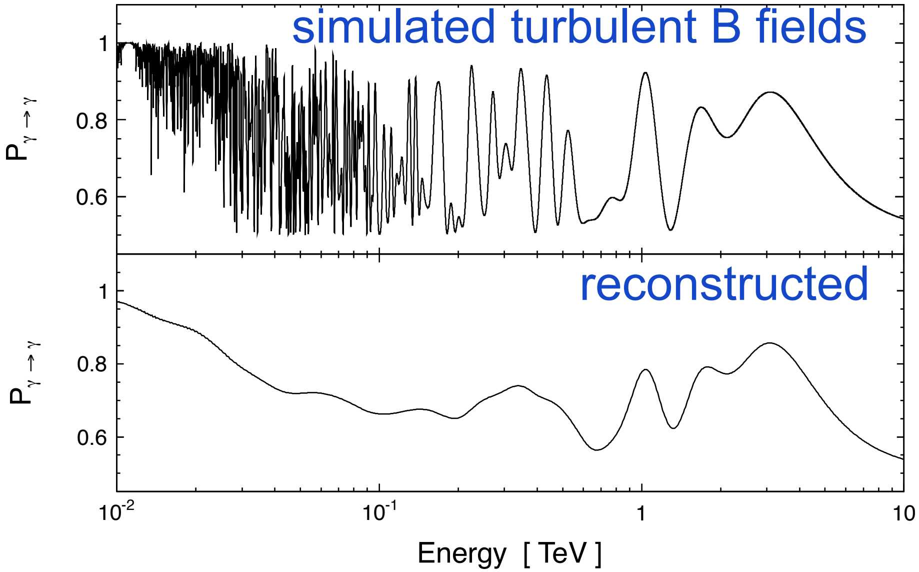
Intrisic source spectrum extracted from measured low-E spectrum



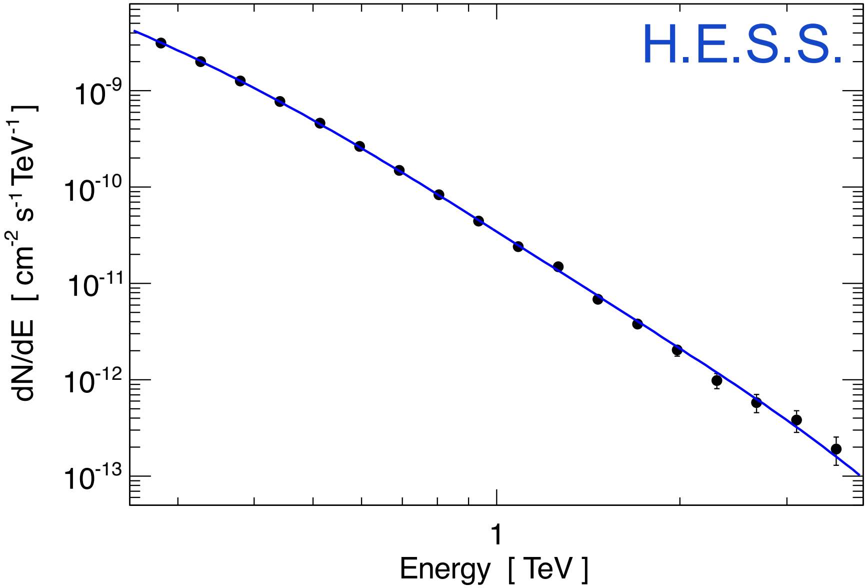
Meyer, Conrad: JCAP12 (2014) 016

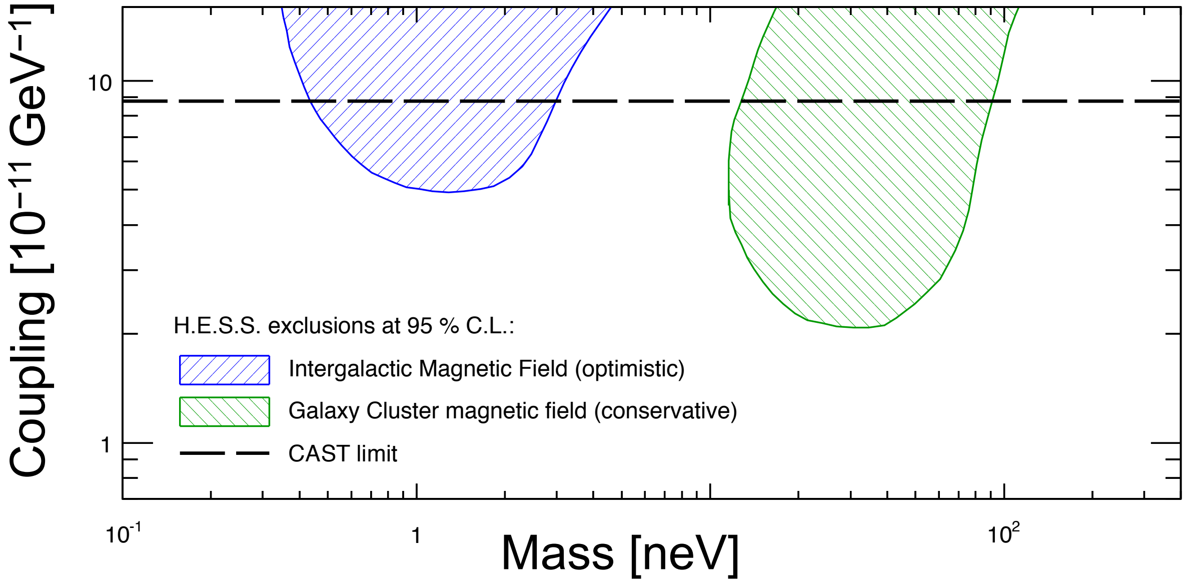
H.E.S.S. search for ALPs-induced spectral wiggles

Photon survival probability

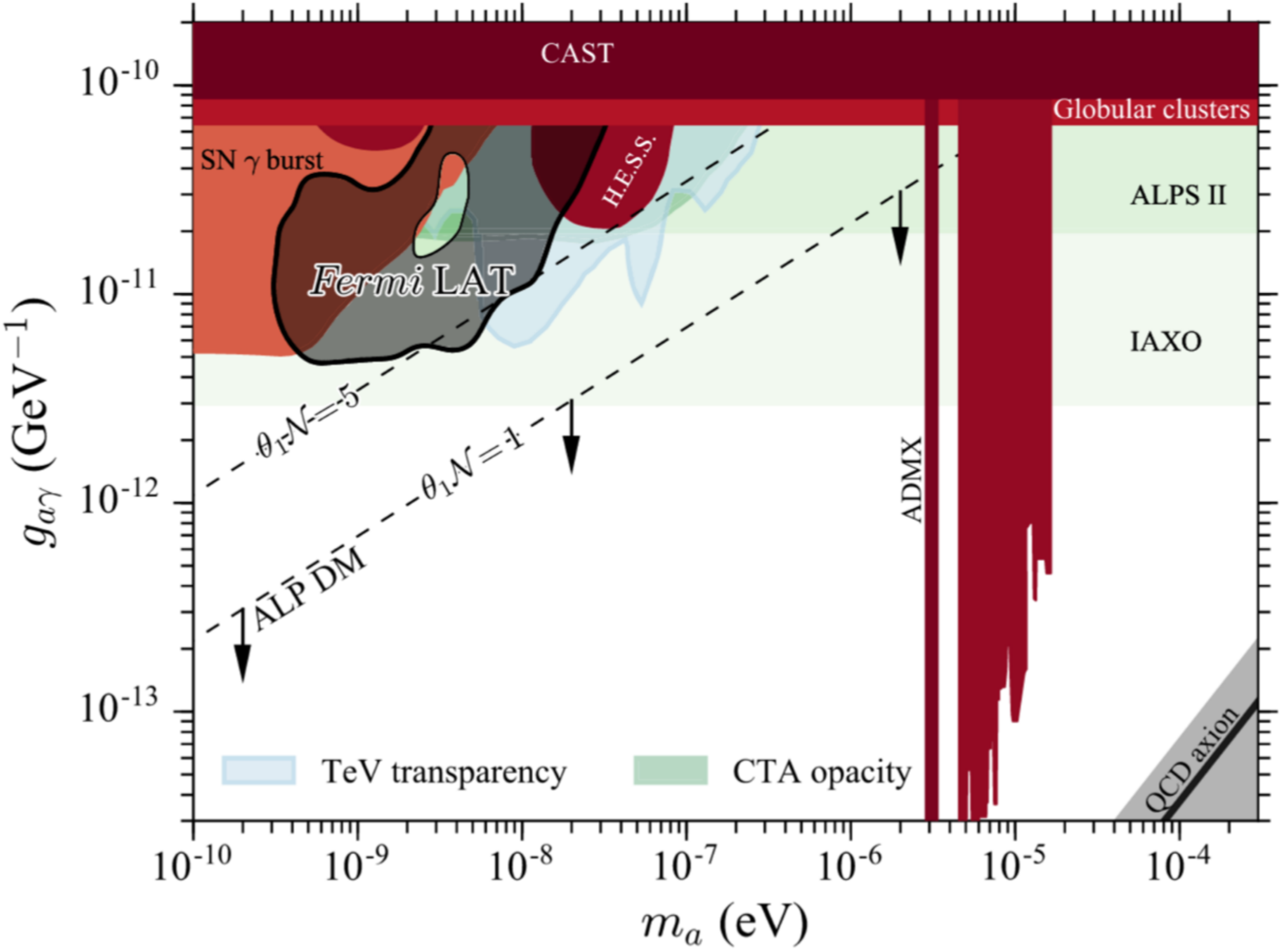


Flux from PKS 2155−304 (z=0.116)





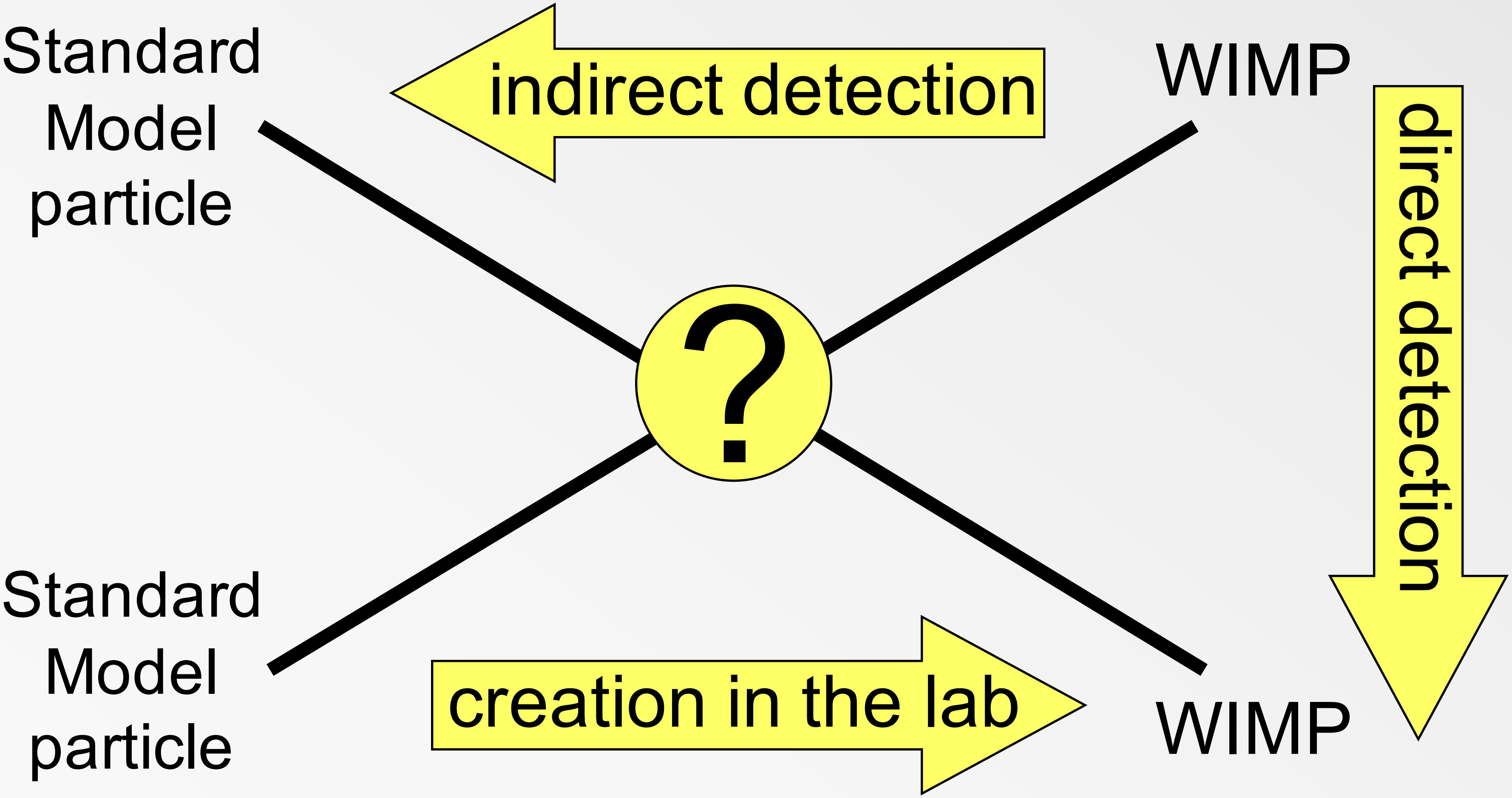
Status and prospects:



M. Ajello *et al.* (The Fermi-LAT Collaboration), Phys. Rev. Lett. 116, 161101

WIMP Dark Matter

WIMP detection - the threefold way



Standard Model particle

indirect detection

WIMP

direct detection

?

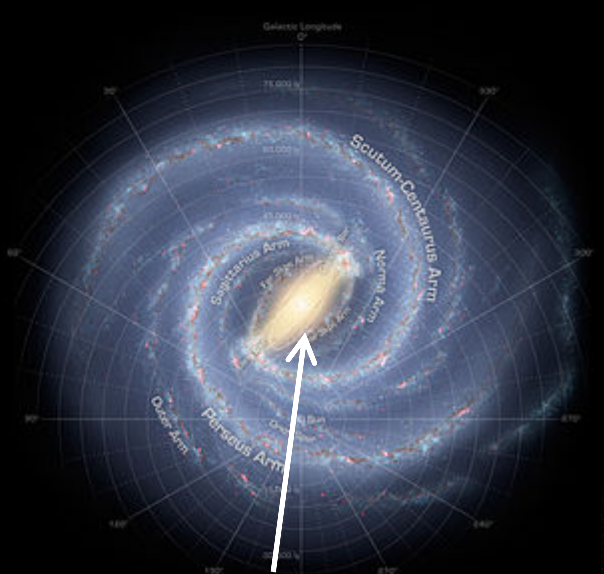
Standard Model particle

creation in the lab

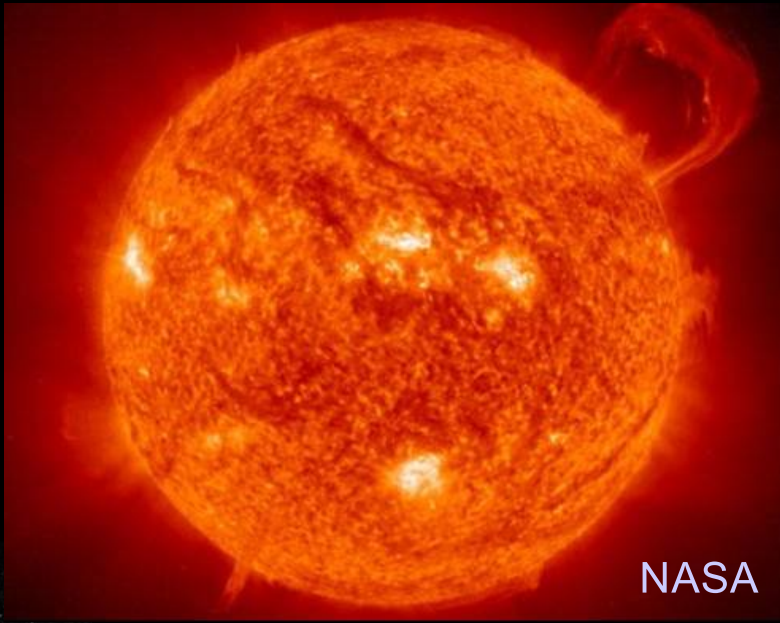
WIMP

Where to look?

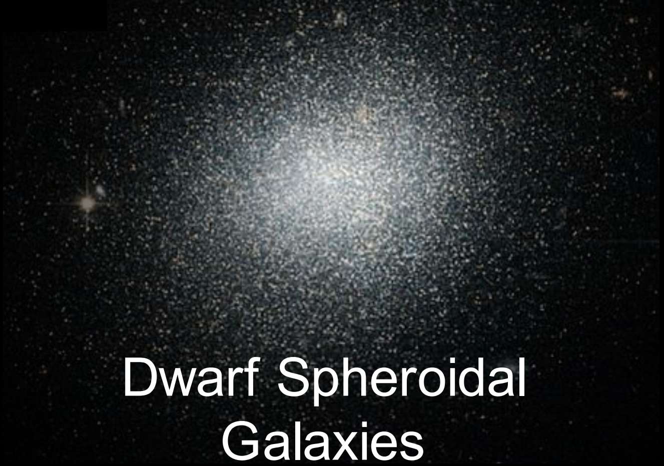
gravitational centres with small astrophysical backgrounds



Galactic Centre

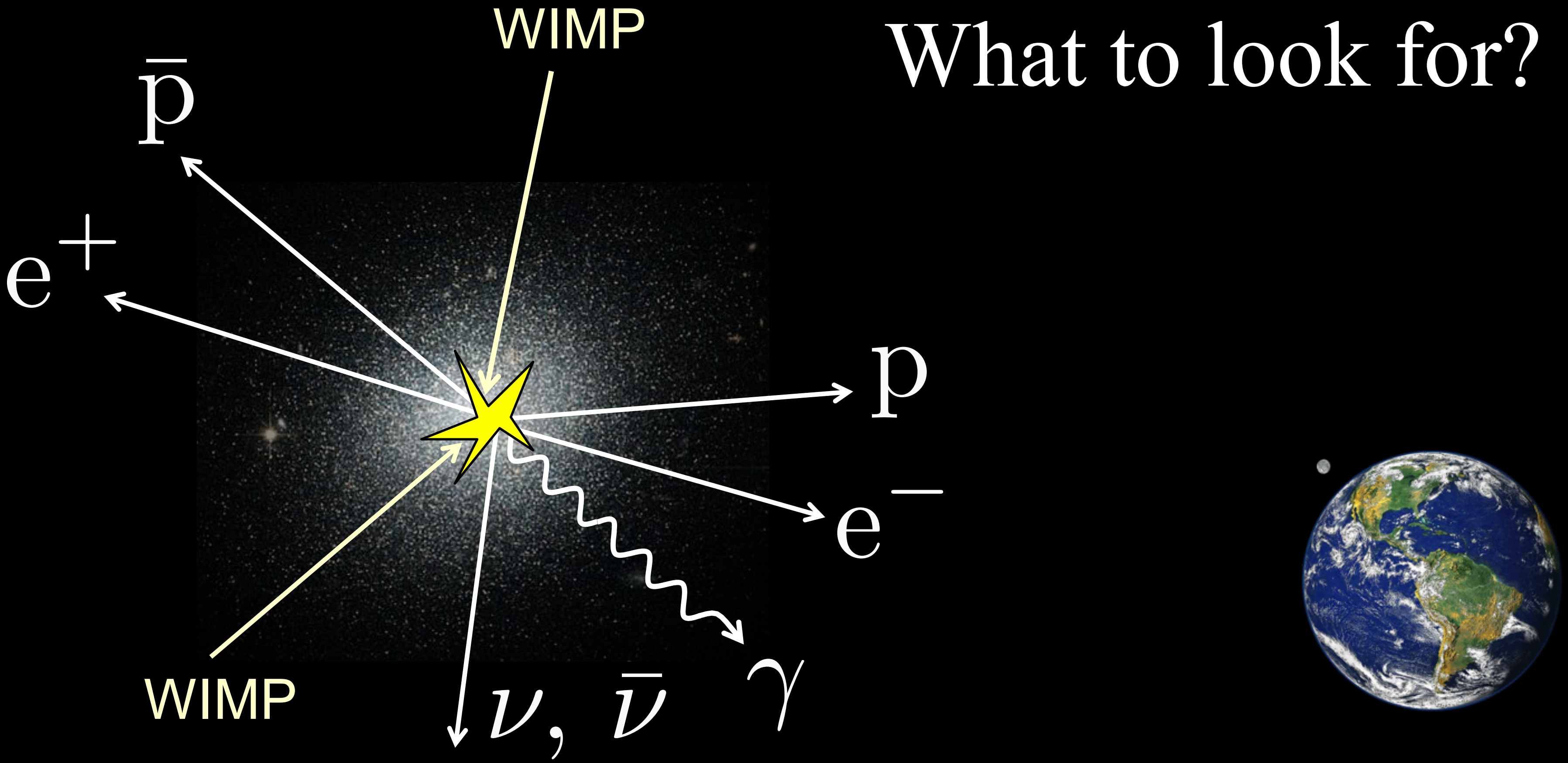

NASA

Sun Core



Dwarf Spheroidal Galaxies

What to look for?



characteristic emission of high energy particles

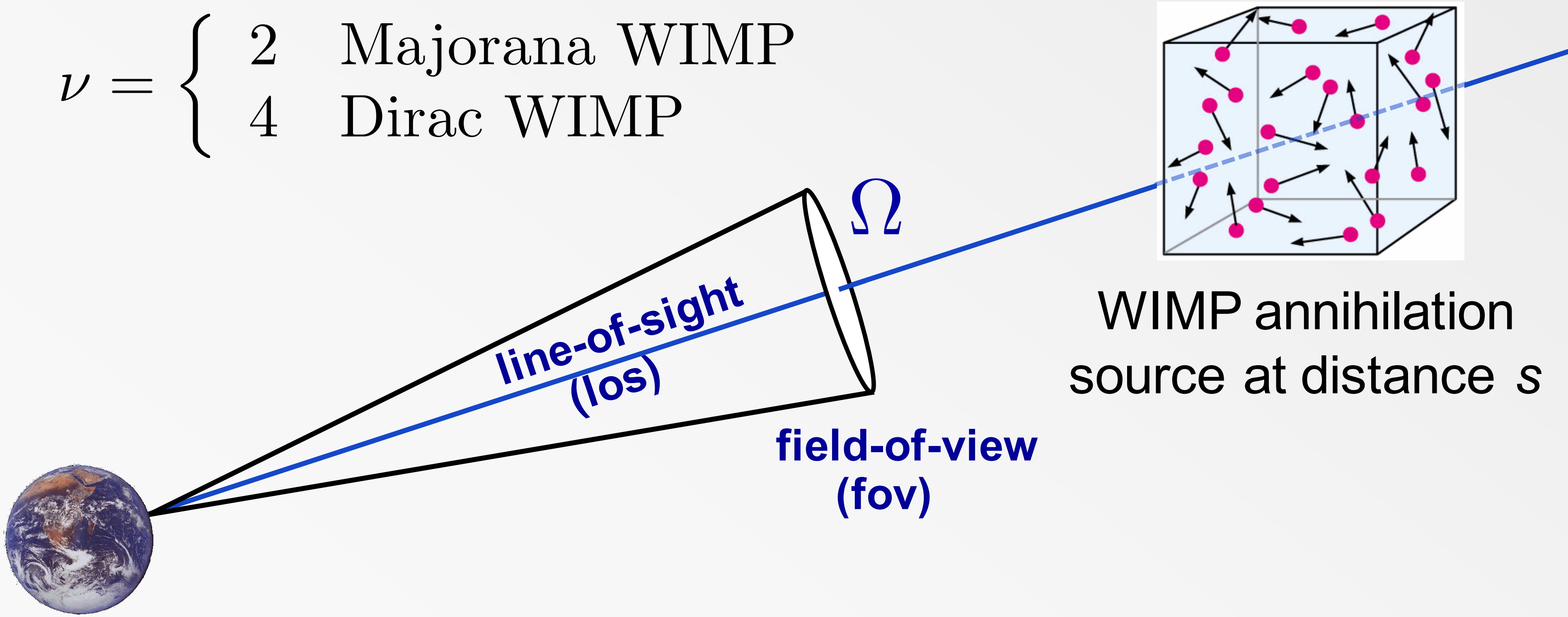
gamma rays
neutrinos
anti-matter

detectable on earth?

Expected fluxes for neutral messengers (ν, γ)

$$\frac{d\phi}{dE} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\nu m_\chi^2}\frac{dN}{dE}}_{\text{particle physics}} \underbrace{\int_{\text{fov}} d\Omega \int_{\text{los}} ds\,\rho^2}_{\text{astrophysical factor } \boldsymbol{J}}$$

$$\nu = \begin{cases} 2 & \text{Majorana WIMP} \\ 4 & \text{Dirac WIMP} \end{cases}$$



$$\frac{d\phi}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\nu m_\chi^2}\frac{dN}{dE}\int_{\text{fov}} d\Omega \int_{\text{los}} ds\,\rho^2$$

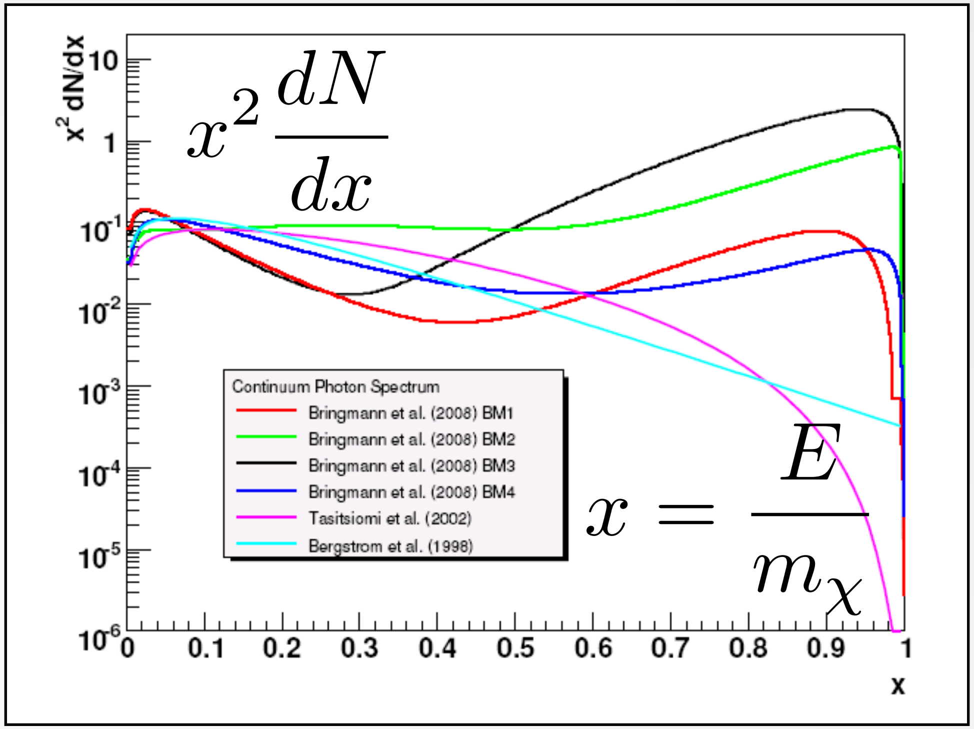
measure this

Constrain $\langle\sigma v\rangle$
as function of m_χ

Decay spectrum for messenger,
known for each annihilation channel

Example:
gamma-ray messenger,
“fragmentation”-functions
for various channels

$$\chi\chi \to \quad W^+W^-$$
$$b\bar{b}$$
$$\tau^+\tau^- \quad \ldots$$

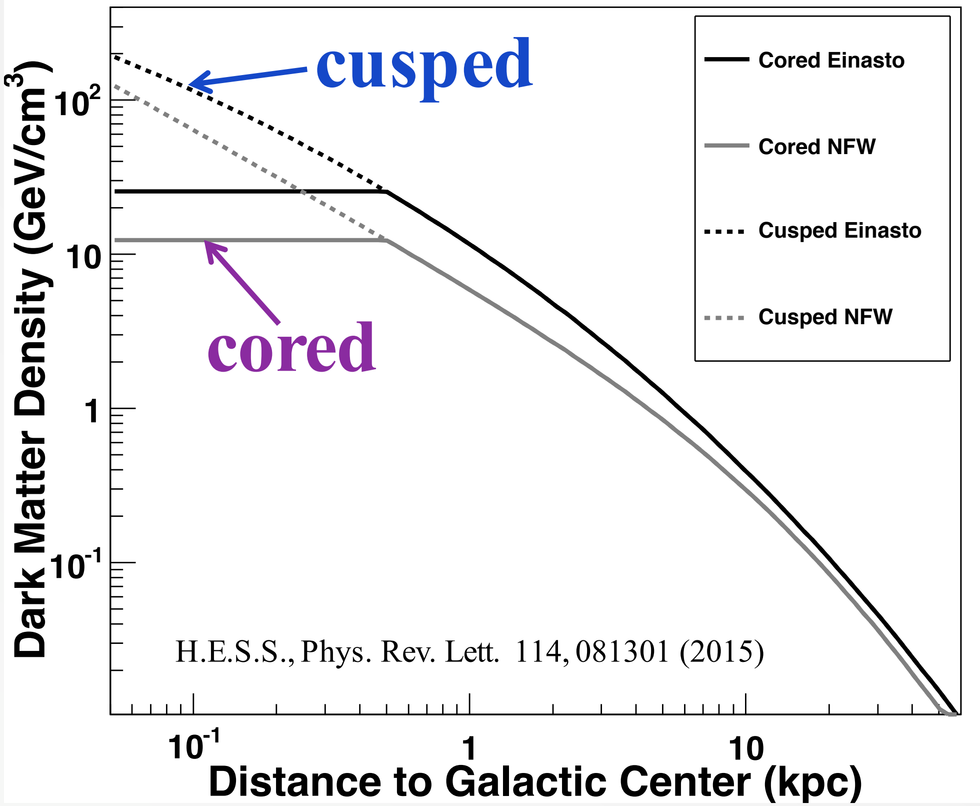


$$\frac{d\phi}{dE} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{\nu m_\chi^2}\,\frac{dN}{dE}\int_{\mathrm{fov}} d\Omega \int_{\mathrm{los}} ds\,\rho^2$$

measure this

Needs DM density profile

- from measured velocity dispersion in dwarf galaxies
- from n-body DM simulations
  → **cusped** profiles
- but baryons (stars, winds, supernovae, ...) dominate in galaxy centres
  → **cored** profiles ???
- substructures (clumps) may boost signals

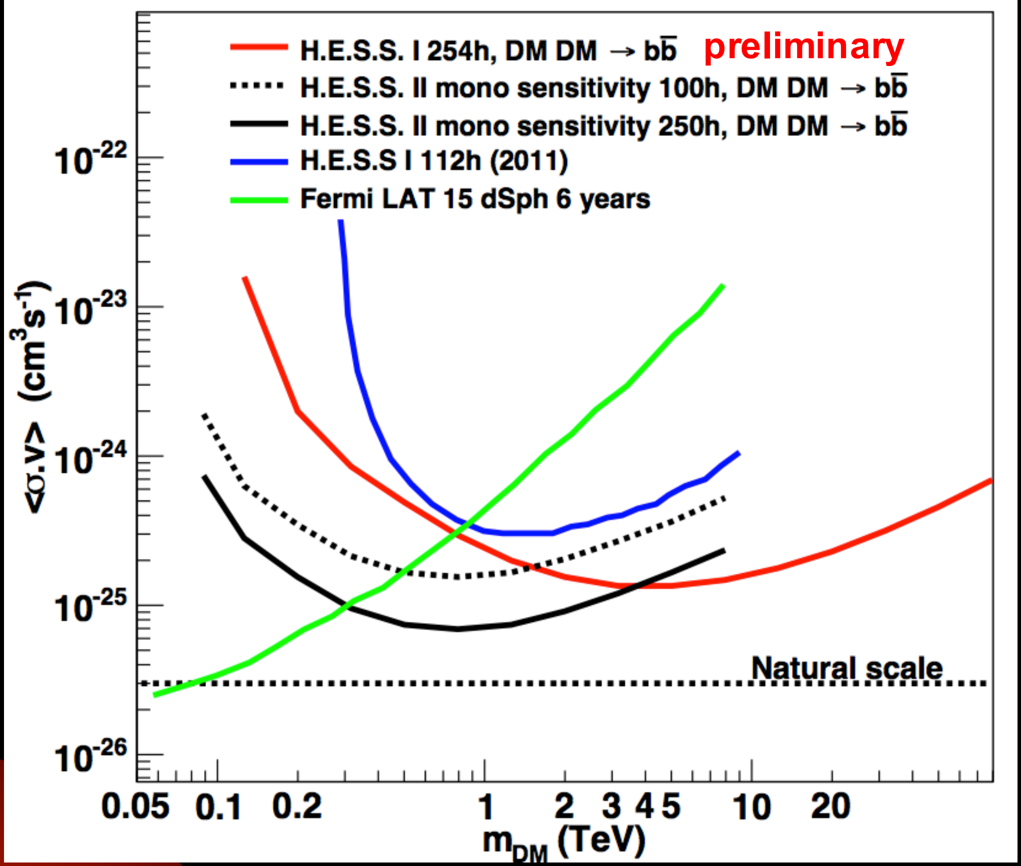


H.E.S.S., Phys. Rev. Lett. 114, 081301 (2015)

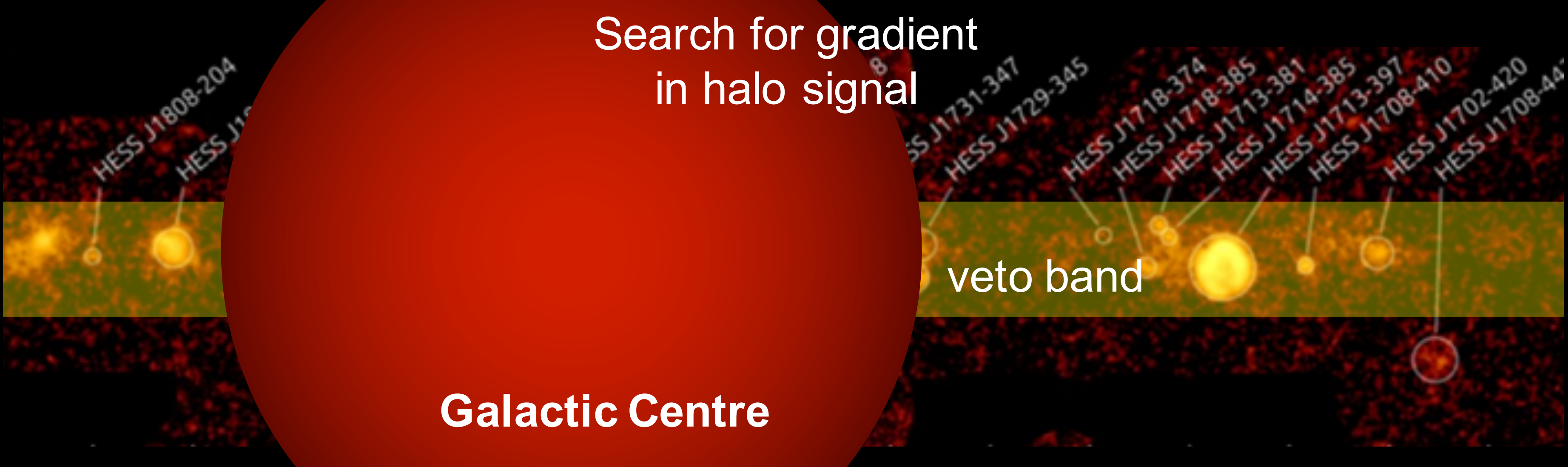
γ-ray limits (examples)

large mass/light ratio

no astrophysical backgrounds



Search for gradient
in halo signal

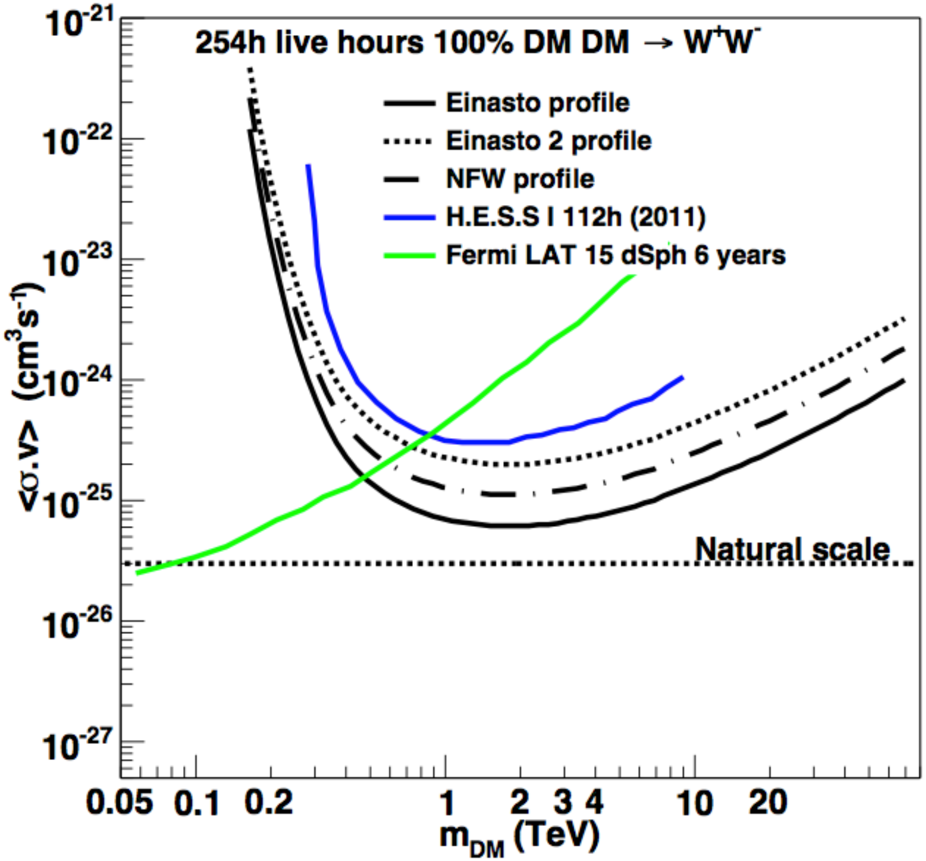


veto band

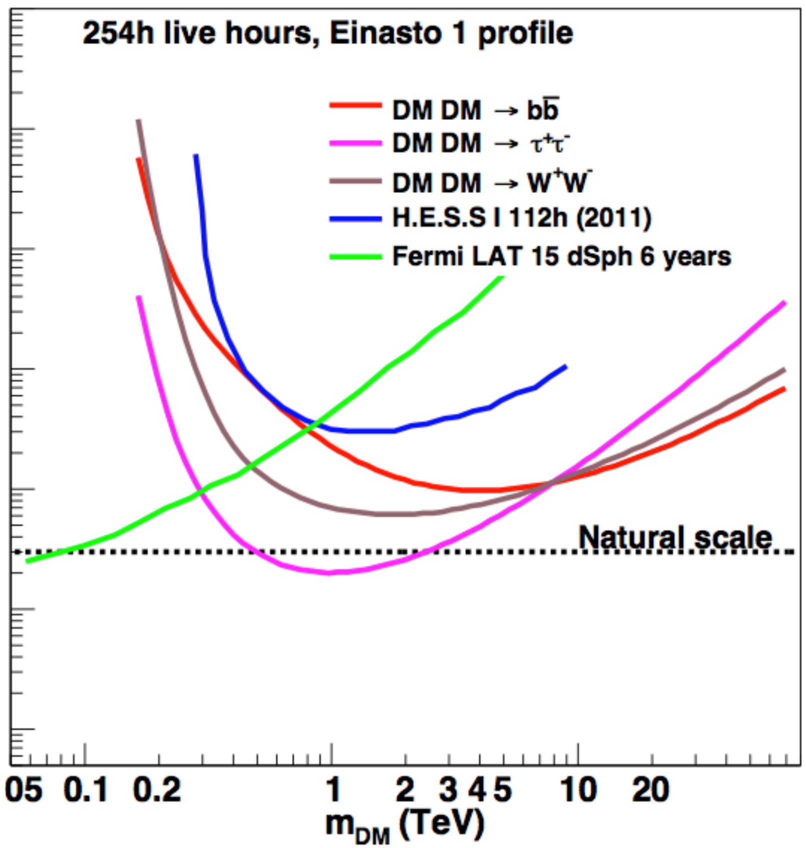
Galactic Centre

Beware: Model dependencies

Astrophysics:
DM profiles
(n-body simulations)

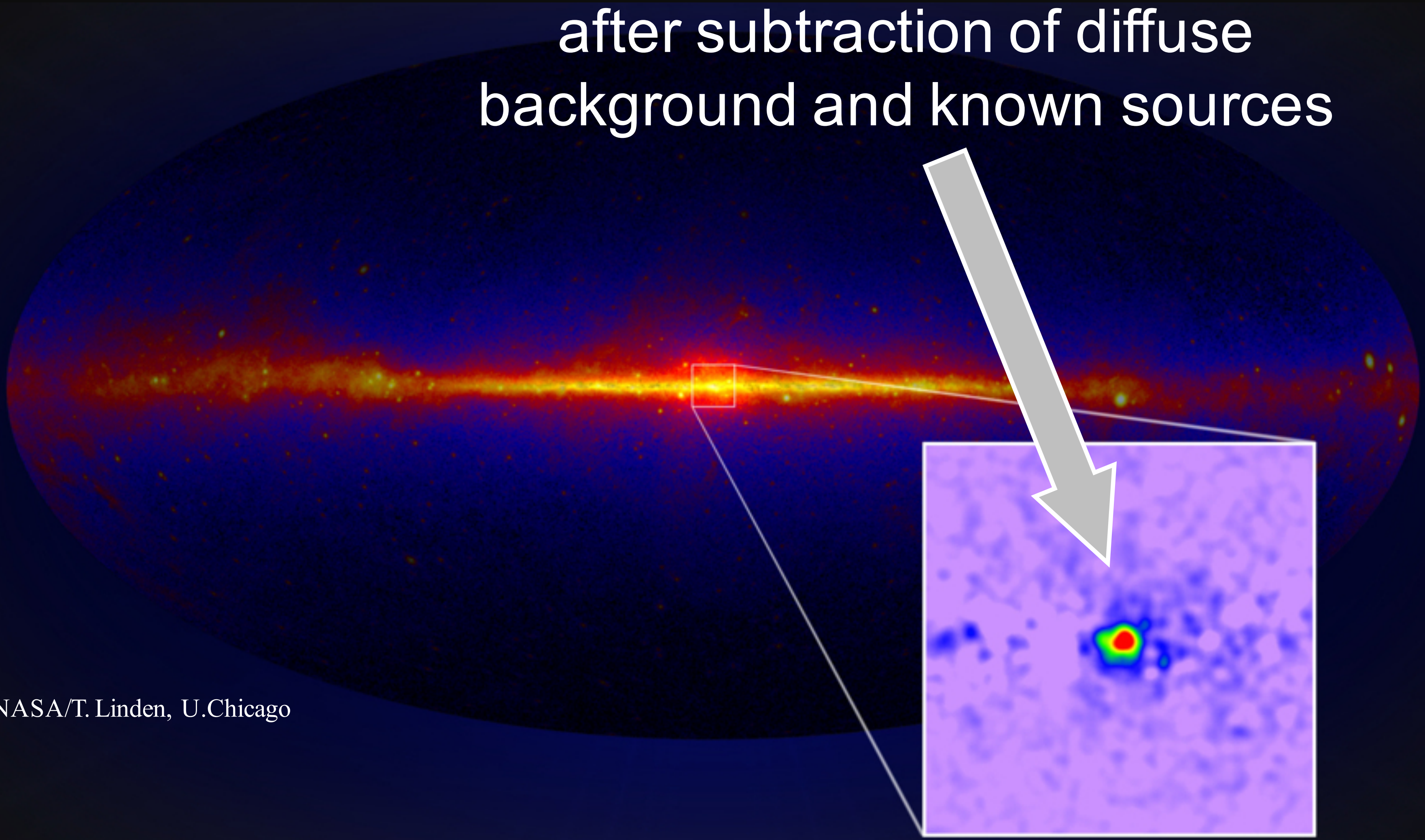


BSM particle physics:
γ rays from various DM annihilation channels



sensitivities reaching thermal relic scale!!

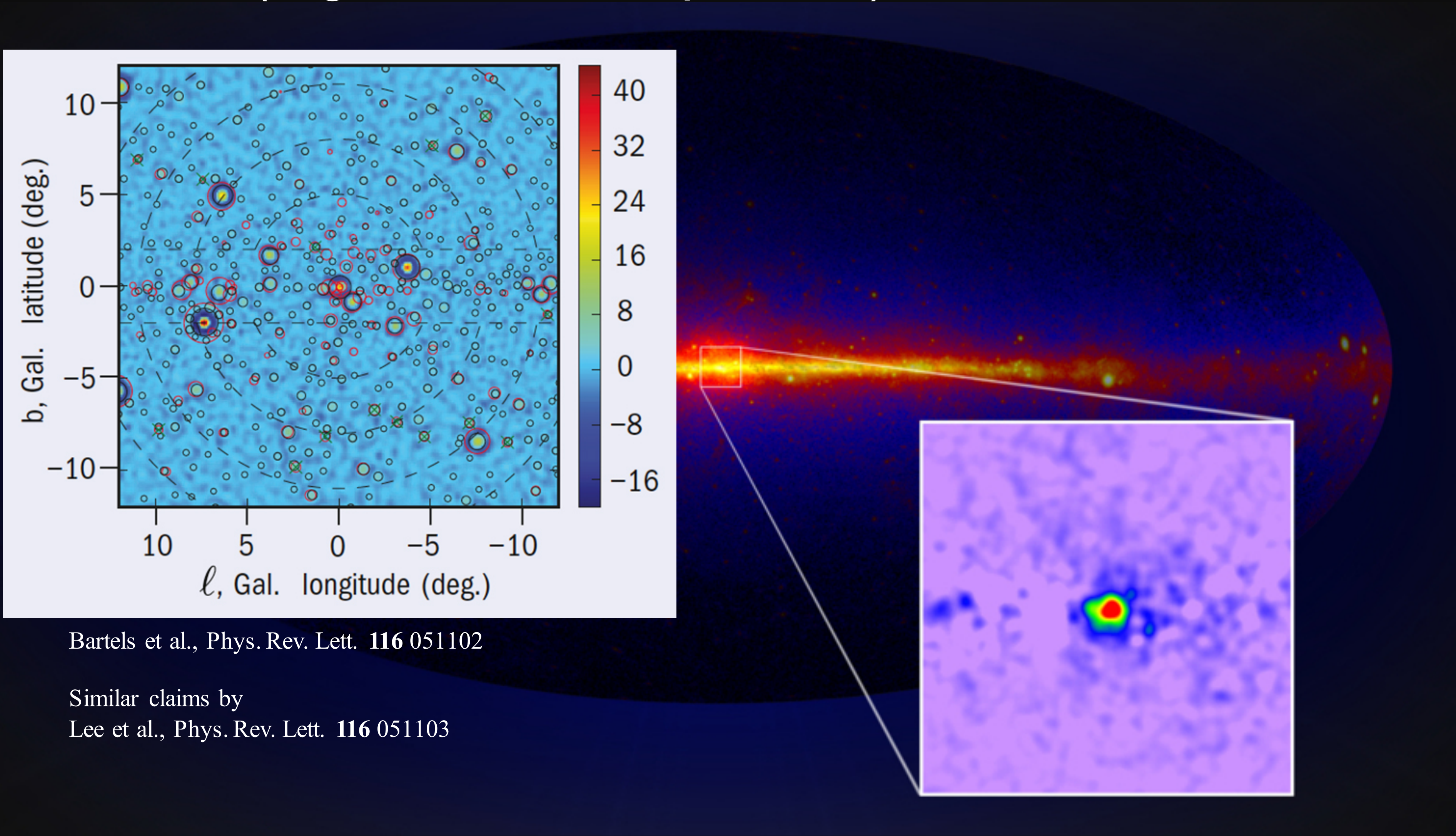
Hot topic: GeV excess in Galactic Centre (Fermi LAT)



after subtraction of diffuse background and known sources

NASA/T. Linden, U.Chicago

New: gamma ray distributions claimed to be “clumpy” ⇒ huge source population just below threshold (e.g. millisecond pulsars)?

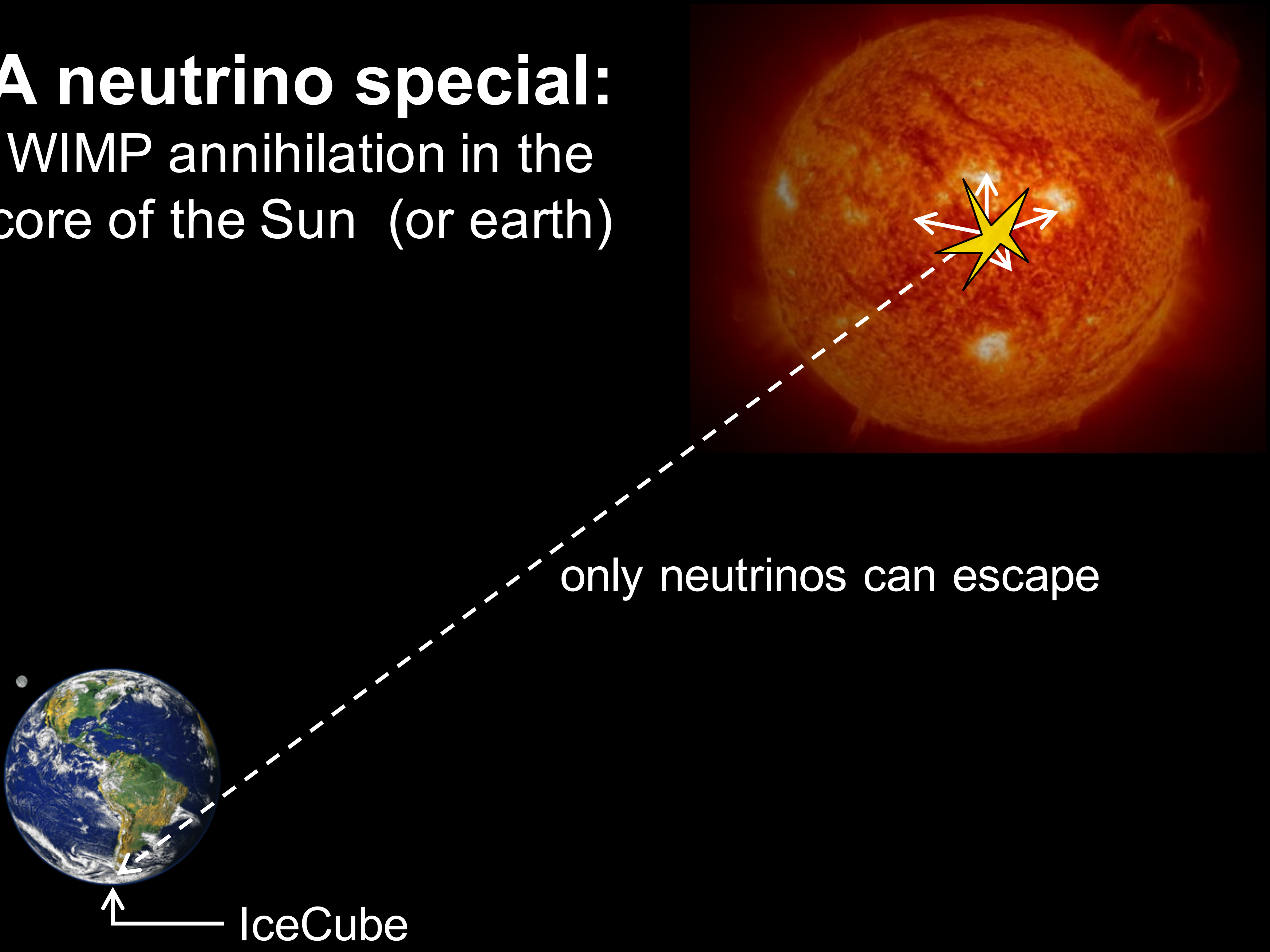


Bartels et al., Phys. Rev. Lett. **116** 051102

Similar claims by
Lee et al., Phys. Rev. Lett. **116** 051103

A neutrino special:

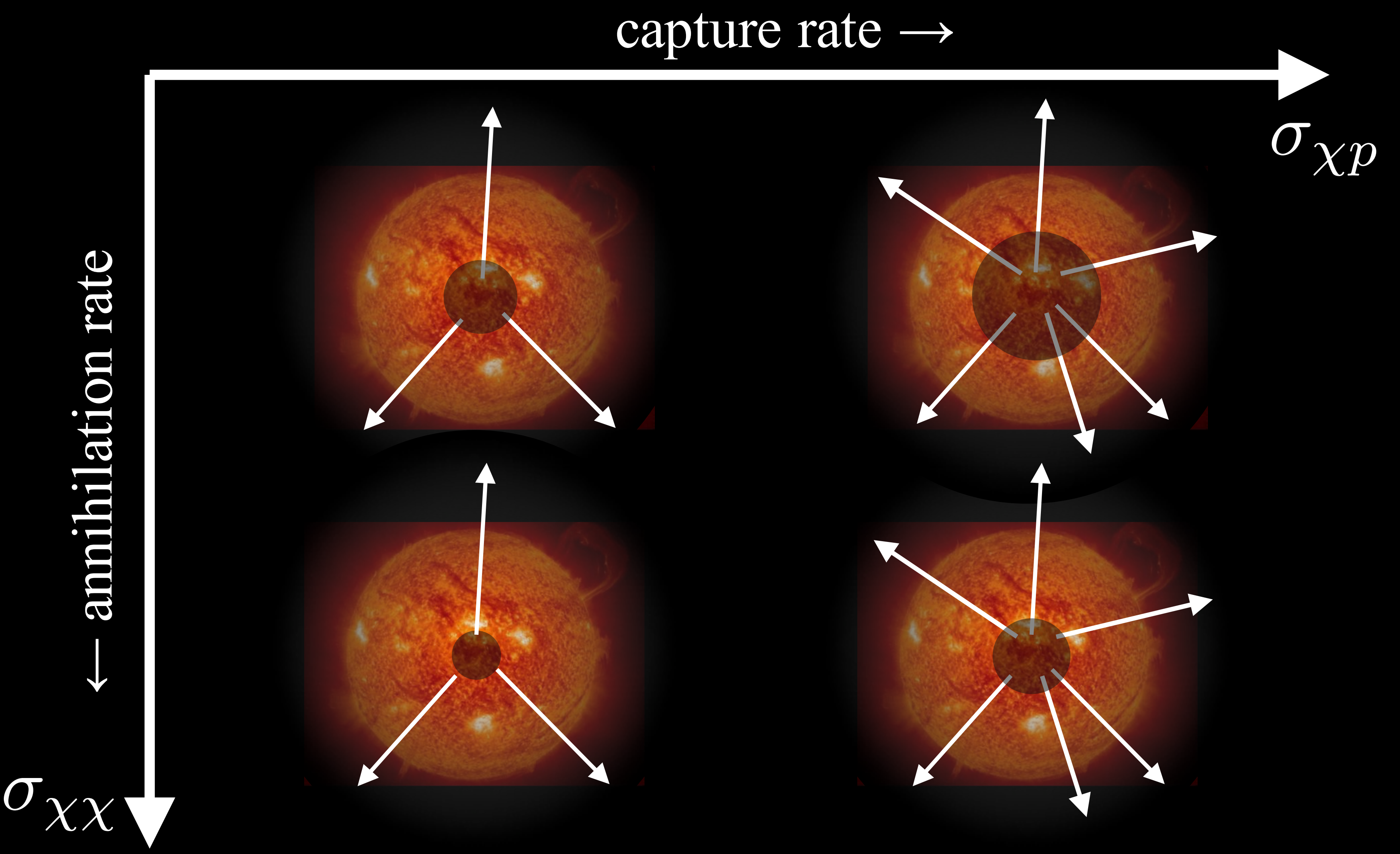
WIMP annihilation in the
core of the Sun (or earth)



only neutrinos can escape

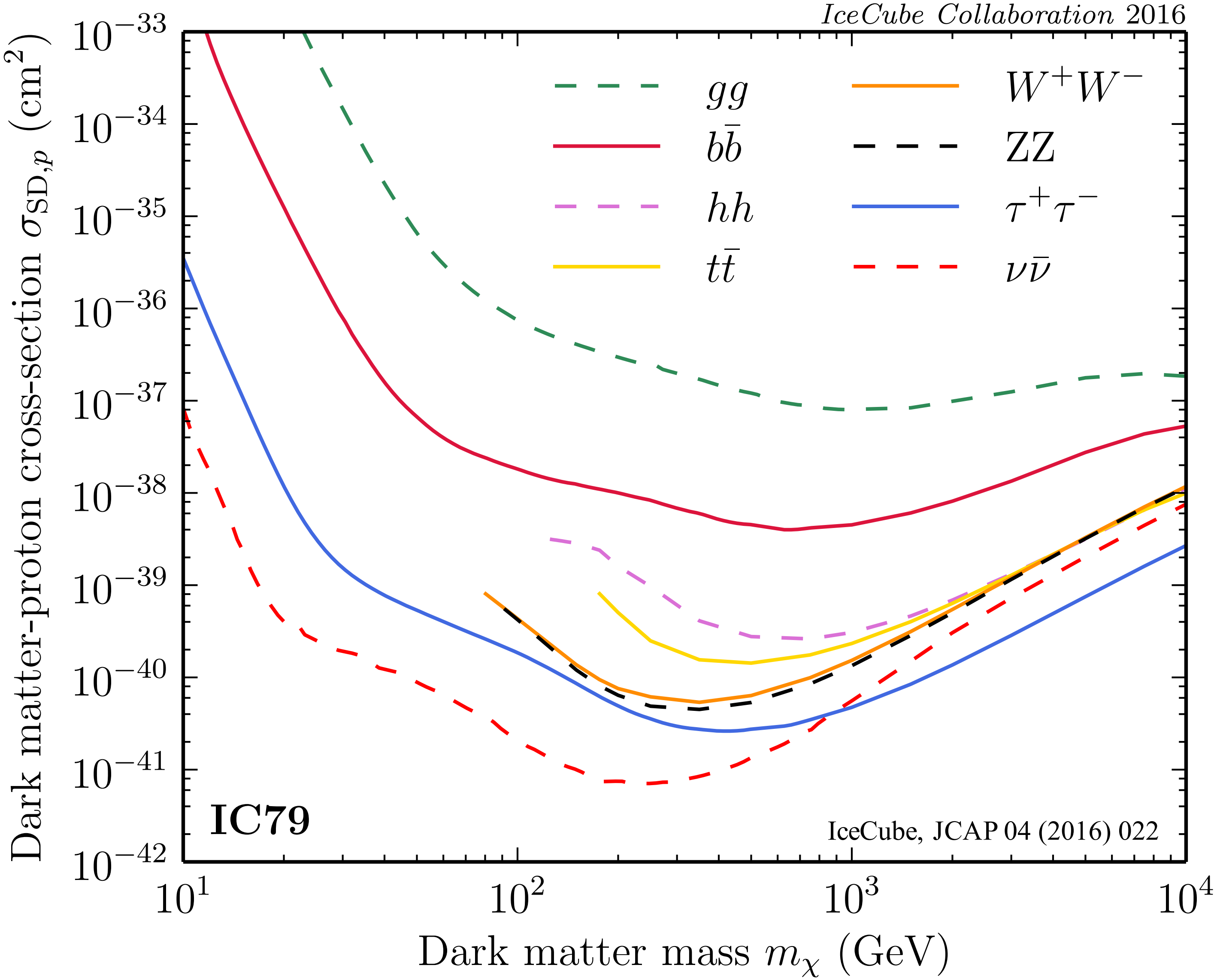
IceCube

Age 4.5×10^9 y ⇒ equilibrium capture vs annihilation rate reached for canonical thermal relic $\langle \sigma v \rangle$

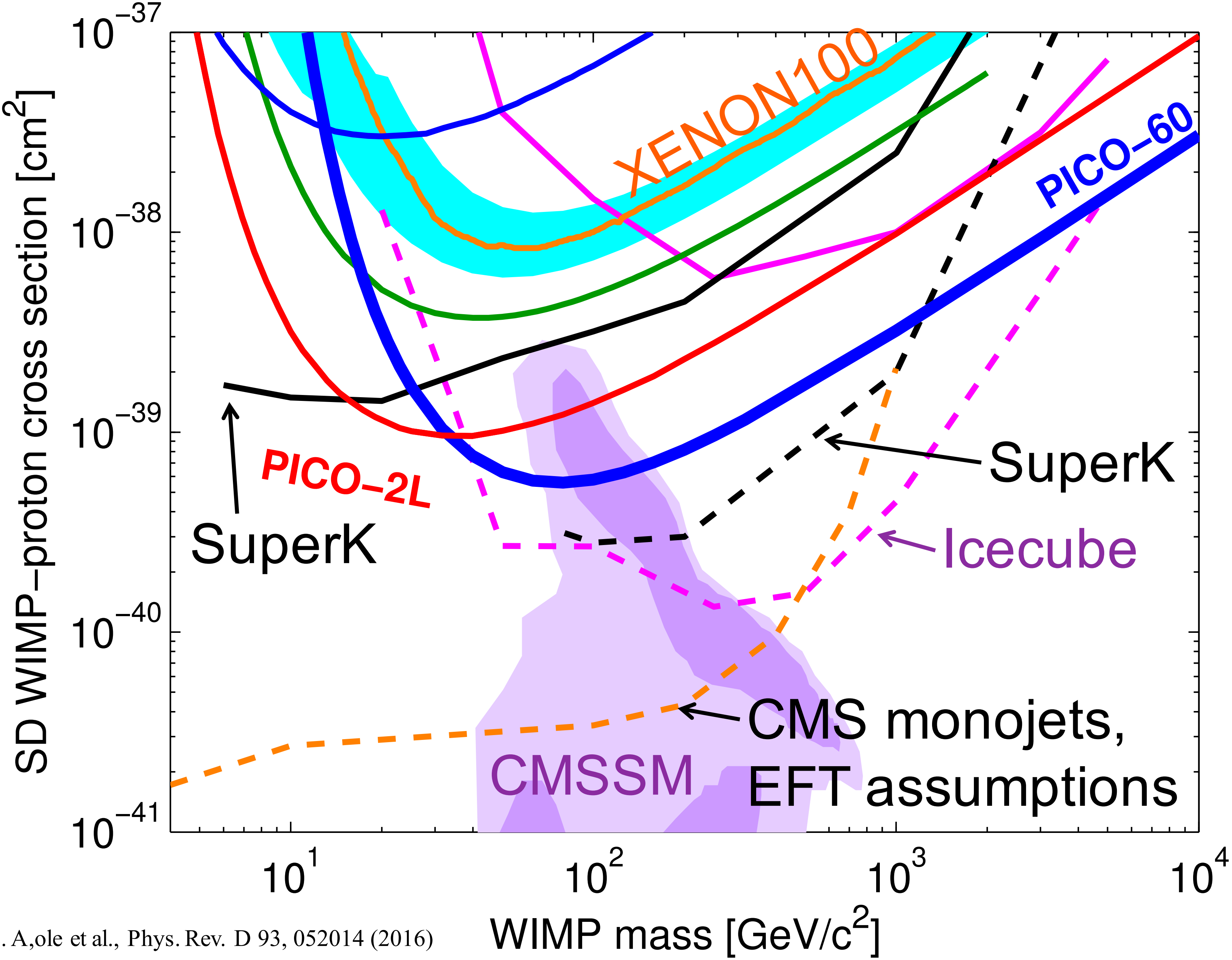


Neutrino flux depends on $\sigma_{\chi p}$, not on $\sigma_{\chi\chi}$!

⇒ competitive limits for $\sigma_{\chi p}$ (spin-dependent x-sect.)

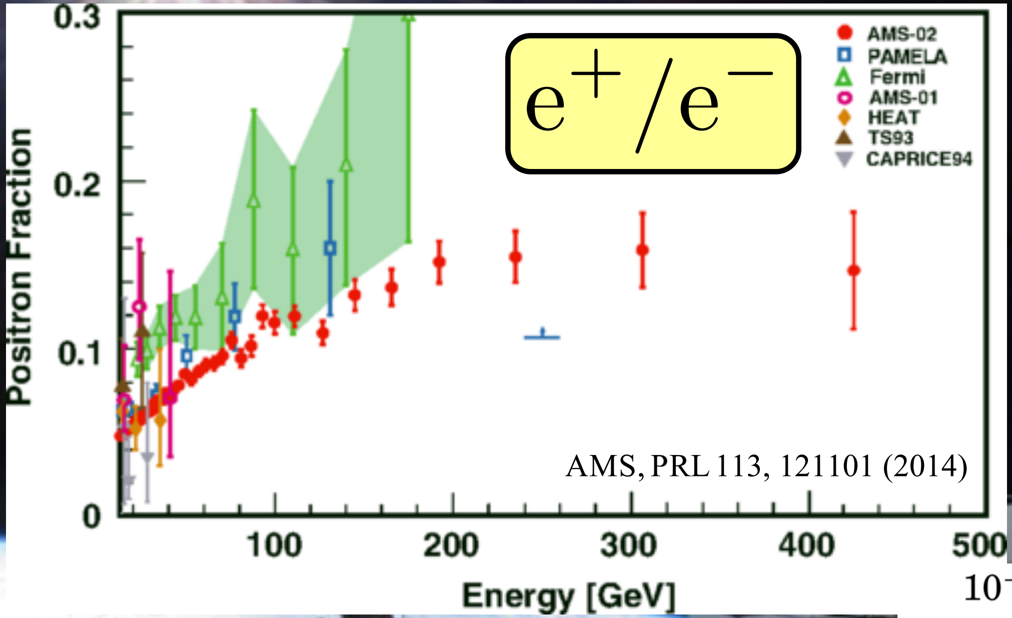


Comparison to direct searches and LHC searches



C. A,ole et al., Phys. Rev. D 93, 052014 (2016)

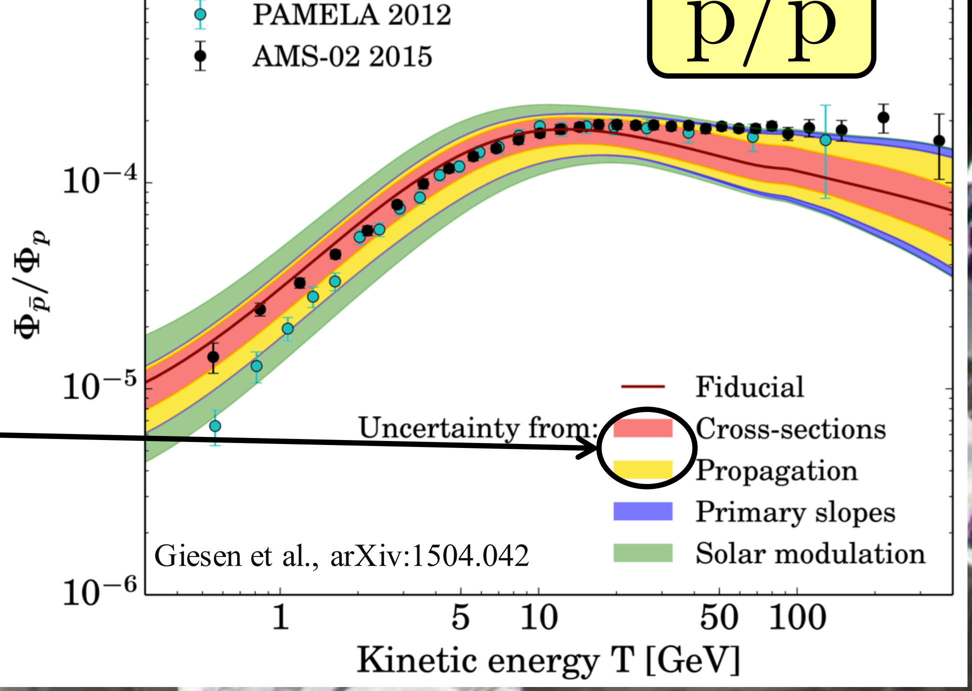
Antimatter Anomalies



AMS, PRL 113, 121101 (2014)

predictions from diffusion-loss equation based propagation models (not as “trivial” as for neutral messengers)

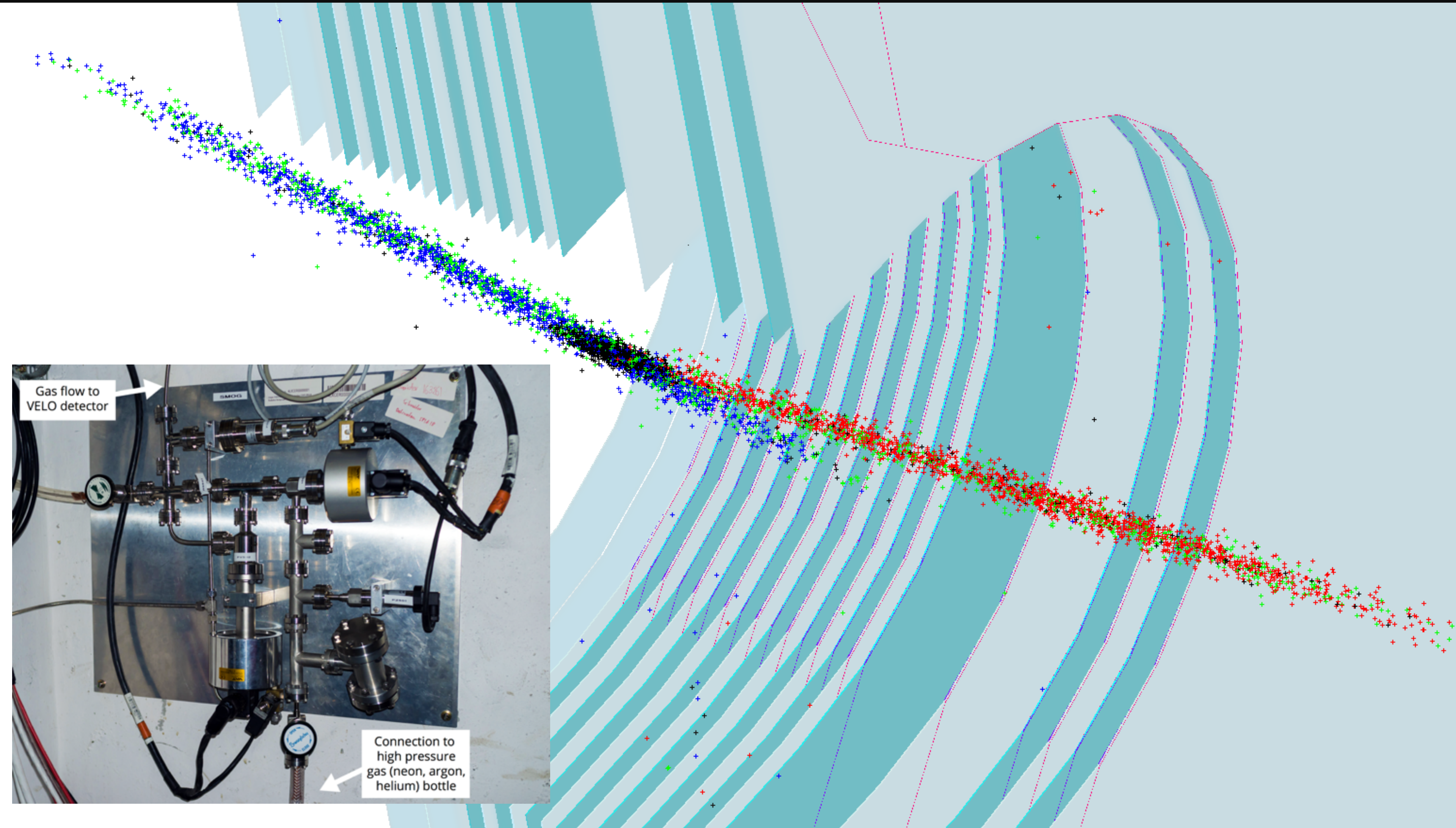
- possible DM hint
- could be astrophysics (pulsars, supernovae...)
- reduce uncertainties!



Giesen et al., arXiv:1504.042

LHCb: special p-He, p-Ne, p-Ar runs

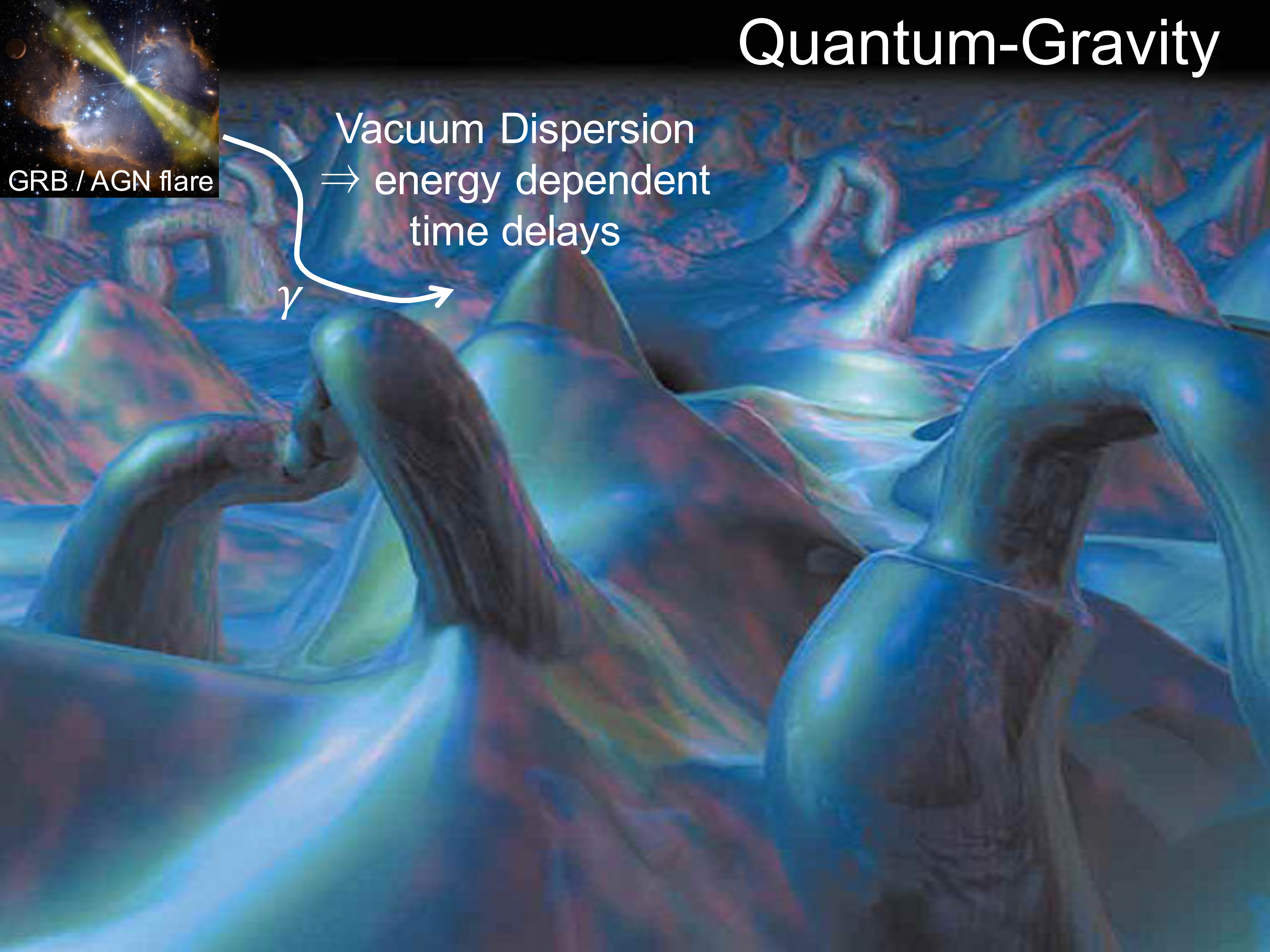
- originally for beam-profile/luminosity measurements
- p-He cross sections for cosmic ray antiproton production



Outline

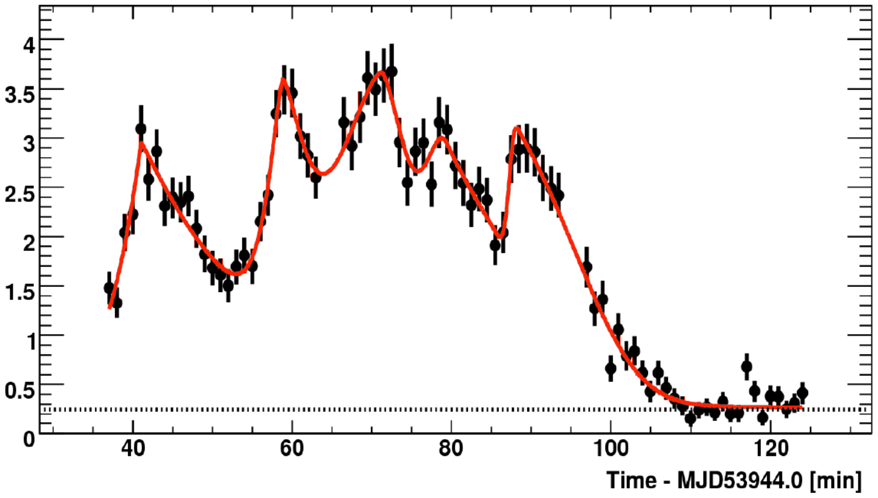
- Cosmic Rays and Air Showers
- Dark Matter: WIMPs and ALPs
- **Quantum Gravity**

Quantum-Gravity

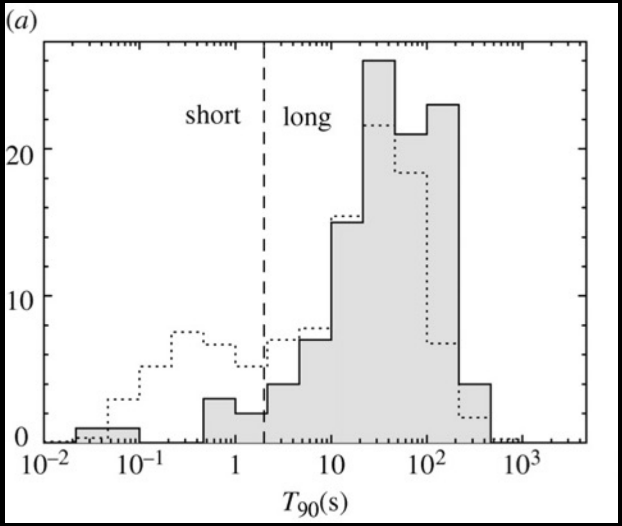


Vacuum Dispersion
⇒ energy dependent
time delays

Very distant objects with burst-like activity



https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2010/07/



P. T. O'Brien, R. Willingale
Phil. Trans. R. Soc. A 2007;365:1179-1188

Photon propagation speed (Taylor expansion)

Power of first non-zero term

$$u(E) \approx c \times \left[1 \mp \frac{n+1}{2} \left(\frac{E}{E_{QG}} \right)^{n} \right]$$

Quantum Gravity scale

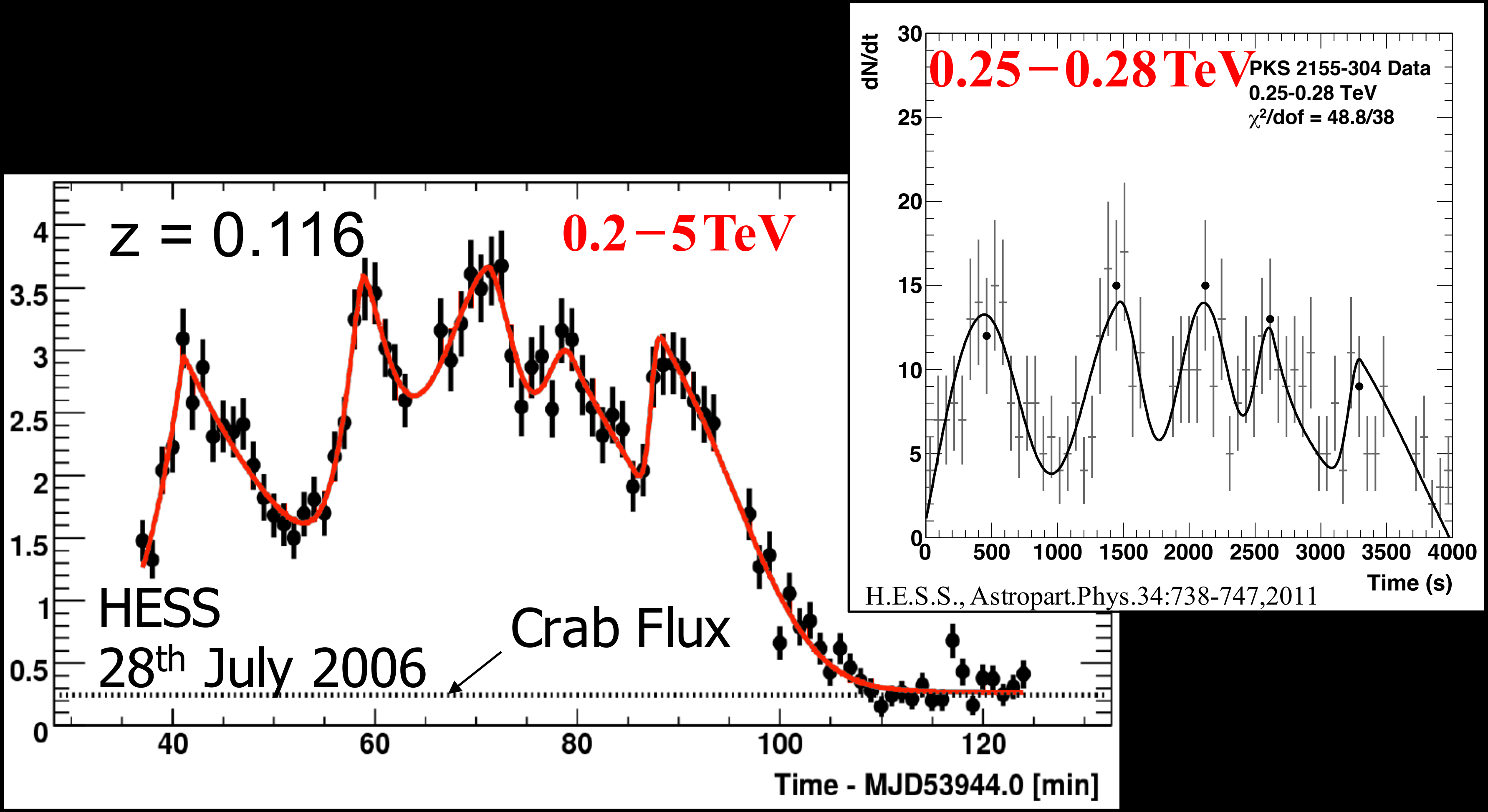
Effective field theory with d = dim(leading operator):

$$n = d - 4$$

unrestricted case: $n = 1$

theories with CPT symmetry: $n = 2$

The Blazar PKS 2155 - an exceptional flare



H.E.S.S., Astropart.Phys.34:738-747,2011

- peak flux > 50 times average
- doubling times ≈ 3 min , $R_{\text{black Hole}}/c \approx 200$ min

Current limits on E_{QG} (95% c.l.)

PKS 2155 flare:
(H.E.S.S.)

$$E_{\mathrm{QG},n=1} > 2.1 \times 10^{18}\mathrm{GeV}$$

$$E_{\mathrm{QG},n=2} > 6.4 \times 10^{10}\mathrm{GeV}$$

GRB 090510 (z=0.9):
(Fermi-LAT)

$$E_{\mathrm{QG},n=1} > 9.3 \times 10^{19}\mathrm{GeV}$$

$$E_{\mathrm{QG},n=2} > 1.3 \times 10^{11}\mathrm{GeV}$$

Planck Scale:

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

Warning: analyses assume no energy dependent delays in the sources

Conclusions

- strong **astro** **&** **particle** links really exist
- some of the **big** questions will require tight cooperation of both fields

Stay fascinated!