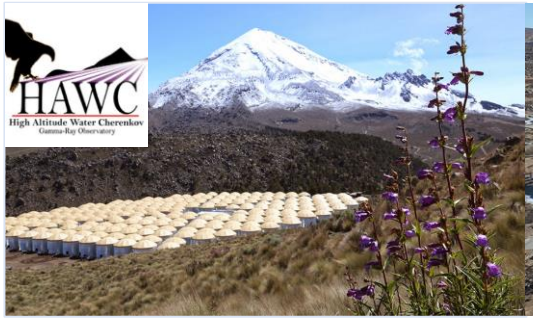
Gamma-ray observations above 100 TeV

Sergey Troitsky
(INR RAS, Moscow)

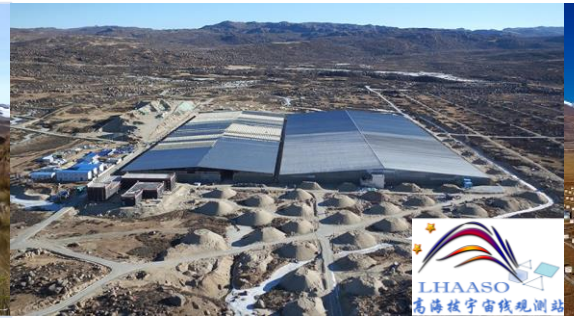
Cosmic rays and neutrinos in the multimessenger era, APC Paris, December 9, 2020

Acknowledgements

Acknowledgements



Amid Nayerhoda



Zhen Cao

Kazumasa Kawata

Pravata Kumar Mohanty

…for discussing the present status of these experiments

many INR colleagues

Leonid Kuzmichev

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Scope and plan

Gamma-ray astronomy above 100 TeV: why, how, where?

*Disclaimer:
LHAASO – see Zhen's talk
future – see Felix's talk

- Introduction: a very special band in astronomy
  pair production and cascades
- Scientific tasks
  cosmic-ray acceleration, HE neutrino diagnostics, UHECR diagnostics, search for new physics
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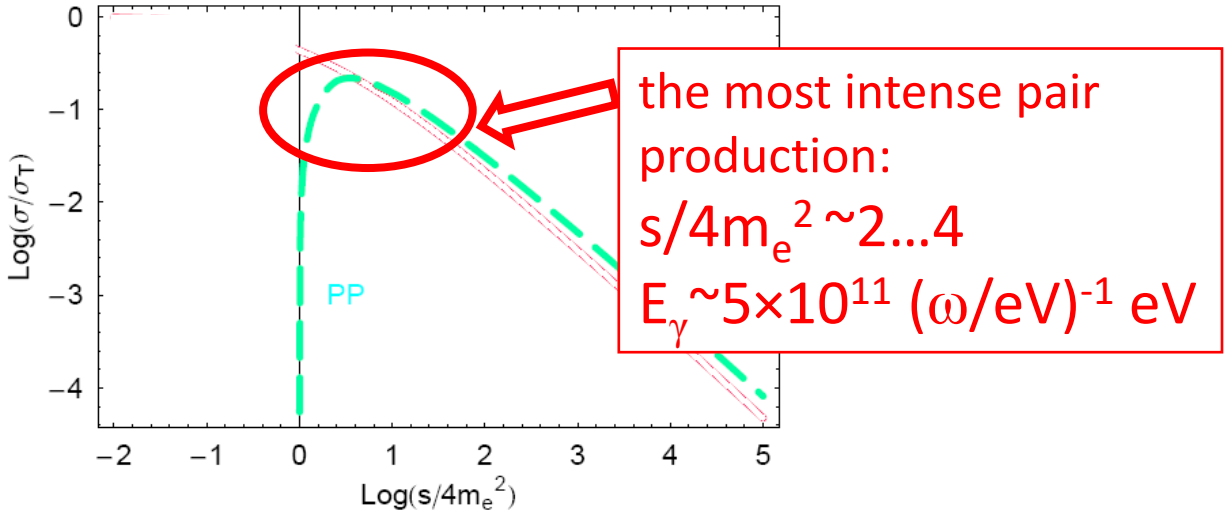
  multimessenger alerts, point sources, Galactic plane, isotropic background

A very special band: pair production

Pair production on background radiation

Nikishov 1962

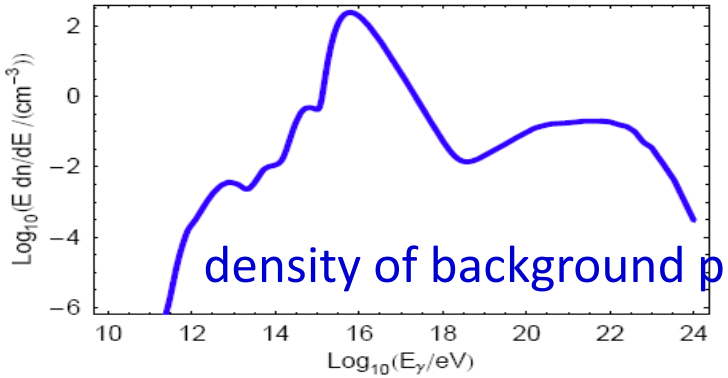
pair-production cross section (PP):



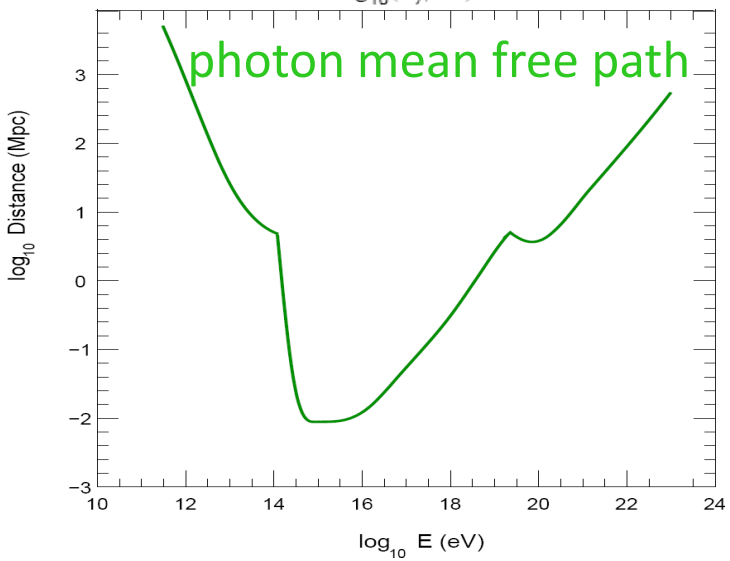
the most intense pair production:

$s/4m_e^2 \sim 2...4$

$E_\gamma \sim 5\times10^{11}\ (\omega/eV)^{-1}\ eV$



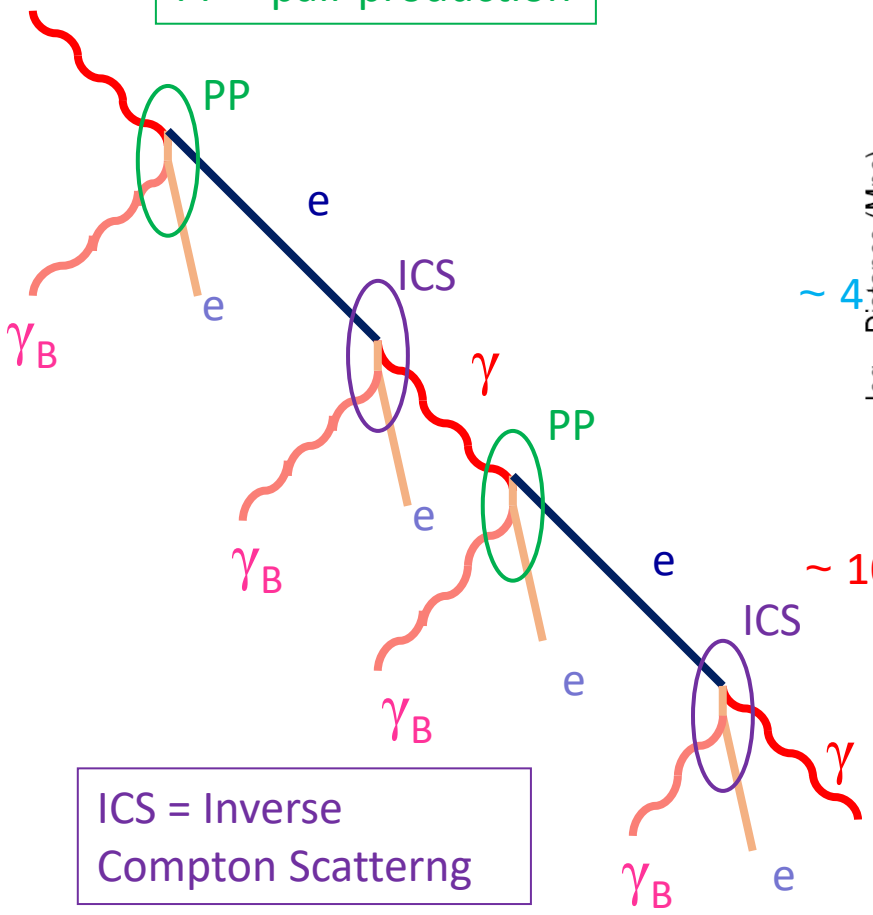
density of background photons



photon mean free path

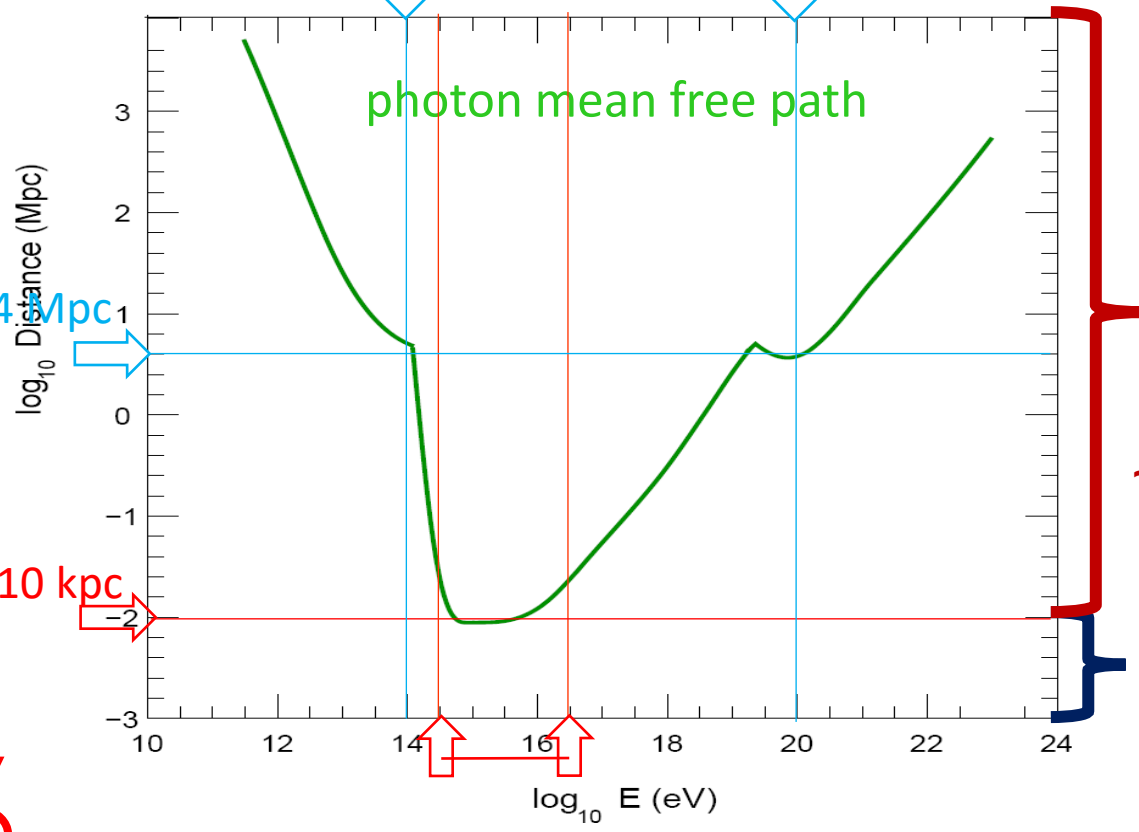
A very special band: fate of E>100 TeV photons

PP = pair production



ICS = Inverse Compton Scatterng

~100 TeV - 100 EeV: Local Cluster

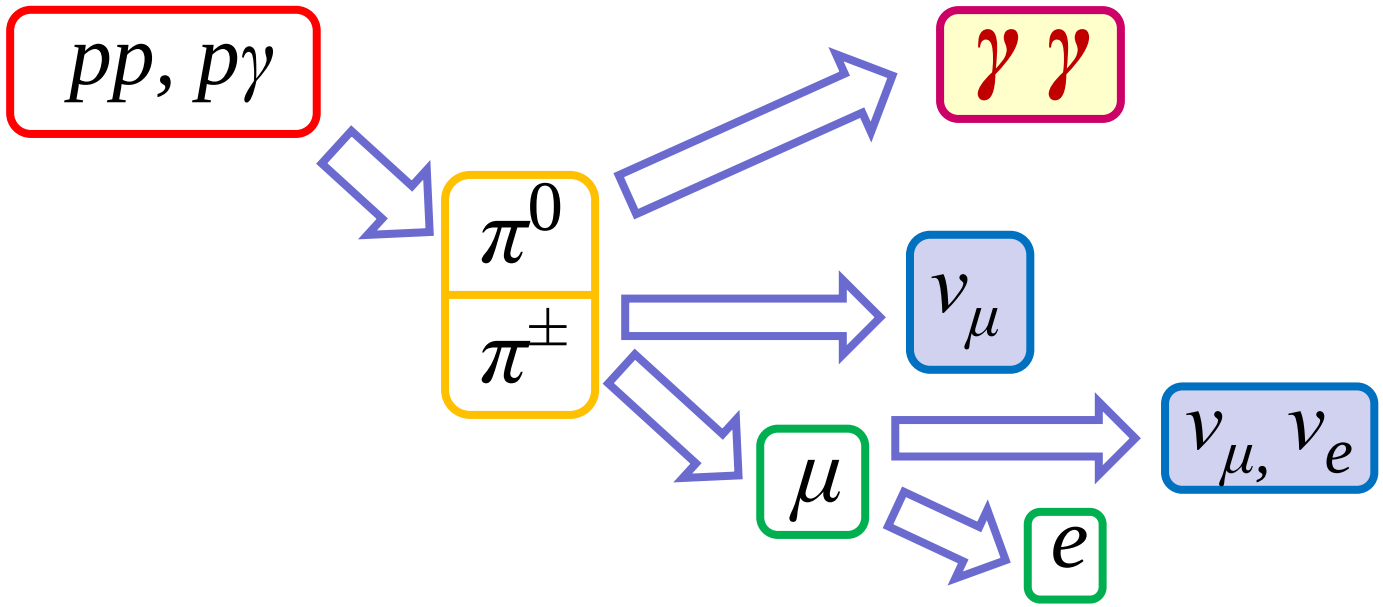


~0.3-30 PeV: Galaxy

Extragalactic photons above the green line cascade, degrade in energy, contribute to the diffuse ~(1-100) GeV background

Galactic photons reach the observer

A very special band: “intrinsically multimessenger”



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Scientific tasks

- cosmic-ray acceleration (covered by other talks)

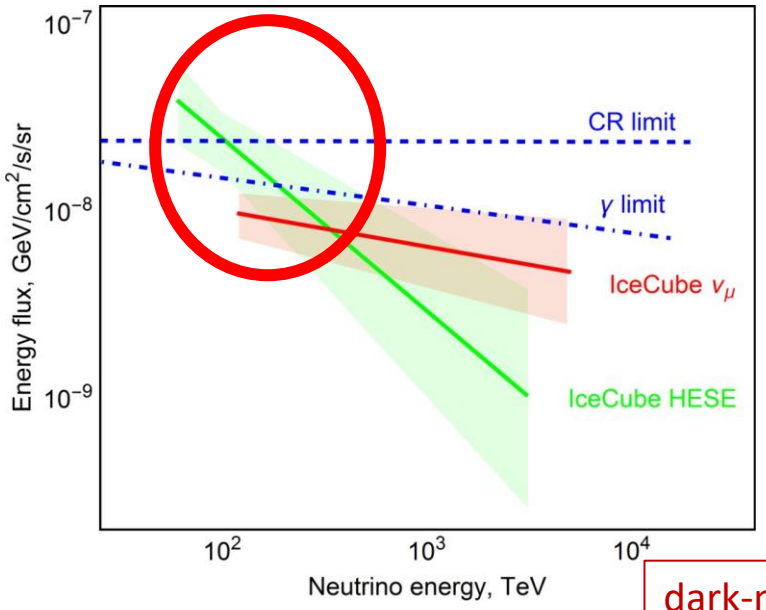
  cosmic rays at 10^{17}-10^{18} eV – Galactic or not?
- high-energy neutrino diagnostics

  contribution of Galactic sources around 100 TeV?
- UHECR diagnostics

  cosmogenic photons as a tool to determine primary composition and source distribution
- New physics searches

  Lorentz-invariance tests, axion-like particles and (super)heavy dark matter

High-energy neutrino diagnostics



- cascade/track tension suggests two components

different energy ranges probed — *Palladino&Vissani 2016, …*

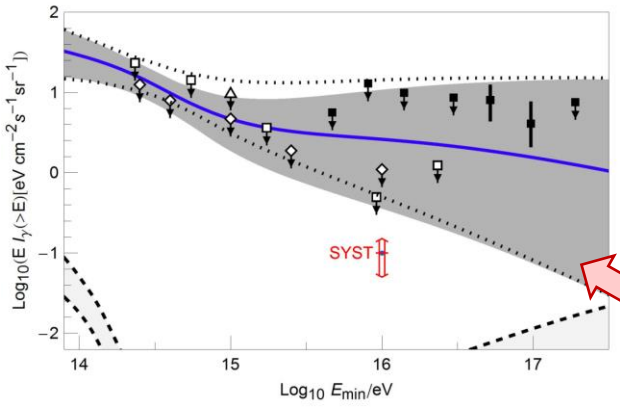
- "track spectrum" explained by radio blazars

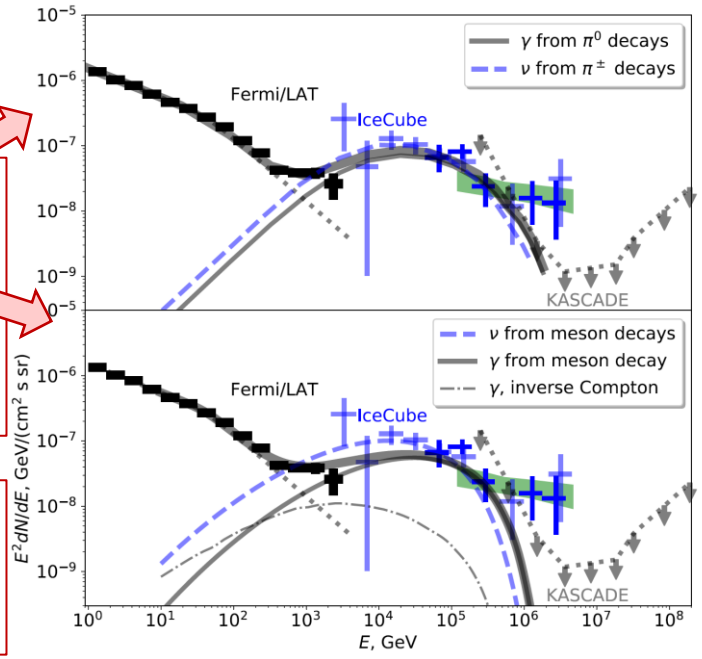
HE+extrapolation to ~10 TeV — *Plavin et al. 2020*

isotropic Galactic?

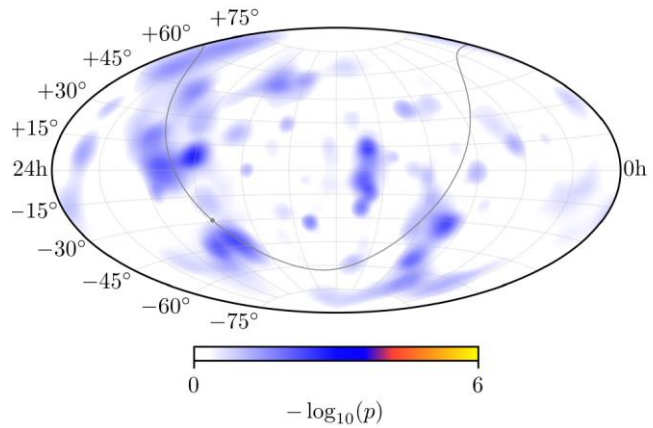
dark-matter decays
or
Local Bubble
Kachelriess et al. 2018

disk or
circumgalactic gas
Kalashev, ST 2014





subdominant disk component?
conventional "PeVatrons" and diffuse Galactic-plane



IceCube 2020

UHECR diagnostics

- large uncertainties in primary composition

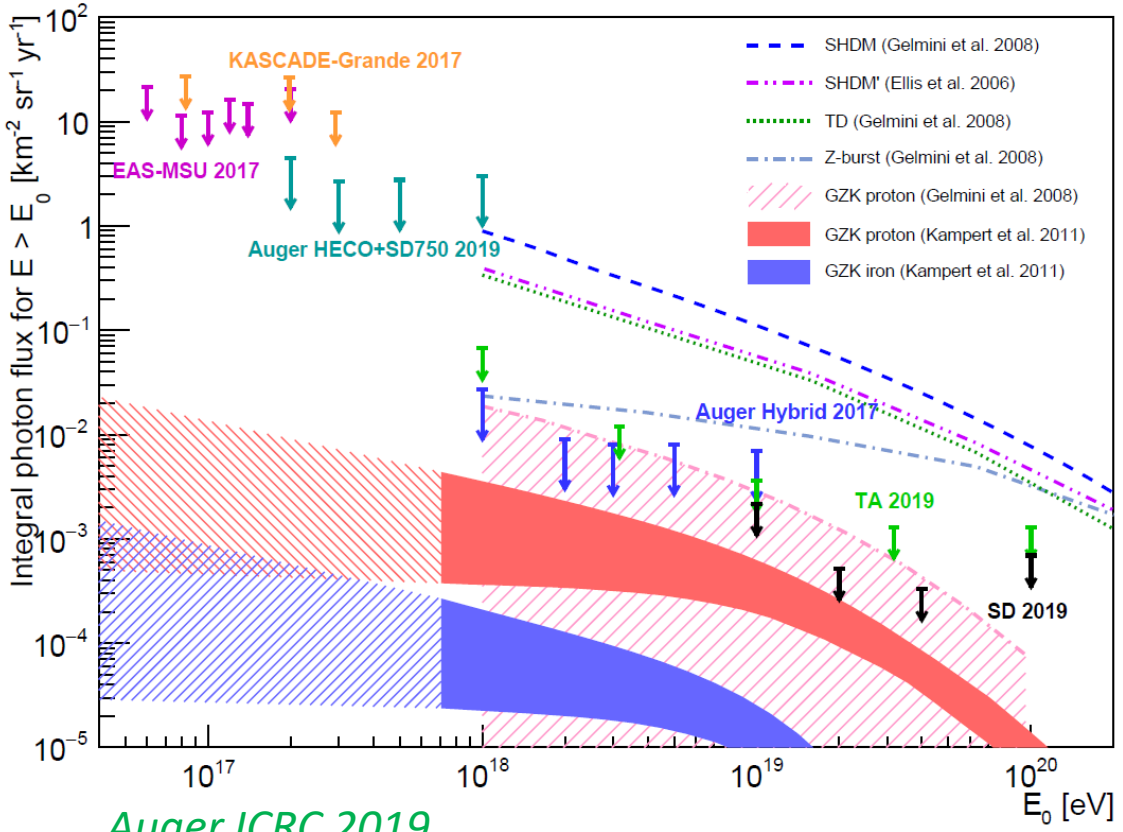
hadronic interaction models, anisotropy of composition etc.

- composition important for interpretation

which sources? GZK or Emax? nearby cosmic accelerators e.g. Cen A?...

- cosmogenic photons as a tool

observational: largely independent on interaction-model uncertainties

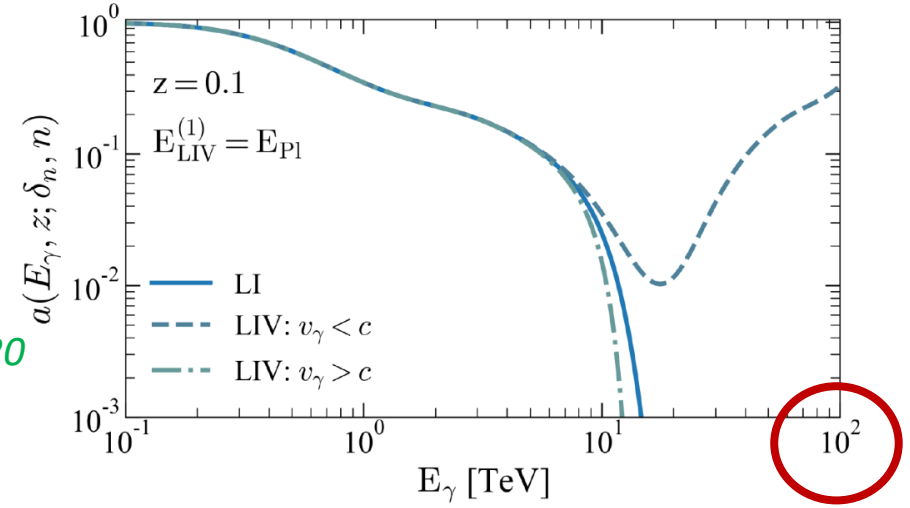


Auger ICRC 2019

New-physics searches: tests of Lorentz invariance

- shift of the pair-production threshold:
  100-TeV photons from distant sources
  (depending on the LIV pattern)

Lang et al. 2019, 2020



- photon decay allowed

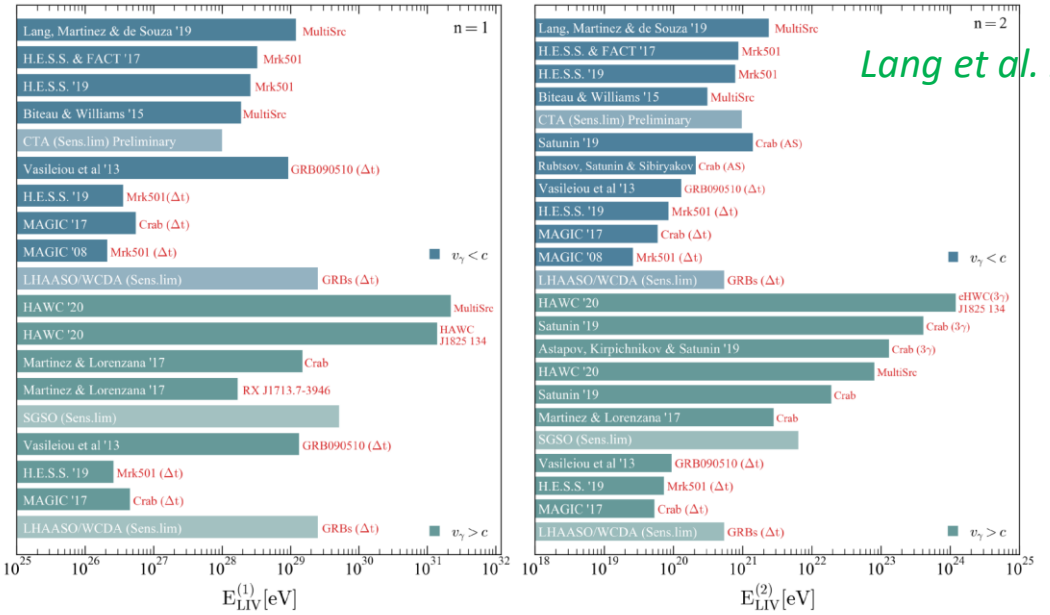
- simultaneous photon arrival
  (but astrophysical assumptions…)

- air-shower suppression!

Vankov, Stanev 2002

Rubtsov, Satunin, Sibiryakov 2012, 2017

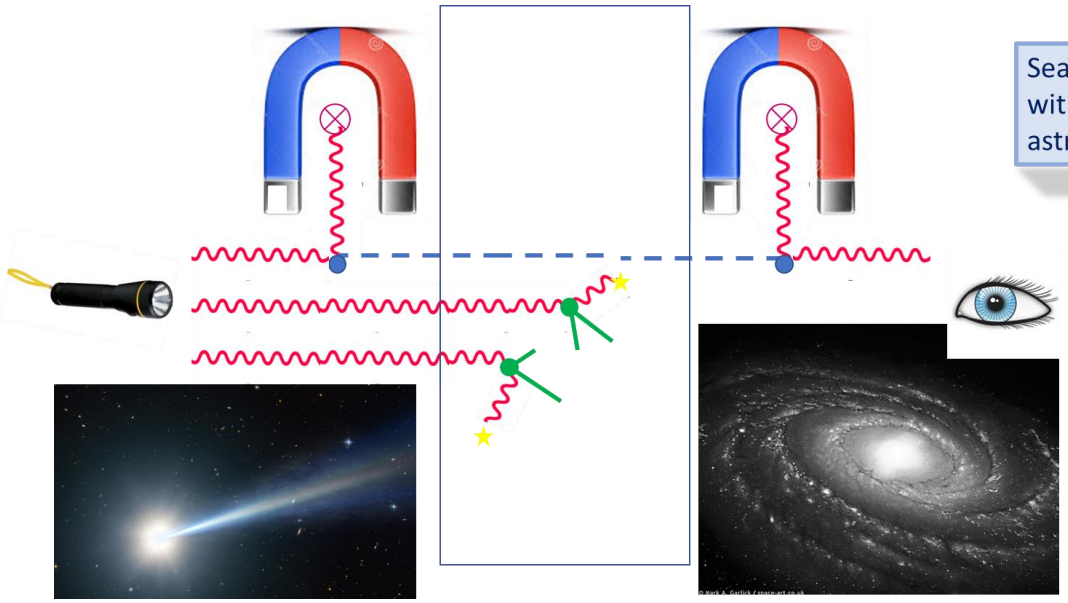
Even a single event gives constraints!



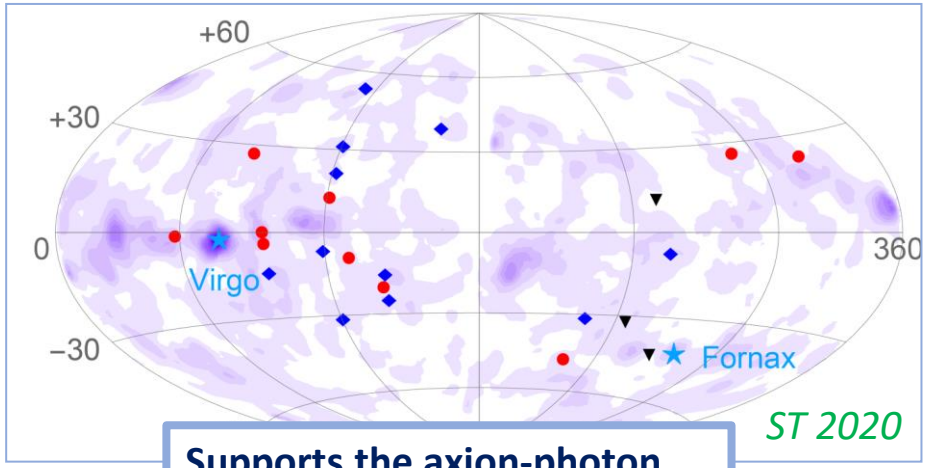
Lang et al. 2020

New-physics searches: axion-like particles

diminish pair-production attenuation



Search for axions with gamma-ray astronomy



ST 2020

Supports the axion-photon mixing in large-scale structure filaments

Fairbairn, Rashba, ST 2009

Blue: BL Lacs correlated with HiRes cosmic rays, E>10^{19} eV

4.1 σ

Gorbunov et al. 2004; HiRes Collaboration 2005

Red: "anomalous" gamma-ray blazars, E>100 GeV

Korochkin, Rubtsov, ST 2019

Black: VHE GRB *(not in the statistical analysis)*

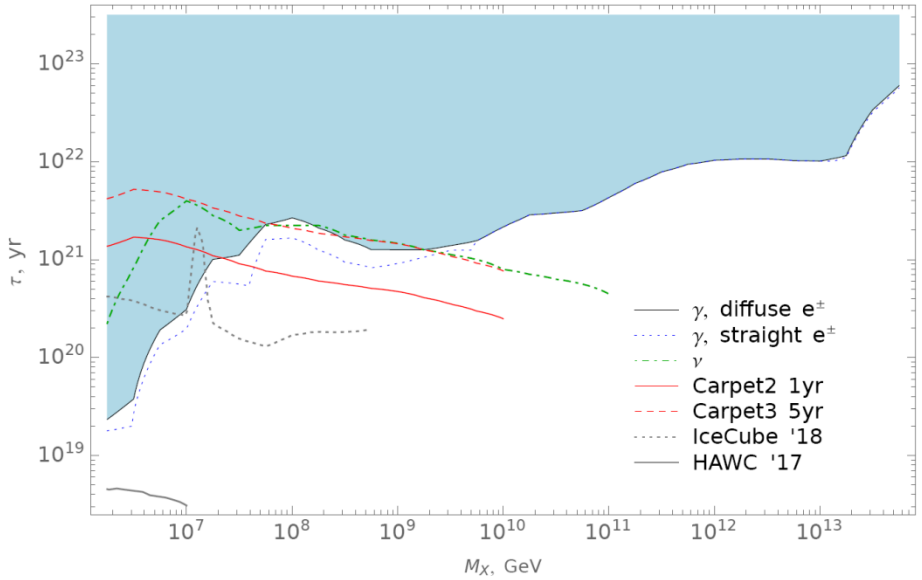
HESS 2020, MAGIC 2020

Shadow: weighted density of nearby galaxies *2MRS 2019*

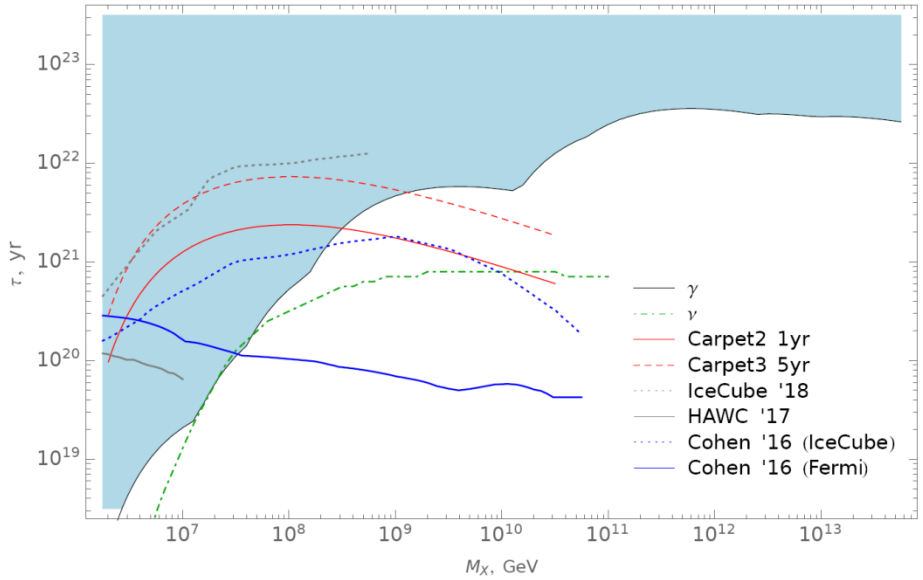
New-physics searches: (super)heavy dark matter

Kuzmin, Rubakov 1997
Berezinsky, Kachelriess, Vilenkin 1997

Photons give the strongest constraints,
even for leptonic decay channels!



(a) $X \to \nu\bar{\nu}$



(b) $X \to q\bar{q}$

Kachelriess, Kalashev, Kuznetsov 2018

- diffuse halo emission
- dwarf galaxies

Scope and plan

Gamma-ray astronomy above 100 TeV: why, how, where?

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Methods: extensive air showers

- energy determination
  - different for primary photons and cosmic rays, even for “calorimetric” methods
- flux, not fraction!
  - electromagnetic showers have lower modelling uncertainties
  - energy scale difference uncertain in the I_γ/I_{CR} denominator

- gamma-hadron separation by task
  - directional+temporal searches (flare alerts) – easy (very low background)
    even a single event gives a signal!
  - point sources – somewhat easy (low background)
  - extended sources (Galactic plane) – harder, depends on the template
  - isotropic diffuse flux – very hard, small signal on top of large background

Methods: gamma-hadron separation

- general: gamma-induced showers are poor of muons and develop slowly

method	technique	drawbacks
muons, direct	shielded vs. unshielded detectors	UHECR modelling, chemical composition, penetrating hadrons
muons, indirect	time profile of the waveform, signal fluctuations	UHECR modelling, chemical composition, large event-by-event fluctuations
Xmax, direct	fluorescent detectors	low exposure, large event-by-event fluctuations
Xmax, indirect	shower age, shape of the front	low separating power
combinations	machine learning	trust to MC in every detail?

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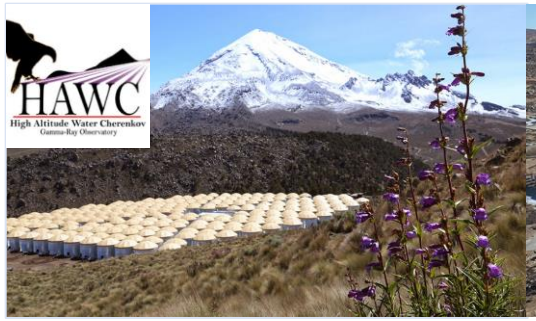
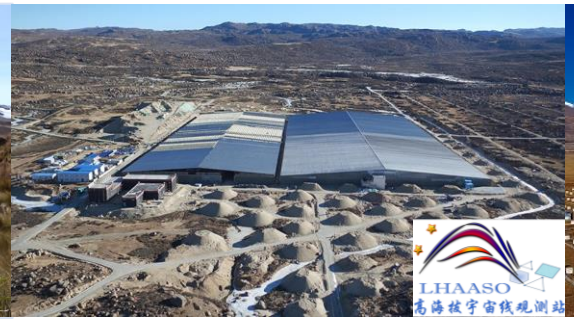
Instruments

currently taking data



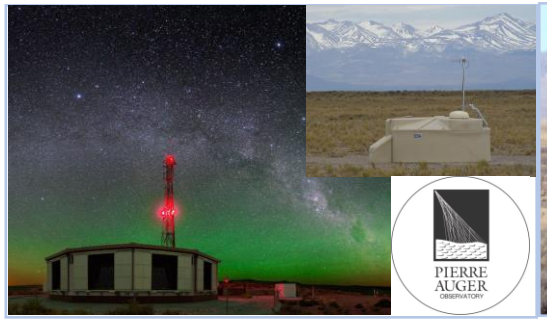
HAWC



LHAASO

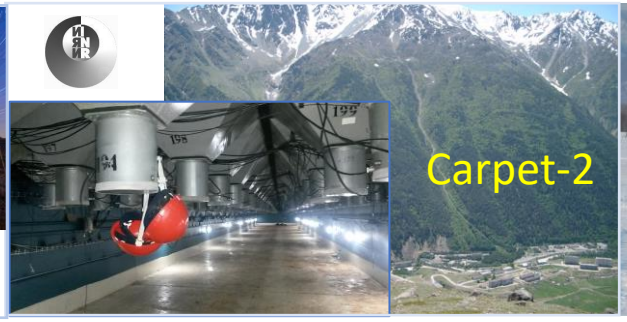
Tibet ASγ+MD

GRAPES-3



Pierre Auger

Telescope Array



Carpet-2

TAIGA

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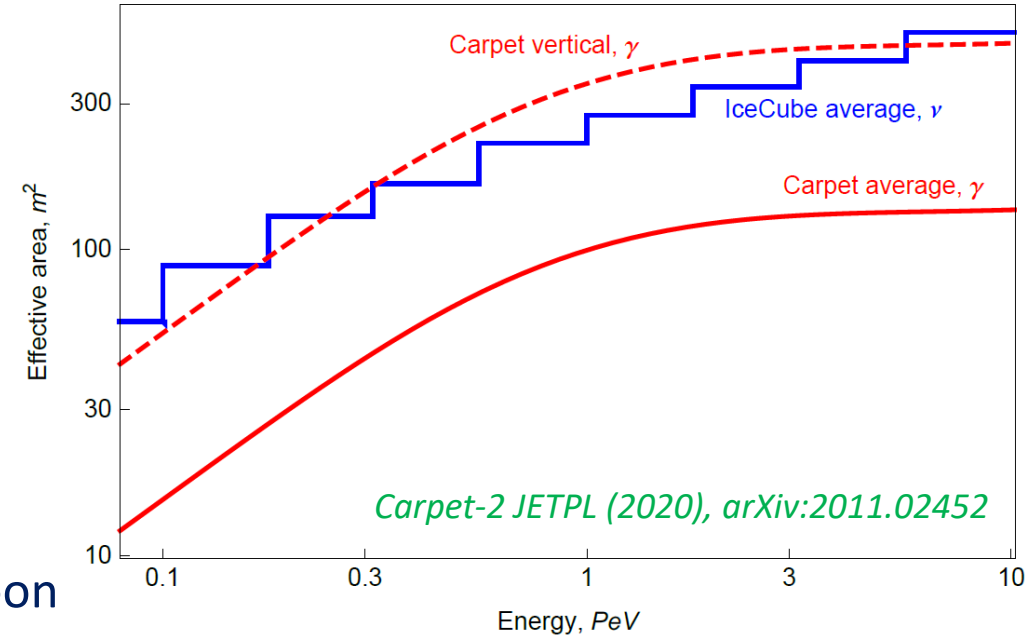
First results: alerts

- IceCube HE neutrino alerts “followed” by HAWC and Carpet-2
- upper limits start to probe flares of Galactic sources

- a recent example: the Cygnus Cocoon neutrino event, Nov 20
  - IceCube 201120A, “BRONZE” alert, 154 TeV
  - naïve fluence estimate ~3 GeV/cm^2
  - poor angular reconstruction, consistent with the Cyg Cocoon
  - star-forming region, a possible HE neutrino source, 1.4 kpc

Yoast-Hull et al. (2017), Bykov et al. (2020)



HAWC, +/- 1 day *GCN 28952*

300 GeV to 100 TeV – no significant detection

RA	Dec	Unc.	p-value	Flux [TeV^-1 cm^-2 s^-1]	Nearby source
305.2	40.0	0.4	0.20	7.9e-12 (+8.0e-12 -5.2e-12)	3HWC J2020+403
309.0	40.4	0.2	0.25	7.2e-12 (+8.3e-12 -5.1e-12)	None
305.1	43.0	0.3	0.84	4.5e-12 (+7.1e-12 -3.6e-12)	3HWC J2020+431
307.6	41.4	0.7	0.91	7.7e-12 (+9.1e-12 -5.8e-12)	3HWC J2031+415

Carpet-2, +/- 12 hours *ATel 14237*

E>100 TeV, fluence <4.2 GeV/cm^2 (90%CL)

Carpet-2, +/- 15 days

E>100 TeV and E>300 TeV

ATel today

2 events observed

p~0.02

(5.5+-2.3) GeV/cm^2

First results: point sources

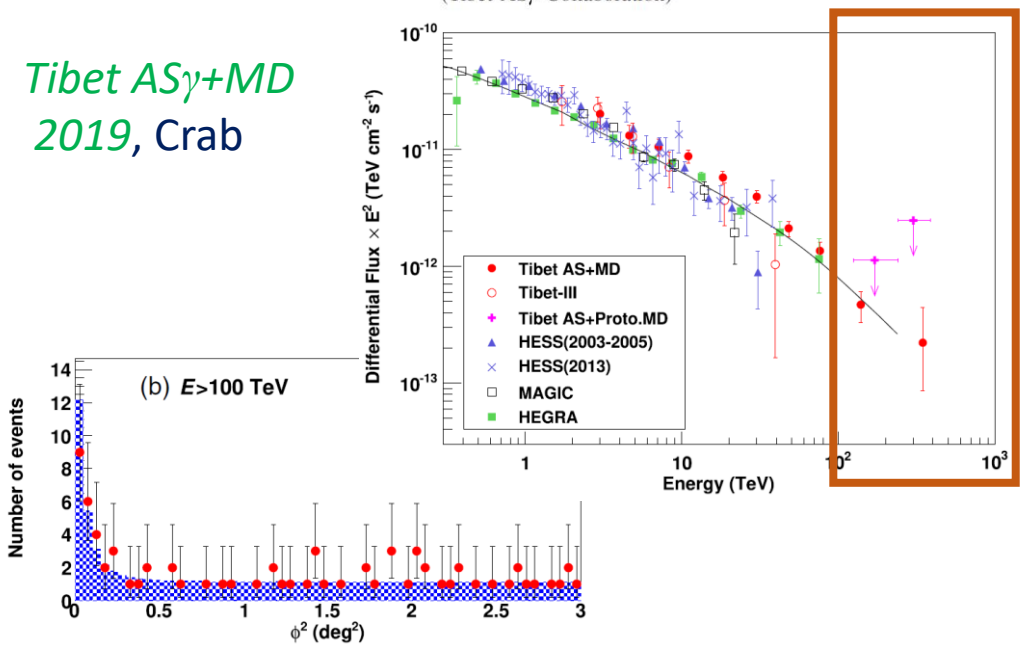
PHYSICAL REVIEW LETTERS 123, 051101 (2019)

Editors' Suggestion | Featured in Physics

First Detection of Photons with Energy beyond 100 TeV from an Astrophysical Source

(Tibet ASγ Collaboration)

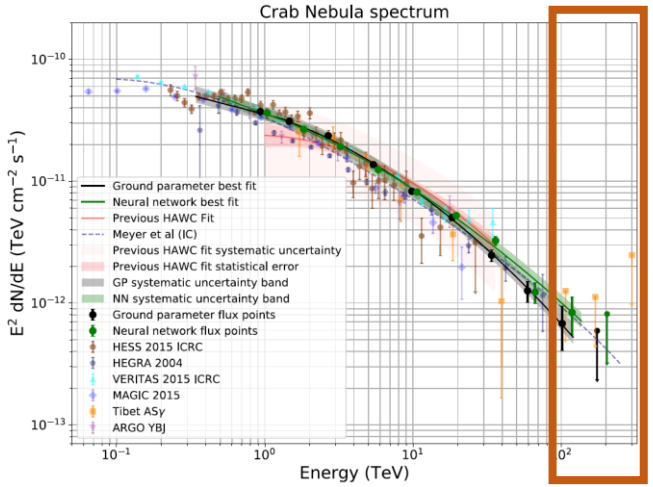
Tibet ASγ+MD 2019, Crab



PHYSICAL REVIEW LETTERS 124, 021102 (2020)

Editors' Suggestion | Featured in Physics

Measurement of the Crab Nebula Spectrum Past 100 TeV with HAWC

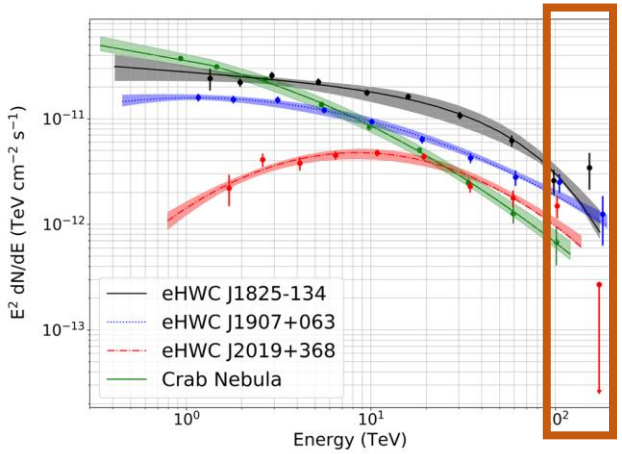


HAWC 2019, Crab

THE ASTROPHYSICAL JOURNAL, 881:134 (13pp), 2019 August 20

https://doi.org/10.3847/1538-4357/ab2f7d

Multiple Galactic Sources with Emission Above 56 TeV Detected by HAWC



HAWC 2019,
3 sources above 100 TeV

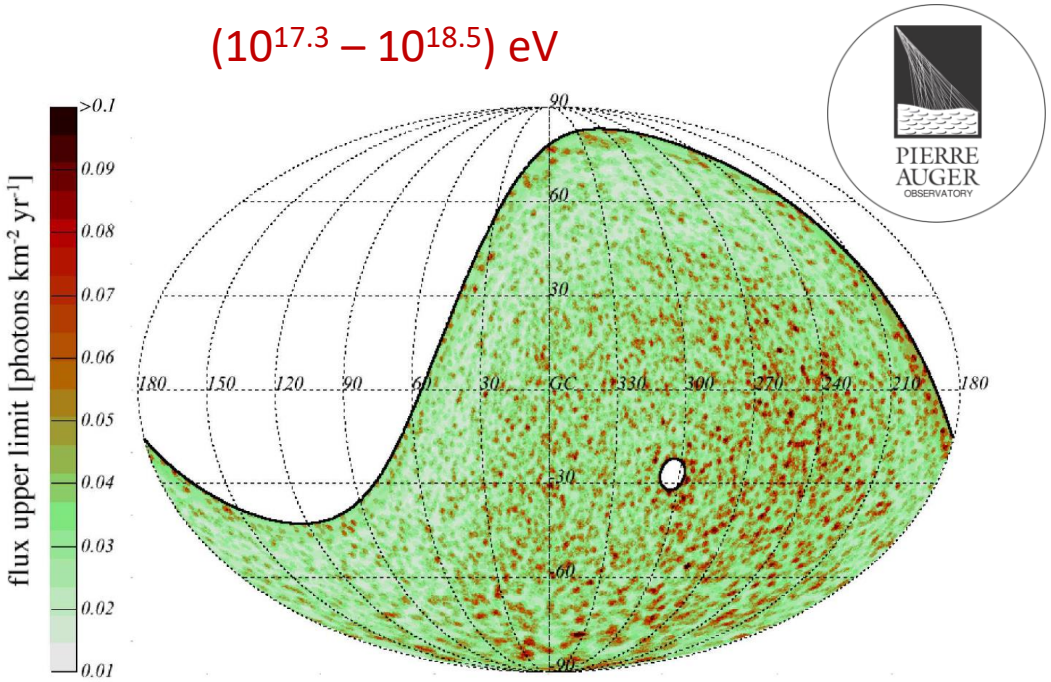
- observations used already for source astrophysics and for Lorentz-invariance tests

+ *LHAASO* results intriguing but unpublished (see Zhen's talk)

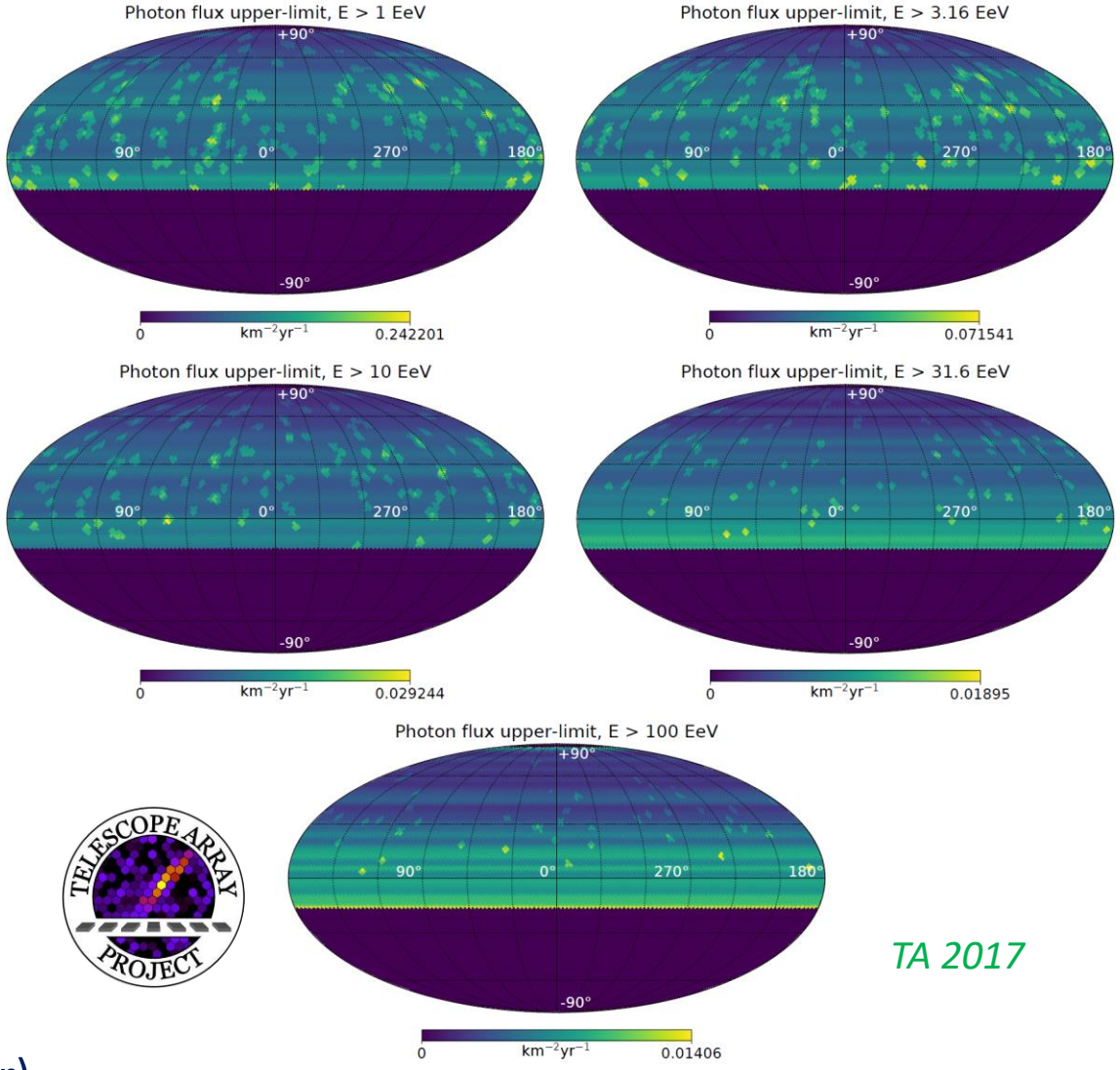
!

First results: point sources

$(10^{17.3} – 10^{18.5})$ eV



Auger 2014

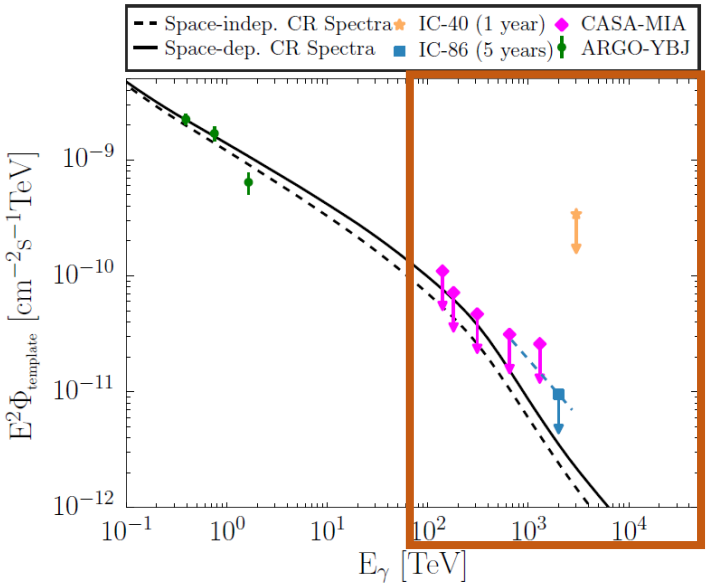


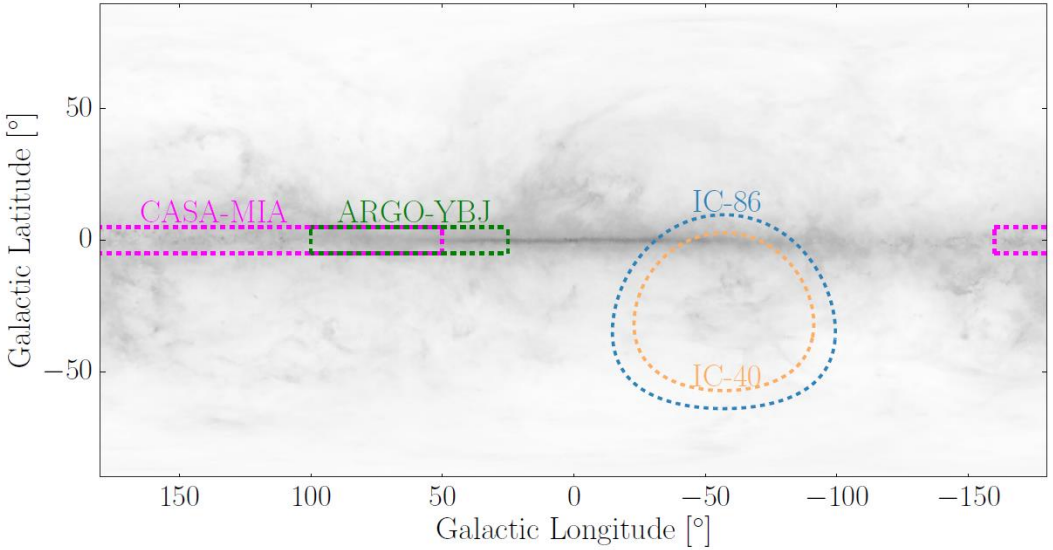
TA 2017

Only upper limits above 10^{17} eV published (so far)

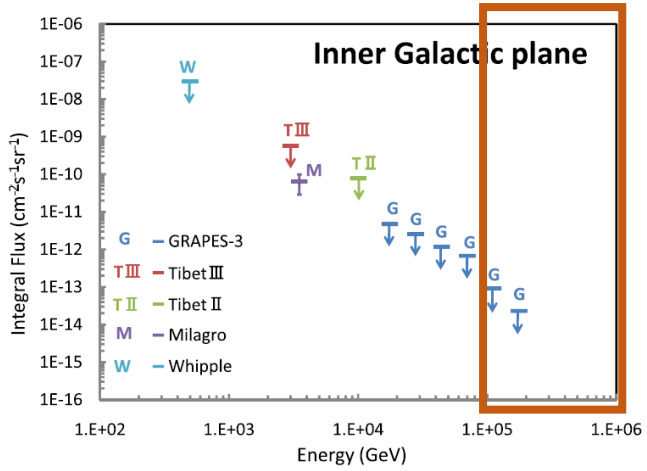
First results: Galactic plane

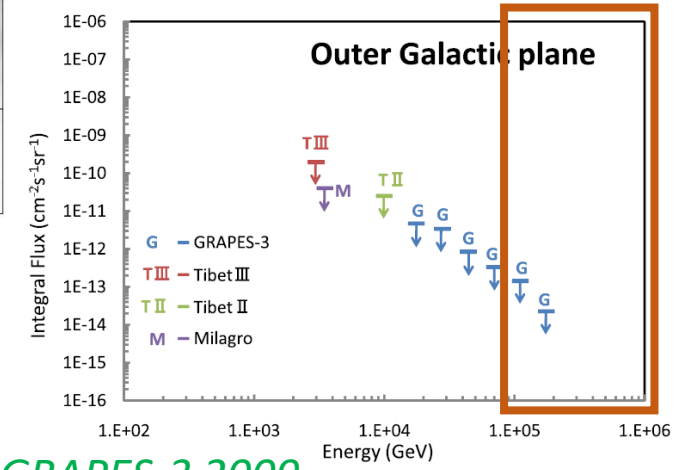
different experiments see different parts, hard to compare





IceCube 2019

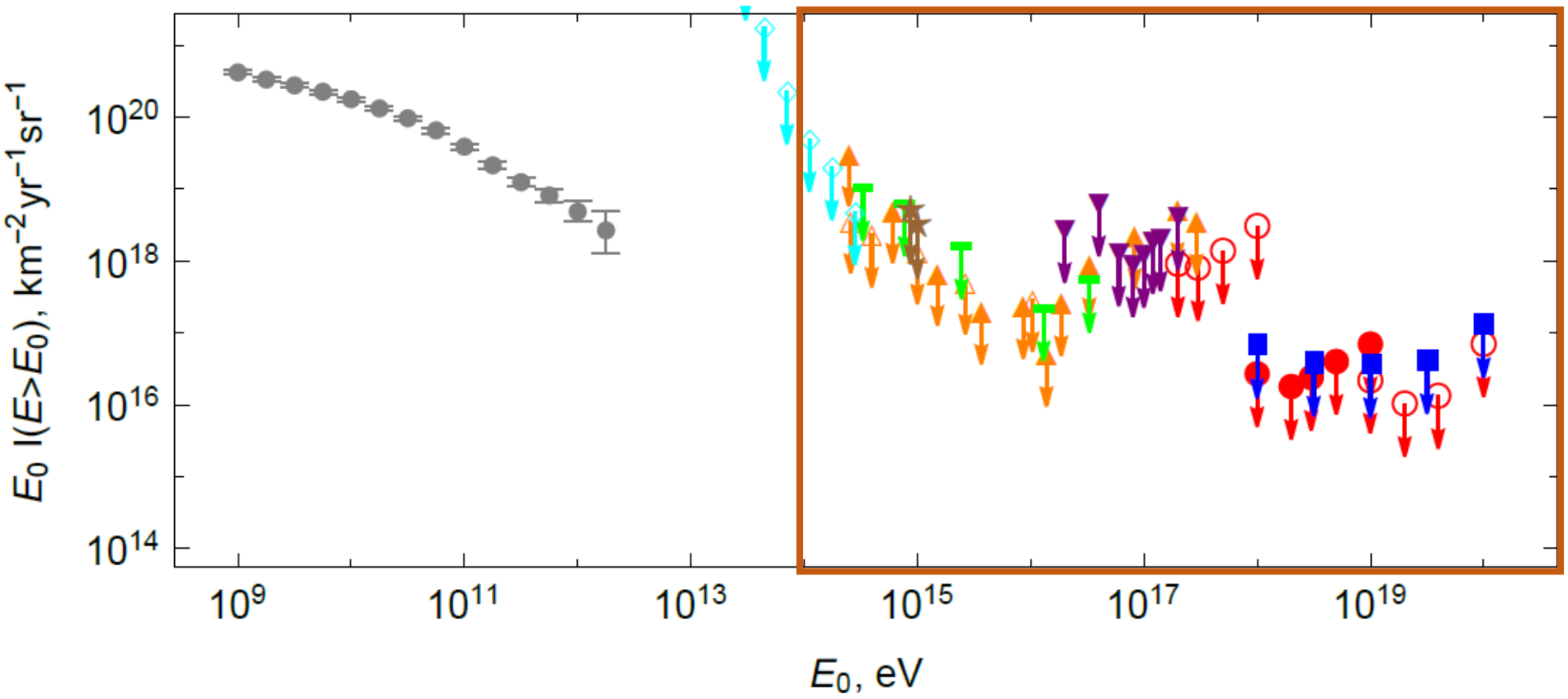




GRAPES-3 2009

Only upper limits above 100 TeV published (so far)

First results: isotropic diffuse flux



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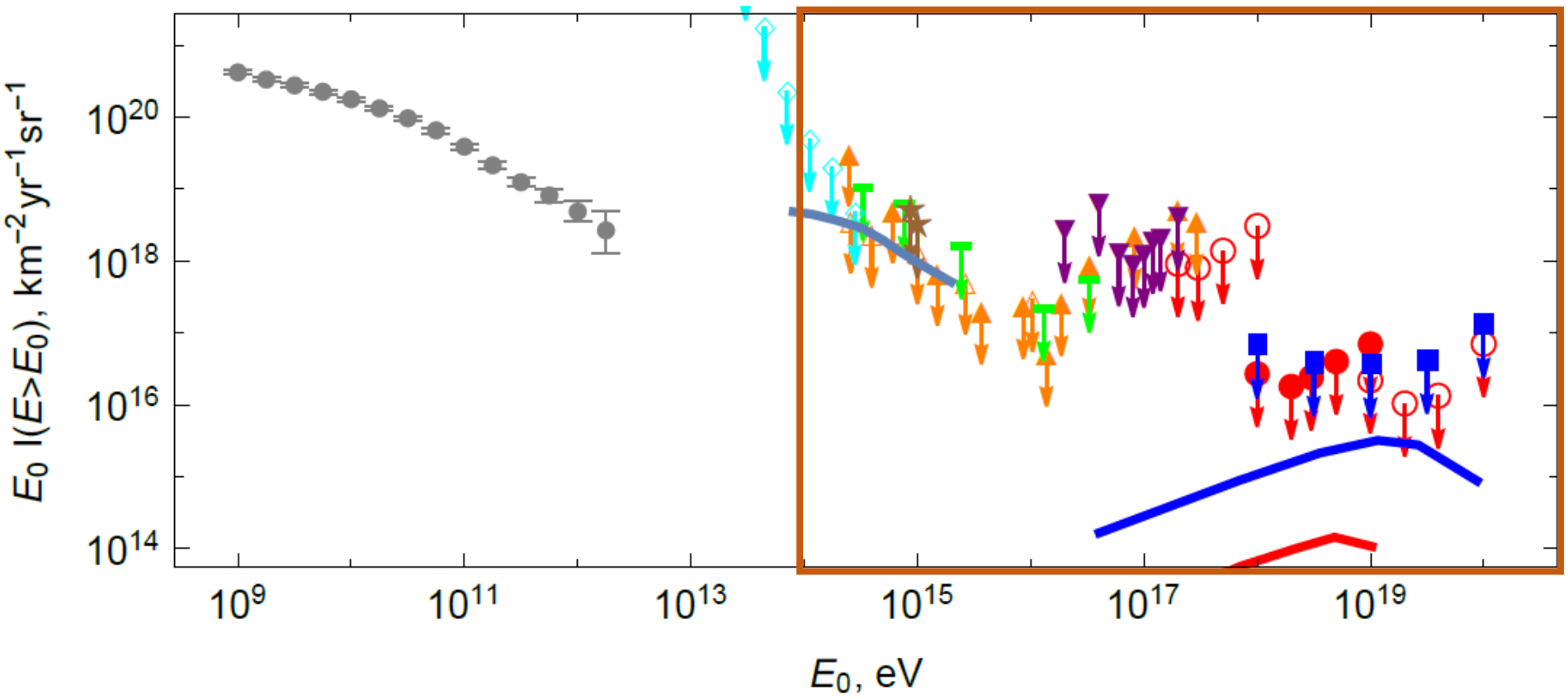
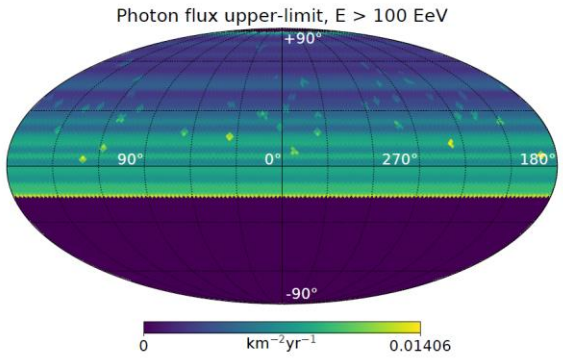
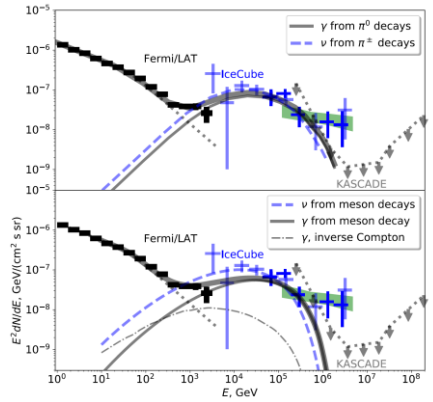
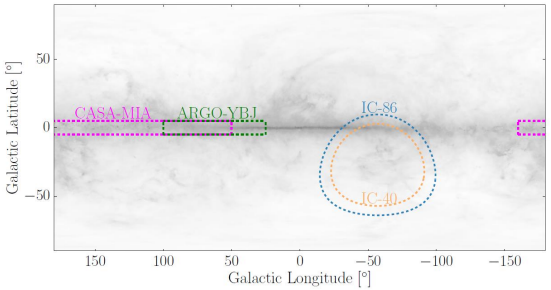


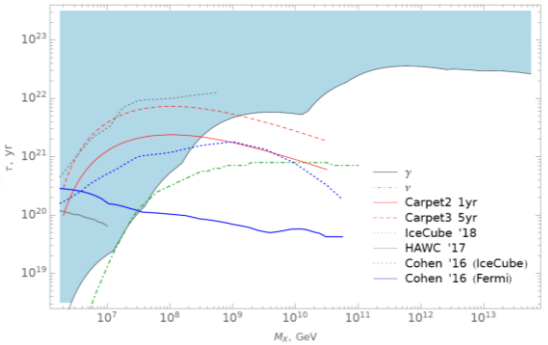
A long way to decisive conclusions at UHECR, but HE neutrino diagnostics next door

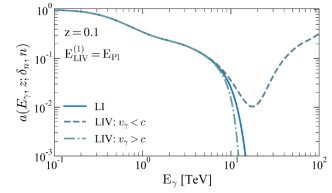
Conclusions:

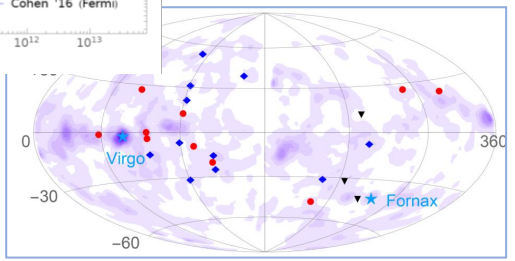






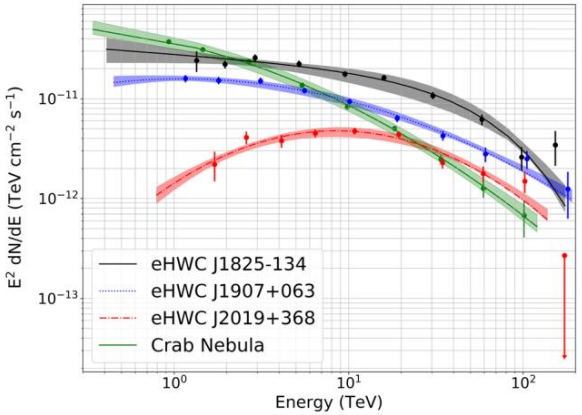






photons above 100 TeV = a new band in astronomy

previously underestimated, but now under intense development
(thanks to questions asked by IceCube, Auger, TA…)

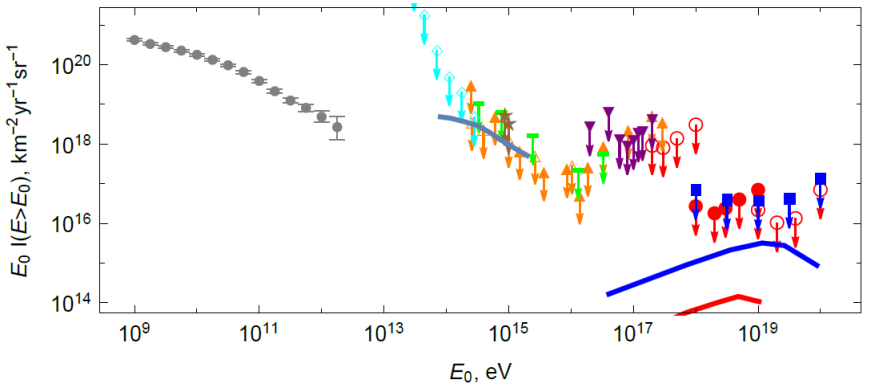


Stay tuned!

Carpet-2, +/- 12 hours *ATel 14237*
E>100 TeV, fluence <4.2 GeV/cm^2 (90%CL)

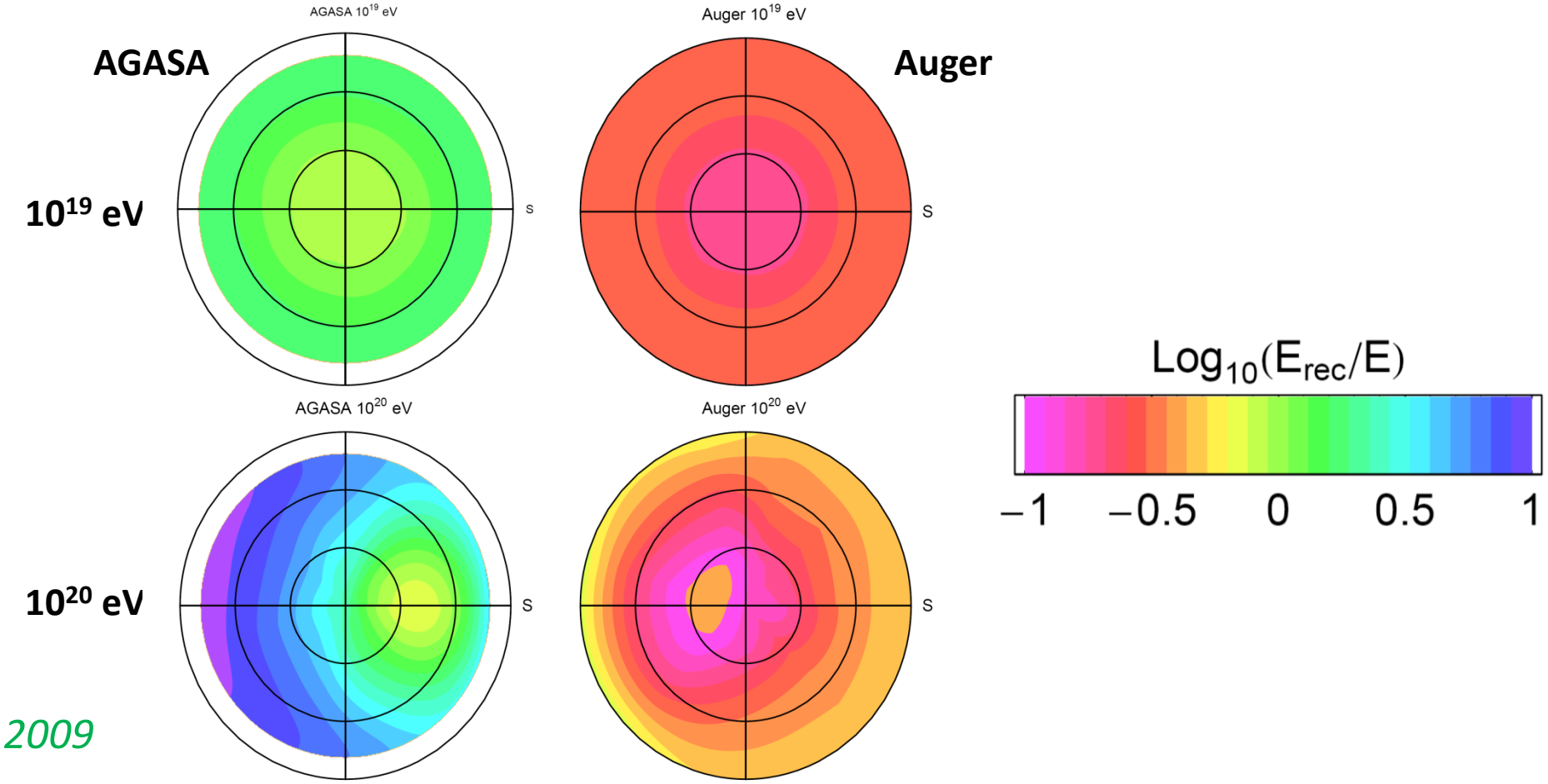
Carpet-2, +/- 15 days
E>100 TeV and E>300 TeV

stay tuned!



BACKUP

Gamma reconstructed energies



Kalashev, Rubtsov, ST 2009