astrophysics with ultra-high-energy cosmic messengers

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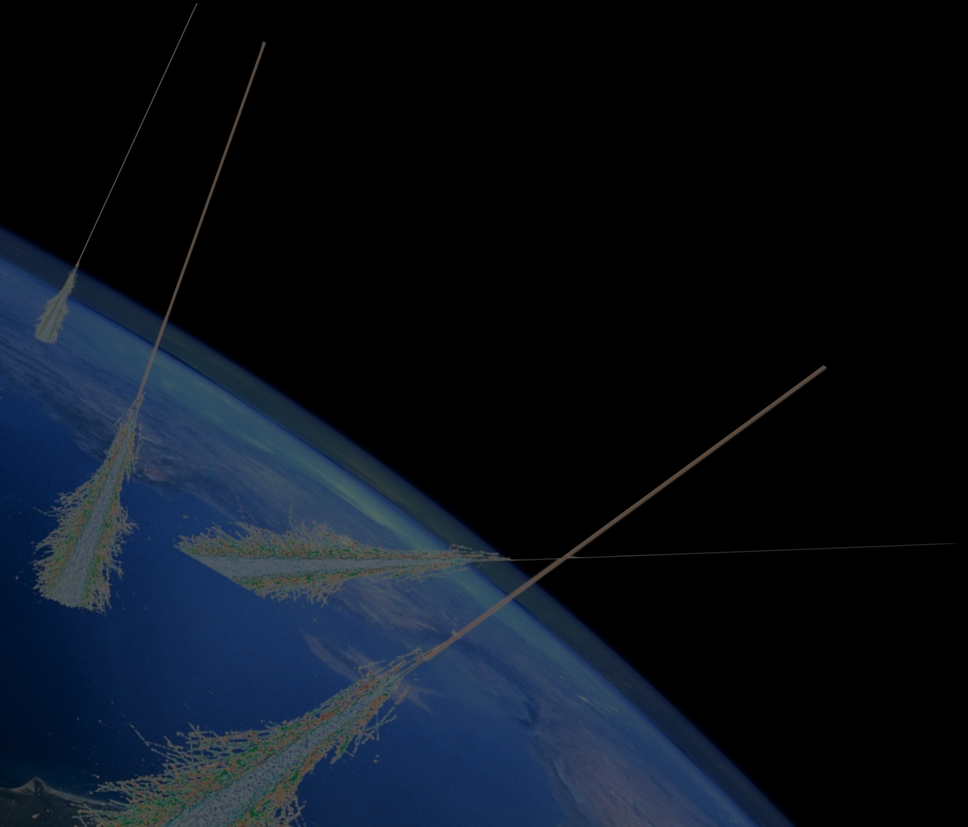
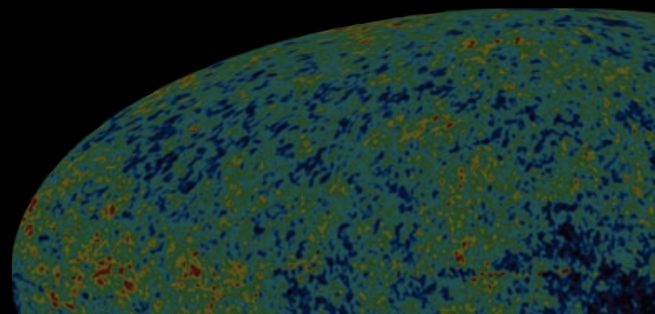
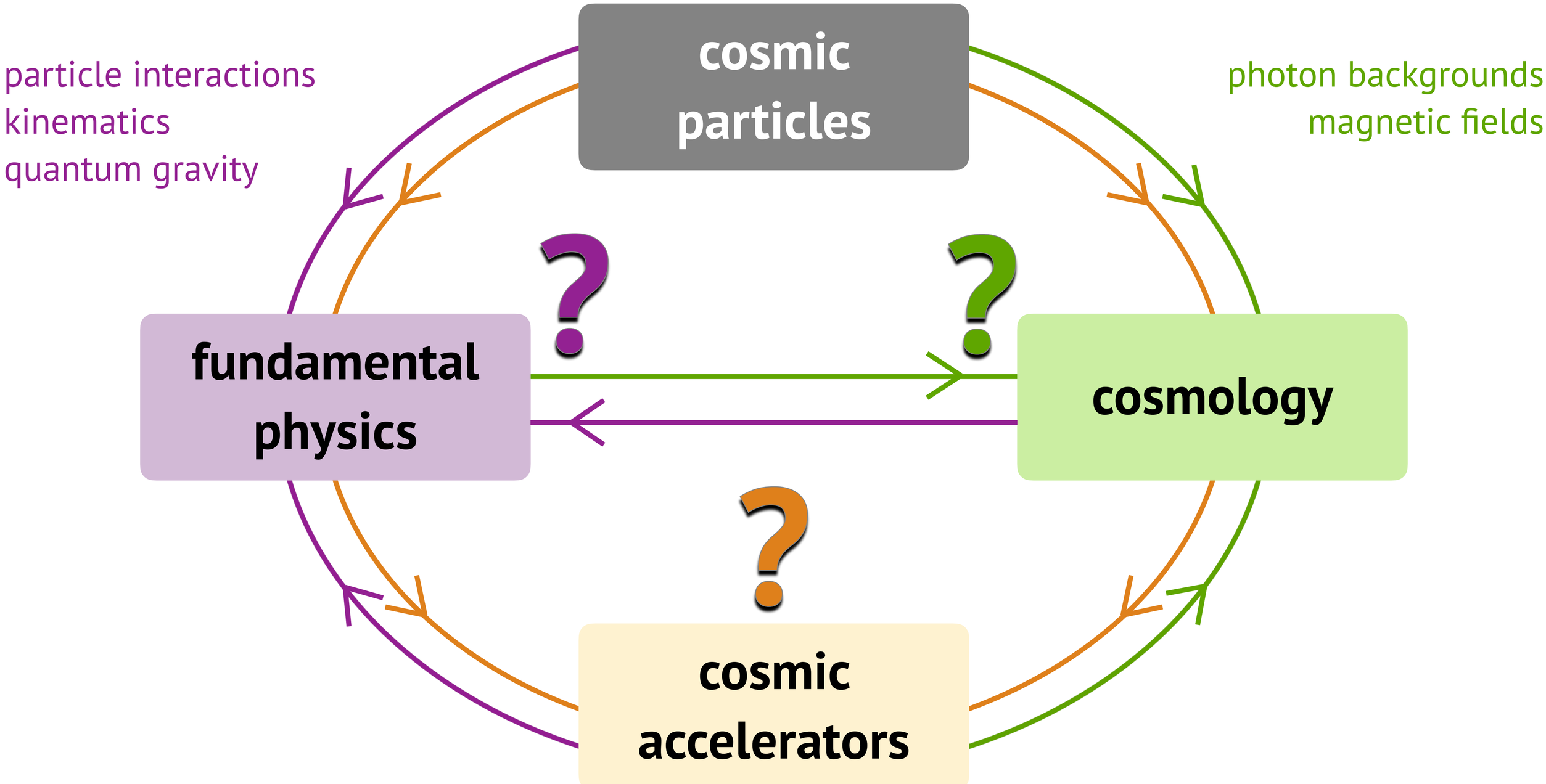


LPPC Seminar, Harvard University
29 March 2023




particle interactions
kinematics
quantum gravity
cosmic particles
photon backgrounds
magnetic fields
?
?
fundamental physics
cosmology
?
cosmic accelerators

UHE particle astrophysics with multiple messengers

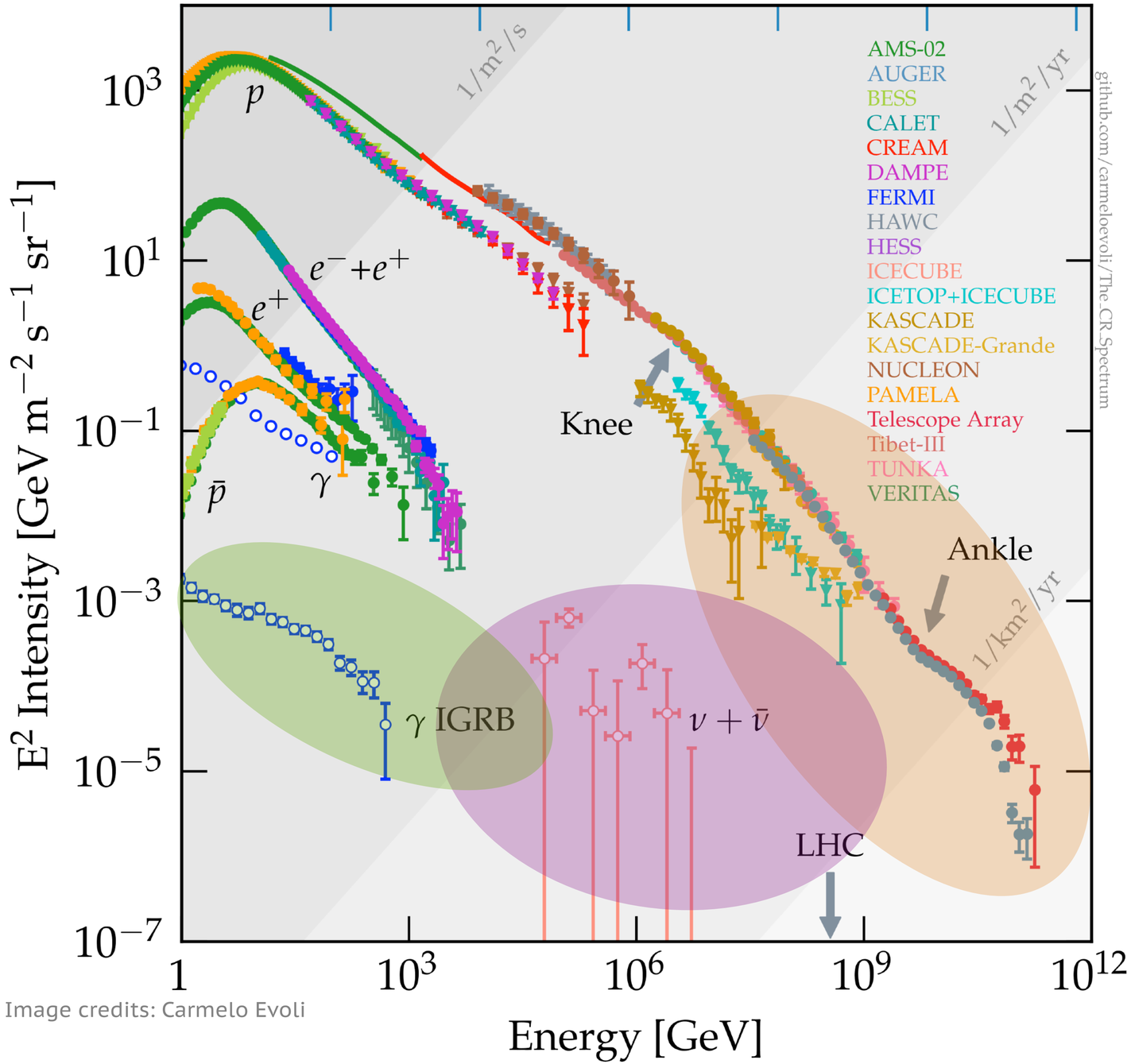
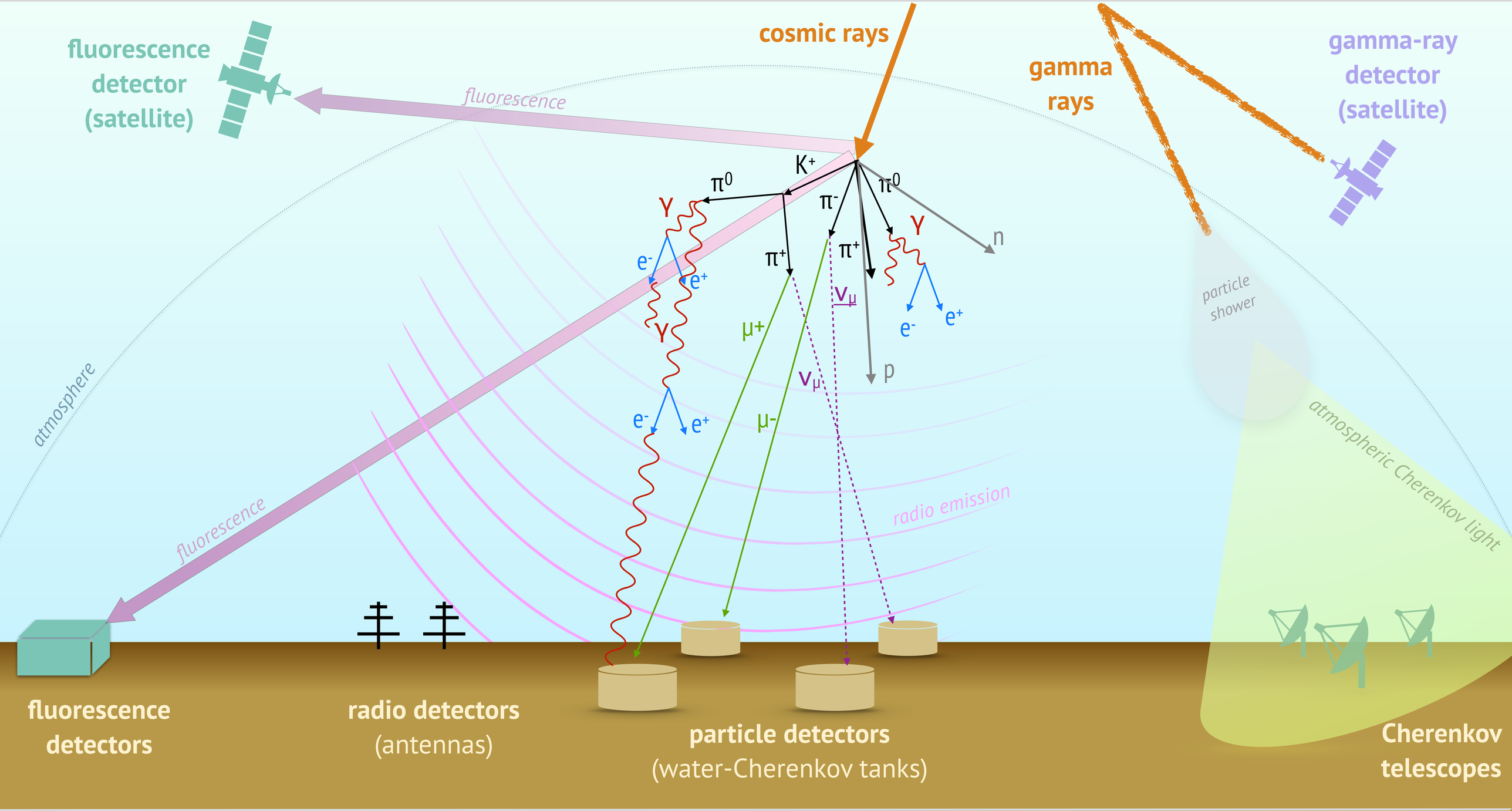


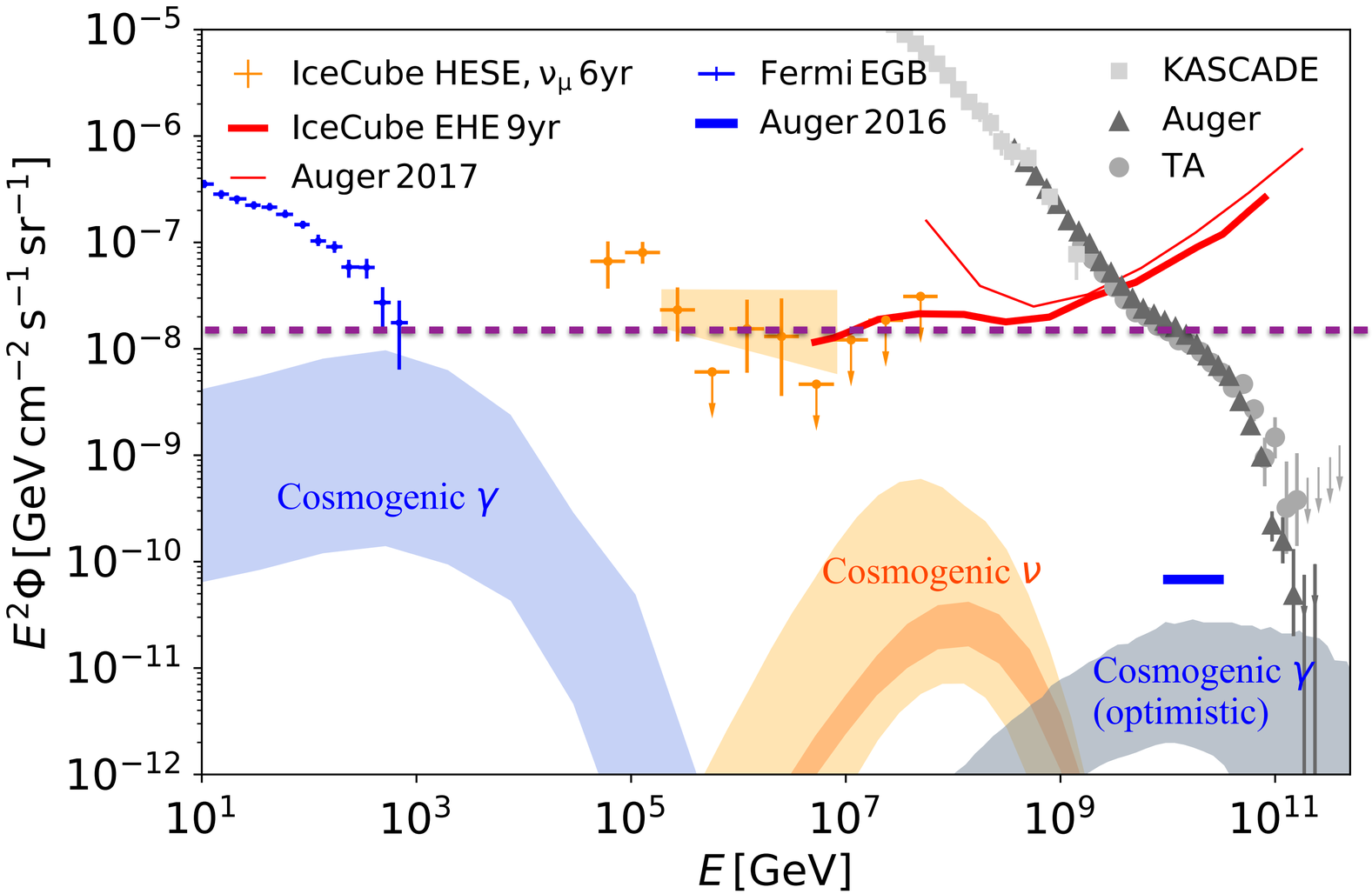
Image credits: Carmelo Evoli

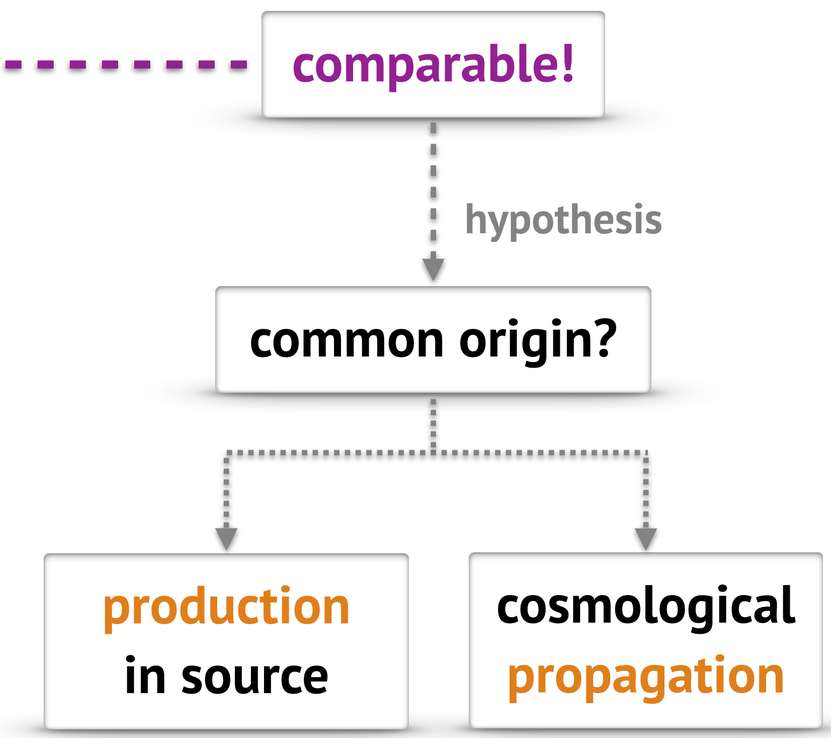
(ultra-)high-energy cosmic messengers. detection principle



ultra-high-energy particle astrophysics: the landscape

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714



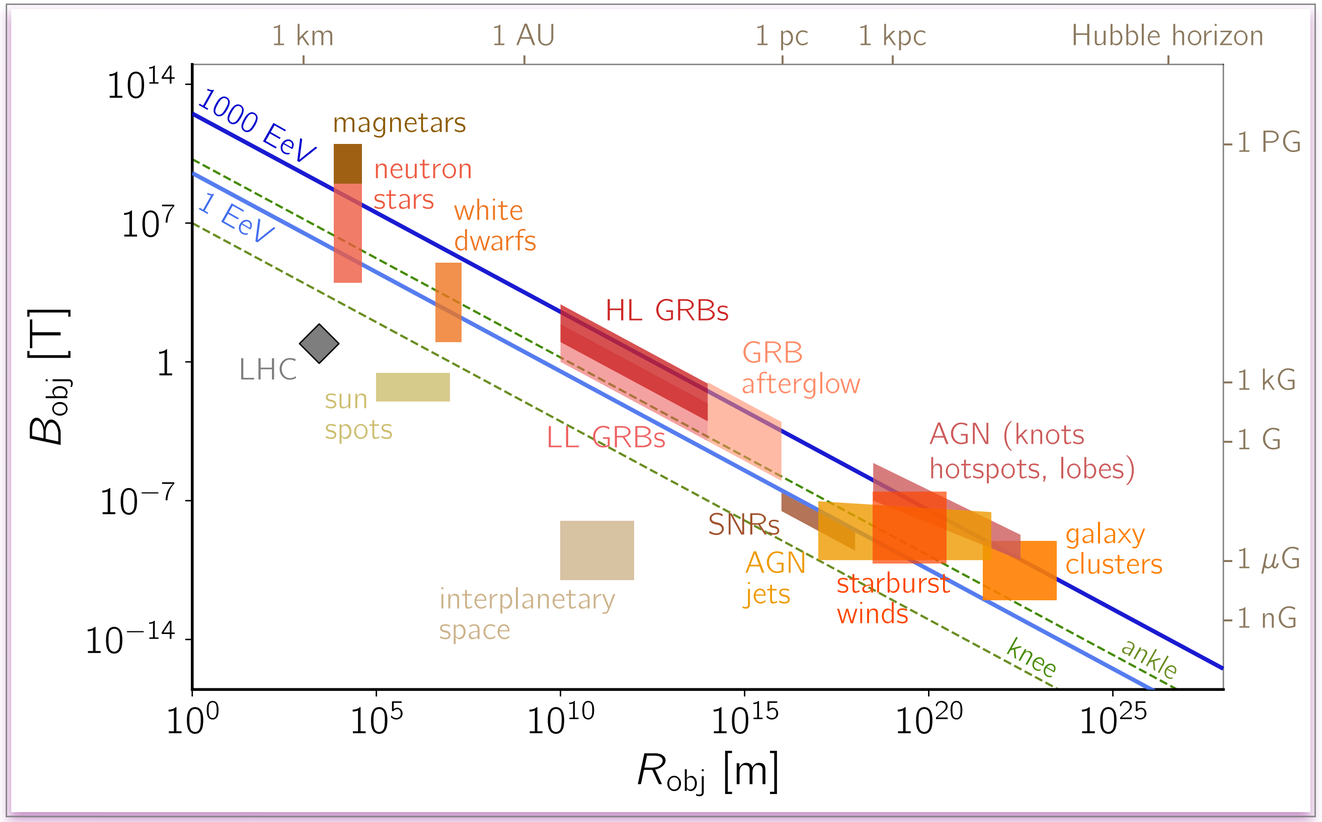


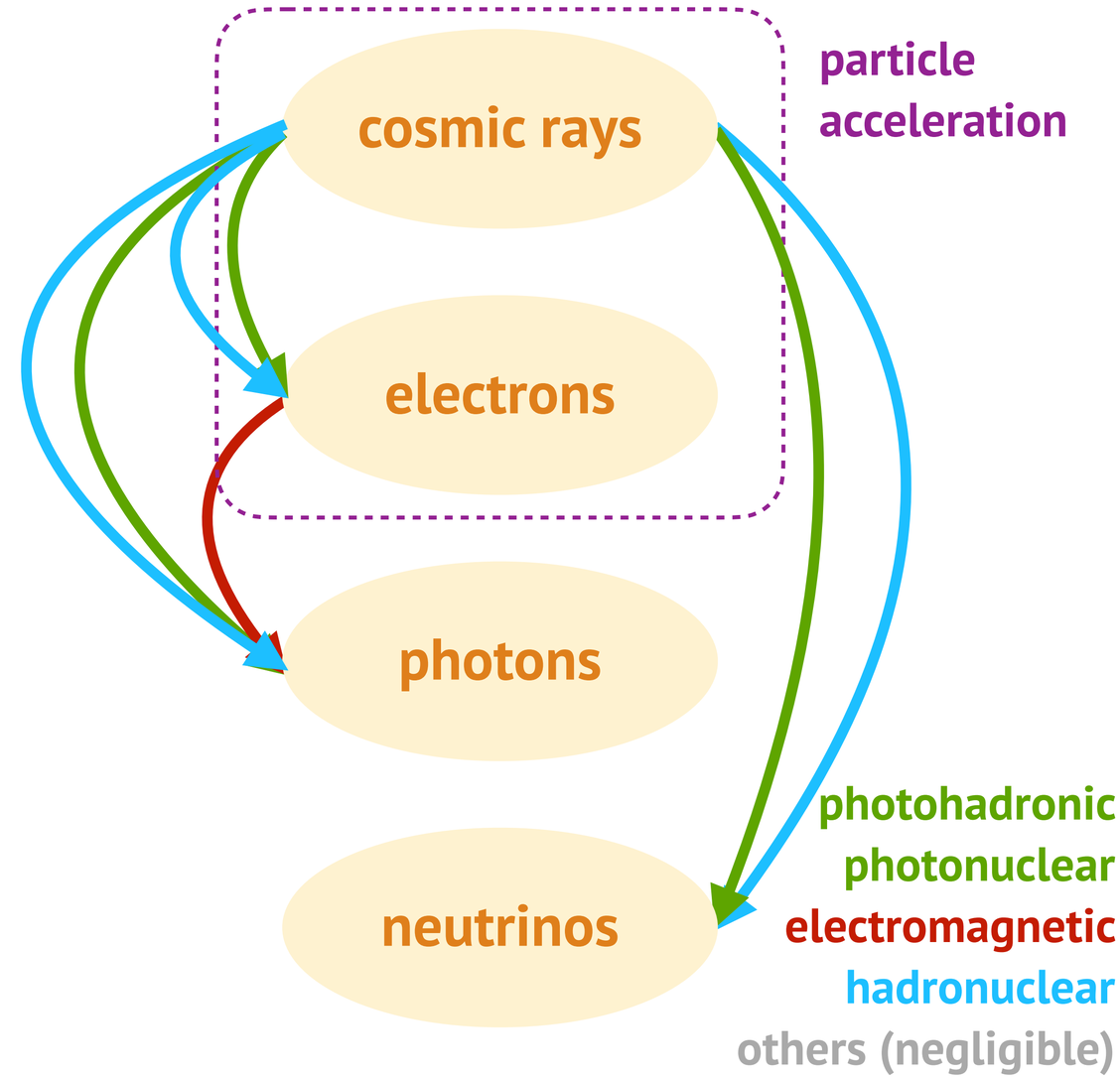
need to understand how particles are produced and how they propagate

connecting the messengers: production & propagation

(ultra-)high-energy cosmic messengers: production and synergies

- **how are (ultra-)high-energy particles produced?**
  - ***charged particles*:** electromagnetic acceleration
  - ***neutral particles*:** particle interactions

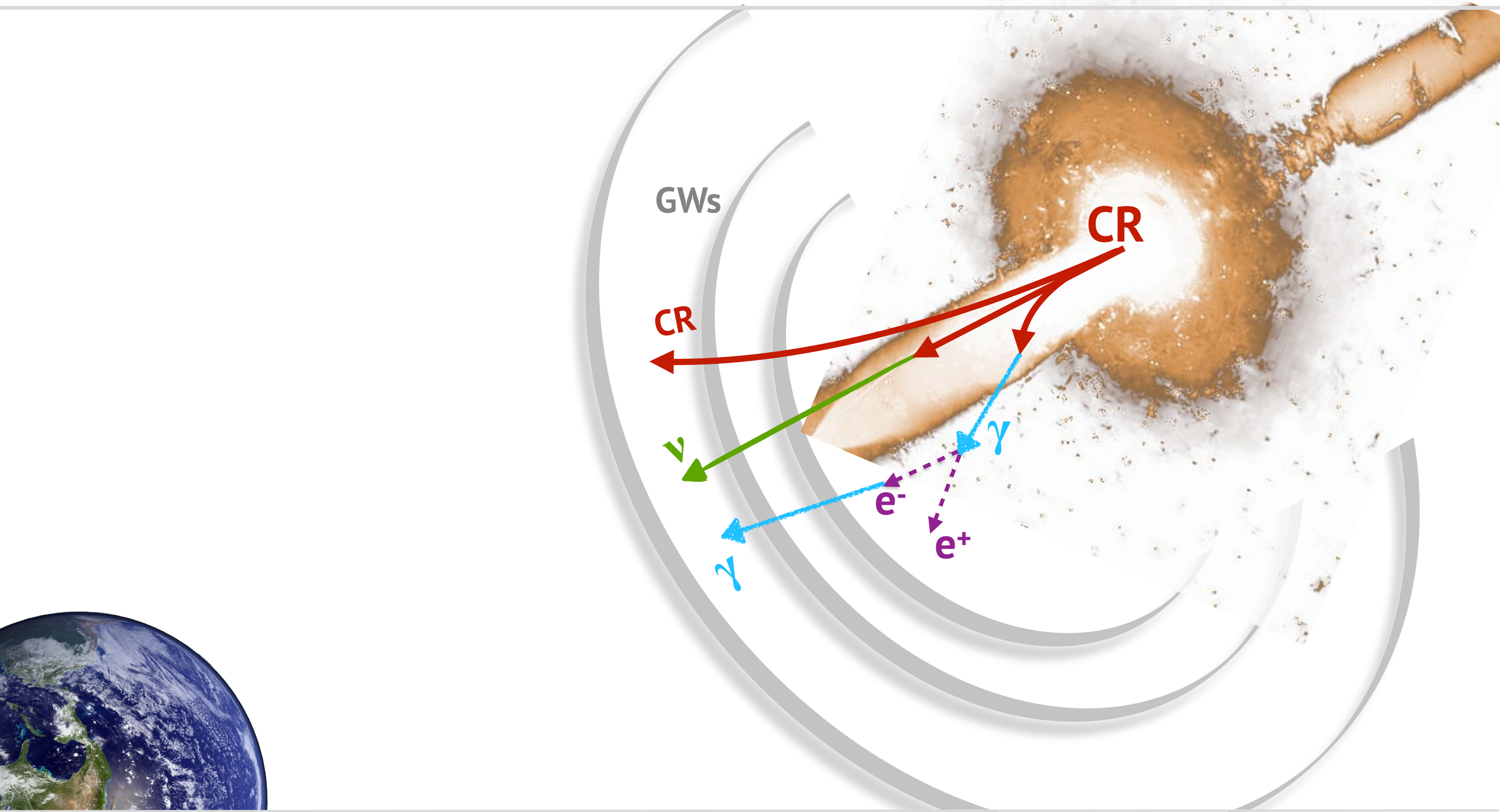




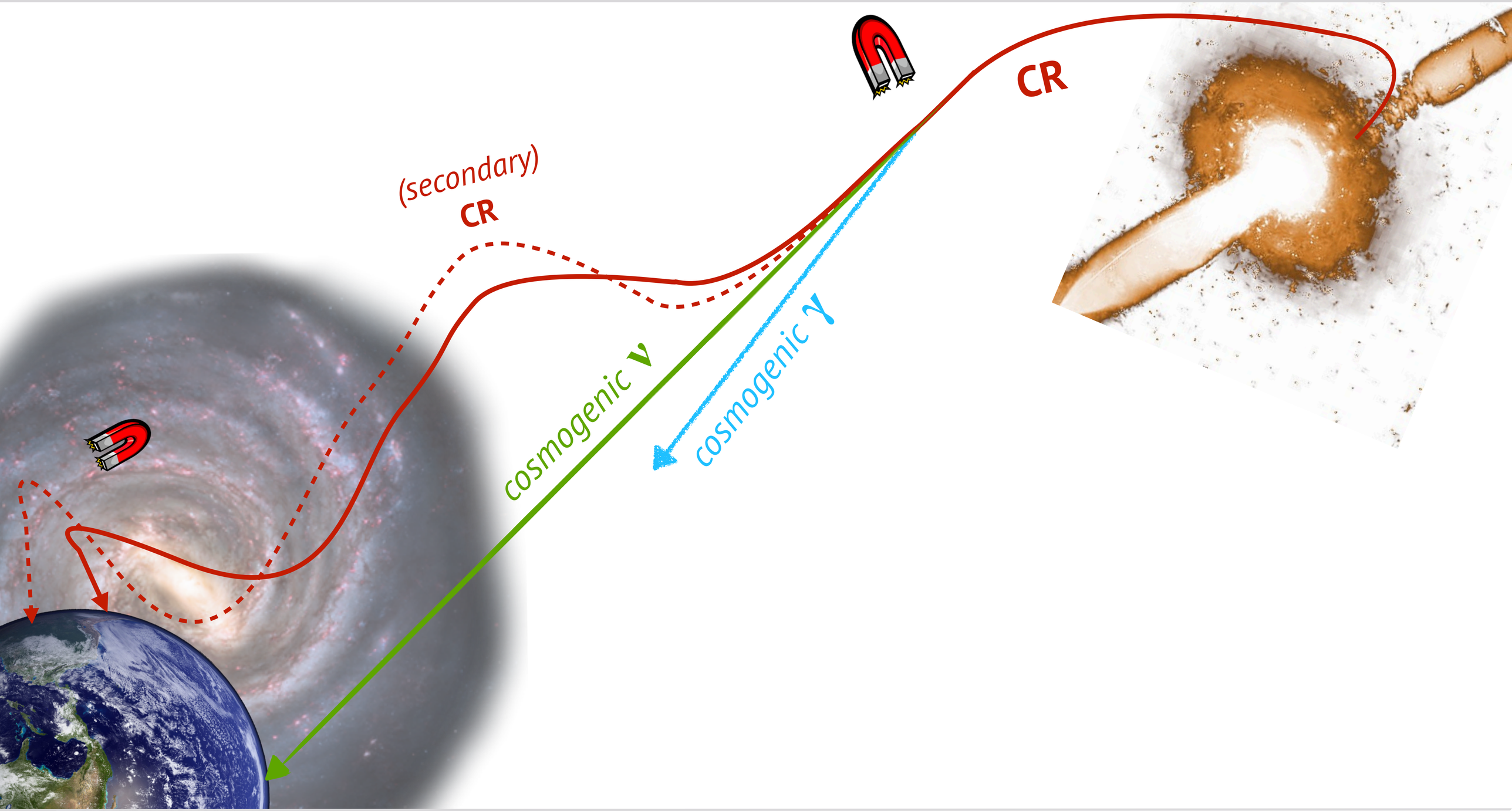
Hillas criterion $E_{\rm max} \sim 2qv_{\rm sh}BR_{\rm L} \sim 10^{18} Z \left(\frac{B}{\mu\rm G}\right)\left(\frac{R}{\rm kpc}\right)$ eV

ultra-high-energy (particle) astrophysics:
messengers above ~ 1 EeV and their by-products

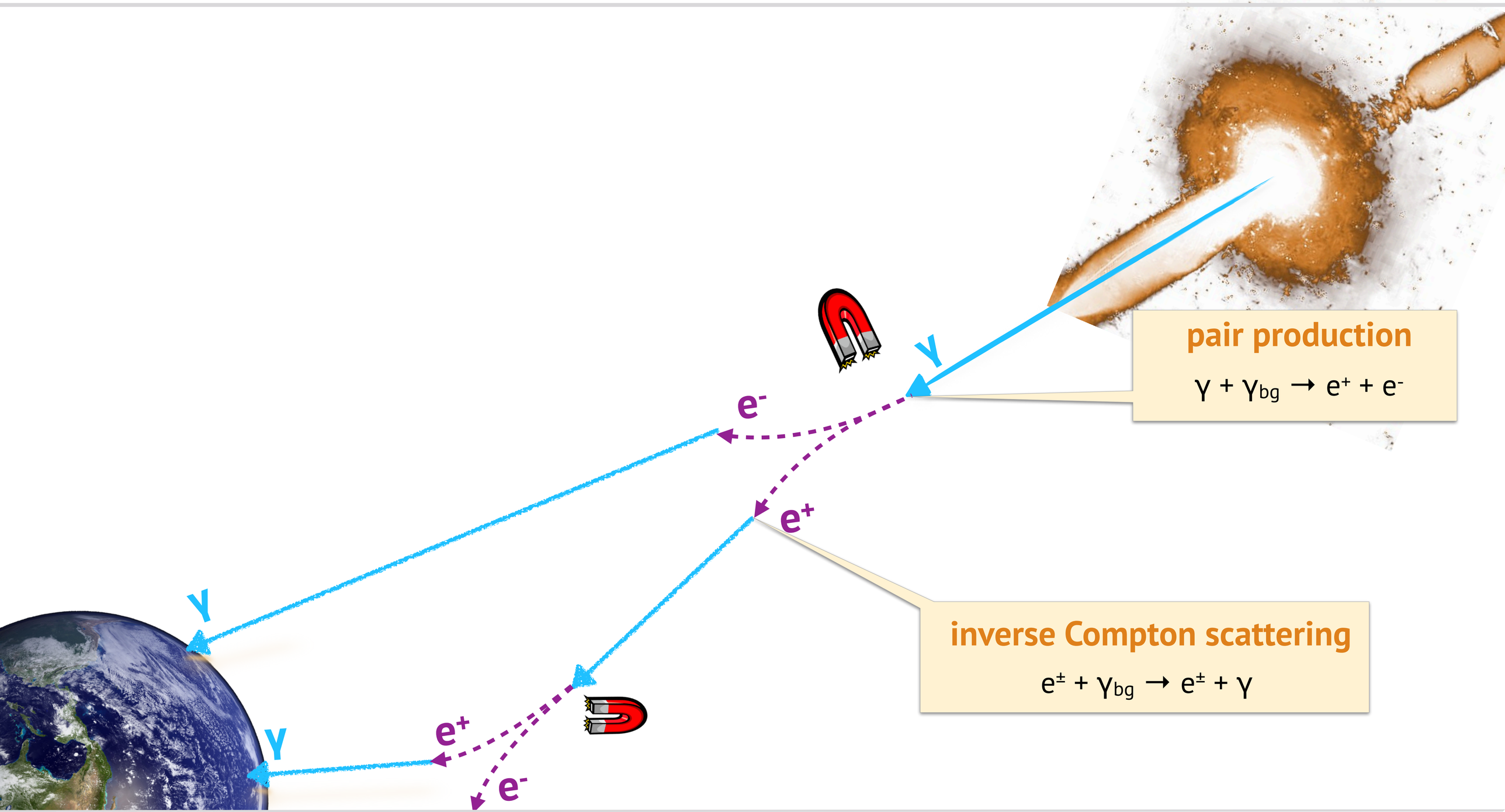
multimessenger picture: sources



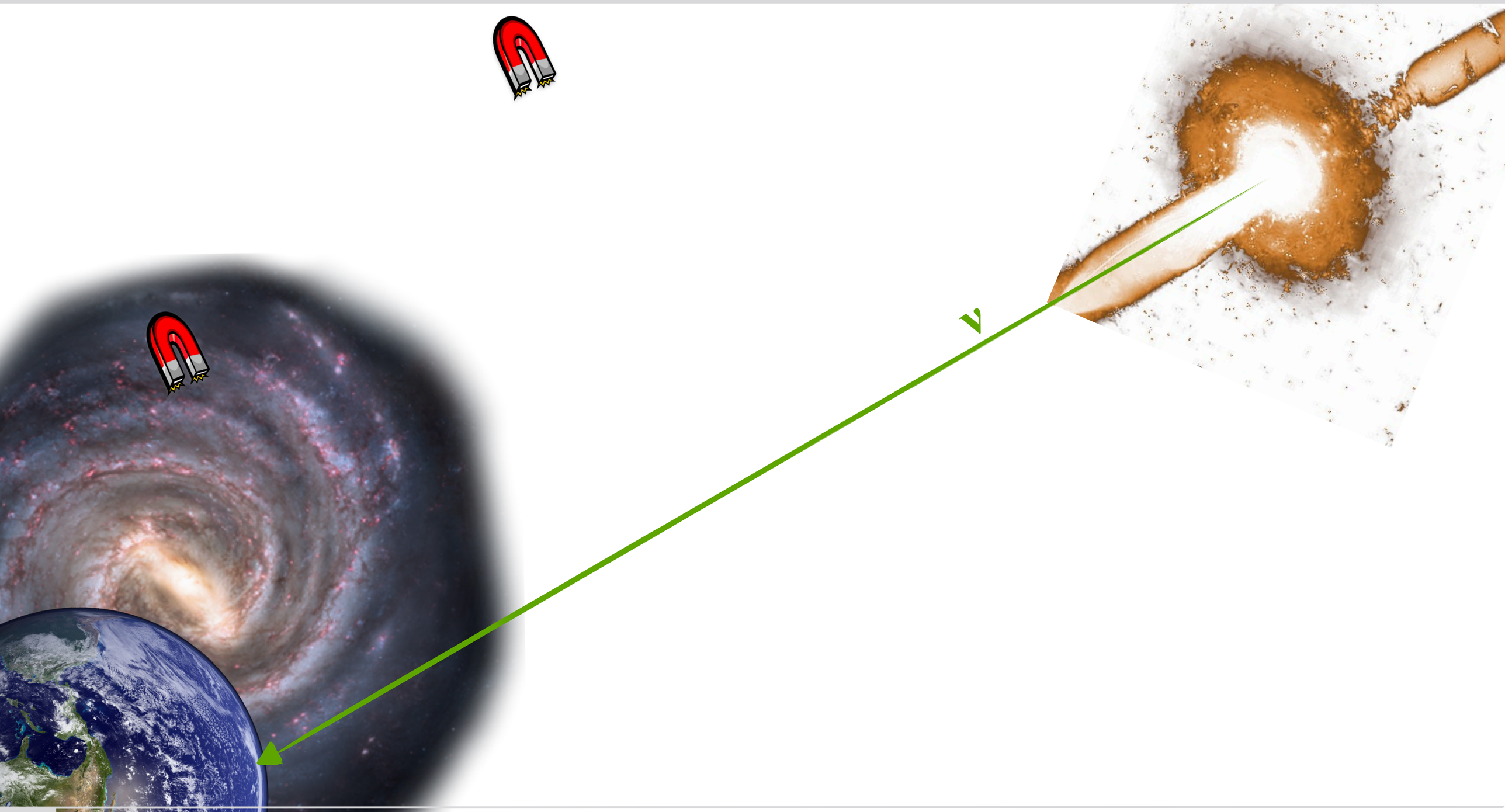
multimessenger propagation picture: cosmic rays



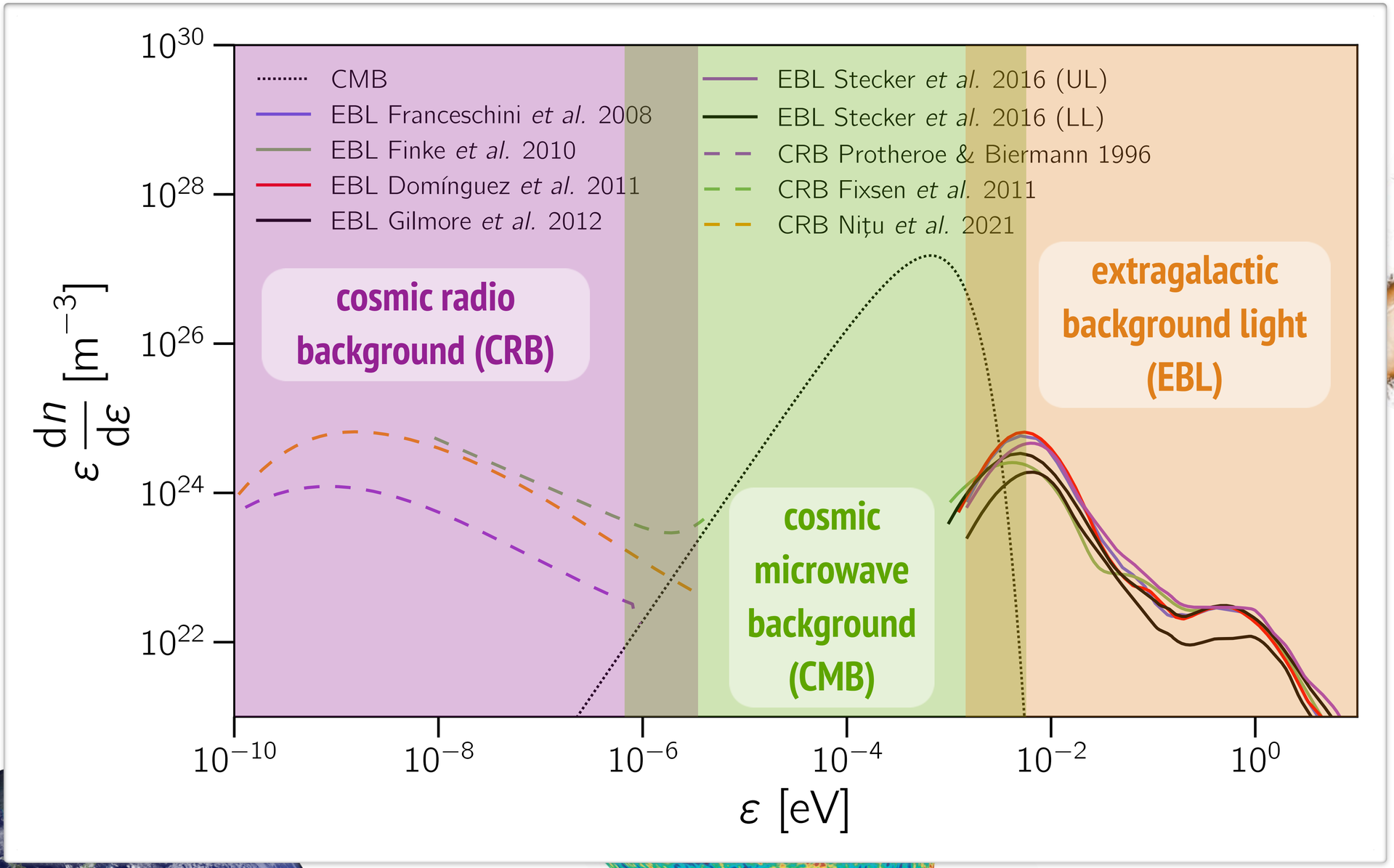
multimessenger propagation picture: gamma rays

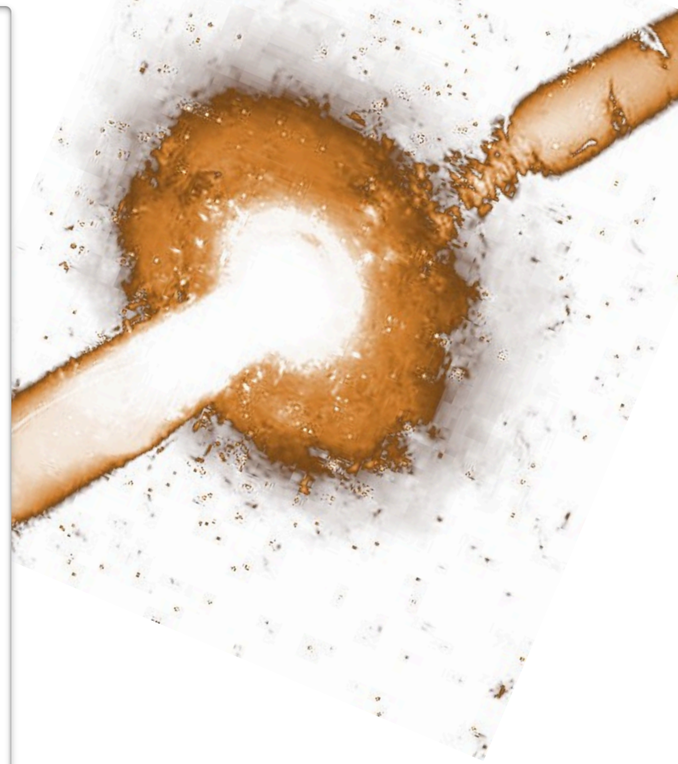


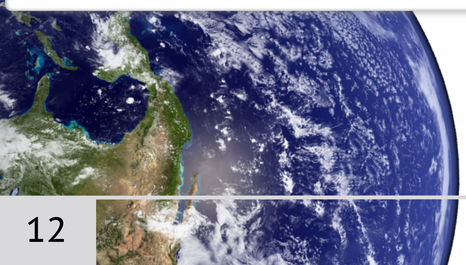
multimessenger propagation picture: neutrinos

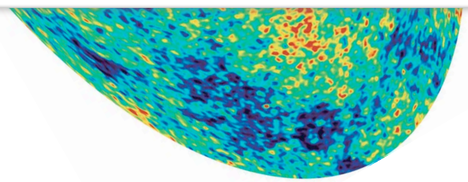


multimessenger propagation picture: photon backgrounds

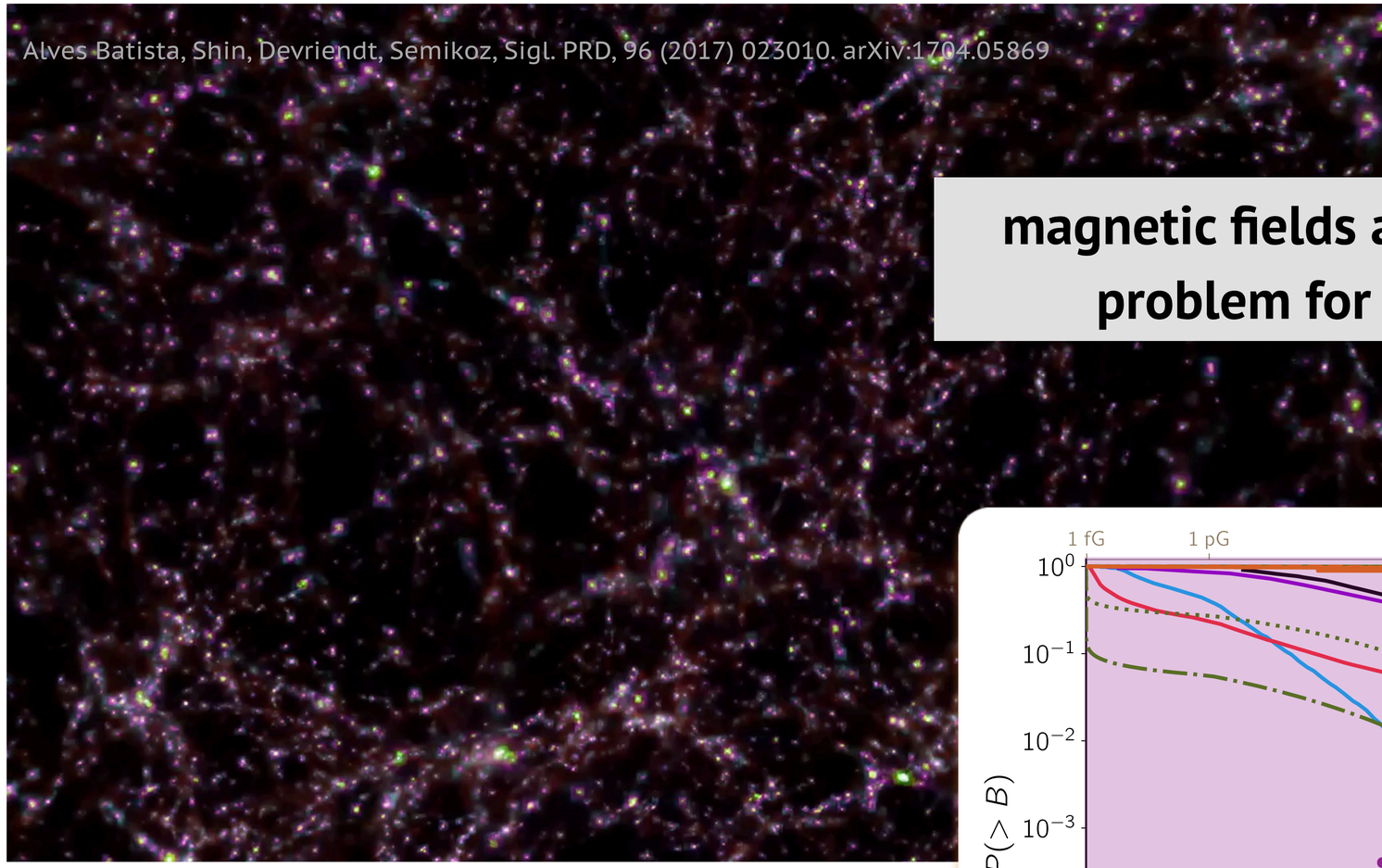




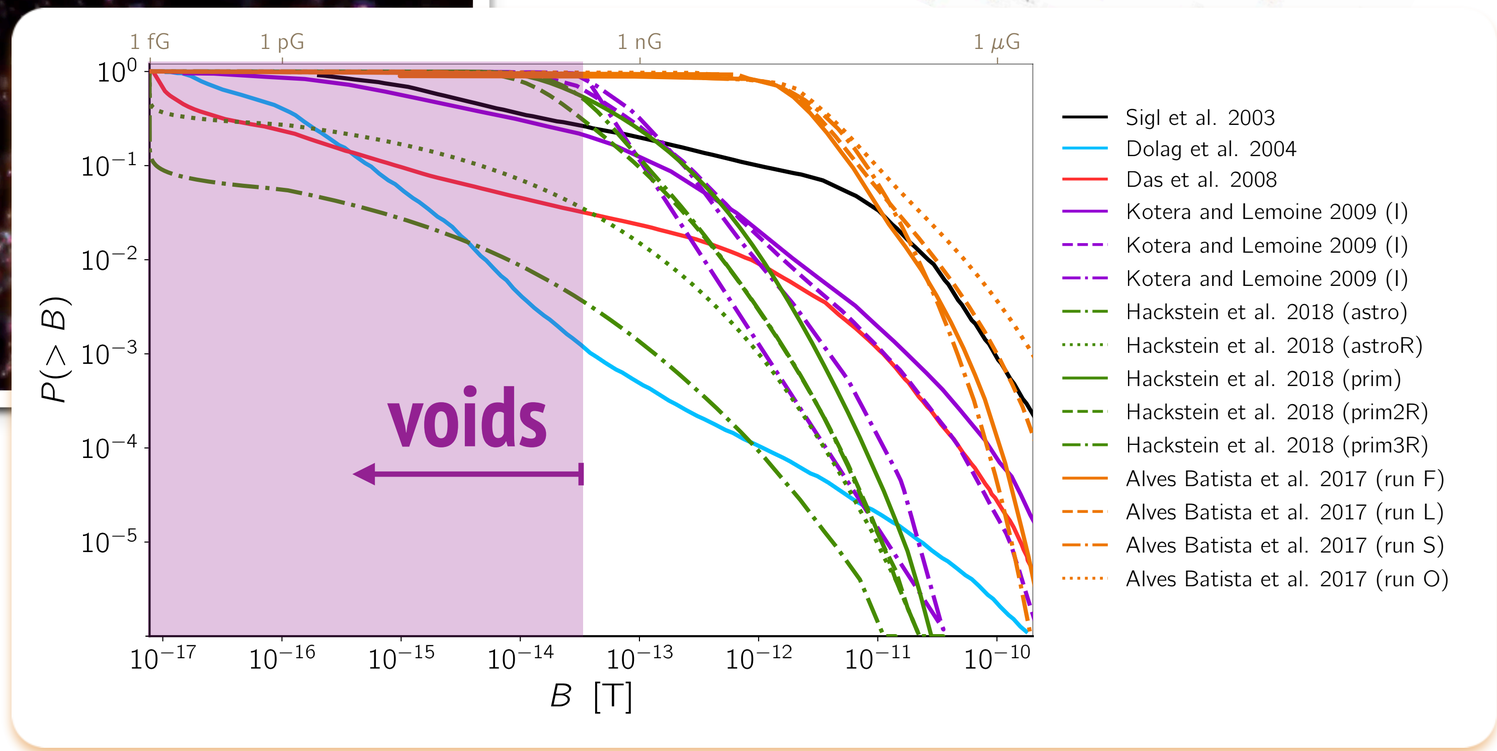




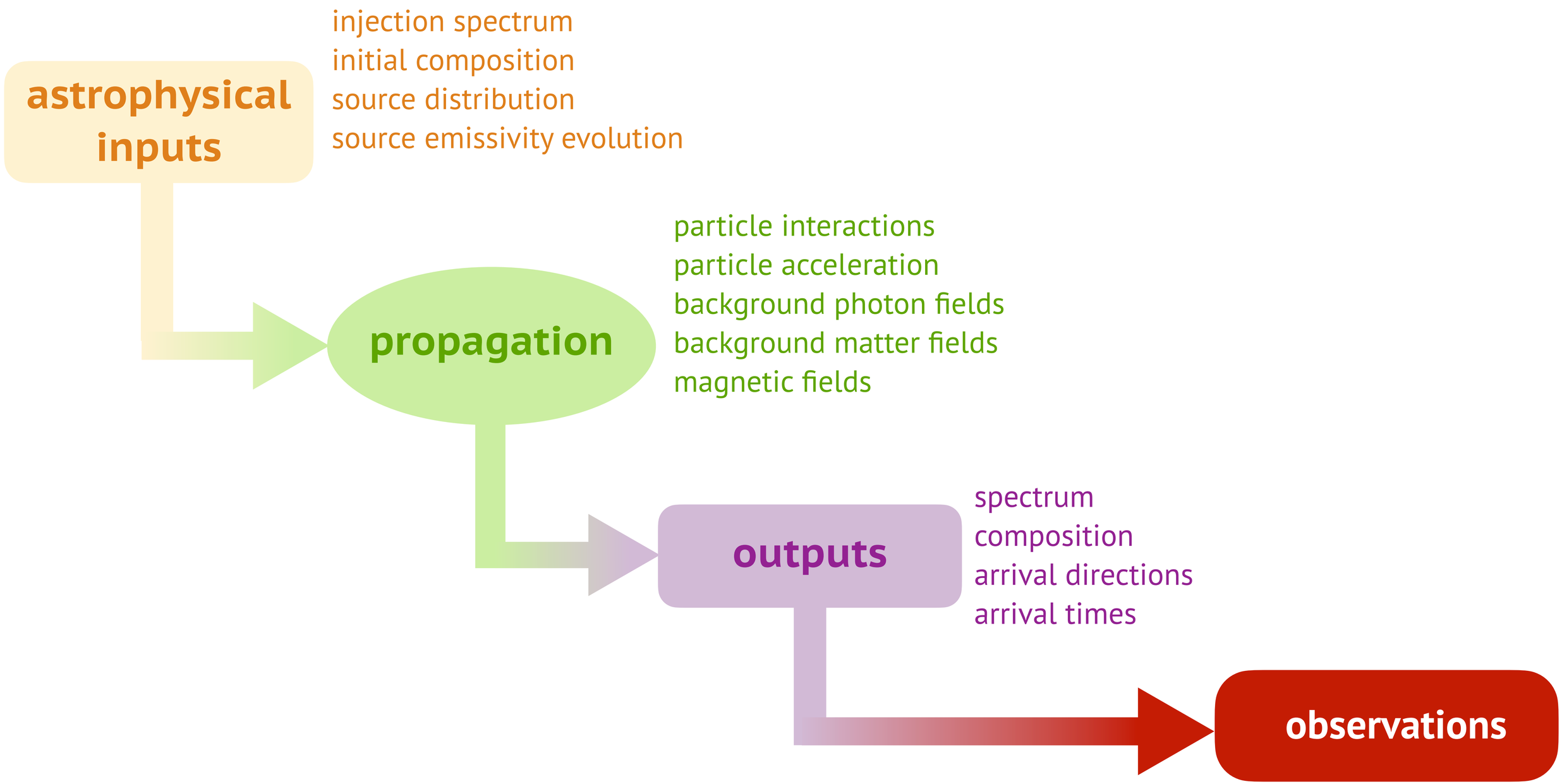
multimessenger propagation picture: intergalactic magnetic fields



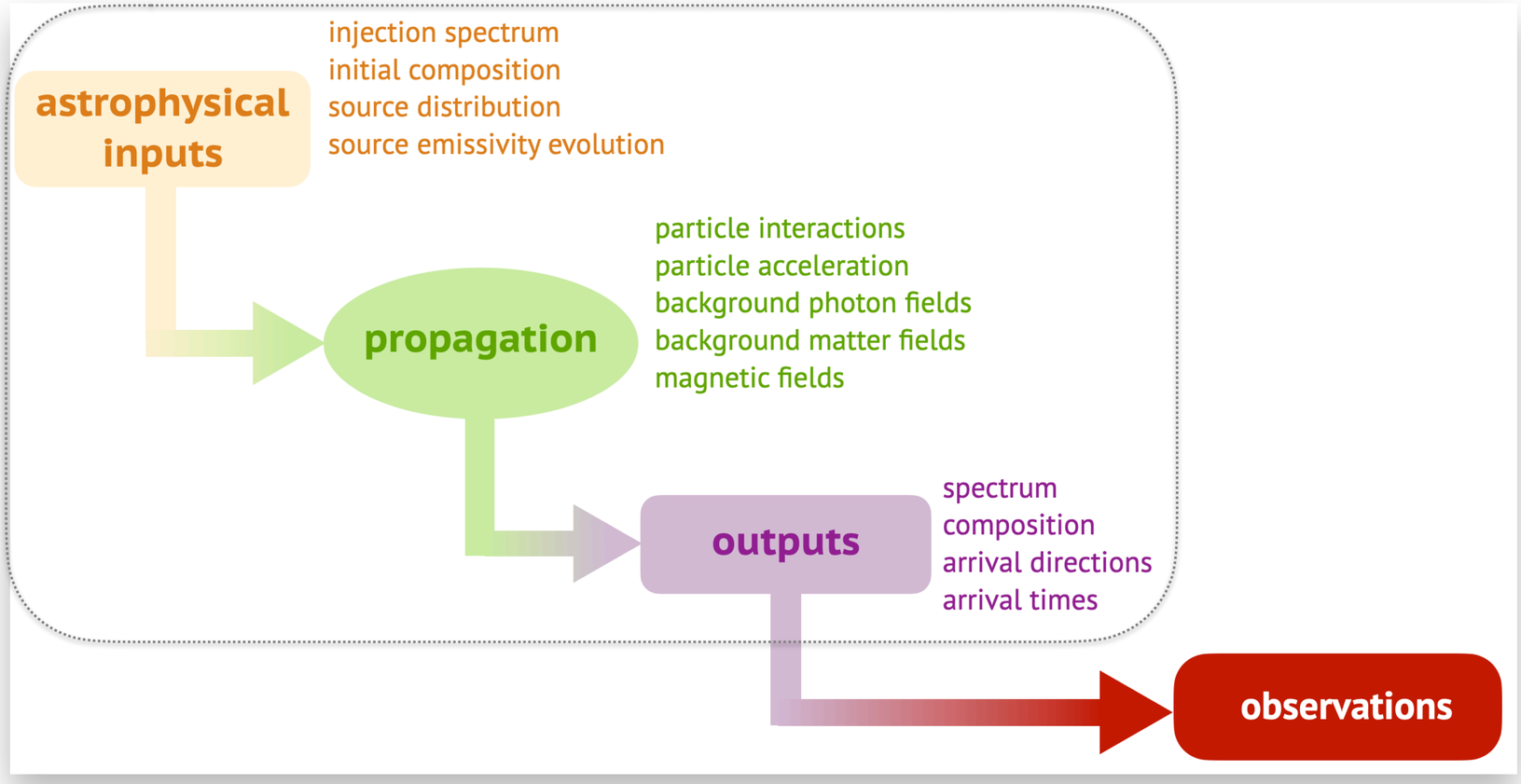
magnetic fields are very uncertain → a problem for UHE astronomy(?)



simulating multimessenger signals



modelling the propagation



CRPropa

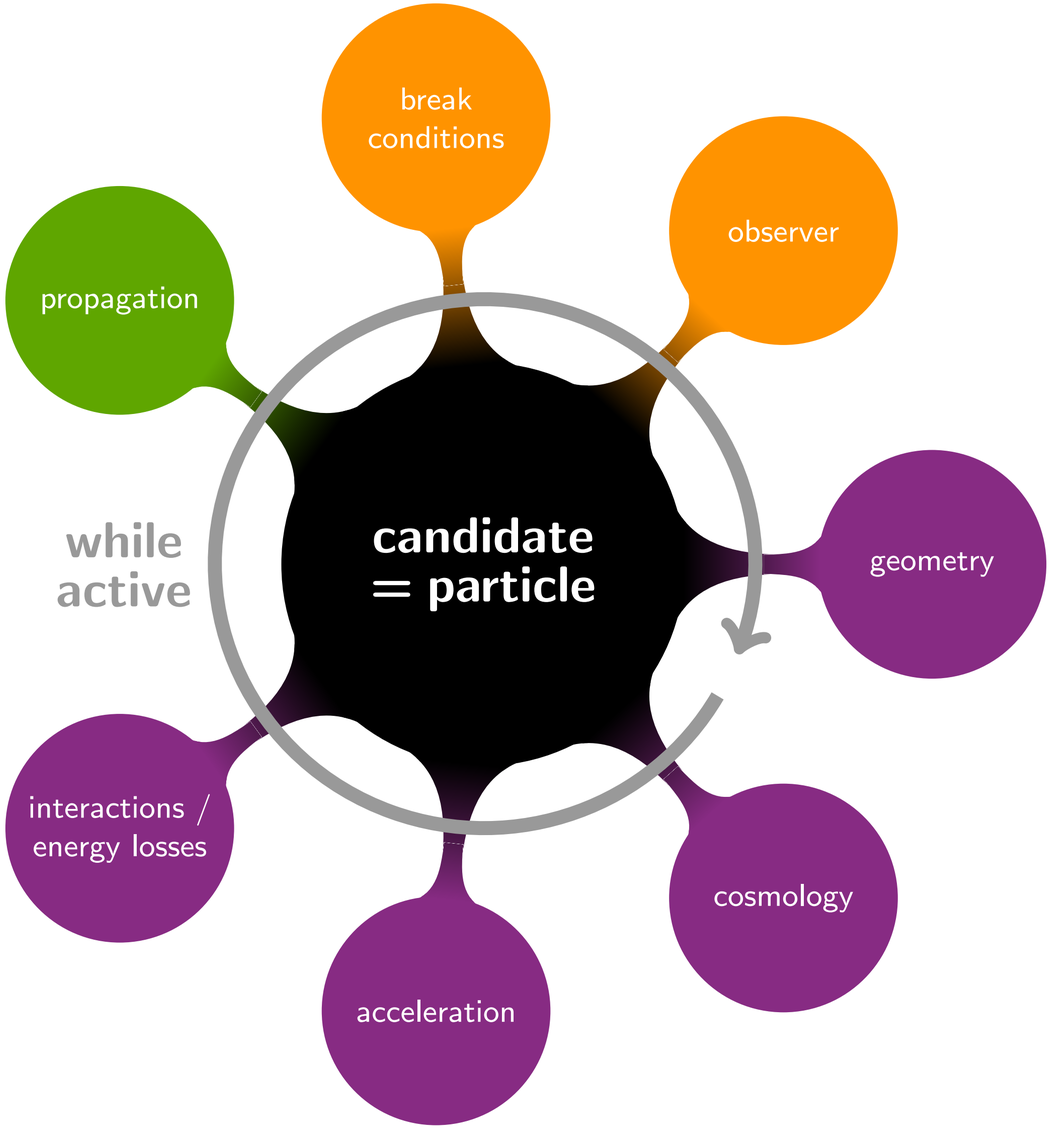
- mixing all ingredients → interpret (fit) observations based on models
- this should be done ***self-consistently for all messengers***
- need to ***scan full parameter space*** of uncertainties

multimessenger simulation framework

the CRPropa framework

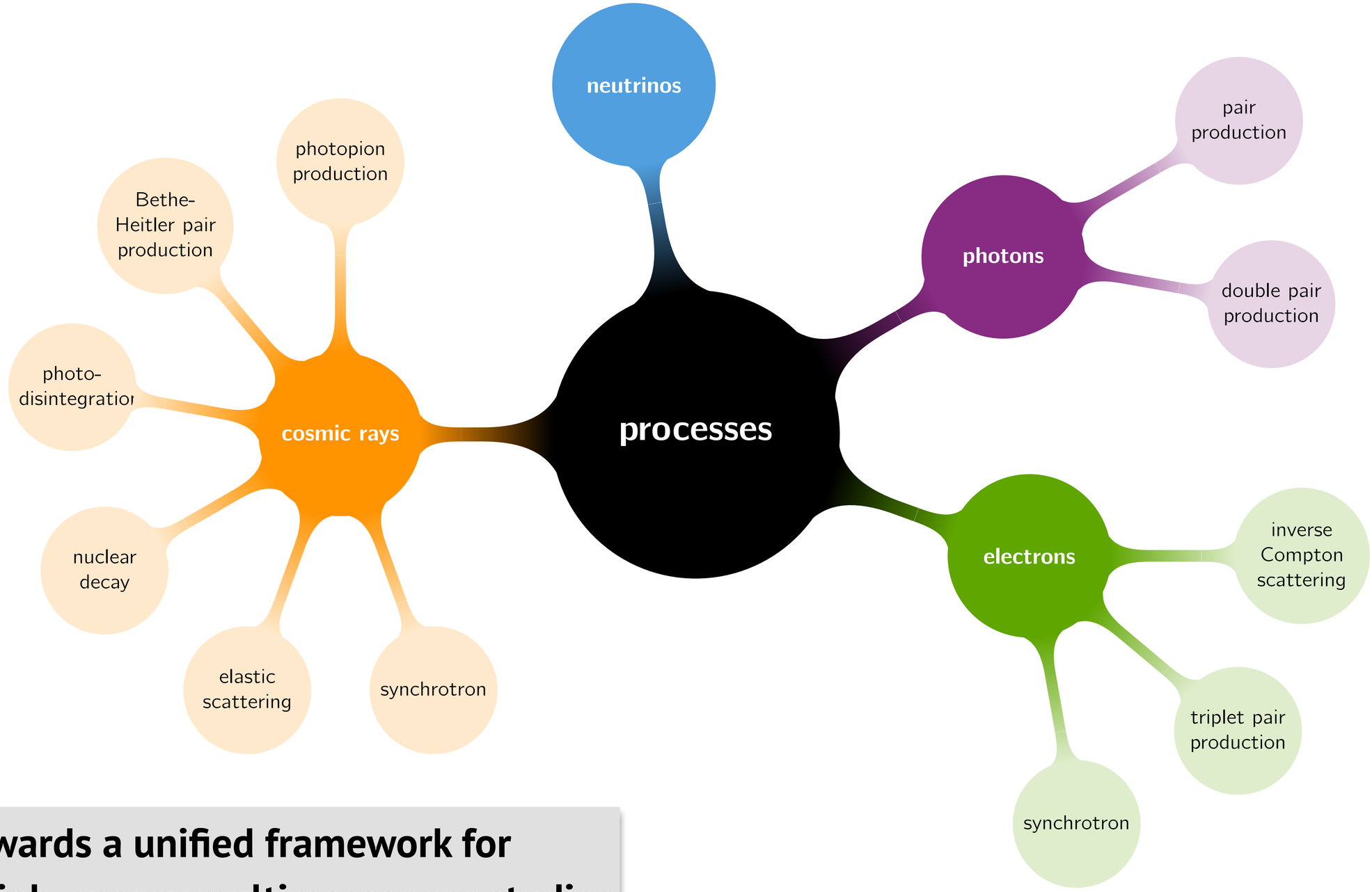
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142
Alves Batista et al. JCAP 09 (2022) 035. arXiv:2208.00107

- publicly available Monte Carlo code
- propagation of high-energy cosmic rays, gamma rays, neutrinos, and electrons
- propagation in *any* environment (Galactic, extragalactic, around sources)
- modular structure
- parallelisation with OpenMP
- development on Github: https://github.com/CRPropa/CRPropa3



crpropa.desy.de

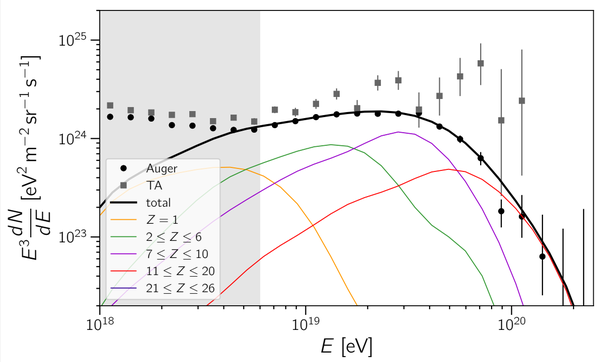
the CRPropa framework: multimessenger connections



towards a unified framework for (ultra-)high-energy multimessenger studies

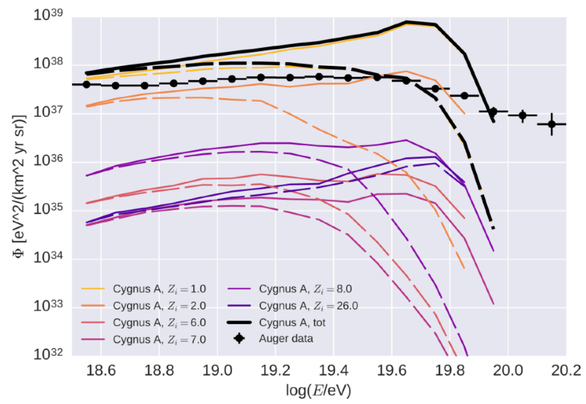
the CRPropa framework: applications

fit UHECR measurements



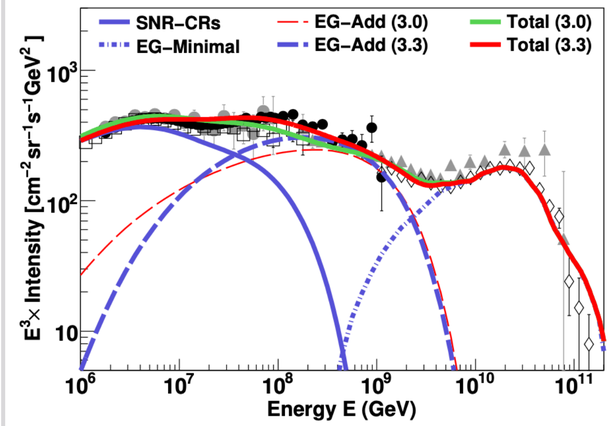
Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

test UHECR source models



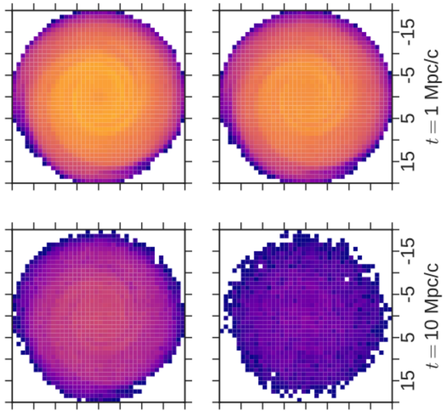
Eichmann et al. JCAP 02 (2018) 036. arXiv:1701.06792

transition G-EG CRs



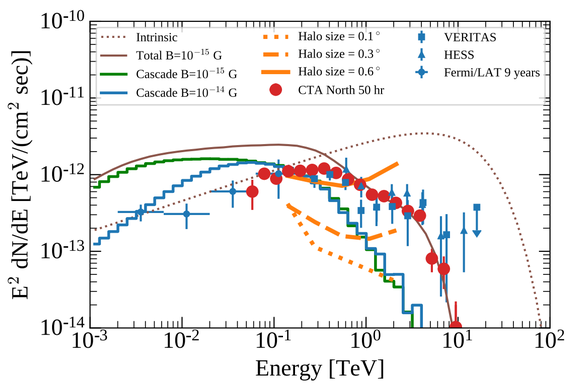
Thoudam et al. Astron. Astrophys. 595 (2016) A33. arXiv:1605.03111

diffusion of Galactic CRs



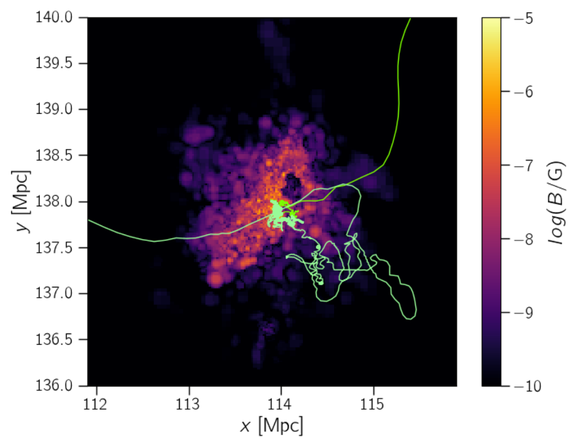
Merten et al. JCAP 06 (2016) 046. arXiv:1704.07484

gamma rays + IGMFs



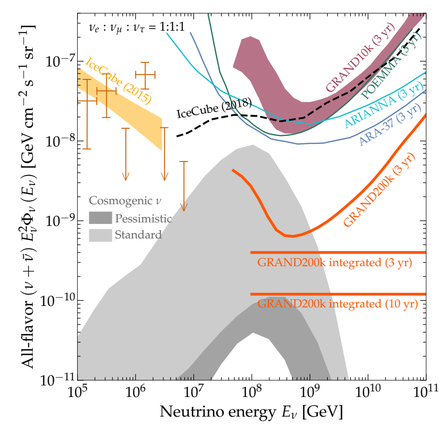
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

neutrinos from galaxy clusters



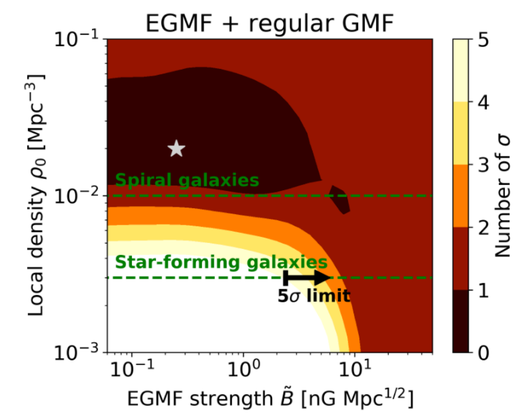
Hussain, Alves Batista, de Gouveia Dal Pino. arXiv:2101.07702

cosmogenic neutrinos



GRAND Collaboration. Science China Phys 63 (2020) 219501. arXiv:1810.09994

EGMF constraints



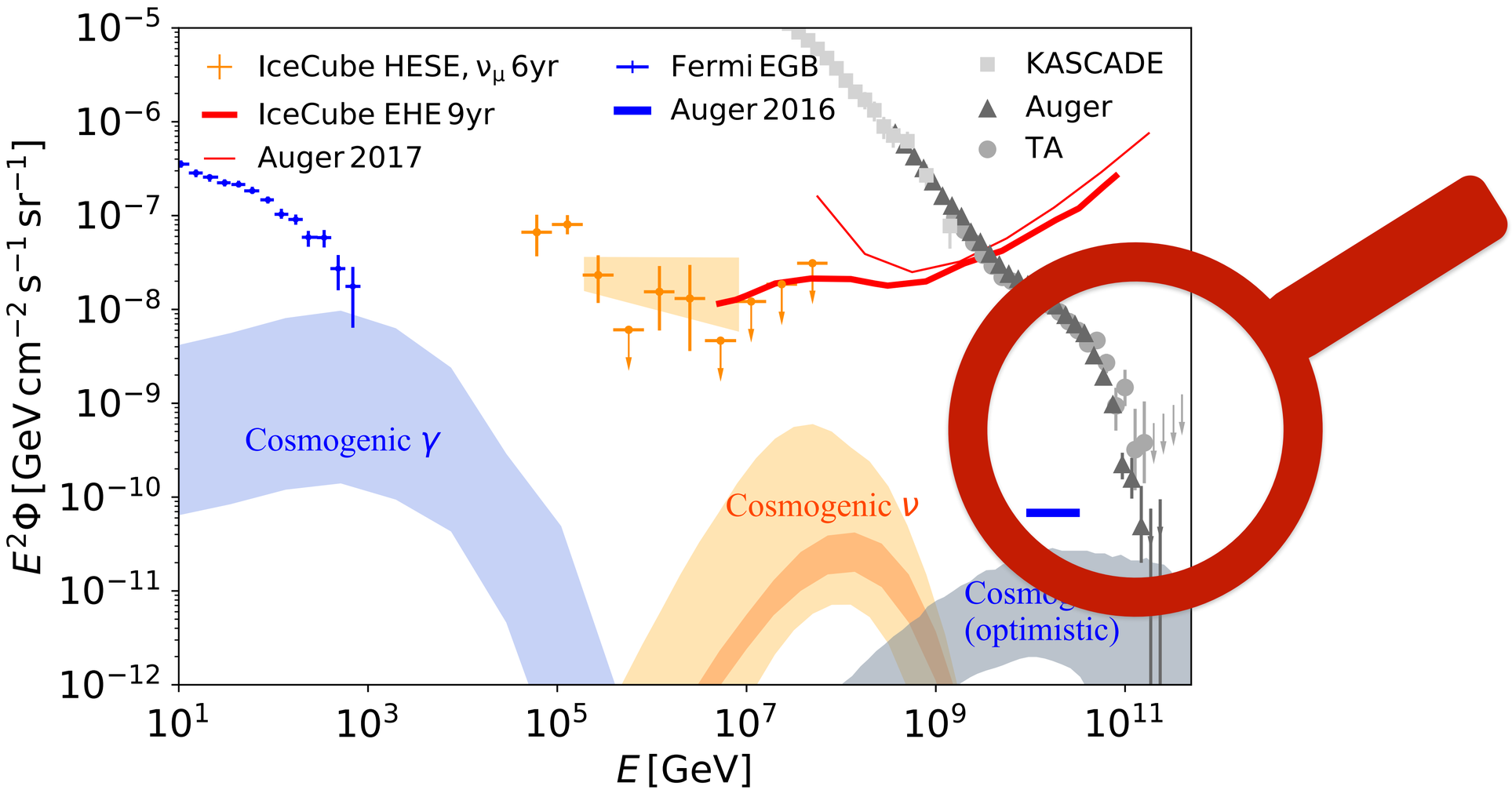
van Vliet, Palladino, Taylor, Winter. MNRAS 510 (2022) 1289. arXiv:2104.05732

... and much more!

making sense of UHE observations

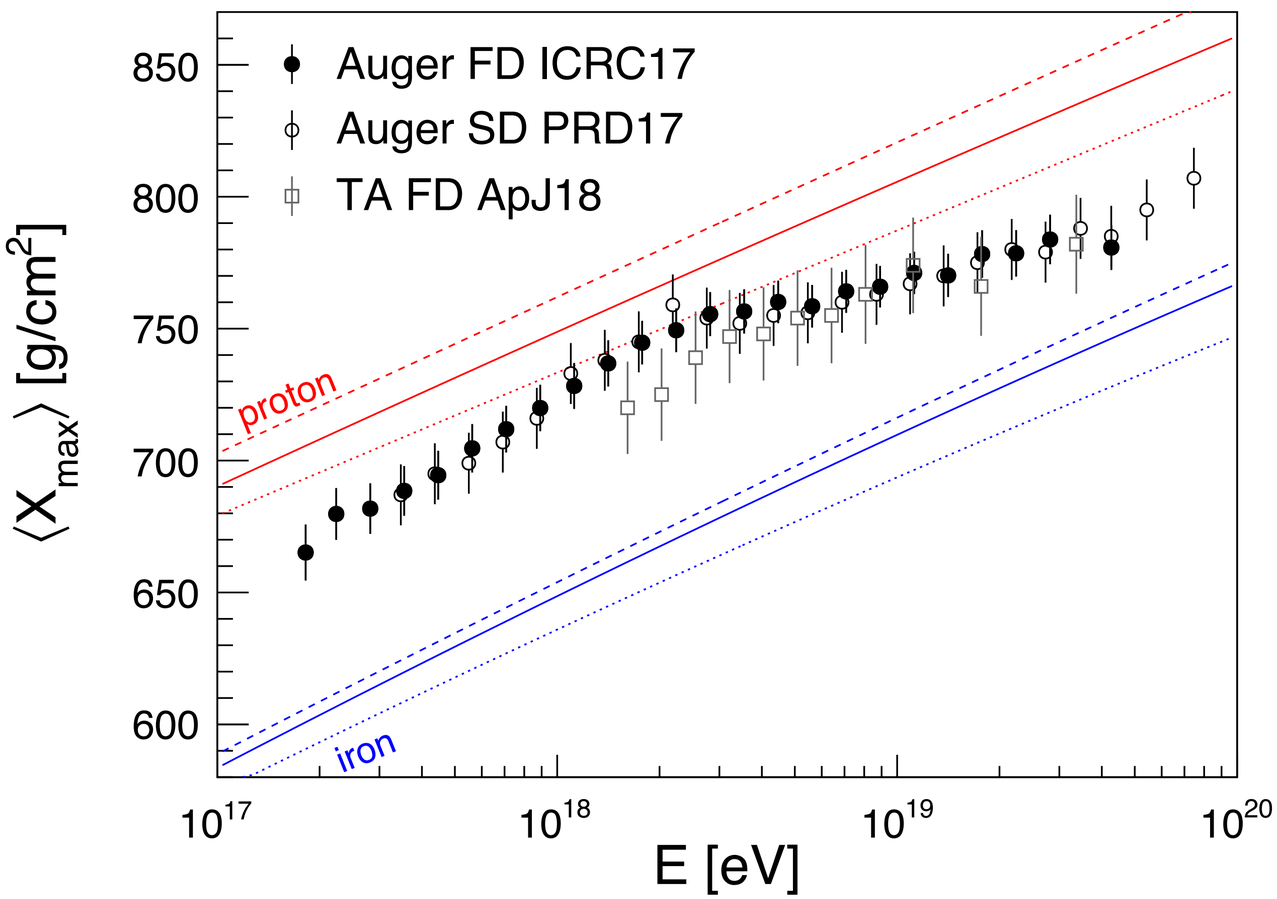
cosmic rays + photons + neutrinos: cosmogenic connections

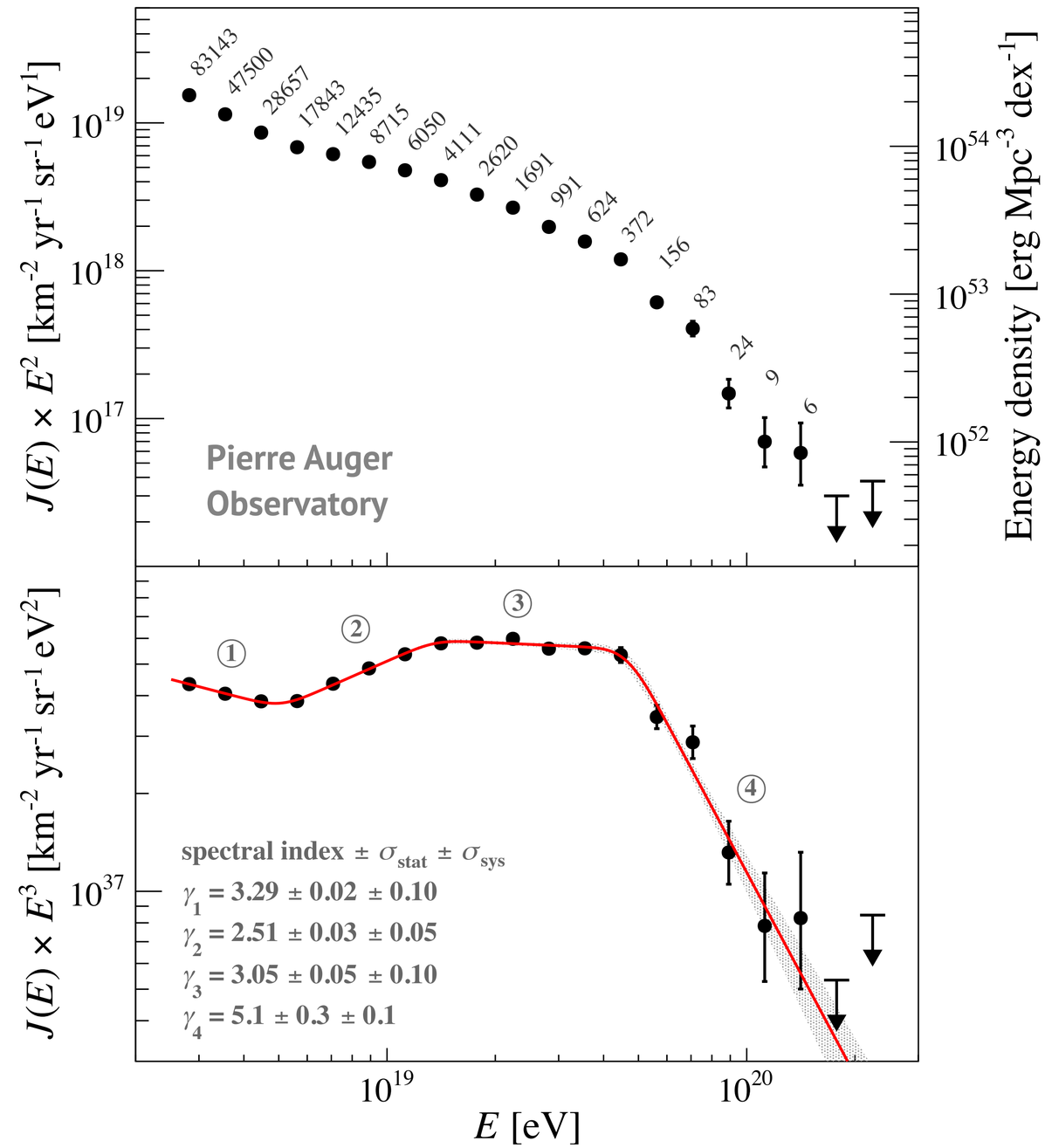
EeV CRs, **PeV neutrinos**, **TeV gamma rays**:
is there a **cosmogenic** connection?



UHECR measurements

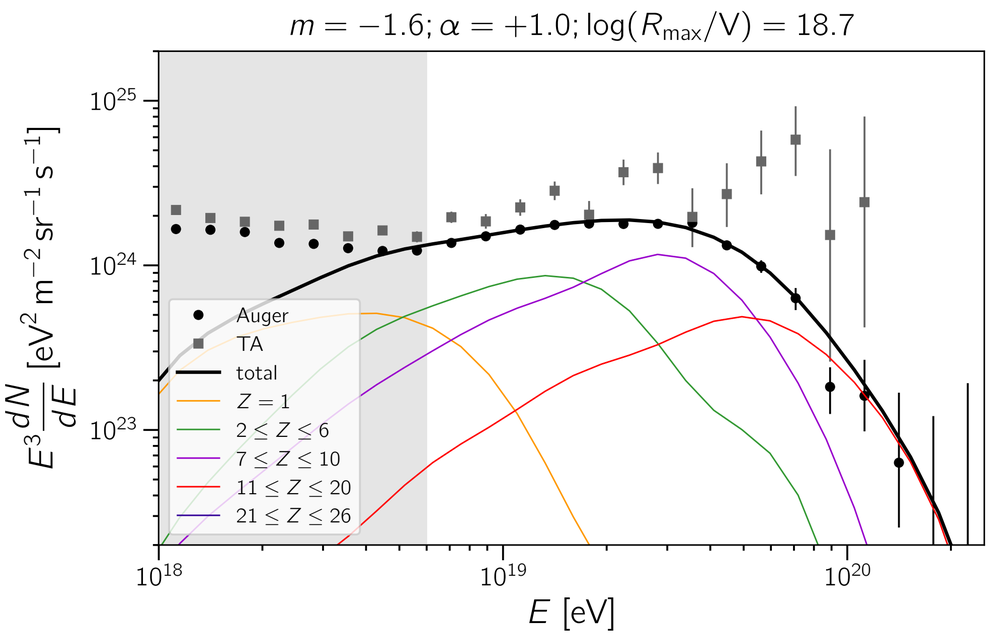
Pierre Auger Collaboration. Phys. Rev. Lett. 125 (2020) 121106. arXiv:2008.06488

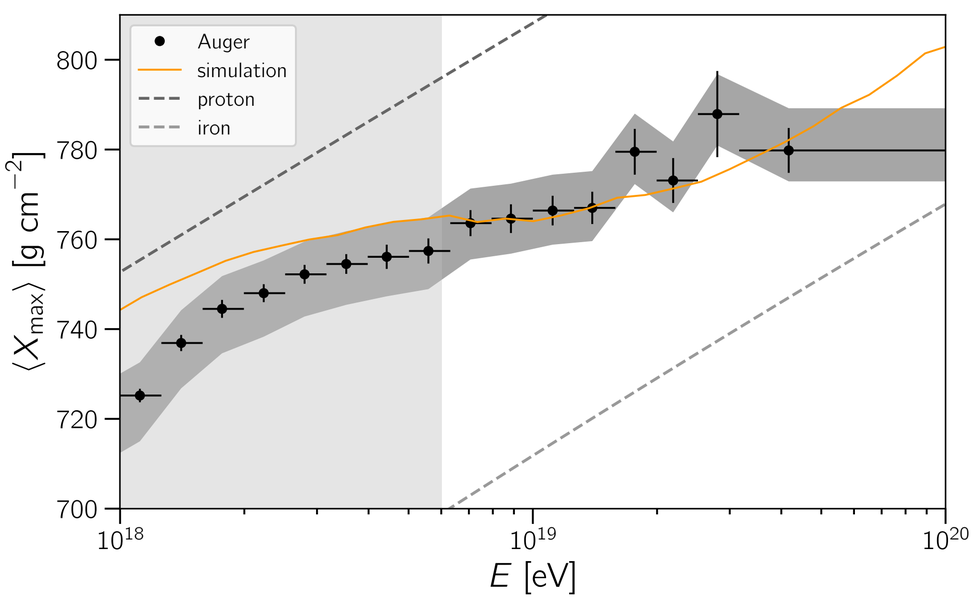


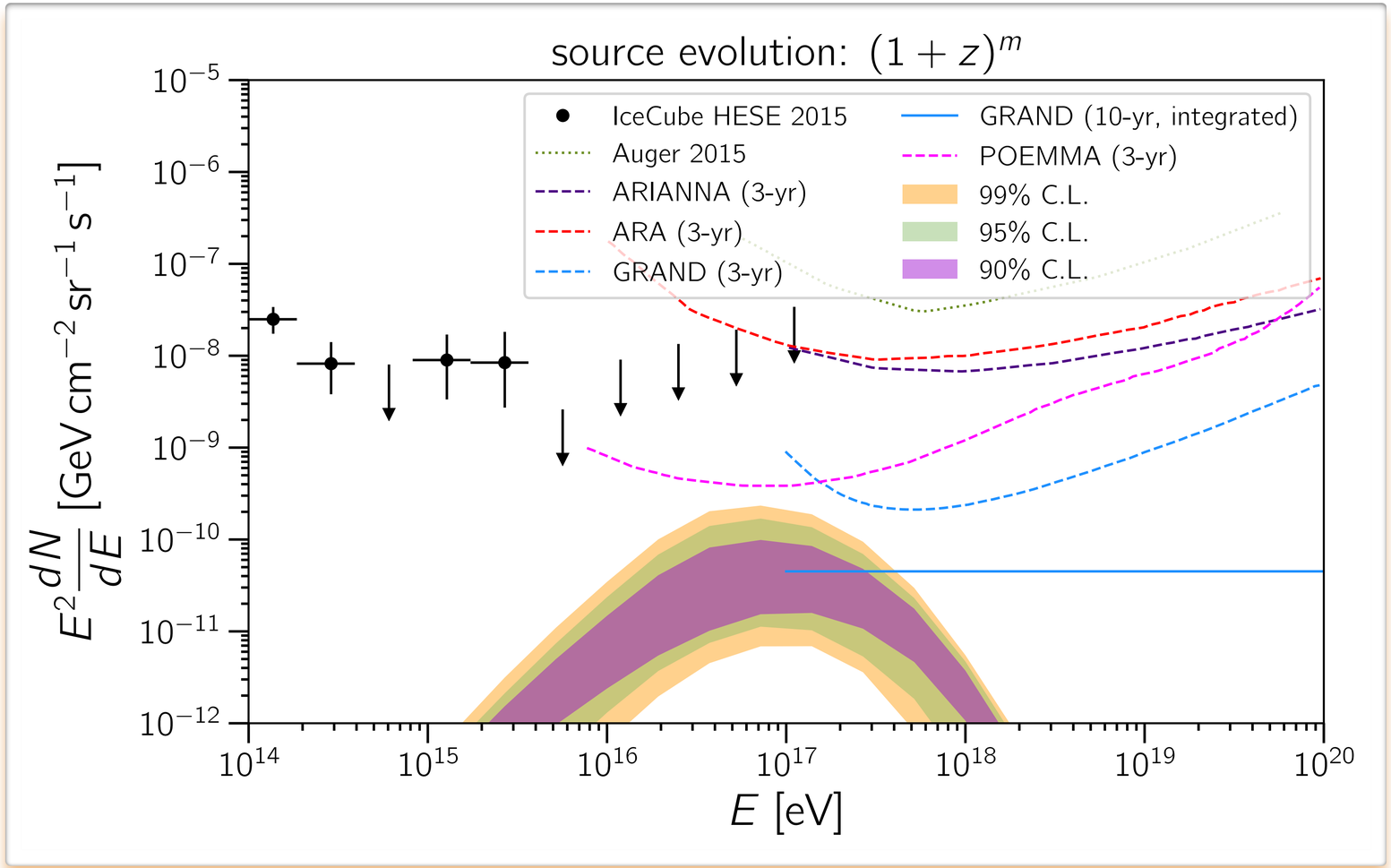


UHECR measurements: fit & cosmogenic neutrino predictions

Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

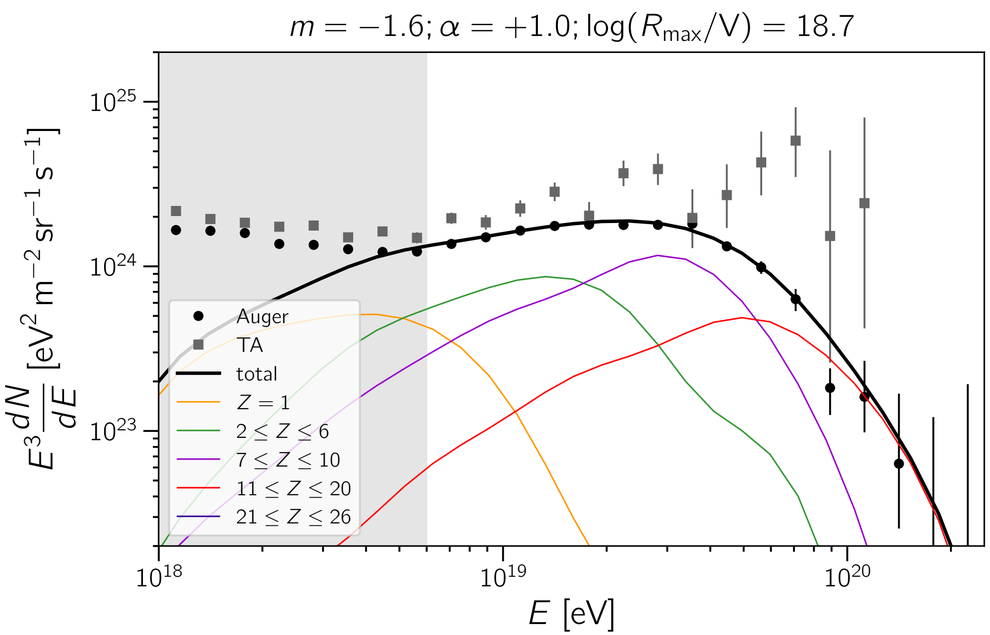


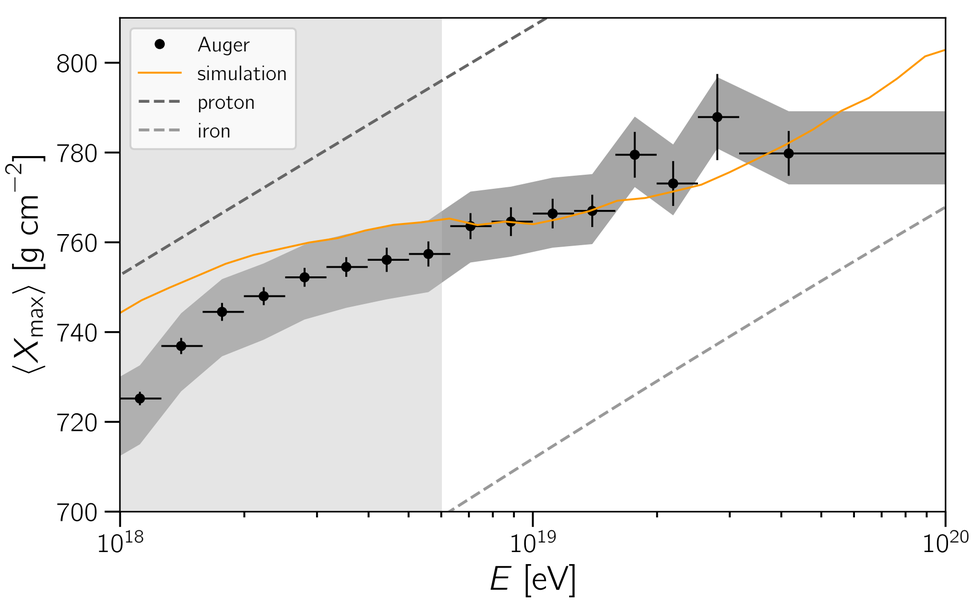


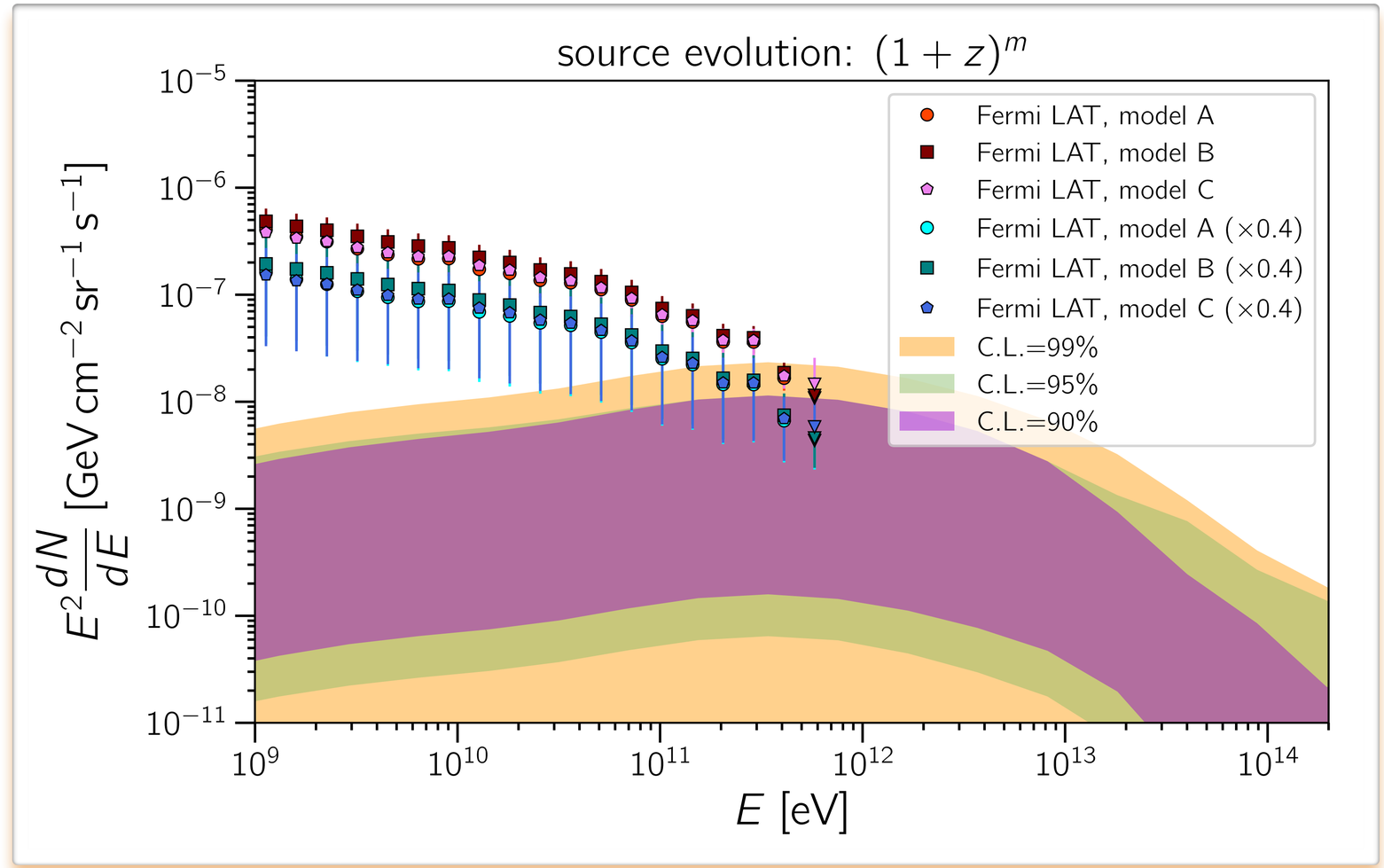


UHECR measurements: fit & cosmogenic photon predictions

Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879





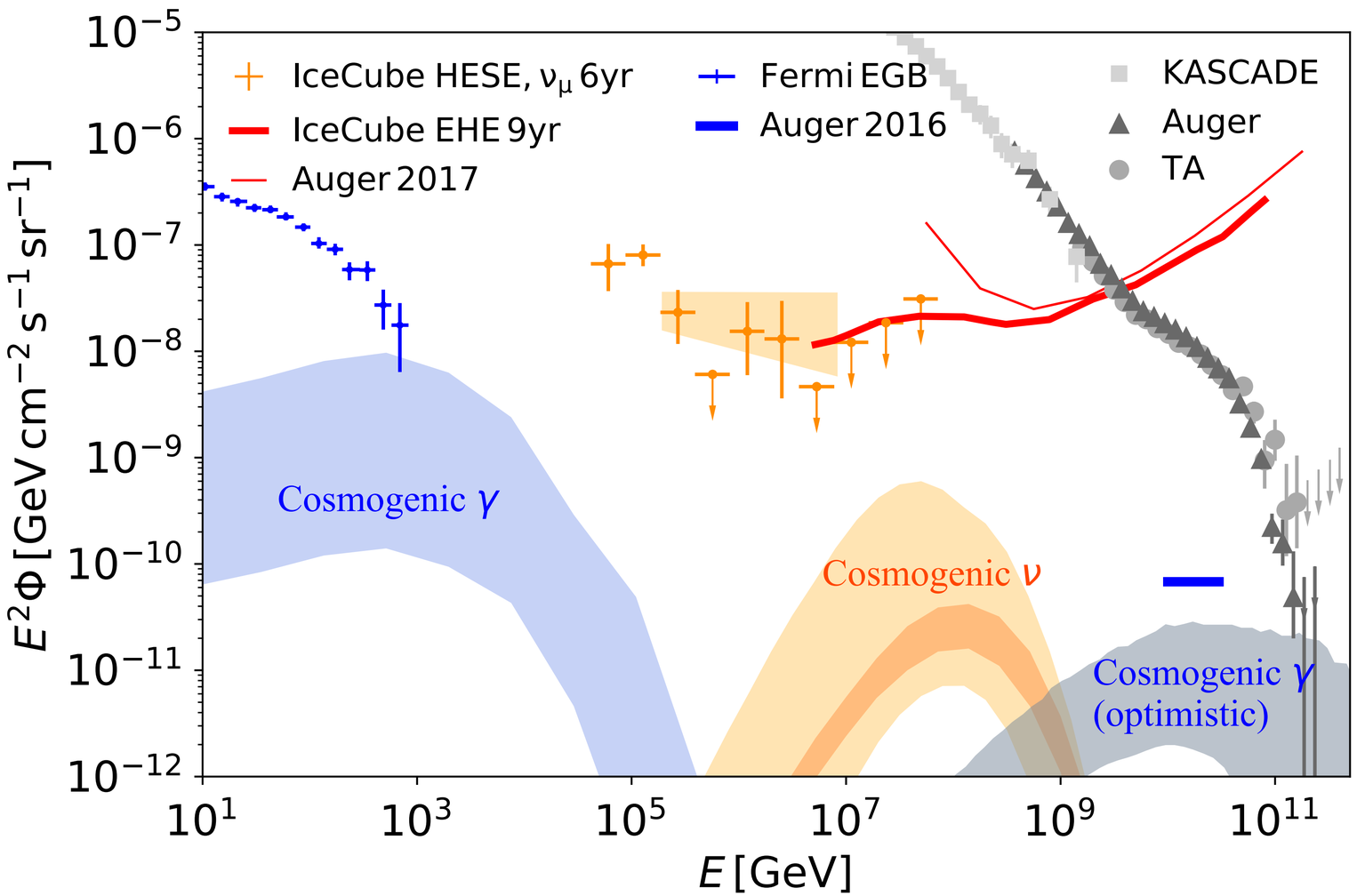


cosmic rays + photons + neutrinos: source connections

EeV CRs, **PeV neutrinos**, **TeV gamma rays**:

is there a **cosmogenic** connection? → **unclear**

is there a **source** connection? ←

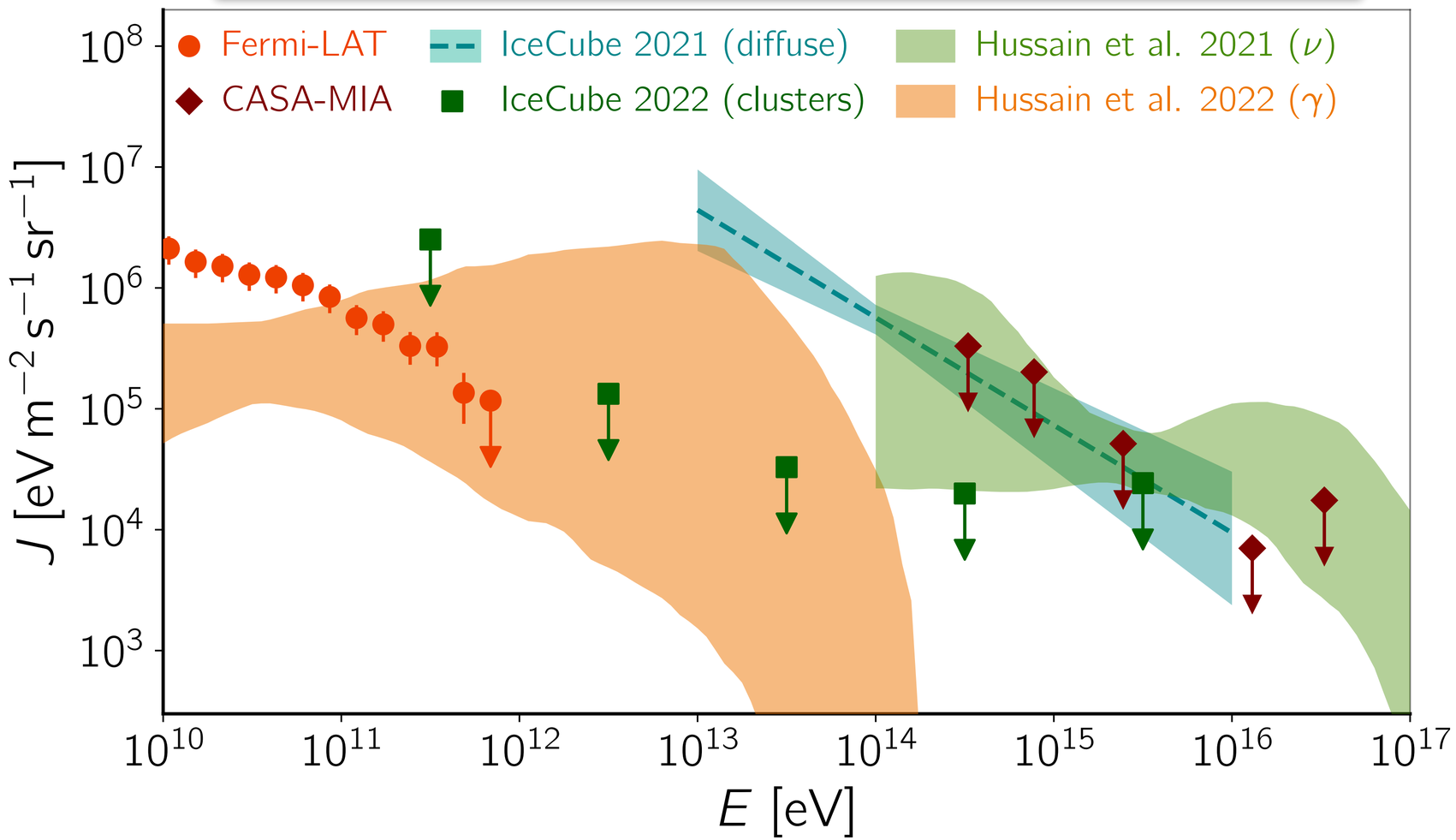


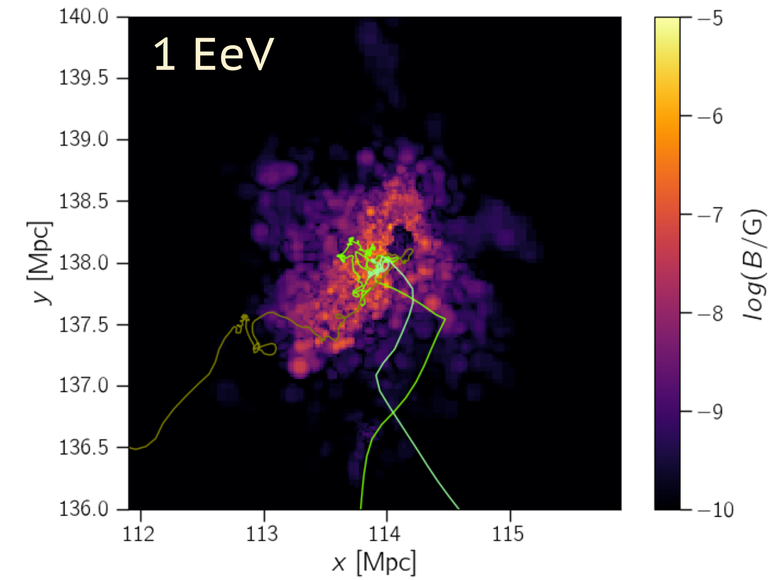
a multimessenger view of galaxy clusters

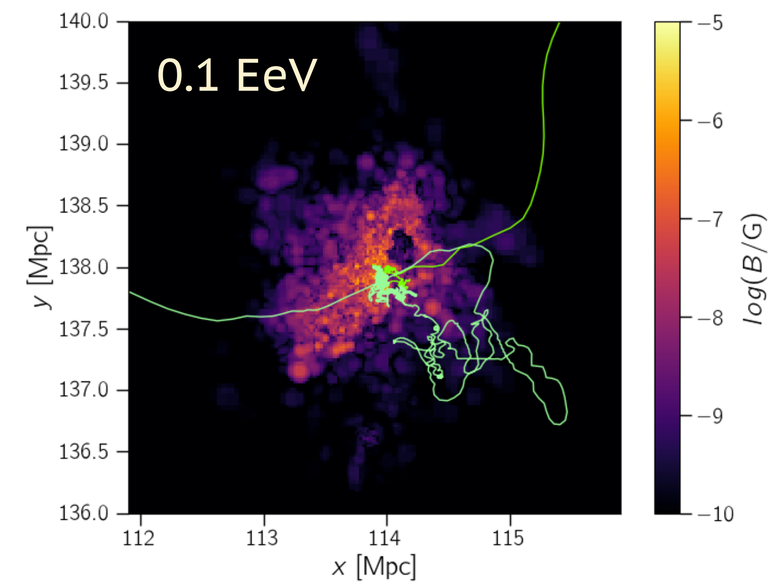
Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. To appear in Nature Comms. arXiv:2203.01260

contribution of clusters to diffuse gamma-ray and neutrino backgrounds may be sizeable



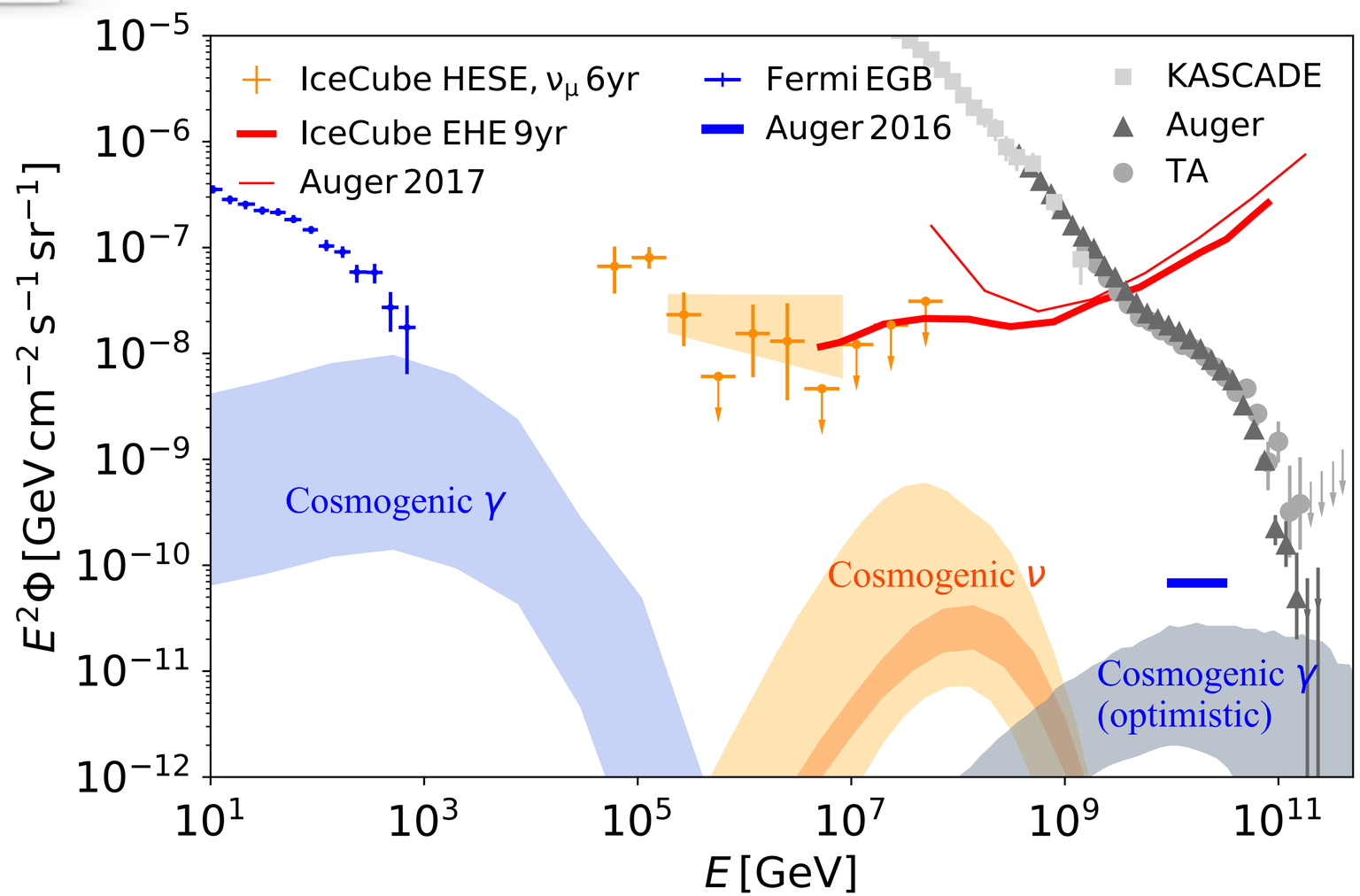




EeV CRs, **PeV neutrinos**, **TeV gamma rays**:

is there a **cosmogenic** connection? → **unclear**

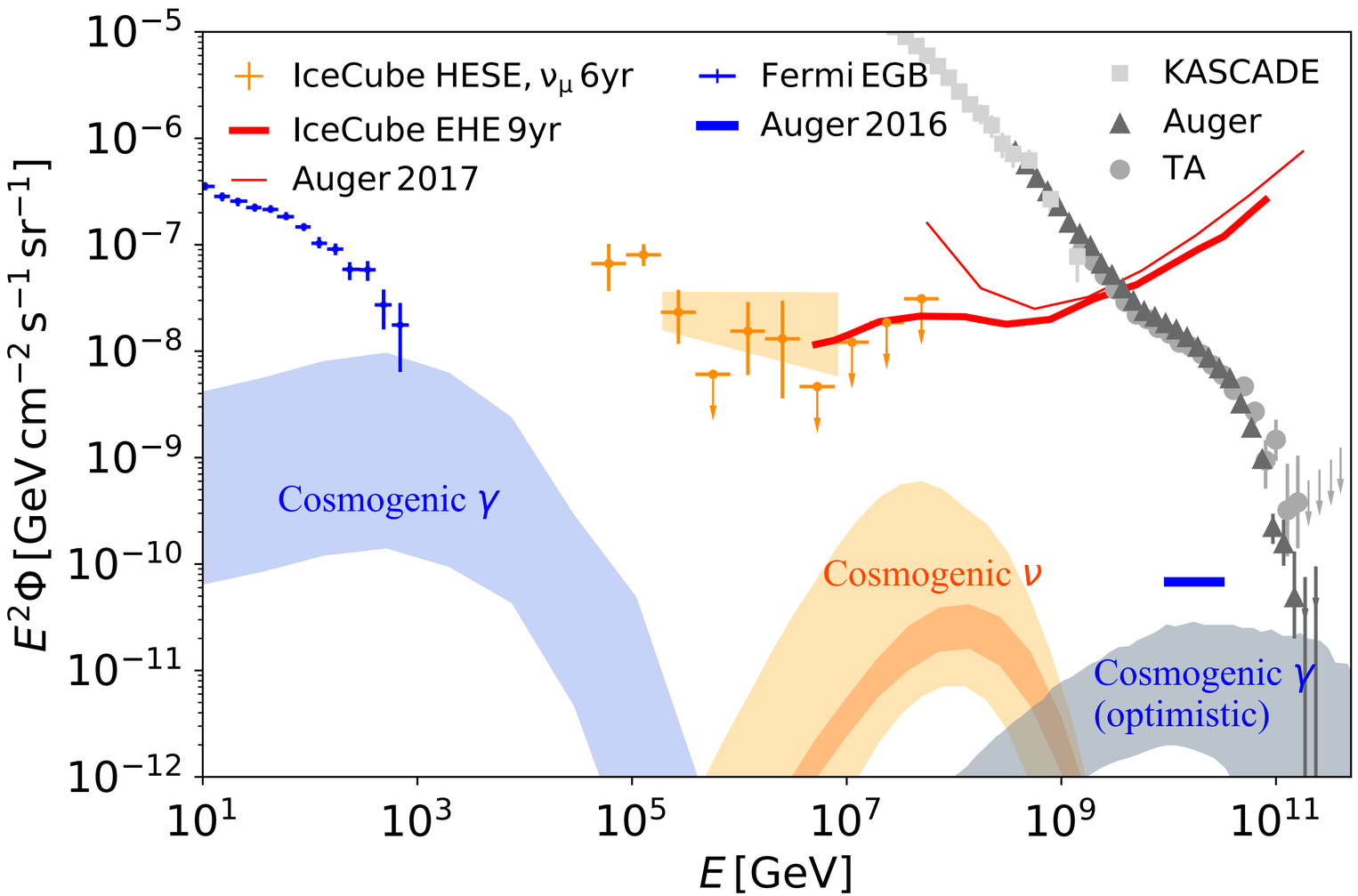
possibly ← is there a **source** connection? ←



EeV CRs, PeV neutrinos, TeV gamma rays:

source or **cosmogenic** origin?

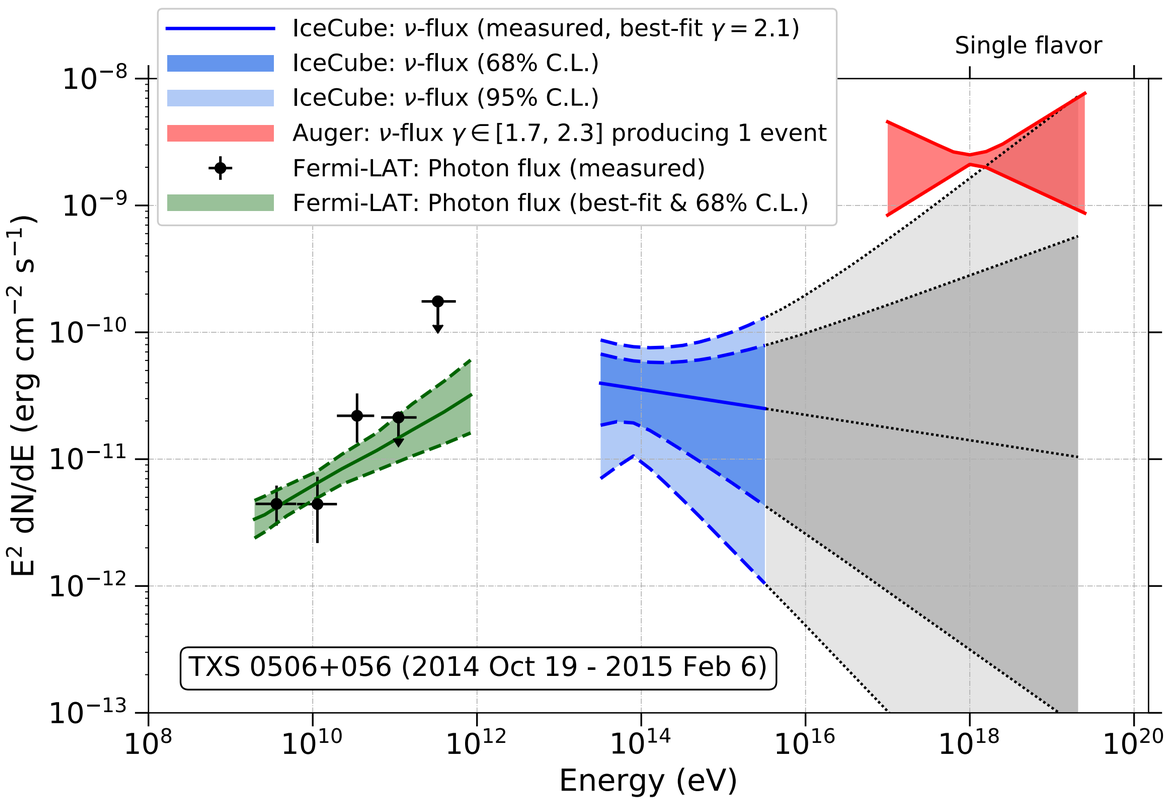
look at individual objects!

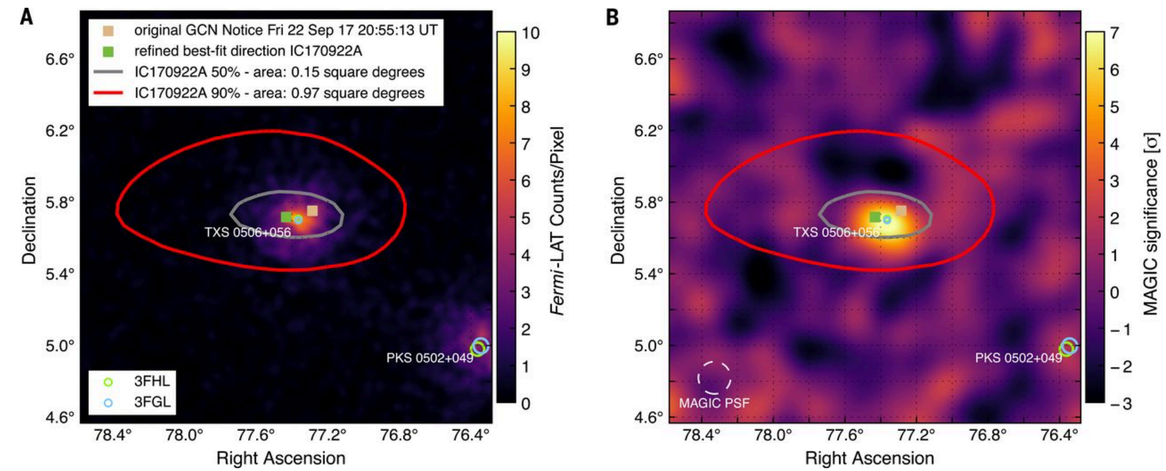


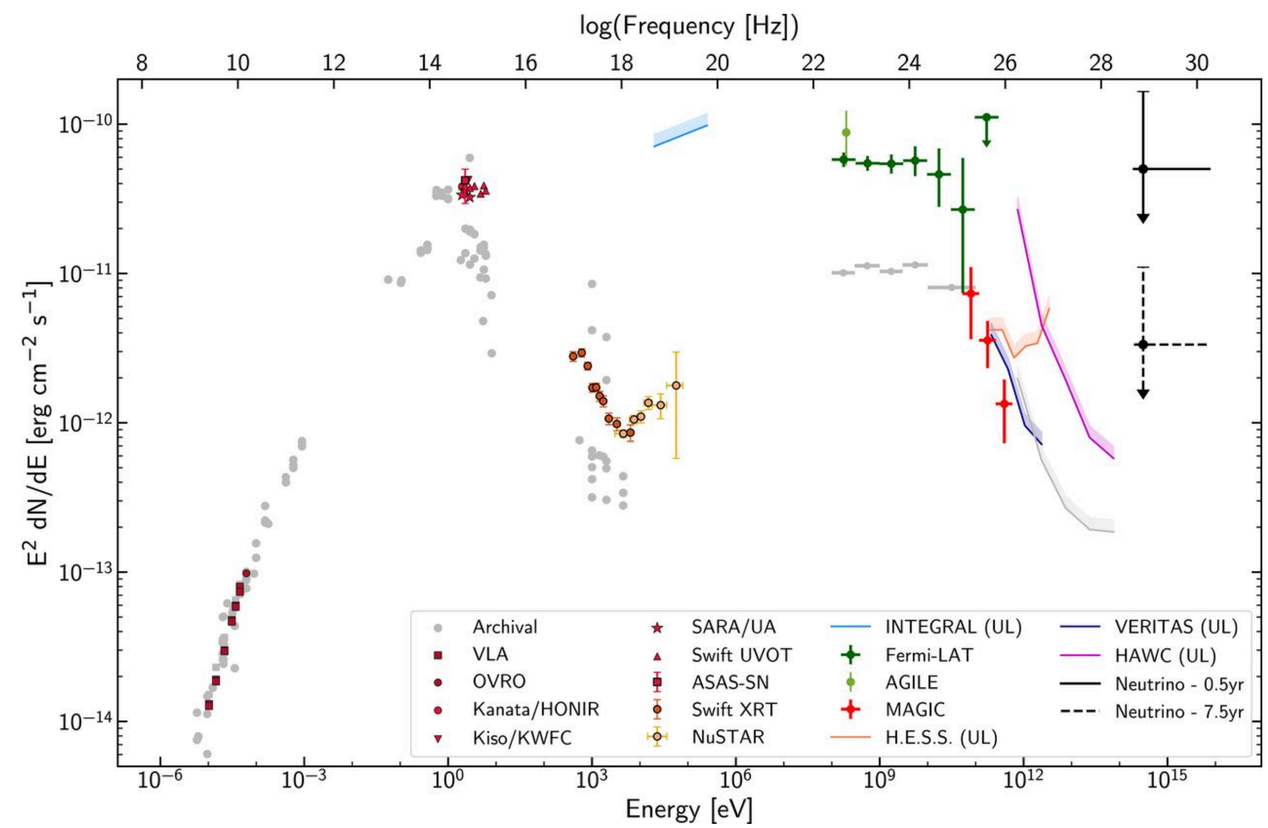
TXS 0506+056: UHE neutrinos

- TXS 0506+056: (possibly) first HE neutrino source to be identified
- observations: neutrino + electromagnetic
- **are there UHE neutrinos as well?**
  - no

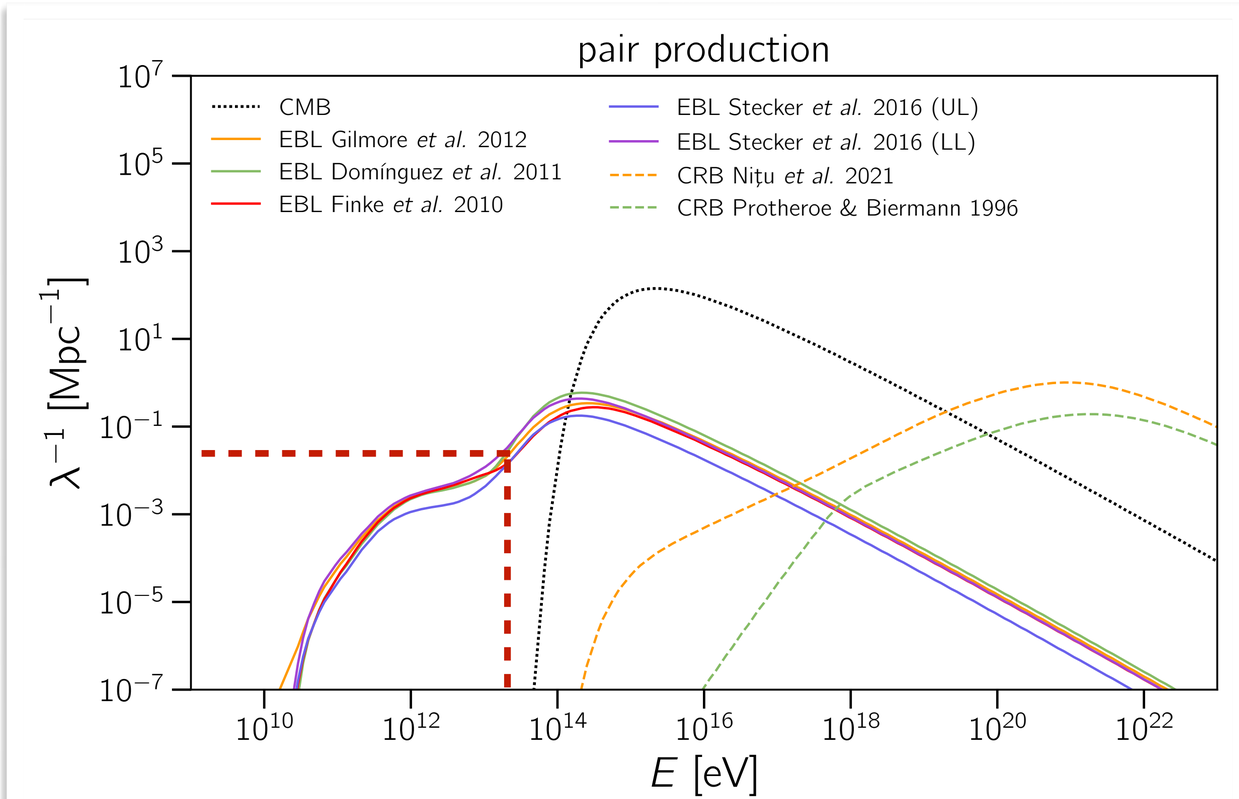
Pierre Auger Collaboration. ApJ 902 (2020) 105. arXiv:2010.10953



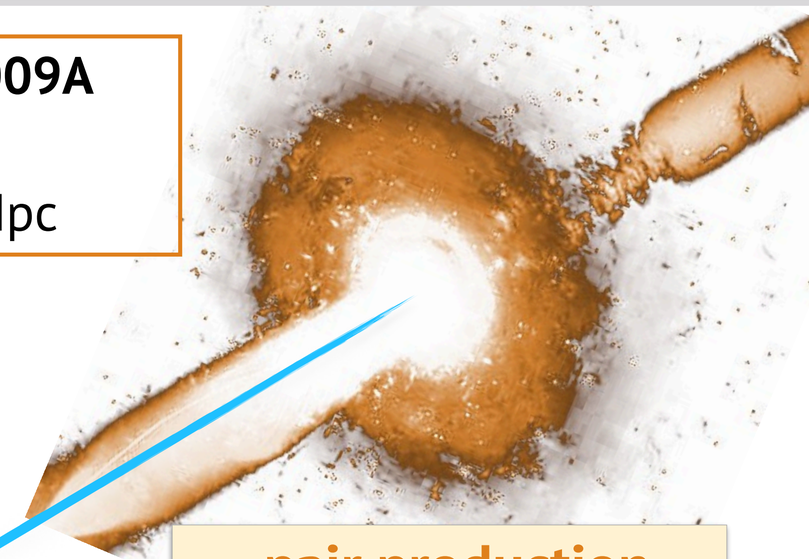




the brightest-ever gamma-ray burst: GRB 221009A



GRB 221009A
z ~ 0.151
D ~ 650 Mpc



pair production

$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$

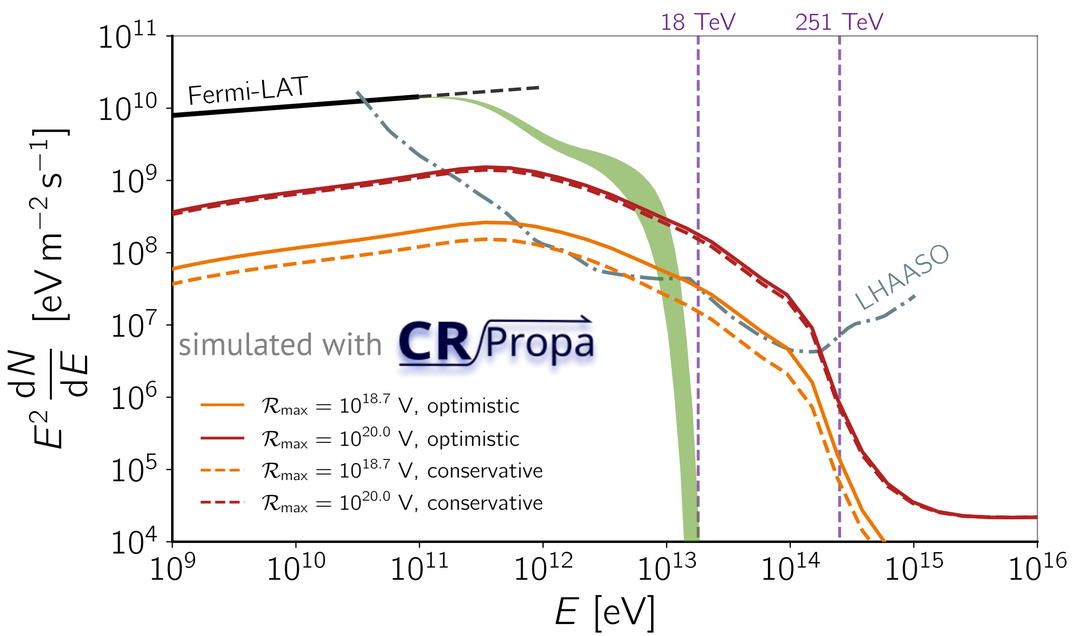
we expect very (very!) few gamma rays with E~18 TeV from this GRB

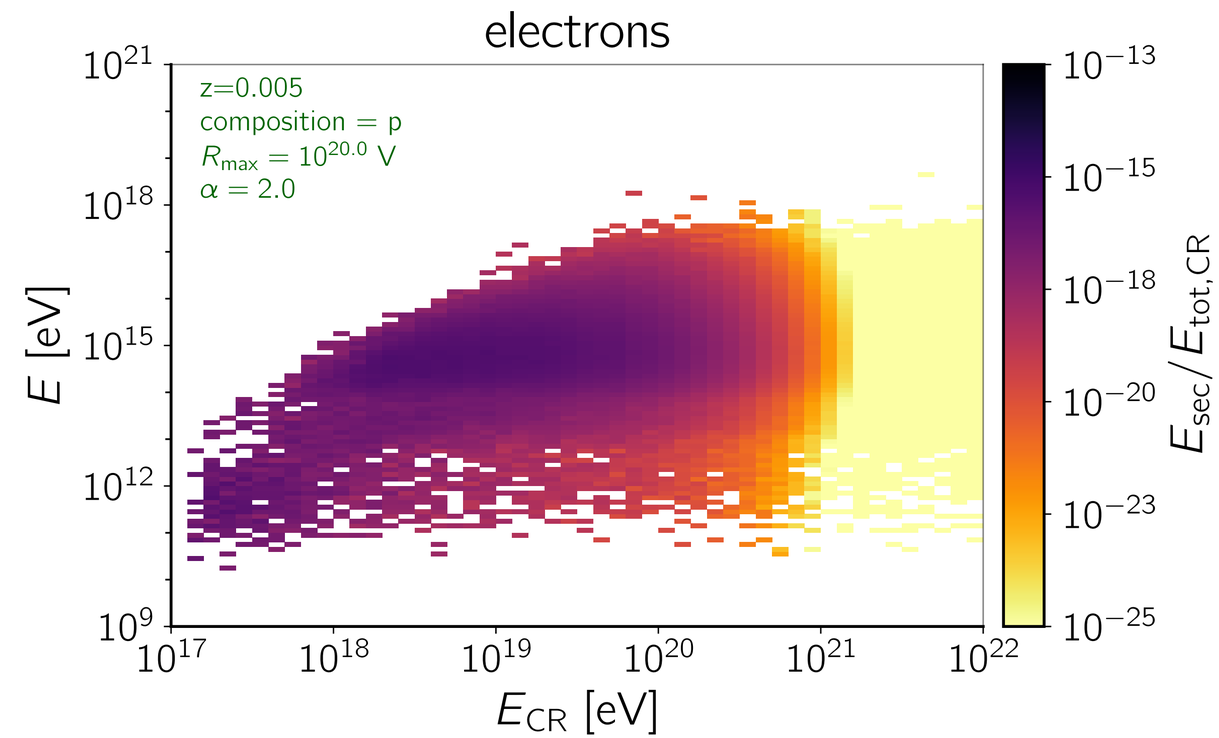
inverse Compton scattering

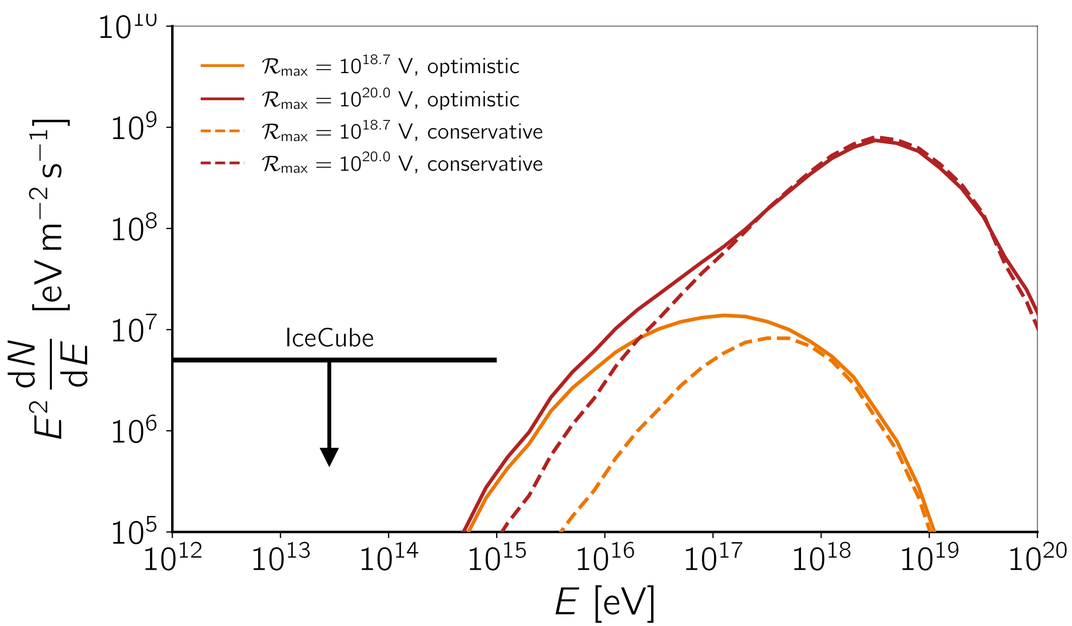
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$

the brightest-ever gamma-ray burst: GRB 221009A

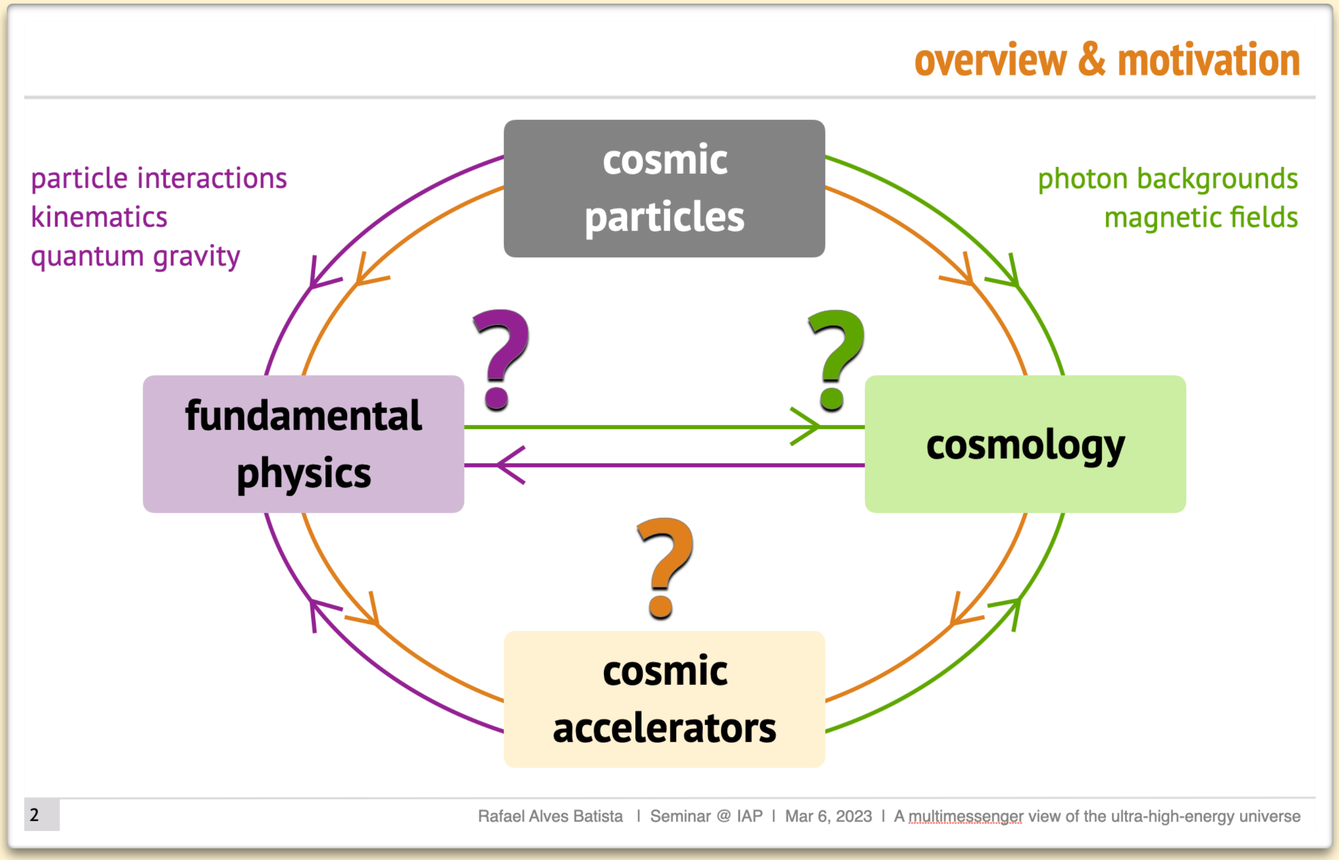
R. Alves Batista. arXiv:2210.12855





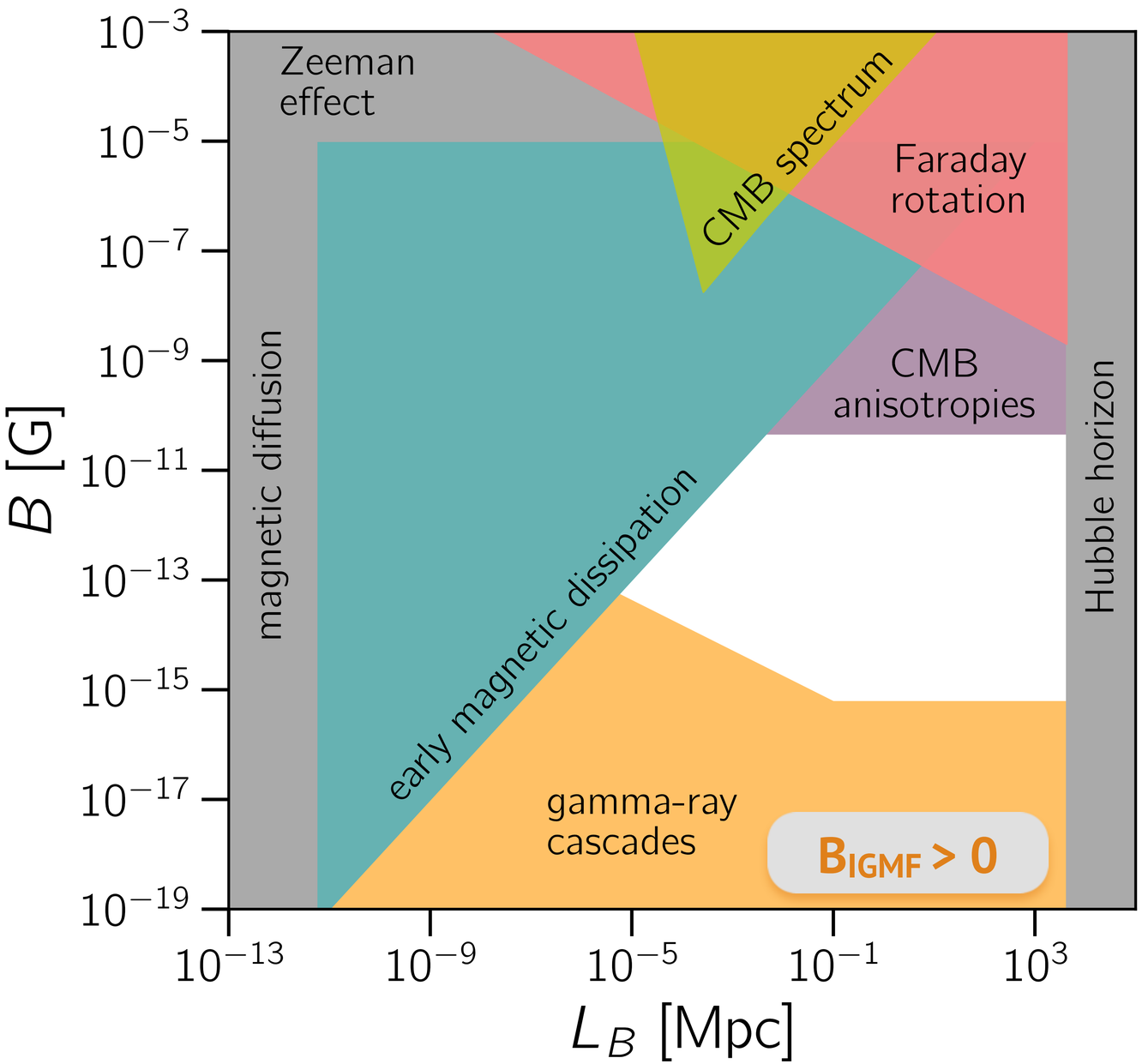


observations can be explained without exotic physics → (*mostly*) Bethe-Heitler pair production by UHECRs



fundamental physics and cosmology

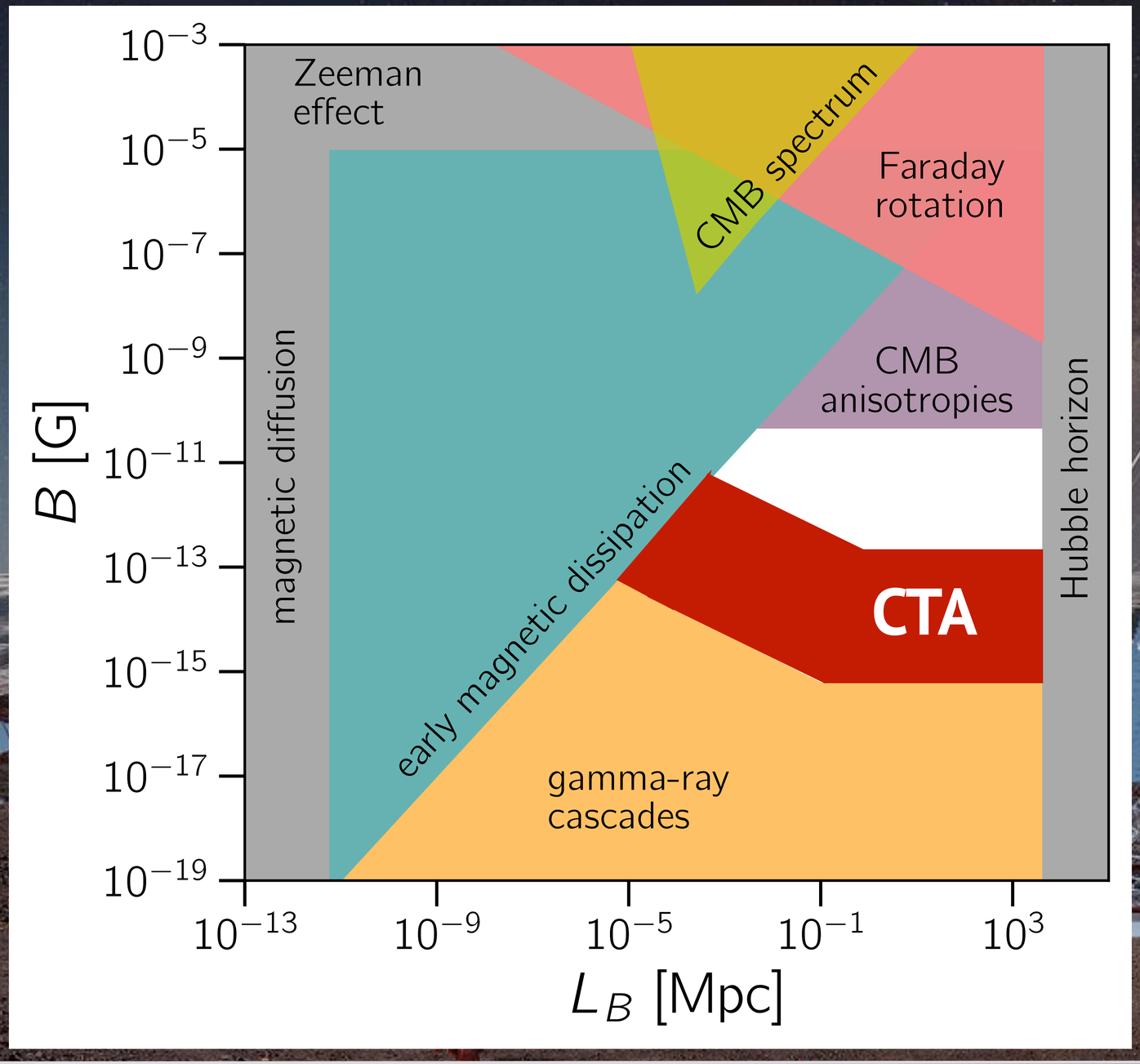
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

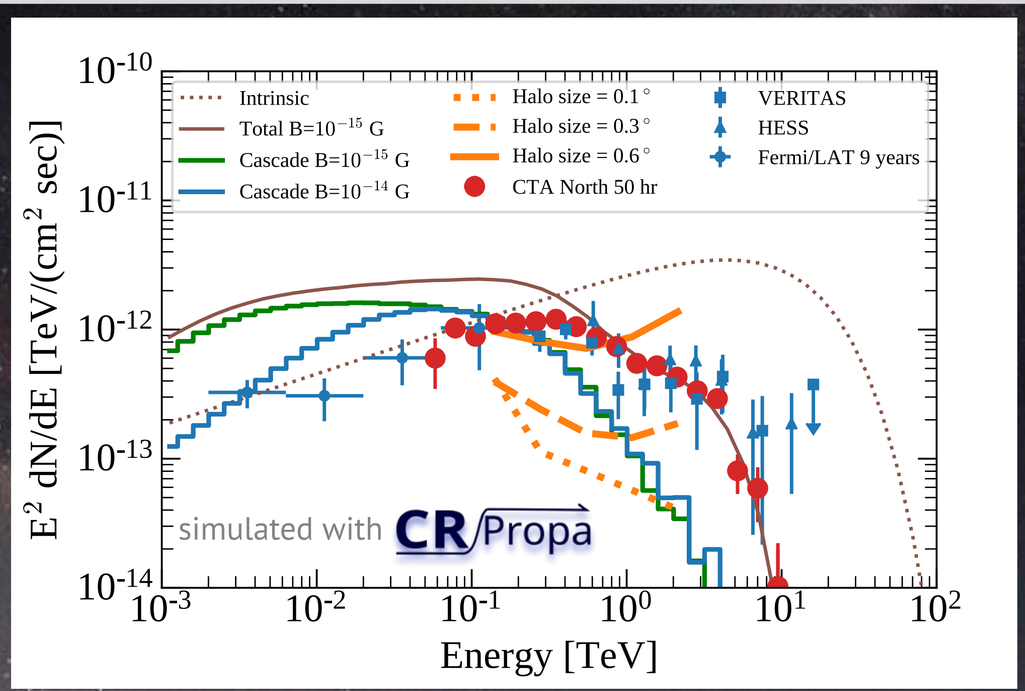


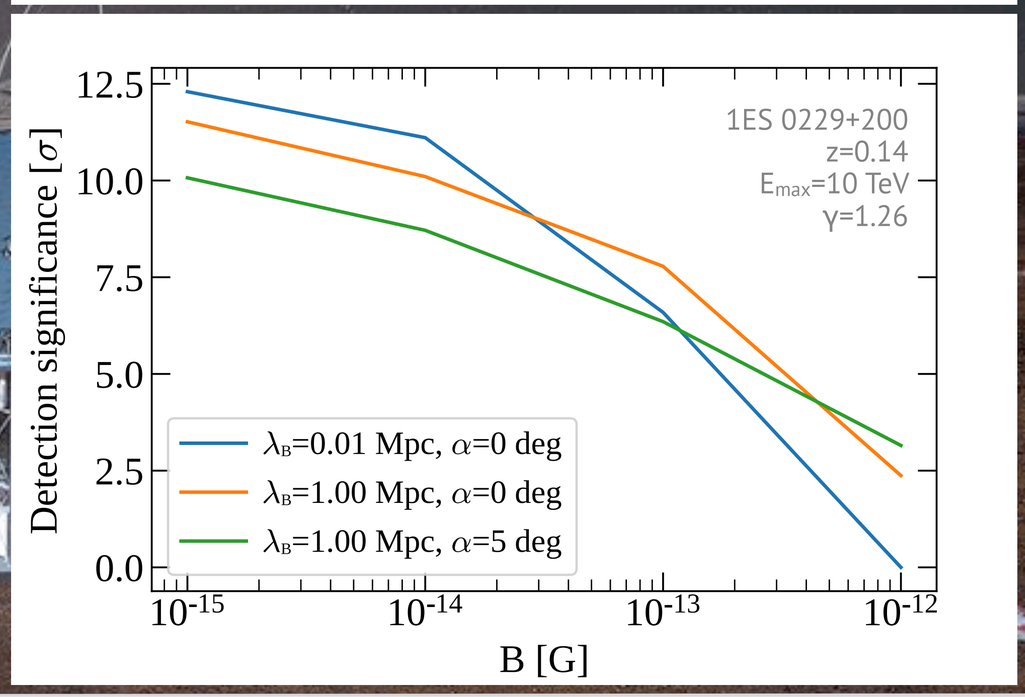
reduce uncertainties in magnetic fields → smaller angular/ temporal uncertainties in multimessenger studies

intergalactic magnetic fields with CTA

CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349







LIV: cosmic rays and photons

Pierre Auger Collaboration. JCAP 01 (2022) 023. arXiv:2112.06773

LIV $$E_a^2 = p^2\left[1+\sum_{n=1}^{\infty}\eta_{a,n}\left(\frac{E_a}{E_{QG}}\right)^n\right]$$

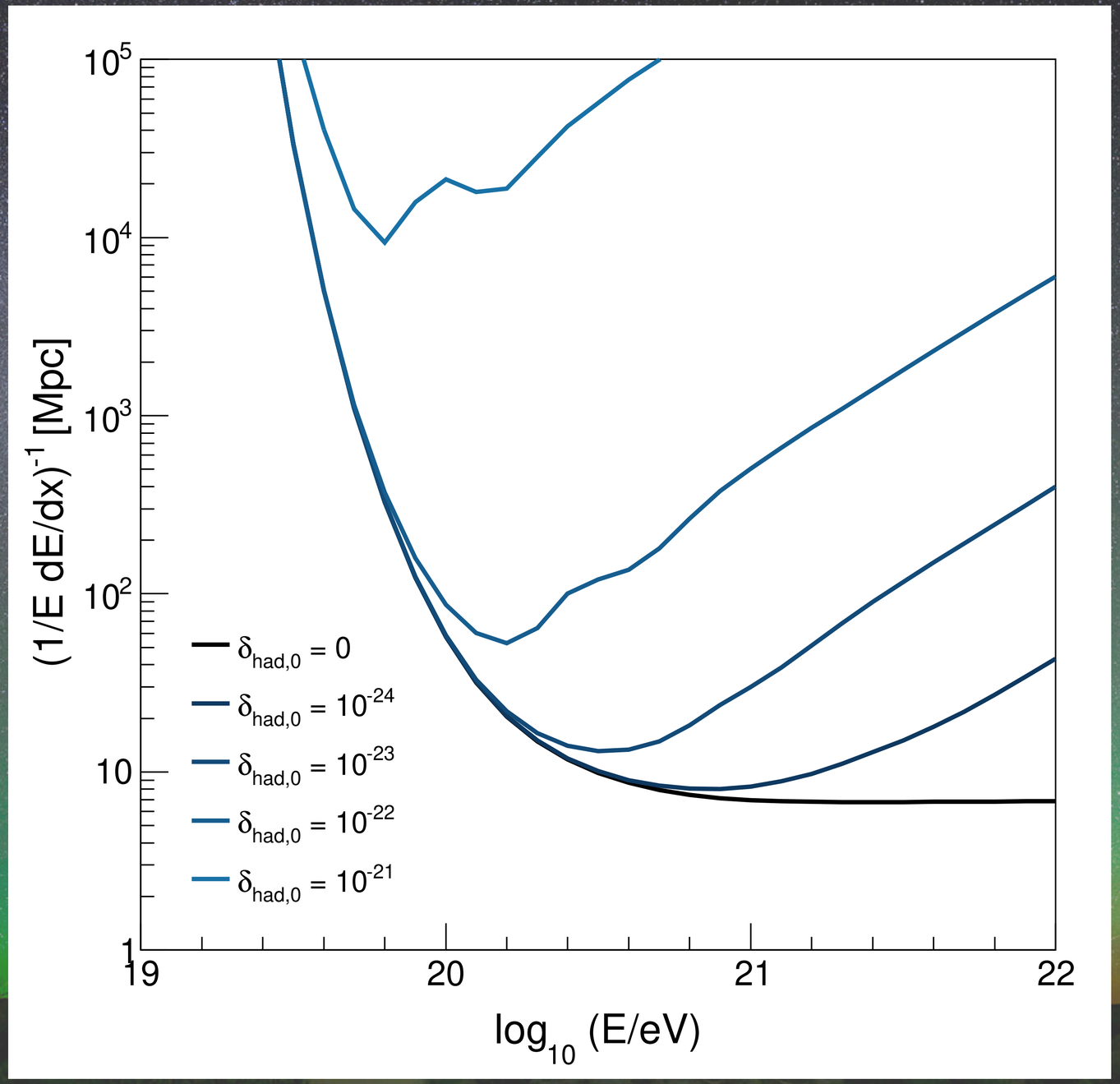
photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$ $\quad$ $\pi^0 \rightarrow \gamma + \gamma$

$p + \gamma_{bg} \rightarrow n + \pi^+$ $\quad$ $\pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

(similar for nuclei)



deformed relativistic kinematics

Lobo, Pfeiffer, Morais, Alves Batista, Bezerra. JHEP 09 (2022) 3. arXiv:2112.12172

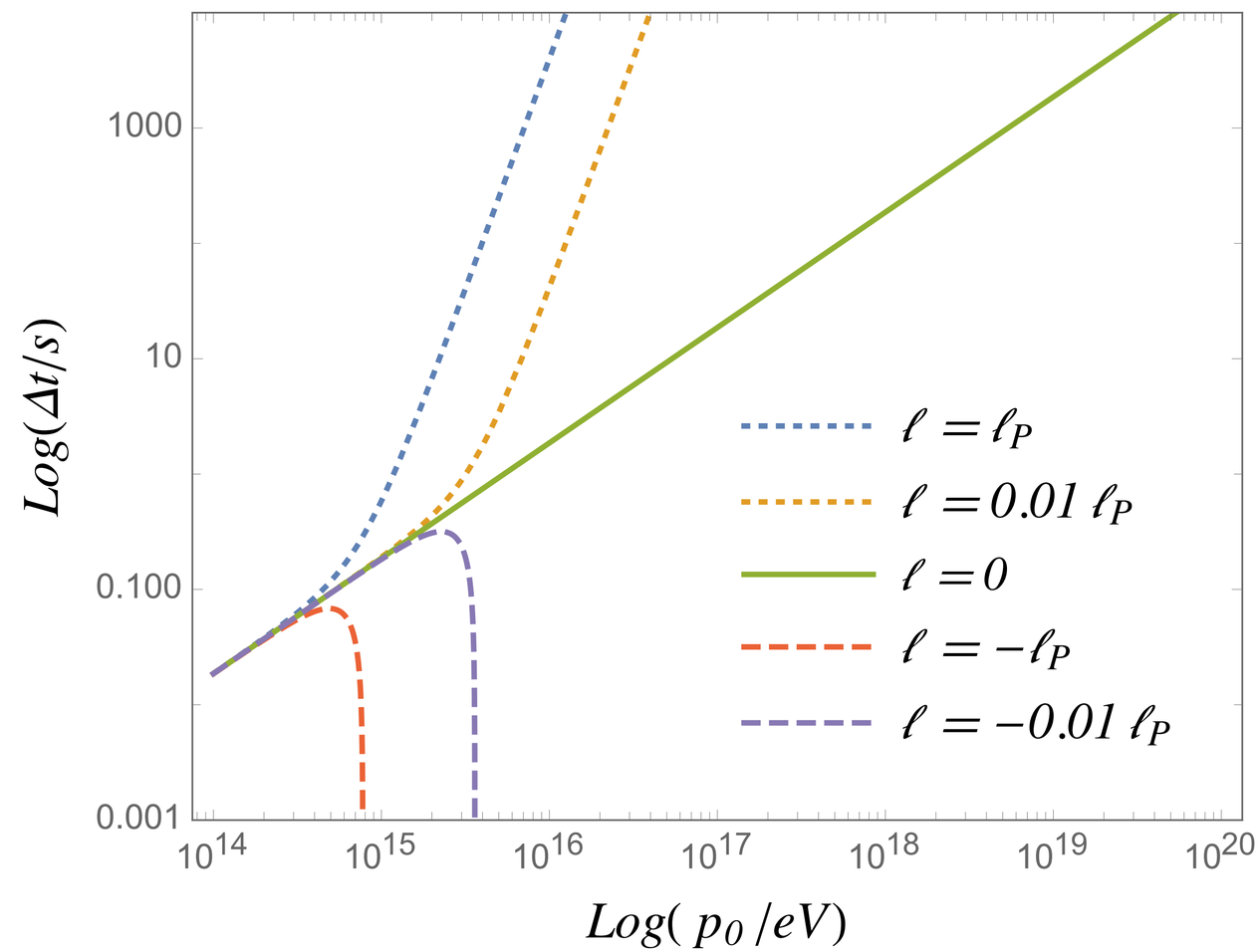
- start off with Finsler geometry
  - defines a causal structure
  - defines observers and their measurements
  - encodes gravity in its dynamics
- compute physical momentum
- lifetime of fundamental particles is modified

$$F(\dot{x}) = \sqrt{\eta(\dot{x},\dot{x})} - \frac{\ell m}{2}\frac{\dot{x}^0\delta_{ij}\dot{x}^i\dot{x}^j}{\eta(\dot{x},\dot{x})}$$

$$p_\mu = m\frac{\partial F}{\partial \dot{x}^\mu} \qquad p_0(v) = \gamma m - \frac{\ell m^2}{2}\left(\gamma^2-1\right)\left(2\gamma^2-1\right)$$

$$p_i(v) = -\gamma m v_i + \ell m^2 v_i \gamma^4$$

$$\tau = \tau_0 \frac{p_0}{m}\left[1 + \frac{\ell}{2}\left(\frac{m^2}{p_0} + \frac{p_0^3}{m^2} - 2p_0\right)\right] \equiv \tau_0 \gamma_{\rm DSR}$$



the future

timeline for UHE observatories

Coleman et al. Astropart. Phys. 149 (2023) 102829. arXiv:2205.05845

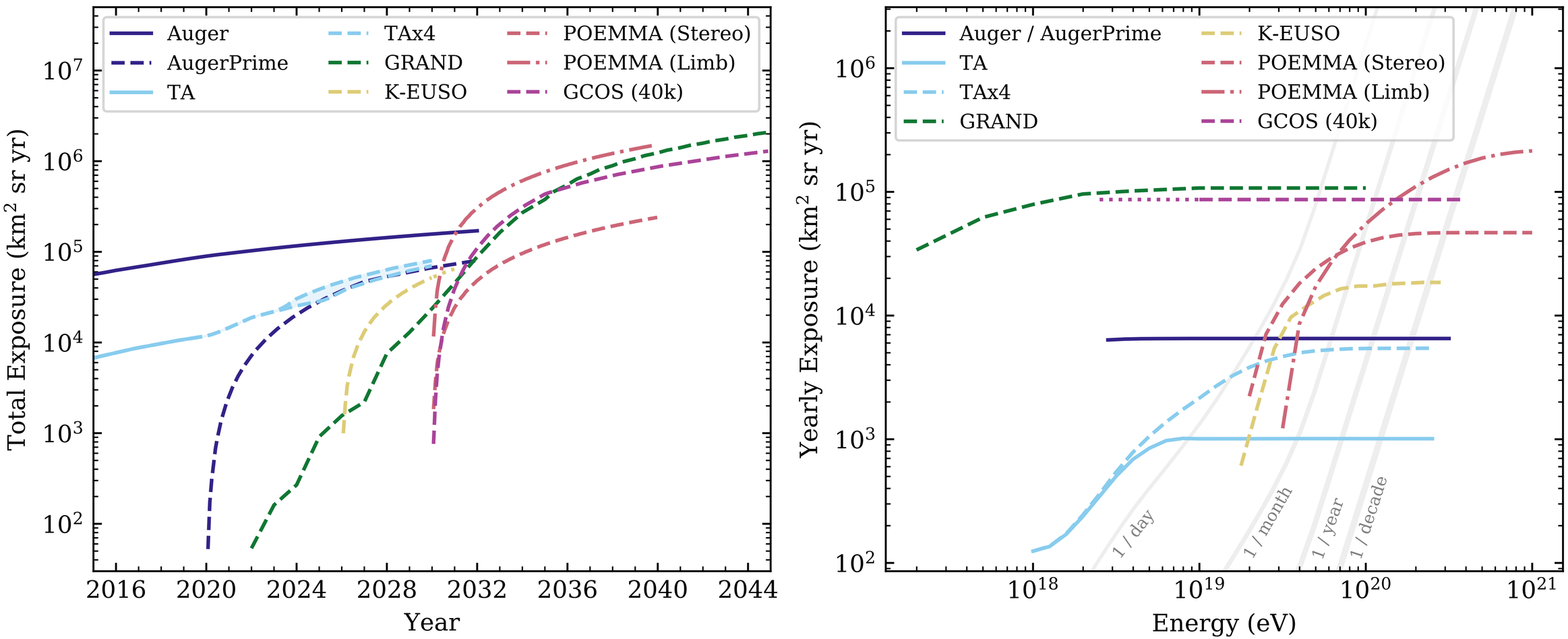
Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program; POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites

2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

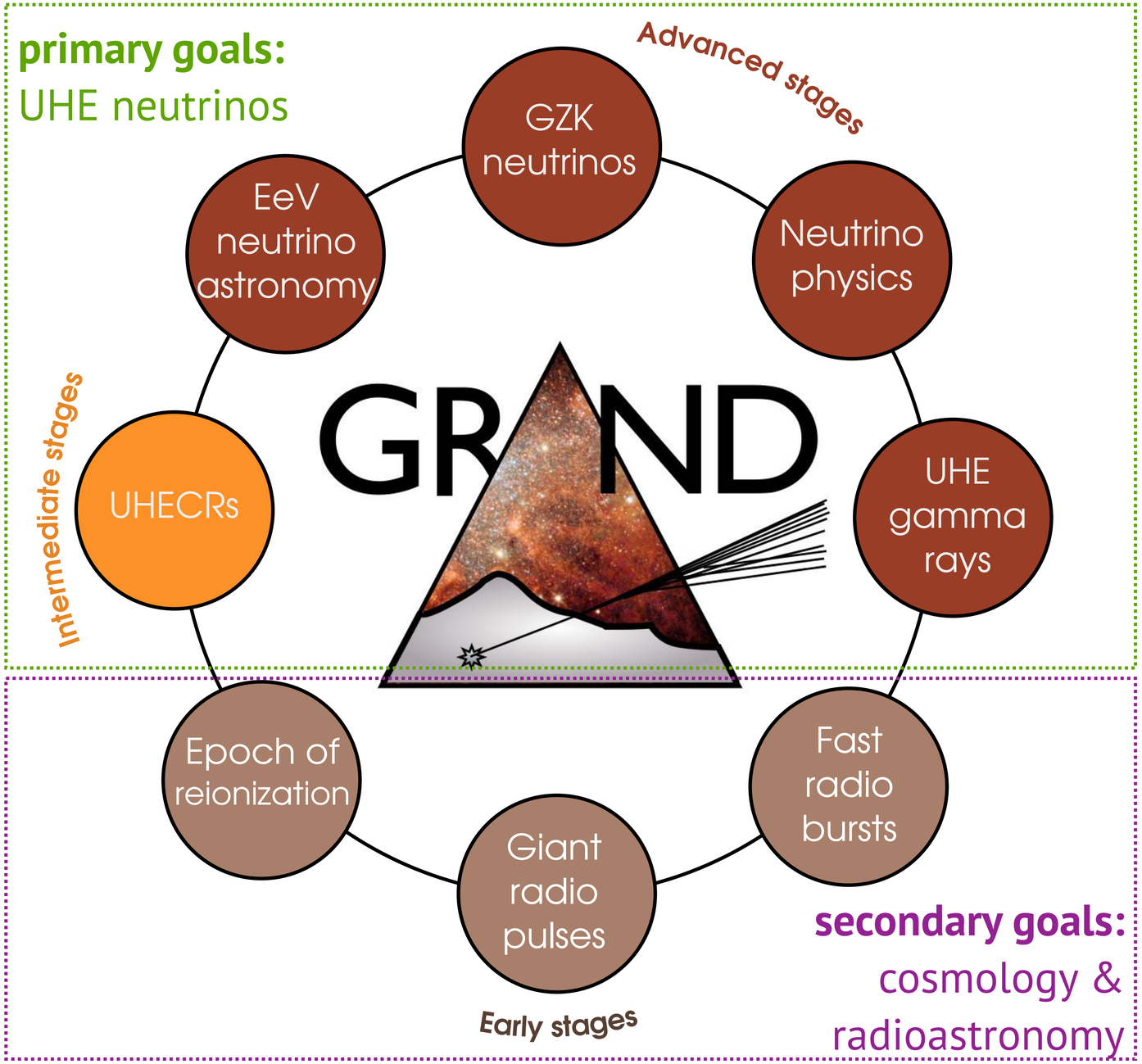
next-generation UHE observatories

Coleman et al. Astropart. Phys. 149 (2023) 102829. arXiv:2205.05845



GRAND: science case

GRAND Collaboration. Science China 63 (2020) 219501. arXiv:1810.09994



GRAND: timeline

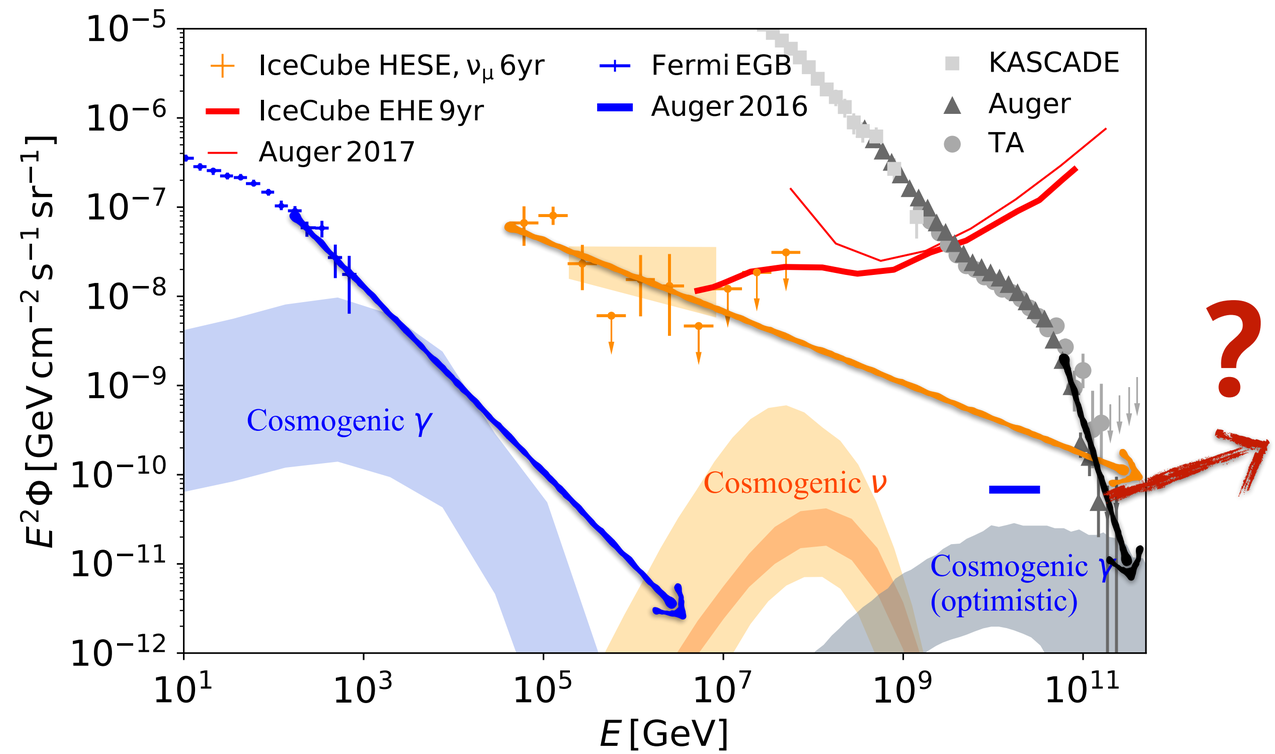
	Prototyping	GRAND10k	GRAND200k
	2022	2025	203X
Goals	**autonomous** radio detection of **very inclined** air-showers **cosmic rays $10^{16.5\text{-}18}$ eV** • Galactic/extragalactic transition • muon problem • radio transients	**1st GRAND sub-array** • **discovery of EeV neutrinos** for optimistic fluxes • radio transients (FRBs!)	sensitive **all-sky** detector **1st EeV neutrino detection and/or neutrino astronomy!**
Setup	• **GRAND@Nançay**: 4 antennas for trigger testing • **GRAND@Auger**: 10 antennas for cross-calibration • **GRANDProto300**: 300 HorizonAntennas over 200 km²	• 10,000 radio antennas over 10,000 km²	• 200,000 antennas over 200,000 km² • 20 sub-arrays of 10k antennas • on different continents
Budget	**2 M€** 100 antennas produced funded by China + ANR PRCI NUTRIG (France) + Radboud University	**13 M€** 1500€/unit	**300M€** in total 500€/unit to be divided between participating countries

GRAND: deployment of prototypes (GP13)

outlook & summary

a summary

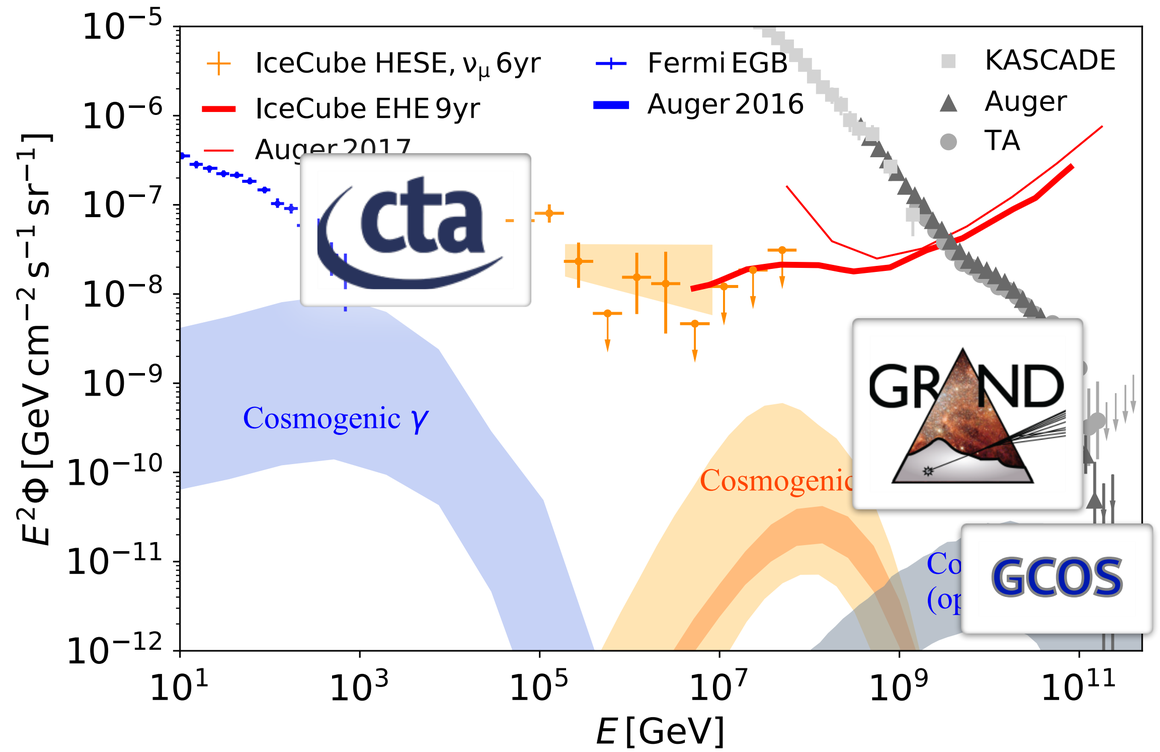
- unknown sources: **EeV UHECRs**, **PeV neutrinos**, **TeV gamma rays** (*part of it*)
  - hypothesis: common origin (cosmogenic or sources)
  - cosmogenic vs. source origin unclear
- **cosmogenic** neutrinos and photons remain undetected
  - could be a background when searching for sources
- how far up in energy (beyond measurements) do the fluxes extend?
  - why is there a cut-off in the UHECR spectrum? GZK effect or maximal acceleration by sources?



- UHE messengers as **cosmological probes**
- UHE messengers as **probes of fundamental physics**

towards a unified ultra-high-energy paradigm

- **theoretical challenges**
  - *self-consistent* modelling of all messengers
  - scan *full parameter* space of uncertainties
  - computational improvements → microscopic transport of particles over cosmological distances
- **external input** needed to move forward
  - knowledge of magnetic fields
  - cosmological photon fields
- **experimental challenges**
  - to be tackled by next-generation observatories



and many other experiments!

thank you

"la Caixa" Foundation

MARIE CURIE ACTIONS

European Commission