Neutral Particles And Multi-Messengers

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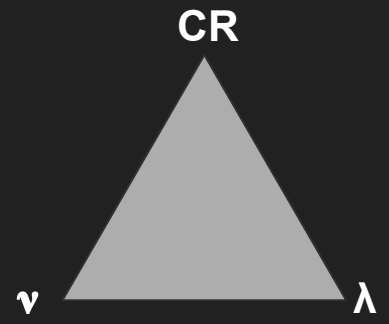
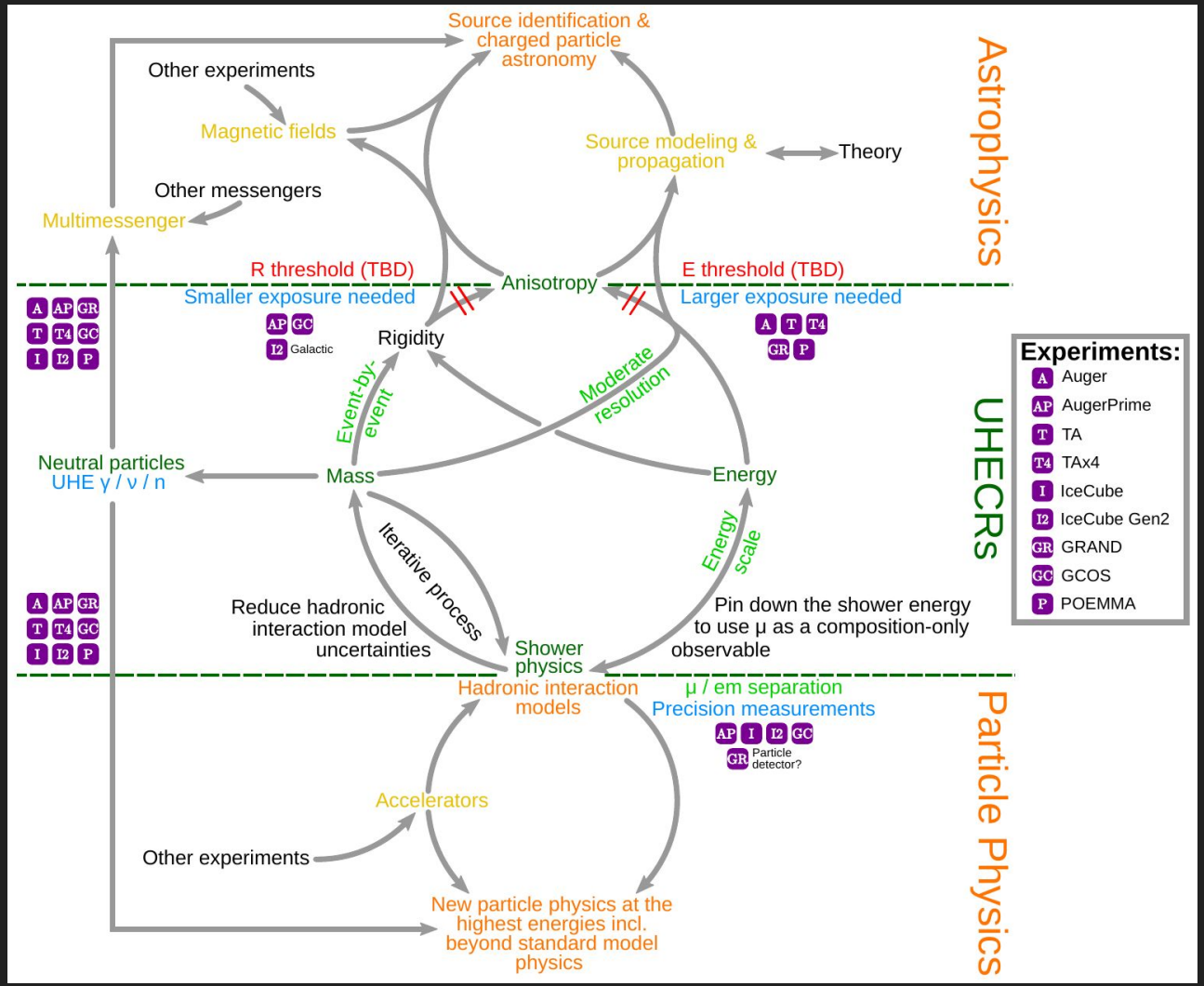



Source identification & charged particle astronomy
Other experiments
Magnetic fields
Source modeling & propagation
Theory
Other messengers
Multimessenger
Astrophysics
R threshold (TBD)
Smaller exposure needed
Anisotropy
E threshold (TBD)
Larger exposure needed
Galactic
Rigidity
Event-by-event
Moderate resolution
Neutral particles
UHE γ / ν / n
Mass
Energy
UHECRs
Iterative process
Energy scale
Reduce hadronic interaction model uncertainties
Pin down the shower energy to use μ as a composition-only observable
Shower physics
Hadronic interaction models
μ / em separation
Precision measurements
Particle detector?
Accelerators
Other experiments
New particle physics at the highest energies incl. beyond standard model physics
Particle Physics
Experiments:
Auger
AugerPrime
TA
TAx4
IceCube
IceCube Gen2
GRAND
GCOS
POEMMA

Relevance of UHECR for Multi Messenger

- Strong link between UHECR, neutrinos and photons
  - Sources of UHECR likely to produce neutrinos and photons too ==> **Astrophysical**
    - Angular correlations may be seen (but no time correlations with UHECR)
- UHECR interactions with low E photon backgrounds (such as CMB) must produce UHE neutrinos and photons ==> **Cosmological**
  - Combined UHE CR, photon and neutrino (MM) observations contribute to decipher the origin and nature of UHECRs
- Photon, neutrino (and neutron) Astronomy can in principle be done with UHECR observatories
  - Contribute to searches and follow up of MM observations in photons and neutrinos (angular and time correlations)

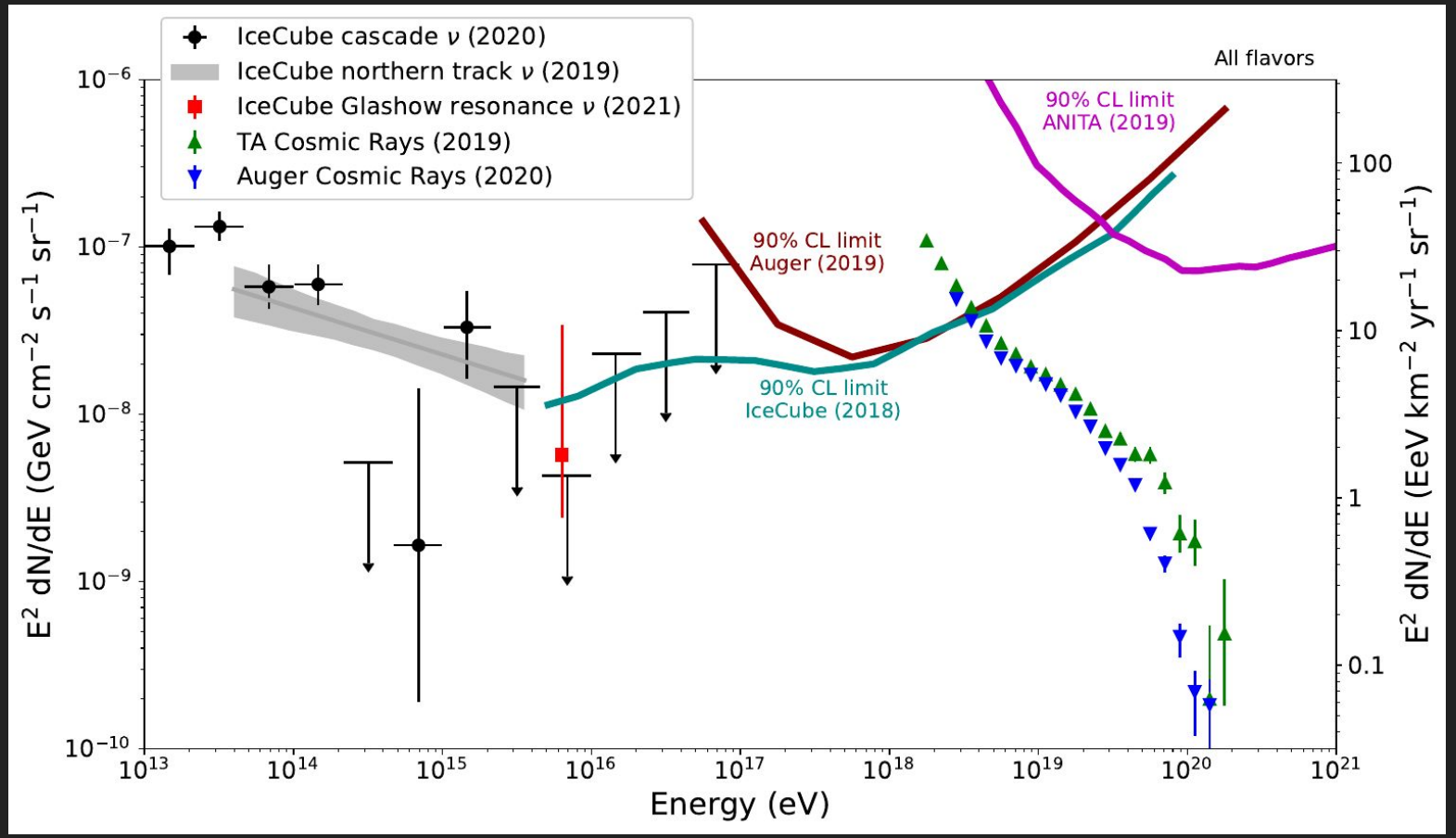
Current status of Multi-Messenger

- Can UHECR be used as messengers?
  - Do not point straight back due to magnetic fields and are not expected in temporal coincidence with neutral particles or gravitational waves
  - Deflection at highest energies (100 EeV) unknown but expected of a few degrees and increasing as E goes down
  - On the other hand, UHECR properties (energy spectrum, mass composition or anisotropies) provide information needed to understand the origin UHECR, high energy photons, neutrinos, and neutrons
- But (fortunately) UHECR observatories are also observatories of UHE neutrinos, photons and neutrons

UHE neutrinos

- Good tracers to point back to UHECR sources
  - Can be observed significantly further away than UHECR
    - 200Mpc vs 4Gpc (<10Mpc for UHE photons)
  - Only messenger that can tell about the cosmological evolution of UHECR sources past a certain redshift
- Observing/identifying neutrinos based on first interaction depth
  - For tau neutrinos observing upward going showers
- Most stringent limits to the neutrino flux at UHE from the neutron star coalescence (2017) was made by Auger
- Flux of astrophysical neutrinos discovered by IceCube
- **Connection** between astrophysical **neutrino flux and the UHECR flux and to the diffuse gamma-ray** background from unresolved extragalactic sources is **unanswered**
- No significant correlations in arrival direction were found from 7-years of neutrino and 11-years of UHECR data (expected due to mixed composition)

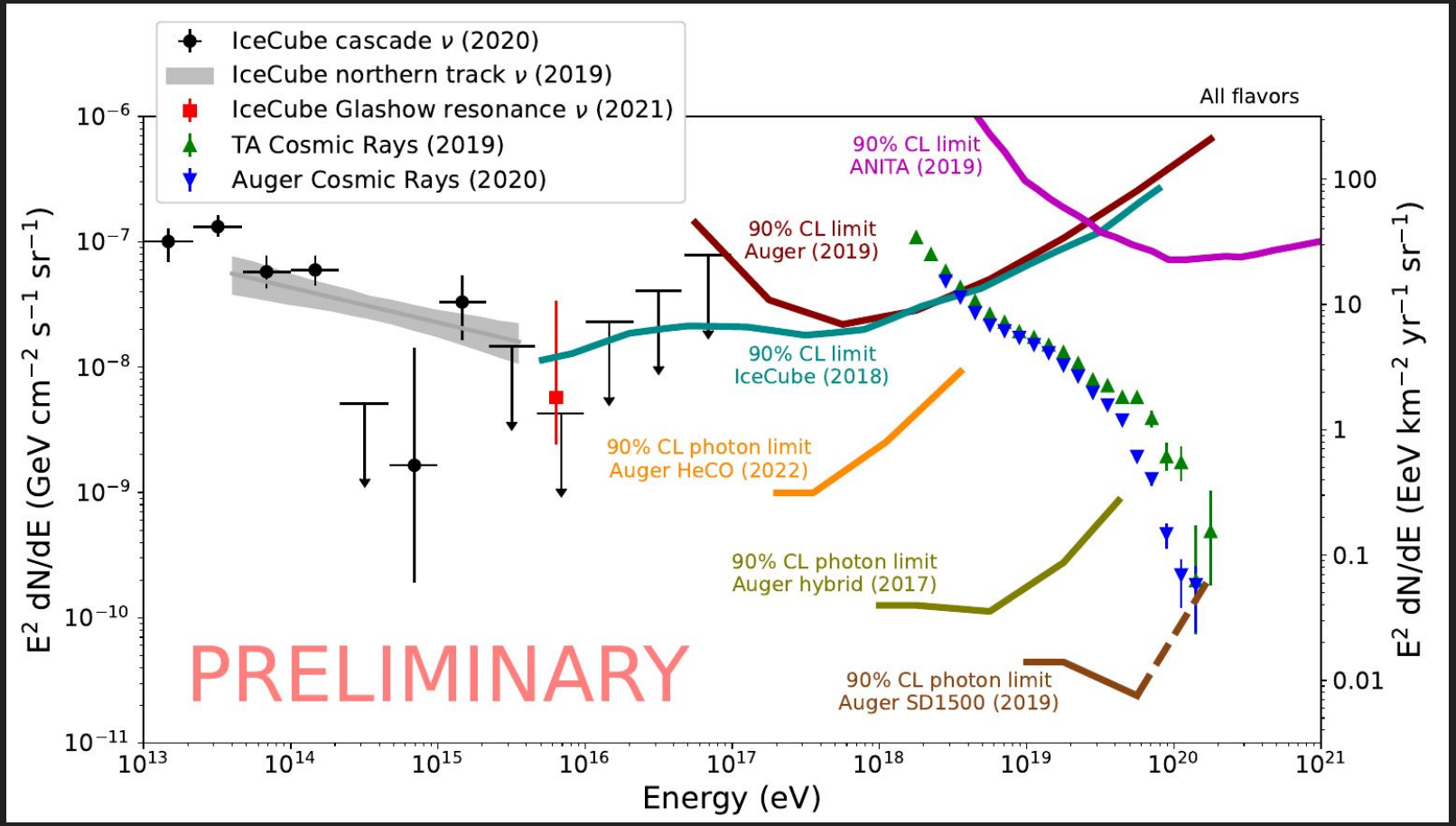
Current status of Multi-Messenger



UHE Photons

- Photons identifiable by reduced muon content and lower shower development (but more tricky then neutrinos)
- Diffuse flux bounds set constraints on SHDM, topological defects, and cosmogenic photon fluxes from the GZK-effect
- Point sources constrained continuation from TeV to EeV as well as SHDM models/processes

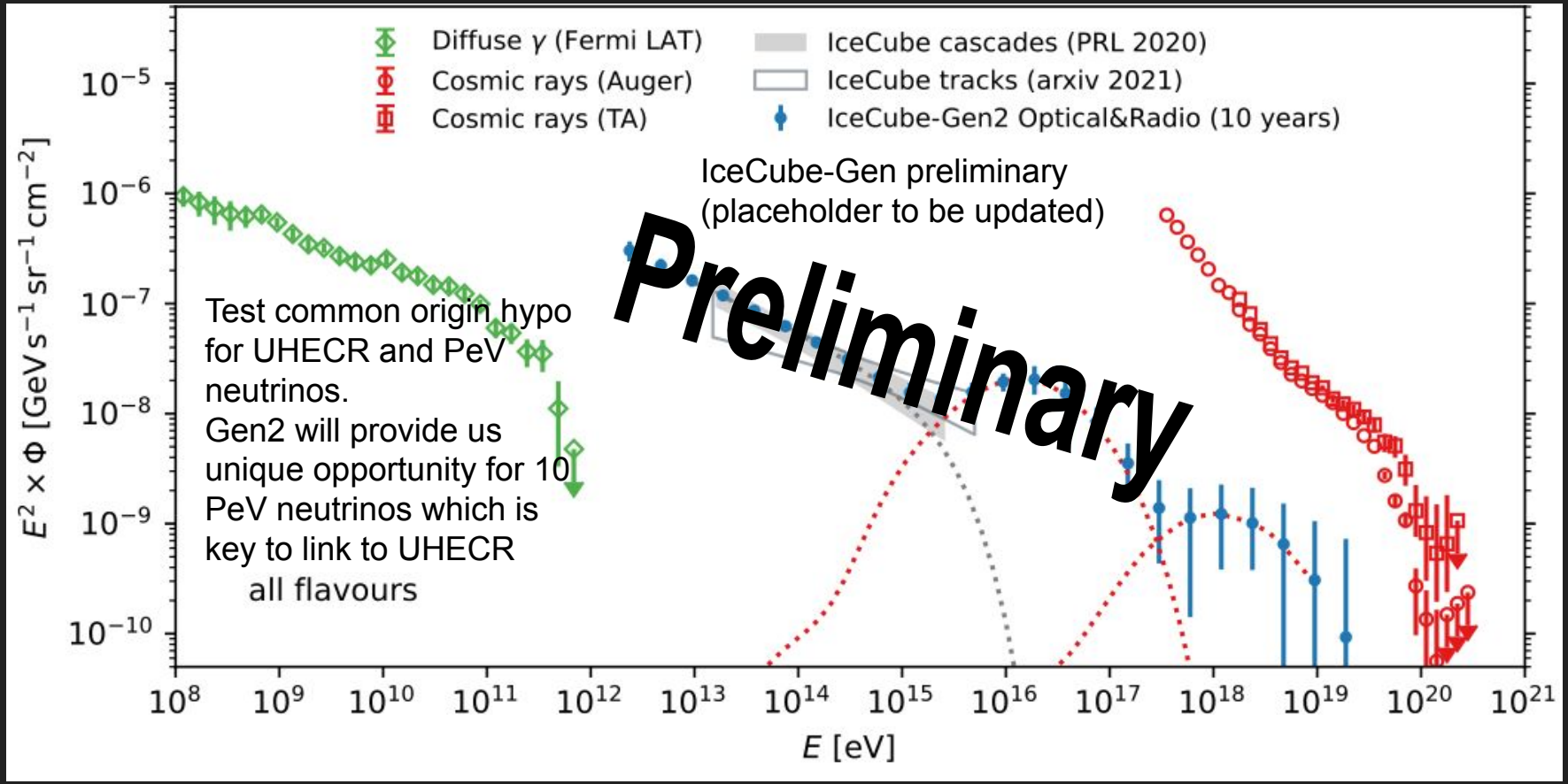
UHE Photons


IceCube cascade ν (2020)
IceCube northern track ν (2019)
IceCube Glashow resonance ν (2021)
TA Cosmic Rays (2019)
Auger Cosmic Rays (2020)
All flavors
90% CL limit
ANITA (2019)
90% CL limit
Auger (2019)
90% CL limit
IceCube (2018)
90% CL photon limit
Auger HeCO (2022)
90% CL photon limit
Auger hybrid (2017)
90% CL photon limit
Auger SD1500 (2019)
PRELIMINARY
E² dN/dE (GeV cm⁻² s⁻¹ sr⁻¹)
E² dN/dE (EeV km⁻² yr⁻¹ sr⁻¹)
Energy (eV)

Multi-Messenger in the next 10 year

- **Wanted:**
  - Precise determination of composition of UHECR on an event-by-event basis by detector enhancements
  - Better measurements of galactic magnetic field
    - Enables correlation studies of UHECR with neutral messengers
  - Better anisotropy measurements and source determination
- Upper bounds to cosmogenic photons will become stronger in the next decade, both because of more statistics becoming available and because of improved analysis techniques being developed
- Large progress in gravitational wave detection
  (more alerts, known events, better follow up)
- Extrapolating limits obtained so far lead to improvements by a factor of 2, 3, 4 for 10 more years of operation for neutrinos, photons, and neutrons, respectively (conservative)
- Strong bounds from stacking analyses

Multi-Messenger in the next 10 year



Multi-Messenger beyond the next 10 year

- Measurement of GZK neutrino flux and comparison to expectations from UHECR as crosscheck of mass/sources at highest energies
- Large number of event alerts
  - Target of Opportunity observations
    (full sky coverage experiments)
- New experiments up to 40 times higher aperture compared to current (next 10 years)
  - Increased statistics at highest energies (more correlation expected)
  - Establish possible recovery, IF exist enhance of proton/CR astronomy