最高エネルギー宇宙線・ガンマ線観測によるマルチメッセンジャー天文学

Multi-messenger astronomy by the highest-energy cosmic rays and gamma rays

Takashi SAKO

Next-generation Neutrino Science and Multi-messenger Astronomy Organization/ICRR, University of Tokyo

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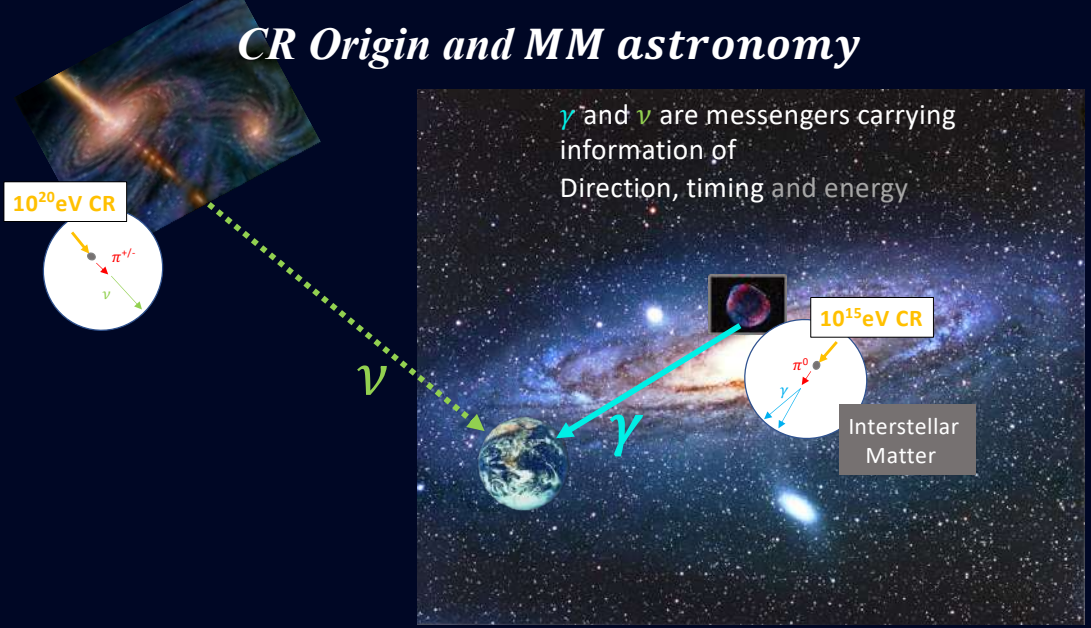
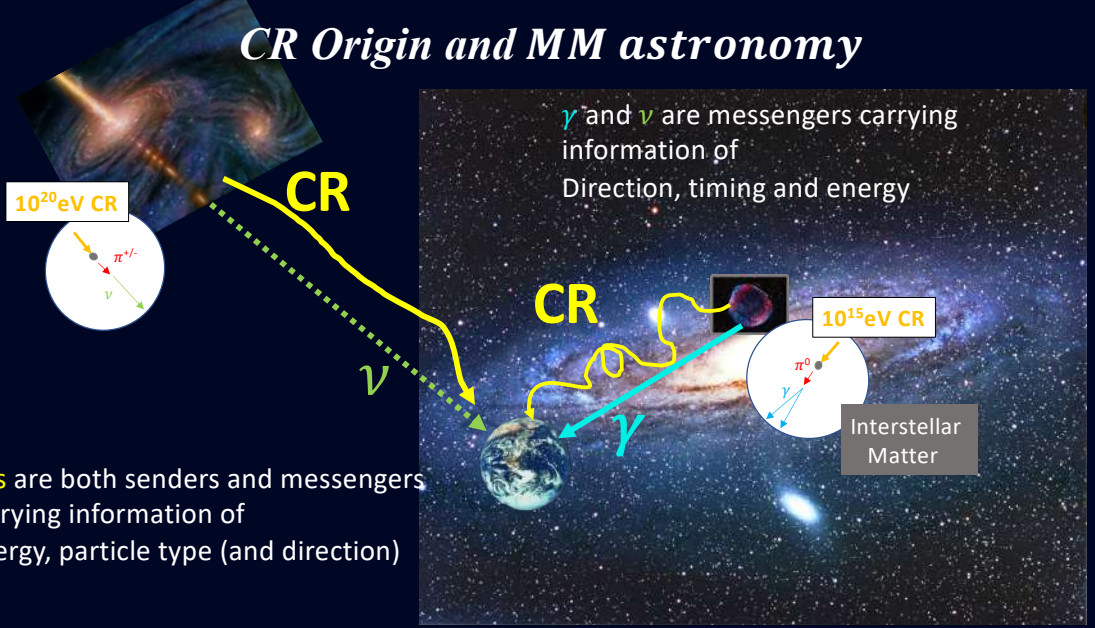
CR Origin and MM astronomy

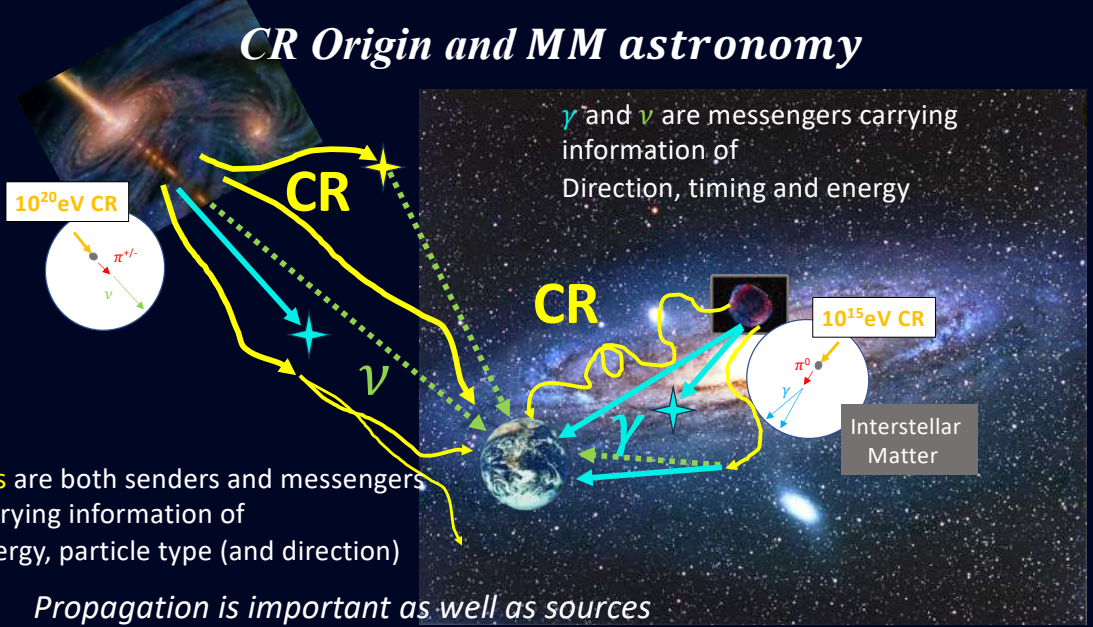


CR Origin and MM astronomy



CRs are both senders and messengers carrying information of
Energy, particle type (and direction)

CR Origin and MM astronomy

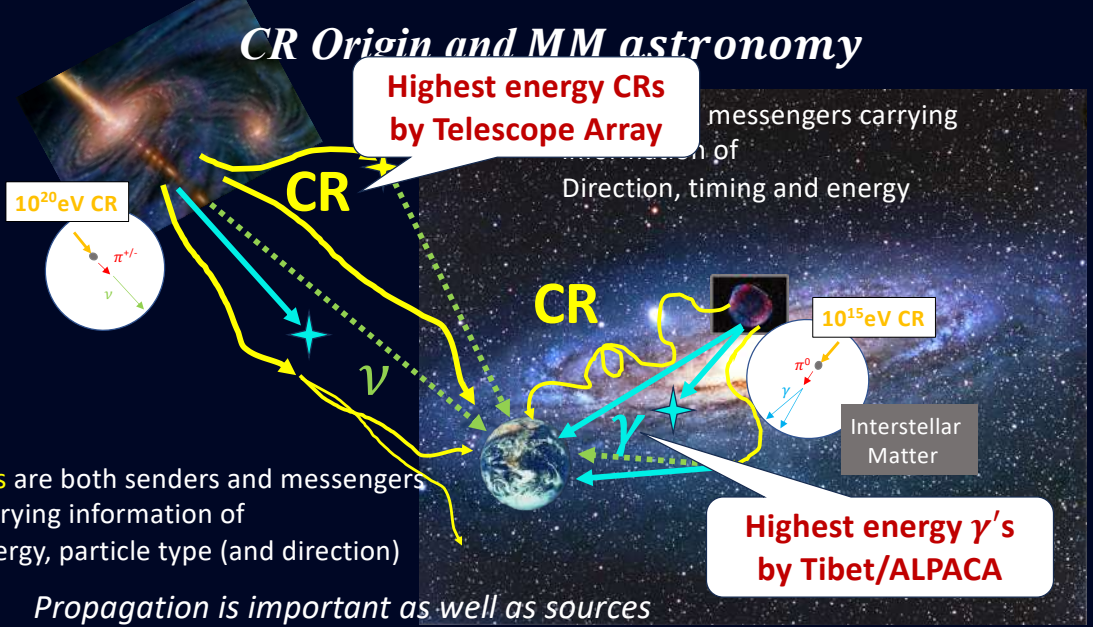


CRs are both senders and messengers carrying information of
Energy, particle type (and direction)

Propagation is important as well as sources

=> MM astronomy of sources AND space (photon field, B field, matter)

CR Origin and MM astronomy



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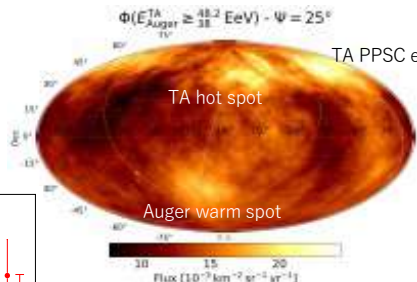
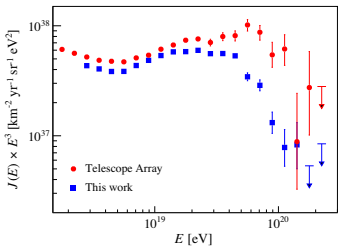
=> MM astronomy of sources AND space (photon field, B field, matter)

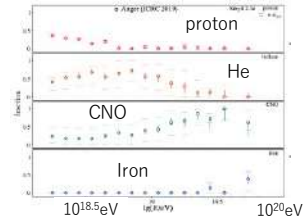
What are known about UHECRs?

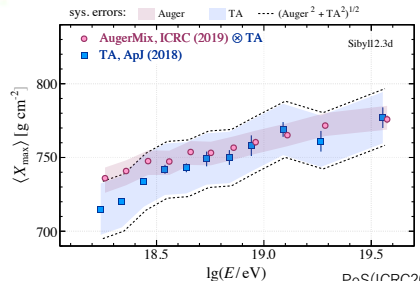


PoS(ICRC2023)521



Auger, PRD 102, 062005 (2020)





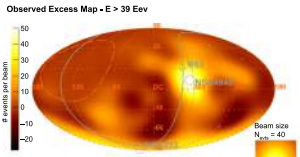
PoS(ICRC2023)281

- Steepening >$10^{19.5}$eV is established => Origin is unknown. North/South difference?
- Anisotropy in the medium angular scale => Concentration along the SGP. No excess from the Virgo.
- Heavier at higher energy => Consistent between TA and Auger.

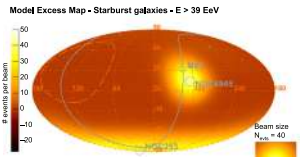
Correlation with candidates (Starburst Galaxies)

1 EeV = 10^{18}eV

Auger, ApJ Lett., 853:L29 (2018)

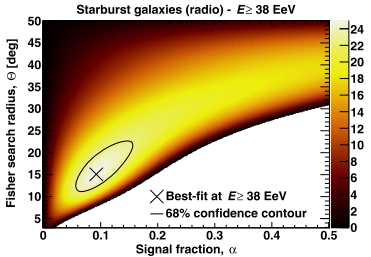


Observation (smeared)



SBG model (smeared)

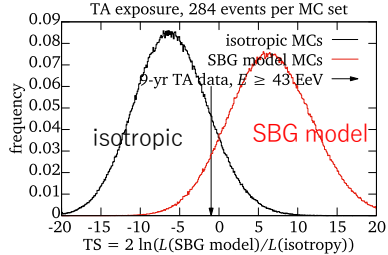
Auger, ApJ, 935:170 (2022)



source contribution

1-α : isotropic

TA, ApJ Lett., 867:L27 (2018)

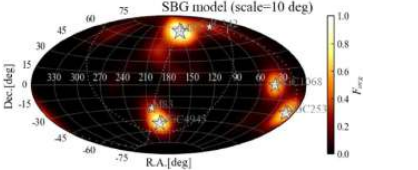


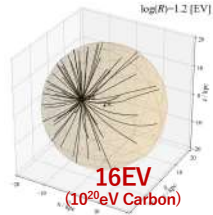
- Auger reported 4σ correlation with nearby Starburst Galaxies >38 EeV
- Only 10% source contribution!
- TA tested with the same model parameters but compatible with both isotropic and SBG hypotheses (lack of statistics)

Anisotropy, mass and magnetic field

R. Higuchi, PhD thesis (2022)
R. Higuchi et al. ApJ, 949:107 (2023)

Source model



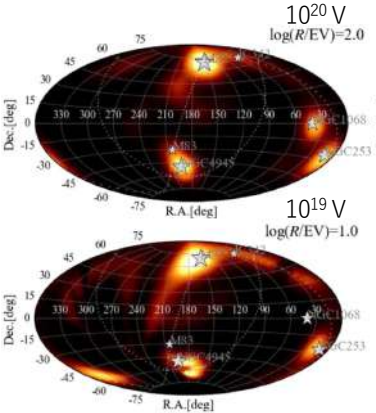


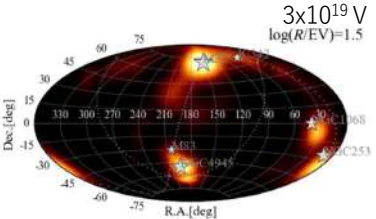
16EV
(10^{20}eV Carbon)

100EV
(10^{20}eV proton)

100 EeV = 10^{20}eV

Galactic magnetic deflection





rigidity = $\frac{pc}{eZ} \cong \frac{E}{eZ}$

Anisotropy, mass and magnetic field

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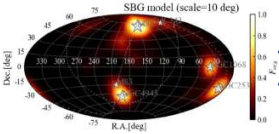
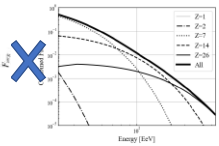
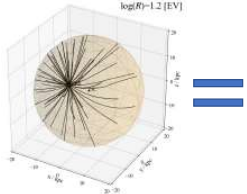
Source model

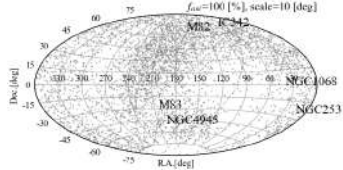


Mass composition

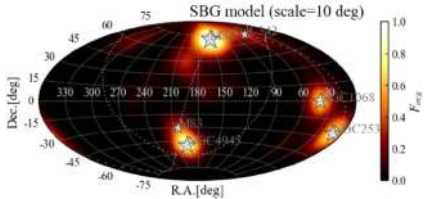


Magnetic deflection





Comparison with B-ignored model



Anisotropy, mass and magnetic field

R. Higuchi, PhD thesis (2022)
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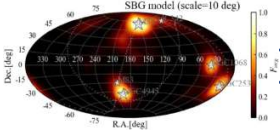
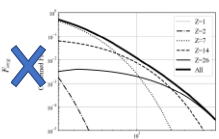
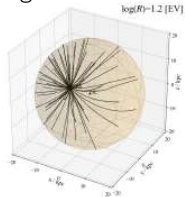
Source model

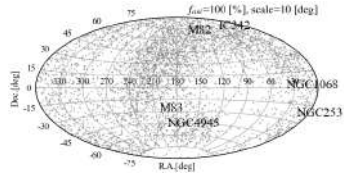


Mass composition

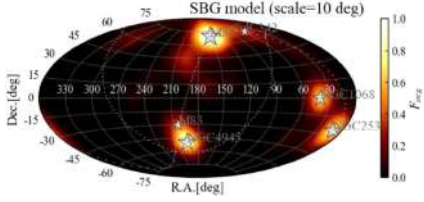


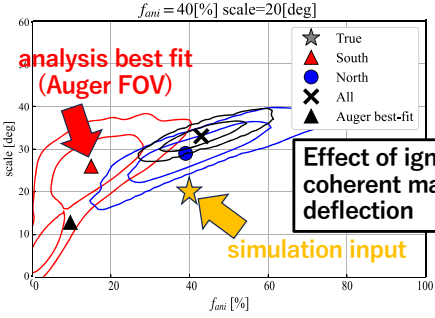
Magnetic deflection





Comparison with B-ignored model

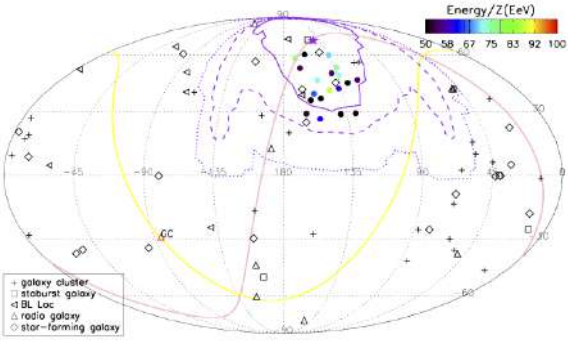


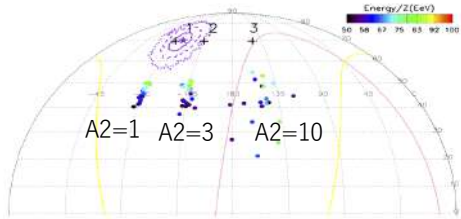


Effect of ignorance of coherent magnetic deflection

Potential source(s) of TA hot spot

(He et al., 2016)



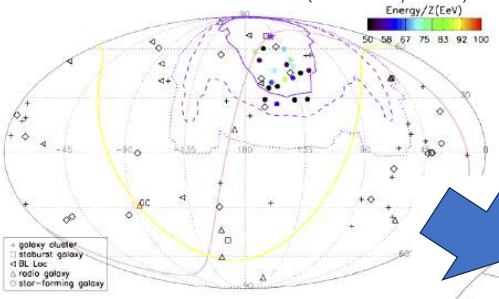


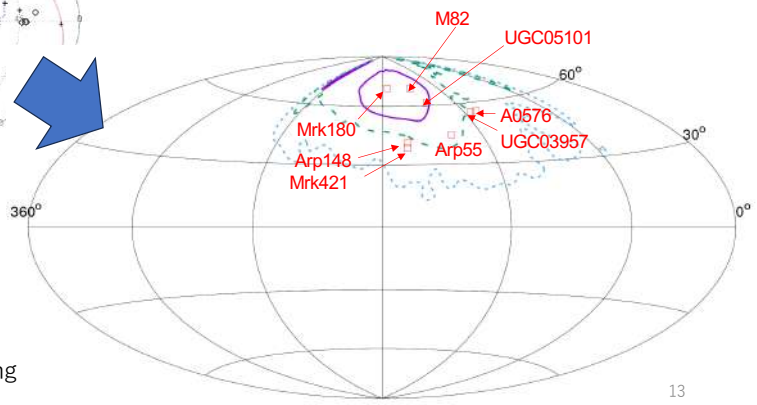
Free parameters

- RA, Dec.: coordinates of the CR source
- A1: Deflection angle at 100EeV by regular magnetic field
- A2: Smearing angle at 100EeV by random magnetic field
- α: Direction of regular magnetic field

Potential source(s) of TA hot spot

(He et al., 2016)



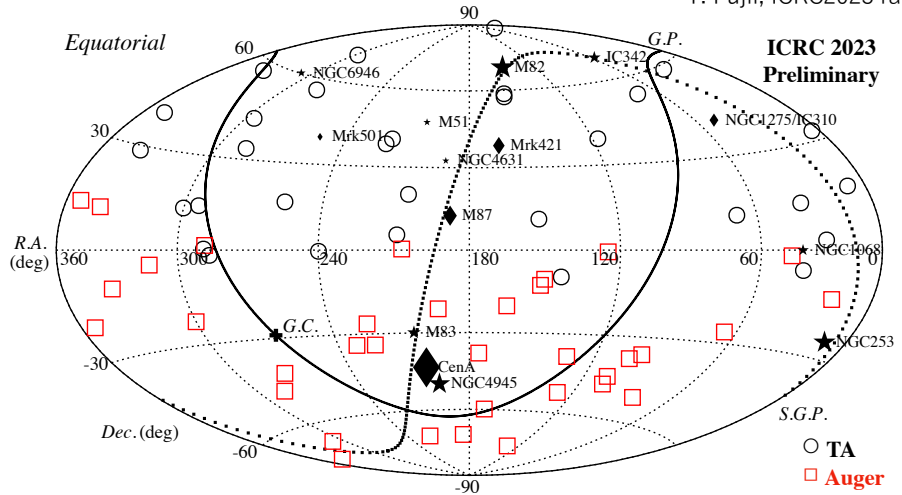


Update with the latest data
(E. Kido, JPS autumn meeting 2023)

isotropic fraction is added in the fitting

Arrival directions of >10^{20}eV CRs

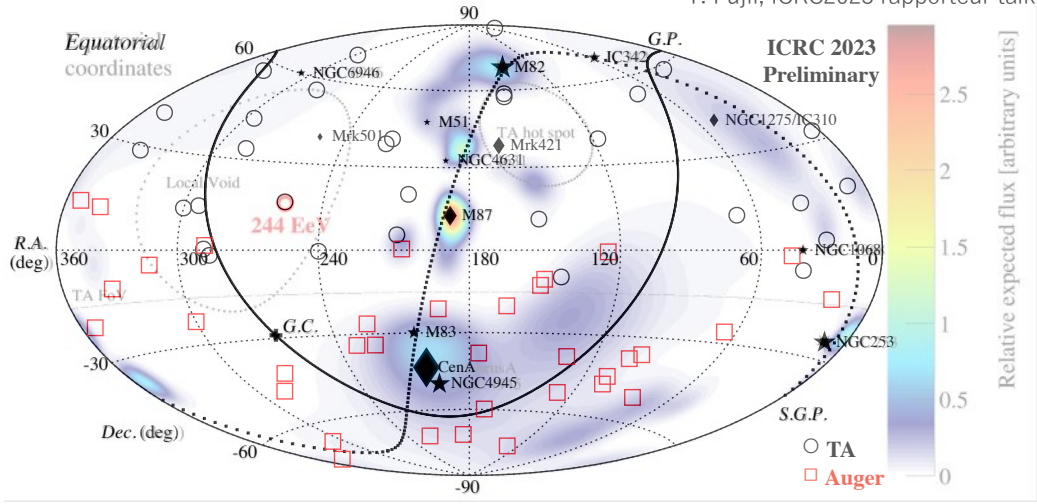
T. Fujii, ICRC2023 rapporteur talk



Isotropic! => Heavy? Exotic?

Arrival directions of >10^{20}eV CRs

T. Fujii, ICRC2023 rapporteur talk



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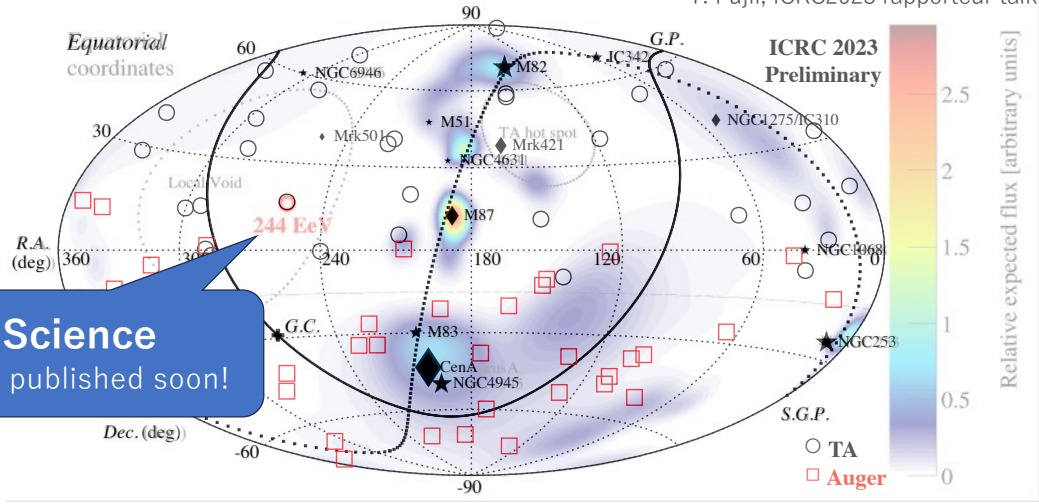


Science
to be published soon!

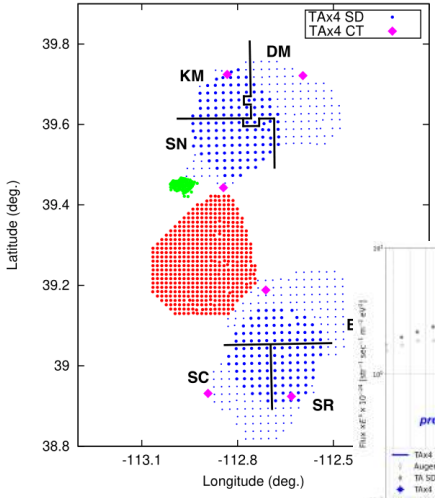
Isotropic! => Heavy? Exotic?

UHECR observations in MM astronomy

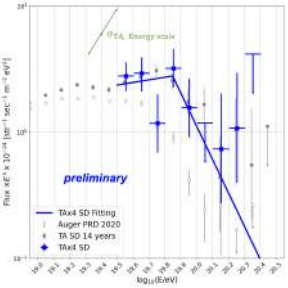
- **Source association**
  - Effect of magnetic field => mass sensitivity
- **Highest energy CR astronomy**
  - $>10^{20}$eV is surprisingly isotropic => more data, mass sensitivity
- **Neutral particles**
  - Neutrinos and gamma's => PID by machine learning
  - Neutrons => galactic sources
- **More data**
  - TAx4 => more events in North
  - Auger prime => SD mass sensitivity
  - GCOS for future

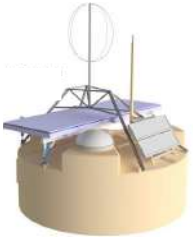
TAx4 and AugerPrime

TAx2.5 (eq.) running



TA, PoS(ICRC2023)308



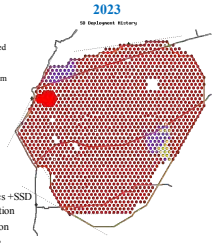


Auger, ICRC2023, CRI 14-06

DEPLOYMENT STATUS

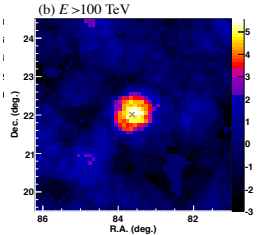
ICRC2023

- **SSD deployment completed**
- **UUB deployment completed** end of June 2023
- Data acquisition and monitoring program as well as the data analysis pipeline updated for AugerPrime
- During deployment **constant commissioning work** to evaluate stability and long-term performances

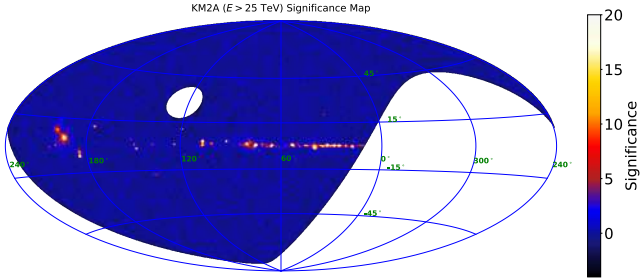


Fabio Convenga (INFN & UNIVAQ), The performances of the upgraded surface detector stations of AugerPrime

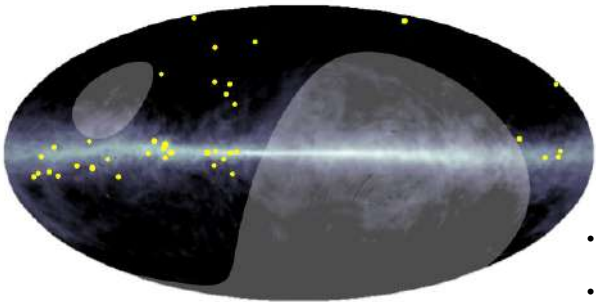
Sub-PeV γ astonomy and galactic CRs



Tibet AS γ Collaboration,
PRL 123, 051101 **(2019)**



LHAASO Collaboration, arXiv:2305.1703v1 (2023)

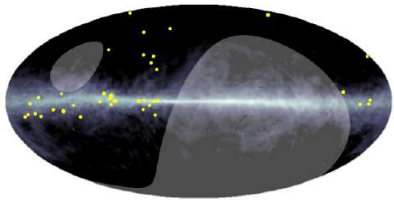


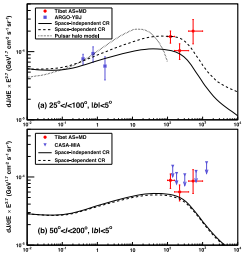
Tibet AS γ Collaboration, PRL 126, 141101 (2021)

- Tibet ASγ opened a new window of astronomy in the sub-PeV range
- Origins and distribution of PeV CRs can be surveyed

Diffuse emission >400TeV γ and IceCube ν

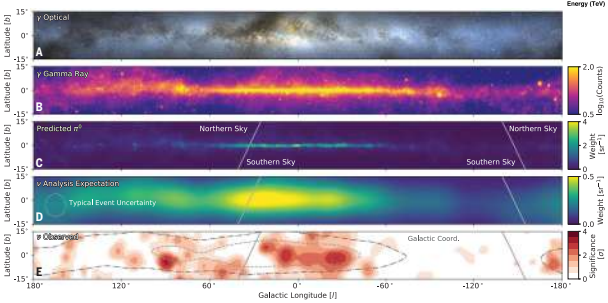
Tibet AS γ Collaboration, PRL 126, 141101 (2021)

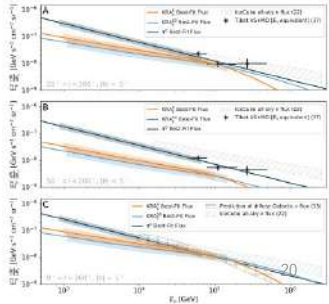




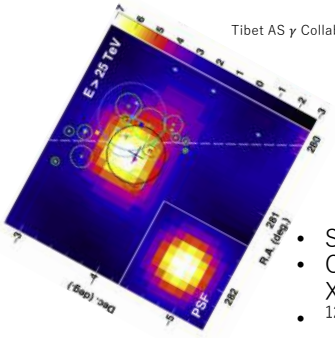
F_γ to F_ν conversion

IceCube Collaboration, Science 380, 1338-1343 (2023)





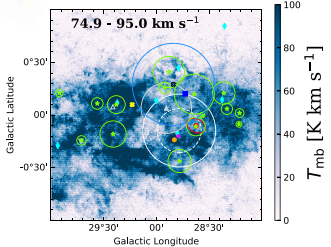
MM astronomy of sub-PeV $\gamma's$

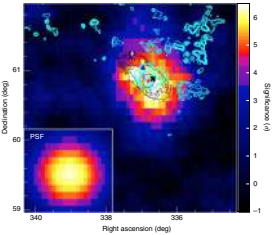


Tibet AS γ Collaboration, ApJ 932:120 (2022)

TASG J1844-038
HESS J1843-033

- SNR G28.6-0.1 in error
- Compact non-thermal X-ray source
- ^{12}CO molecular cloud





SNR G106.3+2.7

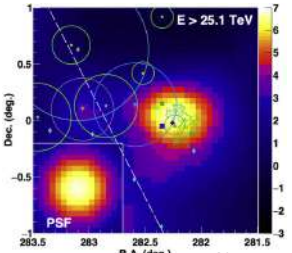
- Offset from PWN
- Coincide with ^{12}CO molecular cloud

Tibet AS γ Collaboration, Nature Astron. 5, 460-464 (2021)

HESS J1849-000

- X-ray pulsar and PWN
- ^{12}CO molecular cloud

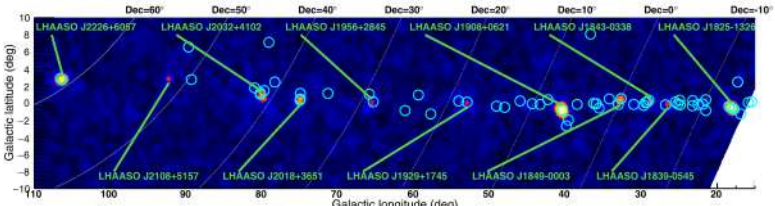
are associated.



Tibet AS γ Collaboration, ApJ 954:200 (2023)

Sub-PeV source w/o VHE association

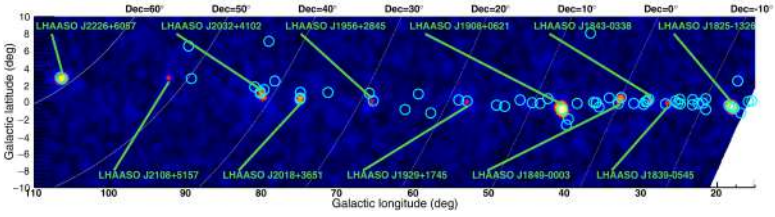
LHAASO Collaboration, Nature 594, 33-36 (2021)



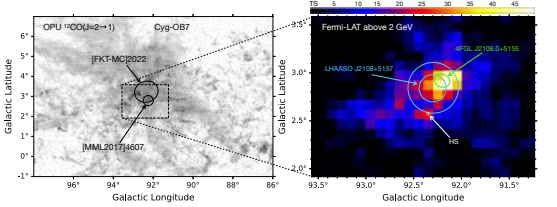
LHAASO J2108

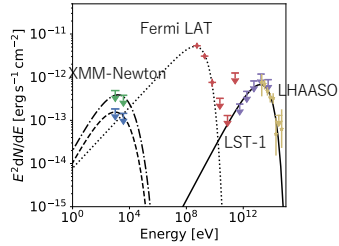
Sub-PeV source w/o VHE association

LHAASO Collaboration, Nature 594, 33-36 (2021)

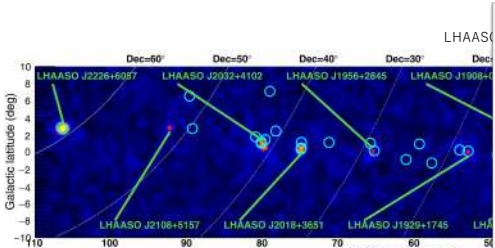


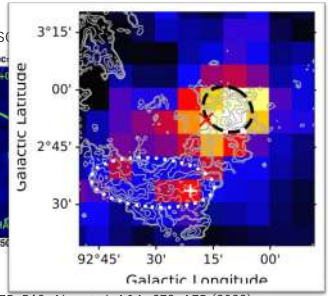
De la Fuente et al., A&A 675, L5 (2023) based on De la Fuente et al., PASJ, 75, 546; Abe et al. A&A, 673, A75 (2023)





Sub-PeV source w/o VHE association





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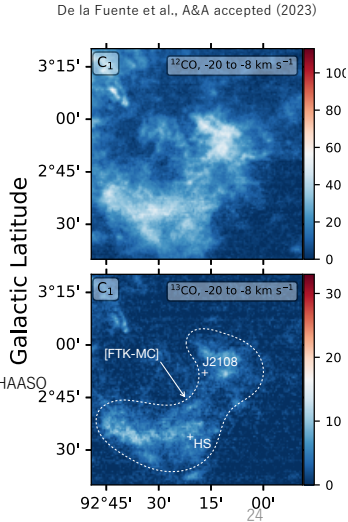
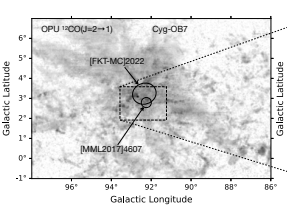
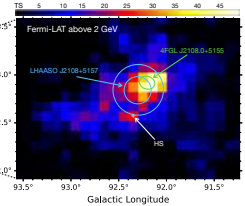
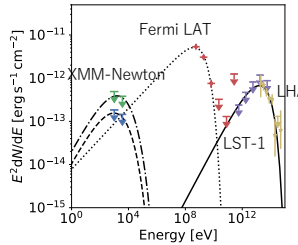
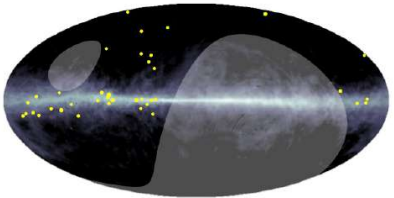


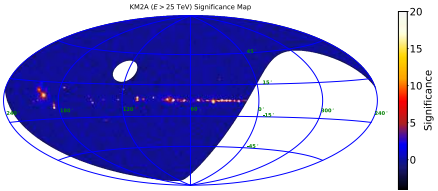






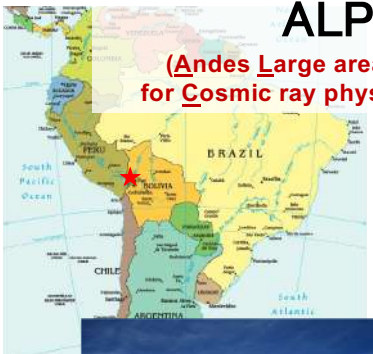
Southern hemisphere!

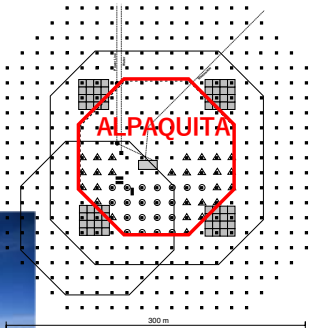




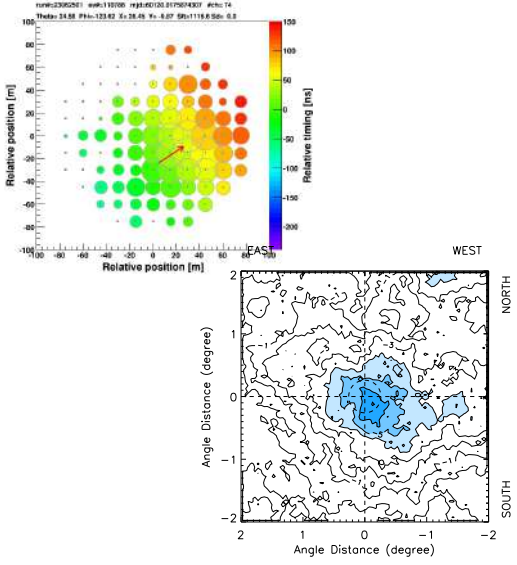
ALPACA

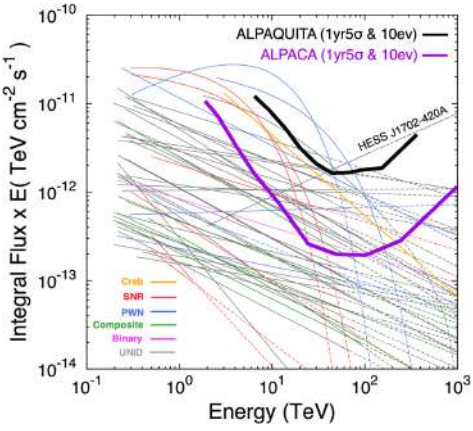
(Andes Large area PArticle detector for Cosmic ray physics and Astronomy)





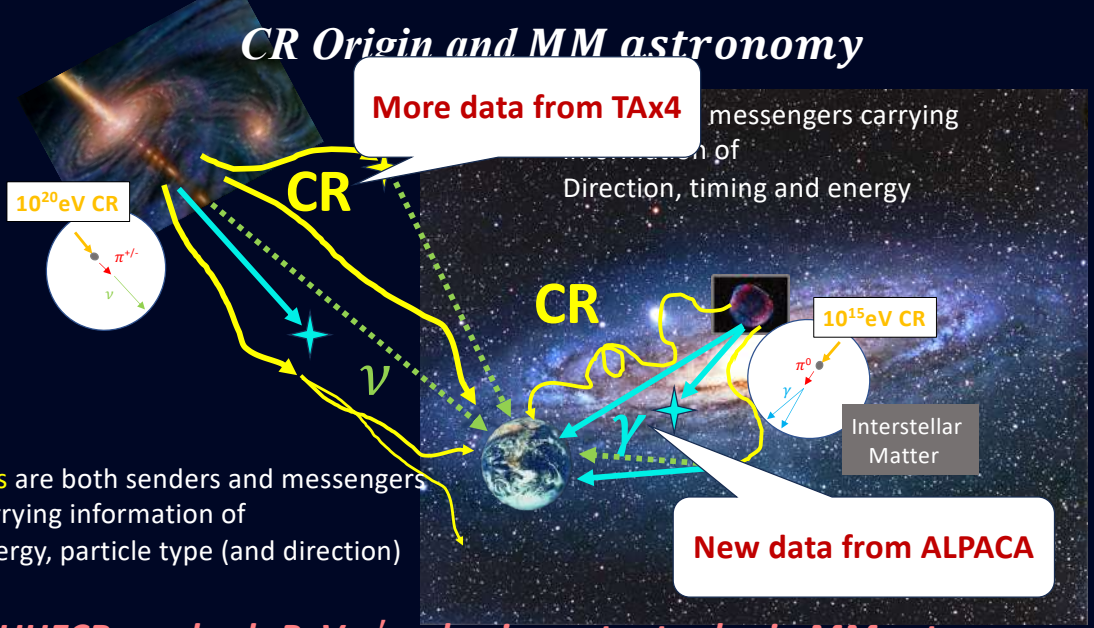
ALPACA joins MM astronomy





- ALPAQUITA SDs stably running => Shadow of the moon
- Construction of ALPAQUITA MD in FY2023-2024
- Full ALPACA in FY2025

CR Origin and MM astronomy



CRs are both senders and messengers carrying information of Energy, particle type (and direction)

UHECRs and sub-PeV γ's play important roles in MM astronomy