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Cosmic rays and gamma-ray astronomy

Ruizhi Yang
University of Science and Technology of China

Outline

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1. Introduction

2. GeV gamma-rays: CR distributions

3. MeV gamma-rays: CR ionizations and star formation

4. TeV/PeV gamma-rays: PeVatron

5. Future plans

Galactic Cosmic Rays (GCR)

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Cosmic Rays: Relativistic particles (mainly protons) in interstellar medium (ISM)

Consensus

- Single power law spectrum from 10 GeV (10^{10} eV) up to 1 PeV (10^{15} eV)
- Energy-dependent confinement in the Galactic halo
- Supernova remnants (SNR) as sources

Detection method

- Direct measurement (ballon, satellite or extensive air shower array), measure the local spectrum and anisotropy
- Indirect measurement (via Gamma-rays / neutrinos). spectrum and distribution in the Galaxy

Spectrum

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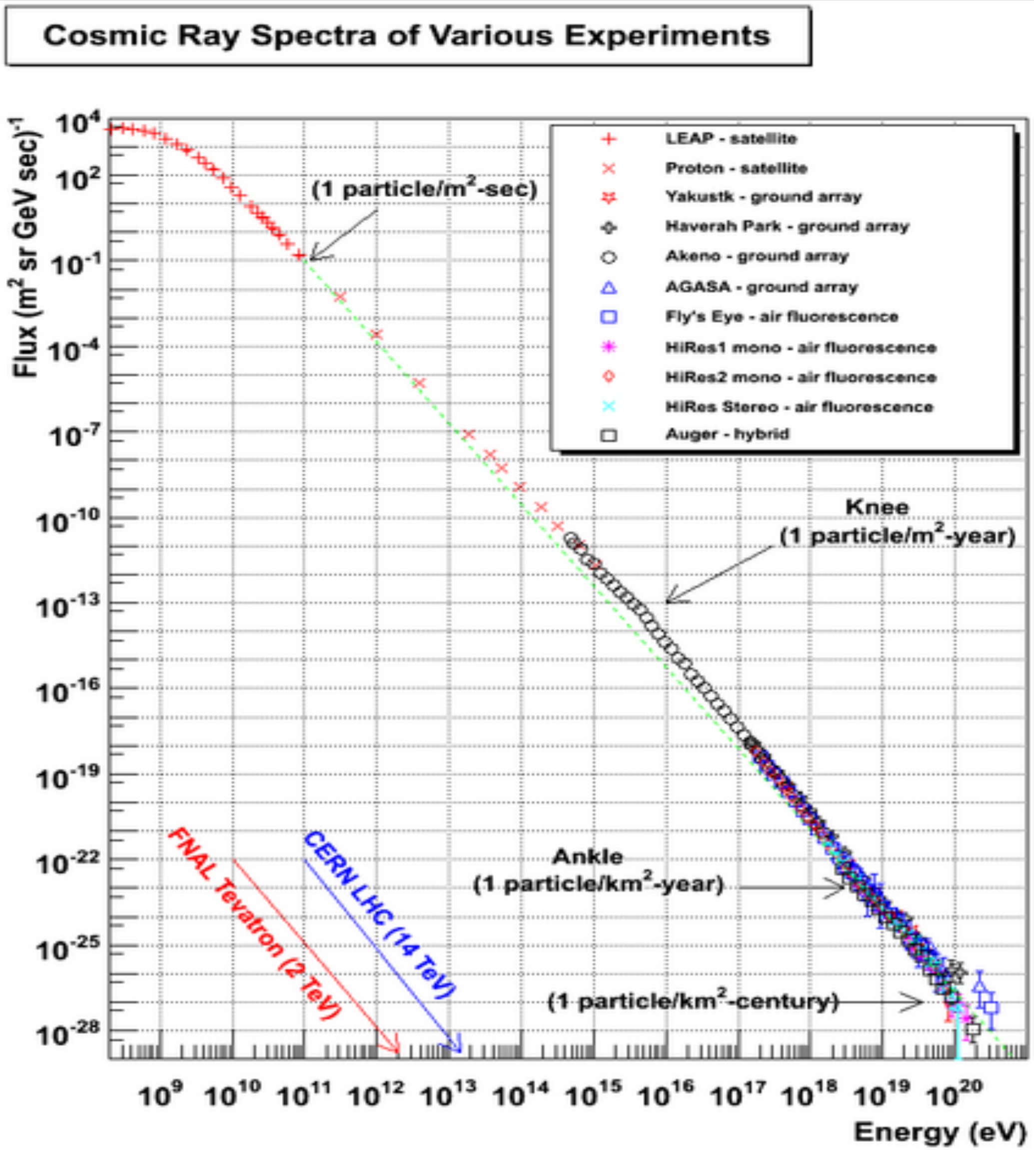
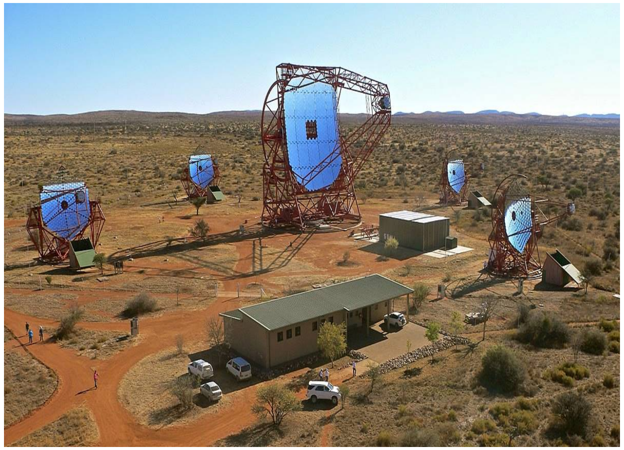


https://www.physics.utah.edu/~whanlon/spectrum.html

Gamma-ray Astronomy

- Atmosphere is opaque for gamma-rays
- Satellite or air shower
- above 100 MeV

Fermi LAT
(0.1 ~ 1000 GeV)

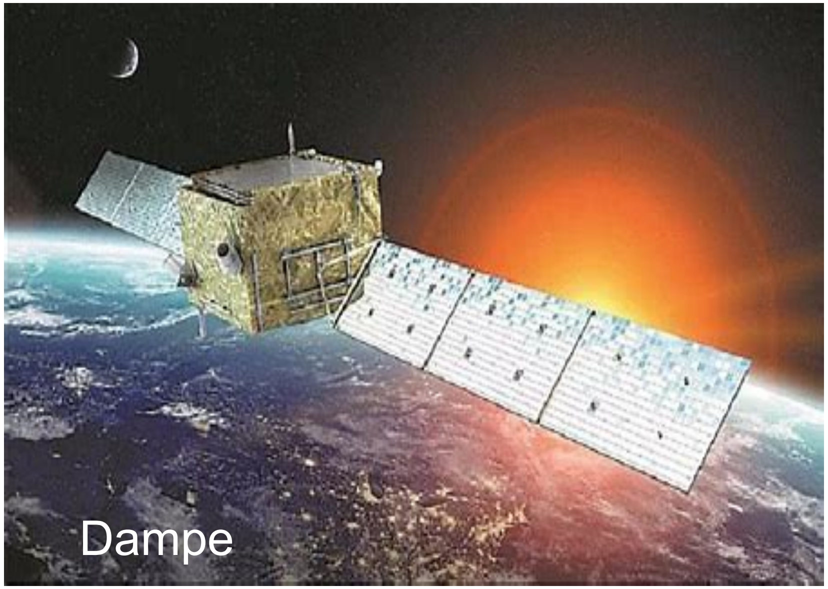


H.E.S.S
(0.1 ~ 10 TeV)

LHAASO
(>1 TeV)

Spaceborne detectors

- pair conversion telescopes
- Large FOV (~ 3 sr)
- 0.1~ 1000 GeV
- small effective area (~ 1 m^2)
- moderate PSF (0.1 - 1 degree)
- continuous monitoring



Air Cherenkov telescope arrays

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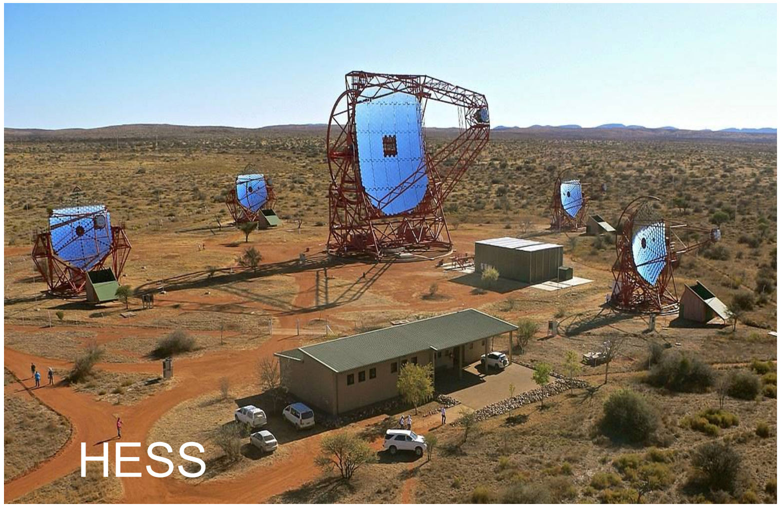
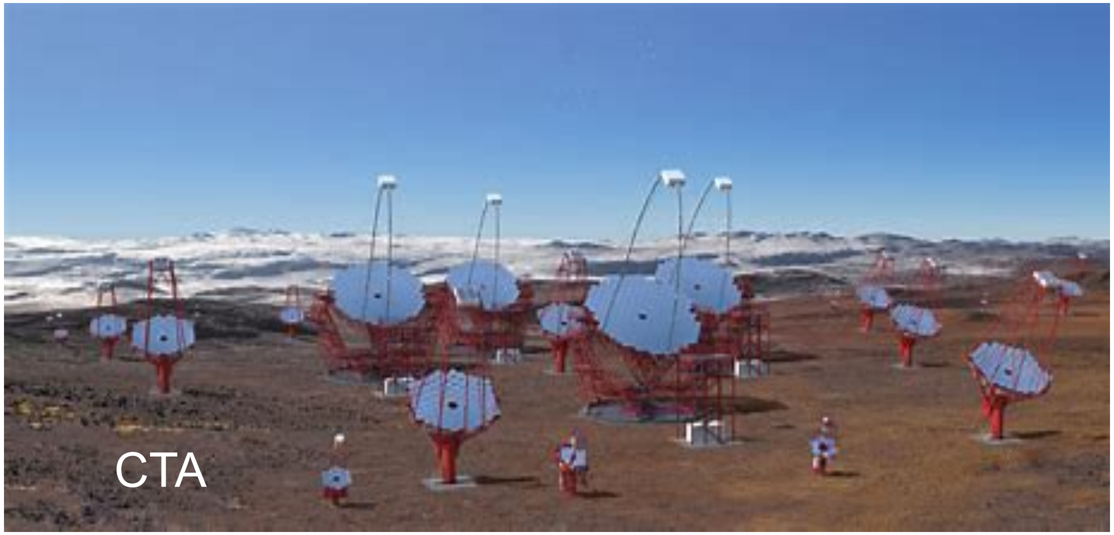
- detect cherenkov light of secondary electrons in air shower.
- small FOV (~ 5 degree)
- 0.1~ 100 TeV
- large effective area (~ 1e5 m^2)
- excellent PSF (down to 1 arcmin)
- only at clear night (without moon)





Extensive air showers

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- detect muon/electrons in air shower (scintillator/water cherenkov).
- large FOV (~ several sr)
- above 1 TeV
- large effective area (~ 1e5 m^2)
- poor PSF (0.3 degree)
- continuous monitoring

Spatial distribution of CRs from GeV gamma-rays

From gamma-rays

- Gamma-ray emission (in molecular clouds or diffuse):

Point sources+ CR interaction with ambient gas + ICs +isotropic

- CR interaction with gas dominates in dense environment.

- Gamma-ray map + gas distribution -> CR distribution

gamma-rays from giant molecular clouds (GMCs)

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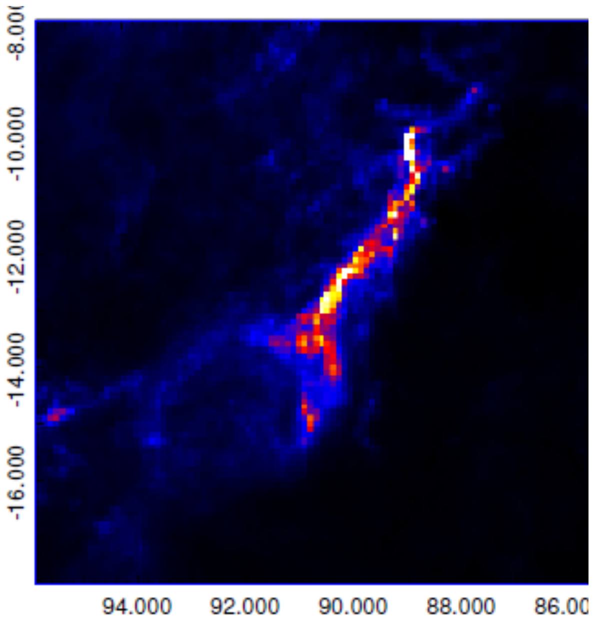
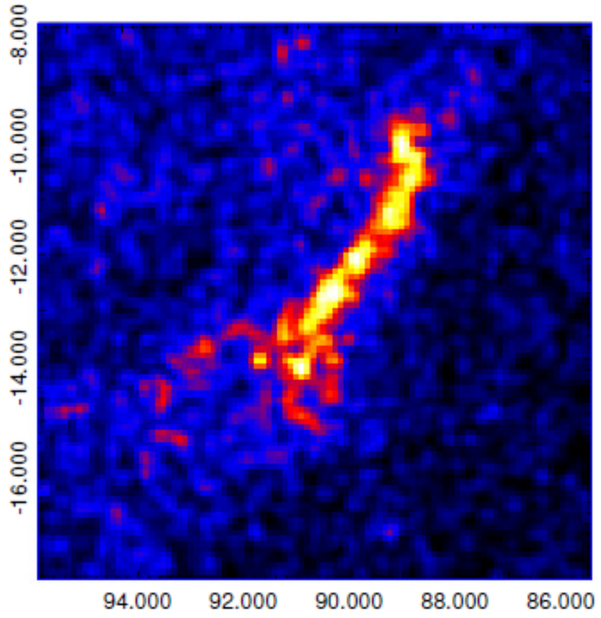
- Gamma-rays show good correlation with gas (CR uniformly distributed inside GMCs)
- Can be used to study the CR spectra



Gas (CO) distribution



gamma-ray observations (GeV)

Derived CR spectrum

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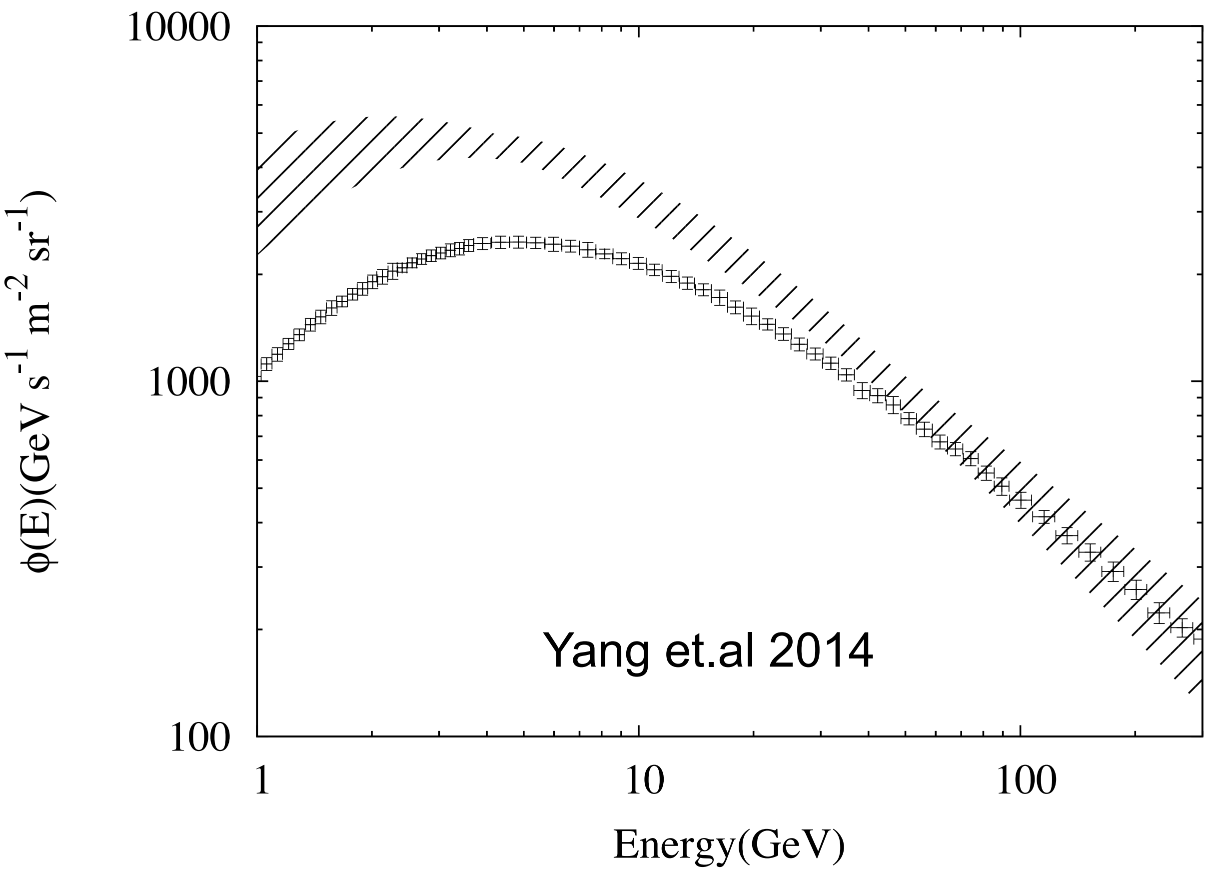

In comparison with the Local Measured CR:
consistent above 10 GeV (solar modulation)

uniform or not?

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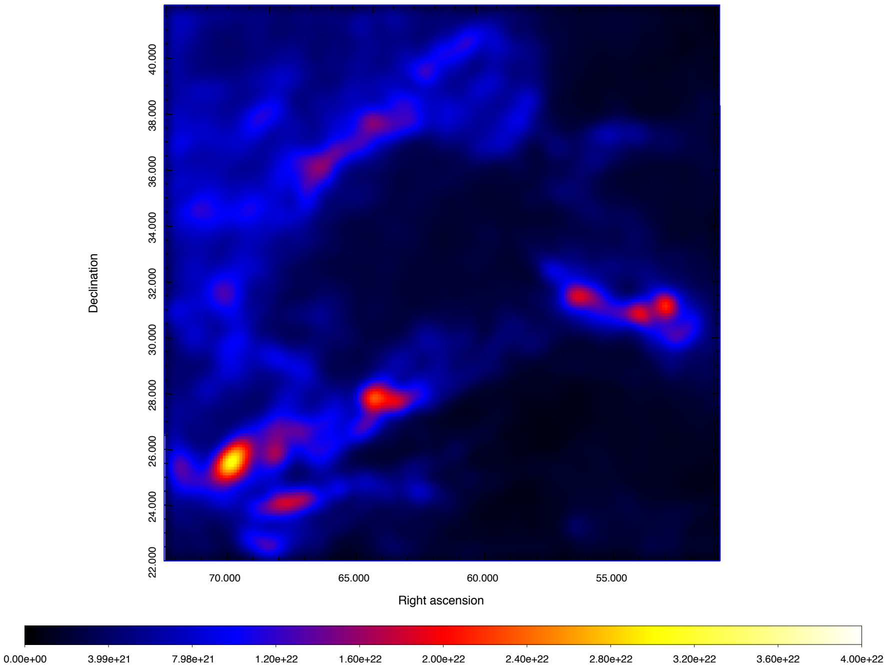
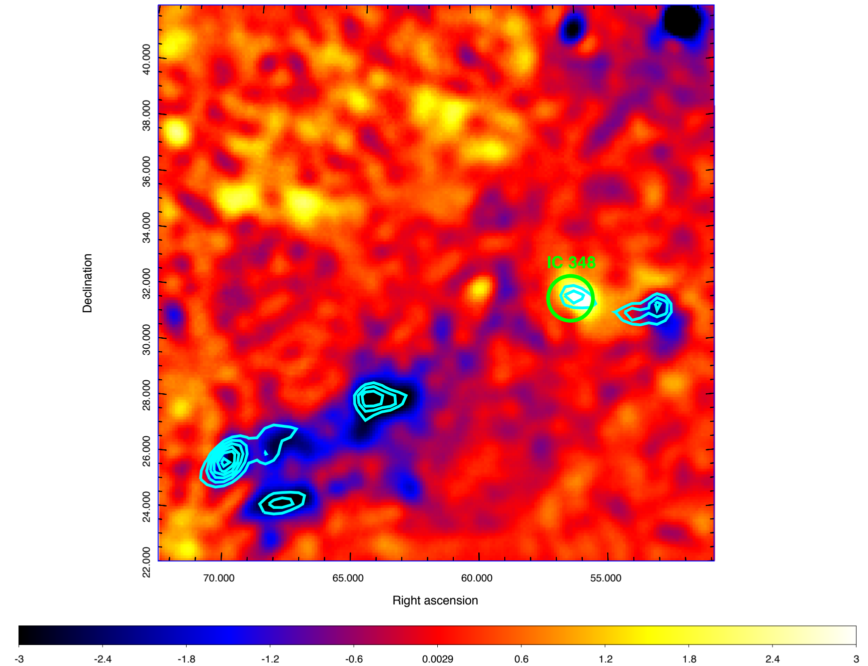
Test the uniformity of CRs

- Some hint of inhomogeneous distribution in Taurus-Perseus region



Dust opacity (gas distribution)



gamma residual (CR density)

Uniform or not?

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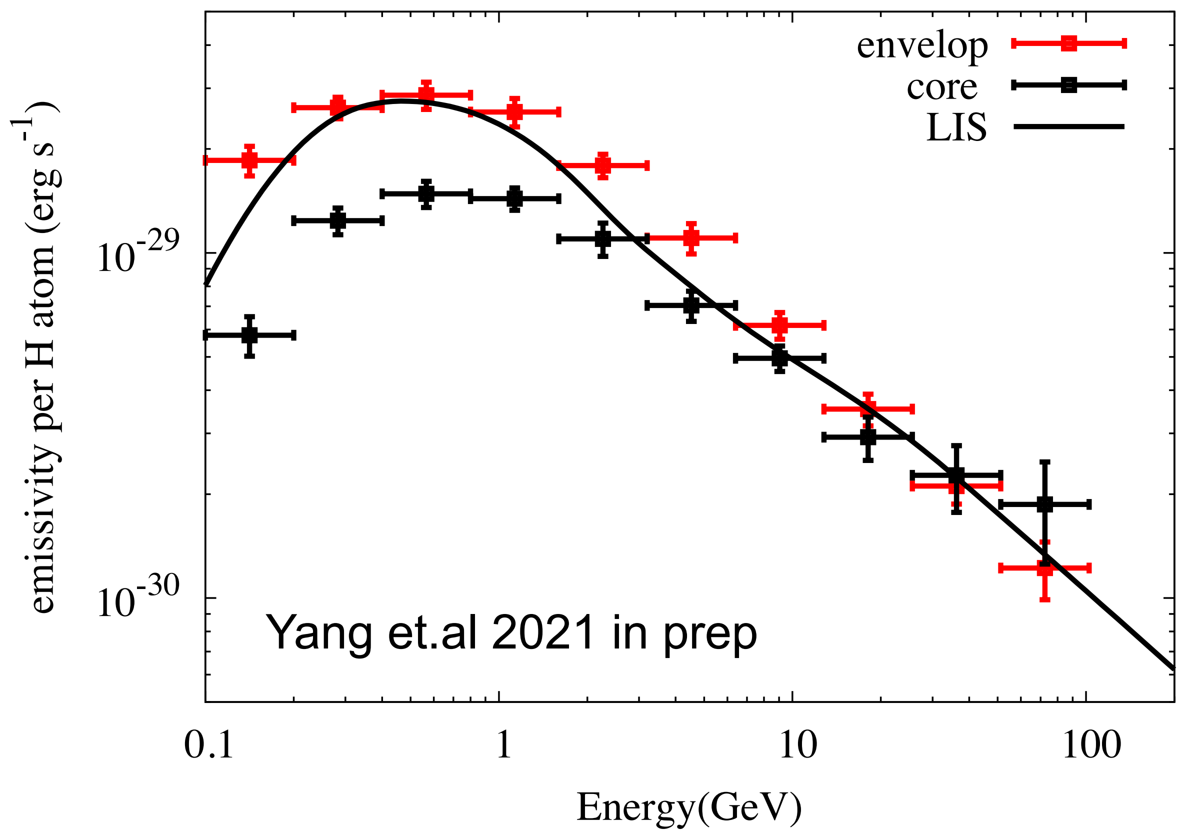
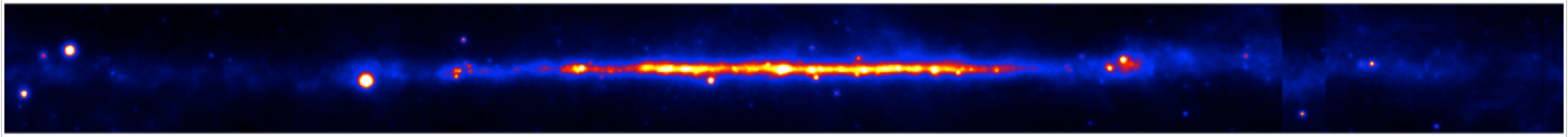
Test the uniformity of CRs

- Low energy CRs cannot penetrate into the core:
  slower diffusion due to higher turbulence inside GMCs?

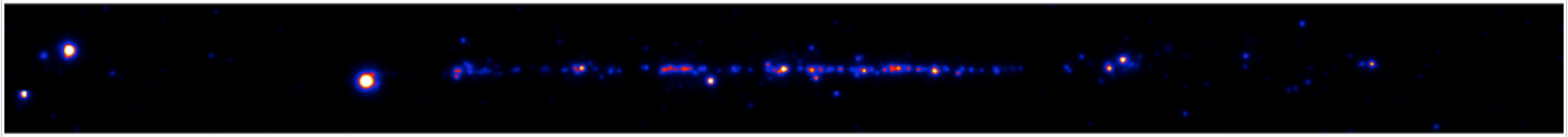


Diffuse gamma-ray emission

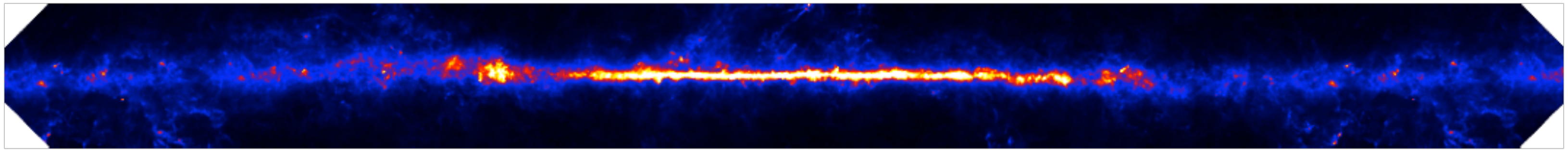
Gamma-ray counts map



Point source contribution



Dust opacity map (gas column)



CR Radial distributions

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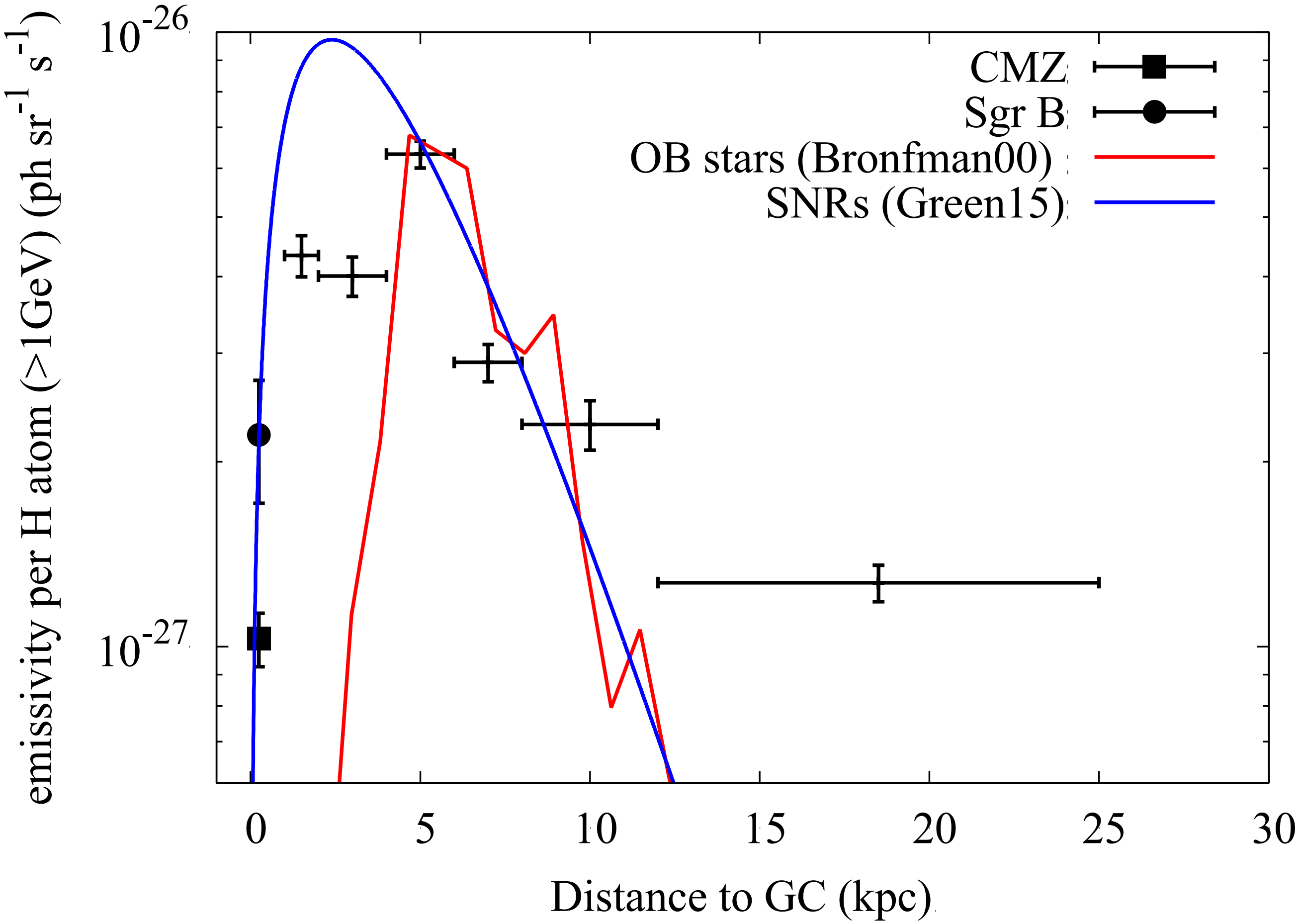

Yang et.al 2016

Hardening towards GC

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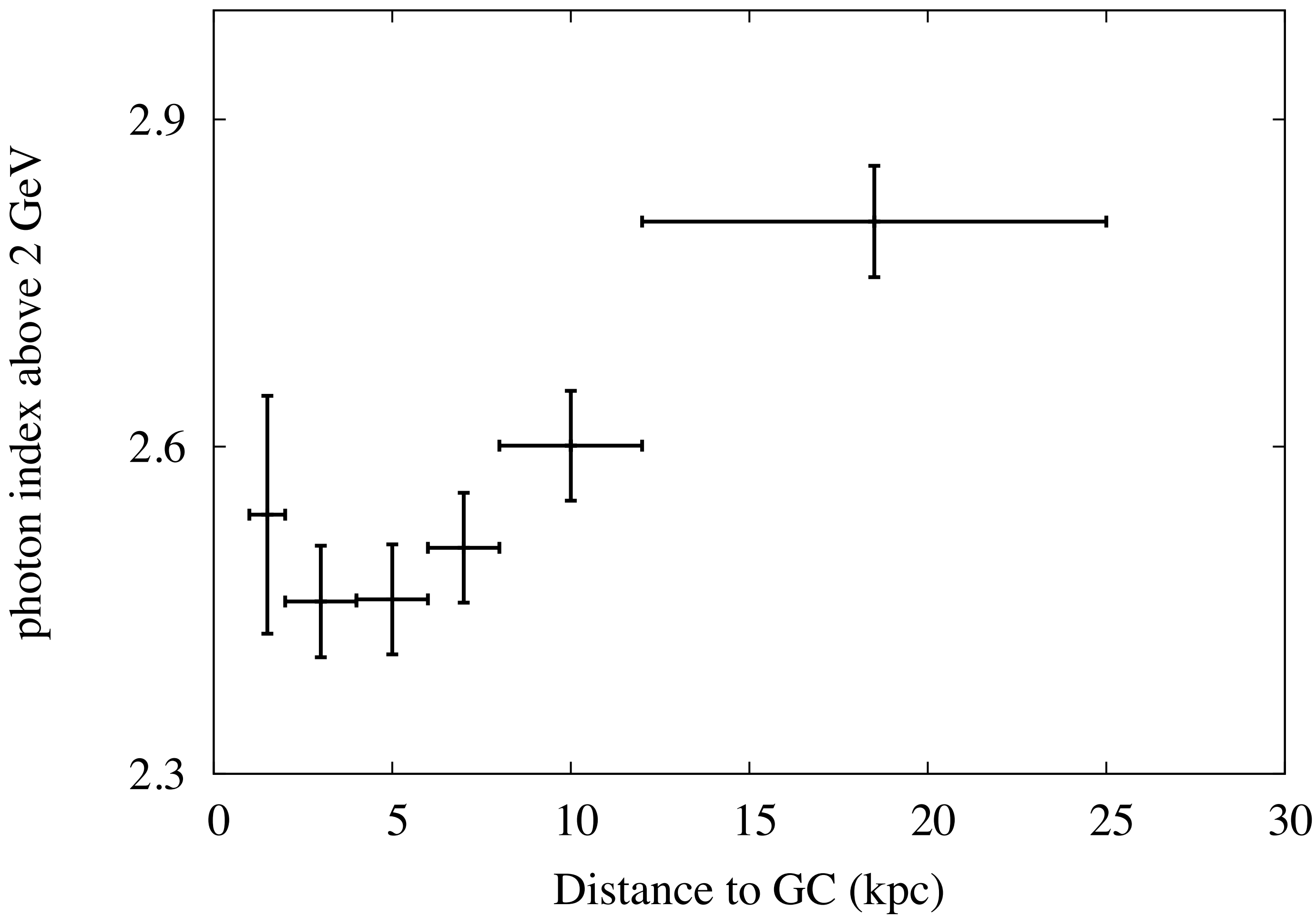
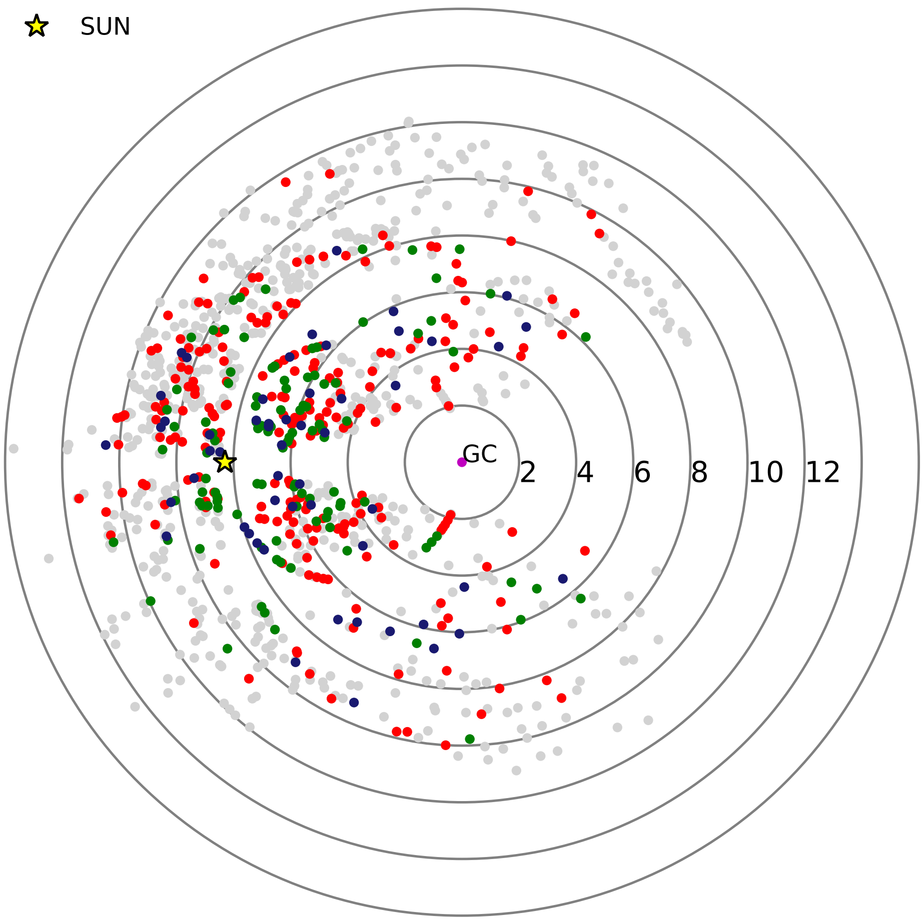


Yang et.al 2016

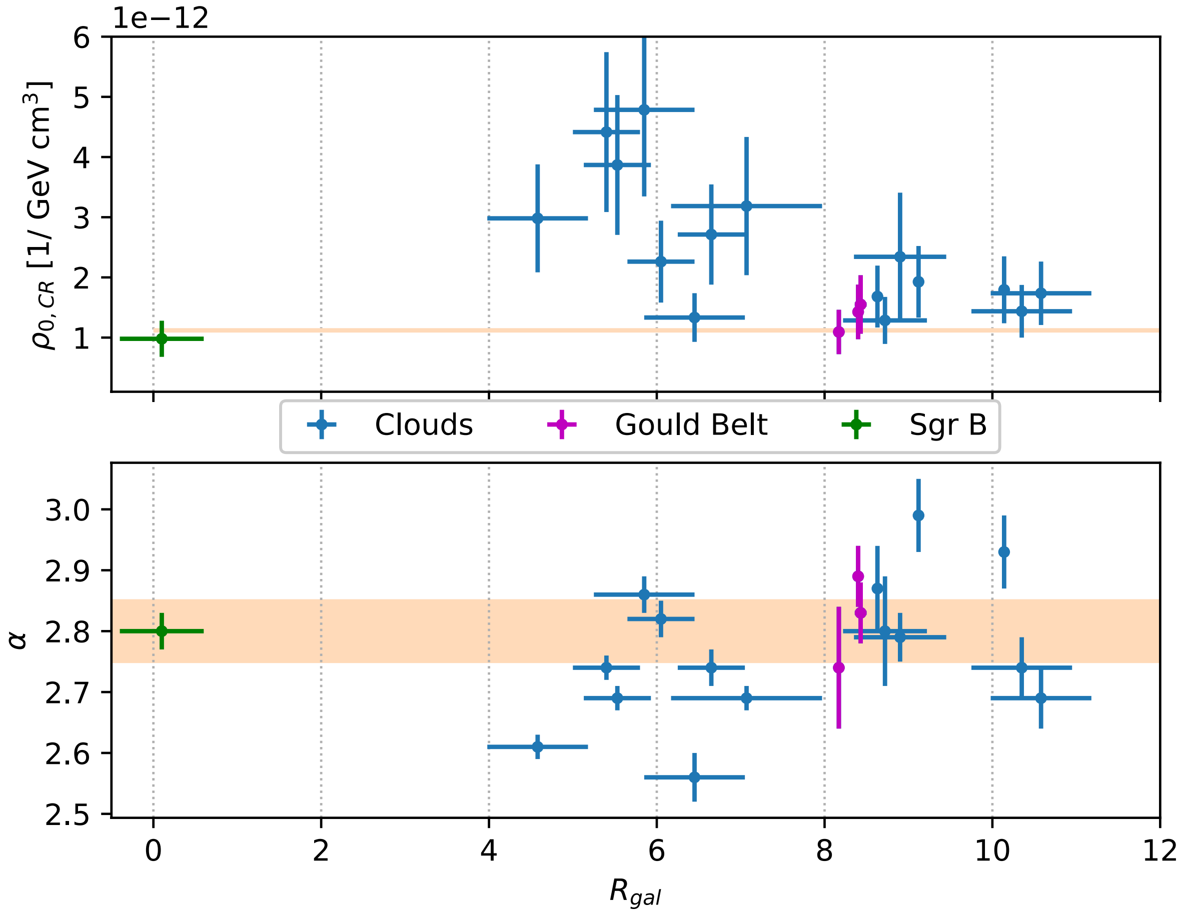
More GMCs!



Aharonian et.al 2019

- Rice et.al (2016) have identified thousands of Molecular Clouds in the Galaxy
- Possible to measure CR density in each position of the Galaxy.

More GMCs



- The enhancement and hardening is caused due to the CR sources?
- A uniform CR "sea" plus some "islands" with higher density and harder spectra?

Aharonian et.al 2019

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MeV gamma-rays

(Liu, Yang and Aharonian A&A 2020)

Low energy (LE) CRs

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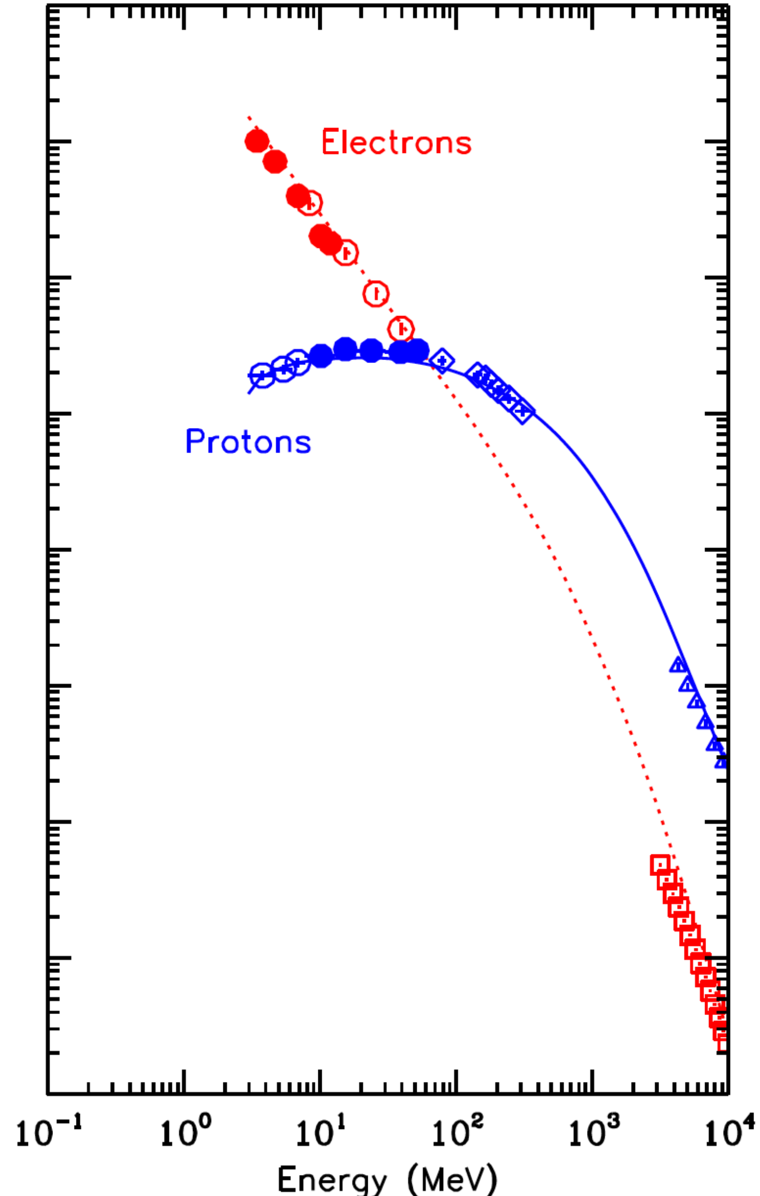
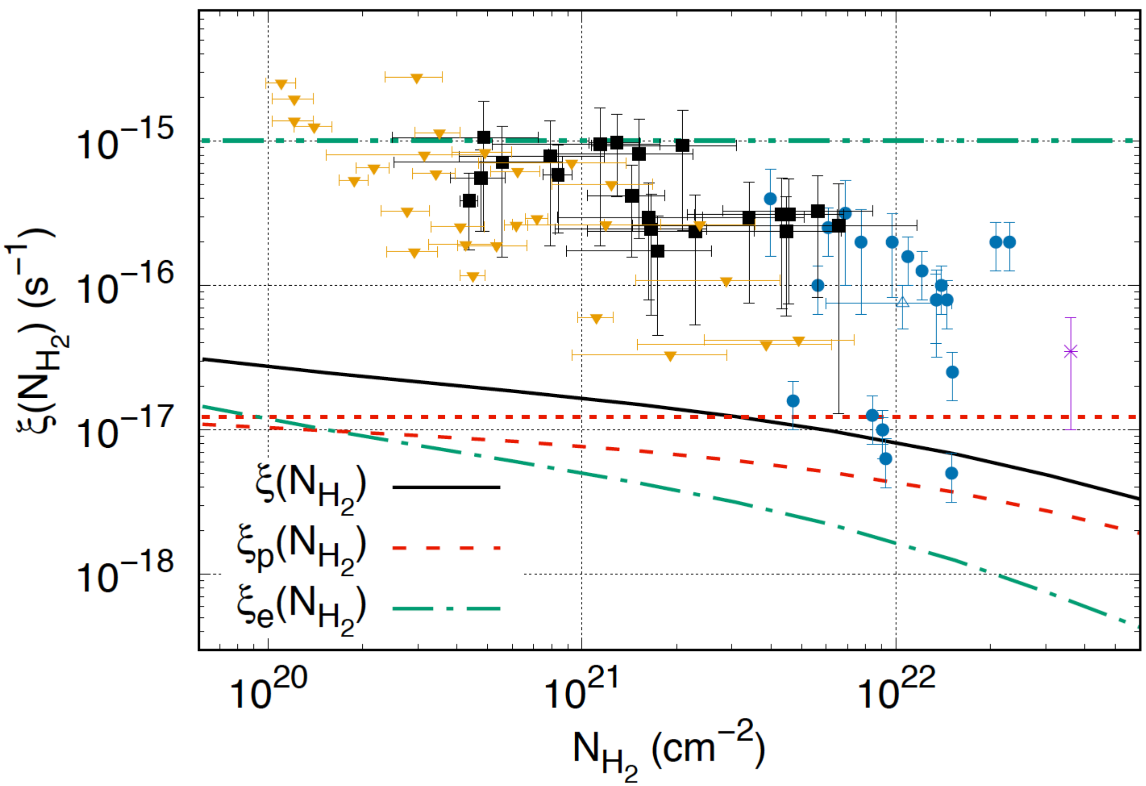
- E < 100 MeV, No pion-decay gamma-rays
- significant contribution to the energy density of ISM (~ eV/cm^3)
- Heating the gas
- Govern the astro-chemistry
- dominate ionization in MCs
- At MeV energy ionization dominate cooling
- Voyager measurement in ISM (Cummings et.al 2016)



LECRs: Ionization

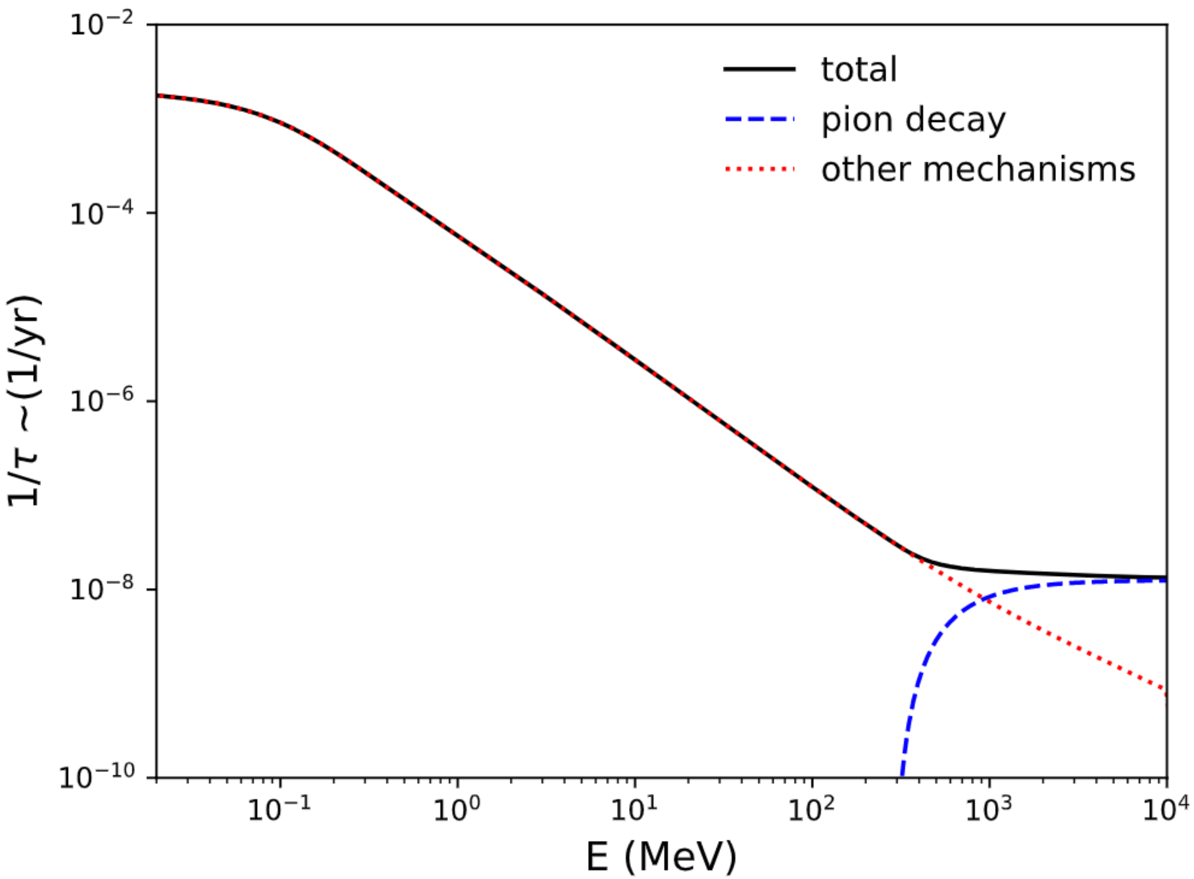
- CR dominates ionization inside MC cores (UV shielded)
- The measured Ionization rates from astro-chemistry are larger than expected



Calculation from Phan et.al 2018, Black curve is the ionization rate assuming voyager measurement is the universal LECR spectrum

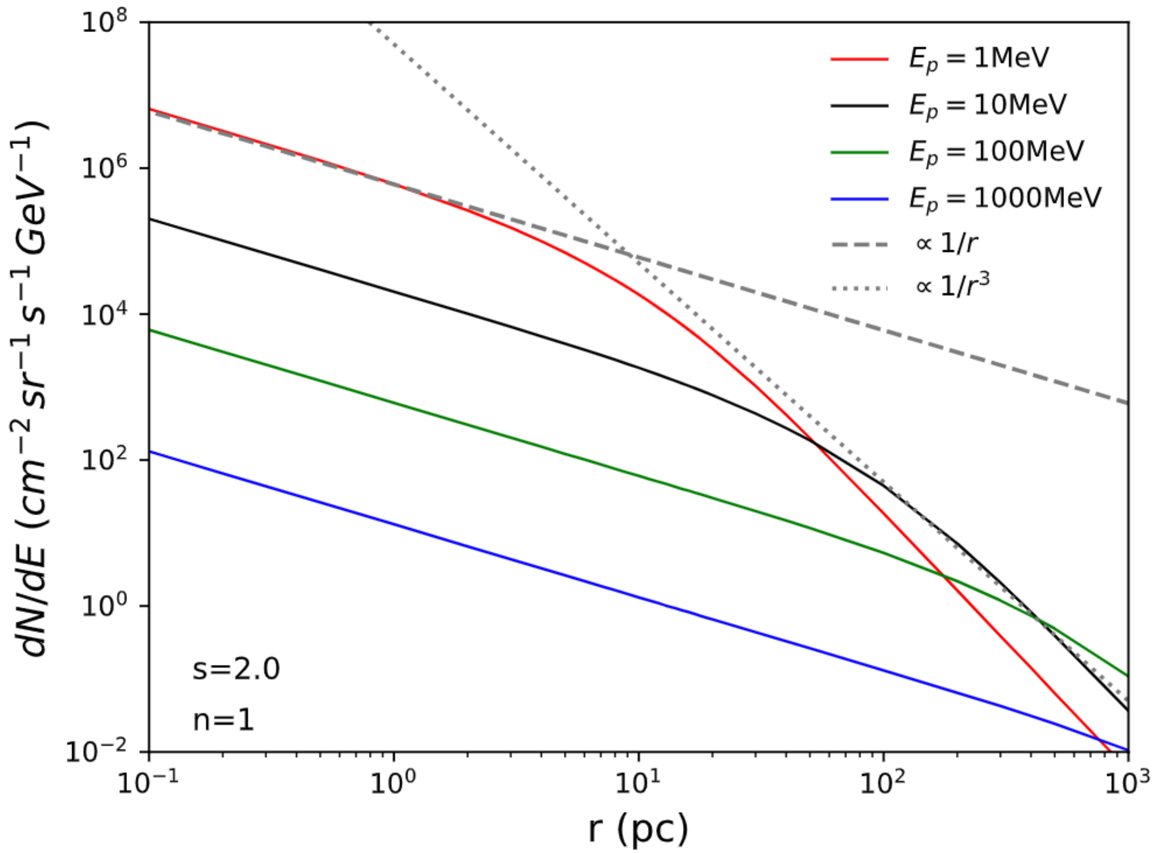
LE CR propagation

- But is the LECR spectrum universal?
- For LECR ionization cooling (see below) is significant in MeV range and the propagation is slow



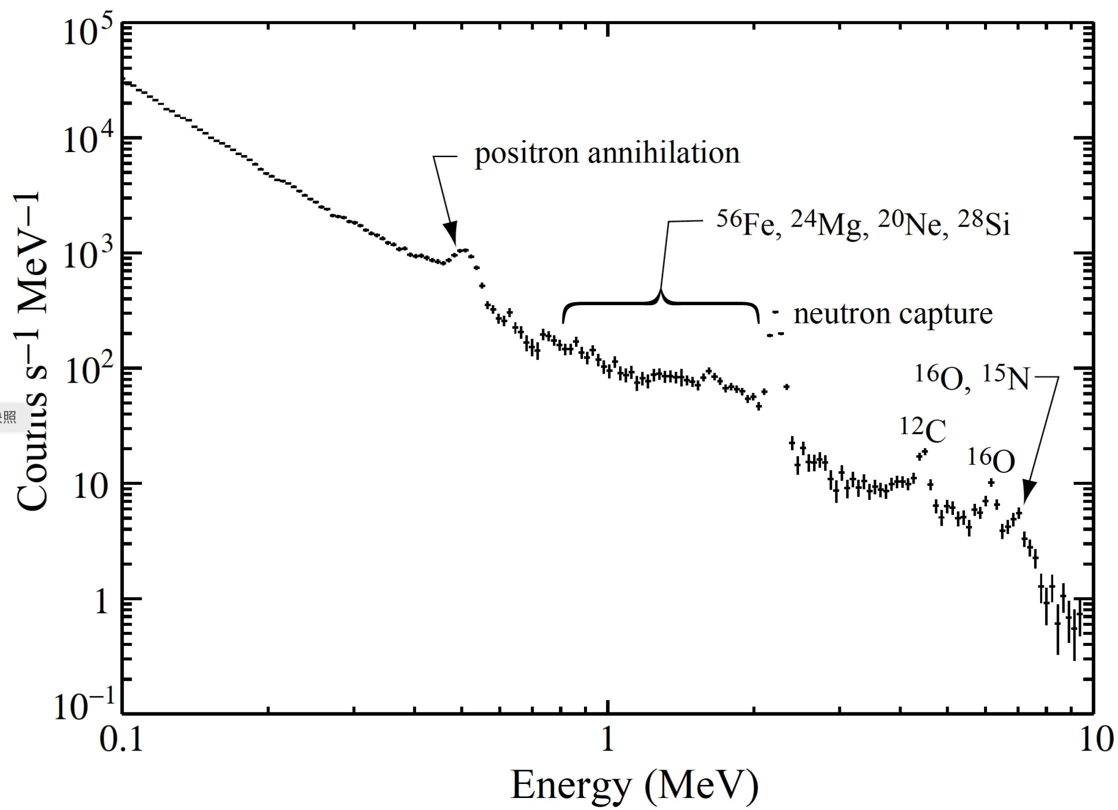
LECR propagation

- LECR should be similar to VHE electrons, cannot propagate far
  Flux can be very different at different distances to the source



Gamma-ray line

- The same CRs can be studied also in gamma-rays through de-excitation line of nuclei
- Well studied in solar flare (Kozlovsky et.al 2002)



Gamma-ray line

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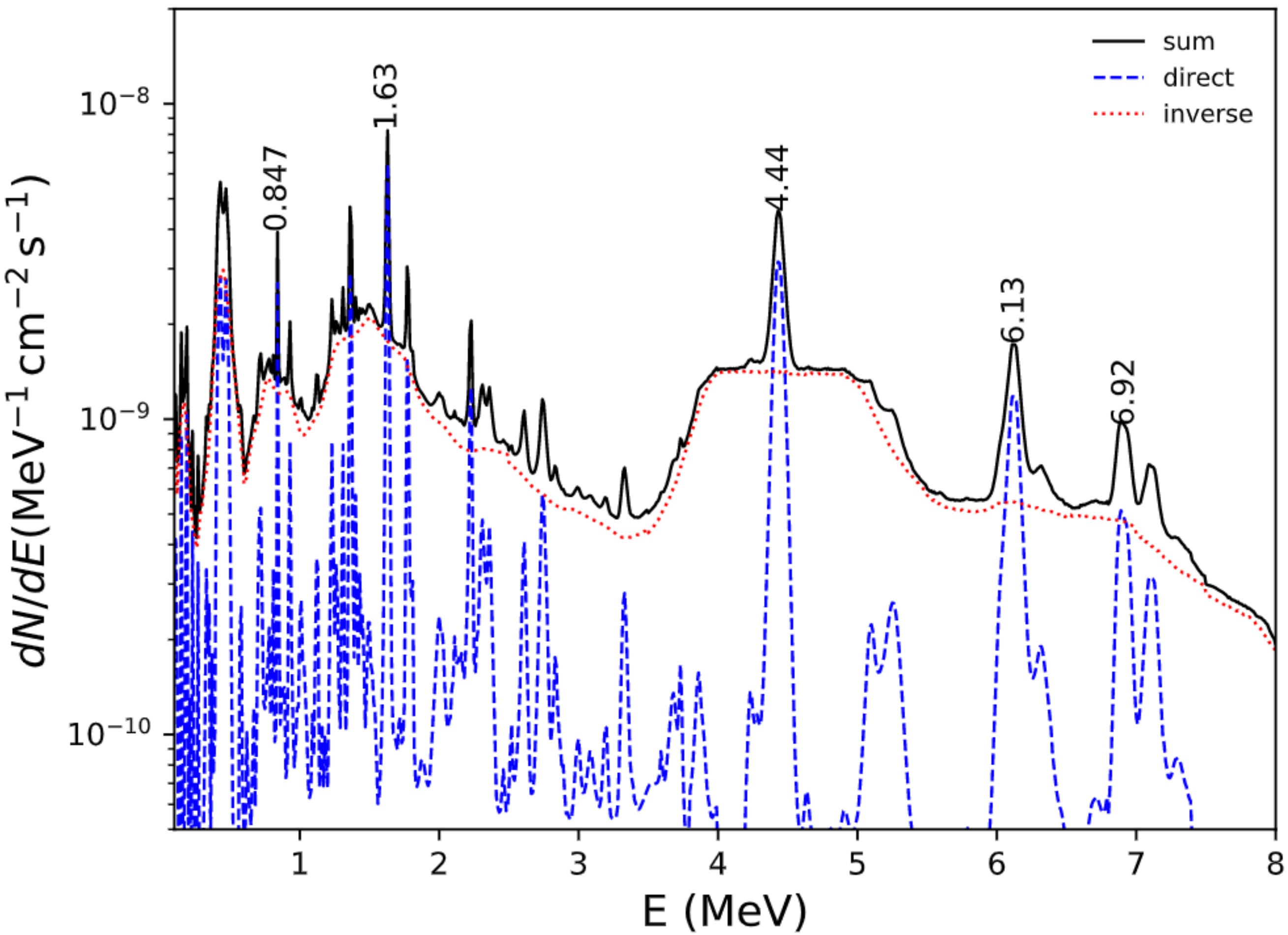
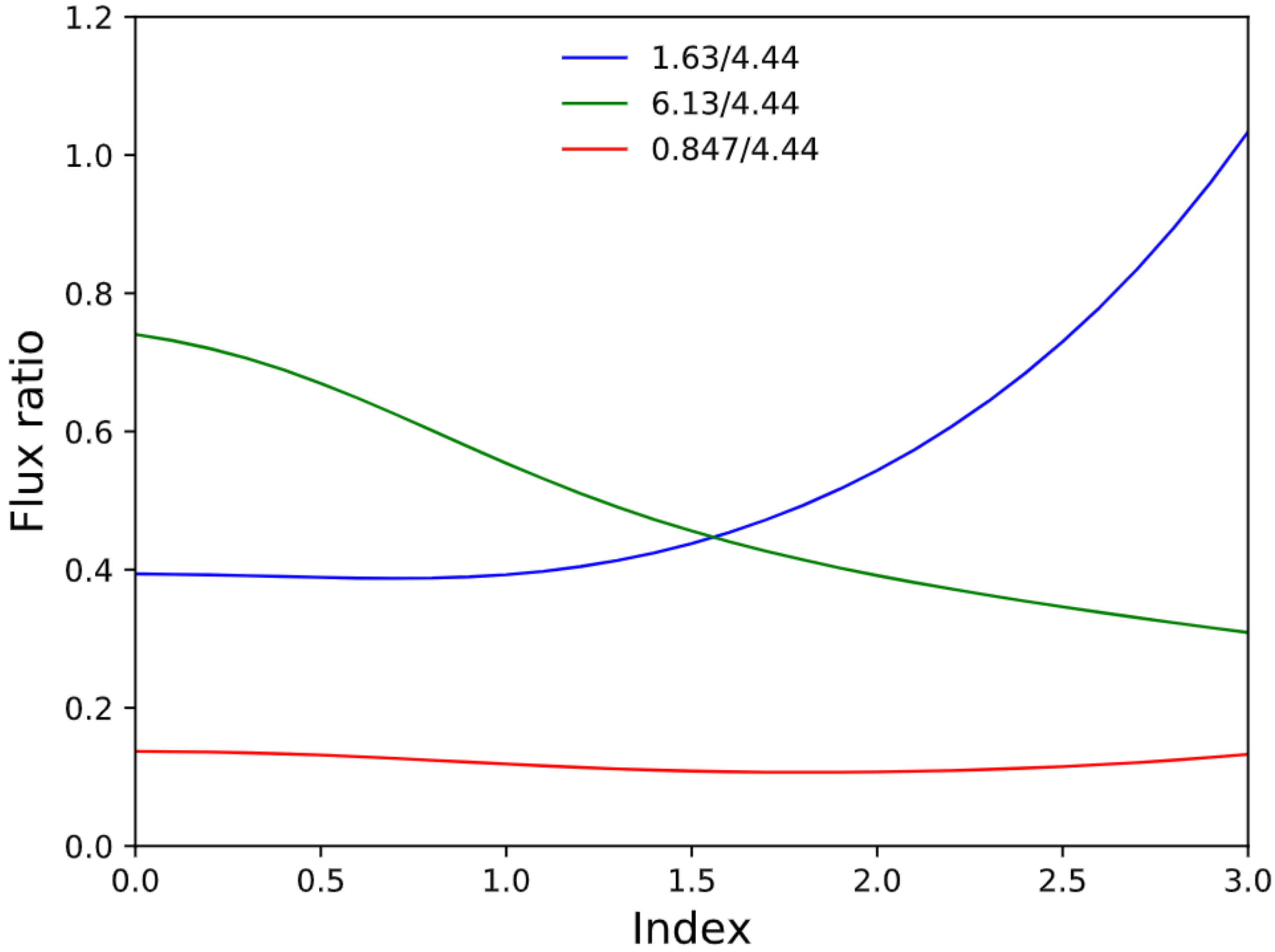


Inverse and direct process

line ratios

Use line ratio to diagnose CR spectrum



line ratios

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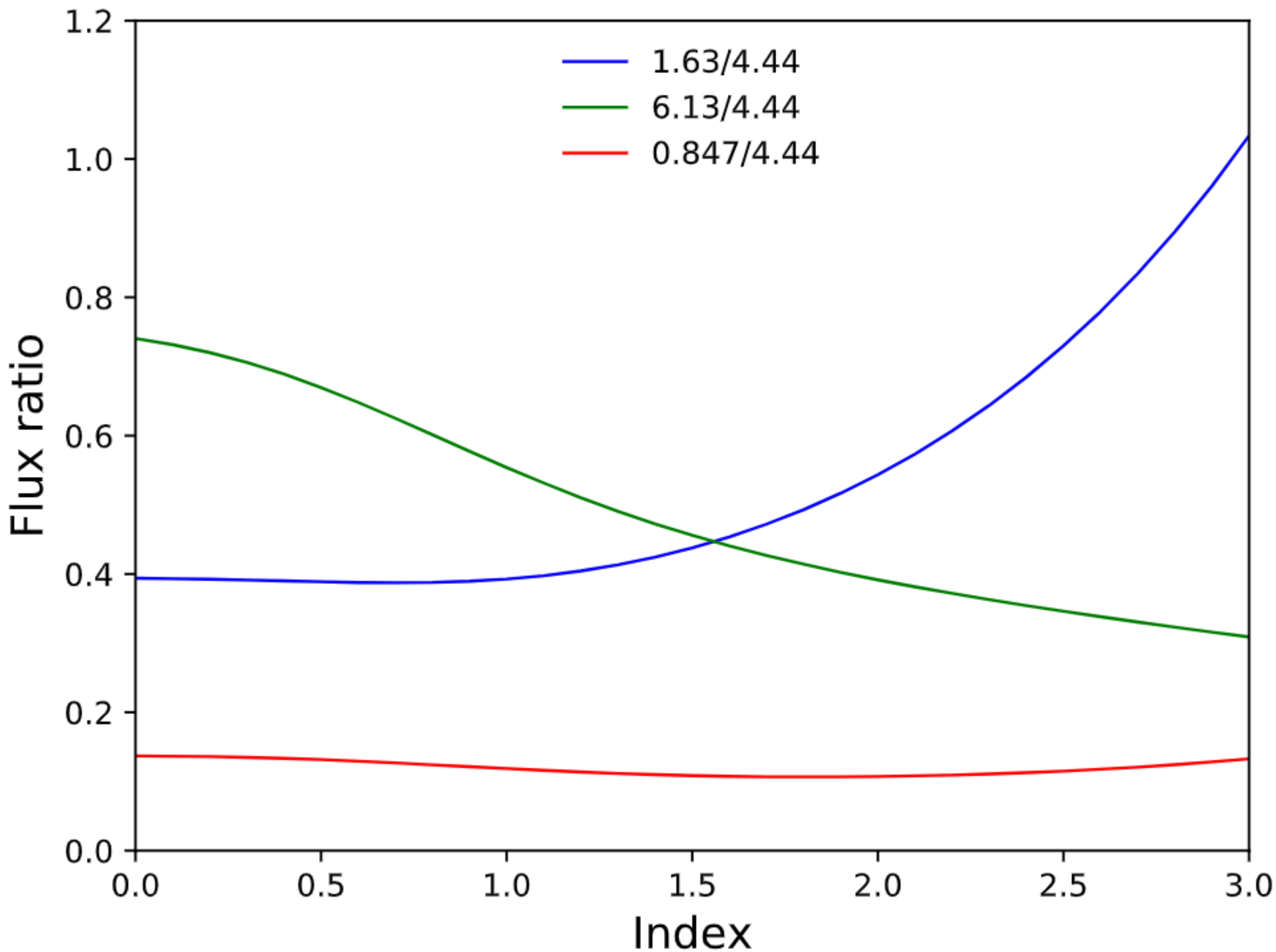
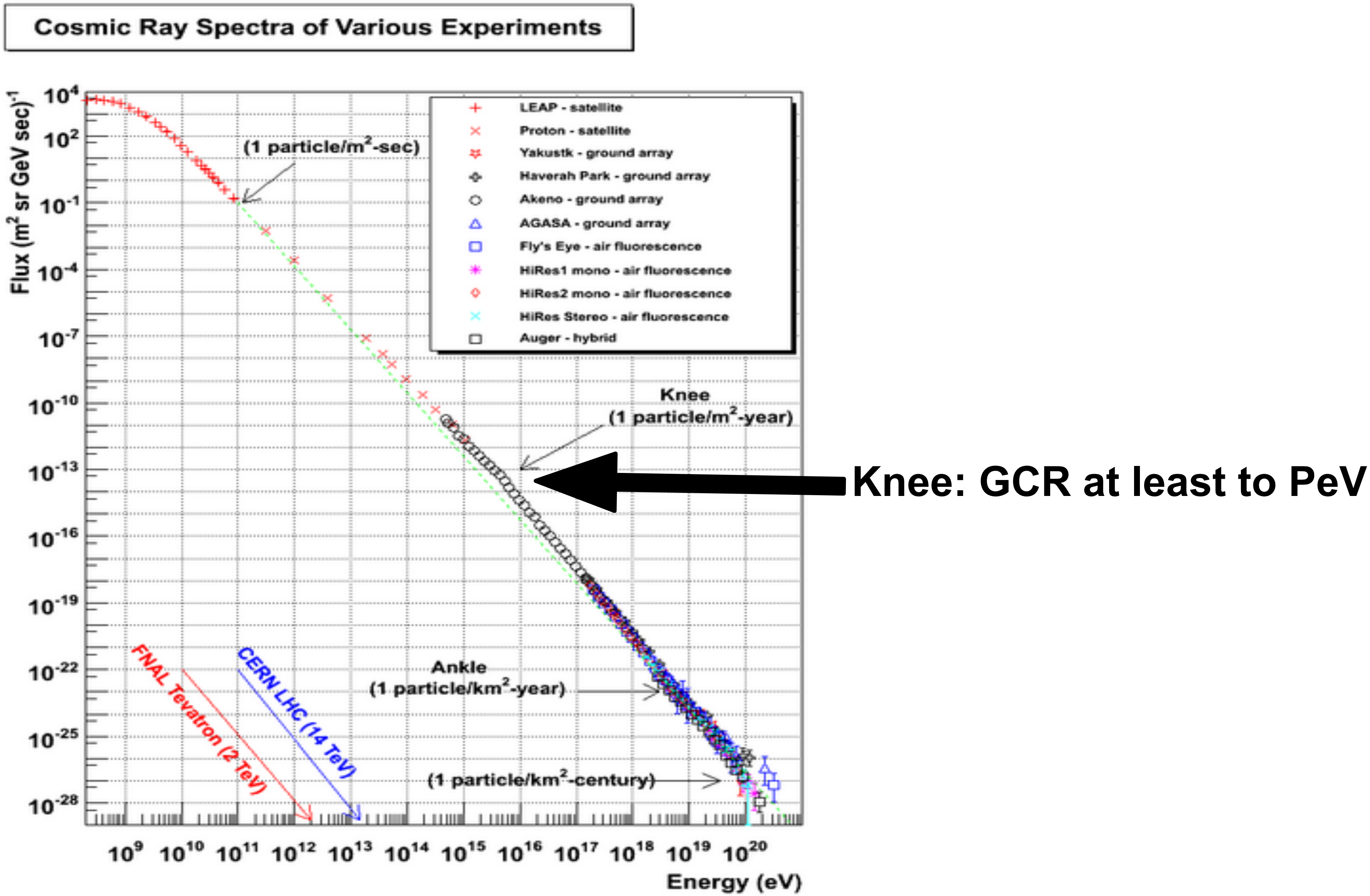
Use line ratio to diagnose CR spectrum



MeV gamma-ray, "LAST" electromagnetic window and interesting physics

PeVatrons

Spectrum



https://www.physics.utah.edu/~whanlon/spectrum.html

SNR as sources

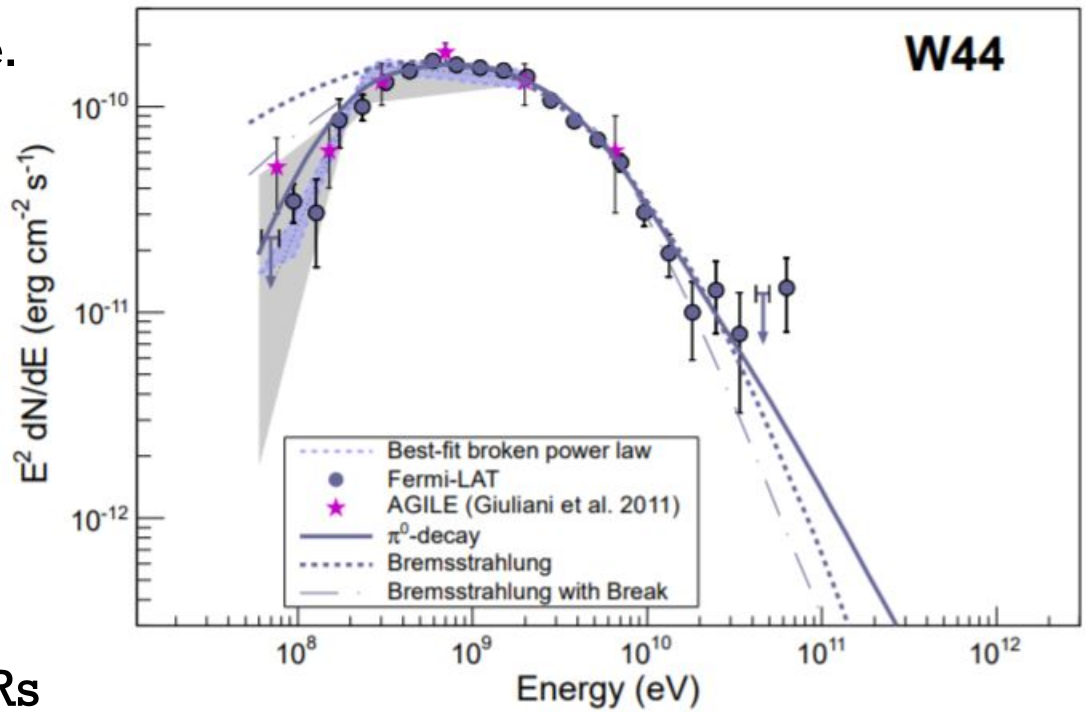
Why SNRs?

- Energy budget reasonable: 1e40 erg/s considering 10% efficiency
- Acceleration: 1st order Fermi acceleration in the shock front
- Observational proofs

SNRs as CR source?

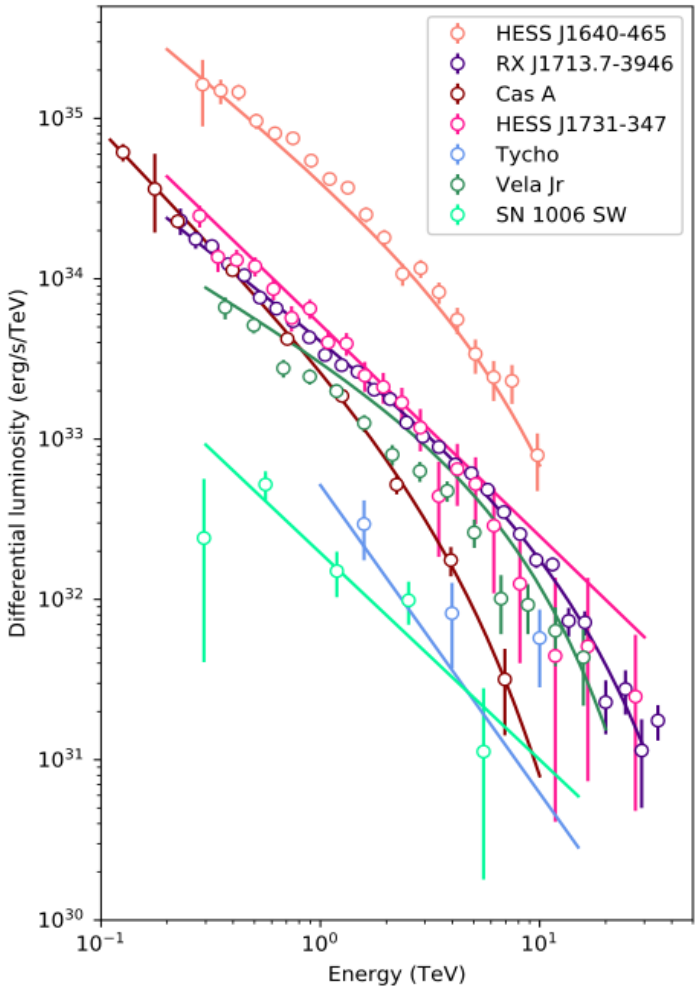
Mid-age SNRs

- Clear Pion-decay feature.
- Hadronic origin or Bremsstrahlung ?
- Break at ~ 10 GeV
- Cannot account for all CRs up to PeV



Fermi Collaboration 2013

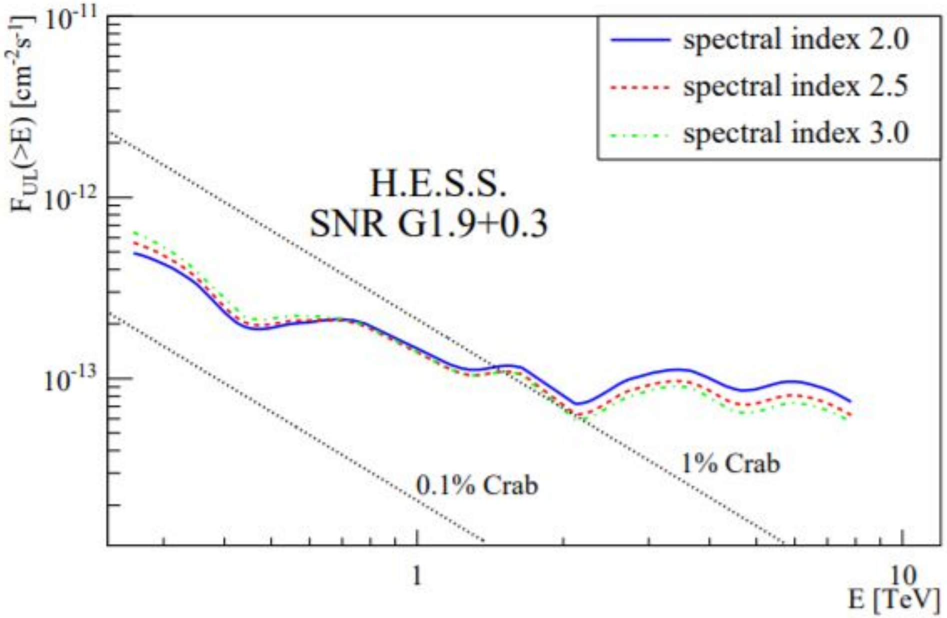
Gamma-ray observation of Young SNRs



- All gamma-ray spectrum of young SNRs shows soft spectrum or early cutoff at ~ 10 TeV
- corresponding to CR energy of 100 TeV
- Hard to address a single power law spectrum of CRs up to PeV

Very young SNRs?

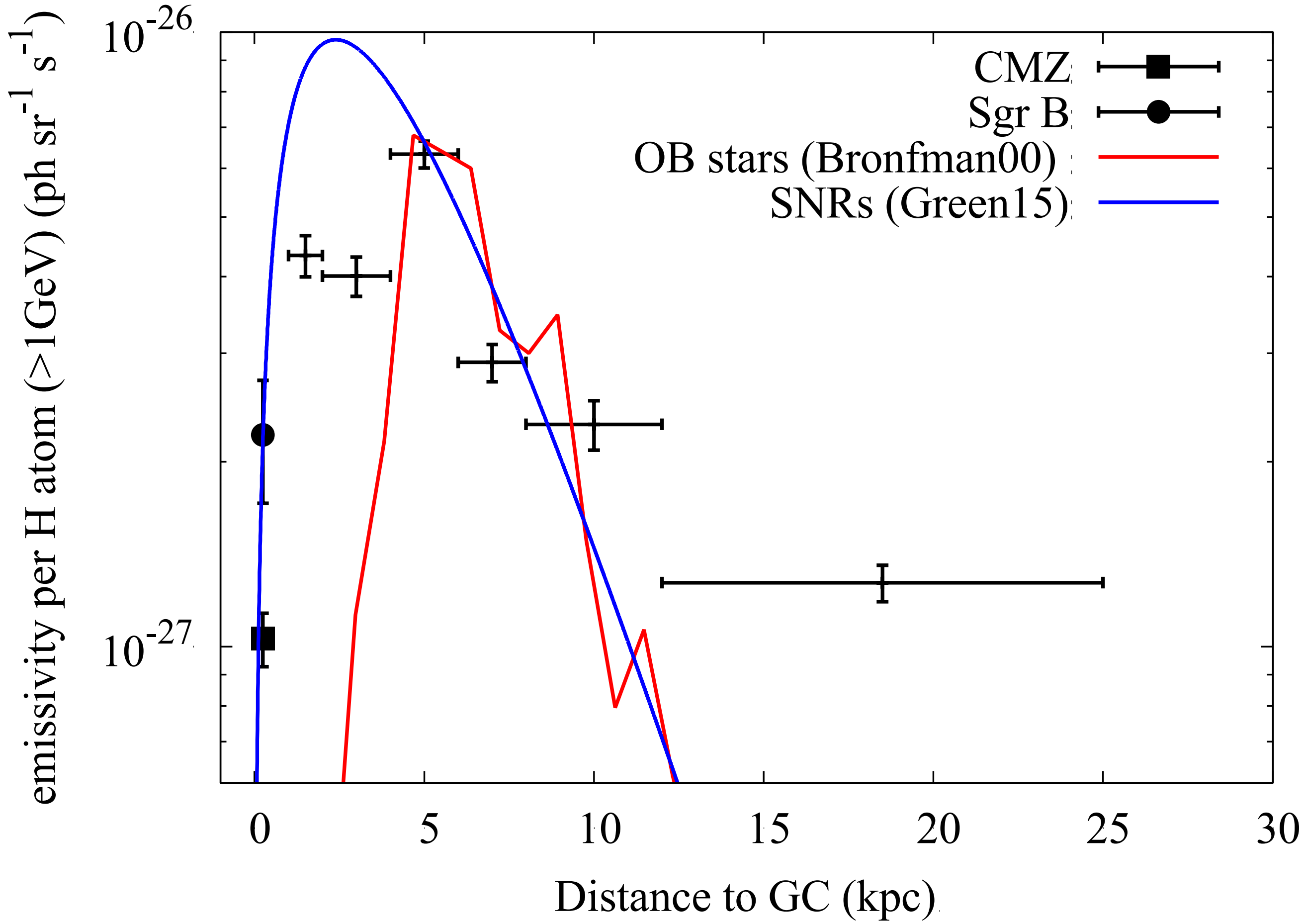
- PeVatron phase could be accomplished only during the first years of the explosion (e.g., Bell et.al 2013)
- The youngest SNR in the Galaxy: G1.9+0.3, t ~ 100 yr
- VHE protons cannot propagate more than 30 pc.
- HESS reveals L(>1 TeV) < 1e32 erg/s can be used to set limit on proton energy budget.
- Considering a high density in the vicinity (near GC), the total energy on VHE protons are below 1e45 erg. Not enough to account for the CR flux up to the knee.



Alternative sources: Young massive clusters

- Isotope measurement favor a superbubble origin. (W.R Binns 2016)
- Most of OB stars exist in associations or clusters, stellar wind can accelerate CRs (Cesarsky & Montmerle 83).
- Efficiency may even better than SNR (high speed wind lasts much longer than SNR shock)
- Sufficient wind power (10^{38} - 10^{39} erg/s for each cluster, more than ~10^{41} erg/s in the Galaxy) to account for CRs

CR Radial distributions



Yang et.al 2016

Young massive clusters

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Westerlund 2 (HST image)

NGC 3603 (VLT image)

- More than dozens of OB stars and WRs
- Compact structures (~ pc)

Young massive clusters

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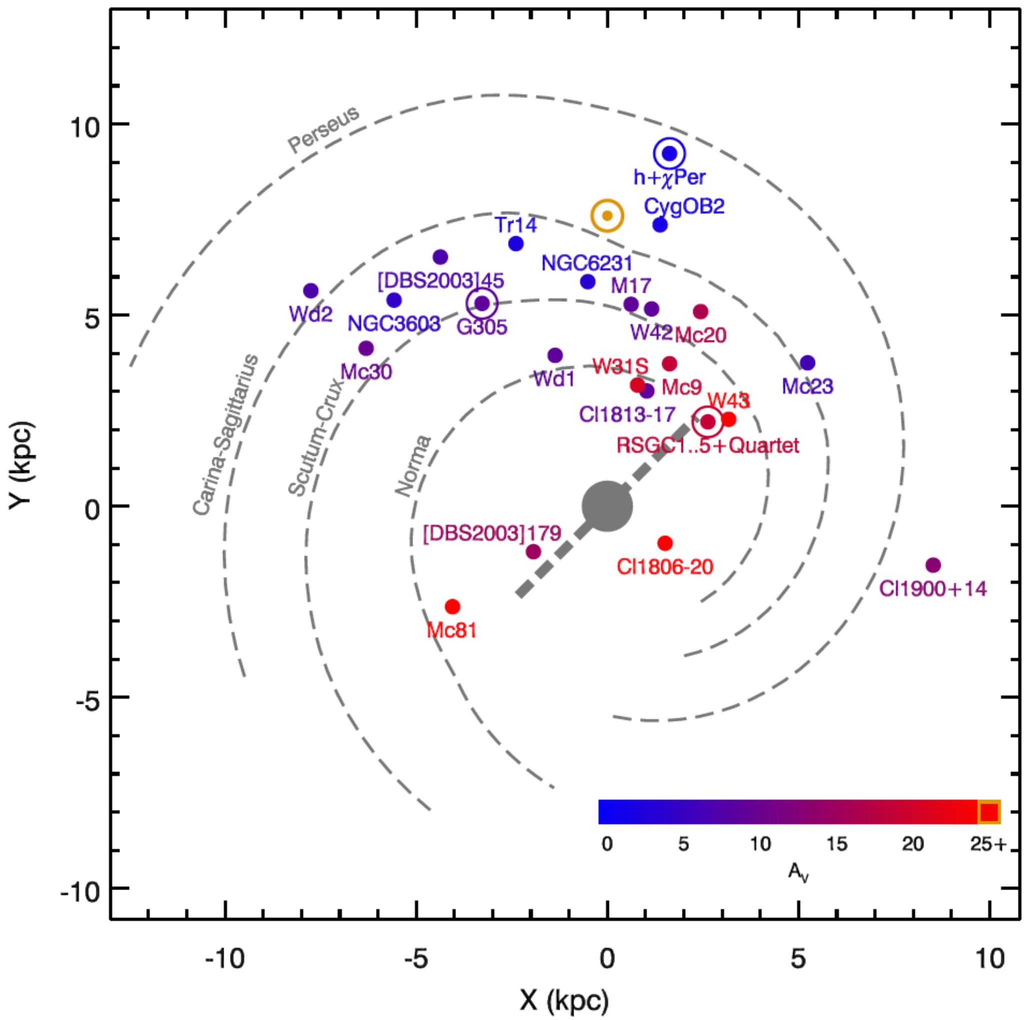


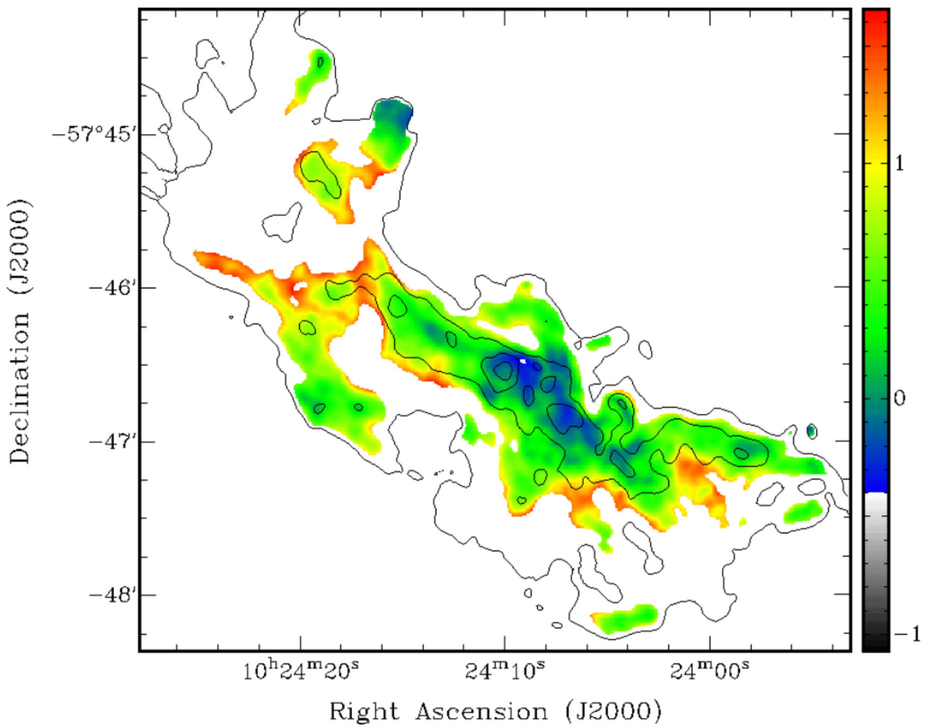
Davies et.al 2011

- ~20 in our Galaxy
- More to be discovered (high extinction in Galactic plane)

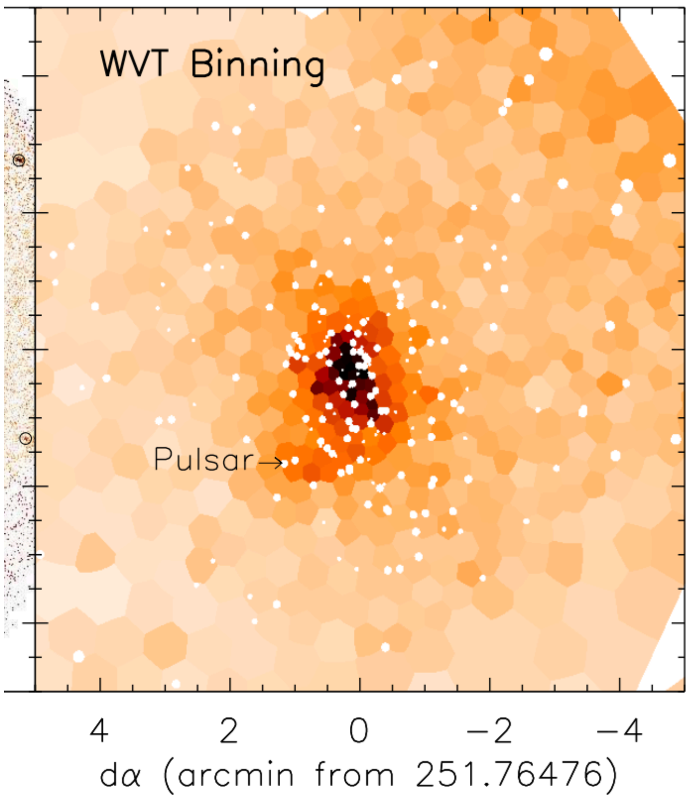
Stellar type	$\log[\dot{M}]$ $M_\odot$ yr^{-1}	V_∞ [km s^{-1}]
WNL	-4.2	1650
WNE	-4.5	1900
WC6-9	-4.4	1800
WC4-5	-4.7	2800
WO	-5.0	3500
O3	-5.2	3190
O4	-5.4	2950
O4.5	-5.5	2900
O5	-5.6	2875

- The wind power of a single young star can be as high as 1e37 erg/s

Acceleration site?



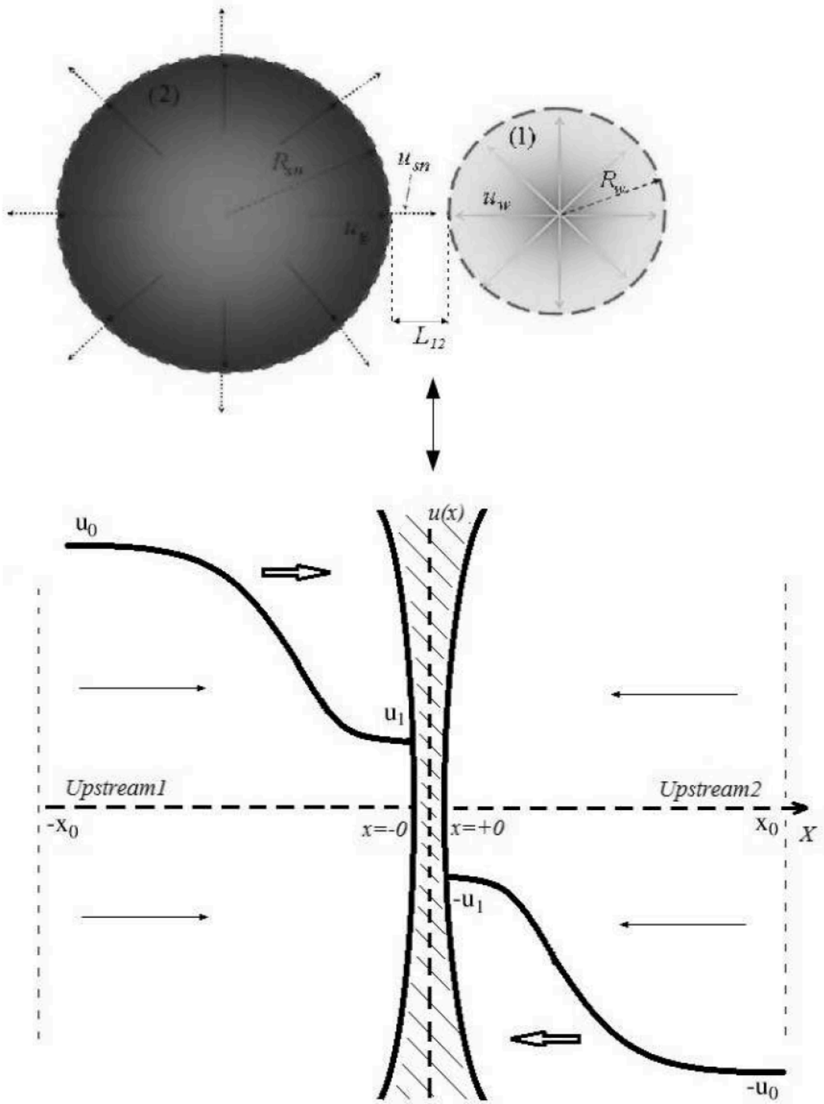
Radio continuum of Westerlund 2
(ACTA 9GHz)



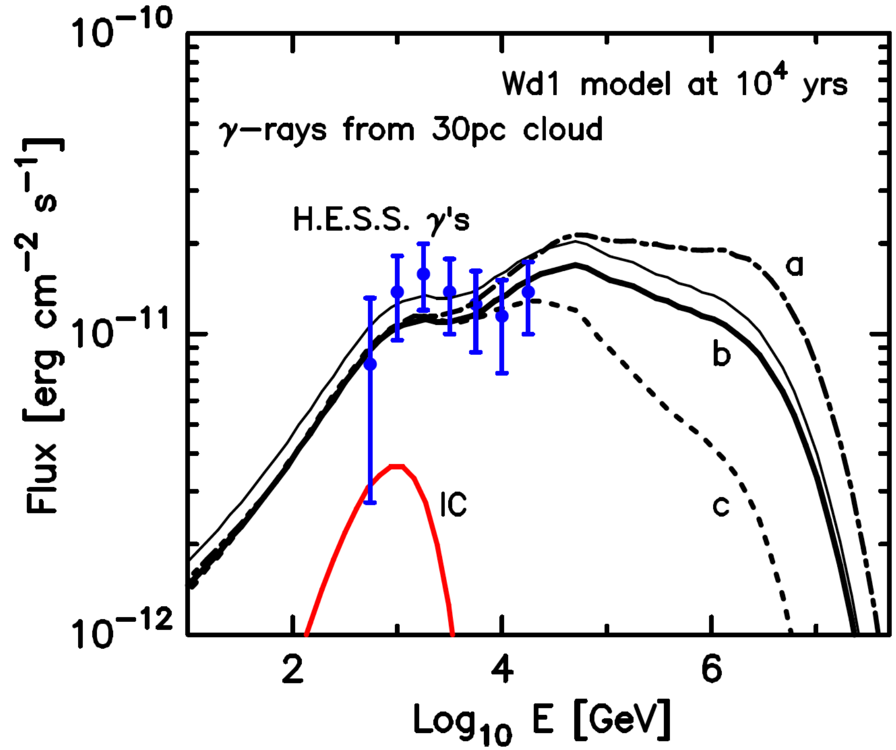
X-ray image of Westerlund 1
(chandra)

- non-thermal Radio and X-rays show hints of particle accelerations

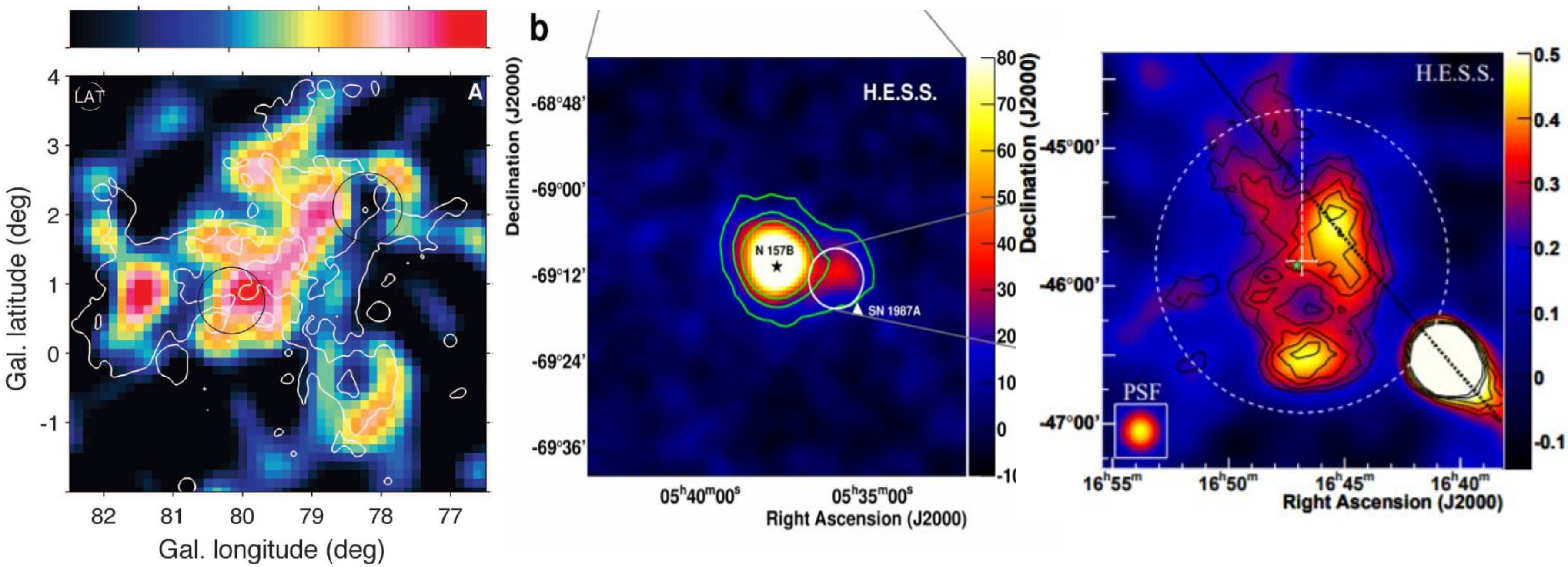
Acceleration site?



Bykov et.al 2014



- One promising site: SNR shock colliding with wind termination
- Can accelerate to PeV



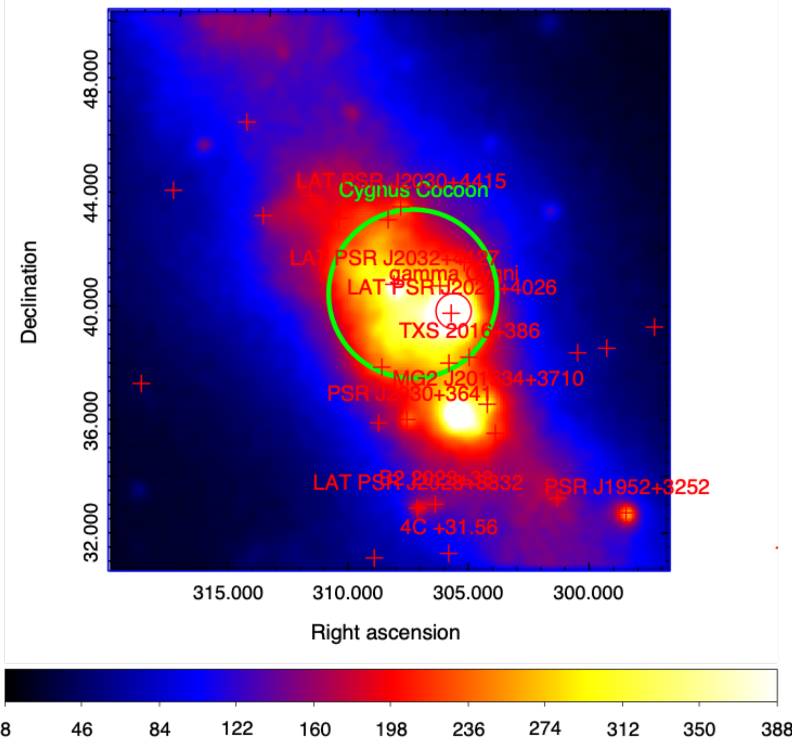
Cygnus Cocoon (Fermi Collaboration 2012)

30 Doradus C (H.E.S.S Collaboration 2015)

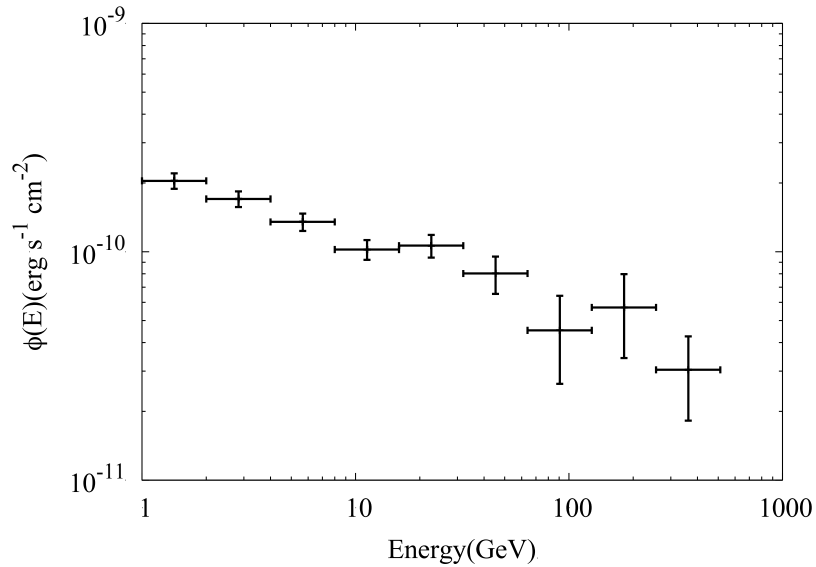
Westerlund 1 (H.E.S.S Collaboration 2011)

Source population

- Cygnus Cocoon



Fermi LAT counts map (>1 GeV)



Spectral Index of -2.2, up to 500 GeV with PASS 8 data.

- More: NGC3603 (Yang & Aharonian 2017), Westerlund 2 (Yang et.al 2018), W43 (Yang & Wang 2020), W40 (Sun et.al 2020) RSGC 1 (Sun et.al 2020)… and more to be discovered and investigated

- All reveal extended gamma-ray emission and hard (2.3 type) gamma-ray spectra

Radial distribution of Cosmic Rays

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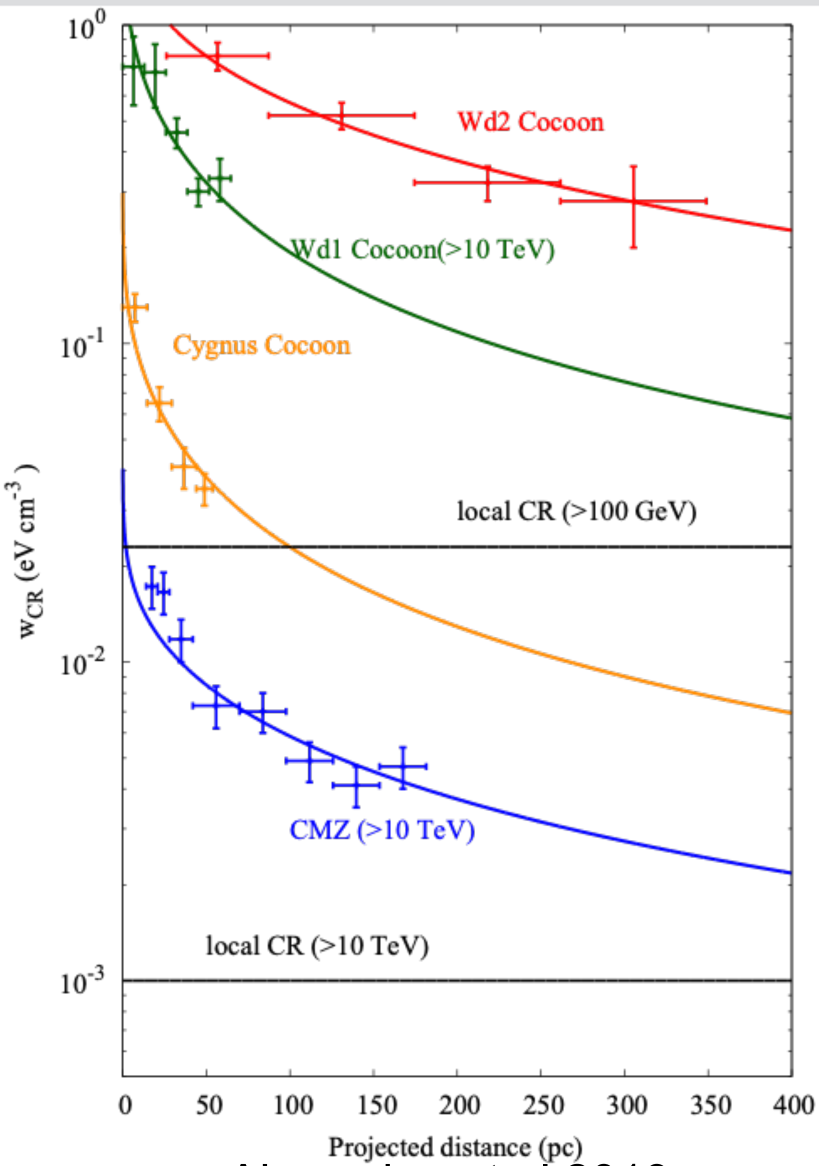
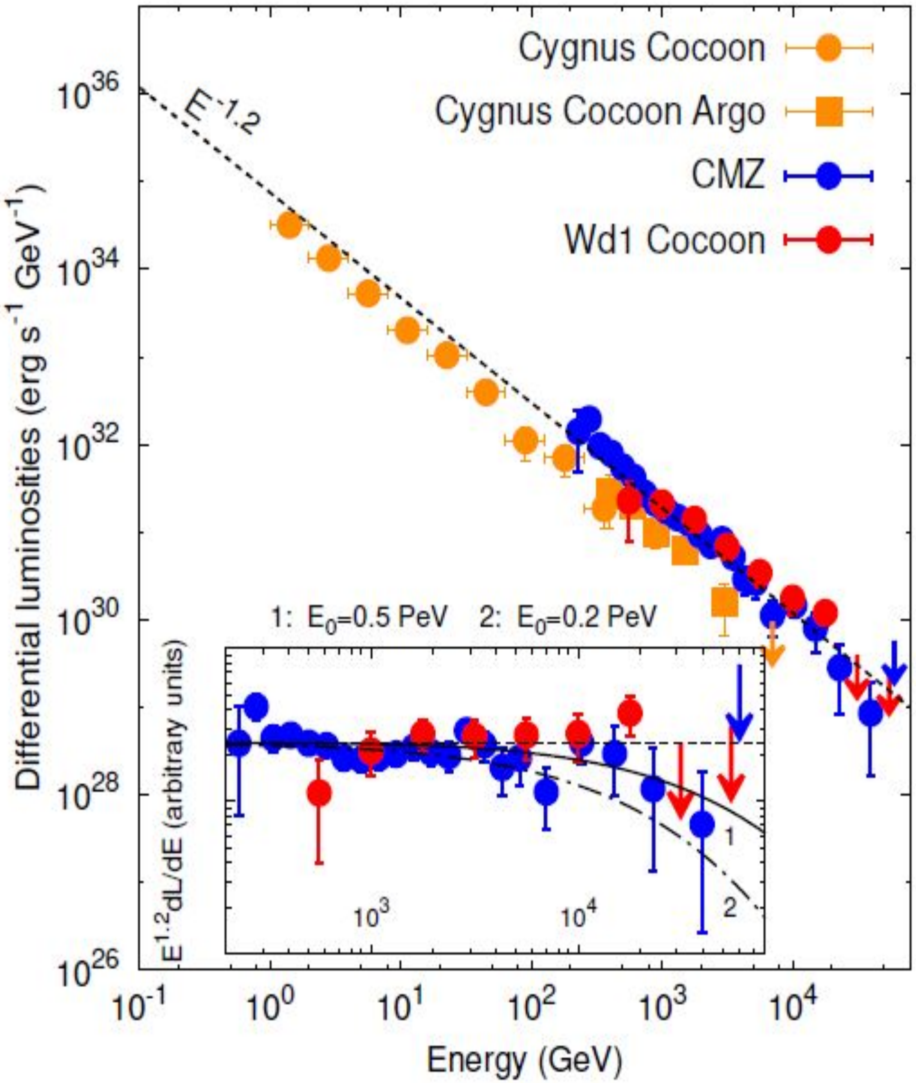


Aharonian et.al 2019

- CR distribution derived by gamma-ray profile and gas distributions
- All four sources (Wd1, Wd2, Cygnus cocoon, GC) show 1/r distribution of CRs
- In diffusion, 1/r profile implies a continuous injection (in the lifetime of clusters)

Massive star clusters

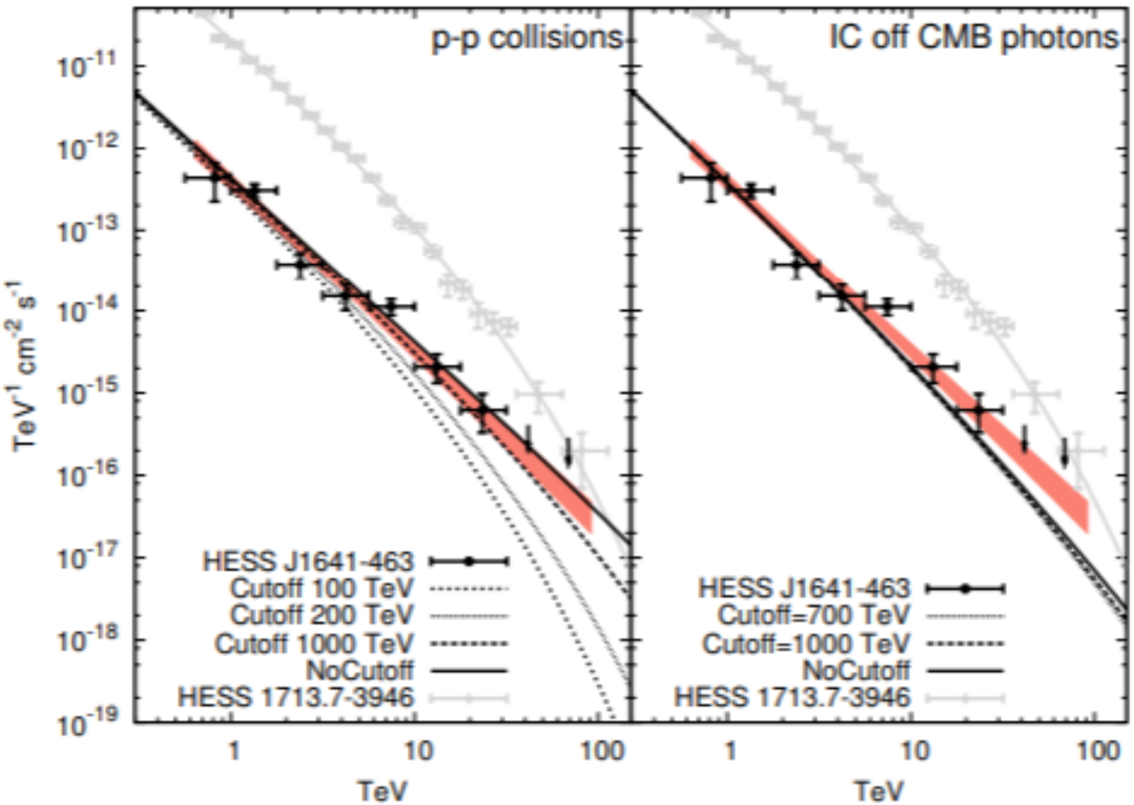


Aharonian et.al 2019

- Cygnus cocoon, Wd 1 and CMZ all emit multi-TeV gamma-ray.
- The spectrum of CMZ and Wd1 put lower limit of cutoff of parent proton spectrum to be several hundred TeV
- PeVatrons?
- LHAASO is the ideal instrument!

PeVatron identification

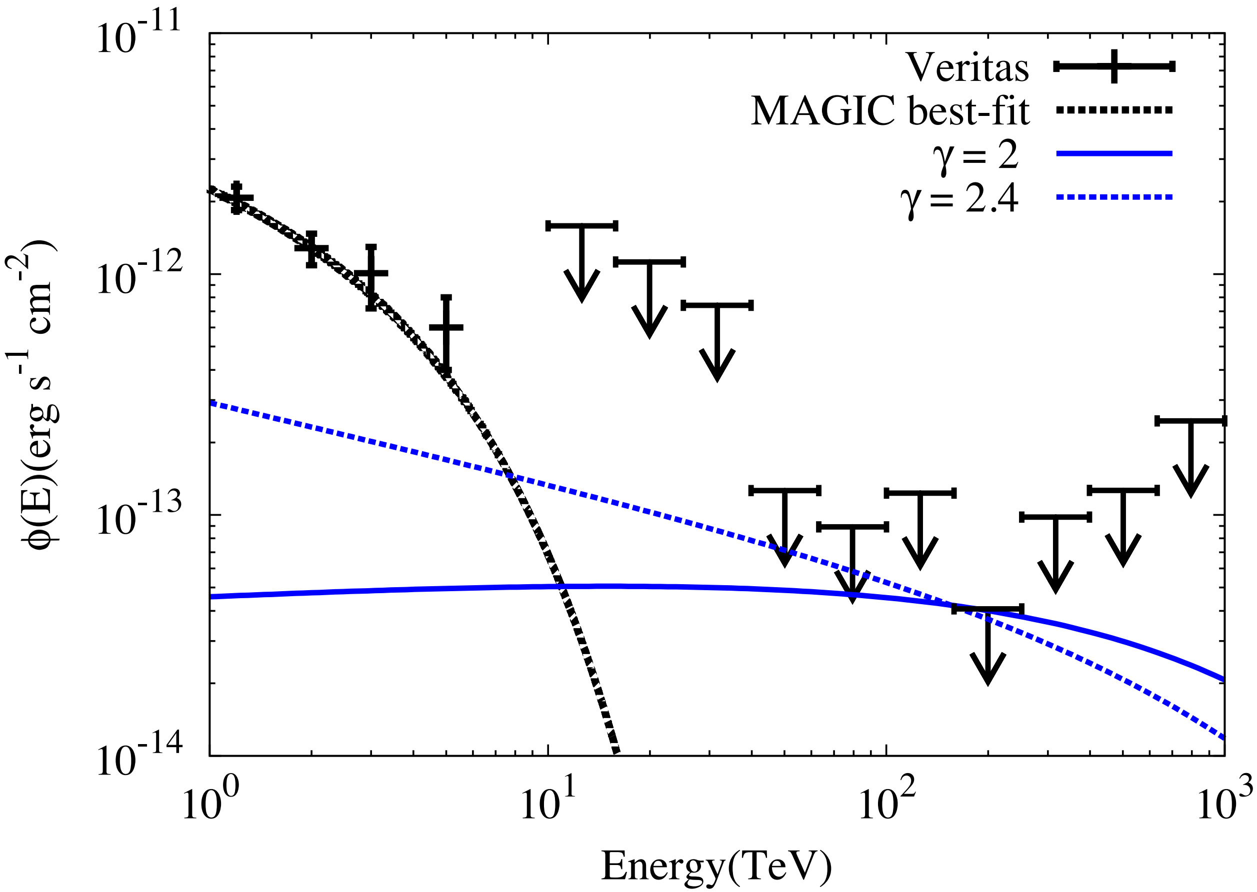
- **Hard gamma-ray spectrum without cutoff can hardly be addressed in leptonic model (cooling and KN effects).**
- **no-cutoff in the gamma-ray spectrum up to 25 TeV => no-cutoff in the parent proton spectrum up to ~ PeV.**



Hess J1641-463
(H.E.S.S collaboration 2016)

LHAASO progress

Cas A upper limit (preliminary)



- total CR injection rate above PeV < 1.5e35 erg/s
- In tension with estimated by Drury 2012 : 1e40erg/s

LHAASO progress

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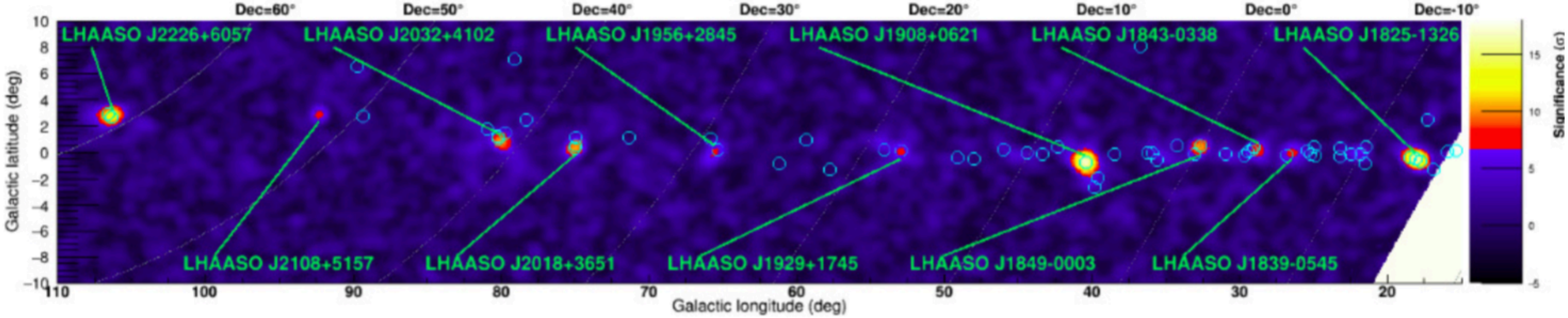
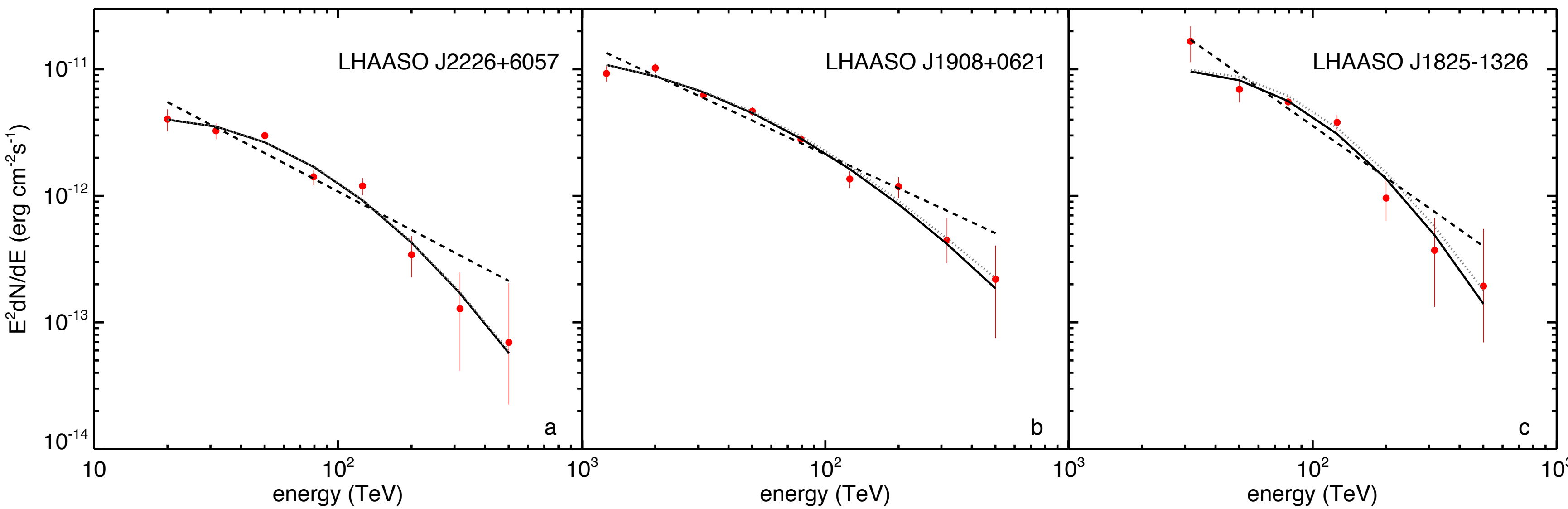
12 UHE sources detected

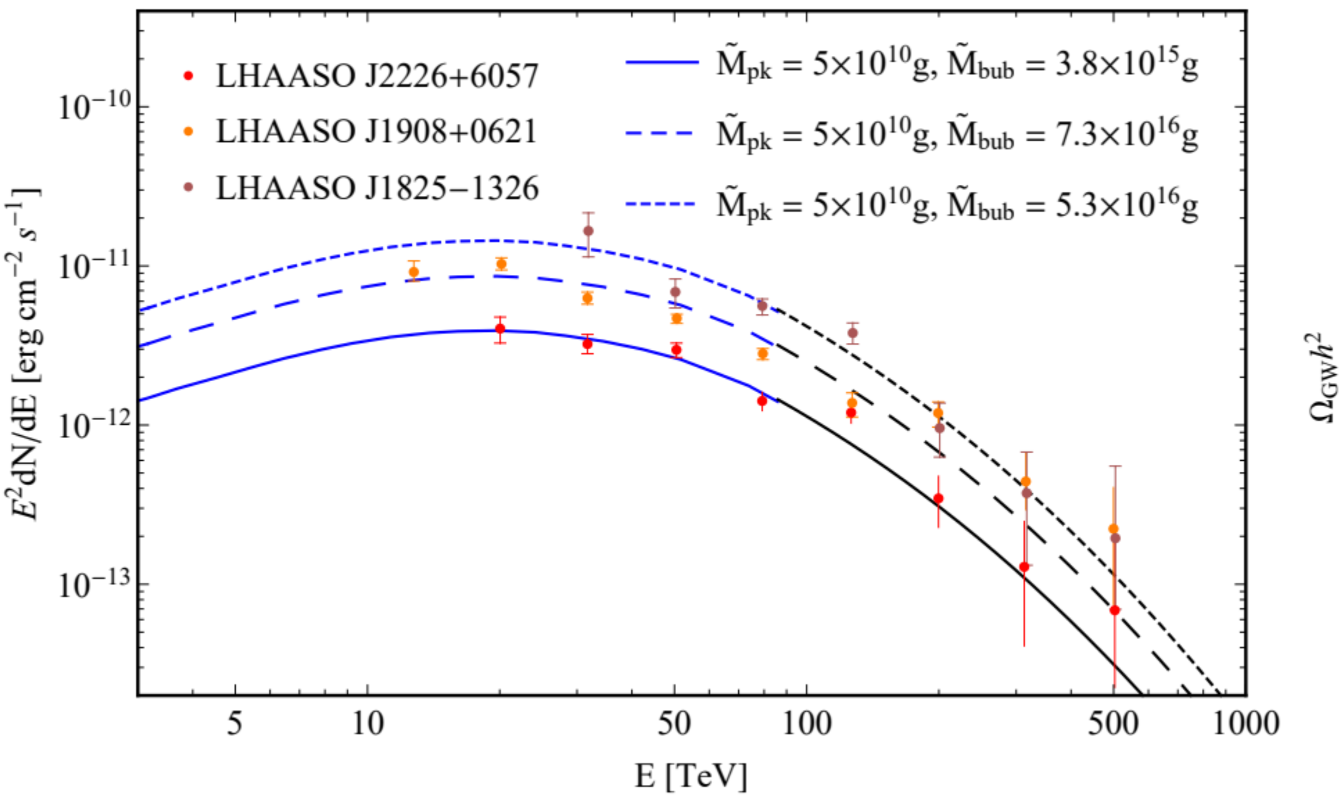




Definitely PeVatrons (hadronic or leptonic)
The Galaxy full of powerful accelerators
but origin still unclear : SNR, YMC, PWN, TeV halo?

LHAASO progress

More exotic origins: e.g., from PBH bubbles



for details, see Cai et.al [arXiv:2105.11481]

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Prospect

Gamma-ray instruments sensitivities

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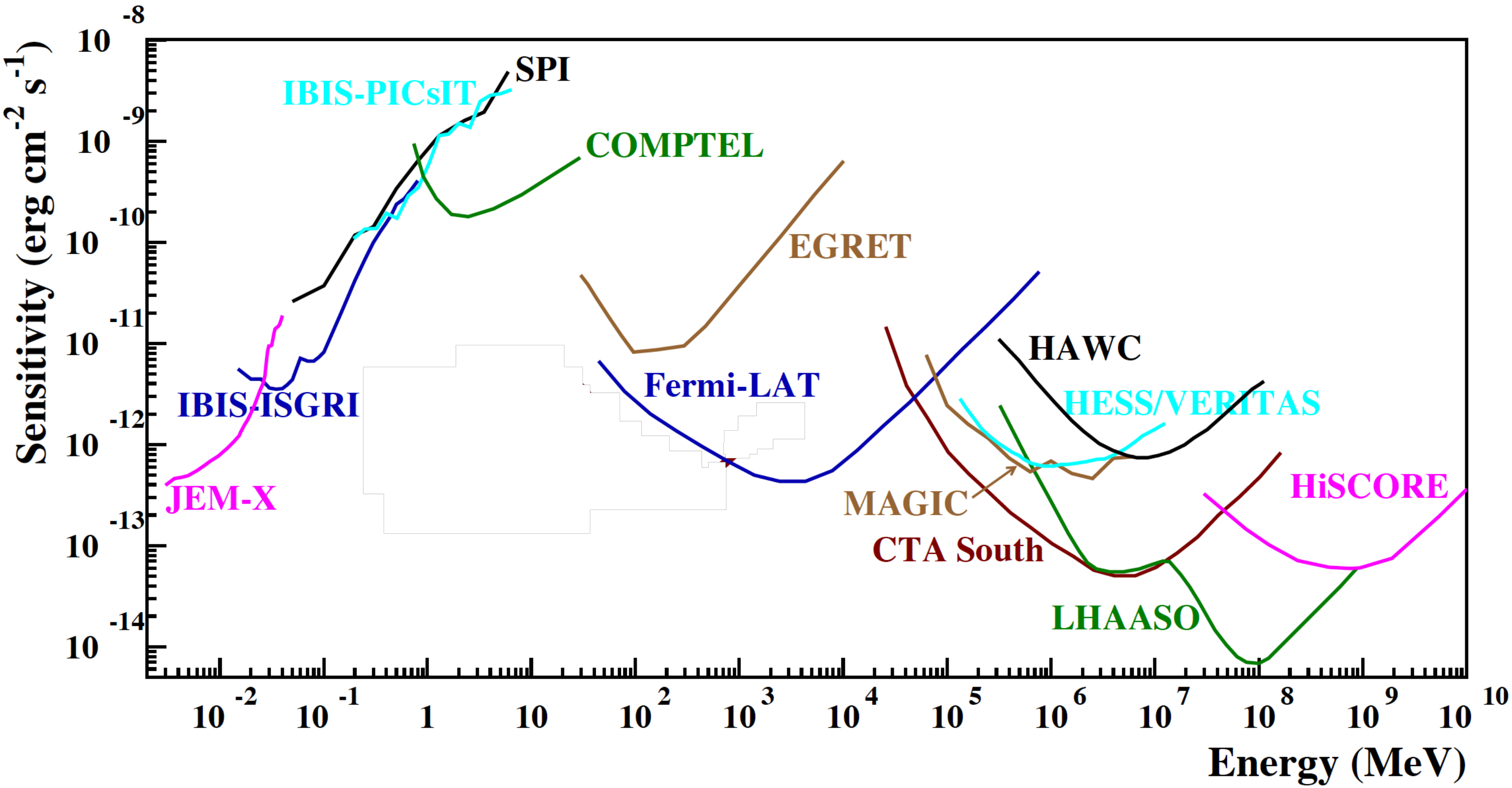

Gamma-ray instruments sensitivities

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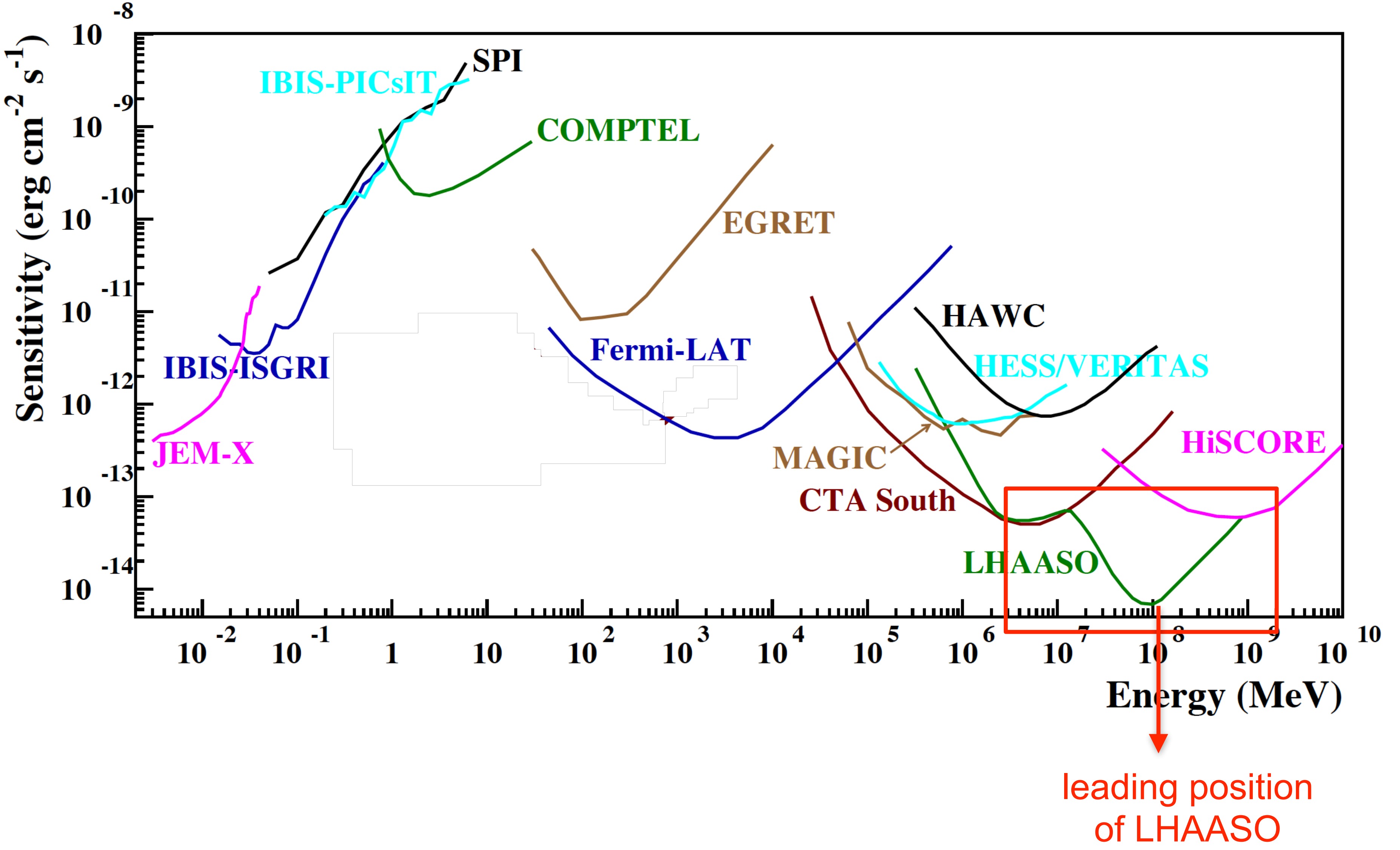

LHAASO sensitivities

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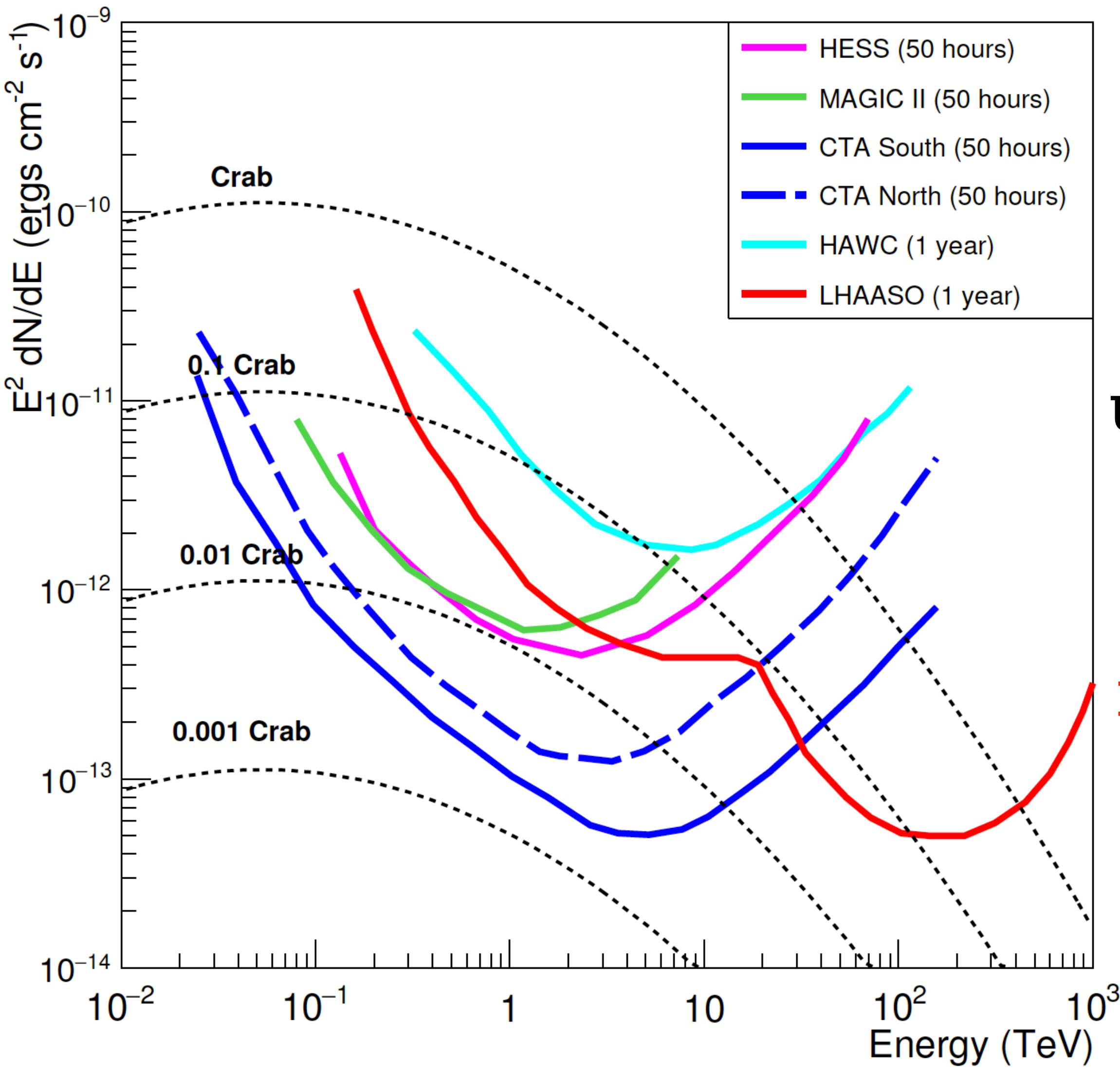

Unprecedented above 50 TeV

ideal PeVatron hunter

But limited angular resolution

IACTs

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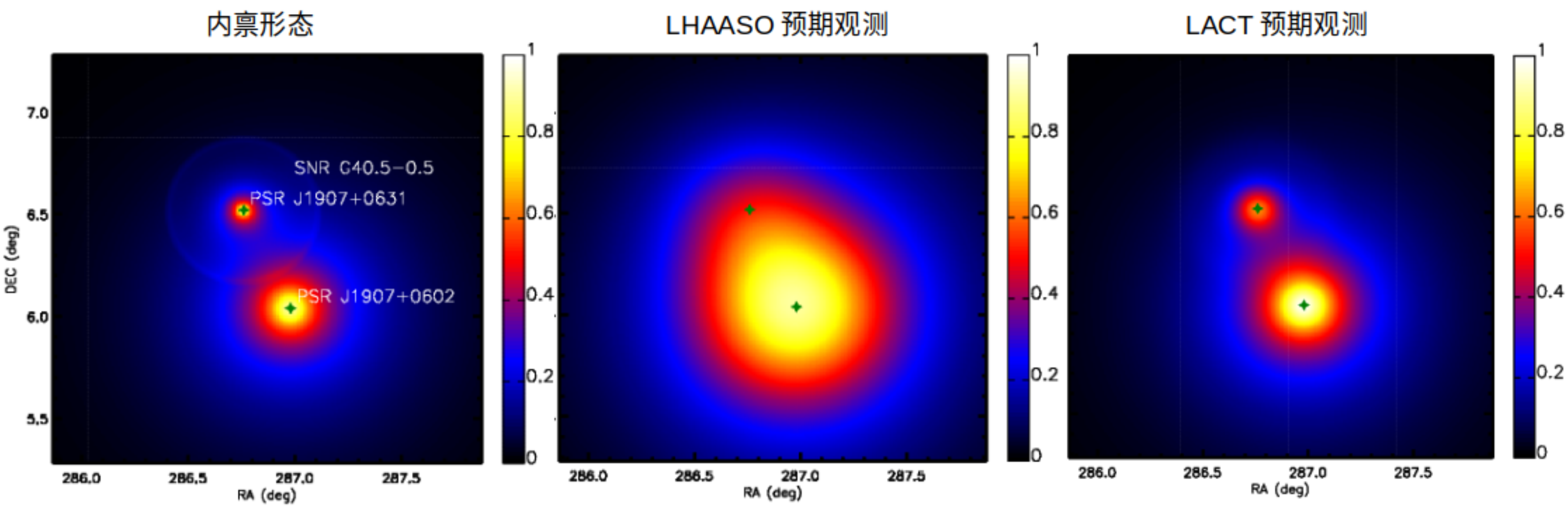
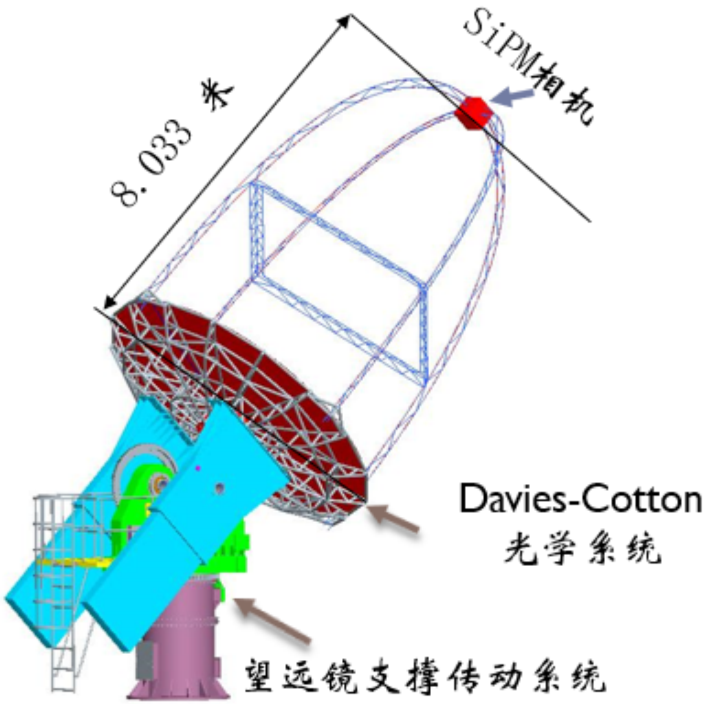
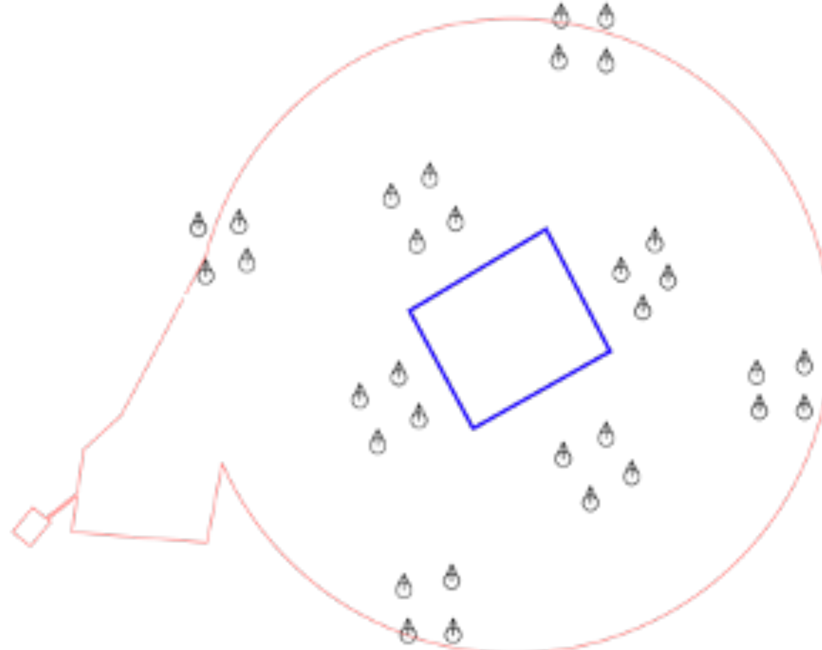
IACTs can provide angular resolutions as good as 0.05 degree

Important in crowded environment.



IACTs in LHAASO site





6m telescopes

8 X 4 arrays in LHAASO site

Prototype nearly finished

First light soon!

Predicted sensitivities

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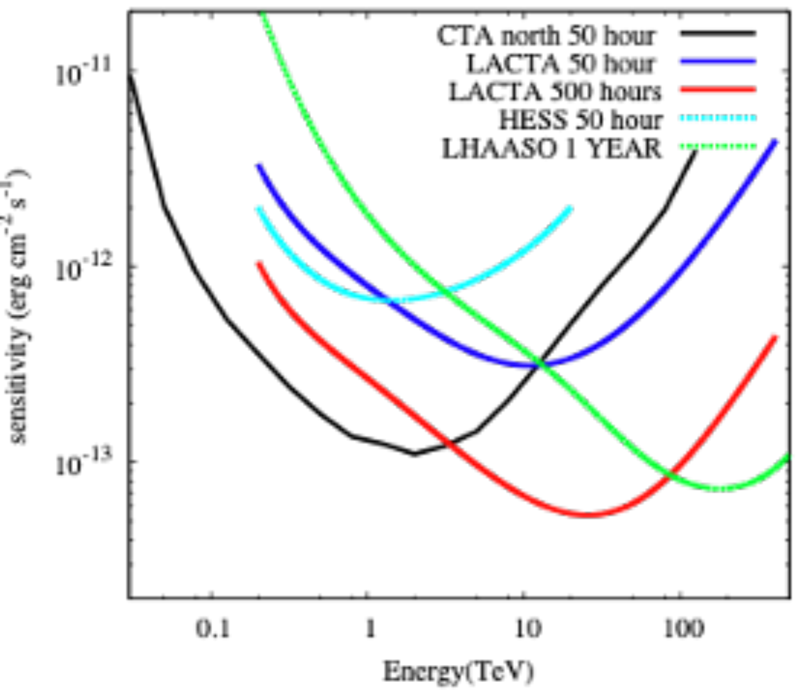
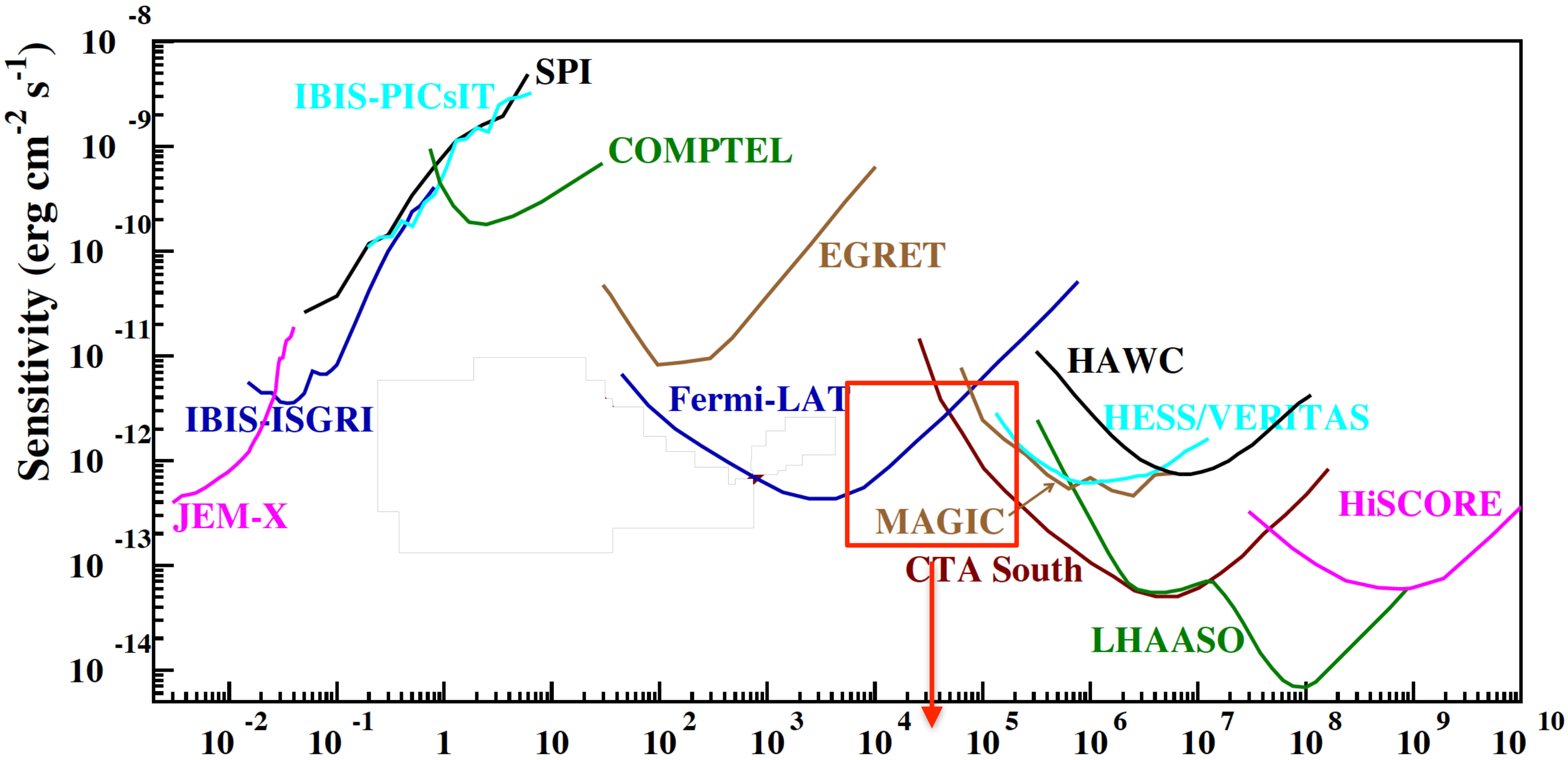
Synergy with LHAASO
Detailed morphology study of PeVatrons, TeV halo, PWN…



目标源	R.A	DEC	每年曝光时间（小时）	50TeV以上光子数（500小时）	100TeV以上光子数（500小时观测）
Crab	83.55	22.05	1090	400	100
LHAASO J1908	287.05	6.35	913	800	110
Cygnus Cocoon	308.05	41.05	1190	200	100
LHAASO J1825	276.45	-13.45	600	1000	350
LHAASO J2226	336.75	60.95	1267	600	140
W43	282.35	-0.05	833		75

Gamma-ray instruments sensitivities

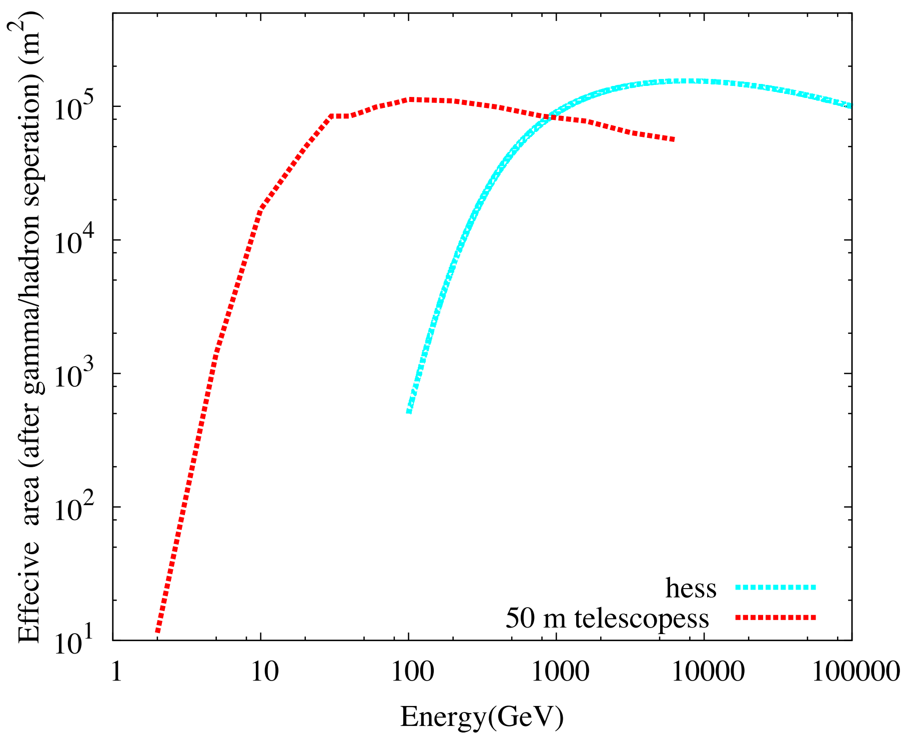


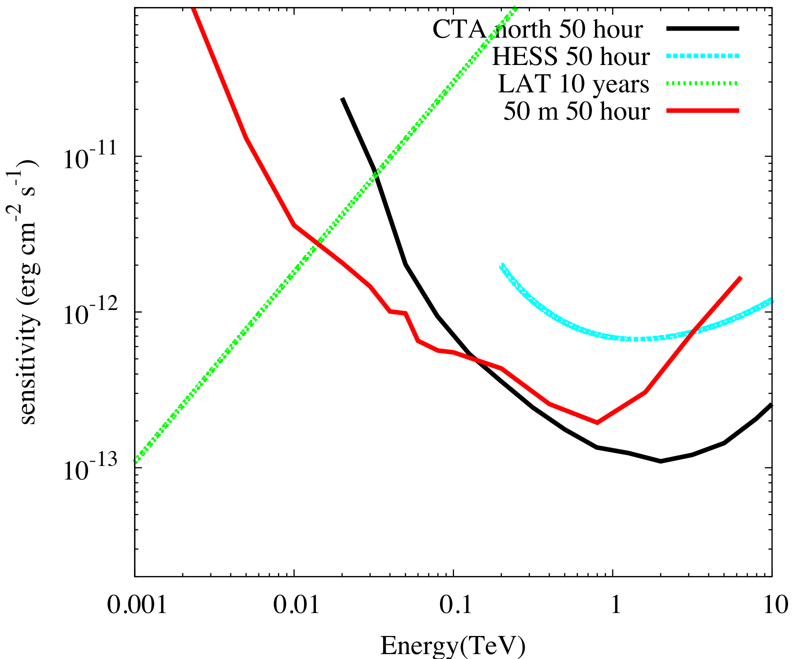
Gap of sensitivities between
10 -100 GeV

Large mirror IACTs

IACTs can still work in this energy range

- Larger mirrors (2 x 50 m in diameter)
- high-QE PMT/SIPM
- Higher altitude
- effective area of 1e4 m^2 at 10 GeV, 1e5 m^2 at 20 GeV
- 15 ~ 100 GeV better sensitivities than LAT and CTA





Possible science

Due to the large effective area, the most interesting area should be time-domain astronomy:

- Pulsar
- GRB
- AGN

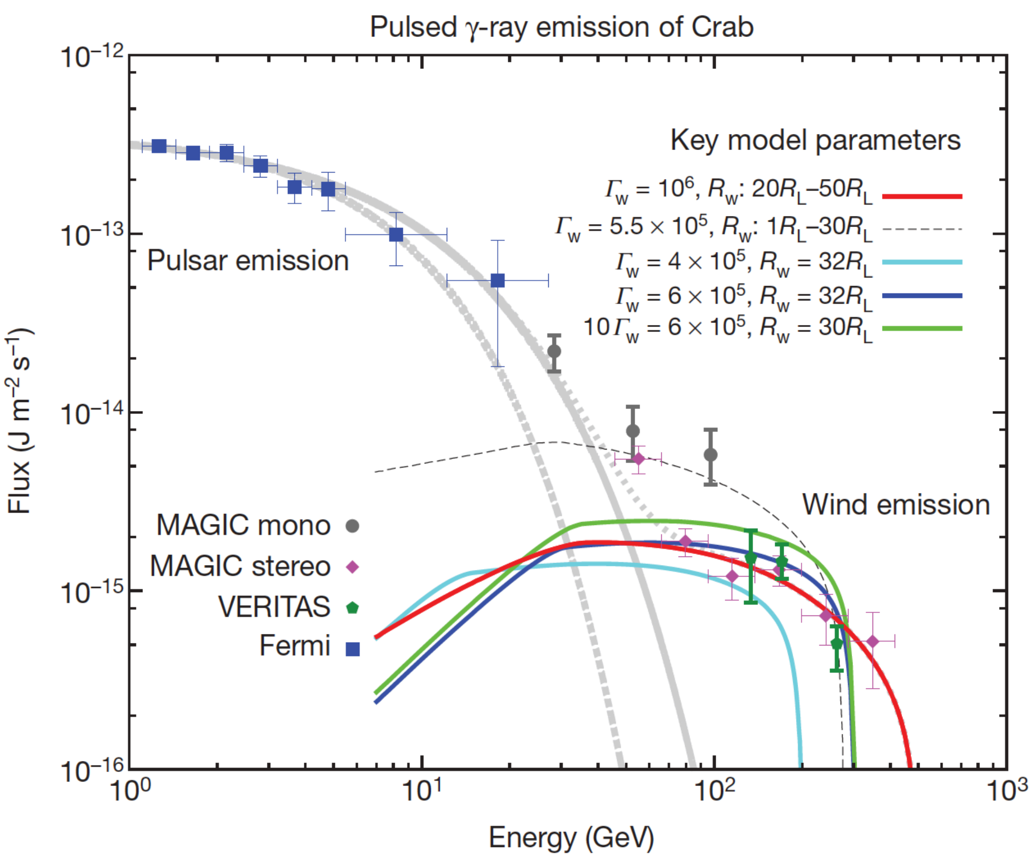
The best sensitivity between 10 and 100 GeV also provide unique window for indirect search for dark matter

Gamma-ray astronomy in the energy range 10 - 1000 GeV

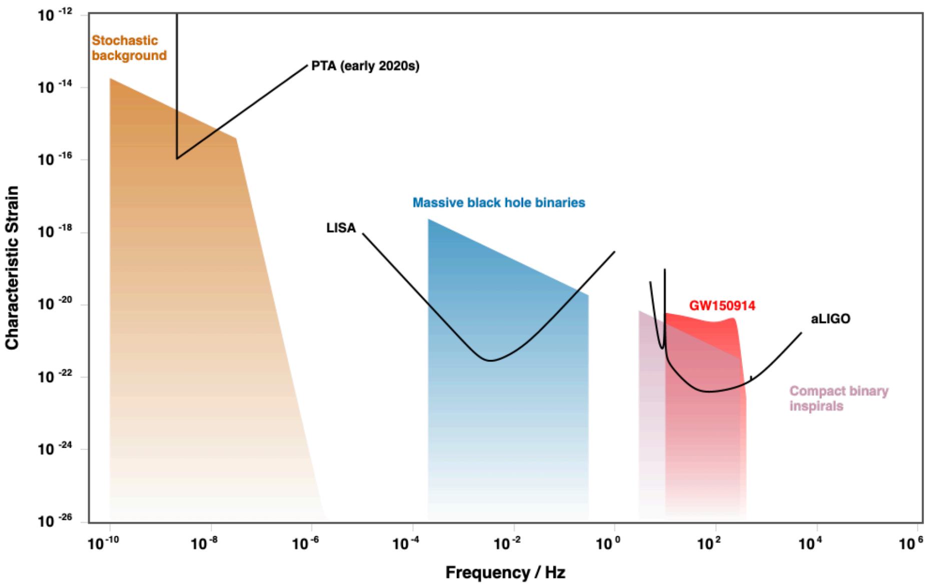
Pulsars

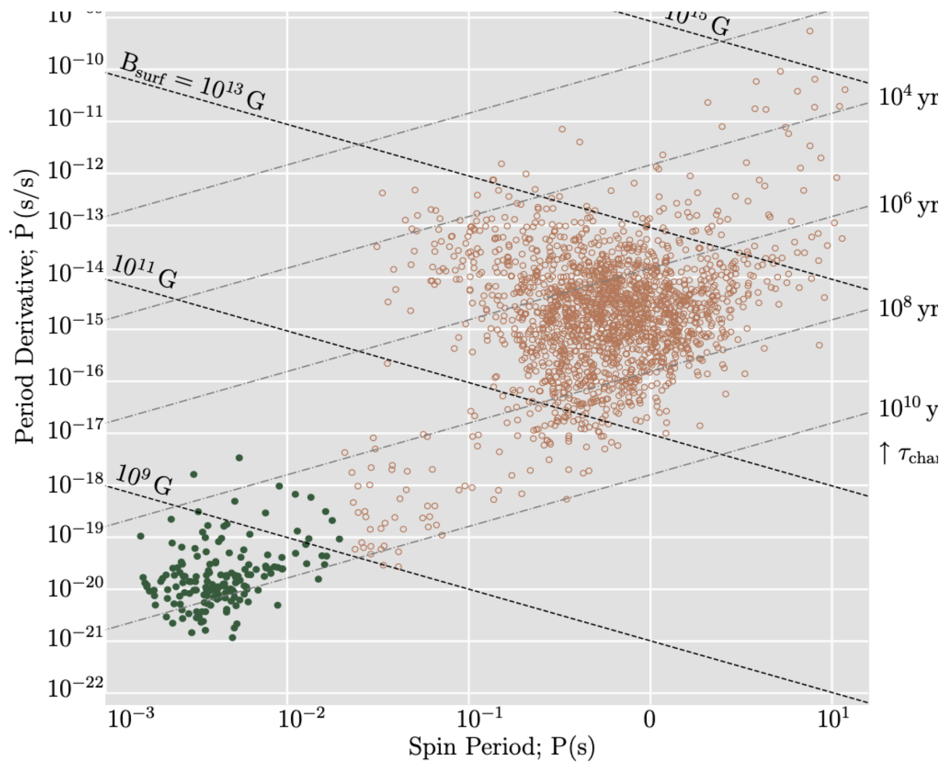
For crab-like bright pulsars, 10 photons per second.

- phase resolved spectrum, accurate measurement of the cutoff spectral shape
- pulsar blind search: broader beam of gamma-ray pulsed emission.
- Pulsar timing array for nano Hertz gravitational waves.
- extra spectral component? IC from Cold relativistic pulsar wind?



PTA for nano-hertz gravitational waves





Compared with radio PTAs:
No "plasma delay" in the ISM

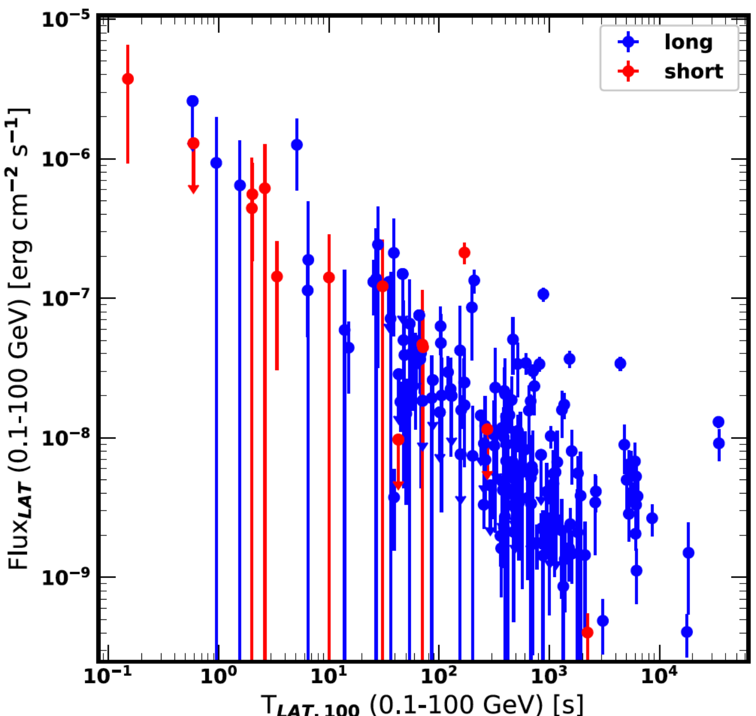
Compared with Fermi LAT:
Much larger effective area (much more photons per time)

GRBs

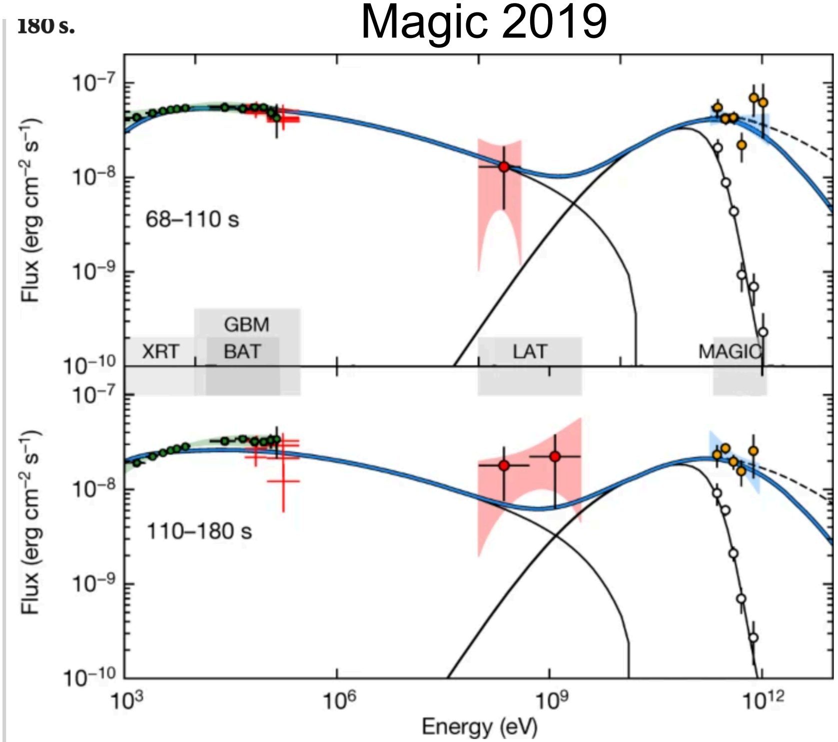
Due to the small FOV, the follow-up observation of the afterglow is favored (GeV afterglow observed by Fermi can last 1000 - 10000 s)

Considering the hard spectrum at GeV range, should detect 100 times fainter GRBs than LAT.

investigating IC emission (gap between LAT and IACT energy range)

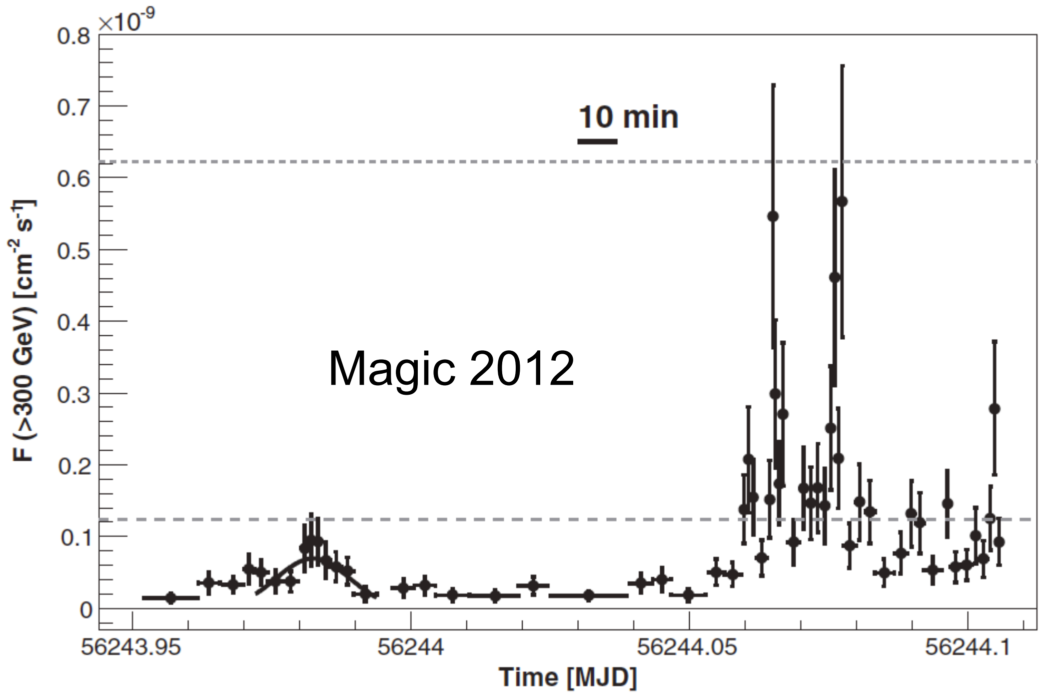


Magic 2019



AGNs

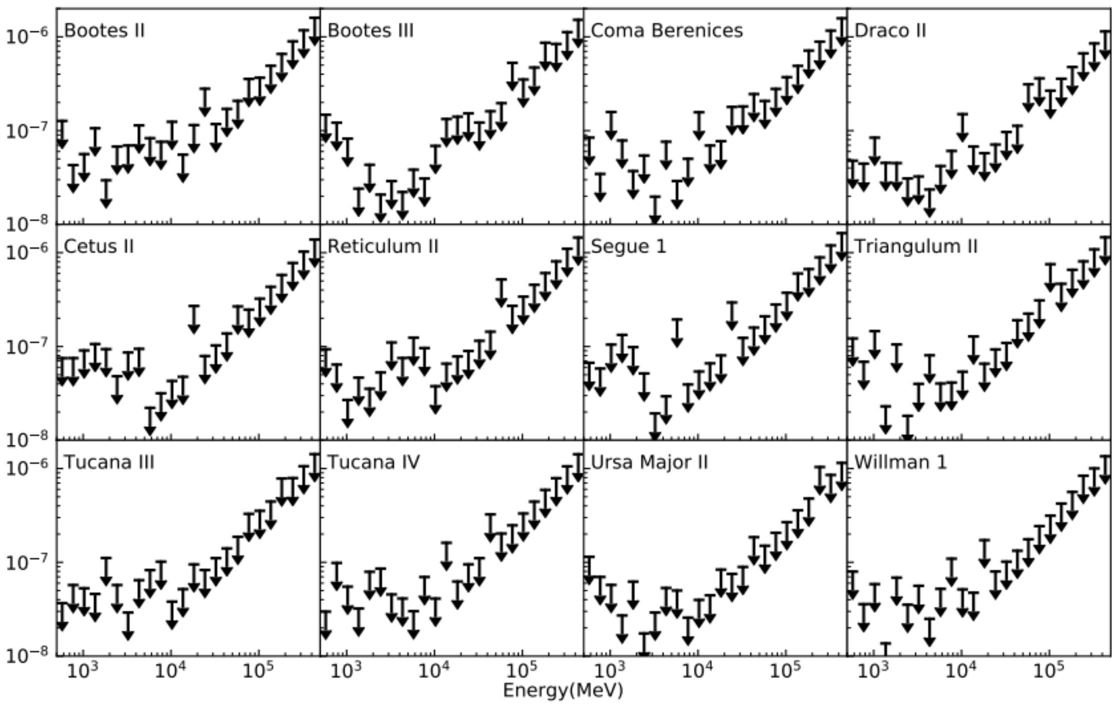
- minute scale variabilities



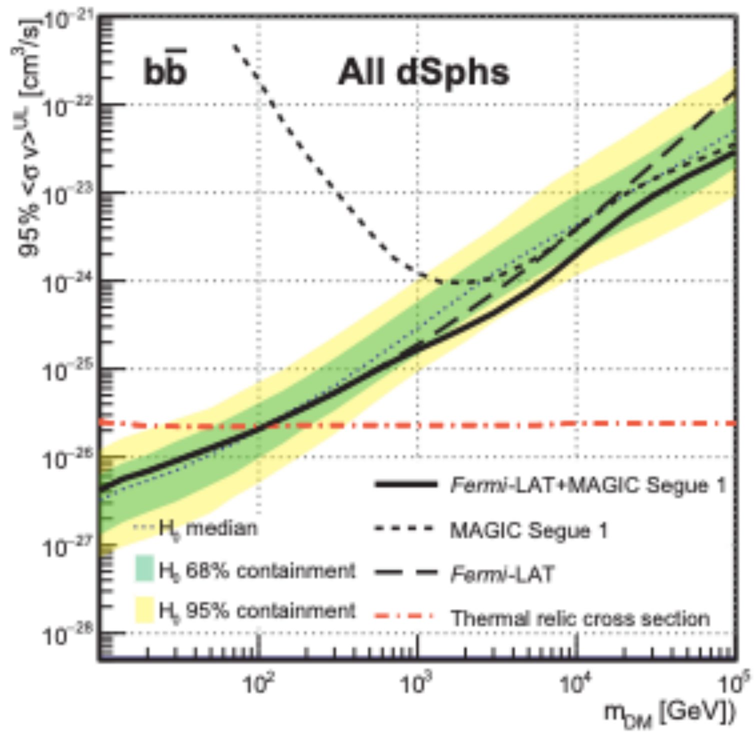
- EBL study
- Temporal correlation with other wavelength

Dark matter search

Dwarf galaxy, galaxy cluster….



Li et.al 2018



MAGIC 2016

Gamma-ray instruments sensitivities

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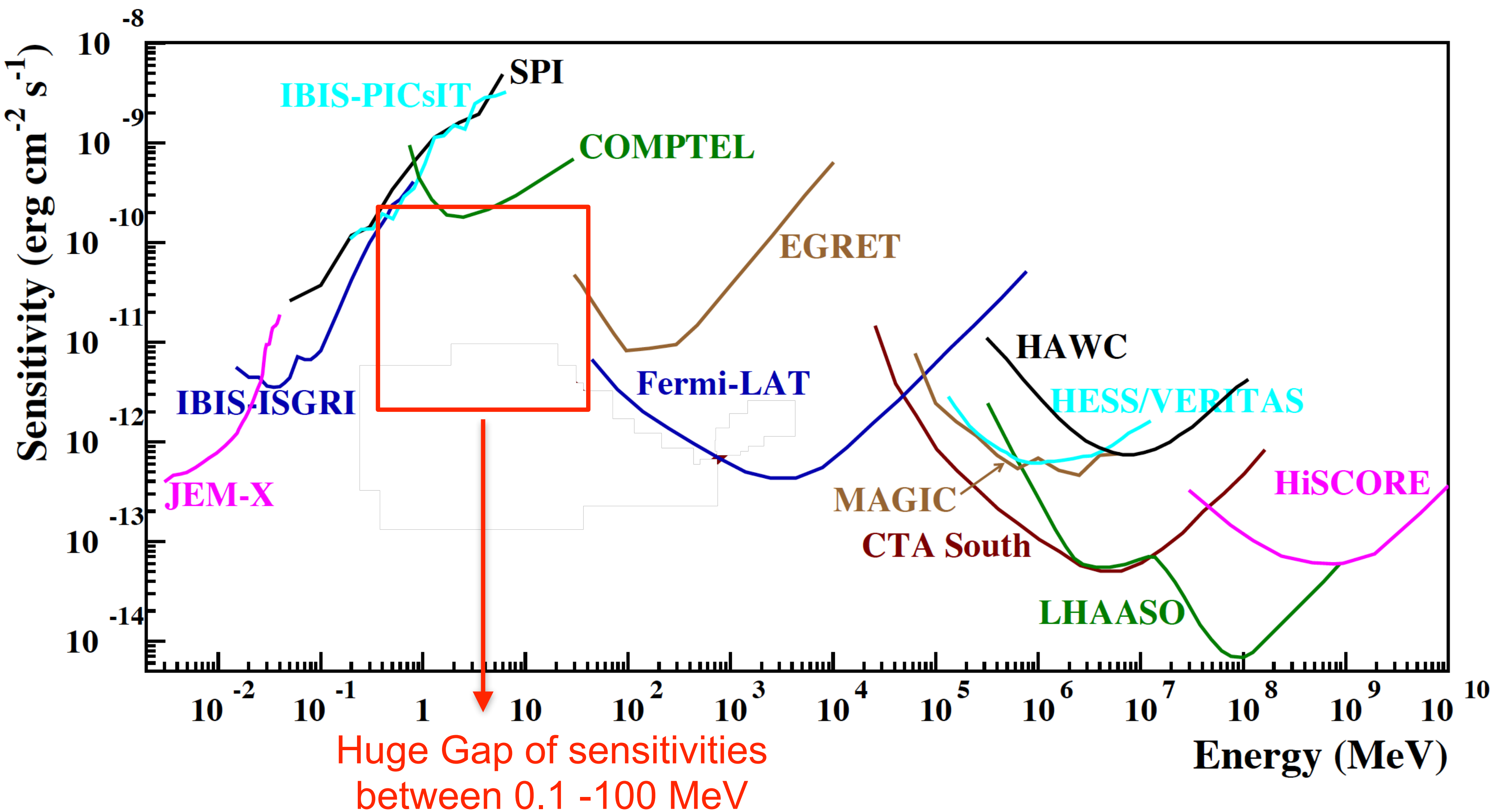
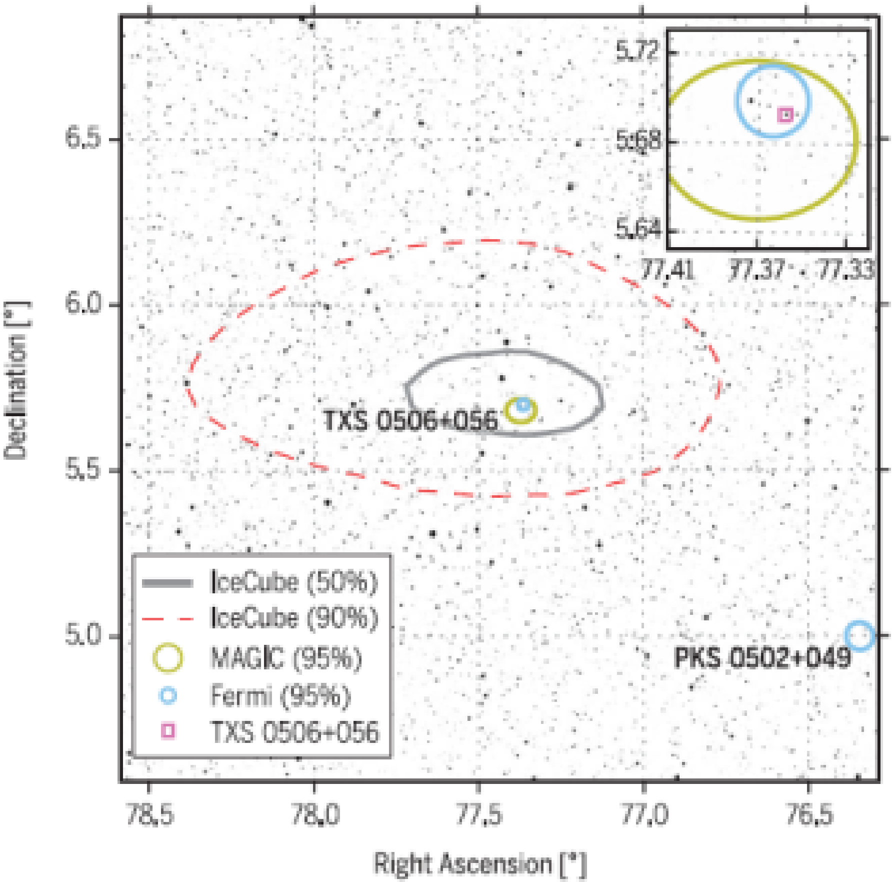
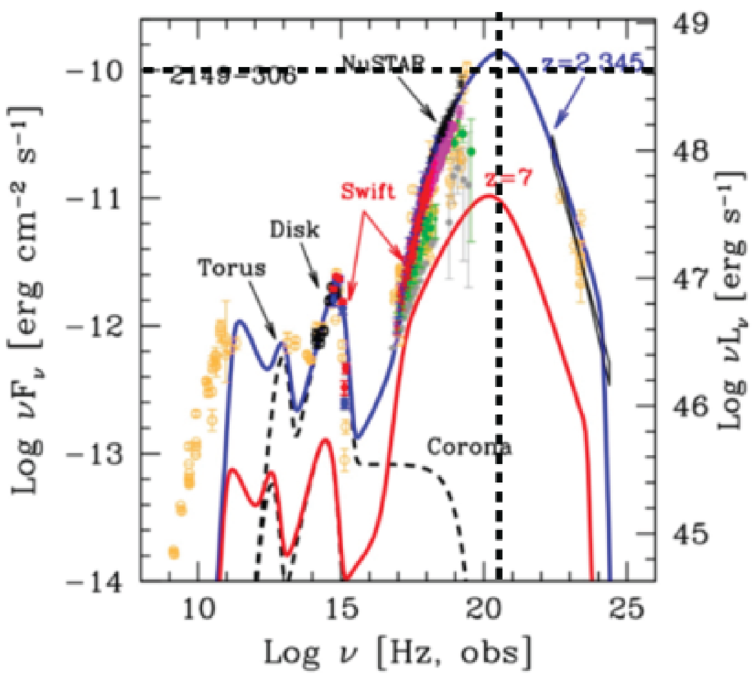


MeV astronomy

Multimessenger connection with neutrino events





Neutrinos from Blazar TXS 0506+056

Most likely from high redshift MeV peaked blazars?

MeV astronomy

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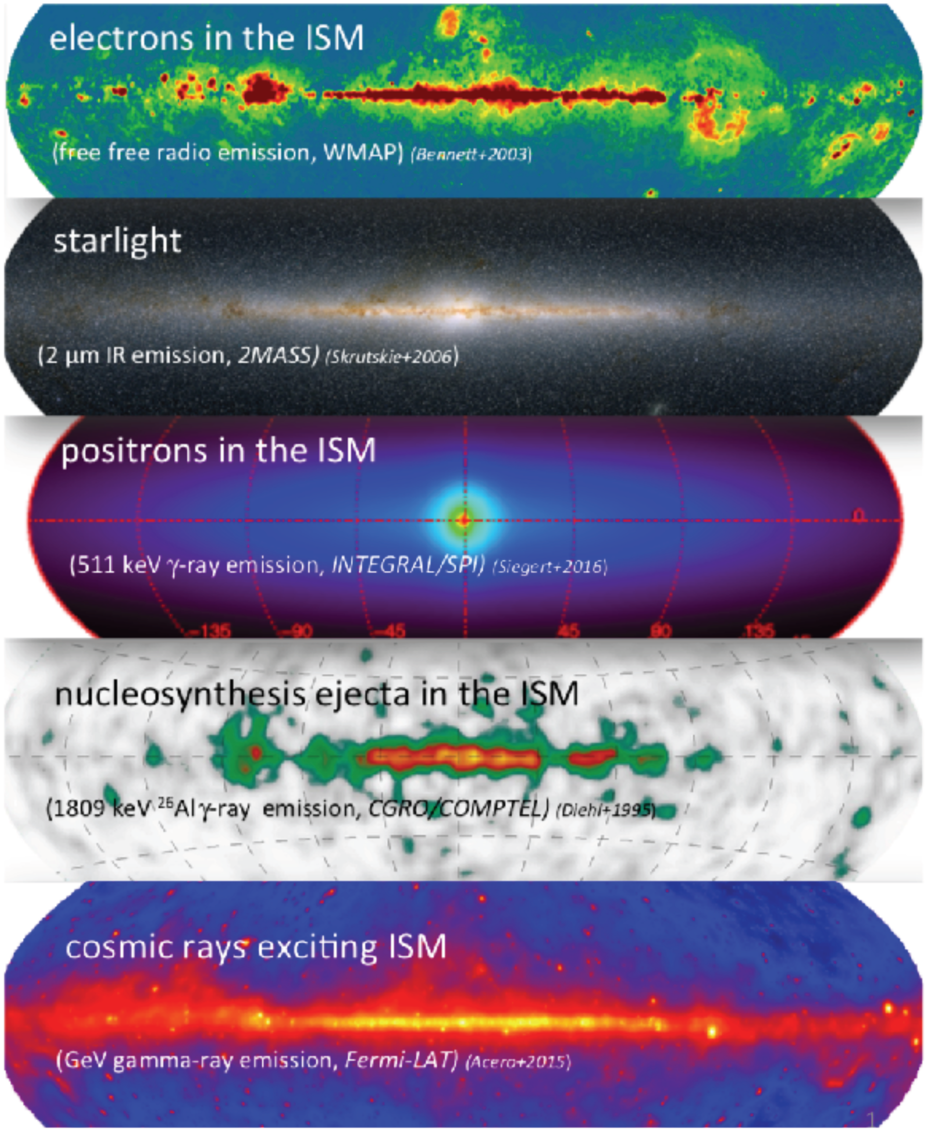
Nuclear Astronomy

Nuclear lines from radioisotope decay

Direct measurement of heavy element production

Low energy cosmic ray



MeV astronomy

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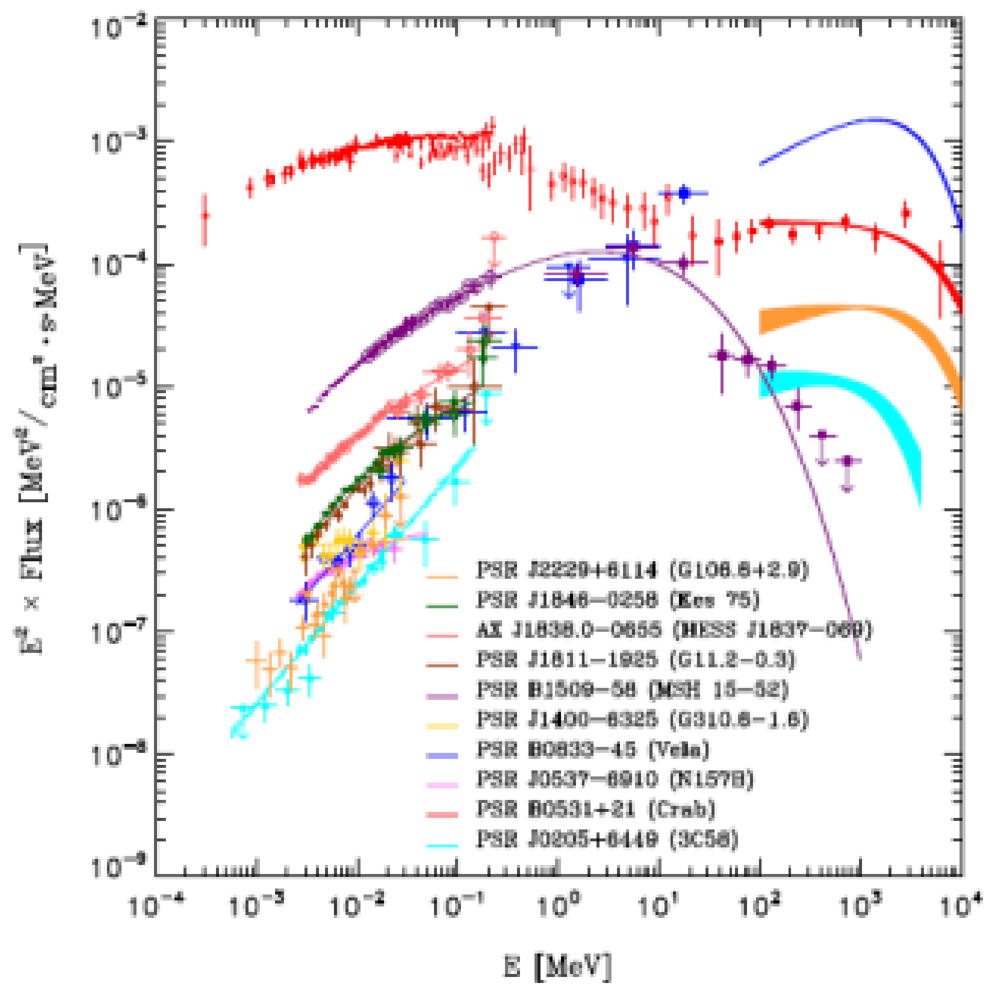
MeV pulsars

Many of pulsars are predicted to be MeV pulsar.

MeV range is the key to understand the emission mechanism of pulsar’s multi-wavelength emission



MeV astronomy

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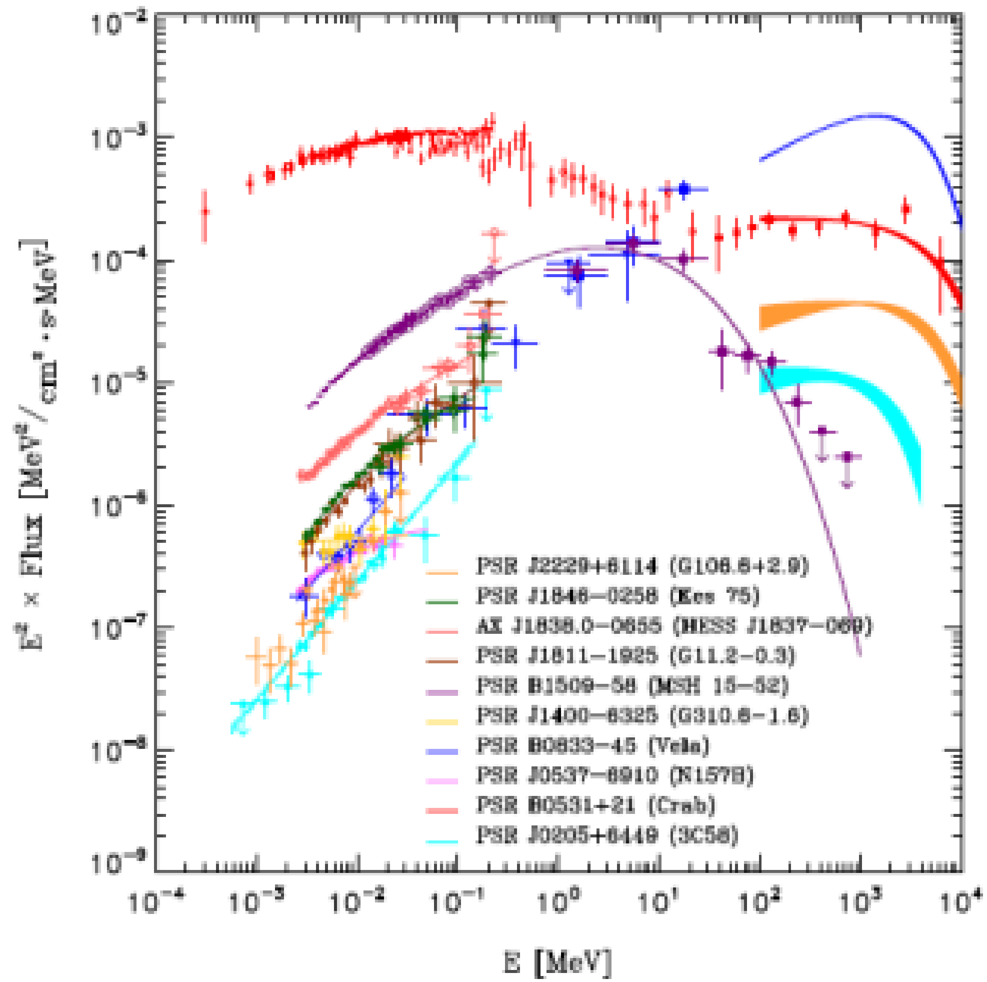
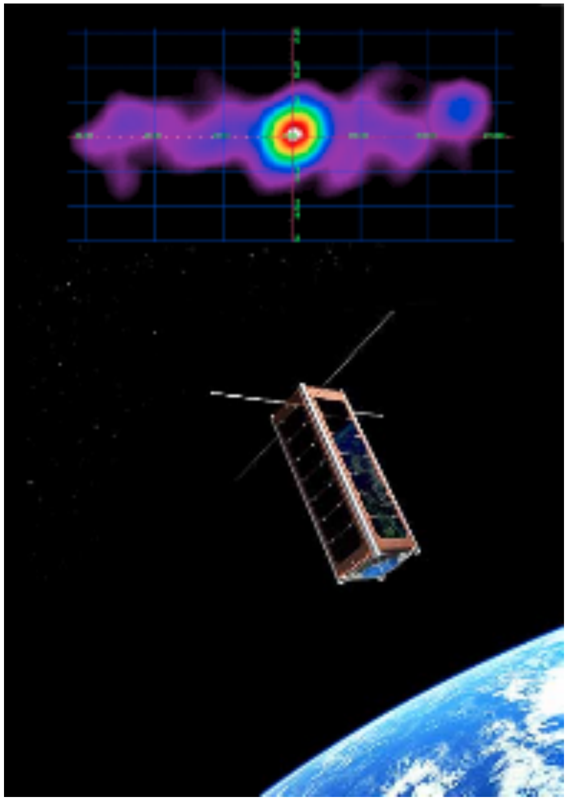
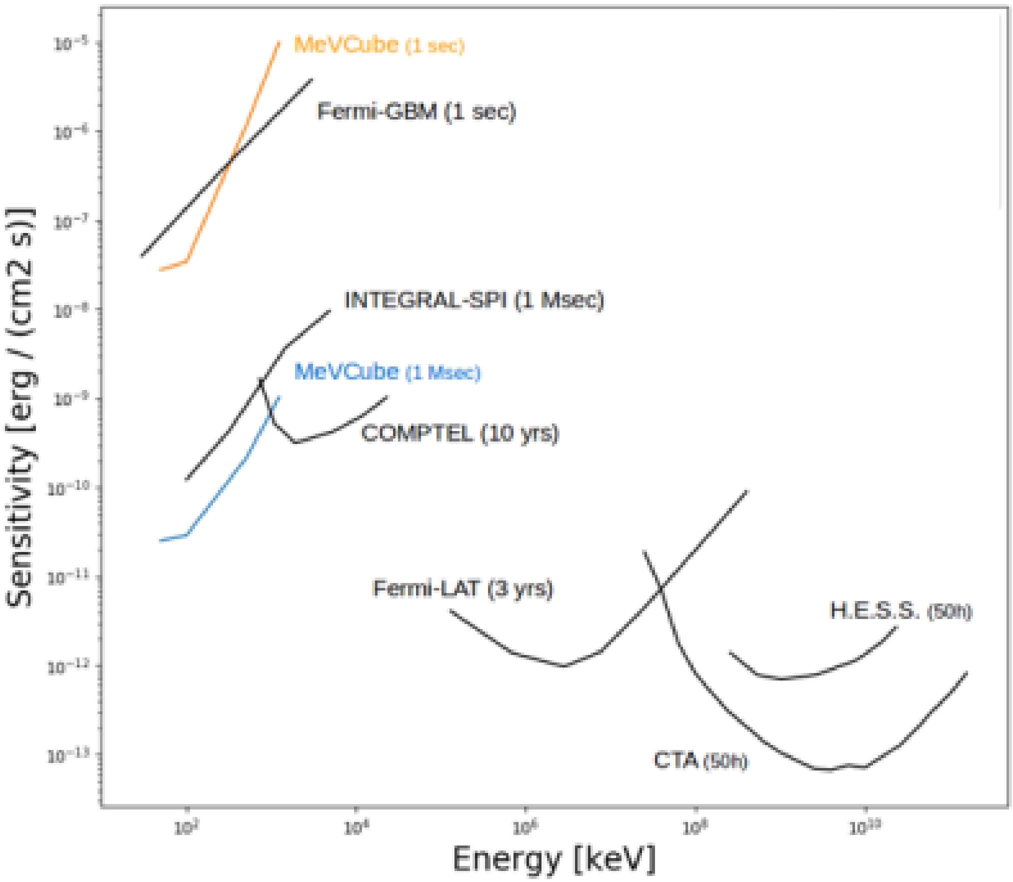


And much more: AGNs, Magnetars, GRBs, polarizations……

On-going projects: MeVcube



IHEP/DESY collaborations



A working horse instrument in MeV range as well as a technical verification for future larger missions

Conclusion

- Gamma-rays are a unique tool to study Cosmic rays and other astrophysics processes

- LHAASO already show great power in Cosmic Ray science

- Further exciting projects:

1. TeV Cherenkov array : Synergy with LHAASO, PeVatron study
2. GeV Cherenkov telescopes: time domain astronomy, gravitational wave
3. MeV astronomy: a brand-new window

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Thanks!