Galactic Factories of CRs:

Understanding CRs through gamma-ray observations

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DESY Colloquium

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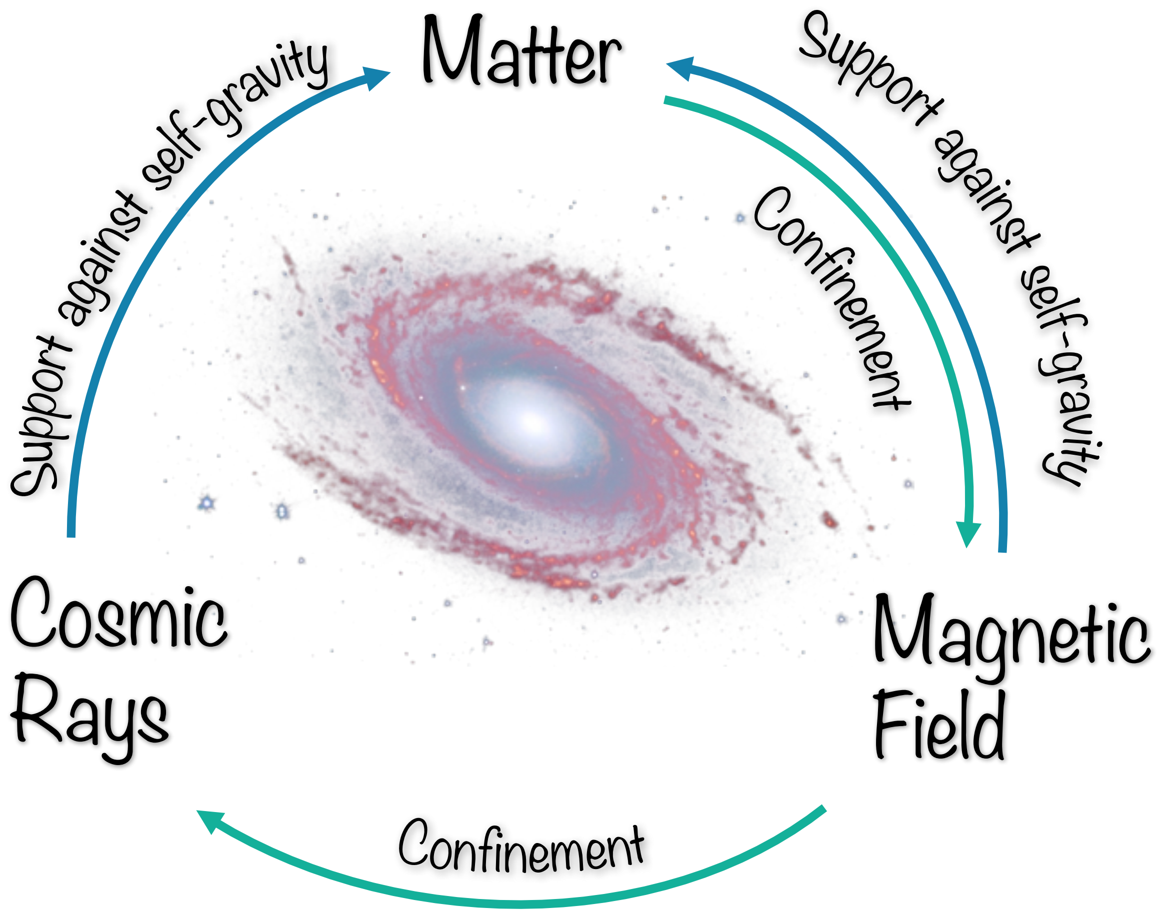
CRs Origin & Propagation: Connecting Galactic Structures



- Basic Component of the ISM: Matter, GCRs and GMF
- GCRs are dynamically important in the Galaxy
- Dynamic balance processes triggers instabilities in the Galaxy structure

ω_{CR}	~1 eV/cm^3
$\omega_B = B^2/8\pi$	~1 eV/cm^3
$\omega^{turb}{}_{gas} = \rho_{gas}\, v^2{}_{turb}$	~1 eV/cm^3

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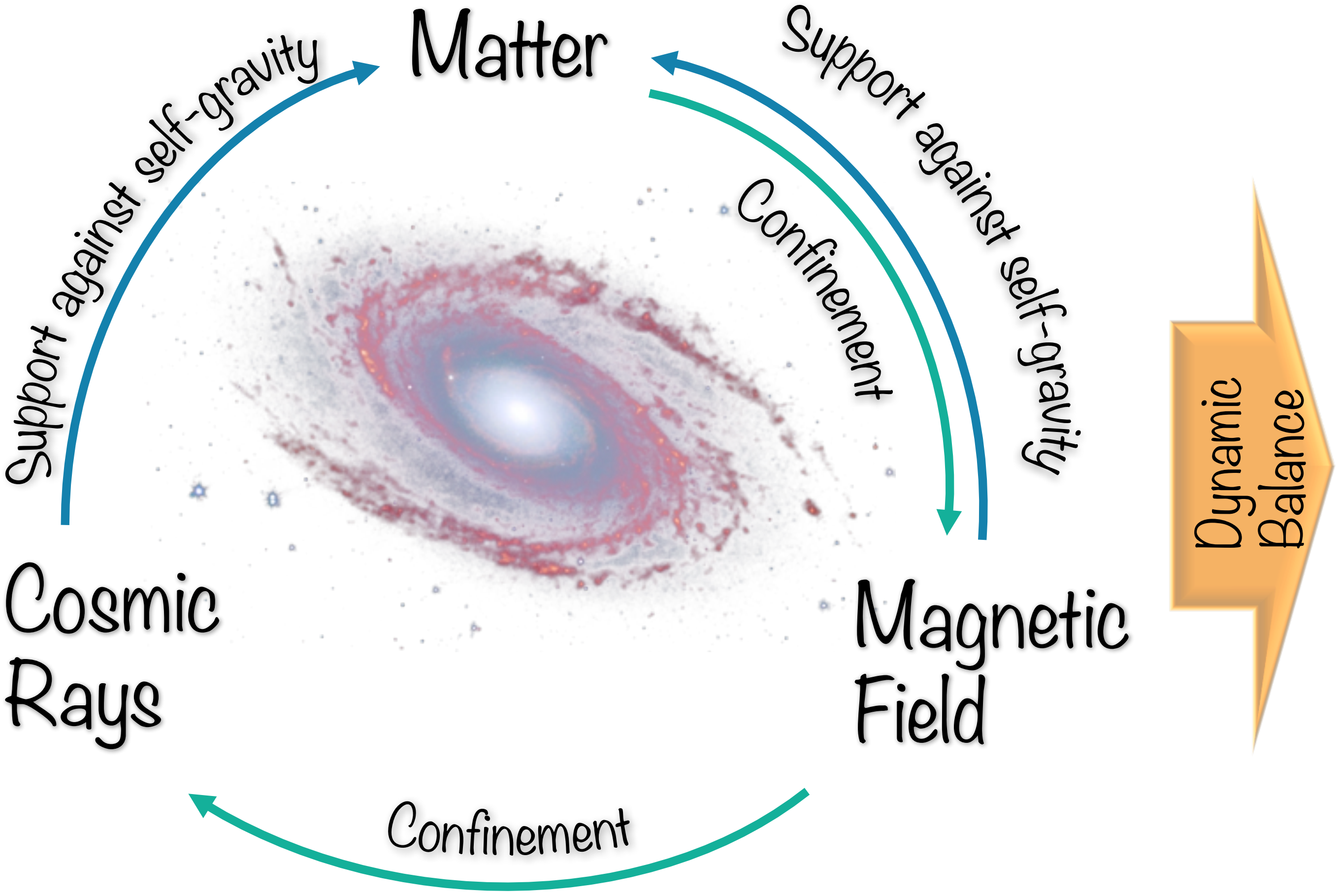

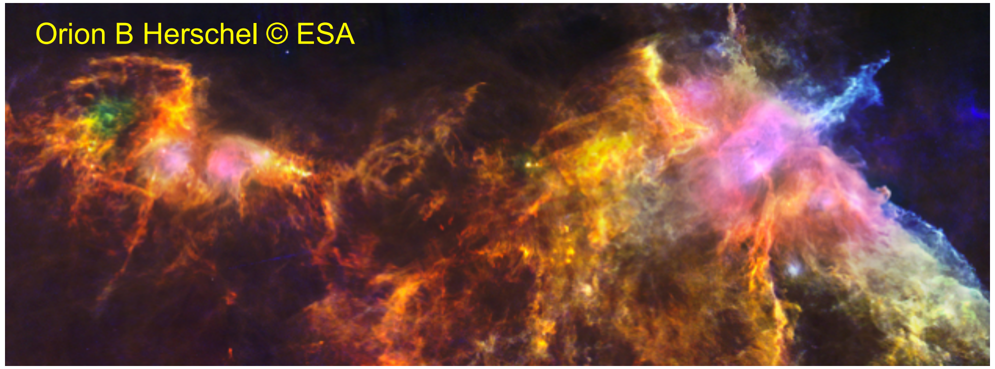

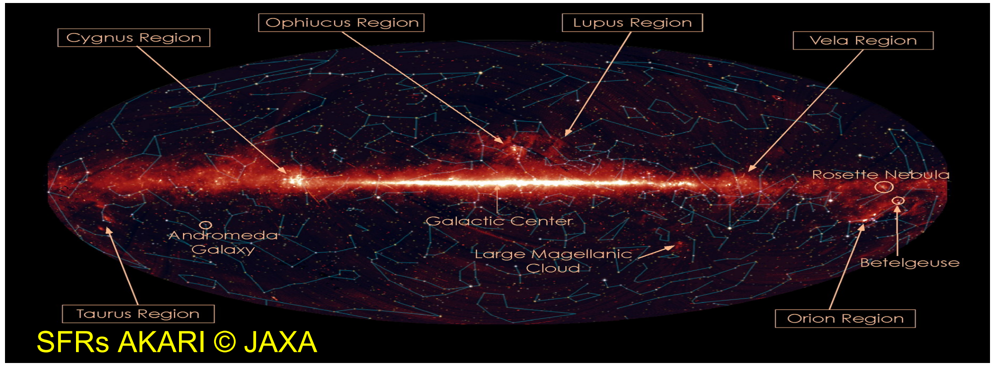

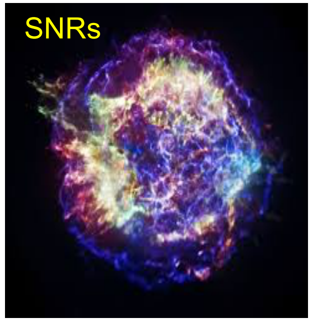

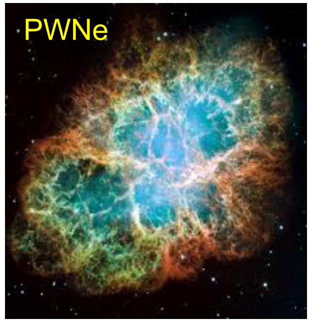

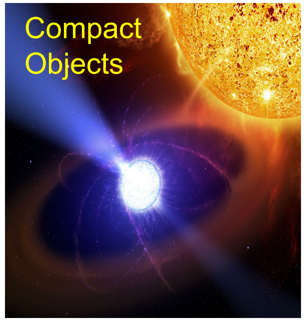

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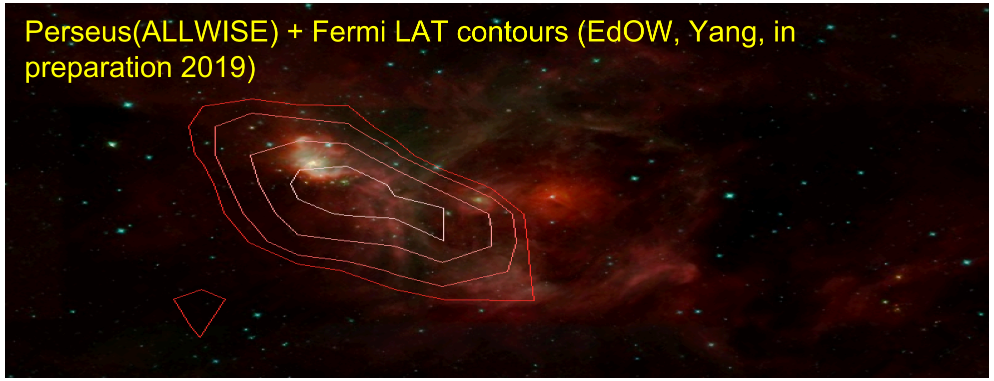
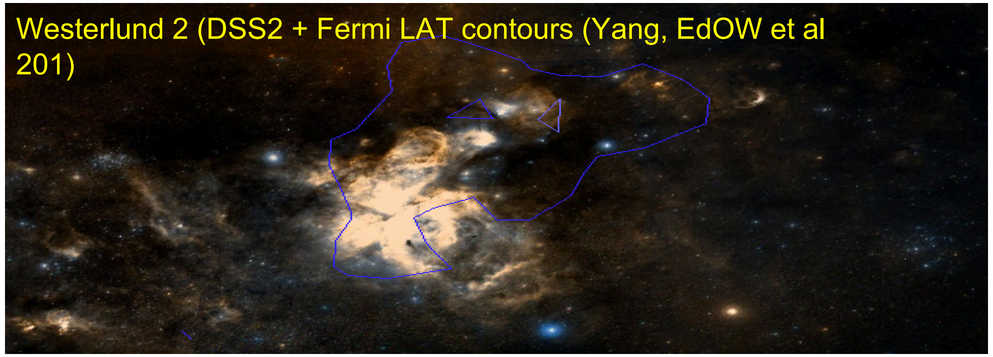
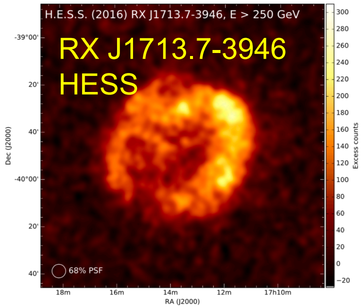
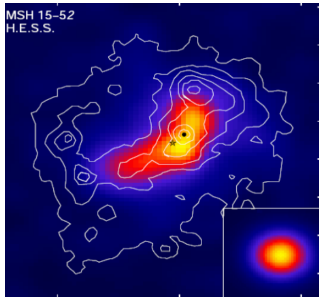
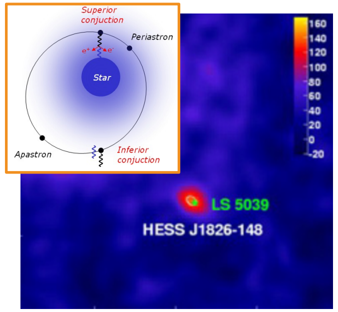
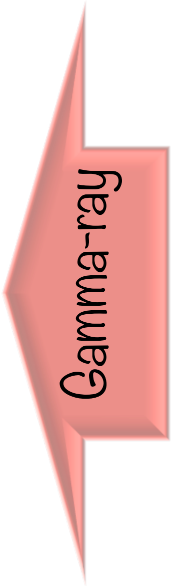


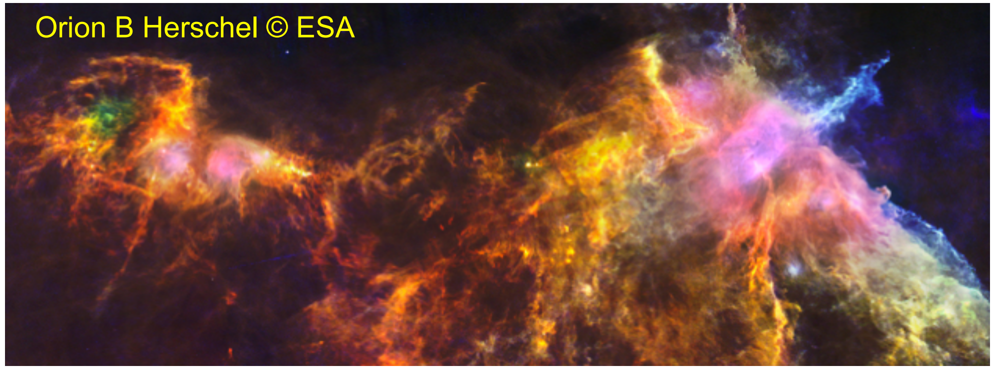


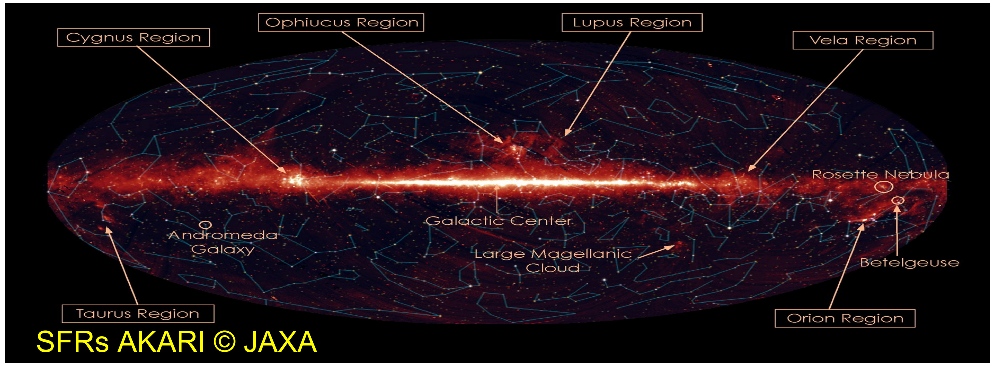


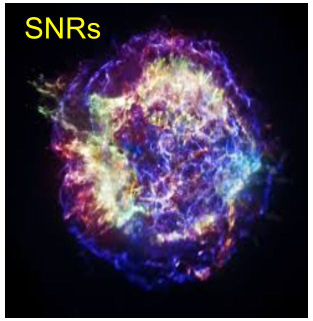


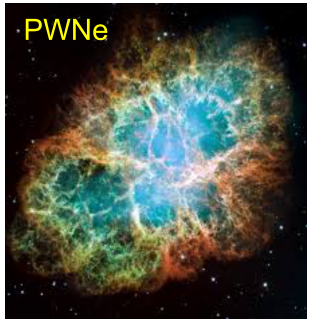


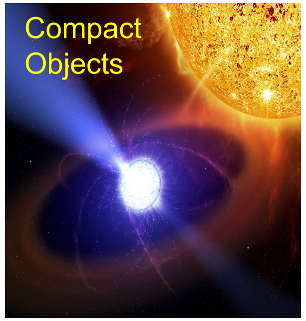




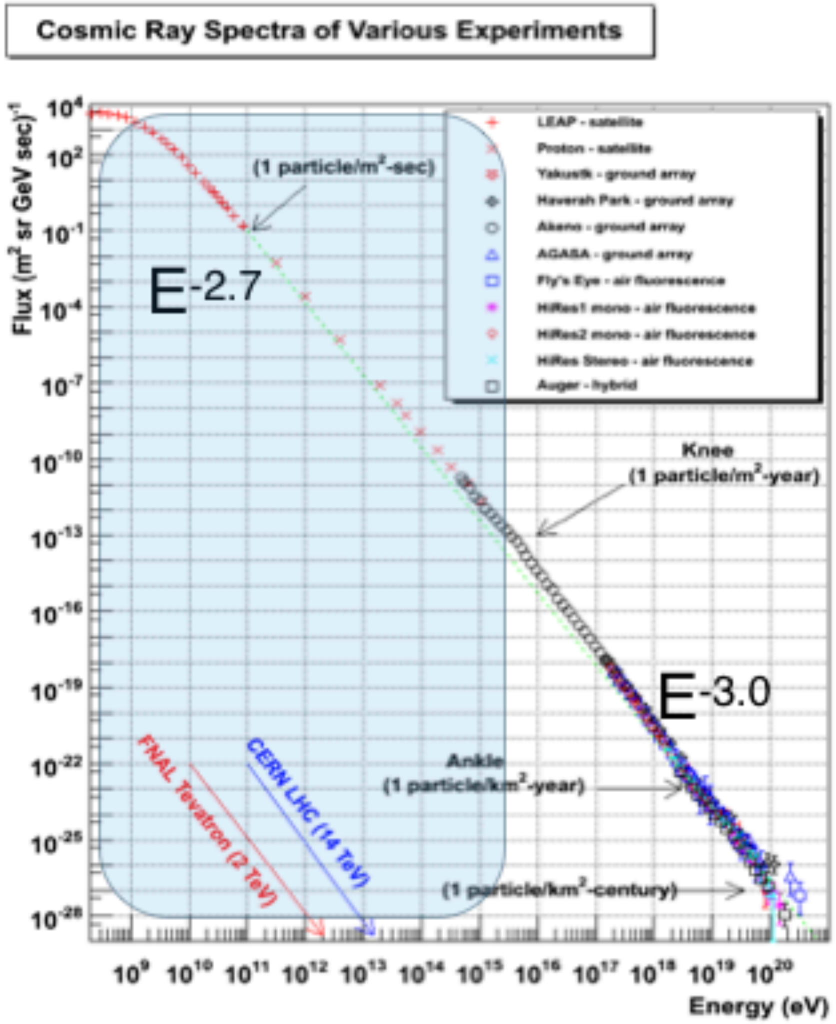








CRs Origin & Propagation: Where & How?



Question since 1912: what is the origin of Cosmic Rays?

Spectrum of CRs

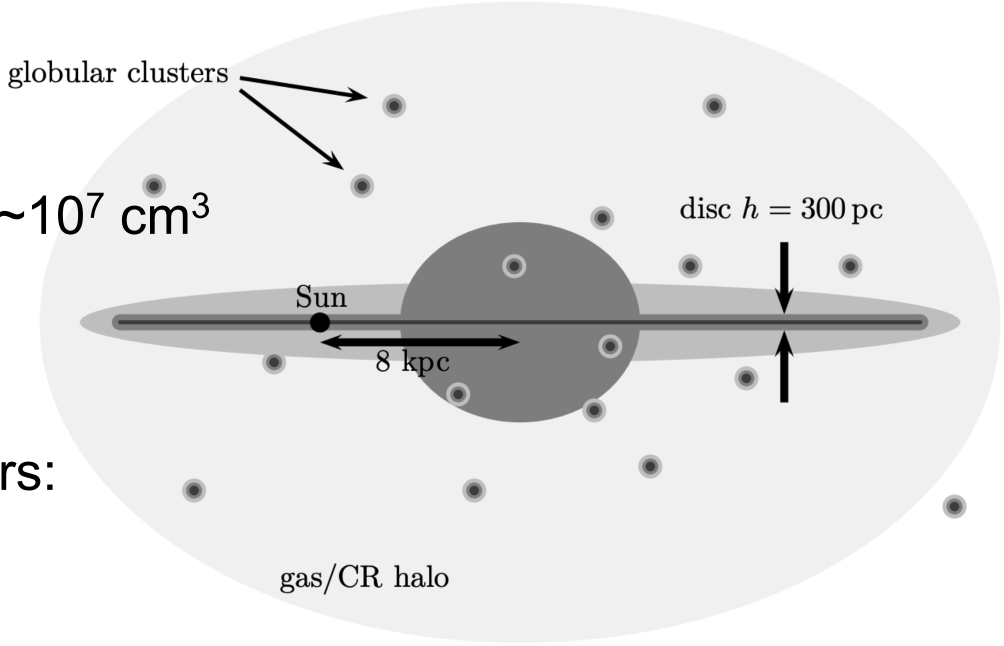
- Extends over 32 orders of magnitude
- Below ~3 PeV CRs are believed to be of Galactic origin
- Luminosity of Galactic CRs $L_{CR} \sim 10^{41}$ erg/s
- Where are PeV CRs accelerated?

CRs Origin & Propagation: Where & How?

Who is powering the CRs?

CR Energetics

- Energy Density of CRs u_{CR}~1 eV/cm^3
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3\times10^{11}$ pc^3 ~10^7 cm^3
- Luminosity $L=u_{CR}*V_{gal}/t_{CR}$



- CR confinement time (nuclear abundance) t_{CR}~10^7 yrs:
  $L=u_{CR}*V_{gal}/t_{CR} = 5\times10^{40}$ erg/s

- Isotropic in the Galaxy

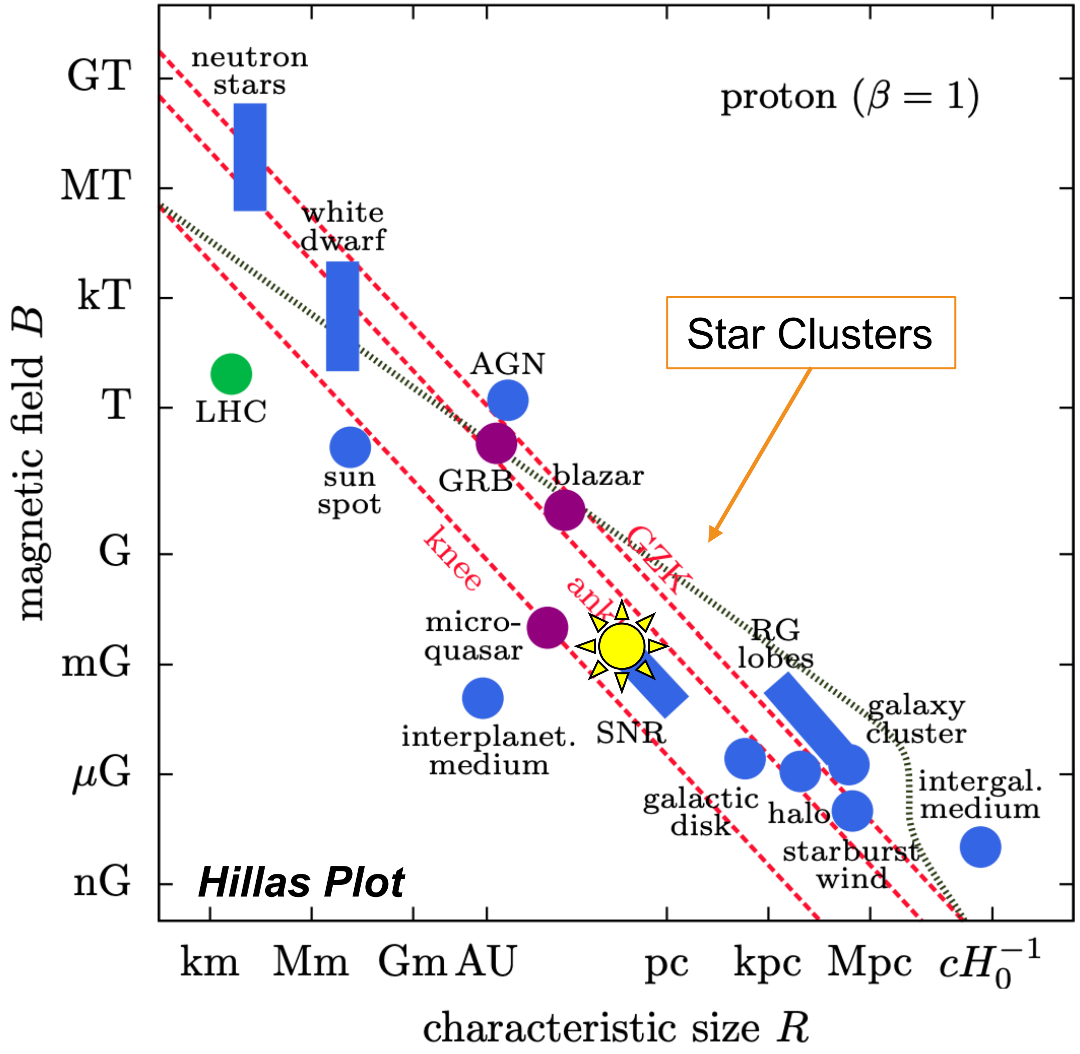
Homogeneity requires t_{recu}<<10^7 yrs (or continuous injection?)

We need accelerators that can provide the right energy budget, up to PeV energies, at the required rate to make the distribution homogeneous.

CRs Origin & Propagation: Where & How?

Who is powering them

Aartsen et al (IceCUBE) 2017



Standard preliminaries

- ✓ $L = u_{CR} * V_{gal} / t_{CR} = 5 \times 10^{40}$ erg/s
- ✓ Homogeneity
- ✓ Up to PeV energies

Confinement condition

necessary condition but not determining

R_L (=E/qB) < R => $E_{max} = \Gamma qBR$

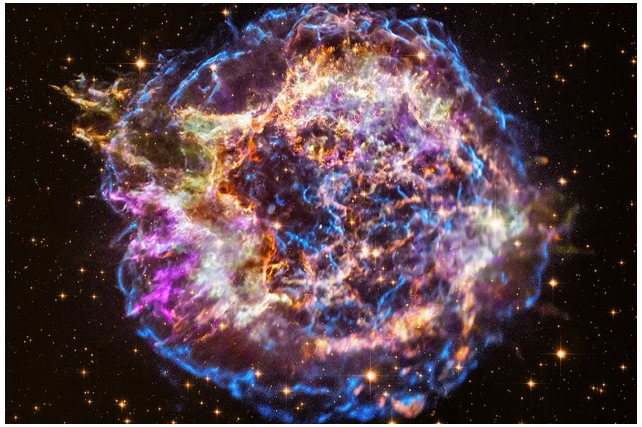
CRs Origin & Propagation: Where & How?

Who is powering them

- ✓ $L = u_{CR} * V_{gal} / t_{CR}$ = 5×10^{40} erg/s
- ✓ Homogeneity
- ✓ Up to PeV energies

Supernova Remnants

- SNe rate is ~2-3 per century
- Explosion energy $E_{kin} = 10^{51}$ erg
- $L_{SN} = 10^{51} / \tau_{recu} = 6 \times 10^{41}$ erg/s
- $V_{sh} > 10^3$ km/s
  => $E_{max} \sim B^{-1/2} V_{sh}$



Stellar Clusters

- L ~10^{38-39} erg/s
- Operating for few T=Myrs
  Wp = fLT ~3×10^{52} erg
- Accelerate CRs in the interacting wind or superbubbles
- Large Shock velocities

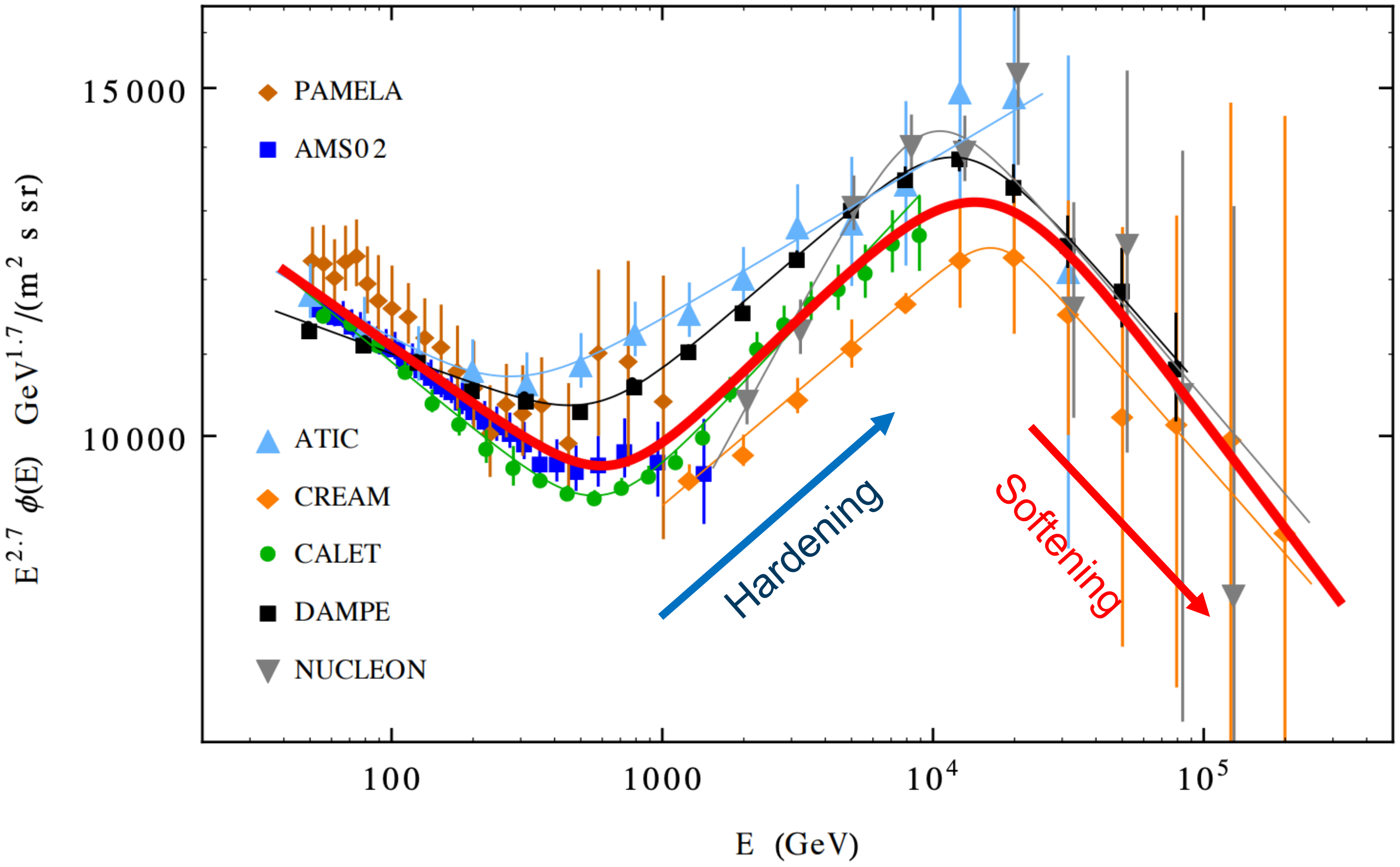
Others? Galactic Center

- Outburst-like event?
  Ekin ~3×10^{54} erg
- Slow outflows?
  L_{IR} ~1.6×10^{42} erg/s

CRs Origin & Propagation: Where & How?

Is it really a featureless power-law up to a few PeV?

Aartsen et al (IceCUBE) 2017



- More than one accelerator class?
- Effect of the CR propagation?

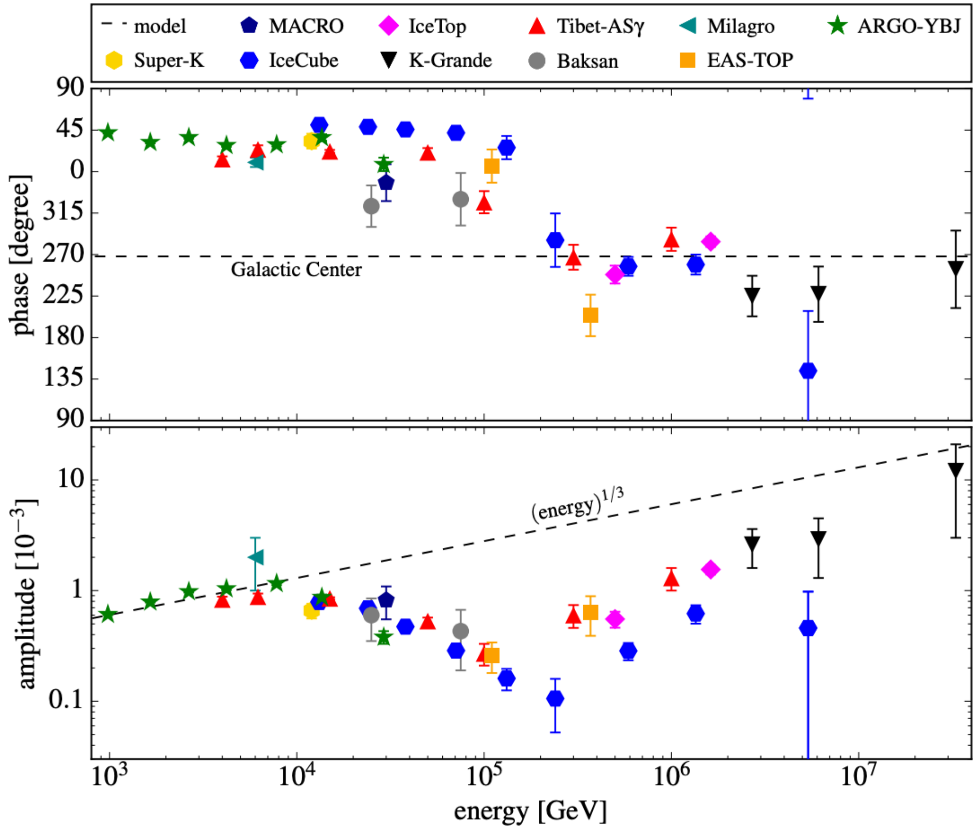
CRs Origin & Propagation: Where & How?

Where do they come from? Anisotropies

At low energies (>100 GeV) the CR flux is compatible with isotropy
At higher energies, CR should drift slowly out in the Galaxy -> Anisotropies?

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{I_1}{I_0} .$$

$10^{-4} \lesssim \delta \lesssim 10^{-3}$, for $E \lesssim 10^{15}$ eV



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CRs Origin & Propagation: Where & How?

Propagation in the Galaxy

- **According to how long they live in the Galaxy**:

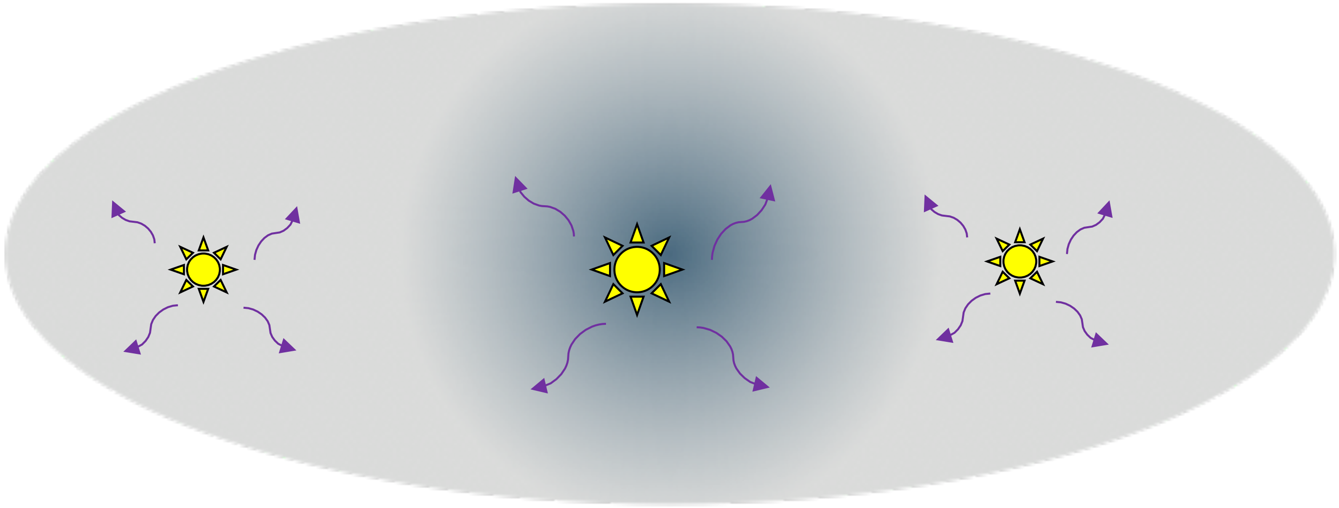
Burst-like

Continuous

$\tau = \frac{h^2}{2D} \approx 8 \times 10^6 \mathrm{yr}\,.$ dN/dE ~$\dot{Q}$/D(E) ~ $E^{-(\alpha + k\delta)}$ k=3/2, 1

D(E) = Do(E/Eo)$^{\delta}$, Do ~$10^{28\text{-}30}$ cm^{2}s^{-1}

t_{recu}<<10^7 yrs or Energetic outburst t>10^7 yrs



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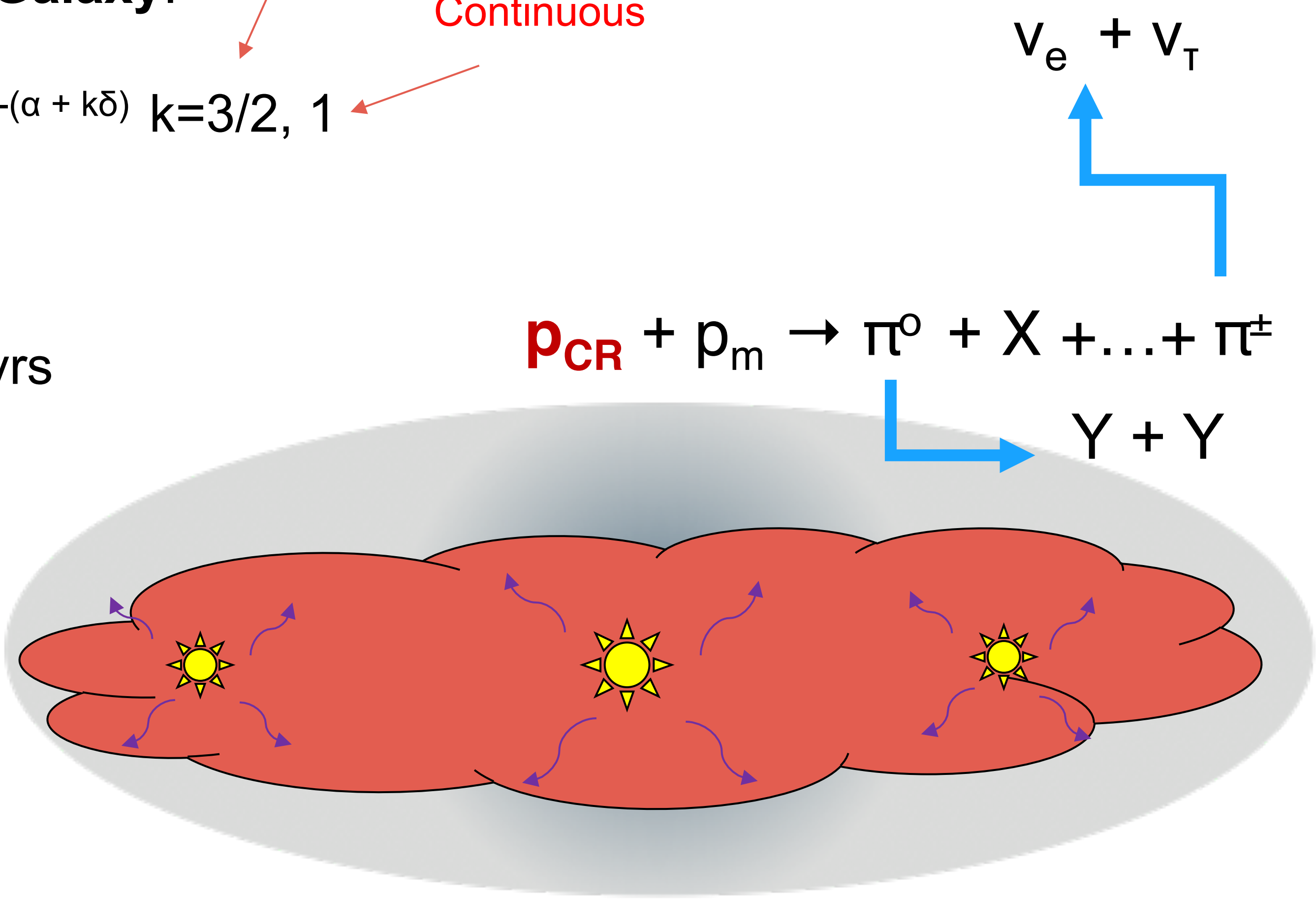
- **From their propagation**

$$w_{CR}(E,r) = \frac{Q_{source}(E)}{4\pi D(E)}\frac{1}{r}$$

- **Tracer = > Gamma-rays or neutrinos**

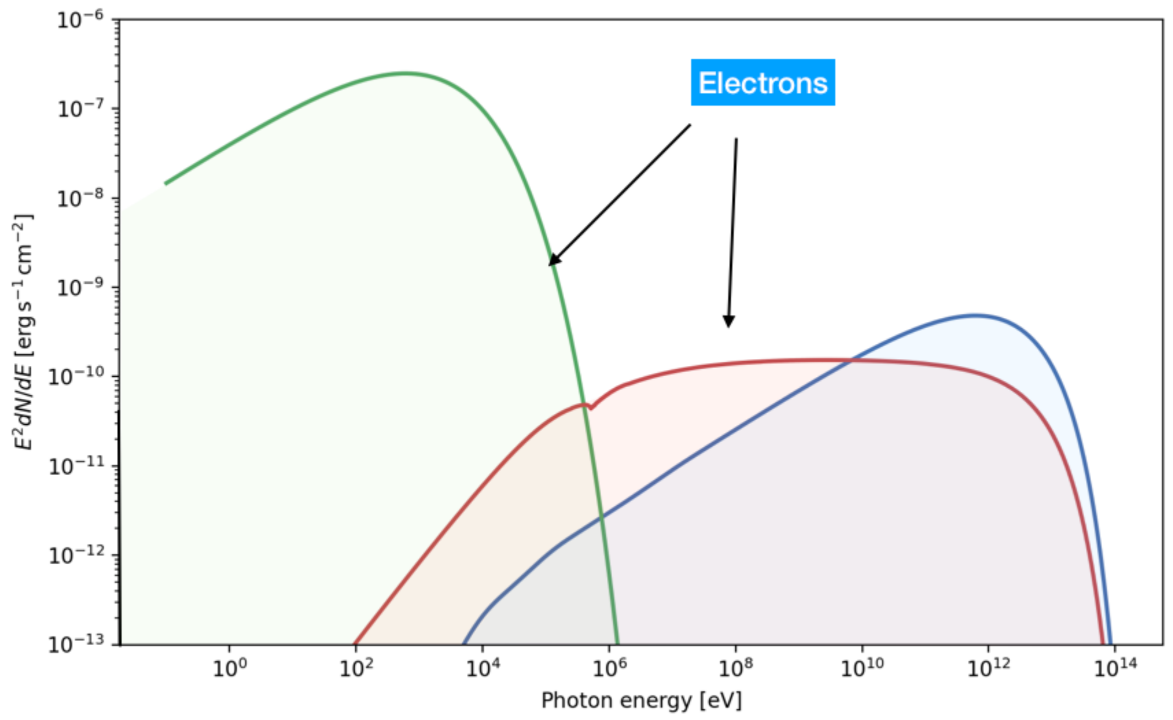


CRs Origin & Propagation: Connecting Galactic Structures

Studying CRs through their radiation imprints

CRs propagate from the accelerator, loosing energy by different means:

Synchrotron: Need magnetic field => Radio/X-ray Synergies
Inverse Compton: Need soft FIR, NIR, CMB photon fields
Bremsstrahlung: Need dense media



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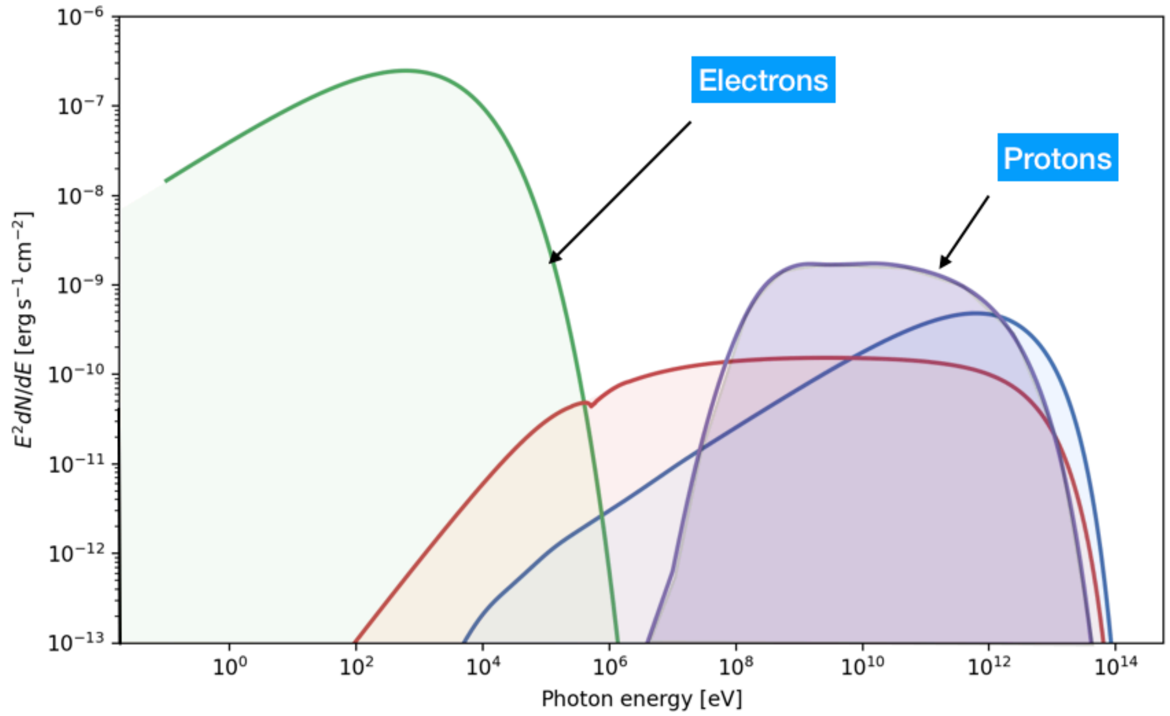

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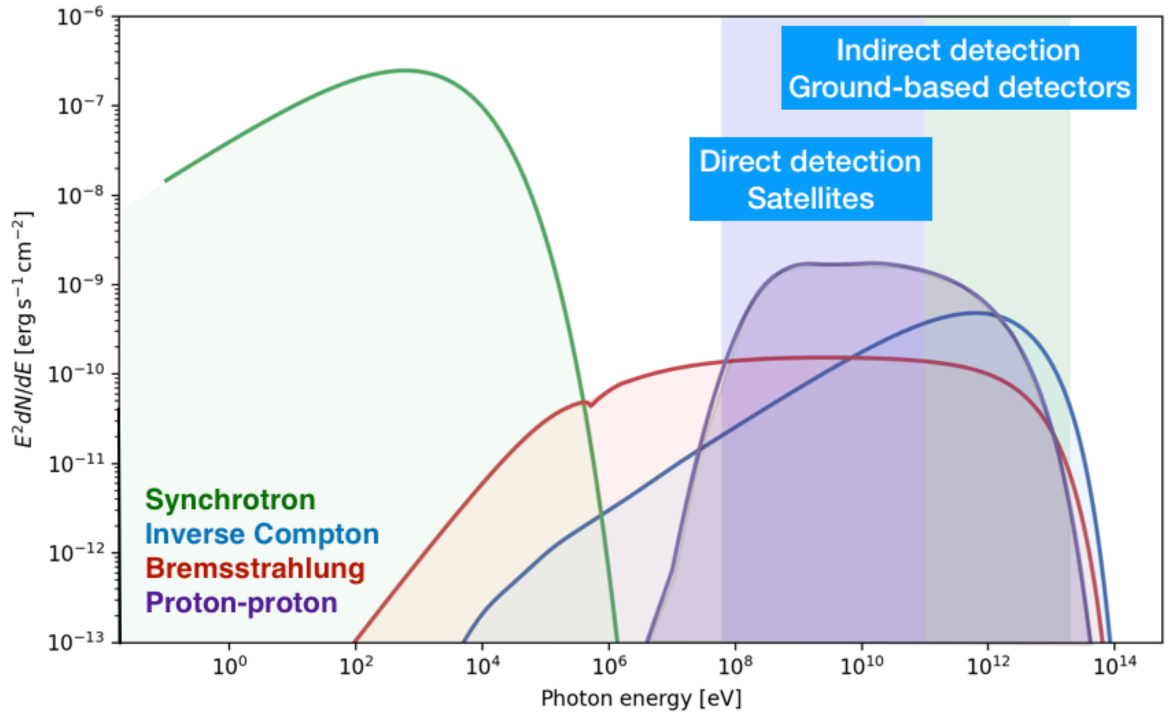


The cooling times has strong implications on the CRs propagation (and source size):

$$T_{syn} \sim 400 \, B_{uG}^{-2} \, Ee_{TeV}^{-1} \text{ yrs}$$

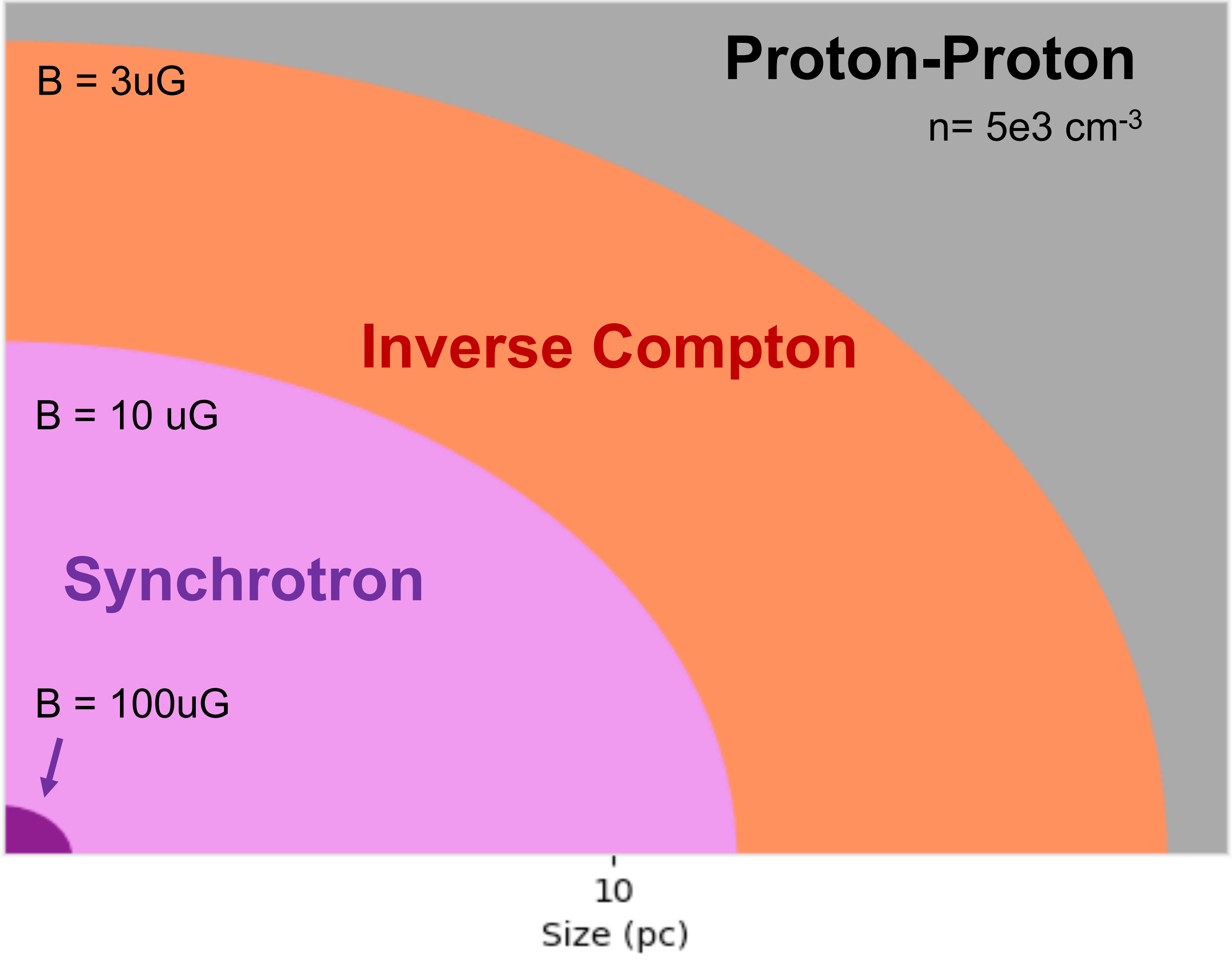
$$T_{IC} \sim 7 \times 10^{3} \, \omega_o^{-1} Ee_{TeV}^{0.7} \text{ yrs}$$

$$T_{pp} \sim 1 \times 10^{15} \, n^{-1} \text{ s} \ (\sim 50 \text{ Myrs})$$

CRs Origin & Propagation: Connecting Galactic Structures

Studying CRs through their radiation imprints

R= $2\sqrt{(D\ t)}$



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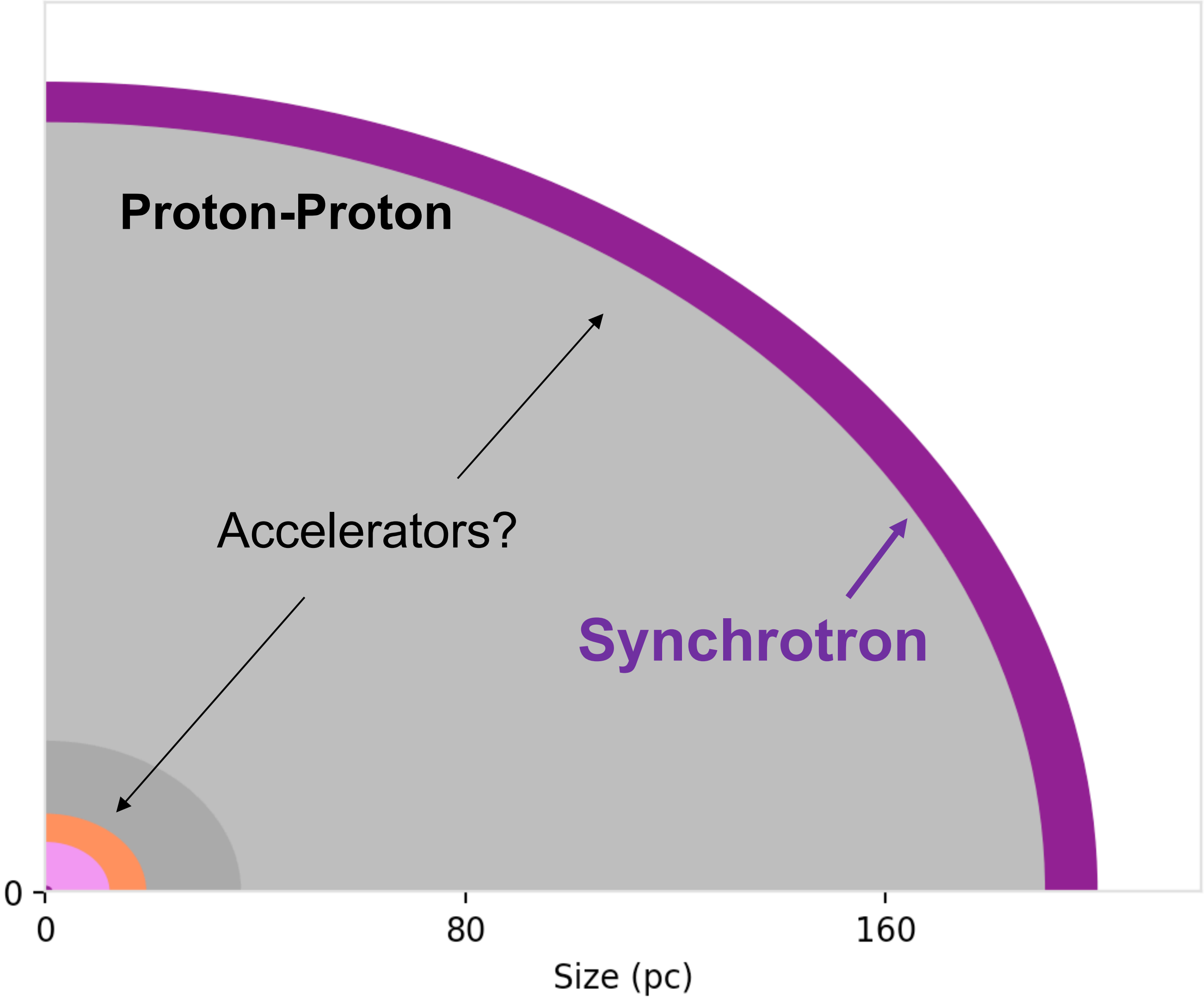

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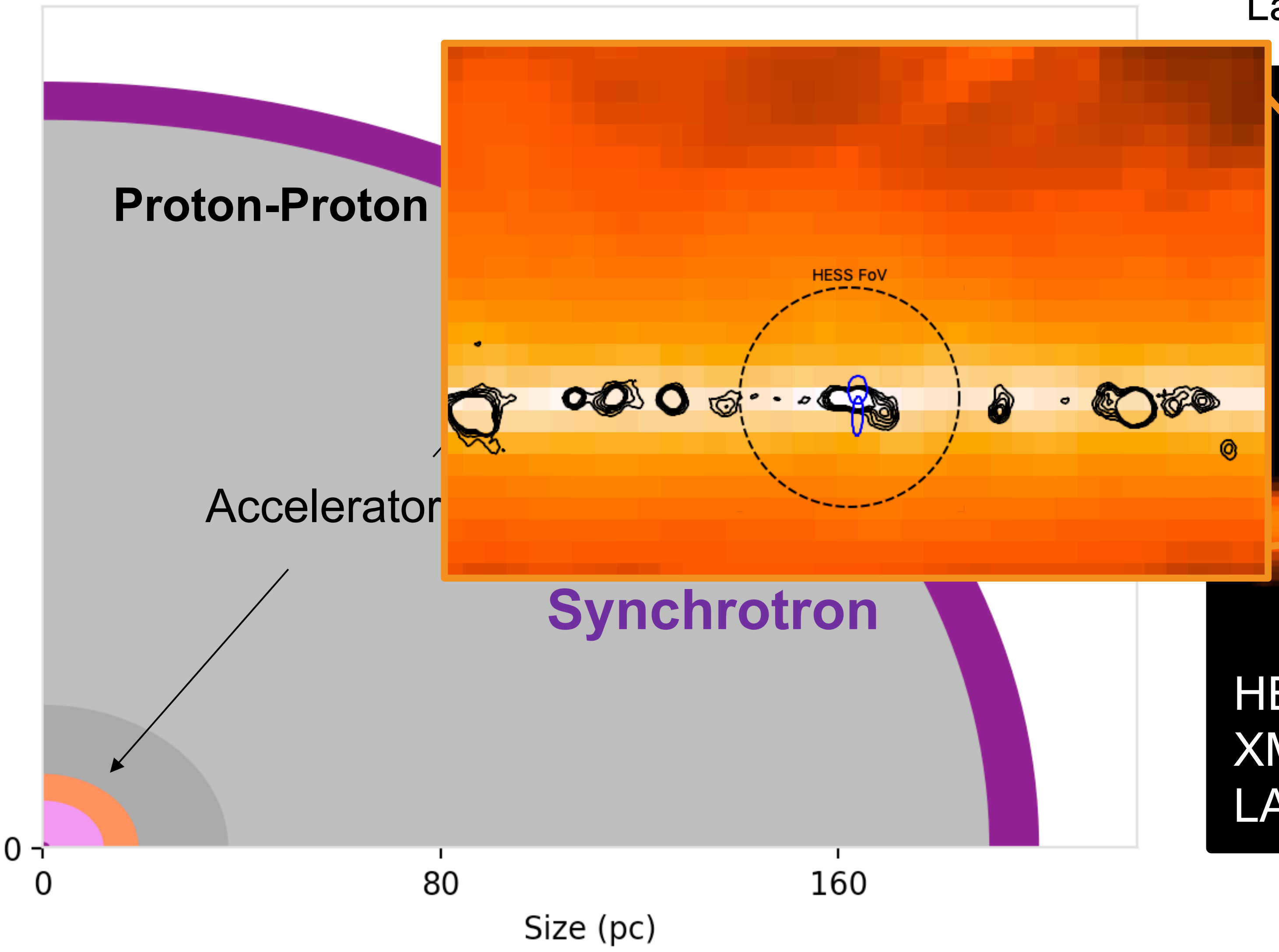
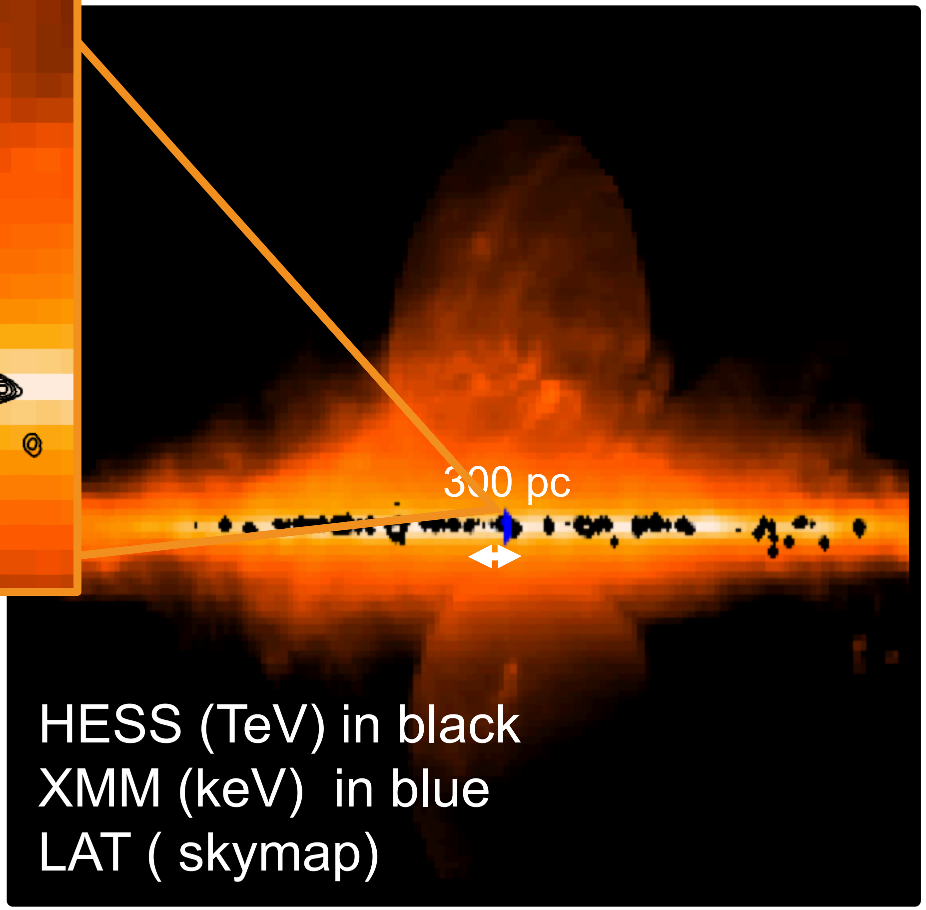
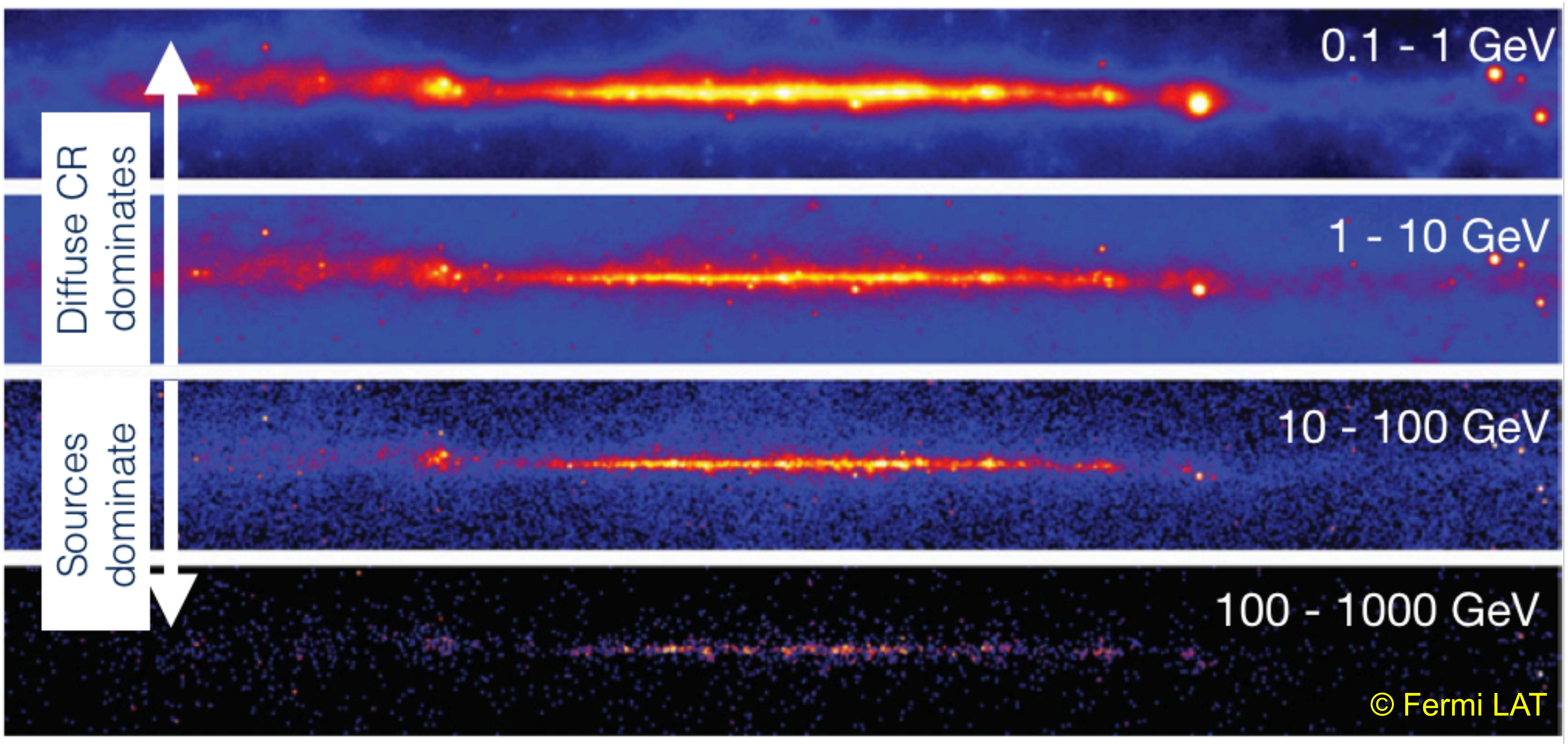


Large Structures in Gamma-rays



Prior: is the CR spectrum in our Solar System special?

Space barometers: Giant Molecular Clouds



Prior: is the CR spectrum in our Solar System special?

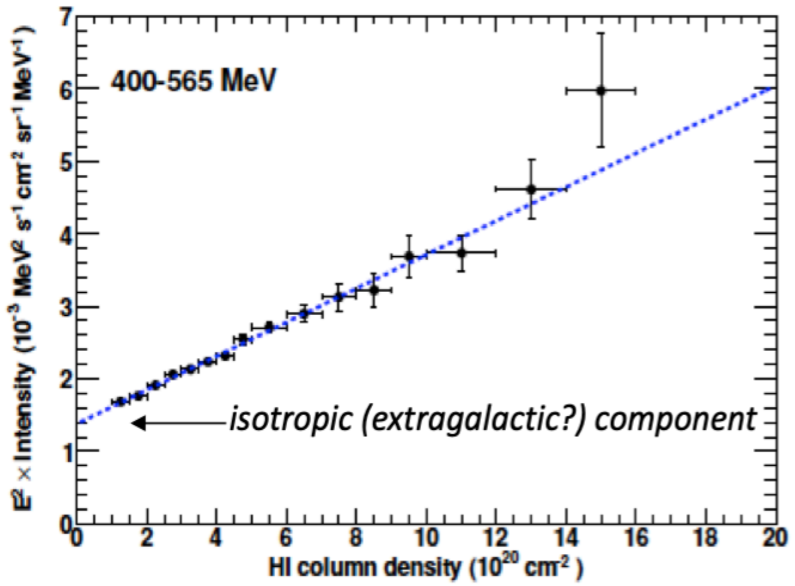
Space barometers: Giant Molecular Clouds

1/ Looking at the average galactic emission:

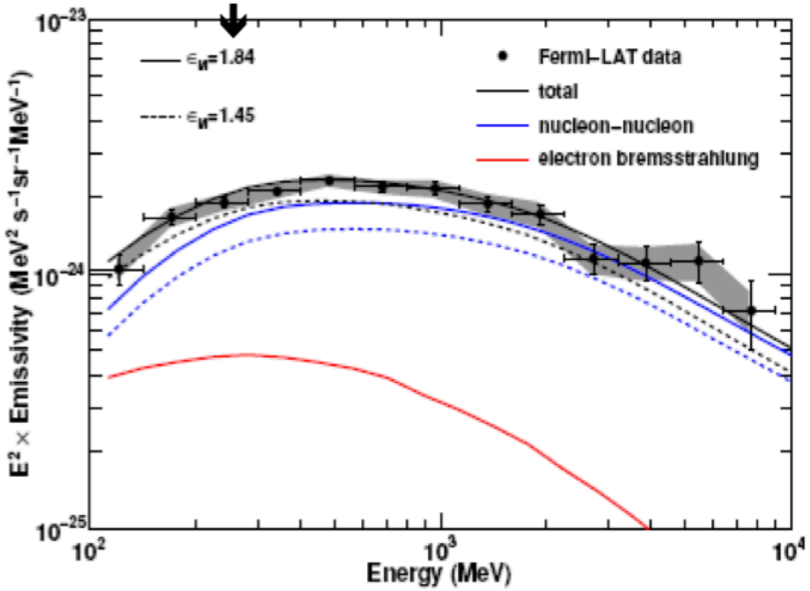
Linear correlation between gamma-ray intensity (0.1-10 GeV) and atomic gas column density

=> the flux of CRs within 1 Kpc is consistent with 10% with the one measured in Earth

Abdo et al., ApJ, 703, 1249, 2009



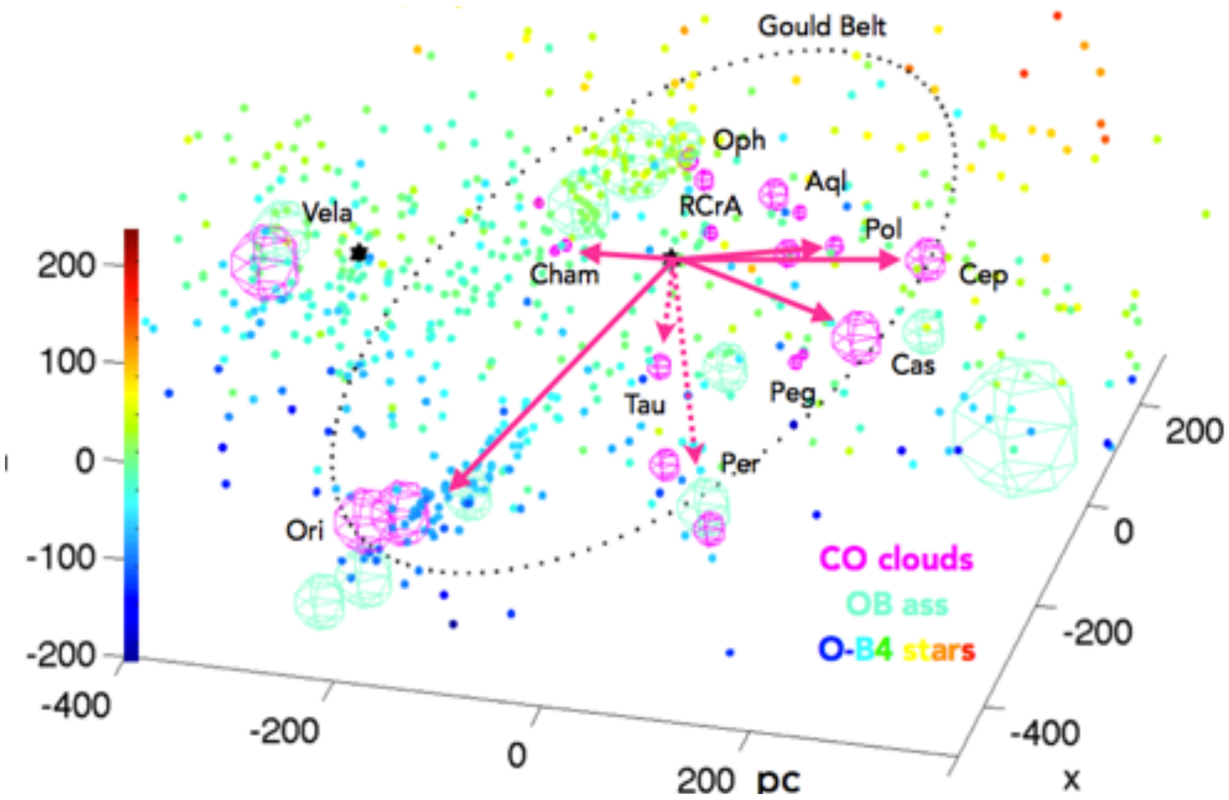
enhancement factor from CRs heavier than p



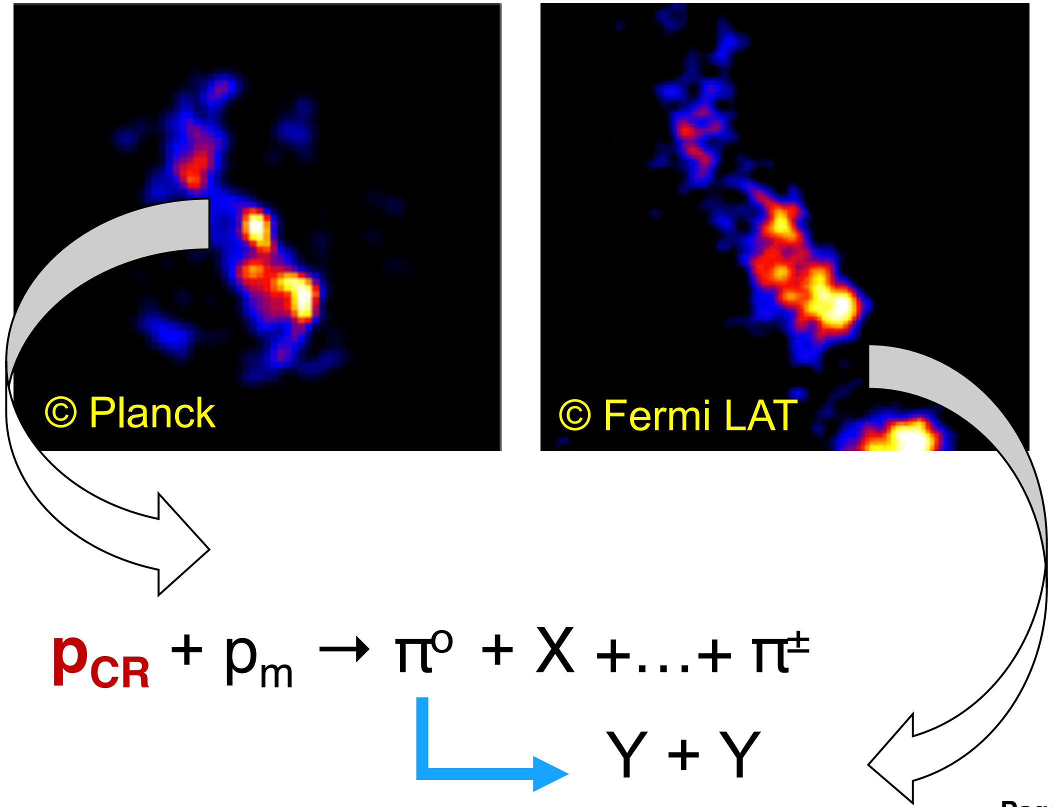
Prior: is the CR spectrum in our Solar System special?

Space barometers: Giant Molecular Clouds

2/ Looking at clean environments – Isolated large Molecular Clouds as Barometers:



Example of Giant Molecular Cloud (GMC):
Orion B



$p_{CR} + p_m \rightarrow \pi^o + X + \ldots + \pi^{\pm}$

Y + Y

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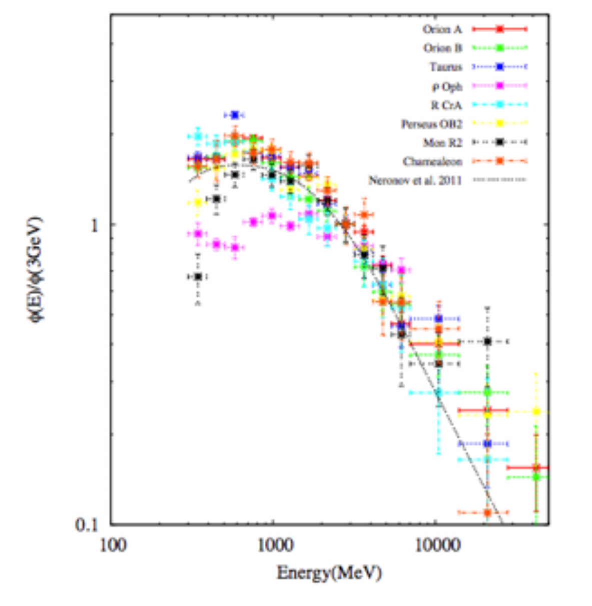
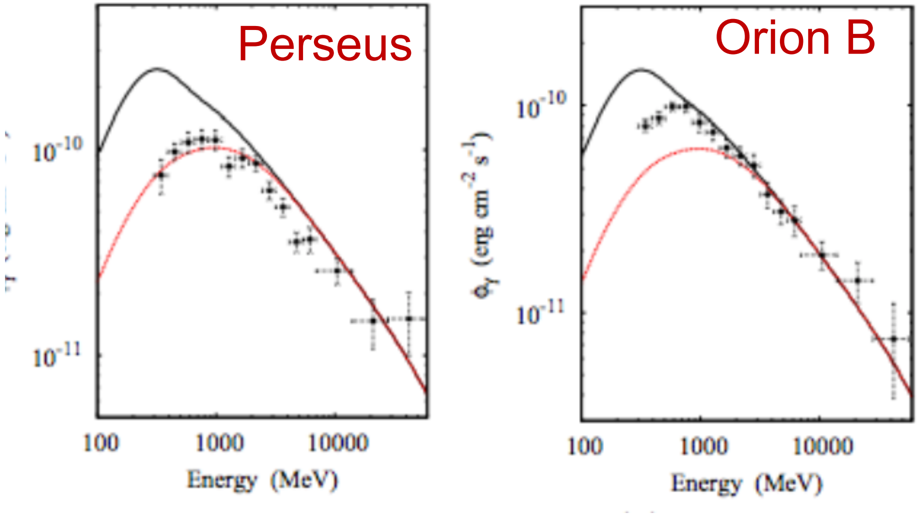
Space barometers: Giant Molecular Clouds

2/ Looking at clean environments – Isolated large Molecular Clouds as Barometers:

Yang, EdOW & Aharonian 2014

#	Region	Mass (Dust / CO) [10^5 $M_\odot$]	Distance [pc]	l [°]	b [°]	M/d^2 [(10^5 $M_\odot$/kpc^2)]
1	ρ Oph	0.12 / 0.08	165	356°	18°	8.4
2	Orion B	0.78 / 0.65	500	205°	-14°	3.9
3	Orion A	1.2 / 0.80	500	213°	-18°	5.2
4	Mon R2	1.1 / 0.80	830	214°	-12°	1.7
5	Taurus	0.30 / 0.23	140	170°	-16°	15.0
6	R CrA	0.01 / 0.01	150	0.5°	-18°	0.8
7	Chamaeleon	0.11 / 0.09	215	300°	-16°	2.4
8	Perseus OB2	0.41 / 0.3	350	158°	-20°	3.3



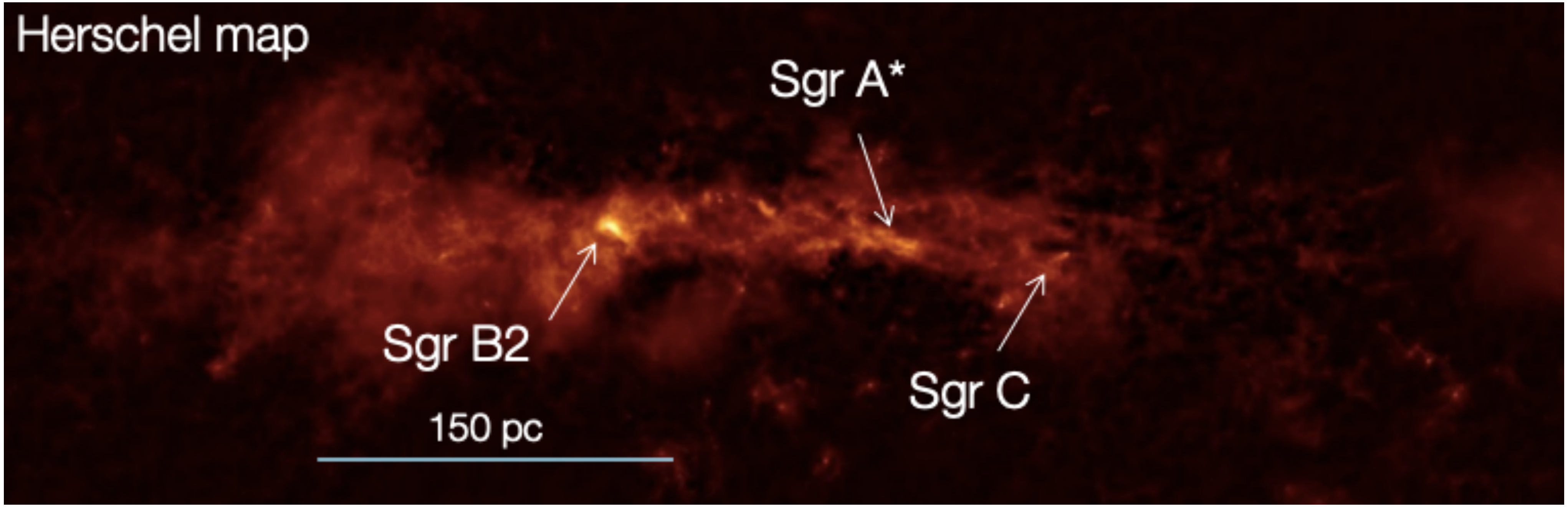


- E> 20 GeV: good agreement with CR spectrum measured at Earth
- Low energy part shows differs from cloud to cloud
- Related to different environment:
  local acceleration, low CR penetration effects, modulation effects?)

We know *reasonably* well the CR in our Galaxy

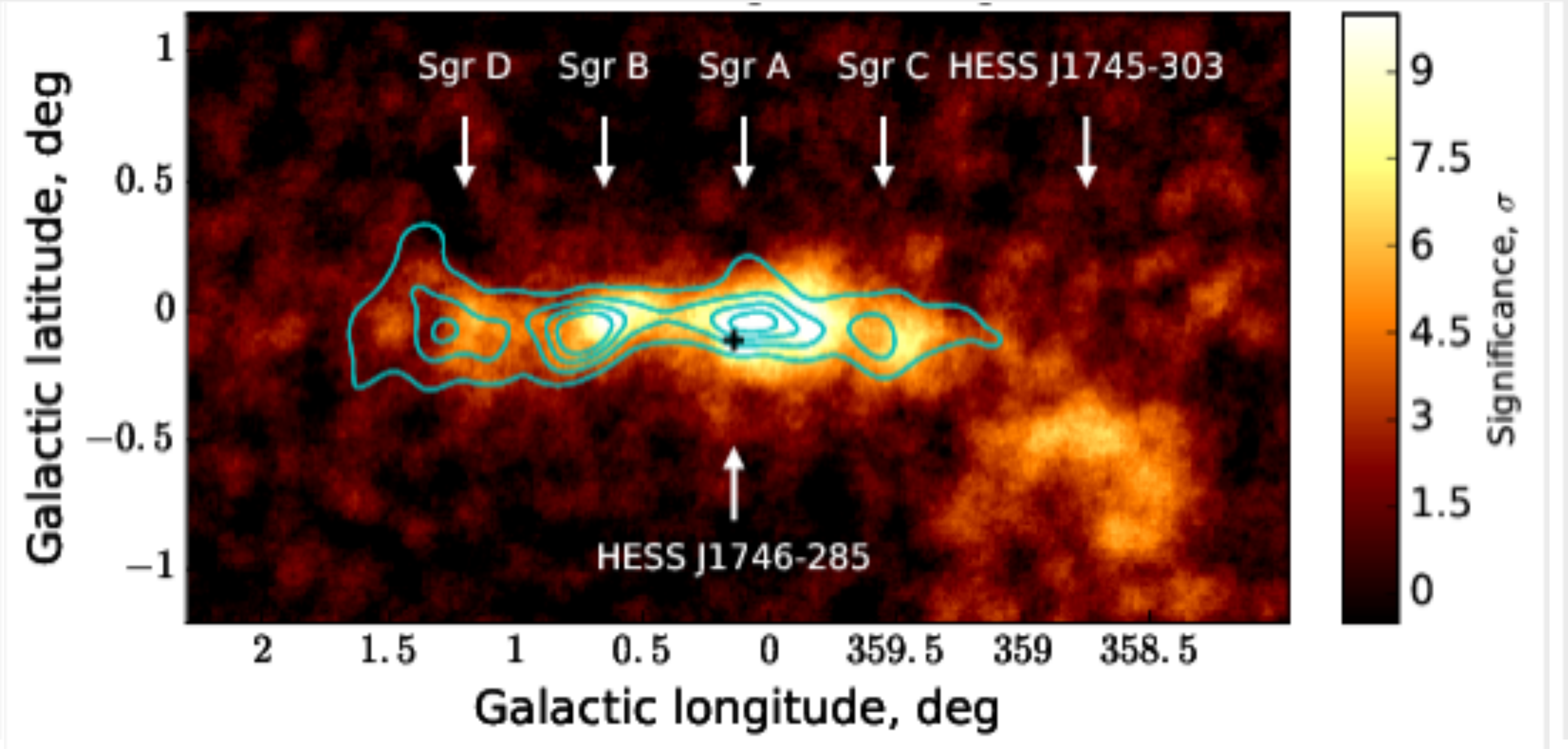
Active Clouds

When a massive cloud a deviation wrt the local CR, indicates an acceleration in the vicinity!



Active Clouds

Diffuse emission correlated with molecular cloud distribution
→ the ratio of the TeV flux to the gas density provides the CR density



HESS Col. 2016

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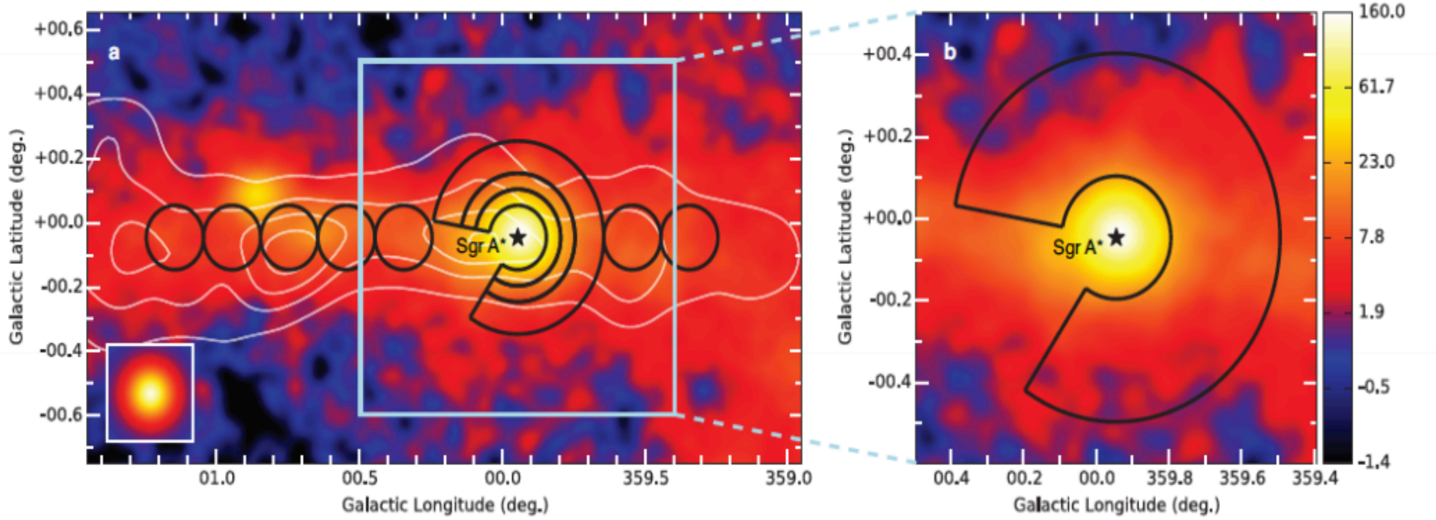
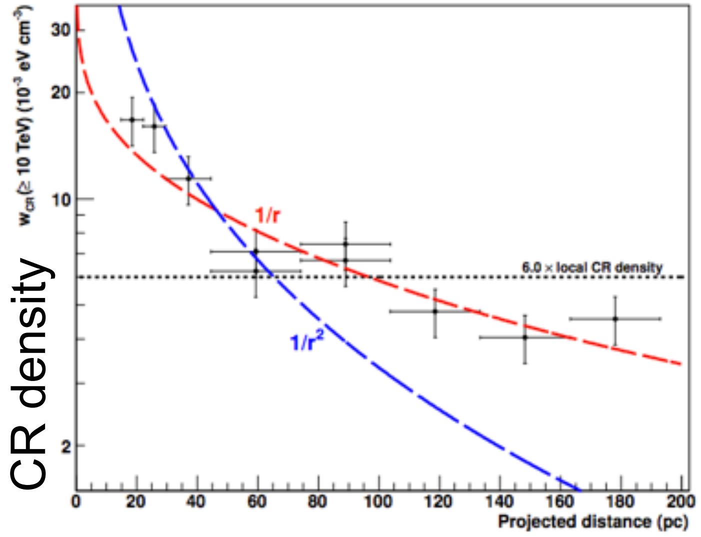
HESS collaboration, Nature 531, 476 (2016)





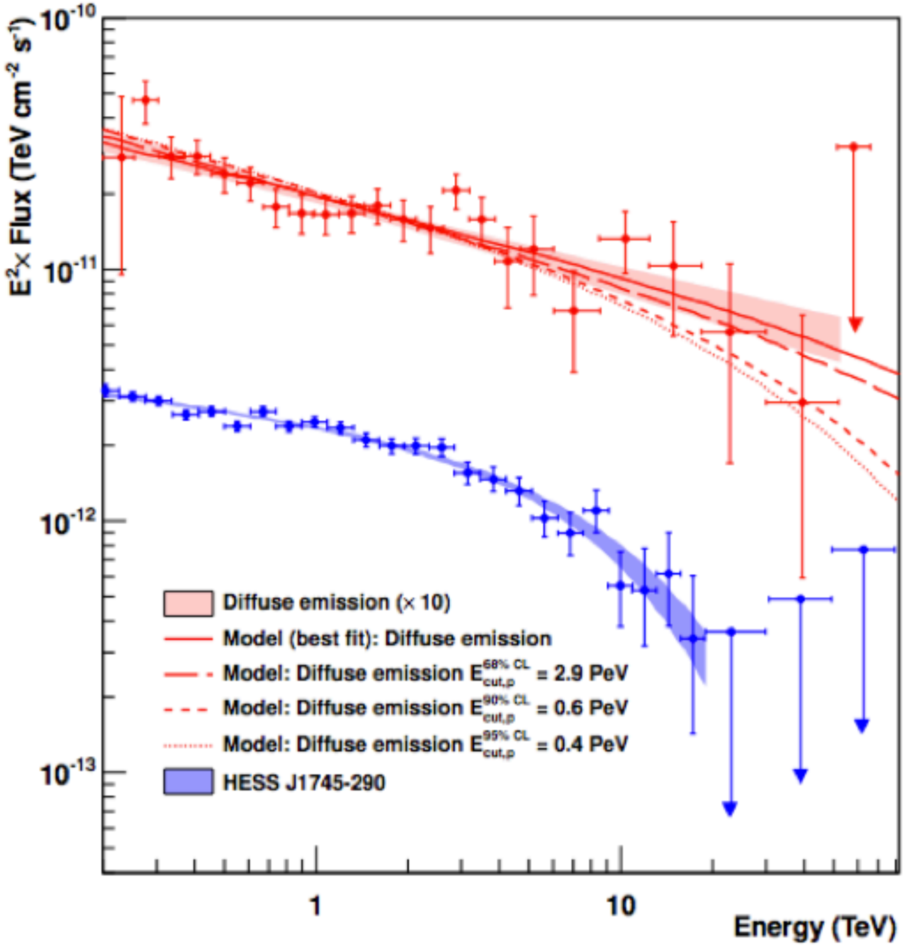
1/r	continuous source
$1/r^2$	wind or ballistic motion
constant	burst like source

Gamma-ray luminosity measurement in several regions

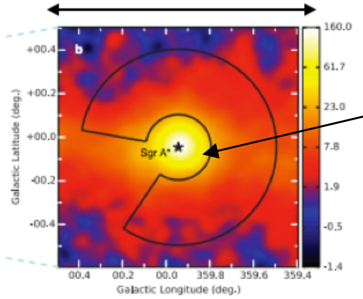
- Use of cloud mass measurements gas density from CS (CO, HCN)
- W_{CR} ~10^{49} erg

Active Clouds

- First evidence of CRs accelerated to PeV energies (diffuse emission)
- Accelerator? a clear cutoff on the point source in the Galactic center (HESS J1745-290)



~70 pc



~5-10% of current star formation

The injection time should be larger than the escape one:

$$\Delta t \geq t_{\rm diff} \approx R^2/6D \approx 2 \times 10^3 (D/10^{30}\ {\rm cm^2 s^{-1}})^{-1}\ {\rm yr},$$

$$\dot{Q}_p(\geq 10\ {\rm TeV}) \approx 4 \times 10^{37} ({\rm D}/10^{30}\ {\rm cm^2 s^{-1}})\ {\rm erg/s}.$$

Rather modest injection for thousands of years:
- Galactic center?
- Stellar clusters in the inner region?

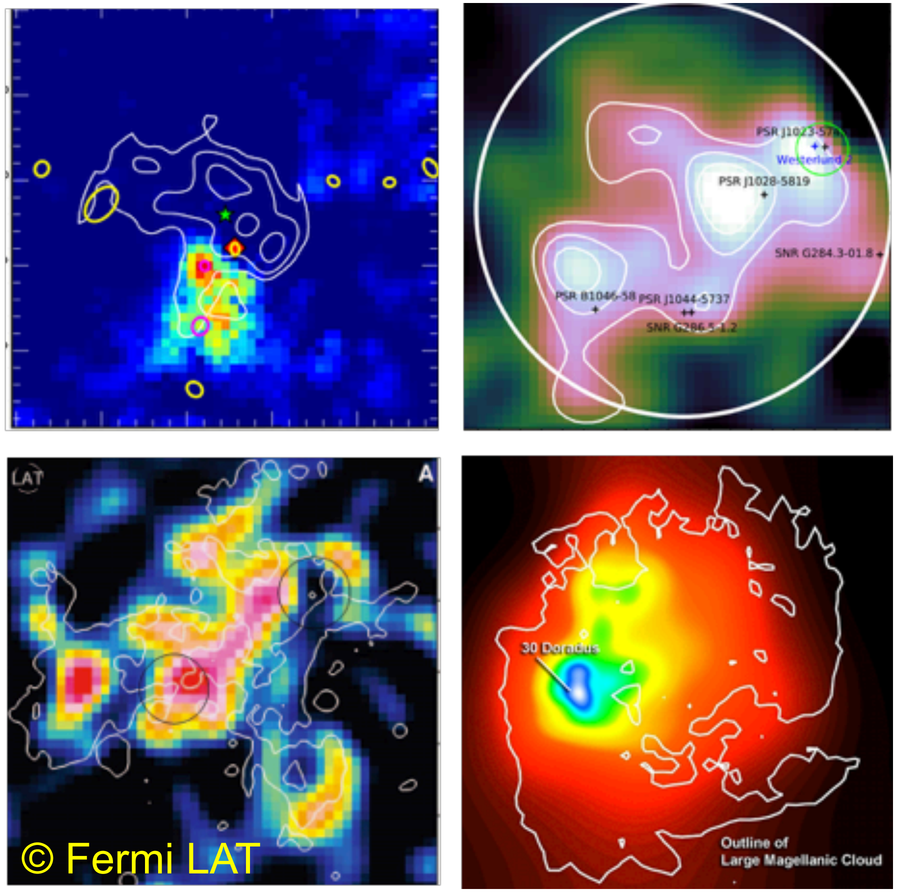
HESS Col. 2016

Star Formation Regions

Can SFR accelerate PeV CRs?

Stellar Clusters: Energy reservoir ~$10^{38\text{-}39}$ erg over ages of $T \geq 10^6$ years

~few degree



Aharonian, Yang, EdOW, 2019

Several large-scale gamma-ray bubbles detected with LAT

- The large size & morphology disfavor a unique leptonic accelerator:
  - Large U_{ph} would result in a peaked emission towards the cluster
  - Electrons can only diffuse up ~30 pc
- Use of cloud mass measurements gas density CO:CfA 1.2 mm-wave Telescope & HI:LAB Survey
- Derive the CR distribution & spectrum

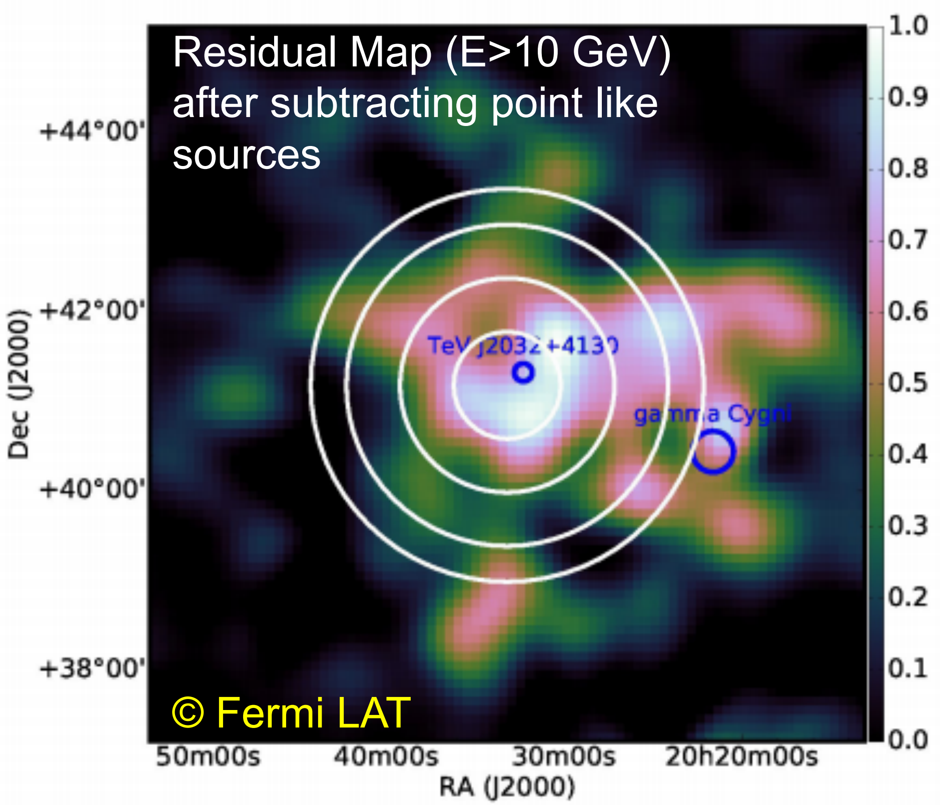
$$W_{\rm tot} = f L_0 T_0 = 3 \times 10^{52} f L_{39} T_6 \ \rm erg$$

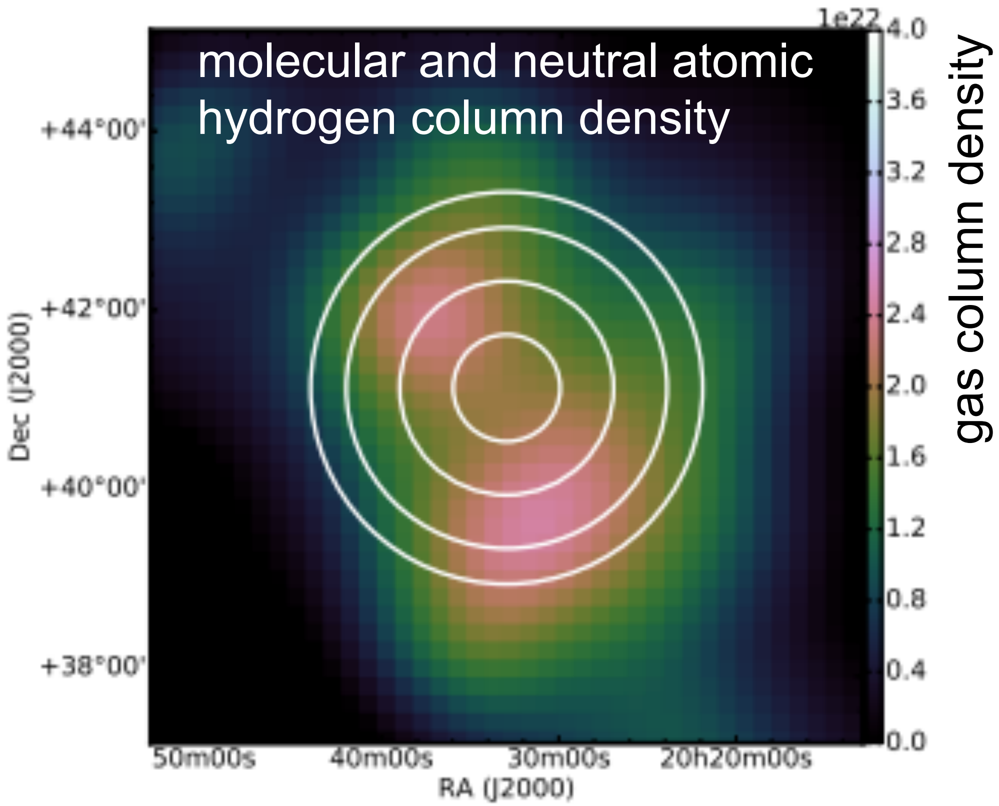
Source	Cygnus Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[39]	3–6	2–7	4–6
Kinetic luminosity, $L_{\rm kin}$, of cluster (erg s^{-1})	2×10^{38} (ref. 17)	1×10^{39} (ref. 40)	1×10^{39} (ref. 41)
Distance (kpc)	1.4	8.5	4
ω_0 (>10 TeV) (eV cm^{-3})	0.05	0.07	1.2

Star Formation Regions

Can SFR accelerate PeV CRs?

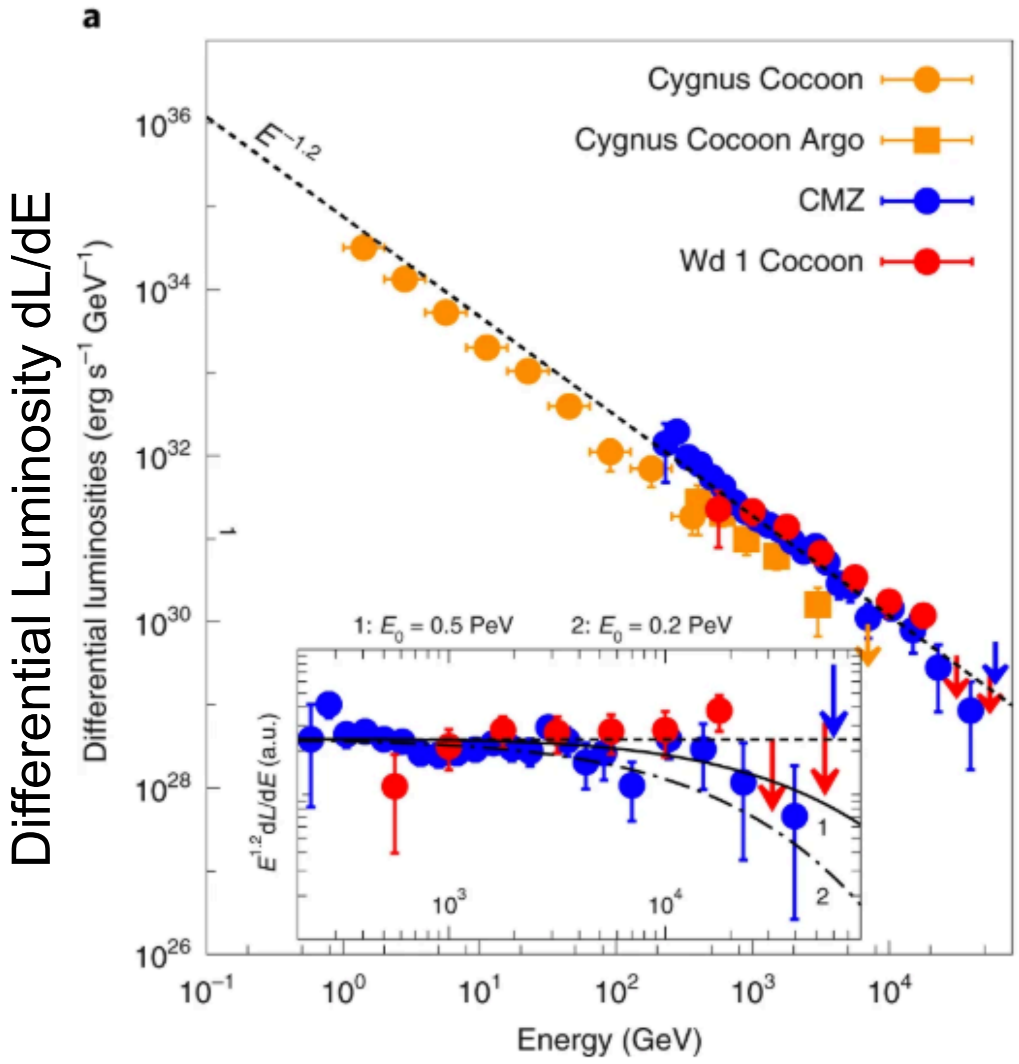
Example: Cygnus Cocoon.





Star Formation Regions

Can SFR accelerate PeV CRs?



The spectra (of some of them) extends to high energies

With remarkably similar shape and spectral index (2.2)

No indication of energy cutoff (with the available statistics)

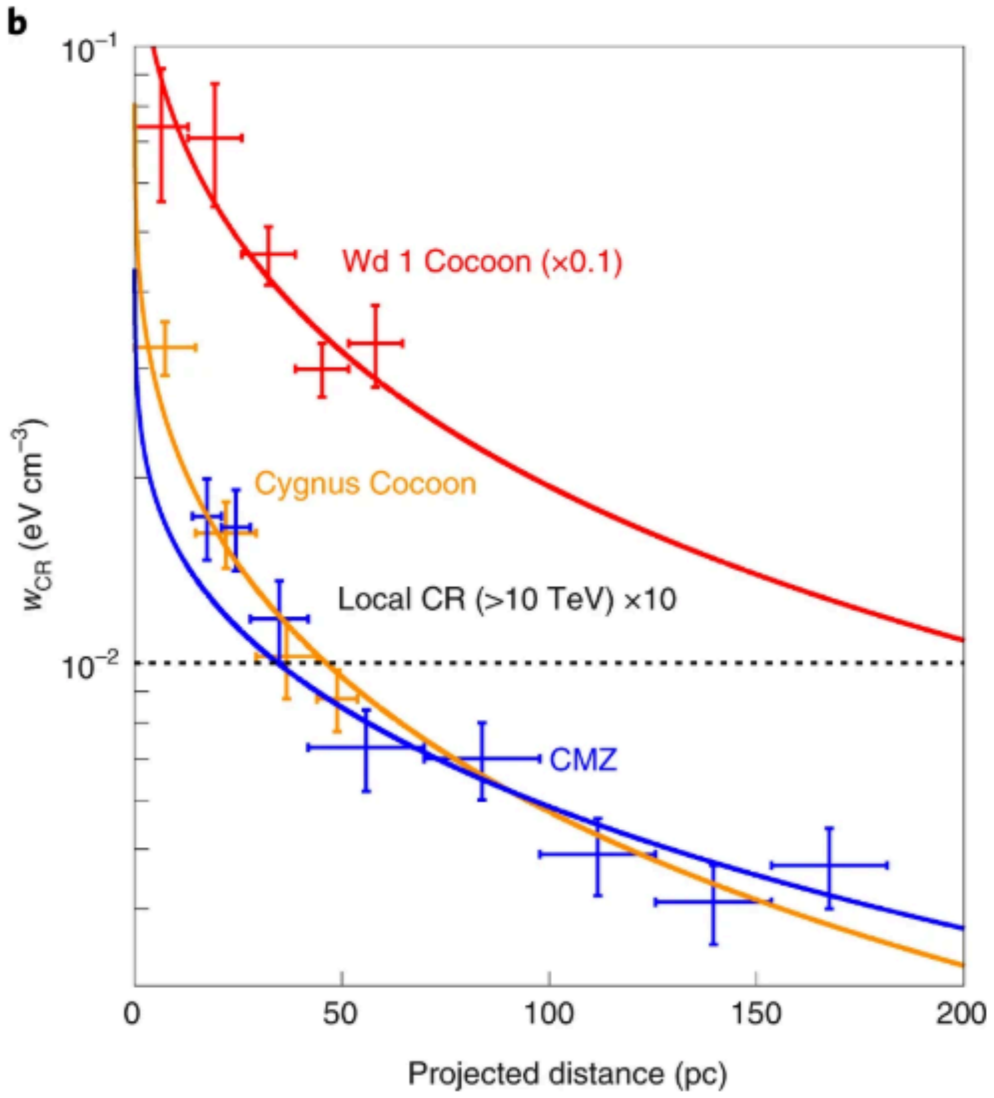
Proton spectrum described with:

$E^{-2.3}\exp(-E/E_o)$ with E_o = 0.2 (1), 0.5 (2) PeV

=> For Kolmogorov-type turbulence, $D(E) \propto E^{1/3}$, we arrive at a 'classical' E^{-2}-type acceleration spectrum.

Star Formation Regions

Can SFR accelerate PeV CRs?



The CR proton radial distribution follows a 1/r line (>10 TeV)
(for the Cygnus Cocoon we extrapolated from LAT energies)

Exceeding the local CR by a factor of 10 (from AMS)

We parametrized the CR density as:

$$w(r) = w_0(r/r_0)^{-1}$$

$$\begin{aligned} W_p &= 4\pi\int_0^{R_0} w(r)r^2\,dr \\ &\approx 2.7\times10^{47}(w_0/1\,\mathrm{eV\,cm^{-3}})(R_0/10\,\mathrm{pc})^2\,\mathrm{erg} \end{aligned}$$

Star Formation Regions

Estimation of the CR density and their transport

We define R as the extension of the source (50 and 300 pc), or more conservatively, the maximum given by the diffusion condition:

$$R_D = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc}$$

Since W_{CR} cannot be larger than W_{tot} => $f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$

$$W_{tot} = f L_0 T_0 = 3 \times 10^{52} f L_{39} T_6 \text{ erg}$$

Measuring the Local diffuse coefficient:
if f=10% => D ~10^{28} cm^{-2} s^{-1}

Halos as large as 300 pc and with a density still 2 order of magnitude larger than the local CR density

Source	Cygnus Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
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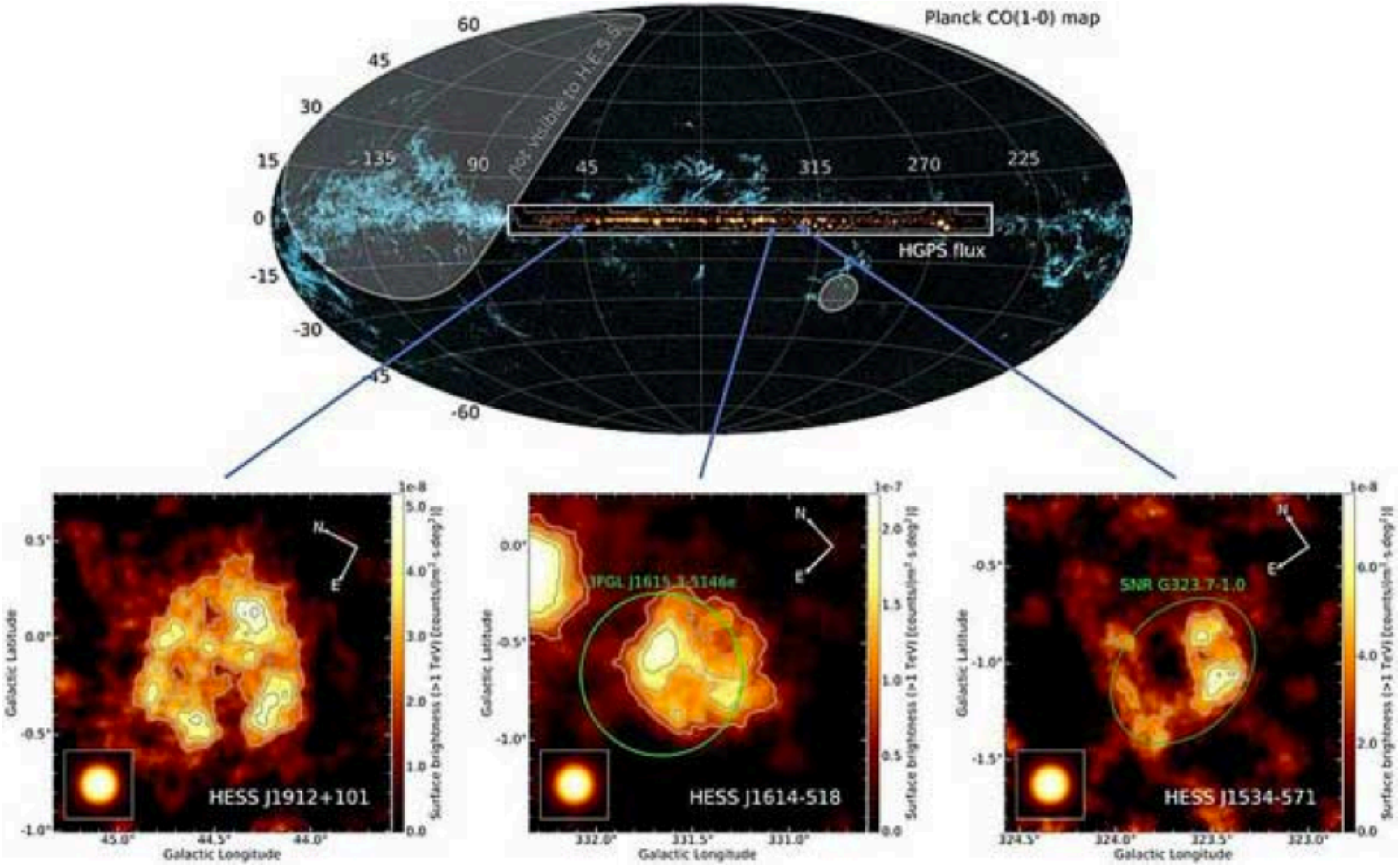
Supernova Remnants

The standard paradigm

CR Standard Paradigm E_{kin} ~10^{51} erg/SN, rate=2-3 century => 10% to sustain the 10^{41}erg/s CR
:

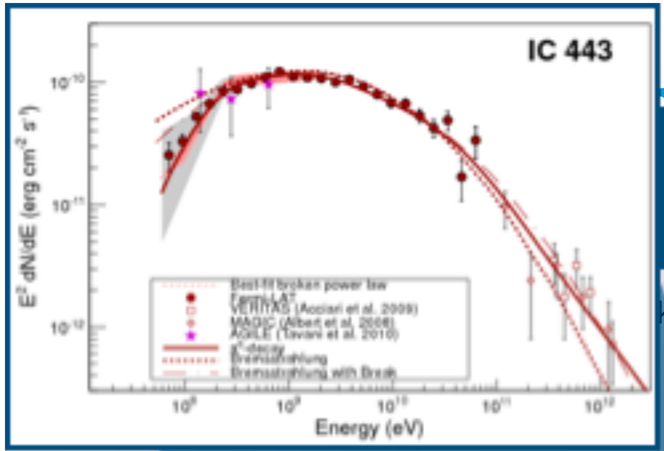


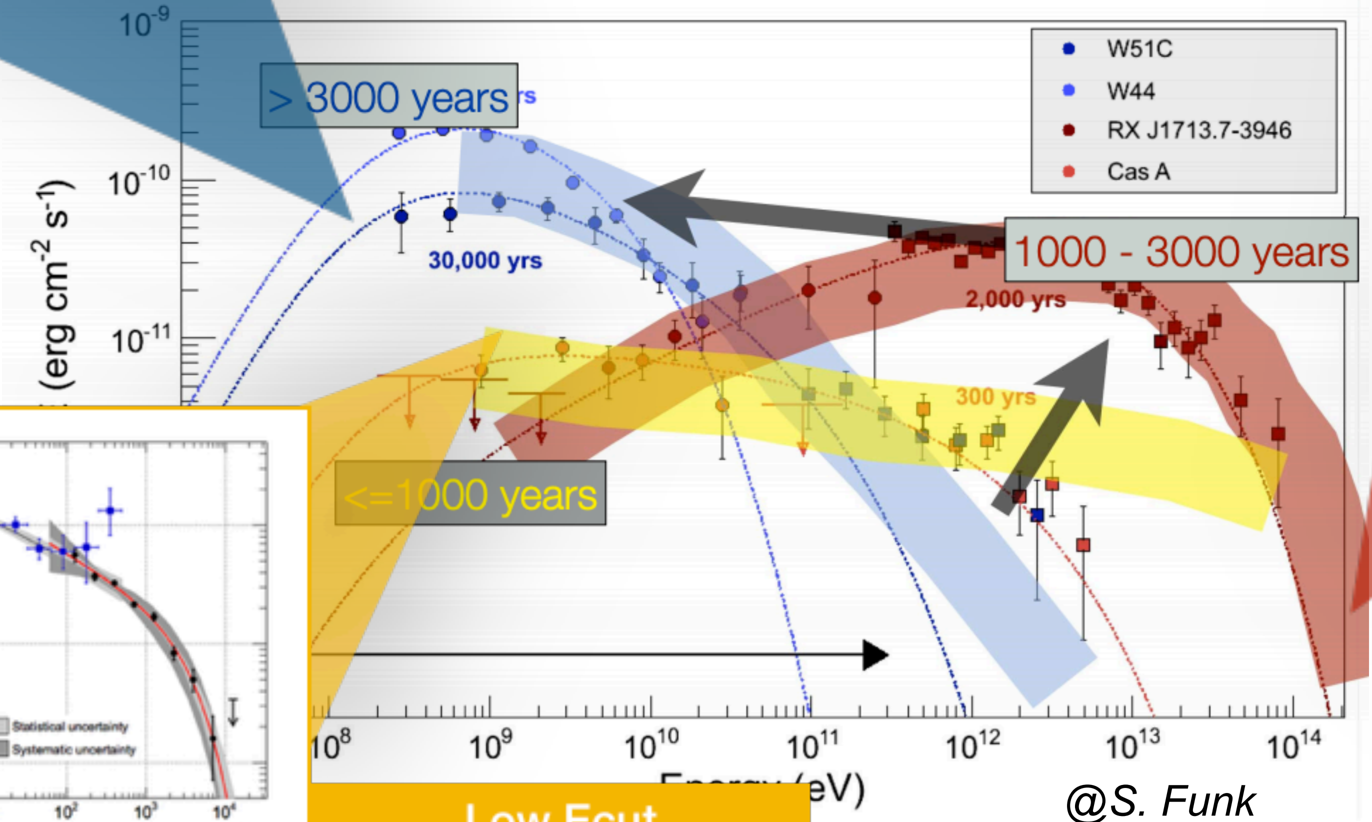
HESS Col. 2017

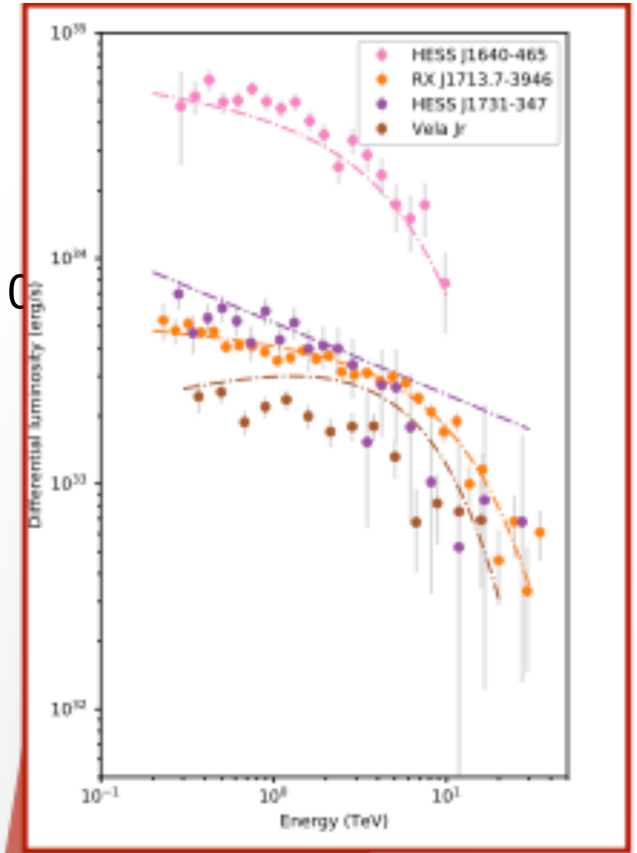
...mnants

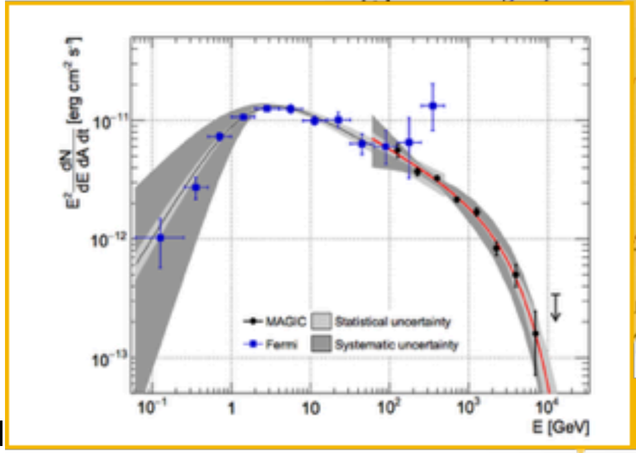
π-peak detected => hadrons!

kin ~10^{51} erg/SN, rate=2-3 century => 10% to sustain the 10









@S. Funk

Conclusions

Factories of CRs

- We have established that (at least a large fraction of) the bulk of CRs (GeV) accelerates in SNRs:

:
  - ✓ Detection of many GeV & TeV SNRs
  - ✓ Magnetic field amplification in shell
  - ✓ Spectral energy distributions (pion decay)

BUT

- We don't have any proof of SNR accelerating CRs to PeV (PeVatrons)
- We see at least one PeVatron in the Galactic center region:
  The emission is hardly compatible with impulsive (SNR) acceleration of CRs
- The Galactic Center alone could have some past active phase and fill the Galaxy (and Fermi bubbles!)
- The Galactic Center region hosts 15% of the stellar activity in our Galaxy
  => Stellar Cluster could accelerate CRs

Conclusions

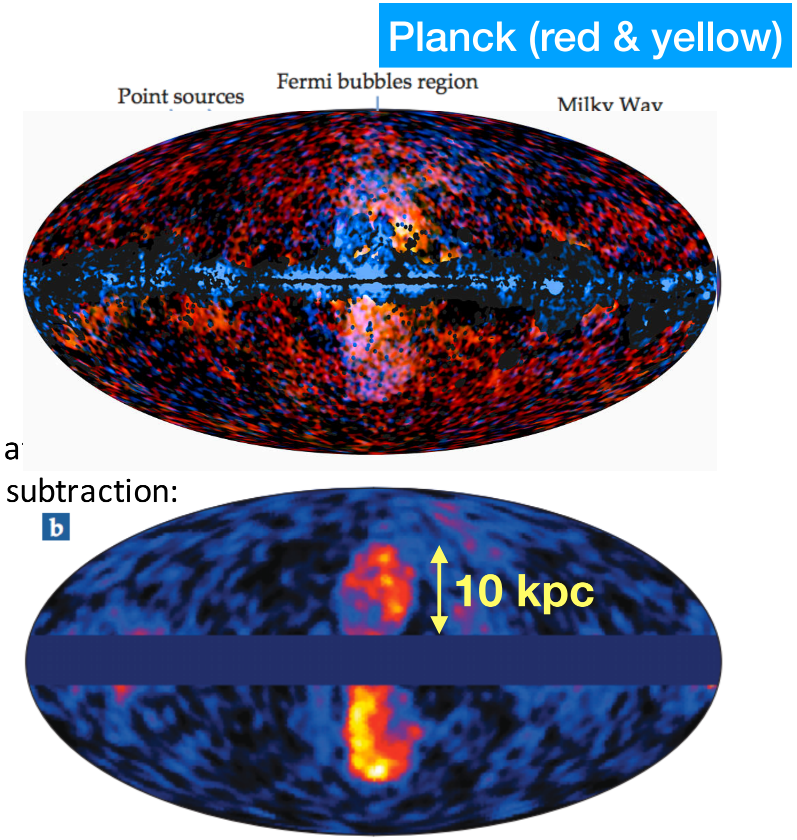
Factories of CRs

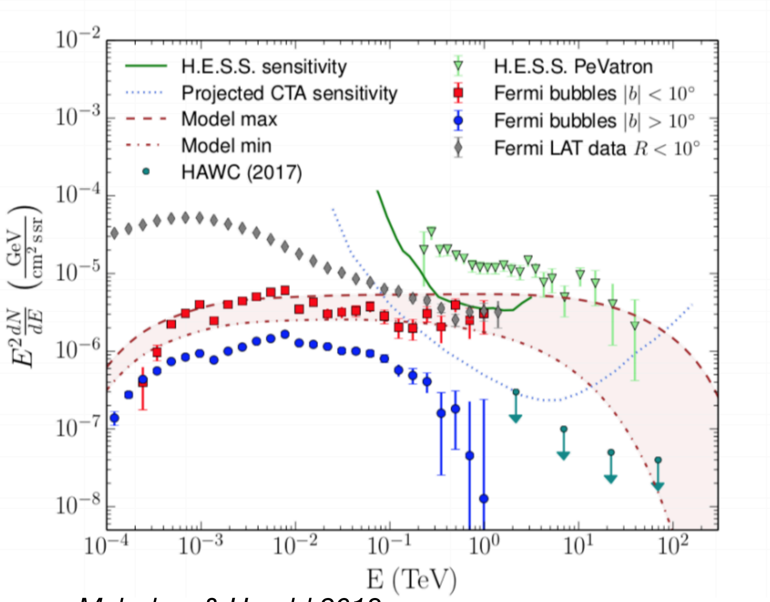
- Stellar Cluster are potentially good sources of PeV CRs
- We observe large ~degree sources in dense regions:
  - The spectrum is compatible with hadronic emission
  - The 1/r profile favors diffusive propagation of CRs vs advecting in winds or single burst-like
  - Stellar cluster can be extremely efficiency in accelerating CRs.
- Still to many things to investigate! How many populations of Galactic sources are there?
  ➔ We need better data and more photons – Time for CTA

BACKUPS

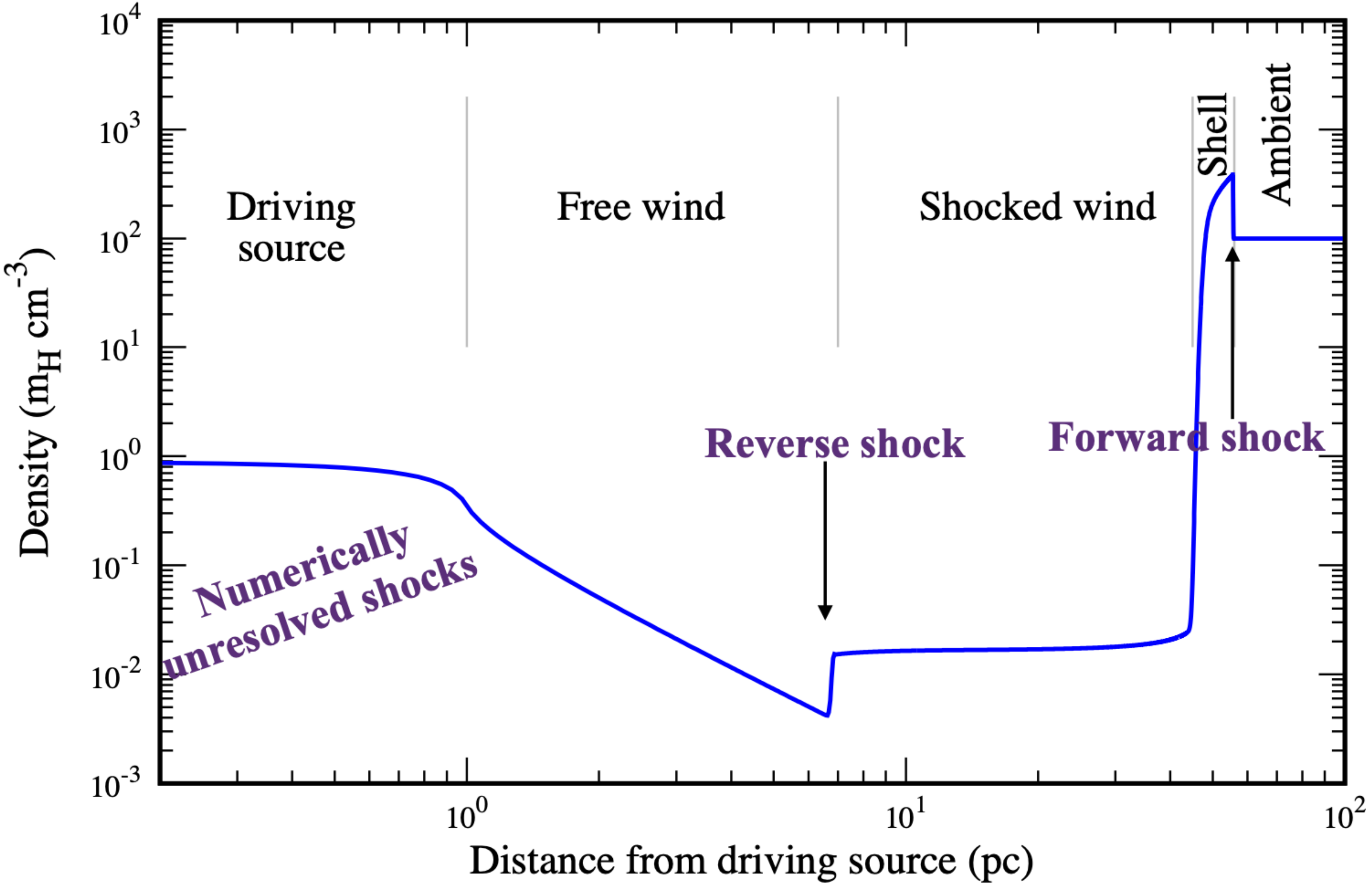
Large HE Structures in the Galaxy

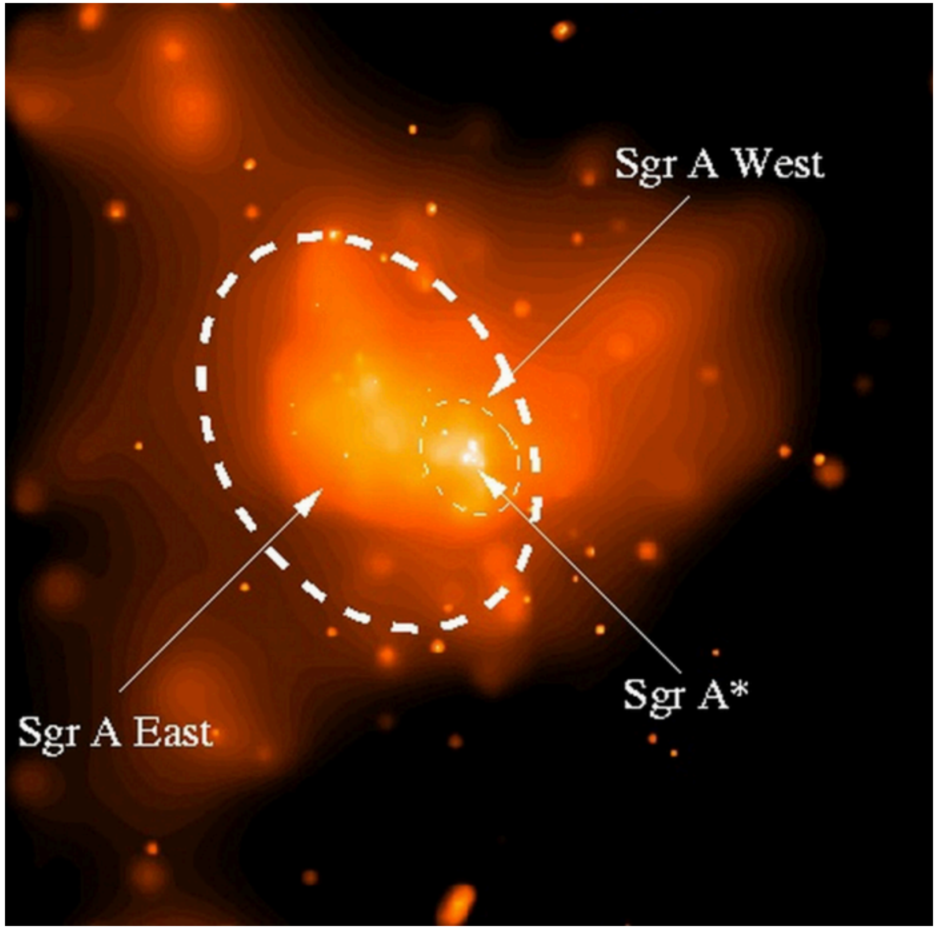
– **The Fermi Bubbles:** Large γ-ray emitting structures extending below and above the Milky Way plane from the galactic center
– E~10^{56}erg: how is the outflow connected to the Gal Center?

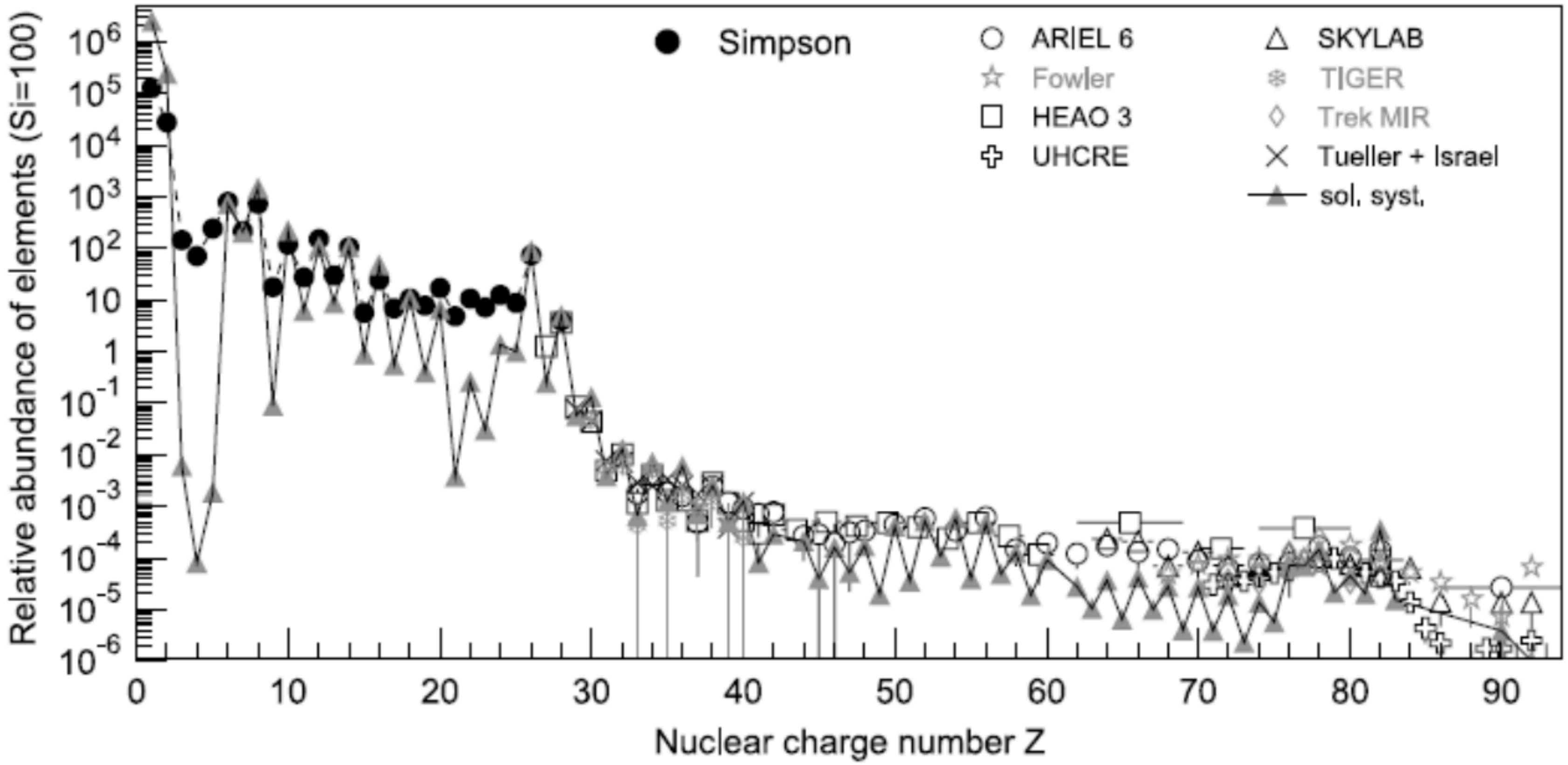




Malyshev & Herold 2018


Driving source
Free wind
Shocked wind
Shell
Ambient
Reverse shock
Forward shock
Numerically unresolved shocks
Density (m_H cm^{-3})
Distance from driving source (pc)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{0}
10^{1}
10^{2}


Sgr A West
Sgr A*
Sgr A East



Simpson
ARIEL 6
Fowler
HEAO 3
UHCRE
SKYLAB
TIGER
Trek MIR
Tueller + Israel
sol. syst.
Relative abundance of elements (Si=100)
Nuclear charge number Z