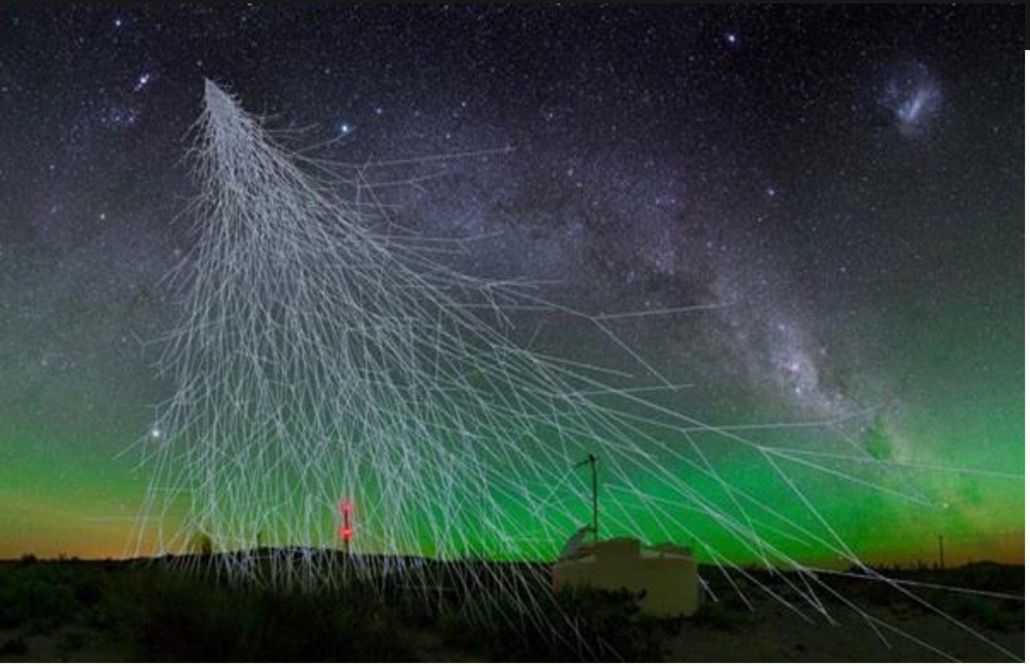
Speaker: Alexandre INVENTAR
PhD Supervisor: Stefano GABICI

γ-ray signatures of particle acceleration in stellar clusters from GeV to PeV

Université Paris Cité

COSMIC RAYS AND WHY DO WE CARE



On Earth: Energetic charged particles:

- Mainly protons
- Other nuclei
- e-, e+, …

➡ Impacts in particle physics and on dark matter

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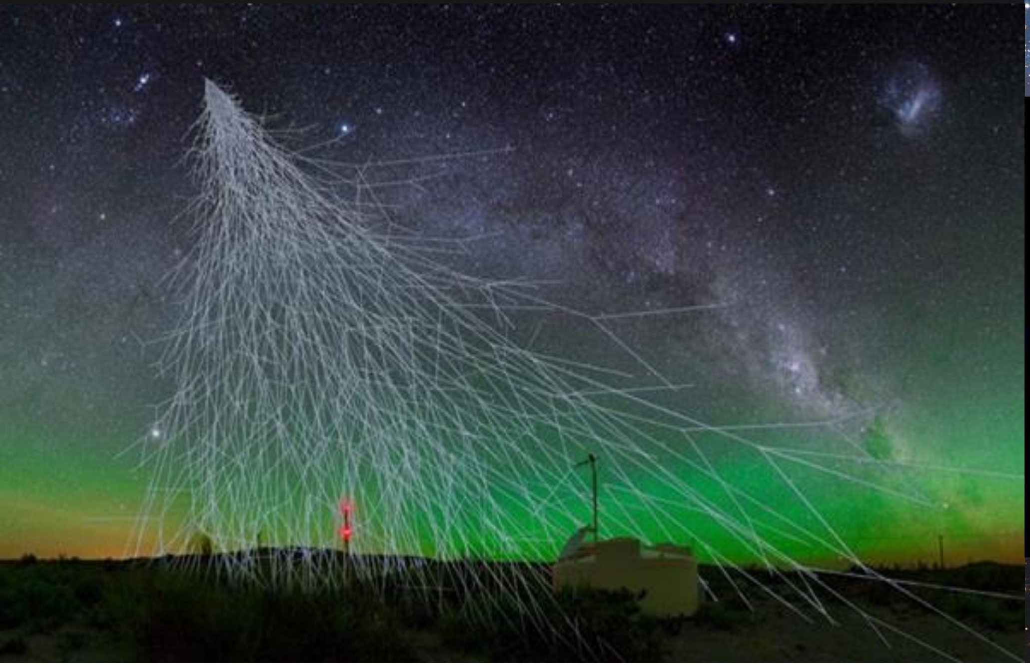

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→ particles deflected

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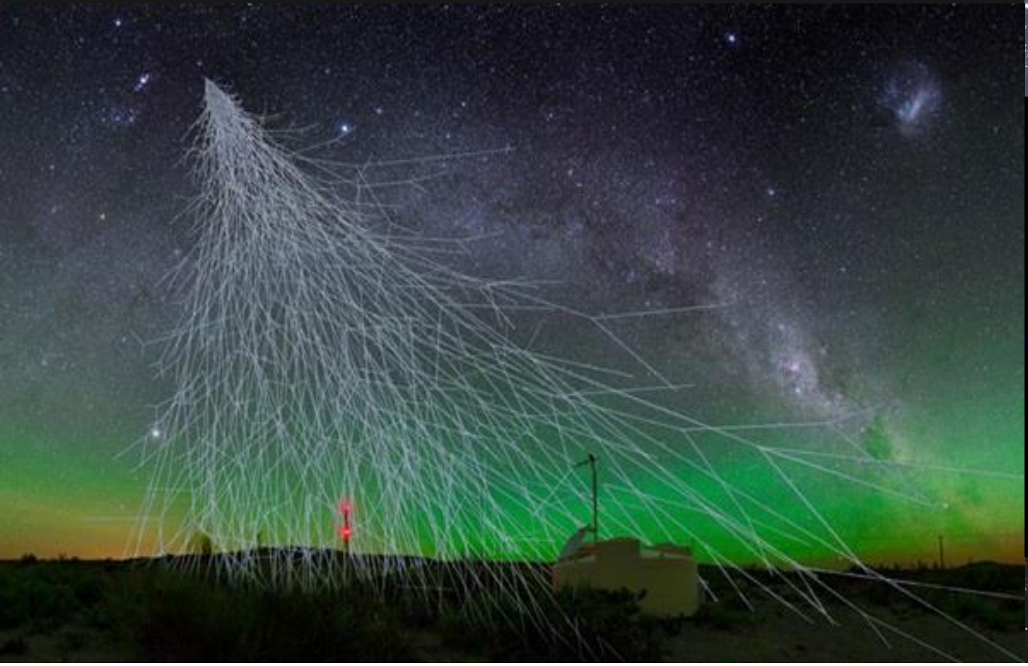

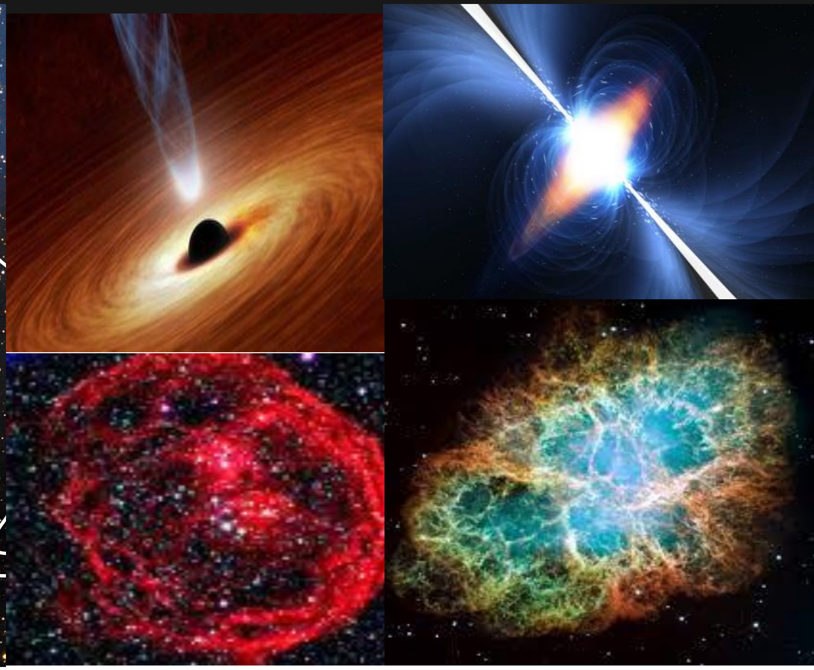

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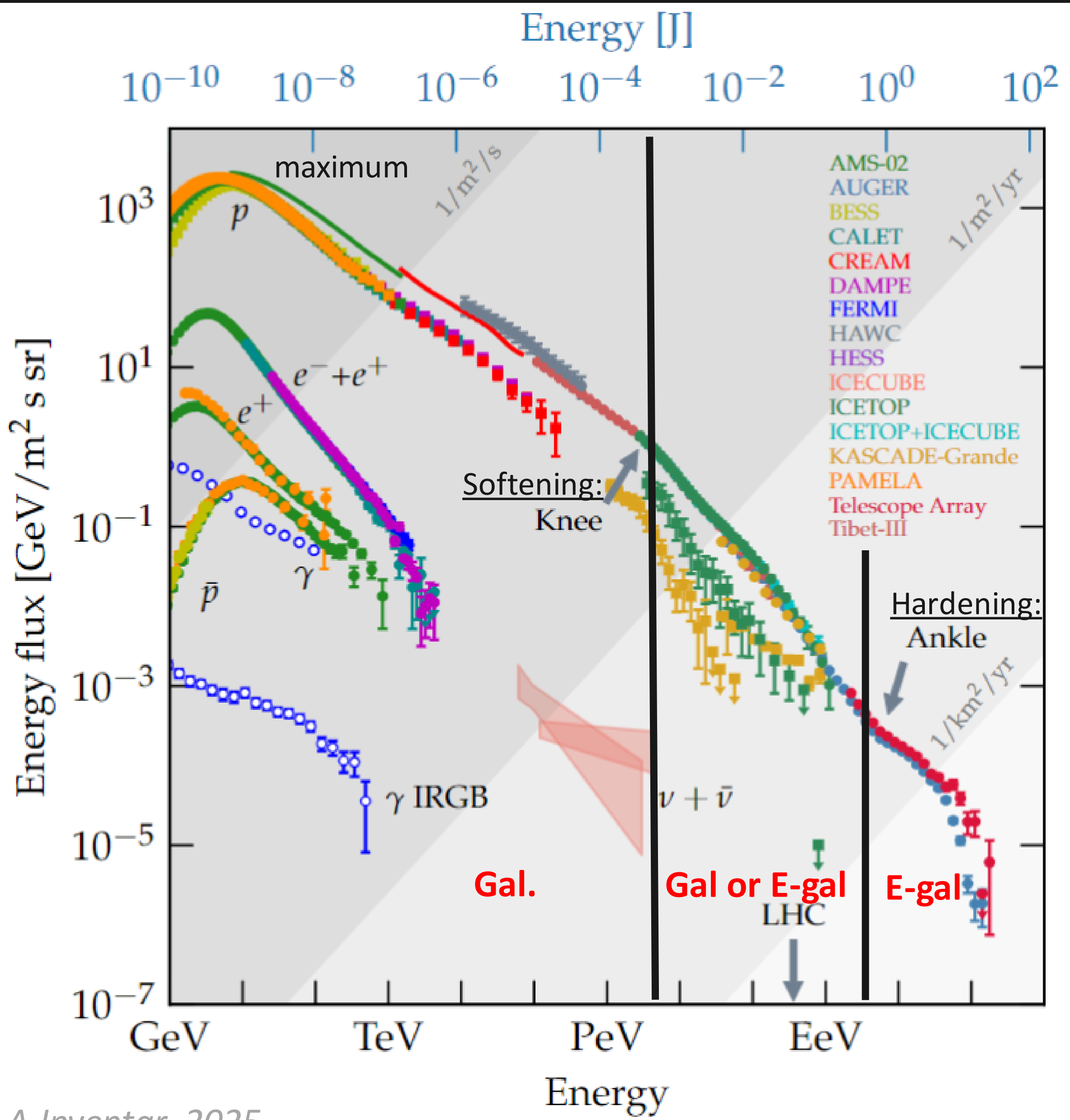
Accelerated from (galactic) sources :
- pulsars
- supernova remnants
- stellar clusters (winds) , etc

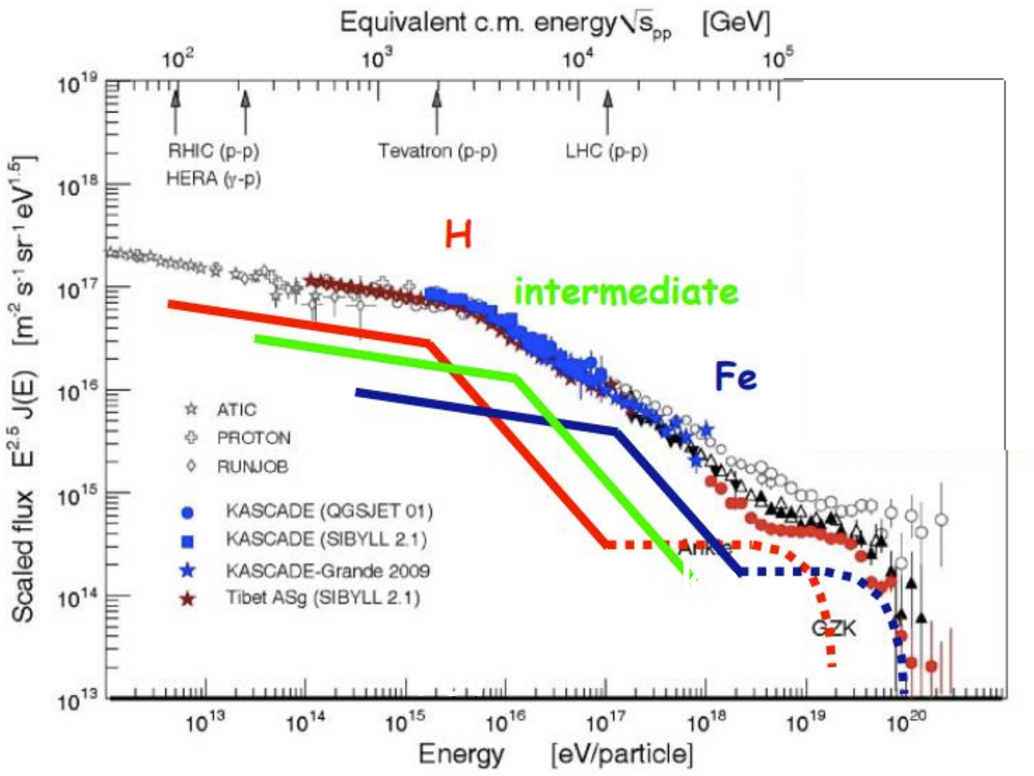
→ Information on accelerating sources and acceleration mechanisms

COSMIC-RAY SPECTRUM AND PEV



What happens at PeV scale ?

- Accelerate protons up to the knee ($\sim$ 3PeV) and Fe to $\sim$ 100 PeV with galactic sources ?



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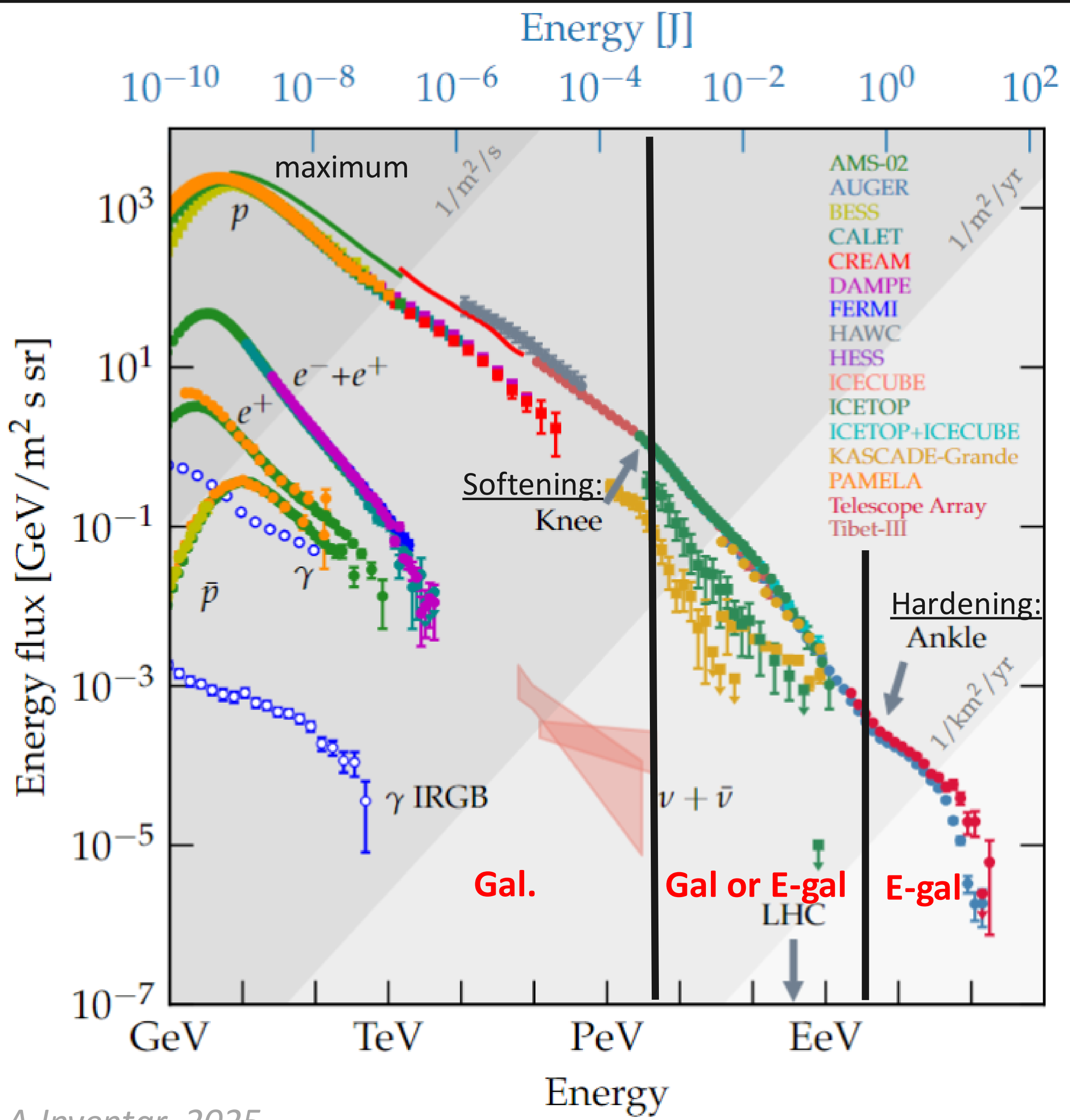

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- Accelerate protons up to the knee ($\sim$ 3PeV) and Fe to $\sim$ 100 PeV with galactic sources ?

- Problem to observe CRs: they are diffused

→ Can't link them to their original sources

→ Use γ-ray astronomy instead : p+p→ $\pi^0 \rightarrow \gamma\gamma$

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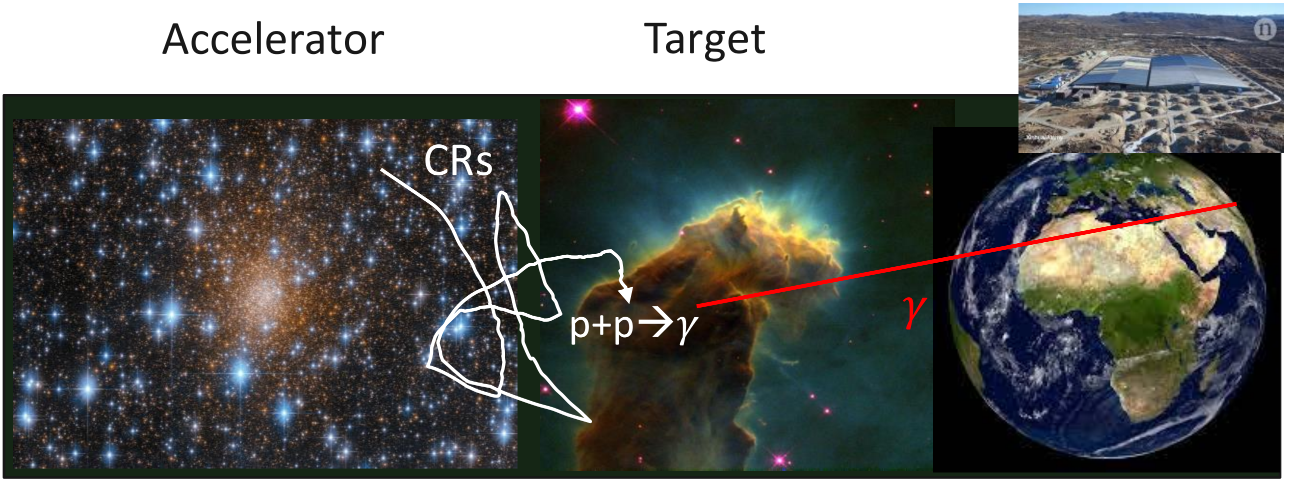
OUTLINE

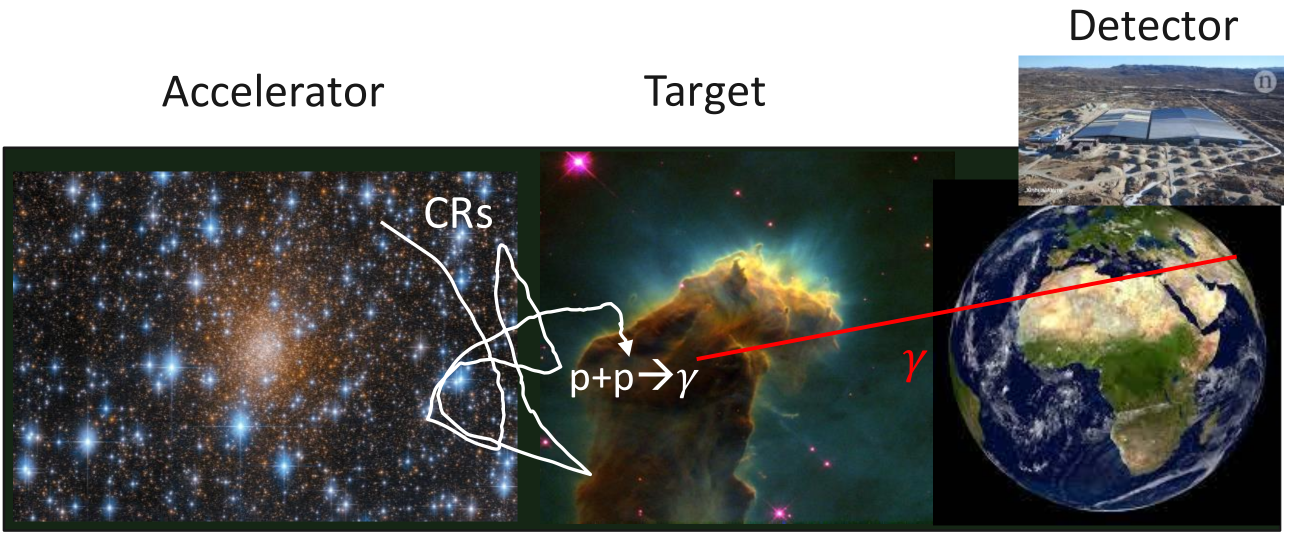
Detector

Accelerator

Target



OUTLINE



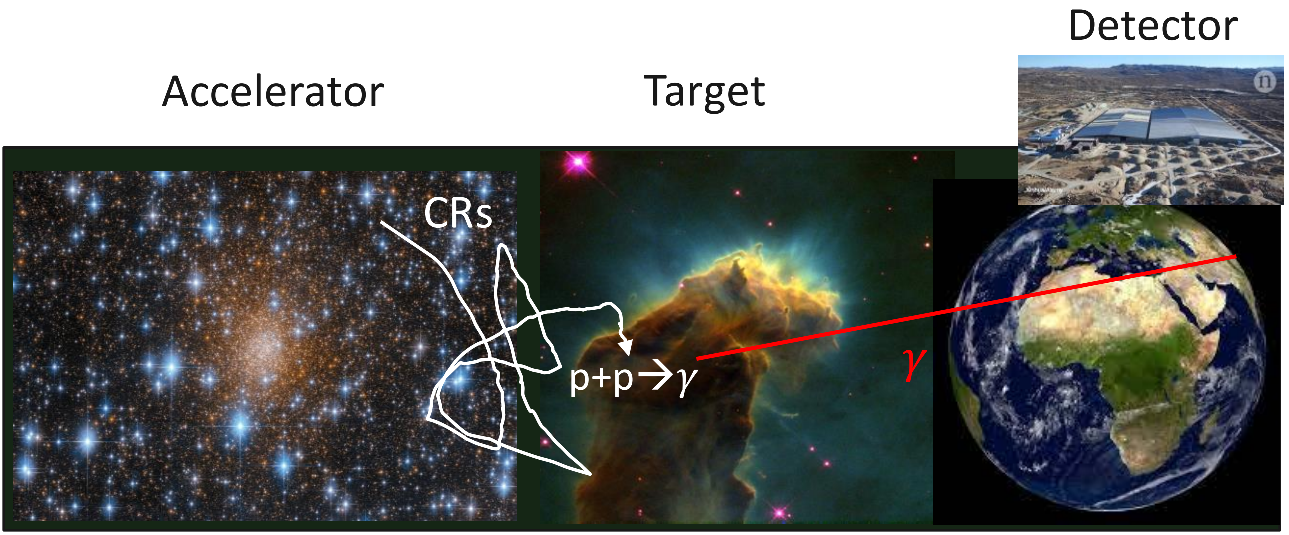
Theory

- For which systems and parameters can we detect an excess of γ-rays?

→Model escape and transport of CRs between sources and targets, and consequent γ rays

- Focus on **continuous injection** (star clusters)

OUTLINE



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→Model escape and transport of CRs between sources and targets, and consequent γ rays

- Focus on **continuous injection** (star clusters)

Theory

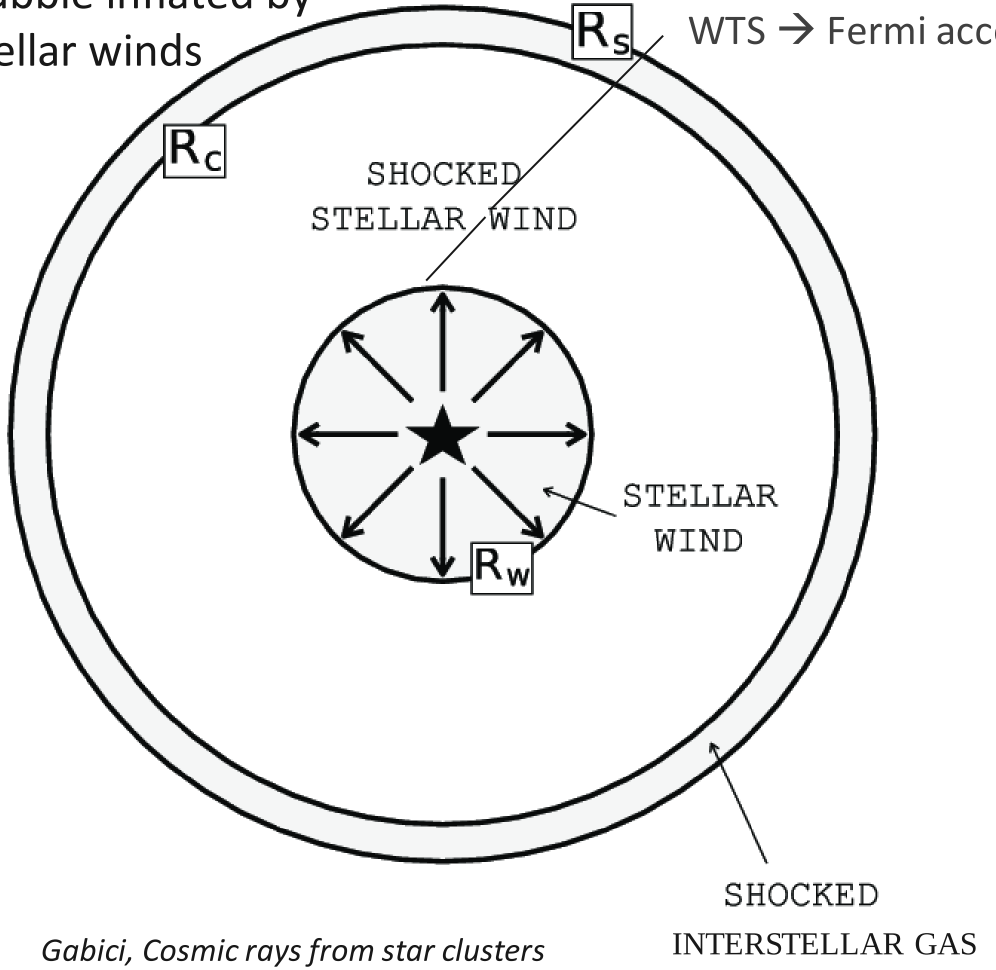
Applications and perspectives

Find corresponding existing systems, compare the model to observed γ-ray flux

→ Obtain better constraints on acceleration parameters
→ Explain unidentified γ –ray sources
→ Identify the contributions of star clusters to CR flux at PeV and below

DIFFERENT HADRONIC γ-RAYS PRODUCTION SCENARIOS WITH STELLAR WIND

Bubble inflated by stellar winds



Gabici, Cosmic rays from star clusters

WTS → Fermi acceleration : $f_{inj} \sim \epsilon_w L_w p^{-\alpha_p} \exp\left(-\frac{E}{E_{max}}\right), \quad \mathbf{4 < \alpha_p < 4.4}$

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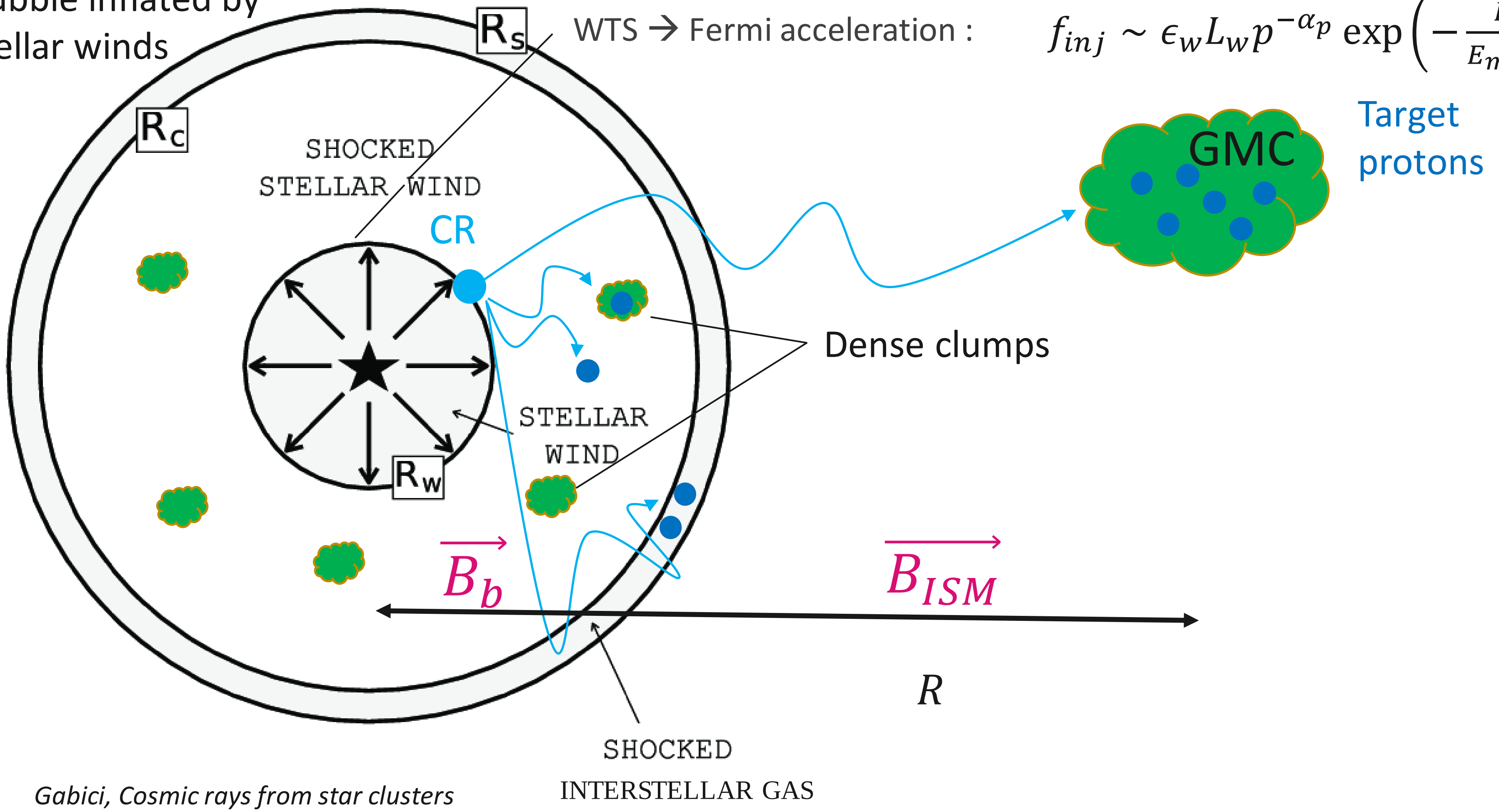

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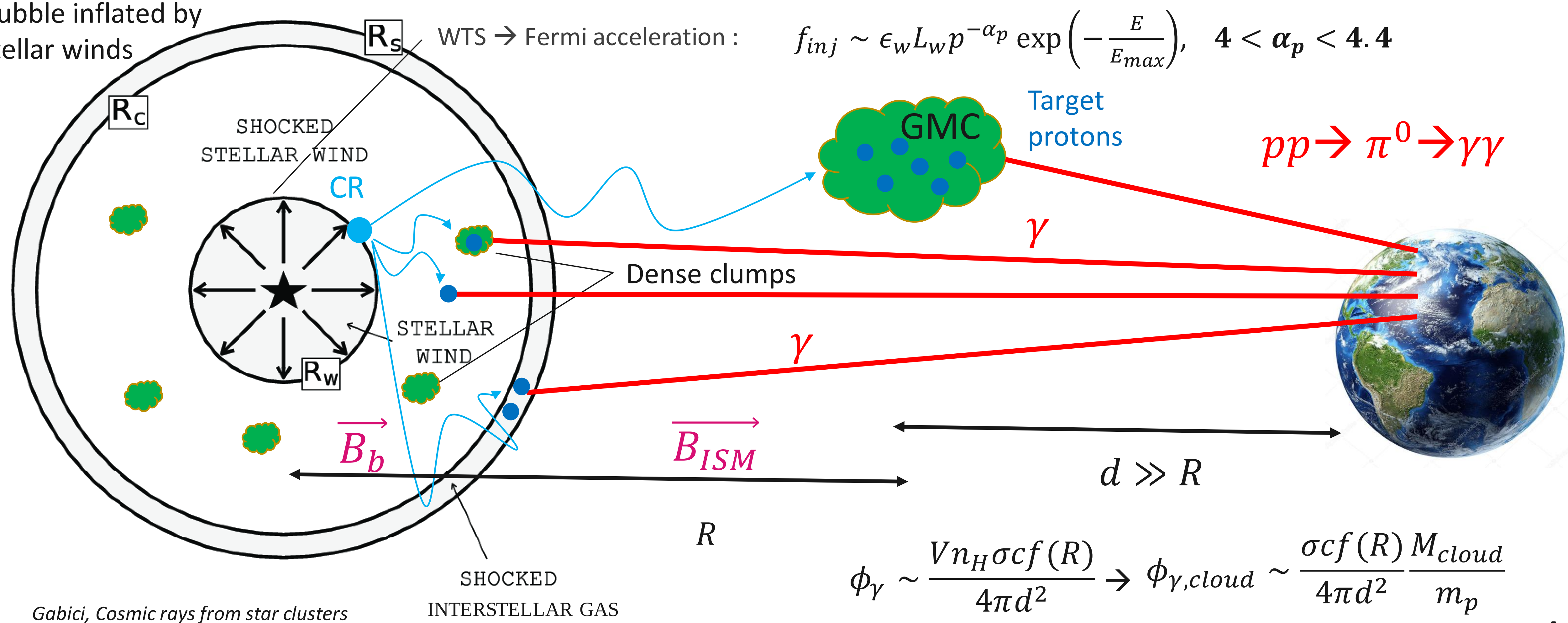

$$\phi_\gamma \sim \frac{V n_H \sigma c f(R)}{4\pi d^2} \rightarrow \phi_{\gamma,cloud} \sim \frac{\sigma c f(R)}{4\pi d^2}\frac{M_{cloud}}{m_p}$$

Gabici, Cosmic rays from star clusters

σ from Kafexhiu et al, 2014

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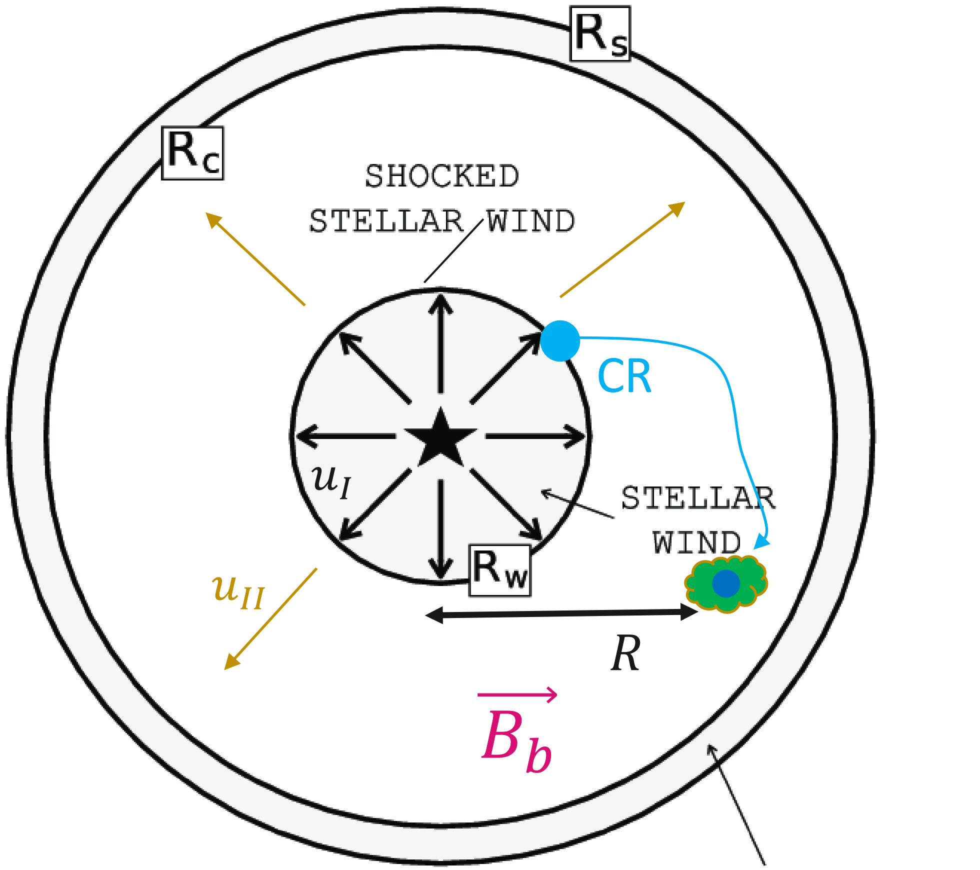
TRANSPORT INSIDE THE BUBBLE: ADVECTION+DIFFUSION



Gabici, Cosmic rays from star clusters

- Advection-diffusion model (*Morlino et al 2021*)
- Case of adiabatic bubble, suppose $u(R < R_w) = u_I$ and $u(R > R_w) = u_{II}\left(\frac{R_w}{R}\right)^2$ with $u_{II} = u(R_w) = \frac{u_I}{4}$

$$A(r,p) = \frac{u_{II}R_w}{D(p)}\left(1 - \frac{R_w}{R}\right) \rightarrow \boxed{f_1(p,R,t) \sim f_{inj}\frac{\left(1 - \mathrm{e}^{A(R)-A(R_s)}\right)}{1 - e^{-A(R_s)}}}$$

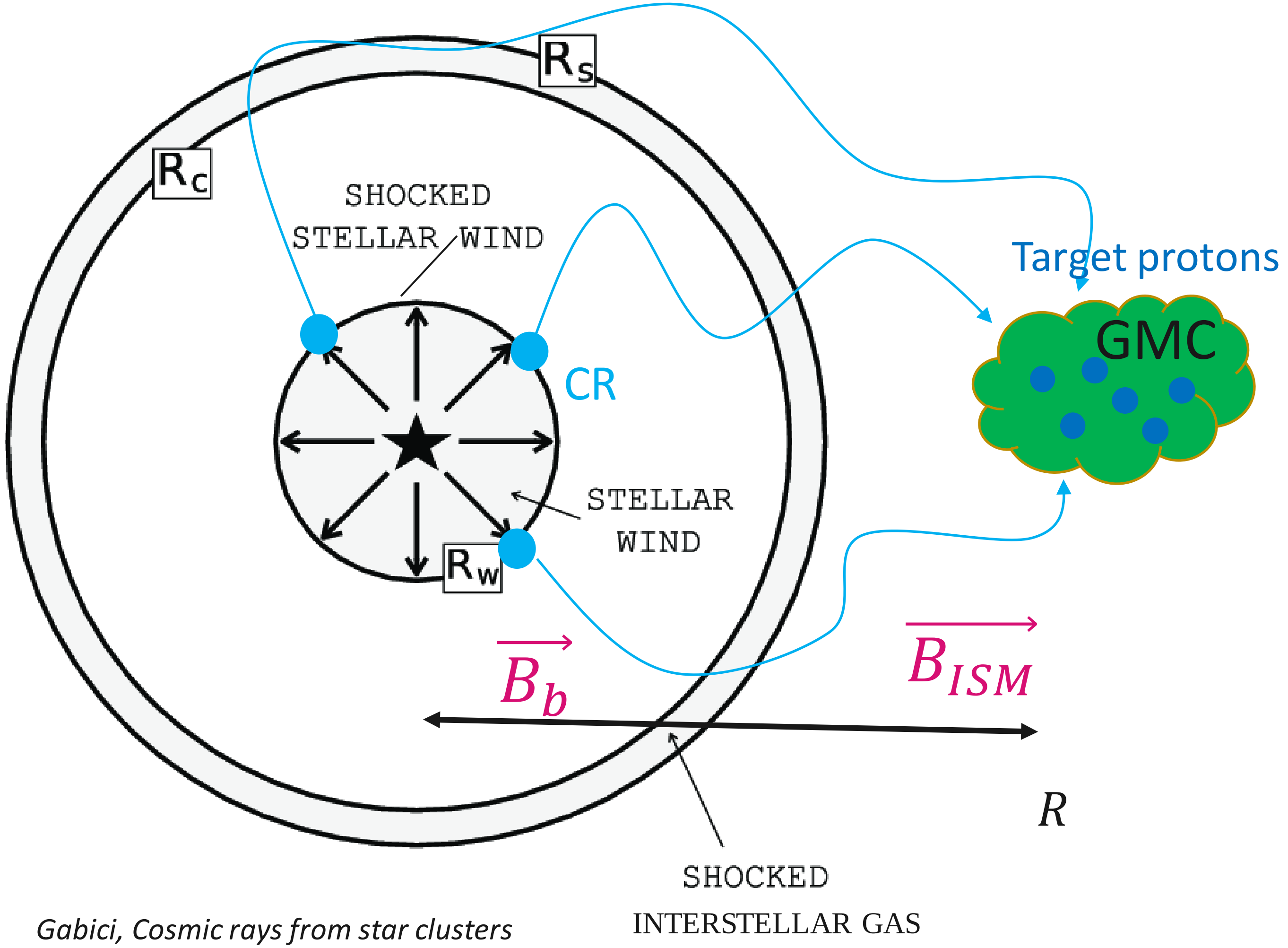
$$D(p) = \frac{D_{10}}{cm^2 s^{-1}}\left(\frac{pc}{10}\right)^{\delta}$$

Assume Bohm diffusion inside the bubble to be able to reach PeV

$\boldsymbol{\delta \sim 1}$

$\boldsymbol{D_{10} \sim 10^{22}}$

TRANSPORT OUTSIDE THE BUBBLE: 3D ISOTROPIC DIFFUSION



Gabici, Cosmic rays from star clusters

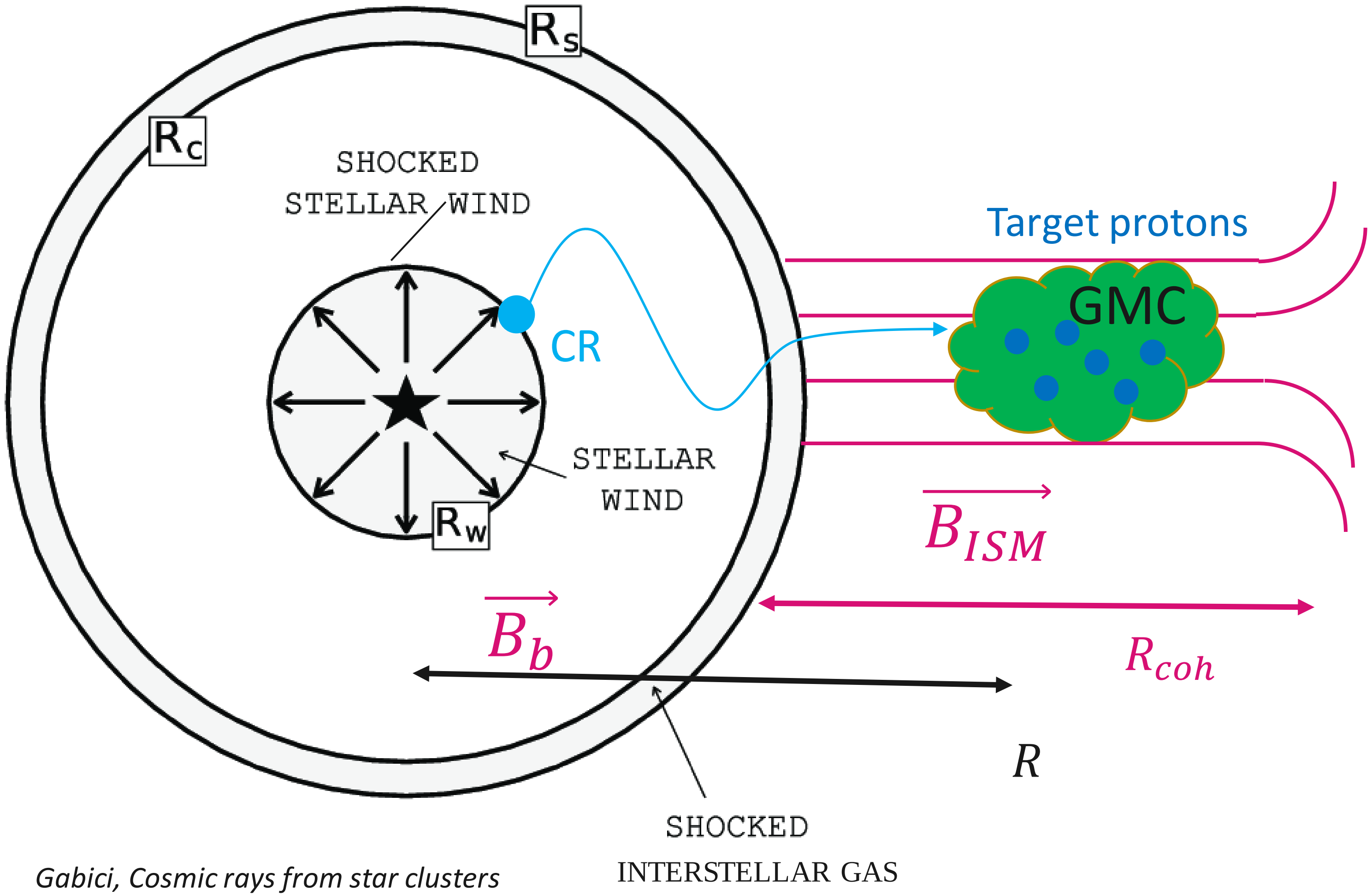
$$\rightarrow f_2(p,R,t) \sim f_{inj} \frac{1}{D(p)R} erfc\left(\frac{R}{4D(E)t}\right)$$

(Aharonian, Atoyan 1996)

$$D(p) = \frac{D_{10}}{cm^2 s^{-1}} \left(\frac{pc}{10}\right)^{\delta}$$

Kraichnan or Kolmogorov diffusion: $\mathbf{0.3 < \delta < 0.6}$, $\mathbf{D_{10} \sim 10^{25} - 10^{28}}$

TRANSPORT OUTSIDE THE BUBBLE: 1D ANISOTROPIC DIFFUSION



Gabici, Cosmic rays from star clusters

$$\rightarrow f_3(p, R, t) \sim \frac{f_{inj}}{4\pi} \frac{R_{coherence} - R}{D(p)\, R_{sh}^2}$$

$$D(p) = \frac{D_{10}}{cm^2 s^{-1}} \left(\frac{pc}{10}\right)^{\delta}$$

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SPATIAL DEPENDENCE OF THE γ-RAY FLUX

- Find maximal distances up to which a detectable excess is possible, at fixed energy

$$\boldsymbol{R_W} \sim 3\left(\frac{0.2N_*}{100}\right)^{\frac{3}{10}}\left(\frac{n_0}{cm^{-3}}\right)^{-\frac{3}{10}}$$

$$\left(\frac{t}{10Myr}\right)^{\frac{2}{5}}\left(\frac{u_W}{3000\ km\ s^{-1}}\right)^{-\frac{1}{2}} \mathrm{pc}$$

$\sim \boldsymbol{5pc}$ for $n_0 \sim 100\ cm^{-3}$

$$\boldsymbol{R_s} \sim 260\left(0{,}2\frac{N_*}{100}\right)^{\frac{1}{5}}\left(\frac{n_0}{cm^{-3}}\right)^{-\frac{1}{5}}\left(\frac{t}{10Myr}\right)^{\frac{3}{5}} pc$$

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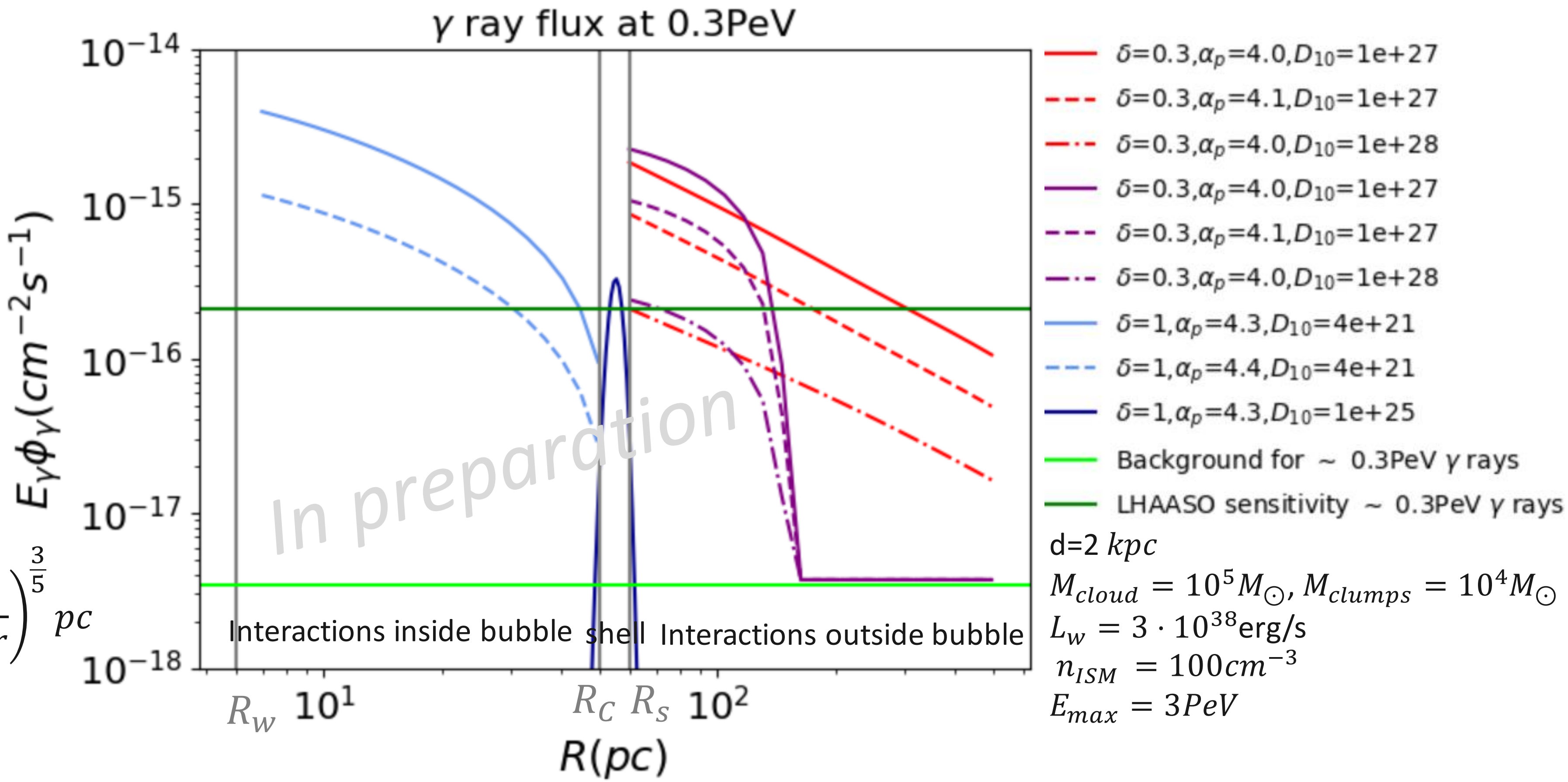

d=2 kpc
$M_{cloud} = 10^5 M_\odot, M_{clumps} = 10^4 M_\odot$
$L_w = 3 \cdot 10^{38}$erg/s
$n_{ISM} = 100cm^{-3}$
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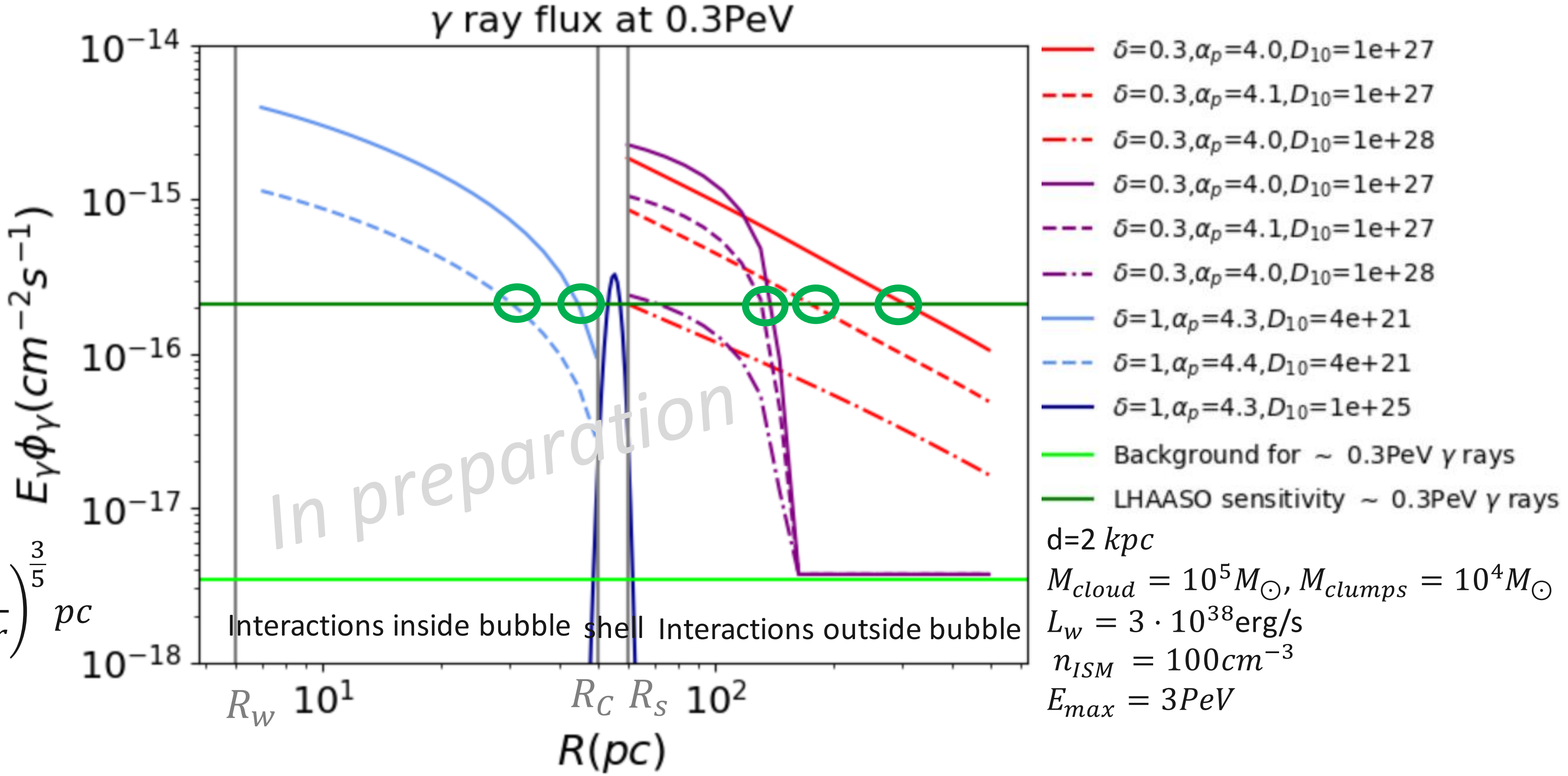
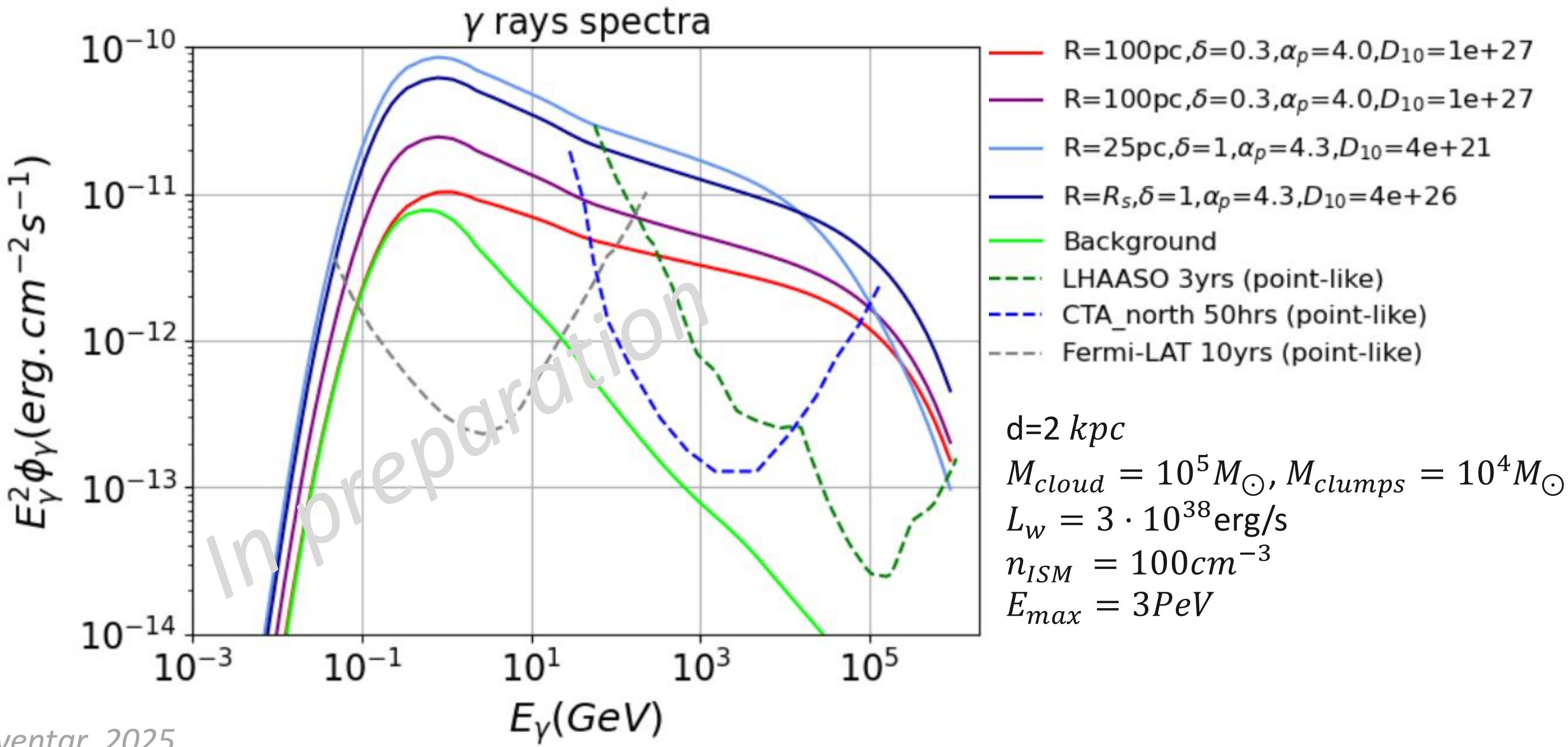


At high energies, sensitivity gives an effective maximal distance to have a detectable excess $\boldsymbol{R_{max,effective}}$

γ-RAY SPECTRA

- Fixing distances, compute the flux for any energy to compare with observed spectra



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→ deduce the minimal parameters configuration enabling a detectable excess

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Constrain
Parameter space

Compare to real data
to deduce parameters

APPLICATION: W43 CLUSTER

Very active region, $L_w \sim 3e38\ erg/s,\ t \sim 6Myr,\ n_{ISM} \sim 100cm^{-3},\ d \sim 5.5\ kpc$

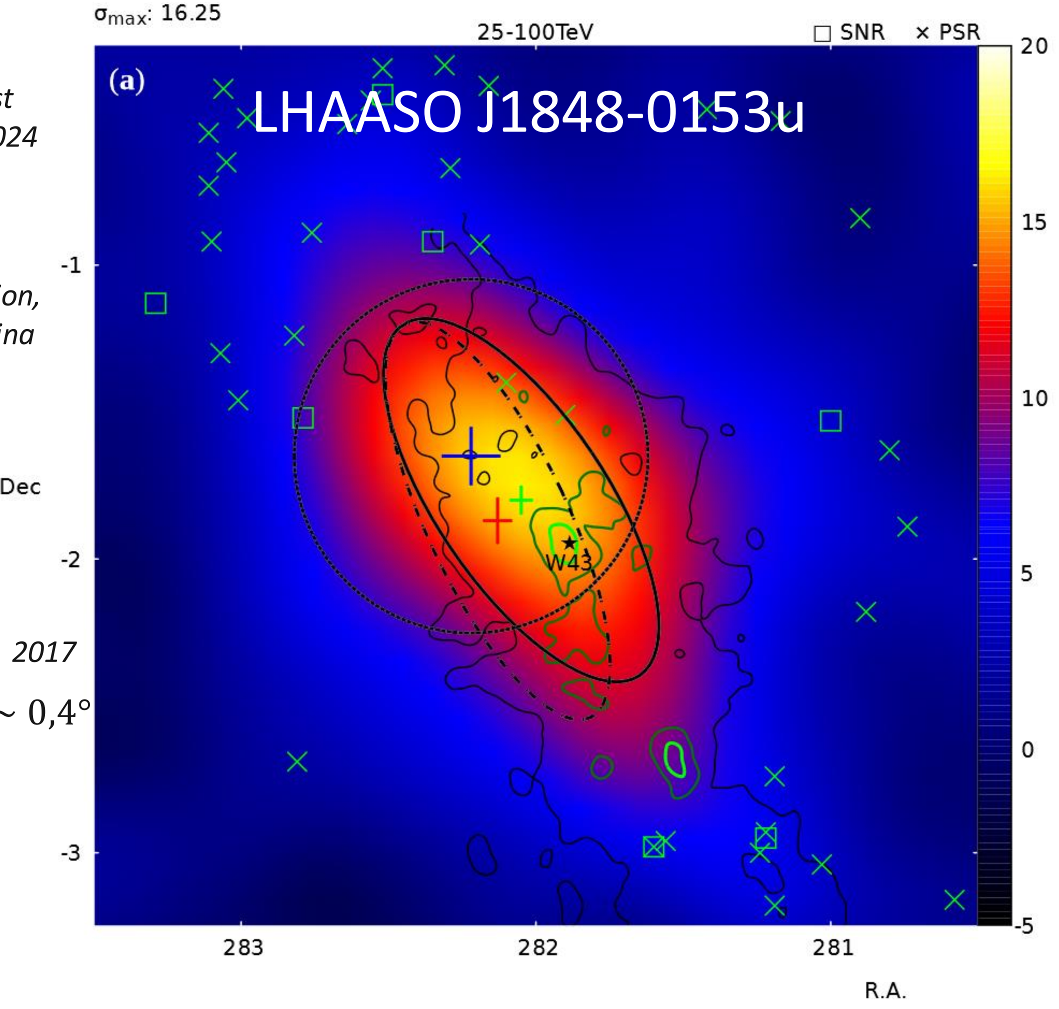
Kharchenko, 2013
Motte, 2002
Seo 2018, Menchiari 2023

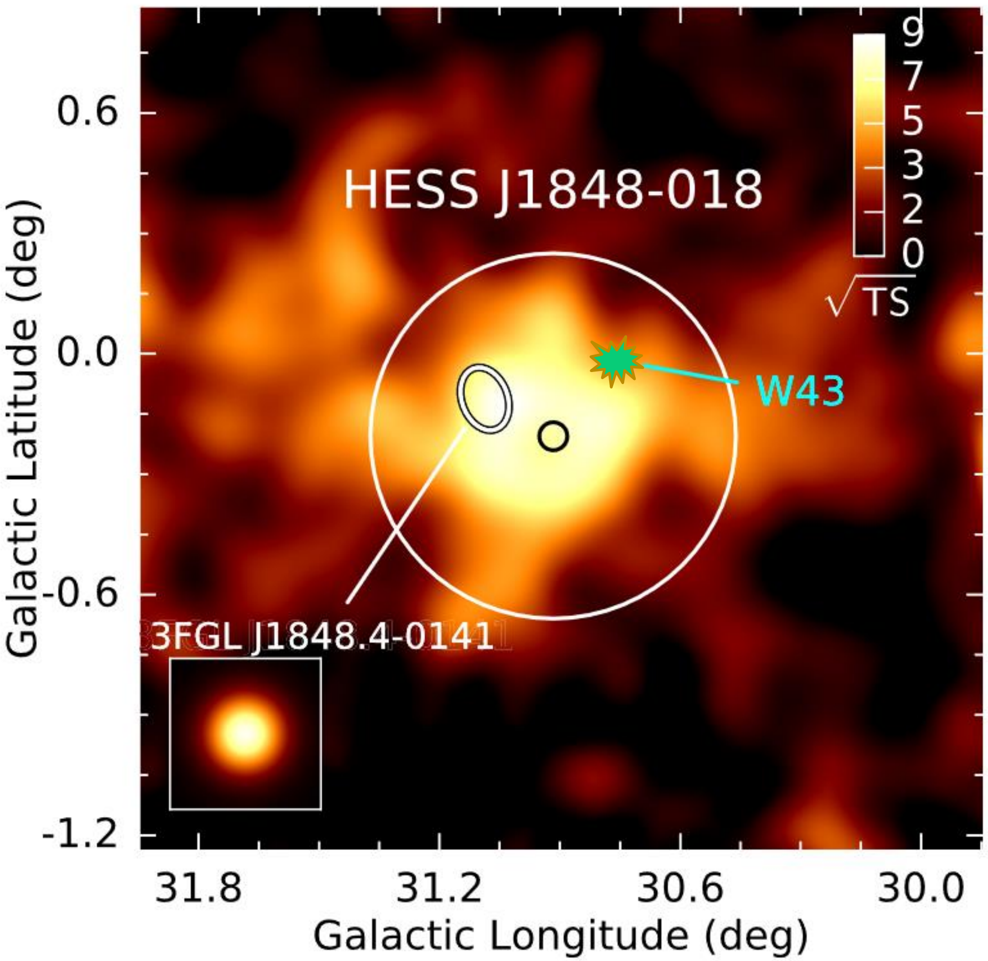
LHAASO 1st catalog, 2024

LHAASO Collaboration, Science China 2024

Miville-Deschenes, 2017

$\sigma_{angular} \sim 0{,}4°$





HESS Galactic plane Survey, 2018

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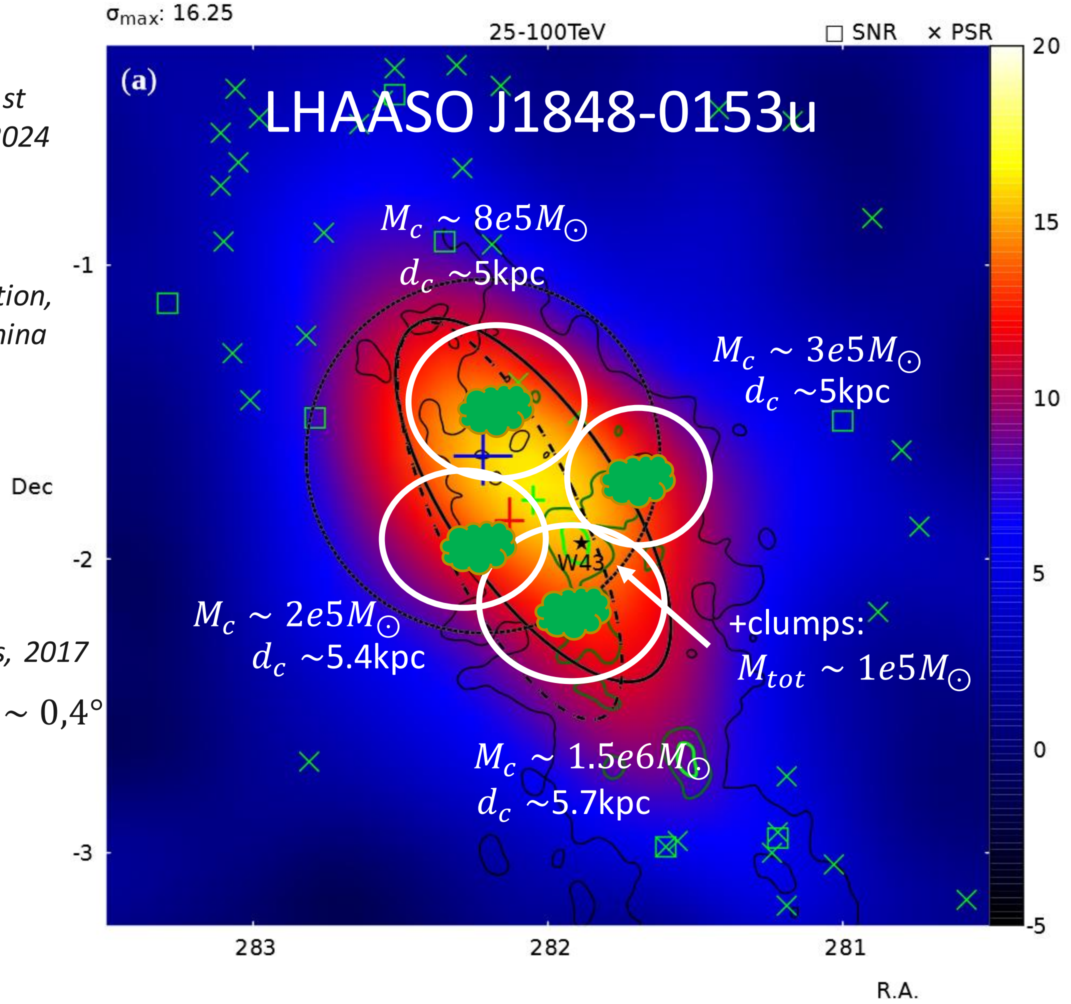
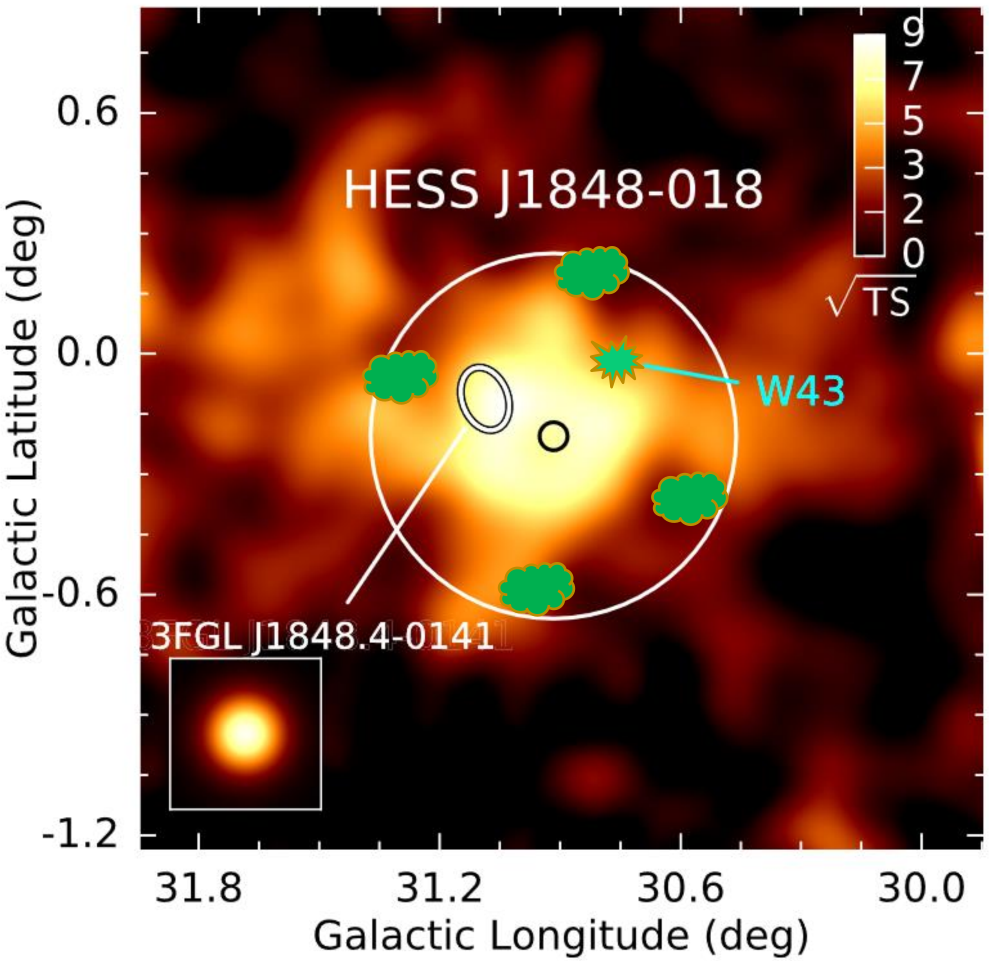
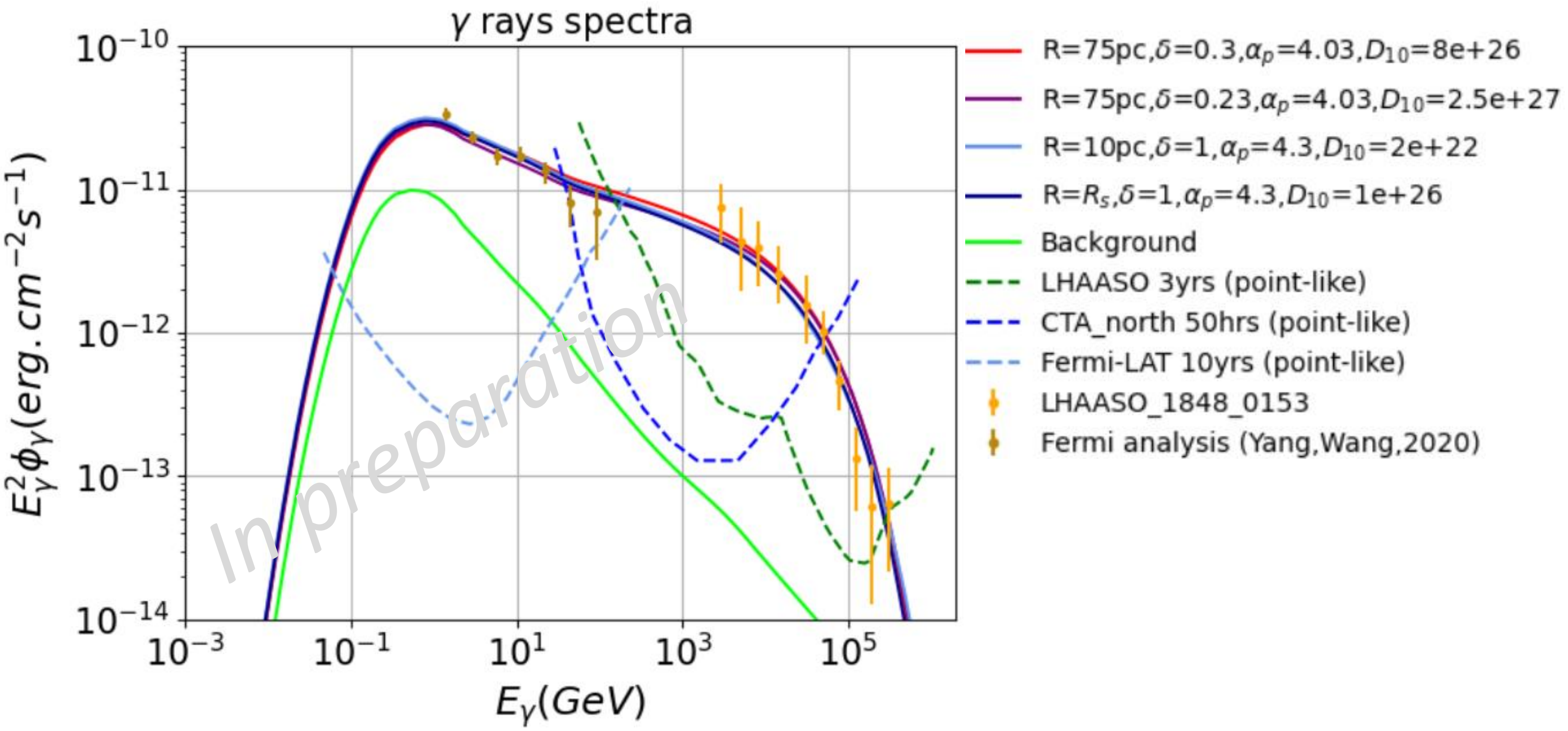




HESS Galactic plane Survey, 2018

- GMC/clumps scenario favored ?
- Leptonic ? Big extension so difficult because of the cooling time

RESULTS



Diffusion coefficient a bit bigger in the 1D scenario

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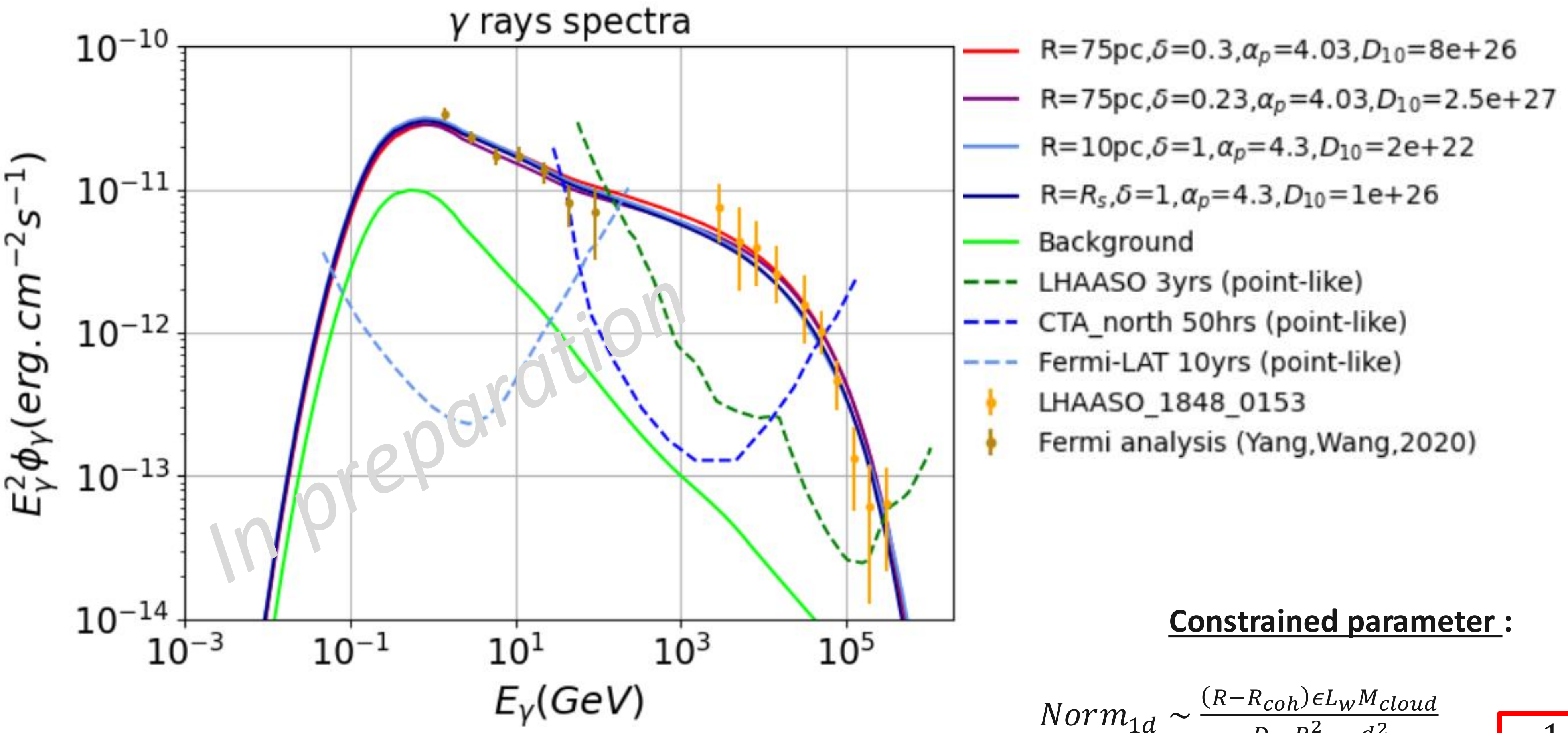

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Within "red or purple" (GMCs) scenarios:

Constrained parameter :

$$Norm_{1d} \sim \frac{(R-R_{coh})\epsilon L_w M_{cloud}}{D_{10} R_{WTS}^2 d^2}$$

$$Norm_{3d} \sim \frac{\epsilon L_w M_{cloud}}{D_{10} R d^2}$$

$$\boxed{\frac{1}{3} < \epsilon \frac{1\,e\,28\ cm^2 s^{-1}}{D_{10}} < 1}$$

$E_{cutoff} \sim 0.4\ PeV$ → a bit below proton knee ($\sim 3PeV$)

CONCLUSION AND PROSPECTS

Theoretical side :

- Can accelerate CRs in stellar bubbles
- Several possible hadronic scenarios for creating γ-rays in stellar bubbles
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