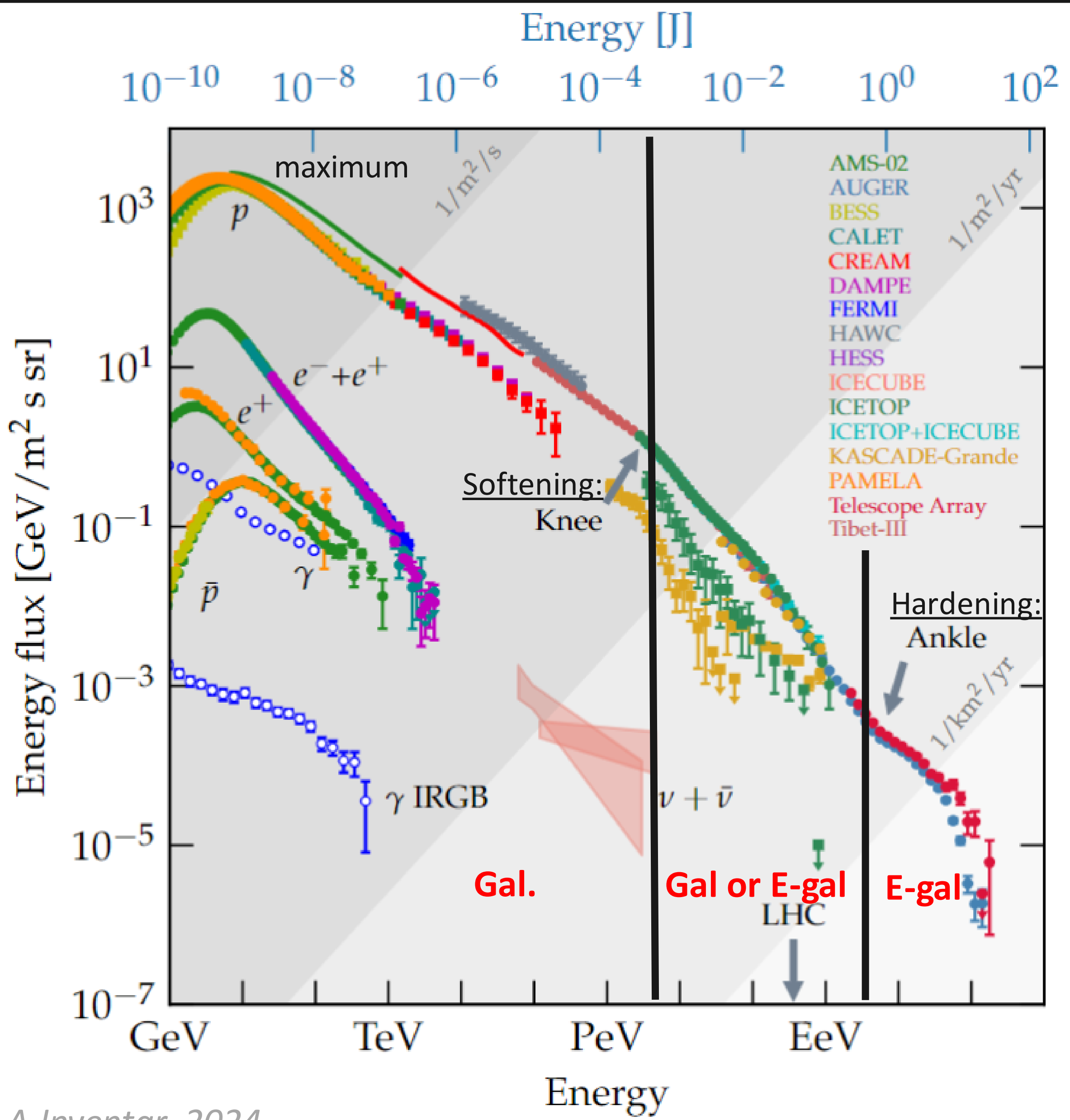
Speaker: Alexandre INVENTAR

PhD Supervisor: Stefano GABICI

γ-ray signatures of particle acceleration from stellar clusters up to PeV energies

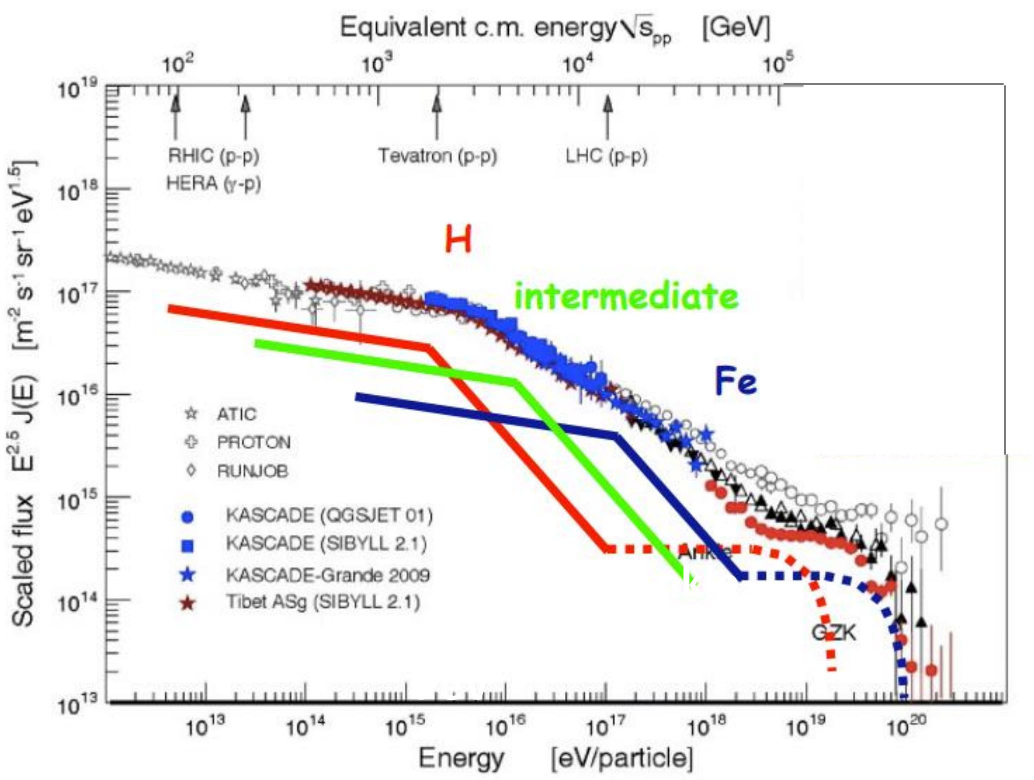
Université Paris Cité

COSMIC-RAY SPECTRUM AND PEV



What happens at PeV scale ?

- Accelerate protons to PeV with galactic sources ?
- Go up to $\sim 100PeV$ and explain the proton knee ?



A.Inventar, 2024

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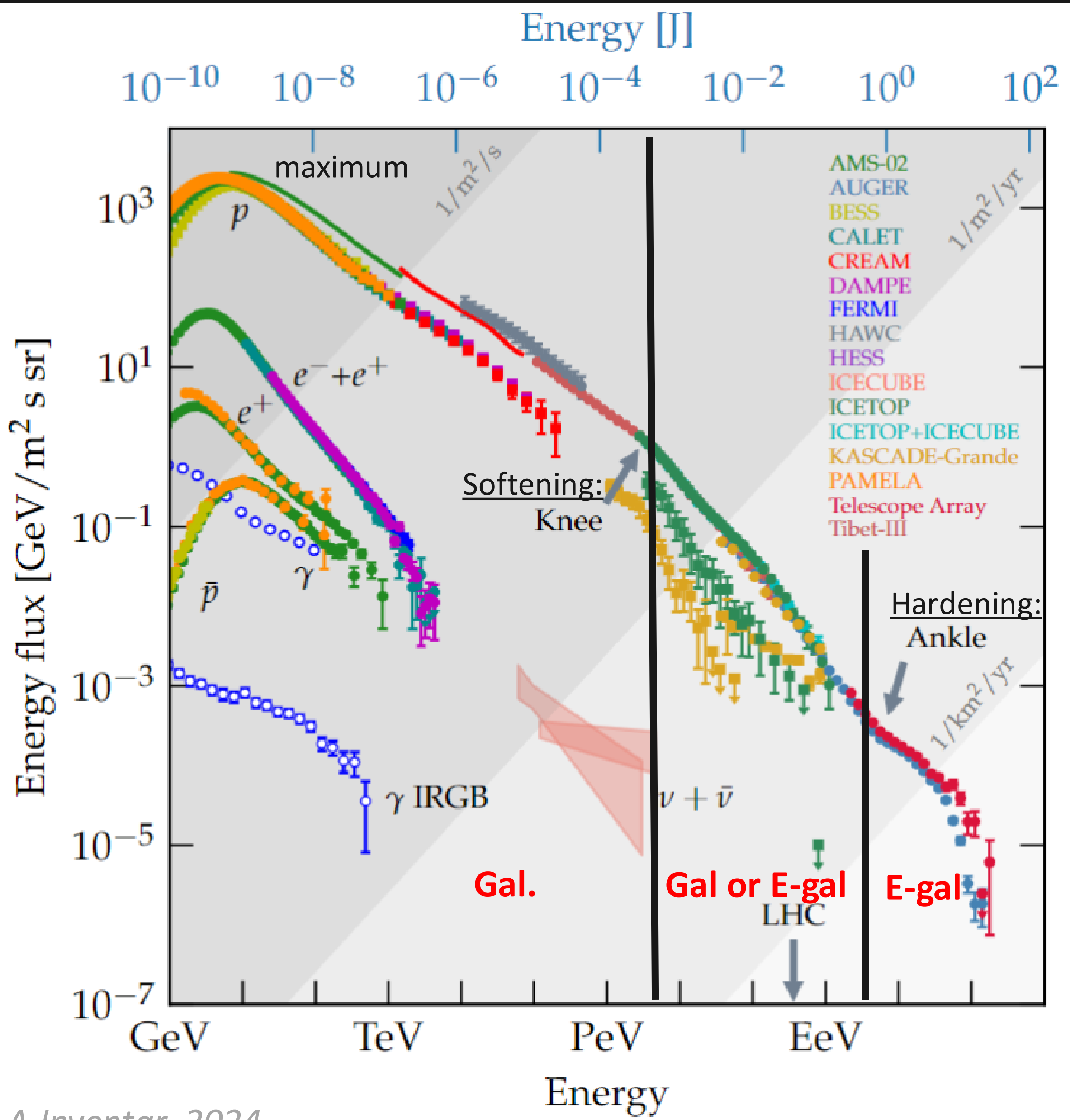

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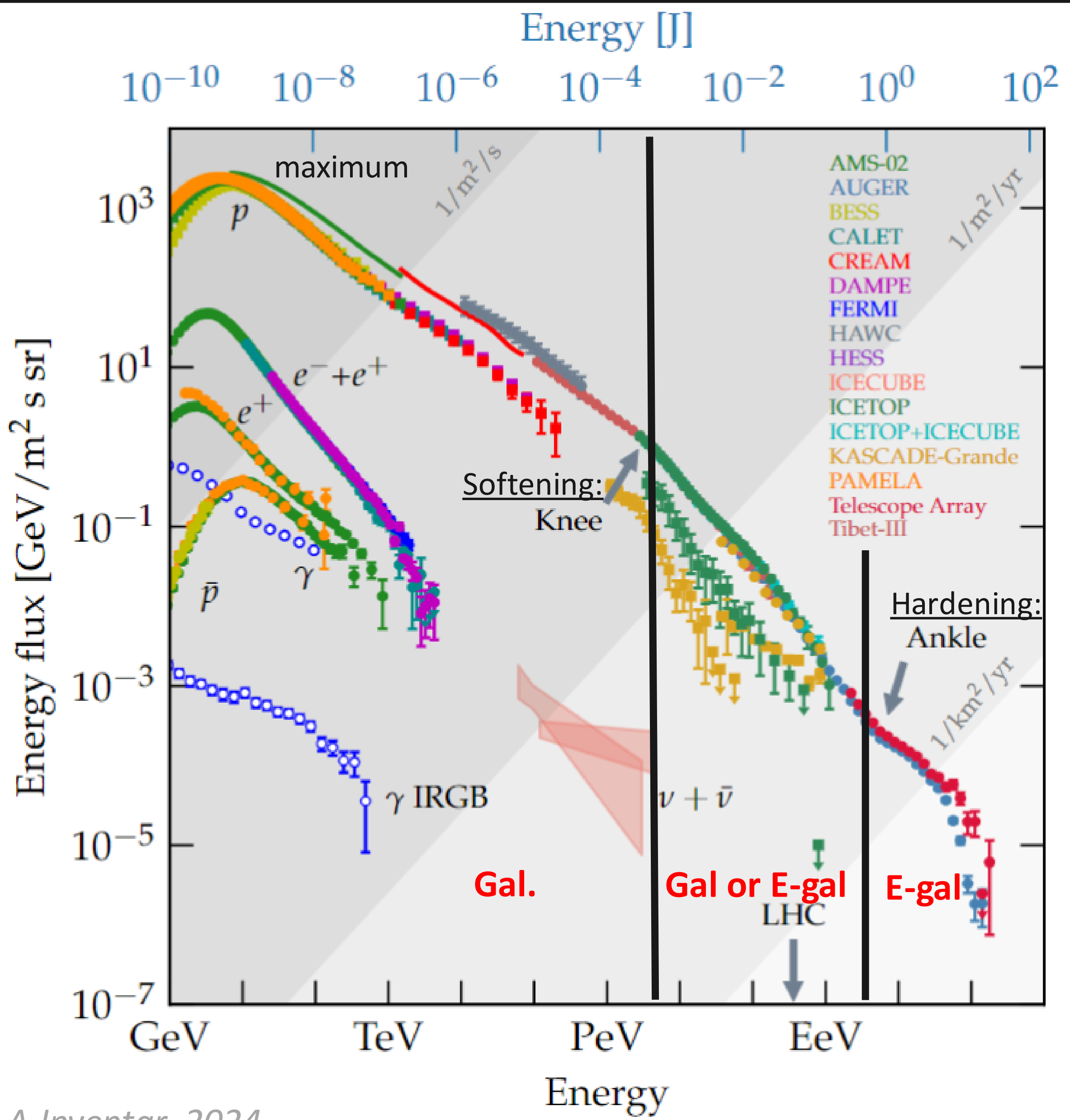

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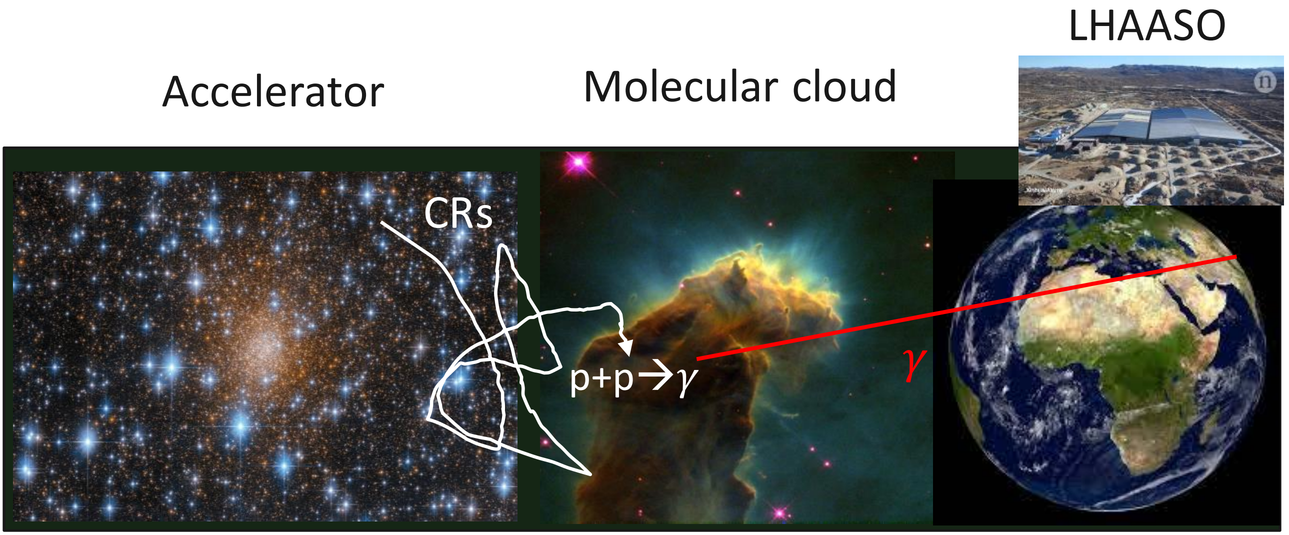
- Problem to observe CRs: CRs diffused

→ Can't link them to their original sources

→ Use γ-ray astronomy instead + molecular clouds: p+p→γ

OUTLINE



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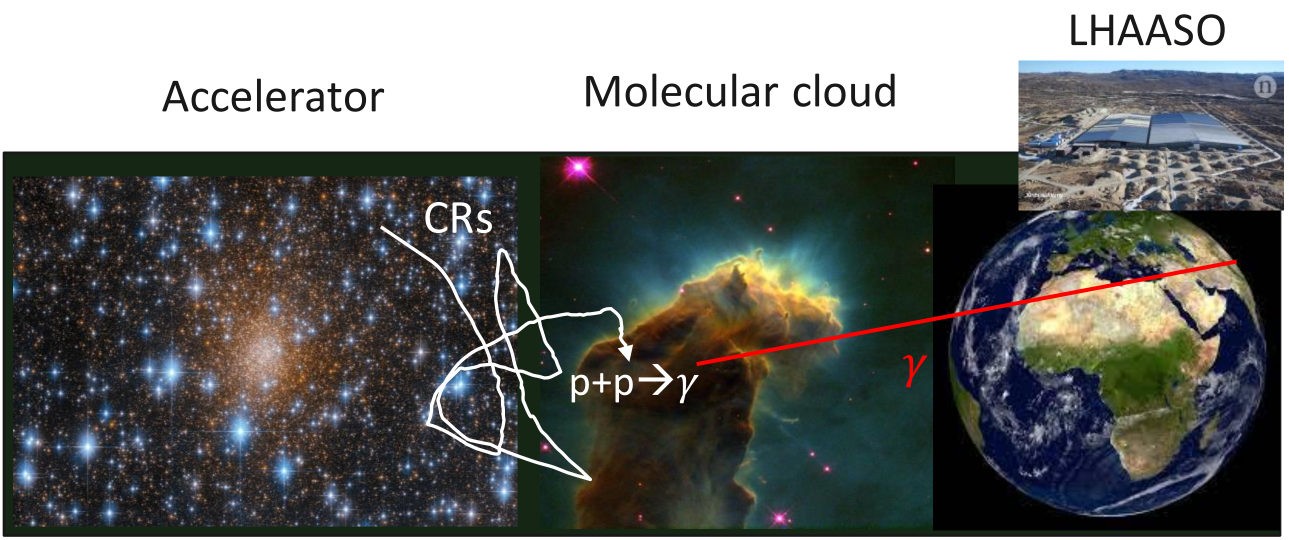

- For which systems and parameters can we detect an excess of γ-rays generated through p-p interactions by CRs accelerated in star clusters?

→Model escape and transport of CRs between sources and molecular clouds, and the consequent production of γ rays at different energies

Theory

- Focus on **YMSCs (stellar wind)**, p^+ and E=3PeV (knee)

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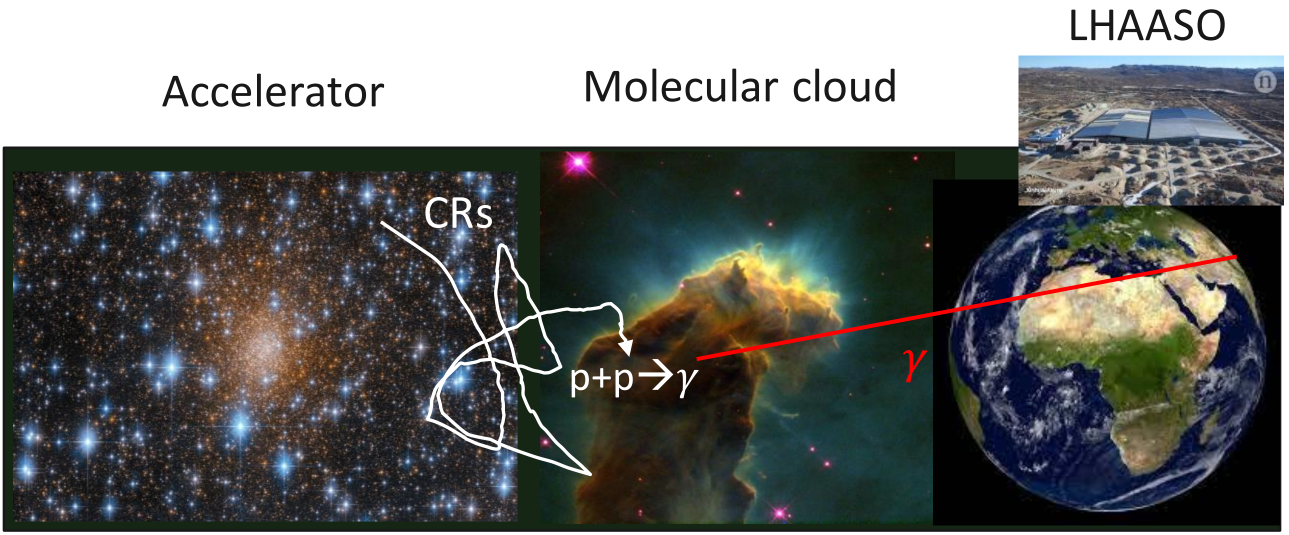

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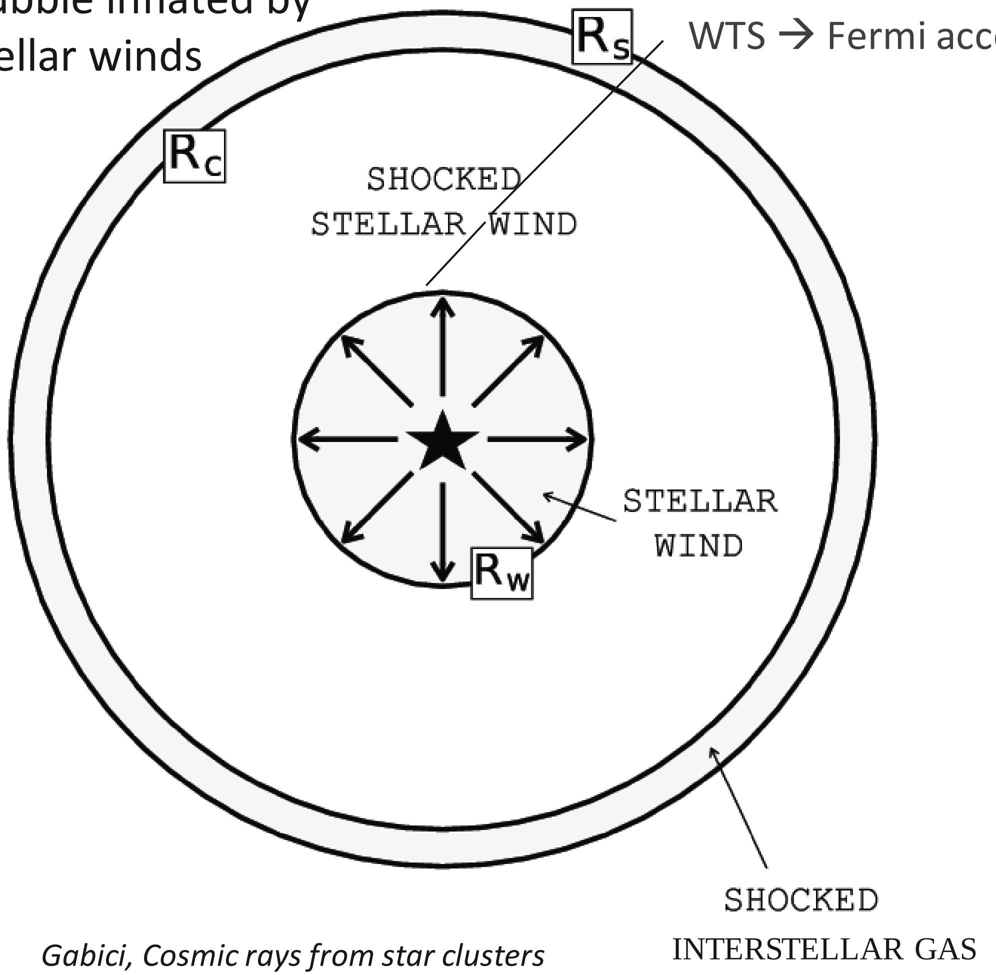
Applications and perspectives

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

→ Identify the contributions of star clusters to CR flux at different energies (especially at PeV)
→ obtain better constraints on different acceleration parameters (WTS efficiency, injection spectrum in the ISM,…)
→ See if it can explain some unassociated PeVatrons (eg molecular clouds far from a cluster)

DIFFERENT HADRONIC γ-RAYS PRODUCTION SCENARIOS WITH STELLAR WIND

Bubble inflated by stellar winds



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

Gabici, Cosmic rays from star clusters

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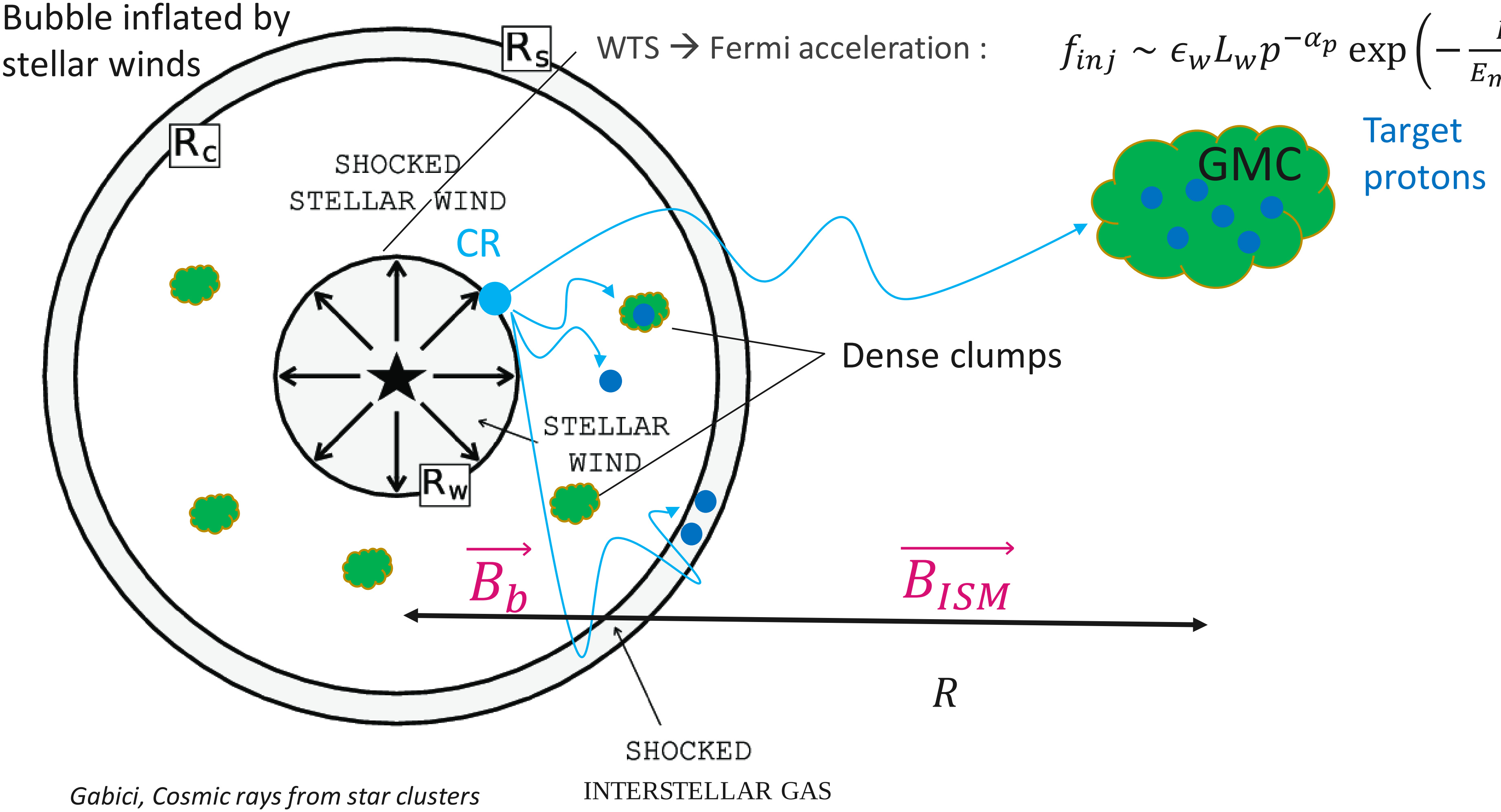

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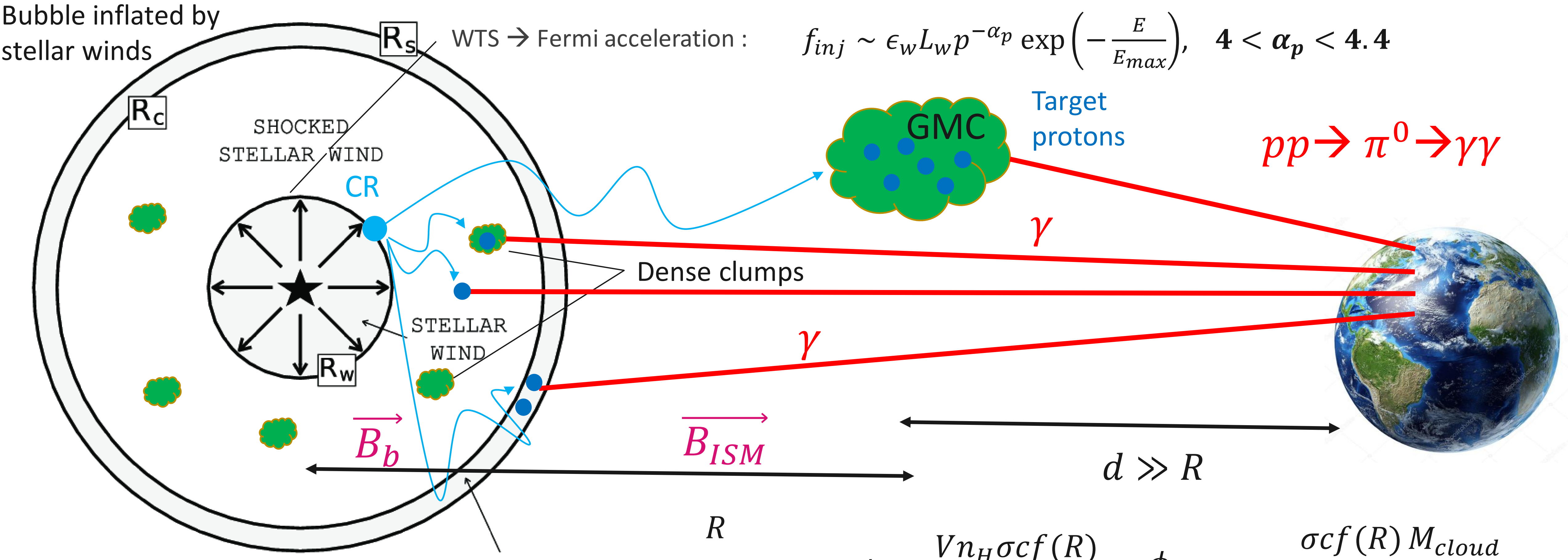
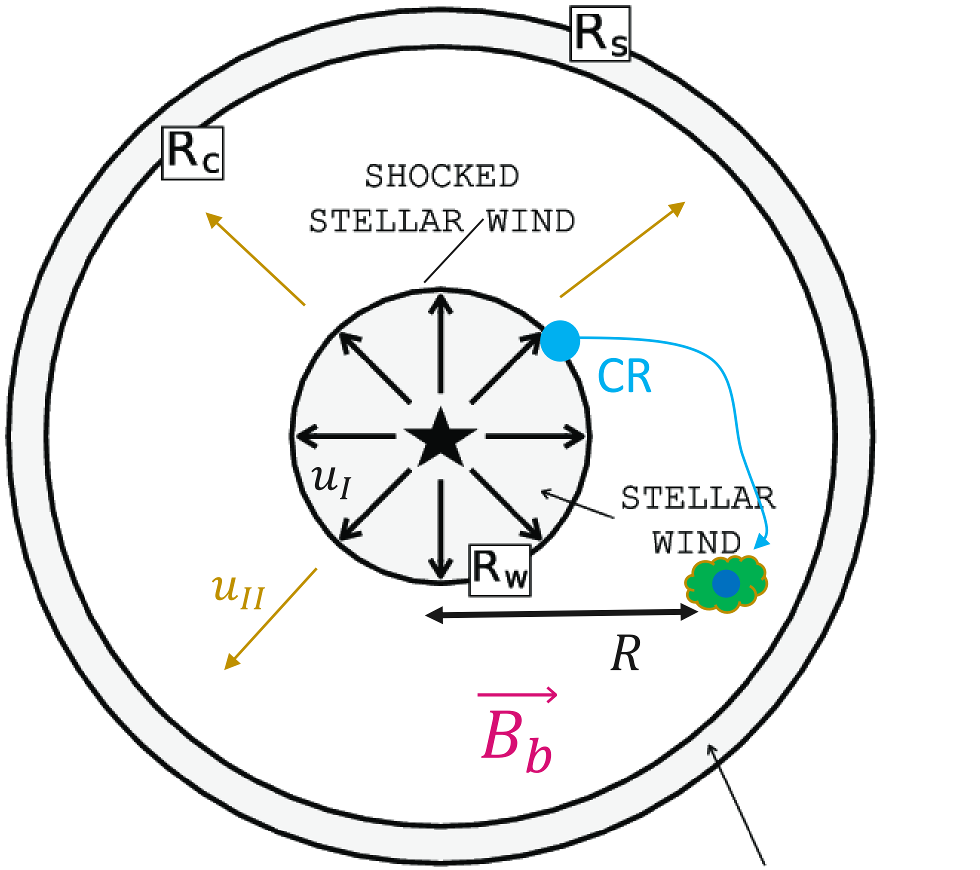


$$\phi_\gamma \sim \frac{V n_H \sigma c f(R)}{4\pi d^2} \rightarrow \phi_{\gamma,cloud} \sim \frac{\sigma c f(R)}{4\pi d^2} \frac{M_{cloud}}{m_p}$$

Gabici, Cosmic rays from star clusters

σ from Kafexhiu et al, 2014

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 $u_{II} = u(R_w) = \frac{u_I}{4}$

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

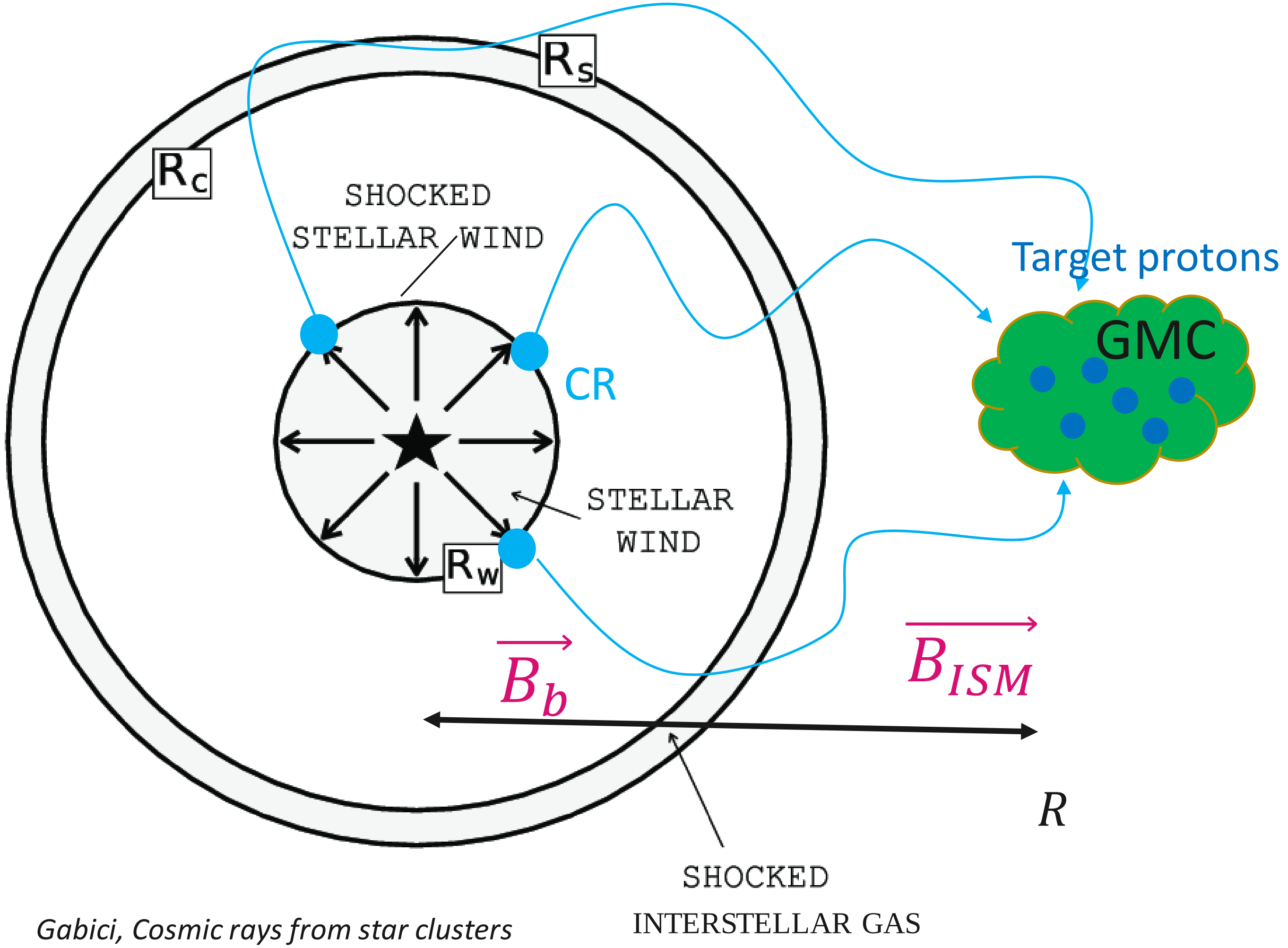
$$D(p) = \frac{D_{10}}{cm^2 s^{-1}}\left(\frac{pc}{10}\right)^{\delta}$$

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

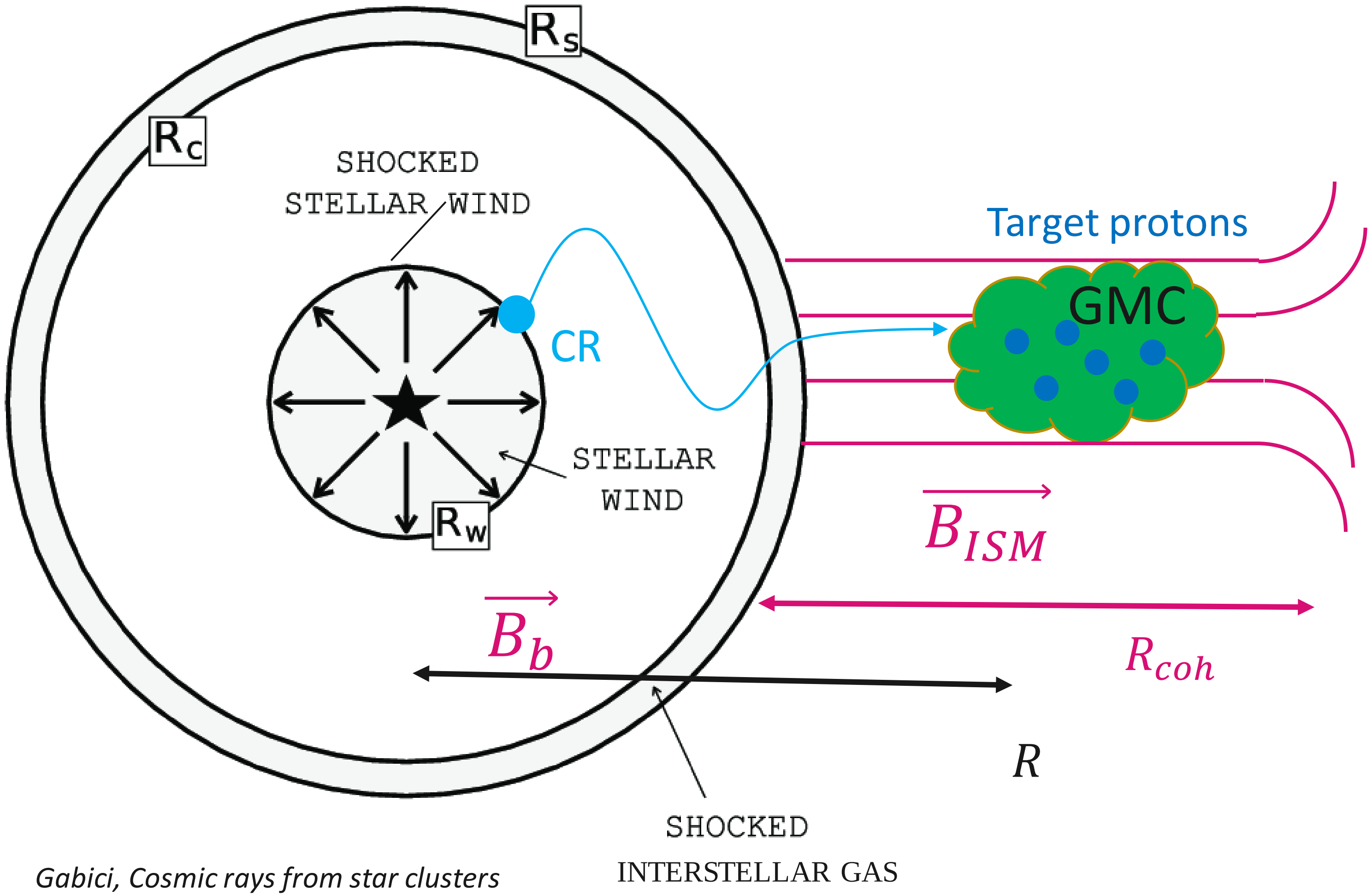
$$\rightarrow f_2(p,R,t) \sim f_{inj}\frac{1}{D(p)R}\, erfc\left(\frac{R}{4D(E)t}\right)$$

(Aharonian, Atoyan 1996)

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

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

TRANSPORT OUTSIDE THE BUBBLE: 1D ANISOTROPIC DIFFUSION



Gabici, Cosmic rays from star clusters

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

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

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

SPATIAL DEPENDENCE OF THE γ-RAY FLUX

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

$$R_W \sim 3\left(\frac{0.2N_*}{100}\right)^{\frac{3}{10}}\left(\frac{n_0}{cm^{-3}}\right)^{-\frac{3}{10}}$$
$$\left(\frac{t}{10Myr}\right)^{\frac{2}{5}}\left(\frac{u_W}{3000\ km\ s^{-1}}\right)^{-\frac{1}{2}}\ \mathrm{pc}$$

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

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

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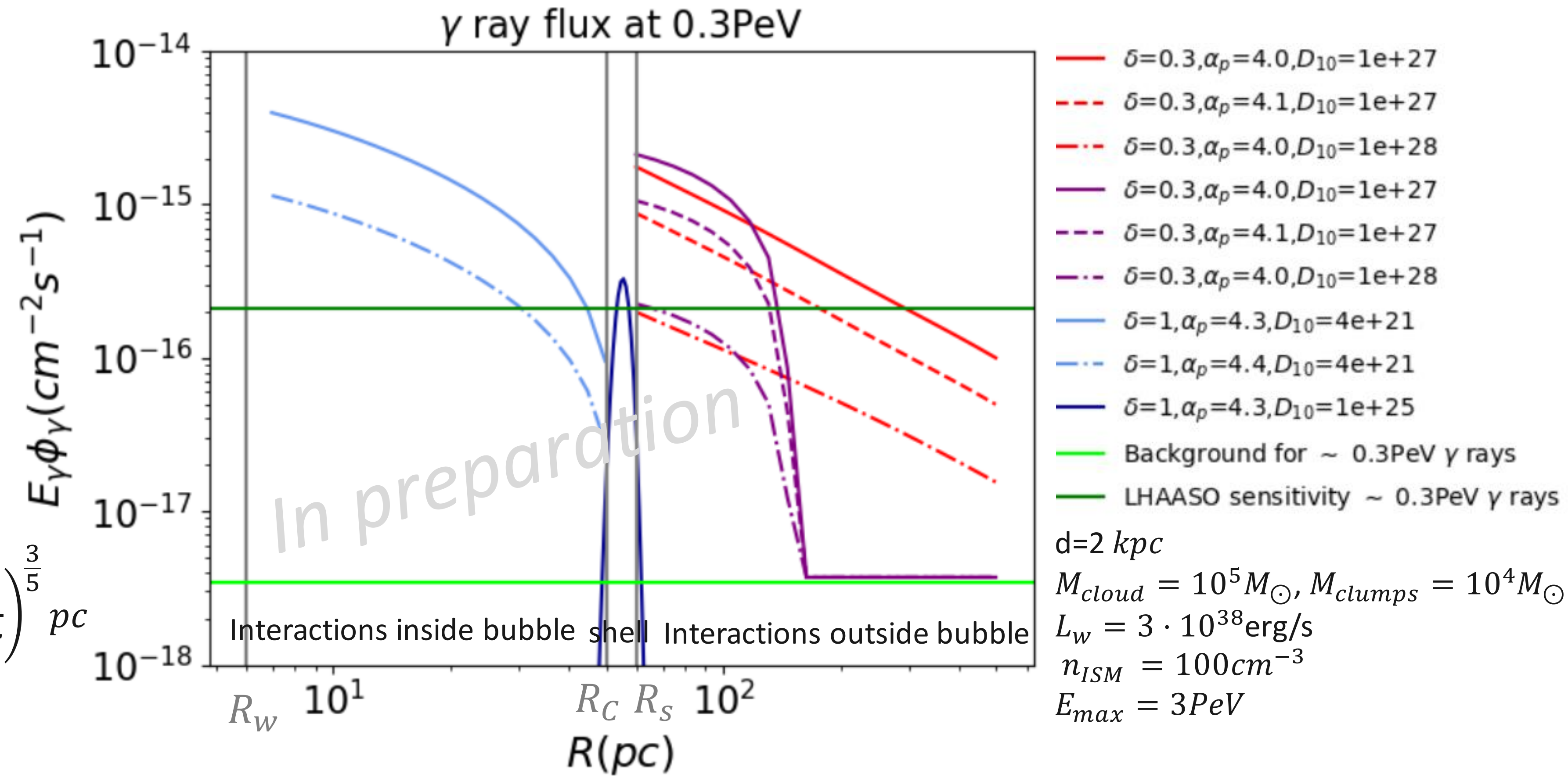

d=2 kpc

$M_{cloud} = 10^5 M_\odot$, $M_{clumps} = 10^4 M_\odot$

$L_w = 3 \cdot 10^{38}$erg/s

$n_{ISM} = 100cm^{-3}$

$E_{max} = 3PeV$

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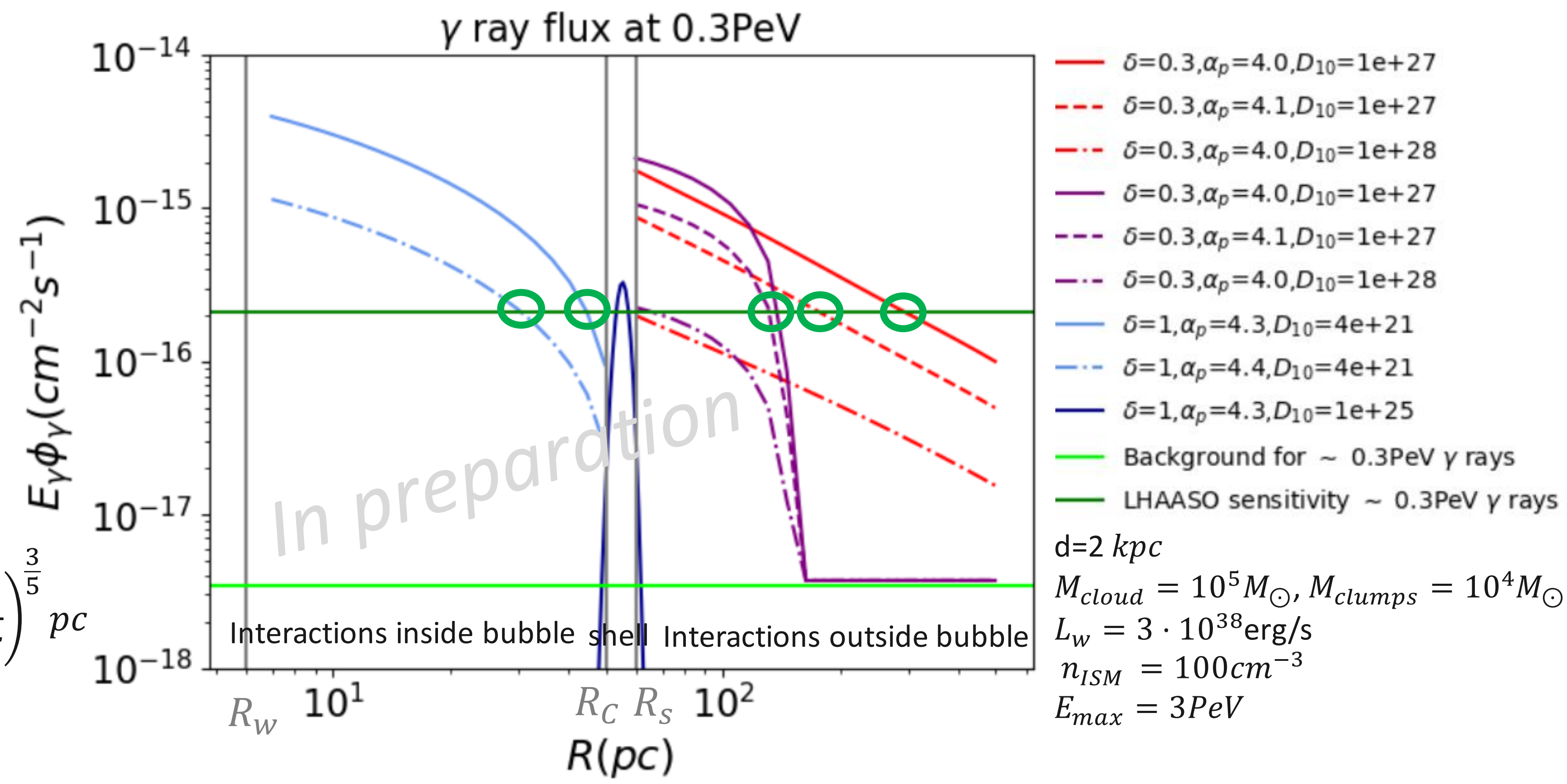

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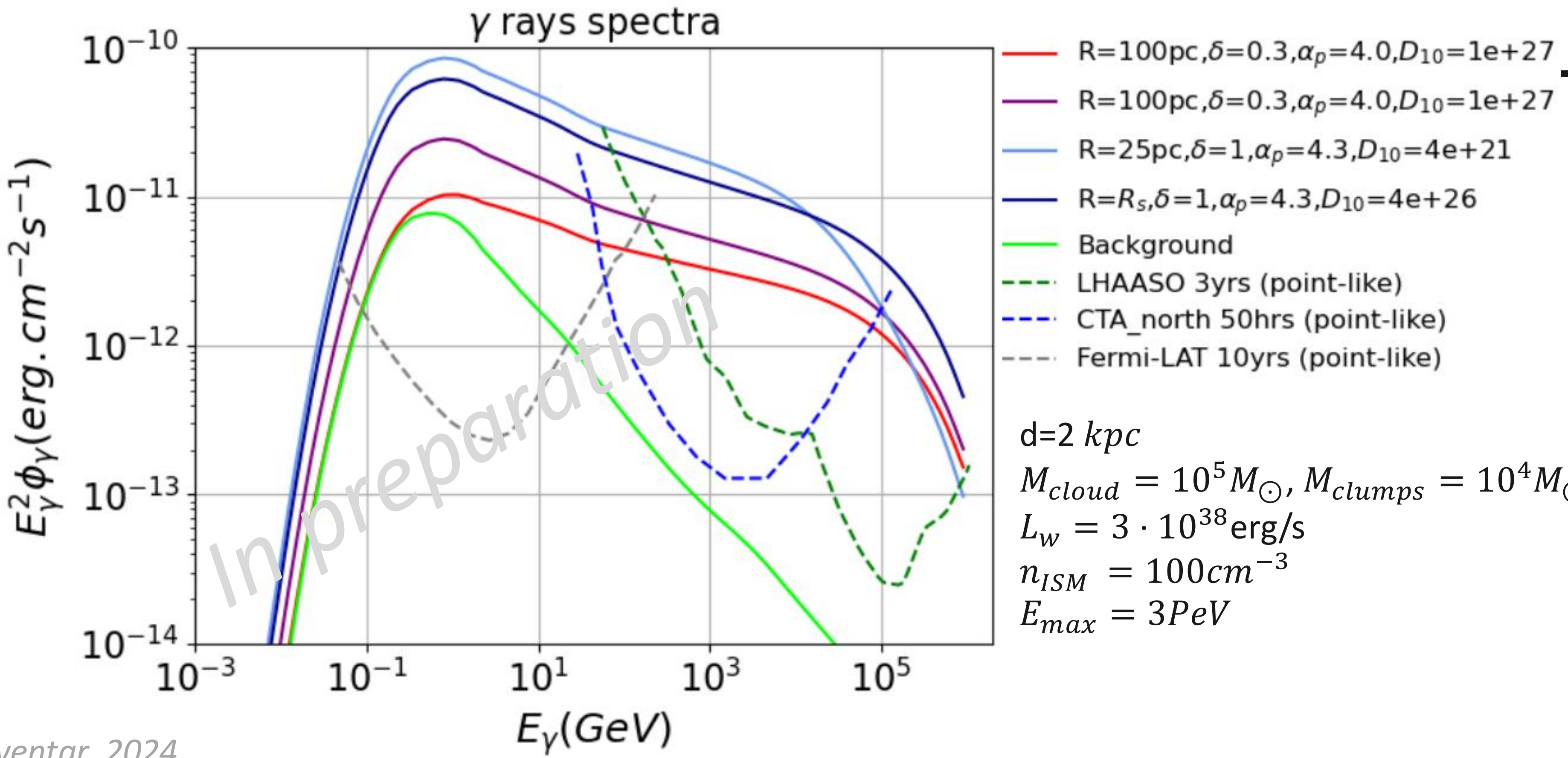
At high energies, sensitivity gives an effective maximal distance to have a detectable excess $\boldsymbol{R_{max,effective}}$

γ-RAY SPECTRA

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



→ Suppression of diffusion coefficient via streaming instabilities

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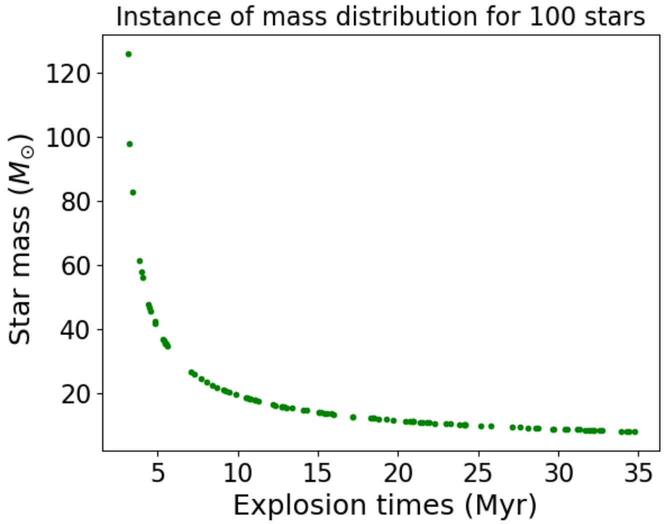
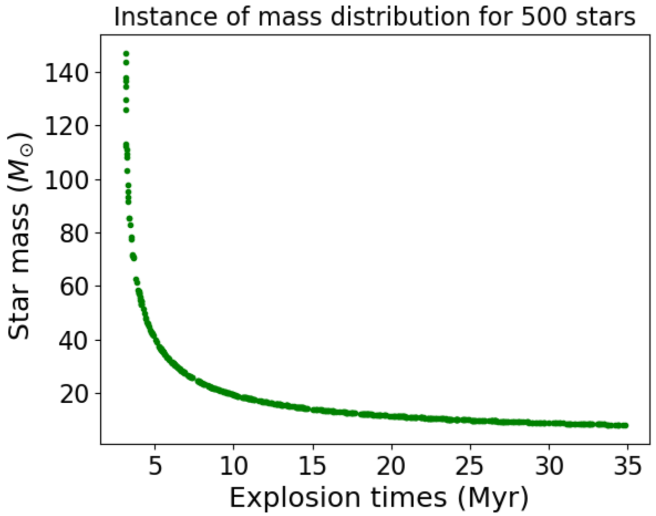
→ deduce the minimal parameters configuration enabling a detectable excess

STAR CLUSTER SIMULATION: HOW LONG CAN THE EXCESS LAST?

- Random sampling with Salpeter law $M^{-2.3}$ for the mass distribution of the cluster
- Cluster 1: 100 stars with $8\mathrm{M}_{\odot} < M < 150\ M_{\odot}$
- Cluster 2: 500 stars with $8\mathrm{M}_{\odot} < M < 150\ M_{\odot}$





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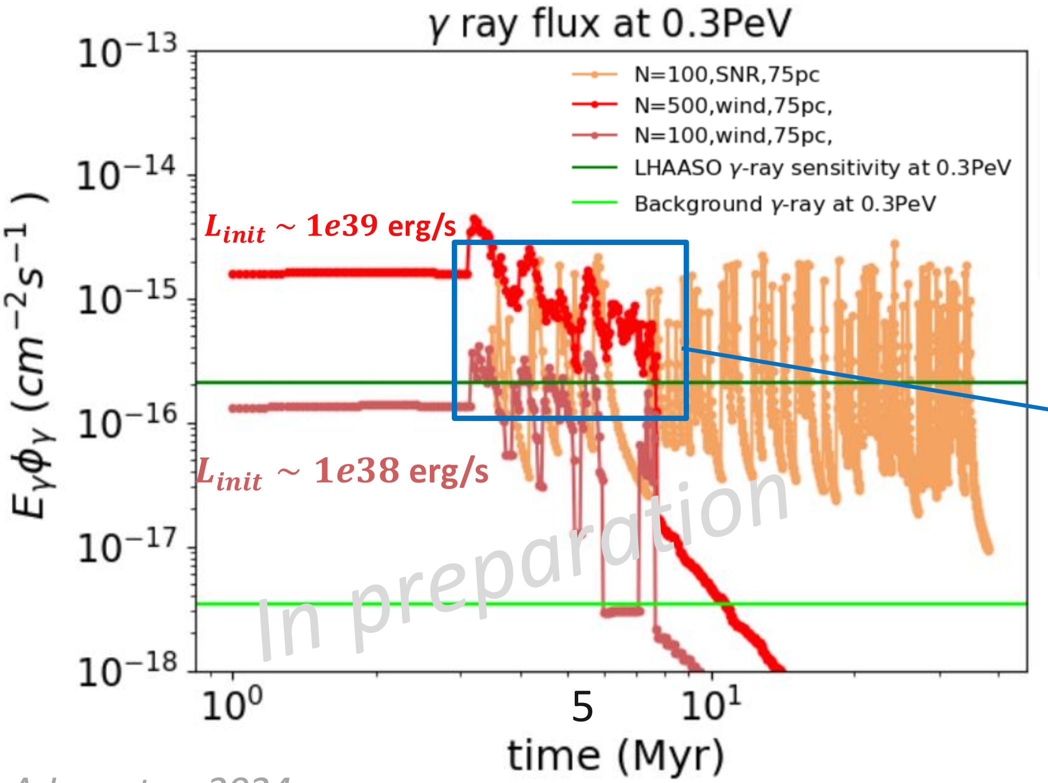
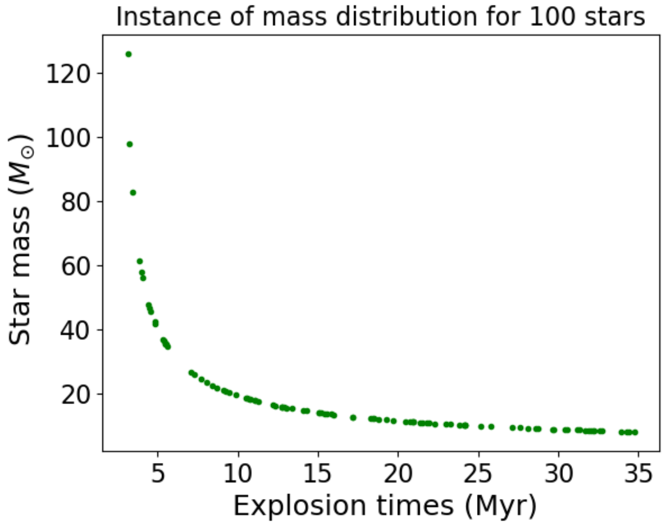
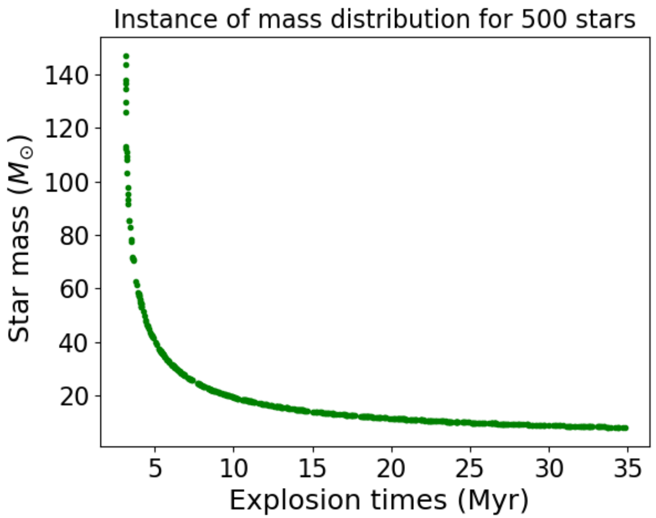






- Most of the luminosity comes from massive stars, that die quickly (with a WR phase before giving a SNR)

→ Either need a lot of MS stars and very young clusters ($<\sim 3Myr$)

→ Or can be a bit older ($\sim 5Myr$) and with less stars, using the WR phase

A.Inventar, 2024

APPLICATION: W43 CLUSTER

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

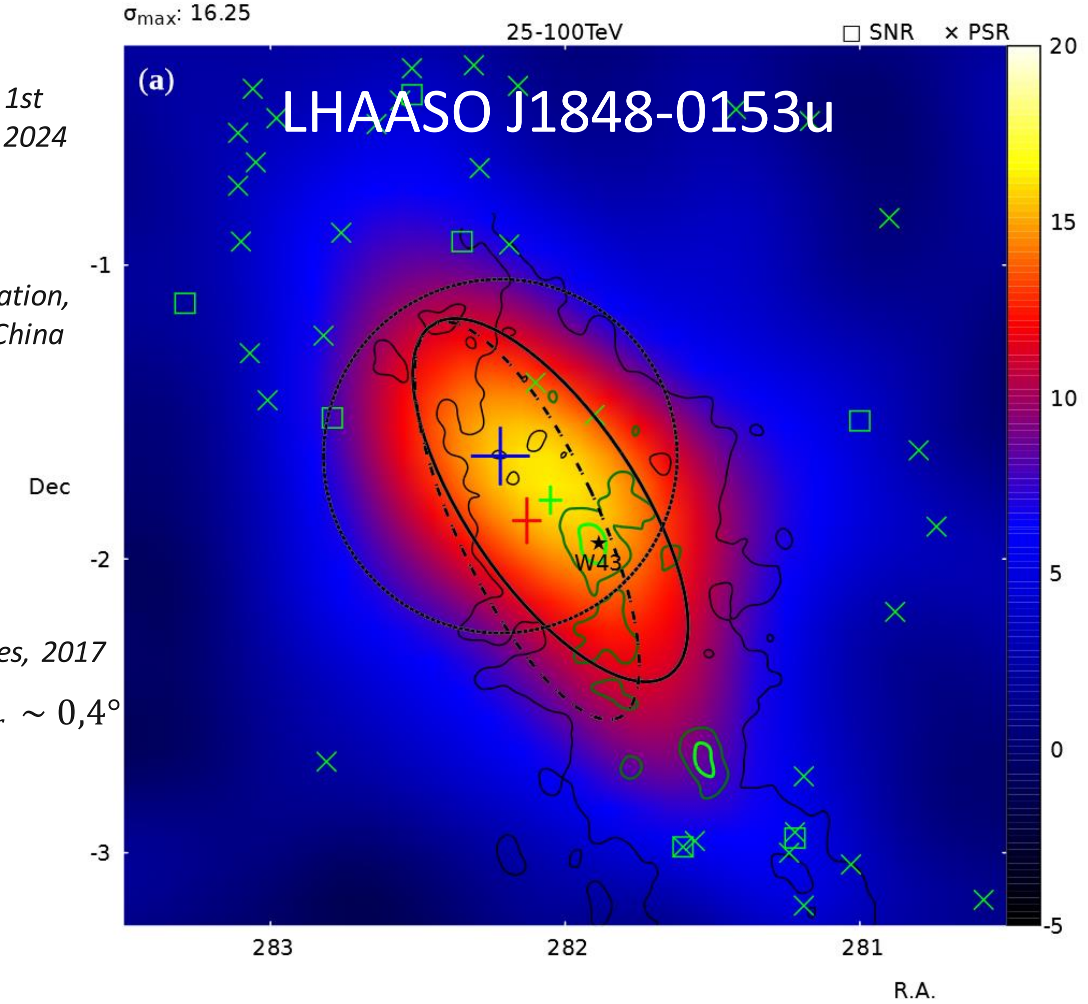
Kharchenko, 2013
Motte, 2002
Seo 2018, Menchiari 2023

LHAASO 1st catalog, 2024

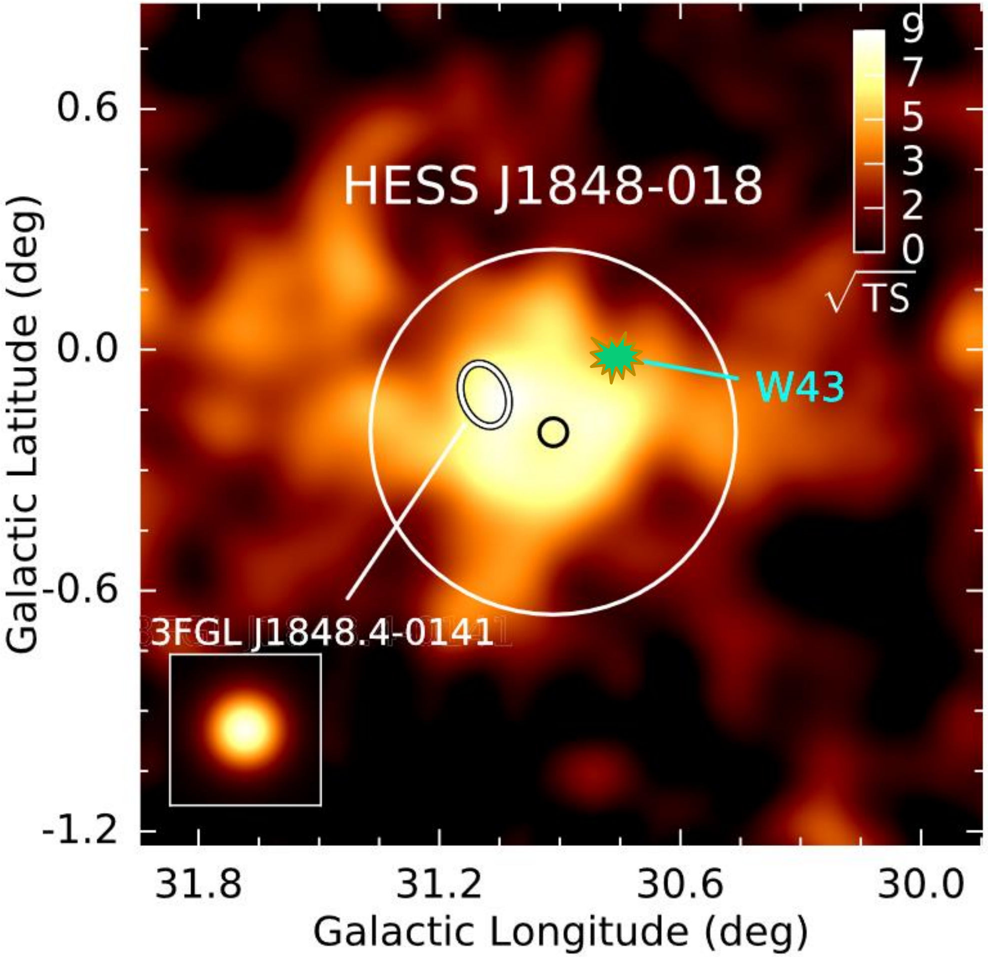
LHAASO Collaboration, Science China 2024

Miville-Deschenes, 2017

$\sigma_{angular} \sim 0{,}4°$



HESS Galactic plane Survey, 2018



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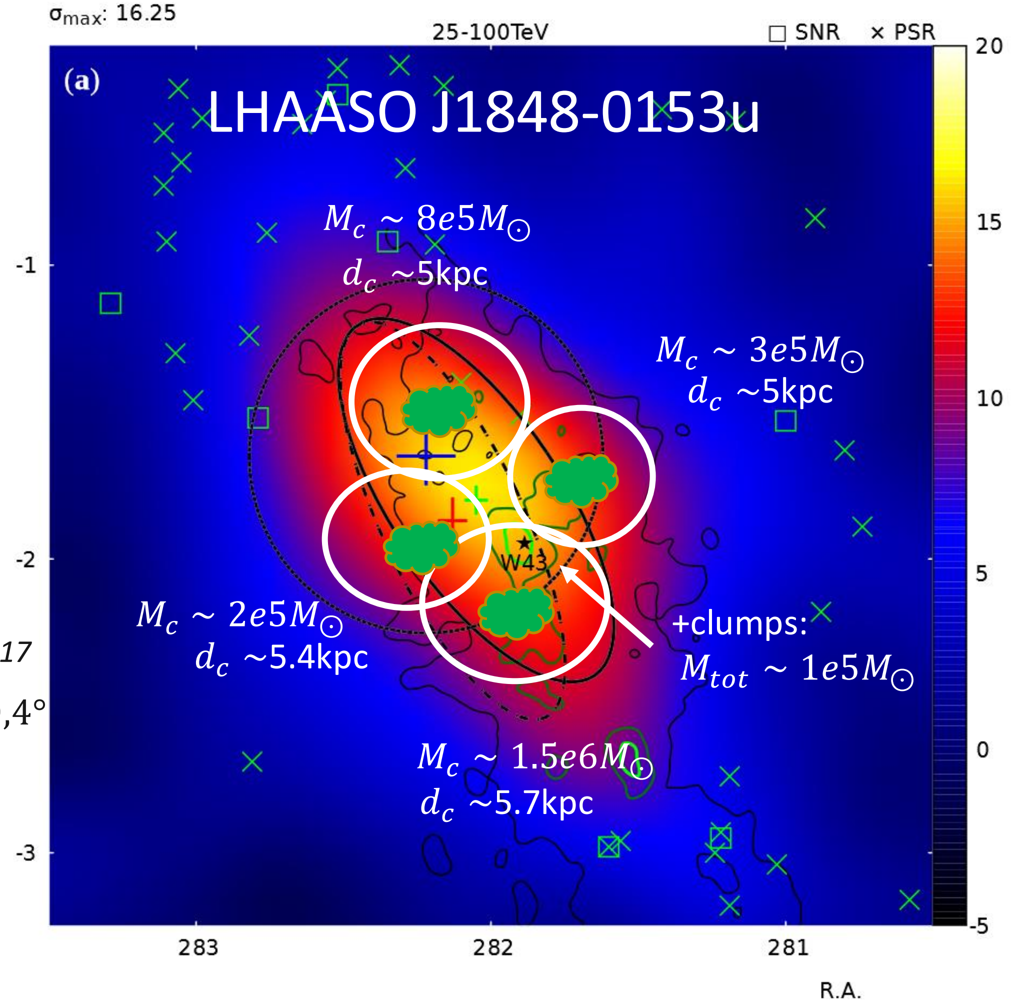

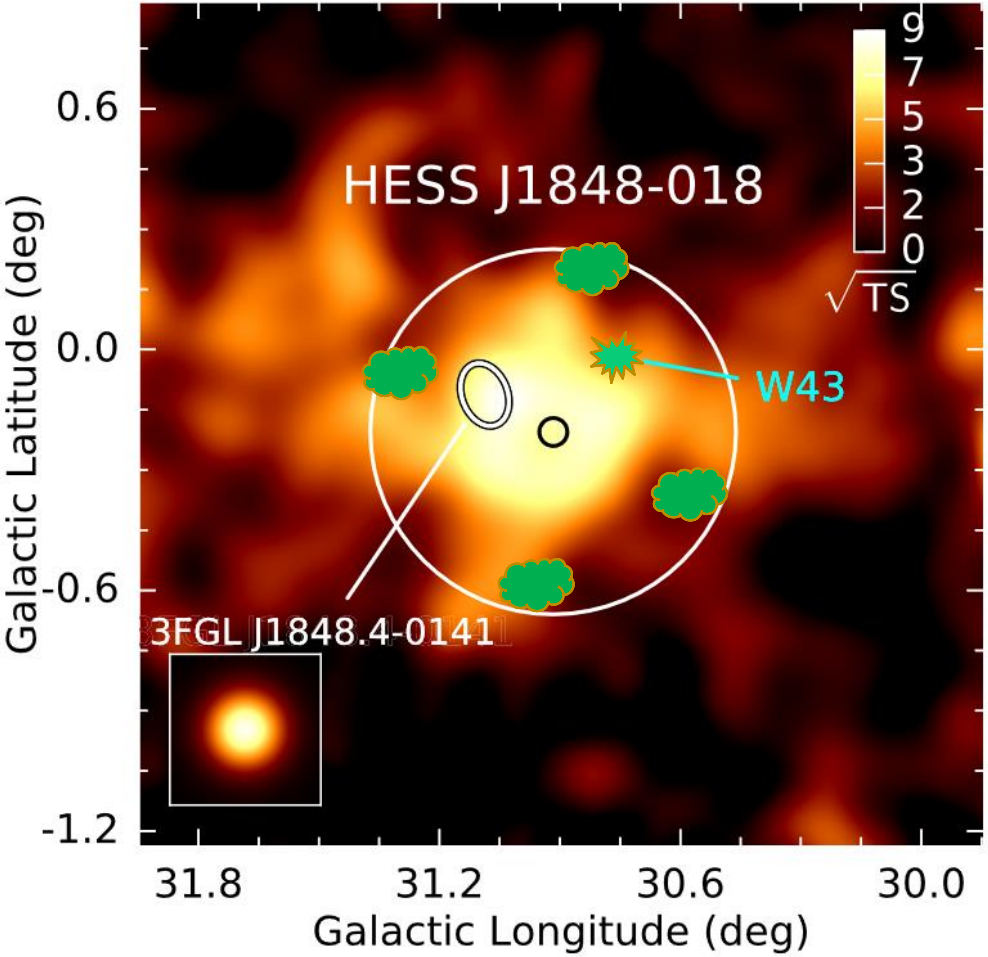

HESS Galactic plane Survey, 2018

- GMC/clumps scenario favored ?
- Leptonic ? Big extension so difficult because of the cooling time, but should do leptonic model to be sure

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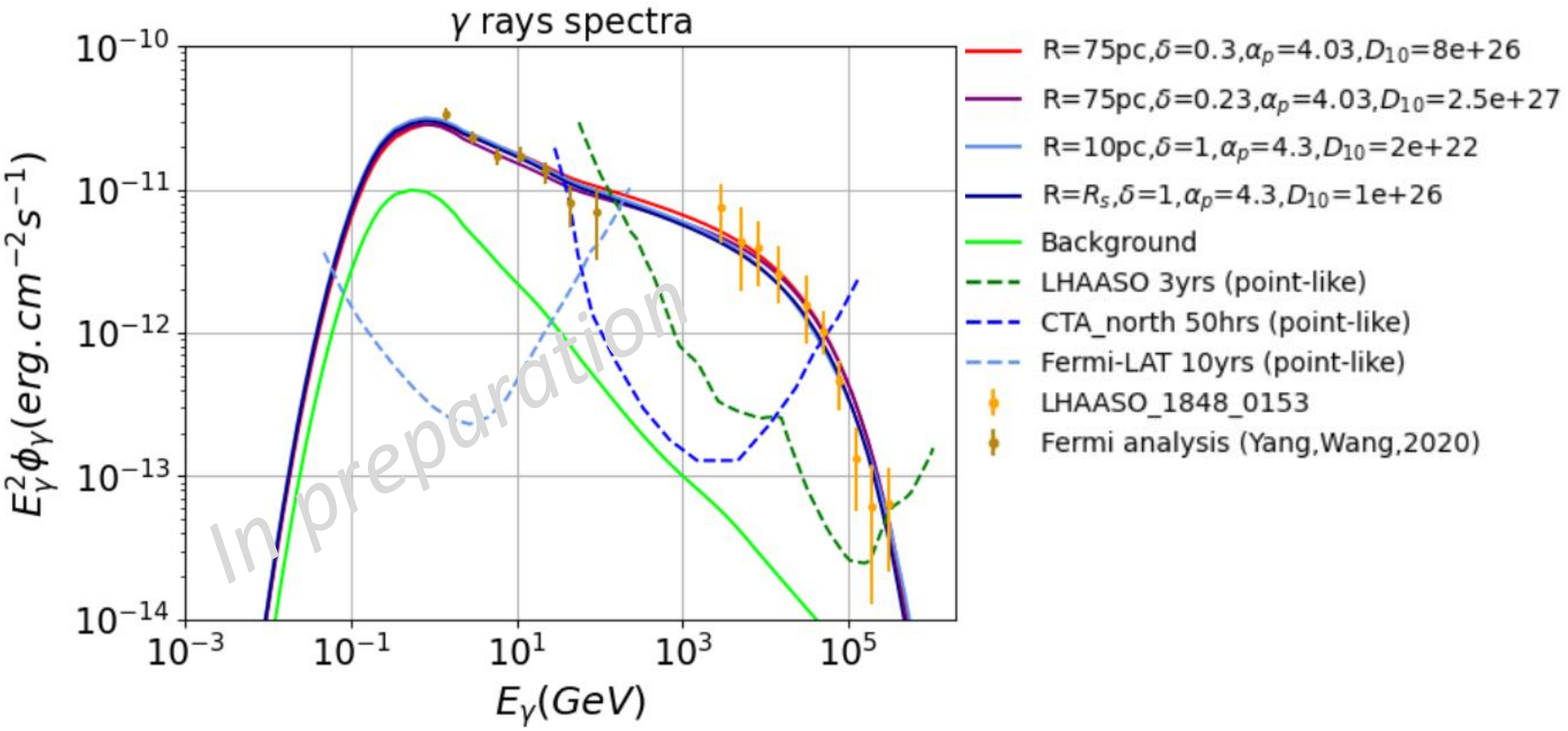
RESULTS



Diffusion coefficient a bit bigger in the 1D scenario

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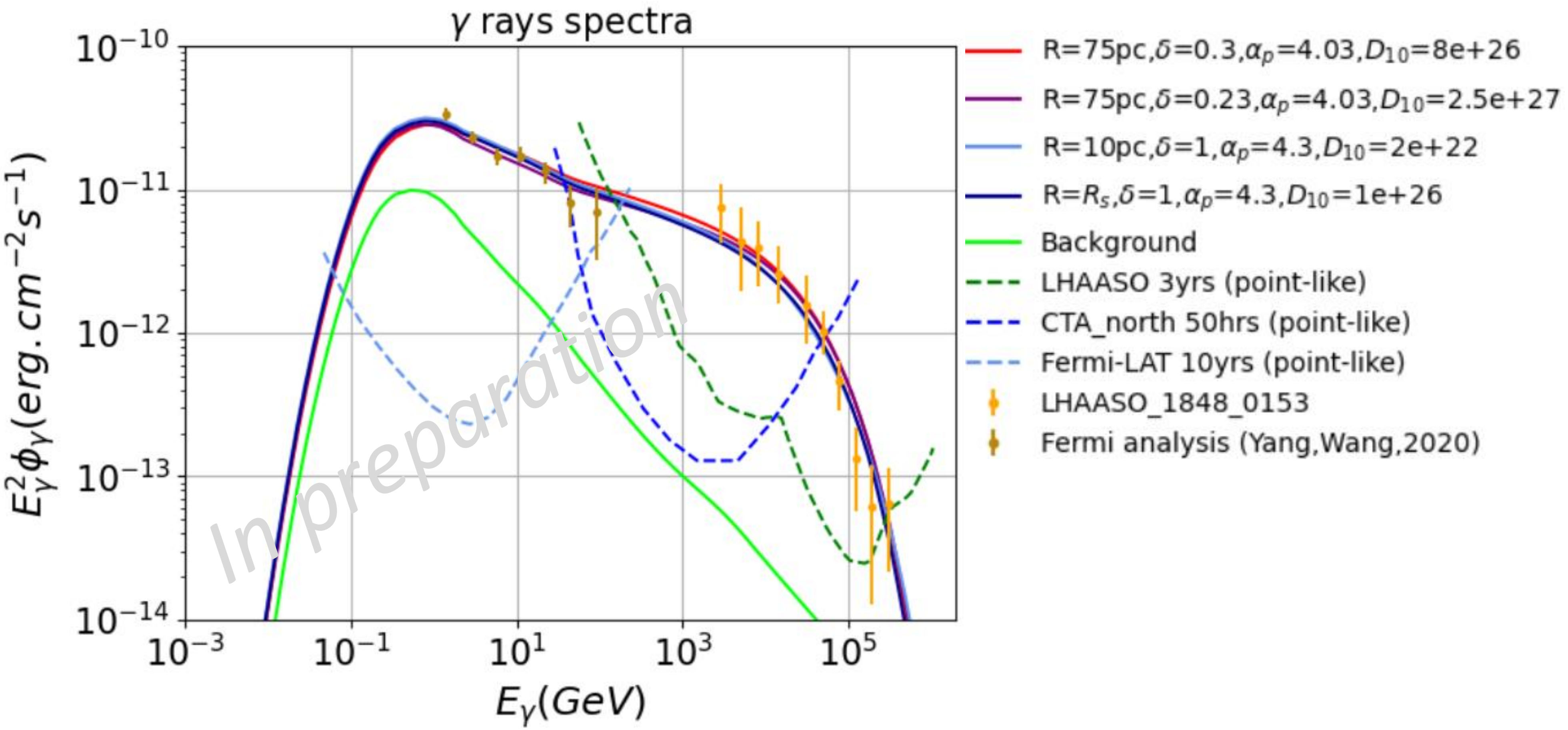

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$E_{cutoff} \sim 0.4\ PeV$ → a bit below proton knee ($\sim 1 - 3PeV$)

$$B \sim \left(\frac{\eta_B L_W}{v_W\ R_{WTS}^2}\right)^{\frac{1}{2}} \sim \left(\frac{\eta_B}{0{,}02}\ \frac{L_W}{3e38\ erg.s^{-1}}\ \frac{3{\cdot}10^8 cm.s^{-1}}{v_W}\ \frac{25pc^2}{R_{WTS}^2}\right)^{\frac{1}{2}}\ 10\mu G \rightarrow E_{max,Hillas} \sim 3 \cdot 10^{12} \frac{v_W}{1000\ km\ \ s^{-1}}\ \frac{B}{\mu G}\frac{2R_{WTS}}{pc} eV \sim 0.9\ PeV$$

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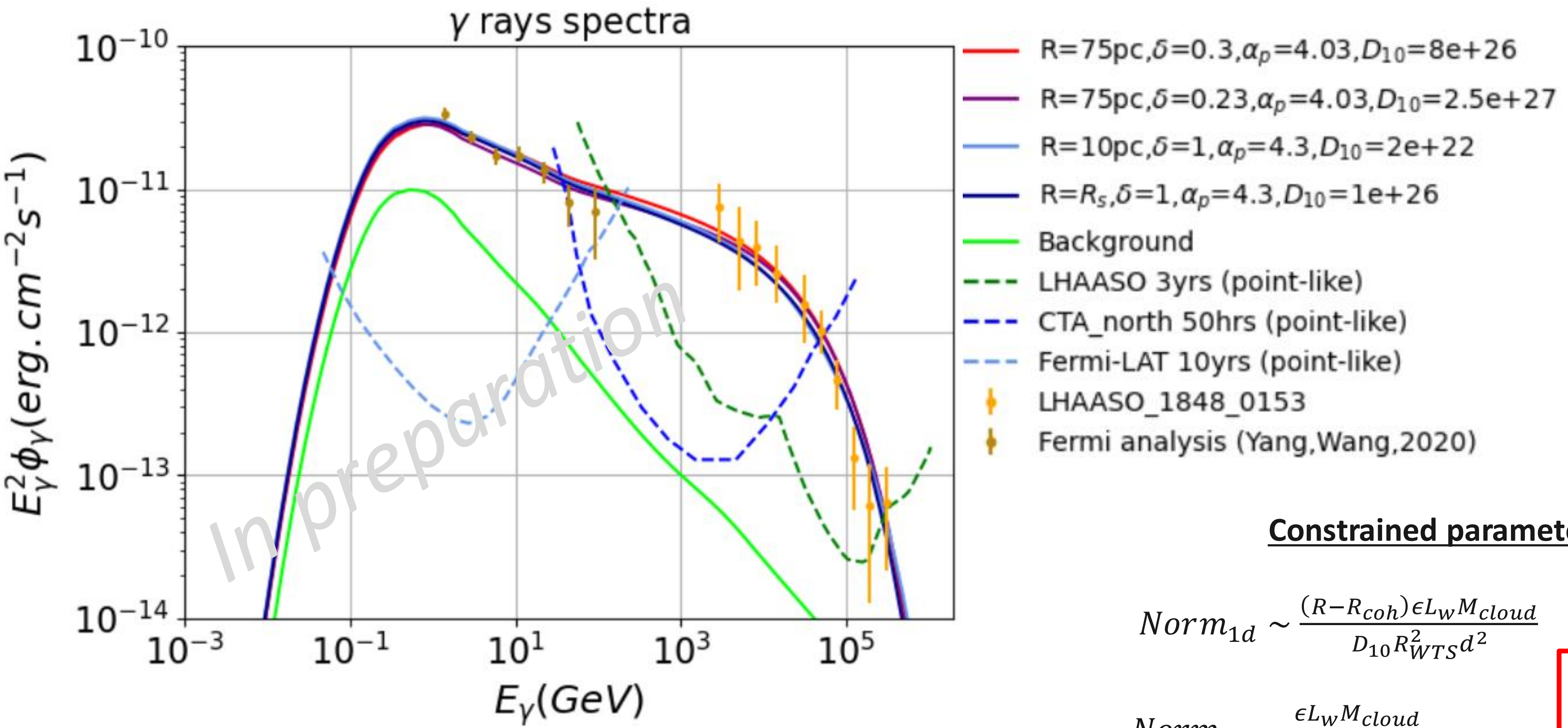

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GMC scenario favored because Bohm inside bubble more compatible with p^{-4} injection ?

Constrained parameter :

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

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

→ Gives $\frac{\epsilon}{D_{10}}$

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CONCLUSION AND PROSPECTS

Theoretical side :

- Several possible hadronic scenarios for creating γ-rays
- Excess around PeV possible with YMSC but result very sensitive to a change of parameters $(\alpha, \delta, D_0, L_w, \dots)$
- Limitation: γ ray detector sensitivity → for GMCs, $R_{max} \sim 300$ pc
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- Observed UHE gamma-ray flux by LHAASO , no SNRs nor pulsars nearby yet, but powerful star cluster and massive GMCs
- We can match datapoints and constrain physical parameters. Main constrained quantity (in GMC scenario) :
- Can explain this emission, and indicate a stellar cluster contribution for PeVatrons !

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

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(See paper in preparation for more details)

Thank you for your attention !