Université Paris Cité

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PhD Supervisor: Stefano GABICI

APC

PeV particles from stellar wind termination shocks

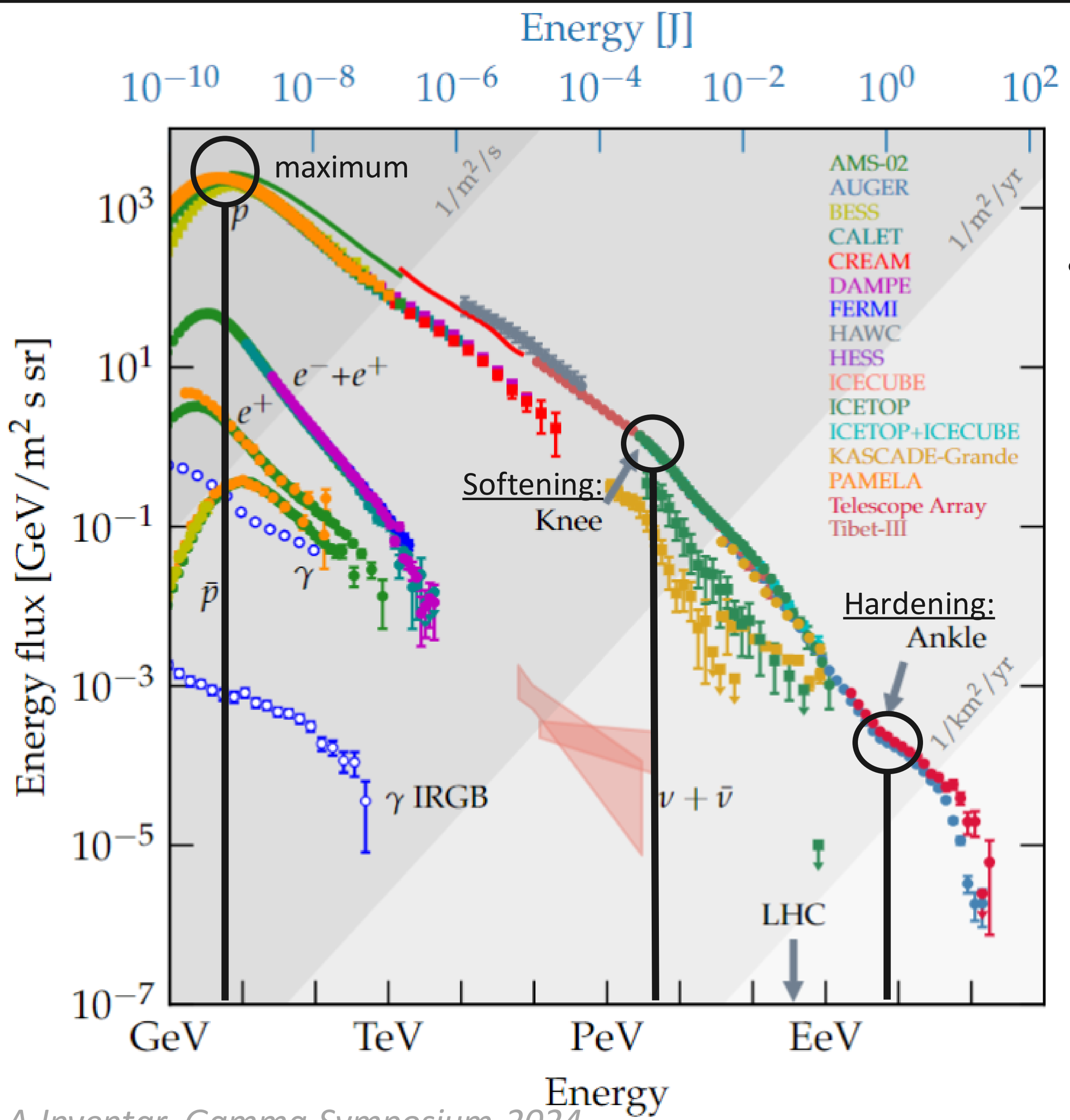
UNIVERSITÀ DEGLI STUDI DI MILANO

γ 2024

8th Heidelberg International Symposium on
High Energy Gamma Ray Astronomy
Milano, 2-6 September 2024

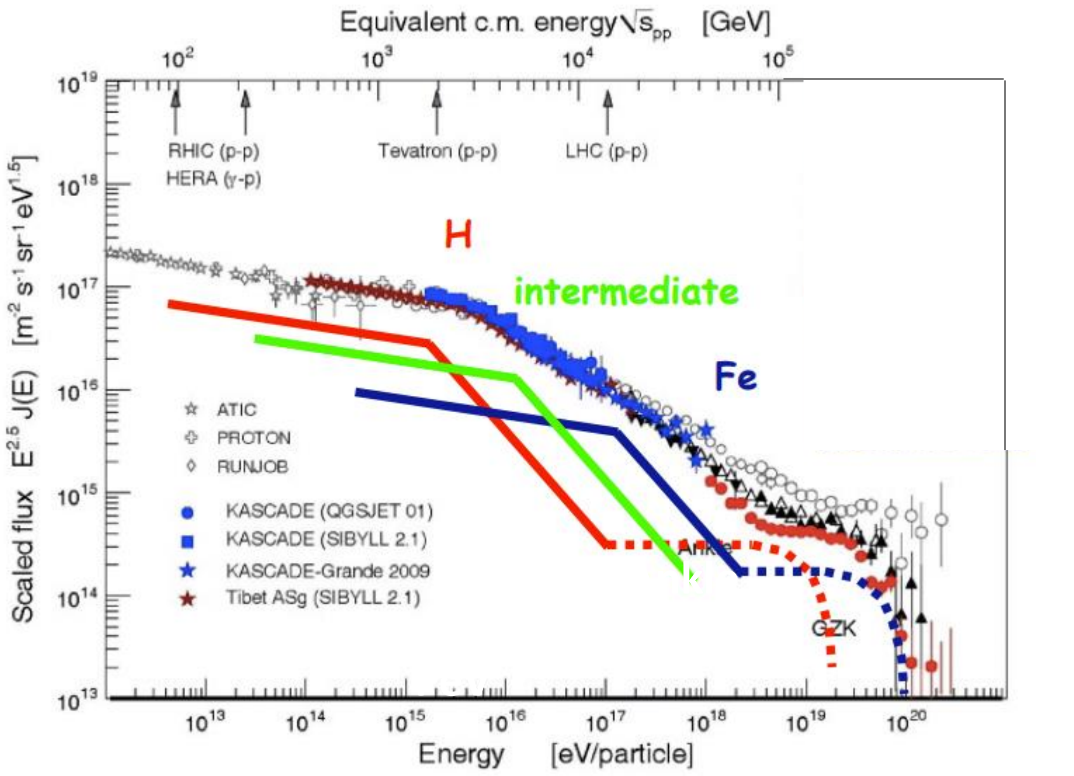
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

COSMIC-RAY SPECTRUM AND PEV



What happens at PeV scale ?

- Change of slope → change in the acceleration process



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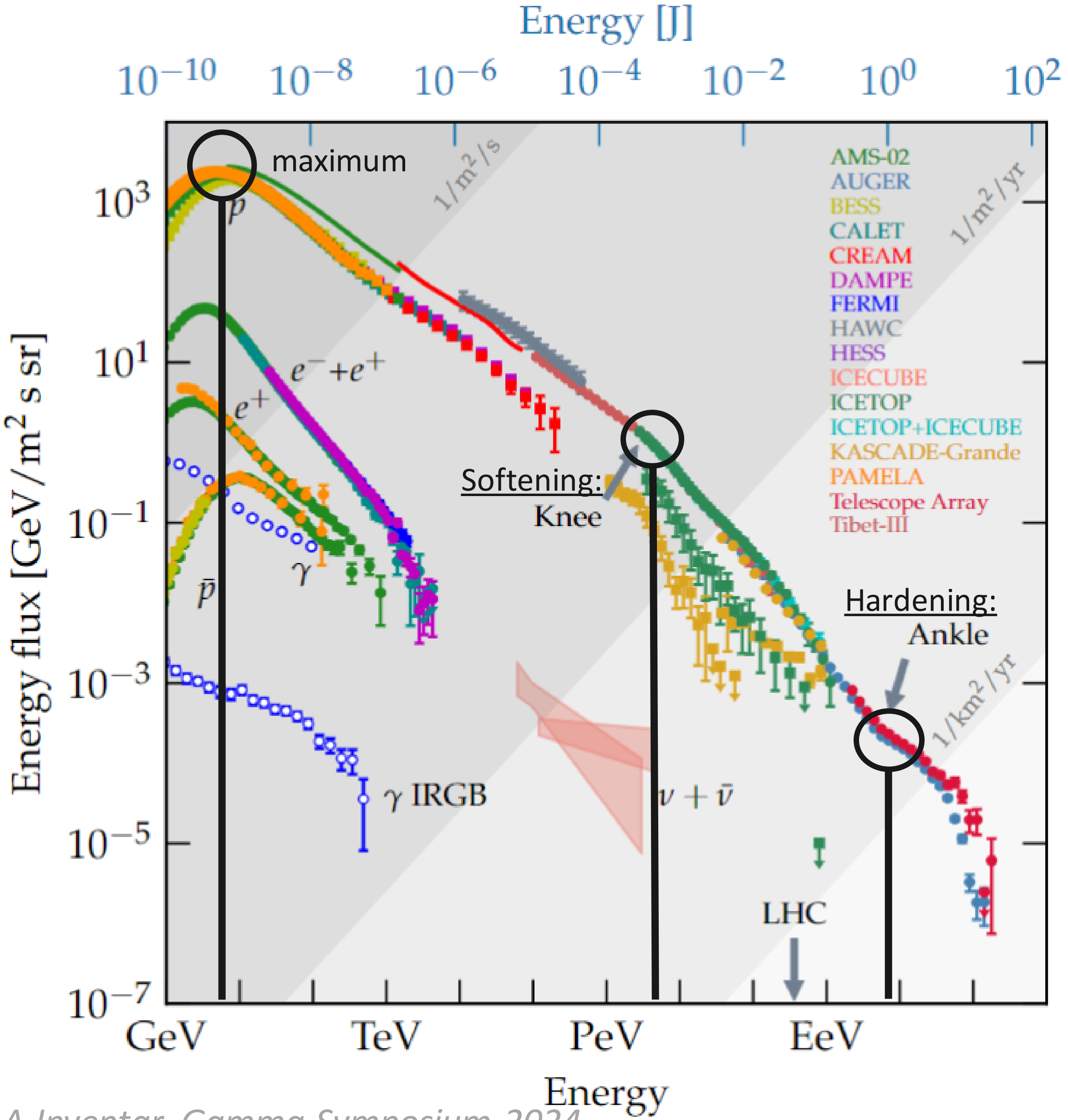

What happens at PeV scale ?

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- Most energetic **protons** accelerated by galactic sources

→ Push galactic acceleration models to their limits to go to PeV

→ Better understand CRs acceleration and the contributions of classes of sources to the spectrum (PeVatrons ?)

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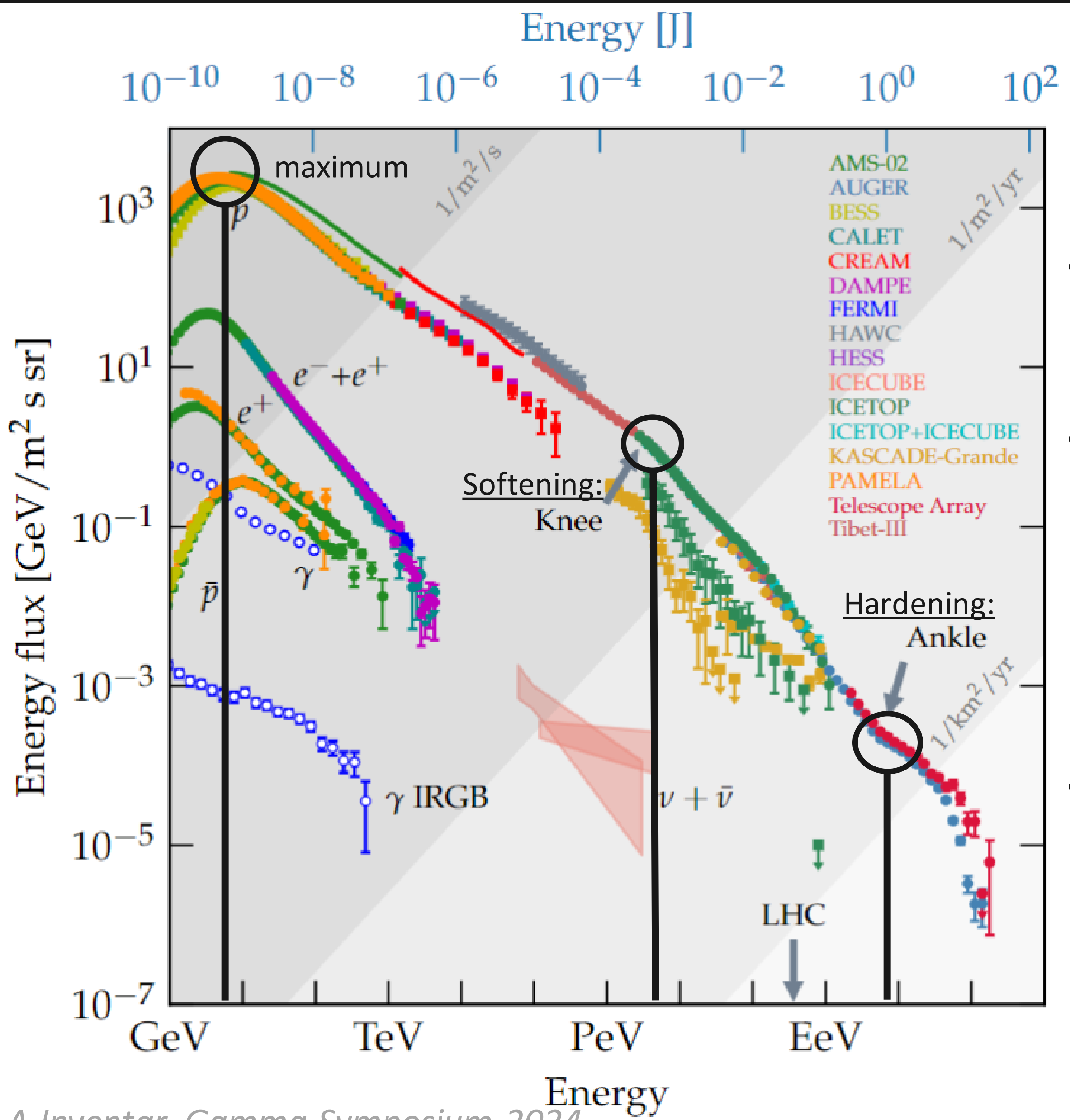

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- Most energetic **protons** accelerated by galactic sources

→ Push galactic acceleration models to their limits to go to PeV

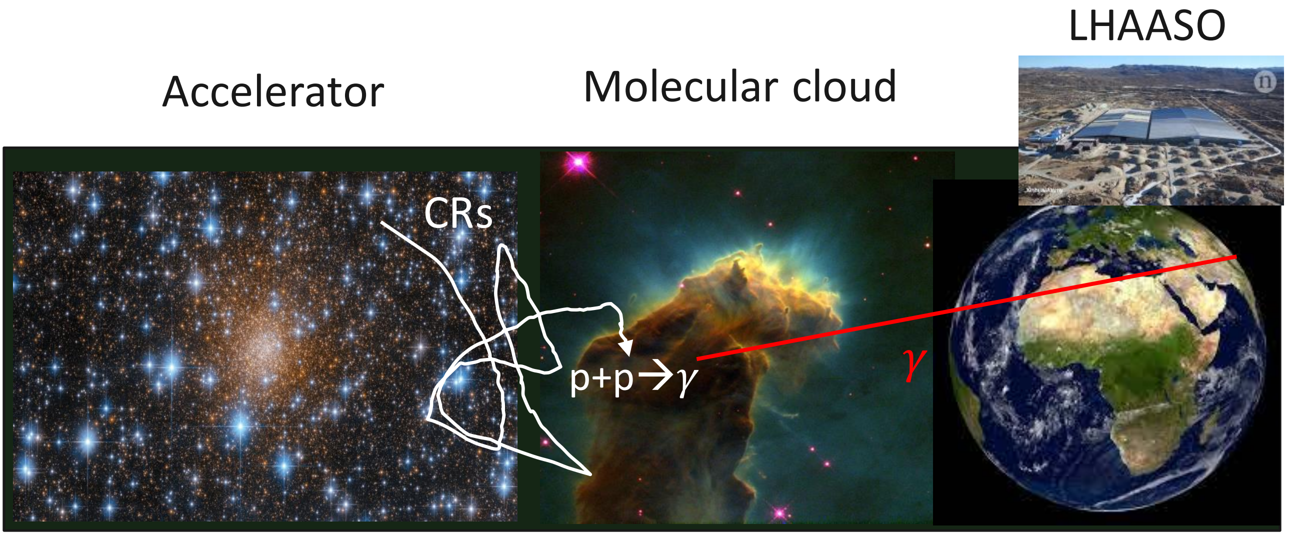
→ Better understand CRs acceleration and the contributions of classes of sources to the spectrum (PeVatrons ?)

- 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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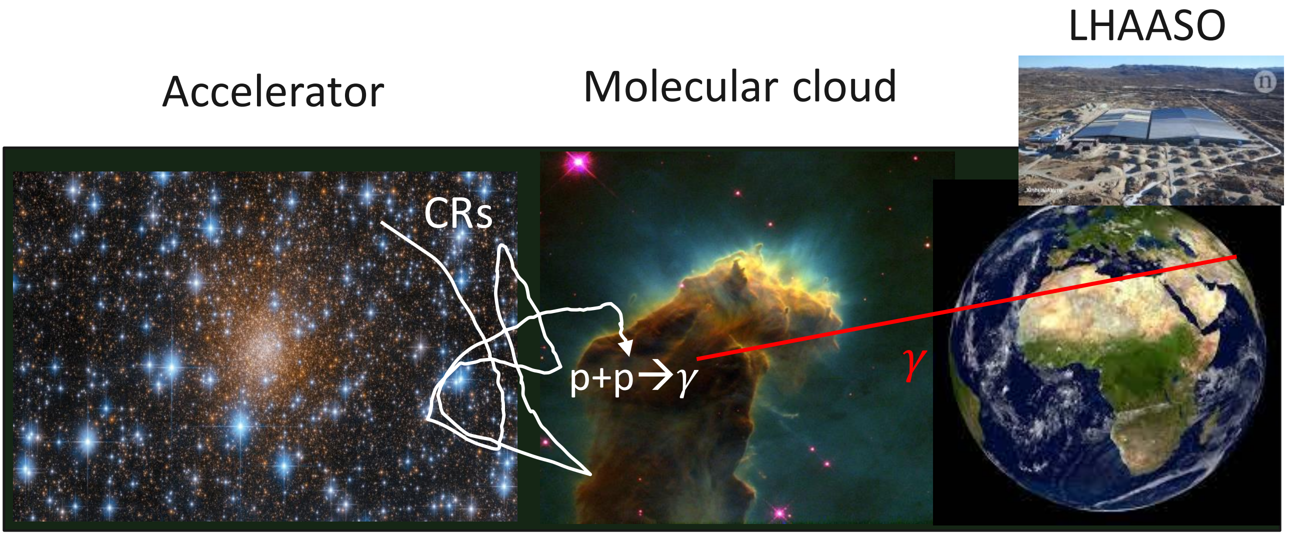

- For which sources and parameters (distance, time,…) can a dense molecular cloud present an excess of γ rays at different energies ?

→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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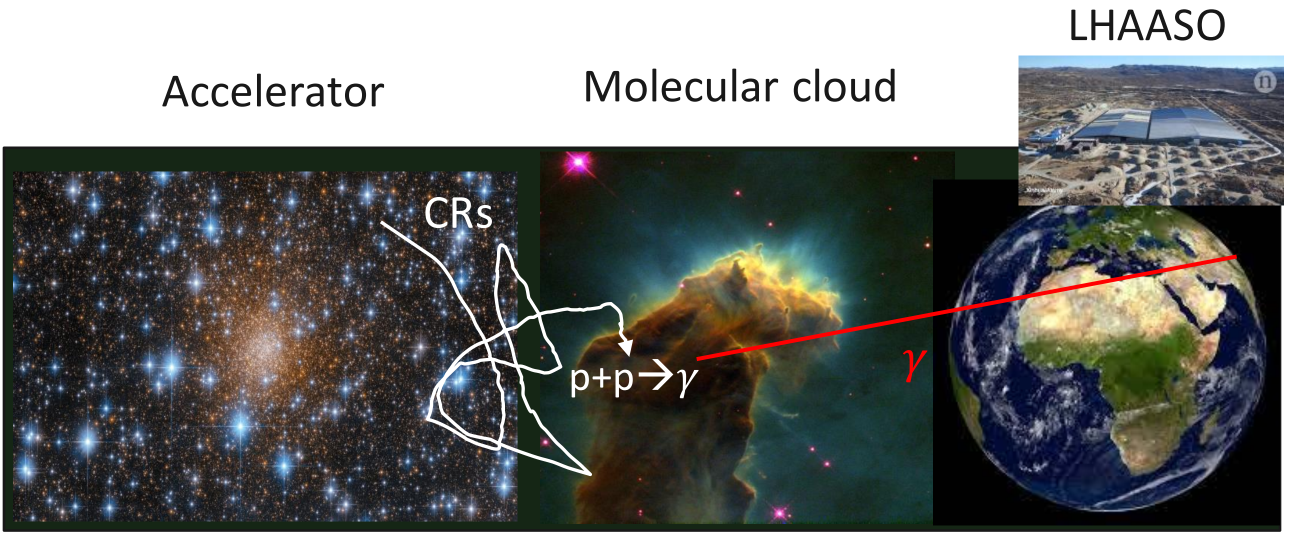

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→Model escape and transport of CRs between sources and molecular clouds, and the consequent production of γ rays at different energies

Theory

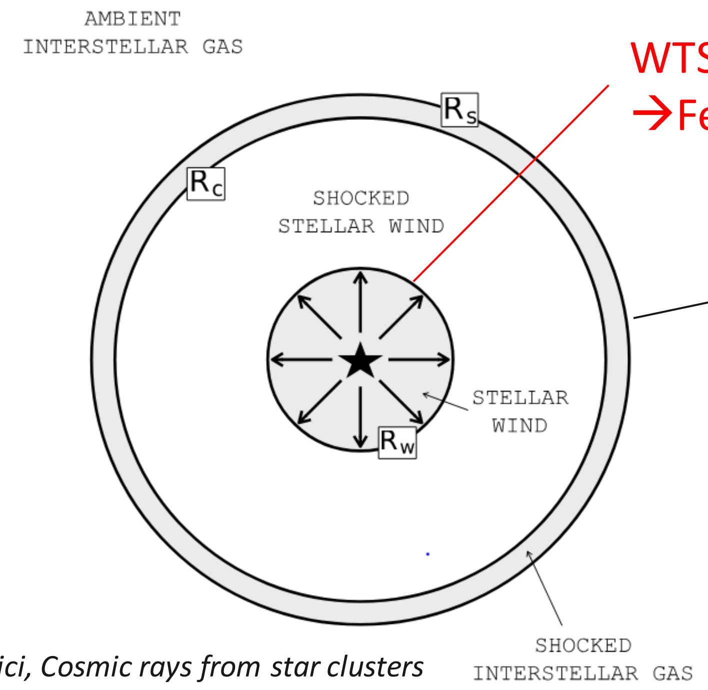
- Focus on **YMSCs (stellar wind)**, p^+ and E=3PeV (knee)

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

→ Identify the contributions of different classes of galactic accelerators to the flux of CRs in the PeV domain.
→ obtain better constraints on different acceleration parameters (WTS efficiency, injection spectrum in the ISM,…)

Applications and perspectives

WTS : ACCELERATION AND ESCAPE



Gabici, Cosmic rays from star clusters

WTS (slowly moving)
→Fermi acceleration by multiple crossings

Forward shock

Bubble inflated by stellar winds
→acceleration in WTS

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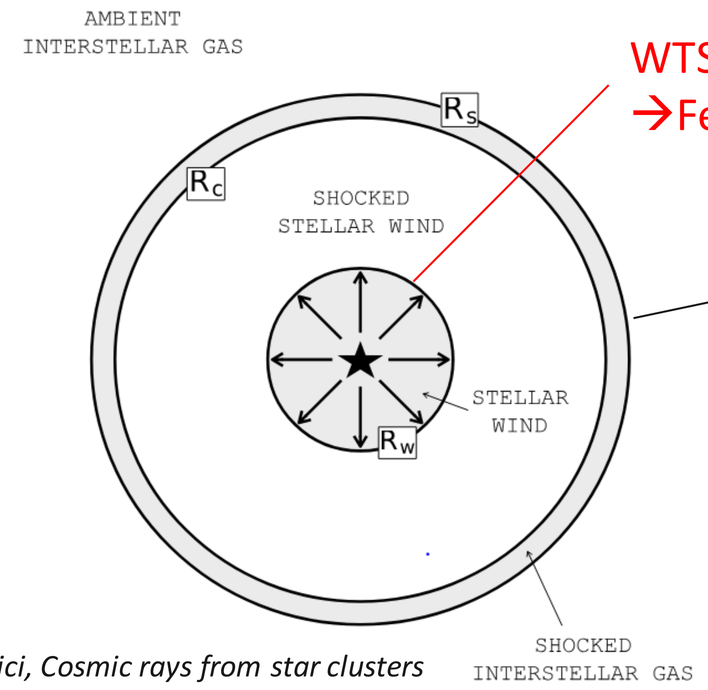

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WTS (slowly moving)
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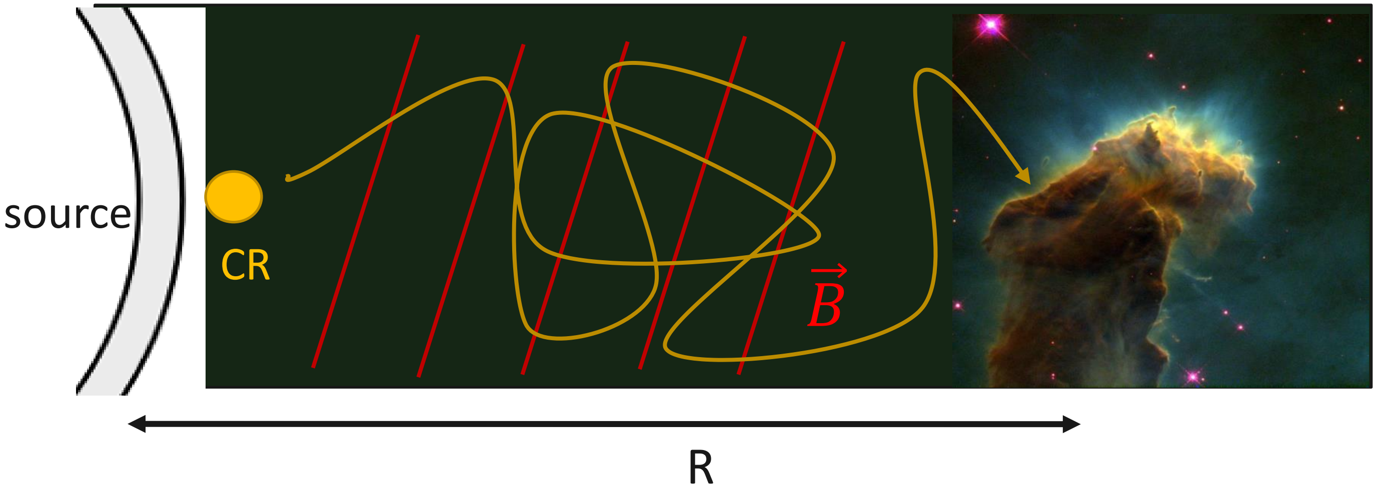
Forward shock

Bubble inflated by stellar winds
→acceleration in WTS

- Take simple injection spectrum in the ISM of the form $E^{-\alpha} \exp\left(-\frac{E}{E_{cut}}\right)$, $\mathbf{2 < \alpha < 2.4}$
- Take Efficiency $\epsilon = \frac{1}{10}$ for both, but goal is to constrain ϵ_{wind}
- Take $E_{cut,wind} = 3PeV$

TRANSPORT MODEL

- Diffusion equation
- Spherically symetric case (3D)
- Isotropic
- Point-like sources



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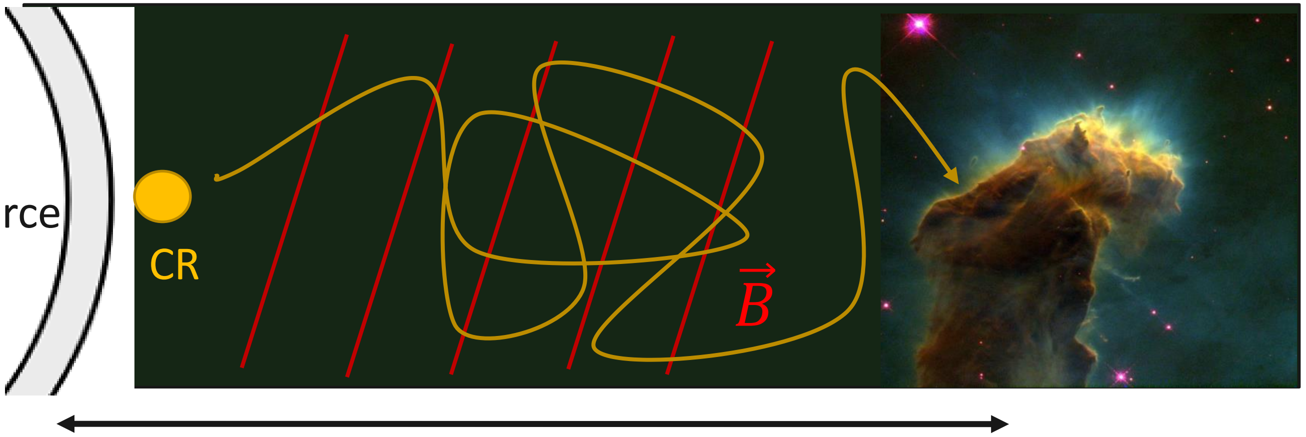
source



R

Particle distribution function

$$\frac{\partial f}{\partial t} = \frac{D(E)}{R^2}\frac{\partial}{\partial R}R^2\frac{\partial f}{\partial R} + \frac{\partial}{\partial E}\left(\frac{E}{\tau_{pp}}f\right) + S(E,R,t)$$

=0 for stationnary solution

Diffusion

Energy losses

Source (injection)

$$D(E) = \frac{D_0}{cm^2 s^{-1}}\left(\frac{E}{10}\right)^{\delta}$$

$\mathbf{0.3 < \delta < 0.6}$

$\mathbf{D_0 \sim 10^{28}}$

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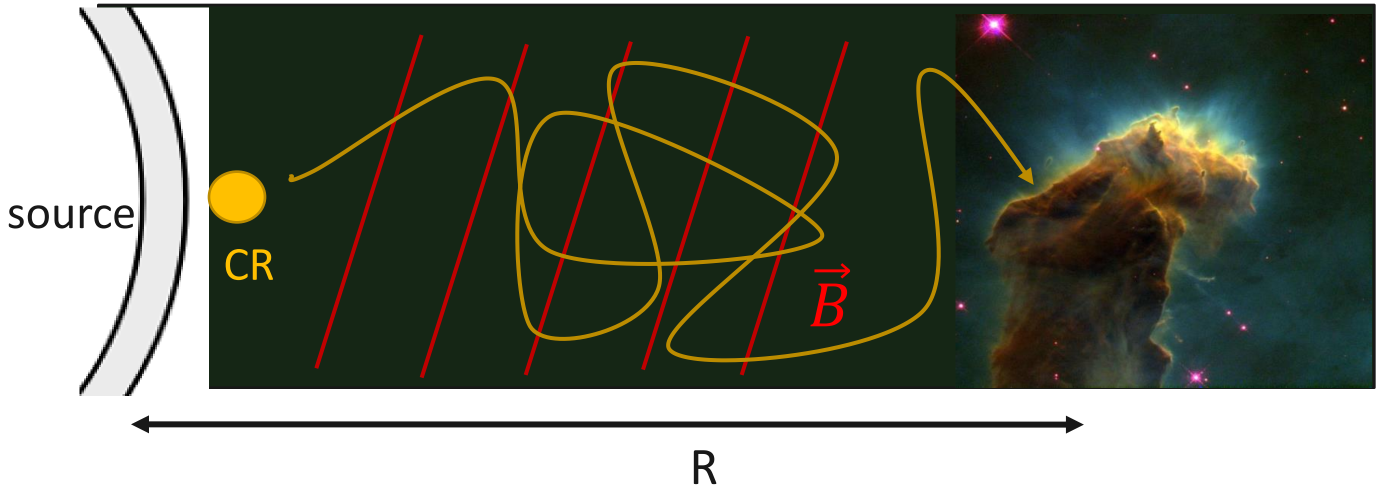

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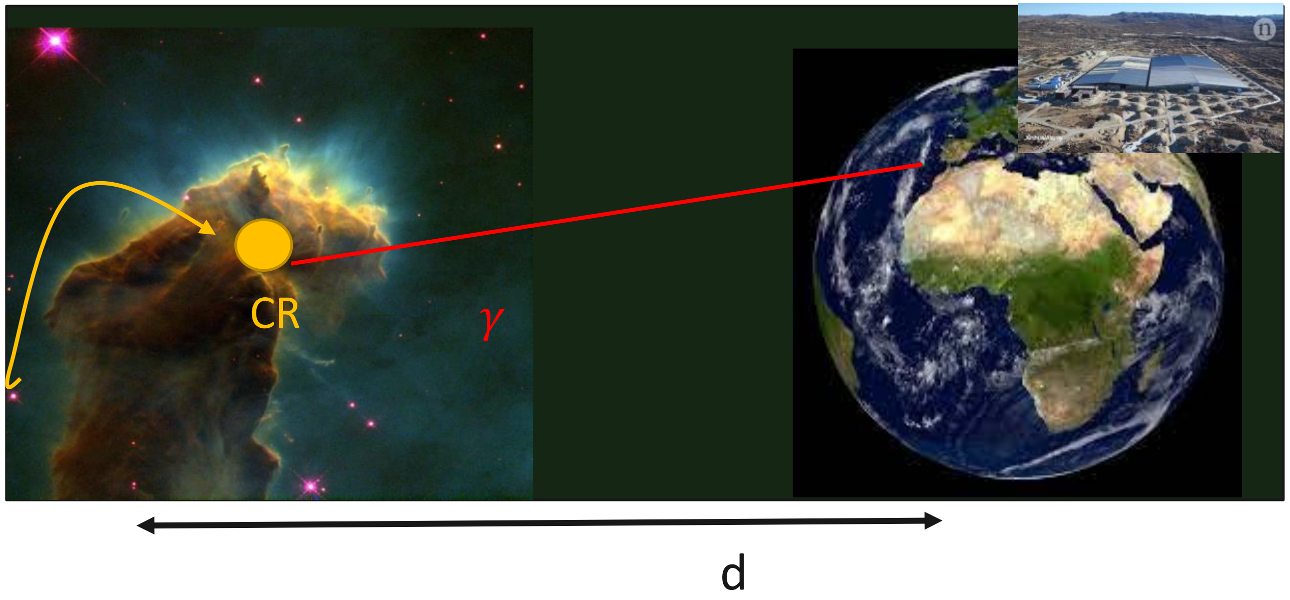
Source (injection)

$$S_{cont}(E,R,t) \sim E^{-\alpha}\exp\left(-\frac{E}{E_{cut,cont}}\right)\delta(R)q$$

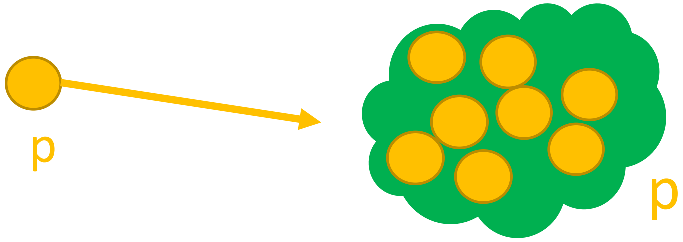
$= f_{inj}$

Analytic solution !
(Aharonian, Atoyan 1996)

P-P INTERACTIONS AND γ RAYS



MCs are very dense → a lot of target protons



$p+p \rightarrow \ldots + \pi_0 \rightarrow 2\gamma$

(π_0 decay)

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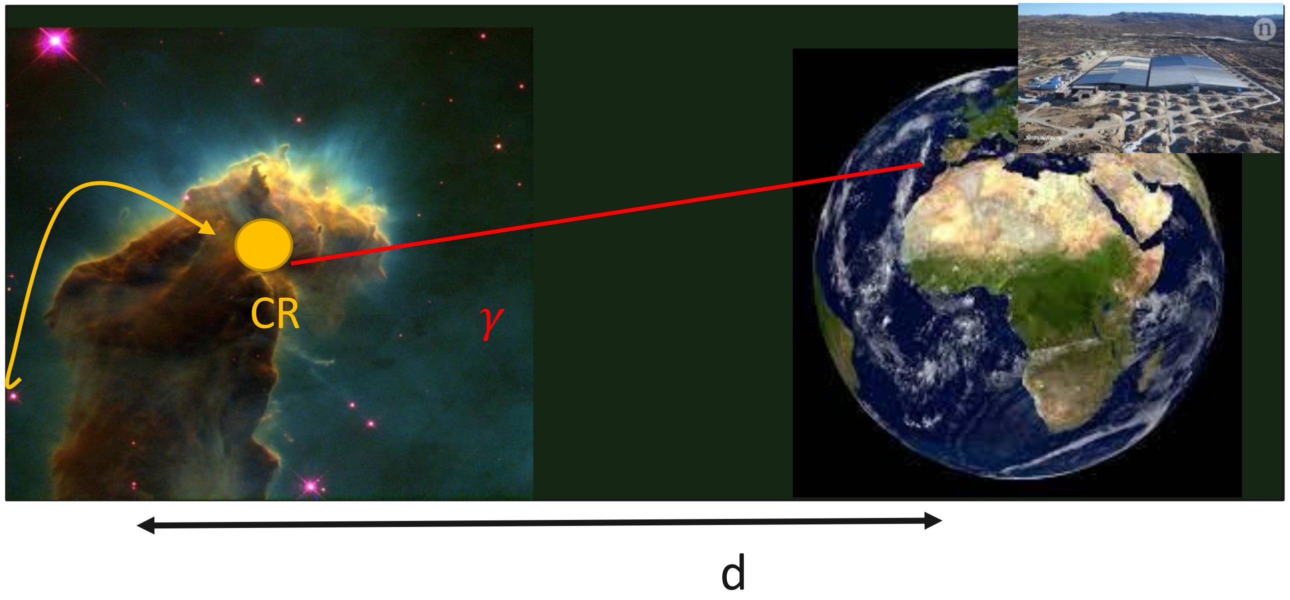

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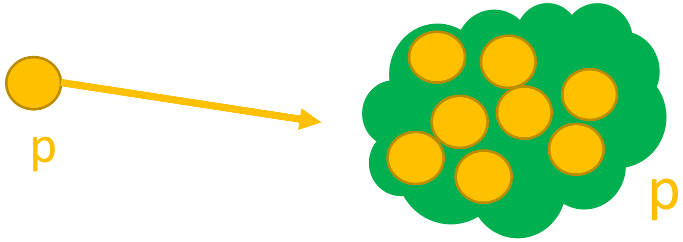


p+p→ … + π_0 → 2γ

(π_0 decay)

γ rays emissivity via p-p interactions : $q_\gamma \sim n_H \sigma c f$

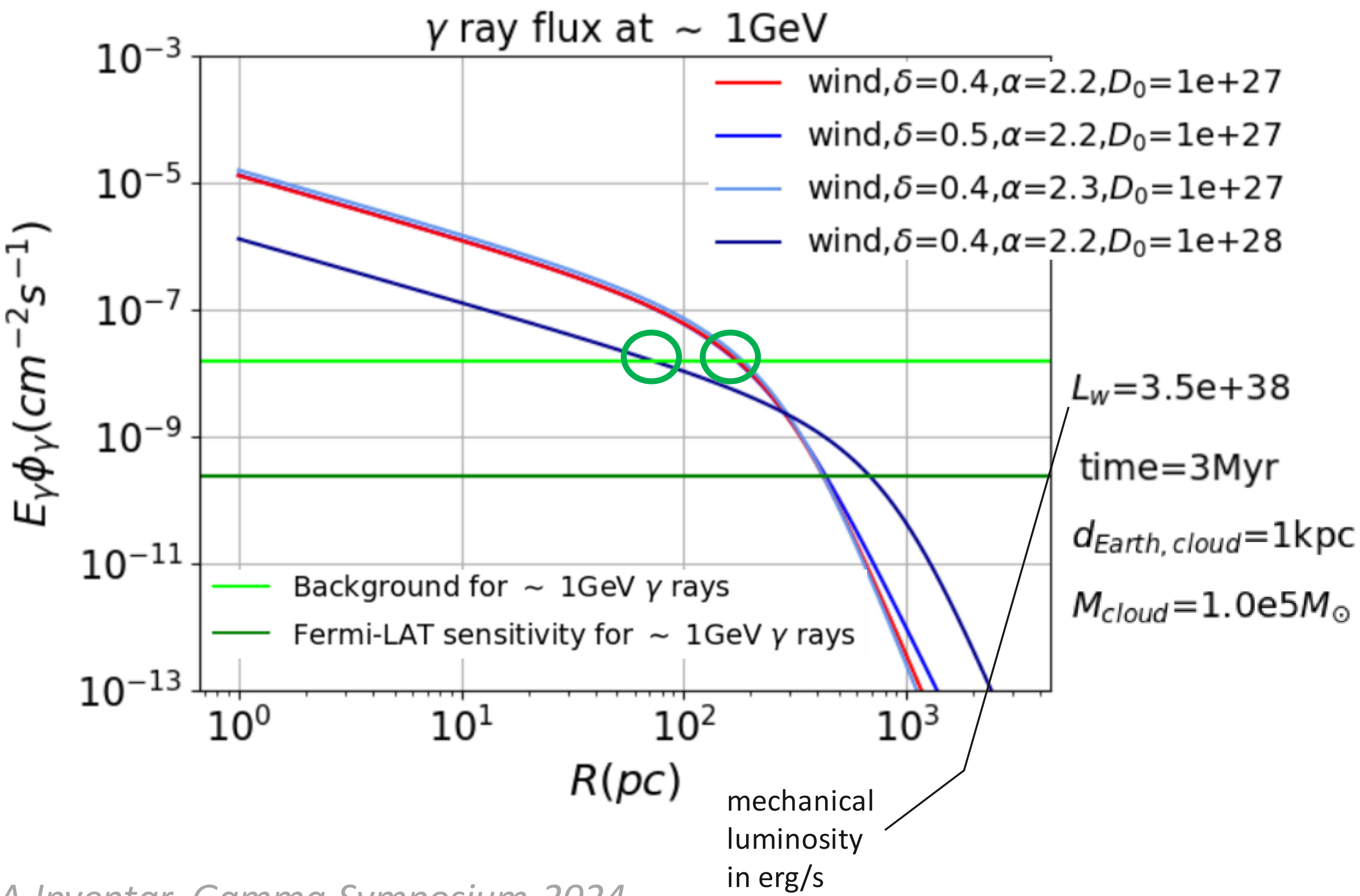
Parametrizations of σ taken from *Kafexhiu et al, 2014*

γ rays flux observed on Earth:

$$\phi_\gamma \sim \frac{q_\gamma}{4\pi n_H d^2} \frac{M_{cloud}}{m_p}$$

γ RAYS FLUX AND DETECTIONS

→Need LHAASO sensitivity (3yrs) +angular resolution, and also the mass of the cloud and its distance to the Earth



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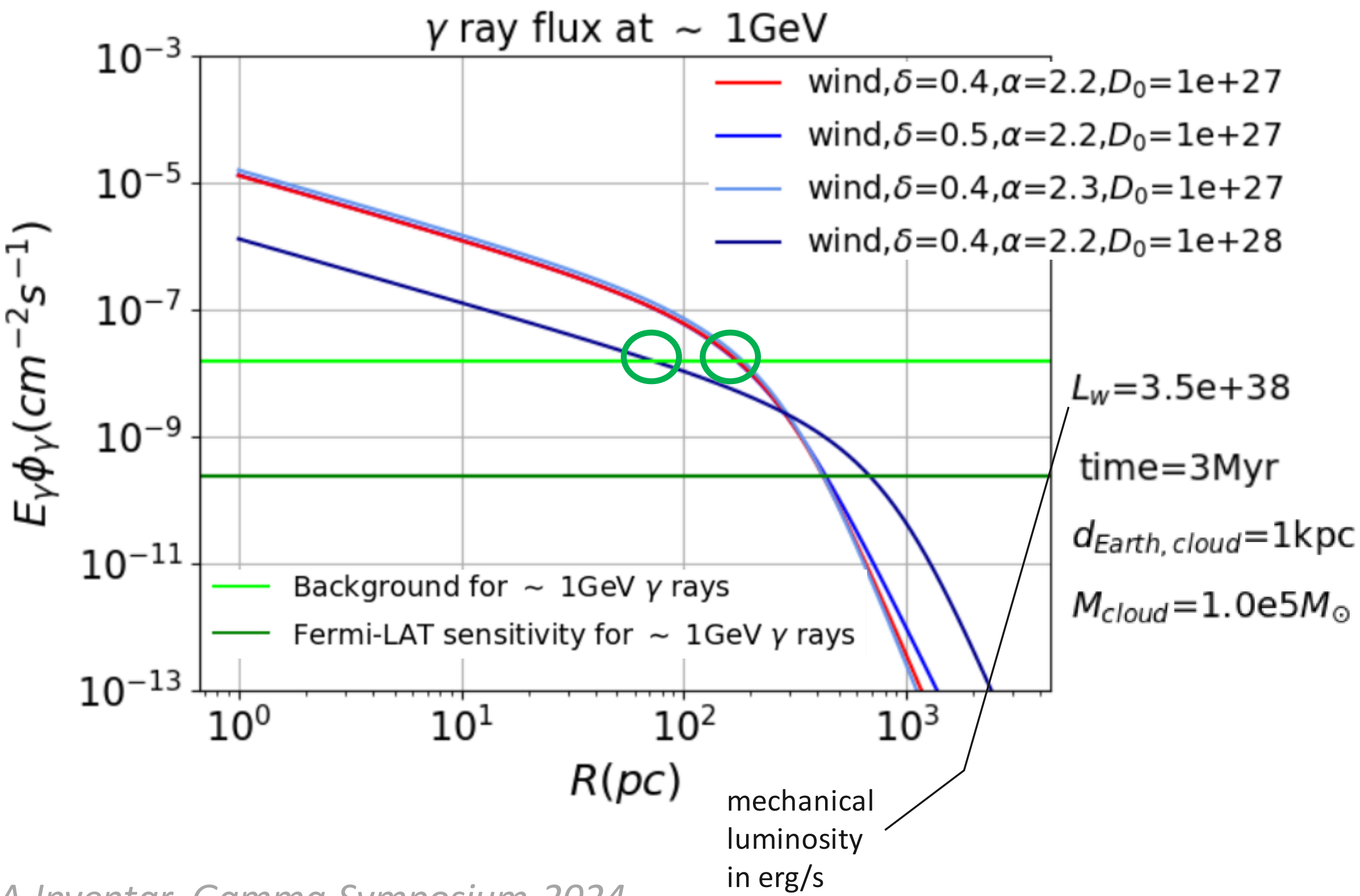

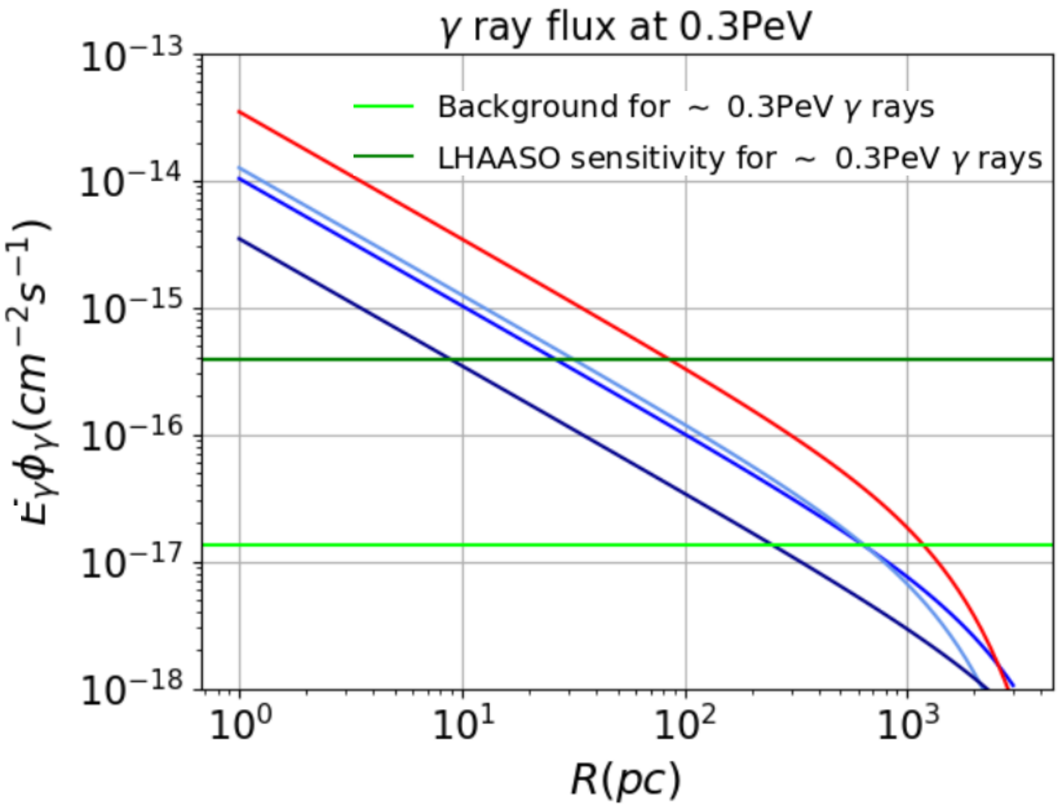

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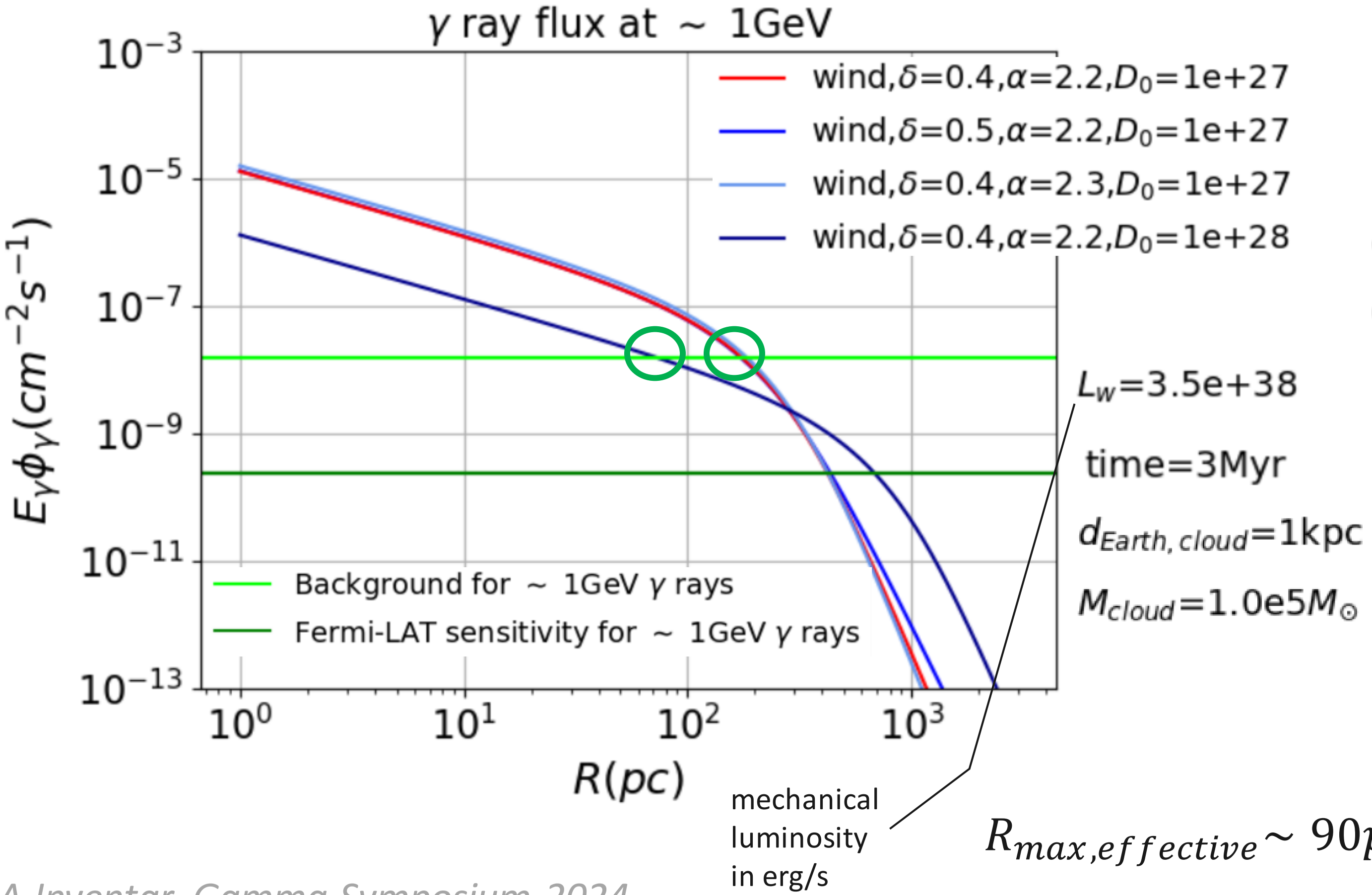
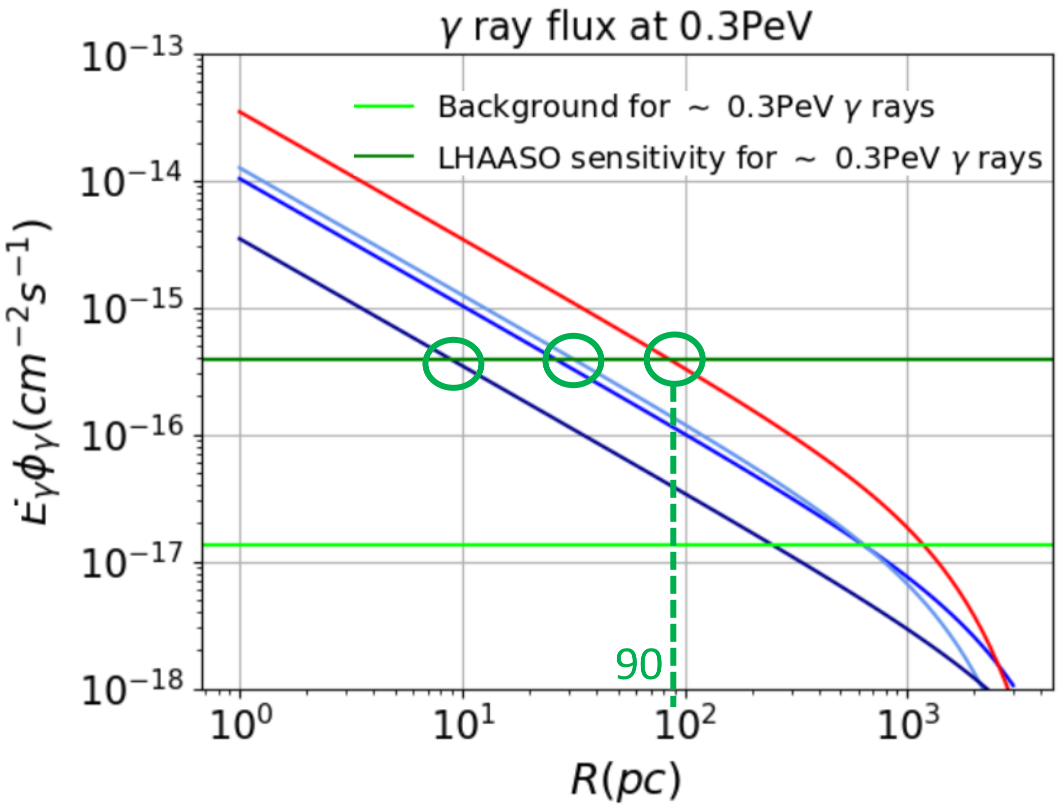


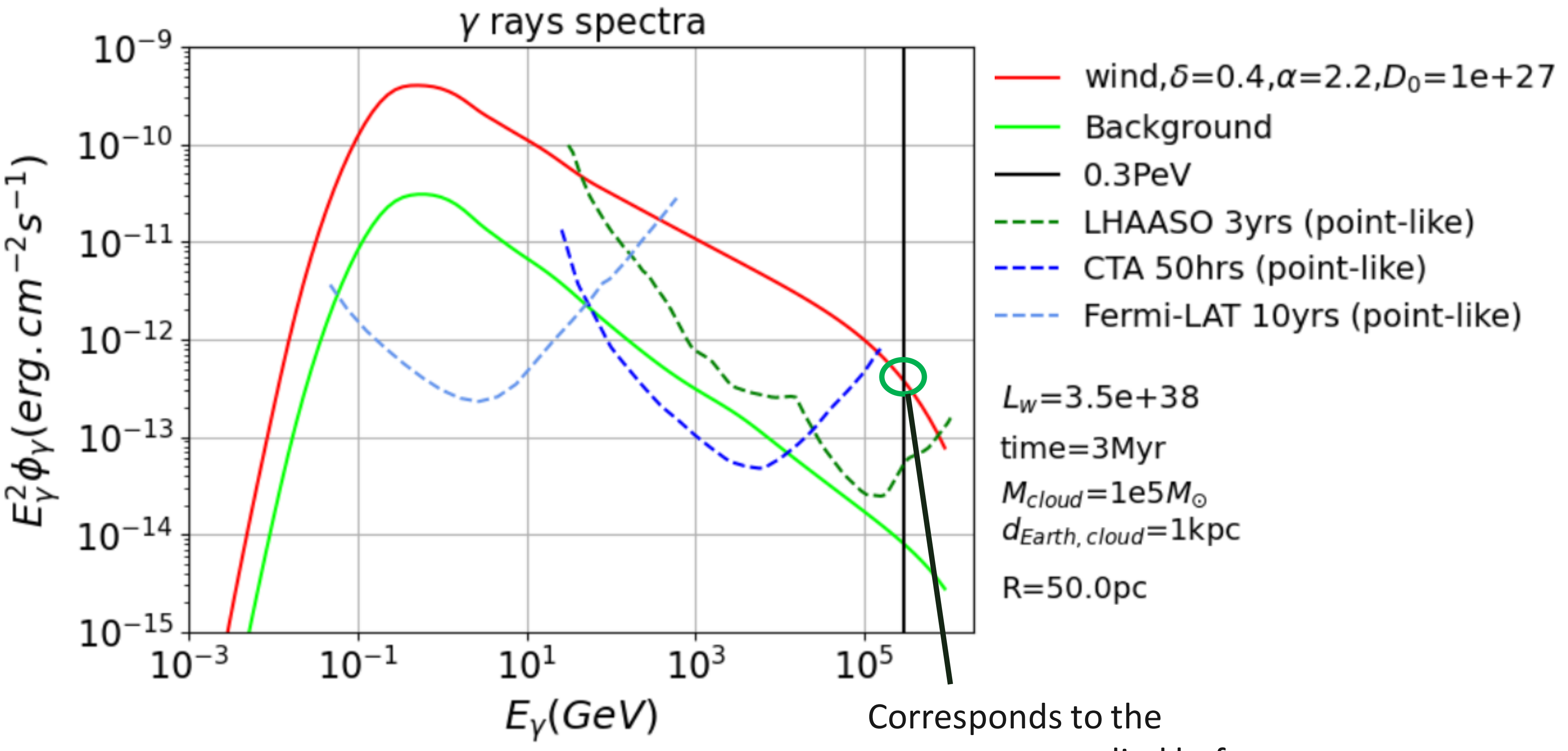
$R_{max,effective} \sim 90pc$



LHAASO sensitivity gives bigger constraint to detect the flux and an $R_{max,effective}$

γ RAYS SPECTRA AT FIXED PARAMETERS

Can fix the distance and see the spectrum at this distance to compare with differential sensitivities:



Corresponds to the parameters studied before

→Suppose a suppression of diffusion coefficient via streaming instabilities

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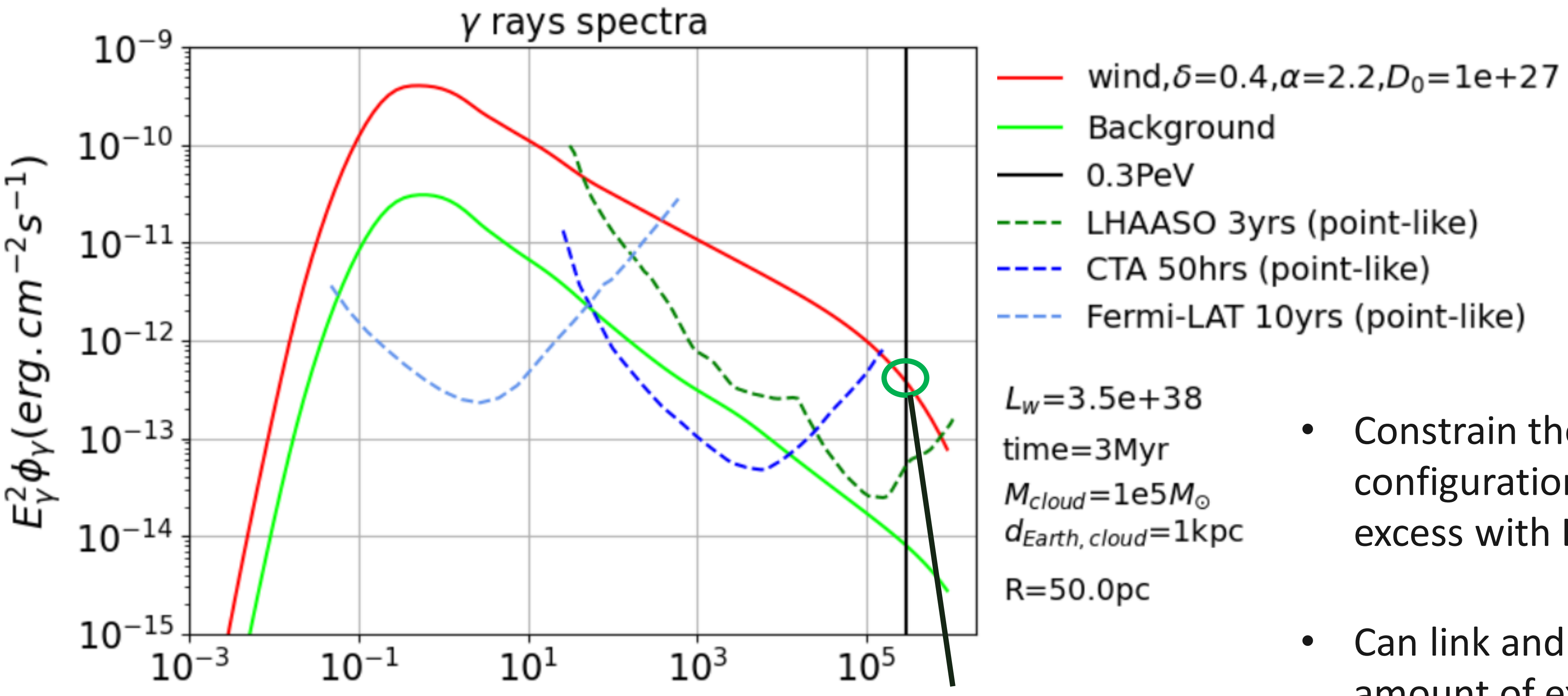


Corresponds to the parameters studied before

→Suppose a suppression of diffusion coefficient via streaming instabilities

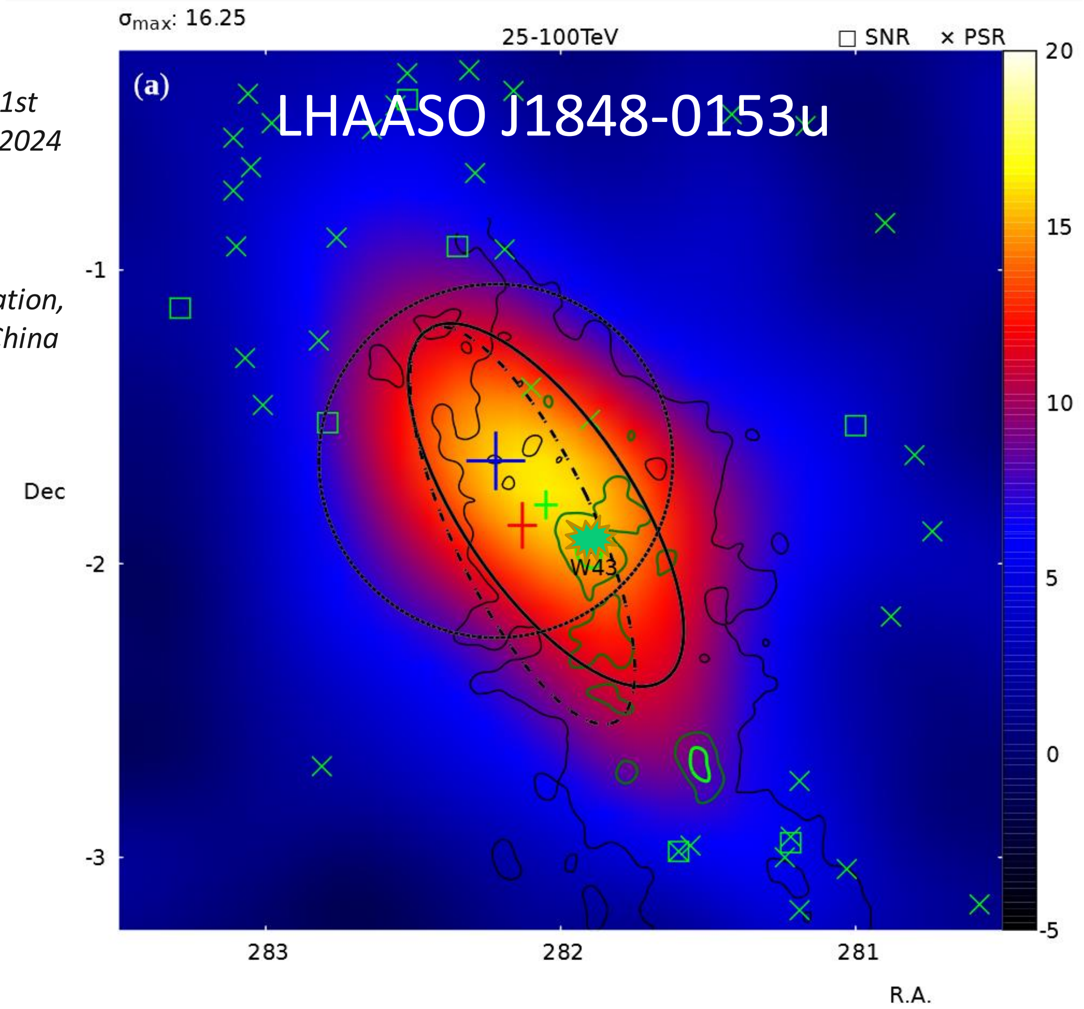
- Constrain the parameter space to find the configurations of parameters that enable detectable excess with LHAASO
- Can link and predict excess at PeV with the amount of excess at lower energies

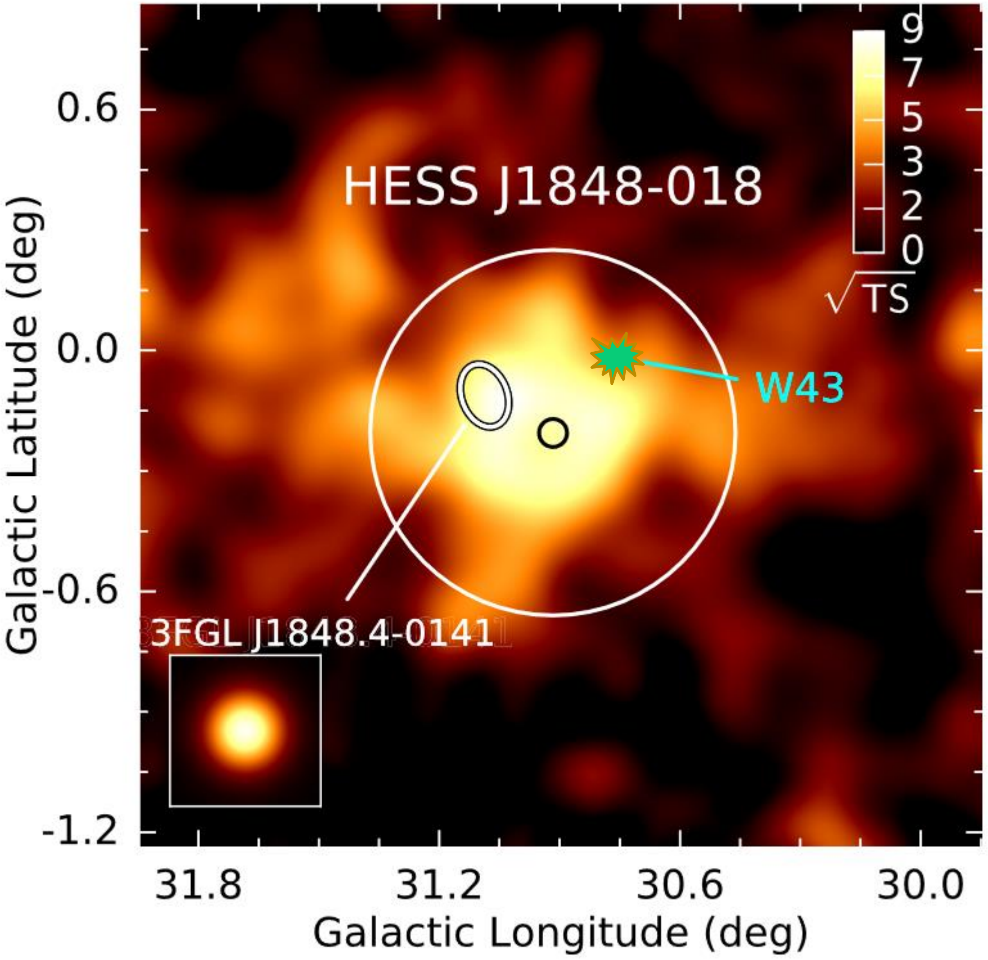
APPLICATION: W43 CLUSTER

VHE/UHE Gamma-ray emission in W43 region, that contains very massive clouds and a powerful star cluster

LHAASO 1st catalog, 2024

LHAASO Collaboration, Science China 2024





HESS Galactic plane Survey, 2018

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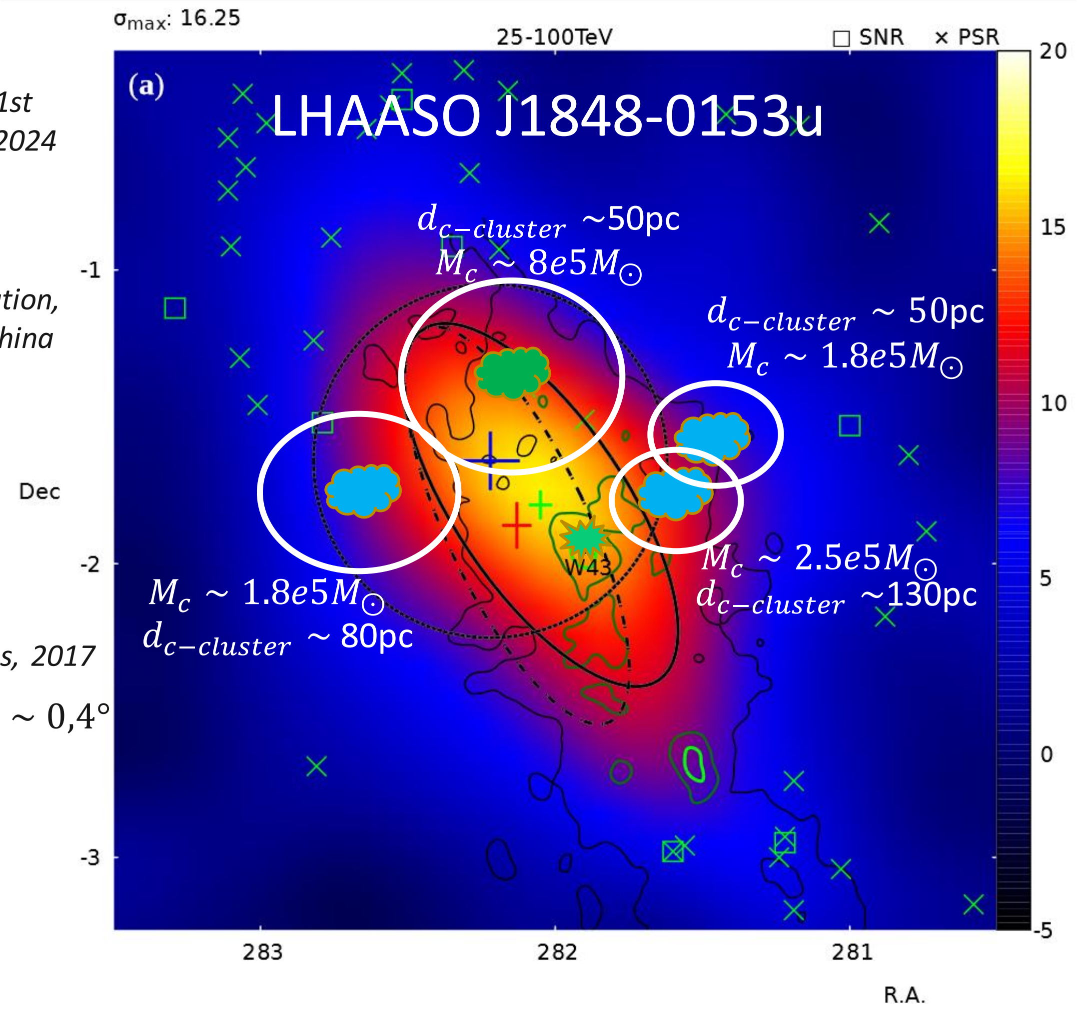
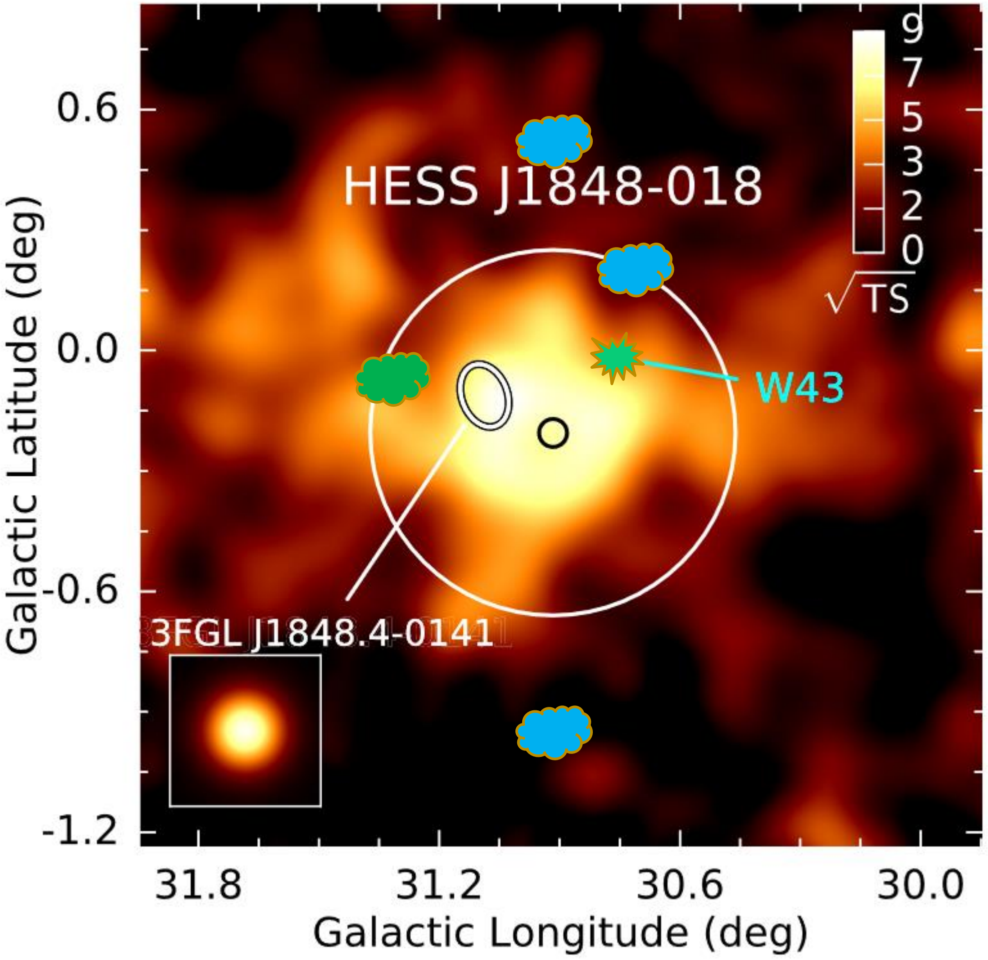
Miville-Deschenes, 2017

$\sigma_{angular} \sim 0{,}4°$

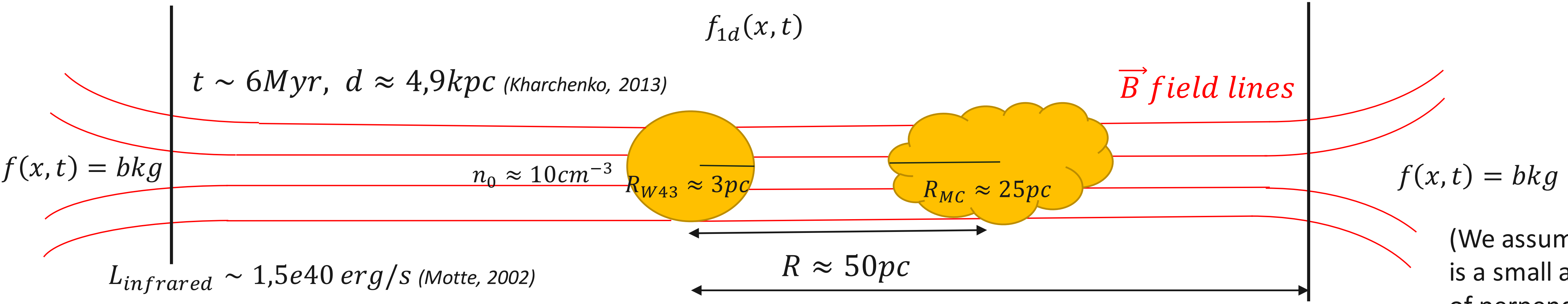




HESS Galactic plane Survey, 2018

Leptonic ? $\tau_{cool,e}$ – too low for this emission size

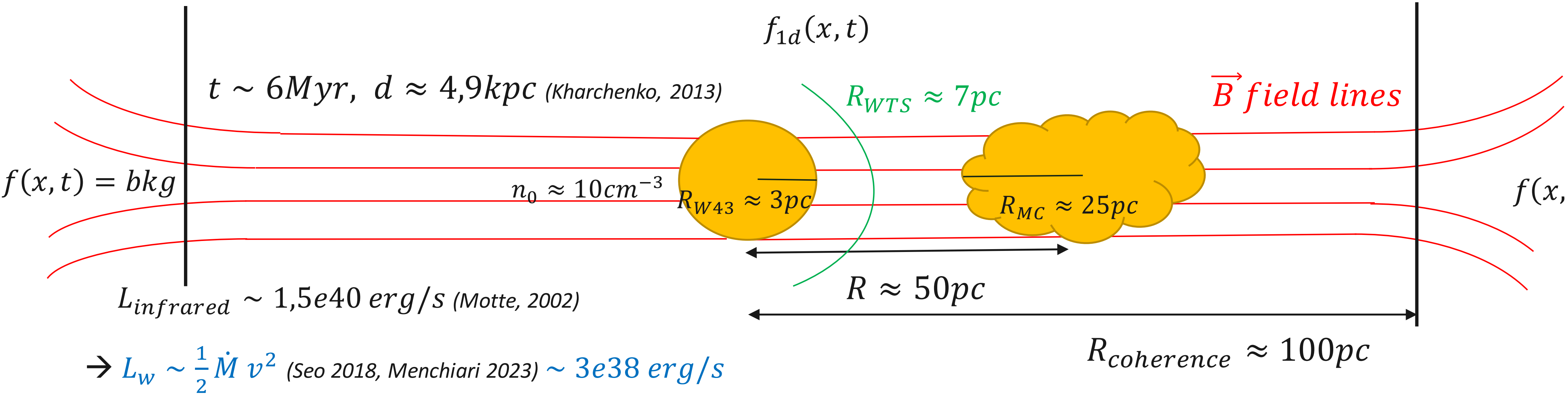
1D LINEAR ANISOTROPIC DIFFUSION MODEL



→ $L_w \sim \frac{1}{2}\dot{M}\,v^2$ (Seo 2018, Menchiari 2023) $\sim 3e38\ erg/s$

(We assume there is a small amount of perpendicular diffusion)

1D LINEAR ANISOTROPIC DIFFUSION MODEL



(We assume there is a small amount of perpendicular diffusion)

- $R_{WTS} \sim 35 \left(\frac{\epsilon\, N_*}{100}\right)^{\frac{3}{10}} \left(\frac{n_0}{cm^{-3}}\right)^{-\frac{3}{10}} \left(\frac{u_W}{3000\ km.s^{-1}}\right)^{-\frac{1}{2}} \left(\frac{t}{10Myr}\right)^{\frac{2}{5}} pc$ *(Weaver 1977, see review Gabici, 2023)*

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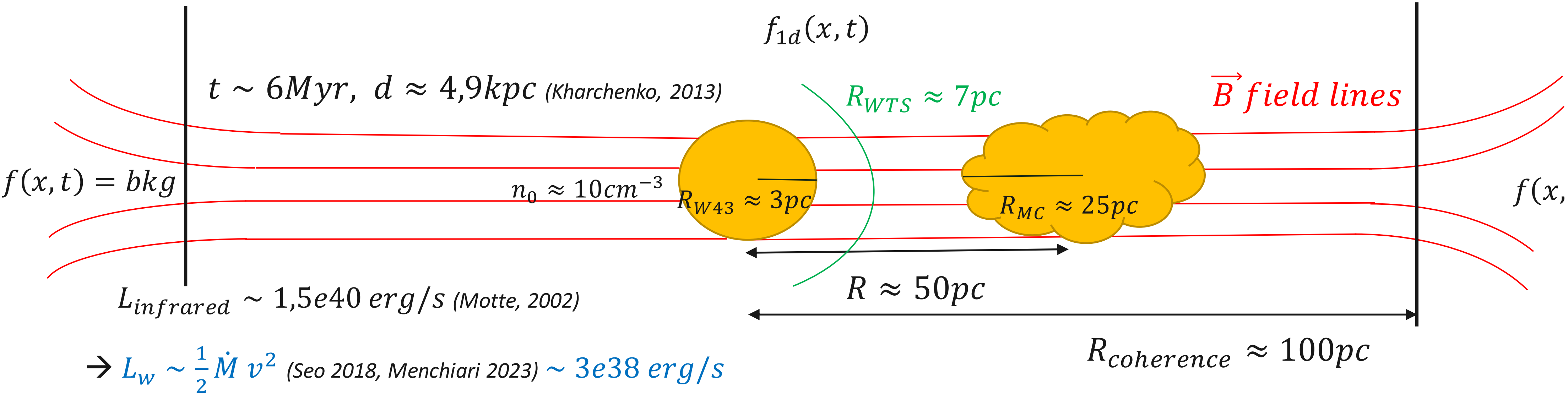

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- Estimation : $\frac{D_a}{D_i} \sim \frac{R\ R_{coherence}}{R_{sh}^2} \sim 100$ (energy dissipated in smaller space) → solves the problem of D_0 suppression

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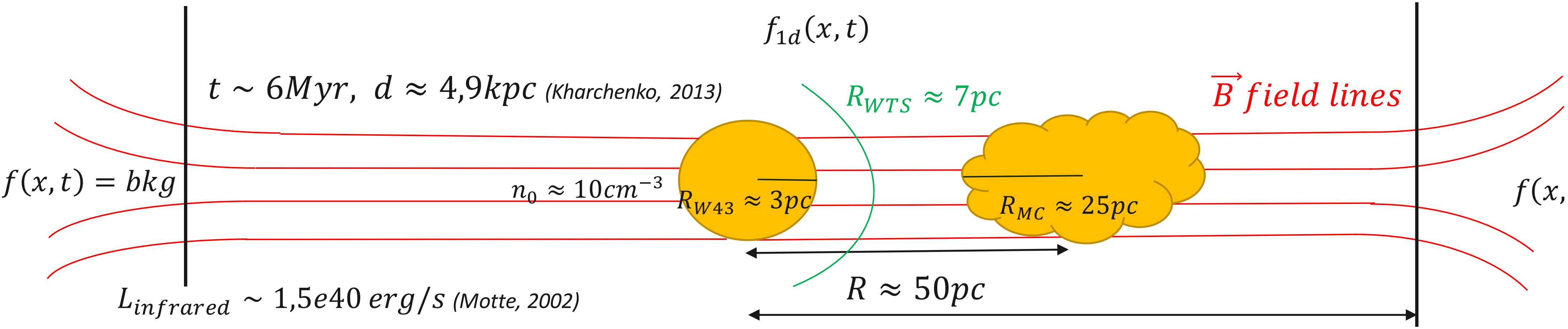

$R_{coherence} \approx 100pc$

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- Analytic solution $f_{1d}(x,t) \sim \frac{R_{coherence} - x}{D_a\, R_{sh}^2} E^{-\alpha}$ → slope $E^{-\alpha-\delta}$ as in 3d but not in 1/R

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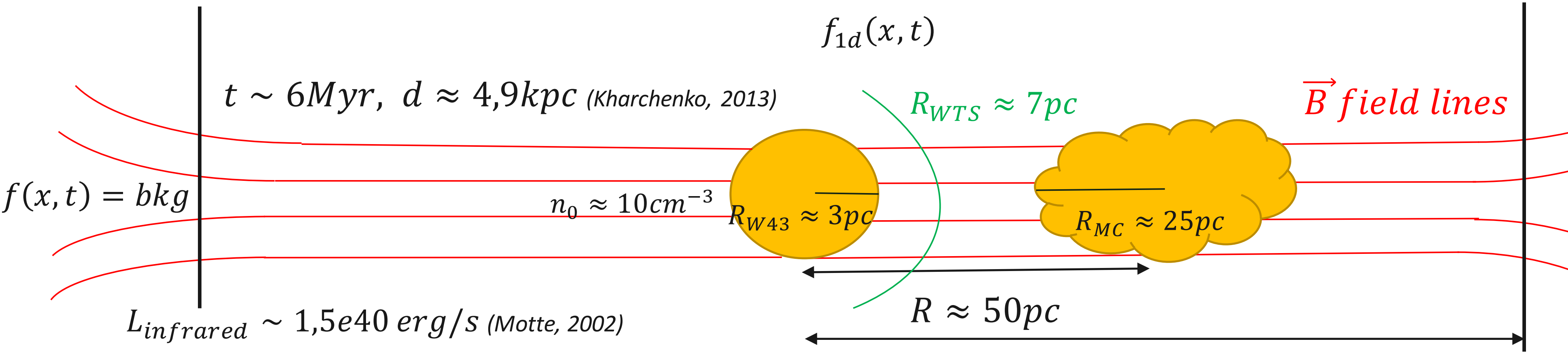

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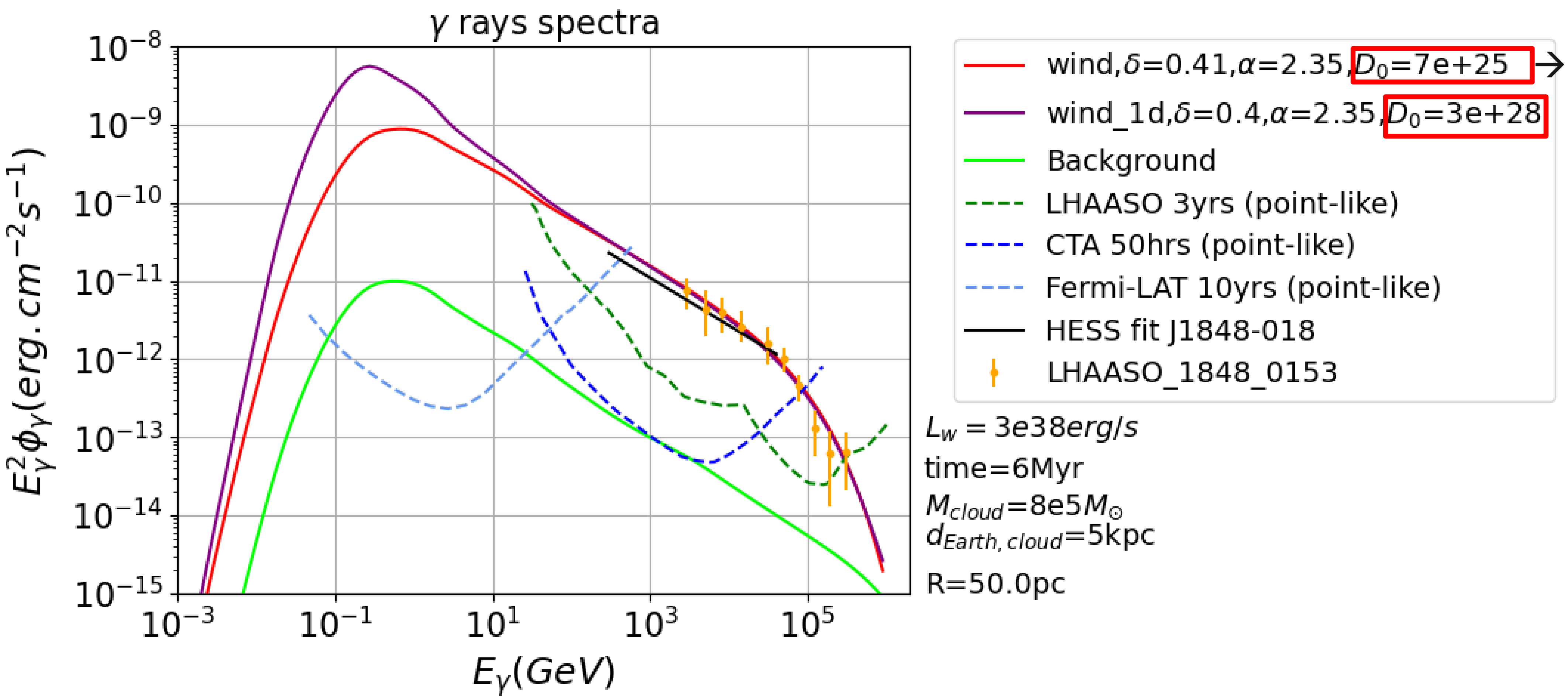
- Other clouds not visible by LHAASO since they are farther, less massive and not in the anisotropy direction

RESULTS



→ Too low

→ $\sim D_{gal}$

$L_w = 3e38 erg/s$
time=6Myr
M_{cloud}=8e5$M_\odot$
$d_{Earth,cloud}$=5kpc
R=50.0pc

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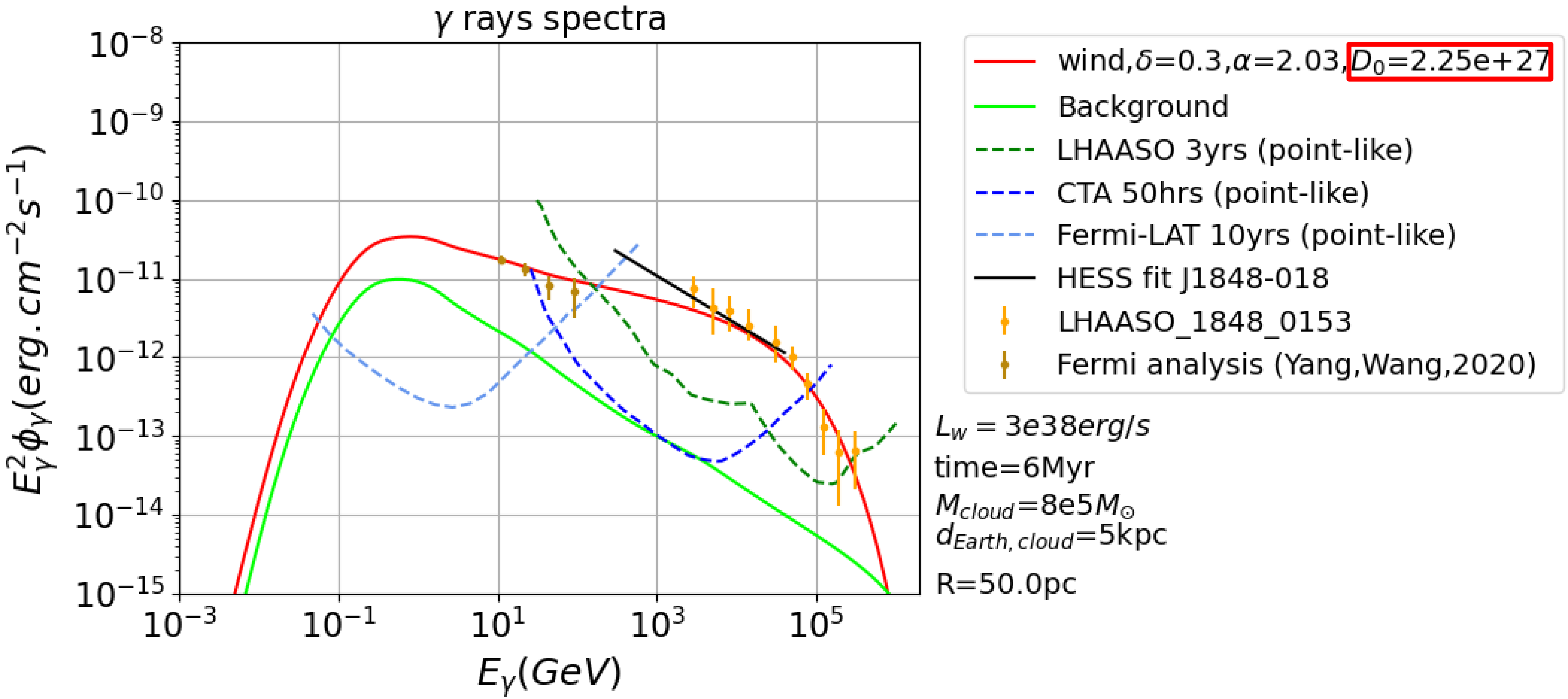

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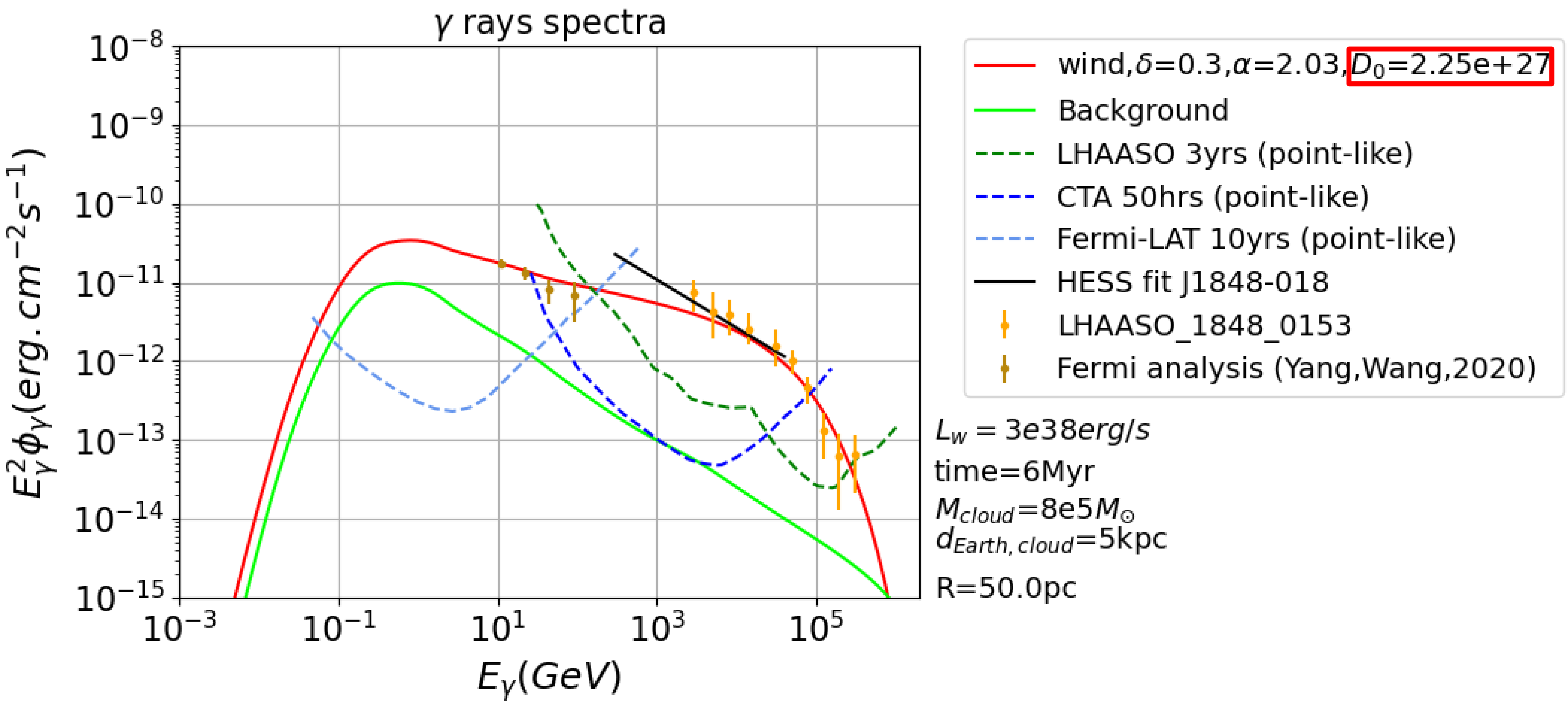

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$E_{cutoff} \sim 0.5 PeV$ → around proton knee (Argo: 0.7 PeV)

$B \sim \frac{\eta_B L_w}{v_W\, R_{WTS}^2} \sim \frac{\eta_B}{0,02}\ \frac{L_w}{3e38\ erg.s^{-1}}\ \frac{3000 km.s^{-1}}{v_w}\ \frac{50pc}{R_{WTS}^2}\ 7\mu G$ → $E_{max,Hillas} \sim 3\cdot 10^{12} \frac{v_w}{1000\ km\ s^{-1}} \frac{B}{\mu G} \frac{2R_{WTS}}{pc} eV \sim 0.9\ PeV$

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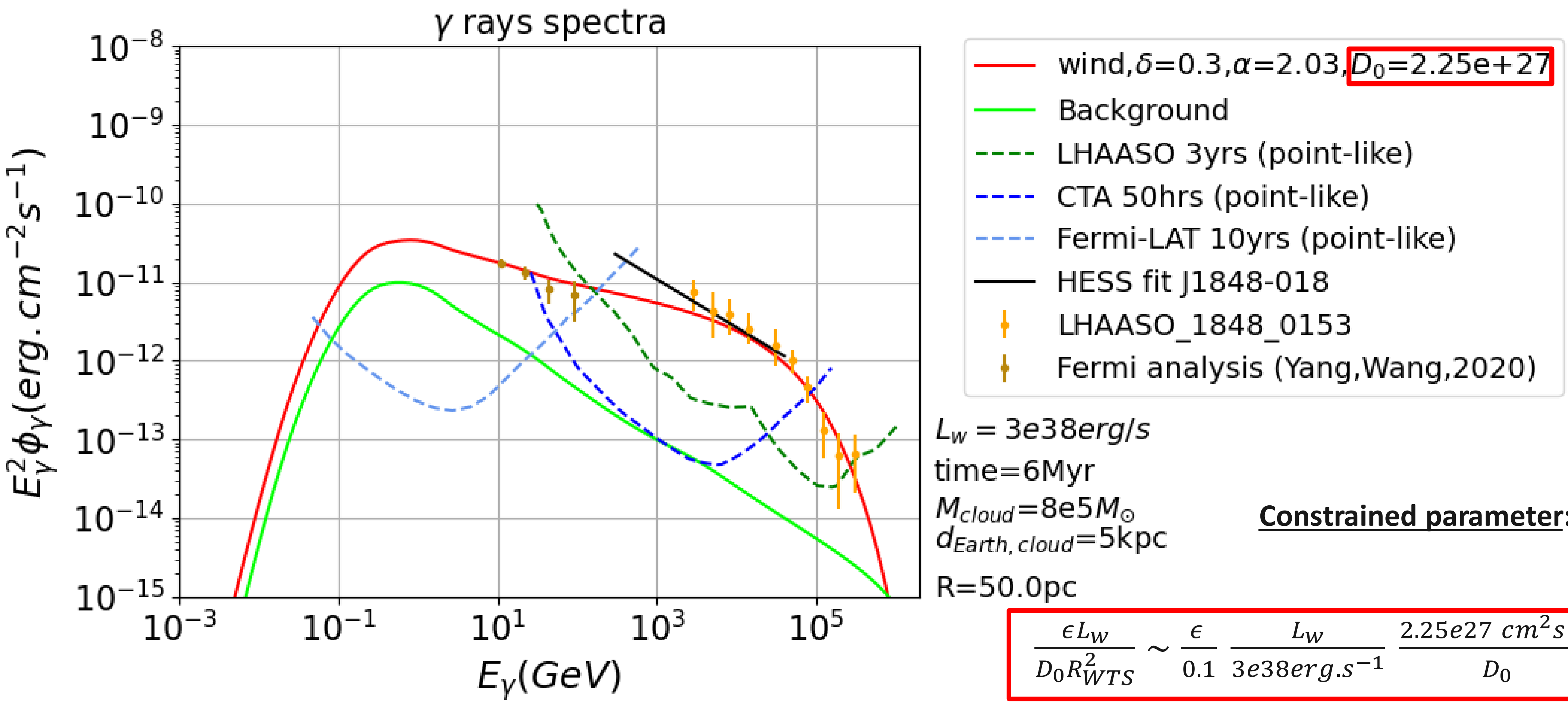

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Constrained parameter:

$$\frac{\epsilon L_w}{D_0 R_{WTS}^2} \sim \frac{\epsilon}{0.1}\frac{L_w}{3e38 erg.s^{-1}}\frac{2.25e27\ cm^2 s^{-1}}{D_0}\frac{49\ pc^2}{R_{WTS}^2}\ 2.7e8\ erg.cm^4$$

→ Gives $\frac{\epsilon}{D_0}$

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CONCLUSION AND PROSPECTS

Theoretical side :

- 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 (LHAASO) sensitivity → for plausible parameters, R must be $\lesssim$ 500 pc
- Needs either D_0 suppression or 1D diffusion
- Can do it for other energies → whole spectra

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Application : W43

- Observed UHE gamma-ray flux by LHAASO , no SNRs nor pulsars nearby yet
- W43: Powerful young cluster ($t = 6Myr, L \sim 3e38erg/s$) + Very massive cloud (M= $8e5M_\odot$)
- Good fit of the datapoints with this system and 3D diffusion
- Inferred parameters are consistent and constrained (slope, D0, cutoff). Main constrained quantity : $\epsilon \frac{1\,e\,28\,cm^2 s^{-1}}{D_0} \sim \frac{1}{2.25}$
- Can indicate a stellar wind contribution for PeVatrons !

Perspectives : More sophisticated models, Apply to other such systems and dark PeVatrons

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- W43: Powerful young cluster ($t = 6Myr, L \sim 3e38erg/s$) + Very massive cloud (M= $8e5M_{\odot}$)
- Good fit of the datapoints with this system and 3D diffusion
- Inferred parameters are consistent and constrained (slope, D0, cutoff). Main constrained quantity : $\epsilon \frac{1\,e\,28\,cm^2s^{-1}}{D_0} \sim \frac{1}{2.25}$
- Can indicate a stellar wind contribution for PeVatrons !

Perspectives : More sophisticated models, Apply to other such systems and dark PeVatrons

(See paper in preparation for more details)

Thank you for your attention !