CTA OZ CONSORTIUM 2017

Modeling of TeV emission from propagating CRs and electrons

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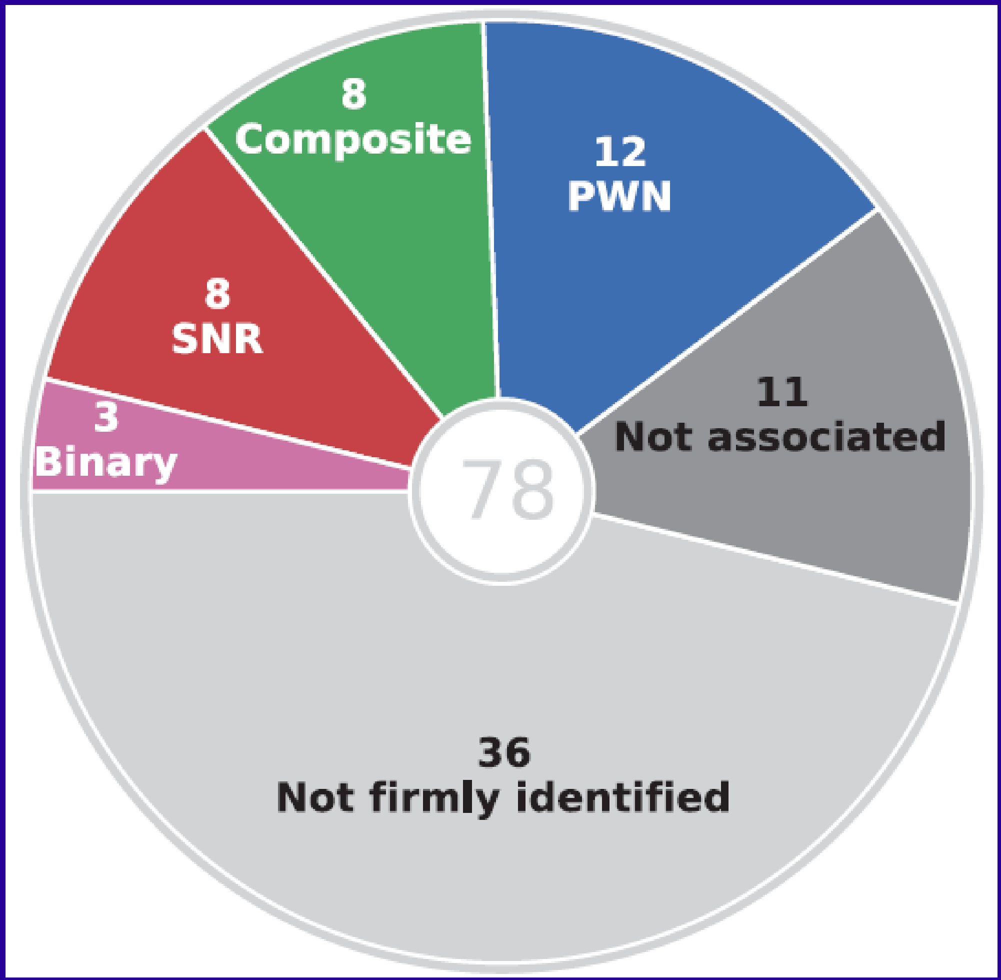
UNIDENTIFIED TeV SOURCE (1)

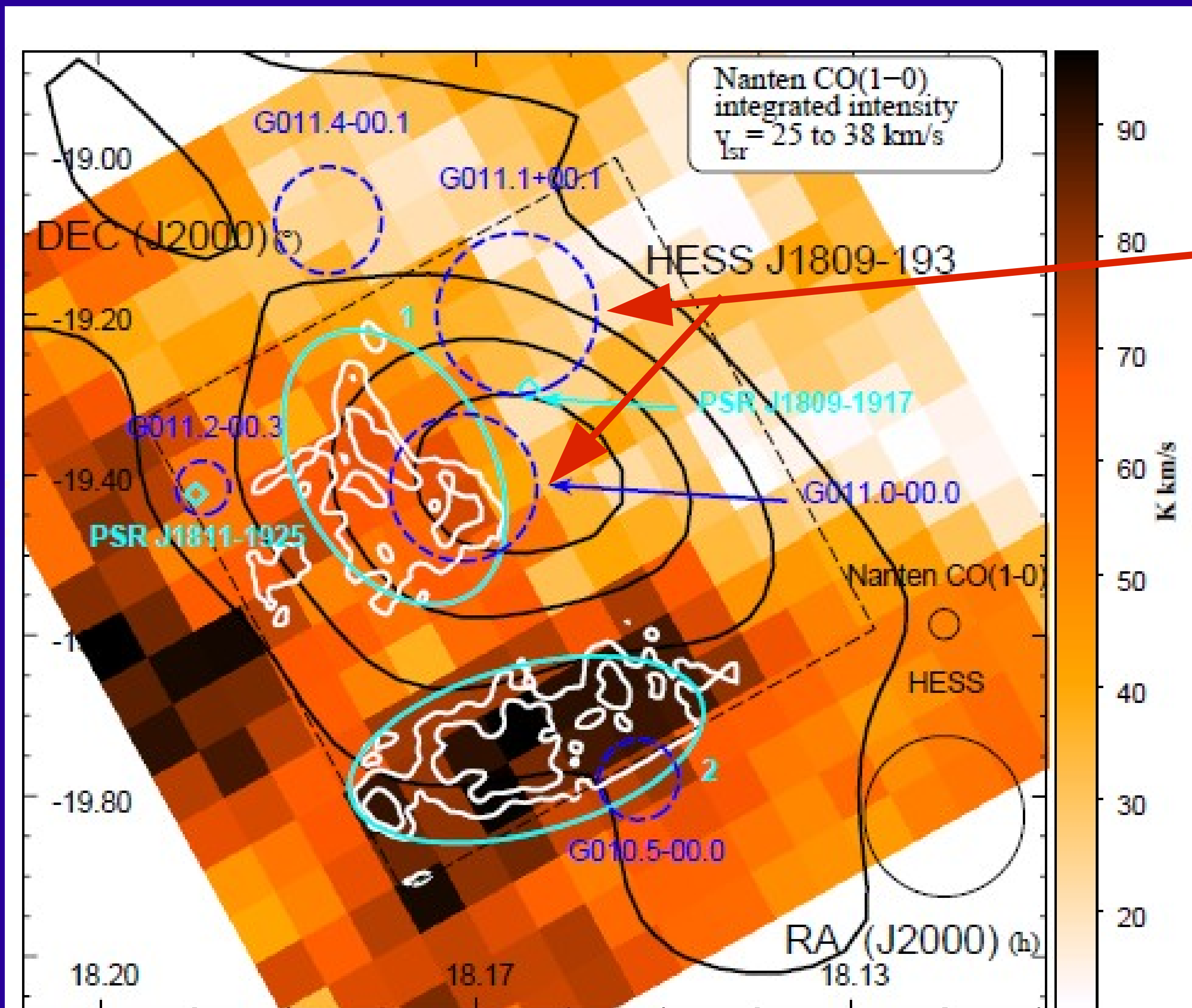


Number of TeV sources detected by HESS
(Donath et al, 2017)

→ **A large number of unidentified TeV sources** :

- Dark sources
(e.g HESS J1616-518, see James talk)
- TeV sources with multiple accelerators possibly contributing to the TeV source

UNIDENTIFIED TeV SOURCE (2) HESS J1809-193

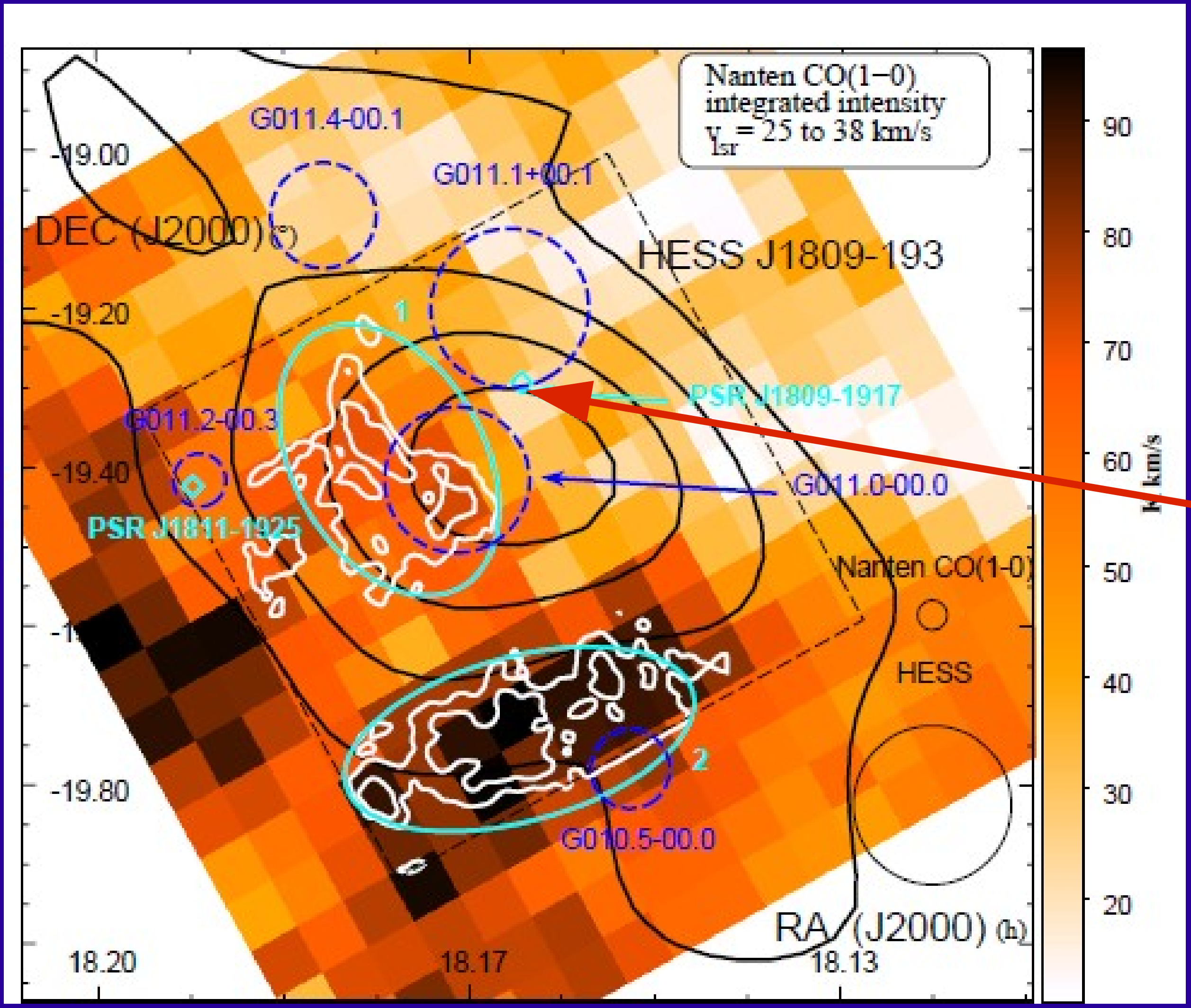


Overlapping accelerators :

→ 2 SNRs **G011.0-00.0**
G011.1+00.1

(no info on age or distance)

UNIDENTIFIED TeV SOURCE (2)
HESS J1809-193



Overlapping accelerators :

→ 2 SNRs **G011.0-00.0**
G011.1+00.1
(no info on age or distance)

→ 1 PWNe powered by
PSR J1809-1917 :
$\dot{E}_{SD}$ = 1.8x10^{36} erg/s
d = 3.7 kpc
τ = 51 kyr

(see James 's talk for more detail)

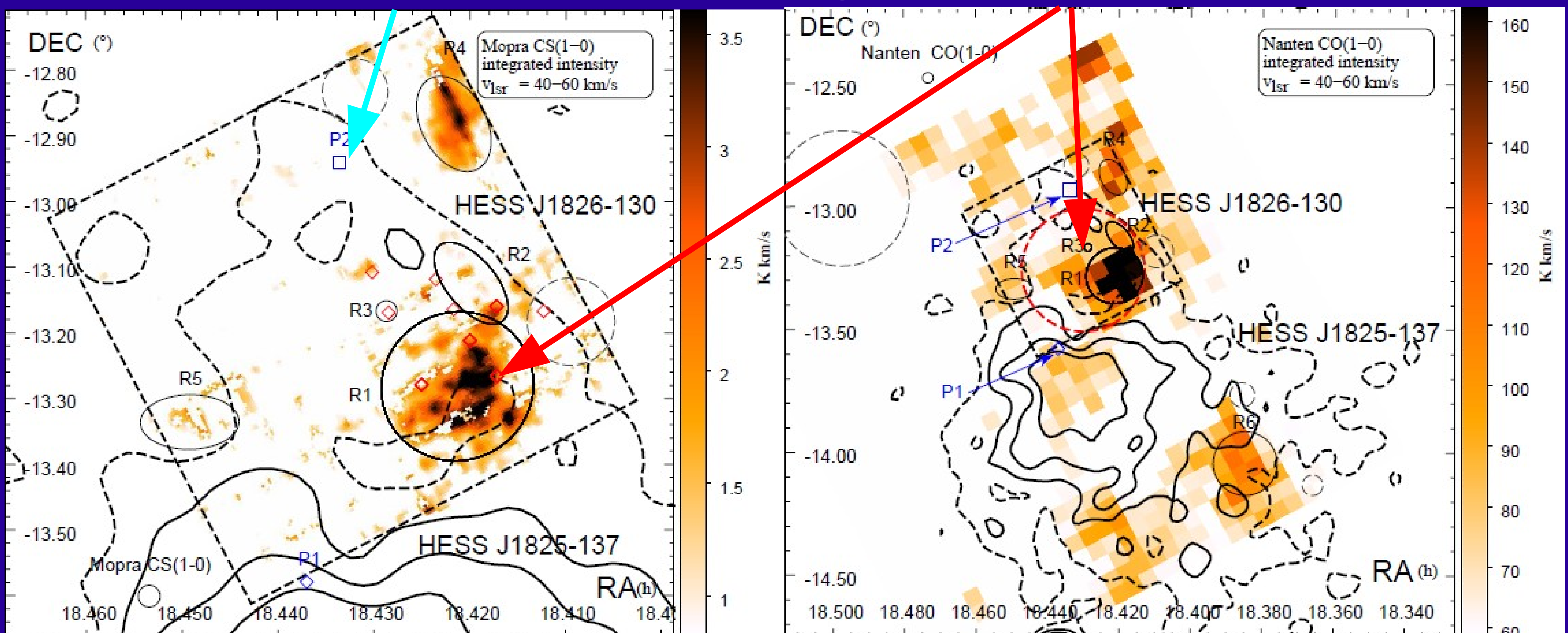
=> NEED TO STUDY THE CONTRIBUTION OF EACH ACCELERATOR

UNIDENTIFIED TeV SOURCE (3)
HESS J1826-130

(See Voisin et al, 2016,
Anguner et al, 2017
And references therein)

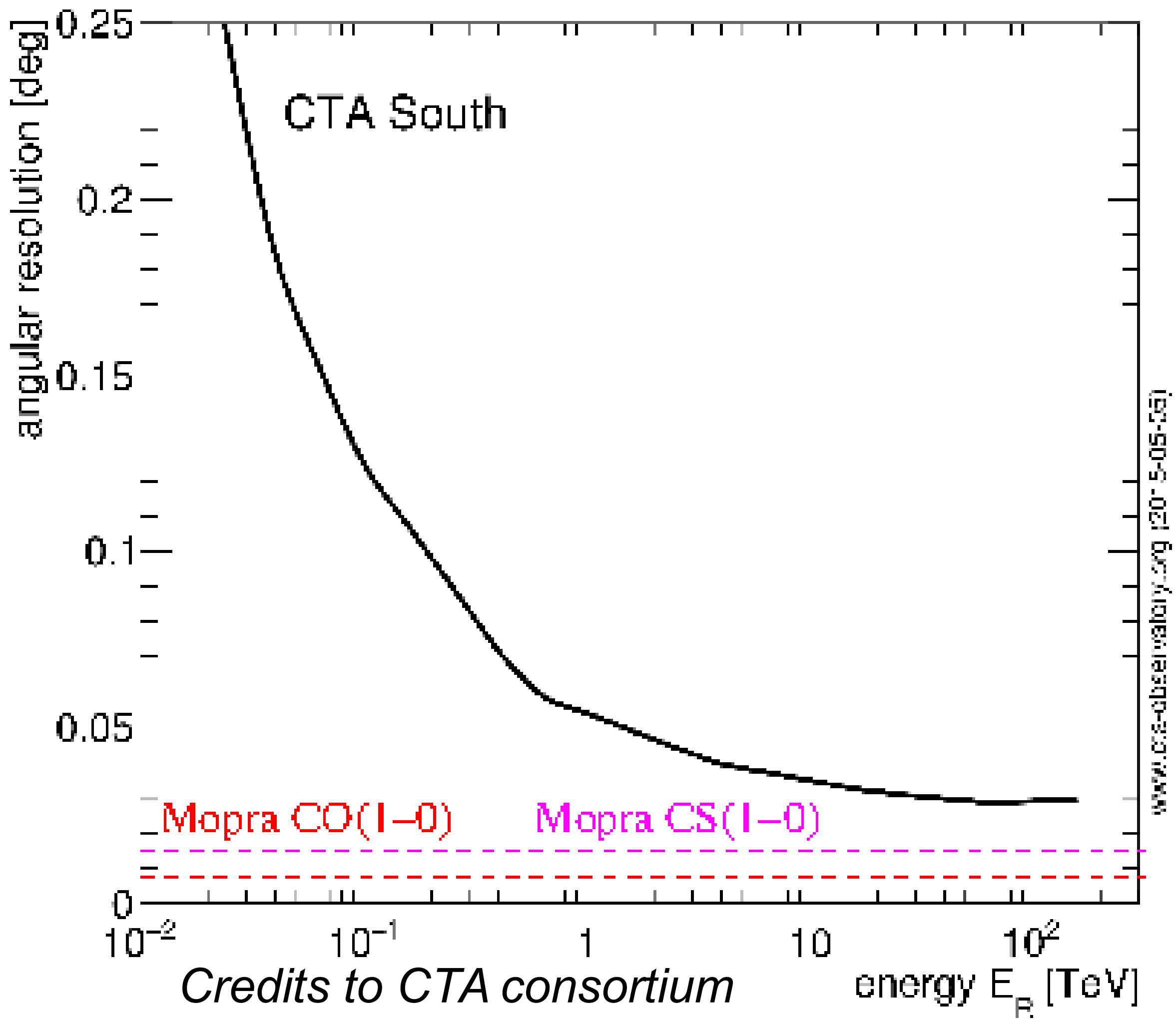
PWN G18.4-0.5 powered by radio quiet gamma-ray pulsar **PSR J1826-1256 (P2)**
=> Leptonic γ-rays from IC radiation **?**

Overlapping **dense molecular clouds** associated with HESS J1825-137 at d~4 kpc
=> **Hadronic γ-rays** from CRs escaping progenitor SNR of HESS J1825-137 ?



=> CONFUSION IN DETERMINING THE CONTRIBUTION FROM EACH HIGH ENERGY SOURCE

CTA PERFORMANCE



Credits to CTA consortium

→ A factor of **10** better sensitivity compared to HESS

CTA beam size at 10 TeV :

→ θ_{68}[10 TeV]~0.035°

Comparable with Mopra data :

θ_{68}[CS(1-0)]~0.016°

θ_{68}[CO(1-0)]~0.008°

=> Study the influence of the structure of molecular clouds on the morphology of the TeV emission

MOTIVATION

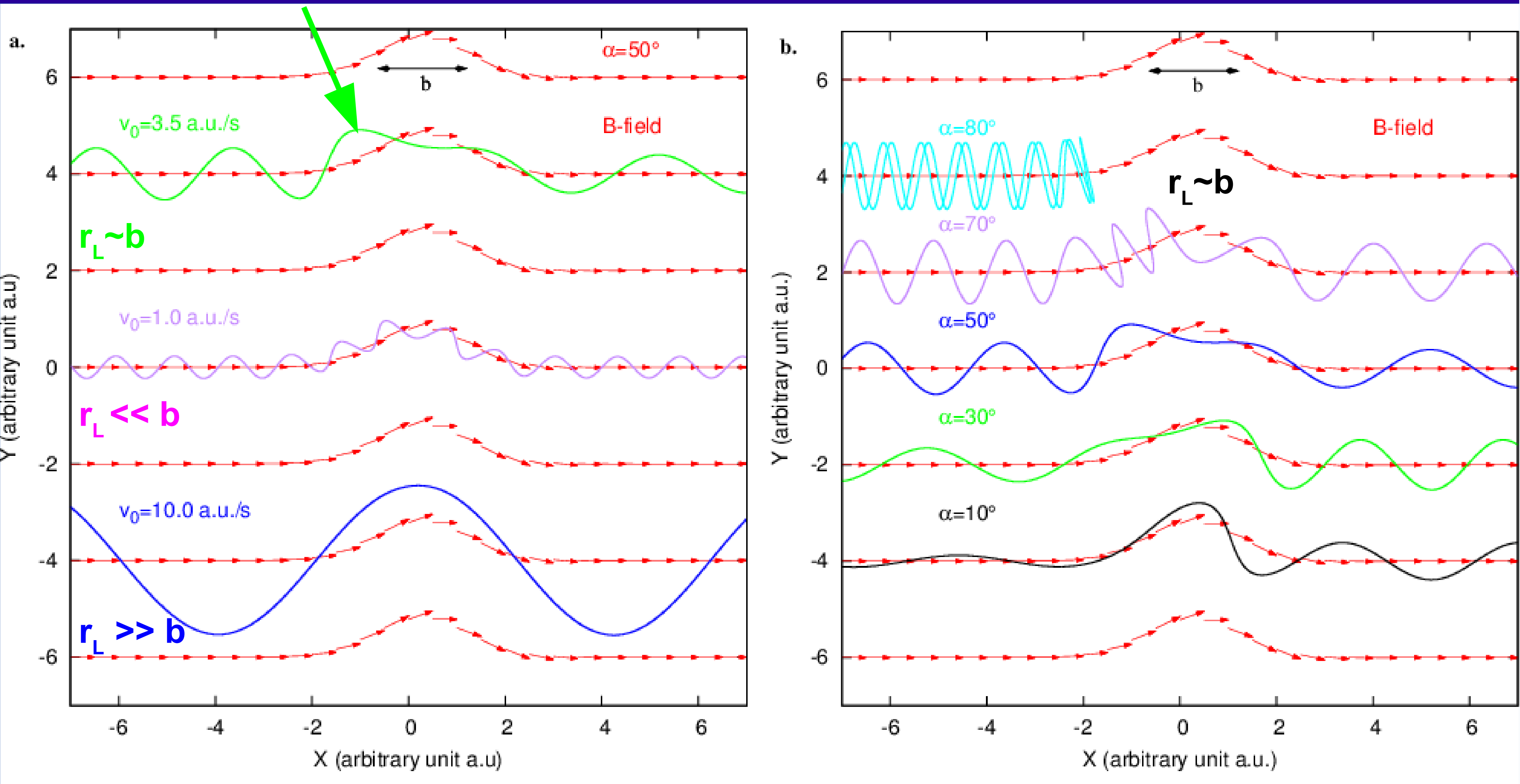
- Study the effects of molecular clouds on the propagation of CRs and high energy electrons escaping impulsive/continuous energy sources.
- Predict key spectral and morphological features in the hadronic/leptonic TeV gamma-ray emission that could be detected by CTA.
- Identify high energy sources that could be detected by CTA
- Disentangle TeV sources with multiple associations (e.g HESS J1809-193)

CR Diffusion physics (1)

$r_L = \gamma mc^2/(ZeBc) \rightarrow$ Larmor radius

Efficient scattering of the particle trajectory only if **$r_L \sim b$**

$\delta B_y \ll B_0$ with scale b



CR Diffusion physics (1)

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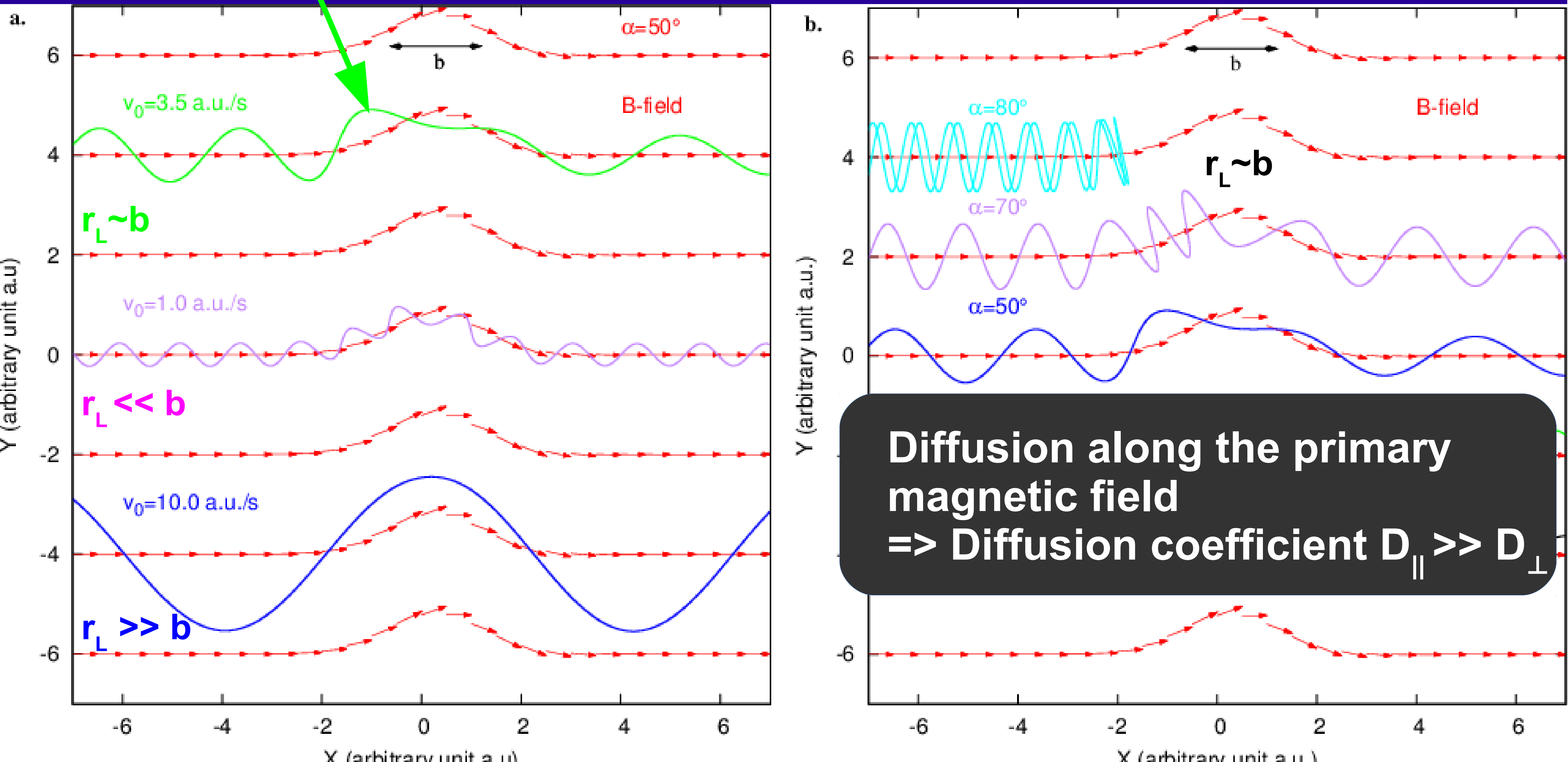
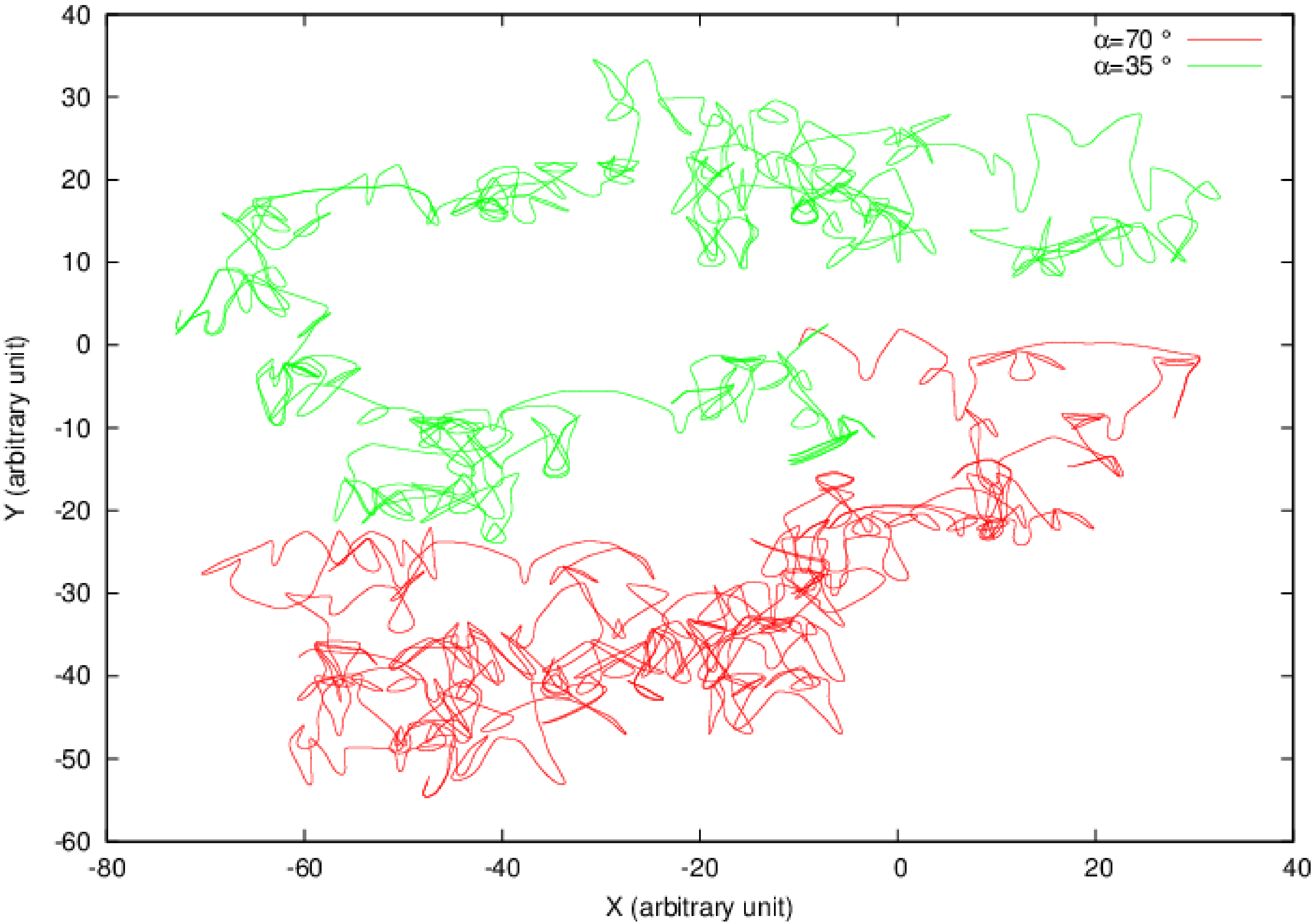


Diffusion along the primary magnetic field
=> Diffusion coefficient $D_{||} \gg D_{\perp}$

CR Diffusion physics (2)

In the case where $\delta B \sim B$ => ISOTROPIC DIFFUSION OF CRs



→ Random walk propagation

→ $D_{xx} \sim D_{yy} \sim D_{zz}$

CR Diffusion physics (3)

=> Diffusion of CRs dependent on the magnetic turbulence

- **Shocks (e.g SNRs) can produce these turbulence**

- **Turbulence caused by precursors CRs (Skilling et al,1975)**

Magnetic turbulence can be described as a combination of wave functions with wavenumber k=2π/b $\delta\mathbf{B}(k) \propto \exp(i\mathbf{k}.\mathbf{x})$

Power-law turbulence distribution $I(k) \propto k^{-s}$

- **s=5/3 (Kolmogorov spectrum) → $D(\gamma) \propto \gamma^{1/3}$**

- **s=3/2 (Kraichnan spectrum) → $D(\gamma) \propto \gamma^{1/2}$**

- **Bohm diffusion → $D(\gamma) \propto \gamma$**

CR Diffusion physics (4) : Transport equation

$n = n(\gamma, r, t) = dn/d\gamma \rightarrow$ energy density distribution of CRs/high energy electrons

General equation :

$$\frac{\partial n}{\partial t} = -\nabla\left(n\mathbf{v}_{\mathrm{A}}\right) - \nabla\left(\overline{\overline{D}}.\nabla n\right) + \frac{\partial}{\partial\gamma}\left(\dot{\gamma}n - \frac{\gamma}{3}\left(\nabla\cdot\mathbf{v}_{\mathrm{A}}\right)\right) + \frac{\partial}{\partial\gamma}\left(\gamma^2 D_{\gamma\gamma}\frac{\partial}{\partial\gamma}\left(\frac{n}{\gamma^2}\right)\right) + S\left(\gamma, \mathbf{r}, t\right)$$

$\overline{\overline{D}} \equiv \overline{\overline{D}}(x,y,z,\gamma) \rightarrow$ Diffusion coefficient tensor

$\dot{\gamma}(\gamma) \rightarrow$ Energy loss rate of a CR/high energy electron with Lorentz factor γ (Synchrotron , IC, Bremsstrahlung, p-p interaction)

$v_A \rightarrow$ Advection speed (e.g jets)

$D_{\gamma\gamma} \rightarrow$ Diffusion in energy space (e.g 2nd order reacceleration)

CR Diffusion physics (4) : Transport equation

n=n(γ,r,t)=dn/dγ → energy density distribution of CRs/high energy electrons

General equation :

$$\frac{\partial n}{\partial t} = -\nabla\left(n\mathbf{v}_\mathrm{A}\right) - \nabla\left(\overline{\overline{D}}.\nabla n\right) + \frac{\partial}{\partial\gamma}\left(\dot{\gamma}n - \frac{\gamma}{3}\left(\nabla\cdot\mathbf{v}_\mathrm{A}\right)\right) + \frac{\partial}{\partial\gamma}\left(\gamma^2 D_{\gamma\gamma}\frac{\partial}{\partial\gamma}\left(\frac{n}{\gamma^2}\right)\right) + S\left(\gamma,\mathbf{r},t\right)$$

→ In our code, advection term, adiabatic losses and 2nd order reacceleration of CRs/high energy electrons are NEGLECTED

→ We also assume the diffusion to be isotropic $\overline{\overline{D}}(x,y,z,\gamma)=D(x,y,z,\gamma)$

→ In my numerical code I therefore solve :

$$\frac{\partial n}{\partial t} = -\nabla\left(D\left(\mathbf{r},\gamma\right).\nabla n\right) + \frac{\partial}{\partial\gamma}\left(\dot{\gamma}n\right) + S\left(\gamma,\mathbf{r},t\right)$$

MODELING THE GAMMA-RAY EMISSION

DISCLAIMER

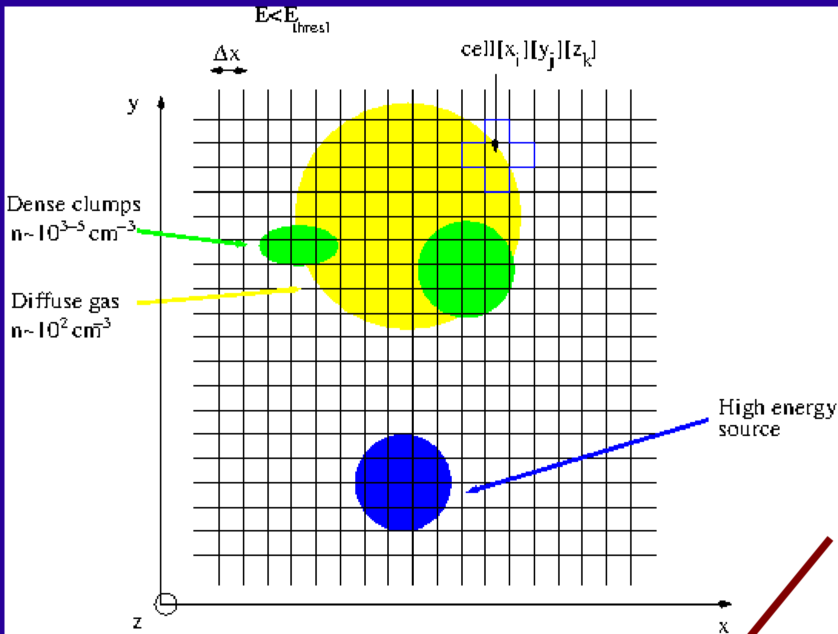
NUMERICAL CODES COMPUTING THE GAMMA–RAY EMISSION FROM THE PROPAGATION OF CRs IN OUR GALAXY ALREADY EXIST !

- **GALPROP** (see Troy's talk) : Model the CR distribution propagating across our Galaxy and the background gamma-ray emission. → Very important for detections of GeV sources with Fermi (*Strong and Moskalenko 1998* for introduction paper)

- **PICARD** (*Kissman et al 2014*)

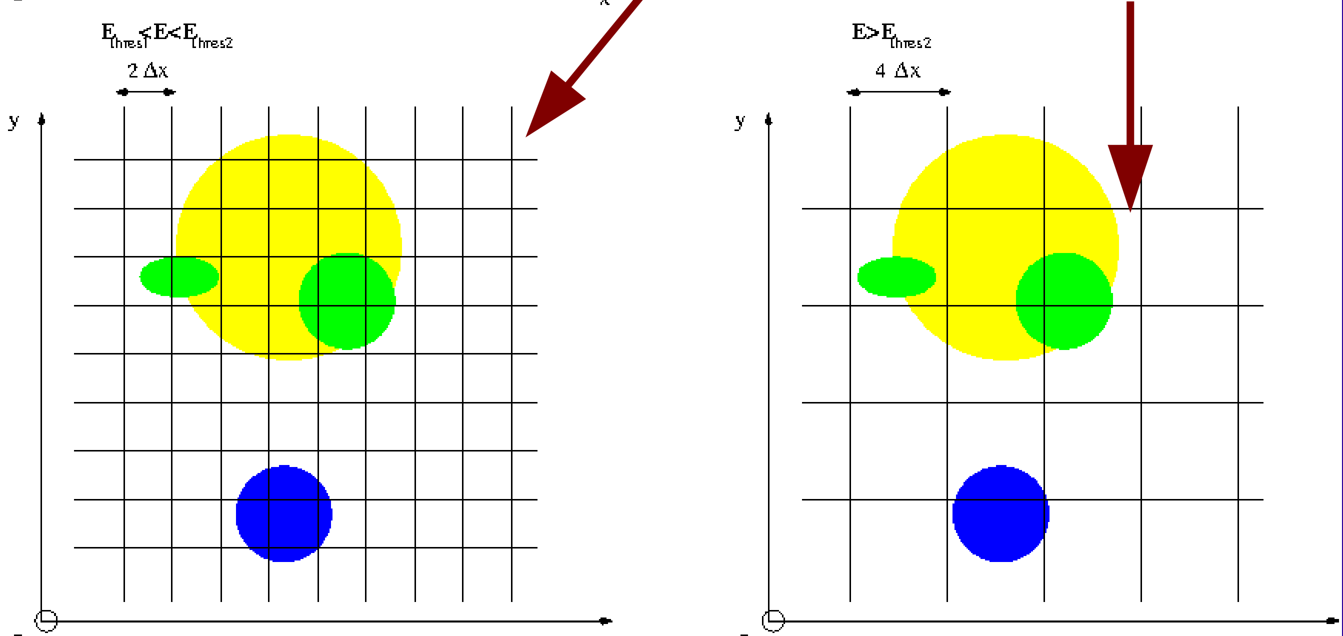
MY MODELING CODE IS AIMING AT STUDYING THE GAMMA-RAY EMISSION ON A MORE LOCAL LEVEL

HOW THE NUMERICAL CODE WORK



120x120x120 cells
At highest resolution

→ Can lower the resolution by 2 and 4 at higher energy to reduce computational time (this feature may disappear in later version...)



1/ Define a template 3D distribution of the **diffuse** and **dense** **molecular gas** in the region based on our **CO(J=1-0)** and **CS(J=1-0)** surveys

2/ Define the property of the **high energy source** :

- **Impulsive**
- **Continuous**

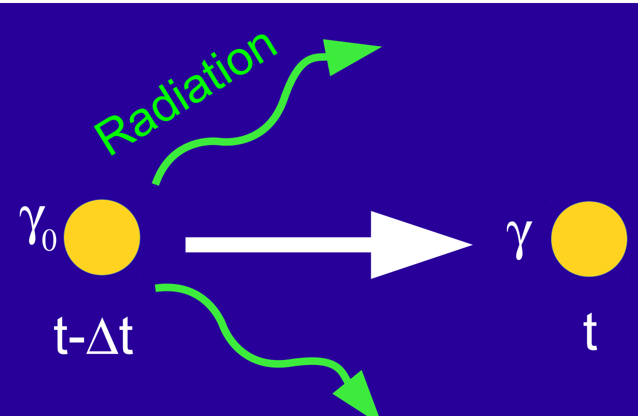
- **Power-law (cutoff)**
- **Broken power-law (cutoff)**

HOW THE NUMERICAL CODE WORK (2)

3/ **For each Δt, solve the discretized equation in each cells:**

$$n\Big|_{\substack{\gamma \\ t \\ x,y,z}} = \sum_{i=x,y,z} \left[\frac{\dot{\gamma}_0}{\dot{\gamma}} D\Big|_{\substack{\gamma_0 \\ t-\Delta t \\ i+\Delta i/2}} \left(n\Big|_{\substack{\gamma_0 \\ t-\Delta t \\ i+\Delta i}} - n\Big|_{\substack{\gamma_0 \\ t-\Delta t \\ i}} \right) + \frac{\dot{\gamma}'_0}{\dot{\gamma}} D\Big|_{\substack{\gamma'_0 \\ t-\Delta t \\ i-\Delta i/2}} \left(n\Big|_{\substack{\gamma'_0 \\ t-\Delta t \\ i-\Delta i}} - n\Big|_{\substack{\gamma'_0 \\ t-\Delta t \\ i}} \right) \right]$$

$\gamma_0, \dot{\gamma}_0 \rightarrow$ Lorentz factor and cooling rate at time t-Δt



$\gamma, \dot{\gamma} \rightarrow$ Lorentz factor and cooling rate at time t

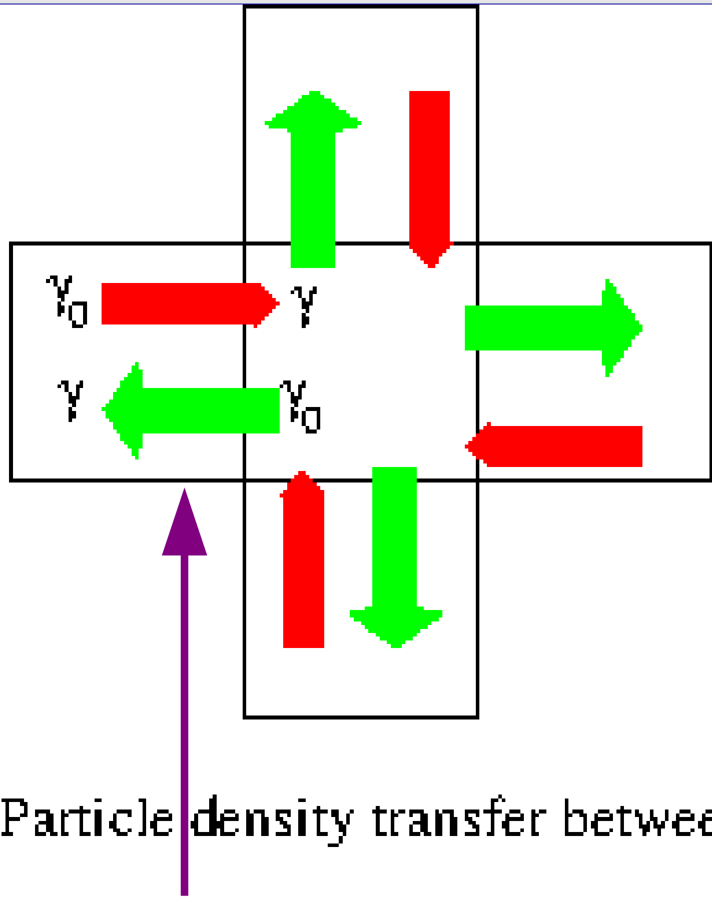
HOW THE NUMERICAL CODE WORK (3)

3/ **For each Δt, solve the discretized equation in each cells:**

$$n\Big|_{x,y,z}^{\gamma,\,t} = \sum_{i=x,y,z} \left[\frac{\dot{\gamma}_0}{\dot{\gamma}} D\Big|_{i+\Delta i/2}^{\gamma_0,\,t-\Delta t} \left(n\Big|_{i+\Delta i}^{\gamma_0,\,t-\Delta t} - n\Big|_{i}^{\gamma_0,\,t-\Delta t} \right) + \frac{\dot{\gamma}_0'}{\dot{\gamma}} D\Big|_{i-\Delta i/2}^{\gamma_0',\,t-\Delta t} \left(n\Big|_{i-\Delta i}^{\gamma_0',\,t-\Delta t} - n\Big|_{i}^{\gamma_0',\,t-\Delta t} \right) \right]$$

D≡(Δt/Δx²)D(γ) → UNITLESS DIFFUSION COEFFICIENT
→ Fraction of the density transferred from one cell to another

HOW THE NUMERICAL CODE WORK (3)



<u>Assumed Diffusion coefficient</u> *Gabici et al (2006)*

$D(\gamma)=3\times10^{27}\,\chi(\gamma mc^2/1\ \mathrm{GeV})^{1/2}\,(B/3\ \mu\mathrm{G})^{-1/2}$

$\chi \equiv$ suppression factor ~0.01-0.1

see Protheroe et al (2008), Gabici et al (2010)

<u>*Crutcher (2010)* relation B vs n_H in dense clouds</u>

$$B = \begin{cases} 10\left(\dfrac{n_\mathrm{H}}{300\ \mathrm{cm}^{-3}}\right)^{0.65} \mu\mathrm{G} & \text{for } n_\mathrm{H} \geq 300\ \mathrm{cm}^{-3} \\ 10\mu\mathrm{G} & \text{for } n_\mathrm{H} < 300\ \mathrm{cm}^{-3} \end{cases}$$

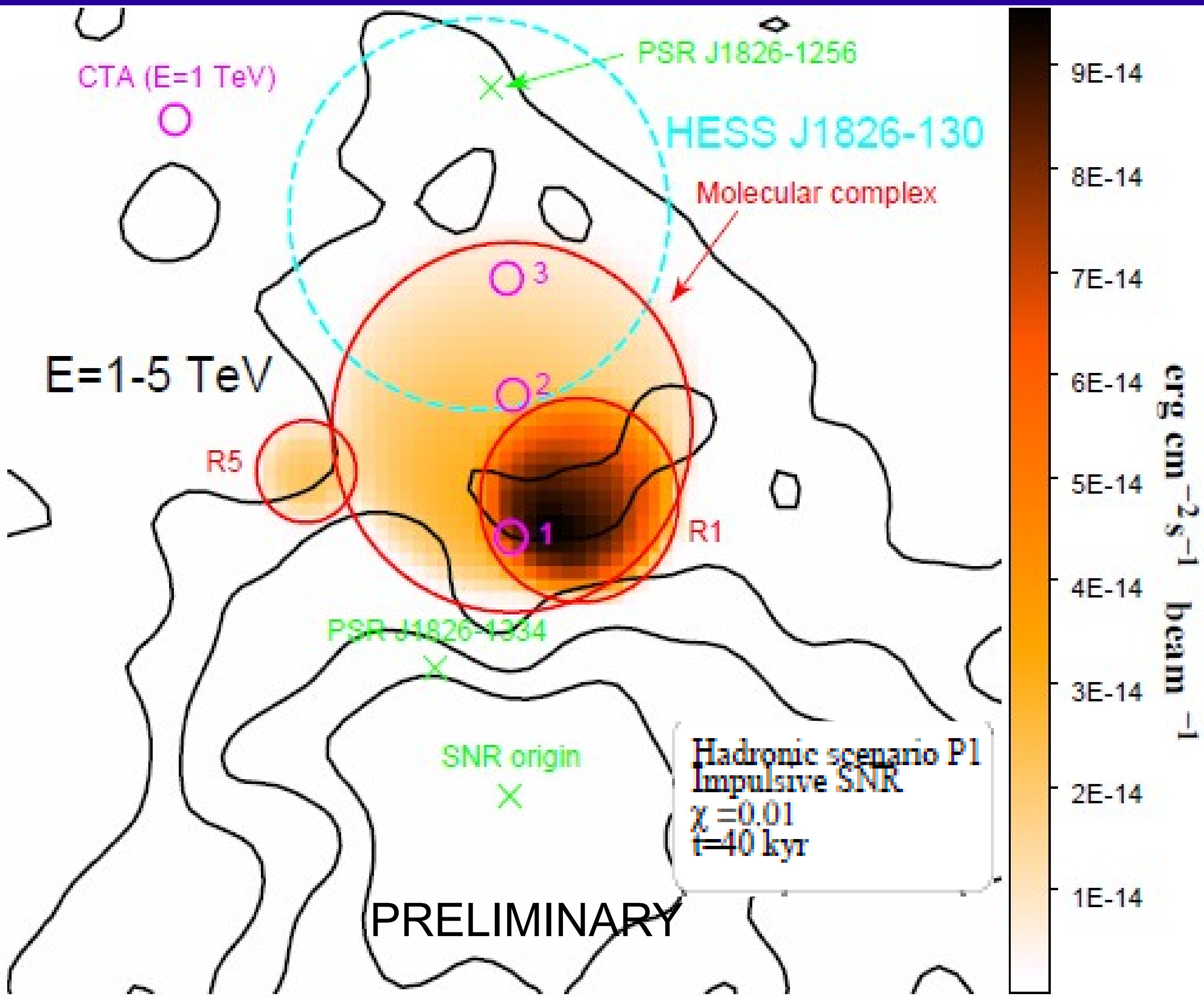
Particle density transfer between cells (left and central grid) :

$$n(\mathrm{cell}[x_i][y_j][z_k], \gamma_0)\,\frac{\dot{\gamma}_0}{\dot{\gamma}}\,\frac{D(\mathrm{cell}[x_i][y_j][z_k]) + D(\mathrm{cell}[x_{i-1}][y_j][z_k])}{2}\,\frac{\Delta t}{\Delta x^2}$$

$$n(\mathrm{cell}[x_{i-1}][y_j][z_k], \gamma_0)\,\frac{\dot{\gamma}_0}{\dot{\gamma}}\,\frac{D(\mathrm{cell}[x_i][y_j][z_k]) + D(\mathrm{cell}[x_{i-1}][y_j][z_k])}{2}\,\frac{\Delta t}{\Delta x^2}$$

RESULTS DISPLAY

→ OUTPUTS THE GAMMA–RAY INTENSITY AT EACH POSITION AND EACH ENERGY BIN AS A FITS CUBE



→ Hadronic scenario :
Gamma-rays overlapping with
The molecular clouds at 4 kpc

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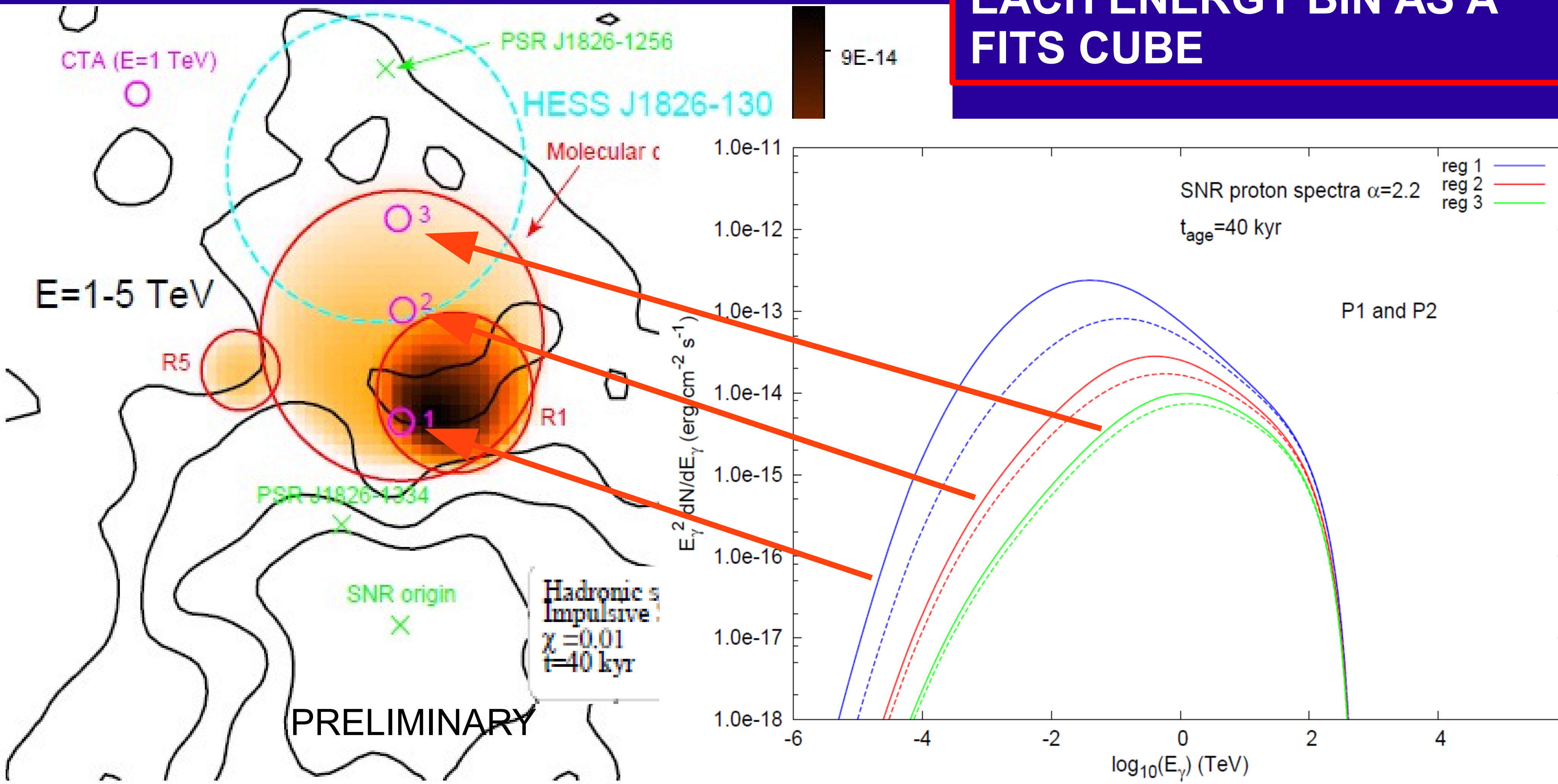

→ Hadronic scenario :
Gamma-rays overlapping with
The molecular clouds at 4 kpc

→ Hardening of the gamma-ray SED expected as we move away from the SNR

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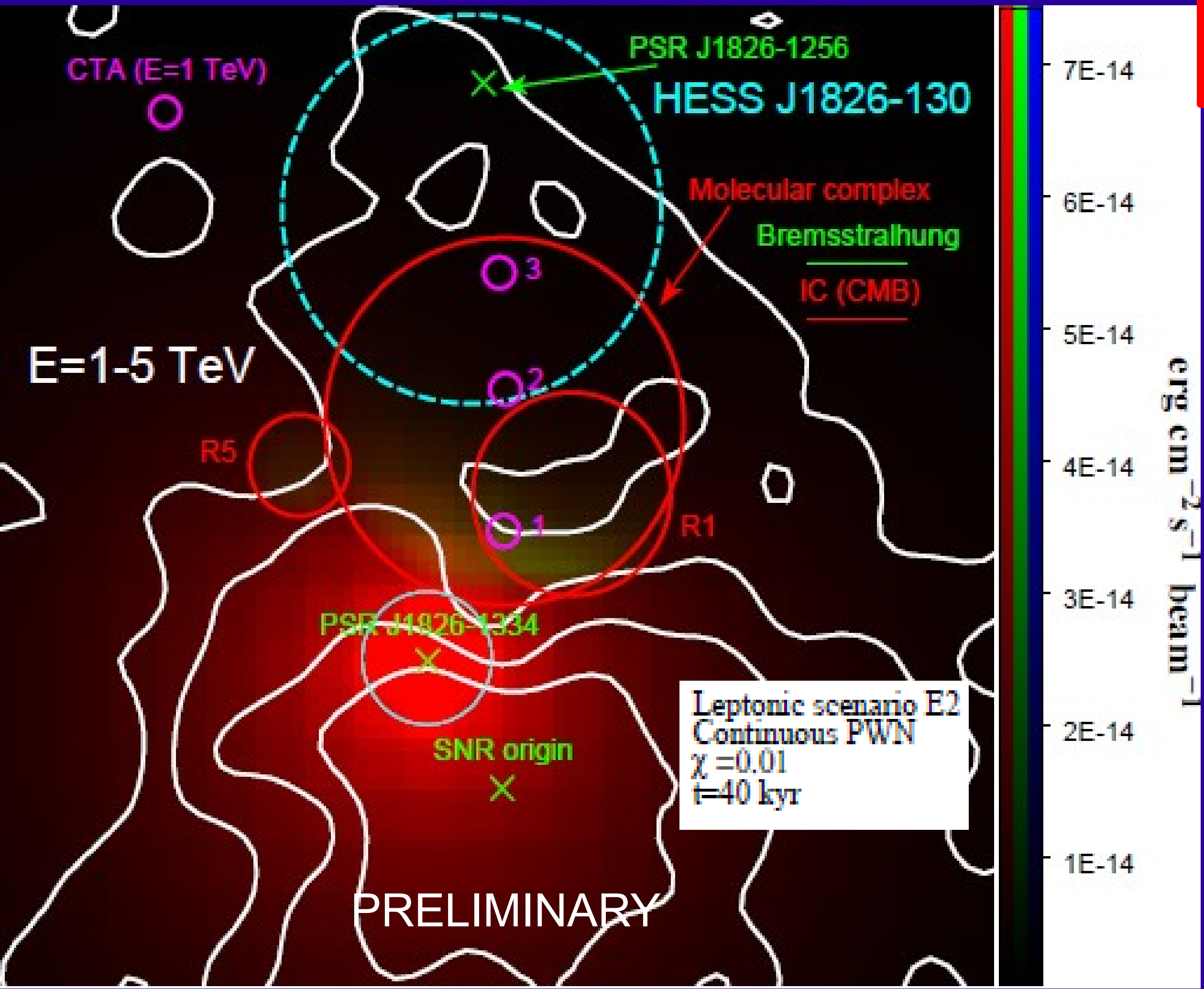

→ Leptonic scenario : TeV gamma-ray emission not overlapping with molecular cloud +Bremsstrahlung may be significant

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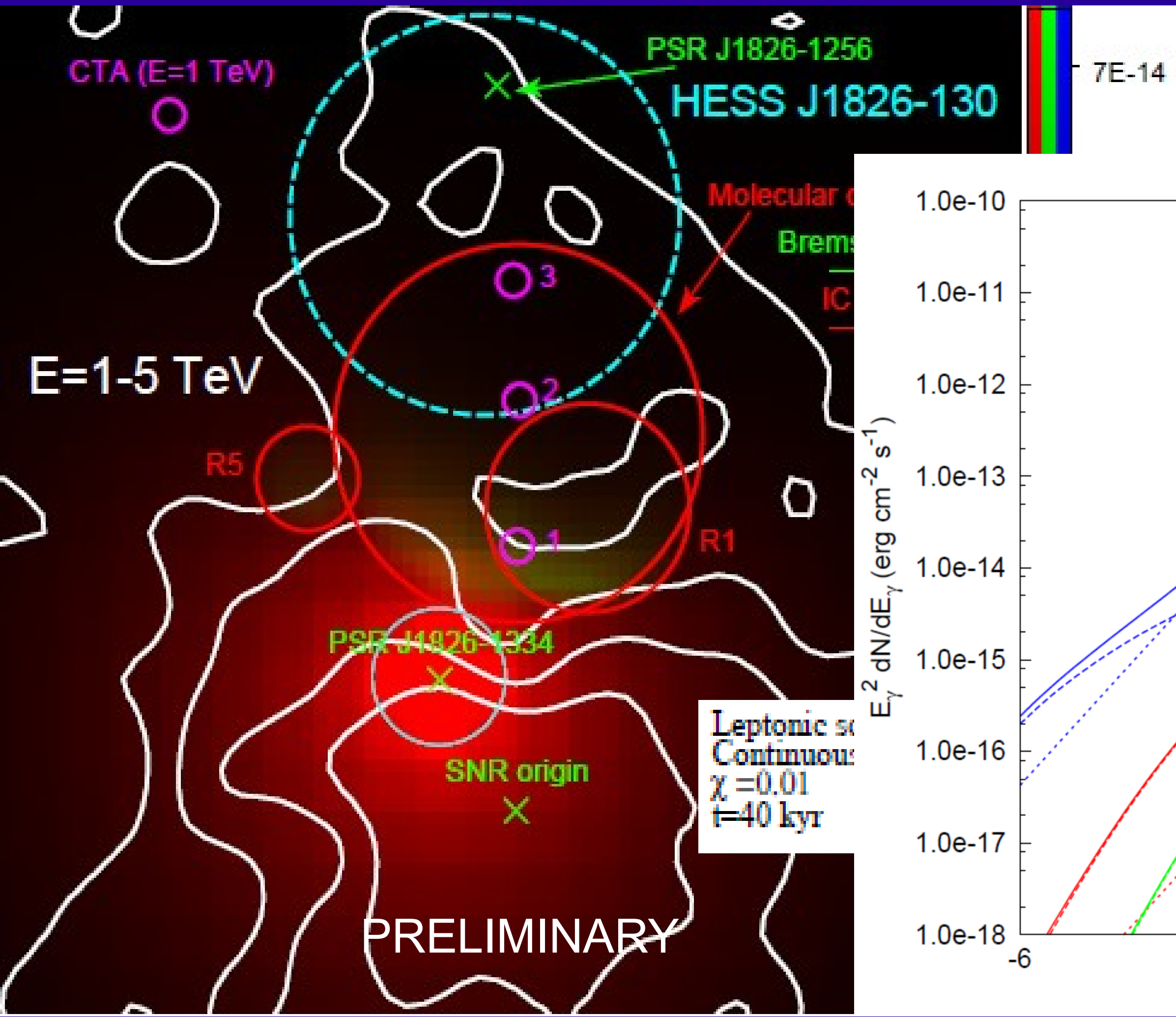
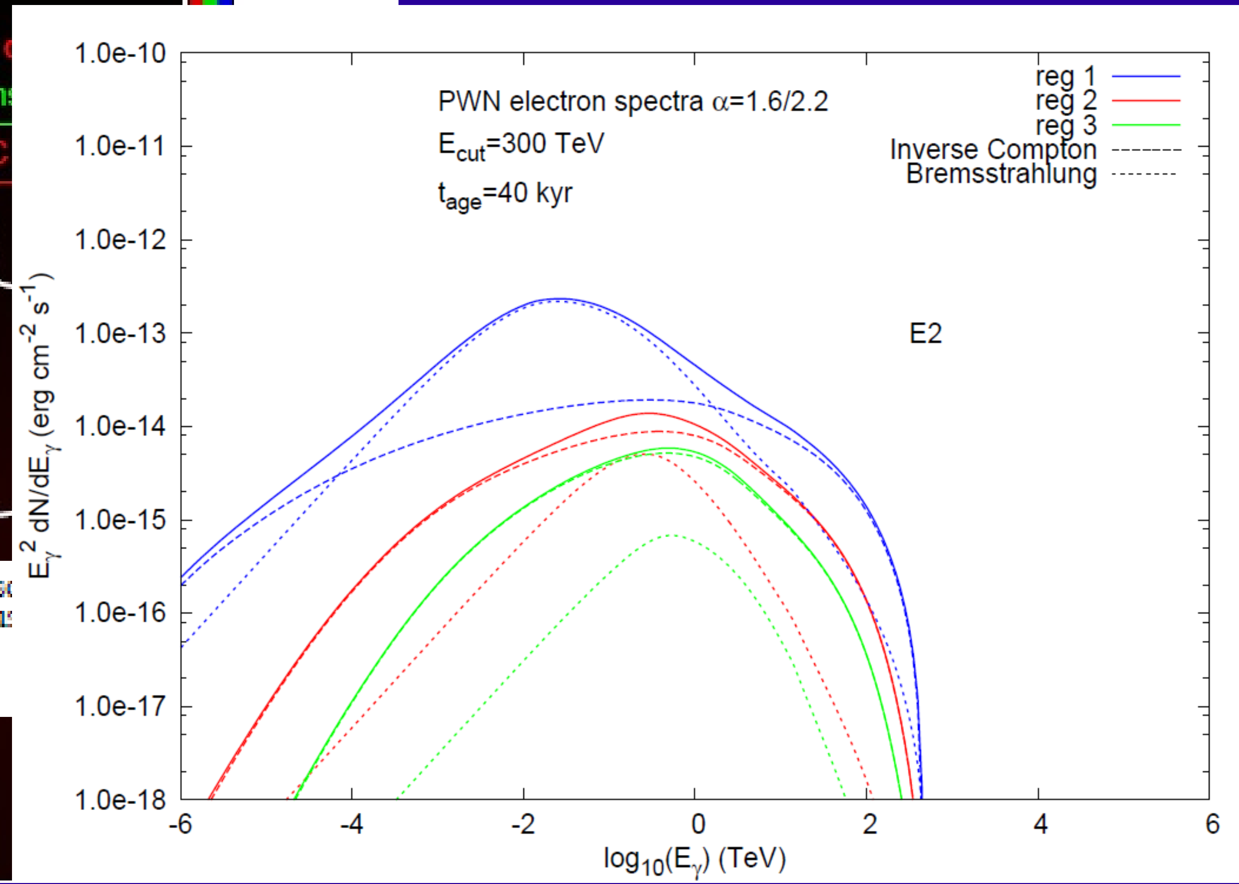
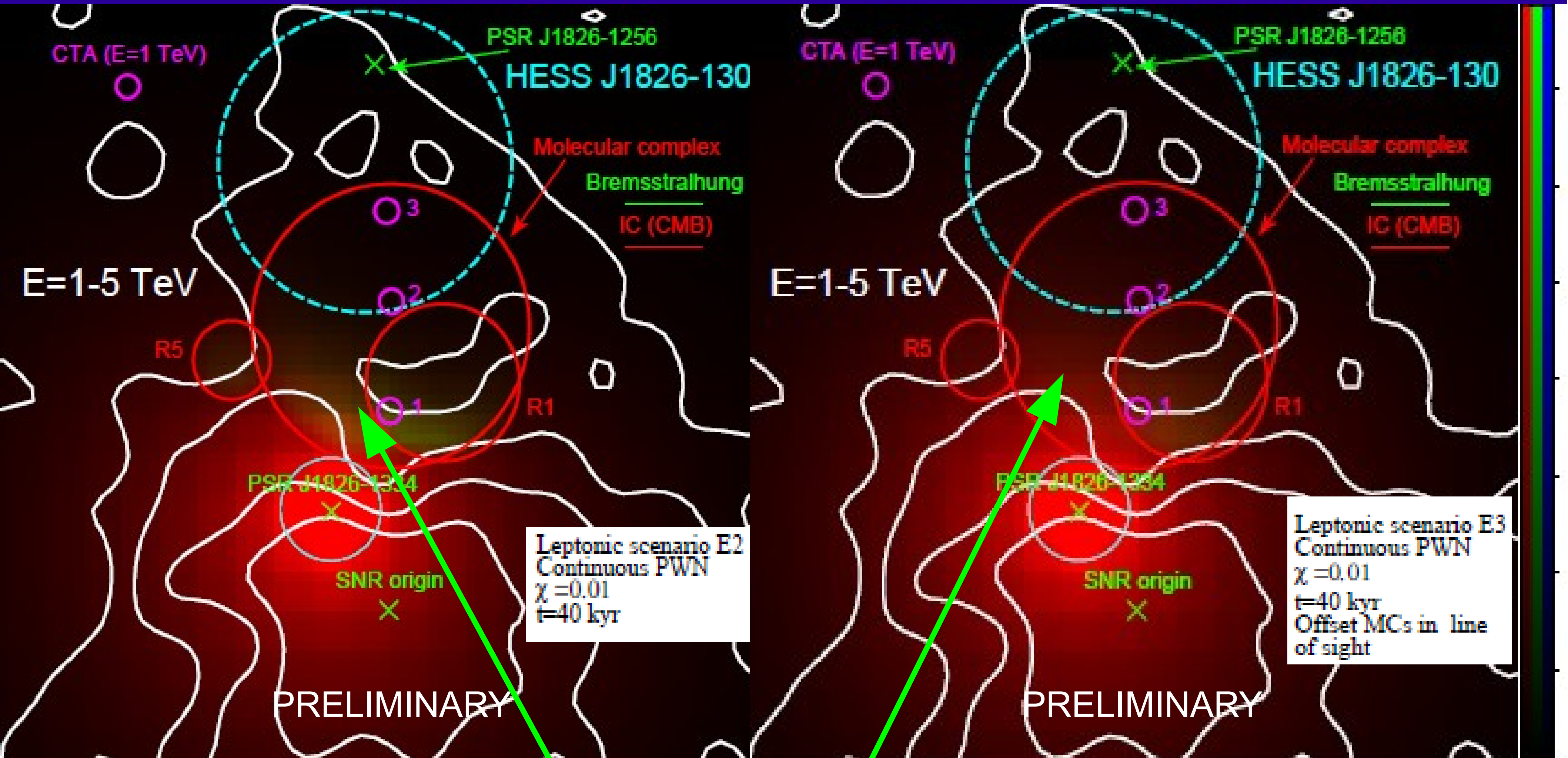




→ Leptonic scenario : TeV gamma-ray emission not overlapping with molecular cloud +Bremsstrahlung may be significant

→ Softening of the TeV gamma-ray SED expected as we move away from the PWN

RESULTS DISPLAY



→ Leptonic gamma-ray morphology somewhat sensitive to the position of molecular clouds => NEED TO MODEL X-RAYS EMISSION !!

UPCOMING UPGRADES AND FUTURE WORK (1)

- IMPLEMENT MODELLING OF THE X-RAY EMISSION → **USEFUL TO OBTAIN FURTHER INFORMATION ABOUT THE MOLECULAR CLOUDS – TeV SOURCE ASSOCIATION**

- **A MORE IN-DEPTH STUDIES OF THE SYSTEMATIC ERRORS FROM THE NUMERICAL COMPUTATIONS → NECESSARY BEFORE PLANNING ANY PUBLICATIONS WITH THIS CODE**

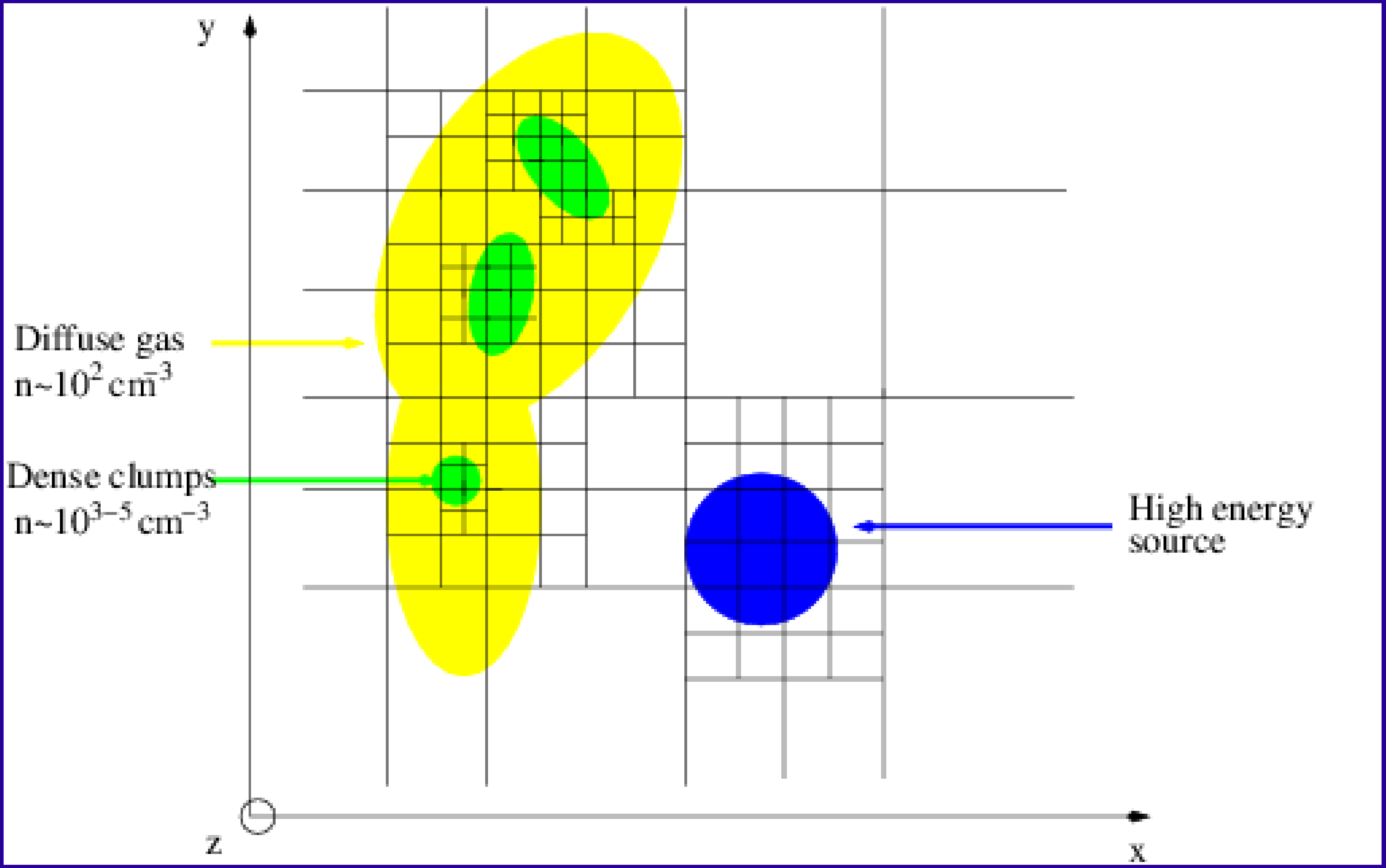
- **IMPLEMENT ARC AND FILAMENT STRUCTURE TO BETTER MATCH THE MORPHOLOGY OF THE GAS OBSERVED WITH THE MOPRA/NANTEN SURVEYS**

- **CONSTRAINT THE COLUMN DENSITY PIXEL BY PIXEL → TO AVOID OVERESTIMATING THE HADRONIC TeV EMISSION IN THE LINE OF SIGHT**

- **MAKE THE CODE MORE COMPUTATIONALLY EFFICIENT → (test various dynamics gridding algorithm e.g OCTREE)**

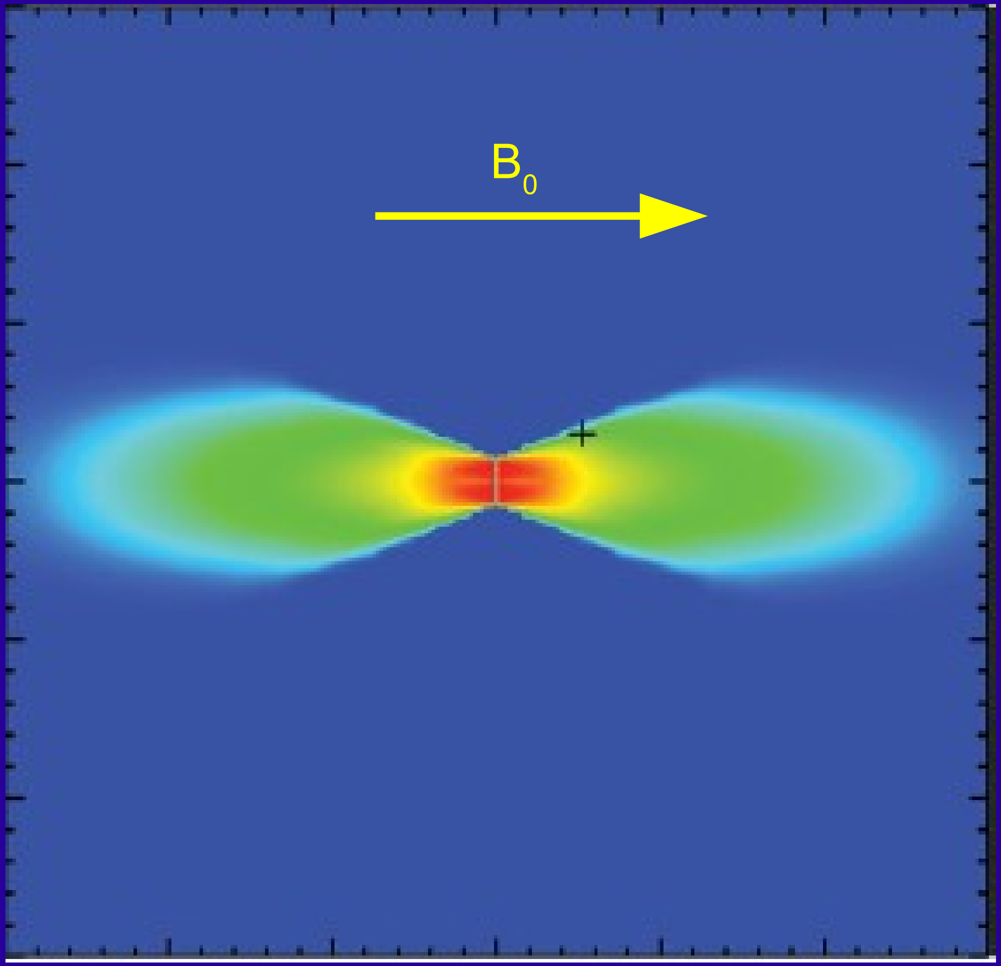
UPCOMING UPGRADES AND FUTURE WORK (2)

- **MAKE THE CODE MORE COMPUTATIONALLY EFFICIENT → (test various dynamics gridding algorithm e.g OCTREE)**



GETTING OVERAMBITIOUS ?

- **ACCOUNT FOR POSSIBLE ANISOTROPY DIFFUSION ALONG PRIMARY B FIELD LINES (?)**



CR overdensity map showing their anisotropic diffusion due to $\delta B/B_0<1$ *(Gabici et al 2013)*

THANKS !

Executive Producer
Gavin Rowell

Code Designer
Fabien Voisin

HPC Programmer
Fabien Voisin

Test designer
Fabien Voisin

Tester
Andrew Curzons
Fabien Voisin

EXPERTISE NEEDED IN :

- CODE DESIGNING
- CODE TESTING
- MODELLING X-RAY EMISSION
- ANISOTROPIC CR DIFFUSION...