UNIVERSITÀ DEGLI STUDI DI PALERMO

Supernova Remnants: an Odyssey in Space after Stellar death
6-11 June 2016, Chania

Modeling the shock-cloud interaction in SN 1006: particle acceleration and non-thermal emission

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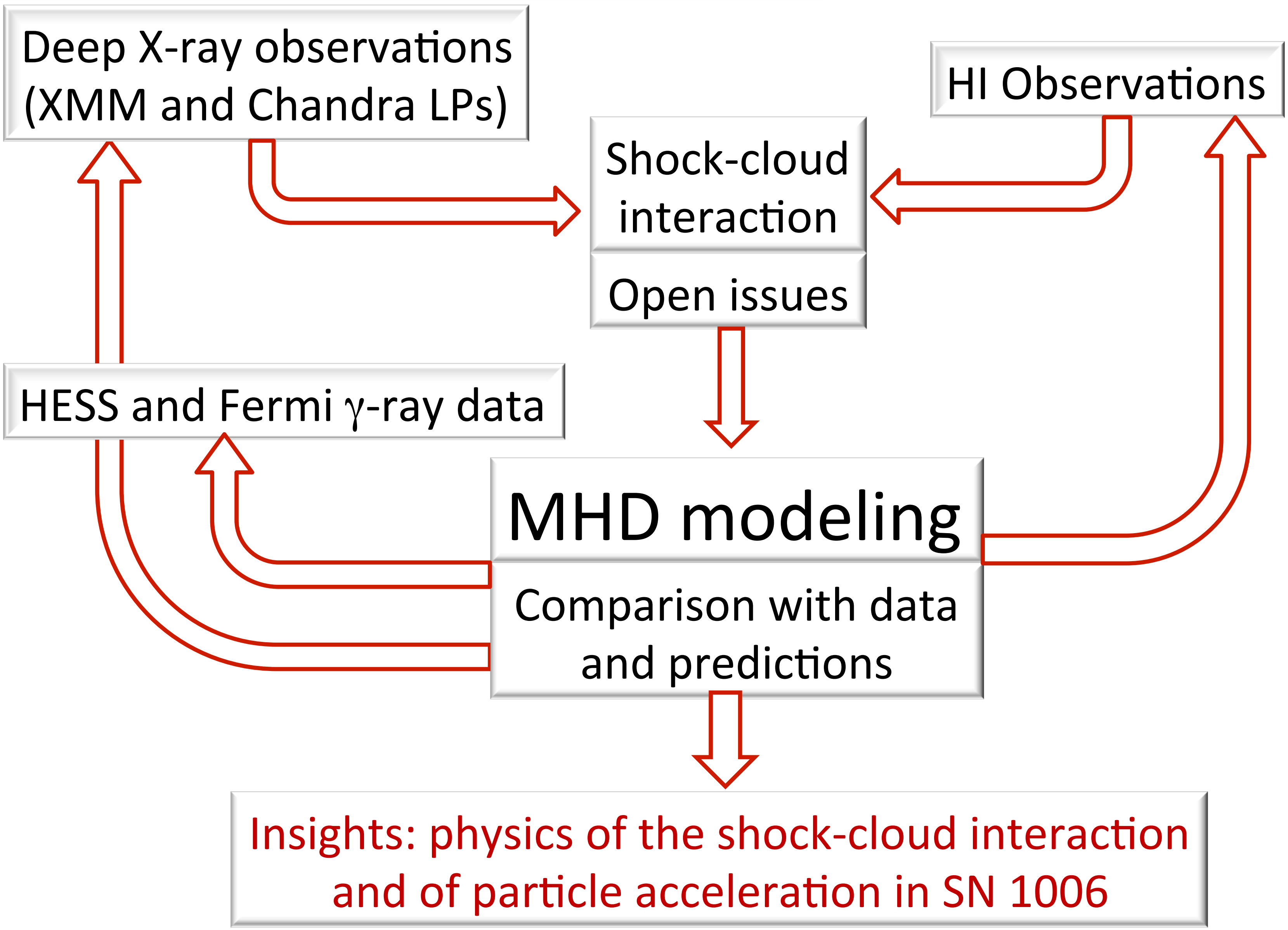
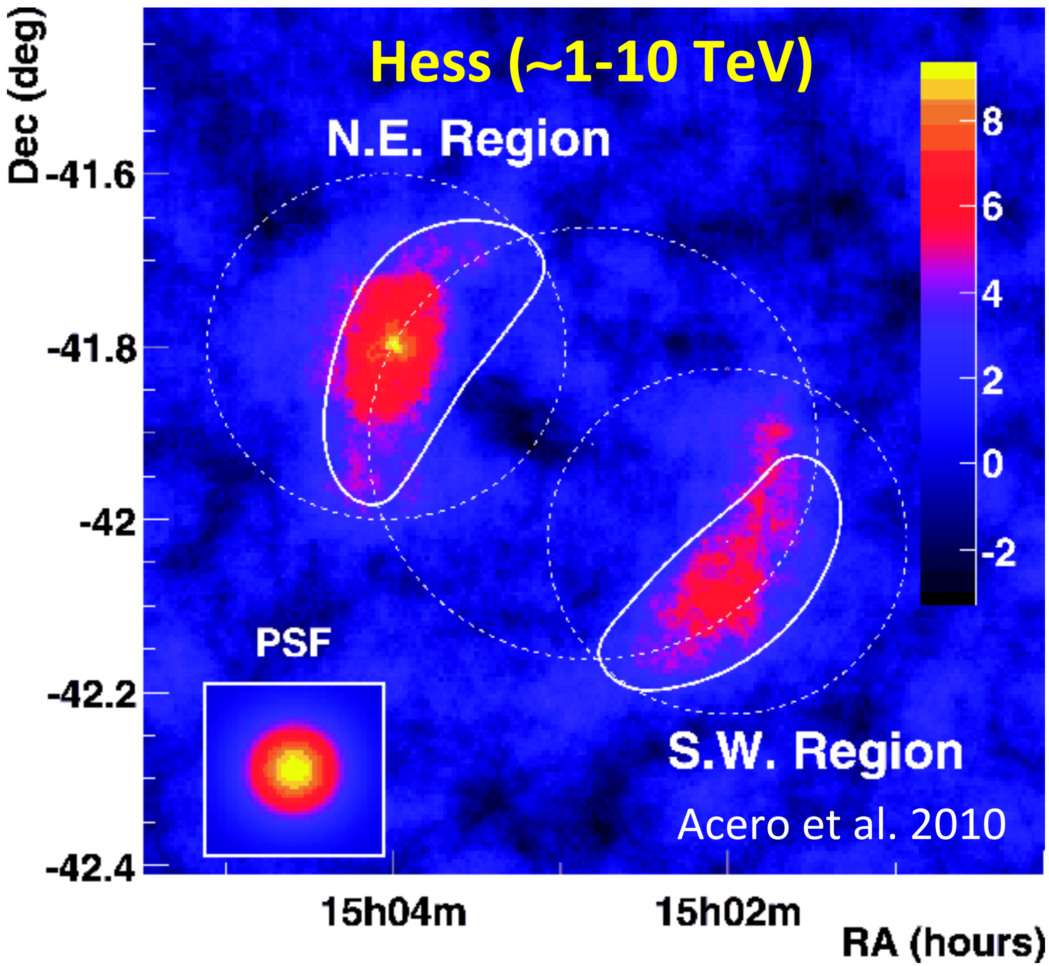
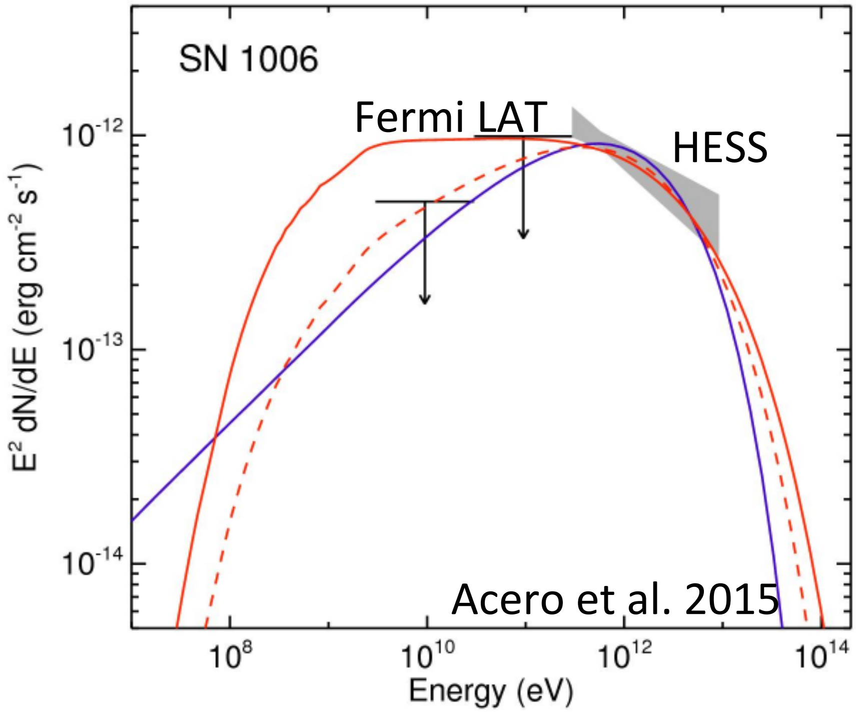
Outline of the work



Cosmic ray acceleration in SN 1006



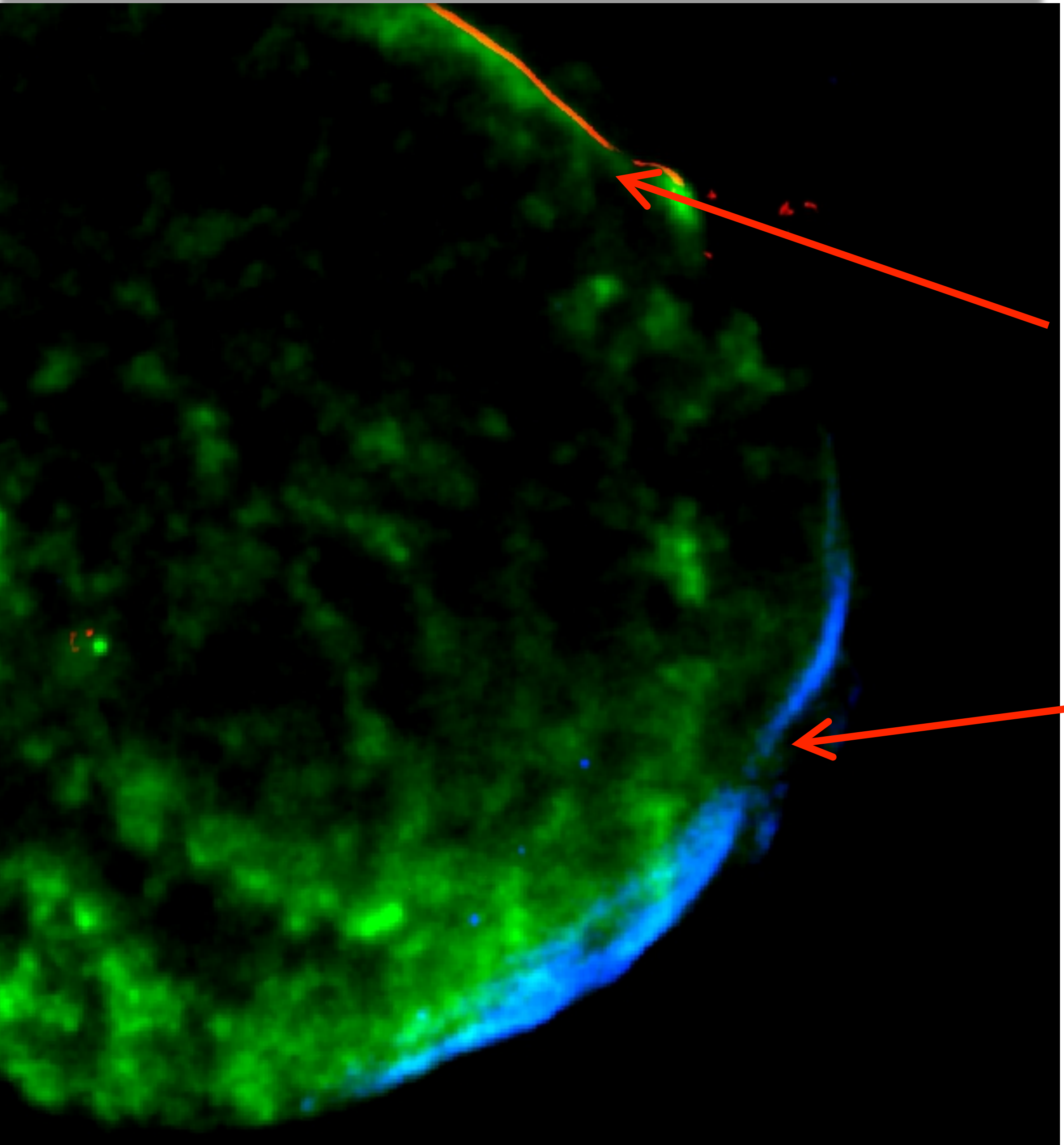


X-rays: electrons accelerated up to ~10 TeV; indications of hadron accel. (Miceli et al. 2012) and MFA (Ressler et al. 2015)

γ-rays: data suggest leptonic origin (Inverse Compton), little space for π^0 decay (hadronic)

Are hadrons accelerated in SN 1006?

The southwestern limb

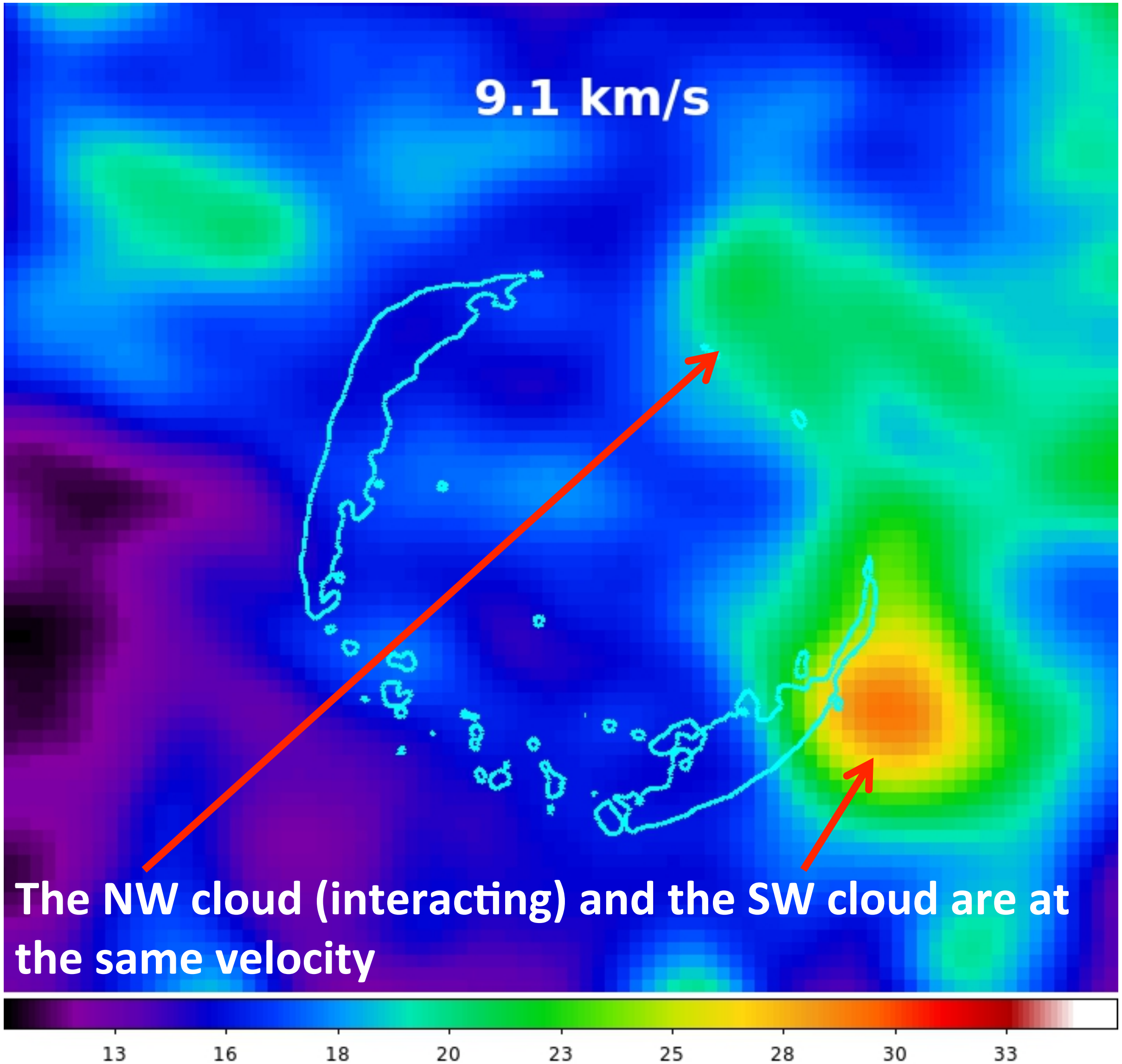


Sharp Hα filament: interaction with dense material (e.g., Ghavamian et al. 2002; Winkler et al. 2003; Raymond et al. 2007).

Indentation

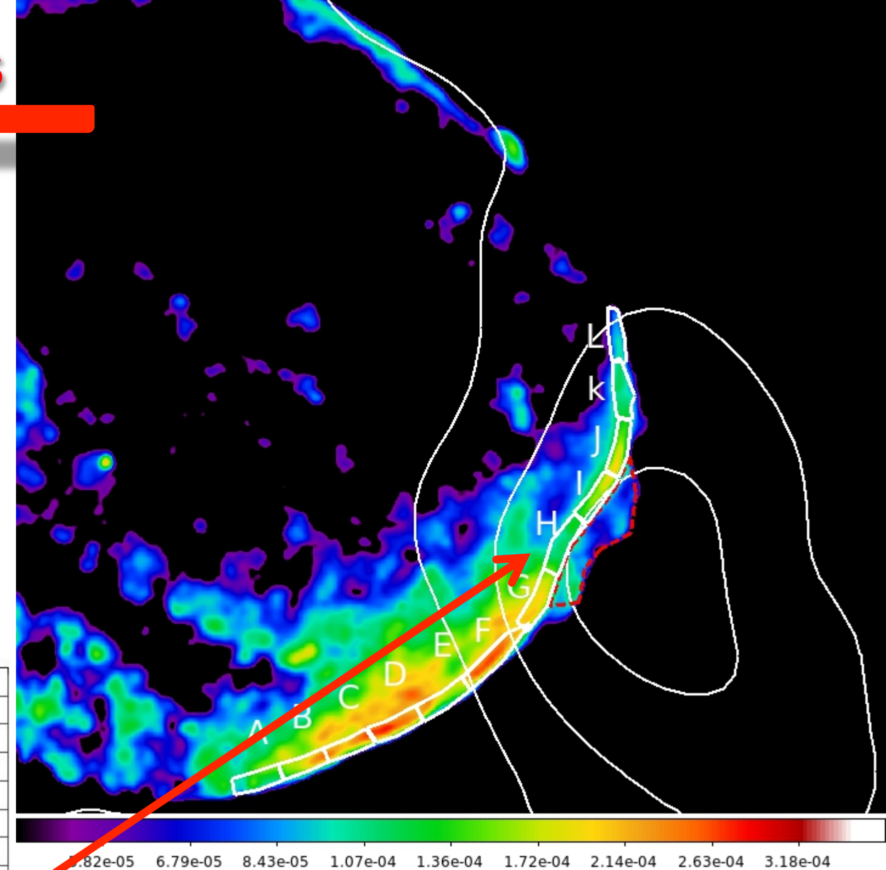
Suggestive of possible interaction with dense evironment

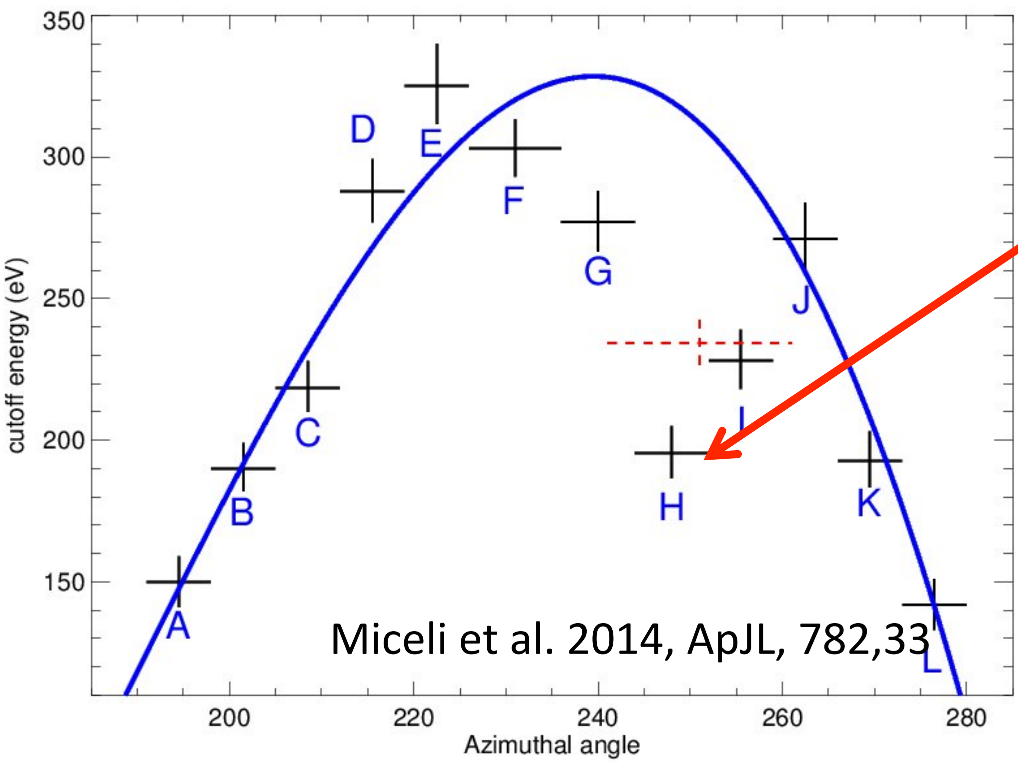
HI observations



XMM-Newton spectral analysis

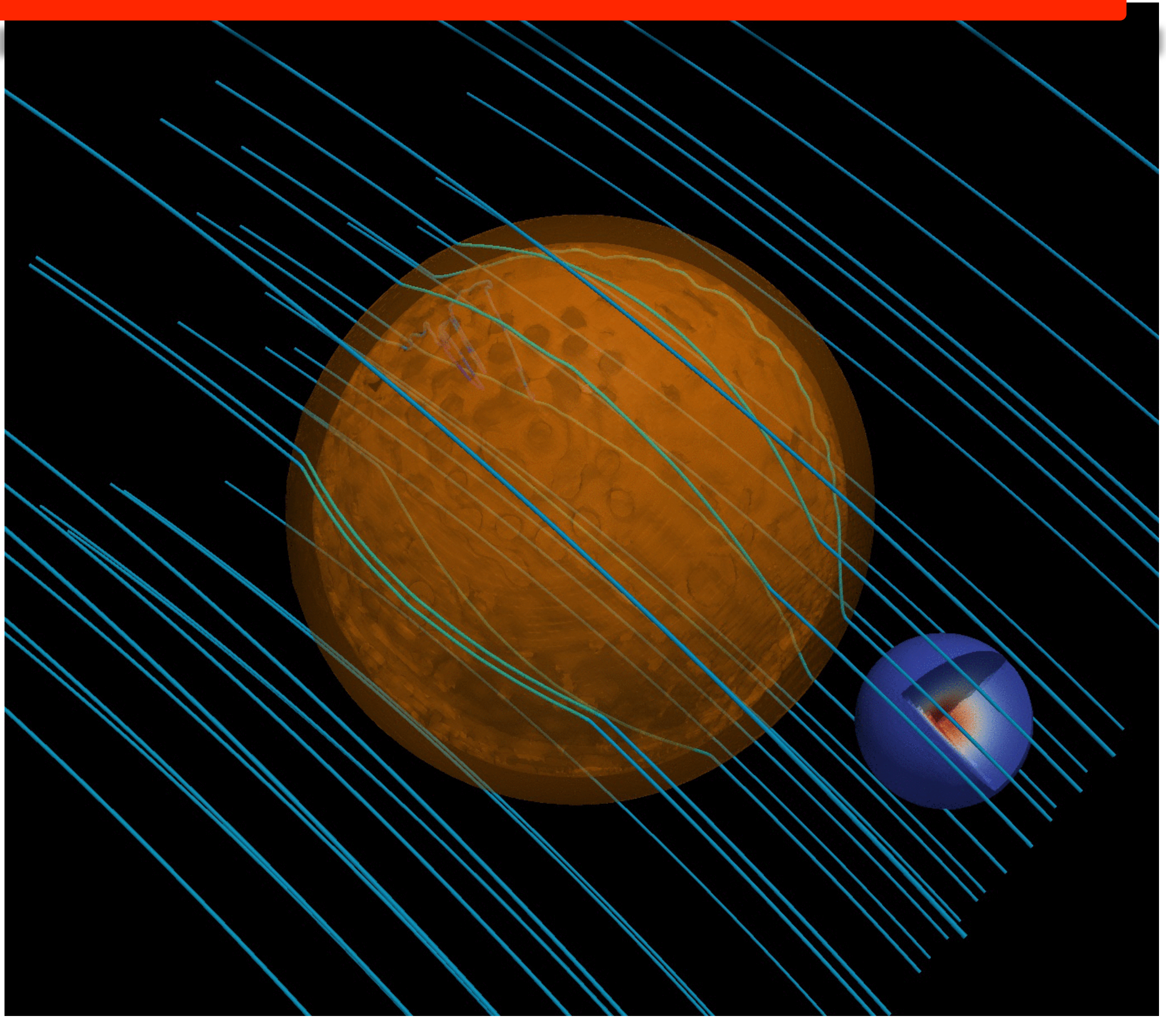
The maximum electron energy is loss-limited (Miceli et al. 2013, 2014) and the cutoff depends on the shock speed (see Zirakashvili & Aharonian 2007, Blasi 2010): $h\nu_0 = \frac{2.2\mathrm{keV}}{\eta(1+\sqrt{\kappa})^2} v_{3000}^2 \frac{16}{\gamma_s^2}$





Density contrast $\rho \sim 1.7$, while radio data suggest ρ~100: **what is the value of the cloud density**?

MHD modeling



Unique combination of particle acceleration and high ambient density: promising site for hadronic emission. Need for deeper diagnostics .

3-D MHD models using the **FLASH** code

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \,,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \mathbf{B}\mathbf{B}) + \nabla P_* = 0 \,,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\mathbf{u}(\rho E + P_*) - \mathbf{B}(\mathbf{u} \cdot \mathbf{B})] = 0 \,,$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0 \,,$$

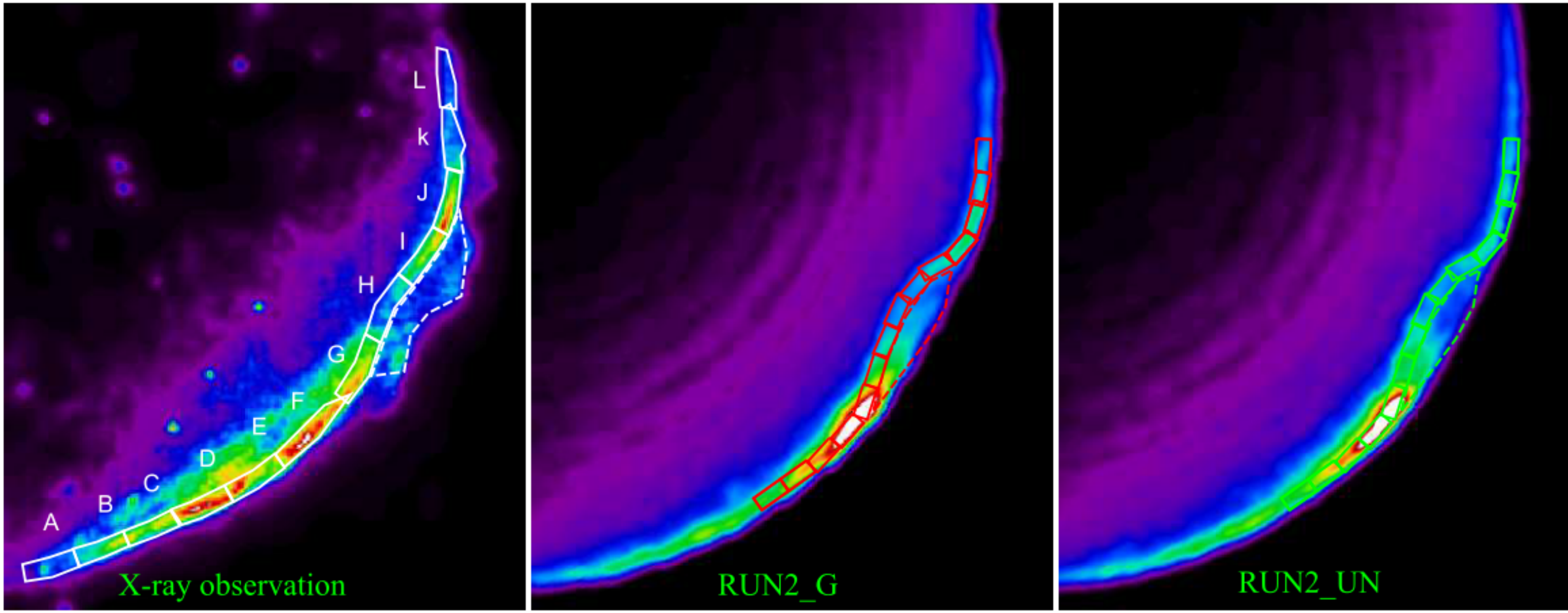
where

$$P_* = P + \frac{B^2}{2} \,, \qquad E = \epsilon + \frac{1}{2}|\mathbf{u}|^2 + \frac{1}{2}\frac{|\mathbf{B}|^2}{\rho} \,,$$

Model	Cloud Radius (10^{18} cm)	Cloud density (min-max, cm^{-3})	Cloud position (center, 10^{19} cm)	Dipole position (pc)
RUN0_G	8.1*	0.07 – 10	(2.6, 0.3, 0.2)	(0, 0, –100)
RUN1_G	8.1*	0.07 – 10	(3.0, 0.3, 0.2)	(0, 0, –150)
RUN2_G	8.1*	0.07 – 10	(2.8, 0.3, 0.4)	(0, 0, –300)
RUN3_G	8.1*	0.07 – 10	(2.8, 0.3, 0.4)	(0, 0, –1000)
RUN1_UN	6.18	0.5	(2.8, 0.3, 0.4)	(0, 0, –300.)
RUN2_UN	5.5	0.5	(2.8, 0.3, 0.4)	(0, 0, –300.)

Synthethic-Observed X-ray emission

We synthesize from the model the X-ray synchrotron emission in the loss-limited scenario (with the **REMLIGHT** code, Orlando et al. 2011)



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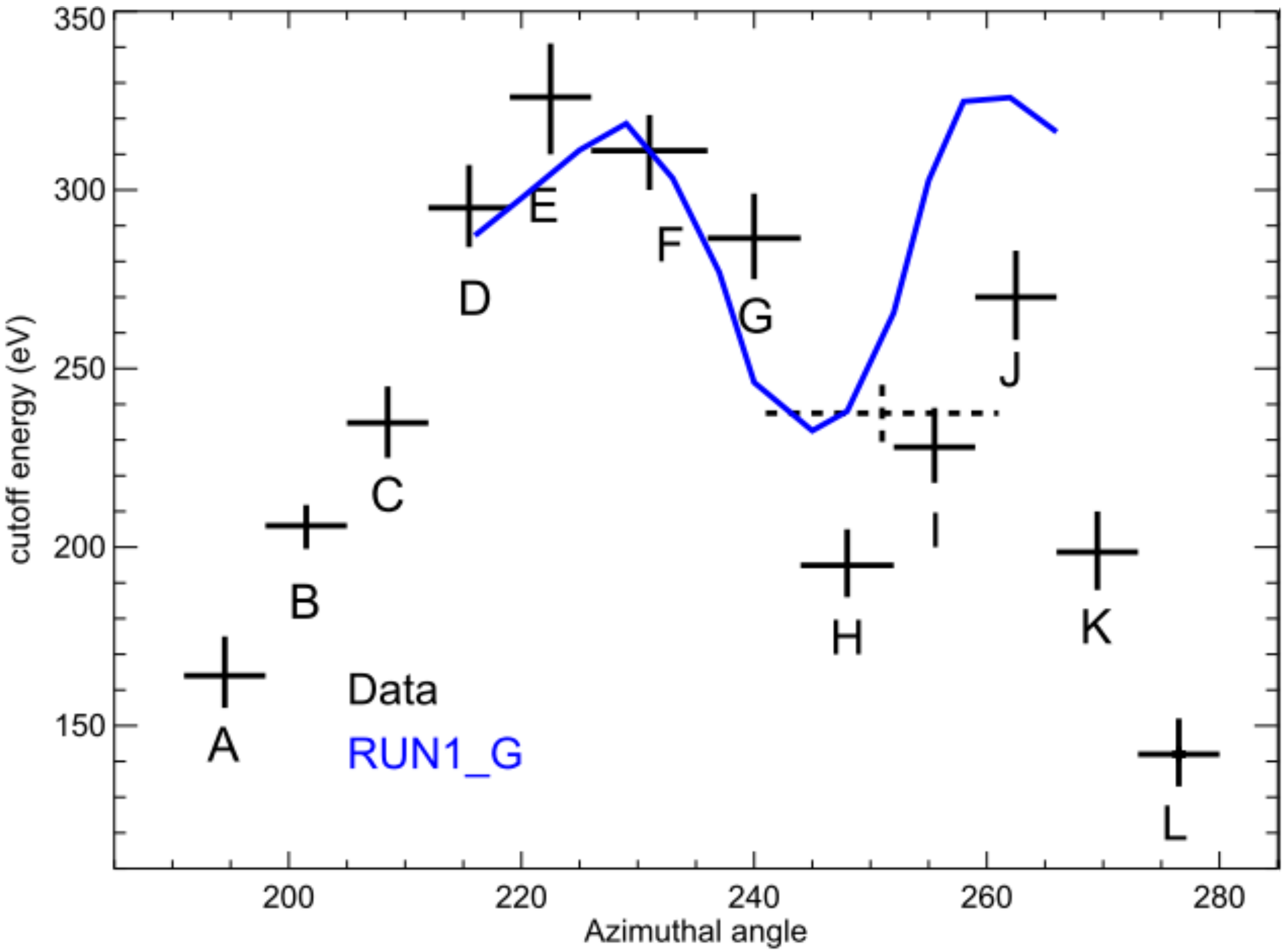
Only model RUN2_G and RUN2_UN can reproduce the observed morphology at the indentation

Synthethic-Observed X-ray emission



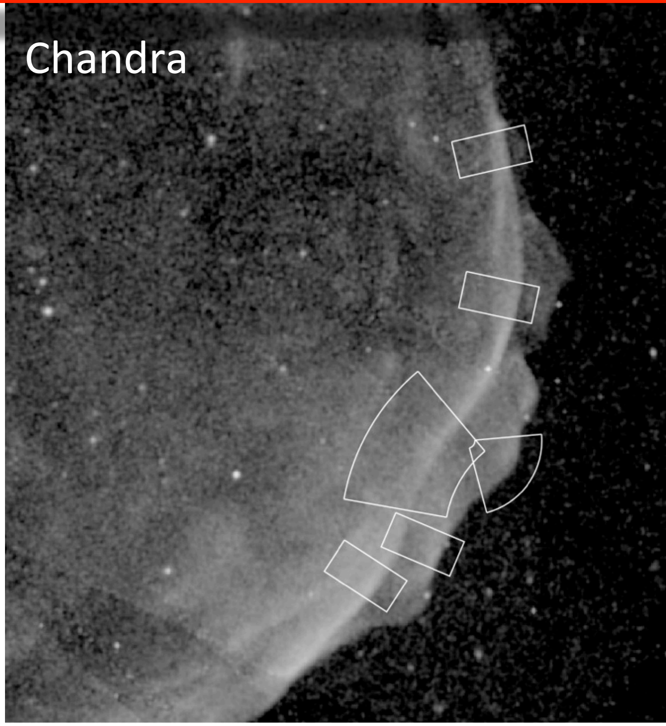
Cloud post-shock density:

RUN2_G: 3 cm^{-3}

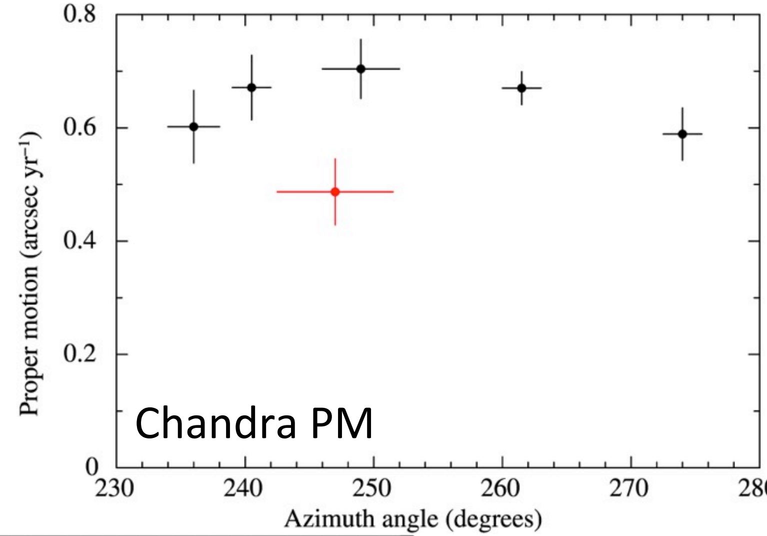
RUN2_UN: 1.5 cm^{-3}

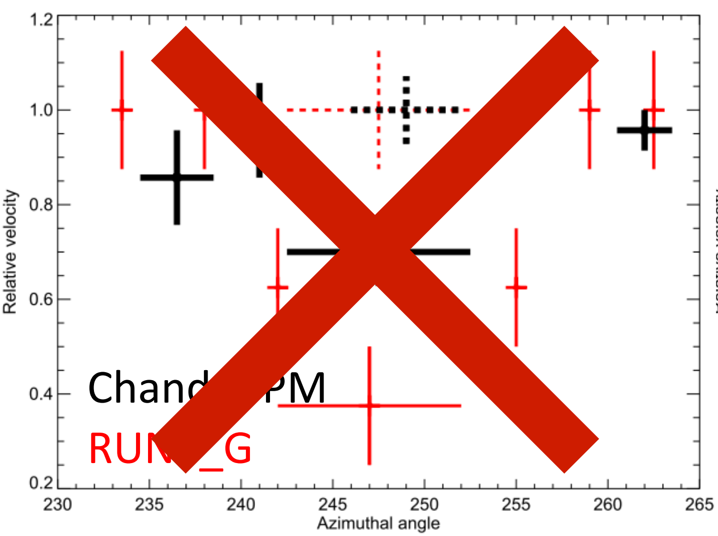
Both models can reproduce the observed azimuthal profile of the synchrotron cutoff energy: **density contrast ~~∝~~ observed cutoff contrast**

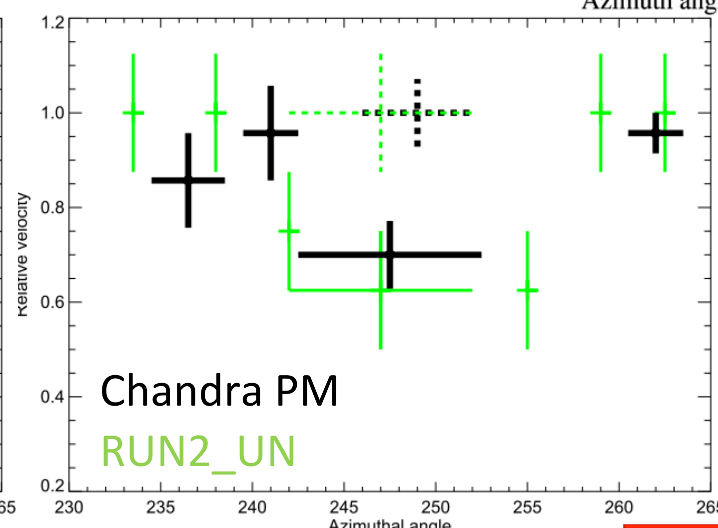
Synthethic-Observed X-ray emission



The Chandra observations reveal a **lower proper motion at the indentation** (thus confirming the interaction with the cloud

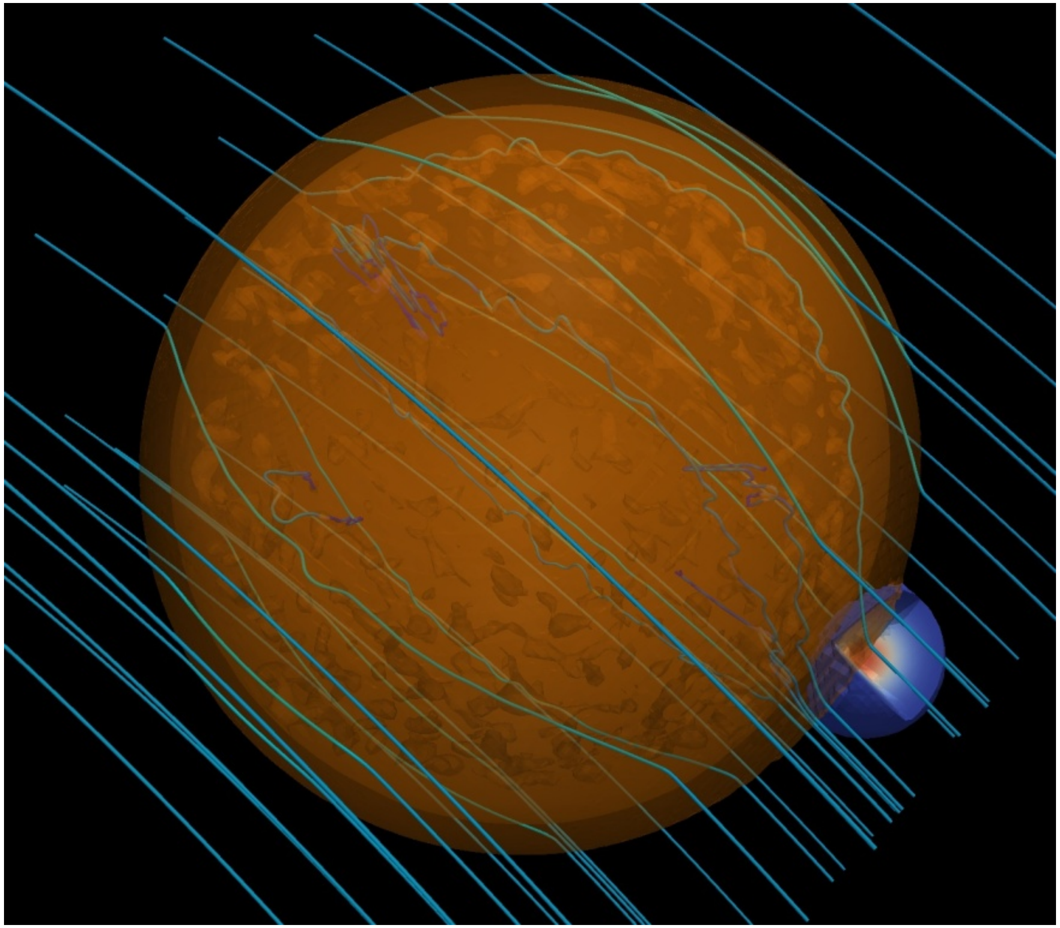






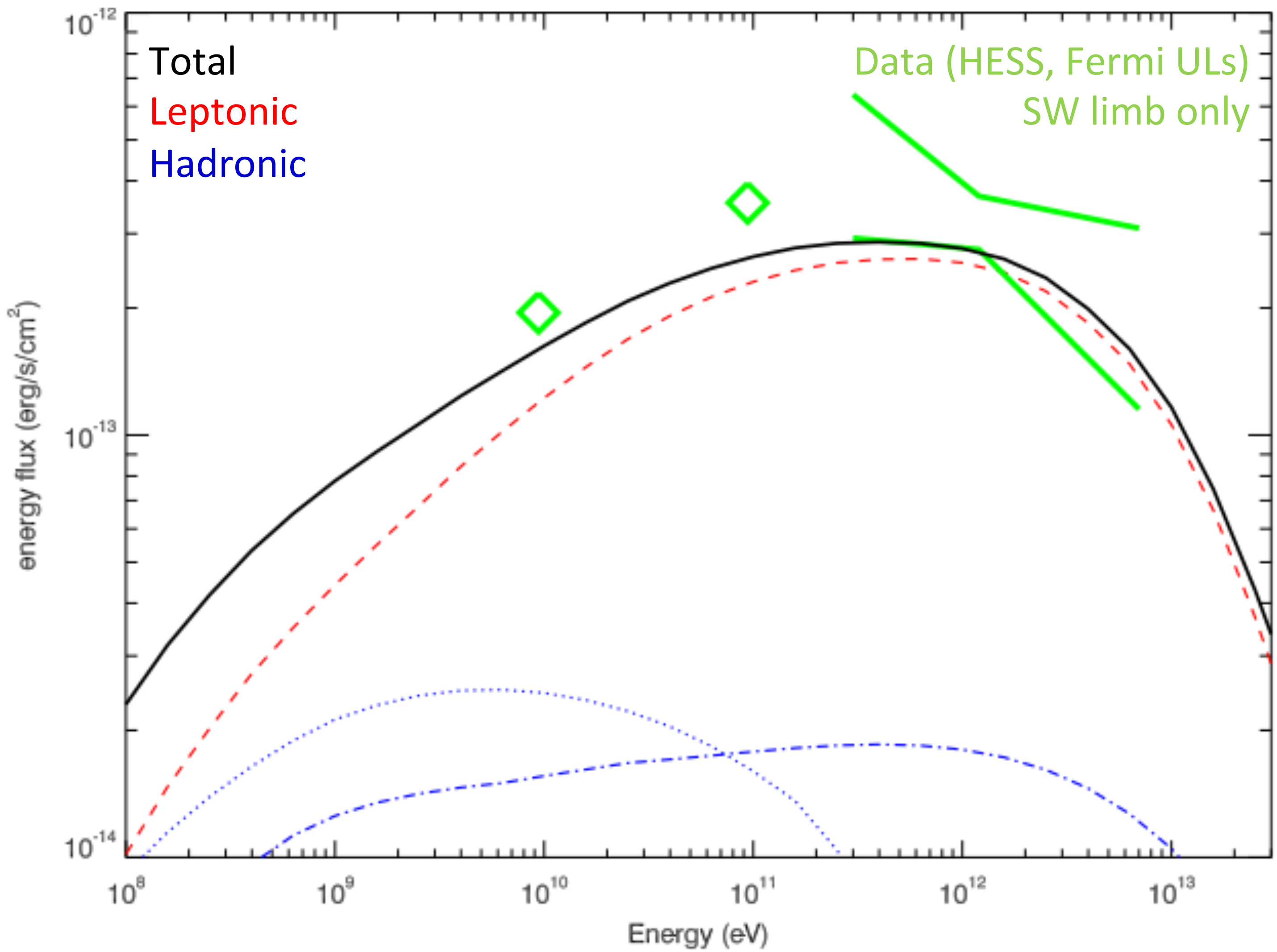
RUN2_G is not consistent with the observed PM

Synthethic γ-ray emission



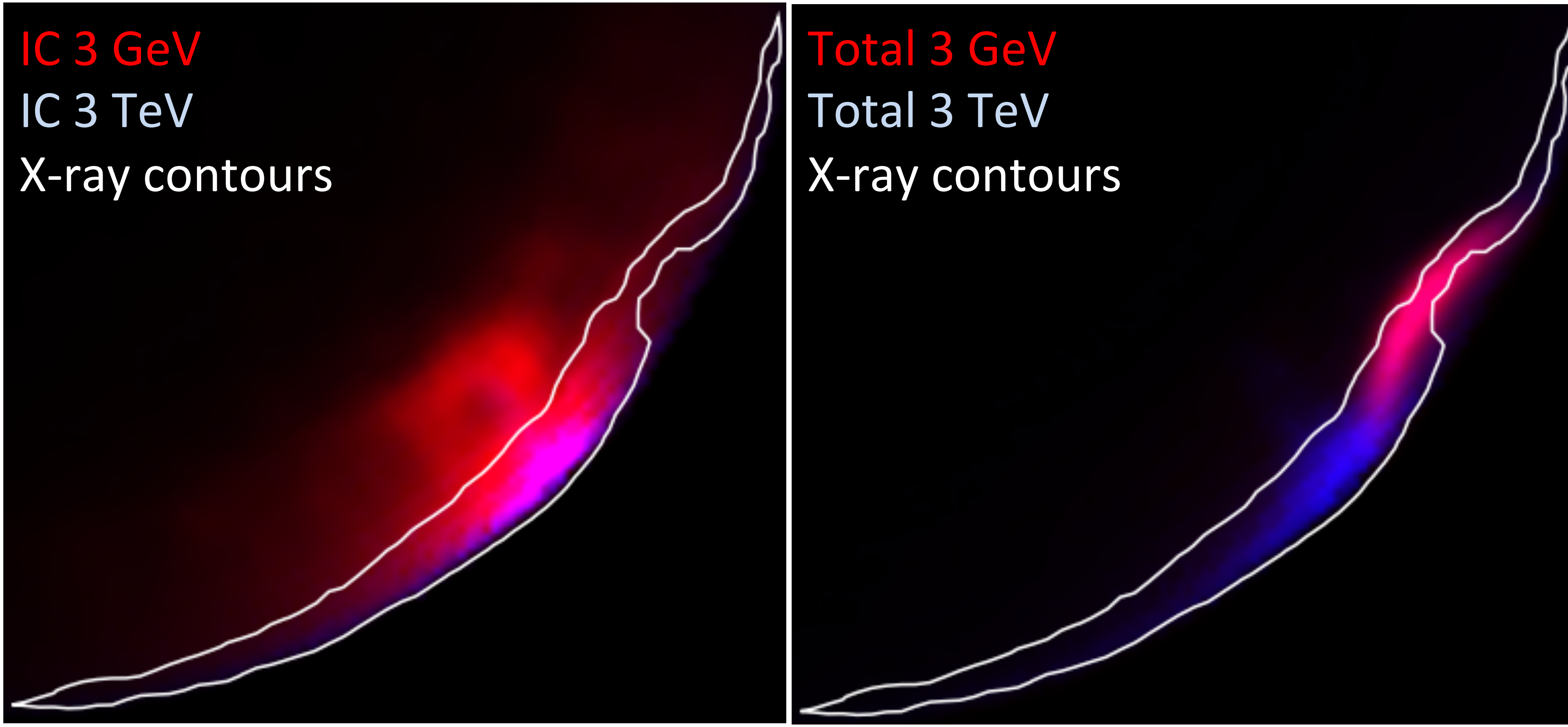
- **IC emission:** (upscattering of CMB) , output of REMLIGHT
- **Hadron emission:** hadrons with a power-law energy distribution with Γ=2
- **Two populations of hadrons** (transmitted shock/main shock) with different E_{cut}; we compute the emission in each cell (by following Kelner et al. 2006), considering the local density

Synthethic-Observed γ-ray emission



$E_p^{SW} = 1 \times 10^{49}$ erg

Expected morphology of the γ-ray emission



Leptonic emission

Leptonic+Hadronic emission

Conclusions

- X-ray and radio observations reveal the presence of an ambient cloud interacting with the SW limb of SN 1006

- 3D MHD models combined with multi-λ data analysis allow us to obtain a deeper level of diagnostics

- Thanks to the comparison between models and the deep ***XMM*** and ***Chandra*** observations, we can understand the origin of the observed (spectral and morphological) features and make accurate predictions

- **The detailed description of the physical conditions allows us to constrain the hadron energy in the SW limb: $E_p^{SW} < 2.5 \times 10^{49}$ erg**