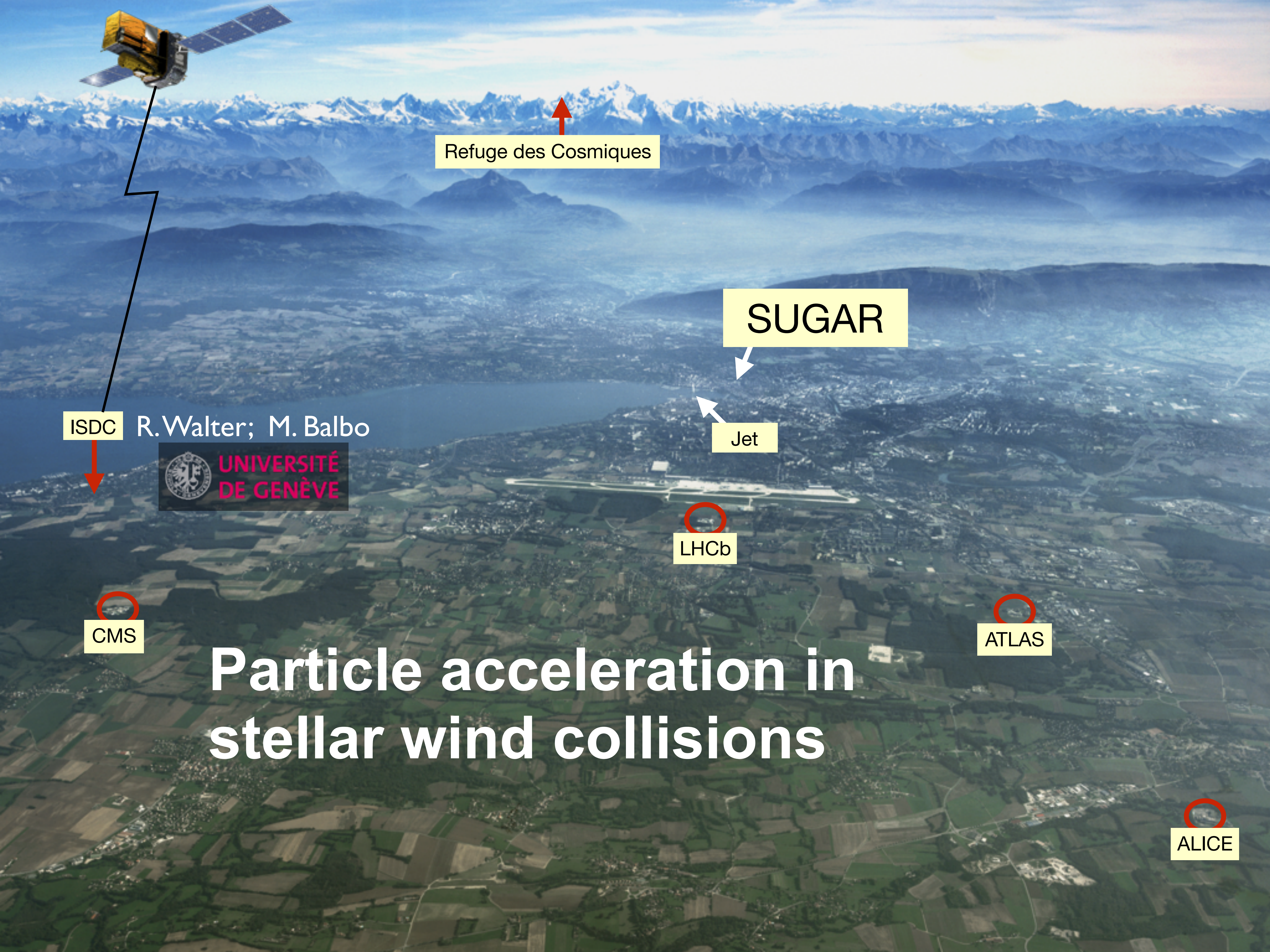
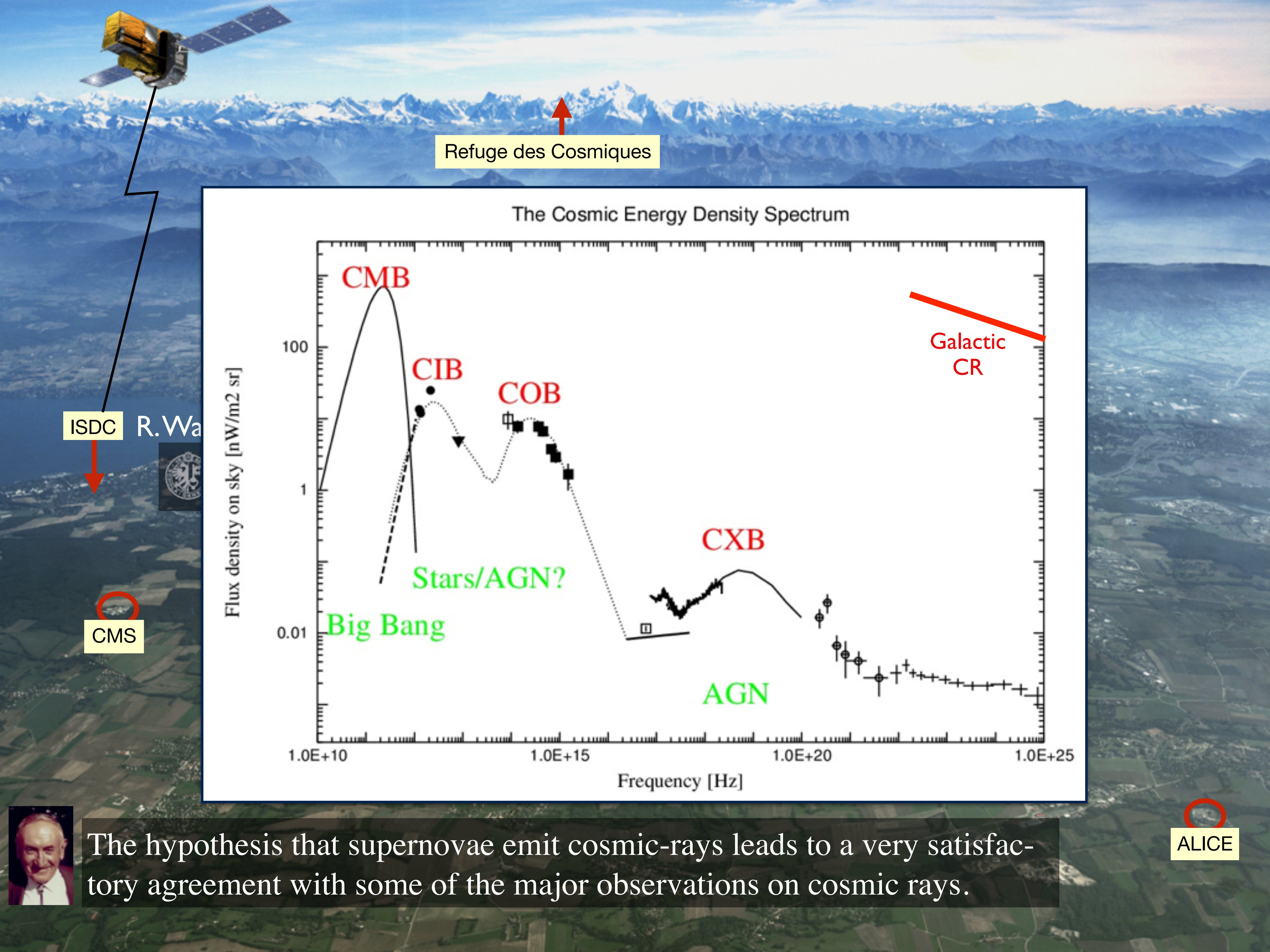
# Particle acceleration in stellar wind collisions

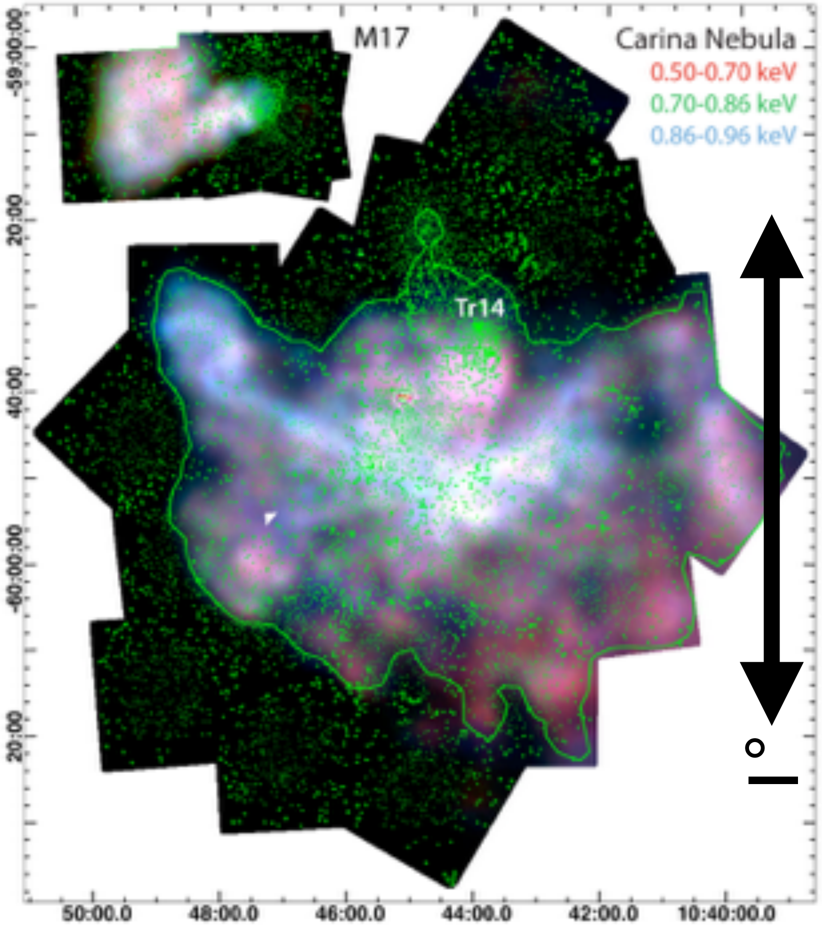
R. Walter; M. Balbo

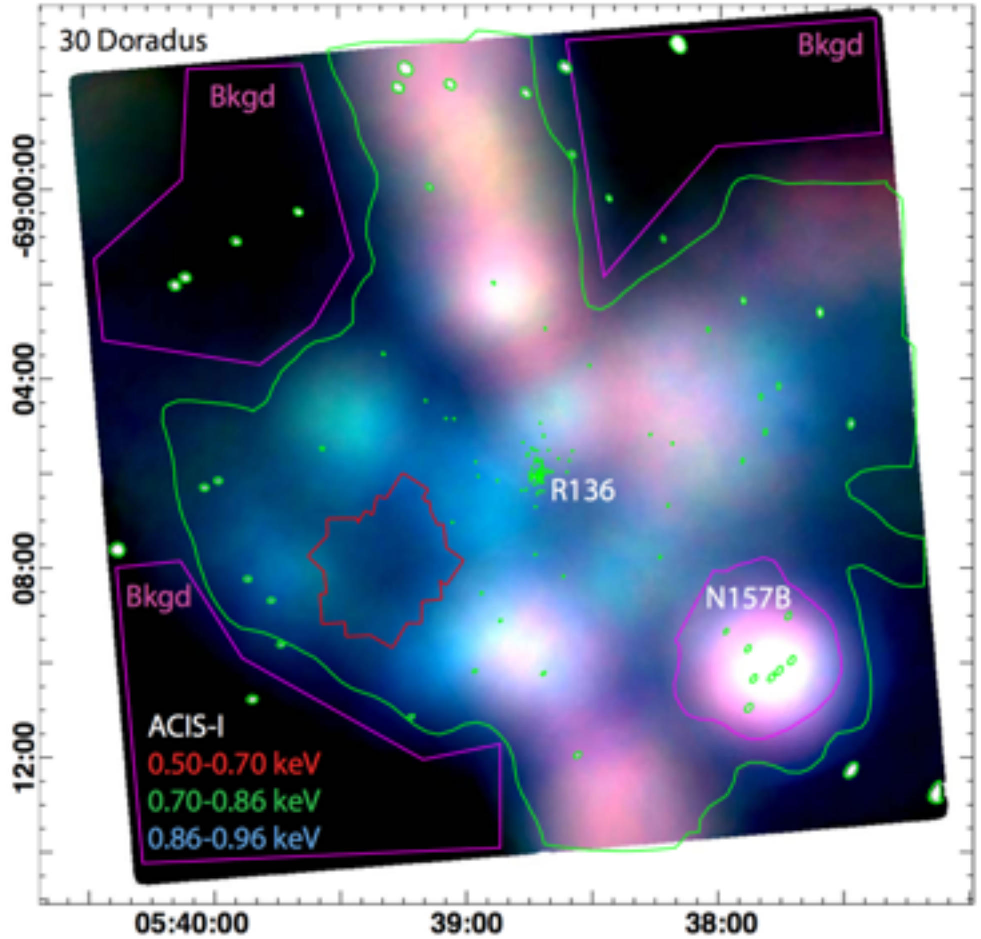
UNIVERSITÉ DE GENÈVE

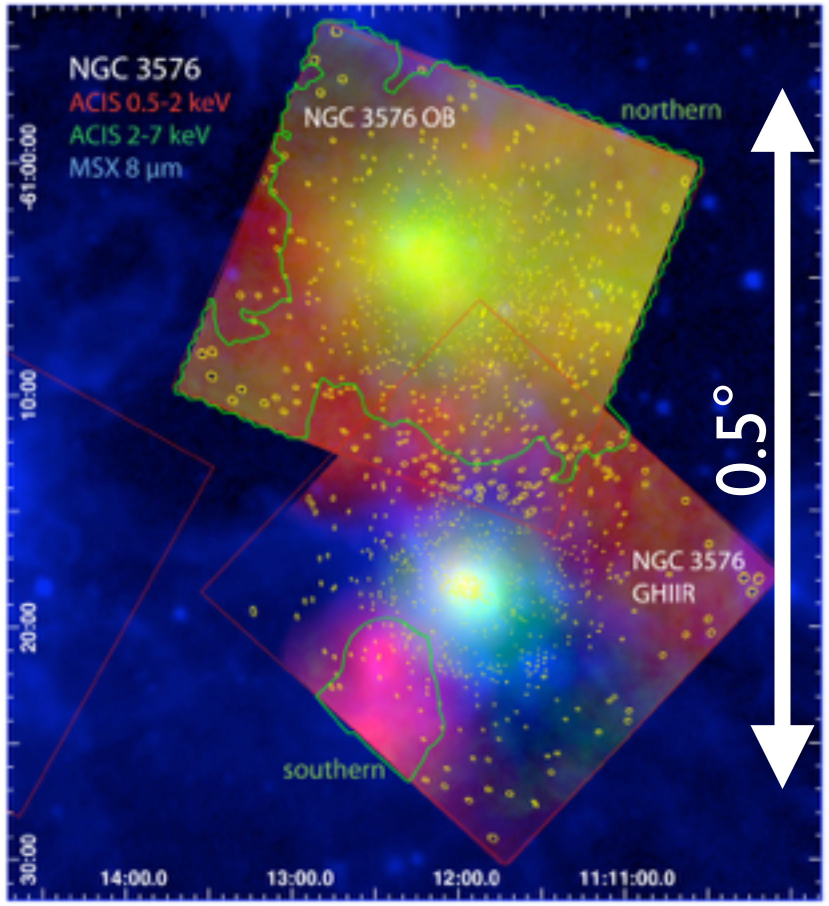



Refuge des Cosmiques
ISDC
CMS
ALICE
The Cosmic Energy Density Spectrum
CMB
CIB
COB
CXB
Galactic
CR
Stars/AGN?
Big Bang
AGN
100
1
0.01
Flux density on sky [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]
The hypothesis that supernovae emit cosmic-rays leads to a very satisfactory agreement with some of the major observations on cosmic rays.

# Stellar wind collisions: thermal emission




X-ray emitting gas unlikely to be from SN (too young, no radio, no polarisation, low velocity)

Diffuse X-Rays from High-Mass Star Forming Regions

| Region | Distance (pc) | Earliest Star[a] | Number O6 or Earlier | Diffuse X-Rays? | Diffuse Area ($pc^2$) | $N_H$ ($10^{21}$ $cm^{-2}$) | $kT$ (keV) | $L_X$[b] ($10^{33}$ ergs $s^{-1}$) | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| LMSFRs[c] | 150–350 | Late B | 0 | No | ... | ... | ... | $\leq 10^{-5}$ | ... |
| Orion Nebula | 450 | O6 | 1 | No | ... | ... | ... | $<10^{-3}$ | 1 |
| Eagle Nebula | 2000 | O5 | 2: | ... | ... | ... | ... | $<10^{-3}$ | 2 |
| Lagoon, NGC 6530 | 1800 | O4 | 3: | No | ... | ... | ... | $<10^{-2}$ | 3 |
| Lagoon, Hourglass | 1800 | O7 | 0 | Probably | 0.04 | 11.1 | 0.63 | $\leq 0.7$[d] | 3 |
| Rosette Nebula | 1400 | O4 | 2 | Yes | 47 | 2 | 0.06, 0.8 | $\leq 0.6$[d] | 4 |
| RCW 38 | 1700 | O5 | 1: | Yes | 2 | 11.5[e] | 2.2[e] | 1.6[e] | 5 |
| Omega Nebula[f] | 1600 | O4 | 7 | Yes | 42 | 4 | 0.13, 0.6 | 3.4 | 4 |
| Arches cluster | 8500 | O3/W-R | >30 | Yes | 14 | 100 | 5.7 | 16 | 6 |
| NGC 3603 | 7000 | O3/W-R | >20 | Yes | 50 | 7 | 3.1 | 20 | 7 |
| Carina Nebula | 2300 | O3/W-R | >30 | Yes | 1270 | 3–40 | 0.8: | 200: | 8 |

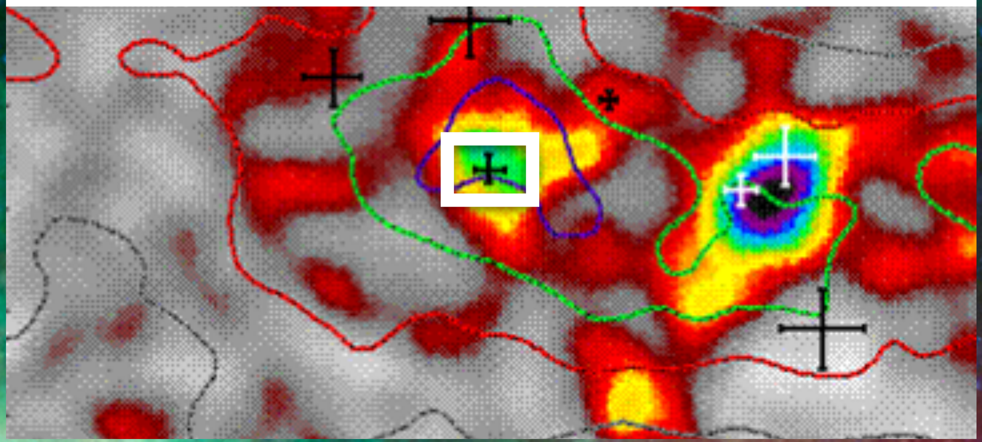
Townsley et al, 2003, 2005, 2011

Numerous high mass stars
ST < O7; $v_w$ > 2-3000 km/s
1-10 MK
$L_X$ ~ 10% of kinetic luminosity
wind-wind or wind-cloud

$L_X < 10^{35}$ erg/s
10% $F_X < 10^{-11}$ erg/s $cm^2$
Detectable within several kpc

# Cygnus region: non thermal emission

## MILAGRO 20 TeV



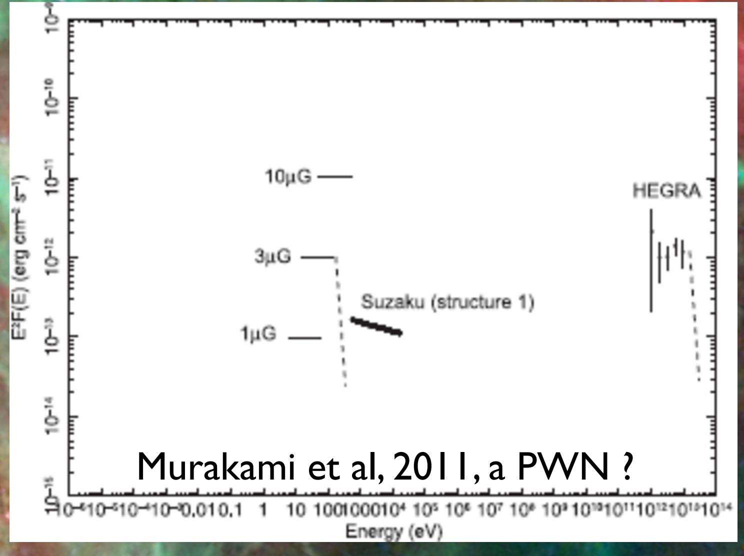
## ICECUBE

6 MGRO sources
51 excess υ>10 TeV
on 90 bkg atmosph. υ
Chance prob < 2%

arXiv:1406.6757


## X-rays

No X-ray diffuse emission reported
Cygnus X-3 at 0.5 °
Hard for coded masks and probably for NuStar as well




Murakami et al, 2011, a PWN ?

CTA

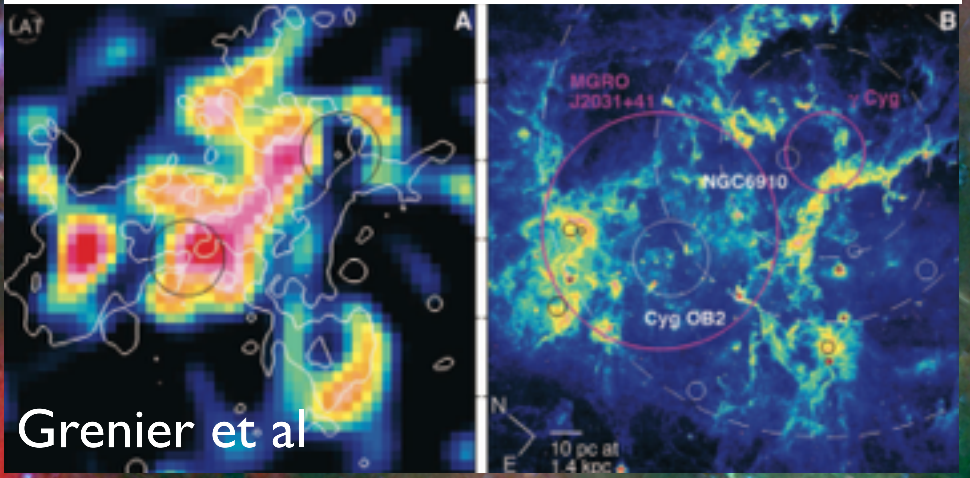
## Veritas

See Amanda's talk

ASTROGAM

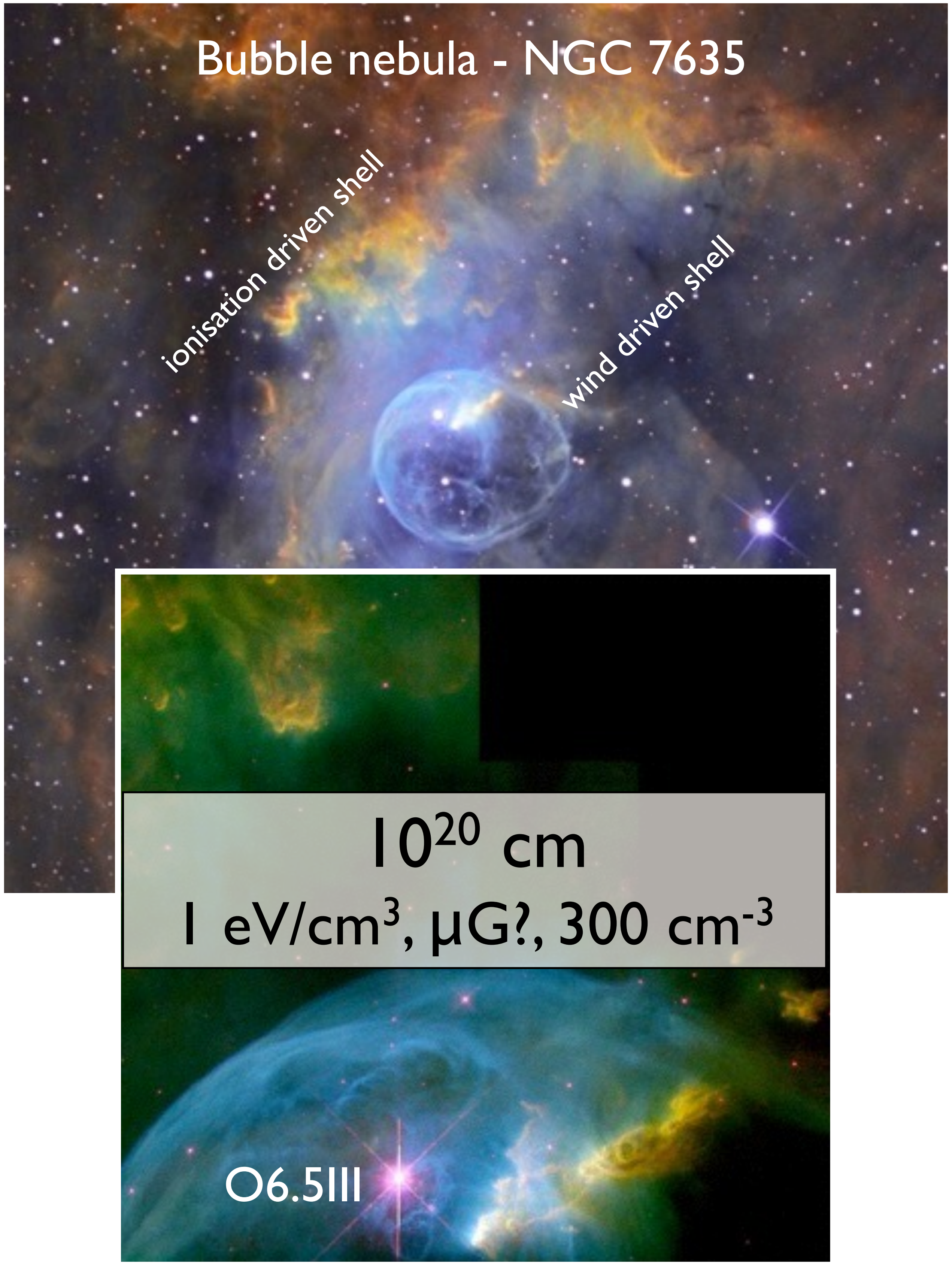
## Fermi

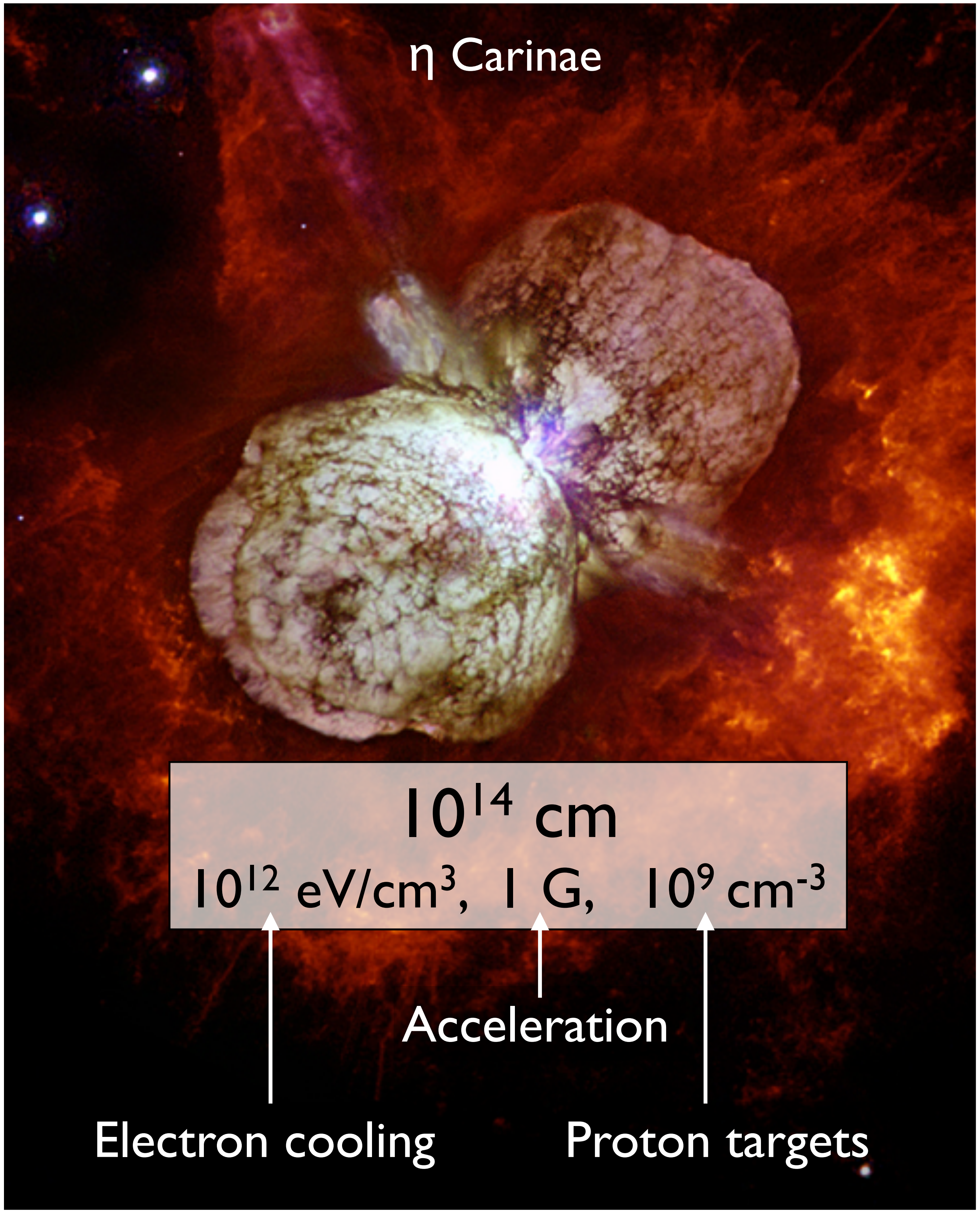
Diffuse emmission 10-100GeV



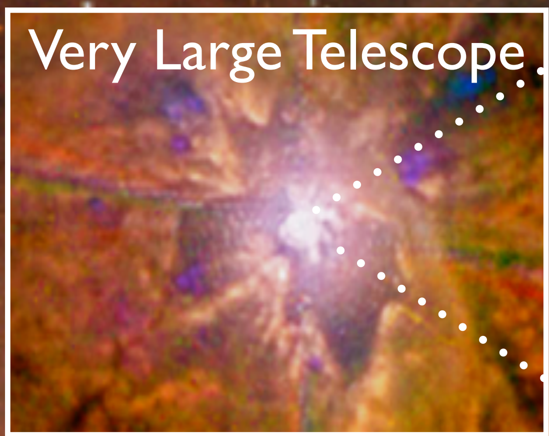

Grenier et al

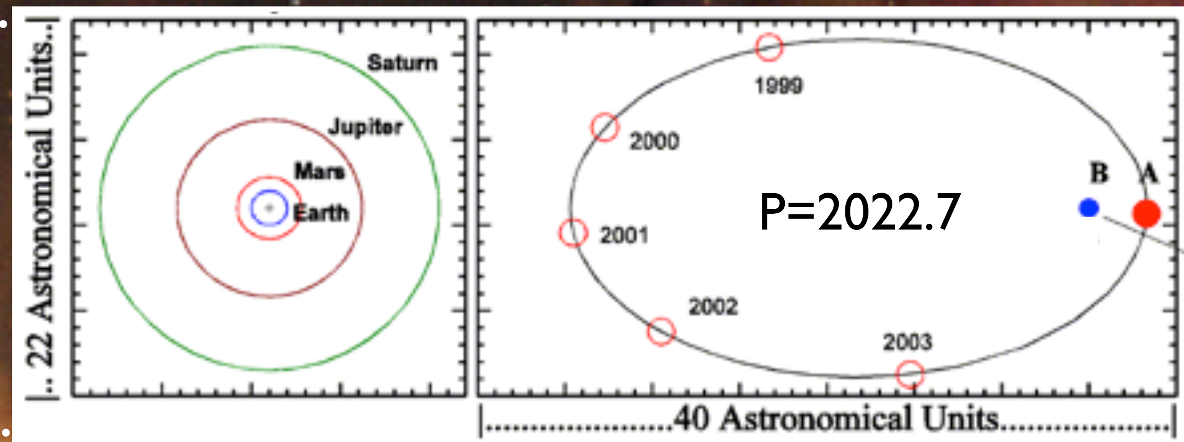
# Gamma-rays from wind driven shocks

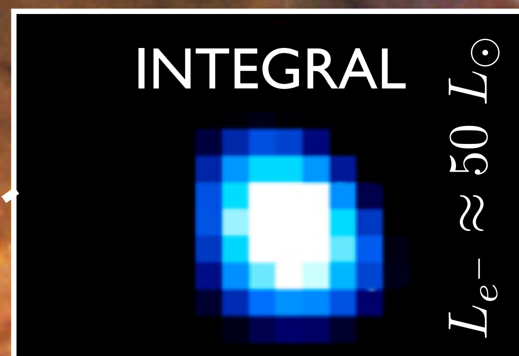


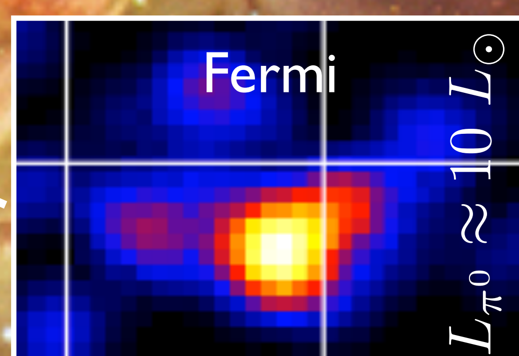
# Eta Carinae



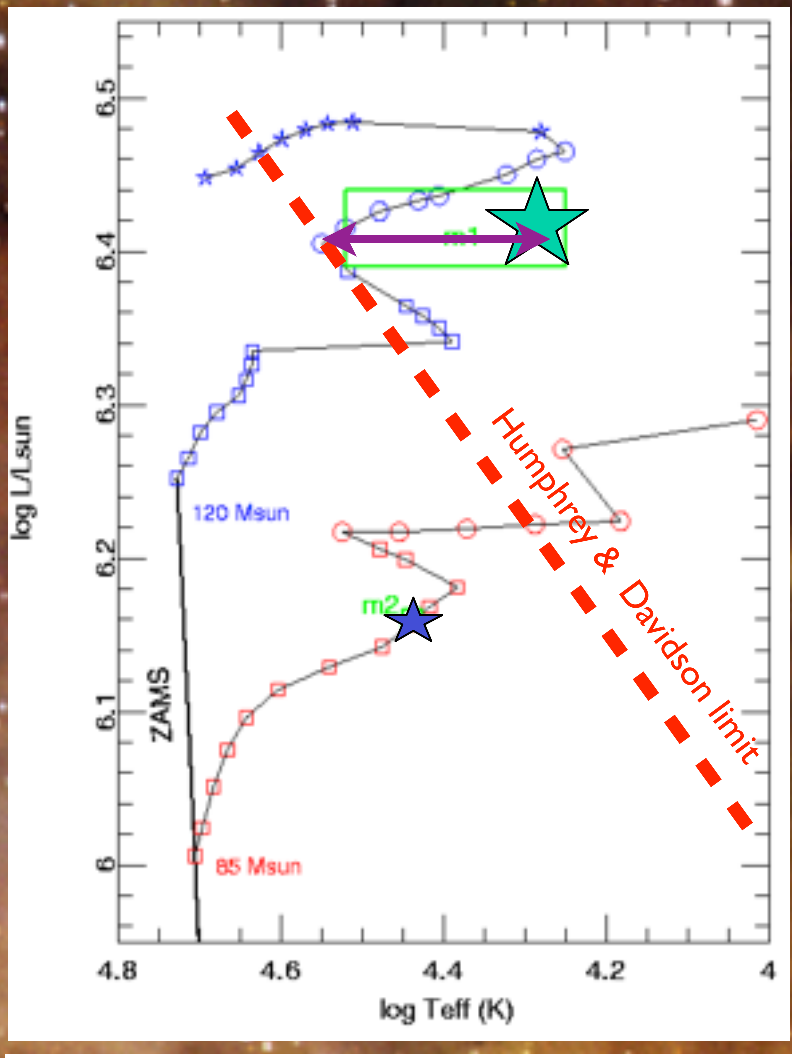



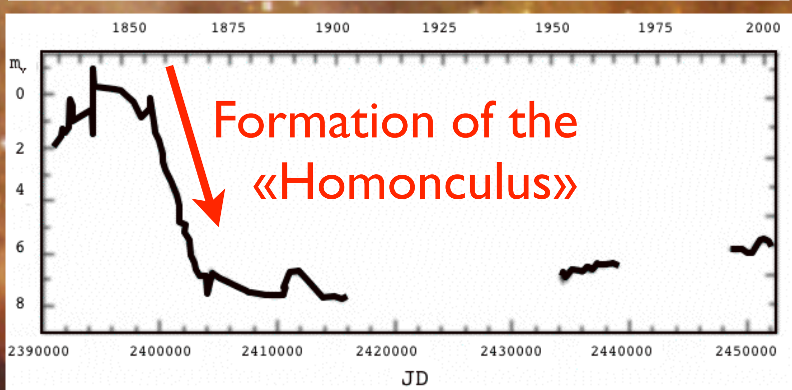




A&A (2008) 477, 29
A&A (2010) 524, 59




A&A (2011) 526, 57



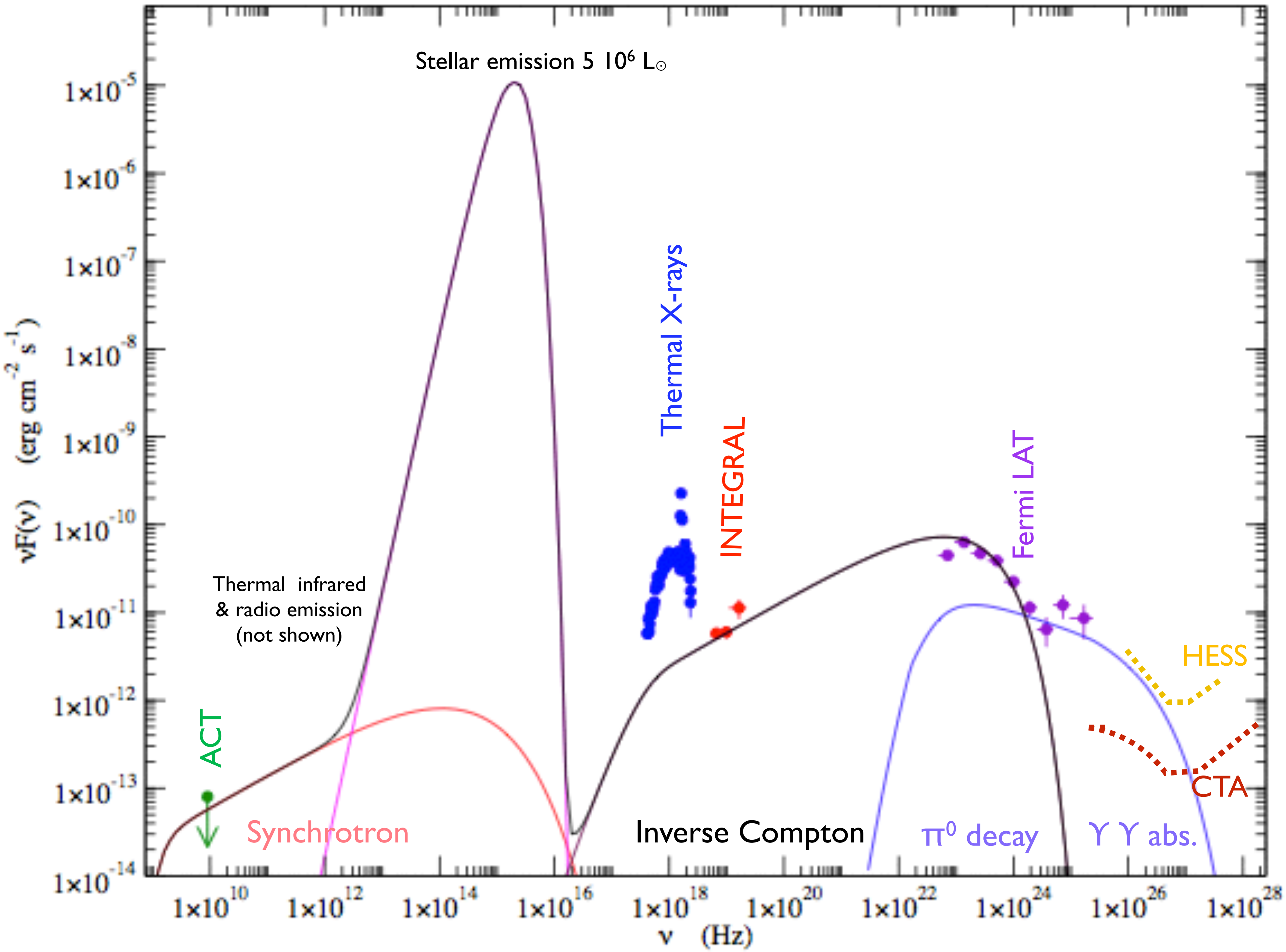



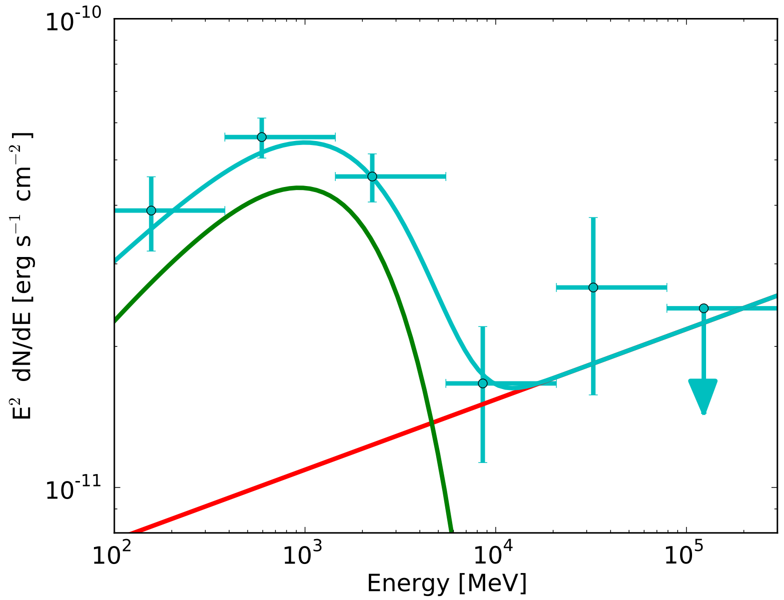

$M \sim 10^{-3.5}\ M_\odot/yr$

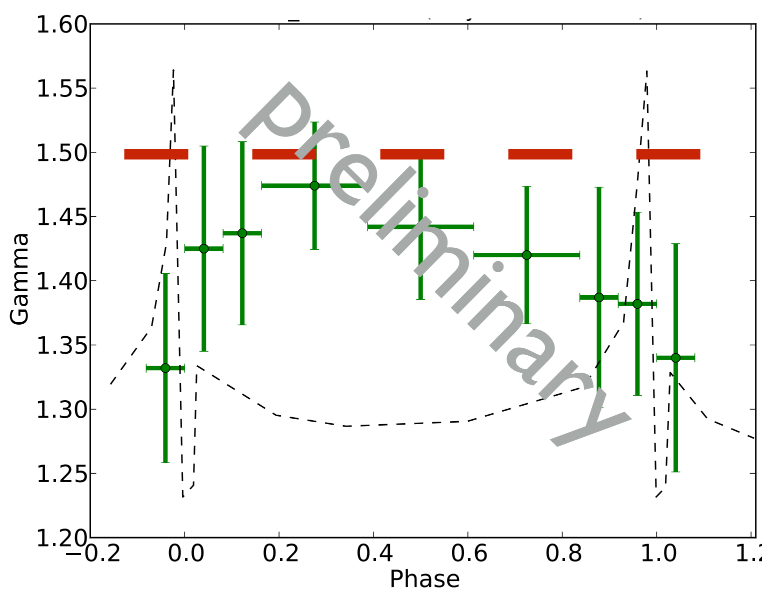
$L_{wind} \approx 2000\ L_\odot$

# Spectral energy distribution

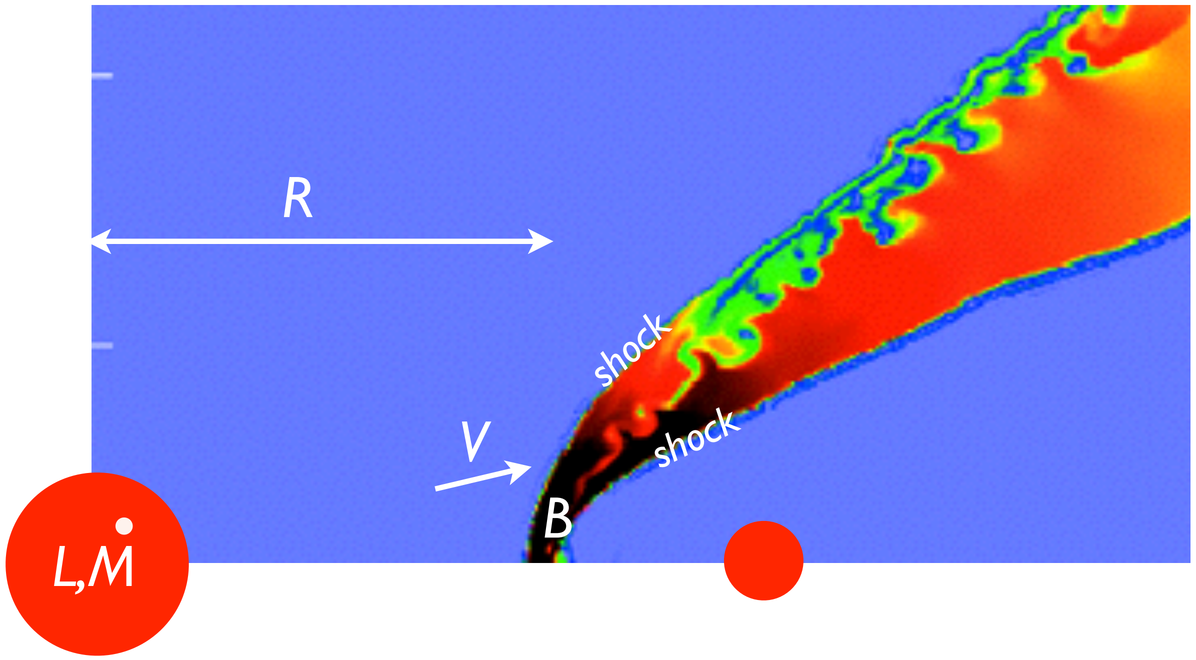
Close to periastron
A&A (2011) 526, 57



# Acceleration and cooling ("one zone")




Spectral fit parameters:

| | Parameter | Value | |
|---|---|---|---|
| Environment | Photon energy density | 2.7 | erg/cm$^3$ |
| | Magnetic field | 0.5 | G |
| | Density | $3 \cdot 10^9$ | cm$^{-3}$ |
| Electron distribution | Powerlaw index | 2.25 | |
| | $\gamma_{\max,e}$ | $10^4$ | |
| | Total energy | $10^{40}$ | erg |
| Proton distribution | Powerlaw index | 2.25 | |
| | $\gamma_{\max,p}$ | $10^4$ | |
| | Total energy | $1.3 \cdot 10^{40}$ | erg |

Shock acceleration is counterbalanced by

- e$^-$ IC scattering $$t_{IC} = \frac{3\gamma m_e c^2}{4\sigma_T c \gamma^2 \beta^2 U_{rad}} = \frac{3\pi R^2 m_e c^2}{\sigma_T \gamma \beta^2 L} \approx \frac{R^2_{10^{14}\mathrm{cm}}}{\gamma_{10^4} L_{5\cdot 10^6 L_\odot}} \times 6 \cdot 10^2 \mathrm{~s.}$$
- p interaction $$t_{pp} = \frac{1}{\sigma_{pp} \delta n c} = \frac{4\pi R^2_{sh} m_p V_w}{\sigma_{pp} \delta \dot{M} c} \approx \frac{R^2_{10^{14}\mathrm{cm}} V_{10^3\mathrm{km/s}}}{\delta_{10} \dot{M}_{10^{-4} M_\odot/\mathrm{yr}}} \times 4 \cdot 10^5 \mathrm{~s}$$

Comparing the Fermi acceleration time scale $$t_{acc} = \frac{R_L}{c} \left(\frac{c}{V}\right)^2$$

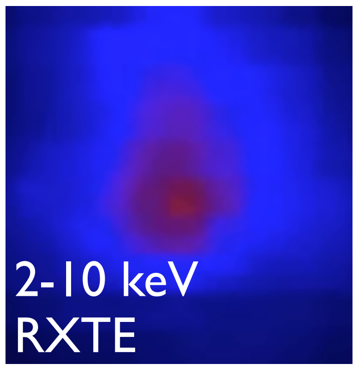
to the cooling times provides: $$\gamma_{max,e} = \sqrt{\frac{3\pi e c^2}{\sigma_T \beta^2}} \sqrt{\frac{B \cdot R^2}{L}} \frac{V}{c} \approx \sqrt{\frac{B_{1\mathrm{G}} \cdot R^2_{10^{14}\mathrm{cm}}}{L_{5\cdot 10^6 L_\odot}}} V_{10^3\mathrm{km/s}} \times 3 \cdot 10^4$$

roughly independent from the orbital phase

Eichler & Usov, 93; A&A (2011) 526, 57

# Observed orbital modulations

The X-ray emission varies by ~4 (excl. "eclipse")
The GeV emission varies by 1.3
The 10 GeV emission varies varies by $8^{+\infty}_{-4}$

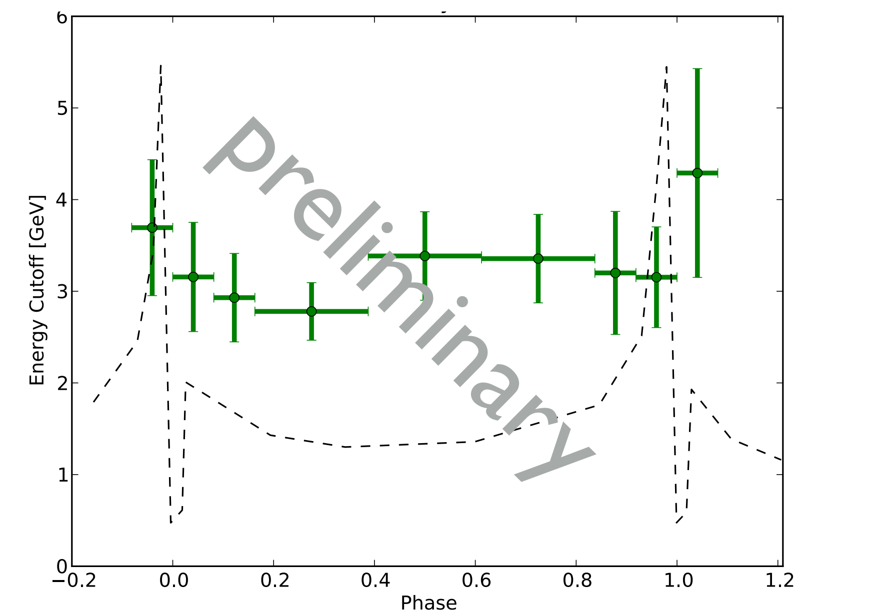


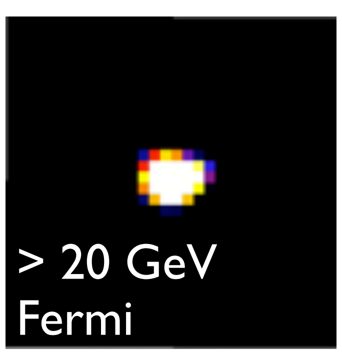

Courtesy M. Corcoran

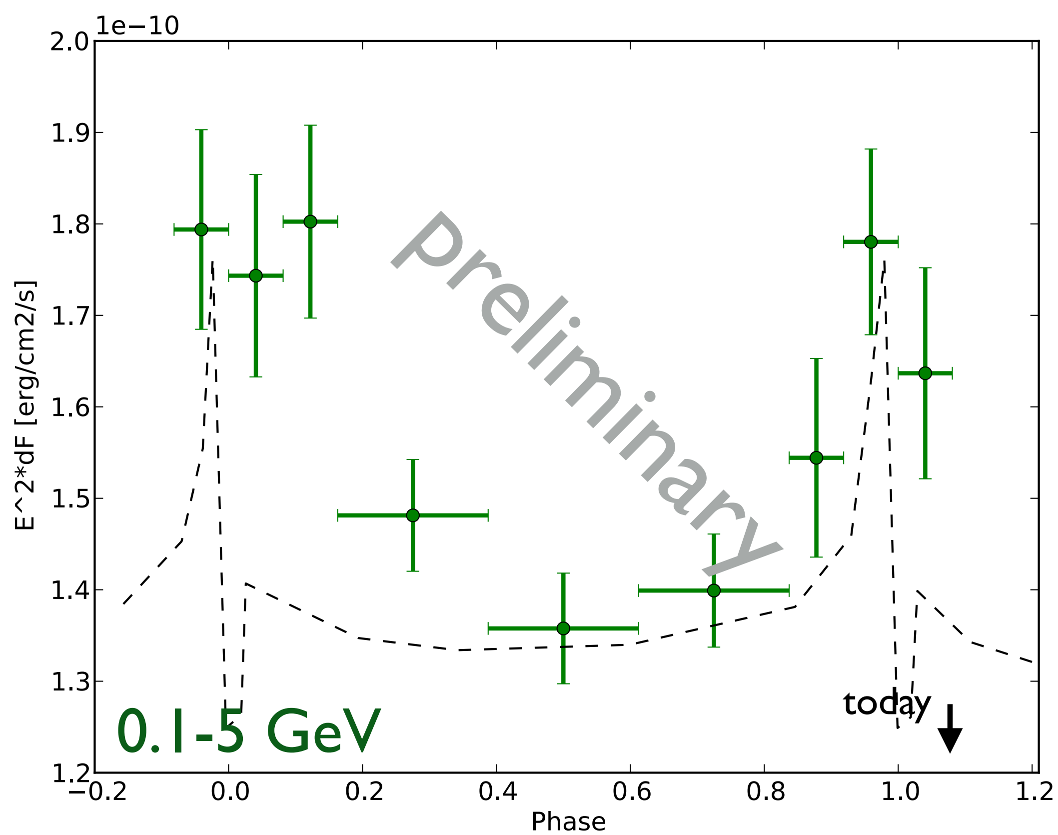
mostly a density effect

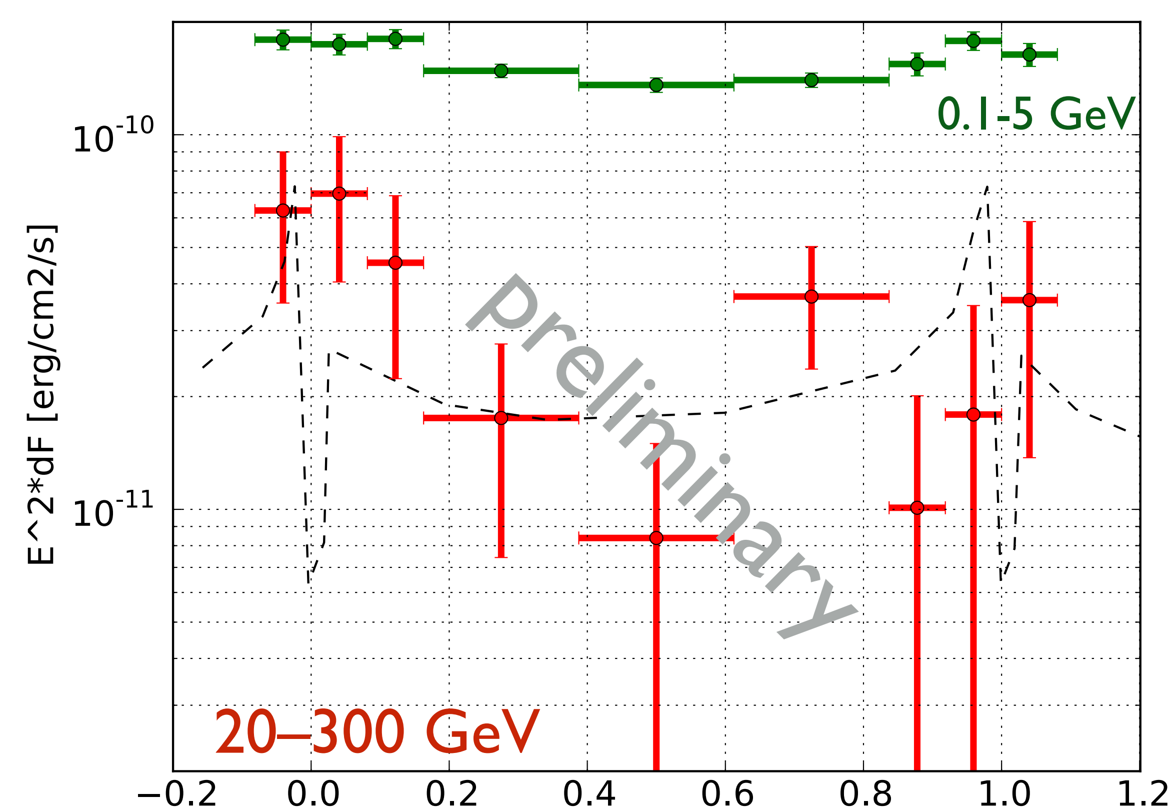
2-10 keV

Preliminary

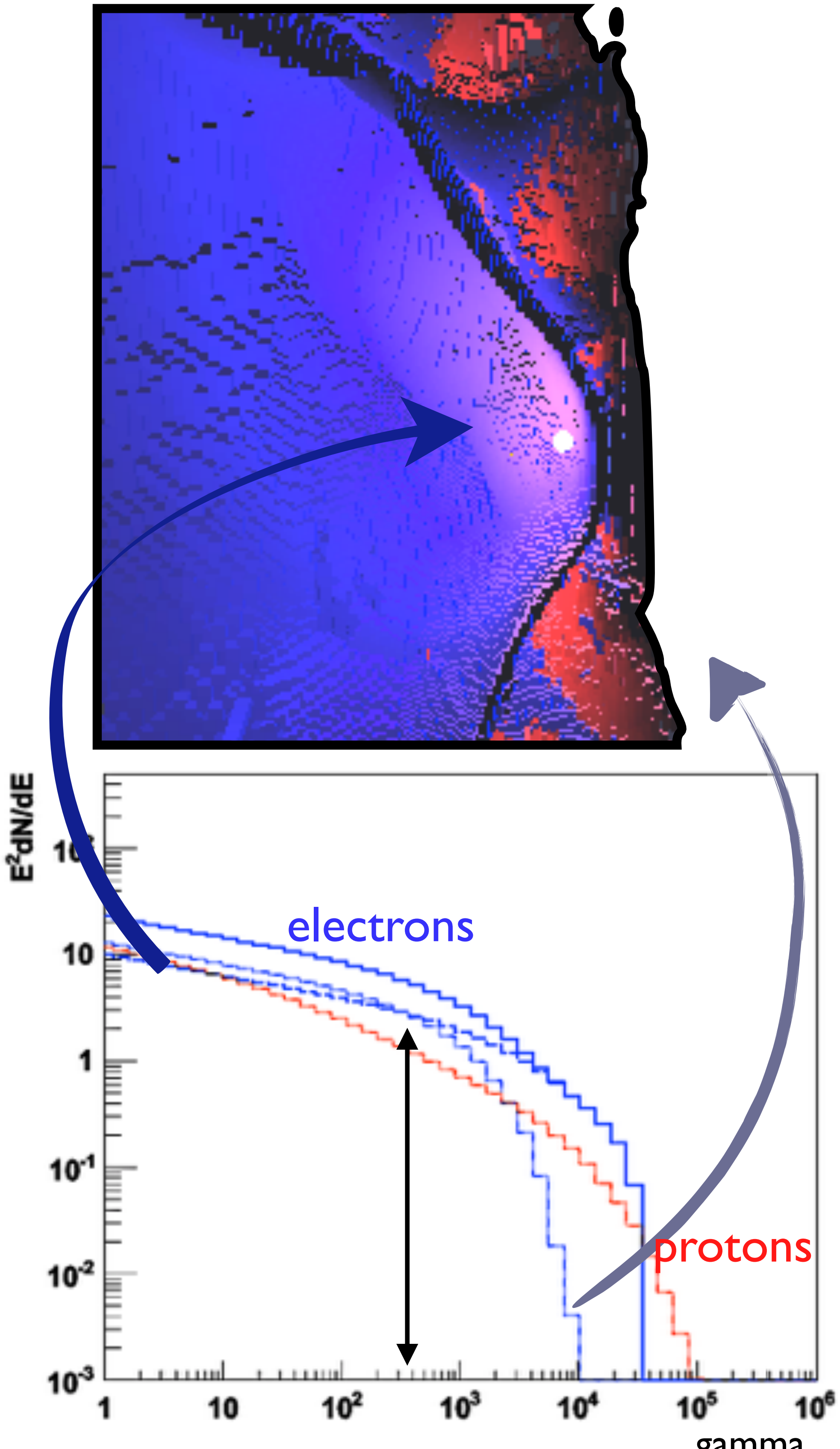


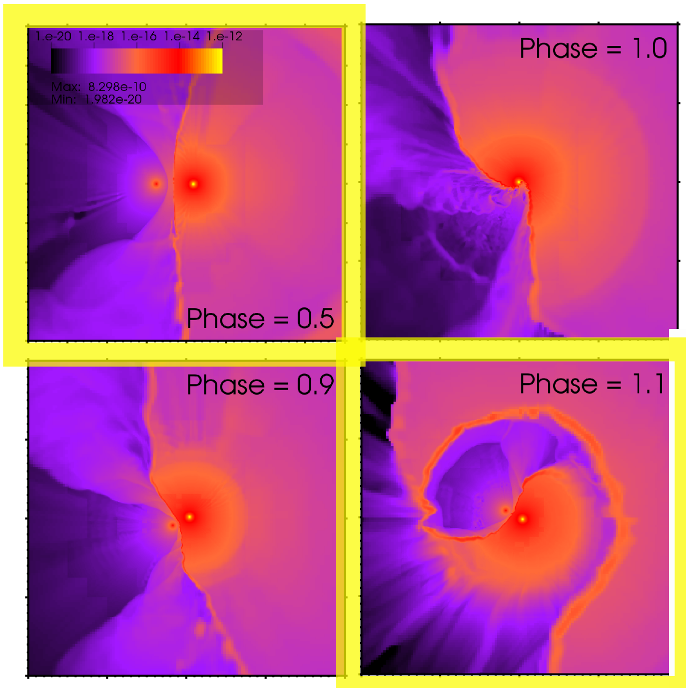



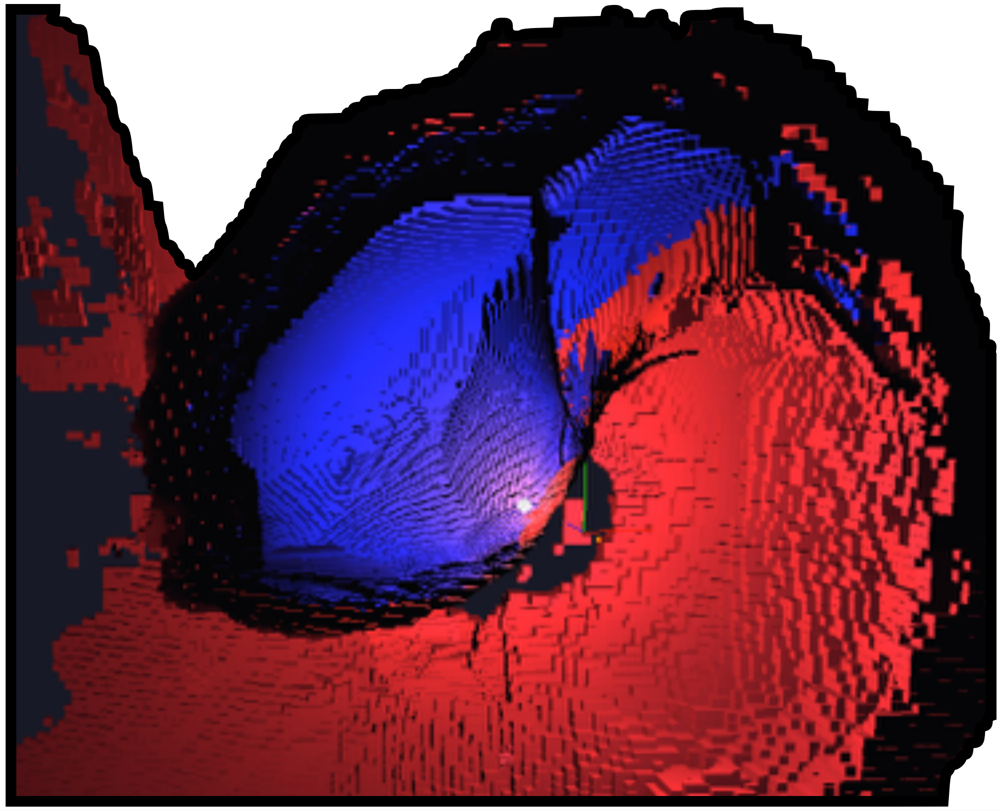
# 3D-hydro-simulations (Flash)

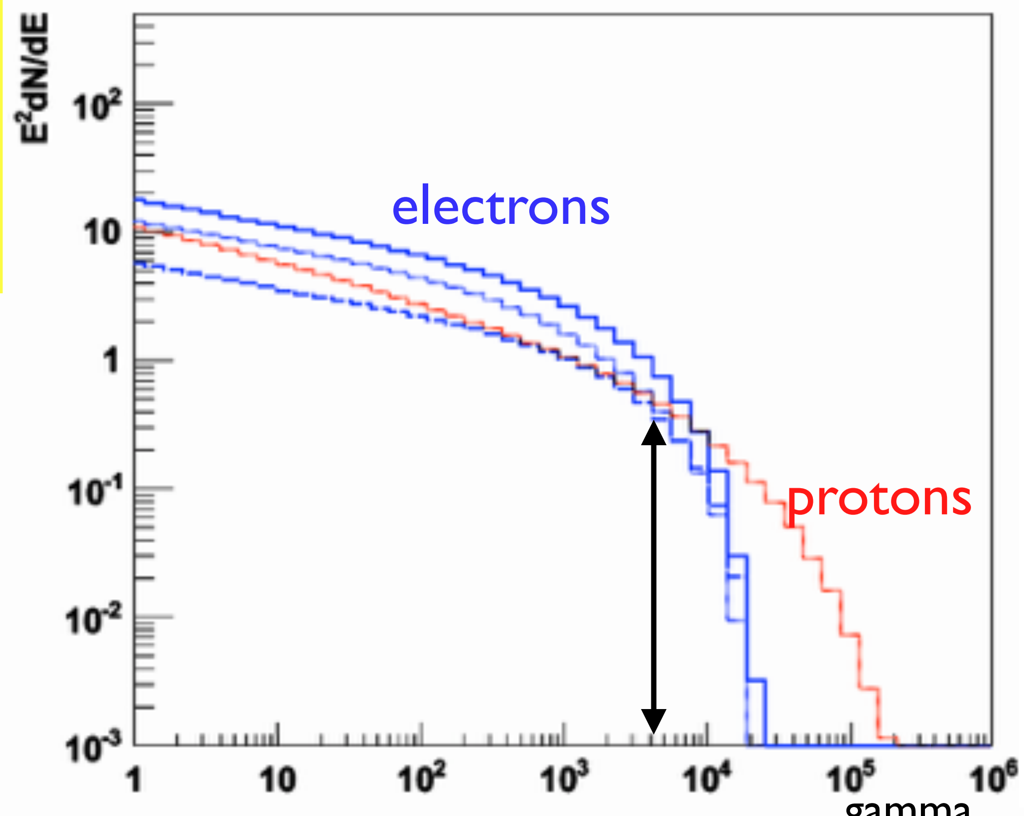



| Parameter | Primary | Secondary |
|---|---|---|
| $M$ ($M_\odot$) | 120 | 30 |
| $R_*$ ($R_\odot$) | 100 | 20 |
| $T_{cs}$ (K) | 25,800 | 30,000 |
| $L_*$ ($10^6 L_\odot$) | 4 | 0.3 |
| $k$ | 0.30 | 0.50 |
| $\alpha$ | 0.52 | 0.68 |
| $\dot{M}$ ($M_\odot\, yr^{-1}$) | $4.8 \times 10^{-4}$ | $1.4 \times 10^{-5}$ |
| $v_\infty$ ($km\, s^{-1}$) | 500 | 3000 |
| B (G) | 2000 | |




Parkin et al, 2011

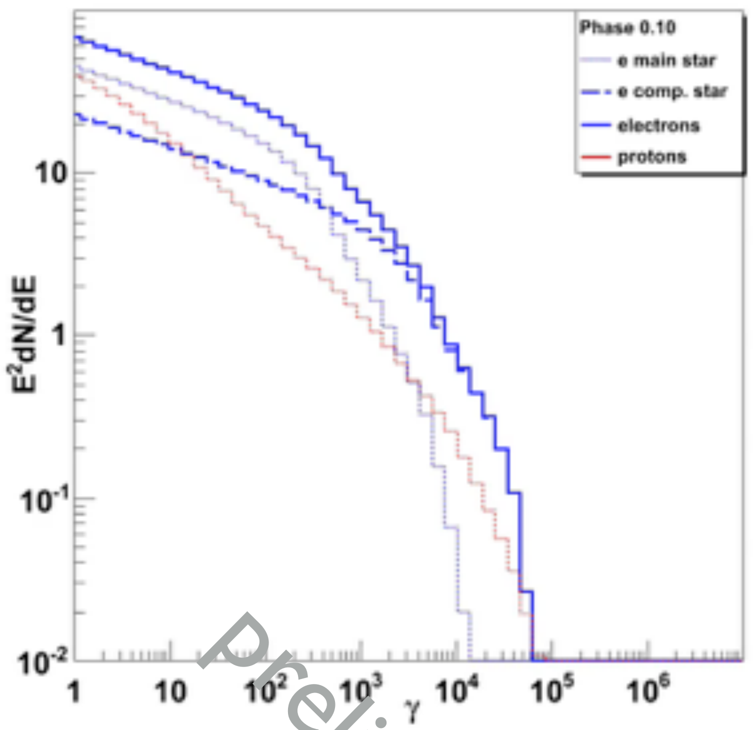


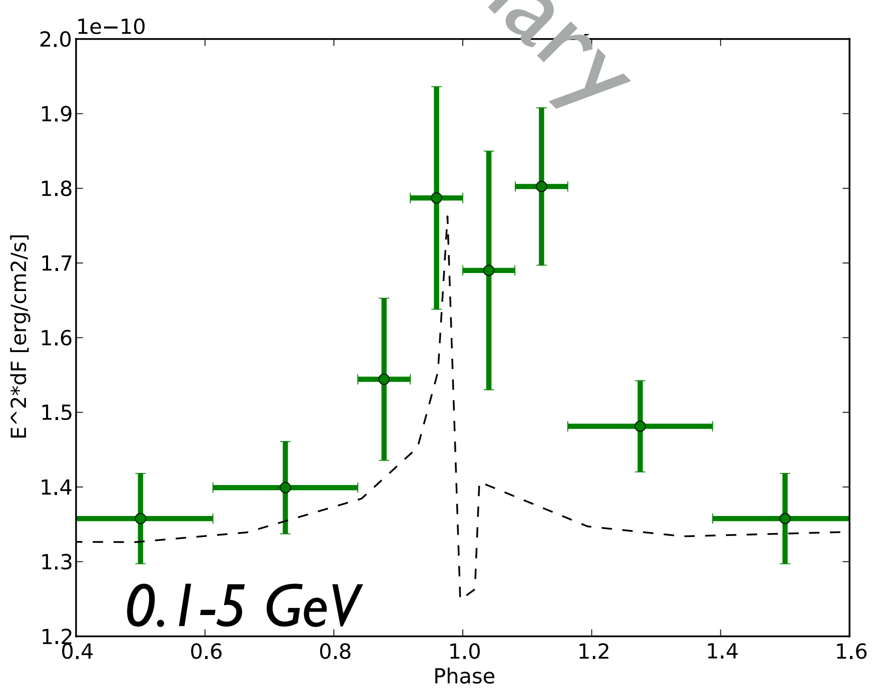



➜ smooth e⁻ spectrum

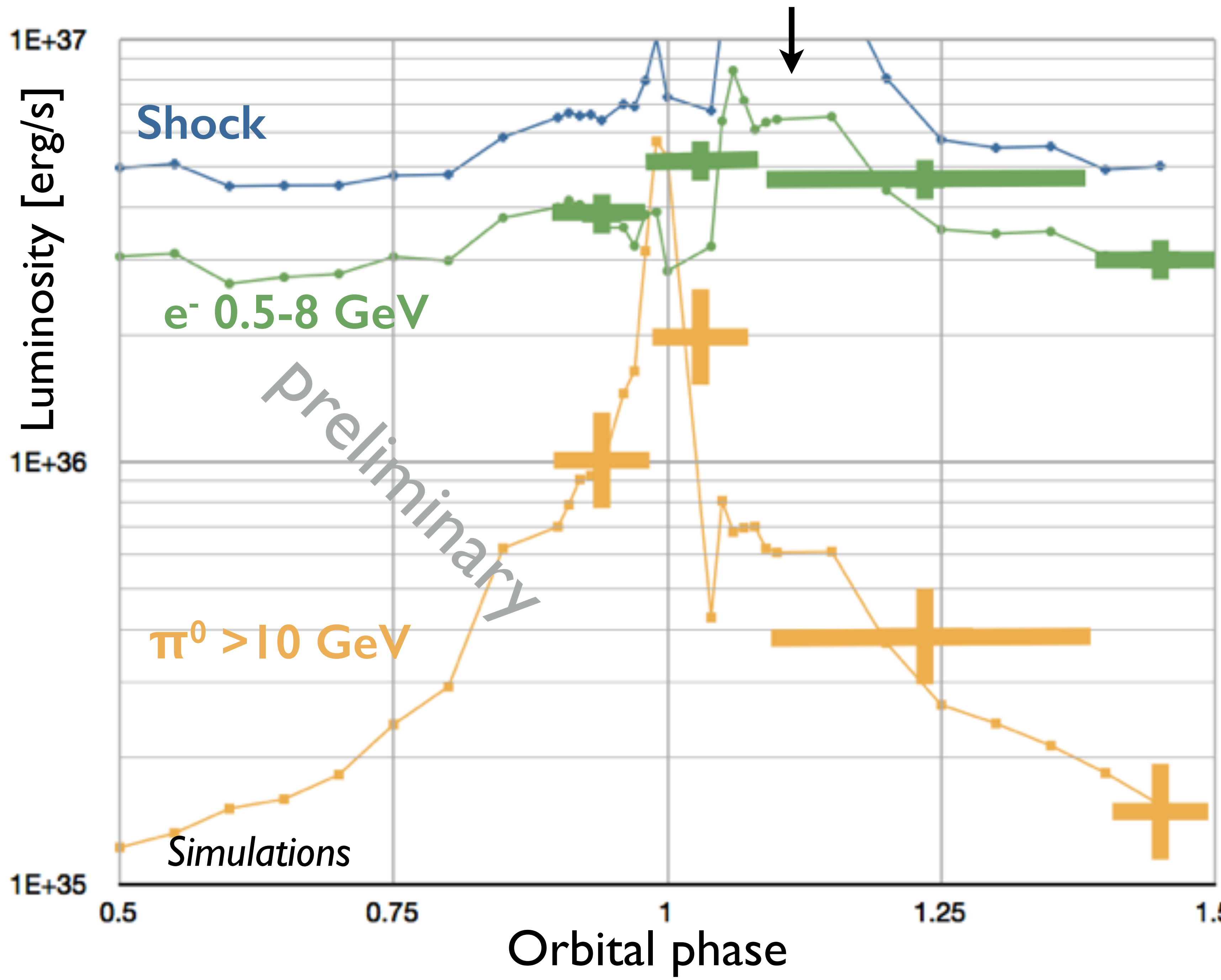
➜ smooth IC spectrum

# Simulated modulations




this «bump» is related to some details of the geometry




Eichler & Usov 93: *«the pionization conversion efficiency should be proportional to $D^{-1}$, unlike the inverse Compton luminosity»*

# Comparing models

1. ***gamma-ray pulsar & PWN*** *(Abdo et al, 2010)*

   Variability excludes the PWN
   Pulsar not detected by Chandra
   Coincidence probability ~$10^{-5}$

2. ***external shock*** *(Ohm et al, 2010)*

   Does not explain more than 20'% of the 50 keV component.
   Cannot explain the >10 GeV component, nor its variability
   A contribution is possible

3. ***two electrons populations*** *(Bednarek & Pabich, 2011)*

   Acceleration parameters vary along the shock surface resulting in a smooth electron spectrum
   Observed variations of the cutoff energy are much smaller than predicted

4. ***electrons & hadrons*** *(Eichler & Usov, 1993; Farnier & Walter,* 2011*)*

   Still working (and somewhat expected)
   IC maximum after periastron

Eta Carinae is likely a Large Hadron Collider

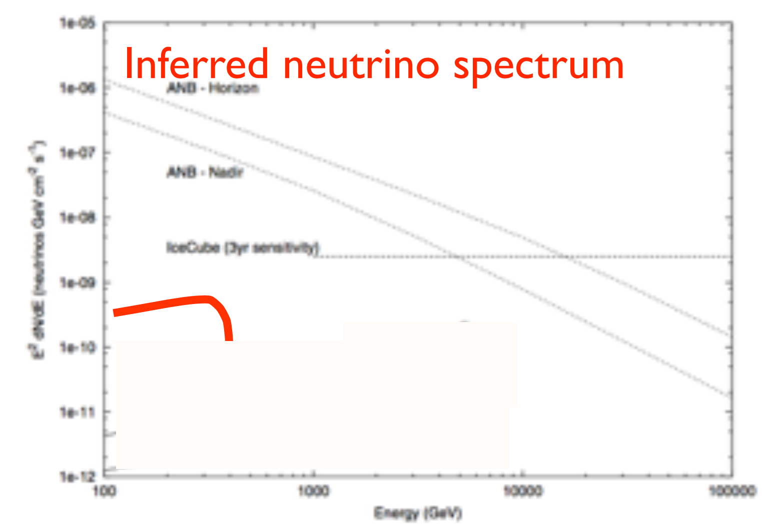
# Summary and energetics

Observations:

- In the GeV, the orbital modulation is < 2
- Above 10 GeV, the flux is strongly modulated with the orbital phase (factor ~ 10)

Wind collision simulations:

- The total electron spectrum is smooth
- The mechanical luminosity available to accelerate electrons is not strongly modulated
- The $\pi^0$ decay emission depends on the density and could be modulated in a similar way as the X-ray emission
- Energetics:
  - Thermal X-rays: 25 $L_\odot$ (2% $L_{shock}$)
  - Synchrotron: < 0.1 $L_\odot$
  - electron acceleration: 50 $L_\odot$ (6% $L_{mec}$)
  - $\pi^0$ emission: 10 $L_\odot$ (2% $L_{mec}$)




---

- η Carinae shows evidences for electronic and hadronic acceleration
- Proton cutoff energy $\gtrsim 10^{13}$ eV, *higher than measured in middle aged SNR*
- Efficiency of particle acceleration ~ 5% (Spitkovsky's simulations: 10%)