(Very-) High Energy End of Pulsar Spectra
What is at stake?

"Phenomenology & Future Prospects"
(Isolated pulsars)

Arache Djannati-Ataï
APC Laboratory, Paris

Third HONEST Workshop
Online, Novembre 2024

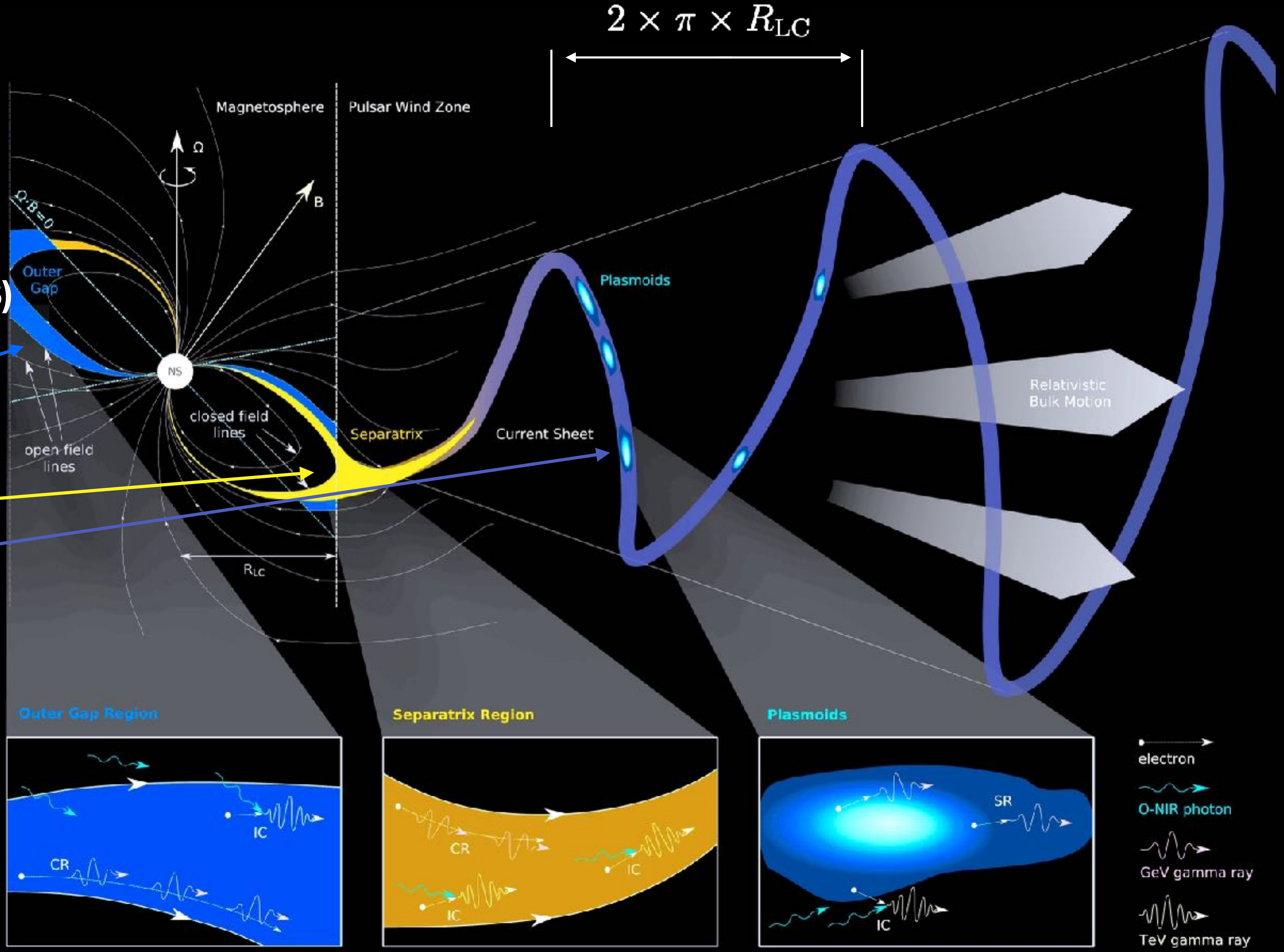
Origin of HE/VHE emission?

- Two main paradigms:
  - Acceleration by $E_{||}$ in gaps ++
  - Acceleration through magnetic reconnection in the current sheet (CS)

- Two main scenarios:
  I- Curvature Radiation CR/IC in
    - Outer Gaps
    - Separatrix-CS

  II- SR/IC in the CS
    - near the LC
    - Boosted emission ~ >> R_{LC}

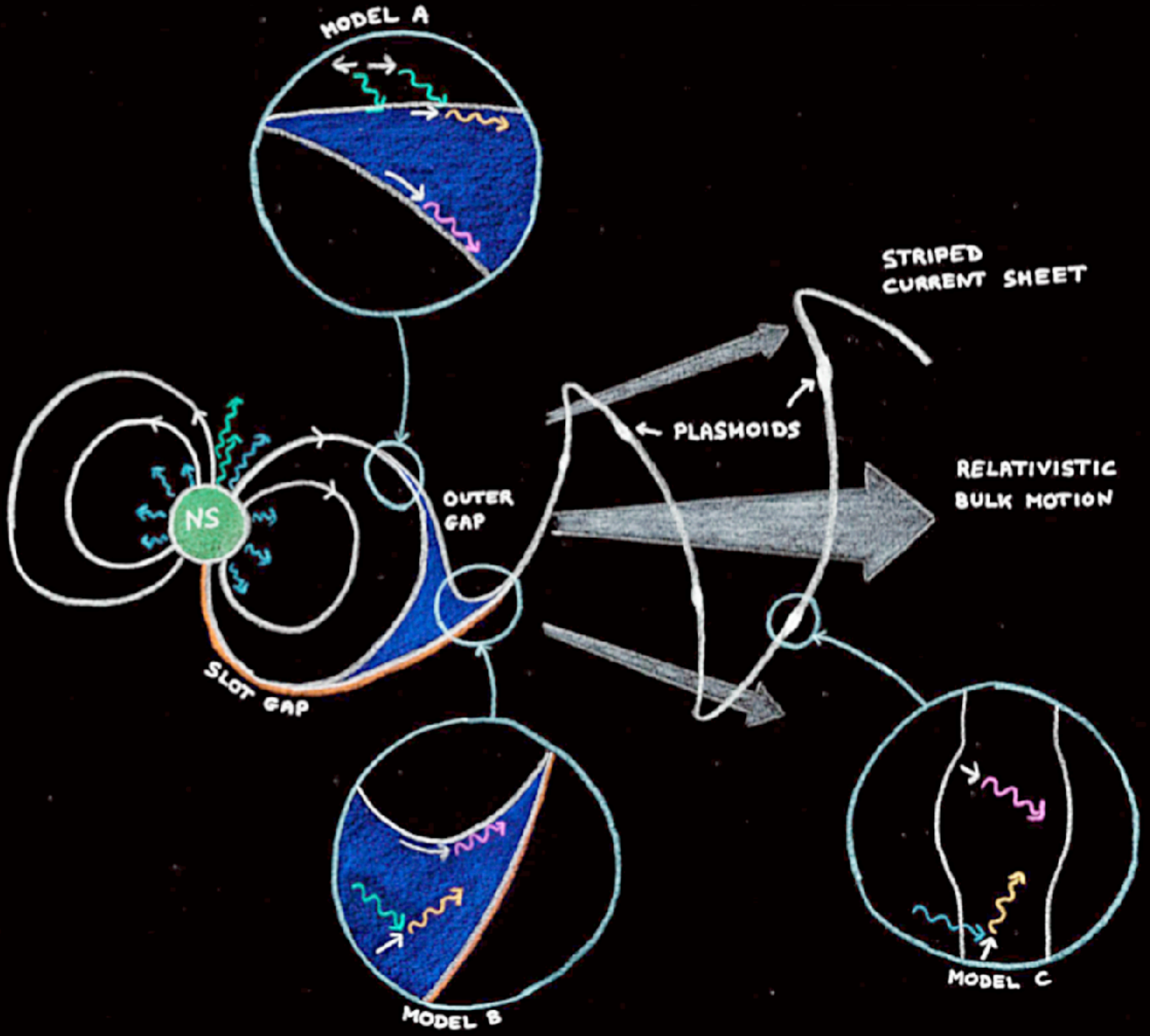
- UV-O-NIR Targets for IC scattering:
  - SR by secondary pairs
  - Along OG or between NS - 0.5 R_{LC}
  - Around CS (isotropic)



Nature Astronomy (2023), Vol 7, p. 1341-1350

The Original cartoon!

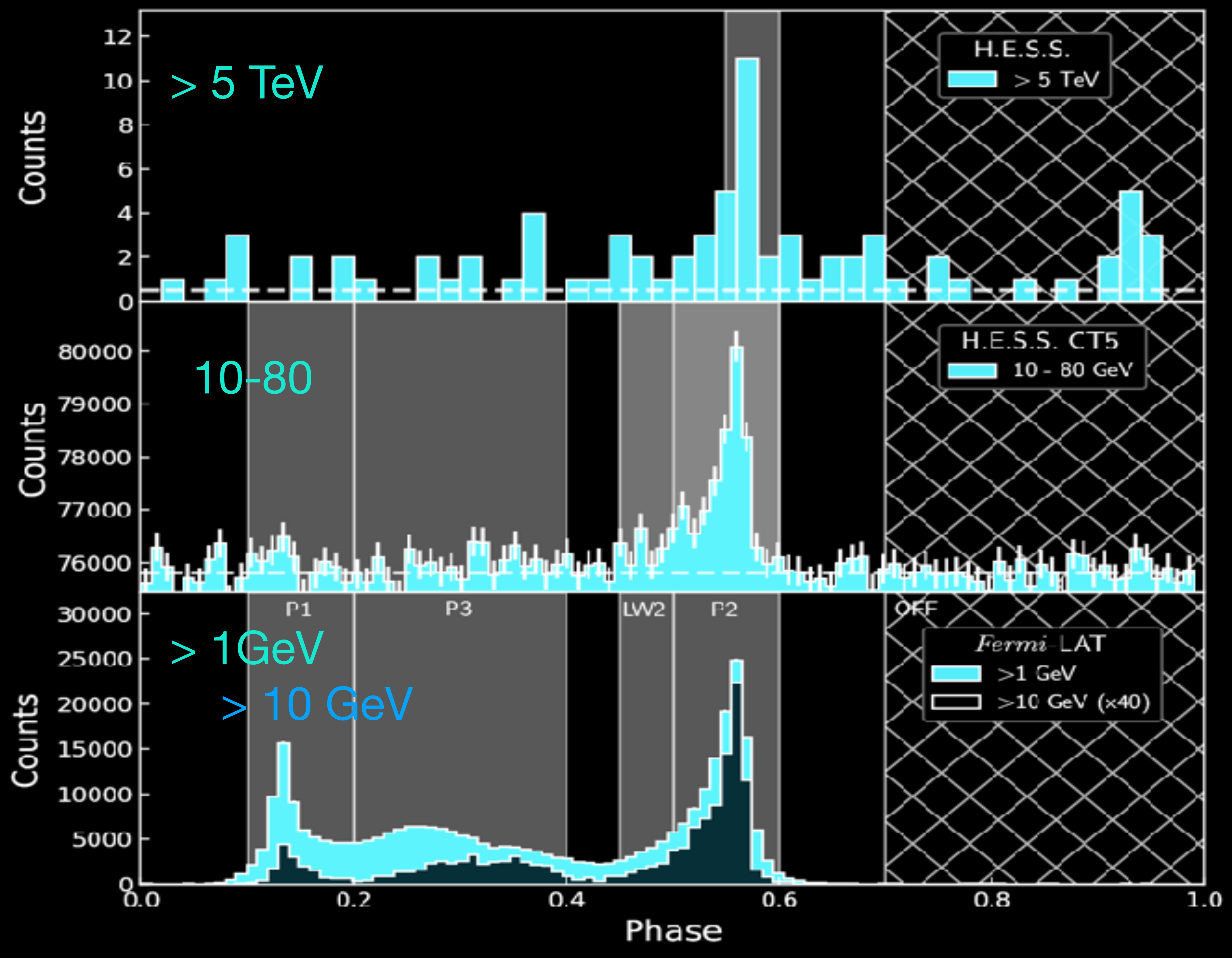
PhD, 2019, APC



Drawn first on the white board (room 596A, APC) by Marion Spir-Jacob during a discussion with ADA (~Nov 2018)

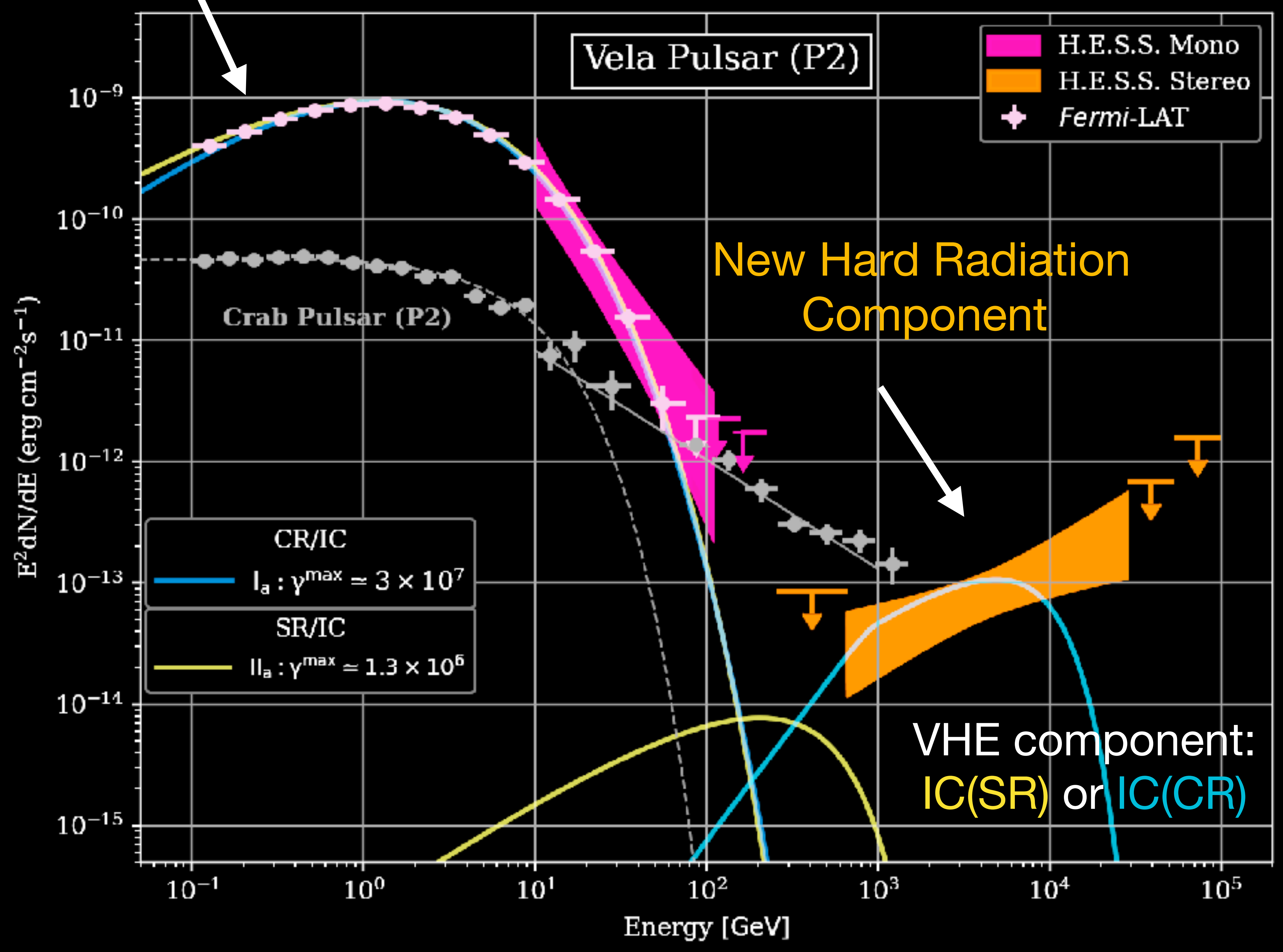
The 20 TeV emitter pulsar : Vela

Nature Astronomy (2023), Vol 7, p. 1341-1350



Phase & width compatible with <100 GeV pulses

HE component:
SR or CR



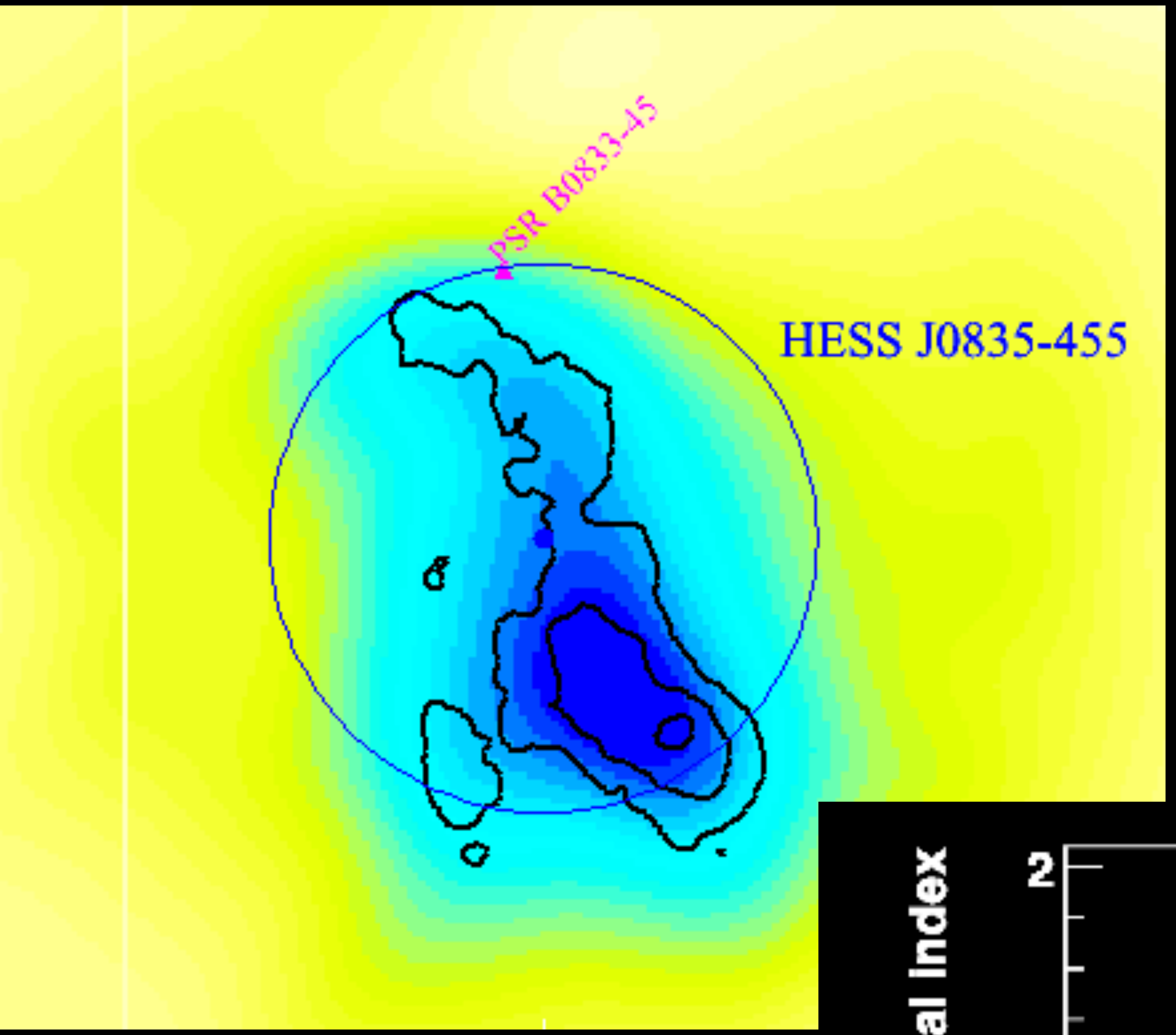
Very hard spectrum

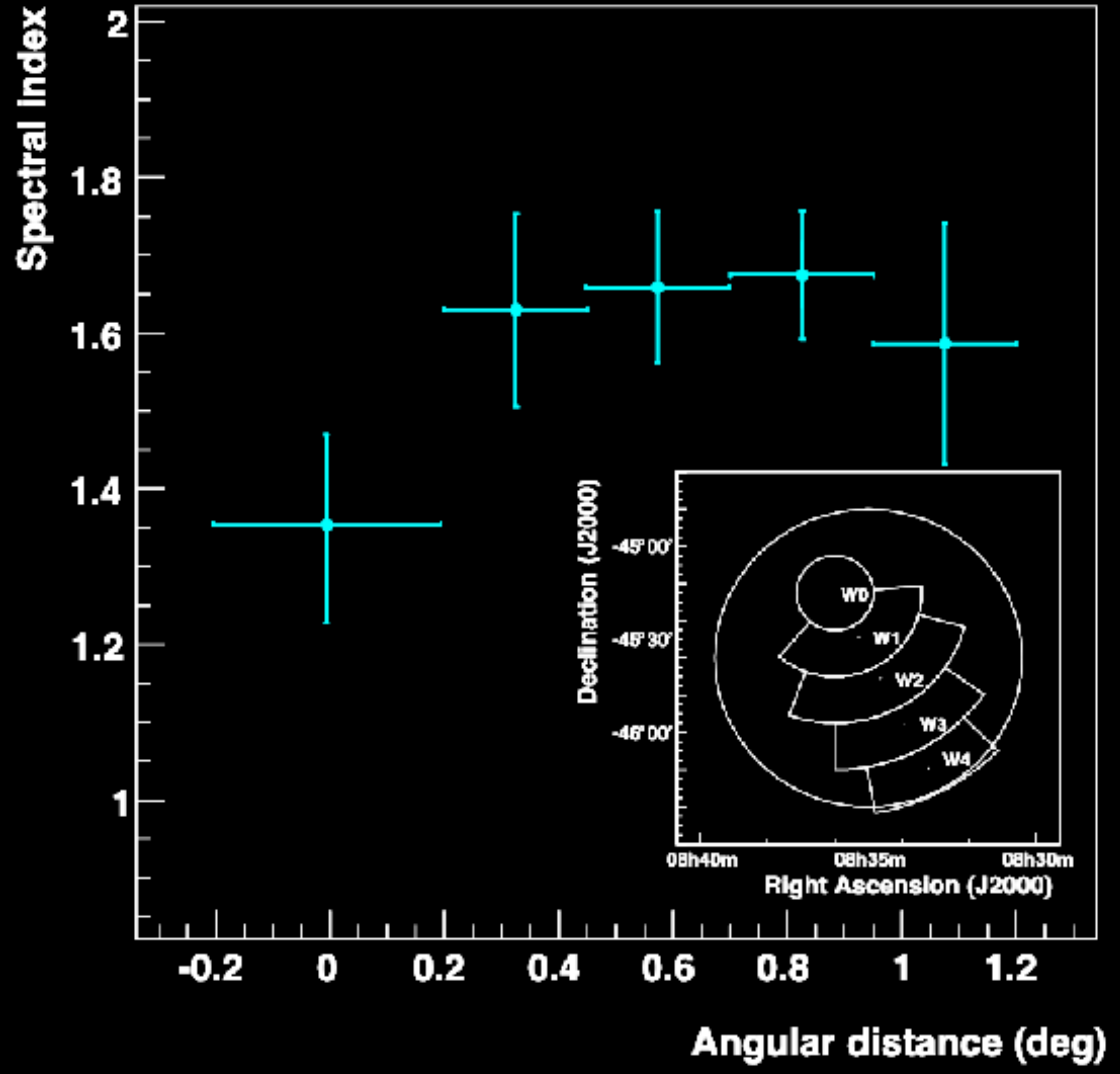
P2 : Γ = -1.4±0.3

New TeV component !

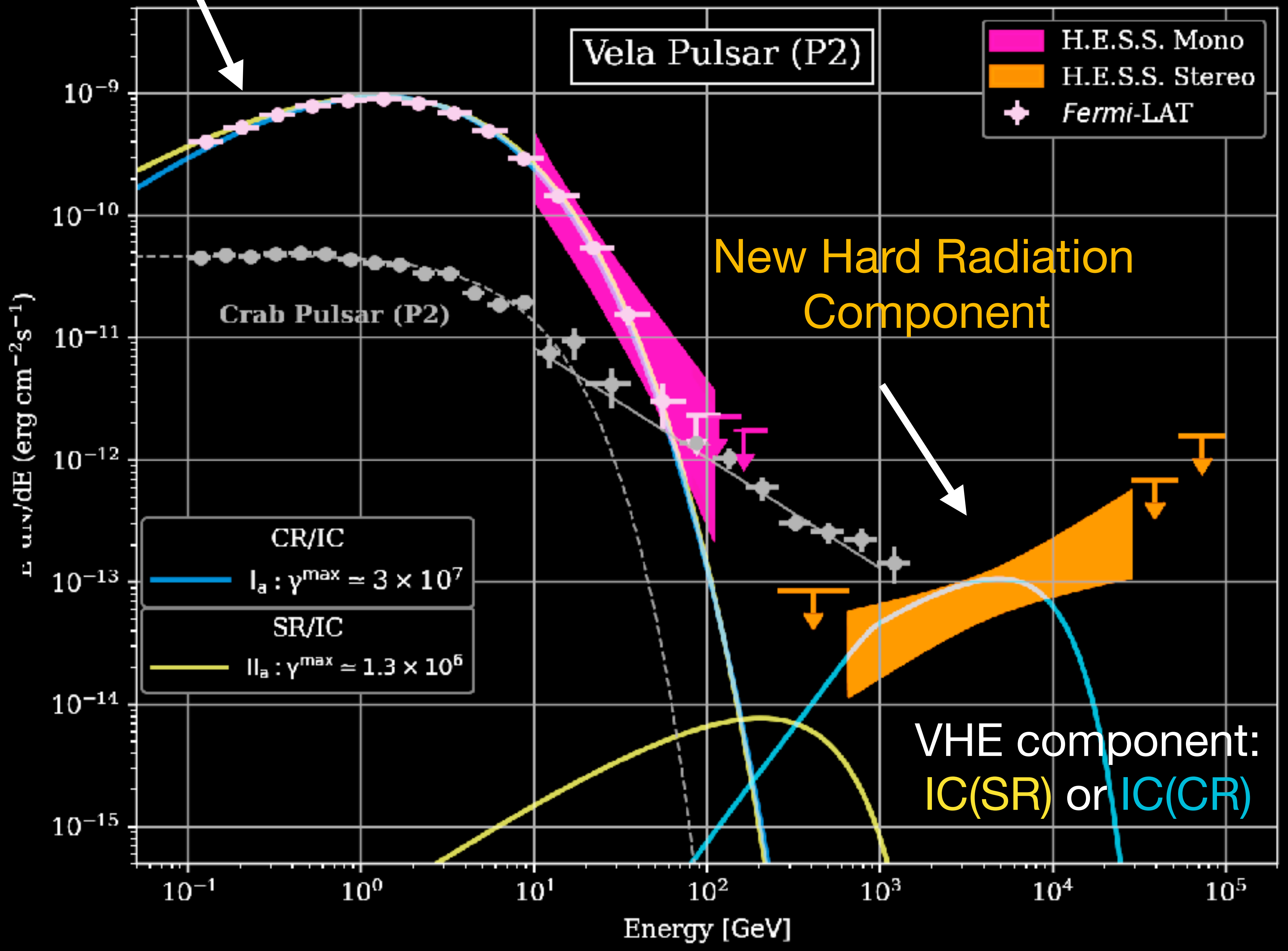
The 20 TeV emitter pulsar : Vela

Nature Astronomy (2023), Vol 7, p. 1341-1350





HE component:
SR or CR



VHE component:
IC(SR) or IC(CR)

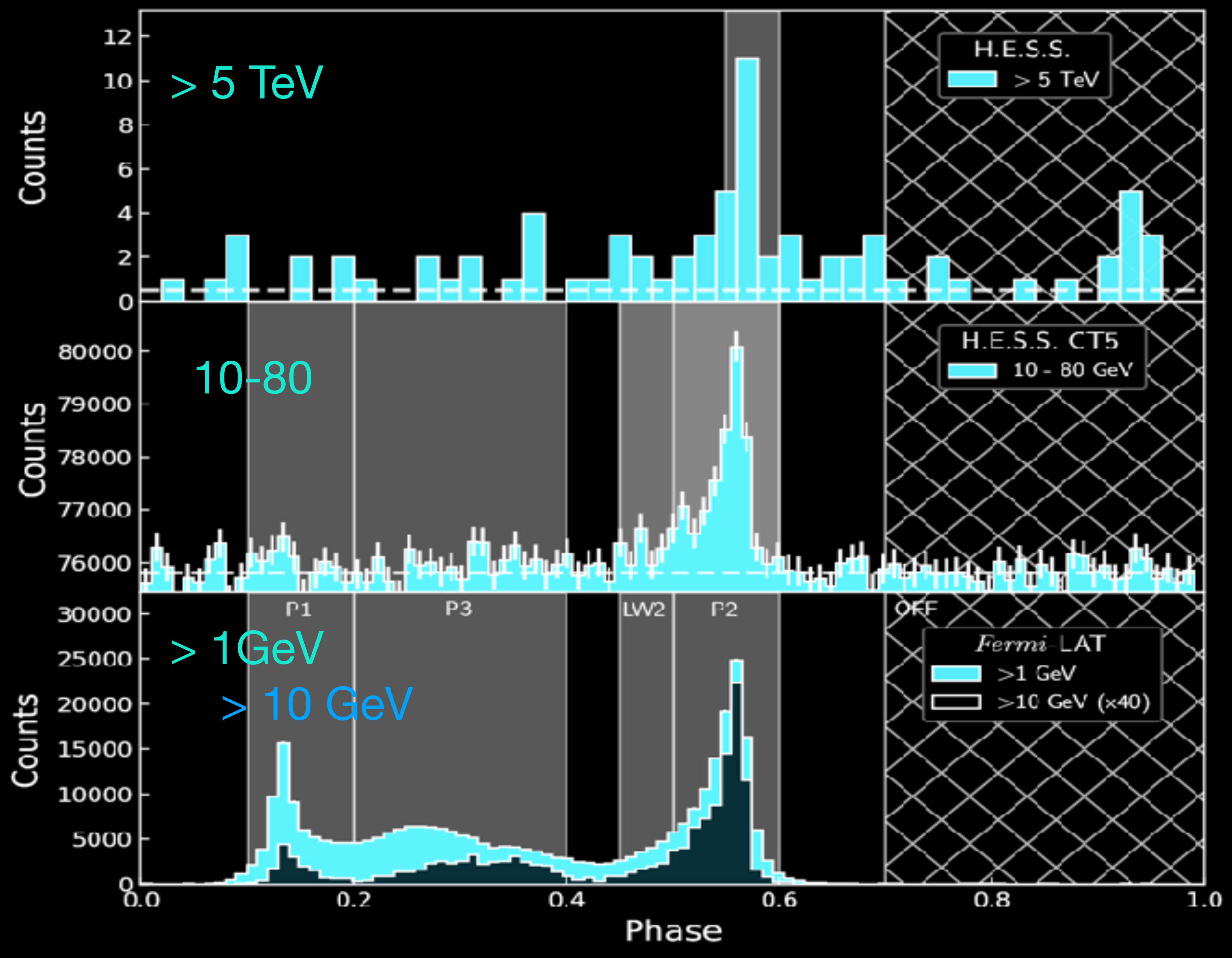
Very hard spectrum

P2 : Γ = -1.4±0.3

New TeV component !

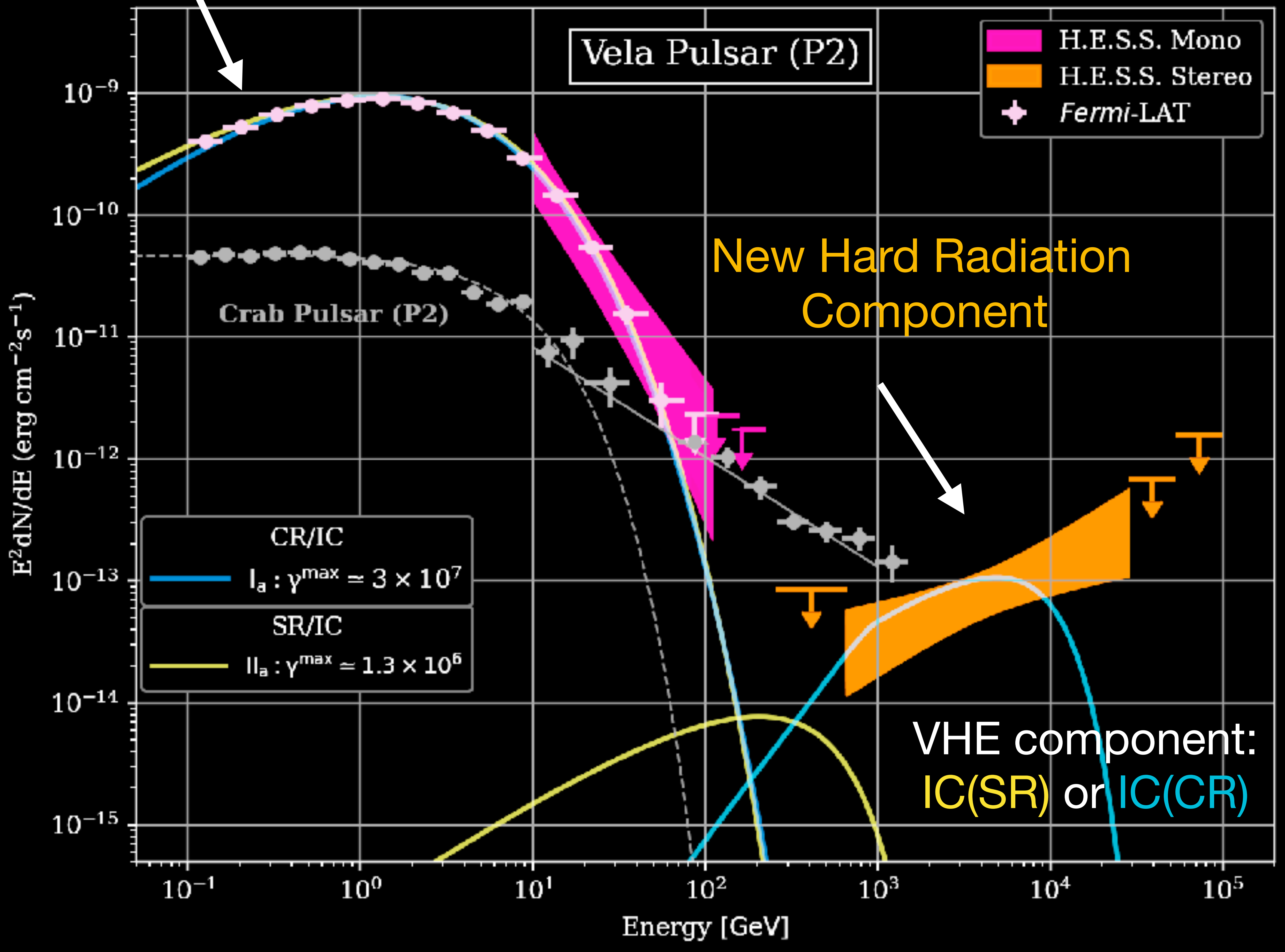
The 20 TeV emitter pulsar : Vela

Nature Astronomy (2023), Vol 7, p. 1341-1350



Phase & width compatible with <100 GeV pulses

HE component:
SR or CR



VHE component:
IC(SR) or IC(CR)

Very hard spectrum

P2 : Γ = -1.4±0.3

New TeV component !

Parameter space !
Maximum Lorentz Factor

Maximum Lorentz Factor

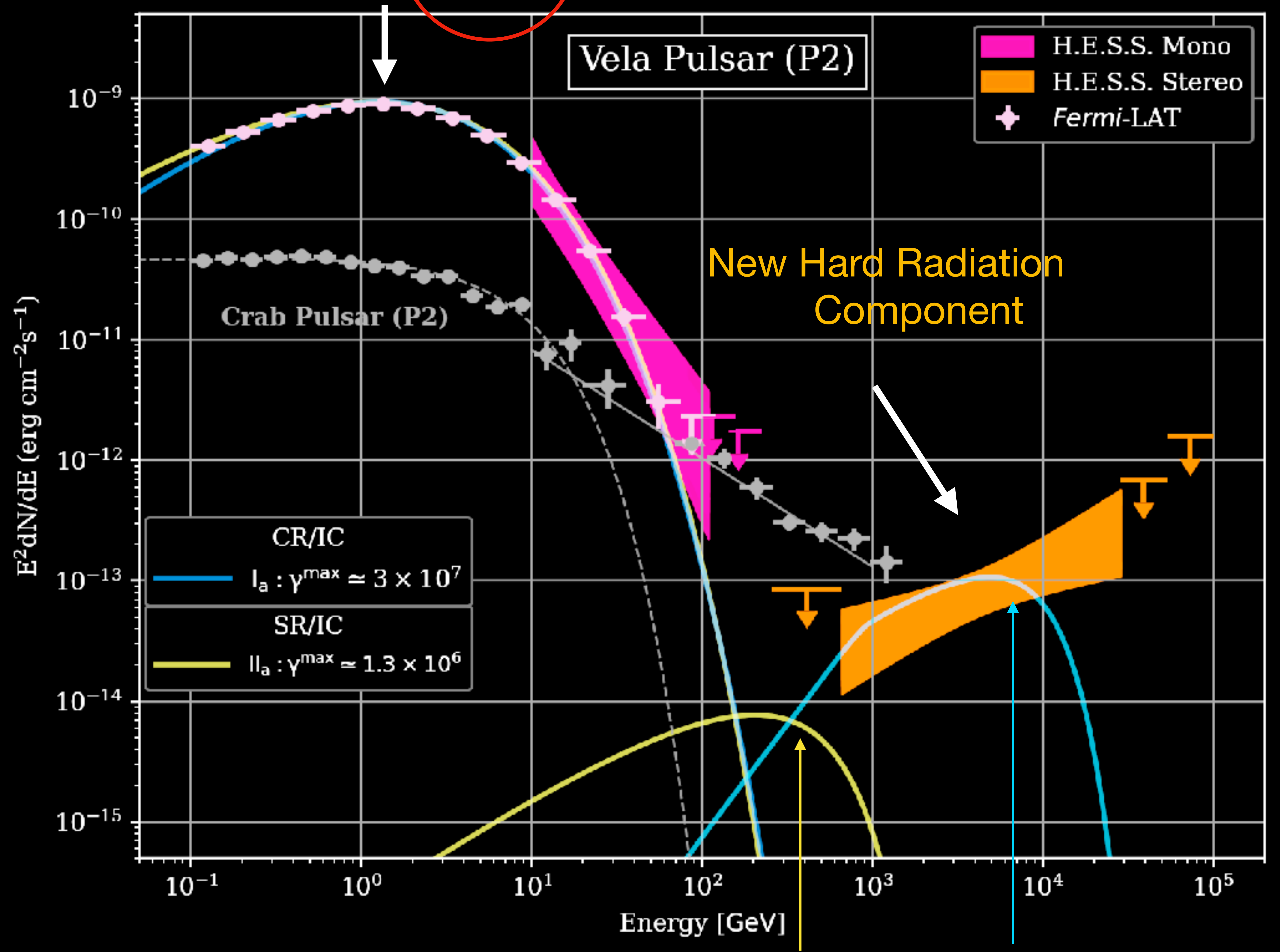
- Two main paradigmes:
  - Acceleration by $E_{||}$ in gaps
  - Acceleration through magnetic reconnection in the current sheet (CS)
- TeV phase aligned with GeV pulsations:
  - Same population & similar spatial regions
  - Not necessarily identical: caustics
- Two main scenarios:
  I- Curvature Radiation CR/IC in Outer Gaps/Separatrix-CS

$$\begin{cases} \gamma_{\rm CR}^{\rm max} \simeq 4\times 10^7\, \xi^{1/2}\eta_{-1}^{1/4} \\ E_{\rm CR}^{\rm max} \simeq 5\,{\rm GeV}\, \xi^{1/2}\eta_{-1}^{3/4} \end{cases} \quad \begin{cases} \eta_{-1} = \eta/0.1 \\ \rho_c = \xi\, R_{\rm LC} \end{cases}$$

II- SR/IC in the CS

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3\times 10^6 (B_\perp/B_{\rm LC})^{-1/2}\,(E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

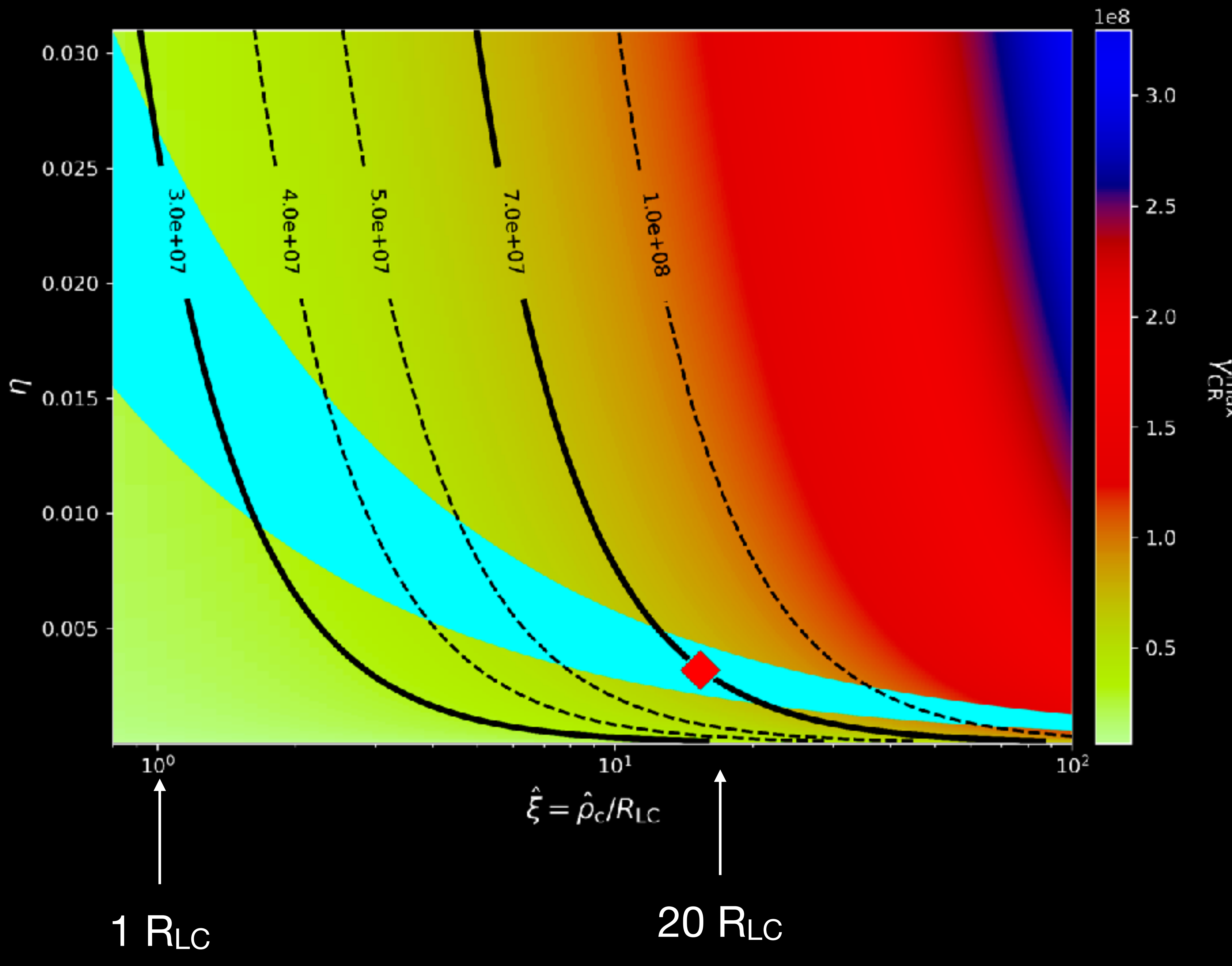
$E_{\rm HE}^{\rm peak} \simeq 1.5\,{\rm GeV}$



- Joint fit to GeV & TeV Components
- Insufficient maximum IC energies
- Normalisation = f(target density)

Maximum Lorentz Factor

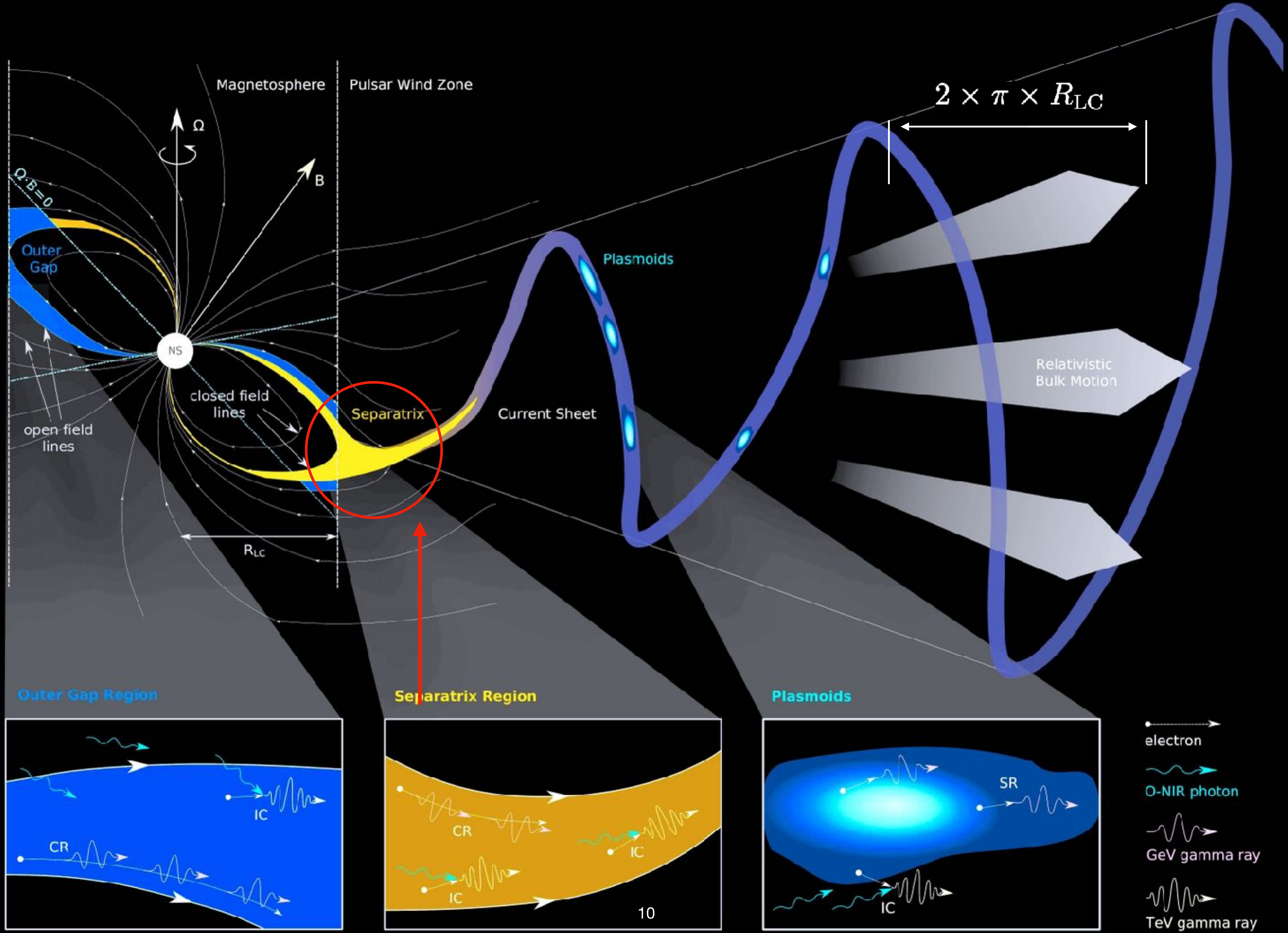
- Fit to theTeV data: $\gamma_{\rm IC}^{\rm max} \gtrsim 7 \times 10^7$
- CR/IC scenario:
  - Constraint by GeV data:
  - Different combinations of $(\eta, \hat{\xi})$ $\eta \ll 0.1 \text{ and } \hat{\xi} \gg 1$
  - Implies a dissipation region beyond the LC where $\rho_{\rm c} \gg R_{\rm LC}$
  - Can provide much higher energies than in traditional magnetospheric models



- SR/IC scenario:
  - Constraint by GeV data and B:

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3 \times 10^6 (B_\perp/B_{\rm LC})^{-1/2} \, (E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

  - Insufficient maximum energy
  - Particles well beyond SR cut-off
  - 2-step acceleration/SR-cooling process
    - Larmor radii > largest plasmoids
    - Re-acceleration after SR-cooling : Caustics
  - Doppler-boosted (bulk motion): $\begin{cases} \Gamma_{\rm w} \gtrsim 5 \\ \simeq 5 R_{\rm LC} \end{cases}$

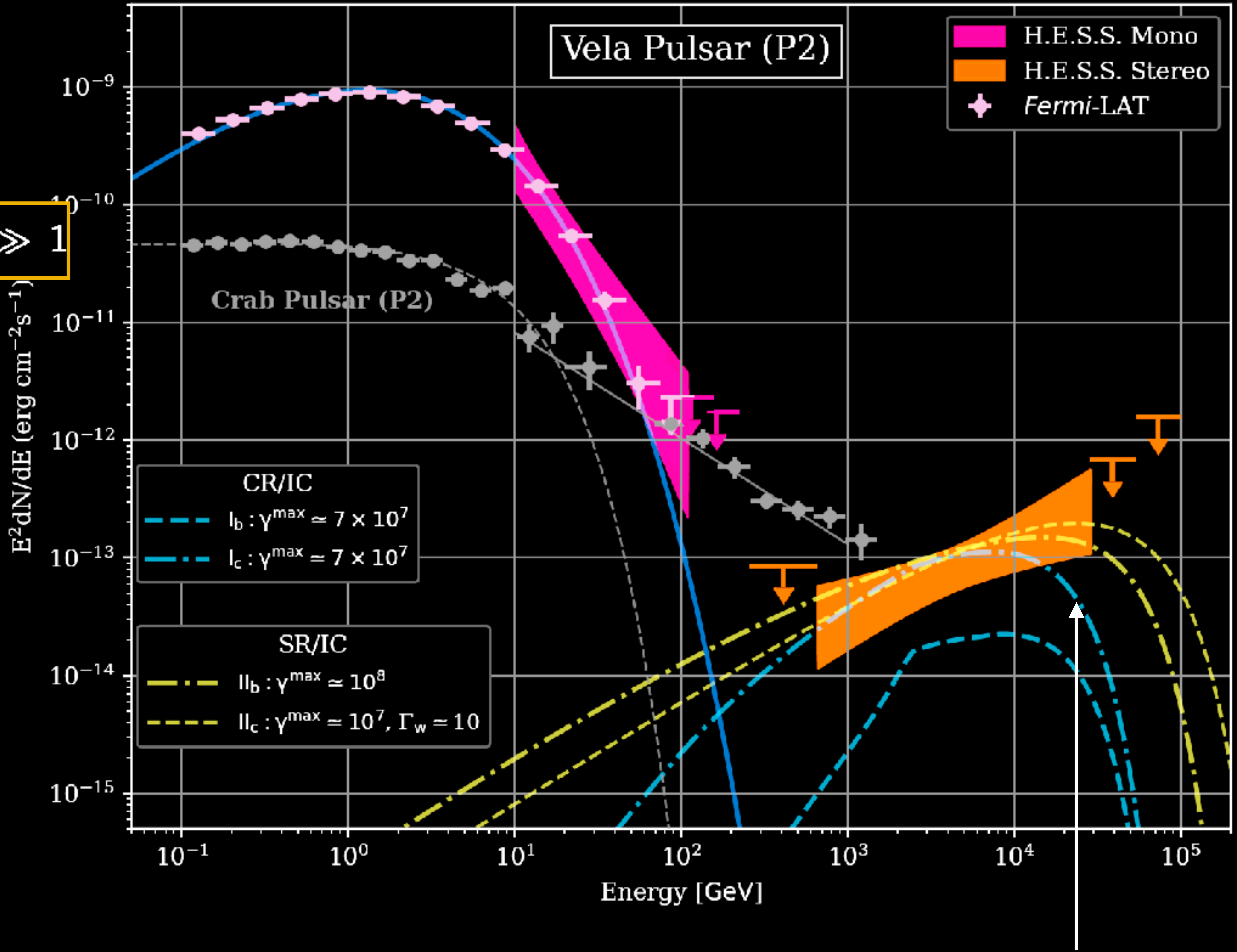

Magnetosphere
Pulsar Wind Zone
$2 \times \pi \times R_{LC}$
Ω
B
Ω·B=0
Outer Gap
NS
Plasmoids
closed field lines
open field lines
Separatrix
Current Sheet
Relativistic Bulk Motion
R_{LC}
Outer Gap Region
Separatrix Region
Plasmoids
IC
CR
SR
electron
O-NIR photon
GeV gamma ray
TeV gamma ray

Maximum Lorentz Factor

- Fit to theTeV data: $\gamma_{\rm IC}^{\rm max} \gtrsim 7 \times 10^7$
- CR/IC scenario:
  - Constraint by GeV data:
  - Different combinations of $(\eta, \hat{\xi})$ $\eta \ll 0.1$ and $\hat{\xi} \gg 1$
  - Implies a dissipation region beyond the LC where $\rho_c \gg R_{\rm LC}$
  - Can provide much higher energies than in traditional magnetospheric models
- SR/IC scenario:
  - Constraint by GeV data and B:

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3 \times 10^6 (B_\perp / B_{\rm LC})^{-1/2} \, (E_{\rm SR}^{\rm max} / 1.5\,{\rm GeV})^{1/2}$$

  - Insufficient maximum energy
  - Particles well beyond SR cut-off
  - 2-step acceleration/SR-cooling process
    - Larmor radii > largest plasmoids
    - Re-acceleration after SR-cooling : Caustics
  - Doppler-boosted (bulk motion): $\begin{cases} \Gamma_{\rm w} \gtrsim 5 \\ \simeq 5 R_{\rm LC} \end{cases}$

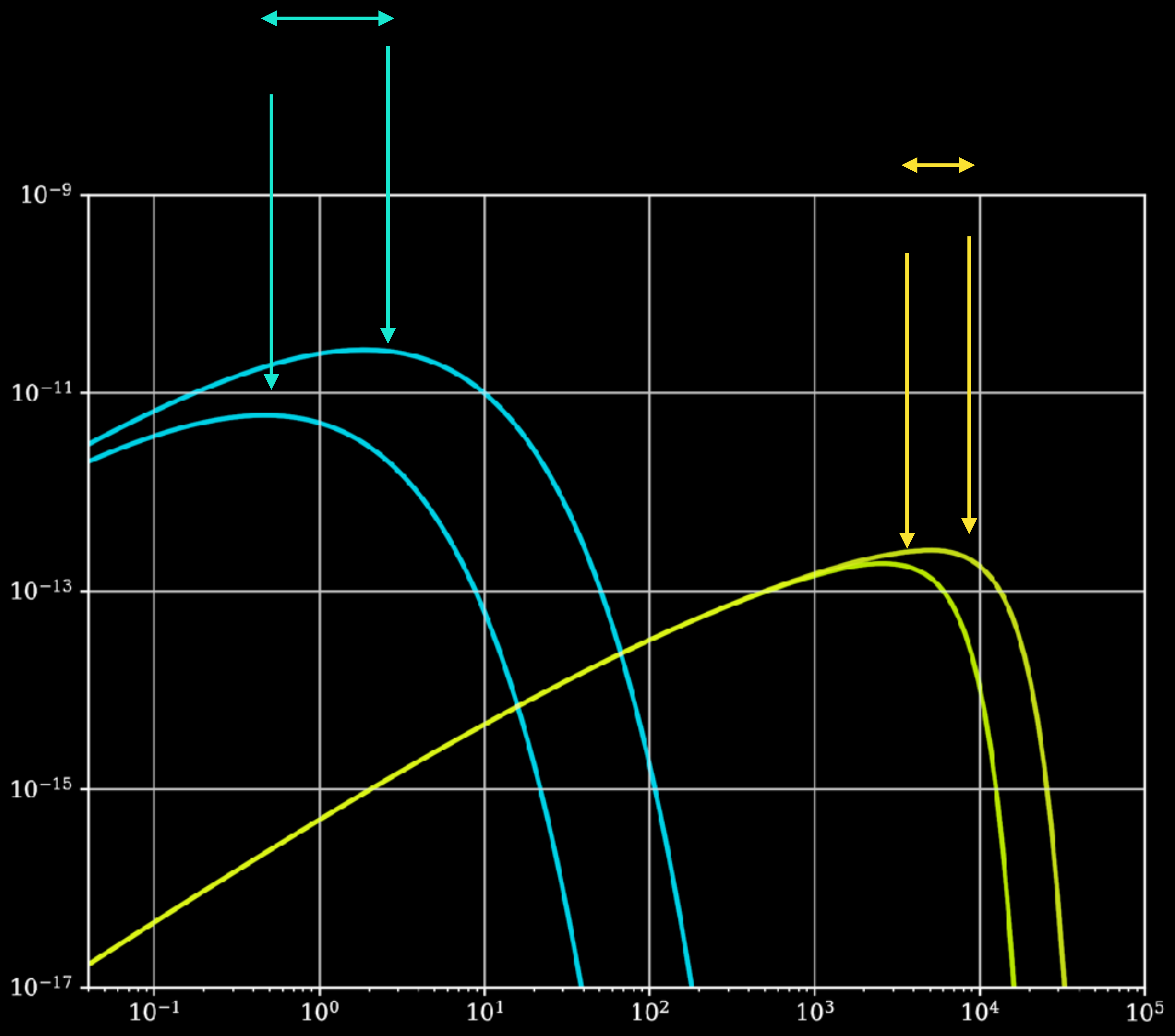


Maximum Lorentz Factor

- GeV Component
- Interpreted as CR
- Same distribution of particles

$$\frac{d^2N}{d\gamma dt} \propto (\gamma/\gamma_0)^{-p} \exp\left[-(\gamma/\gamma^{\max})^{\beta}\right]$$

- The GeV peak energy (or variations of it) is not the best measure of the maximum
- The IC component (in the KN regime) is unambiguous !

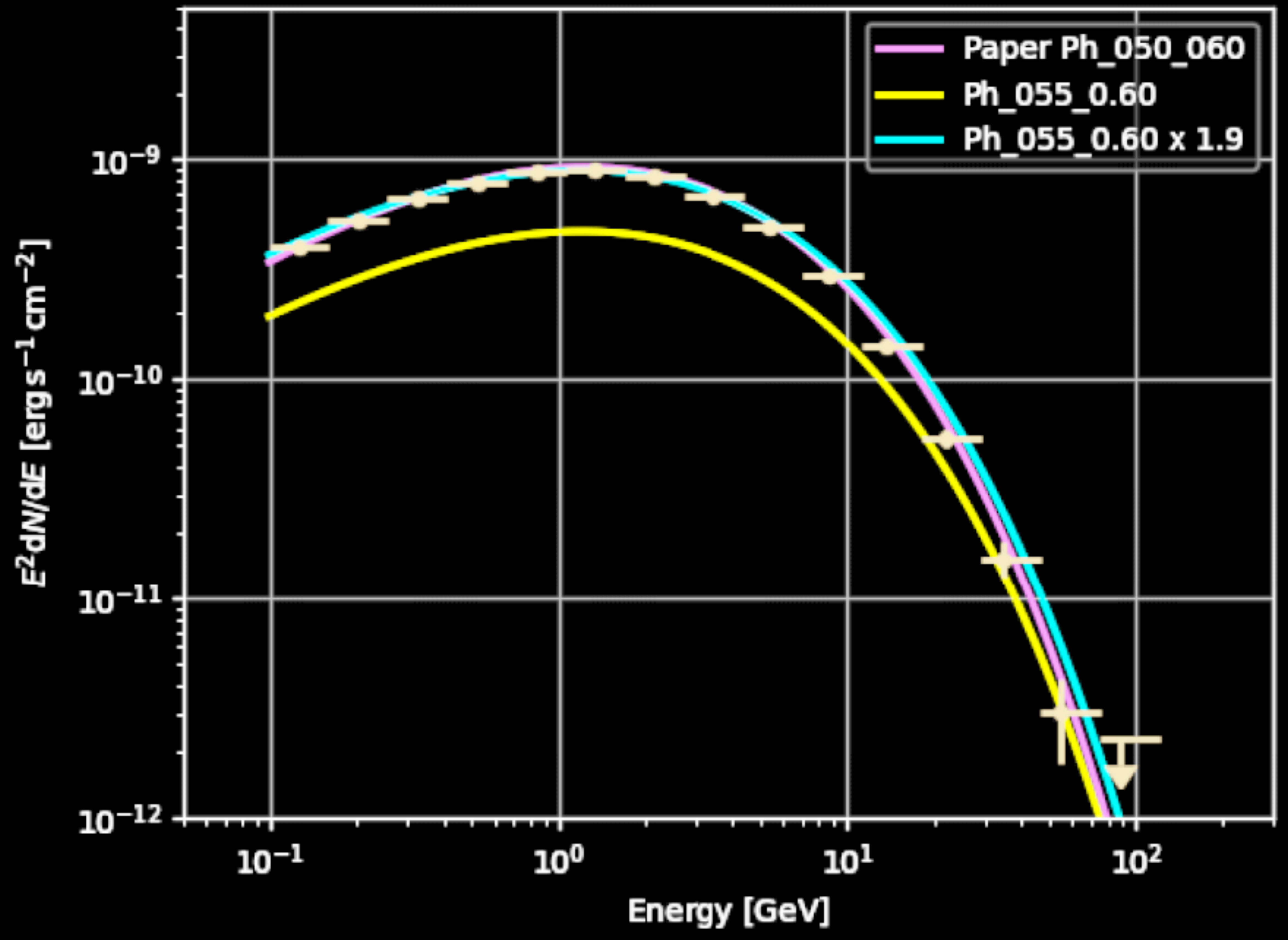


Maximum Lorentz Factor

- GeV Component
- Interpreted as CR
- Same distribution of particles

$$\frac{d^2N}{d\gamma dt} \propto (\gamma/\gamma_0)^{-p} \exp\left[-(\gamma/\gamma^{\max})^{\beta}\right]$$

- The GeV peak energy (or variations of it) is not the best measure of the maximum
- The IC component (in the KN regime) is unambiguous !
- GeV E_peak should be derived based on a finely phase-resolved spectrum
- However even for Vela with huge statistics one still gets a sub-exponential cutoff even with very fine binning



Maximum Lorentz Factor

- Fit to theTeV data: $\gamma_{\mathrm{IC}}^{\max} \gtrsim 7 \times 10^{7}$
- CR/IC scenario:
  - Constraint by GeV data:
  - Different combinations of $(\eta, \hat{\xi})$ $\eta \ll 0.1$ and $\hat{\xi} \gg 1$
  - Implies a dissipation region beyond the LC where $\rho_{\mathrm{c}} \gg R_{\mathrm{LC}}$
  - Can provide much higher energies than in traditional magnetospheric models

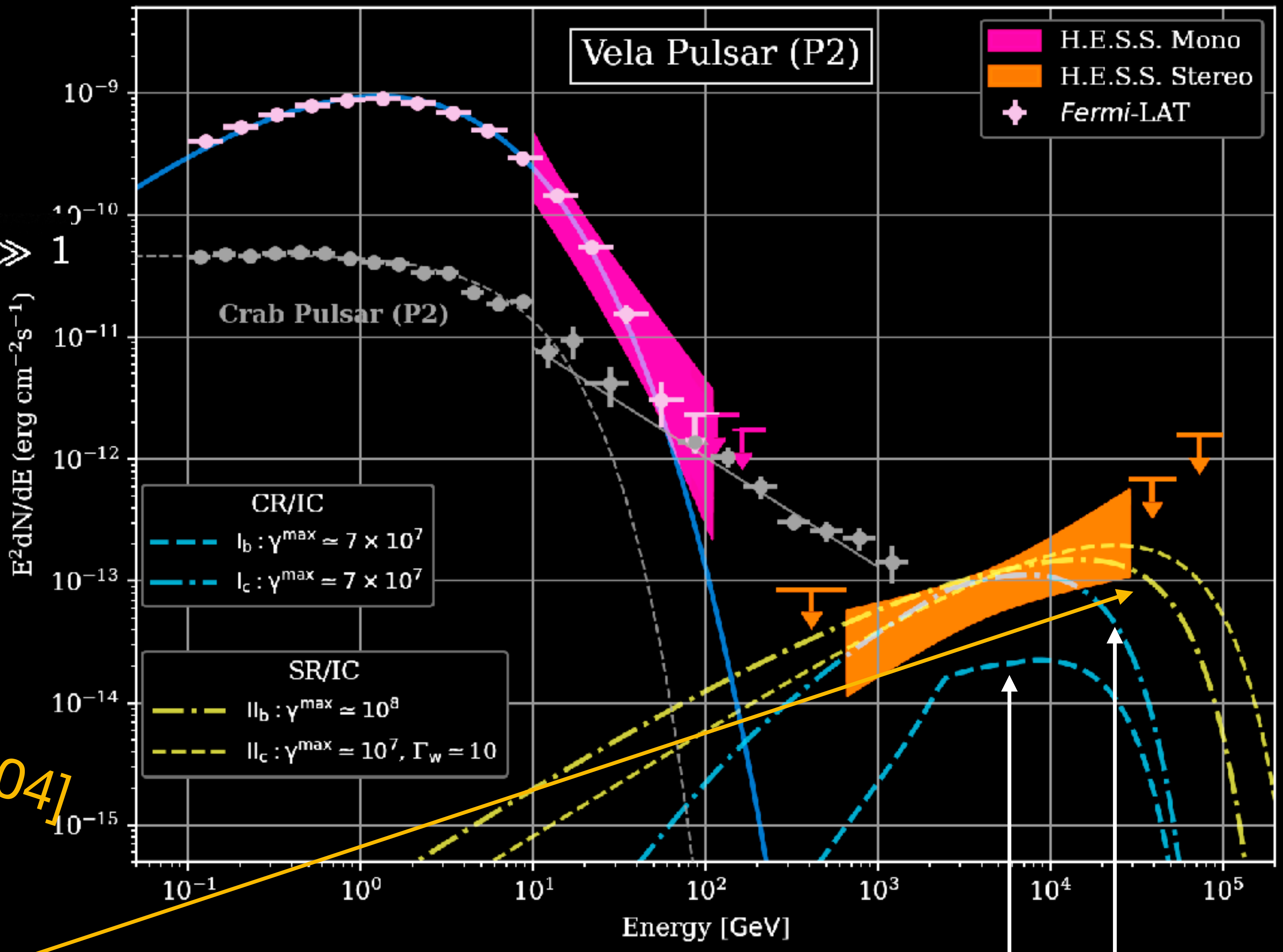
- SR/IC scenario:
  - Constraint by GeV data and B:

$$\gamma_{\mathrm{SR}}^{\max} \simeq 1.3 \times 10^{6} (B_{\perp}/B_{\mathrm{LC}})^{-1/2} \left(E_{\mathrm{SR}}^{\max}/1.5\,\mathrm{GeV}\right)^{1/2}$$

[Kirk 2004]

  - Insufficient maximum energy
  - Particles well beyond SR cut-off
  - 2-step acceleration/SR-cooling process
    - Larmor radii > largest plasmoids
    - Re-acceleration after SR-cooling : Caustics
  - Doppler-boosted (bulk motion):

$$\begin{cases} \Gamma_{\mathrm{w}} \gtrsim 5 \\ \simeq 5 R_{\mathrm{LC}} \end{cases}$$



- Effect of target photons energy range: [0.1 - 4] eV, vs [0.005 - 4] eV

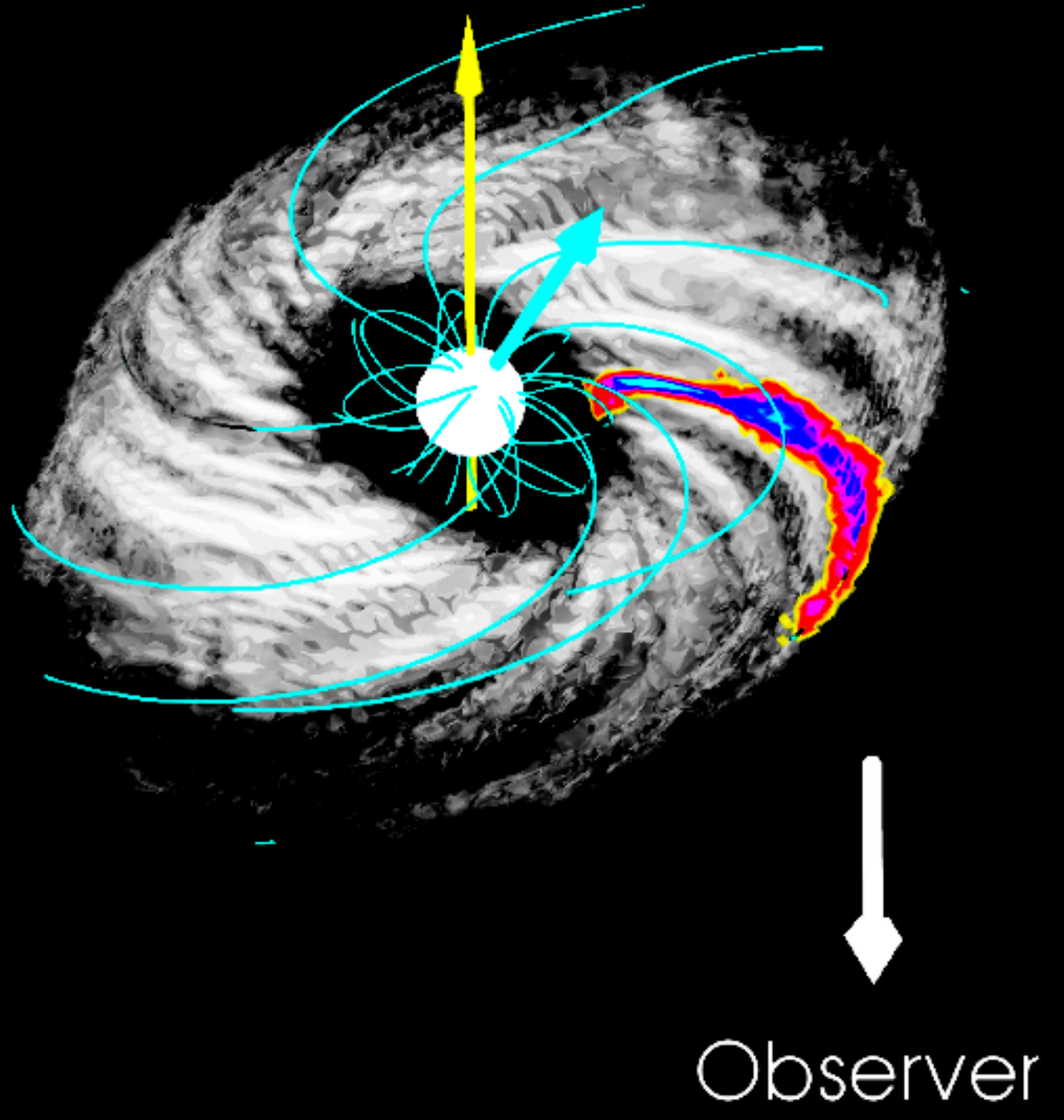
Maximum Lorentz Factor

- Fit to theTeV data: $\gamma_{\rm IC}^{\rm max} \gtrsim 7 \times 10^7$
- CR/IC scenario:
  - Constraint by GeV data:
  - Different combinations of $(\eta, \hat{\xi})$ $\eta \ll 0.1$ and $\hat{\xi} \gg 1$
  - Implies a dissipation region beyond the LC where $\rho_{\rm c} \gg R_{\rm LC}$
  - Can provide much higher energies than in traditional magnetospheric models

- SR/IC scenario:
  - Constraint by GeV data and B:

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3 \times 10^6 (B_\perp/B_{\rm LC})^{-1/2} \, (E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

  - Insufficient maximum energy
  - Particles well beyond SR cut-off
  - 2-step acceleration/SR-cooling process
    - Larmor radii > largest plasmoids
    - Re-acceleration after SR-cooling : Caustics
  - Doppler-boosted (bulk motion): $\begin{cases} \Gamma_{\rm w} \gtrsim 5 \\ \simeq 5 R_{\rm LC} \end{cases}$



[B. Cerutti et al. 2016]

Boosted SR/IC

$\hat{r} = r/R_{\rm LC}$, $B'(\hat{r}) = B(\hat{r})/\Gamma_{\rm w}$

$E_{\rm SR}^{\rm max\prime} = E_{\rm SR}^{\rm max}/2\,\Gamma_{\rm w}$,

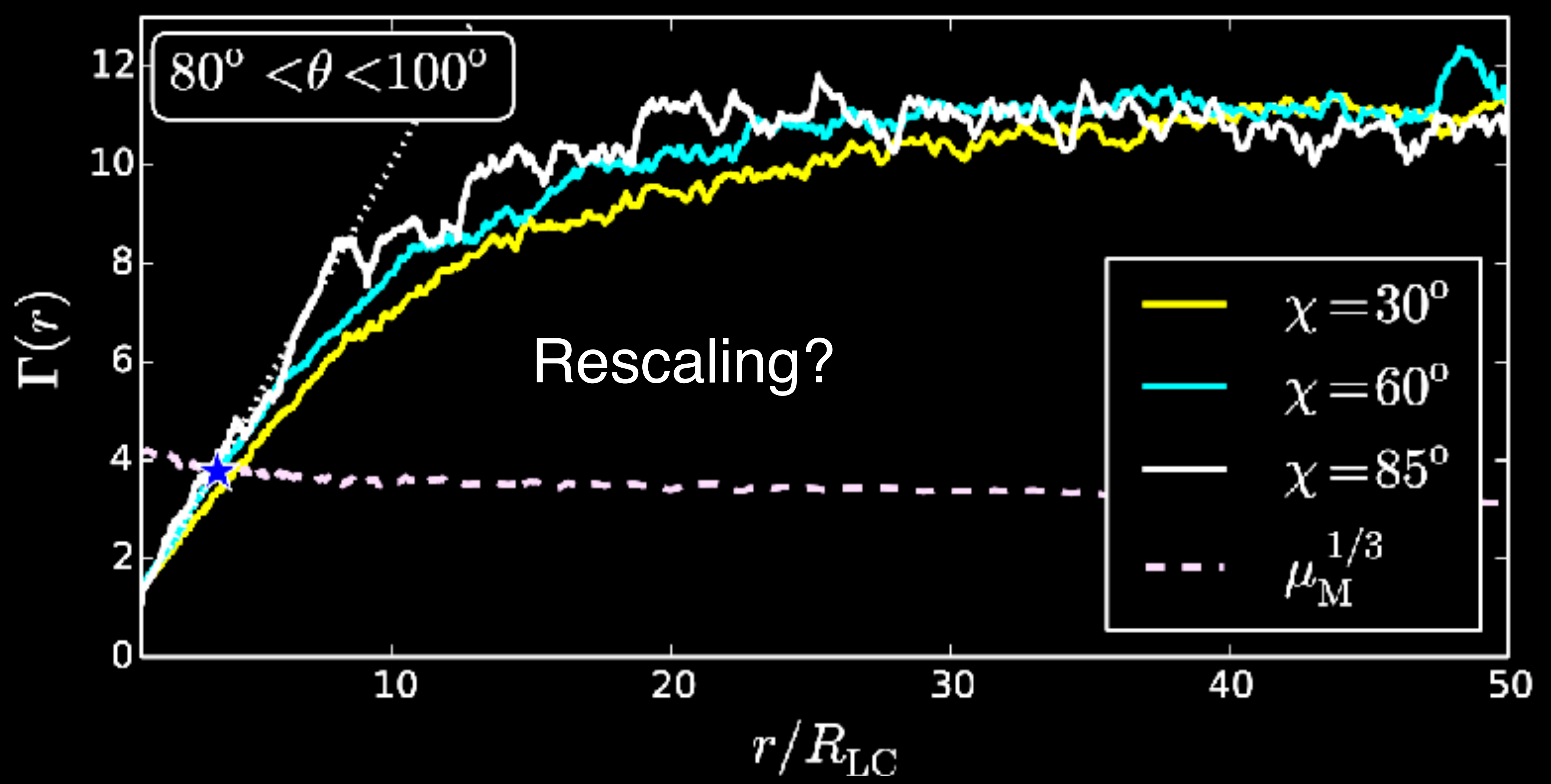
$B(\hat{r}) \sim B_{\rm LC}/\hat{r}^2$ in the near wind region

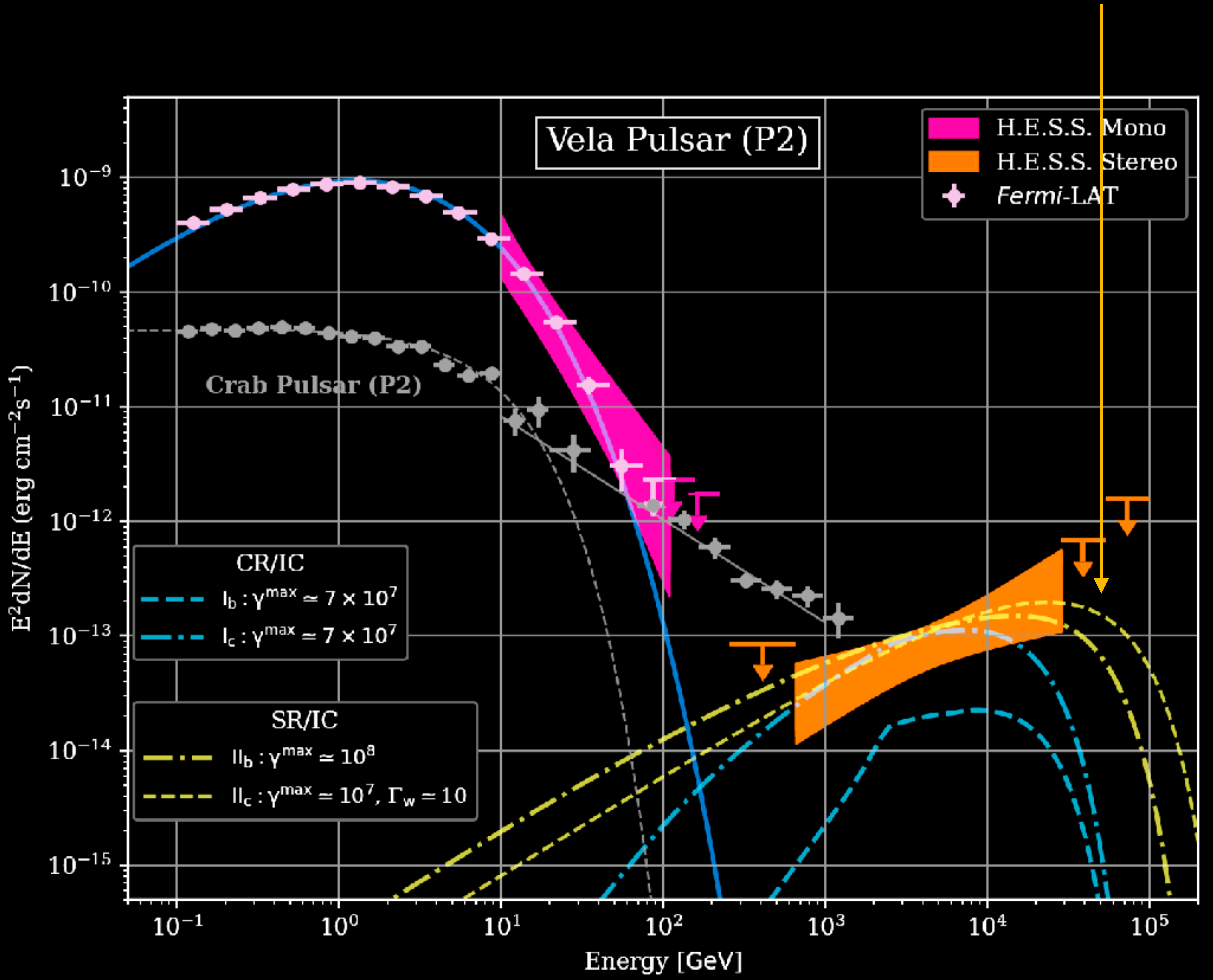
$$\begin{cases} \gamma_{\rm SR}^{\rm max\prime} \simeq 10^6 (\frac{E_{\rm SR}^{\rm max}}{1.5\,{\rm GeV}})^{1/2}\,\hat{r} \\ \gamma_{\rm IC}^{\rm max} = 2\times\Gamma_{\rm w}\,\gamma_{\rm SR}^{\rm max\prime} \end{cases}$$

$$\Gamma_{\rm w} \simeq 22 \left(\frac{E_{\rm SR}^{\rm max}}{1.5\,{\rm GeV}}\right)^{-1/2} \left(\frac{E_{\rm VHE}}{20\,{\rm TeV}}\right) \hat{r}^{-1}$$

$$\begin{cases} \Gamma_{\rm w} = (1+\hat{r}^2)^{1/2} \\ \Gamma_{\rm w} \simeq \hat{r}_{\rm e} \simeq 5. \end{cases}$$

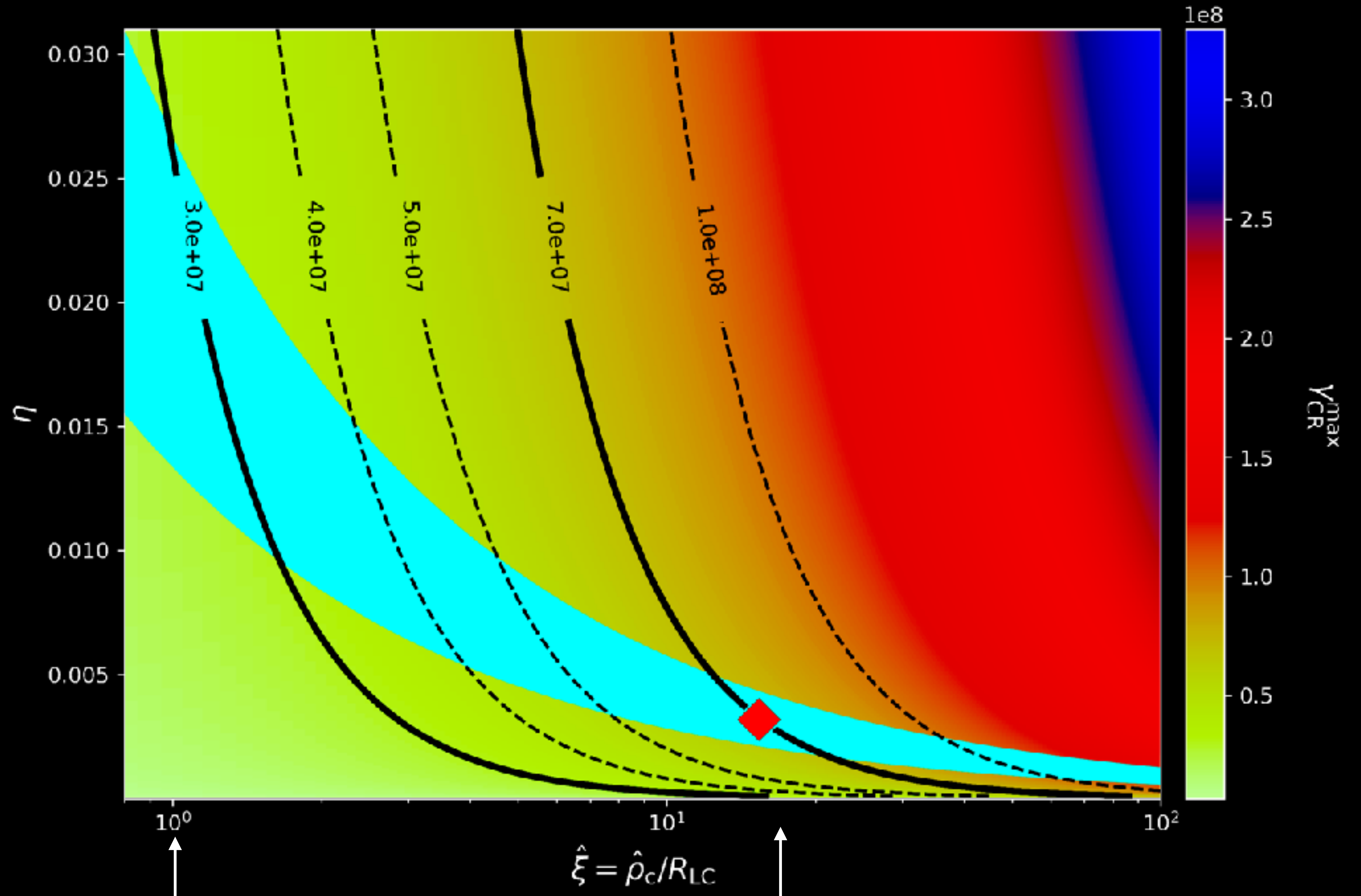
[B. Cerutti et al. 20xx]





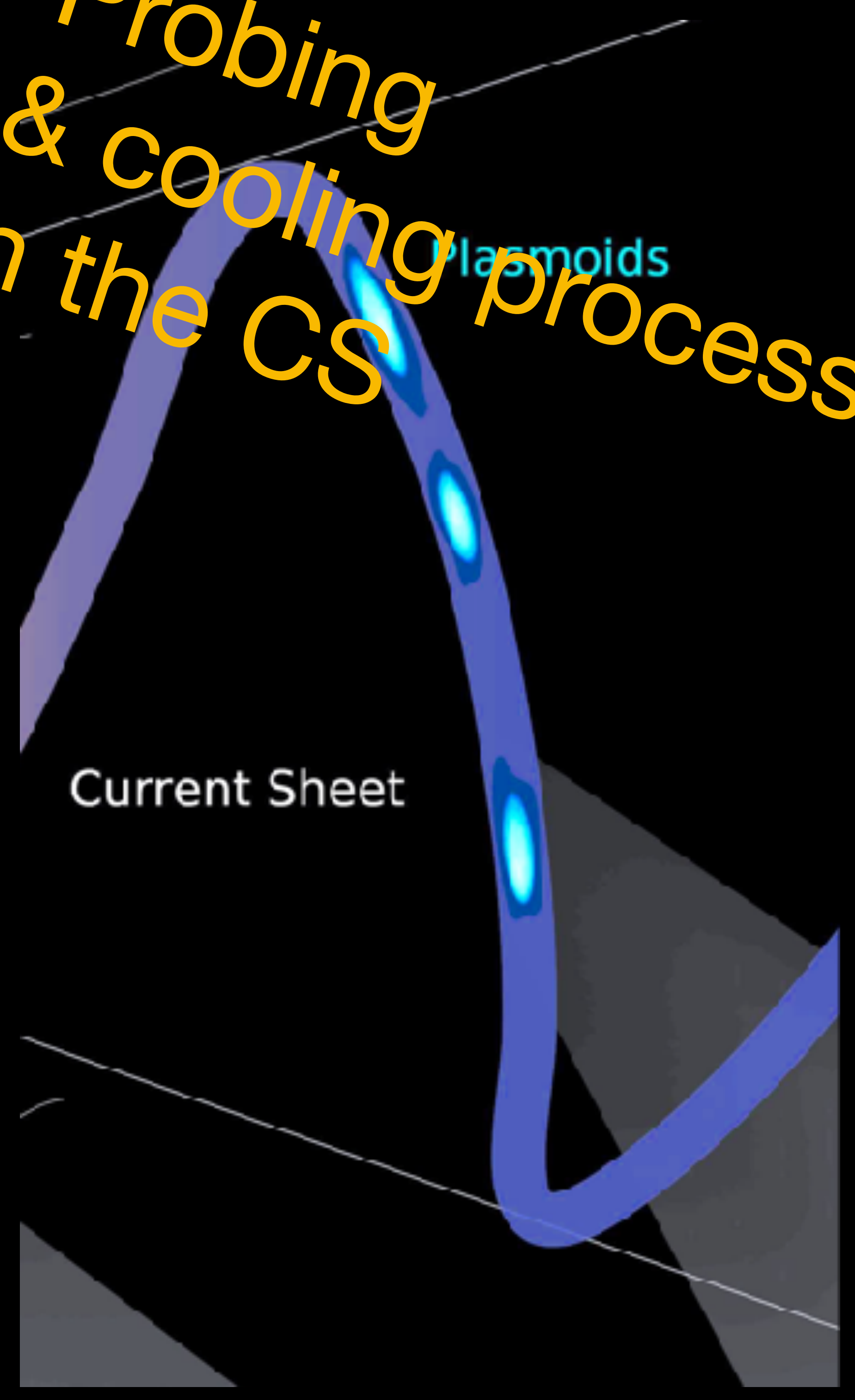
Probing
Magnetic conversion efficiency
acceleration & emission zone
Particle trajectories

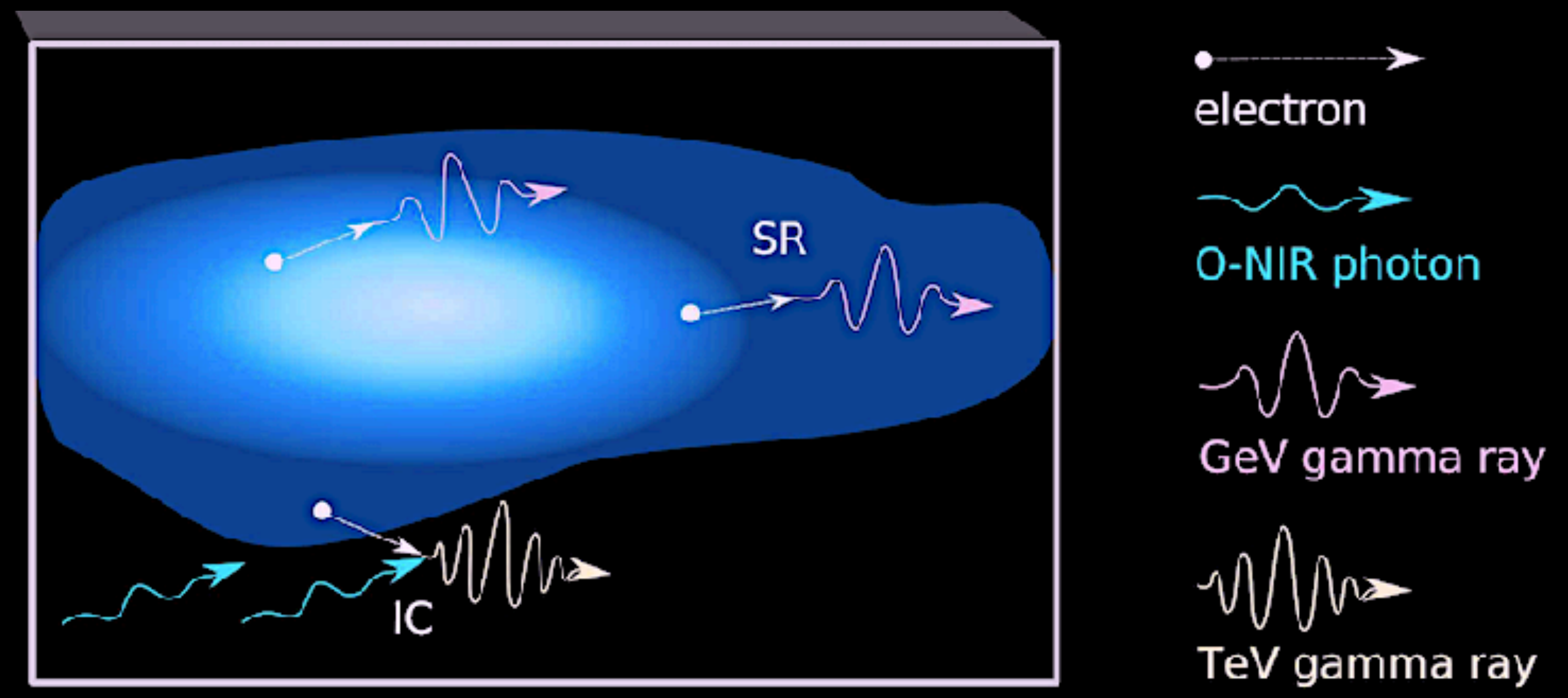
Probing
(Re-)acceleration & cooling processes deep
In the CS



1 R_{LC}

20 R_{LC}

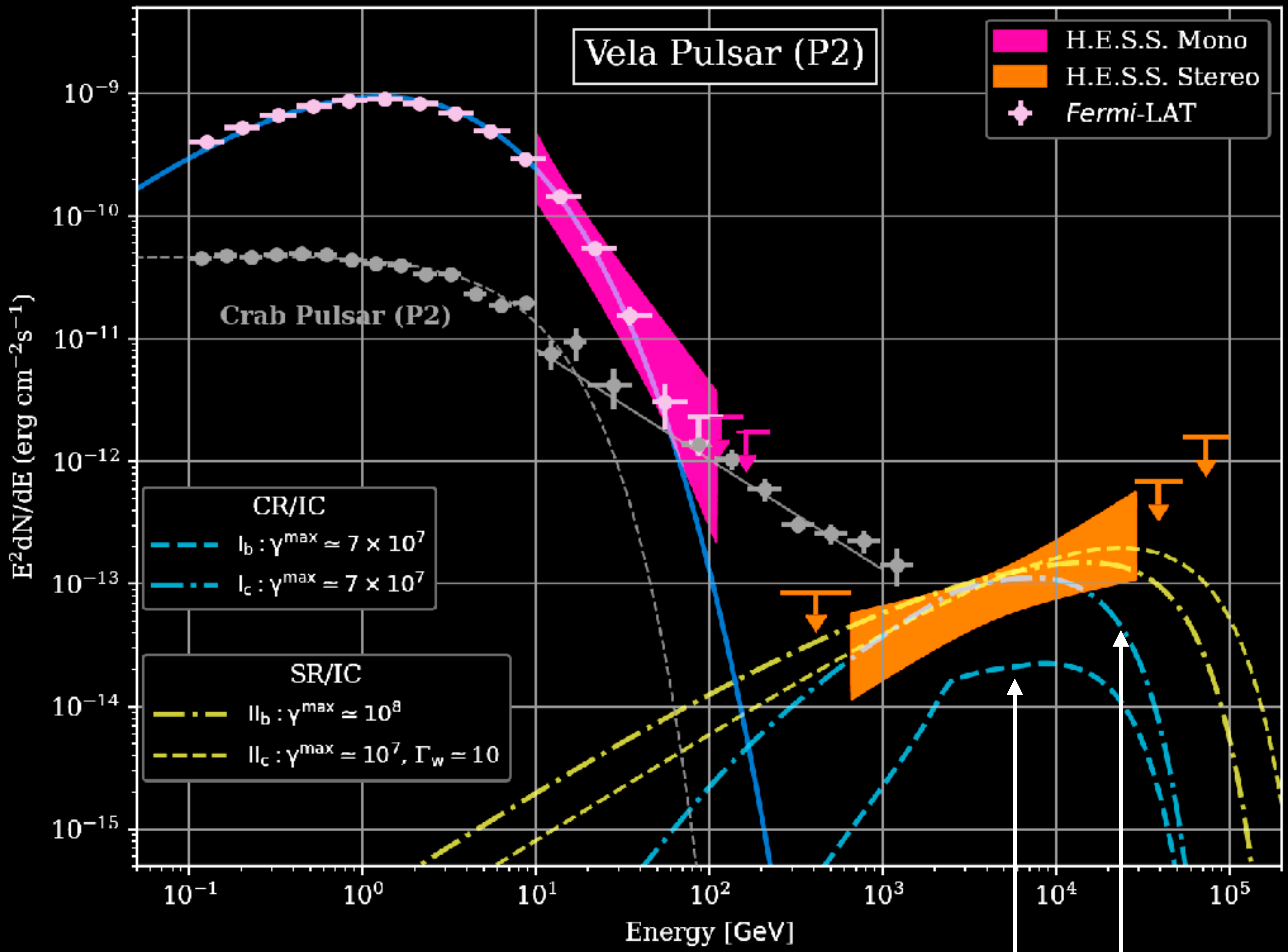




Parameter space !
IC Target Photon Density

IC Targets

- IC targets :
  - Radio
  - Non thermal SYN (IR-O-UV, X,..),
  - Thermal X-rays (NS)
  - Other
- VHE index & luminosity is function of target εmin:
  - e.g.: NIR-O targets for Vela

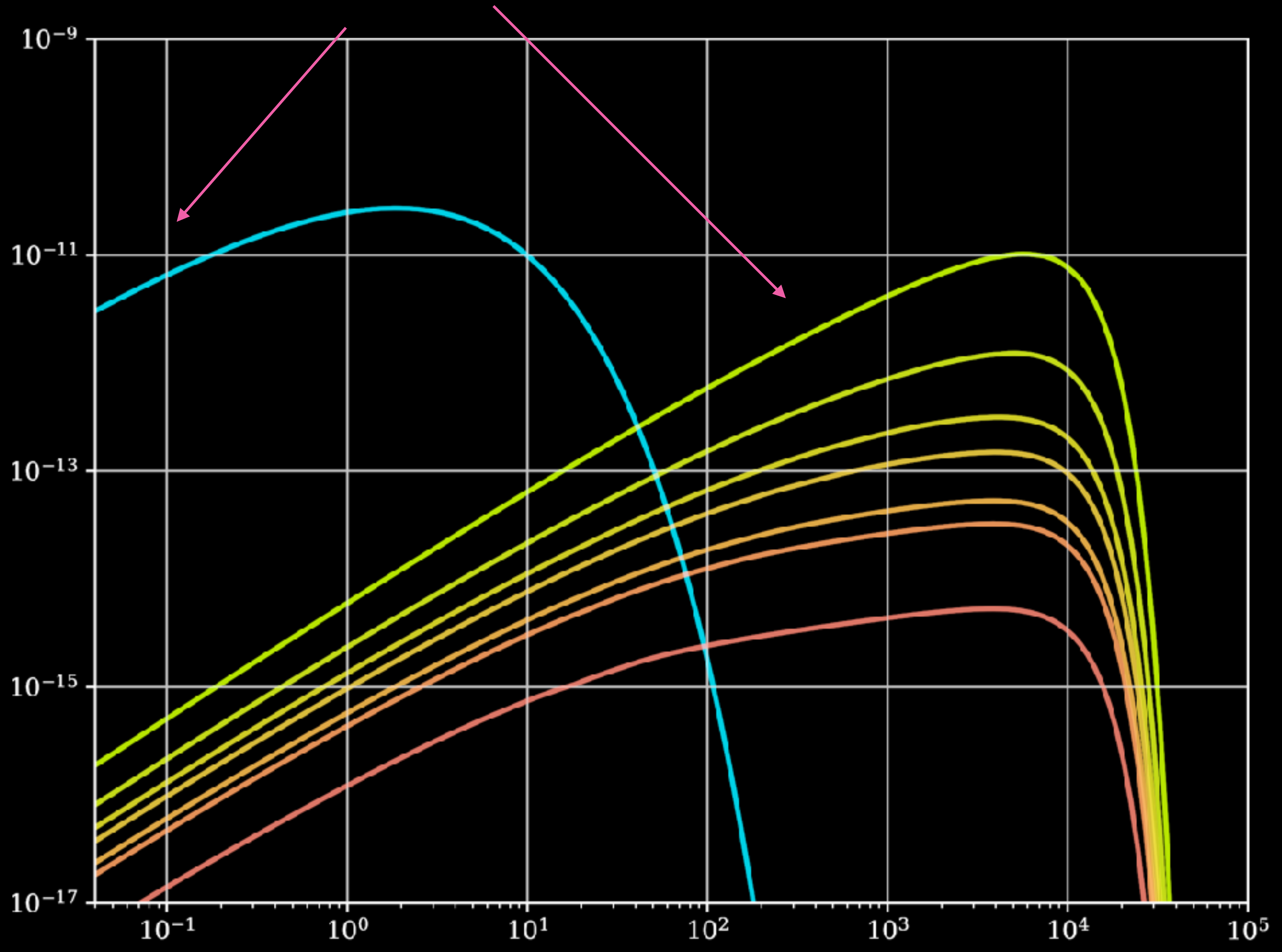


- Effect of target photons energy range: [0.1 - 4] eV, vs [0.005 - 4] eV

IC Targets

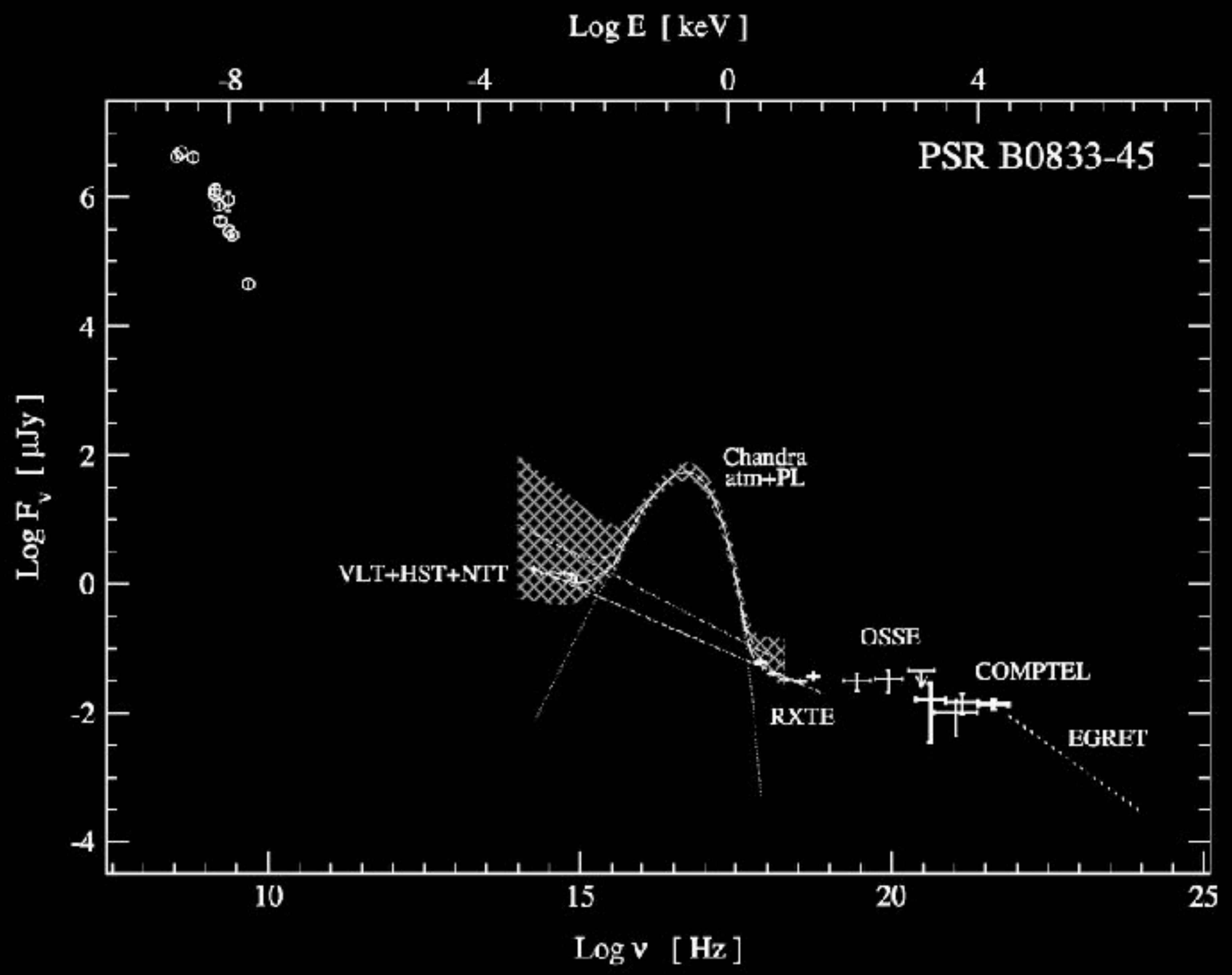
- IC targets :
  - Radio
  - Non thermal SYN (IR-O-UV, X,..),
  - Thermal X-rays (NS)
  - Other
- VHE index & luminosity is function of target εmin:
  - e.g.: NIR-O targets -> UV -X targets
  - Thomson to KN regime

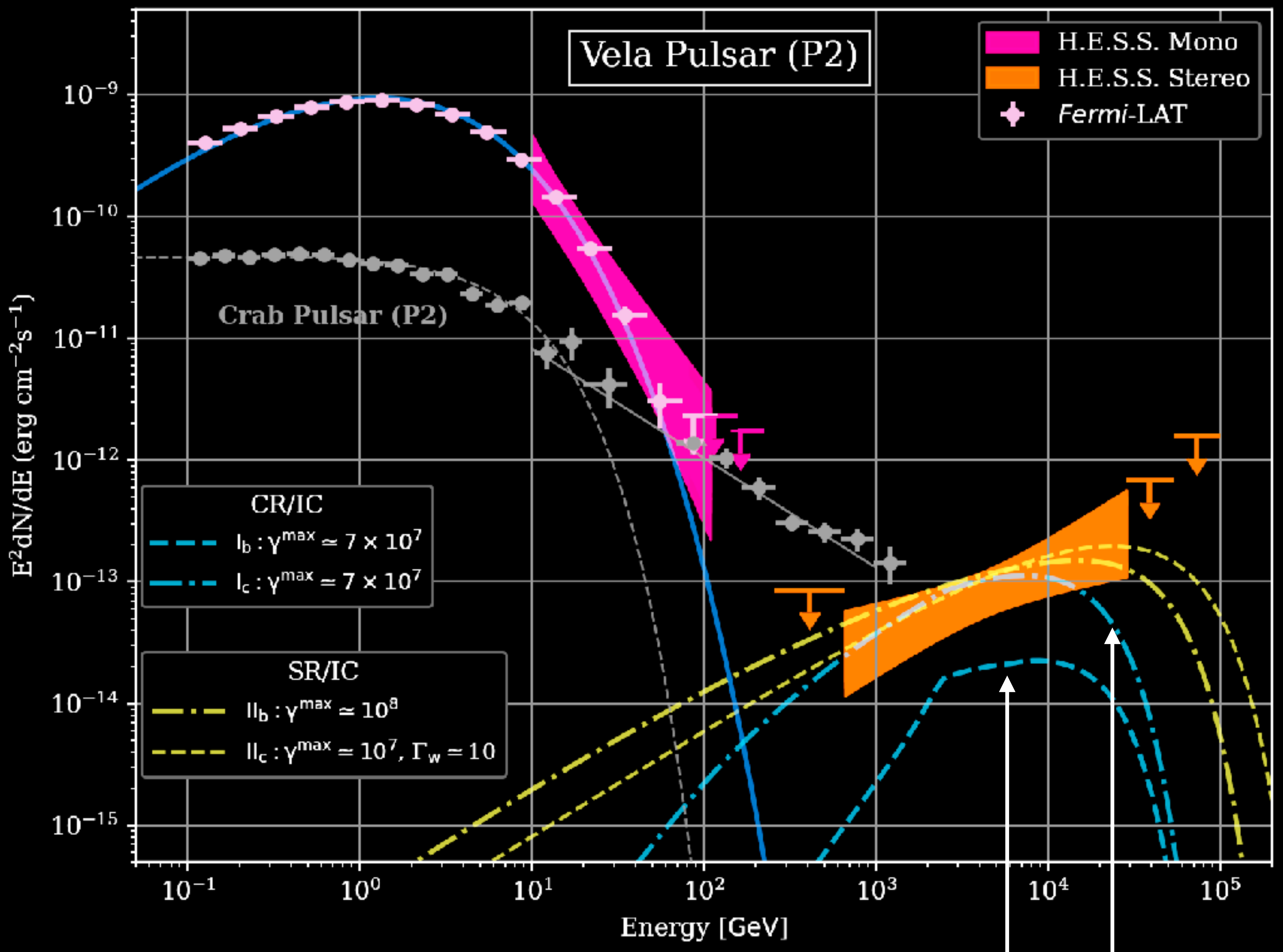
$$\alpha^{IC}_{Th} \sim -(p+1)/2$$
$$\alpha^{IC}_{KN} \sim -(p+1)$$



IC Targets

- IC targets :
  - Radio
  - Non thermal SYN (IR-O-UV, X,..),
  - Thermal X-rays (NS)
  - Other
- VHE index & luminosity is function of target ε_{min}:
  - e.g.: NIR-O targets for Vela



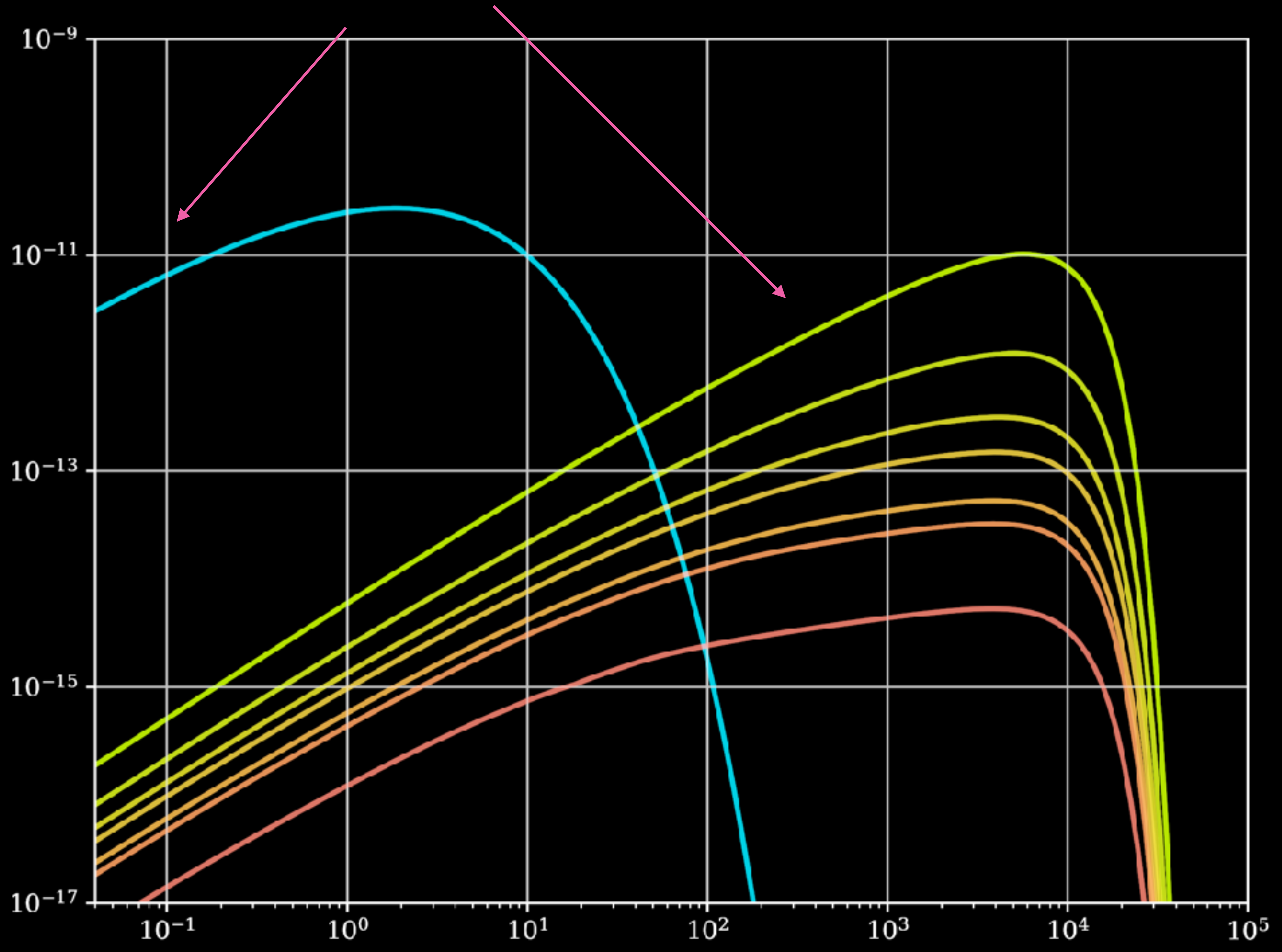


- Effect of target photons energy range: [0.1 - 4] eV, vs [0.005 - 4] eV

IC Targets

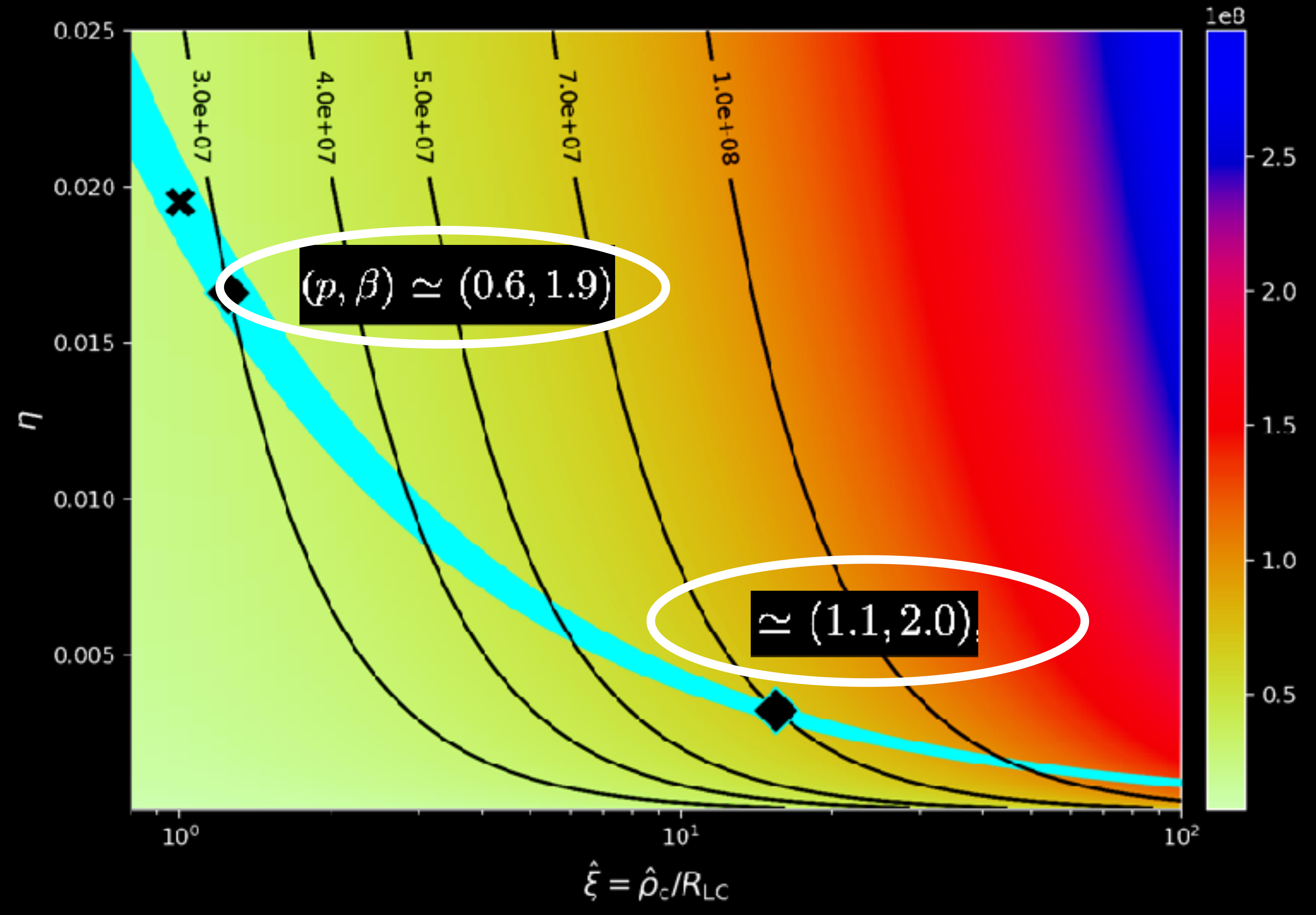
- IC targets :
  - Radio
  - Non thermal SYN (IR-O-UV, X,..),
  - Thermal X-rays (NS)
  - Other
- VHE index & luminosity is function of target εmin:
  - e.g.: NIR-O targets -> UV -X targets
  - Thomson to KN regime
- Degeneracies :
  - Target energy range (min)
  - IC Interaction volume
  - Assuming same population !
  - Underlying particle distribution

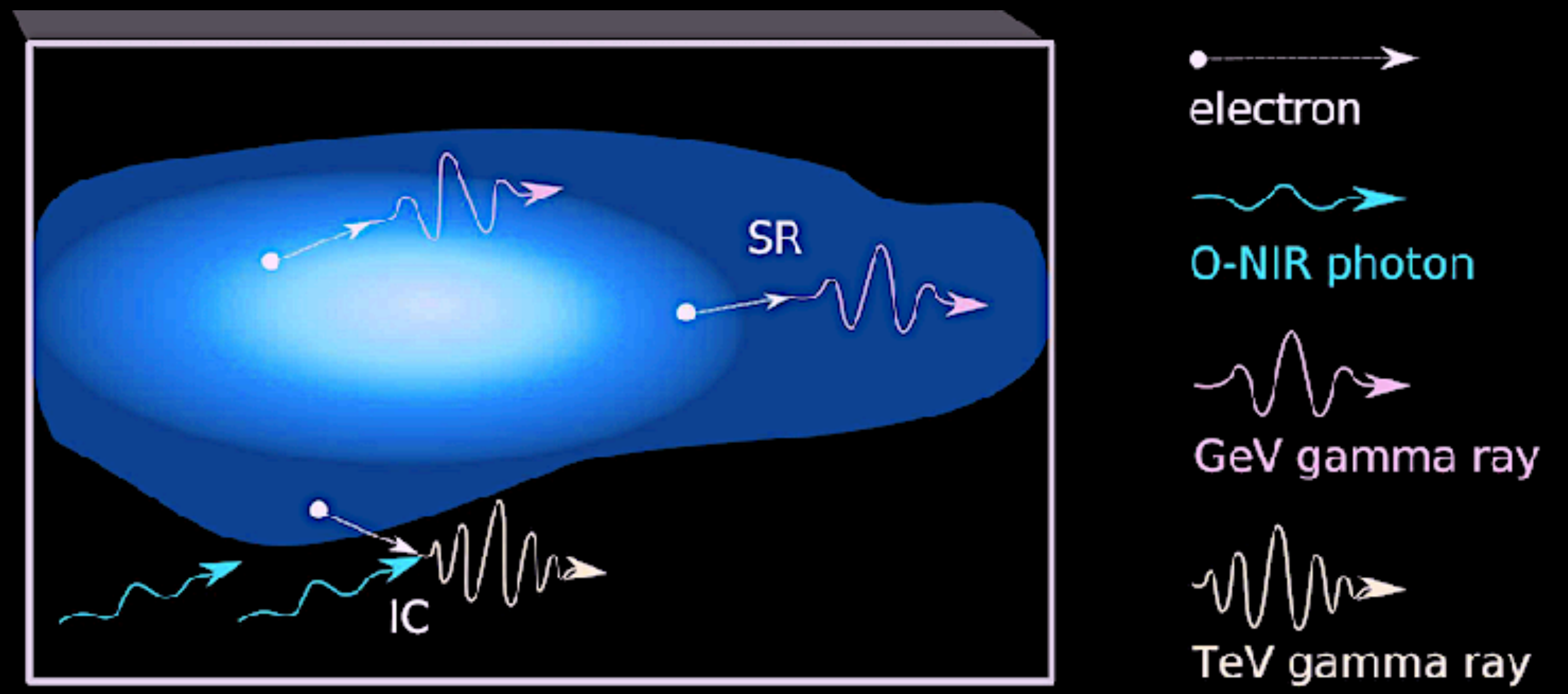
$$\alpha^{IC}_{Th} \sim -(p+1)/2$$
$$\alpha^{IC}_{KN} \sim -(p+1)$$



CR/IC & SR/IC

$$\frac{d^2N}{d\gamma dt} \propto (\gamma/\gamma_0)^{-p} \exp\left[-(\gamma/\gamma^{\max})^{\beta}\right]$$





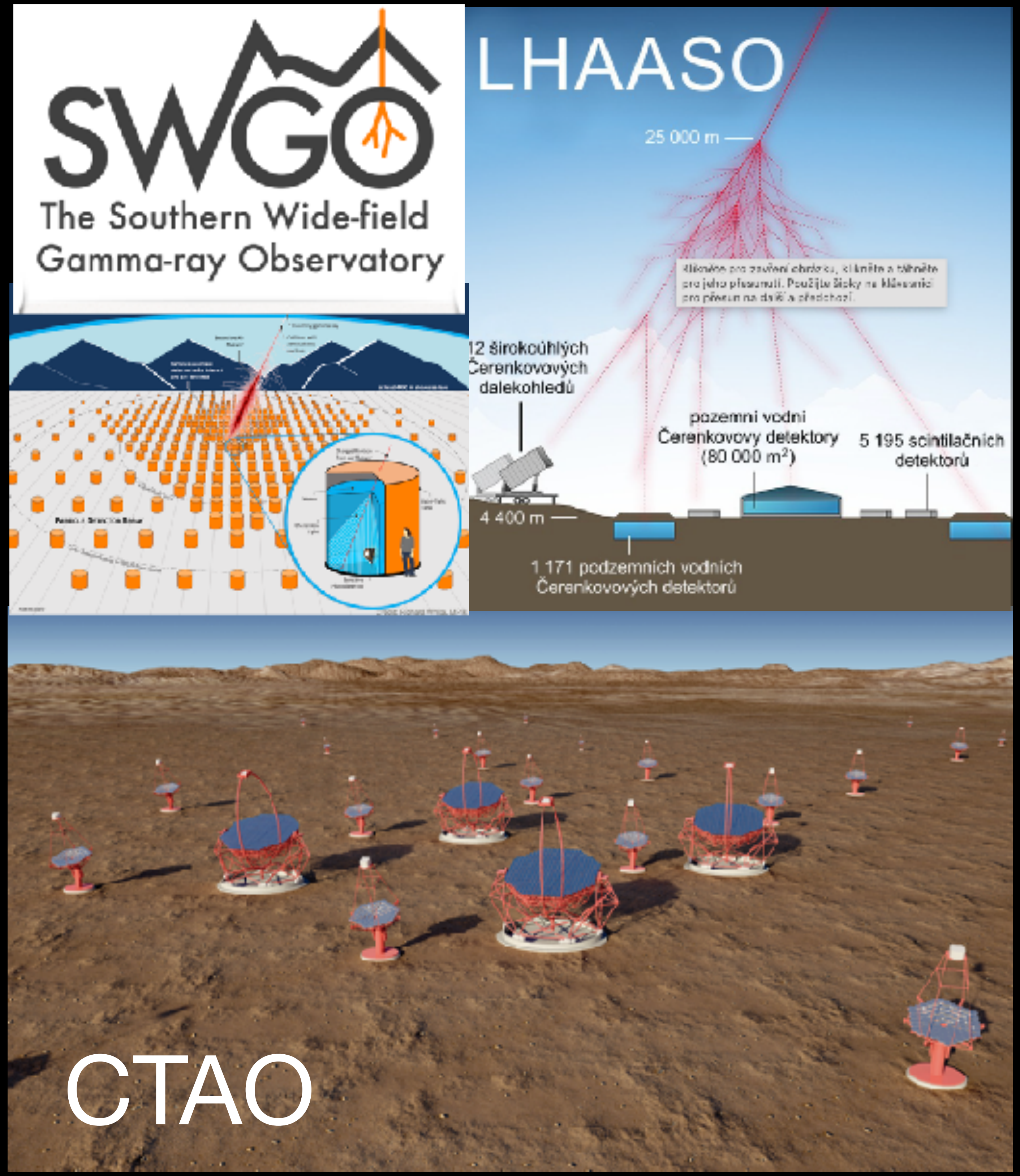
$$\rho_L \simeq 4 \times 10^{-3}\, R_{\rm LC}\, (\gamma^{\max}/7 \times 10^7)$$

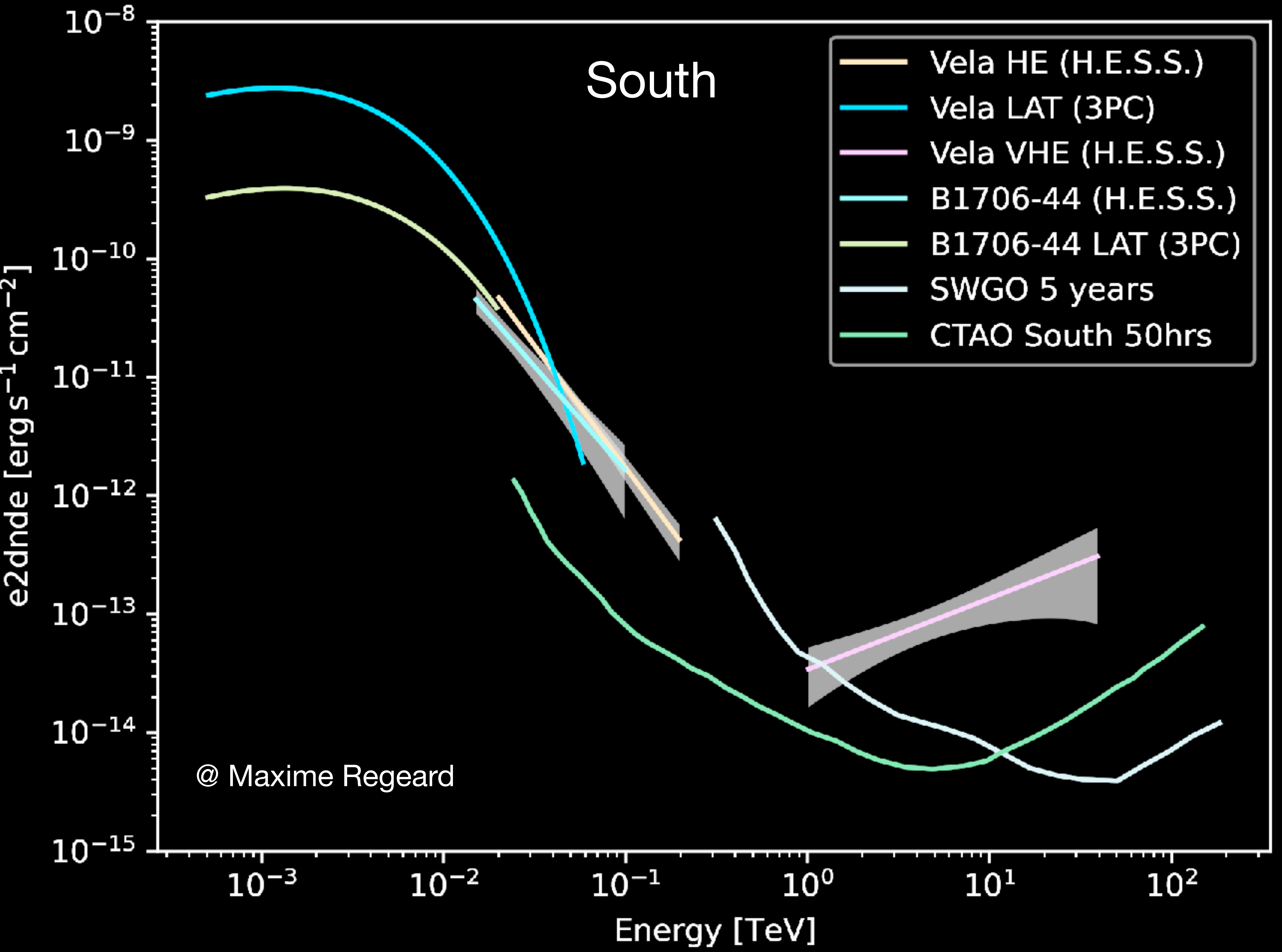
$$p \simeq 1,\ \beta \simeq 1.8$$

Perspectives

Perspectives

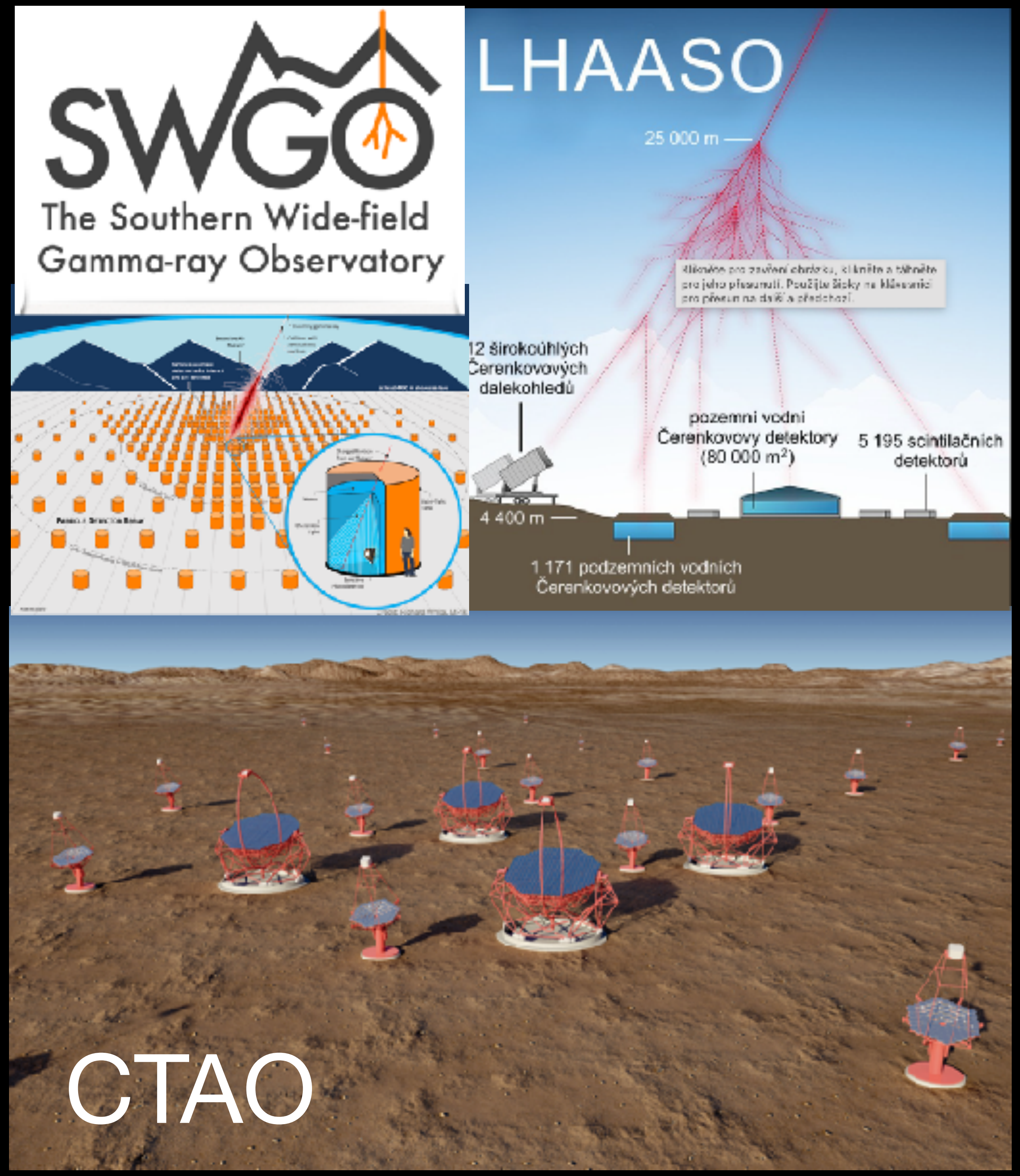
Observational

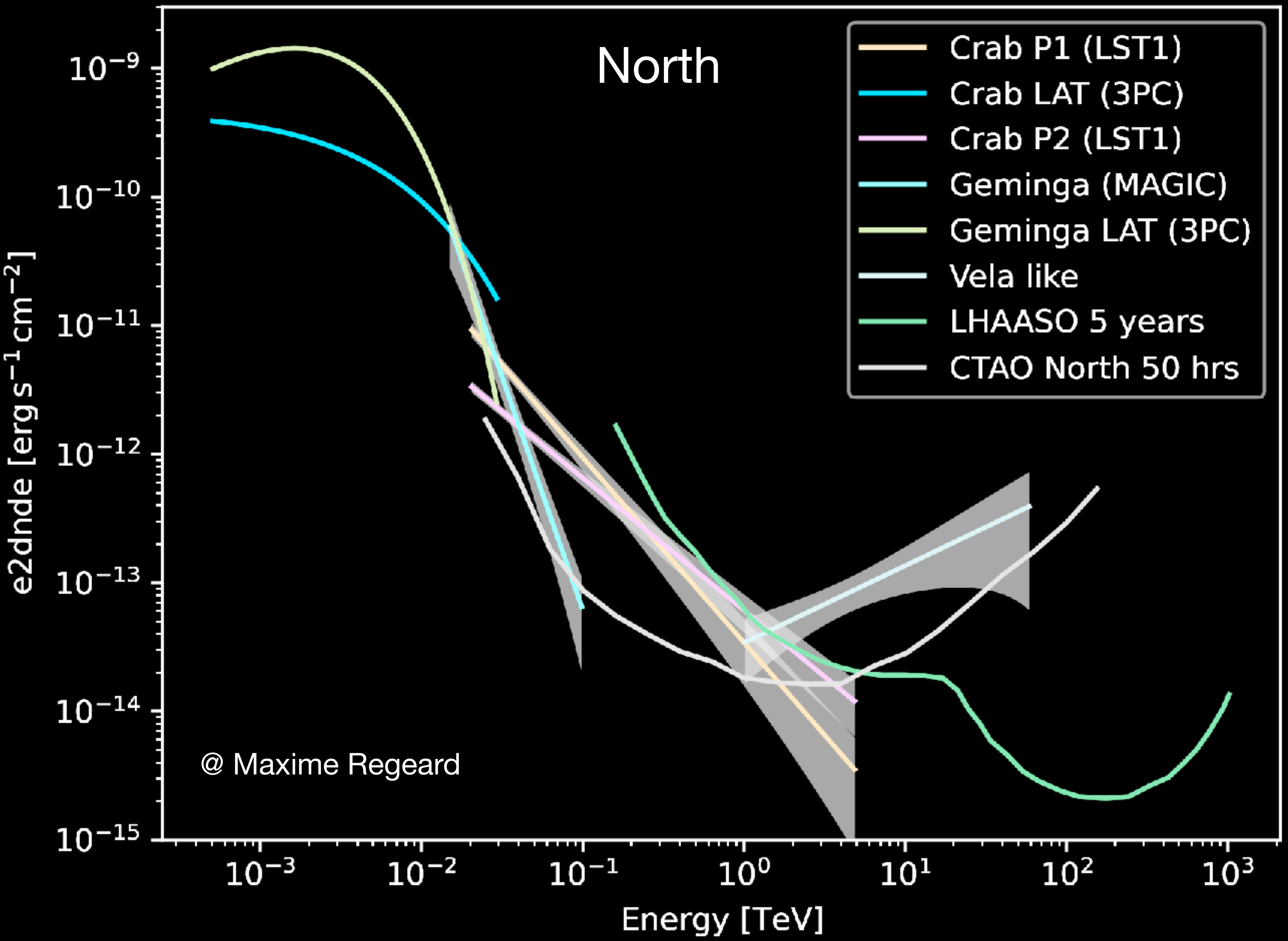




Perspectives

Observational

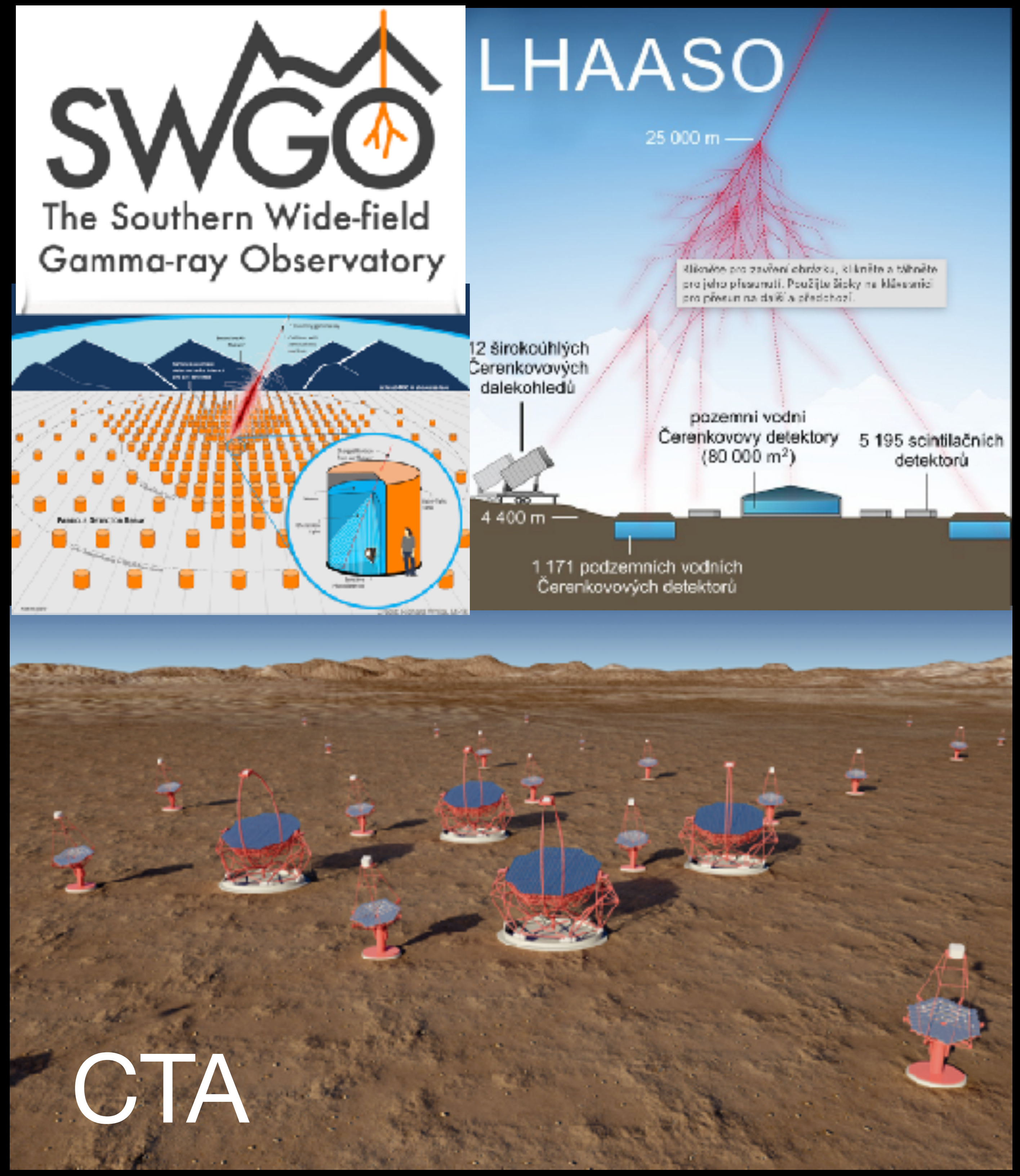


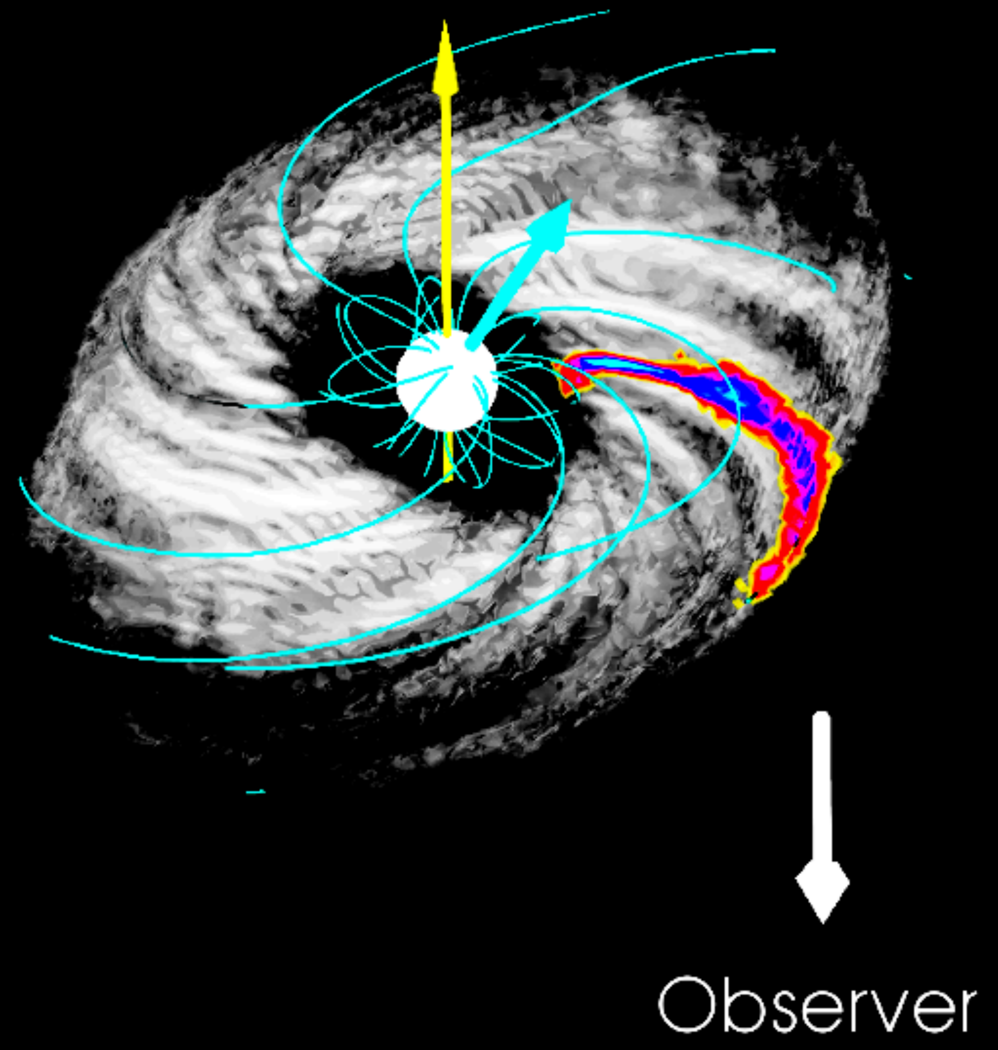


Perspectives

Observational

- The discovery of 20 TeV pulsations from Vela opened a new observation window (The discovery of the TeV luminous PSR J1509-5850 does even more so)
- The TeV pulsar family has very few members but already many challenges to emission models
- We still don’t know the E_max : both CR/IC and SR/IC can work
- If >100 TeV γ rays: boosted emission in the CS
- Many other questions: LC evolution with E
- Can TeV IC reveal new features in the LC?
- <100 GeV range is also very critical:
  Crab-like tails or curved Vela-like spectra?
  [See Maxime’s talk]
- Multi-Wavelength modelling including radio and X-rays …
- New sensitive instruments : TeV pulsar population ?!
  Statistical studies : L_{TeV} dependence on inclination? etc





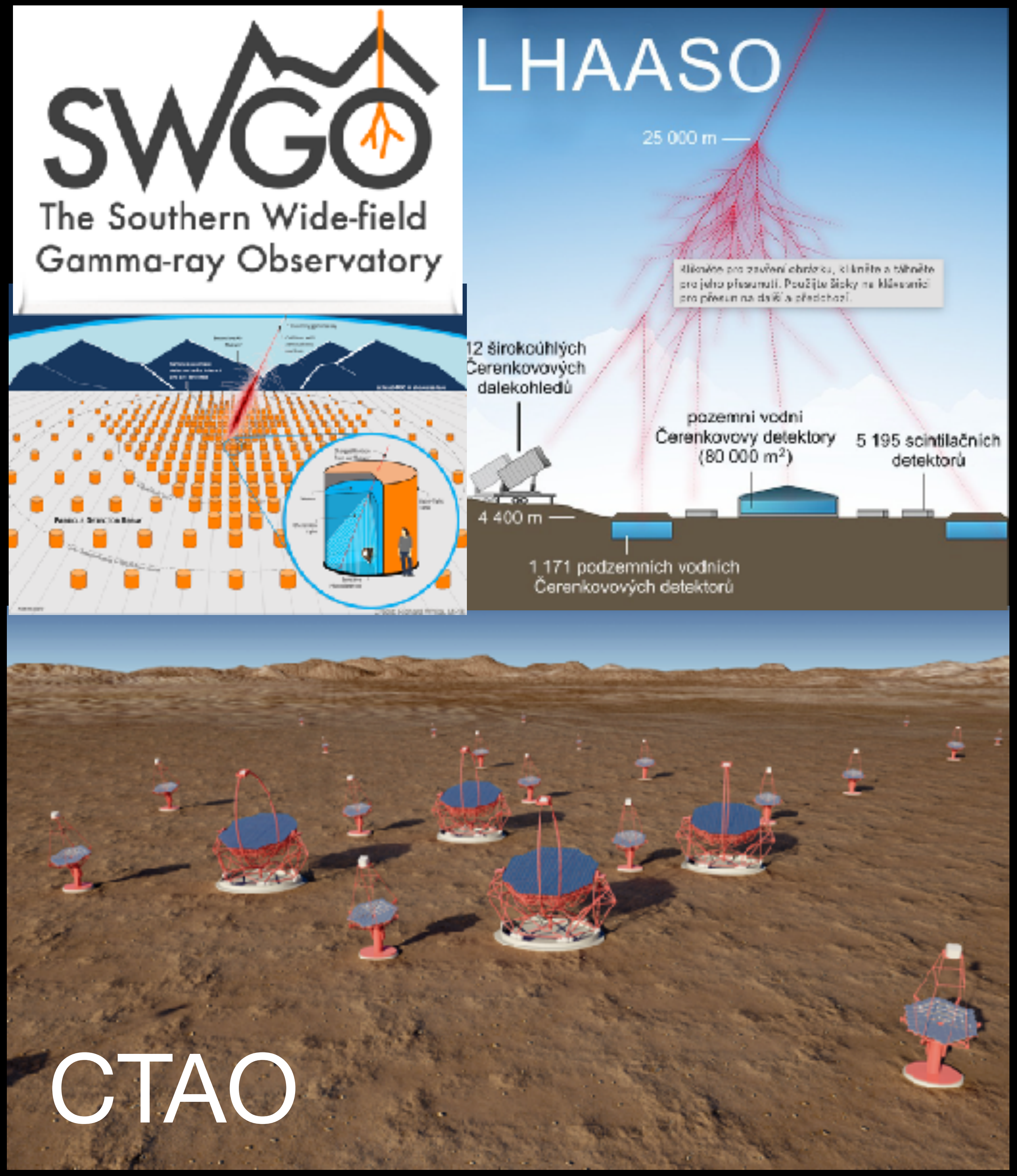
Perspectives

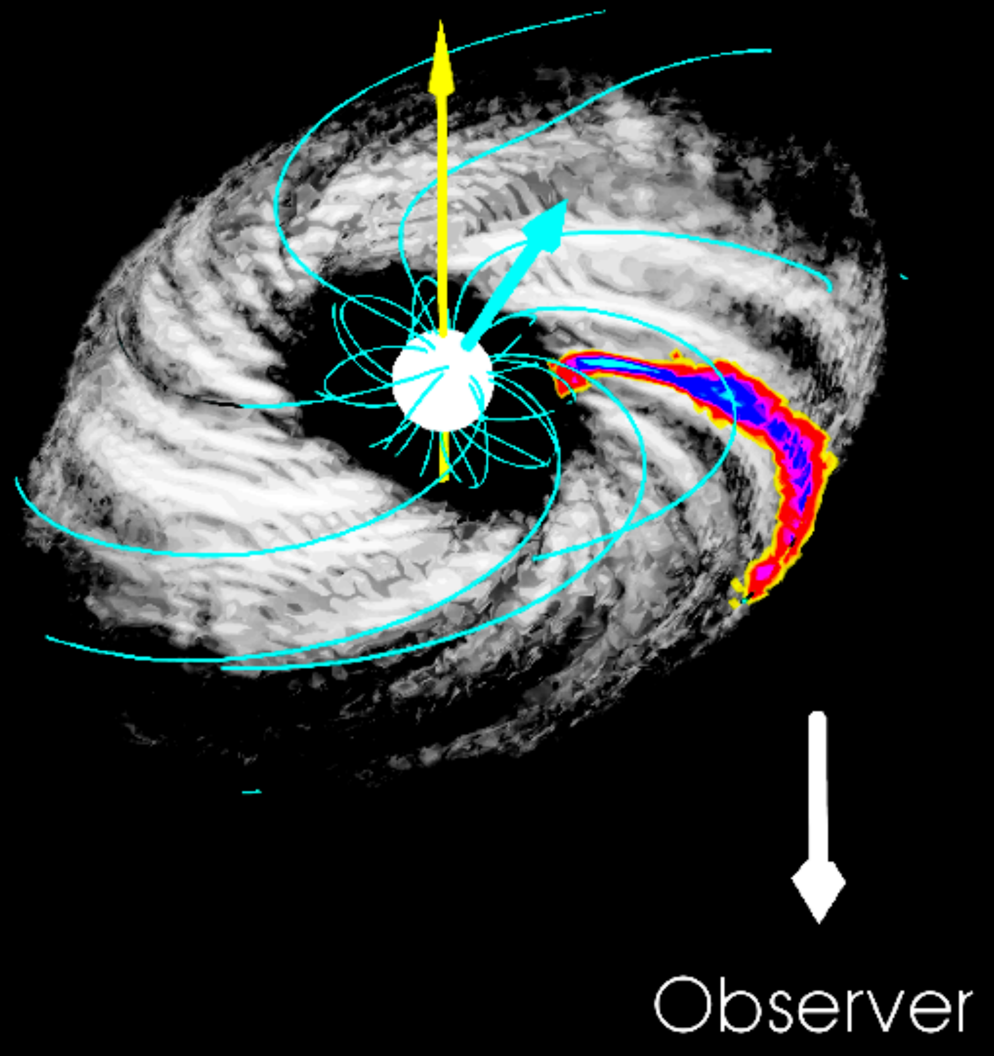
Observational

- The discovery of 20 TeV pulsations from Vela opened a new observation window (The discovery of the TeV luminous PSR J1509-5850 does even more so)
- The TeV pulsar family has very few members but already many challenges to emission models
- We still don’t know the E_max : both CR/IC and SR/IC can work

Warning !
Based on one single multi-TeV IC detection

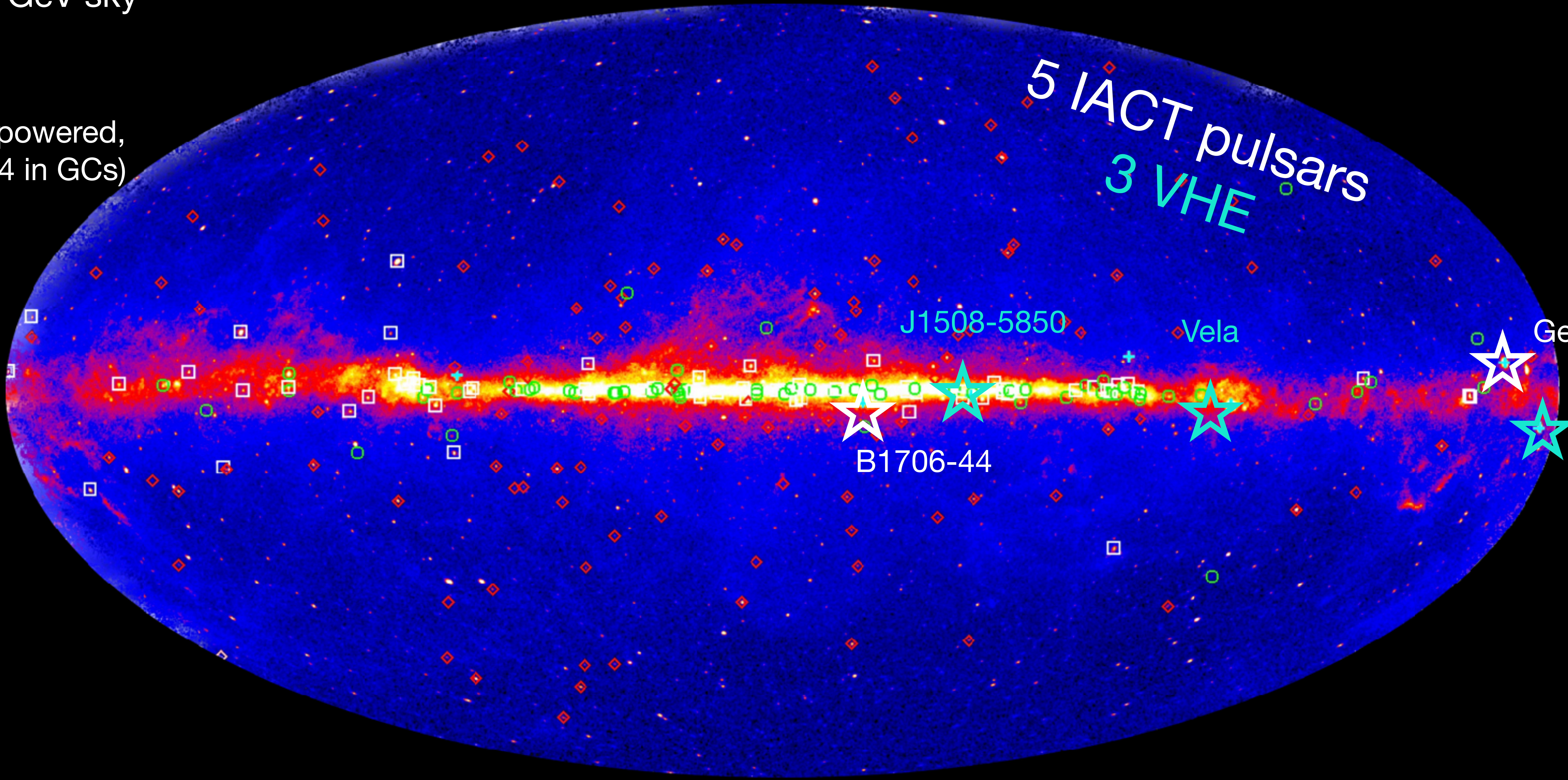
- If >100 TeV γ rays: boosted emission in the CS
- Many other questions: LC evolution with E,
- Can TeV IC reveal new features in the LC?
- <100 GeV range is also very critical:
  Crab-like tails or curved Vela-like spectra?
  [See Maxime’s talk]
- Multi-Wavelength modelling including radio and X-rays …
- New sensitive instruments : TeV pulsar population ?!
  Statistical studies : L_{TeV} dependence on inclination? etc





Fermi-LAT > 1 GeV sky

Radio :
~3500 rotation powered,
~681 MSPs (354 in GCs)



- 3PC 384 pulsars listed, 255 with 4FGL-DR3 counterparts
- 136 Young or Middle-aged
- 73 Radio-loud γ-ray (29%)
- 63 Radio-quiet γ-ray (25%)
- 119 γ-ray MSPs : 25 Isolated, 94 Binary (47%)
- 36 Black Widows (27) and Redbacks (9)

- 2 HE pulsars (~100 GeV):
  - Geminga
  - B1706-44
- 3 VHE pulsars (>~100 GeV):
  - Crab ~1.5 TeV
  - Vela ~ 20 TeV
  - J1509-5850 ~10 TeV