THE CRAB NEBULA

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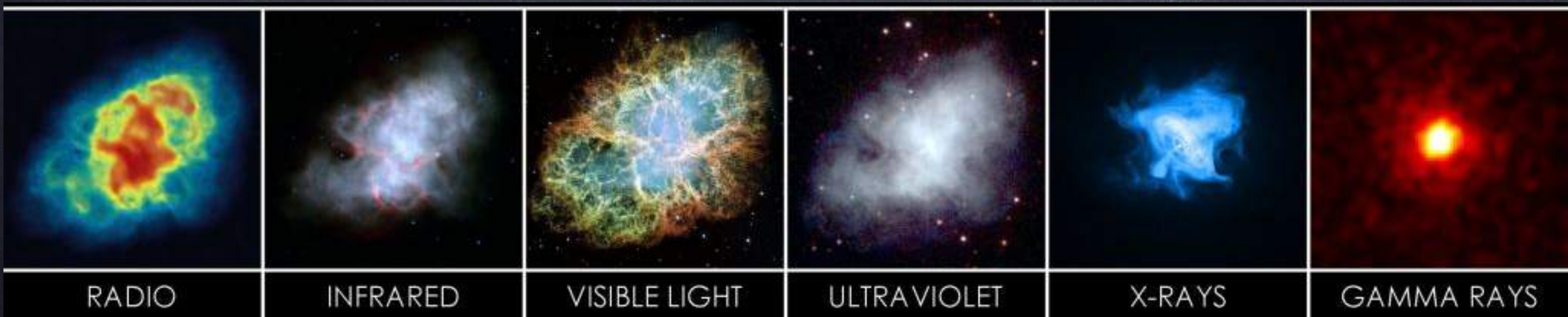
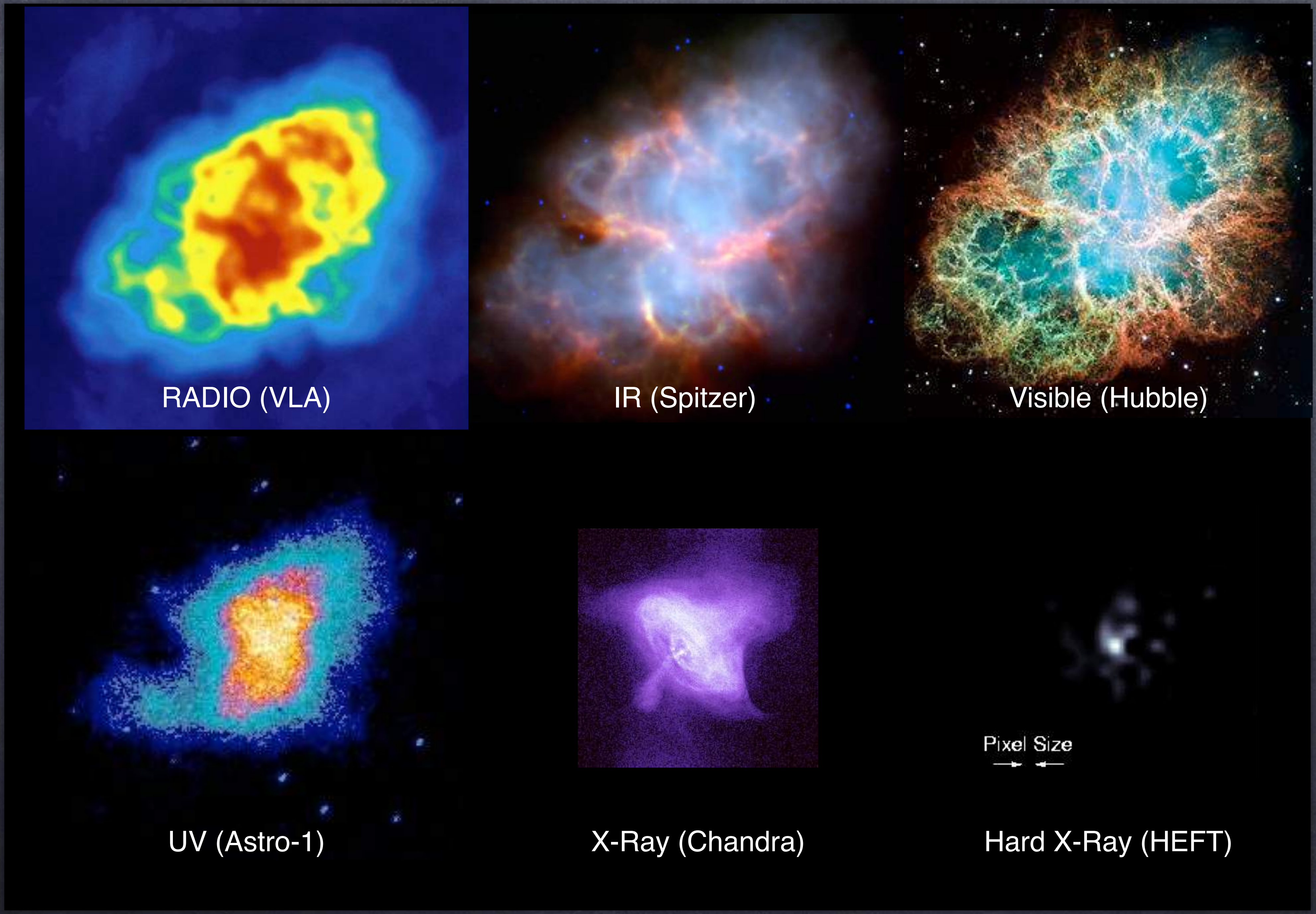


"THE BEST STUDIED OBJECT IN THE UNIVERSE OUTSIDE THE SOLAR SYSTEM"

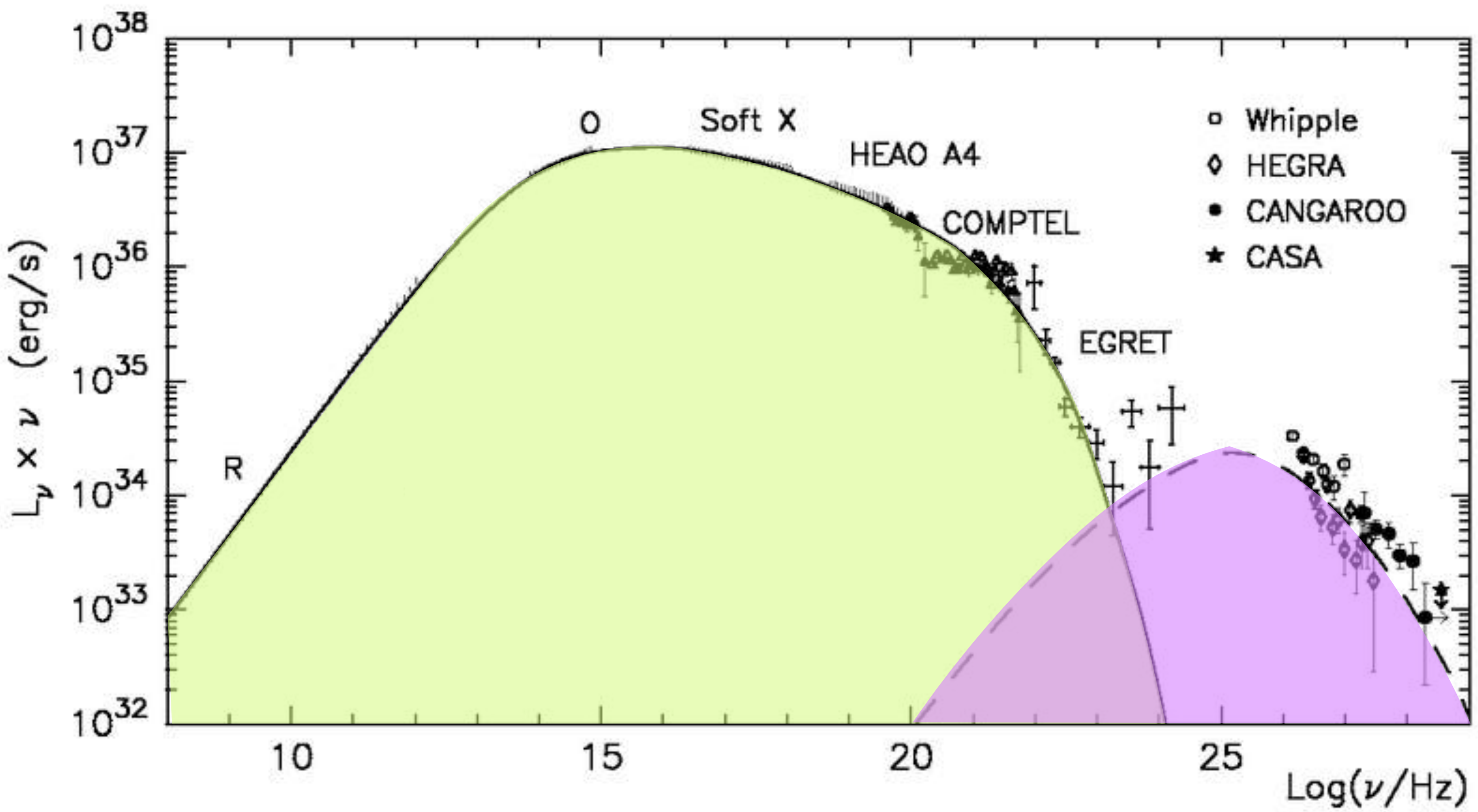


Citation from J. Hester 2008

THE CRAB NEBULA SPECTRUM

BROAD BAND NON-THERMAL SPECTRUM

CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]



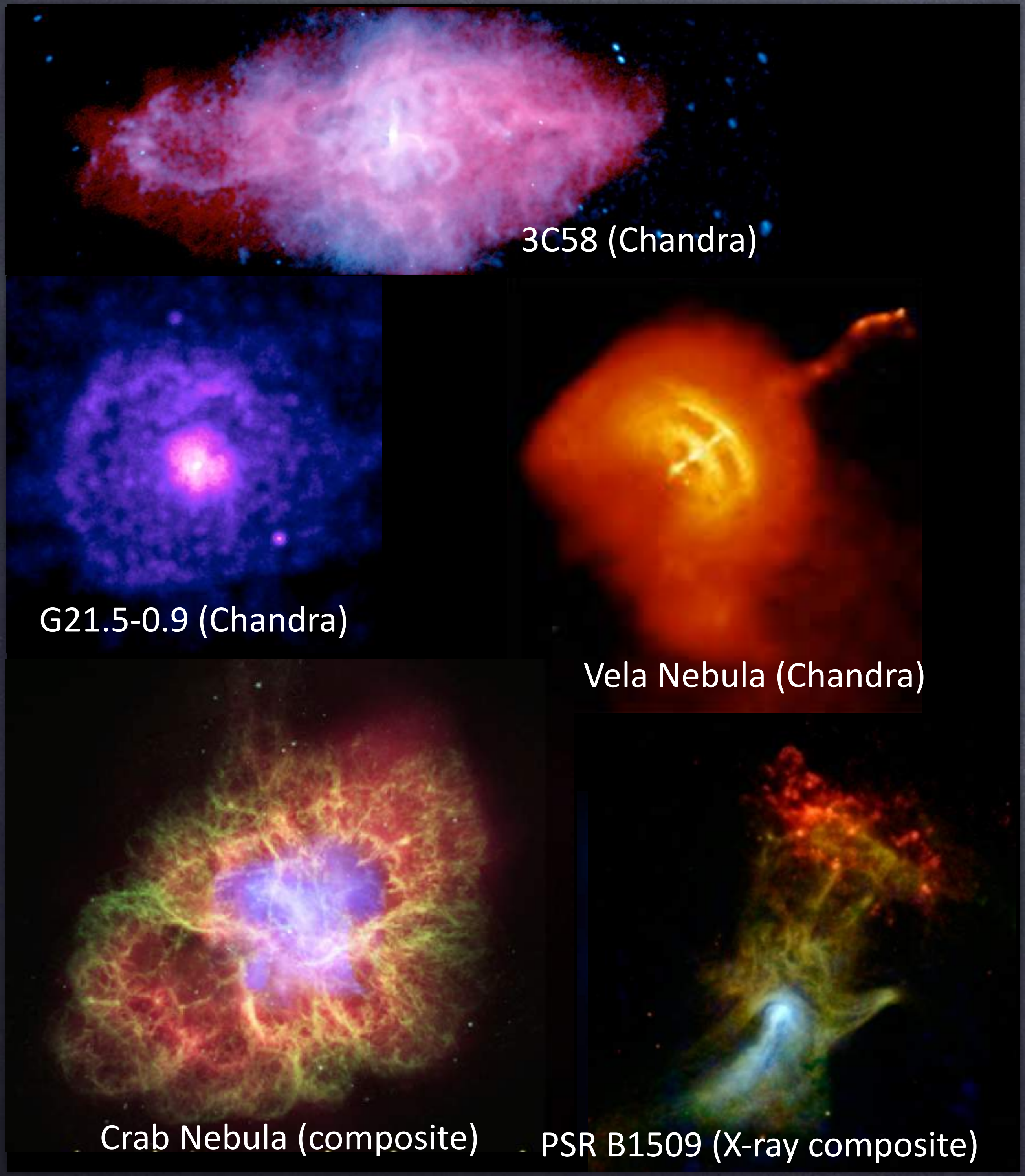
synchrotron radiation by relativistic particles in the nebular B field

Inverse Compton scattering with local photon field

PARTICLES AND FIELD

FROM ROTATIONAL ENERGY LOST BY PULSAR [Pacini 1967]

THE CRAB NEBULA AS A PROTOTYPE



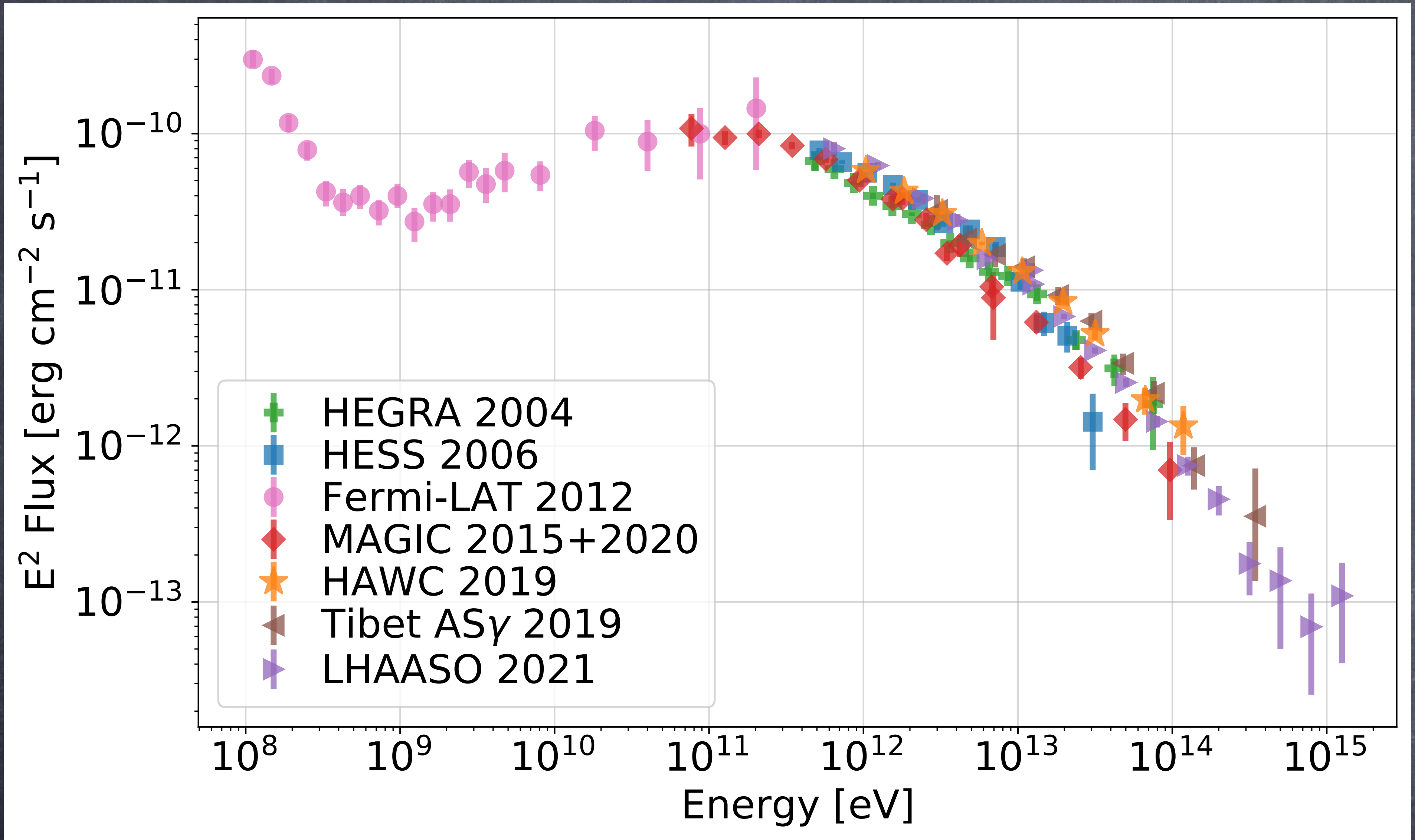
PULSAR WIND NEBULAE OR PLERIONS

SNRs WITH

- CENTER FILLED MORPHOLOGY
- BROAD NON THERMAL SPECTRUM
- FLAT RADIO SPECTRUM

$$F_\nu \propto \nu^{-\alpha}, \quad \alpha < 0.5$$

THE CRAB NEBULA IN GAMMA-RAYS



Amato & Olmi 2021

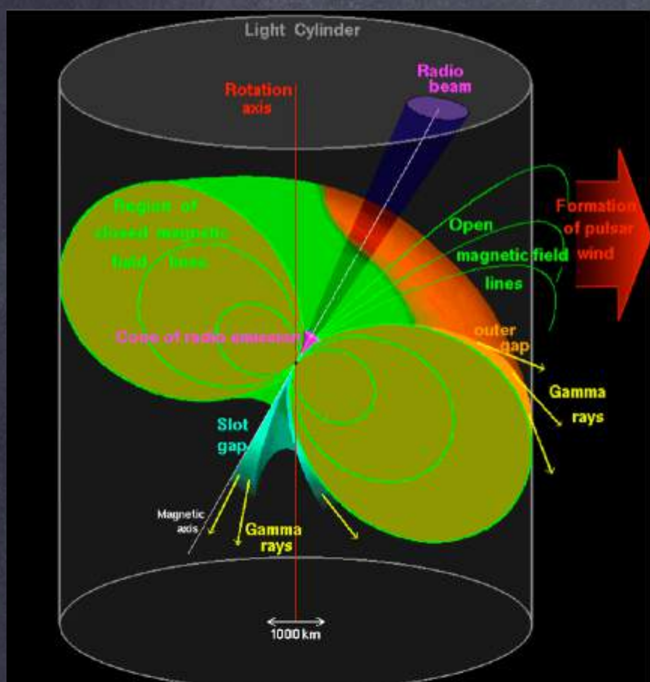
THE ONLY ESTABLISHED GALACTIC PEVATRON!!!

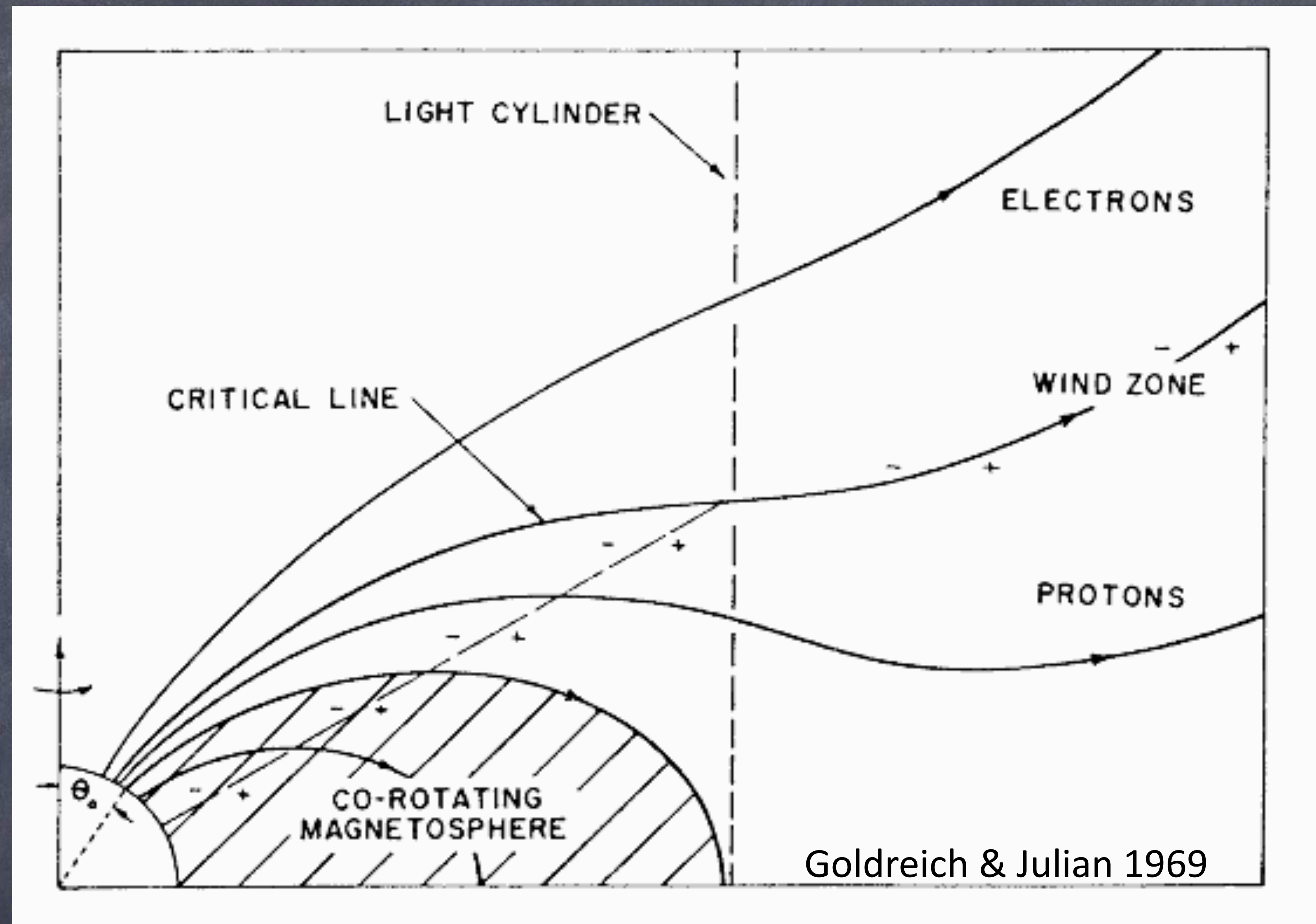
FOR ICS ON CMB

$$\epsilon_\gamma \approx 0.37\ (E_e/\text{PeV})^{1.3}\ \text{PeV}$$

HIGHEST ENERGY LHAASO DATA POINT ⟷ $E_e \approx 2.4$ PeV

THE CENTRAL ENGINE





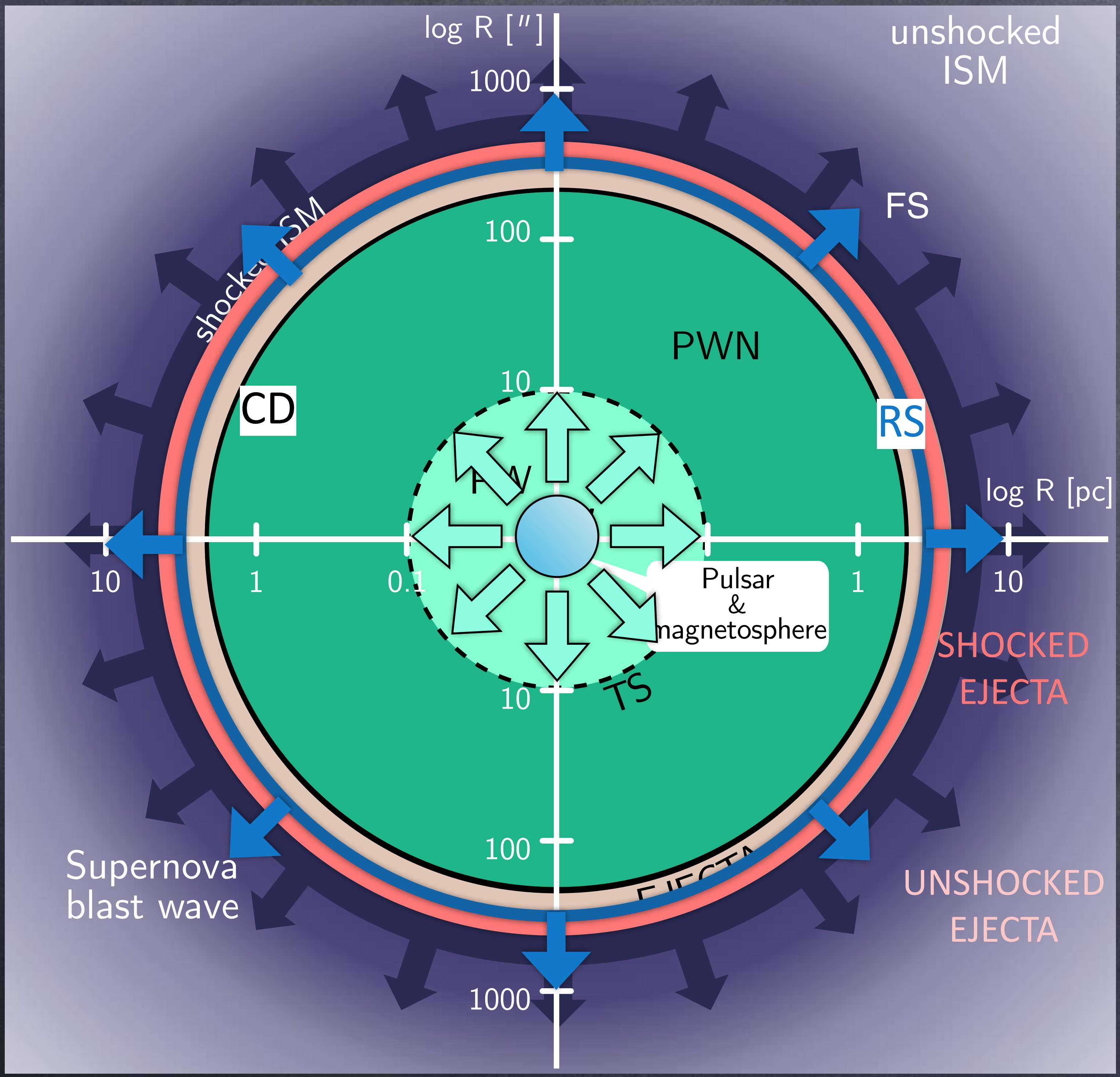
Goldreich & Julian 1969

PULSAR WIND ENERGY FLUX:

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma)$$

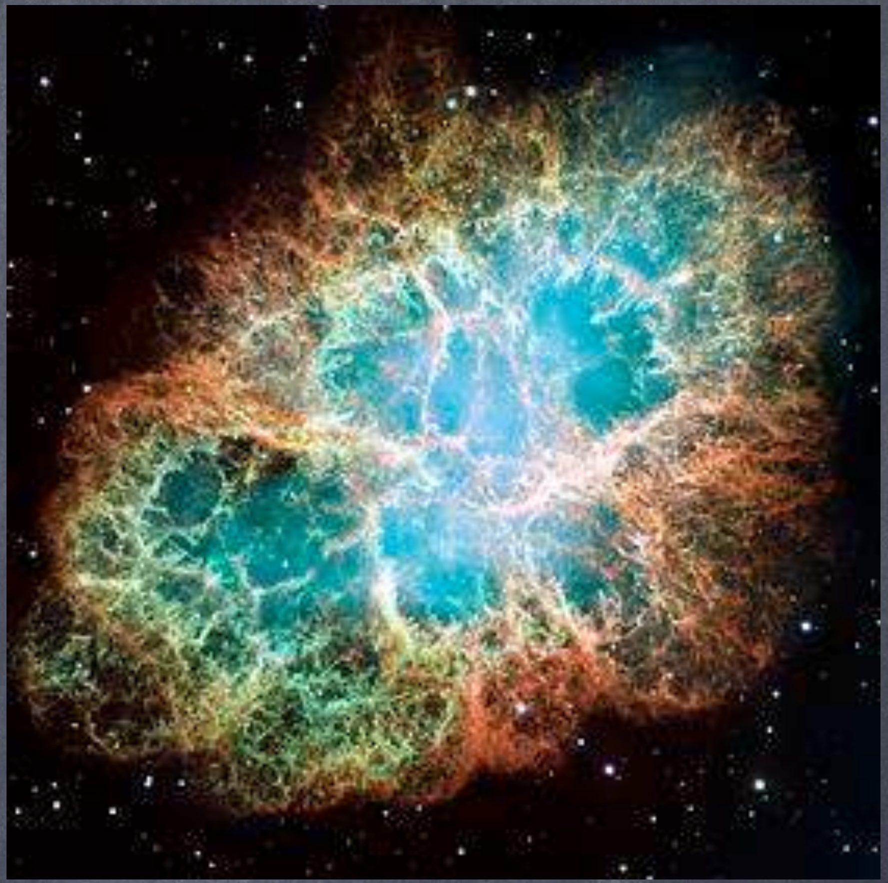
$$\sigma = \frac{B^2}{4\pi\ n_+\ m_e\ c^2\ \Gamma^2}$$

BASIC PICTURE OF A PWN



Adapted from Kennel & Coroniti 1984

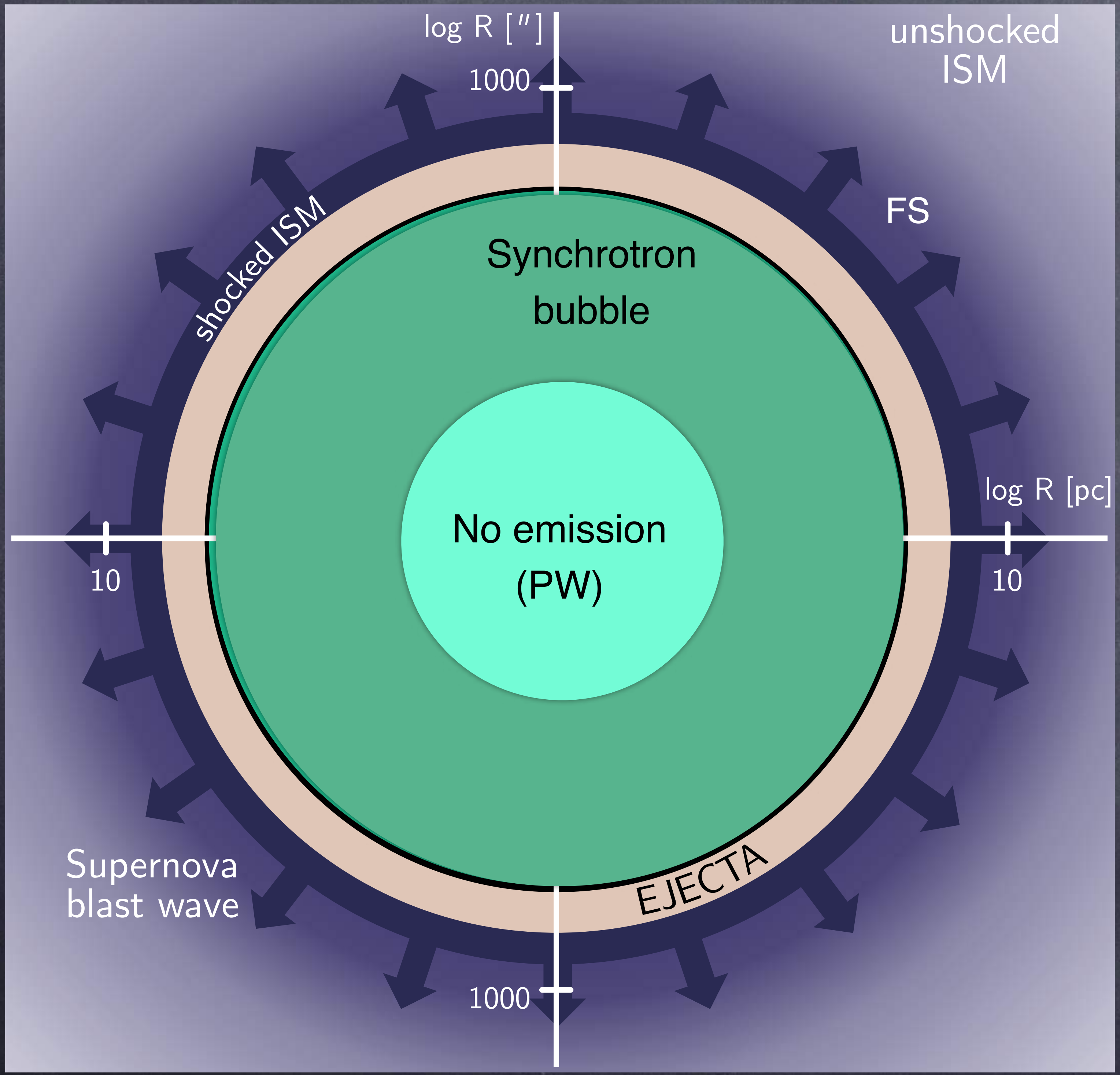
[Del Zanna & Olmi 2017]



$$\frac{\dot{E}}{4\pi c R_{TS}^2} = P_{PWN} = \frac{\dot{E}\ t}{4\pi R_N^3}$$

$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

THE TERMINATION SHOCK



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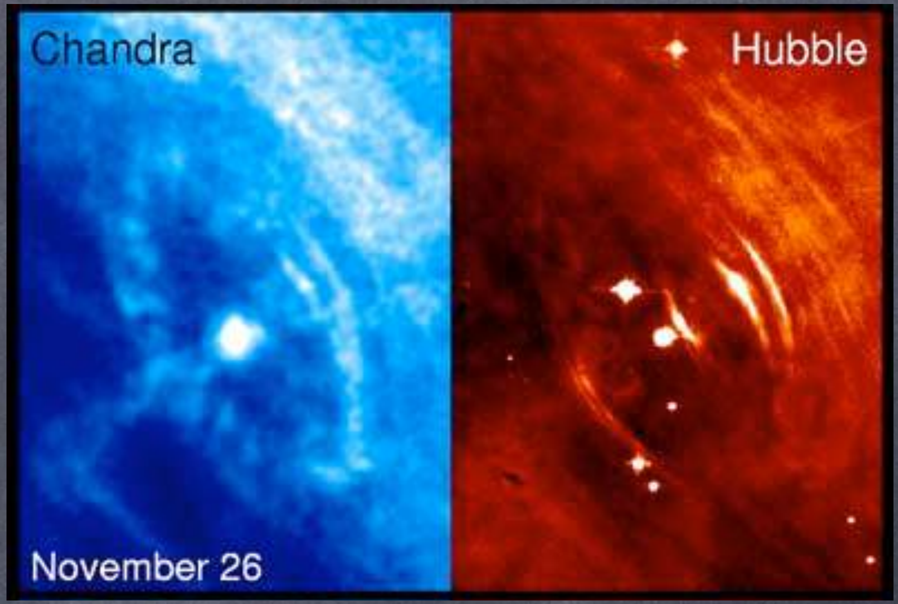
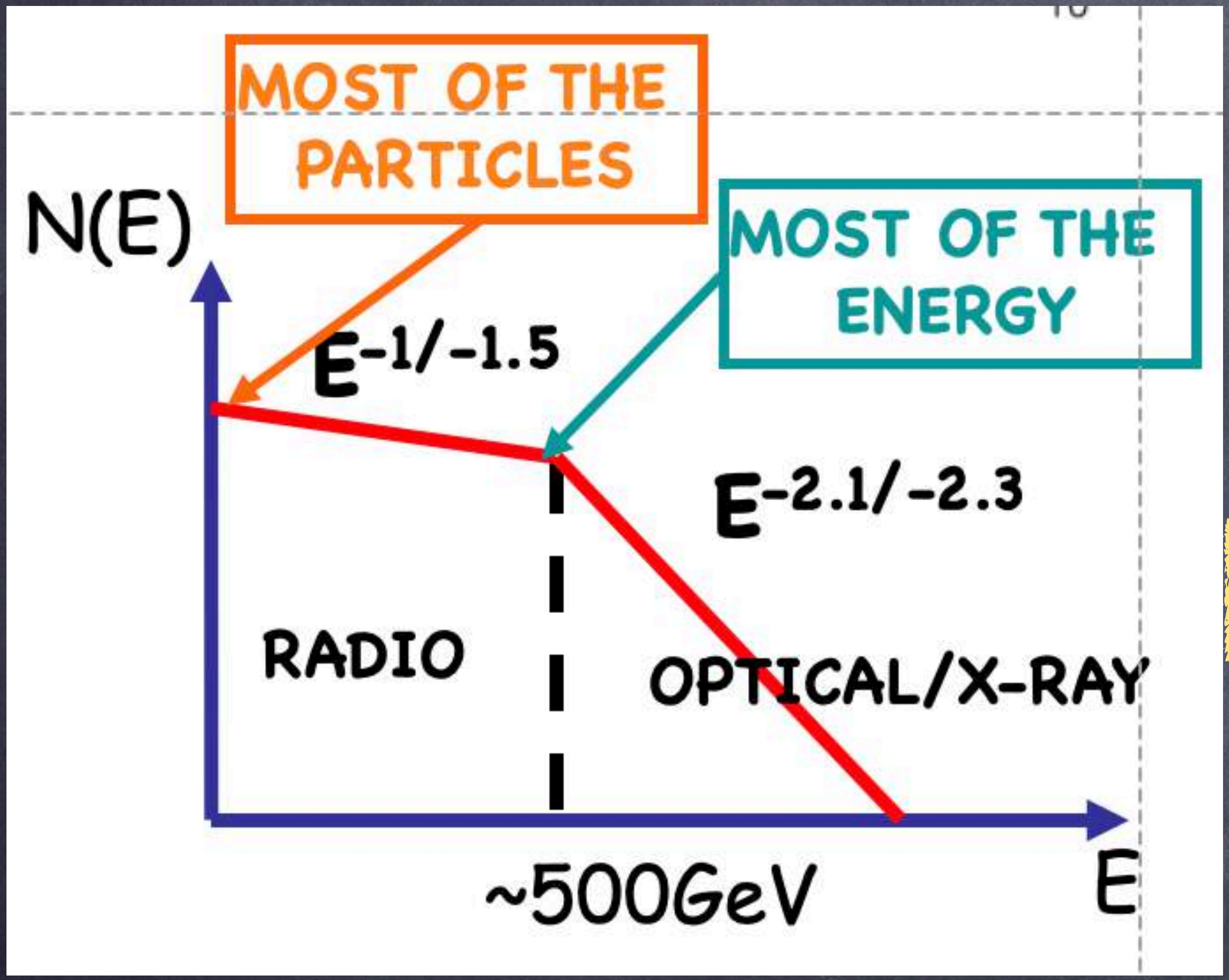


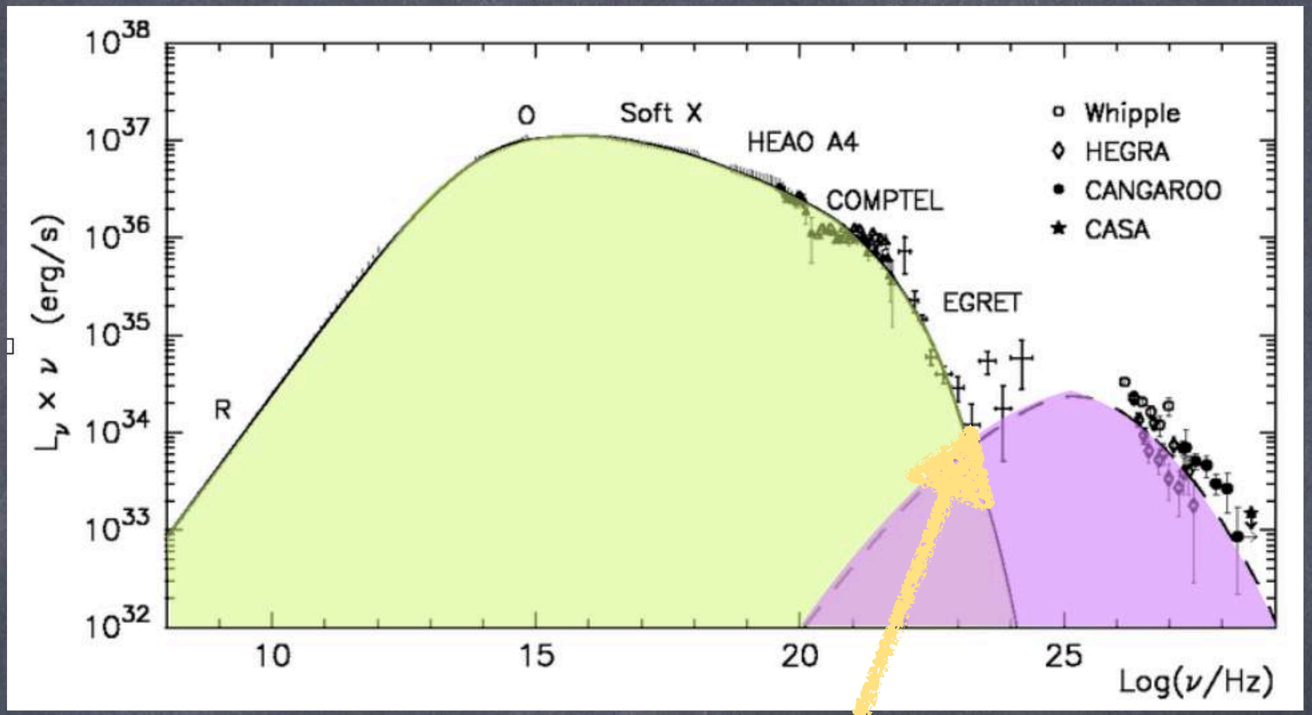
$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

DISSIPATION AND PARTICLE ACCELERATION AT TS

EMITTING PARTICLES



ONE ZONE MODELS
(Pacini & Salvati 1973, EA+ 2000, Bucciantini+ 2011….)
(also Fraschetti & Pohl 2017 for log-parabola injection)



PeV ELECTRONs

$B_{NEB} \approx 100\ \mu G$

$L_{NEB} > 20\,\%\,\dot{E}$

EXTRAORDINARY ACCELERATOR!

BUT….

HOW ARE PARTICLES ACCELERATED????

- ★EFFICIENCY OF ACCELERATION >20%
- ★MAXIMUM ENERGY >PeV

COLLISIONLESS SHOCK (*)

POSSIBILITIES DEPEND ON

COMPOSITION OF THE FLOW

?

MAGNETIZATION

?

MAGNETIC INCLINATION → HIGHLY RELATIVISTIC

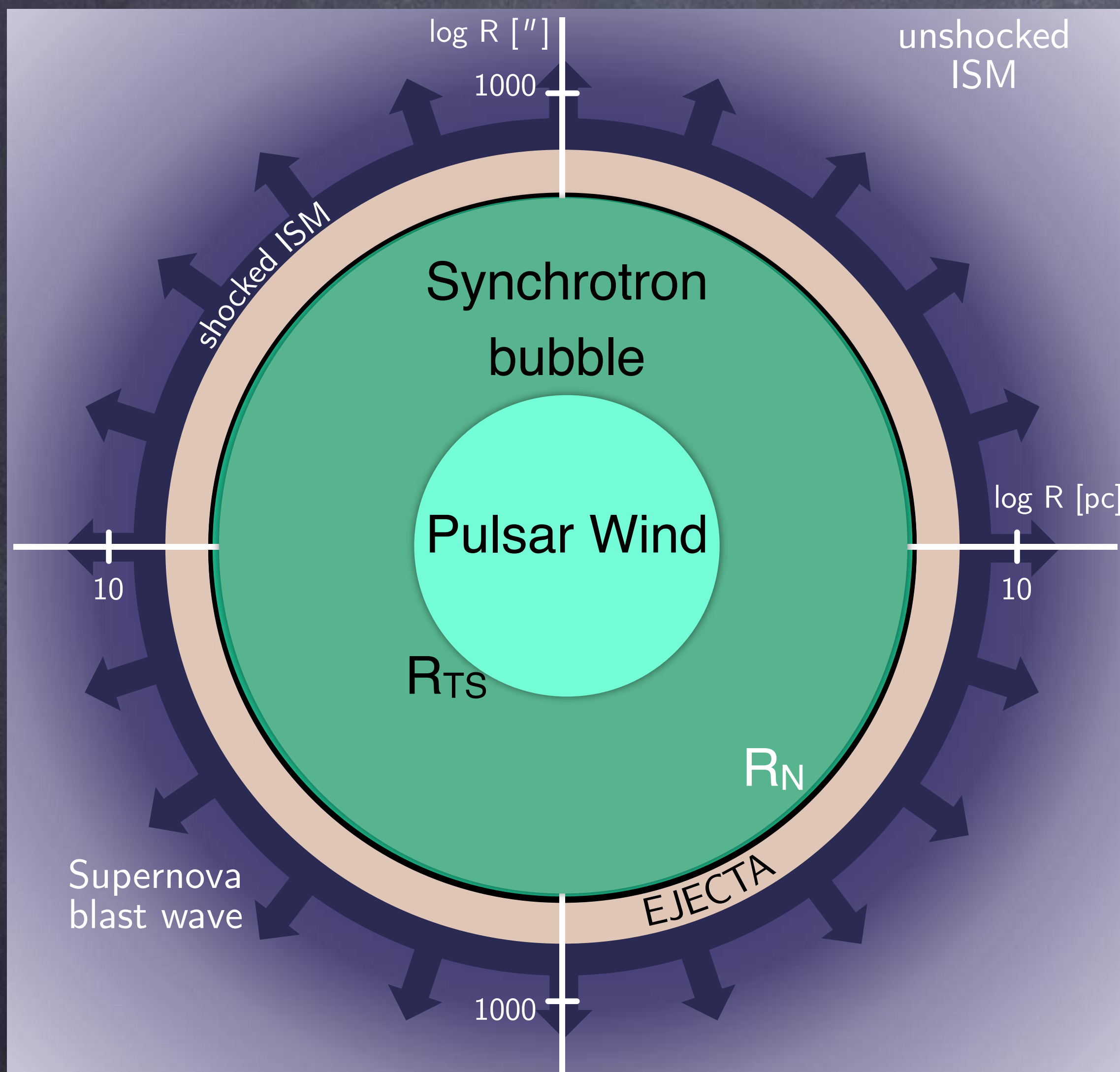
$\Downarrow$

PERPENDICULAR SHOCK

CONSTRAINING THE WIND MAGNETIZATION

1D/2D STATIC MODELS OF PWNE

[Rees & Gunn 1974, Kennel & Coroniti 1984, Emmering & Chevalier 1987, Begelman & Li 1992]



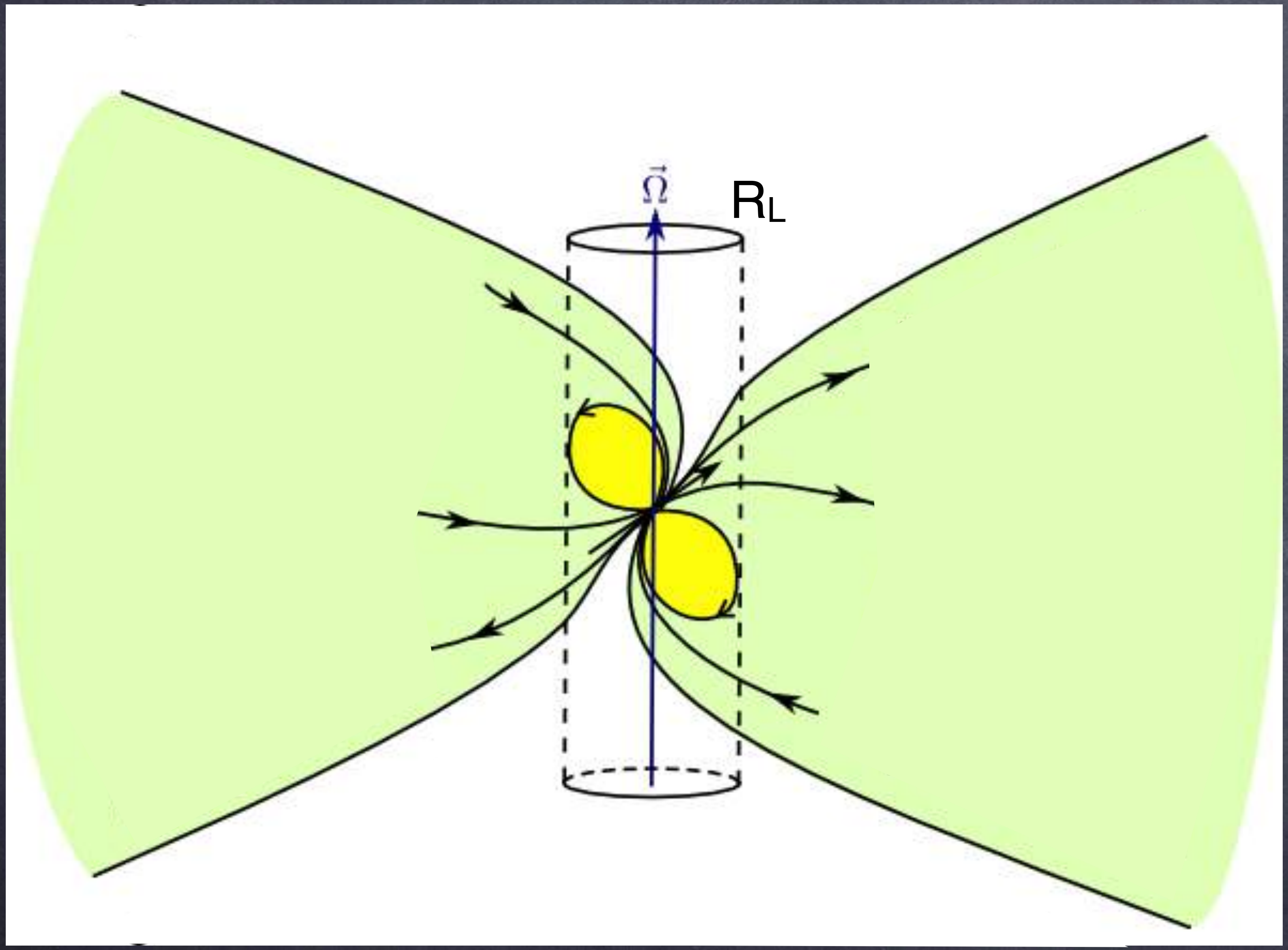
- particle spectral index(es) → $\gamma = 2.3$
- wind Lorentz factor → $\Gamma = 3 \times 10^6$
- wind magnetization → $\sigma = v_N/c \approx 3 \times 10^{-3}$
- particle injection rate → $\dot{N} \approx 10^{38}\ s^{-1}$

FROM DYNAMICS AND RADIATION MODELING OF OPTICAL /X-RAY EMISSION

THE σ PROBLEM

FROM PULSAR THEORIES:

$$\sigma \sim 10^4 @ R_L$$



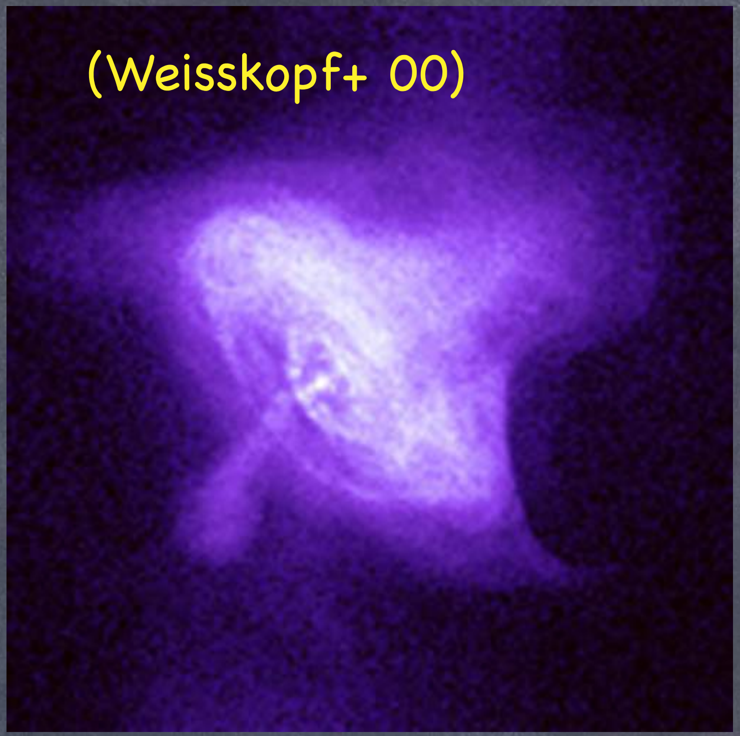
FROM 1D PWN MODELS:

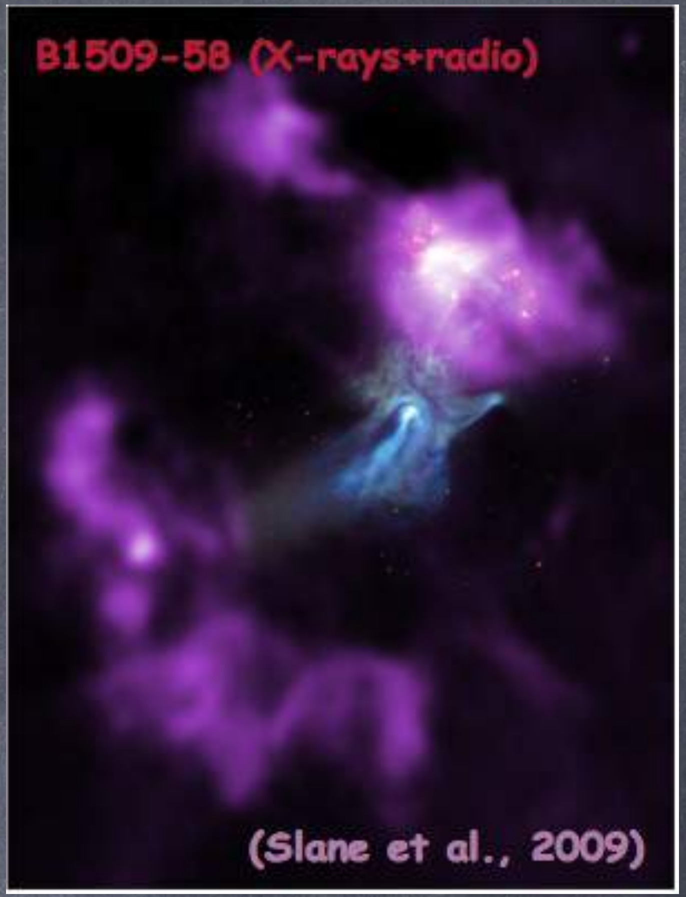
$$\sigma \sim 10^{-3} @ R_{TS}$$

$$R_{TS} \sim 10^9 R_L$$

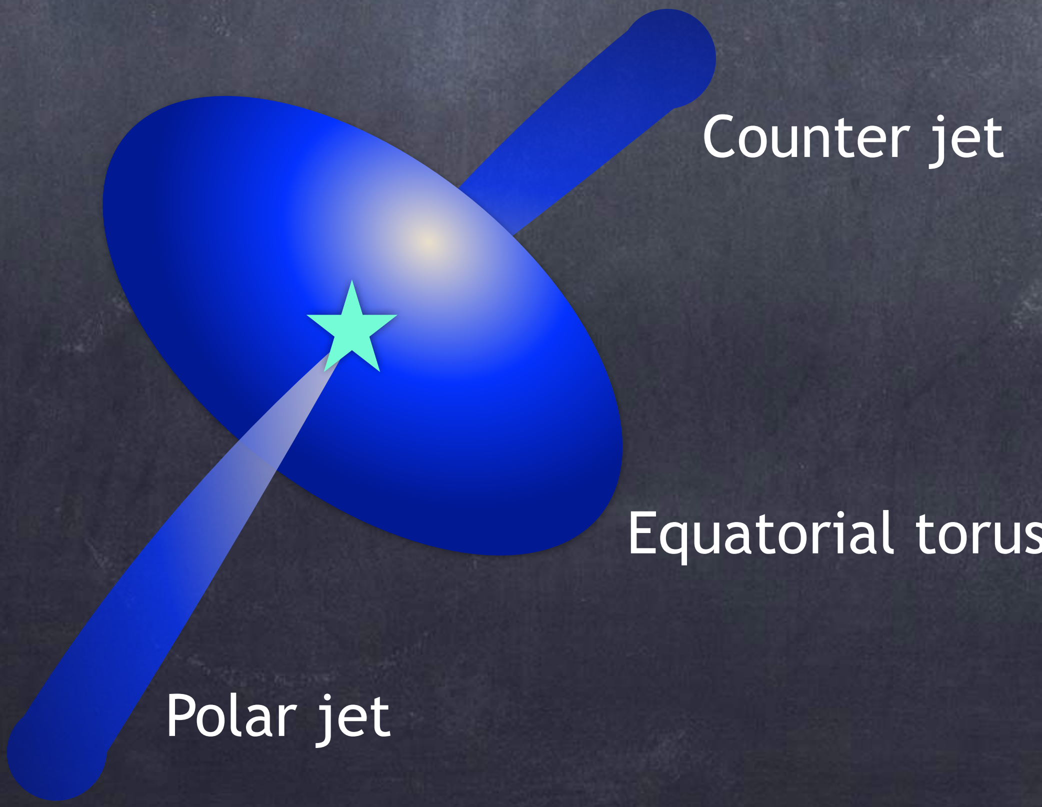
BUT ENERGY CONVERSION DIFFICULT TO EXPLAIN

CHANDRA'S VIEW OF PWNE

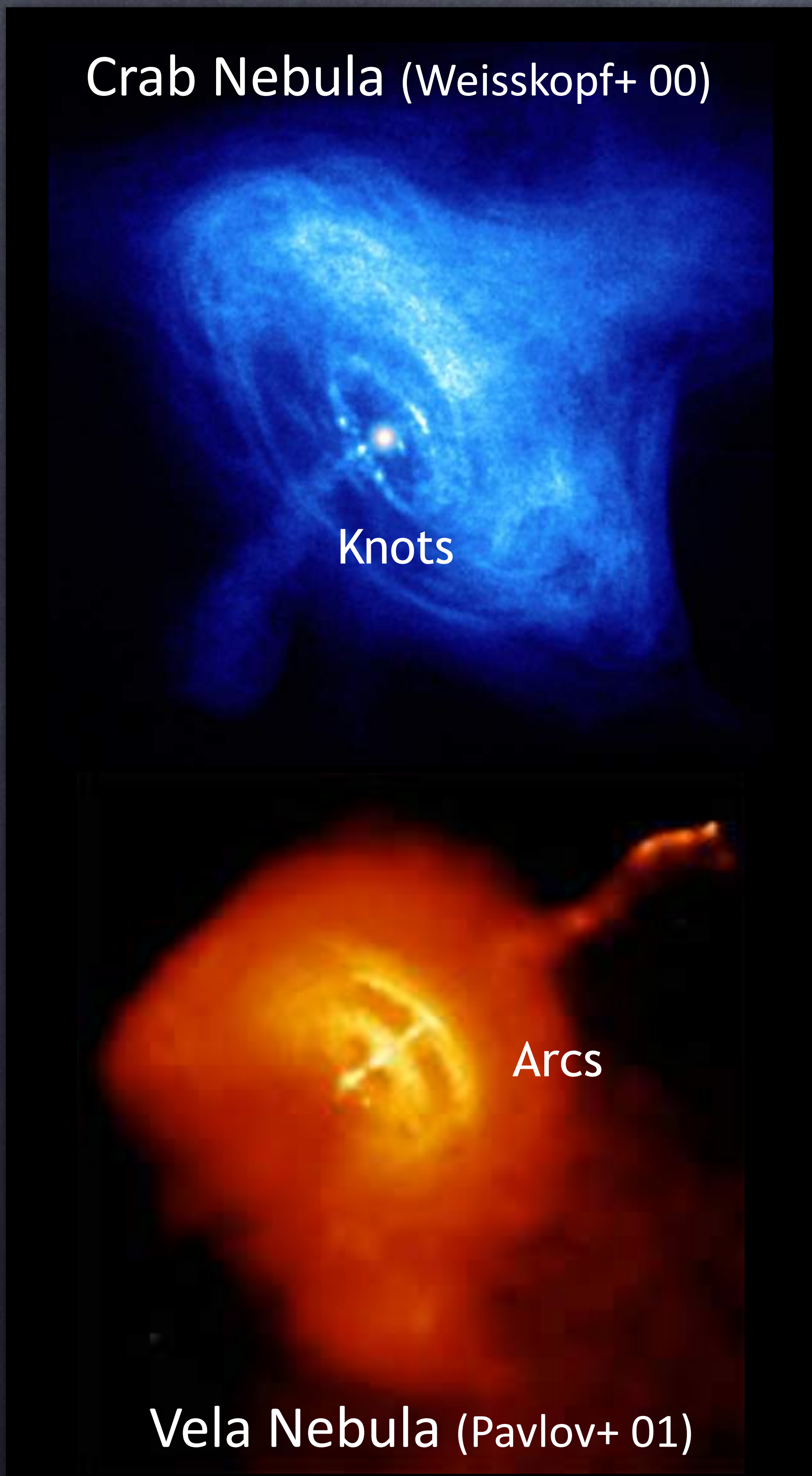




Jet-torus morphology of inner nebula



THE JET PUZZLE



JET FROM
R<R_{TS}

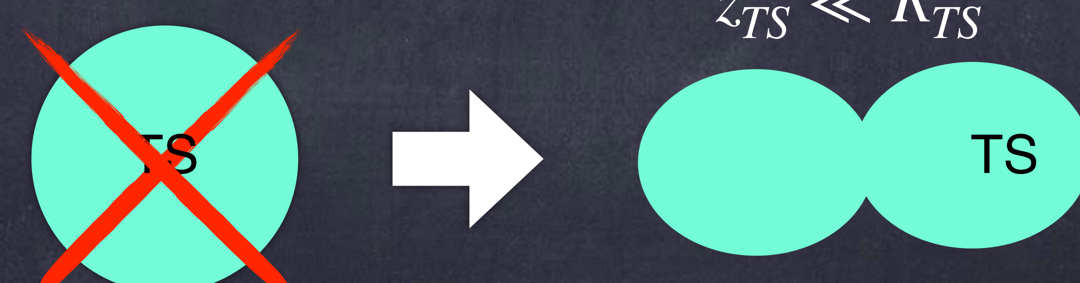
BUT NO MAGNETIC COLLIMATION IN RELATIVISTIC FLOWS
[Lyubarsky & Eichler 01]

$$\Gamma \gg 1 \;\rightarrow\; \rho\vec{E} + \vec{J}\times\vec{B} \sim 0$$

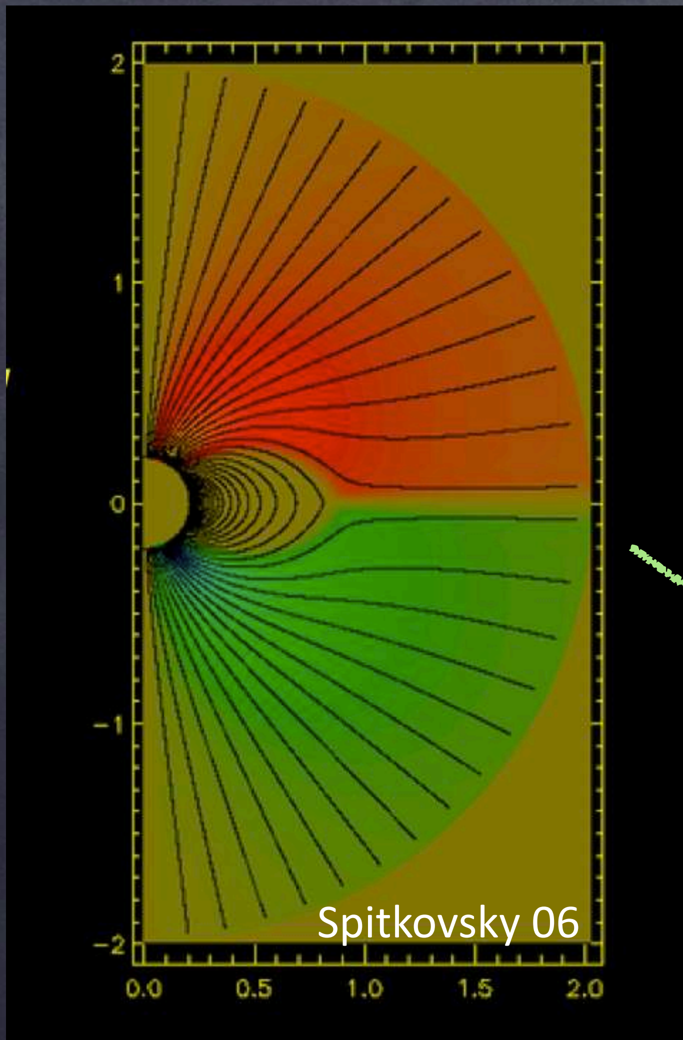
$$F \propto \sin^2(\theta)$$

[Bogovalov & Khangoulian 02, Lyubarsky 02]

$$z_{TS} \ll R_{TS}$$



THE ANISOTROPIC PULSAR WIND

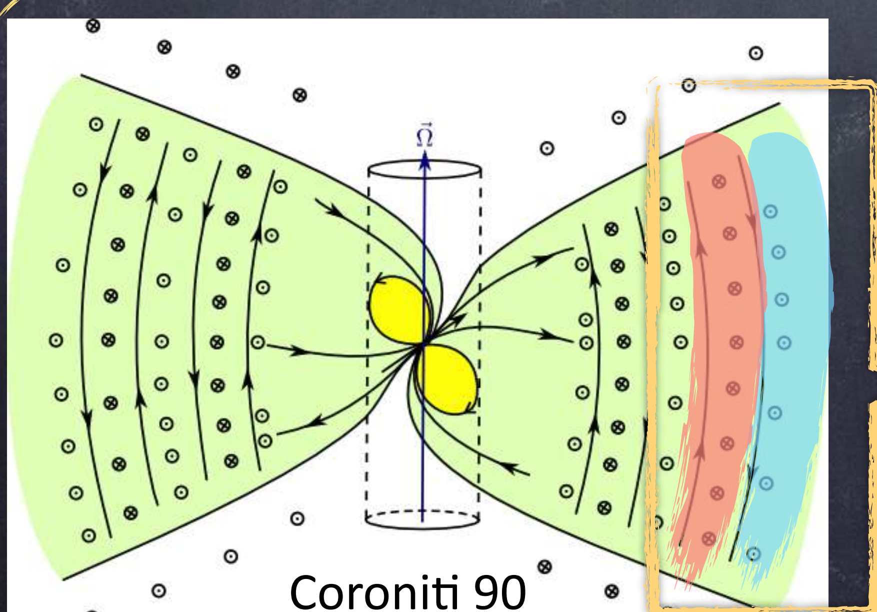


Spitkovsky 06

Komissarov & Lyubarsky 03, 04; Del Zanna+ 04, 06; Bogovalov+ 05
Camus+ 09; Volpi+ 08; Olmi+ 14, 15

$$F(\theta) \propto \sin^2(\theta)$$

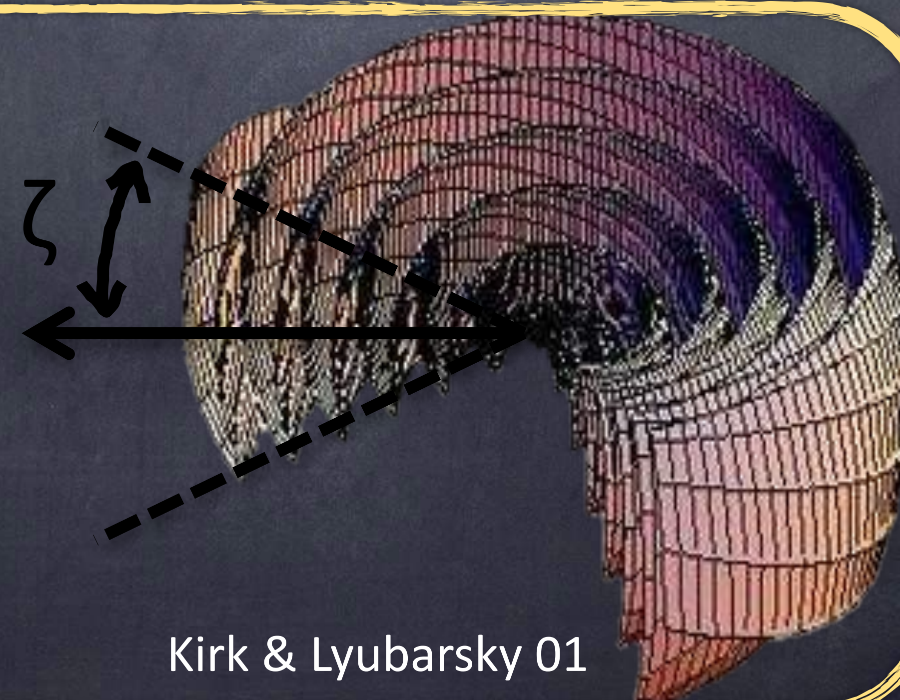
$$B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)$$



Coroniti 90

alternating stripes of opposite B polarities

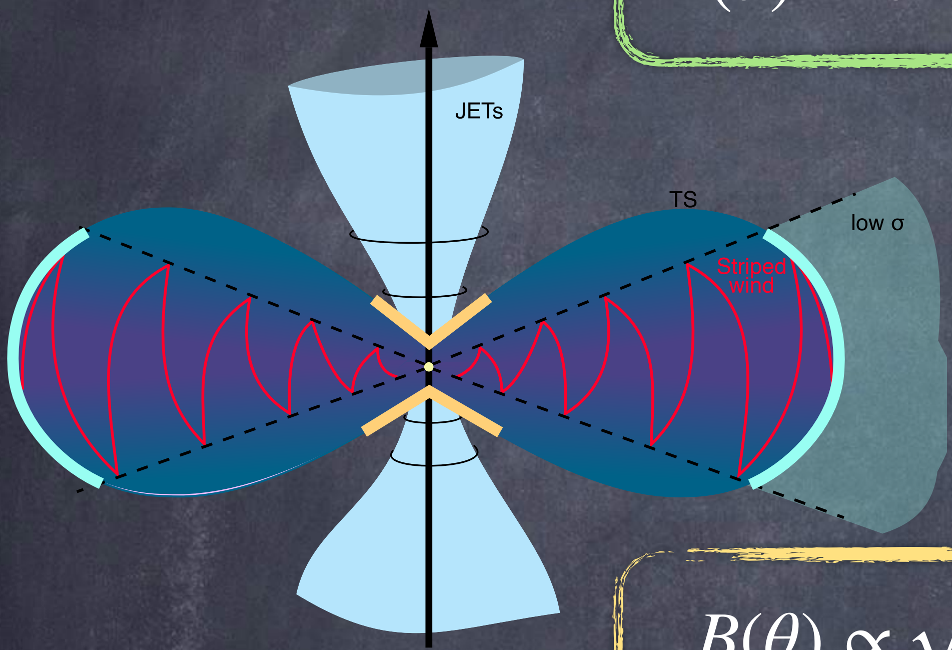
dissipation in current sheet



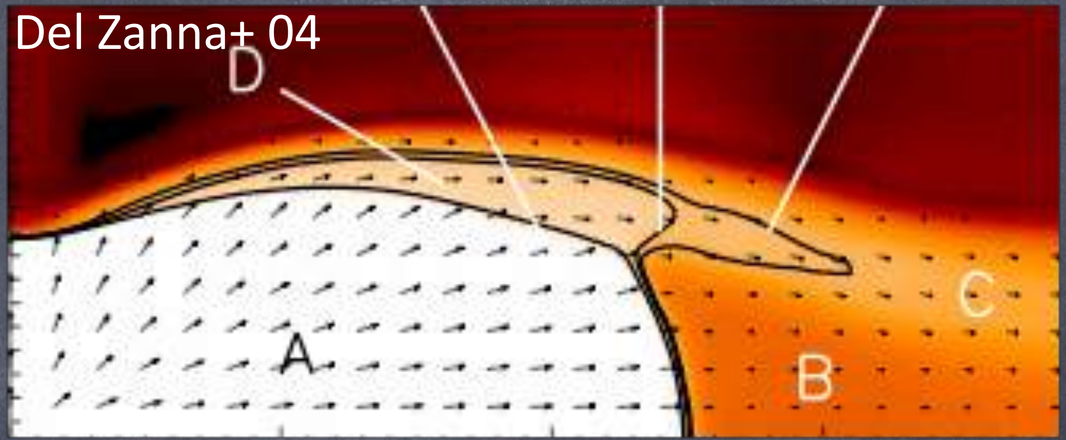
Kirk & Lyubarsky 01

2D MHD NUMERICAL MODELING: RINGS AND TORII

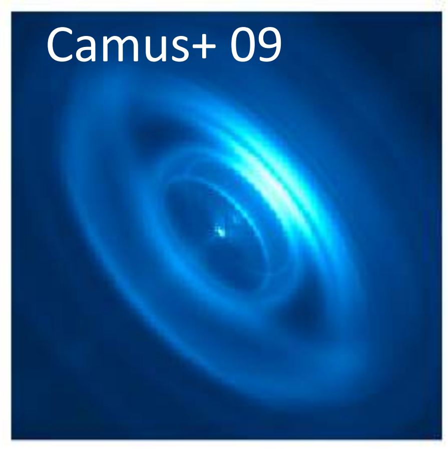
$$F(\theta) \propto \sin^2(\theta)$$

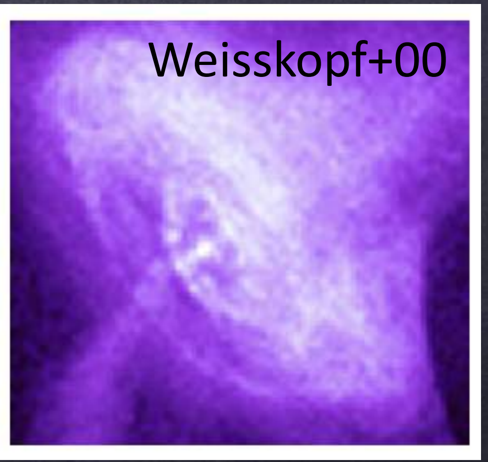


$$B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)$$

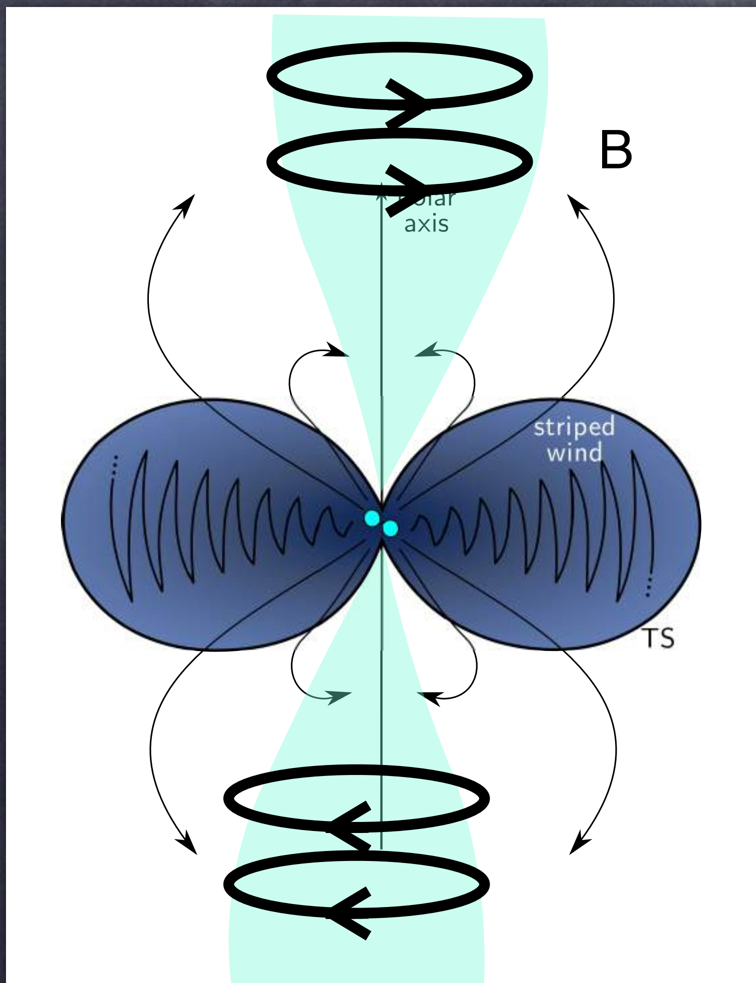


A: ULTRARELATIVISTIC WIND
B: SUBSONIC OUTFLOW
C: SUPERSONIC FUNNEL

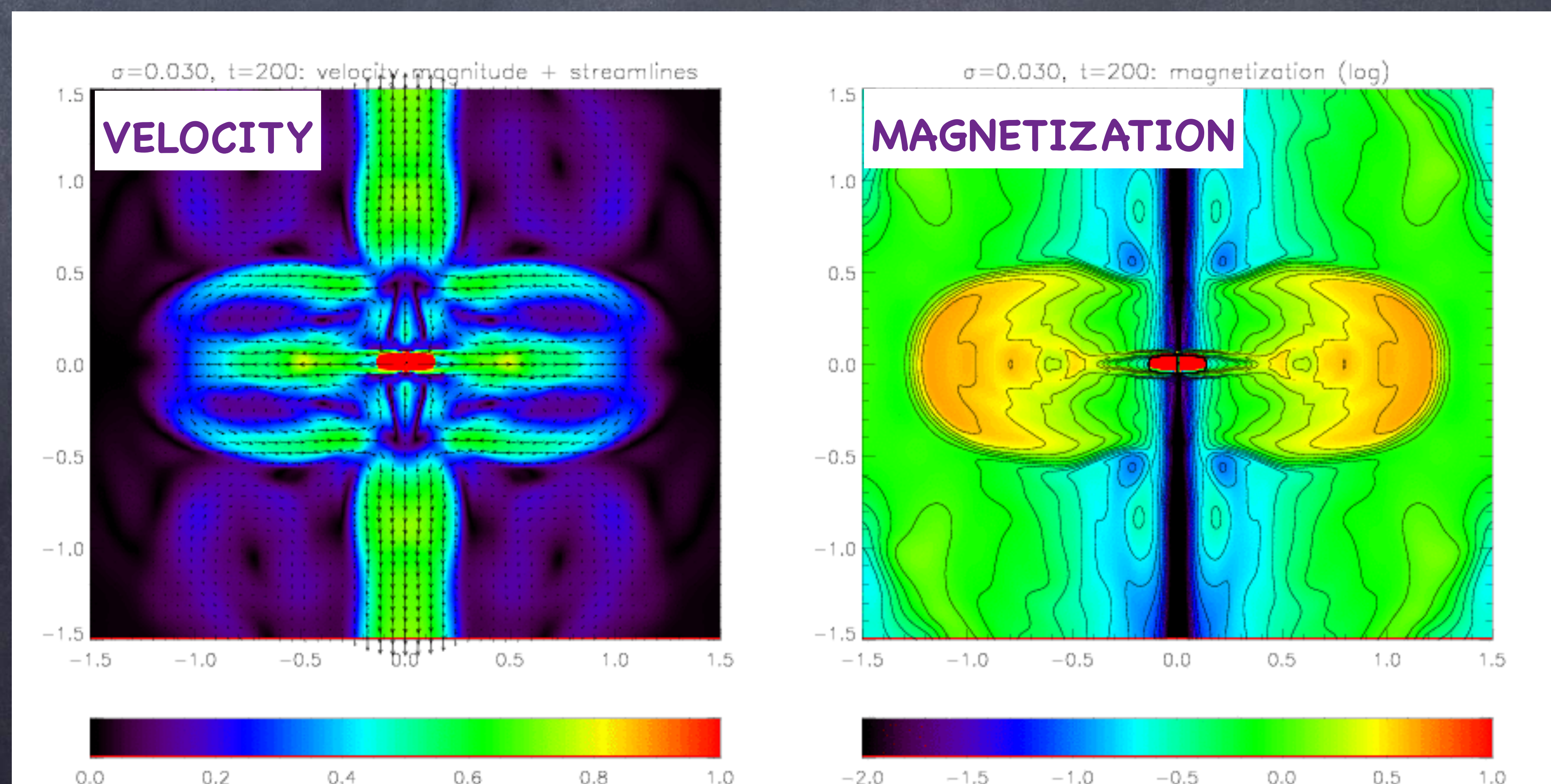




2D MHD NUMERICAL MODELING: JETS



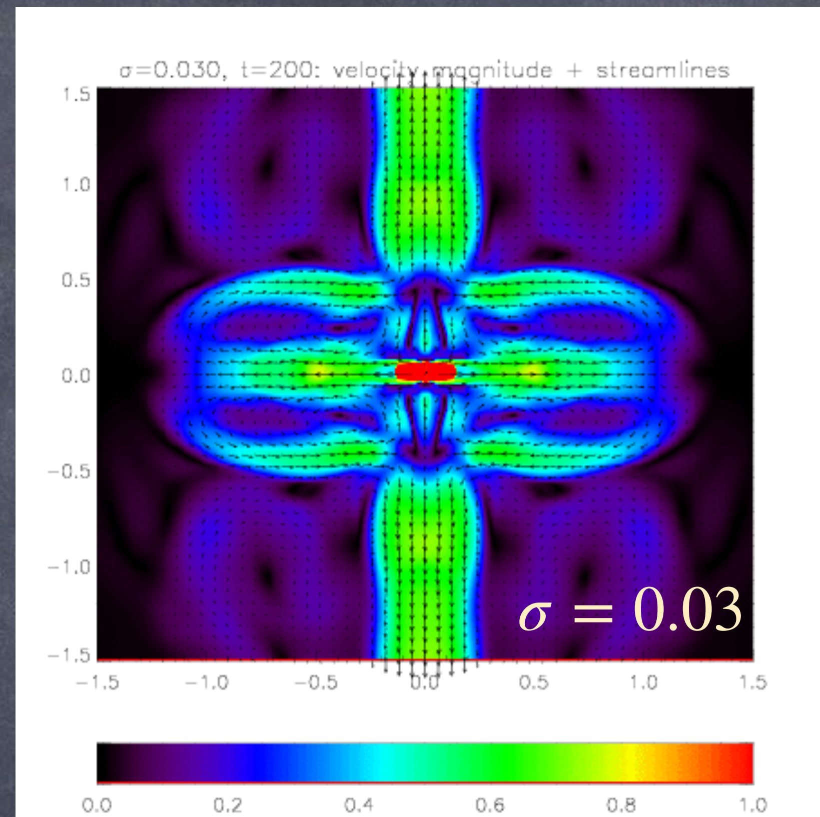
IN 2D JETS REQUIRE σ>0.03

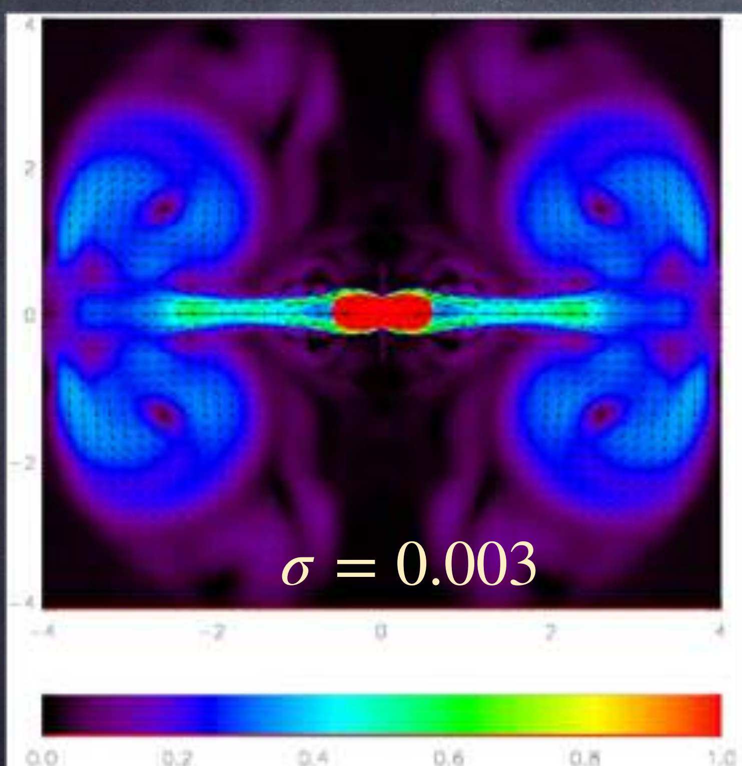


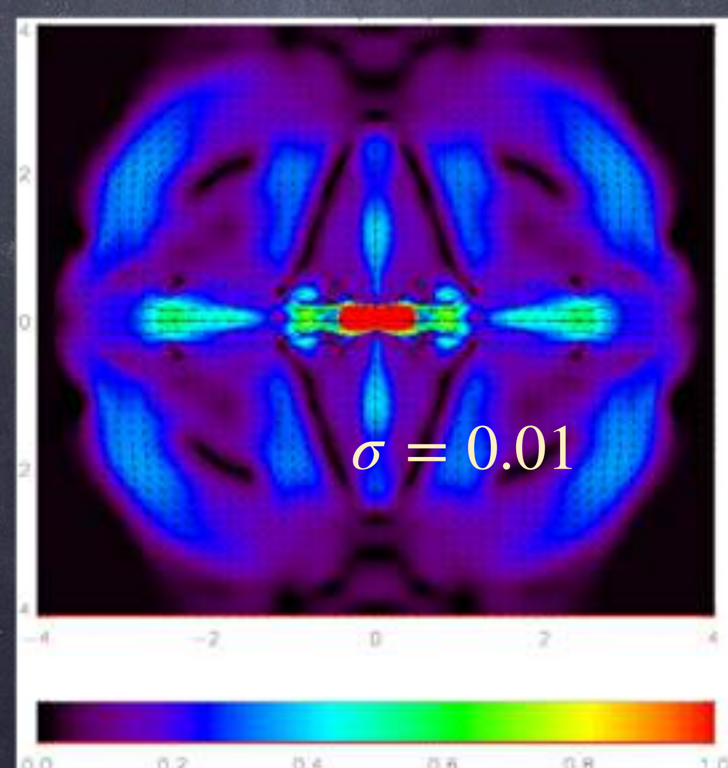
EQUIPARTITION NEEDED FOR JET FORMATION

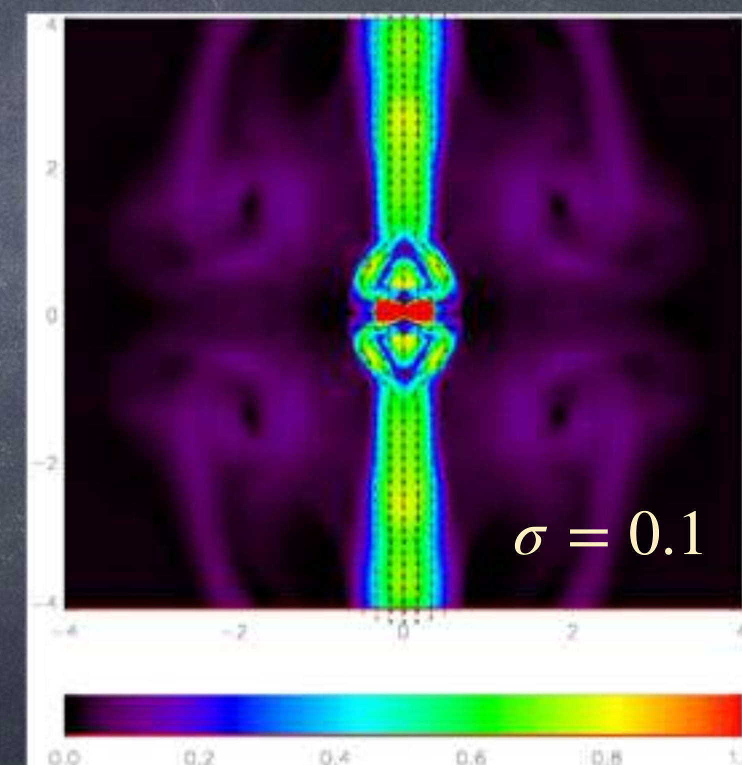
Del Zanna, EA, Bucciantini 04, 06

MAKING A JET



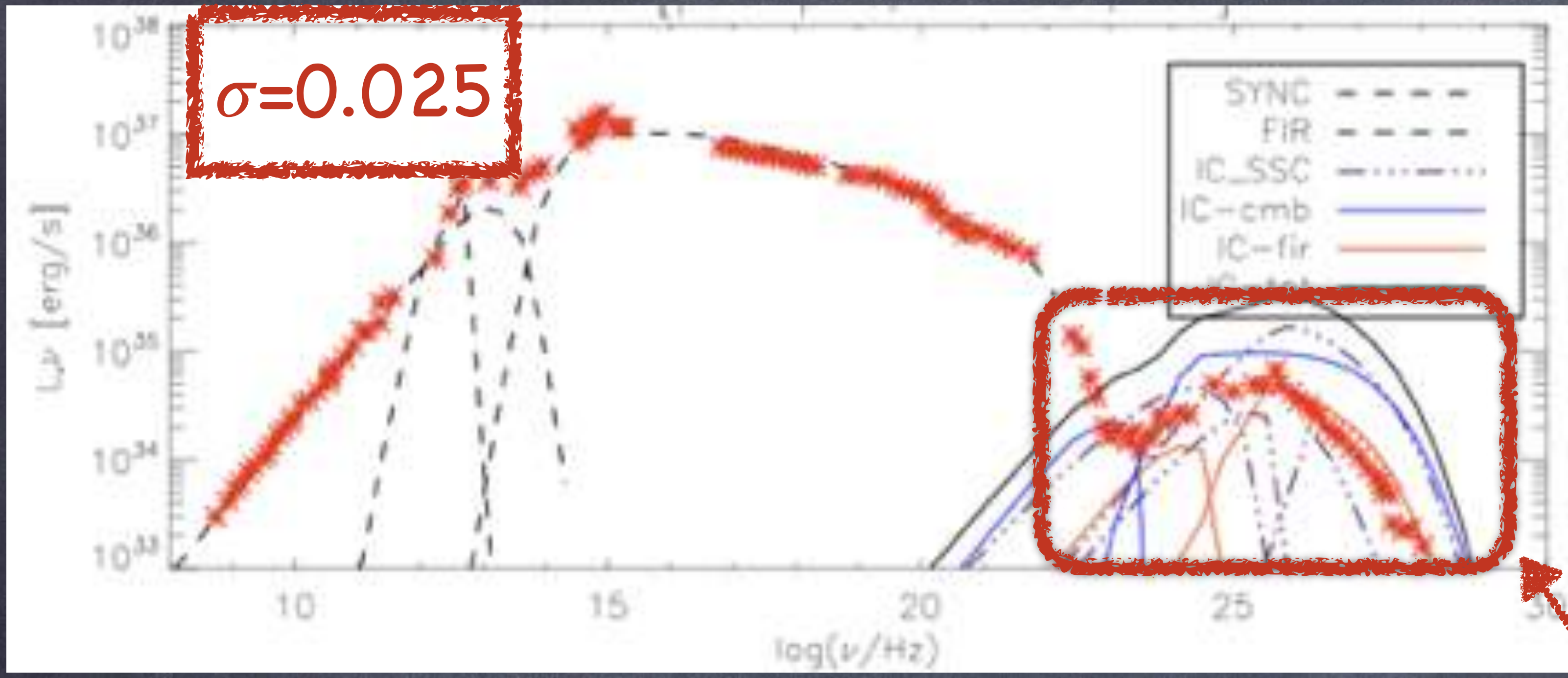


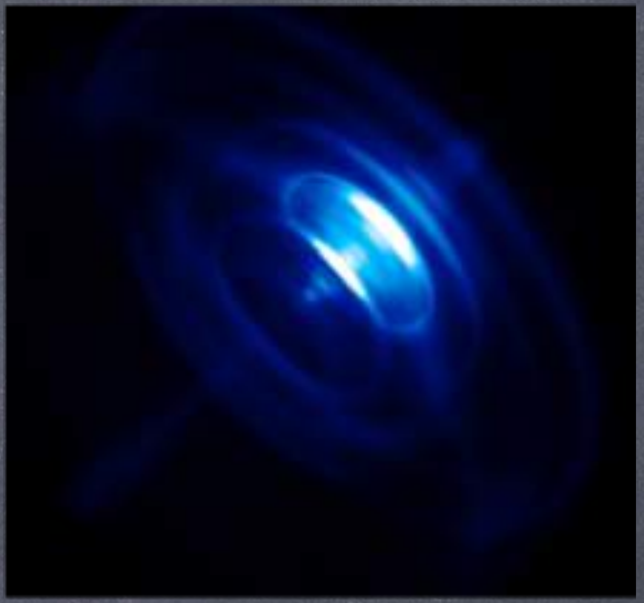




Del Zanna, EA, Bucciantini 04, 06

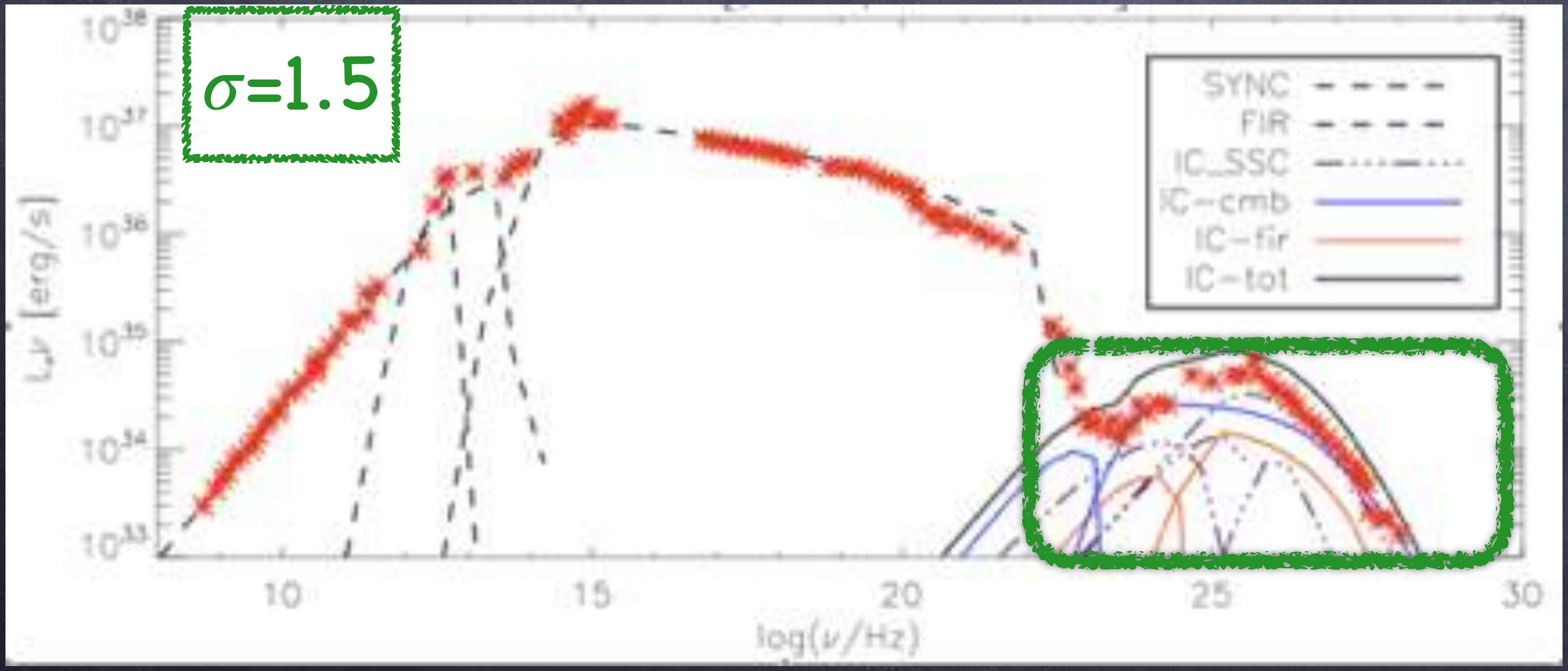
BEHIND PRETTY PICTURES

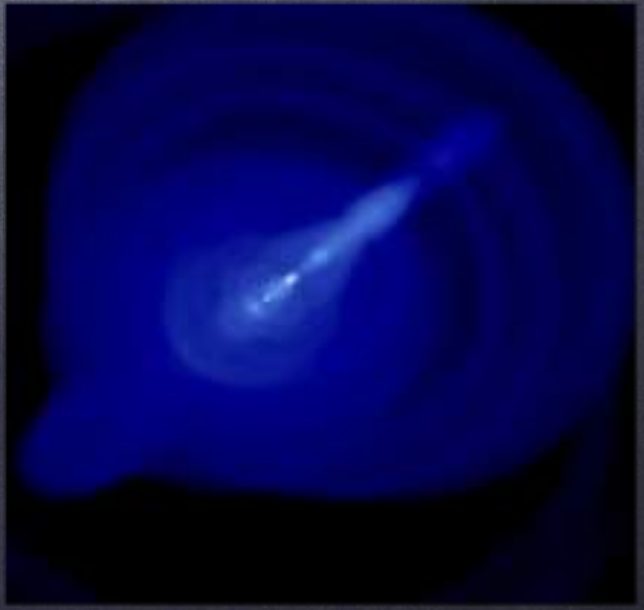




Volpi+ 08, Olmi+14

$B_{sim} \approx 10^{-5}\ G$



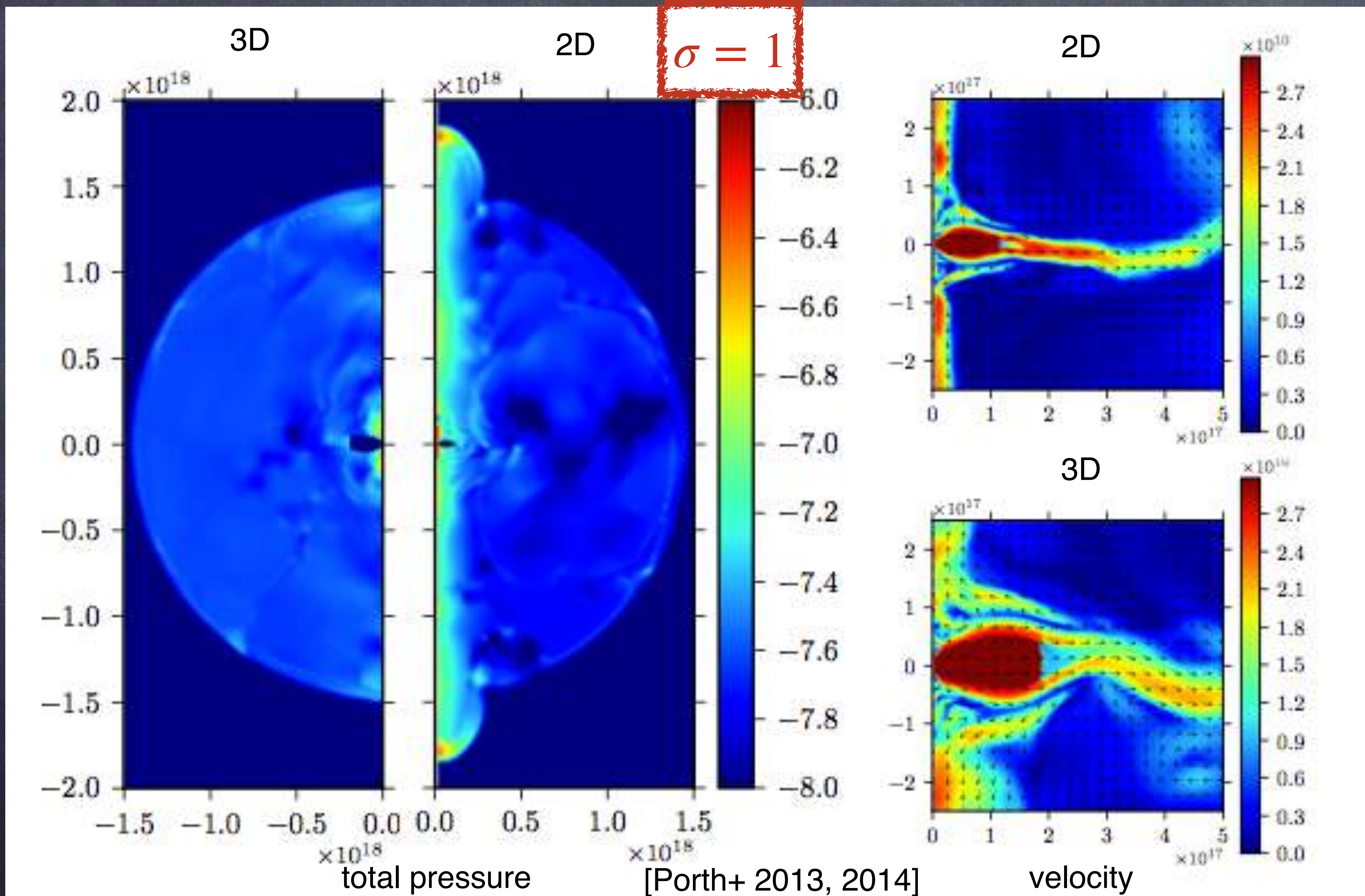


$B_{obs} \approx 10^{-4}\ G$

3D RMHD SIMULATIONS

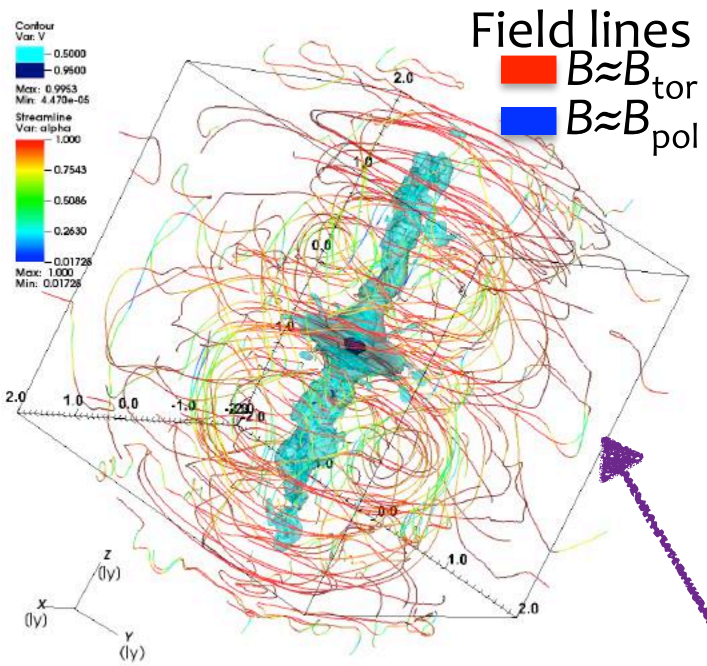
GLOBAL DYNAMICS DIFFERENT

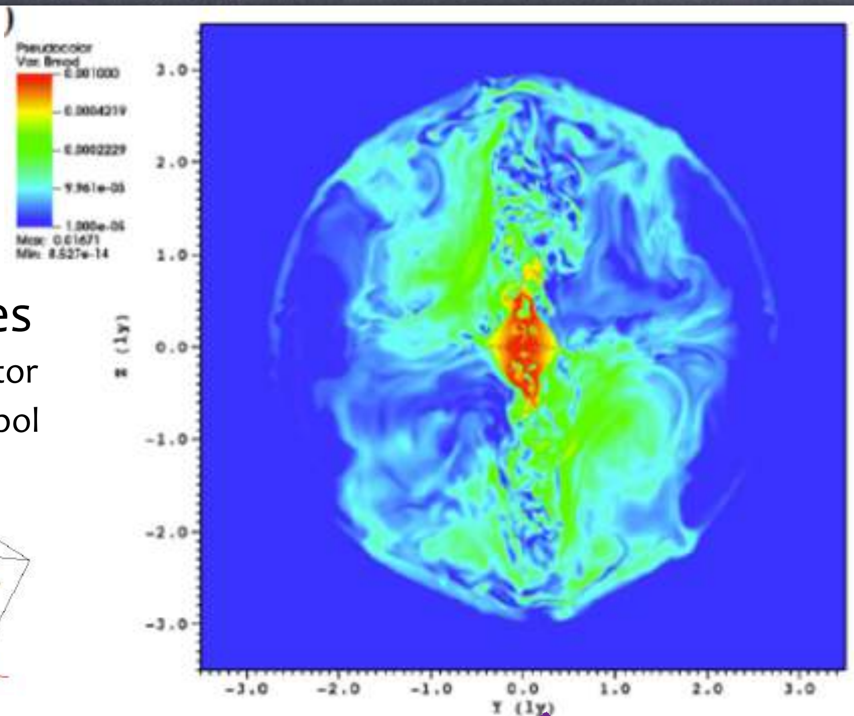
INNER DYNAMICS SIMILAR



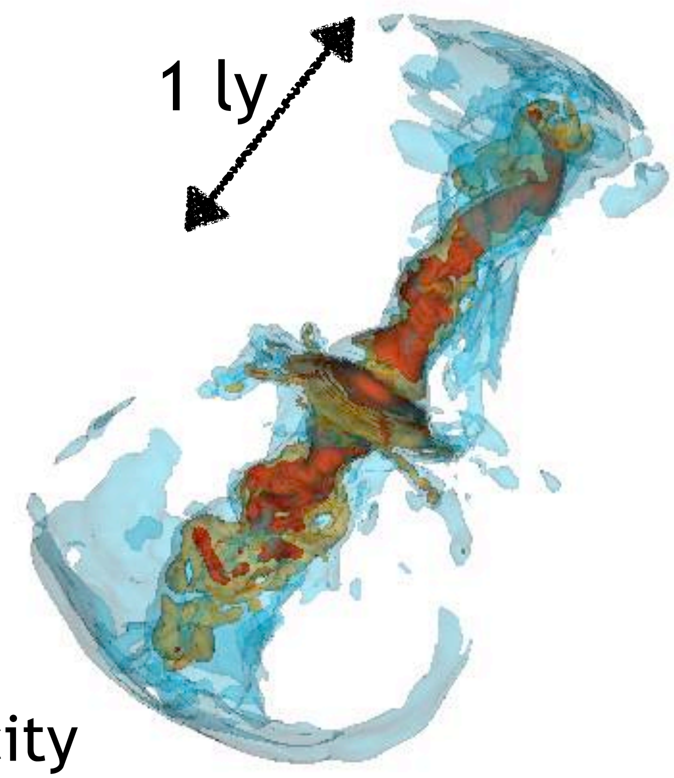
EARLY SUGGESTION (Begelman 98): KINKS REDUCE HOOP STRESS WITH LITTLE DISSIPATION

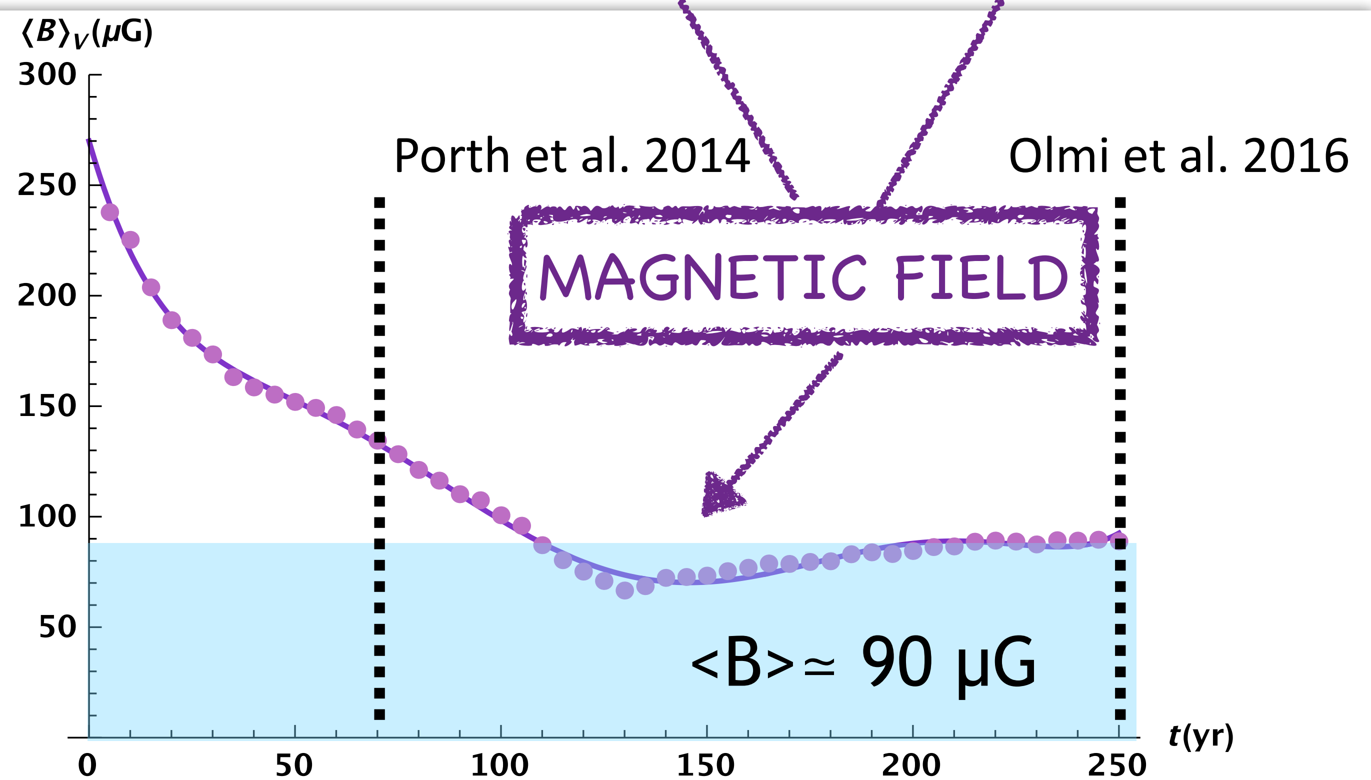
LONGER 3D RMHD SIMULATIONS





SELF SIMILAR PHASE FULLY REACHED





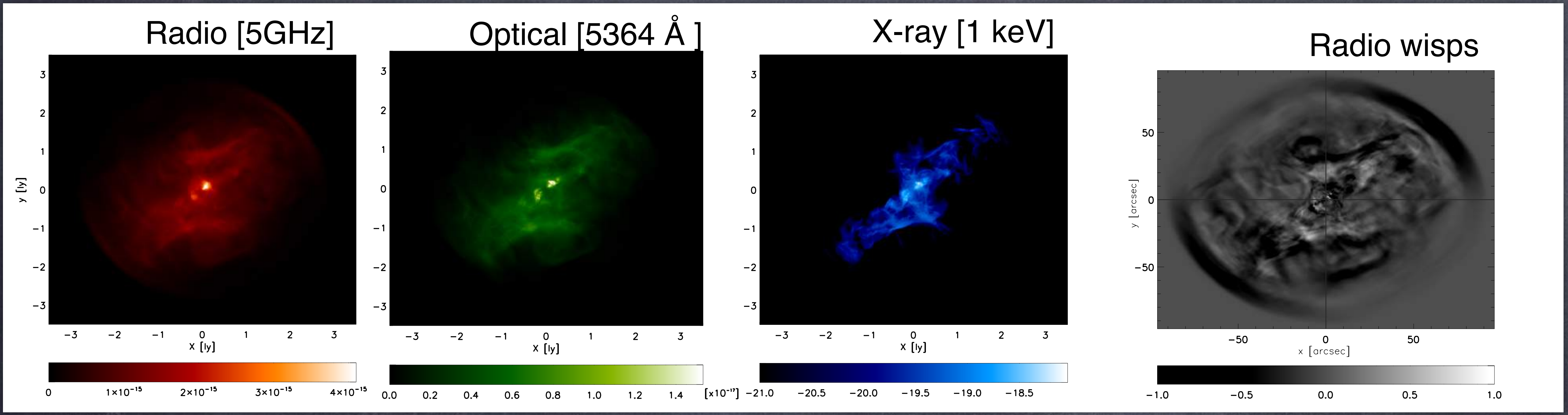
σ=1.5

ALL IS SOLVED?

✓ SHRINKAGE AND WISPS VARIABILITY OK

- NO BRIGHT X-RAY TORUS

Olmi+ 16



...NOT YET...

AVERAGE FIELD STILL TOO LOW →

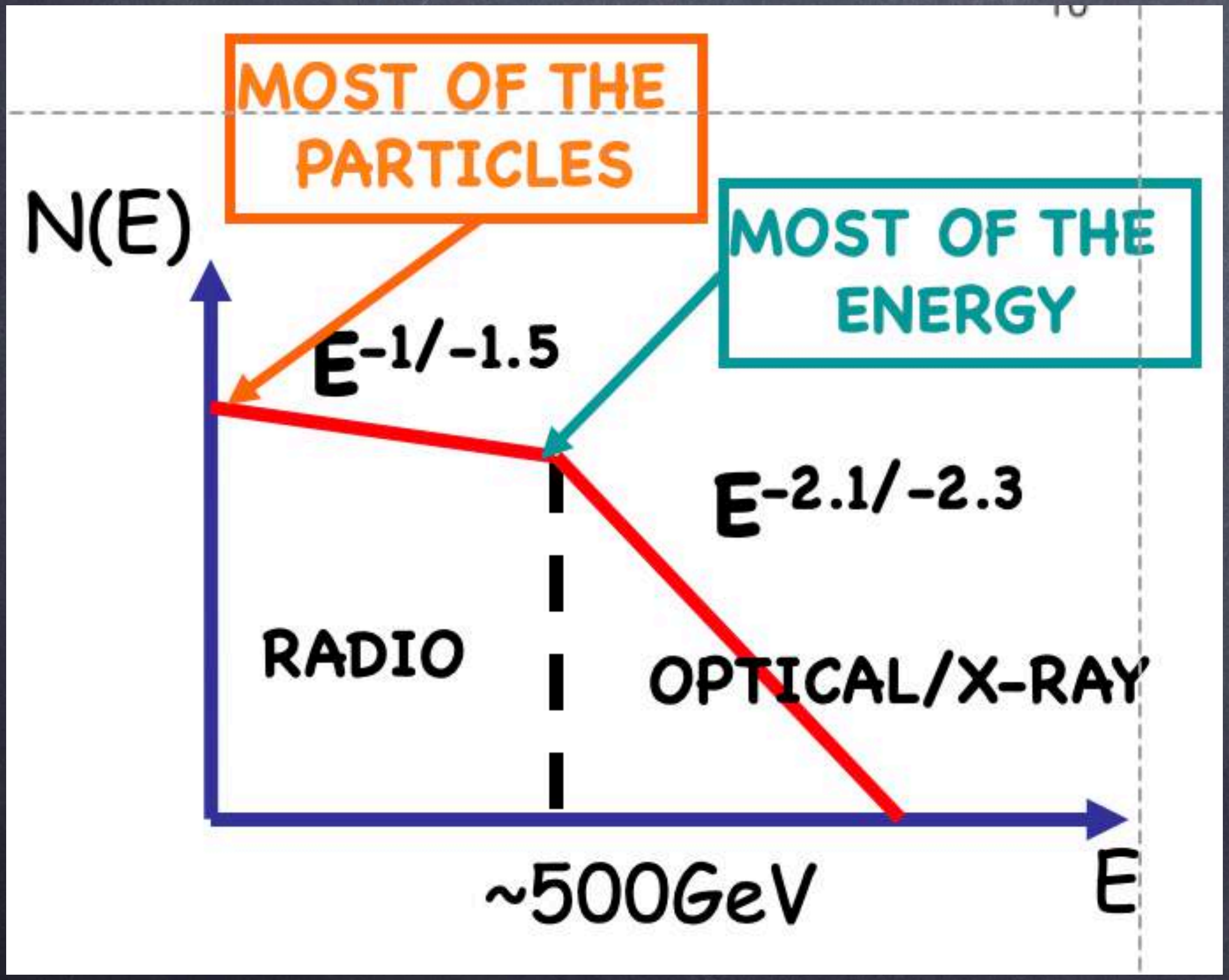
- ARTIFICIAL STEEPENING OF X-RAY PARTICLE SPECTRUM STILL NEEDED
- IC SPECTRUM STILL OVERESTIMATED

EVEN HIGHER σ NEEDED ON AVERAGE

DIFFERENT LOCATIONS OF PARTICLE ACCELERATION?

CONSTRAINING THE PULSAR MULTIPLICITY

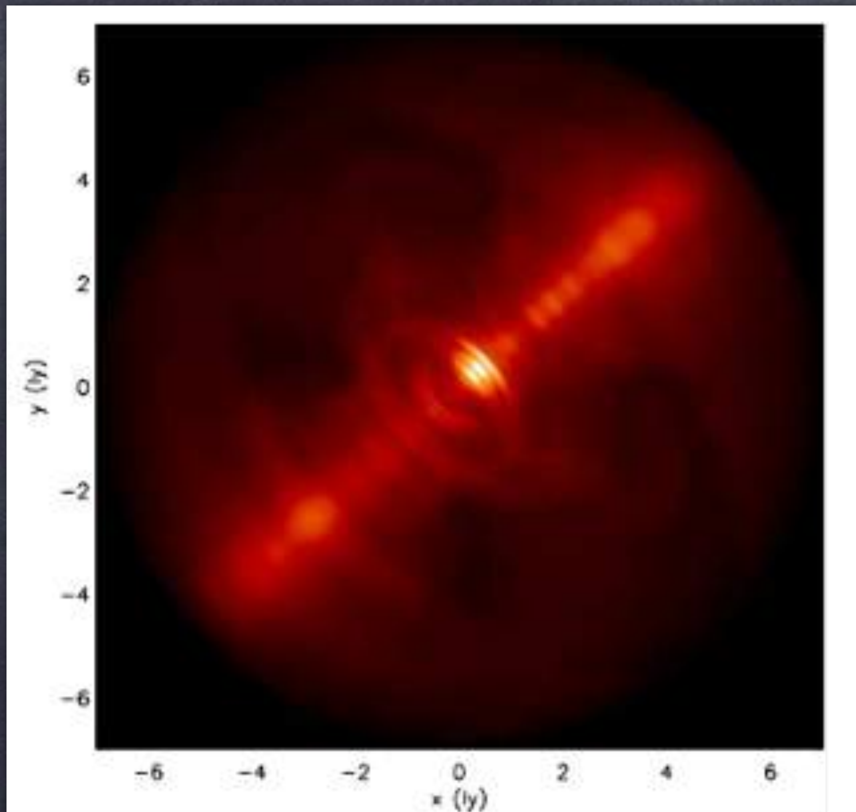
κ IS CONSTRAINED BY RADIO EMITTING PARTICLES



RADIO EMITTING PARTICLES
HAVE LONG LIFETIMES:
DO NOT NEED TO BE PART OF
THE FLOW

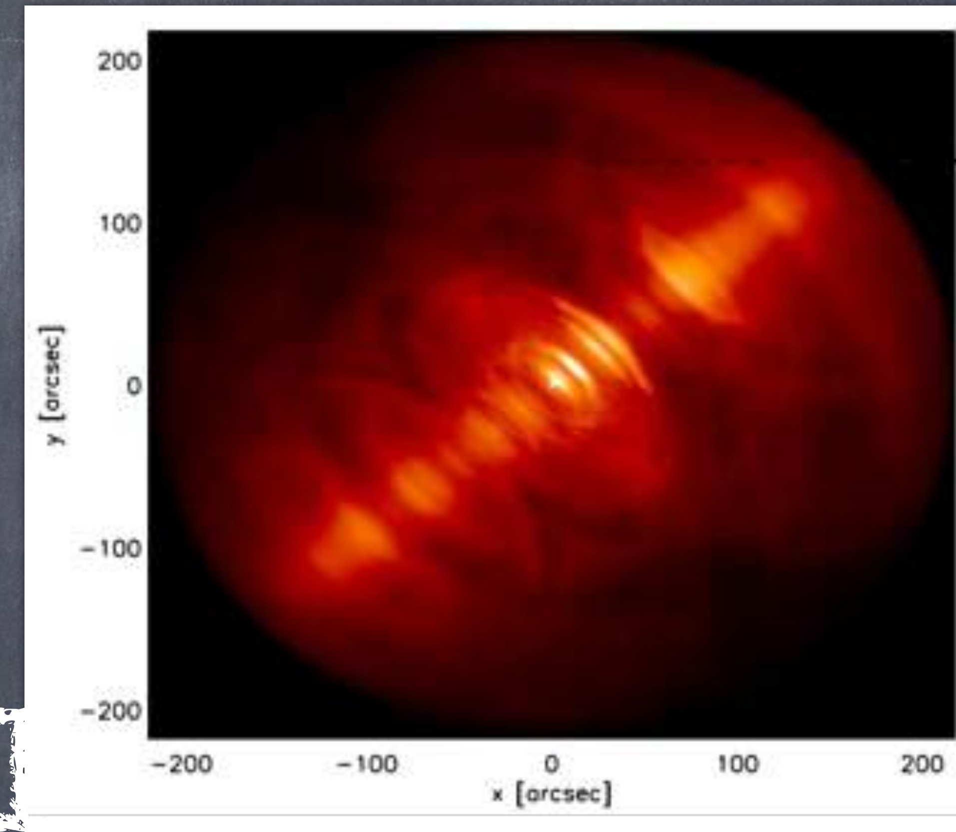
IF PART OF THE FLOW
$\kappa \approx 10^6$ $\Gamma \approx 10^4$
OTHERWISE
$\kappa \approx 10^3$–10^4 $\Gamma \approx 10^6$–10^7

RADIO EMISSION

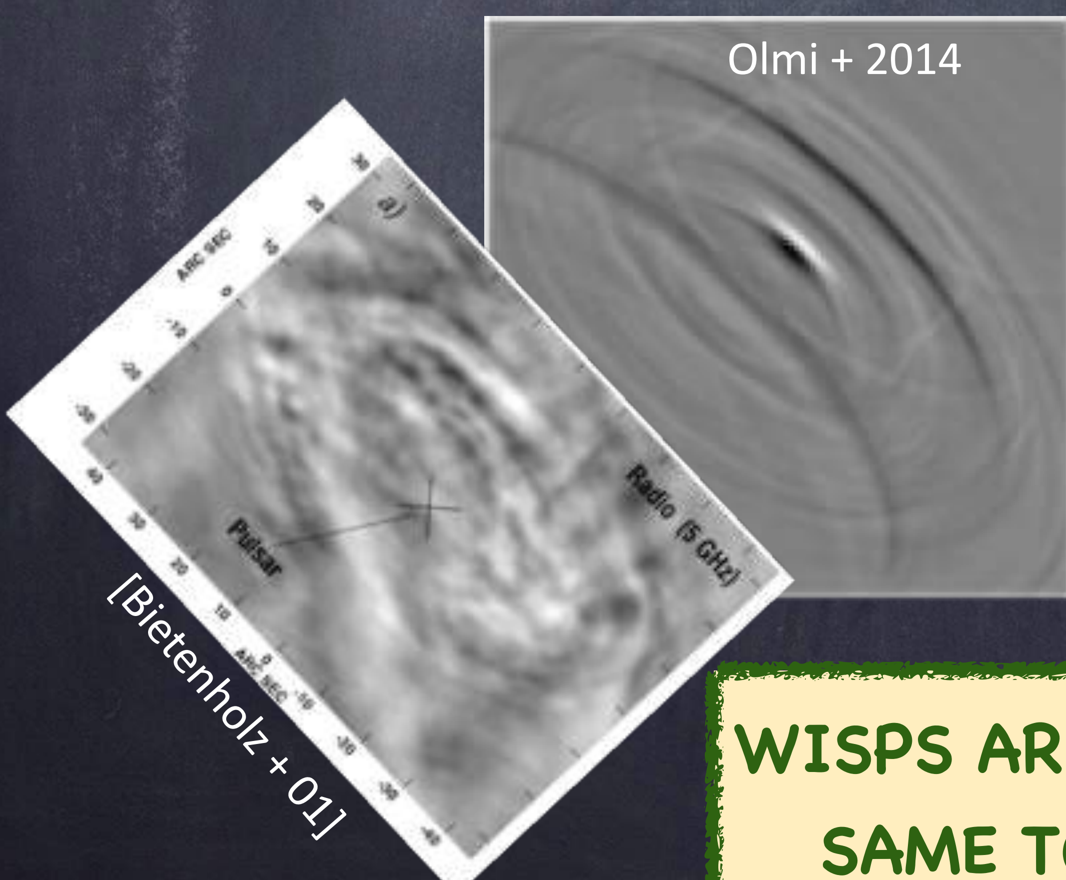


SHOCK ACCELERATION & ADVECTION

EMISSION MAPS CANNOT DISTINGUISH



UNIFORM INJECTION



WISPS ARE THE SAME TOO

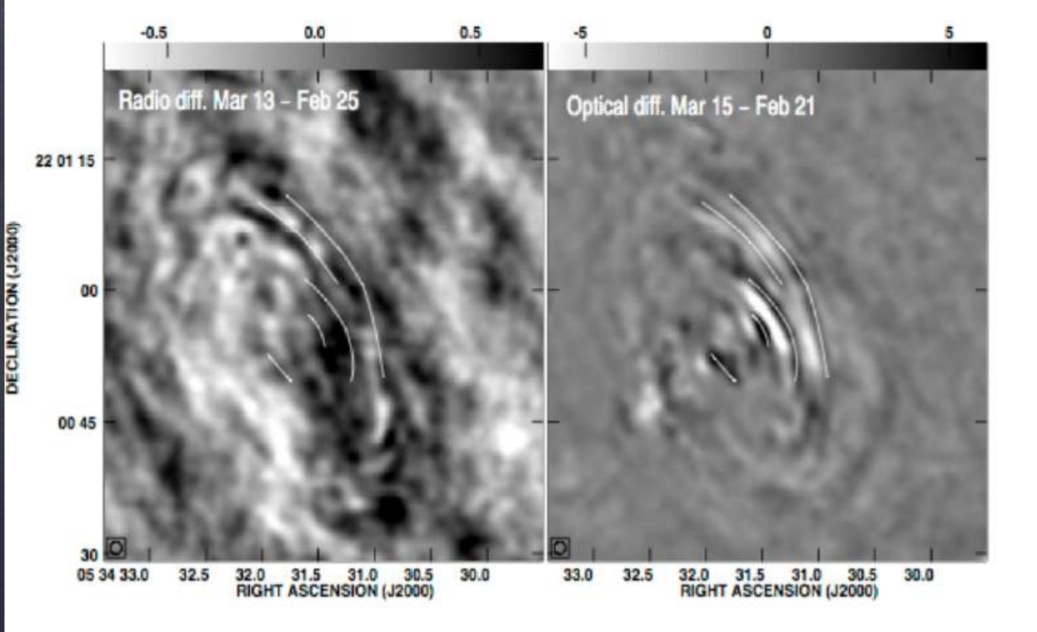
RADIO PARTICLES DO NOT NEED TO BE CURRENTLY ACCELERATED AT THE SHOCK

$\kappa \sim 10^3 - 10^4$ IS VIABLE

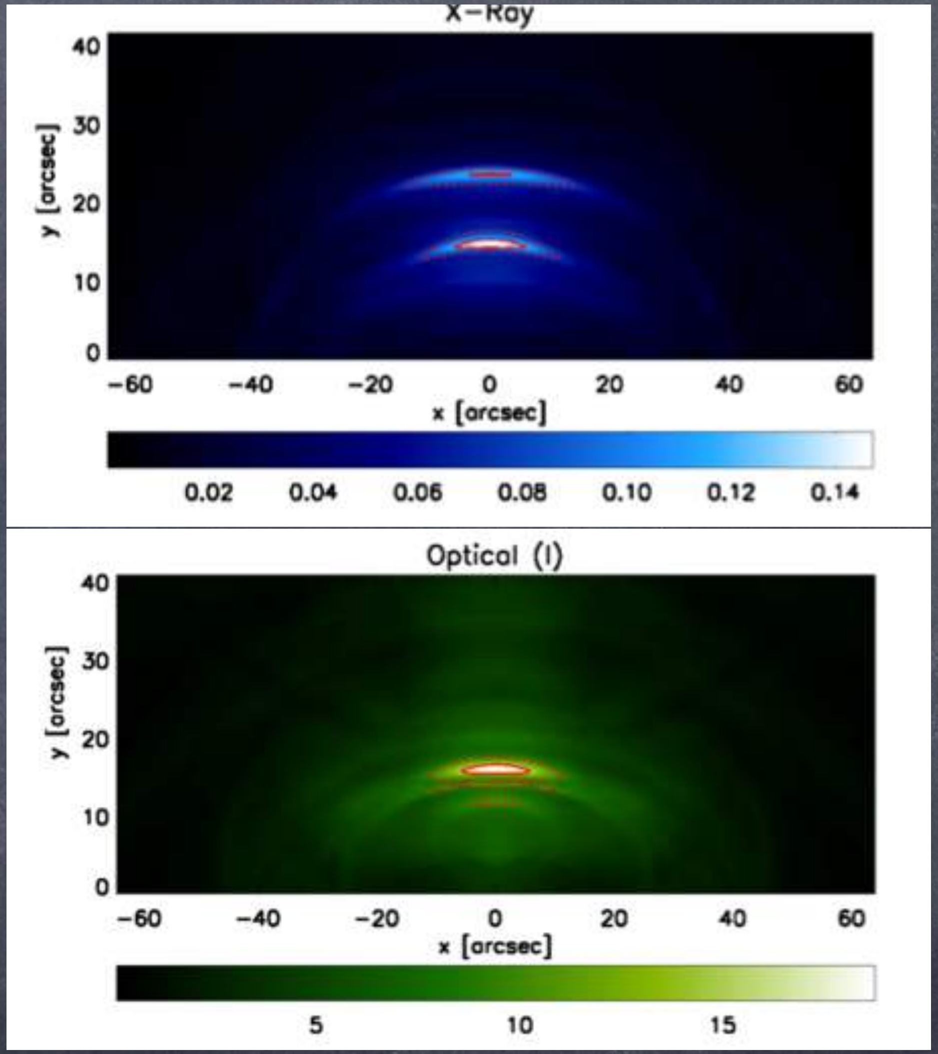
CONSTRAINING THE LOCATIONS OF PARTICLE ACCELERATION

VARIABILITY IN THE INNER NEBULA

RADIO VS OPTICAL WISPS

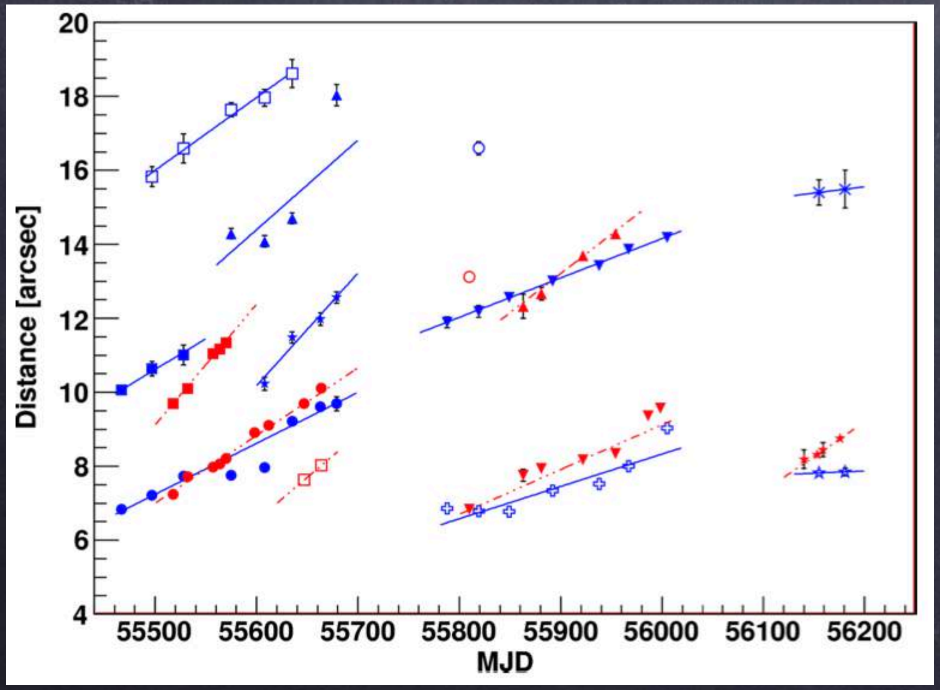


[Bietenholtz + 2004]



[Olmi et al. 2015]

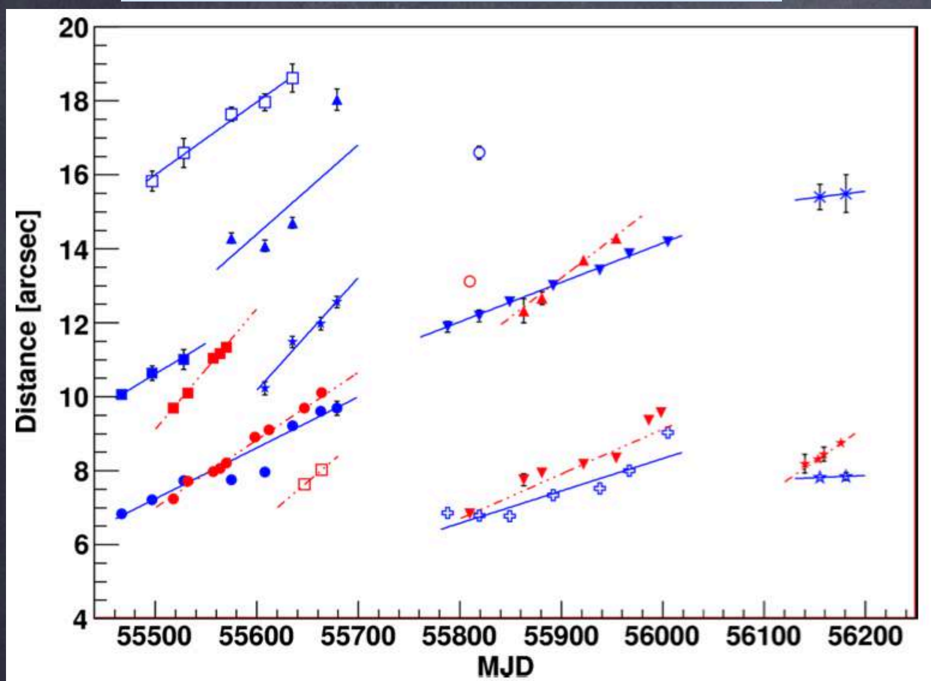
X-RAY VS OPTICAL WISPS



[Schweizer et al. 2013]

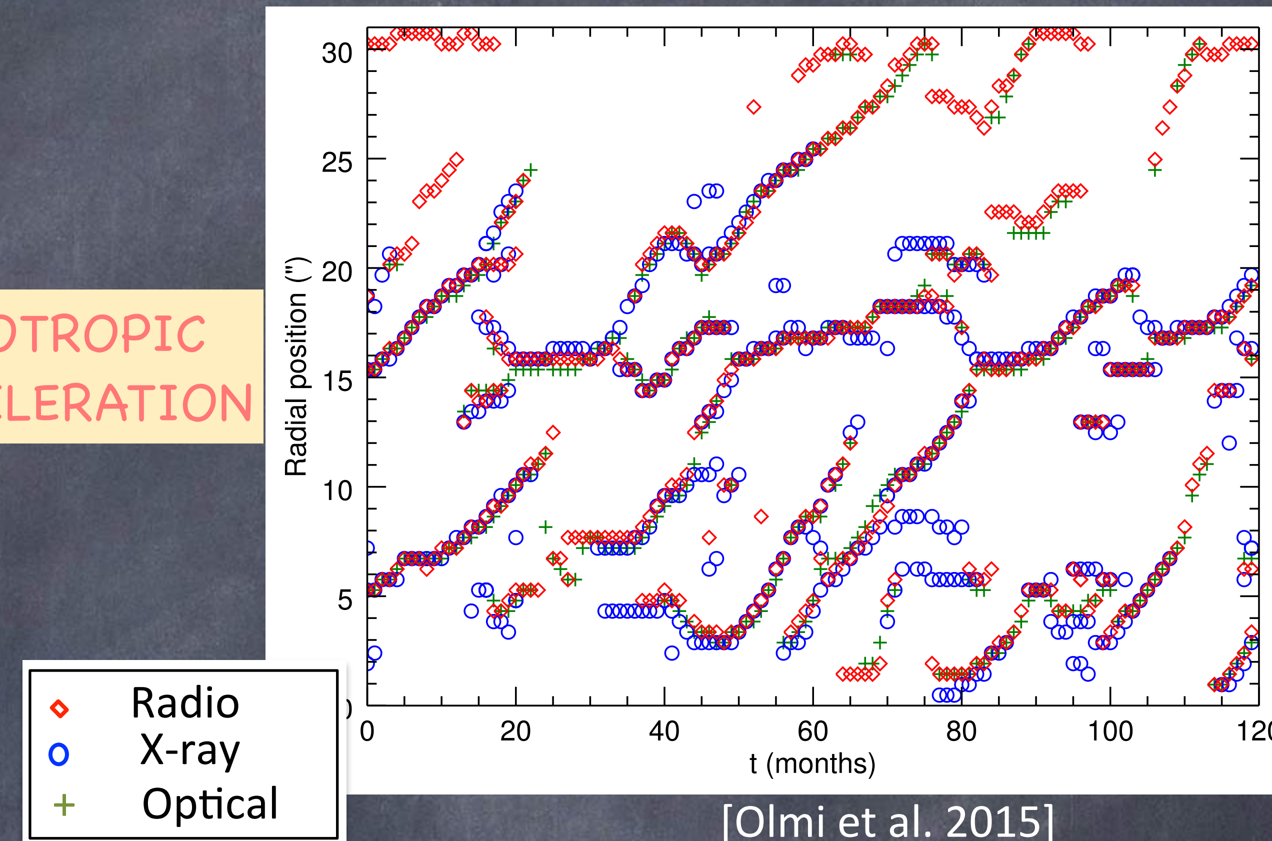
HINTS ON LOCATIONS OF PARTICLE ACCELERATION

X-RAY VS OPTICAL WISPS

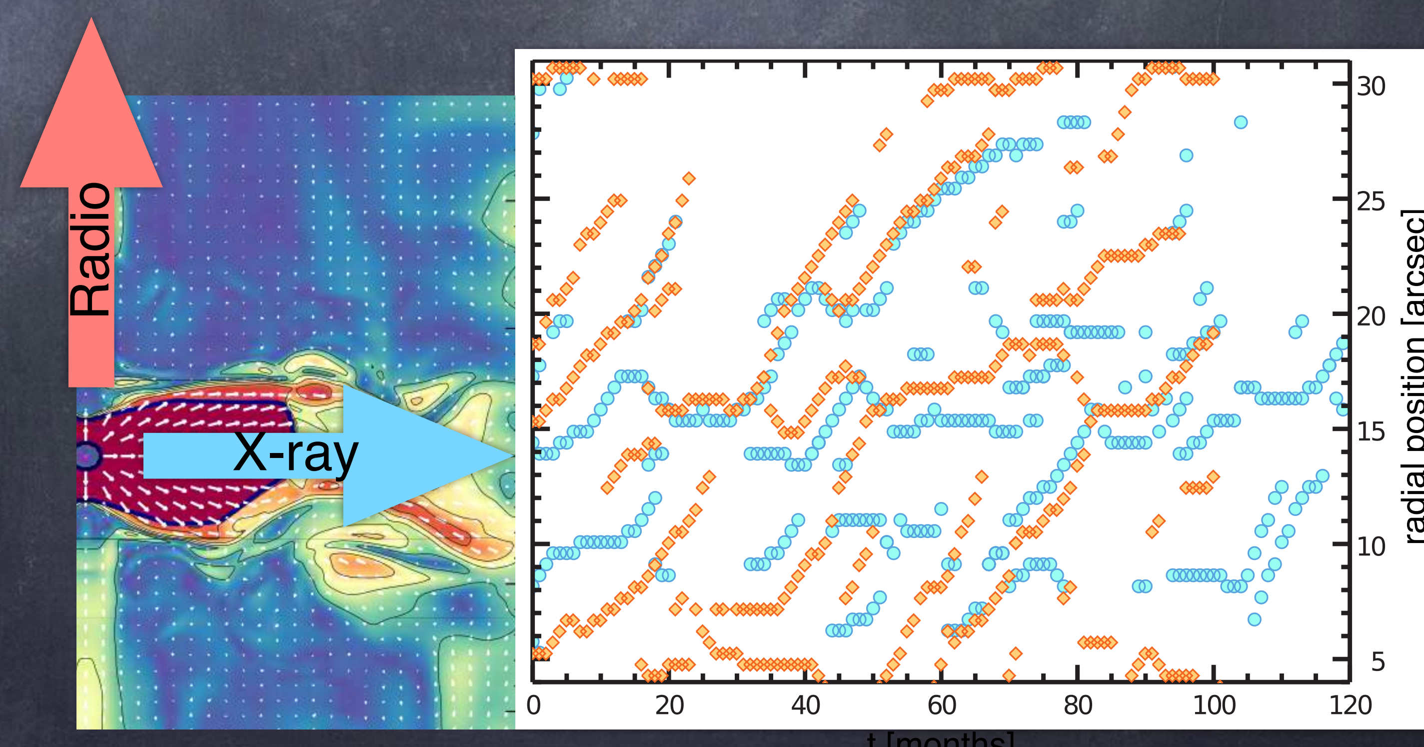


[Schweizer et al. 2013]

ISOTROPIC ACCELERATION



[Olmi et al. 2015]



X-RAY EMITTERS FROM EQUATOR

LOWER ENERGY ANYWHERE

TAKE HOME MESSAGE

NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES → $\sigma \gtrsim 1$

MODELLING OF RADIO EMISSION → $\kappa \approx \mathrm{few} \times 10^3$ AND $\Gamma > \mathrm{few} \times 10^6$ VIABLE

MODELLING OF MULTIFREQUENCY VARIABILITY OF INNER NEBULA → ACCELERATION OF LOW AND HIGH ENERGY PARTICLES IN DIFFERENT REGIONS

ACCELERATION MECHANISMS

PARTICLE ACCELERATION MECHANISMS (BEST STUDIED)

FERMI MECHANISM

✓EFFICIENT AT UNMAGNETIZED e^+-e^- RELATIVISTIC SHOCKS [Spitkovsky 08]

- NO ACCELERATION AT σ>0.001 SUPERLUMINAL SHOCKS [Sironi & Spitkovsky 09, 11]
- TOO SLOW TO GUARANTEE MAXIMUM ENERGY OBSERVED IN CRAB [Pelletier+ 17]

✓POSSIBLY EFFICIENT AT HIGHLY TURBULENT MODERATELY MAGNETIZED SHOCKS [Lemoine 17, Giacinti & Kirk 18, Cerutti & Giacinti 20]

✓RIGHT SPECTRUM FOR X-RAYS

DRIVEN MAGNETIC RECONNECTION:

✓BROAD AND HARD PARTICLE SPECTRA IF $\sigma \geq 30$ AND $\kappa > 10^8$ [Sironi & Spitkovsky 11b]

- FOR THIS LARGE κ WIND LIKELY TO DISSIPATE BEFORE SHOCK [Kirk & Skjeraasen 03]

RESONANT CYCLOTRON ABSORPTION:

✓SPECTRA AND ACCELERATION EFFICIENCY DEPEND ON ENERGY FRACTION IN IONS: U_i/U_{TOT}=0.8-0.6, γ=1.5-3, ε_{ACC}=0.3-0.03 [Hoshino+ 92, EA & Arons 06; Stockem+ 12]

✓HIGHER σ IMPLIES FASTER ACCELERATION

- NO ACCELERATION IF $\kappa > m_i/m_e$

PARTICLE ACCELERATION MECHANISMS (MORE RECENTLY PROPOSED)

SHOCK CORRUGATION

- FORMULATED TOGETHER WITH B DISSIPATION [Lemoine 17, Lyutikov+12]
- INTERESTING SCENARIO FOR SPEEDING UP FERMI PROCESS

TURBULENT ACCELERATION AT THE SHOCK

- ASSUMES DIFFERENT TURBULENCE LEVELS AT DIFFERENT SHOCK LATITUDES [Giacinti & Kirk 18]
- PRODUCES HARD (STEEP) SPECTRA FOR LOW (HIGH) TURBULENCE LEVEL
- INTERESTING LATITUDE DEPENDENCE OF SPECTRAL INDEX
- ACCELERATES ONE SIGN OF CHARGES PREFERENTIALLY

- ANISOTROPIC FIELD HELPS PROVIDING THE TURBULENCE [Cerutti & Giacinti 20]
- SPECTRUM HARDENS WITH INCREASING MAGNETIZATION

ACCELERATION BY HIGH σ TURBULENCE

- ENERGY DEPENDENT ANISOTROPY OF PARTICLE DISTRIBUTION MIMICS FLAT PARTICLE SPECTRA AT LOW ENERGY [Comisso+ 18,19,20, Luo+21]
- WHERE? ON WHAT SCALES? MAXIMUM ENERGY?
- IMPORTANT BROAD IMPLICATIONS!

PARTICLE ACCELERATION MECHANISMS: SUMMARY OF REQUIREMENTS

FERMI MECHANISM → MAGNETIZATION: REQUIRES LOW (HOWEVER SEE VARIANTS)

DRIVEN MAGNETIC RECONNECTION → MAGNETIZATION: REQUIRES HIGH

DRIVEN MAGNETIC RECONNECTION → PLASMA MULTIPLICITY: REQUIRES HIGH

ION CYCLOTRON ABSORPTION IN ION DOPED PLASMA → PLASMA MULTIPLICITY: REQUIRES LOW

TAKE HOME MESSAGE

NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES → $\sigma \gtrsim 1$

MODELLING OF RADIO EMISSION → $\kappa \approx \text{few} \times 10^3$ AND $\Gamma > \text{few} \times 10^6$ VIABLE

MODELLING OF MULTIFREQUENCY VARIABILITY OF INNER NEBULA → ACCELERATION OF LOW AND HIGH ENERGY PARTICLES IN DIFFERENT REGIONS

IMPLICATIONS ON ACCELERATION MECHANISMS

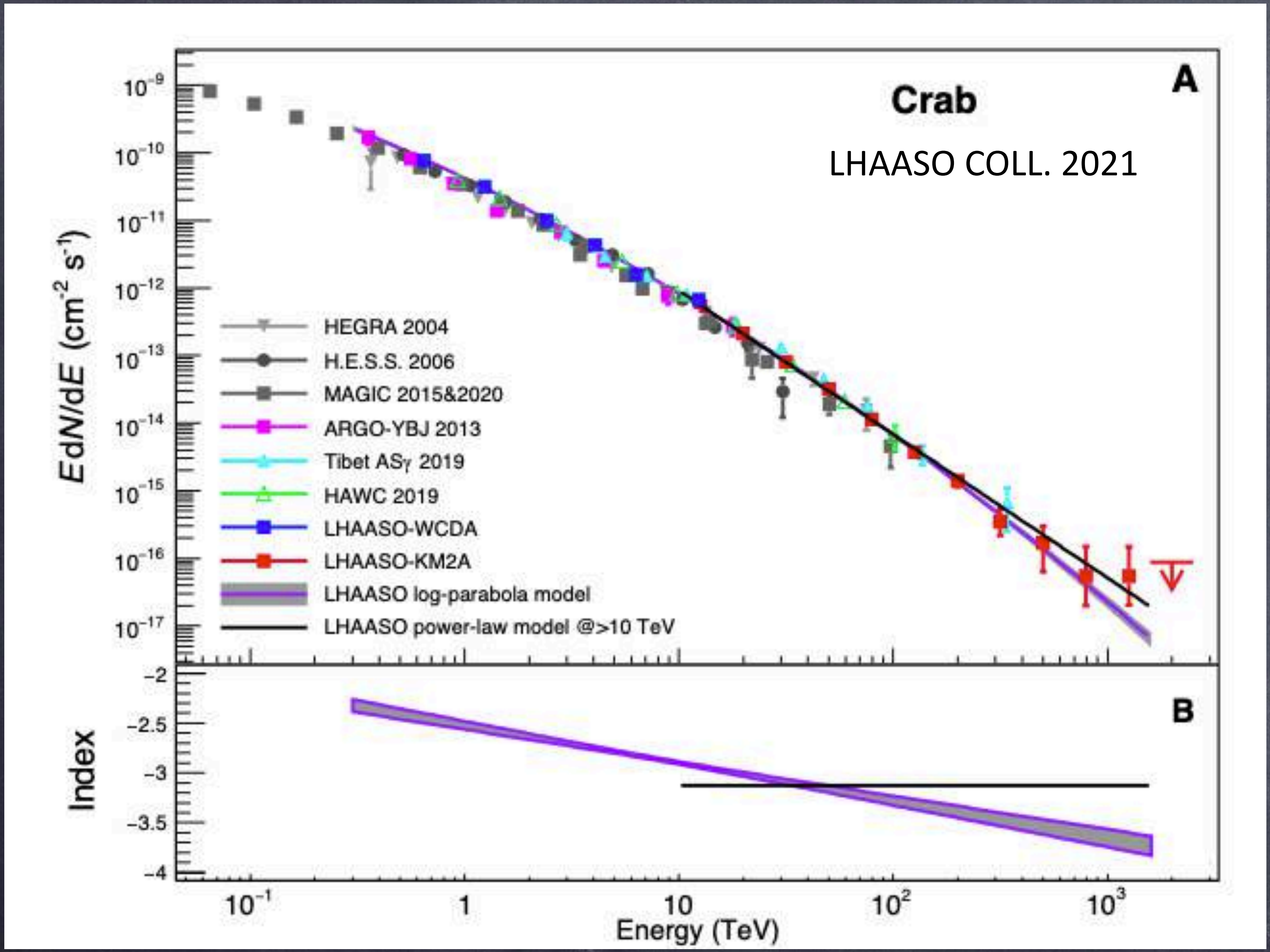
NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES → $\sigma \gtrsim 1$ → TOO LARGE FOR FERMI ACCELERATION BUT TURBULENCE MIGHT HELP

MODELLING OF RADIO EMISSION → $\kappa \approx \text{few} \times 10^3$ AND $\Gamma > \text{few} \times 10^6$ VIABLE → ION CYCLOTRON VIABLE

MODELLING OF MULTIFREQUENCY VARIABILITY OF INNER NEBULA → ACCELERATION OF LOW AND HIGH ENERGY PARTICLES IN DIFFERENT REGIONS → LOW ENERGY FROM TURBULENT ACCELERATION IN THE NEBULA?

NEWS FROM THE >100TeV (UHE/EHE?) GAMMA-RAYS

THE CRAB @>100 TeV



$$\epsilon_\gamma^* = 1.1 \text{ PeV}$$

IC ON CMB

↓

$$E_e \approx 2.15 \left(\epsilon_\gamma/\text{PeV}\right)^{0.77} \text{ PeV}$$

↓

$$E_e^* \approx 2.4 \text{ PeV}$$

THIS ALREADY CONSTRAINS B-FIELD!!!

$$\frac{dN}{d\epsilon_\gamma} = 8.2 \times 10^{-14} \left(\frac{\epsilon_\gamma}{10 \text{ TeV}}\right)^{-\Gamma} \text{cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$$

$$1 \text{ TeV} \le \epsilon_\gamma \le 1 \text{PeV}$$

$$\Gamma = 2.9 + 0.19 \log_{10}(\epsilon_\gamma/10\ TeV)$$

MAXIMUM ENERGY IN A PWN

STRICT LIMIT FROM THE PSR POTENTIAL DROP $\Phi_{PSR} = \sqrt{\dot{E}/c}$

$$E_{max,abs} = e\xi_E B_{TS}\ R_{TS}$$

$$\frac{B_{TS}^2}{8\pi} = \xi_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

$$E_{max,abs} = e\xi_E\ \xi_B^{1/2}\sqrt{\dot{E}/c} \approx 1.8\ PeV\ \xi_E\ \xi_B^{1/2}\ \dot{E}_{36}^{1/2}$$

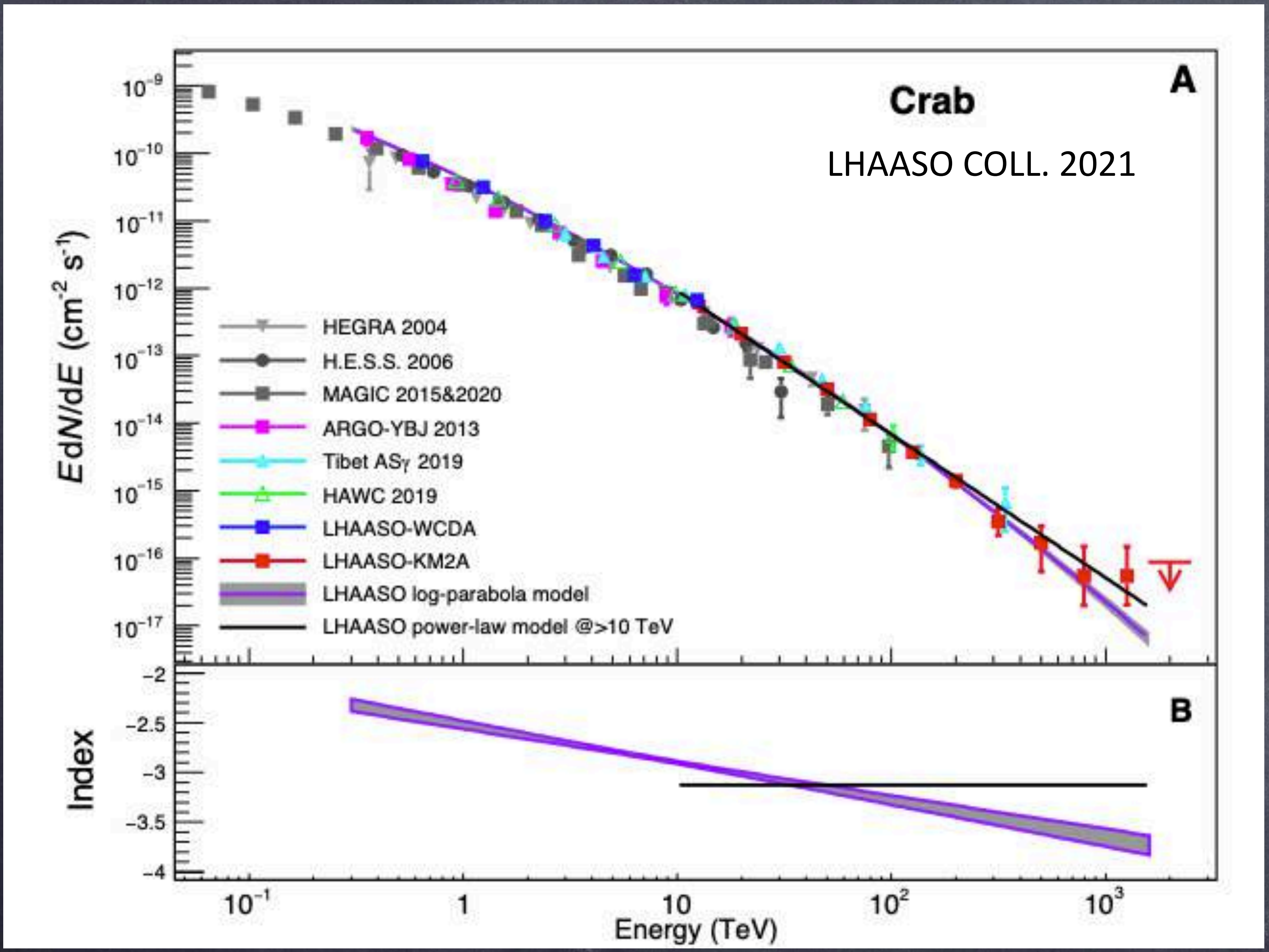
$$E_{max,Crab} \approx 30\ \mathrm{PeV}$$

IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LIKELY LOSS LIMITED

$$t_{acc} = \frac{E}{e\xi_e Bc} < t_{loss} = \frac{6\pi(mc^2)^2}{\sigma_T c B^2 E}$$

$$E_{max} \approx 6\ PeV\ \xi_e^{1/2}\ B_{-4}^{-1/2}$$

THE CRAB @>100 TeV



$$\epsilon_\gamma^* = 1.1 \text{ PeV}$$

IC ON CMB

$$E_e \approx 2.15 \left(\epsilon_\gamma/\text{PeV}\right)^{0.77} \text{ PeV}$$

$$E_e^* \approx 2.4 \text{ PeV}$$

$$E_{max} \approx 6\ PeV\ \xi_e^{1/2}\ B_{-4}^{-1/2}$$

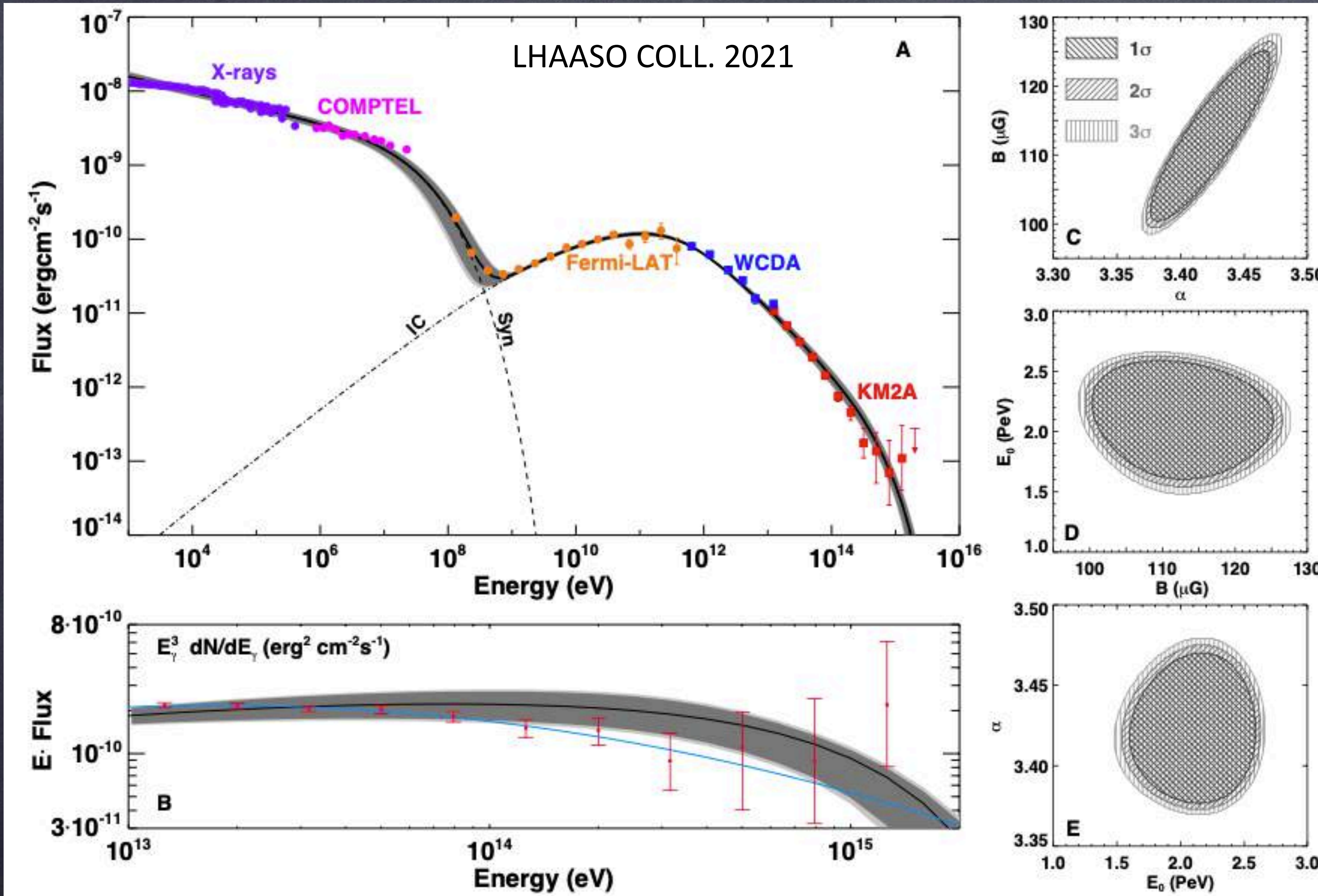
$$B_{\max} \approx 6.5 \times 10^{-4}\ \xi_e^{1/2} \text{ G}$$

$$\frac{dN}{d\epsilon_\gamma} = 8.2 \times 10^{-14} \left(\frac{\epsilon_\gamma}{10 \text{ TeV}}\right)^{-\Gamma} \text{cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$$

$$1 \text{ TeV} \leq \epsilon_\gamma \leq 1 \text{PeV}$$

$$\Gamma = 2.9 + 0.19 \log_{10}(\epsilon_\gamma/10\ TeV)$$

EXTENDED SED AND ITS IMPLICATIONS



$B_{\rm SED} \approx 112\ \mu$G

EMITTING PARTICLES:

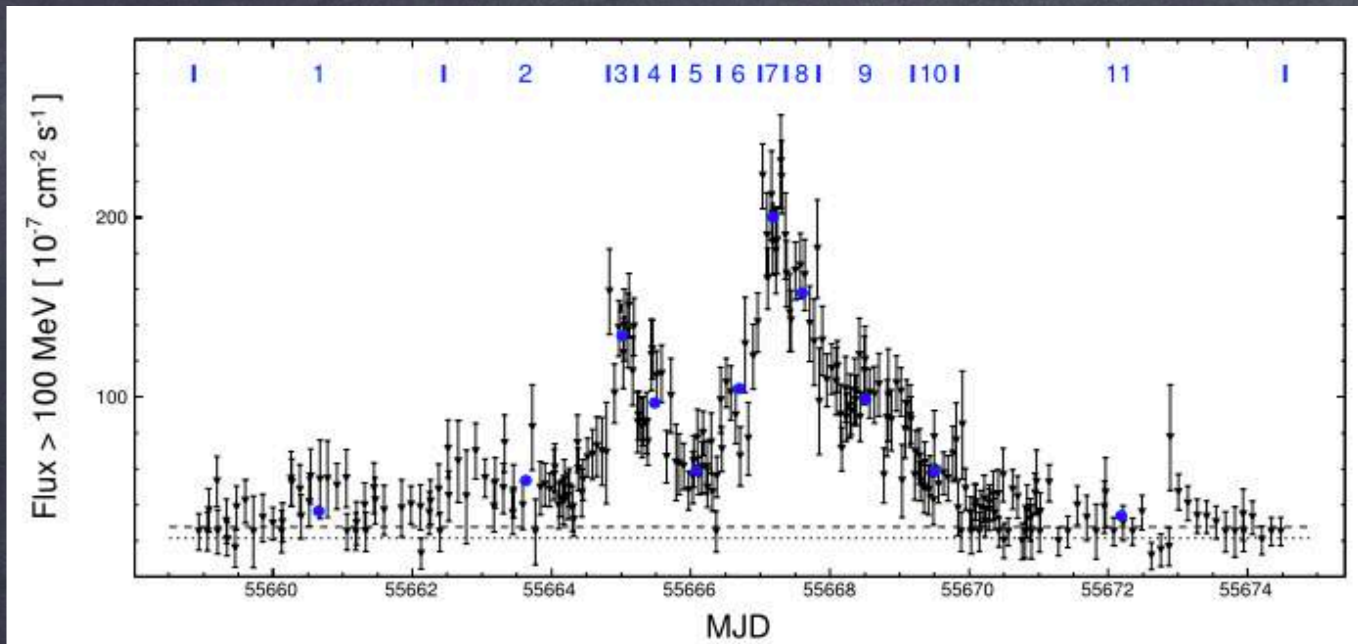
$$\frac{dN_e}{dE_e} \propto E^{-3.42}\exp[-(E/2.15\ \text{PeV})^2] \qquad E \geq 0.76\ \text{TeV}$$

OTHER ESTIMATES

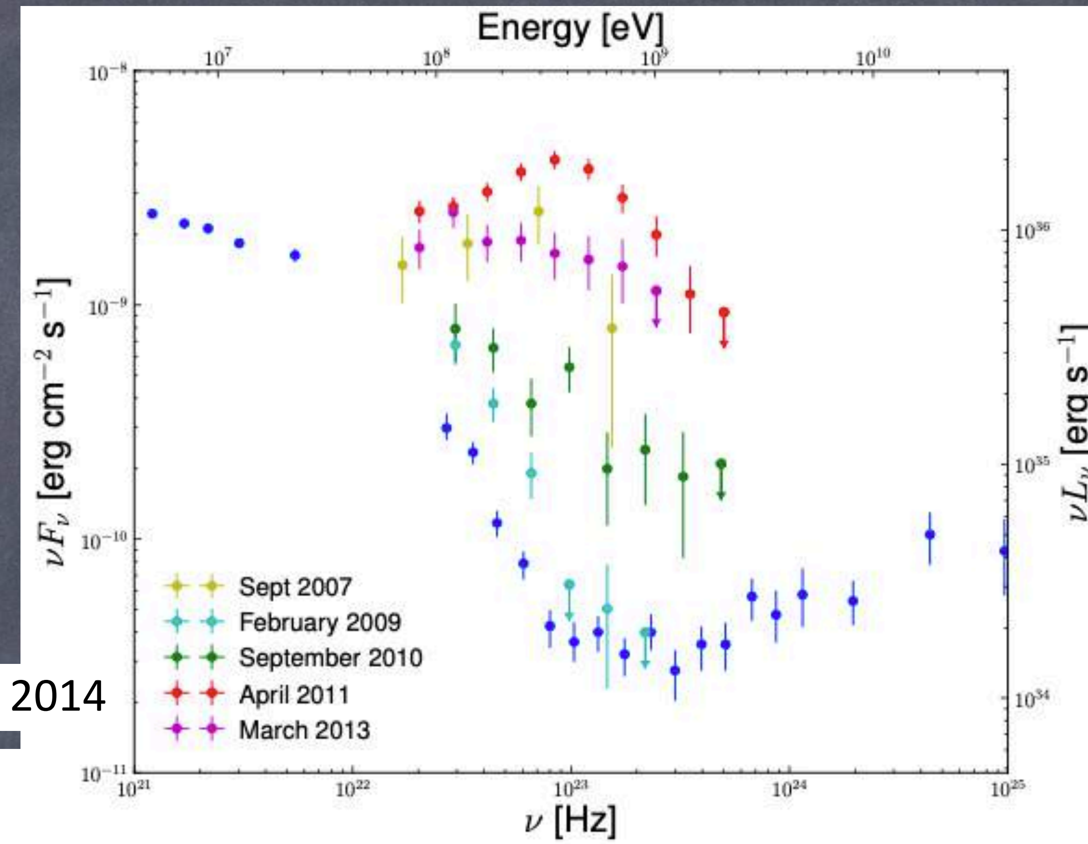
$E_0 \approx 0.3 - 0.5$ TeV

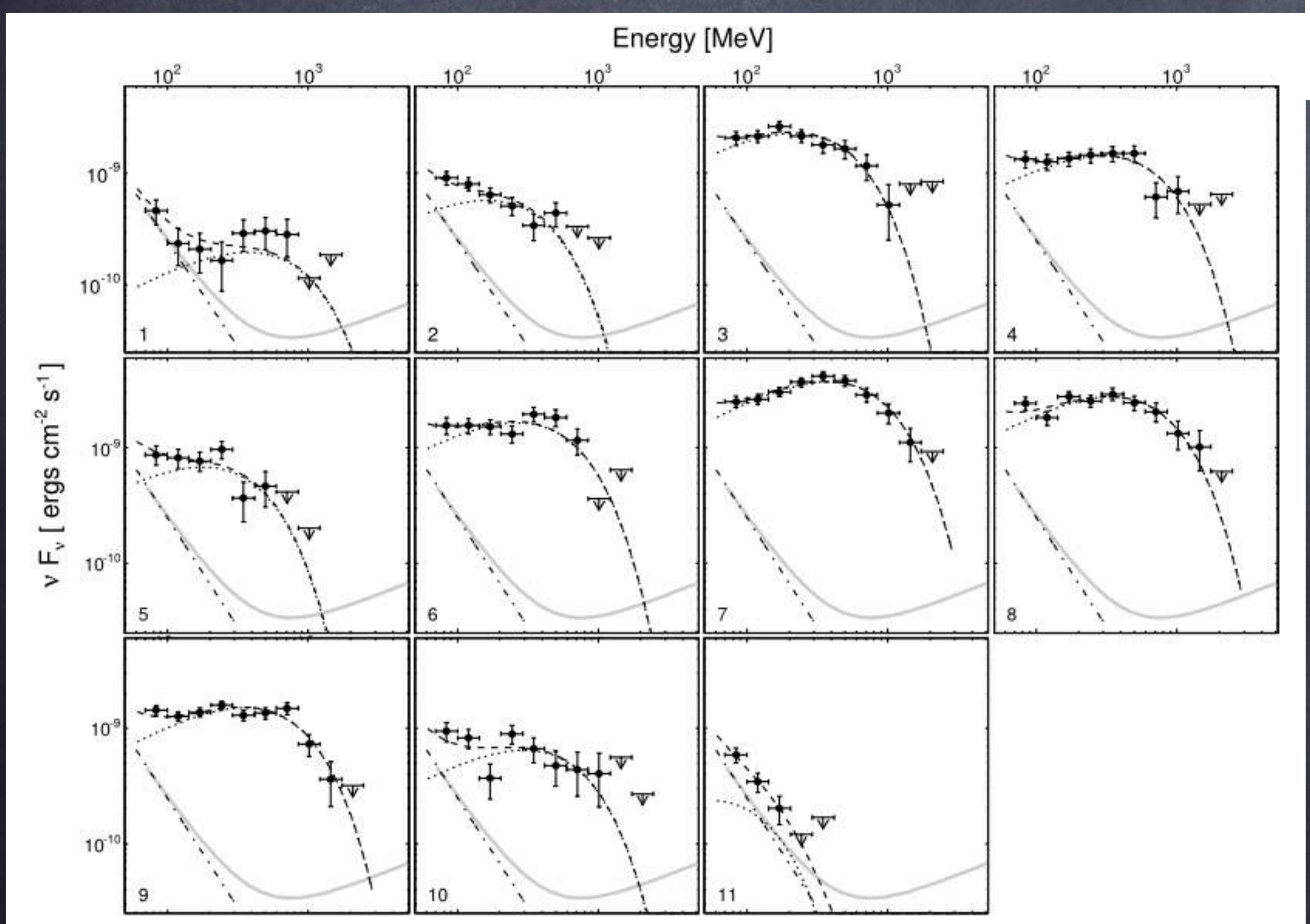
[Bucciantini, Arons, EA 2011, Torres+ 2013]

CRAB FLARES



Buehler & Blandford 2014





$$E_{max} \approx 6\ PeV\ \xi_e^{1/2}\ B_{-4}^{-1/2}$$

$$\epsilon_{\rm max,sync} \approx 230\ \xi_e\ {\rm MeV} \qquad t_{\rm var} \approx 70\ {\rm d}\ \xi_e^{-1/2} B_{-4}^{-3/2}$$

IN BRIGHTEST FLARE
FLUX DOUBLES WITHIN 8 HR

(*)

$$B \approx 3.5\ {\rm mG} \qquad l \lesssim 10^{-2} {\rm pc}$$

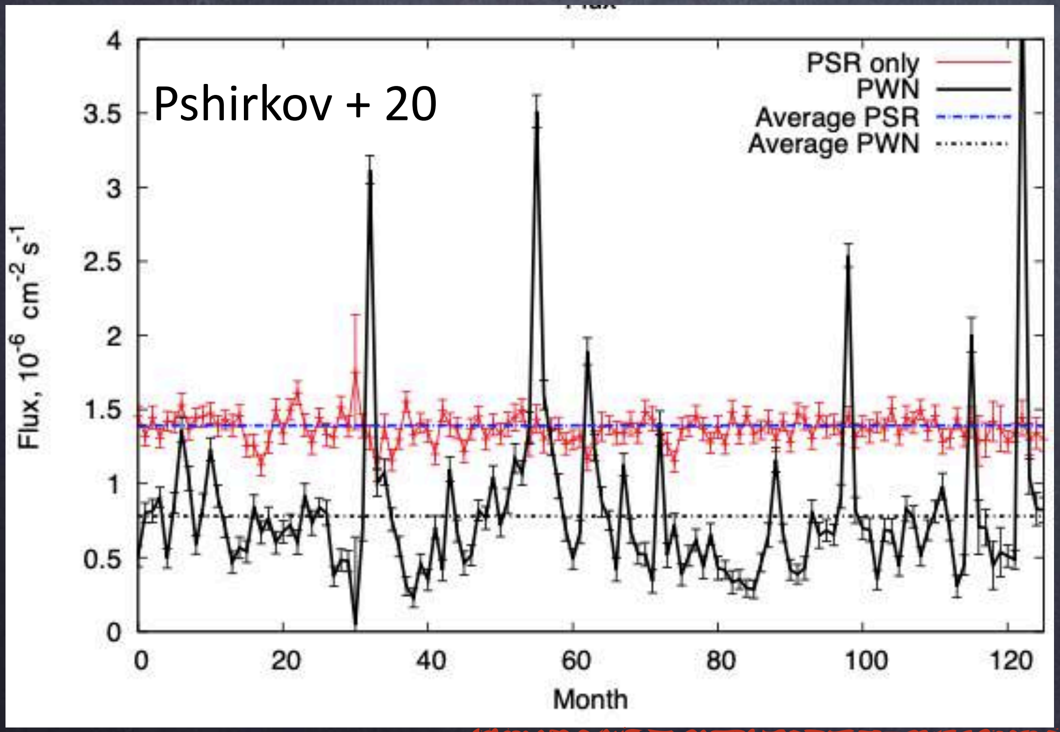
CRAB FLARES AND DIPS

$\xi_e \approx 1$ REQUIRED IN ANY CASE

MAGNETIC RECONNECTION?
[Cerutti+ 12,13,+++; Sironi & Cerutti 17]

RATE POSSIBLY TOO LOW…
MAYBE EXPLOSIVE RECONNECTION?
[Yuan+ 2016]

FLUX IN THE 100-300 MeV RANGE
ALSO SHOWS DIPS [Pshirkov + 20]

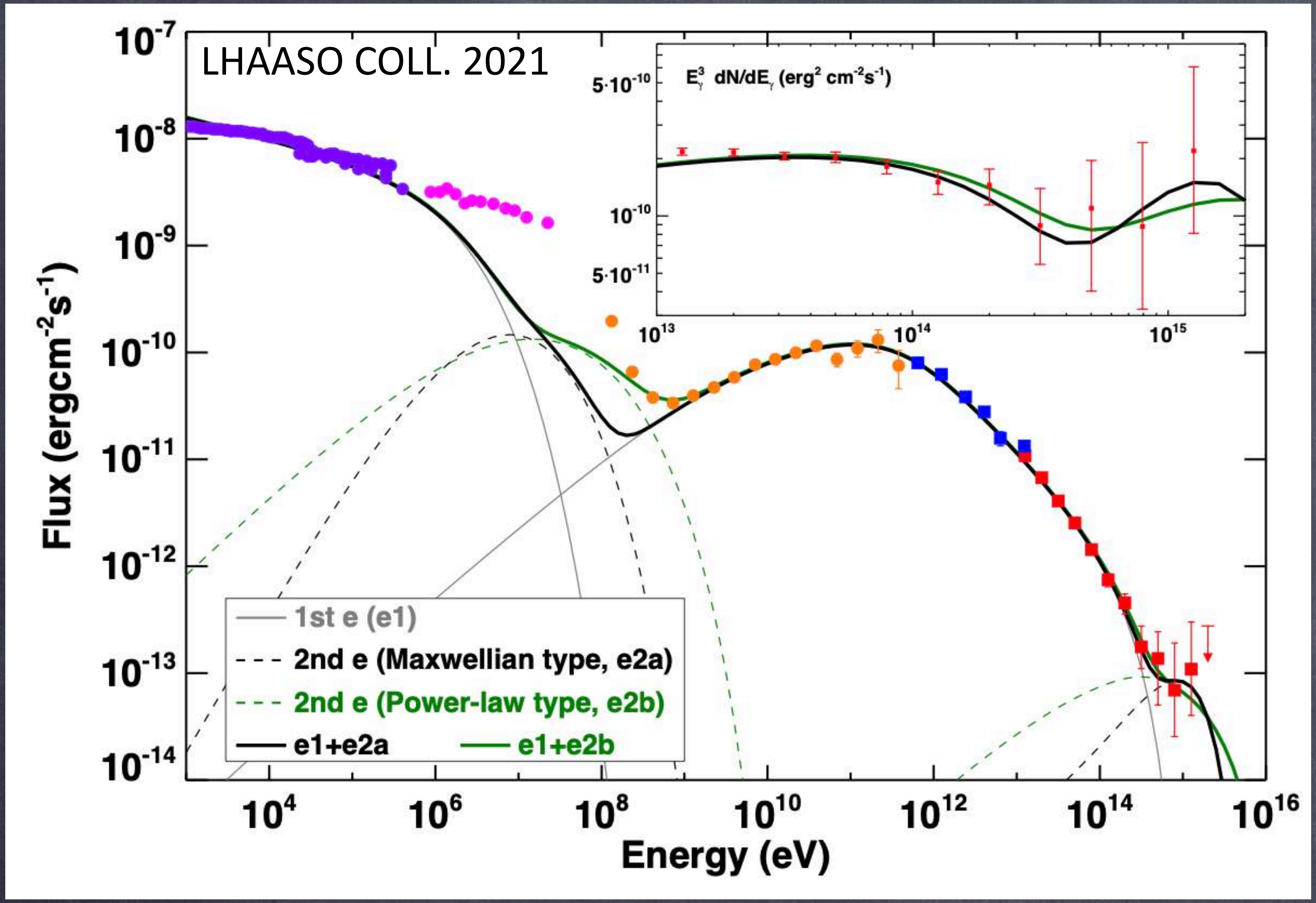


MAGNETIC FIELD VARIATIONS
IN THE INNER NEBULA? [Bykov + 12]

- B-FIELD ENHANCEMENT BY A FEW IMPLIES BIG CHANGES IN CUT-OFF REGION
- IN ADDITION DOPPLER BOOSTING AVAILABLE IN OBLIQUE REGIONS OF TS

- MULTI-WAVELENGTH SIGNATURES?
- ACCELERATION MECHANISM?

MULTIPLE POPULATIONS?



$$\frac{dN_2}{dE_2} \propto E_e^2 \exp(-E_e/400\text{TeV})$$

$$B_2 \approx 30\ \mu\text{G}$$

$$\frac{dN_e}{dE_e} \propto E_e^{-1.5} \exp(-E_e/2\text{PeV})$$

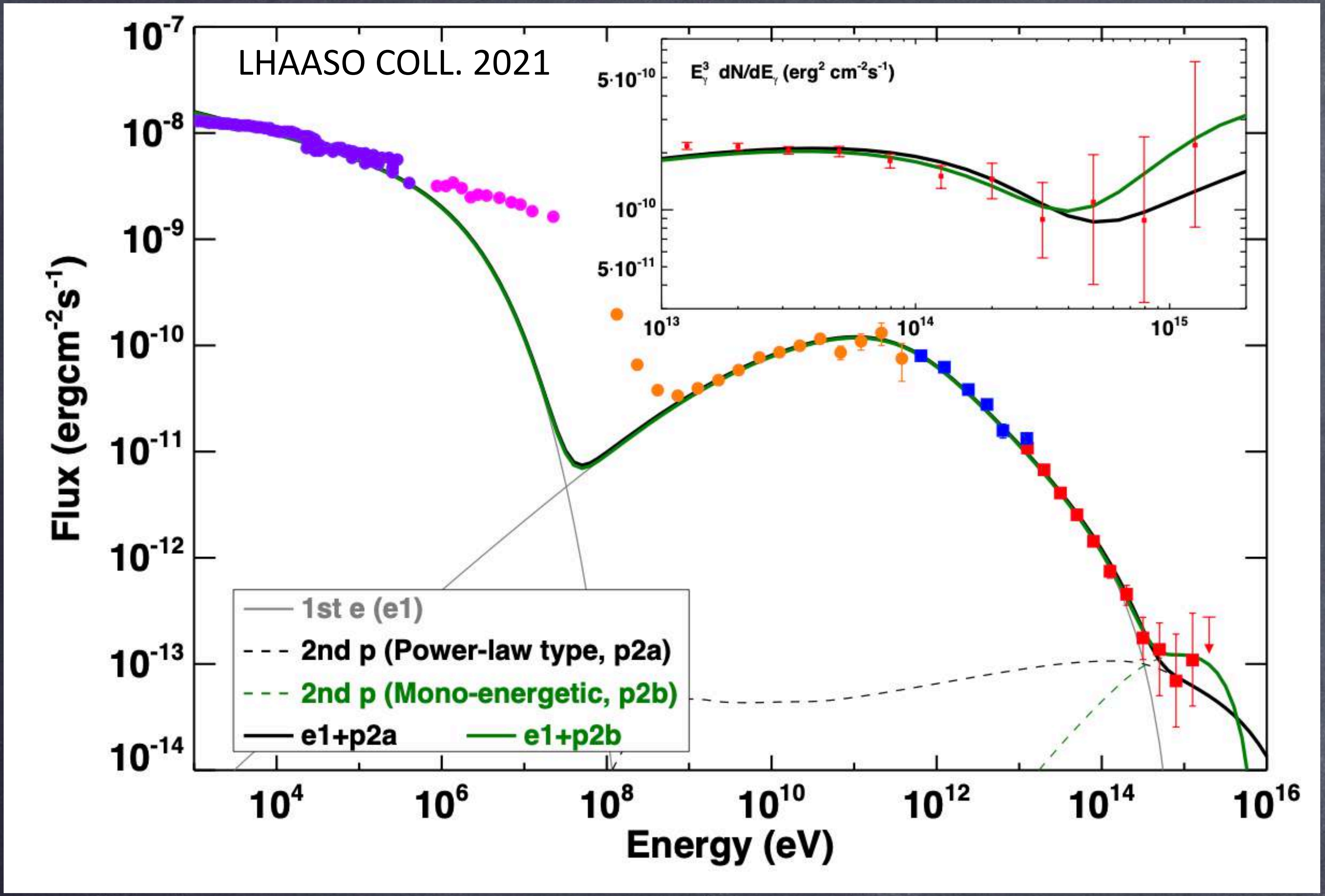
$$W_{e,2} \approx 10^{44}\ \text{erg}$$

$$\frac{dN_e}{dE_e} \propto E^{-2.4} \exp[-(E/0.8\ \text{PeV})^2]$$

$$W_{e,1} \approx 8 \times 10^{48}\ \text{erg}$$

$$B_1 \approx 110\ \mu\text{G}$$

PROTONS?



$$\frac{dN_p}{dE_p} \propto E_p^{-2} \exp(-E_p/30\ \mathrm{PeV})$$

$$\frac{dN_p}{dE_p} \propto \delta(E_p - 10\ \mathrm{PeV})$$

$$t_{\rm pp} = 1.5 \times 10^7\ (n/10\ \mathrm{cm}^{-3})^{-1}\ \mathrm{yr}$$

$$L_\gamma \approx W_p/t_{pp}$$

$$W_p \approx 3 \times 10^{46}\ \mathrm{erg}$$

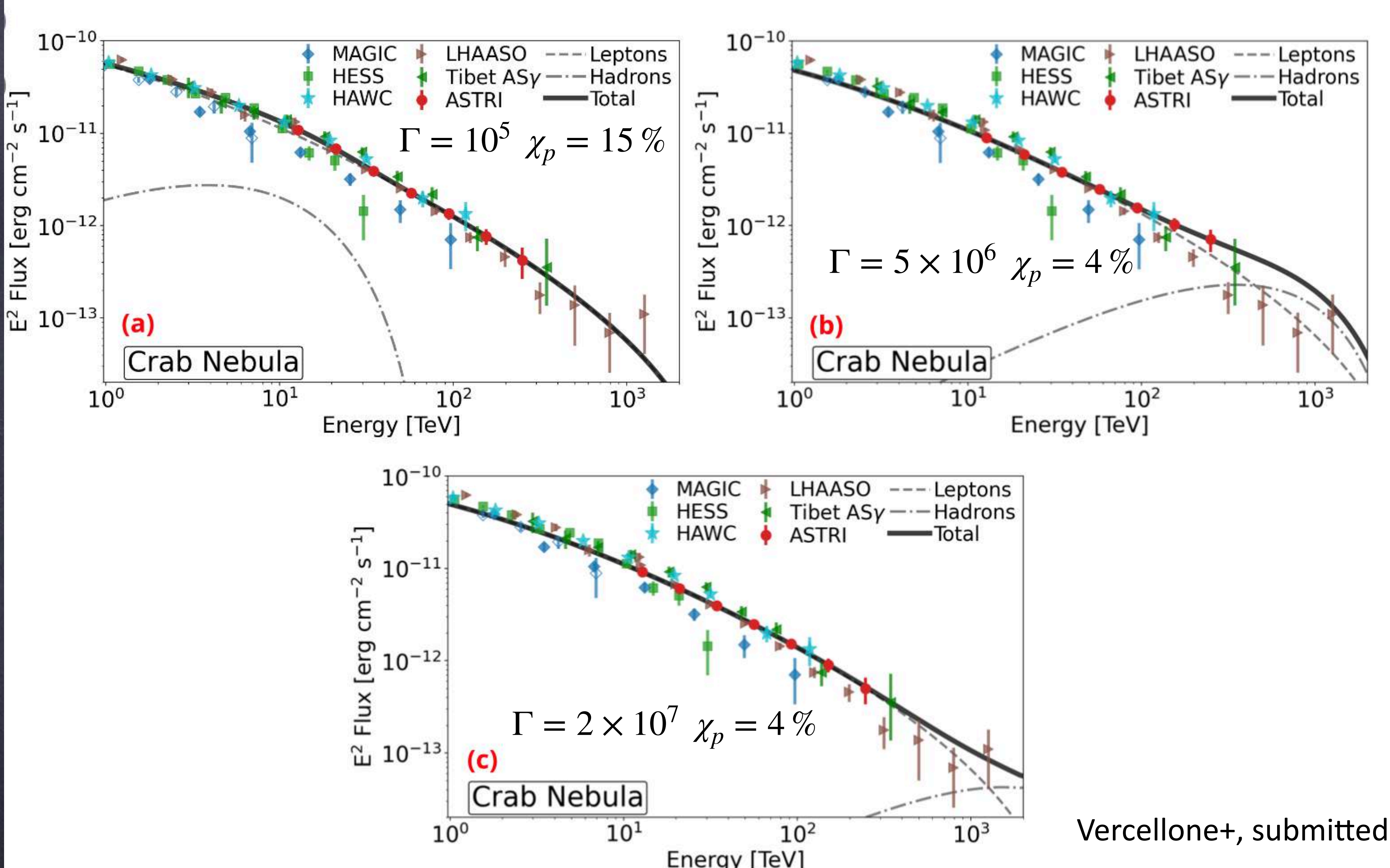
$$t_{\rm esc} = R_N^2/D_B \approx 300\ \mathrm{yr}\ B_{-4}\ E_{16}^{-1}$$

$$\dot{E}_p \sim 3 \times 10^{36} \mathrm{erg/s} \approx \text{few}\ \%\ \dot{E}$$

FOR DIRAC DELTA CASE
AND BOHM DIFFUSION

$$L_\gamma = W_p/t_{pp} = \dot{E}_p\ t_{\rm esc}/t_{pp}$$

ACCOUNT FOR TIME-EVOLUTION



Vercellone+, submitted

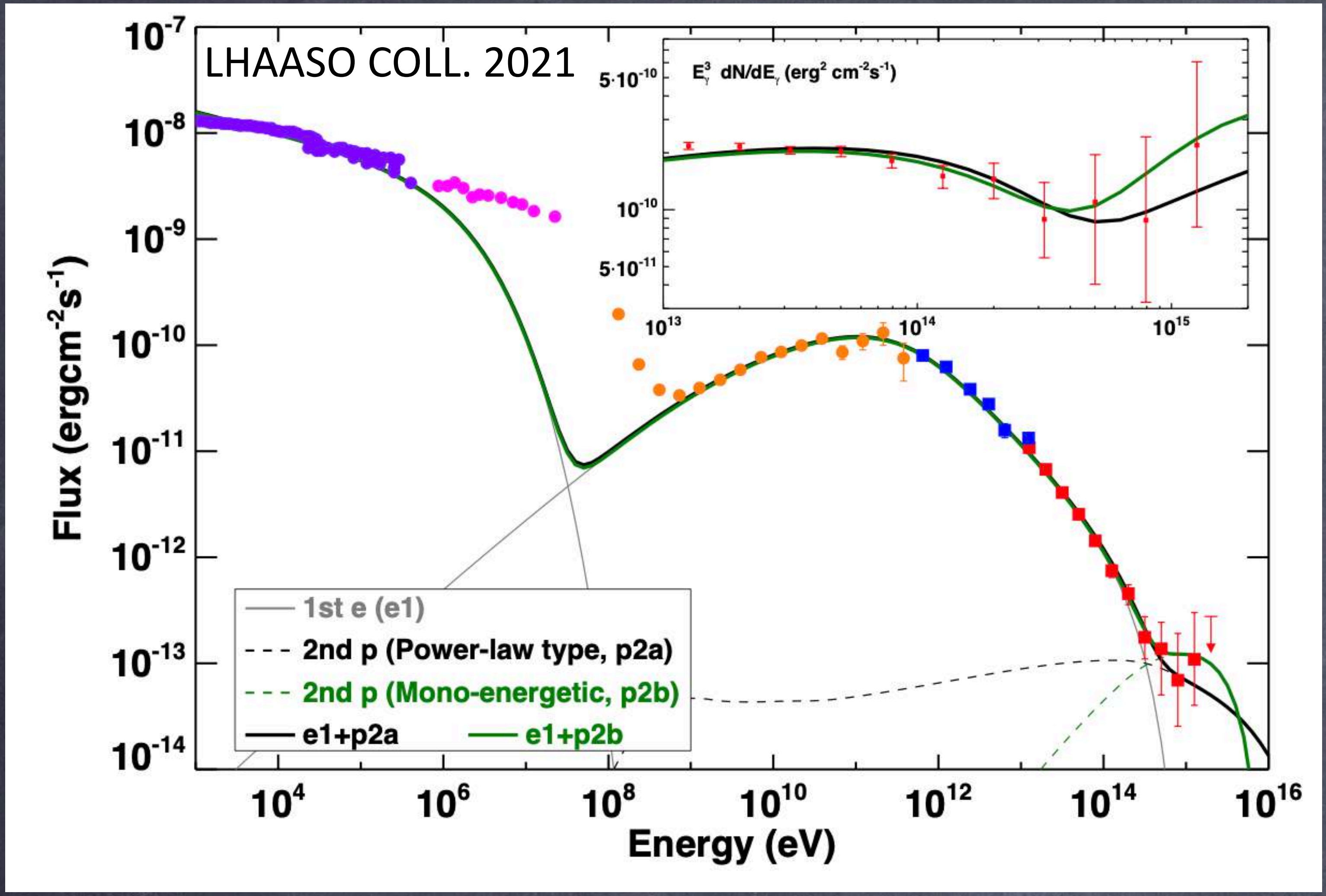
FOR DIRAC DELTA
AND
BOHM DIFFUSION

$$Q_p(E) \propto \delta(E - m_p c^2 \Gamma)$$

[EA & Arons 06; EA, Guetta, Blasi 03]

IONS AT THIS LEVEL IRRELEVANT FOR ACCELERATION UNLESS TINY SHOCK SECTOR

PROTONS?



$$\frac{dN_p}{dE_p} \propto E_p^{-2} \exp(-E_p/30\ \mathrm{PeV})$$

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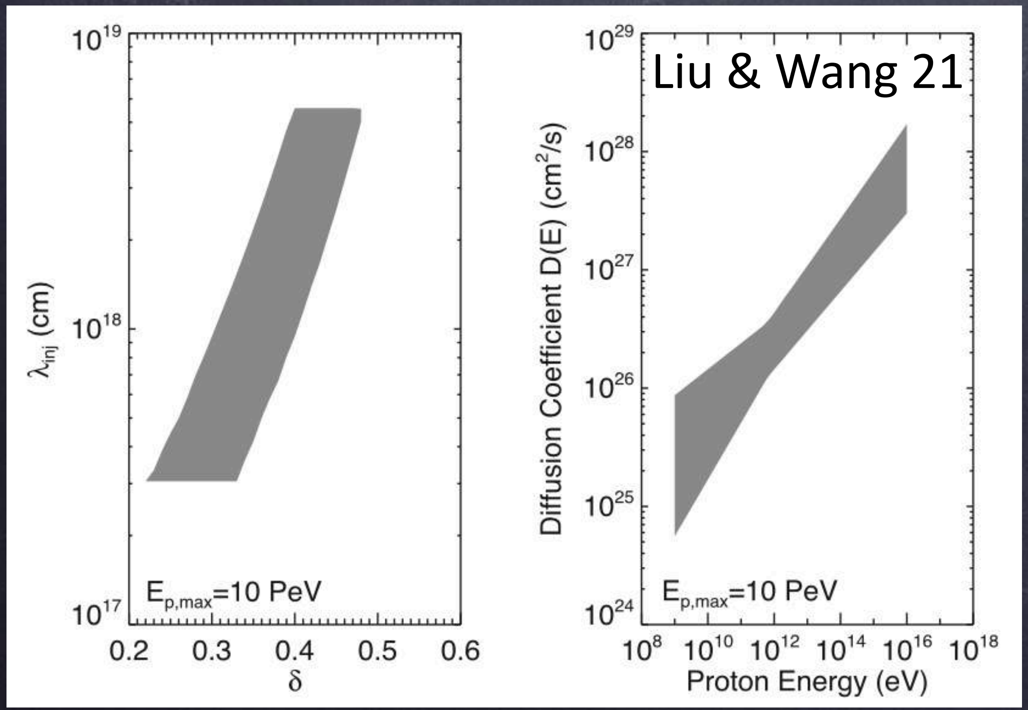

DIFFERENT ENERGY DISTRIBUTION AND PRESCRIPTION FOR ESCAPE [Liu & Wang 21]:

$$\dot{E}_p \leq (10 - 50)\ \%\ \dot{E}$$

CAN ONE STILL REPRODUCE THE OVERALL SED?

SUMMARY AND CONCLUSIONS

- NEBULAR DYNAMICS AND PLASMA PROPERTIES:
  - 3D MHD SIMULATIONS NEEDED TO FULLY ACCOUNT FOR MORPHOLOGY AND SPECTRUM
  - σ> A FEW REQUIRED AT TS
  - TURBULENCE AND DISSIPATION IN THE BULK OF THE NEBULA
  - BUT SED IMPOSES AVERAGE FIELD $\sim 100\mu\mathrm{G}$

- PARTICLE ACCELERATION MECHANISMS:
  - FERMI MECHANISM HELPED BY CORRUGATION IN EQUATORIAL REGION?
  - TURBULENCE ALSO HELPS WITH RECONNECTION AT TS?
  - RADIO PARTICLES DO NOT NEED TO BE PART OF THE FLOW AND SPECTRUM CAN RESULT FROM ACCELERATION IN HIGH σ TURBULENCE
  - MULTIPLICITY CAN BE SMALL ENOUGH FOR ION CYCLOTRON… BUT ENOUGH IONS?

- CRAB IS A LEPTONIC PEVATRON, BUT ALSO HADRONIC AND TO WHAT LEVEL?