THE CRAB NEBULA AT VERY HIGH ENERGIES

Barbara Olmi

OAPA-OAA

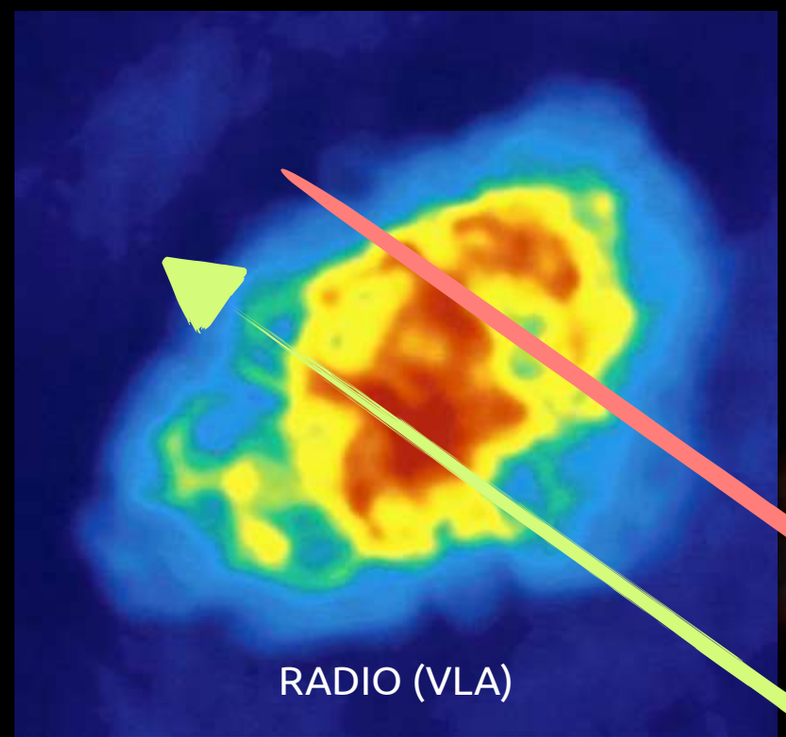
INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

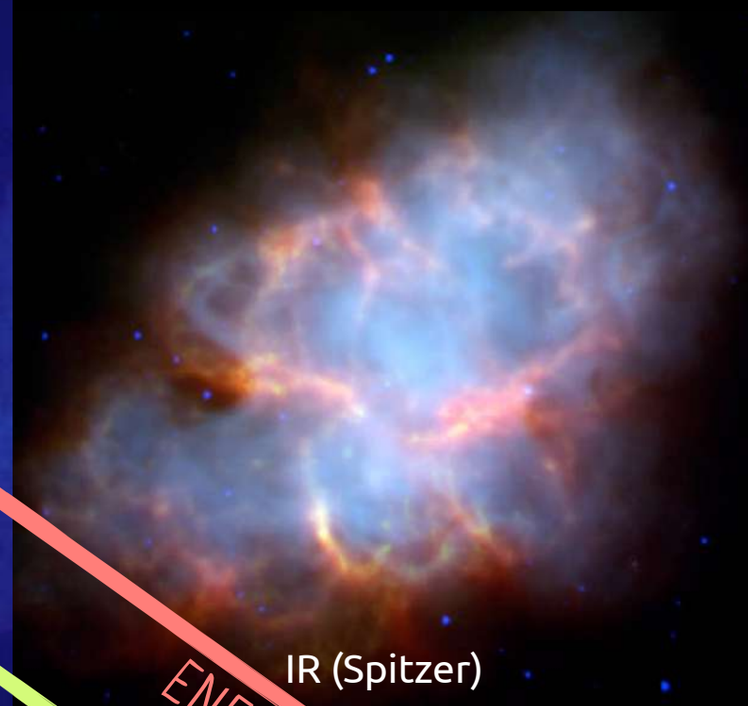
HONEST 2 PeVatrons and their environments
HOT TOPICS IN HIGH ENERGY ASTROPHYSICS

November 29-30, December 1 2022

AN OVERVIEW OF THE CRAB NEBULA

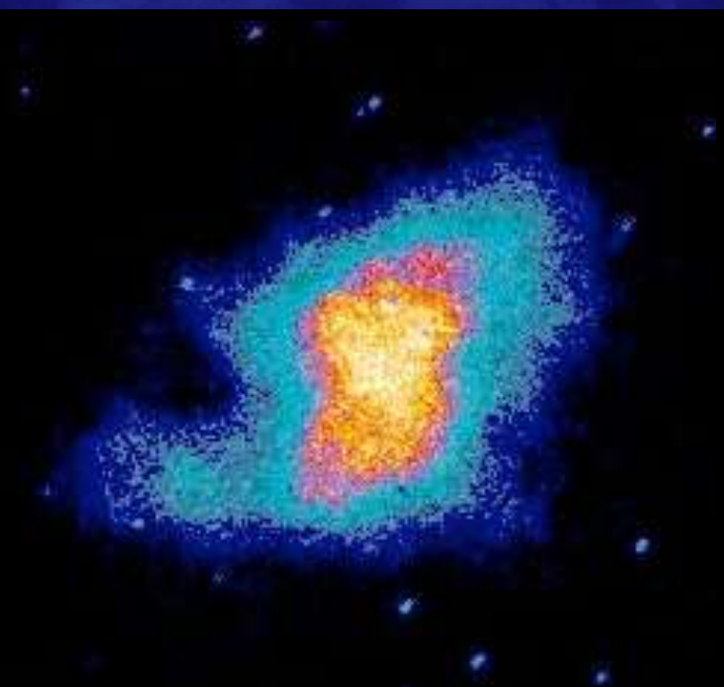
From Radio to X-rays:



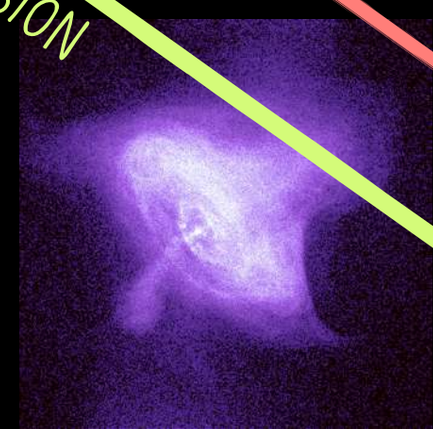


ENERGY

EXTENSION



UV (Astro-1)



X-Ray (Chandra)

Hard X-Ray (HEFT)

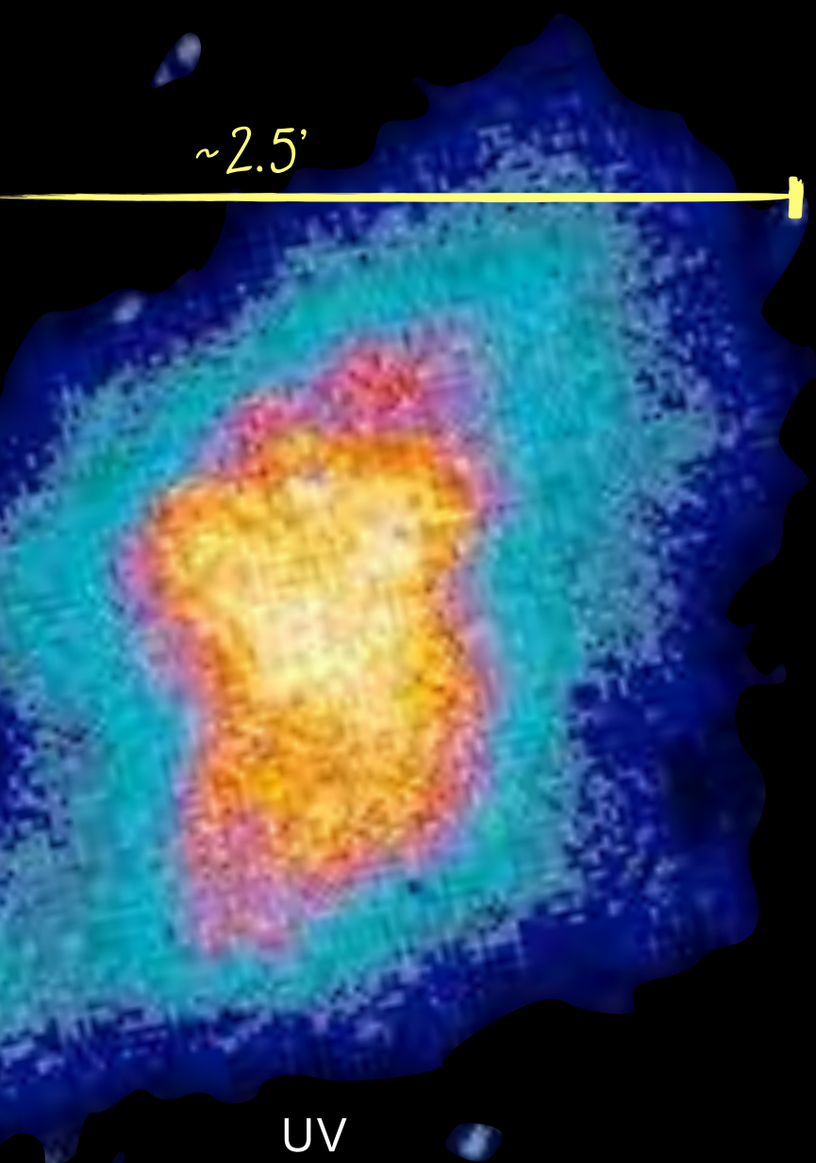
NB: images are not in scale!

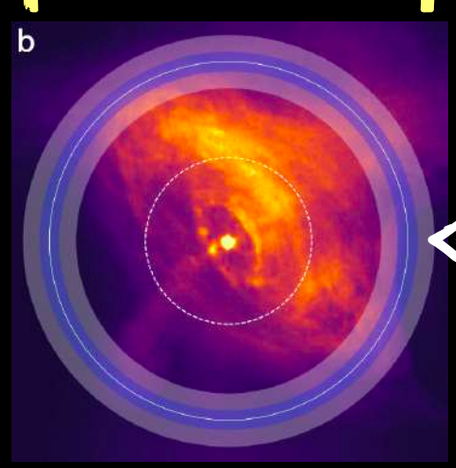
AN OVERVIEW OF THE CRAB NEBULA

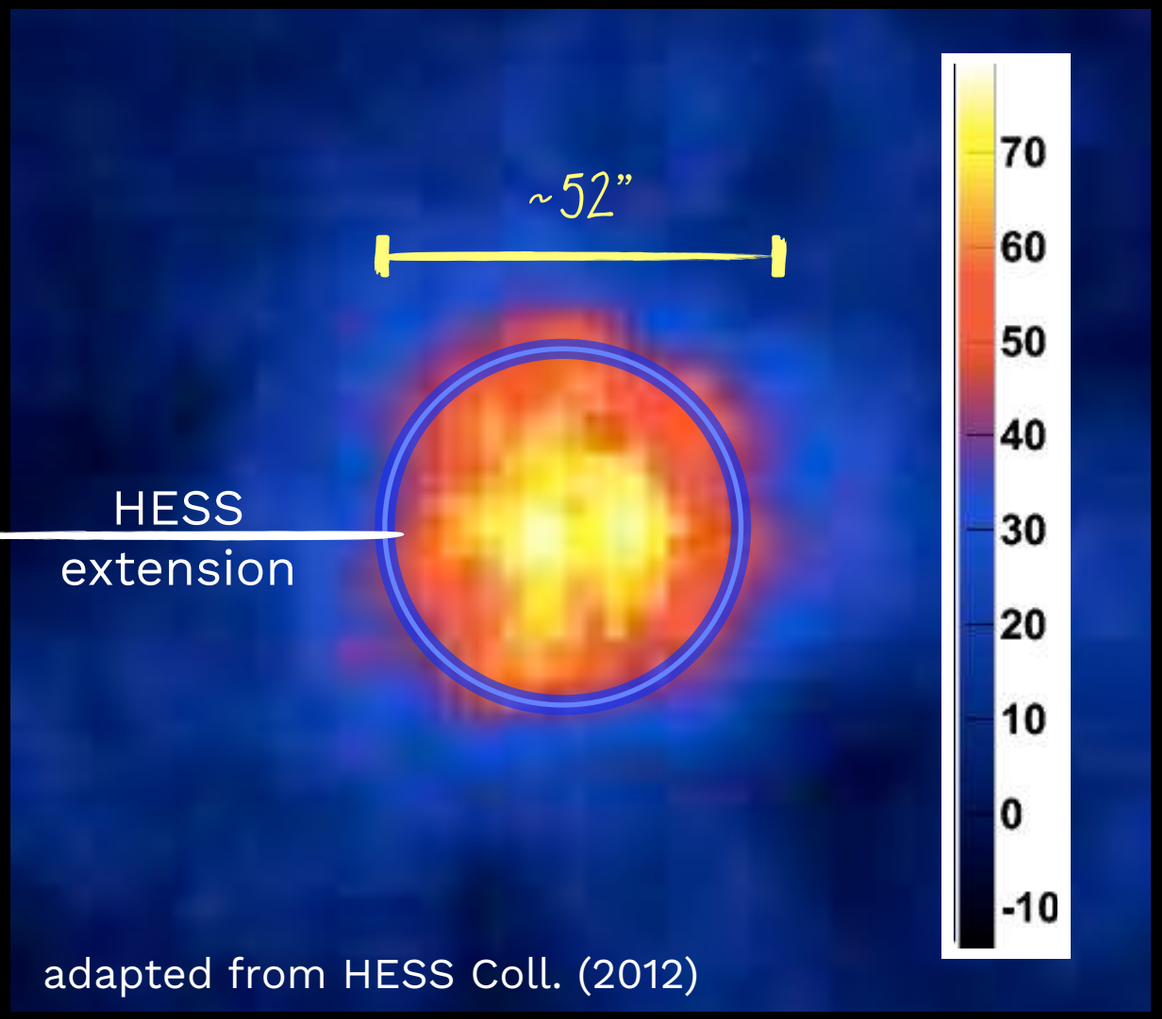
Gamma-rays

Suffer from the poor resolution of present instruments: no morphology at VHE

First measure of the Crab extension @ 700 GeV-5 TeV by HESS show a size comparable with the X-ray nebula [HESS Coll. 2020, Nat. Astr.]



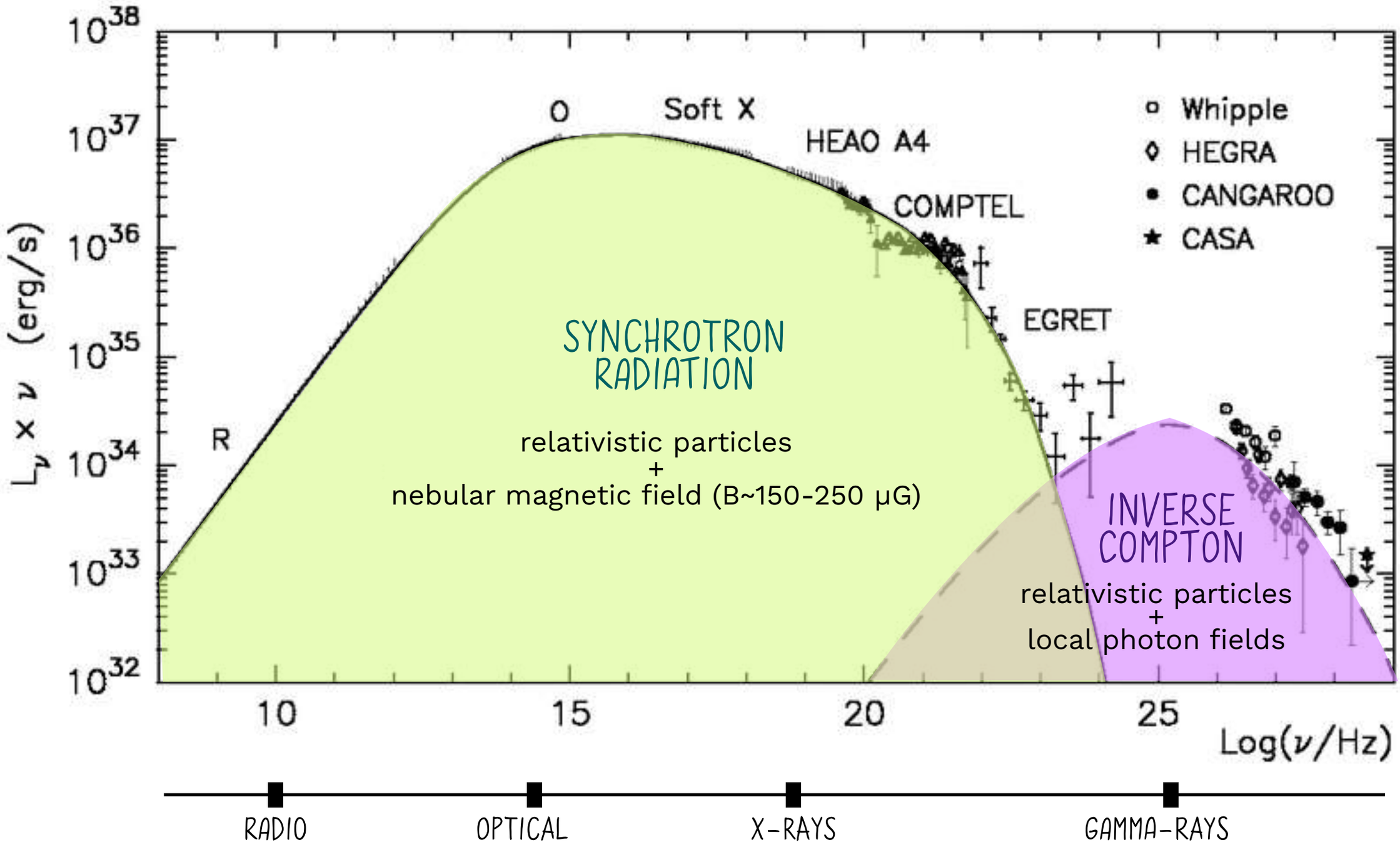




TeV gamma rays produced by the same leptons emitting at X-rays

AN OVERVIEW OF THE CRAB NEBULA

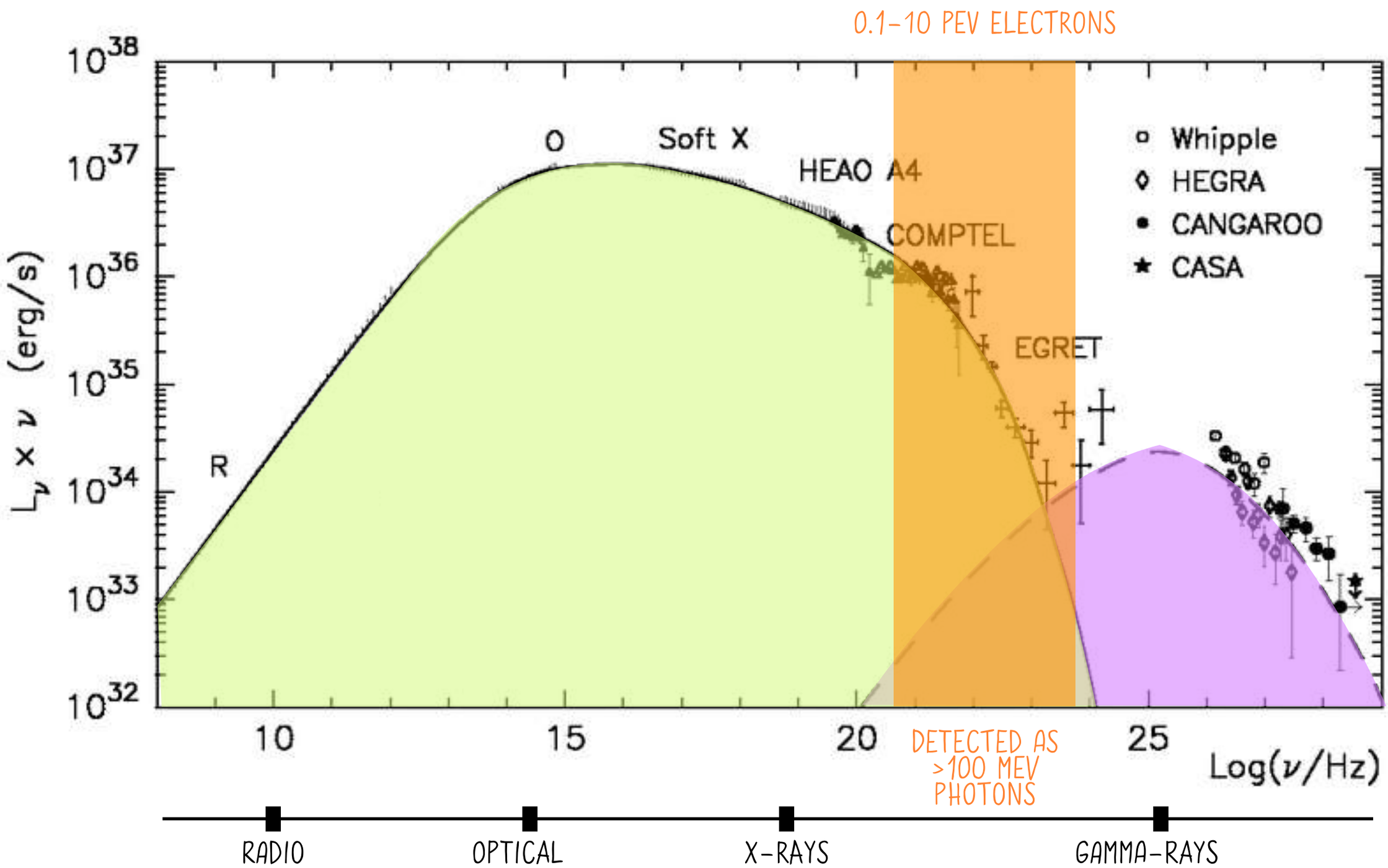
Extended non-thermal spectrum



The CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]

THE CRAB NEBULA IS A PEVATRON

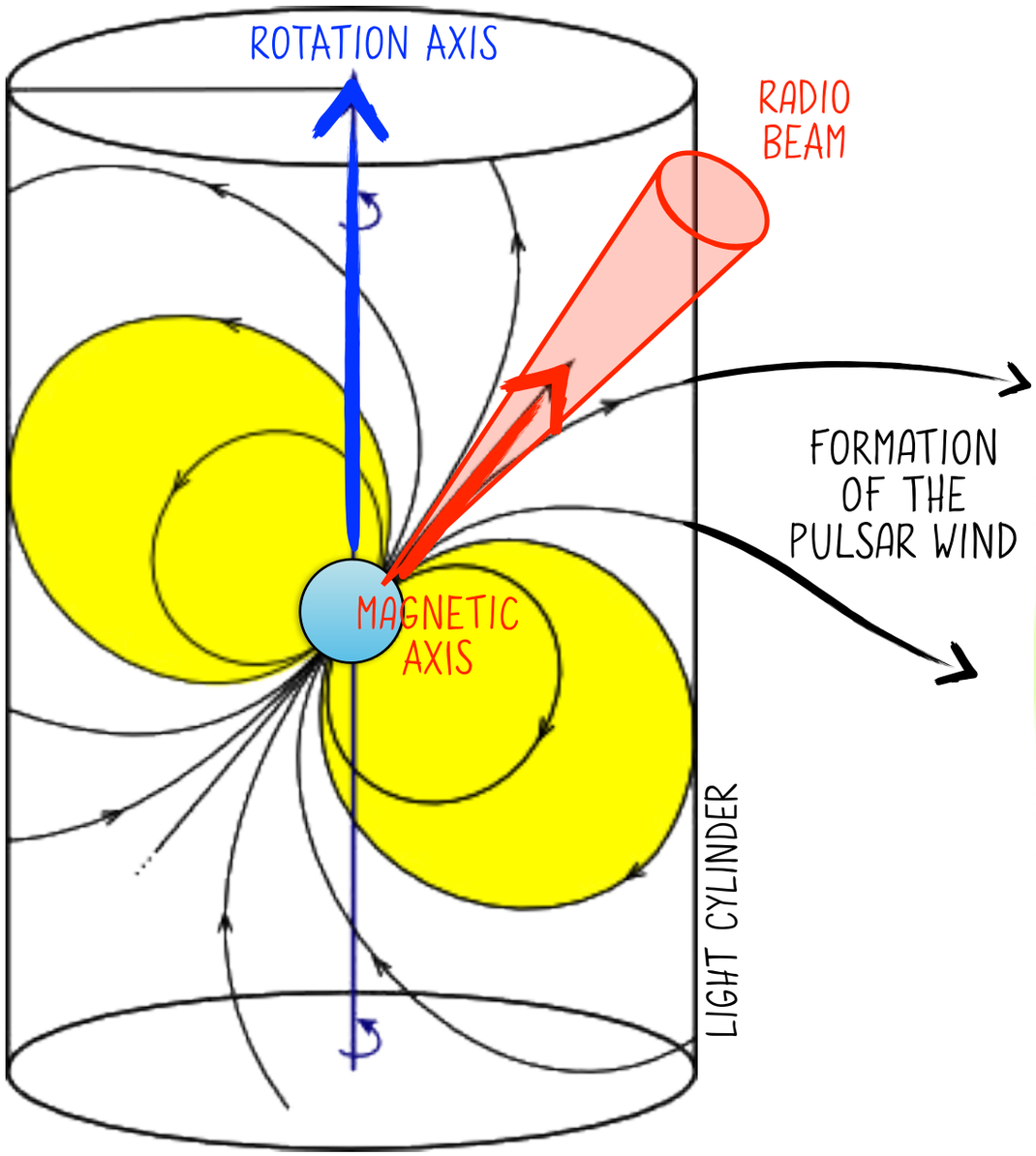
The Crab is the unique established leptonic PeVatron in the Galaxy



The CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]

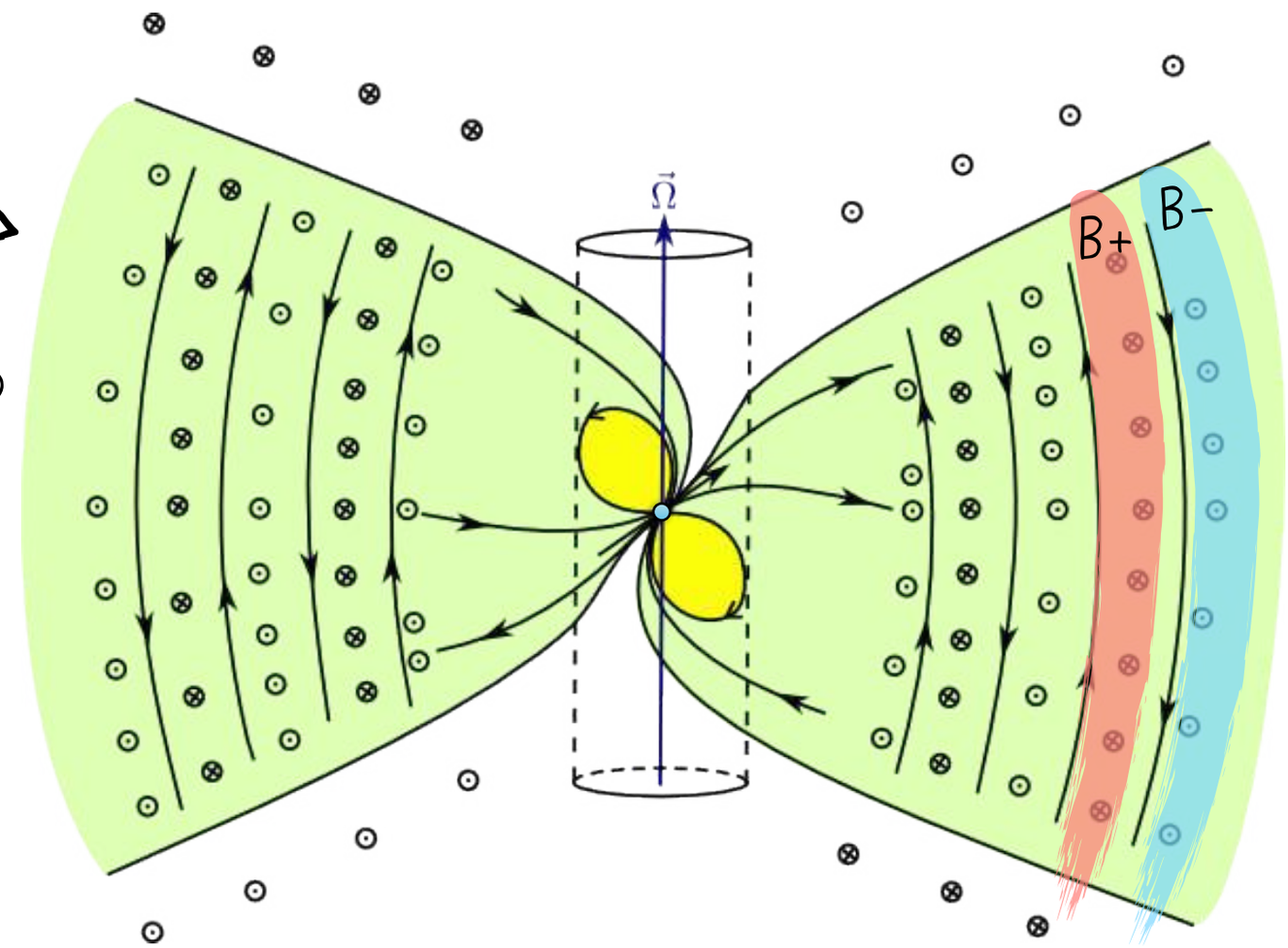
THE CENTRAL ENGINE

PULSAR = ROTATING MAGNET THAT SLOWS DOWN DUE TO ELECTROMAGNETIC TORQUE [PACINI 1969]



CLOSED MAGNETOSPHERE

FORMATION OF THE PULSAR WIND



OPEN MAGNETOSPHERE

INJECTION FROM THE PULSAR:

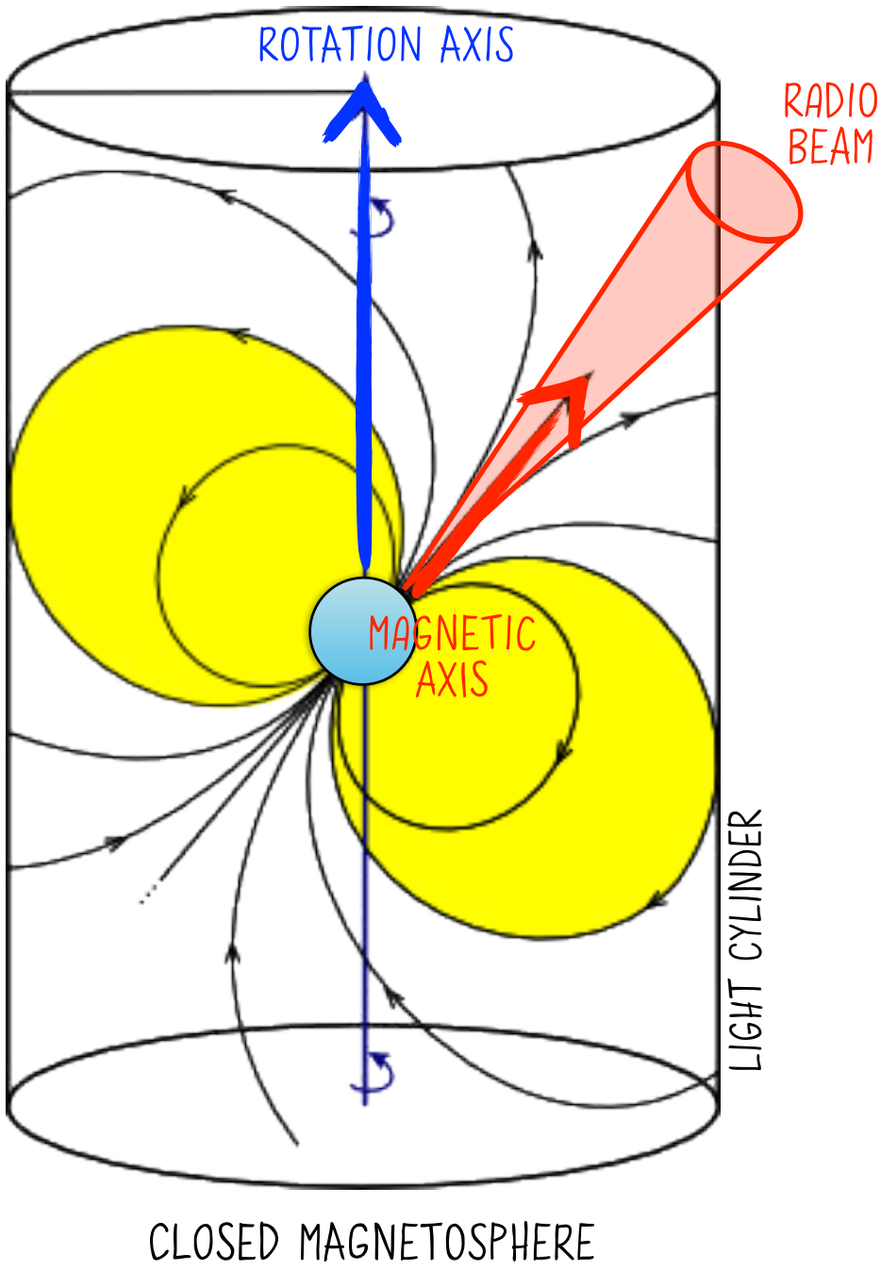
RELATIVISTIC PARTICLES AND MAGNETIC FIELD

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma) \sim 5 \times 10^{38}\,\mathrm{erg/s}$$

wind magnetization:

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

THE NATURE OF THE WIND



PRIMARY PARTICLES - extracted at the star surface [Goldreich & Julian rate]

$$\dot{N}_{GJ} = \dot{E}/e \sim 2.7 \times 10^{30} \left(\frac{B_{pc}}{10^{12}\,G} \right) \left(\frac{P}{1\,s} \right)^{-2} s^{-1}$$

can be both ions (m_i) or electrons (m_e)

SECONDARY PARTICLES - generated in e.m. cascades in the magnetosphere (leptons only)

ions ~ 1/k electrons

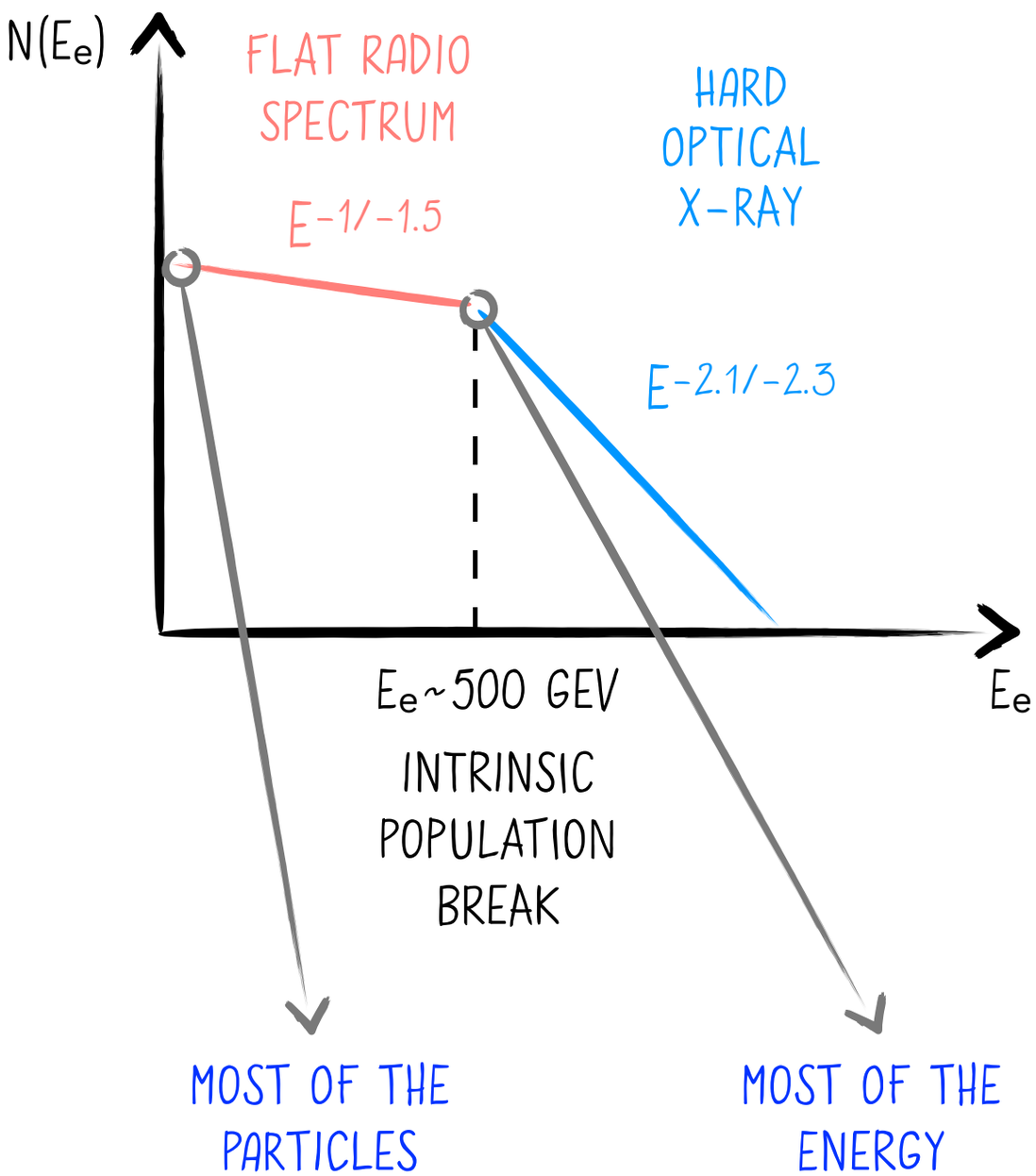
pulsar pair multiplicity:
κ = secondary/primary electrons ~10^4-10^7

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

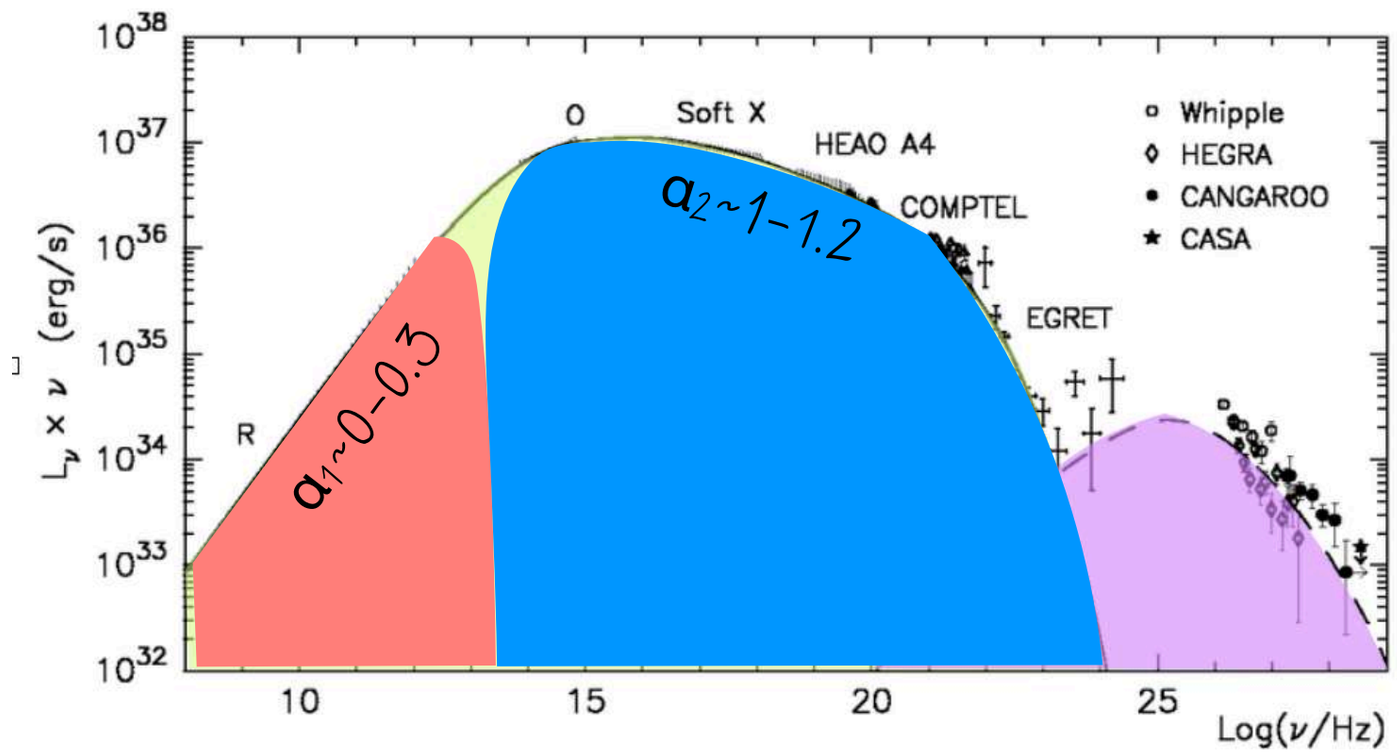
PARTICLES SPECTRA VS SED

PARTICLE SPECTRUM

@ INJECTION



SED



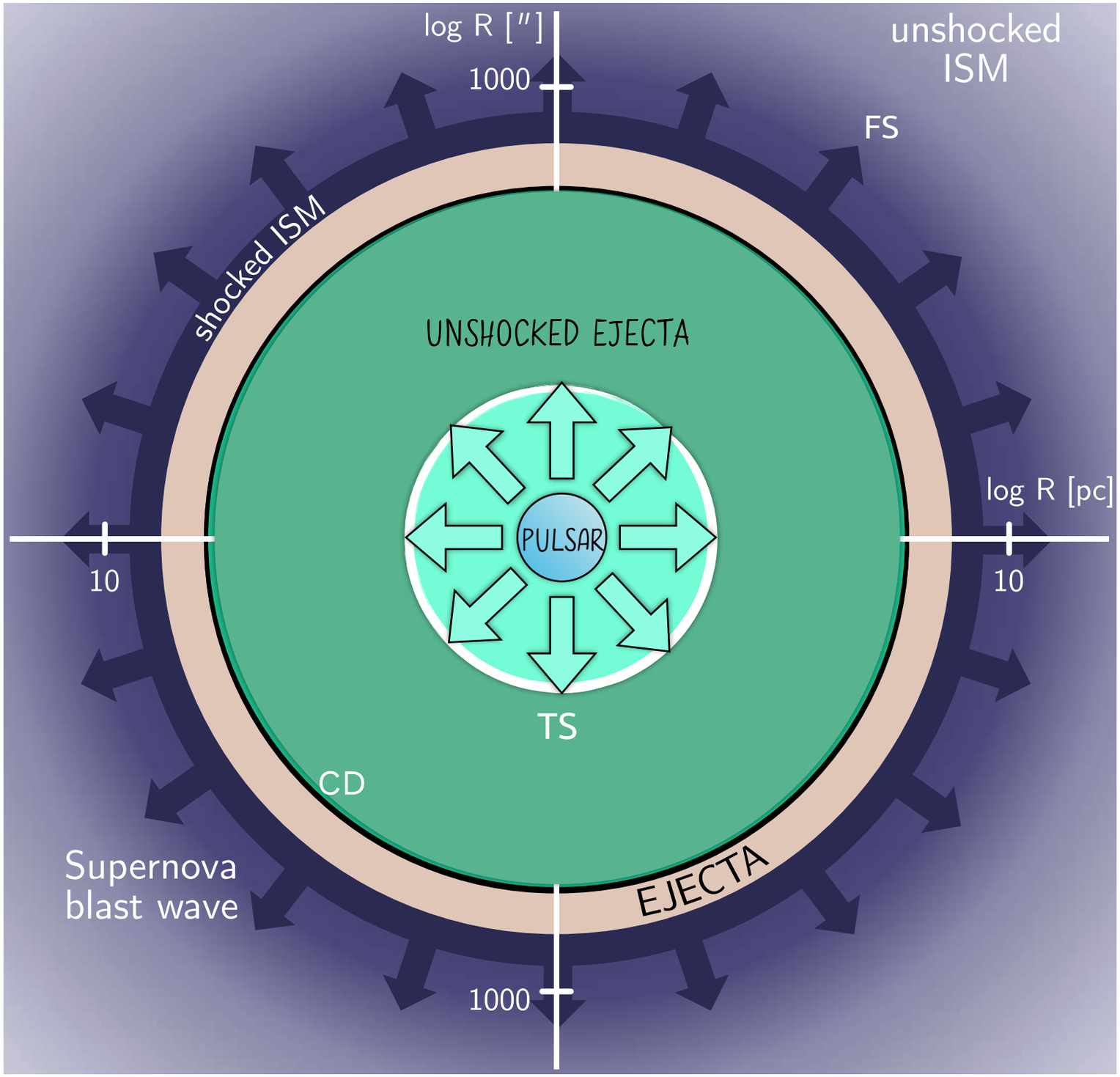
THE CRAB NEBULA IS AN EXCELLENT ACCELERATOR:

20-30% OF $\dot{E}$ CONVERTED INTO EMISSION

UNDERSTANDING THE CRAB NEBULA STRUCTURE

1D-2D STATIC MODELS

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



Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

VERY SIMPLIFIED DESCRIPTION
BUT CAN ACCOUNT FOR A NUMBER OF
PROPERTIES, AMONG WHICH:

#1 POSITION OF THE TERMINATION SHOCK

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

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

UNDERSTANDING THE CRAB NEBULA STRUCTURE

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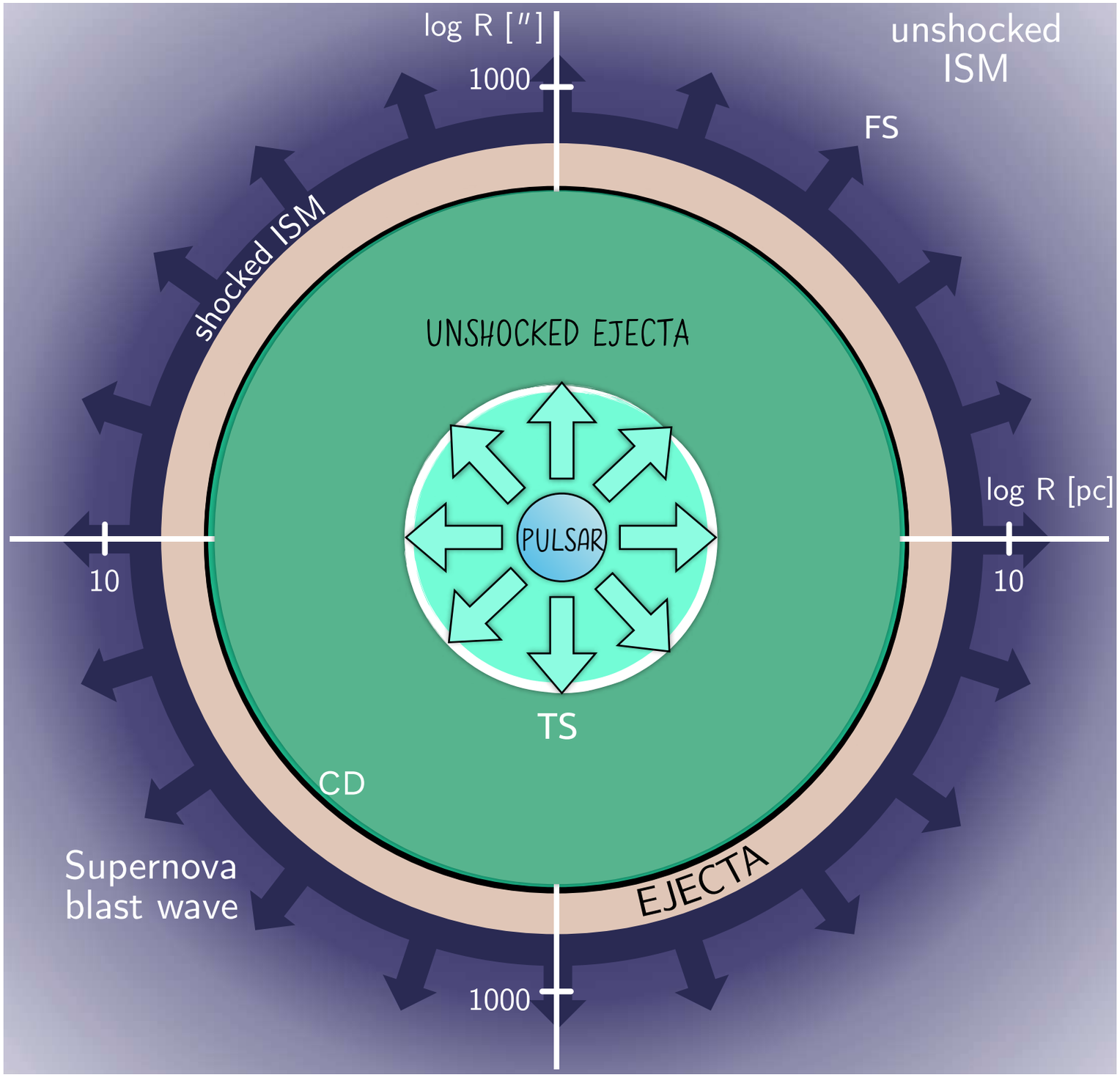


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

VERY SIMPLIFIED DESCRIPTION
BUT CAN ACCOUNT FOR A NUMBER OF
PROPERTIES, AMONG WHICH:

#1 POSITION OF THE TERMINATION SHOCK

#2 PARTICLES SPECTRAL INDEX (X): $\gamma = 2.3$

#3 WIND LORENTZ FACTOR: $\Gamma = 3 \times 10^6$

#4 NEBULAR MAGNETIZATION: $\sigma \sim 10^{-3}$

#5 INJECTION RATE: $\dot{N} \sim 10^{38}\,\mathrm{s}^{-1}$

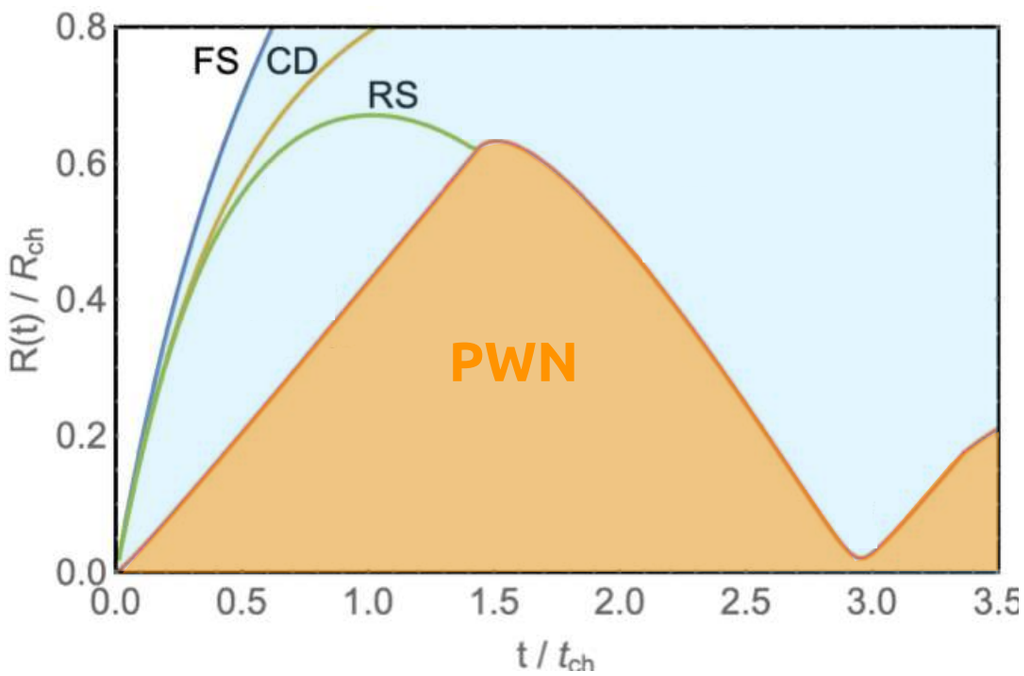
UNDERSTANDING THE CRAB NEBULA STRUCTURE

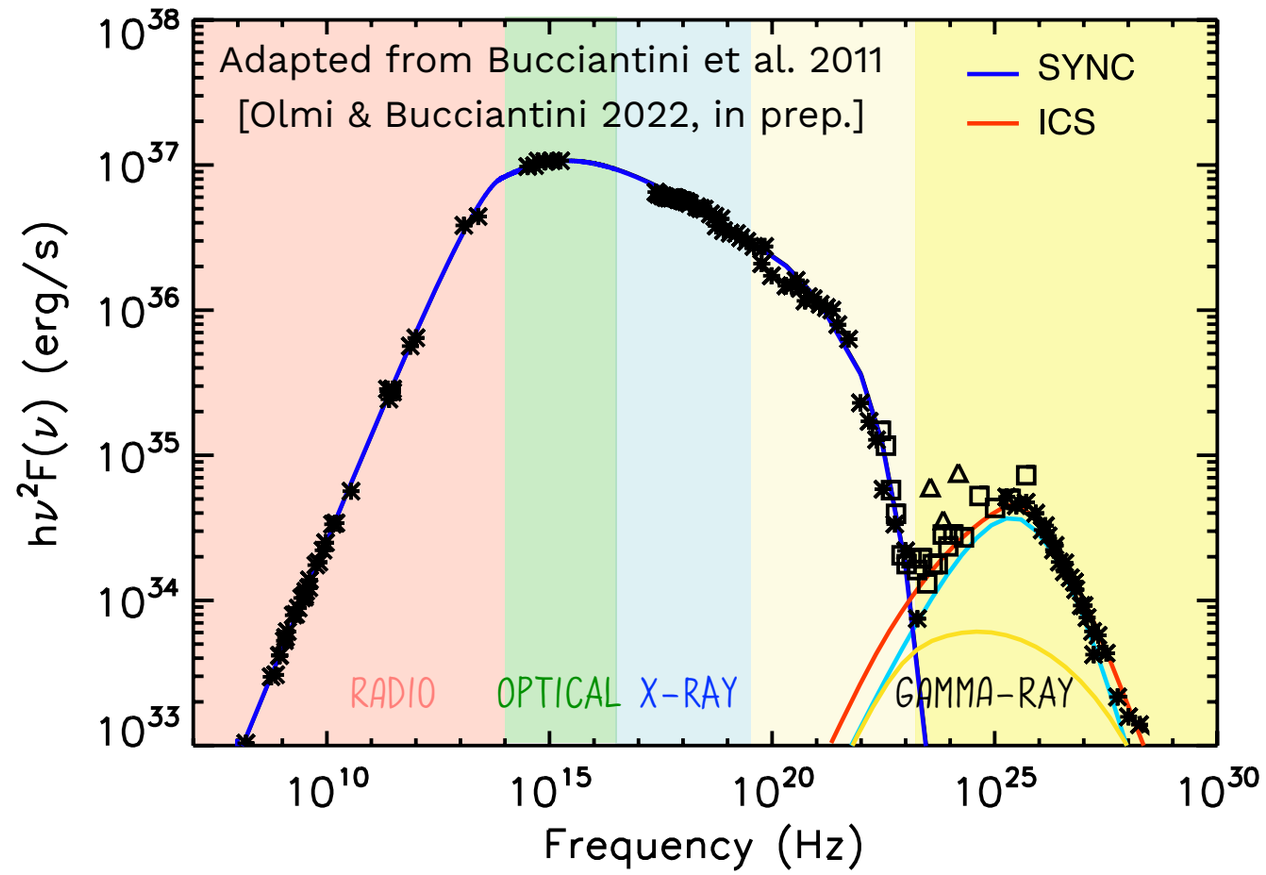
ONE ZONE MODELS

[Pacini & Salvati 1973, Reynolds & Chevalier 1984, Gelfand et al. 2009, Bucciantini et al. 2011, Torres et al. 2014, + many others]

PWN RADIUS CONFUSED WITH THE SHELL OF SWEPT UP EJECTA AT BOUNDARY.

STILL SIMPLIFIED BUT ALLOW FOR "DYNAMICAL" +RADIATIVE EVOLUTION OF THE NEBULA





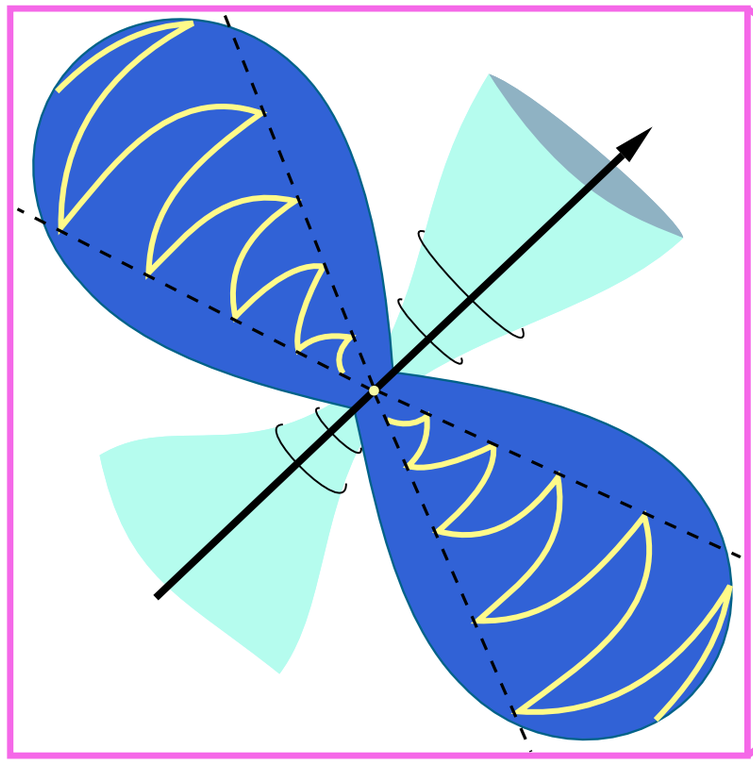
Parameter	Symbol	Crab
SN explosion energy (10^{51} erg)	E_{SN}	1
Mass of the ejecta ($M_\odot$)	M_{ej}	9.5
ISM density (cm^{-3})	ρ_0	0.1
Ejecta density index	α	0
Initial PSR luminosity (10^{38} erg s^{-1})	L_0	35
Spin-down time (yr)	τ	730
Braking index	β	2.33
Age (yr)	t	950
Fraction of L that goes into pairs	η_e	0.8
Low-energy injection index	γ_1	1.5
High-energy injection index	γ_2	2.35
Peak energy ratio	μ_e	1.54×10^{-5}
Minimum energy ratio	ν_e	1.1×10^{-8}
Break energy (eV)	ϵ_c	4×10^{11}
Fraction of magnetic energy	η_M	0.11
Fraction of L that goes into ions	η_p	0

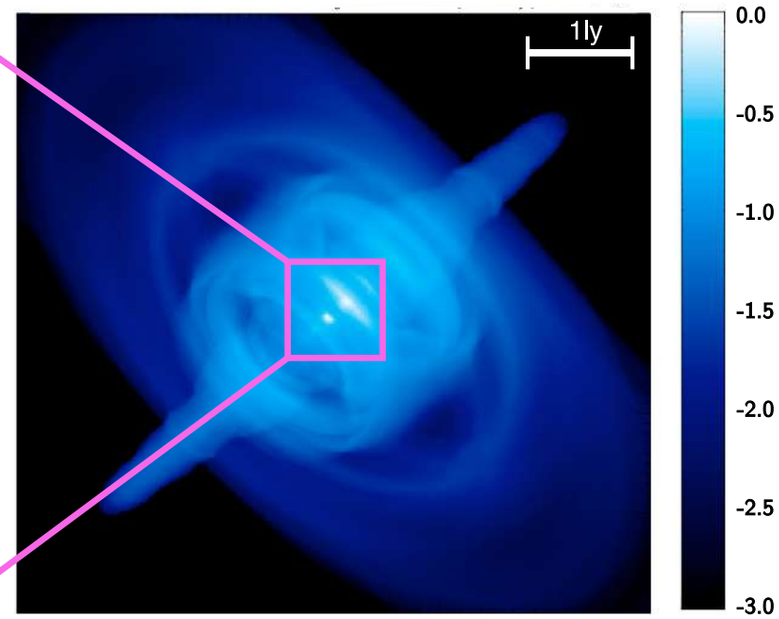
> TO TEST THE SYSTEM PHYSICAL PARAMETERS

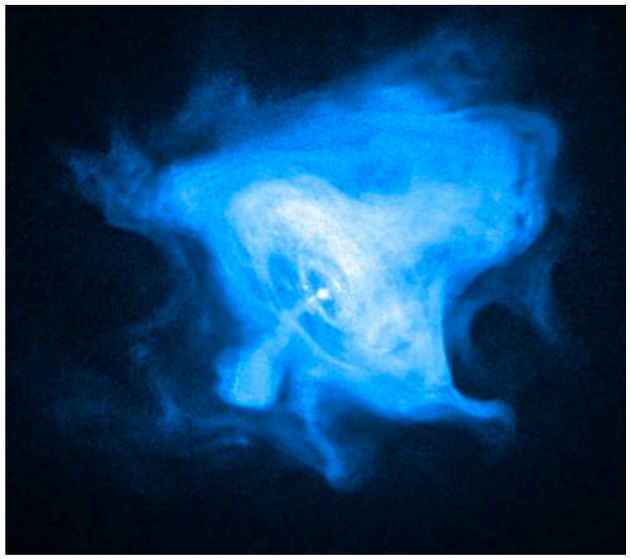
A DEEPER LOOK

2D AXISYMMETRIC MODELS

[Komissarov & Lyubarsky 2003-2004, Del Zanna et al. 2004-2006]







[Olmi & Bucciantini 2022, in prep.]

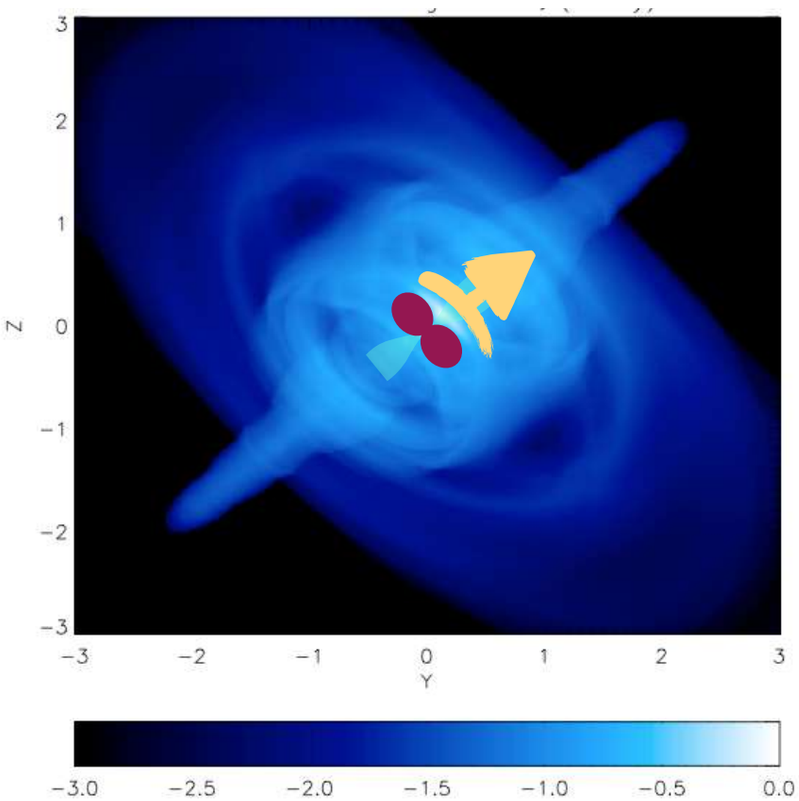
THE COMPLEX INNER NEBULA REQUIRES 2D MODELS TO BE REPRODUCED:

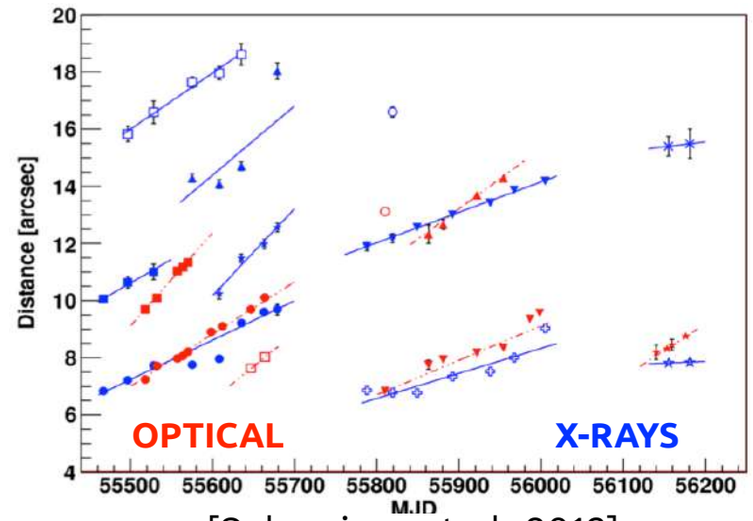
- ANISOTROPIC ENERGY FLUX IN THE WIND
- OBLATE TS
- FORMATION OF JETS (ONLY FOR $\sigma \gtrsim 10^{-2}$)
- INNER NEBULA VARIABILITY

CONSTRAINING THE ACCELERATION MECHANISM(S)

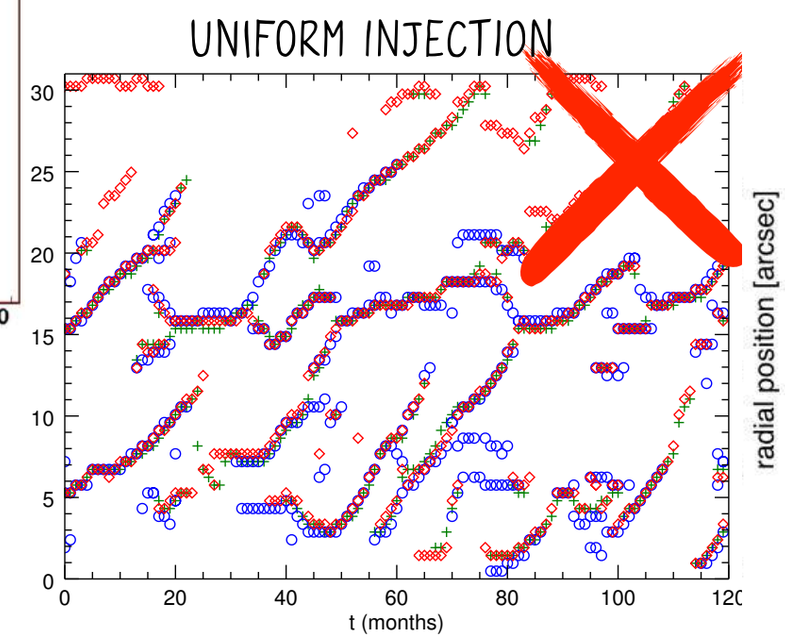
INNER NEBULA VARIABILITY

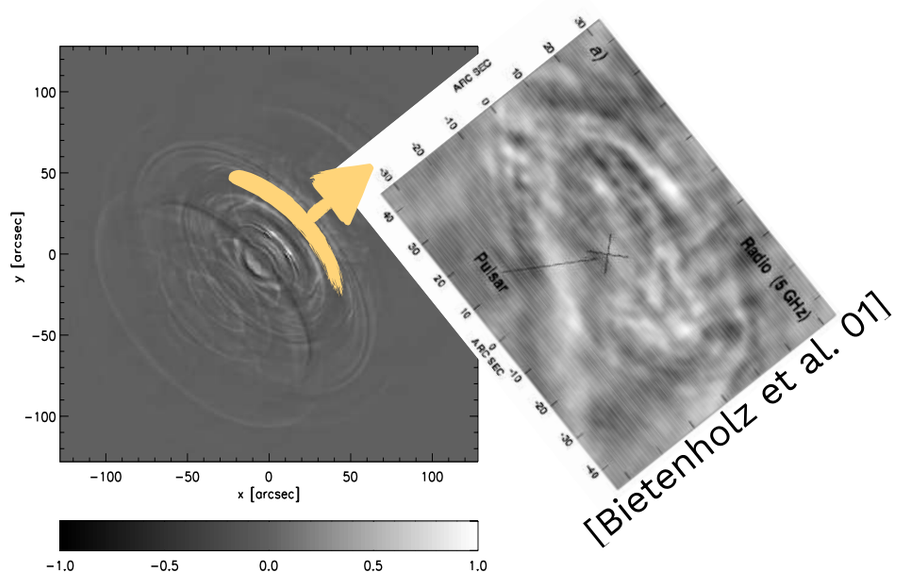
[Camus et al. 2009, Olmi et al. 2014]





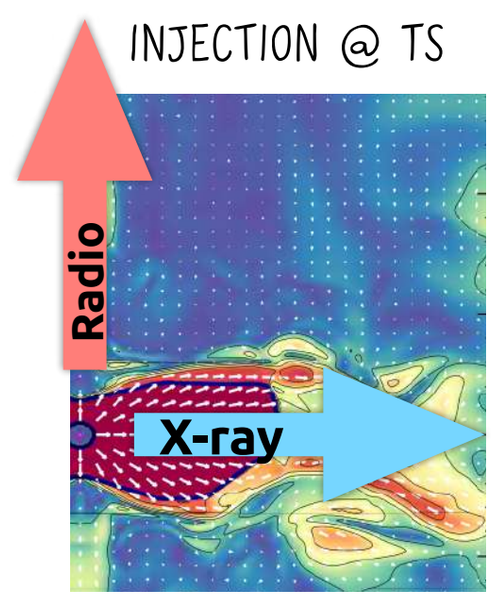
[Schweizer et al. 2013]

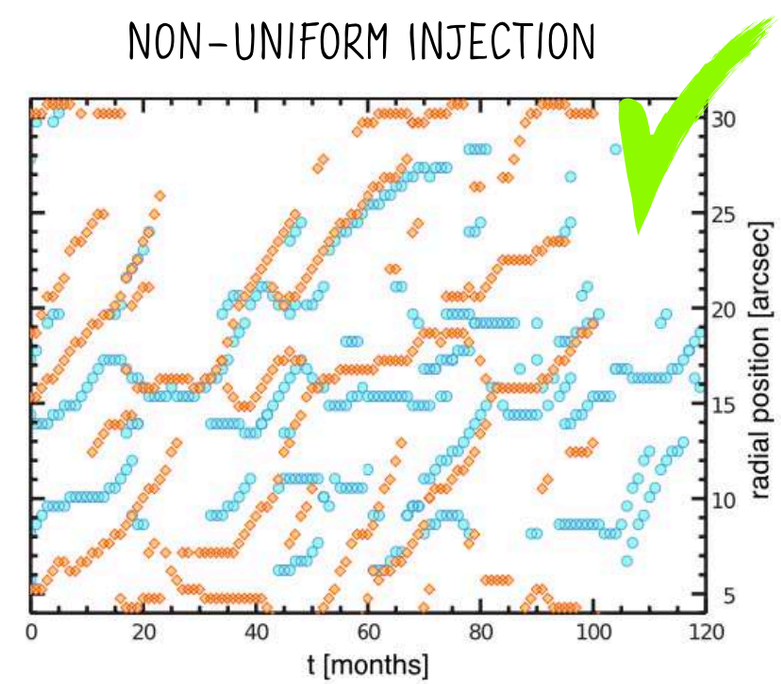




[Bietenholz et al. 01]

RADIO WISPs
[Olmi et al. 2014]

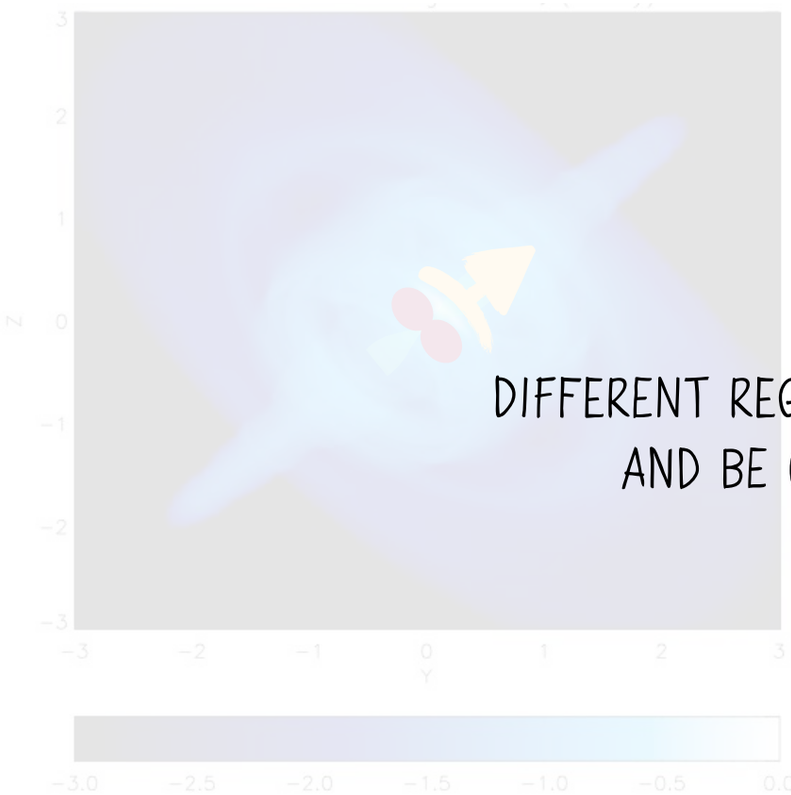


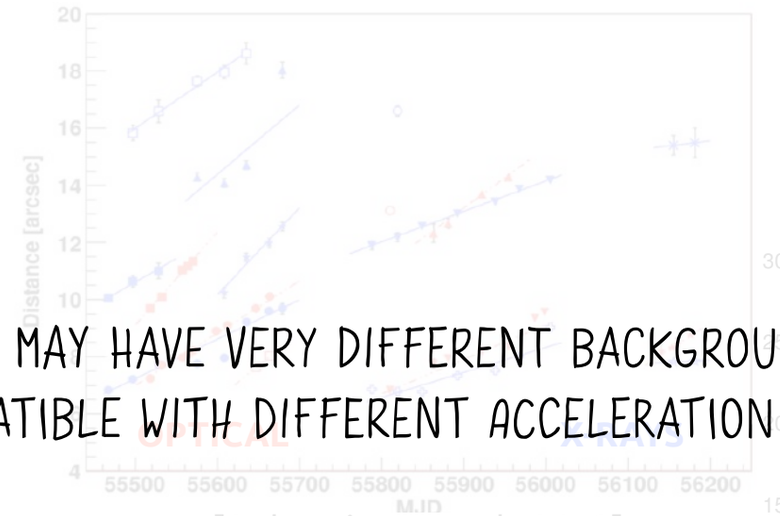


CONSTRAINING THE ACCELERATION MECHANISM(S)

INNER NEBULA VARIABILITY

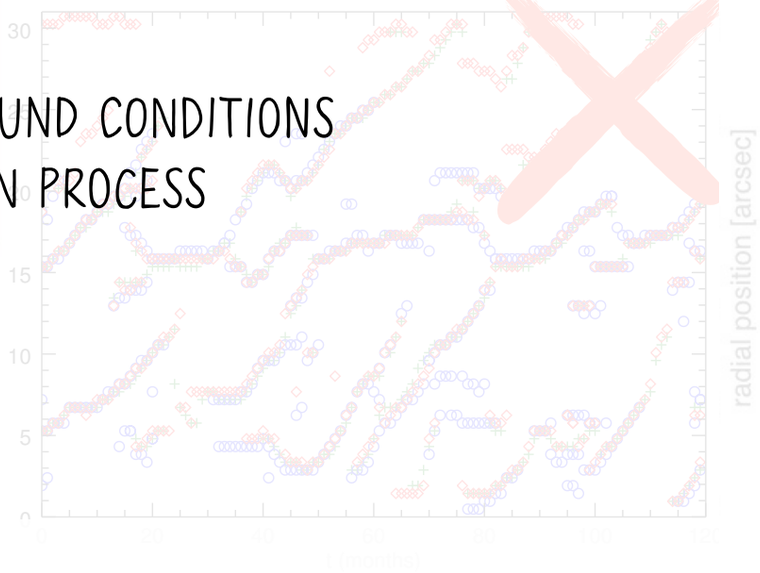
[Camus et al. 2009, Olmi et al. 2014]



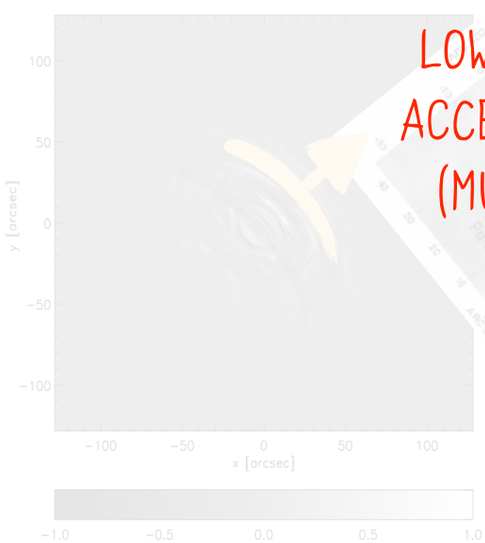


[Schweizer et al. 2013]

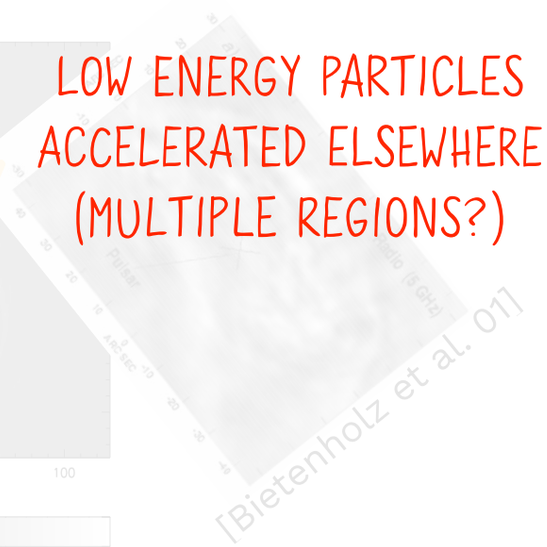
UNIFORM INJECTION



DIFFERENT REGIONS MAY HAVE VERY DIFFERENT BACKGROUND CONDITIONS AND BE COMPATIBLE WITH DIFFERENT ACCELERATION PROCESS



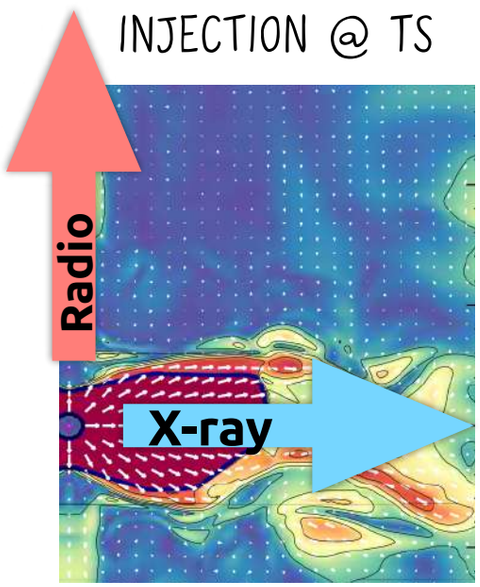
LOW ENERGY PARTICLES ACCELERATED ELSEWHERE (MULTIPLE REGIONS?)



[Bietenholz et al. 01]

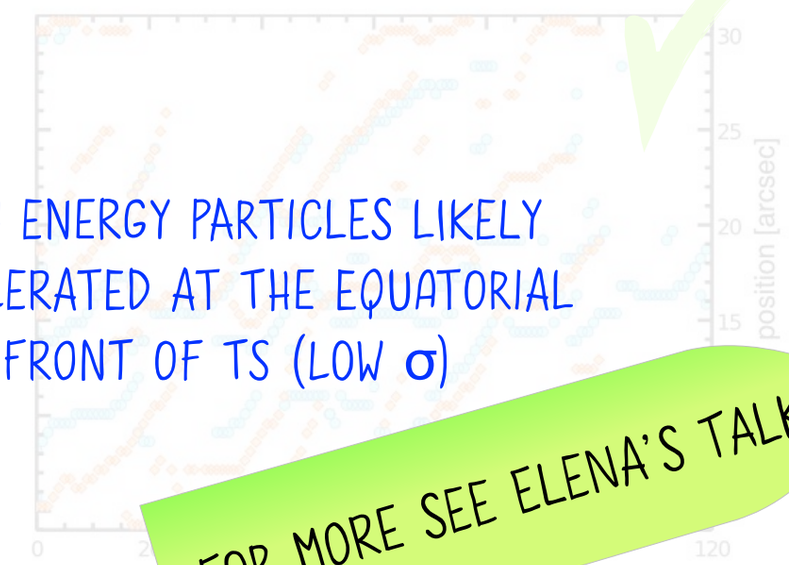
RADIO WISPs
[Olmi et al. 2014]

INJECTION @ TS



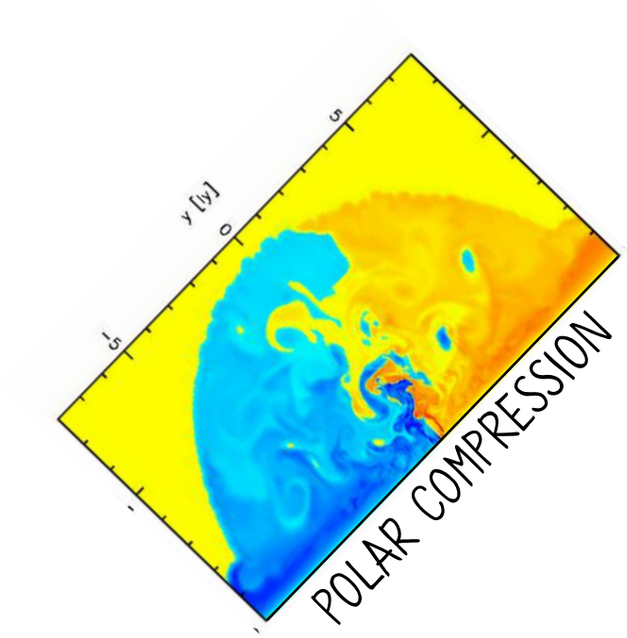
HIGH ENERGY PARTICLES LIKELY ACCELERATED AT THE EQUATORIAL FRONT OF TS (LOW σ)

NON-UNIFORM INJECTION



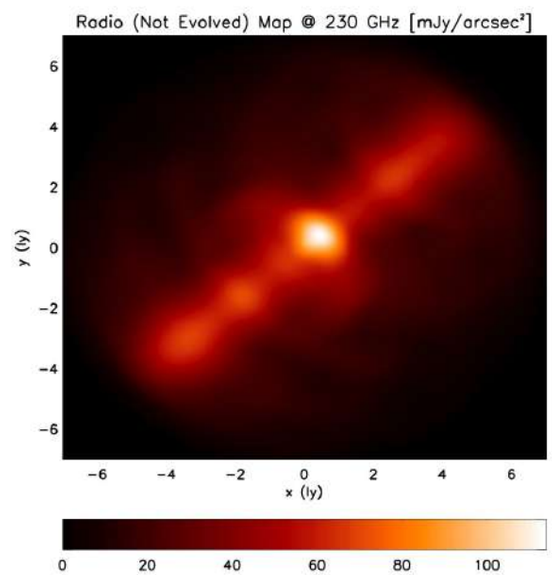
FOR MORE SEE ELENA'S TALK

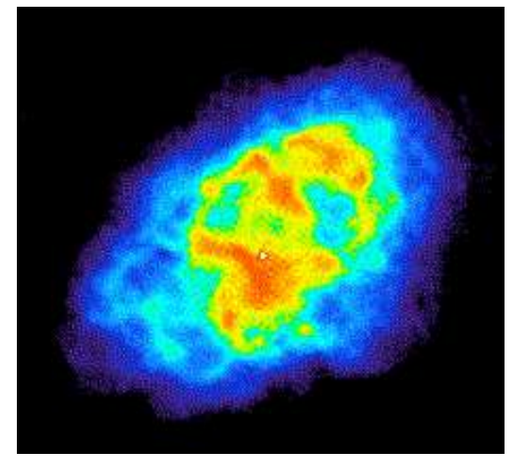
THE PROBLEM WITH THE SPECTRUM (I.E. THE FIELD)



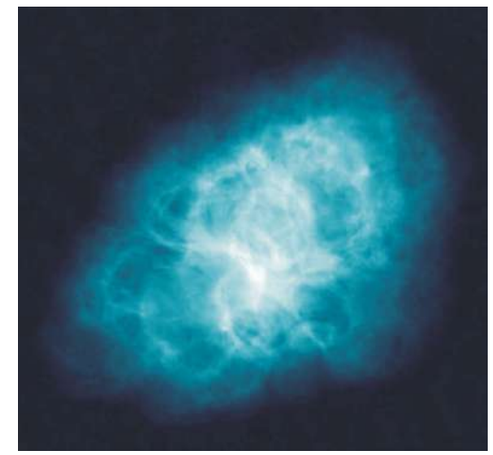
$B^{AVE} \sim 50\ \mu G$

RADIO EMISSION IS NOT UNIFORM: TRACES THE FIELD COMPRESSION



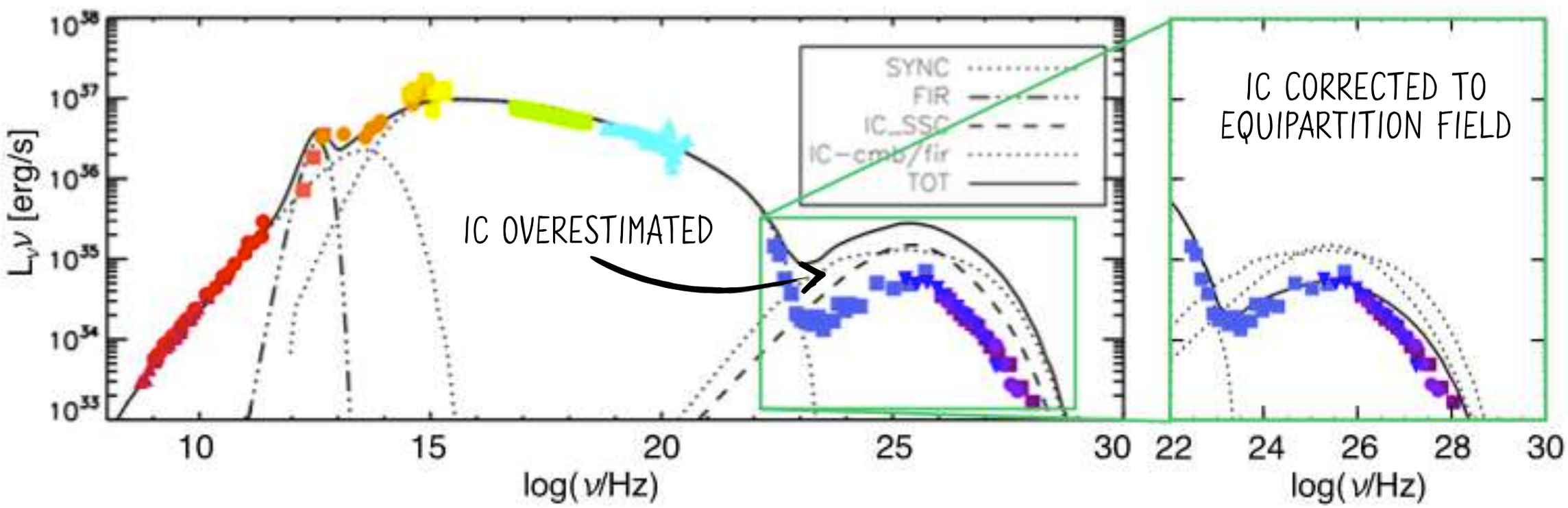


VLA



NRAO

HIGH-ENERGY SPECTRUM NEEDS ARTIFICIAL STEEPENING TO COMPENSATE LOWER ENERGY LOSSES

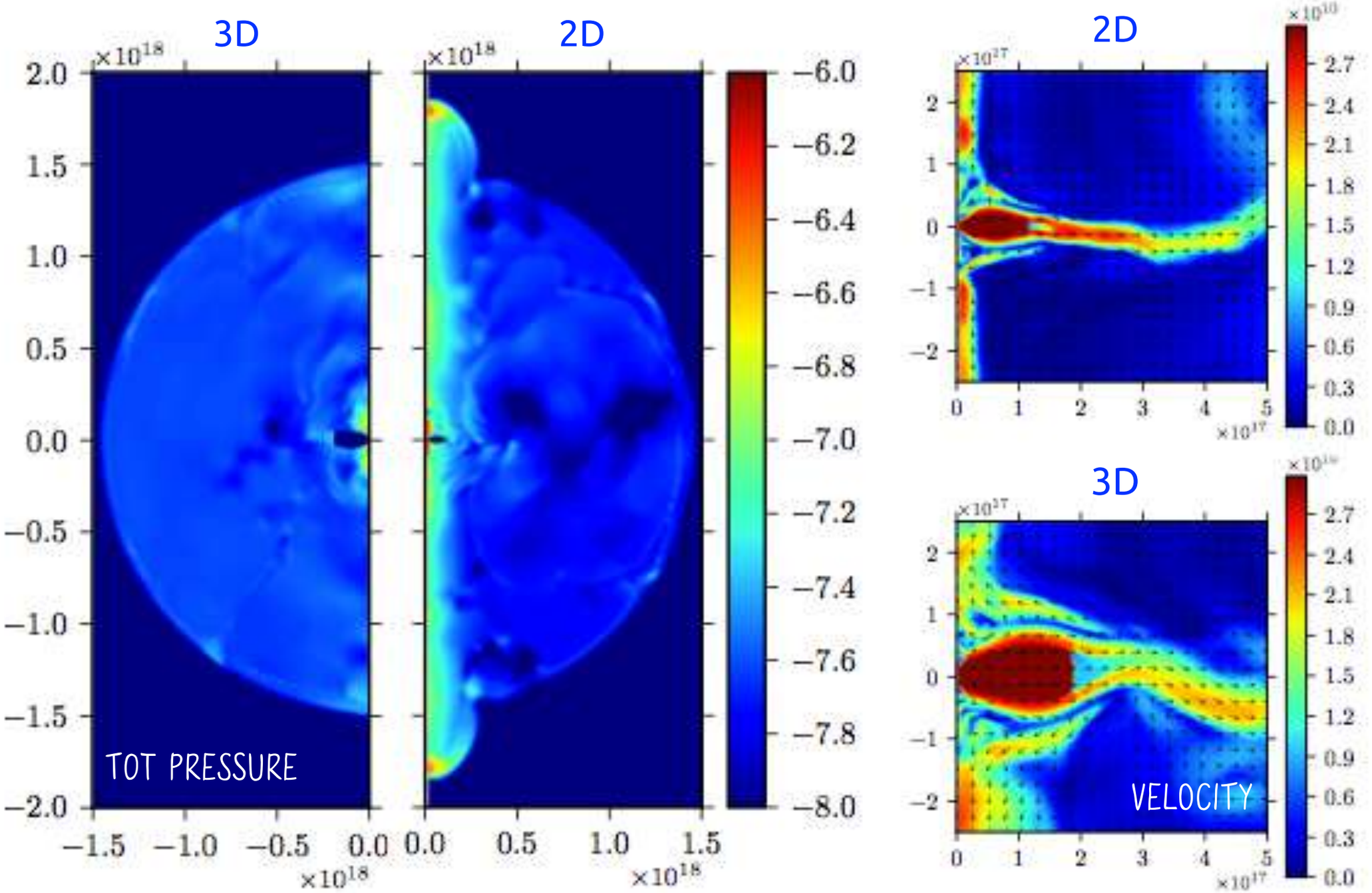


THE 3D STRUCTURE AND MAGNETIC FIELD

σ=1 3D OPENS TO LARGE DISSIPATION (KINK) AND ALLOWS TO REACH HIGH MAGNETIZATIONS (AT INJECTION!)

GLOBAL DYNAMICS IS DIFFERENT...

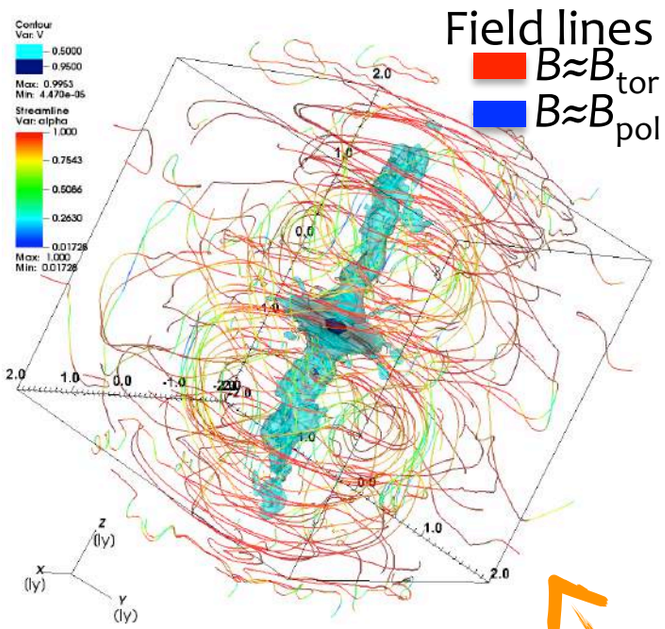
BUT INNER DYNAMICS IS SIMILAR!

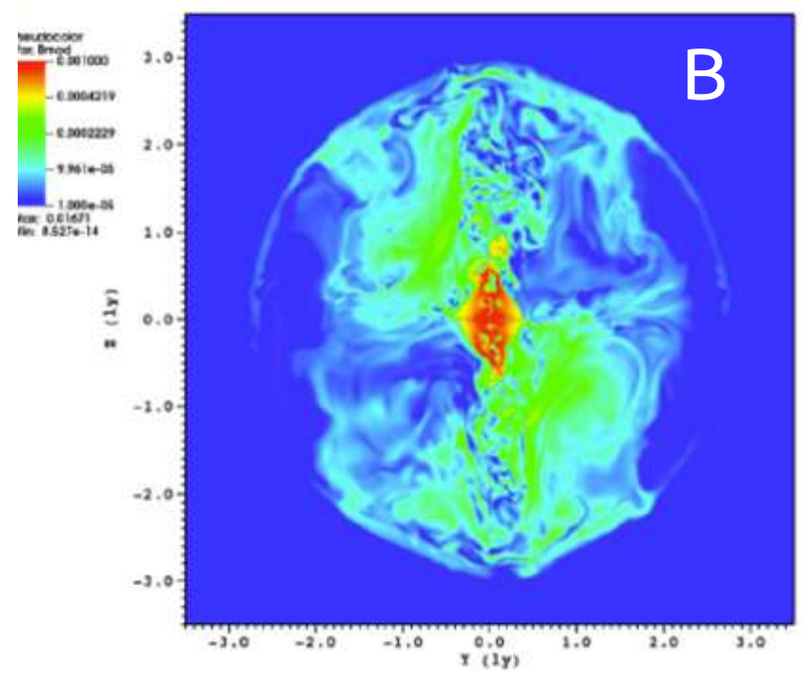


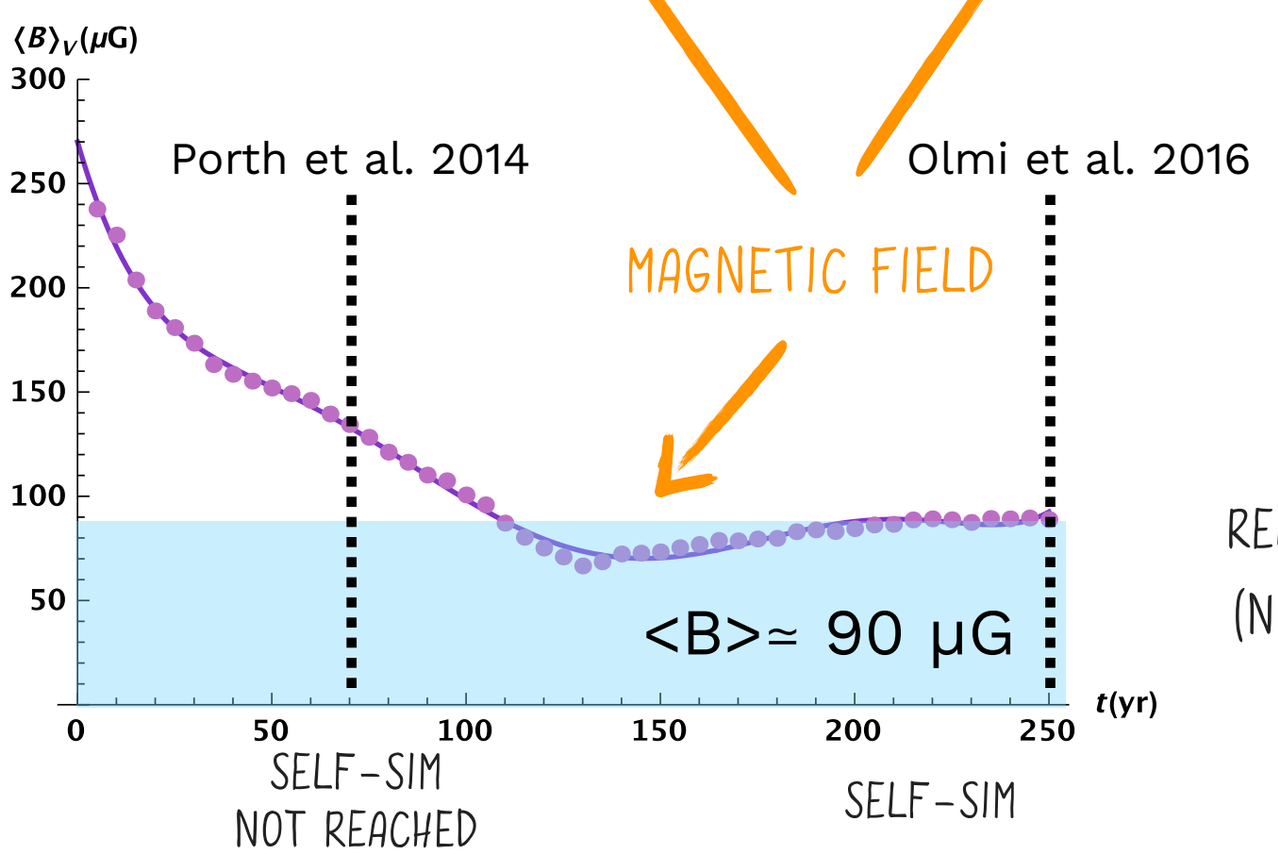
[Porth et al. 2013, 2014]

...BUT IT IS STILL NOT ENOUGH!

σ=1.5







SAME PROBLEMS WITH INTEGRATED SPECTRUM!

LARGER σ ?

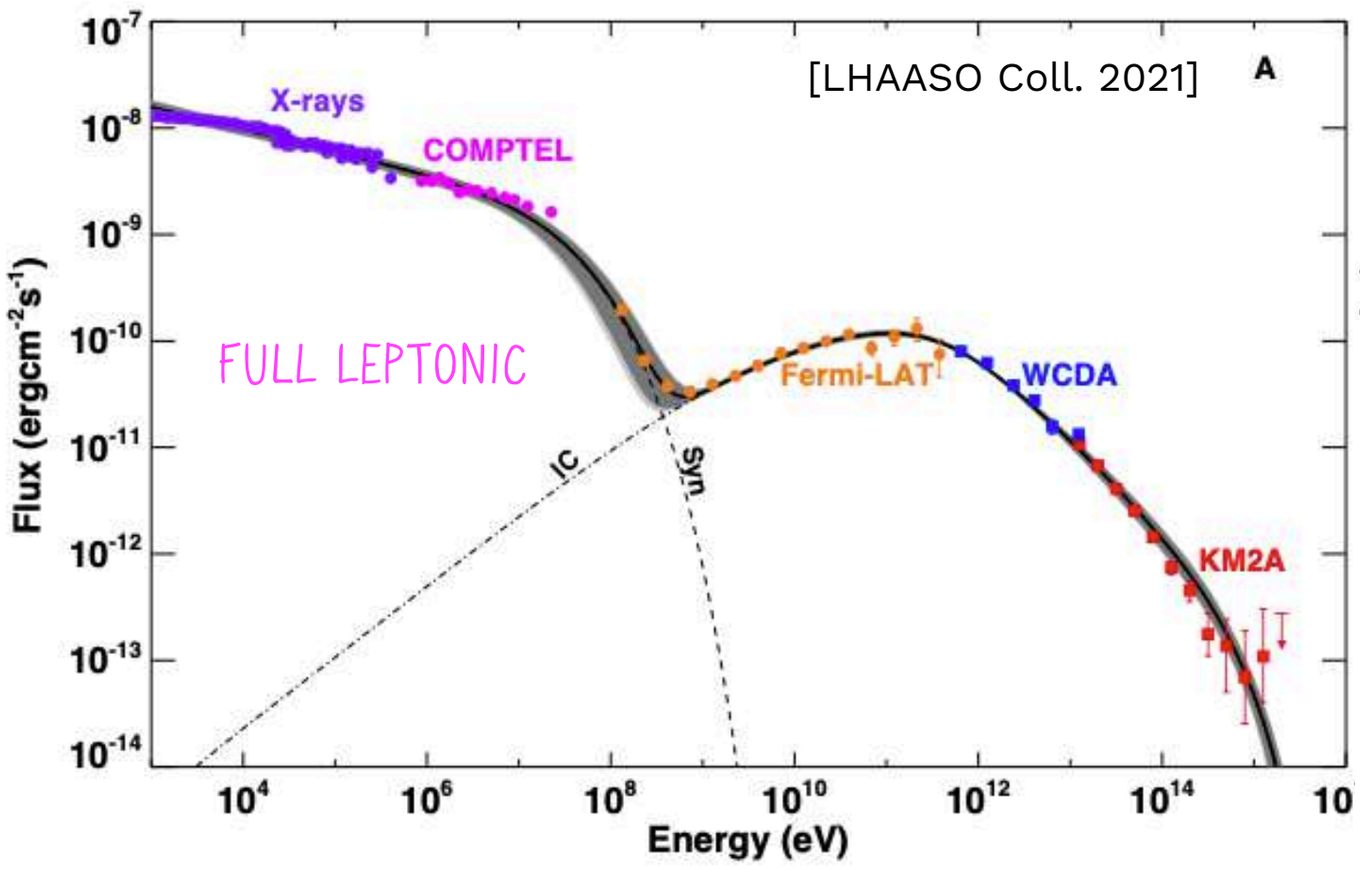
RELAXED FIELD STILL TOO LOW
(NOT DIFFERS MUCH FROM 2D)

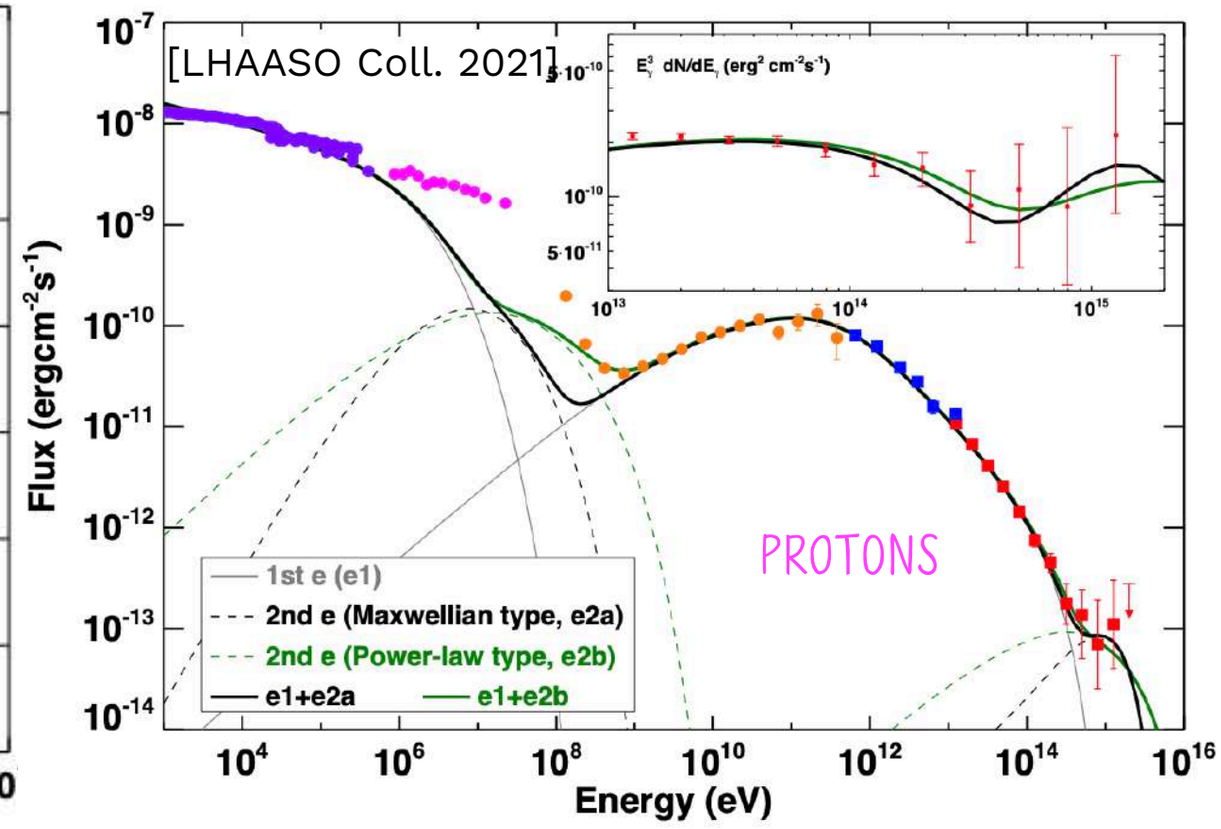
THE CRAB NEBULA @ >100 TEV

Nature of the emission:

CONSTRAINING THE WIND COMPOSITION AND NEBULAR FIELD FROM SED

SED COMPATIBLE WITH FULLY LEPTONIC SPECTRUM OR WITH LEPTONIC+HADRONIC



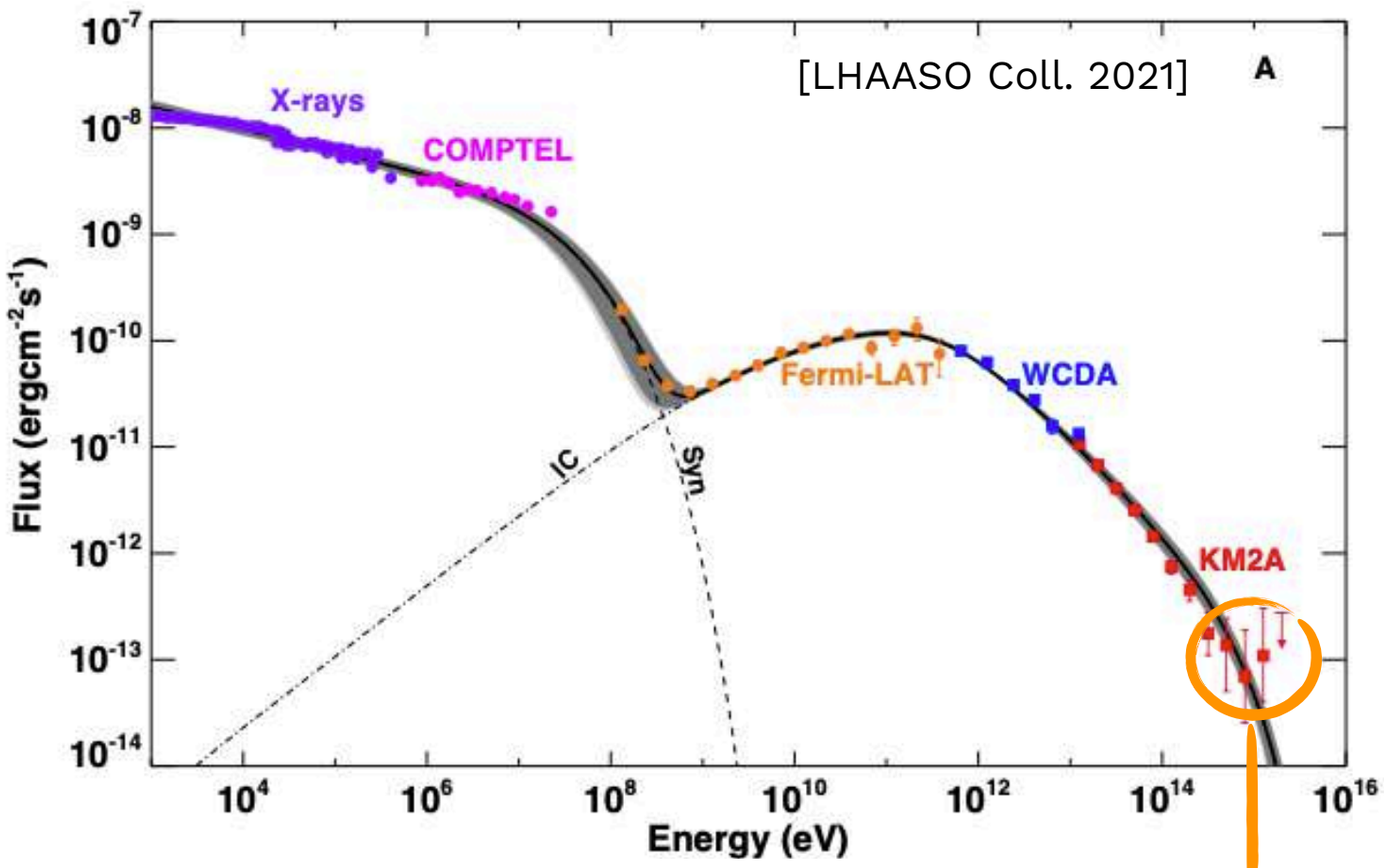


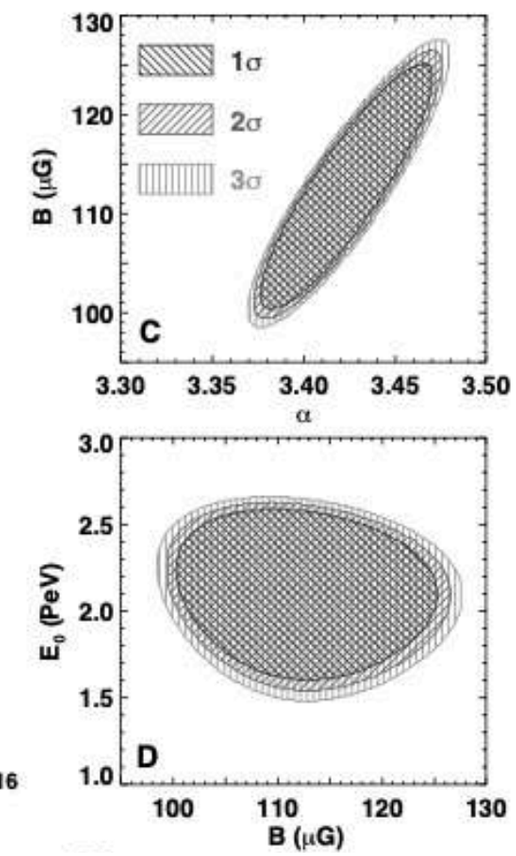
NON-EVOLVED SEDS

THE CRAB NEBULA @ >100 TEV

Nature of the emission:

CONSTRAINING THE NEBULAR FIELD:





EXTENDED SED CONSTRAINS THE AVERAGE NEBULAR FIELD:

$B^{AVE}_{SED} \sim 112\ \mu G$

LAST POINT CONSTRAINS ACCELERATION FIELD:

$B^{ACC} \sim 650\ \mu G$

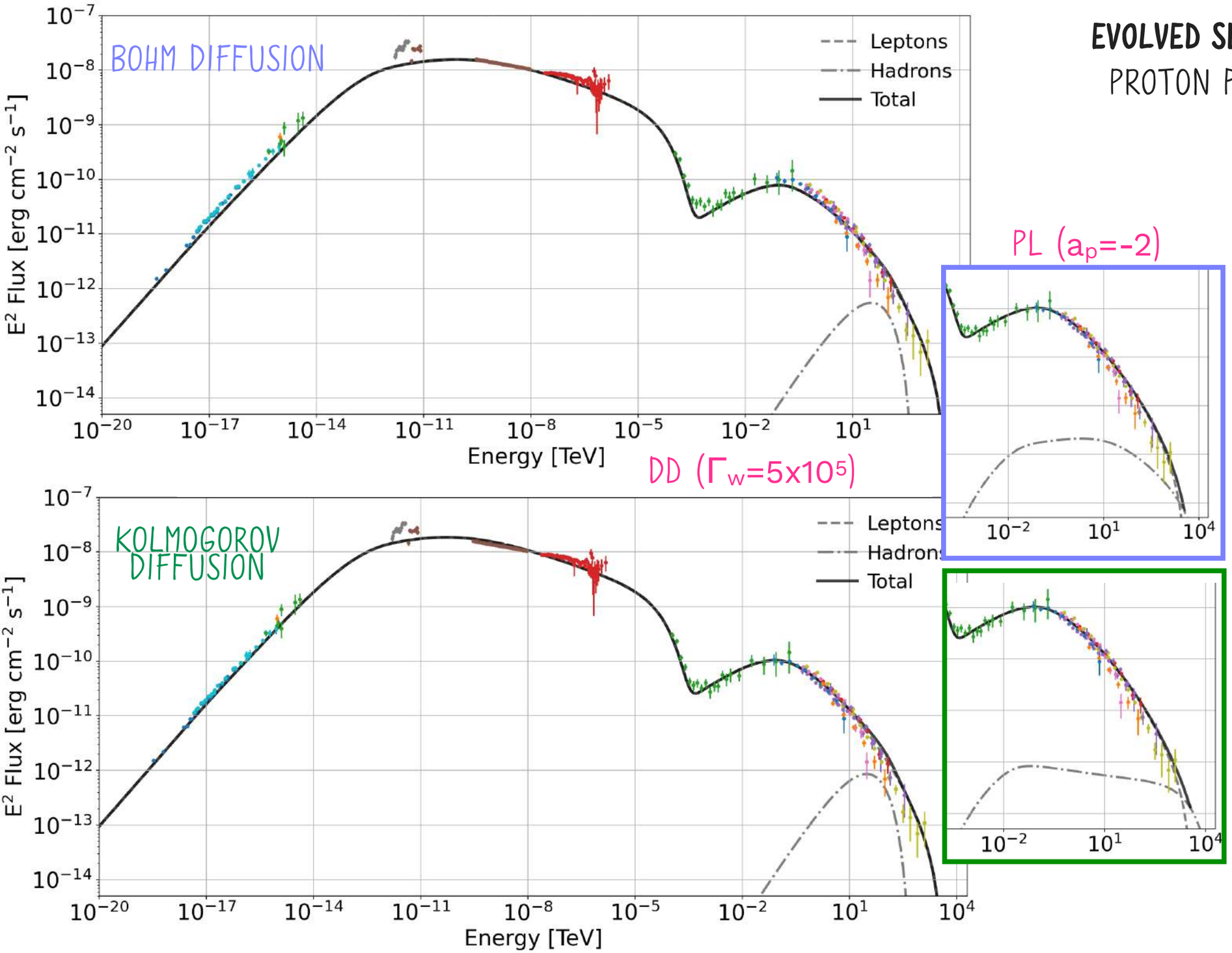
FROM LAST LHAASO POINT:

$$E_e \approx 2.15 \left(\frac{\epsilon_\gamma}{\text{PeV}}\right)^{0.77} \text{PeV} \xrightarrow{\epsilon_\gamma \approx 1.1\,\text{PeV}} E_e \approx 2.4\ \text{PeV}$$

THE CRAB NEBULA @ >100 TEV

Nature of the emission:

CONSTRAINING THE HADRONIC COMPONENT (IF ANY)



EVOLVED SEDS CONSIDERING DIFFERENT PROTON POPULATIONS AND DIFFUSION COEFFICIENTS:

$$\frac{dN}{dt} = Q_{1,2}(E) - \frac{N(E,t)}{\tau_{esc}}$$

$$\tau_{esc} = \frac{R_N^2(t)}{D(E,t)}$$

DIRAC DELTA (DD):

$$Q_1(E) \propto \frac{\dot{E}}{m_p c^2 \Gamma_w} \delta(E - m_p c^2 \Gamma_w)$$

POWER LAW (PL):

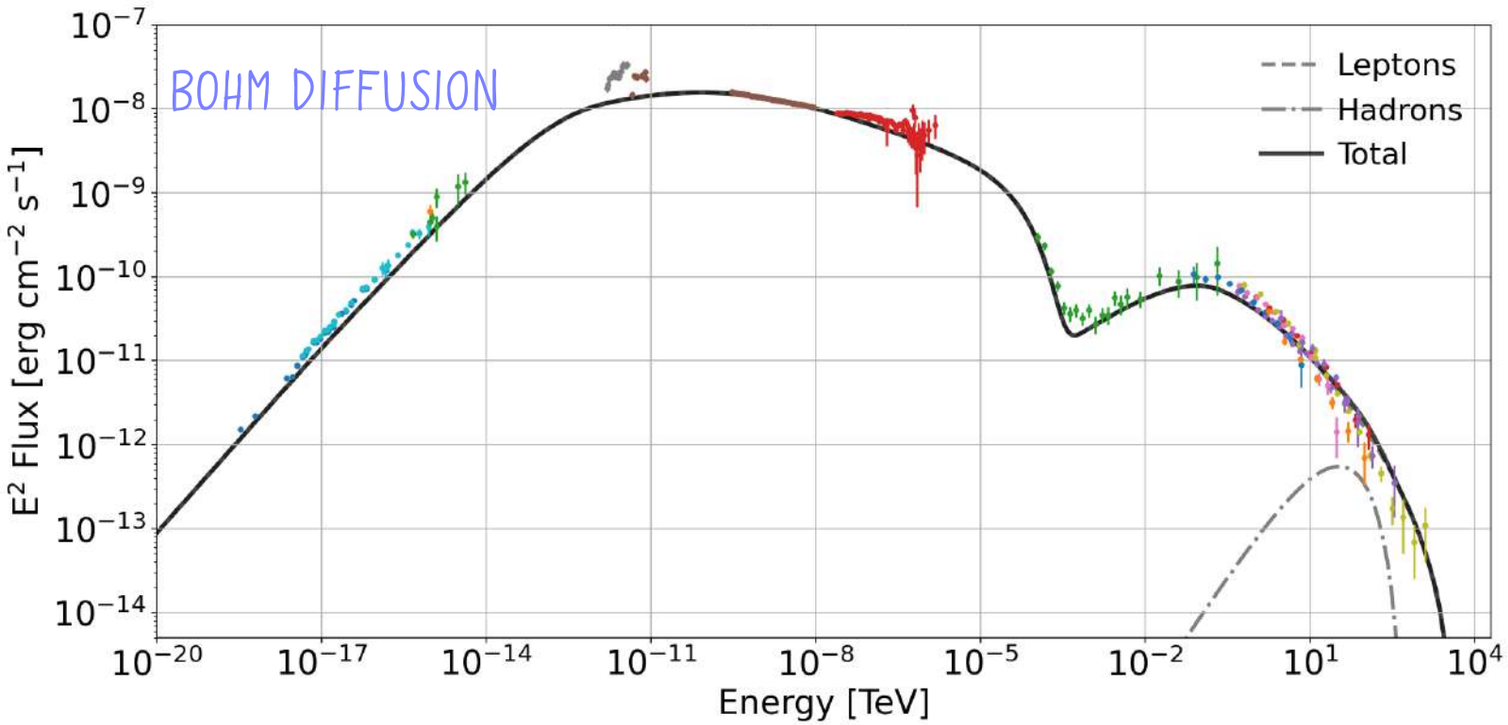
$$Q_2(E) \propto \frac{\dot{E}}{E^2}$$

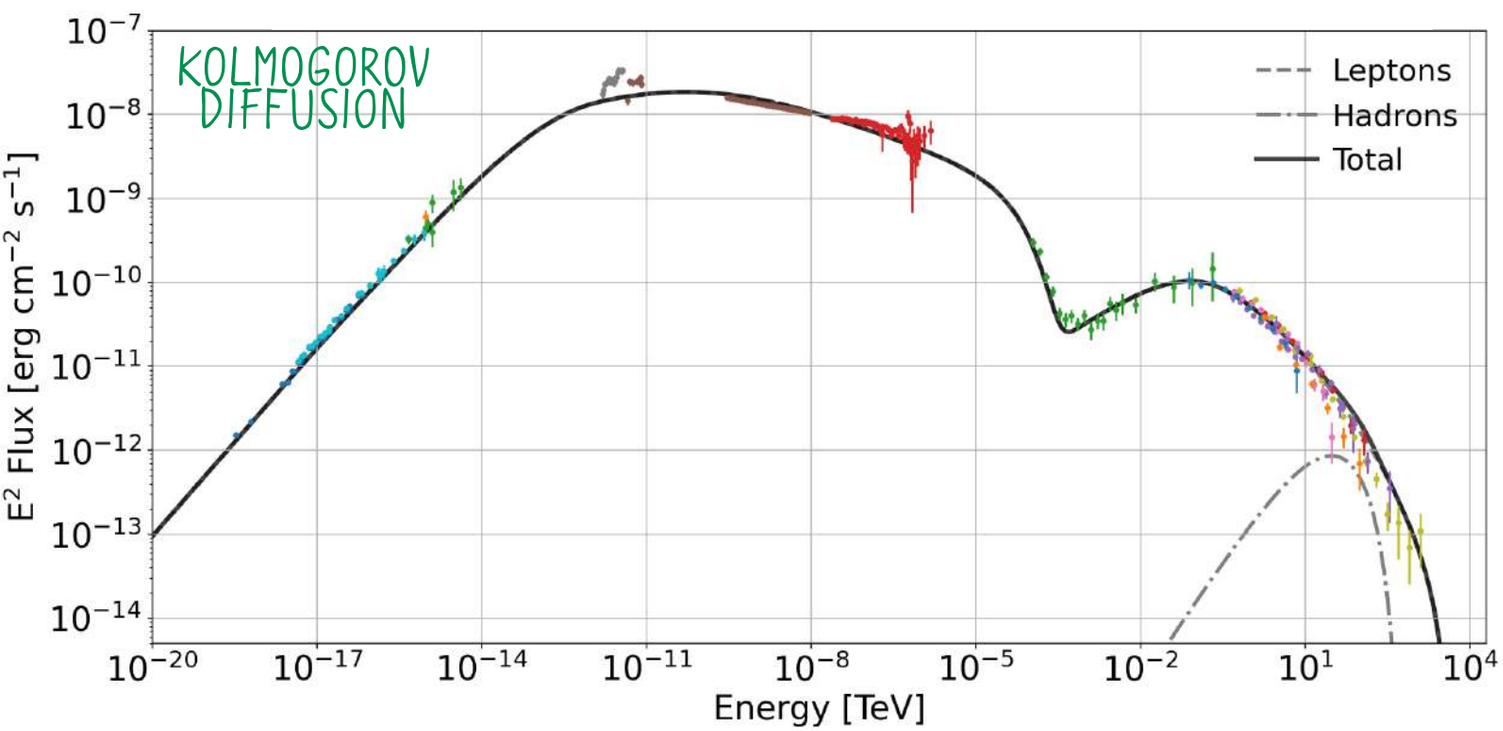
[Amato, Olmi & Fiori, in prep., Vercellone et al. 2022]

THE CRAB NEBULA @ >100 TEV

Nature of the emission:

CONSTRAINING THE HADRONIC COMPONENT (IF ANY)





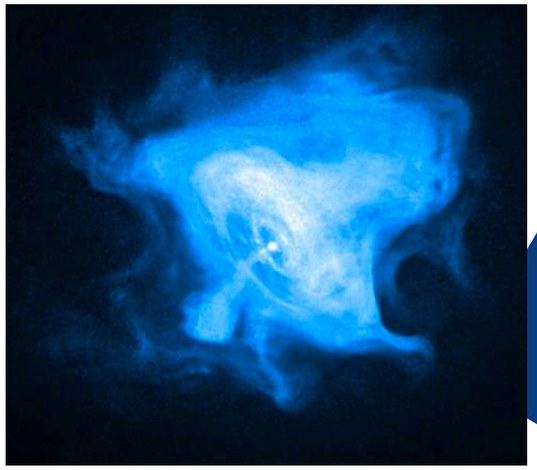
EVOLVED SED CAN ONLY BE REPRODUCED WITH A SMALL AMOUNT OF HADRONS (~4%)

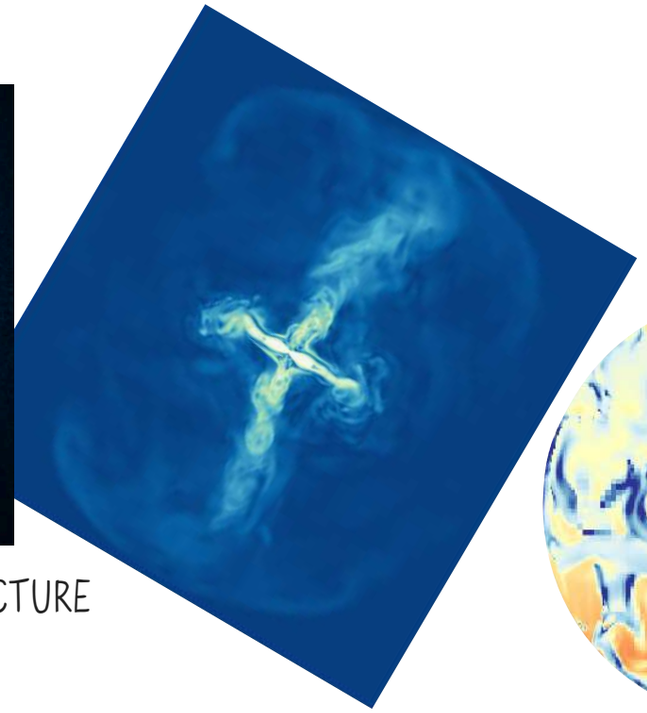
EVEN IF PRESENT THEY CANNOT BE ENERGETICALLY DOMINANT

[Amato, Olmi & Fiori, in prep.]

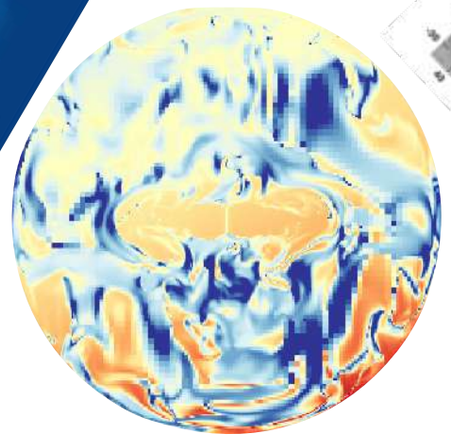
CONCLUDING REMARKS

WE HAVE UNDERSTOOD MANY OF THE PROPERTIES OF THE CRAB NEBULA ...

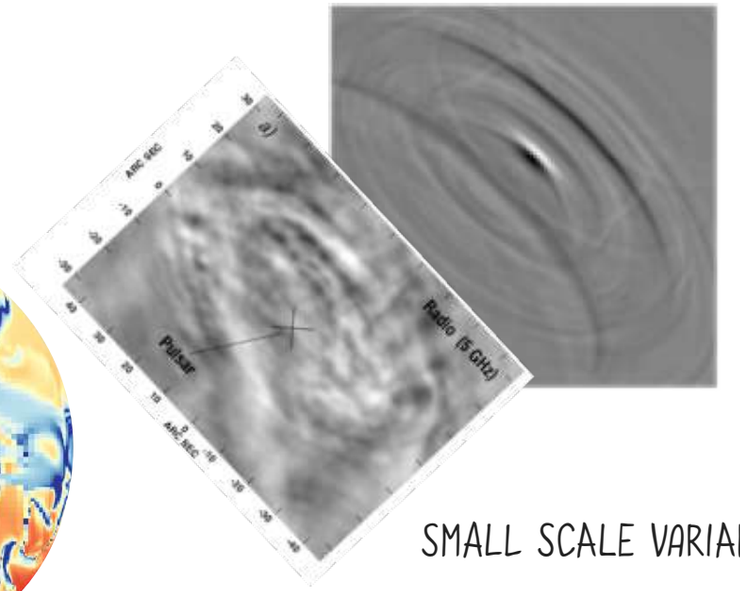




JETS, TORUS, 3D STRUCTURE



COMPLEX MAGNETIC FIELD AND DISSIPATION



SMALL SCALE VARIABILITY

... BUT ALSO STILL HAVE MANY OPEN QUESTIONS:

- WHAT IS(ARE) THE PARTICLE ACCELERATION MECHANISM(S) → ELENA'S TALK
  - ↳ WHAT IS THE REAL WIND MAGNETIZATION?
    WHAT IS THE NATURE OF THE LOW ENERGY EMITTING COMPONENT?
- IS THE CRAB AN HADRONIC PEVATRON TOO?
- CRAB FLARES

ENERGETIC ARGUMENTS

IN YOUNG SYSTEMS ACCELERATION MIGHT BE RADIATION LIMITED (DEPENDS ON B):

$t_{acc} \leq t_{loss}$ $\gamma_{max} = [6\pi e/(\sigma_T B)\ \xi_E]^{1/2}$

$|\vec{E}| = \xi_E B,\ \xi_E \leq 1$

$\approx 230\ \xi_E$ MeV

$\varepsilon_{max,\,sync} = 3/2\ h/(2\pi)\ eB/(m_e c)\ \gamma^2_{max}$

IN ALL OTHER CASES WHAT SETS THE MAXIMUM ENERGY IS THE PULSAR POTENTIAL DROP

$E_{max} = e\ \xi_E\ B_{TS}\ R_{TS}$ maximum available energy at dissipation region (R_{TS})

$B_{TS} = 1/\ R_{TS}\ [\xi_B\ \dot{E}/c]^{1/2}$ magnetic field at TS (from pressure equilibrium)

$E_{max} = e\ \xi_E\ [\xi_B\ \dot{E}/c]^{1/2}$

$E_{max} \propto e\ \varphi_{PD}$ $[\xi_E, \xi_B \leq 1]$

$\varphi_{PSR} = [\ \dot{E}/c]^{1/2}$