Gamma-rays from pulsars

Witnessing the propagation of cosmic rays

Pierrick Martin (CNRS/IRAP, Toulouse)

pierrick.martin@irap.omp.eu

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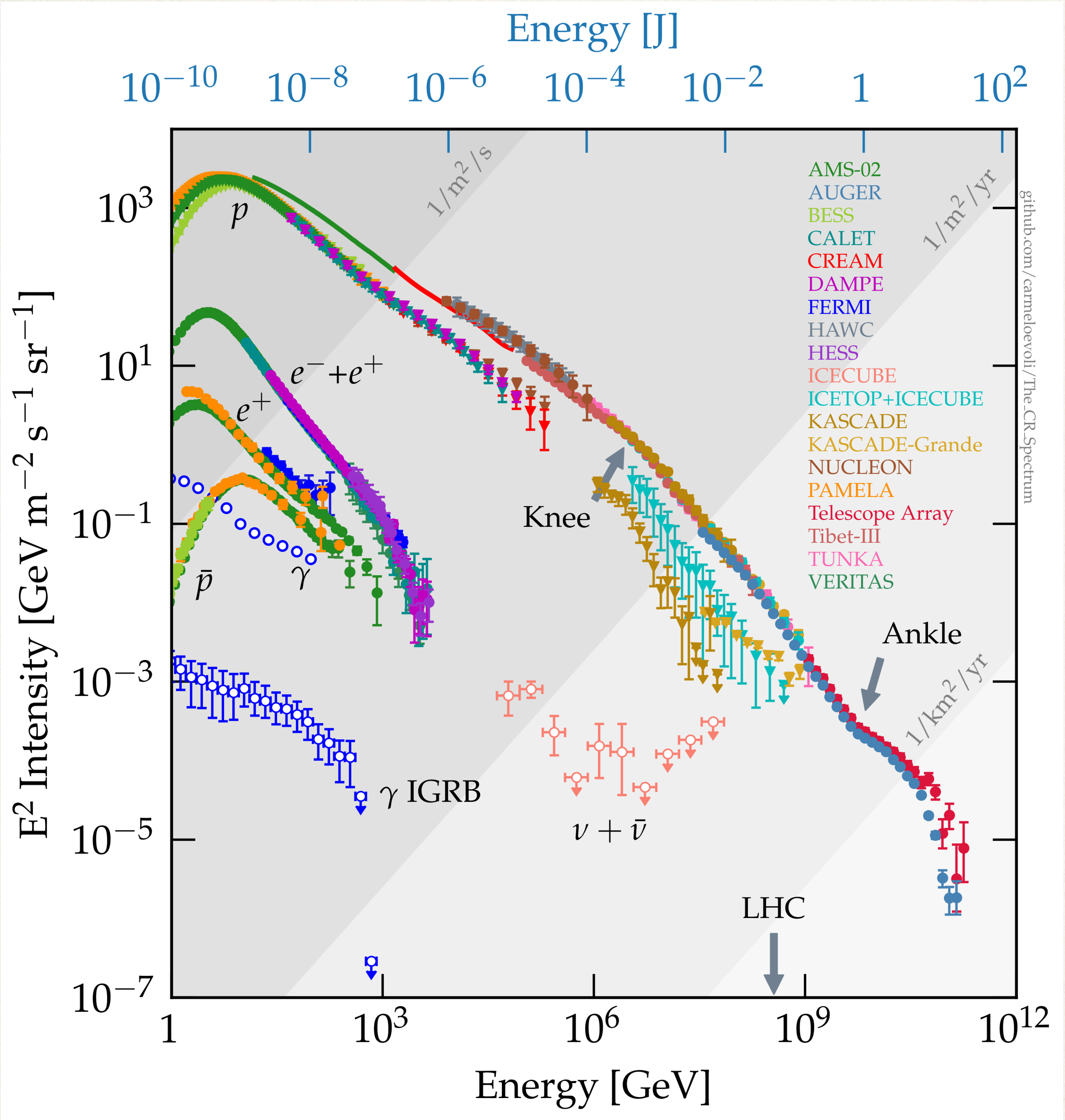
AGENCE
NATIONALE
DE LA
RECHERCHE

Outline

- I - About cosmic rays in astrophysics
- II - Pulsars, pulsar wind nebulae, pulsar halos
- III - Recent developments in gamma-ray astronomy
- IV - Pulsars as window on cosmic-ray propagation
- V - Summary and perspectives

Non-thermal particles in solar neighborhood



Evoli 2020

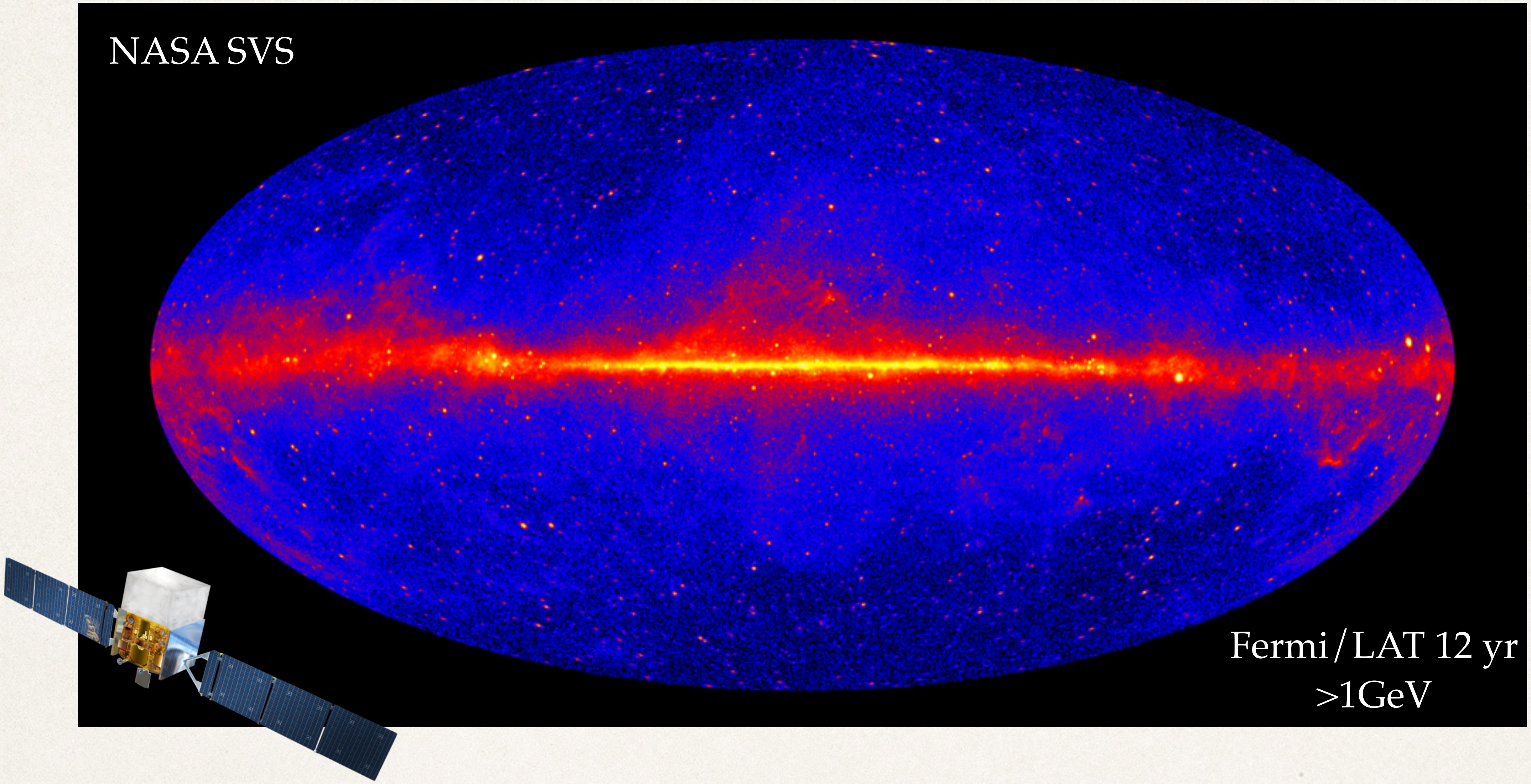
Direct ground and space cosmic-ray **measurements**

Cosmic rays:
mostly protons+nuclei (>98%)
electrons ~100x less numerous

Huge spectral expanse
$F(E) \propto E^{-\alpha} \quad \alpha(E) \sim 2.5 - 3.0$
Most energy in **1-10GeV** particles

This talk:
Galactic cosmic rays
E<1-10PeV

Non-thermal particles in the Milky Way



NASA SVS

Fermi/LAT 12 yr
>1GeV

$$p_{\mathrm{CR}} + p_{\mathrm{ISM}} \rightarrow \pi^0 \rightarrow \gamma\gamma \qquad\qquad e_{\mathrm{CR}} + \gamma_{\mathrm{ISM}} \rightarrow e_{\mathrm{CR}} + \gamma_{\mathrm{X,GeV,TeV}}$$

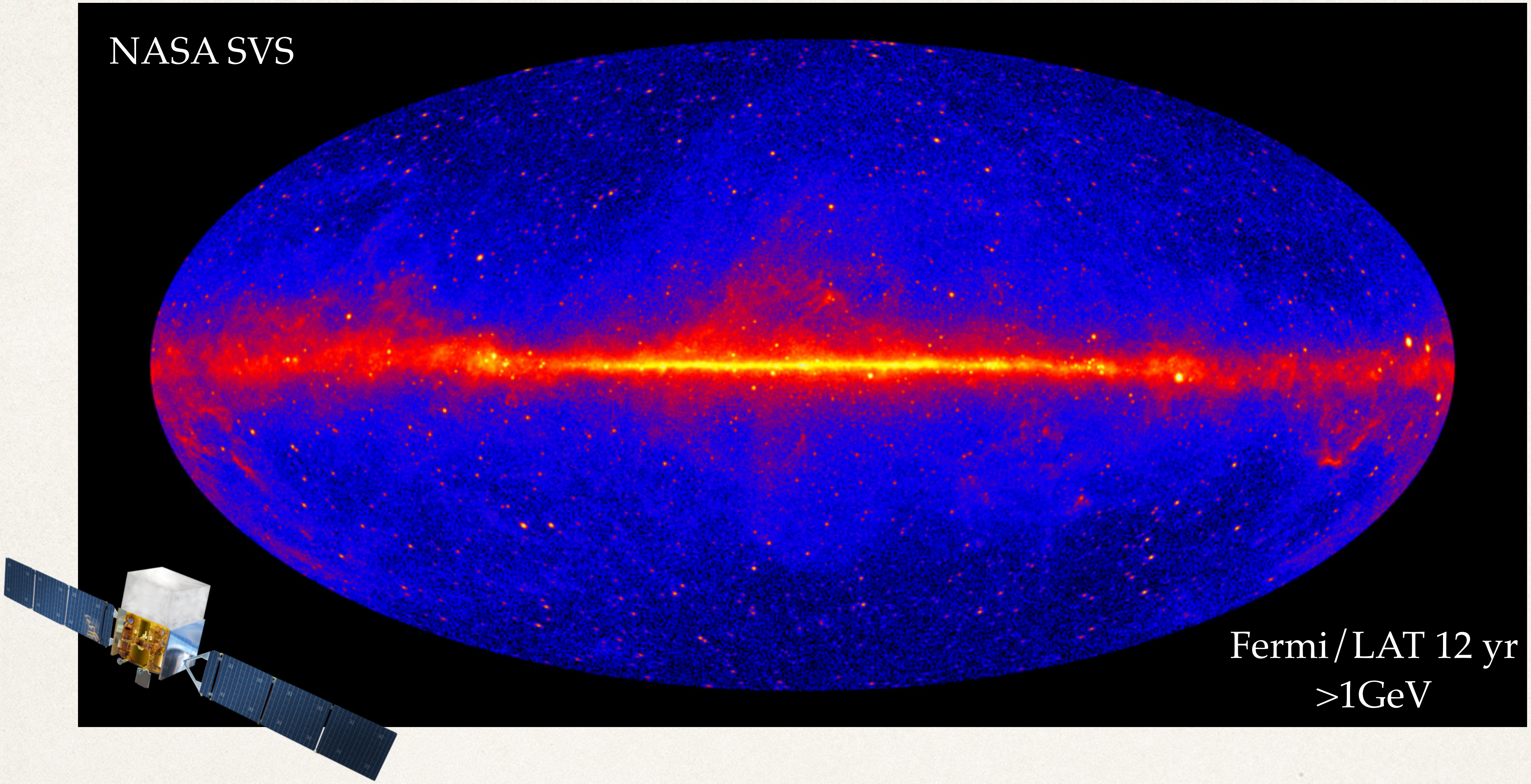
Galactic emission = **discrete sources + diffuse glow**

Discrete sources = **pulsars**, **supernova** remnant, star-forming regions

Diffuse **fills** the whole **Galaxy** (and correlates with gas)

Diffuse **outshines** sum of discrete sources (by 5-10 at 0.1-10GeV)

Non-thermal particles in the Milky Way



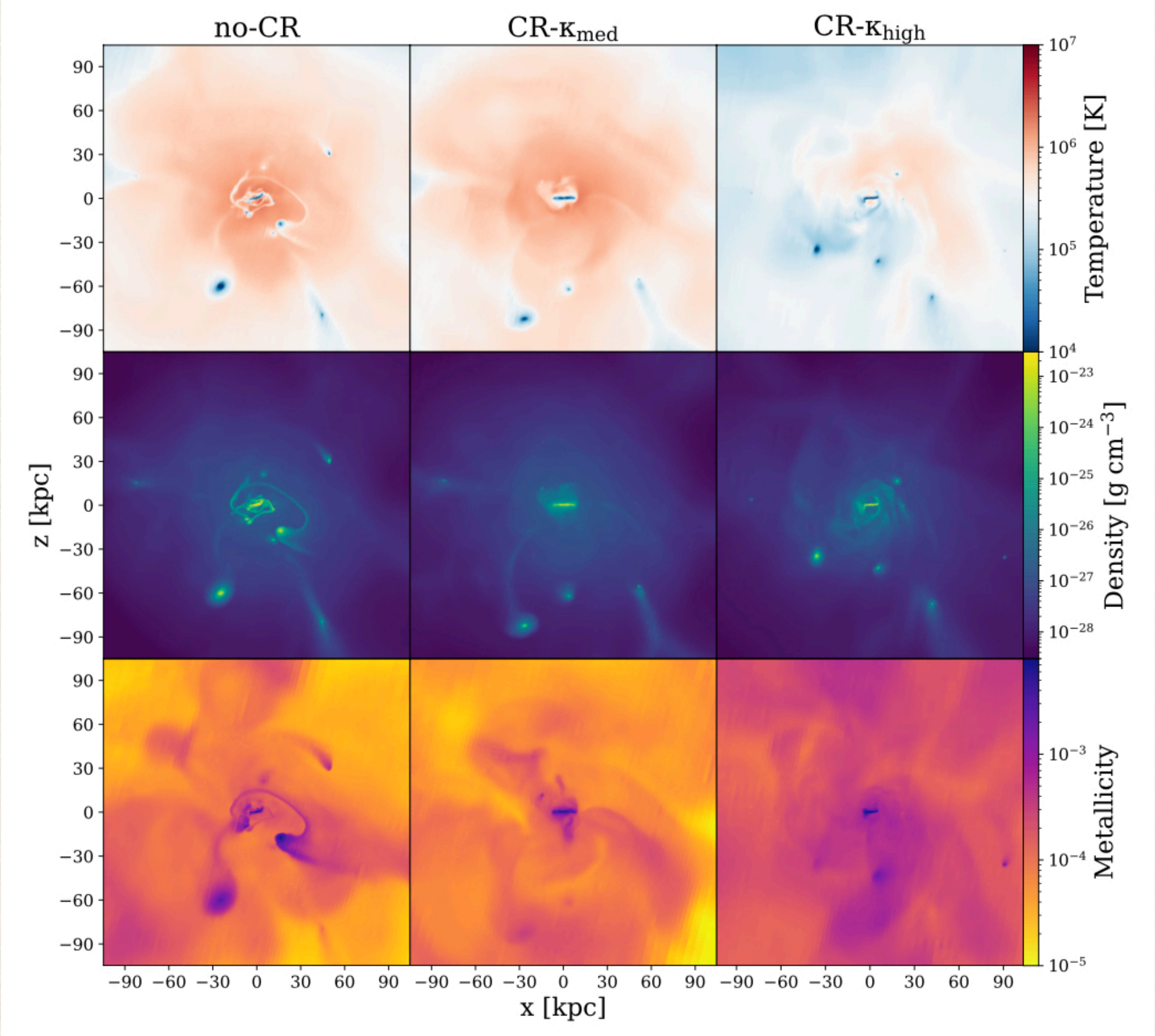
NASA SVS

Fermi/LAT 12 yr
>1GeV

CRs manage to **escape from accelerators** and propagate out to large distances
CRs experience **non-trivial transport**: charged particles in magnetic turbulence

Same GeV picture in other star-forming galaxies: SMC, LMC, M31,…

Why do CRs matter at all ?



De Felippis et al. 2024

cosmic rays:
specific **energy redistribution**
from star formation
in galactic ecosystem

impact on
interstellar medium structure
galactic **outflows**
star formation regulation

100 kpc-scale
astrophysical effects
rooted in AU-scale
plasma physics processes

Owen et al. 2023
Ruszkowski&Pfrommer 2023

Part I: summary

- Cosmic rays in astrophysics
    - There exist non-thermal particle populations in galaxies
    - They are connected to the star-formation activity
    - It is a specific energy redistribution mode in the ecosystem
    - Understanding cosmic-ray transport matters !
    - Gamma rays are prime information channel for that

Pulsars and pulsar wind nebulae

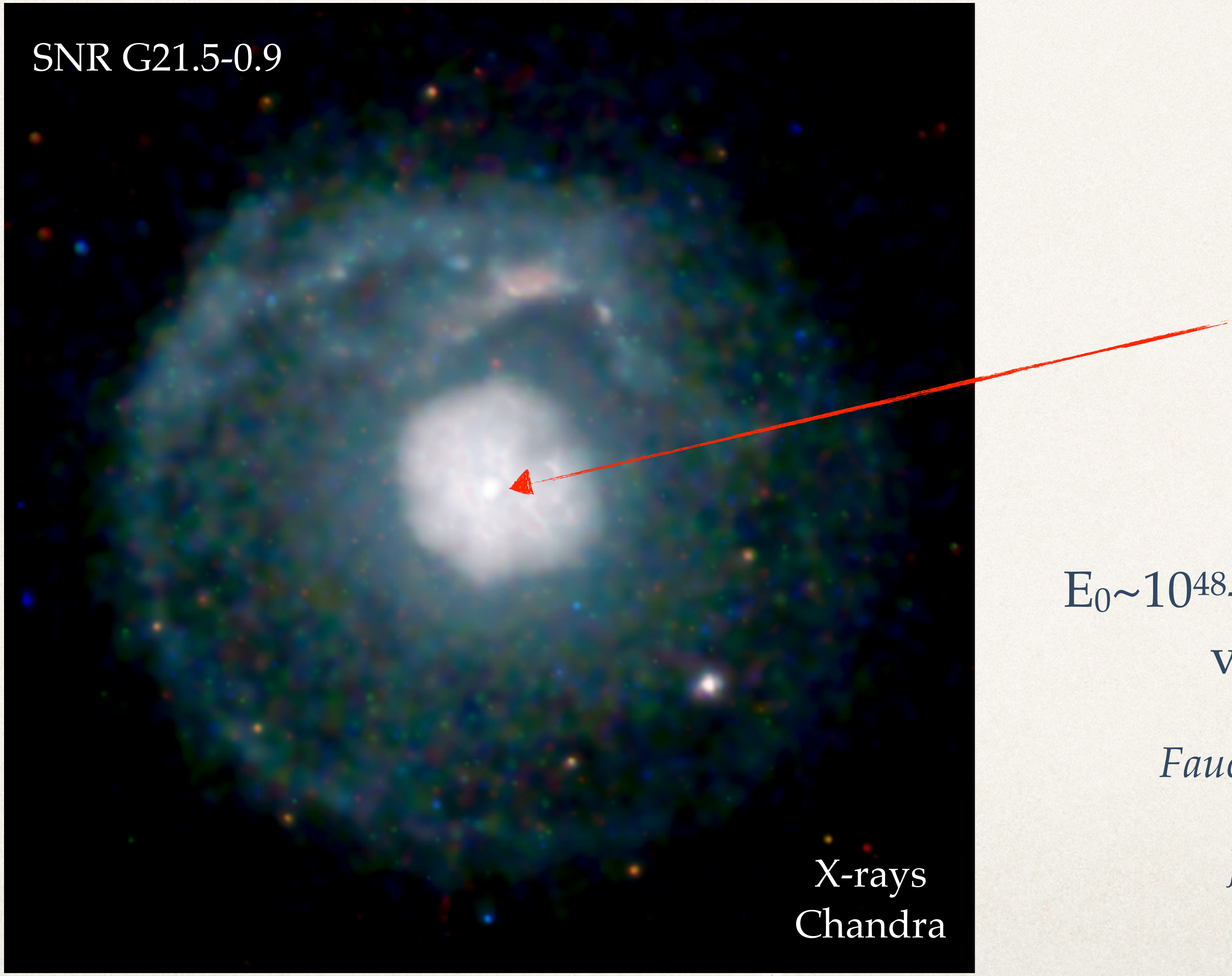
Star with initial mass $10 - 100 M_\odot$

Sukhbold et al. 2016

Core-collapse supernova explosion

Ejection of stellar envelope $2 - 15 M_\odot$ at $10^3 - 10^4$ km/s

Compact object: $1 - 2 M_\odot$ NS or $5 - 15 M_\odot$ BH



NASA/CXC
Matheson & Safi-Harb 2005

Neutron star

$R \sim 12$km

$P_0 \sim 10\text{-}100$ ms

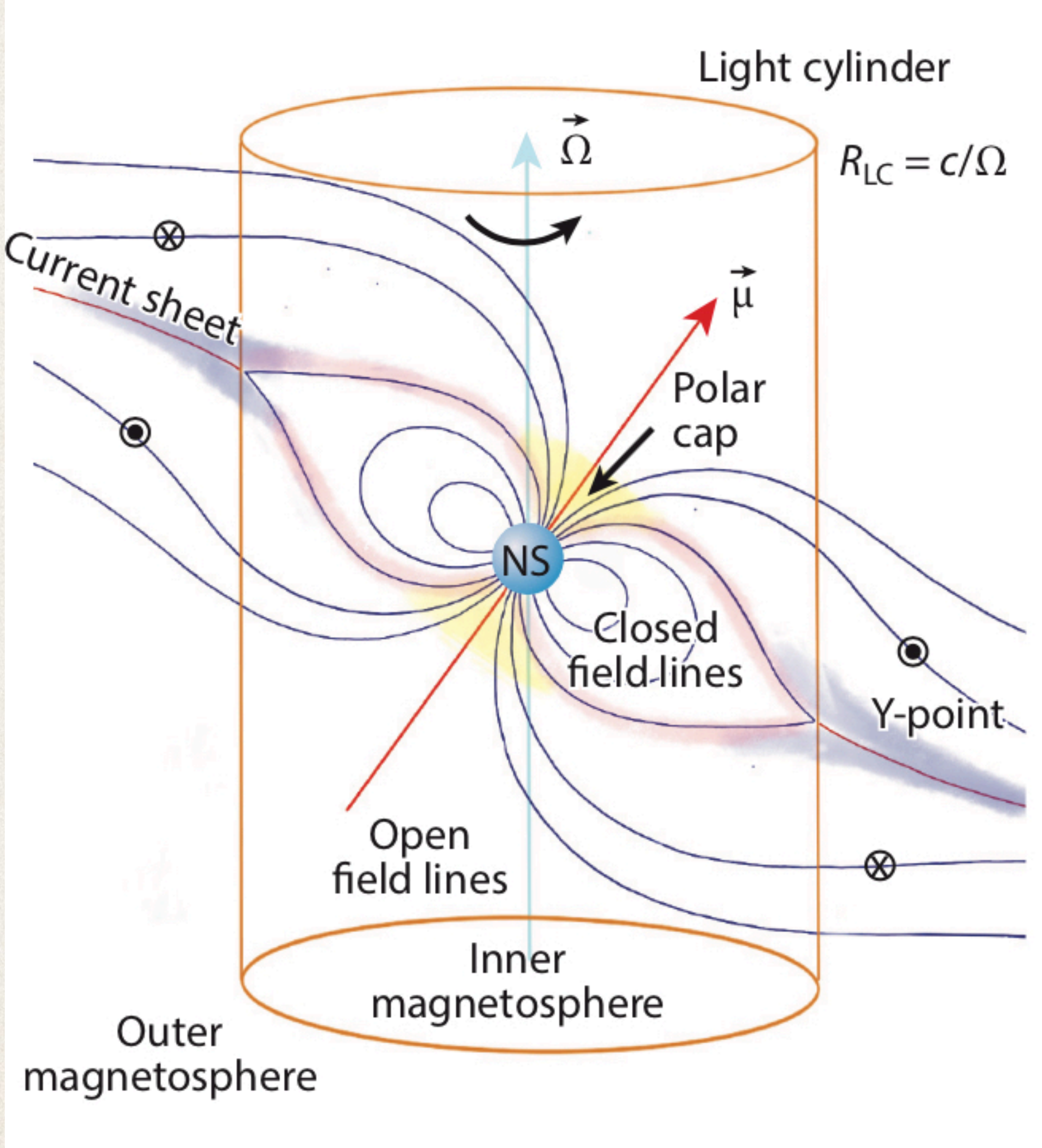
$B_0 \sim 10^{12}\text{-}10^{13}$ G

$E_0 \sim 10^{48}\text{-}10^{49}$ erg $< E_{SN} \sim 10^{51}$ erg

$v \sim 100\text{-}1000$km/s

Faucher-Giguère et al. 2006
Watters et al. 2011
Johnston et al. 2020
Verbunt et al. 2017

Pulsars and pulsar wind nebulae



Amato 2024
Philippov&Kramer 2022
Cao et al. 2024

Magnetized conducting rotator
⇒ pole-equator potential difference

$$\Delta\Phi_\infty = \frac{B_\star R_\star^2 \Omega}{2c} \simeq 10^{17} - 10^{18}\mathrm{V}$$

Charges ripped off the surface
Steady-state configuration:

$$\rho(\mathbf{r}) = \rho_{\rm GJ} \quad \Rightarrow \quad \mathbf{E}\cdot\mathbf{B} = 0$$

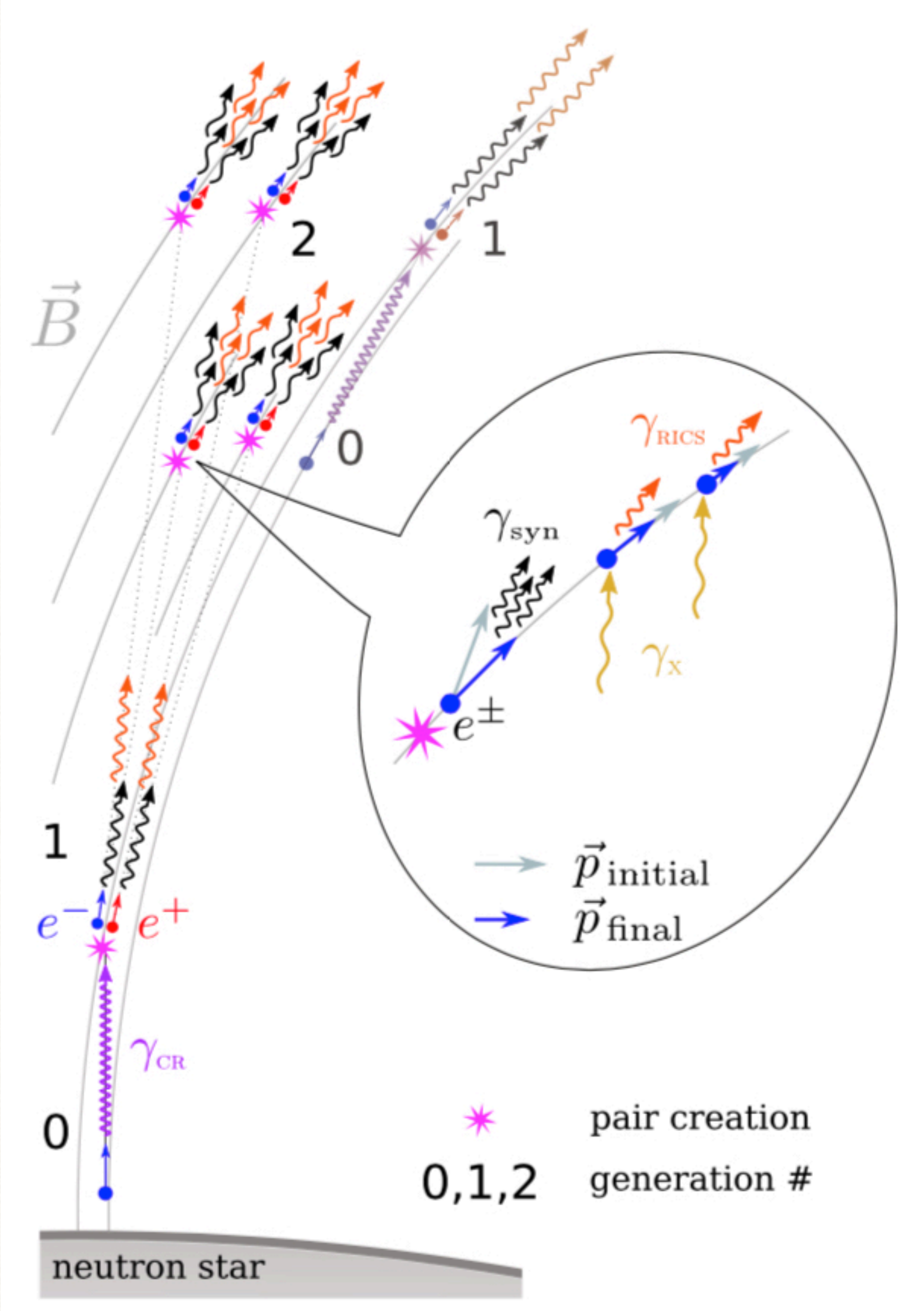
Goldreich&Julian 1969

Force-free corotating magnetosphere
Open field lines from polar cap

$$\Delta\Phi_{\rm PC} = \frac{R_\star}{R_{\rm LC}}\Delta\Phi_\infty \simeq 10^{-3}\Delta\Phi_\infty$$

Deviations from $\rho_{\rm GJ}$ set potential drop available for particle acceleration
$(\mathbf{E}\cdot\mathbf{B} \neq 0)$

Pulsars and pulsar wind nebulae



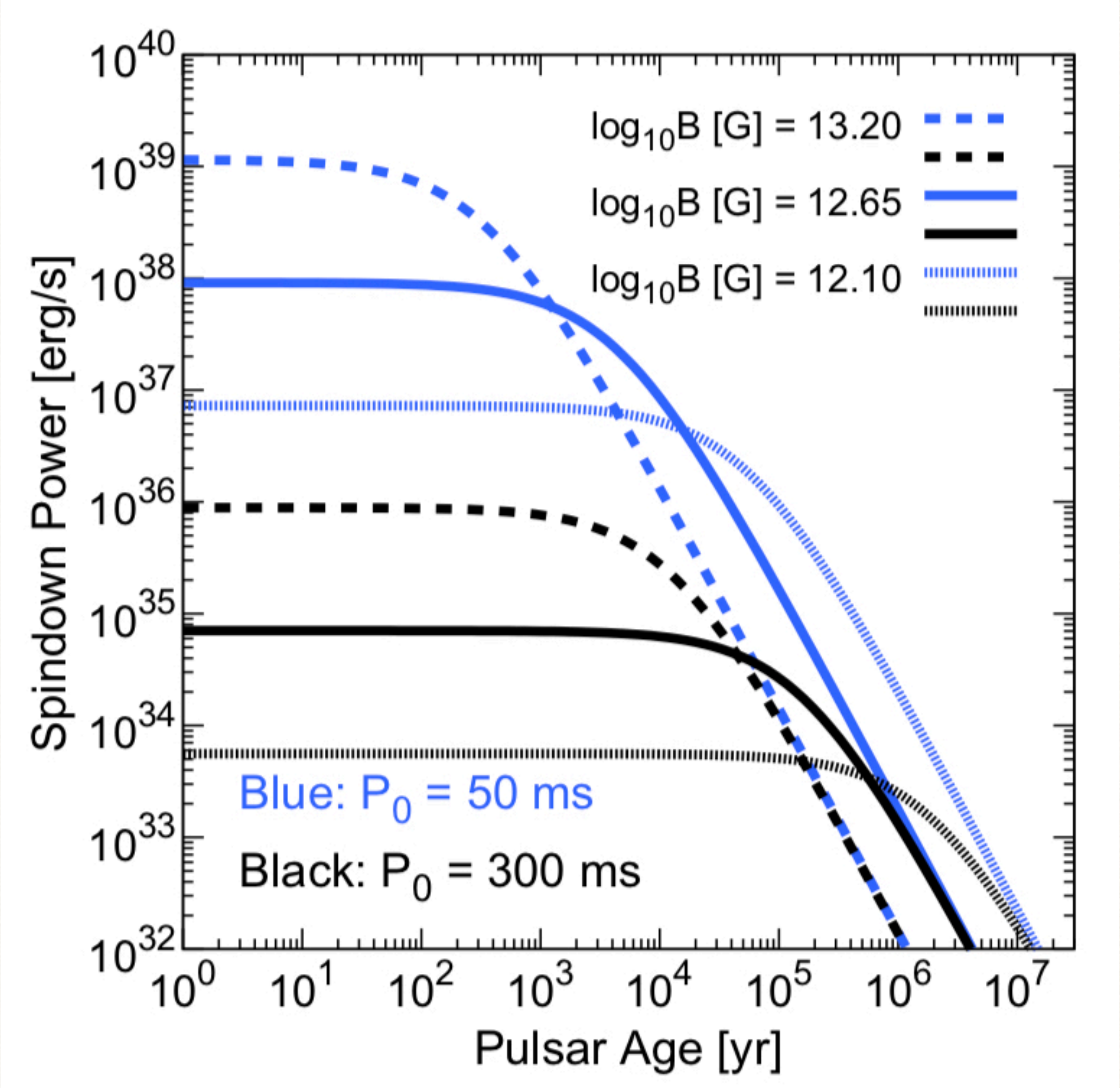
Timokhin&Harding 2019

Particle acceleration
→ curvature or synchrotron radiation
→ **pair cascades** in intense fields

$$n_e = \kappa n_{\rm GJ}$$
$$\kappa = 10^3 - 10^5 \text{ (magnetosphere models)}$$
$$\kappa = 10^5 - 10^7 \text{ (nebular emission)}$$

Pulsars:
ultrarelativistic **pair factories** !

Pulsars and pulsar wind nebulae



Sudoh et al. 2019

Open field lines feed
relativistic magnetized outflow:
pulsar wind → spin-down

$$\dot{E} = 4\pi^2 I_\star \frac{\dot{P}}{P^3} = \frac{2}{3}\frac{(2\pi)^4 B_\star^2 R_\star^6}{P^4 c^3} = \frac{\dot{E}_0}{(1+t/\tau_0)^2}$$

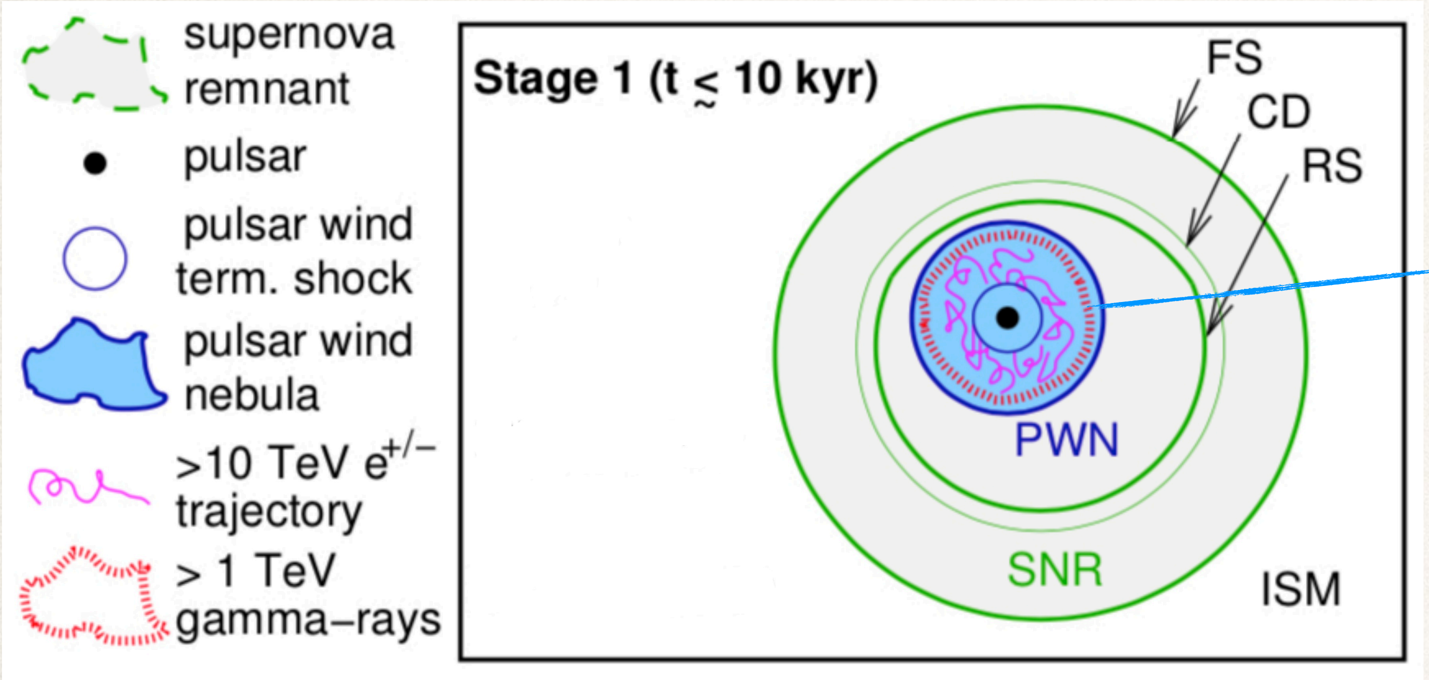
Constant $\dot{E}_0 = 10^{36} - 10^{40}\mathrm{erg/s}$
for $\tau_0 = 10^2 - 10^5\mathrm{yr}$
followed by $\dot{E} \propto t^{-2}$

Problem:
limited handle on rotational history
(for individual objects)

$$E_{\mathrm{rot}} \propto \dot{E}_0 \tau_0 \propto \frac{1}{P_0^2}$$

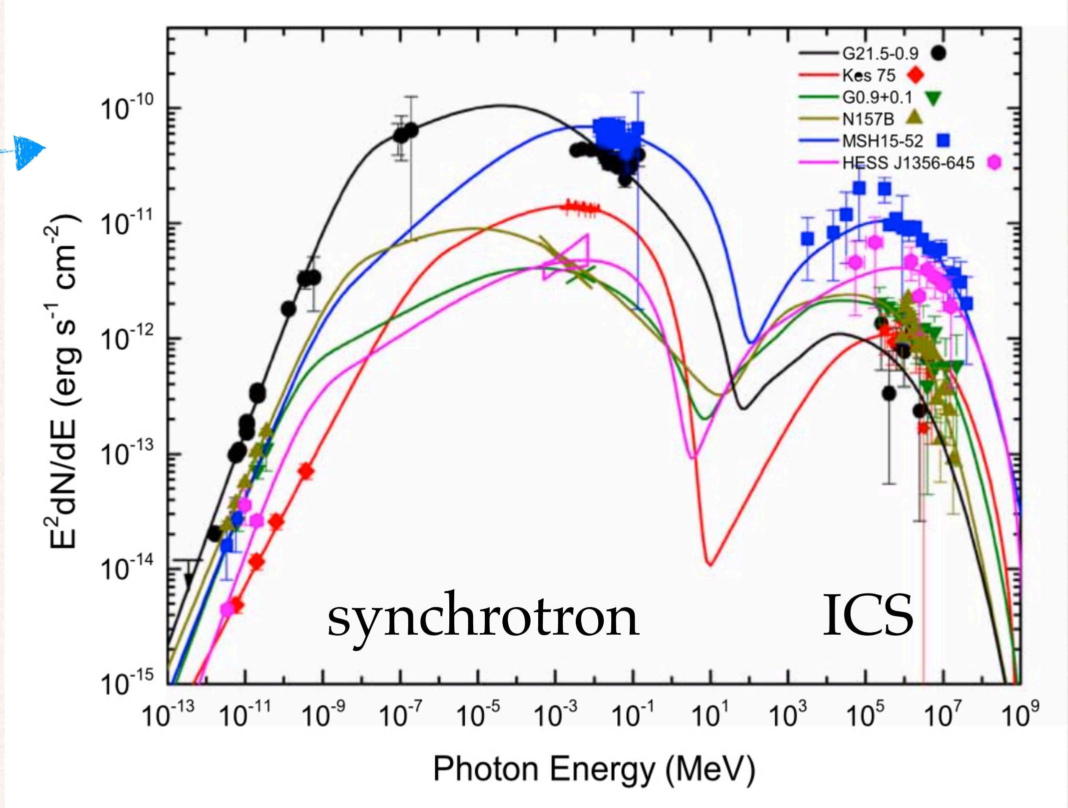
Pulsars and pulsar wind nebulae

Giacinti et al. 2020



Stage I:
free expansion in cold ejecta

Zhu et al. 2023



Relativistic pulsar wind to match non-relativistic expanding ejecta

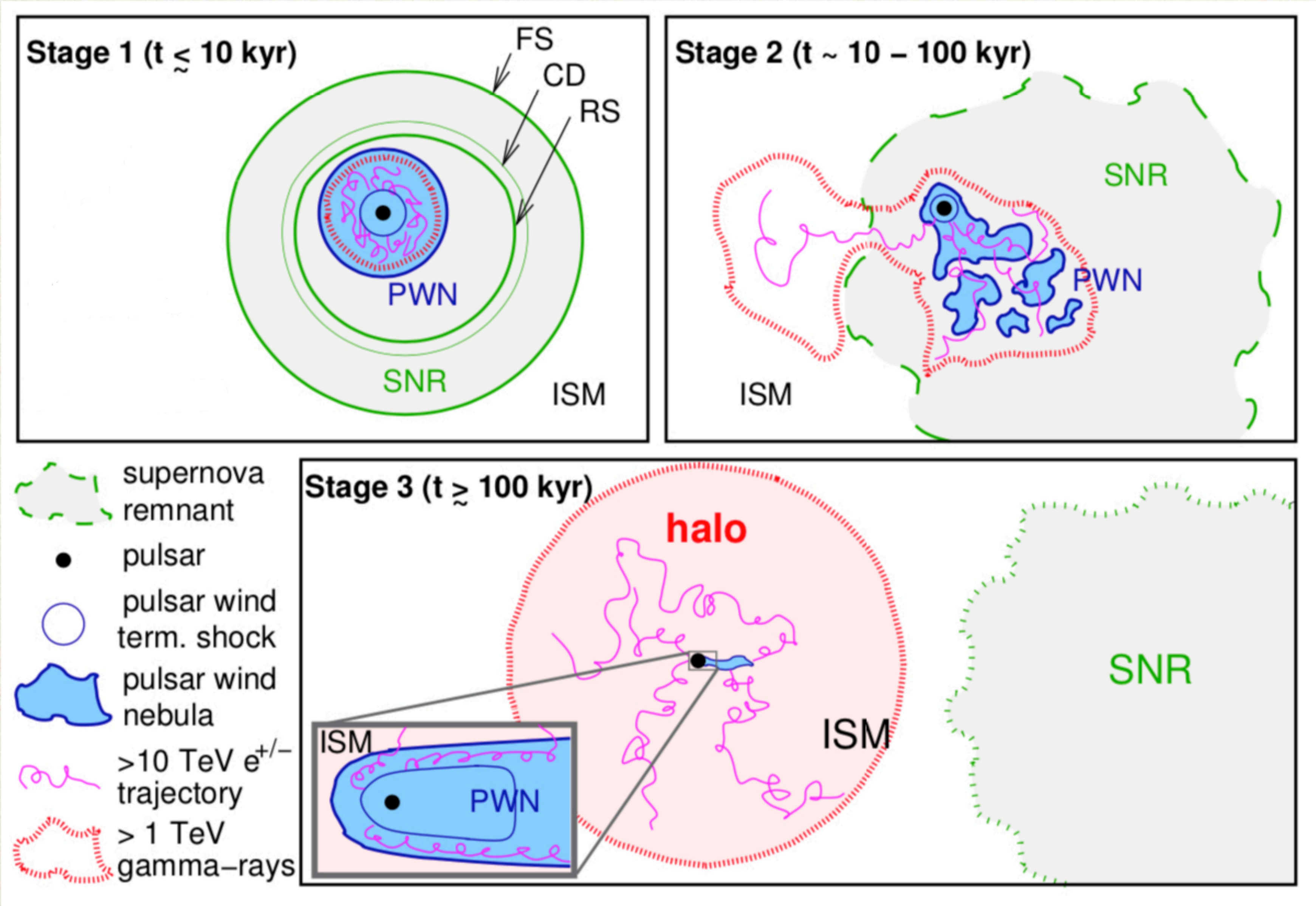
Dissipation of kinetic energy at **termination shock**

Most energy into **accelerated particle** with peak energy **0.1-1TeV**

Pulsar wind nebula: bubble of **magnetized** plasma and **relativistic pairs** (+ions ?)
synchrotron and inverse-Compton **broadband source**

Shortcut: σ problem !

Pulsars and pulsar wind nebulae



Giacinti et al. 2020

Stage I:
free expansion
in cold ejecta

Stage II:
reverse-shock interaction,
reverberation/disruption/
mixing

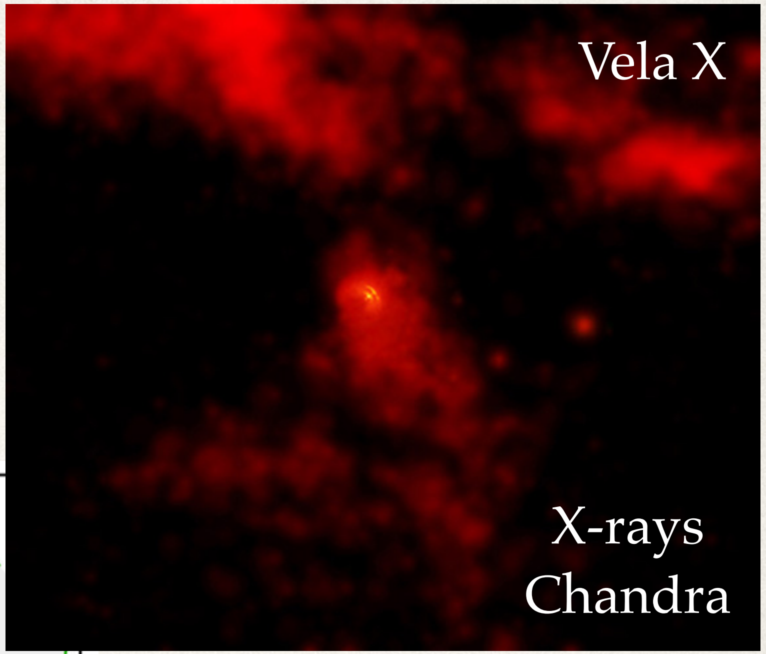
Stage III:
escape from original
nebula/remnant, bow-shock

Wide **range of possible outcomes** in advanced stages
(depending on pulsar+remnant+ISM properties)
Probably the majority of accessible systems in gamma rays

Pulsars and pulsar wind nebulae

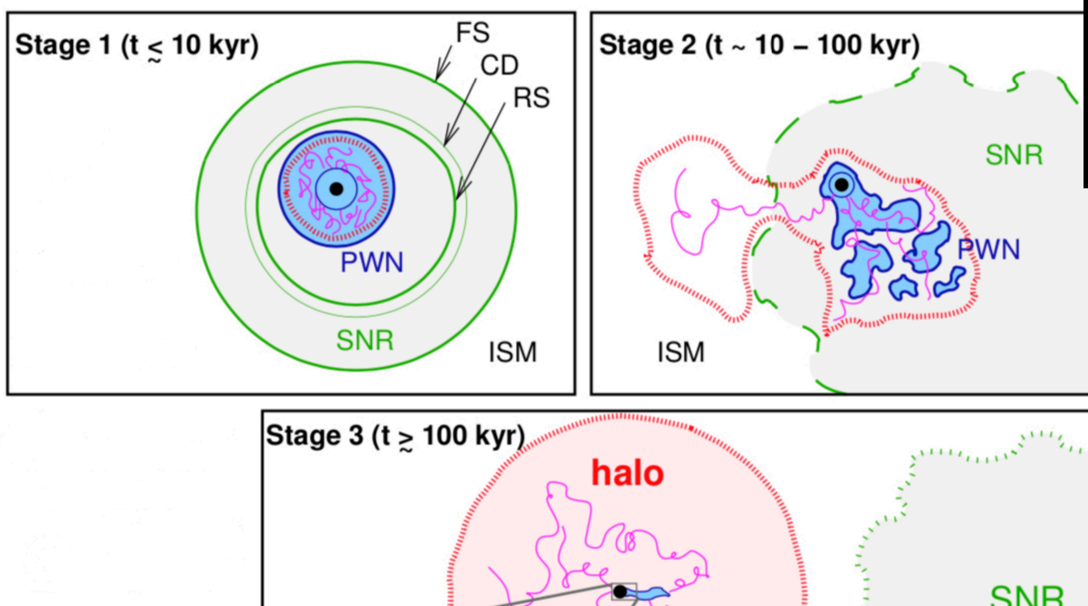
X-rays
Chandra

NASA/CXC
Matheson & Safi-Harb 2005

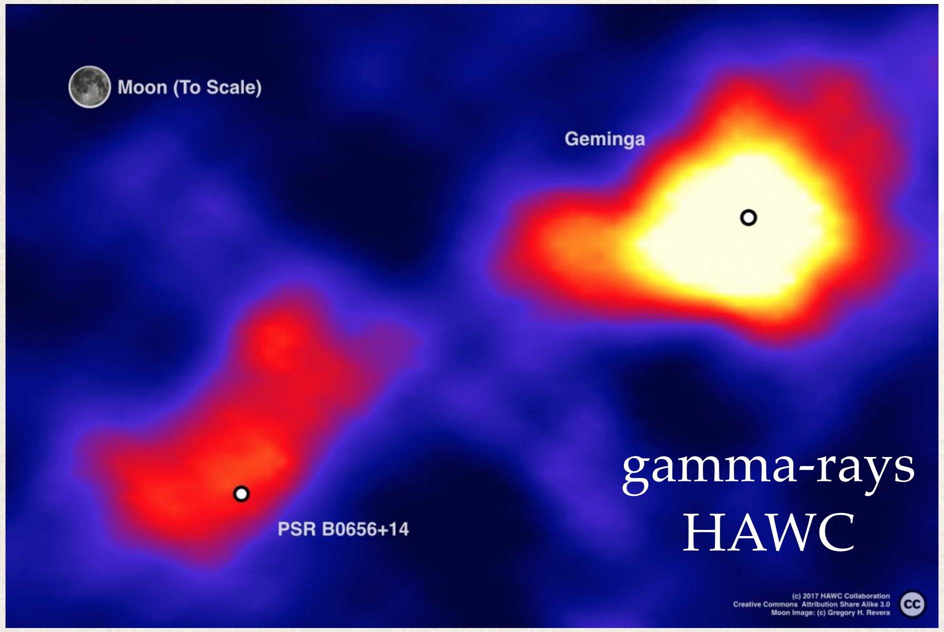


X-rays
Chandra

NASA/SAO/CXC



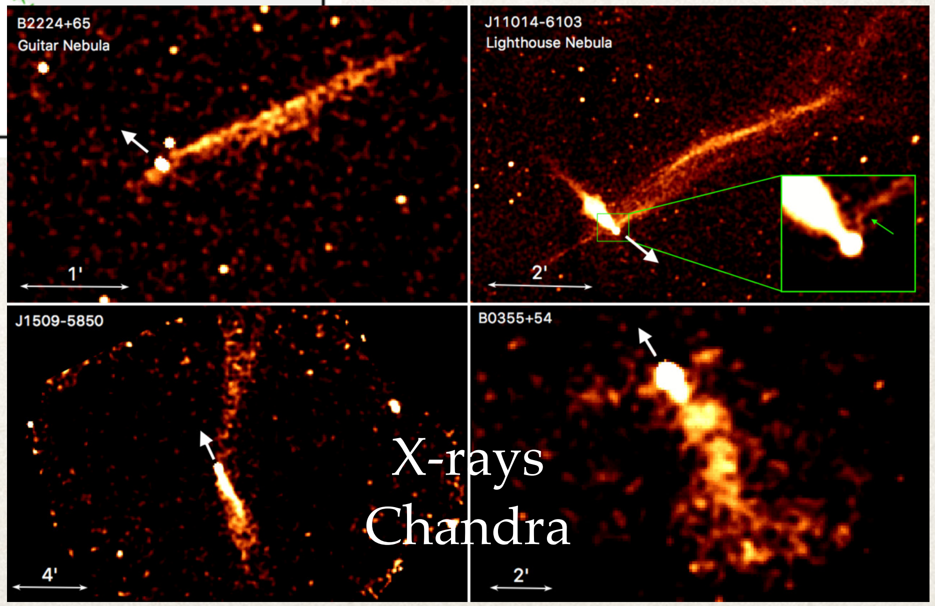
Abeysekara et al. 2017



gamma-rays
HAWC

?

Kargaltsev et al. 2017



X-rays
Chandra

Part II: summary

- Pulsars in high-energy astrophysics
    - Rapidly rotating highly magnetized neutron stars
    - Pair factories and very efficient particle accelerators
    - Rotational energy dissipated in relativistic magnetized wind
    - PWN, bubble of shocked pulsar wind filled of relativistic pairs
    - Broadband emitter, radio to VHE/UHE gamma-rays

Recent developments in gamma-ray astronomy

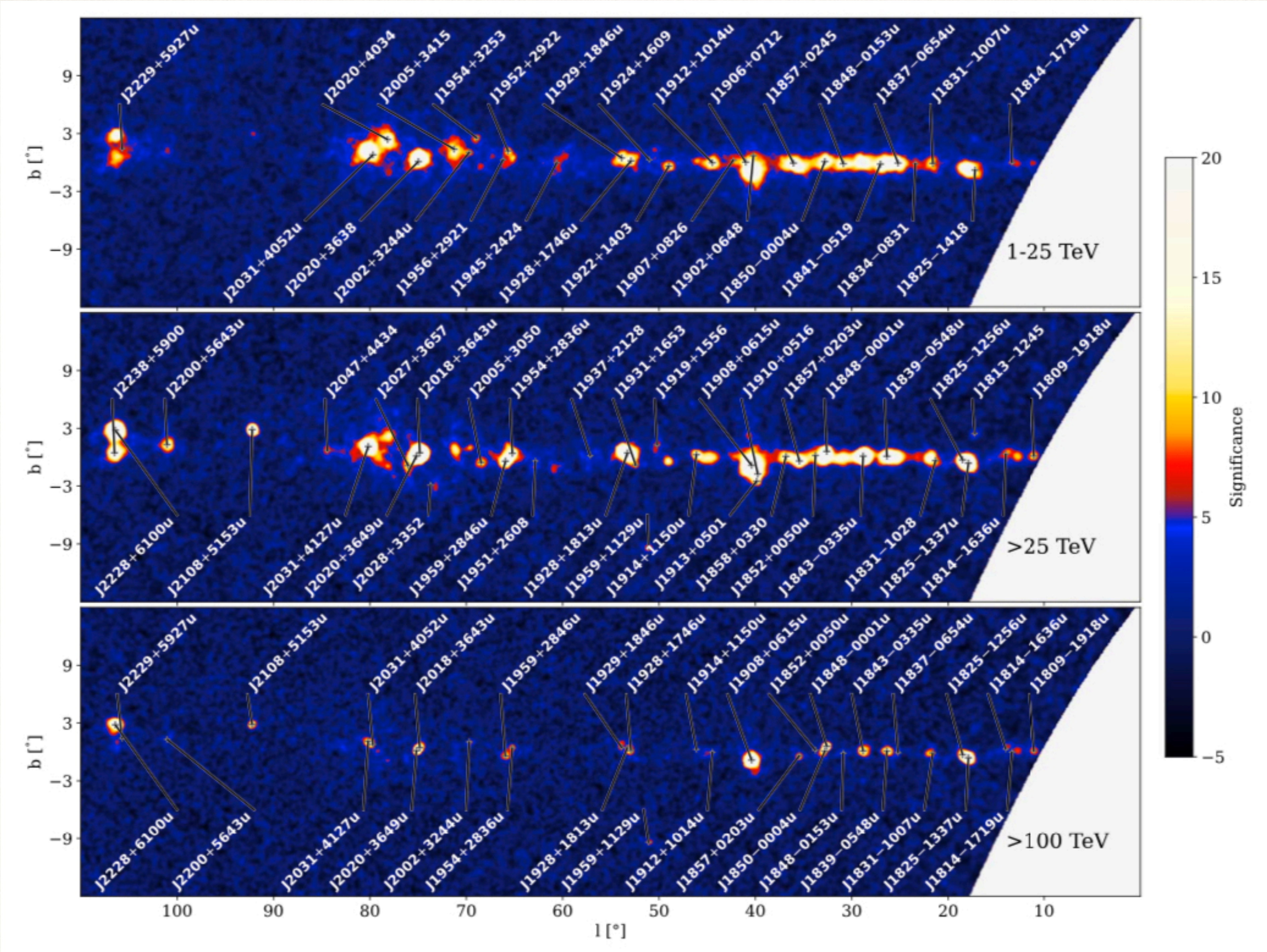
- Recent experimental developments
    - Extension of spectral range >50-100TeV
    - Growing variety of angular scales
    - Ever-increasing exposure
    - Large surveys and routine release of catalogs

Cao 2021

LHAASO
Large High Altitude Air
Shower Observatory
China, Sichuan
1.3 km^2 @ 4410m a.s.l.
Fully deployed July 2021

WCDA (~0.5-20TeV)
KM2A (~10TeV-2PeV)

Recent developments in gamma-ray astronomy



LHAASO 2021
12 sources >100 TeV

Cao et al. 2021

10/12
correlated
with pulsars

Now LHAASO 2024
90 sources including 43 sources >100 TeV

Cao et al. 2024

Recent developments in gamma-ray astronomy

The dawn of pulsars in the VHE/UHE skies
(<100GeV to >100TeV)

Extended sources **positionally coincident** with pulsars

Abdalla et al. 2018b,
Albert et al. 2020,
Albert et al. 2021,
Cao et al. 2021,
Cao et al. 2024

Population synthesis can account for most detected sources

Fiori et al. 2022
Martin et al. 2022b

Flux and maximum energy consistent with **spin-down power**

Torres et al. 2014
Zhu et al. 2023
Abdalla et al. 2018b
de Ona Wilhelmi et al. 2022

Broadband gamma-ray spectrum consistent with **inverse-Compton**

Breuhaus et al. 2021
Breuhaus et al. 2022
Sudoh et al. 2021

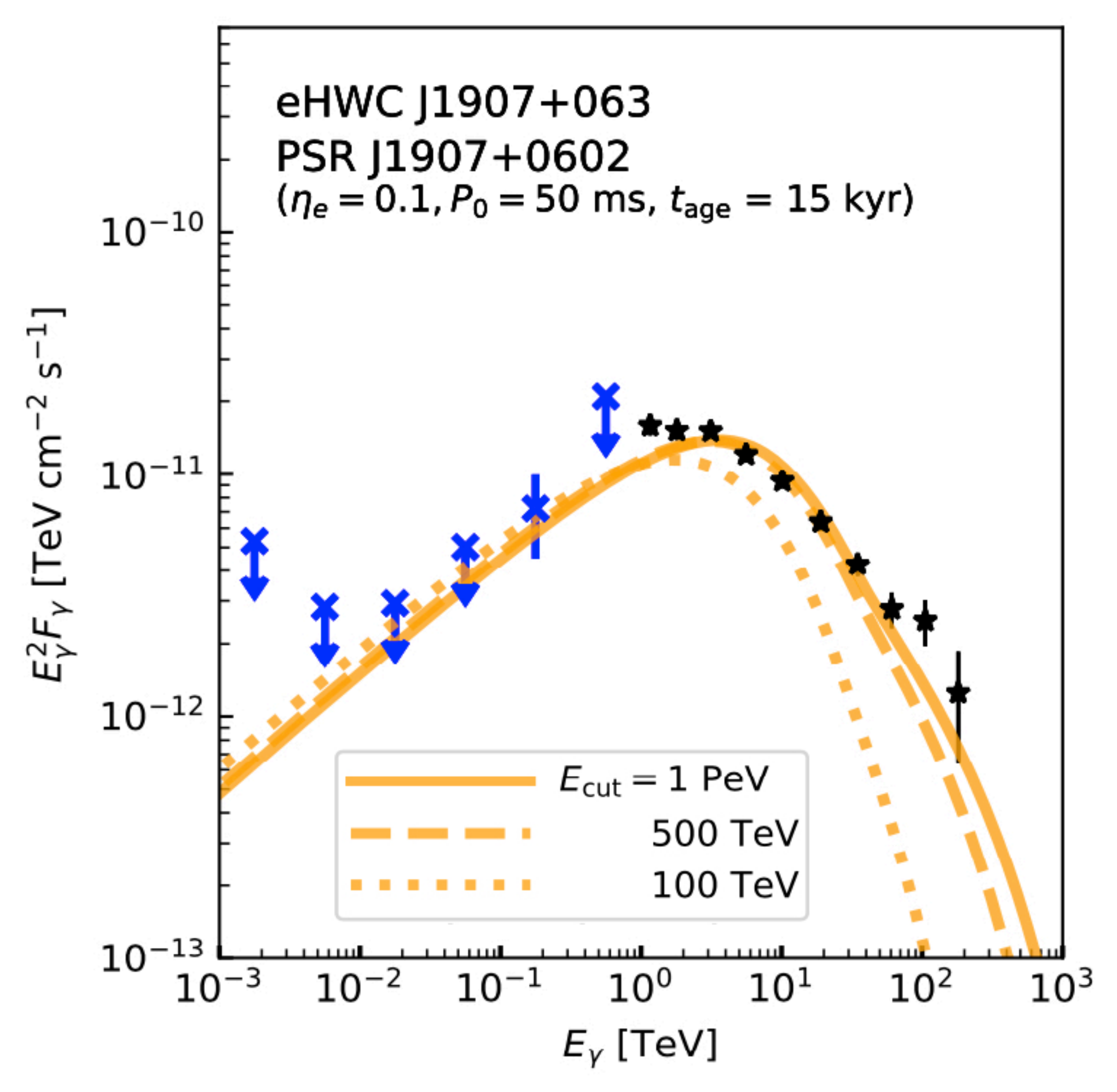
Recent developments in gamma-ray astronomy

Broadband spectrum
consistent
with **inverse-Compton**
Pion decay
would overshoot
<1TeV measurements

No sign of cutoff
in pair spectrum
before 100s TeV

Pair injection efficiency
~10-100% spin-down

Bucciantini et al. 2011, Torres et al. 2014



Sudoh et al. 2021

Recent developments in gamma-ray astronomy

LHAASO >100TeV sources:
Highest electron energy
nearly **saturates** the
maximum **potential drop**

Hillas criterion in the wind

$$E_{\max} = qEL = q\frac{v}{c}BL \lesssim qBL$$

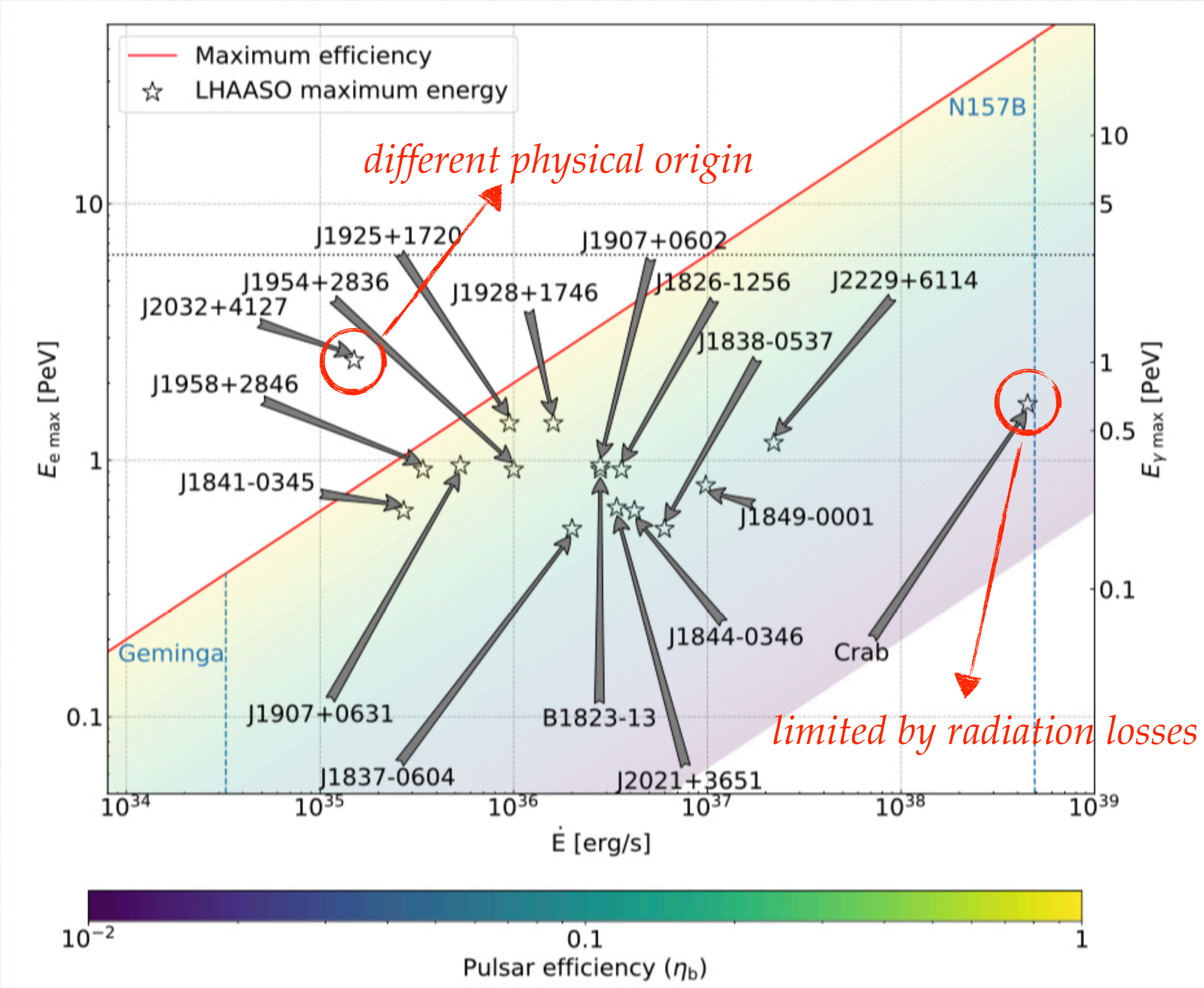
$$E_{\max} = q\Delta\Phi_{\rm wind}$$

$$\Delta\Phi_{\rm wind} \simeq \Psi_{\rm mag}/R_{\rm LC} = \Delta\Phi_{\rm mag}$$

$$\Psi_{\rm mag} = B_{\rm LC}R_{\rm LC}^2$$

Arons 2003

Reflects strongly magnetized
relativistic flow



different physical origin

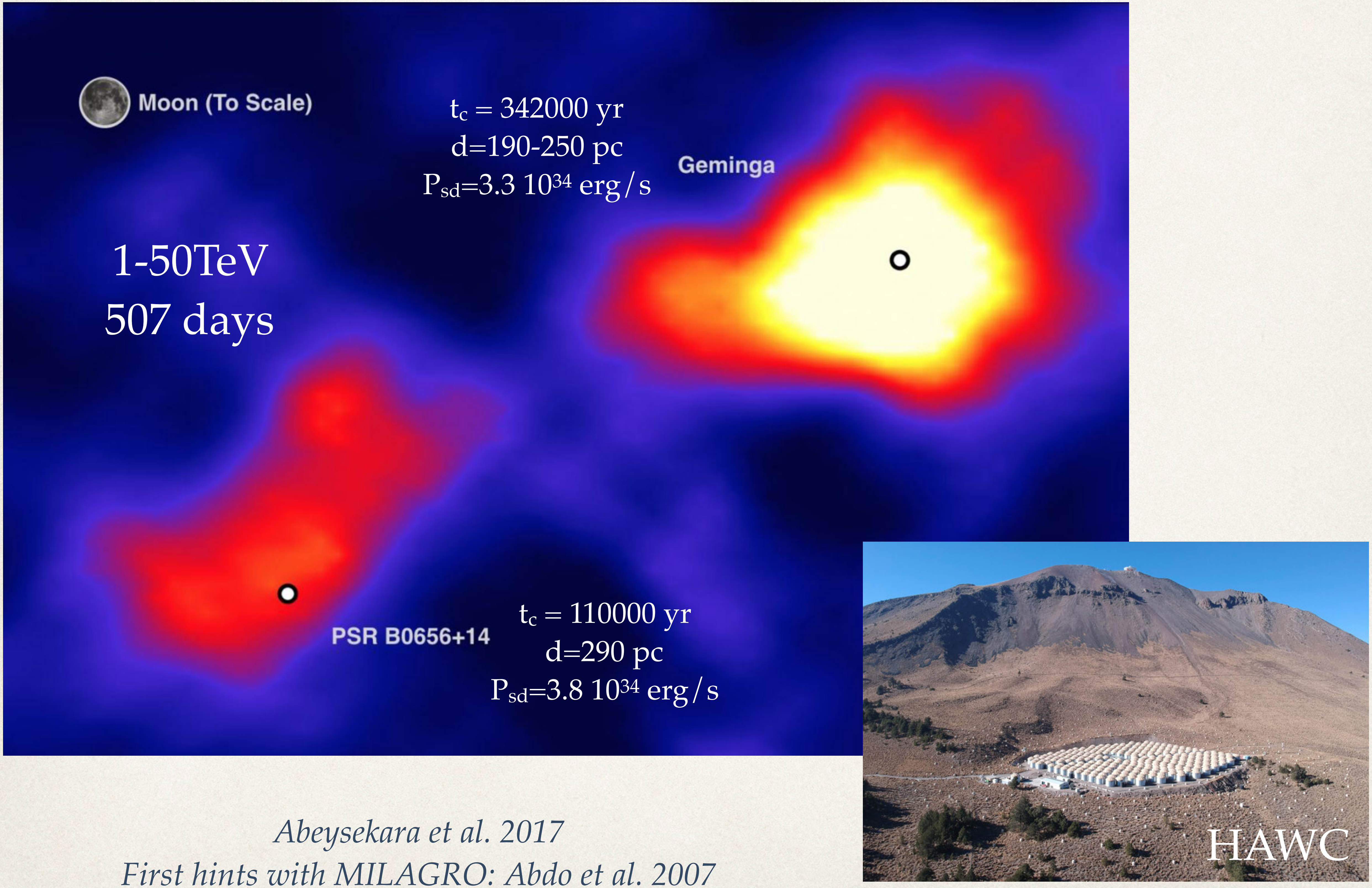
limited by radiation losses

de Ona Wilhelmi et al. 2022

Part III: summary

- The dawn of pulsars/PWNe in the VHE/UHE skies
    - Extension of spectral coverage above 10-100TeV
    - Now probing emission on variety of angular scales
    - Pulsars appear as major Galactic sources
    - Very efficient particle/pair accelerators

Pulsar TeV halos



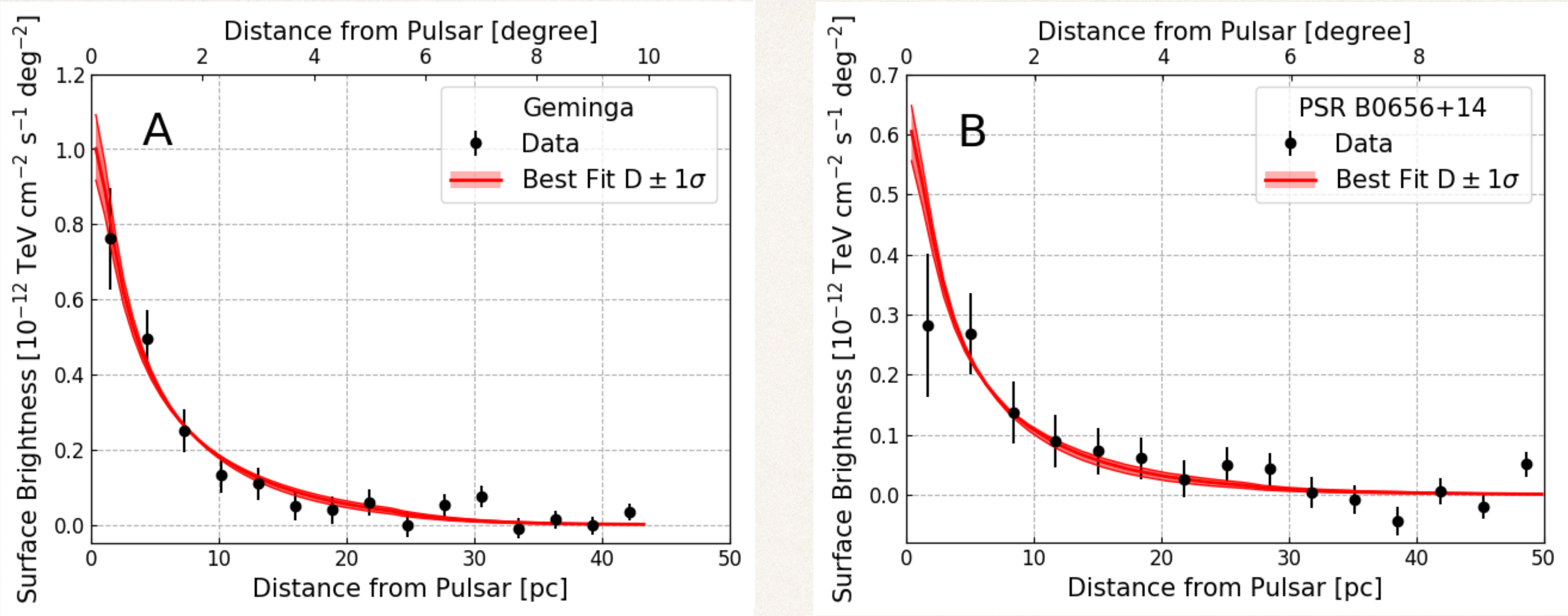
t_c = 342000 yr
d=190-250 pc
P_{sd}=3.3 10^{34} erg/s

1-50TeV
507 days

t_c = 110000 yr
d=290 pc
P_{sd}=3.8 10^{34} erg/s

Abeysekara et al. 2017
First hints with MILAGRO: Abdo et al. 2007

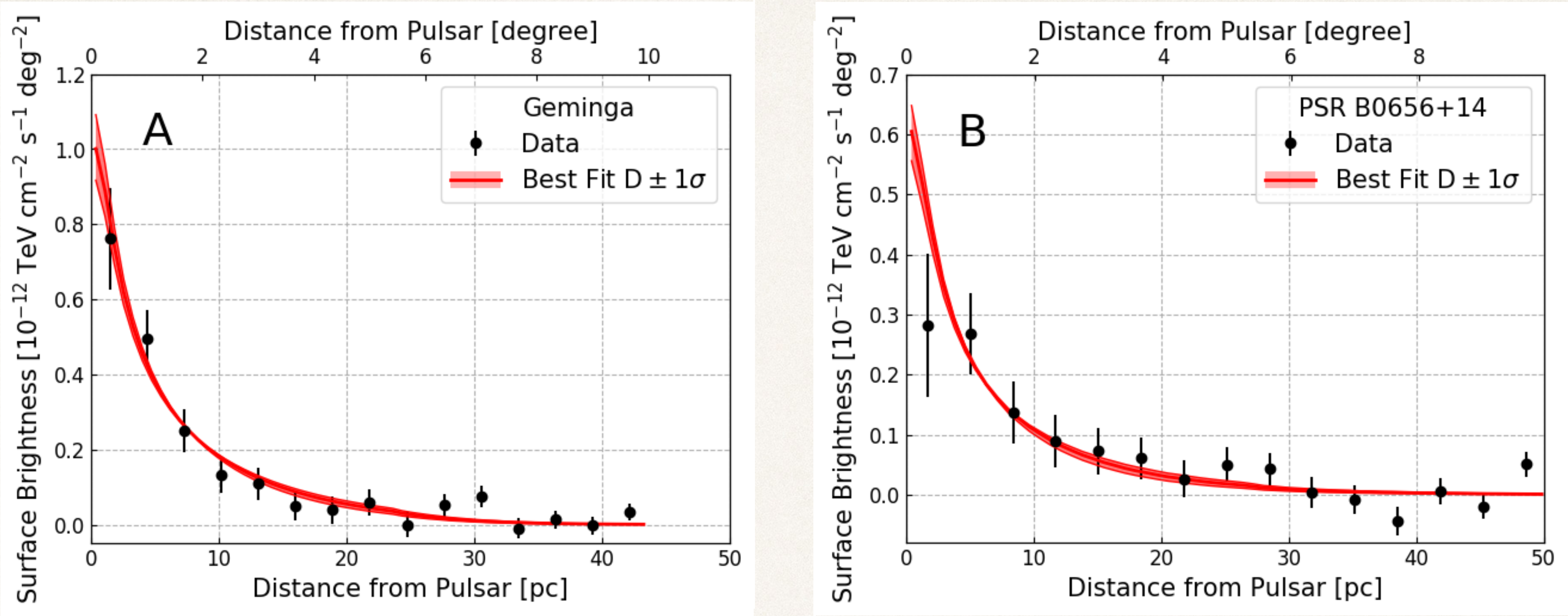
Pulsar TeV halos



Abeysekara et al. 2017

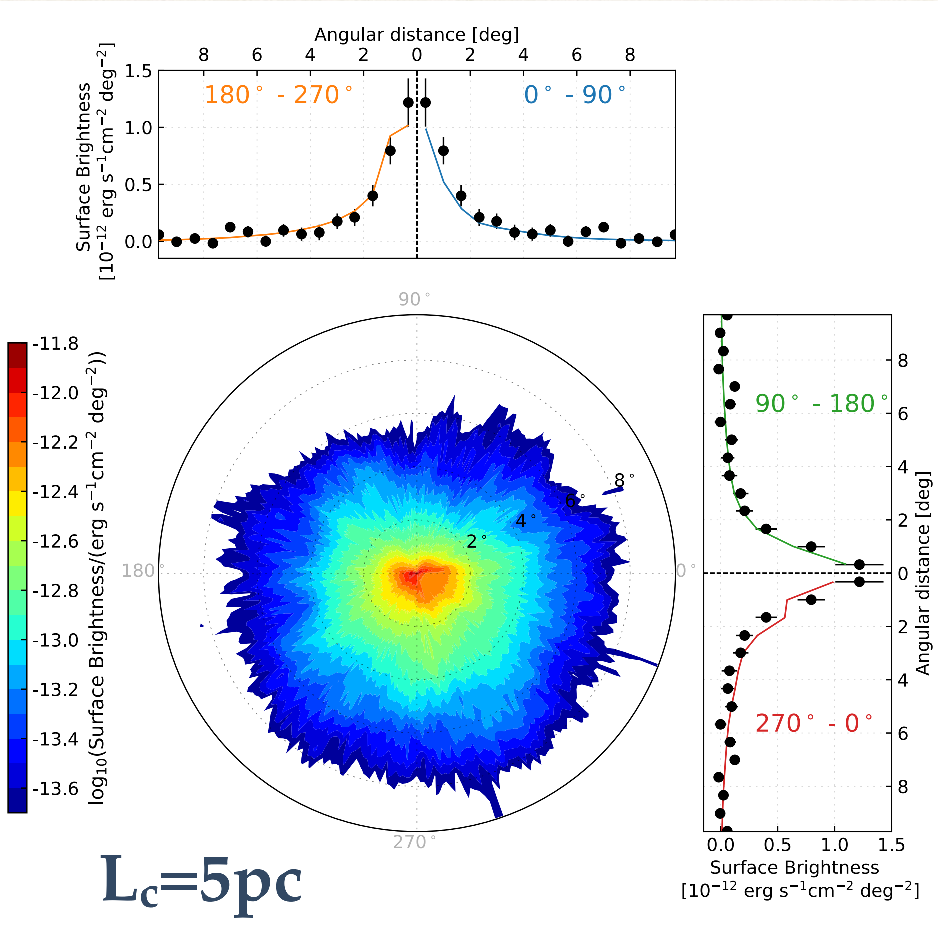
- Modeling the observed intensity profiles
  - few **10% of spin-down** power into >1GeV power-law spectrum of pairs
  - **diffusion-loss** transport **in the ISM**
  - **inverse-Compton** scattering of ambient photons (CMB, IR)
  - **suppressed diffusion** within >30pc, with $\mathbf{D_{HALO} \sim D_{ISM}/100\text{-}1000}$
  - *(direct mapping of emitting pairs since CMB is main radiation field)*

Pulsar TeV halos

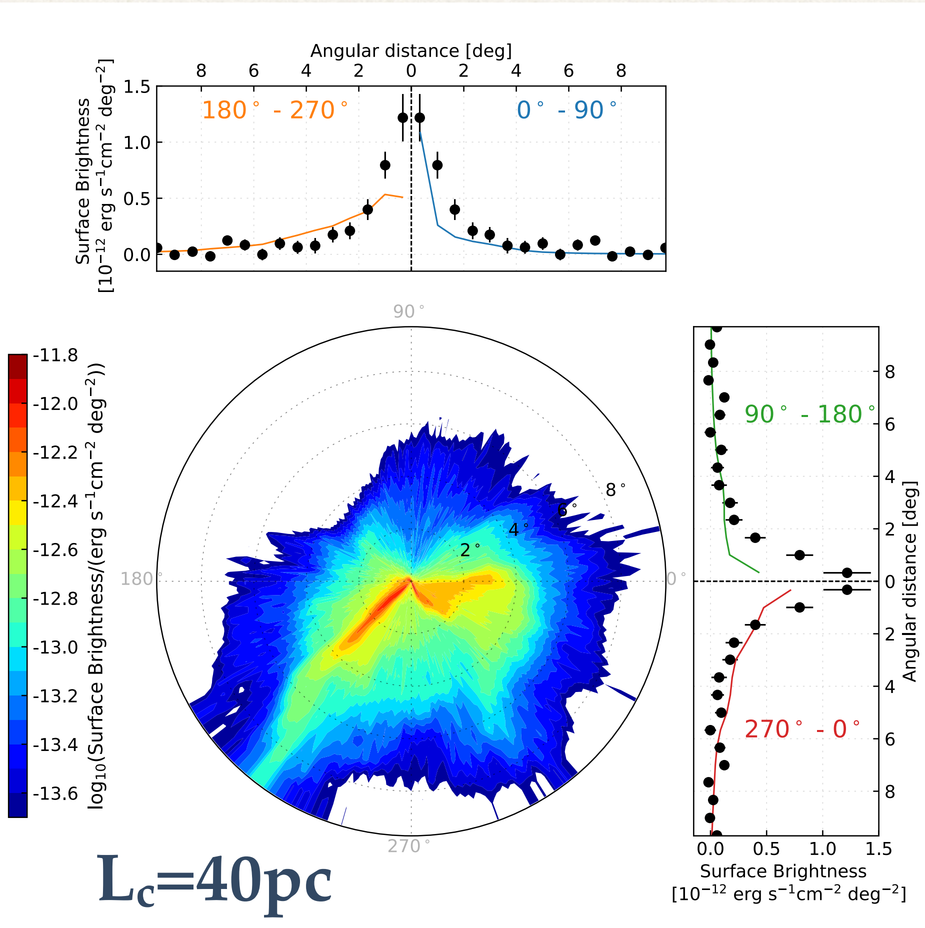


- Theoretical possibilities for **suppressed diffusion**
  - **Self-confinement** by streaming pairs *Evoli et al. 2018, Mukhopadhyay et al. 2021*
  - **Pre-existing** fluid turbulence *Lopez Coto&Giacinti et al. 2018, Fang et al. 2019*
  - Pre-existing kinetic turbulence *Mukhopadhyay et al. 2021*

Pulsar TeV halos



L_c=5pc



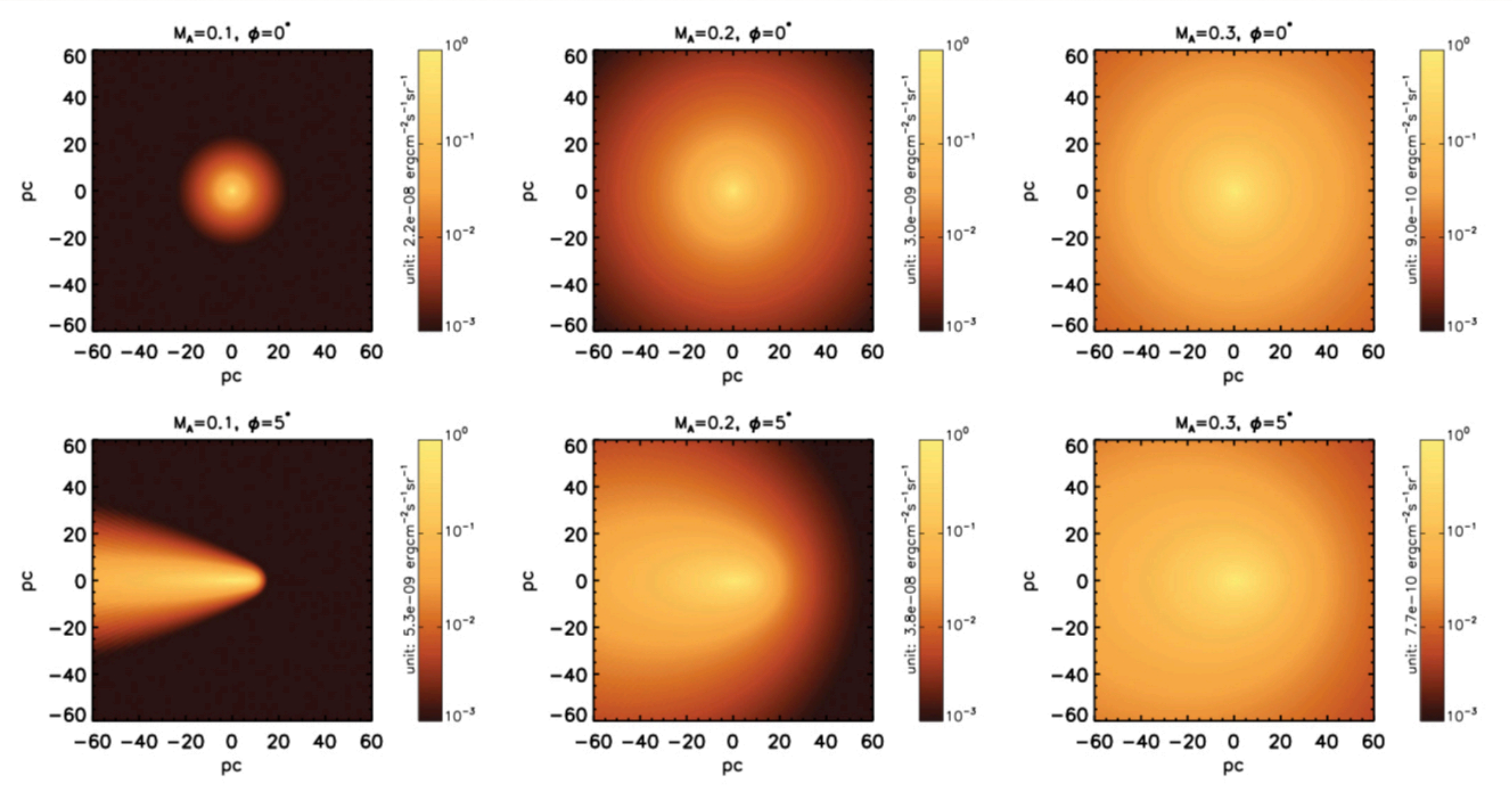
L_c=40pc

Lopez-Coto & Giacinti 2018

First-principle 40-500TeV electron transport
in synthetic isotropic 3D static turbulence
HAWC measurement for Geminga ⇒ **B_{rms}=3μG** and **L_c<5pc**

Pulsar halos as indirect **opportunity to probe turbulence** in localized regions
supernova remnants, star-forming regions, superbubbles,…

Pulsar TeV halos



Liu et al. 2019, De la Torre Luque et al. 2023

$$D_\perp = M_A^4 D_\parallel$$

with
turbulence
strength

$$M_A = \frac{\delta v}{v_A} = \frac{\delta B}{B_0}$$

Xu&Yan 2013

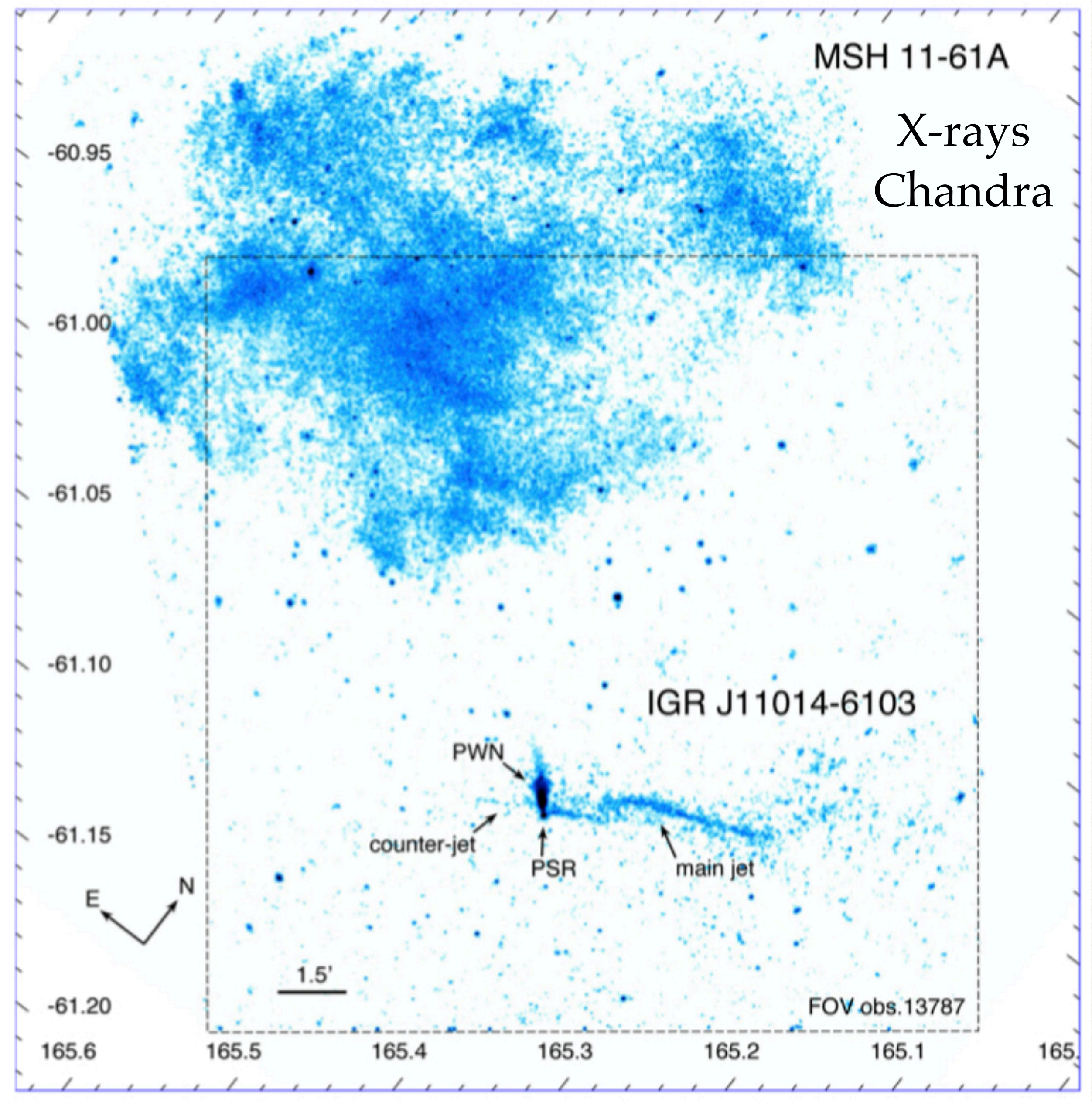
Variant of the same idea: ~field-aligned **anisotropic** interstellar **diffusion**

Issues:

Stringent conditions on inclination and M_A
Perpendicular transport is diffusive on large-scales $> L_c$
Expect elongated TeV halos elsewhere

Amato&Recchia
in prep.

Pulsar X-ray misaligned jets



Pavan et al. 2014,2016

~0.5-15pc coherent jets
handful of systems

Kargaltsev et al. 2017

Olmi et al. 2024:
charge-separated collimated escape
non-resonant streaming instability
magnetic field **amplification** O(10)
length = saturation time scale
width = synchrotron loss time scale

Complementary probe (also radio jets) to light up the ambient field
Tracing **less turbulent** medium ?

Particle escape in pulsars/PWNe: halos

$$\begin{aligned} N_{\mathrm{halos}} &\sim R_{\mathrm{PSR}} \times \tau_{\mathrm{halos}} \\ &\sim 2\,\mathrm{PSR}/100\mathrm{yr} \times 5.10^{5}\,\mathrm{yr} \\ &\sim 10000\ \mathrm{halos} \end{aligned}$$

Are TeV halos everywhere ?

Interpretation of **extended** gamma-ray **sources**

Linden et al. 2017
Di Mauro et al. 2020

Contribution to **diffuse** emission as **unresolved** population

Linden&Buckman 2018,
Hooper&Linden 2022,
Martin et al. 2022b

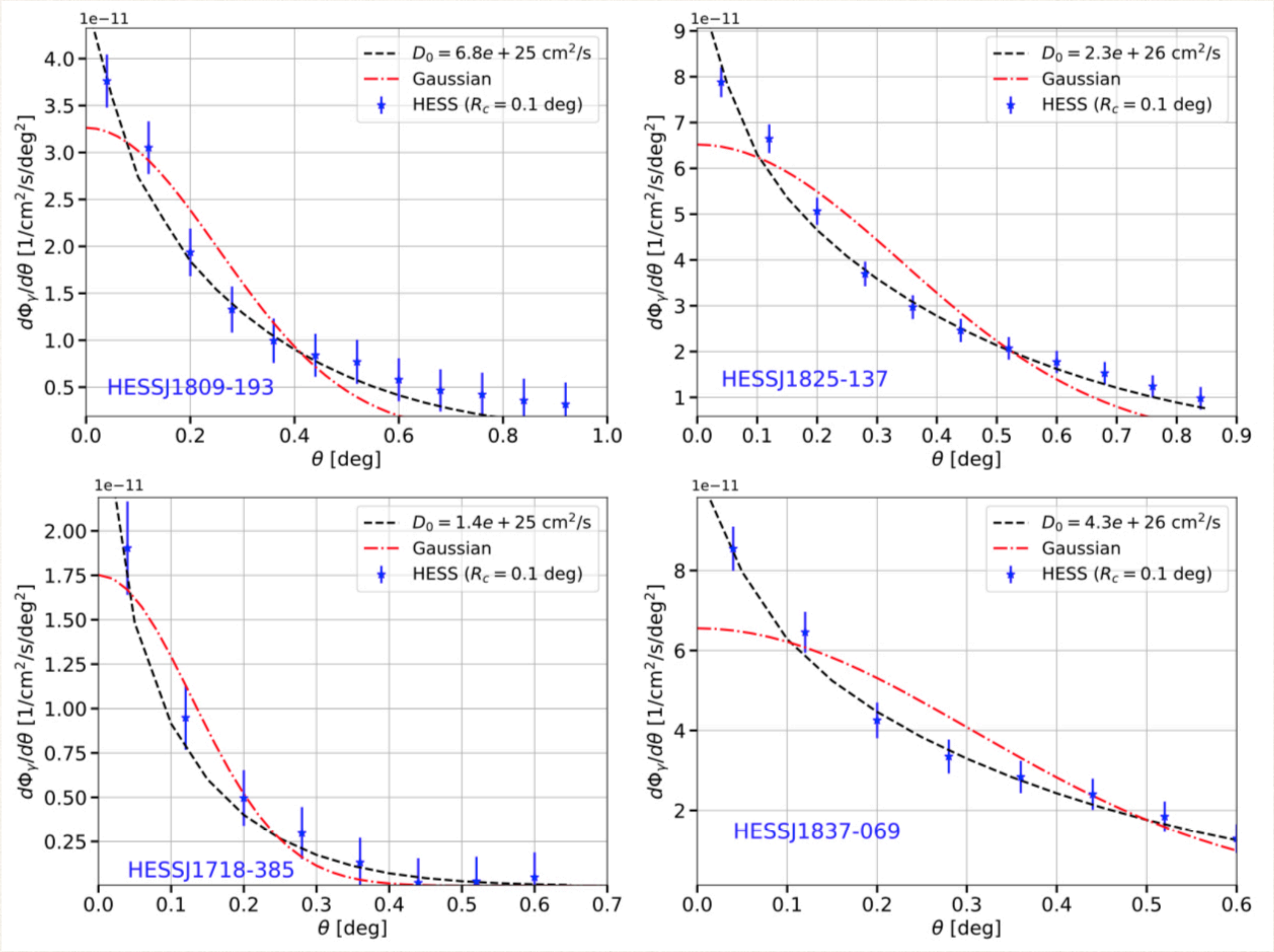
Impact on interpretation of local **positron** and electron **fluxes**

Profumo et al. 2018,
Fang et al. 2018,2019,
Manconi et al. 2020,
Martin et al. 2022a,
Schroer et al. 2023

Effect on large-scale transport of GCRs from **inhomogeneous diffusion**

Jacobs et al. 2023,
Johannesson et al. 2019

Particle escape in pulsars/PWNe: halos



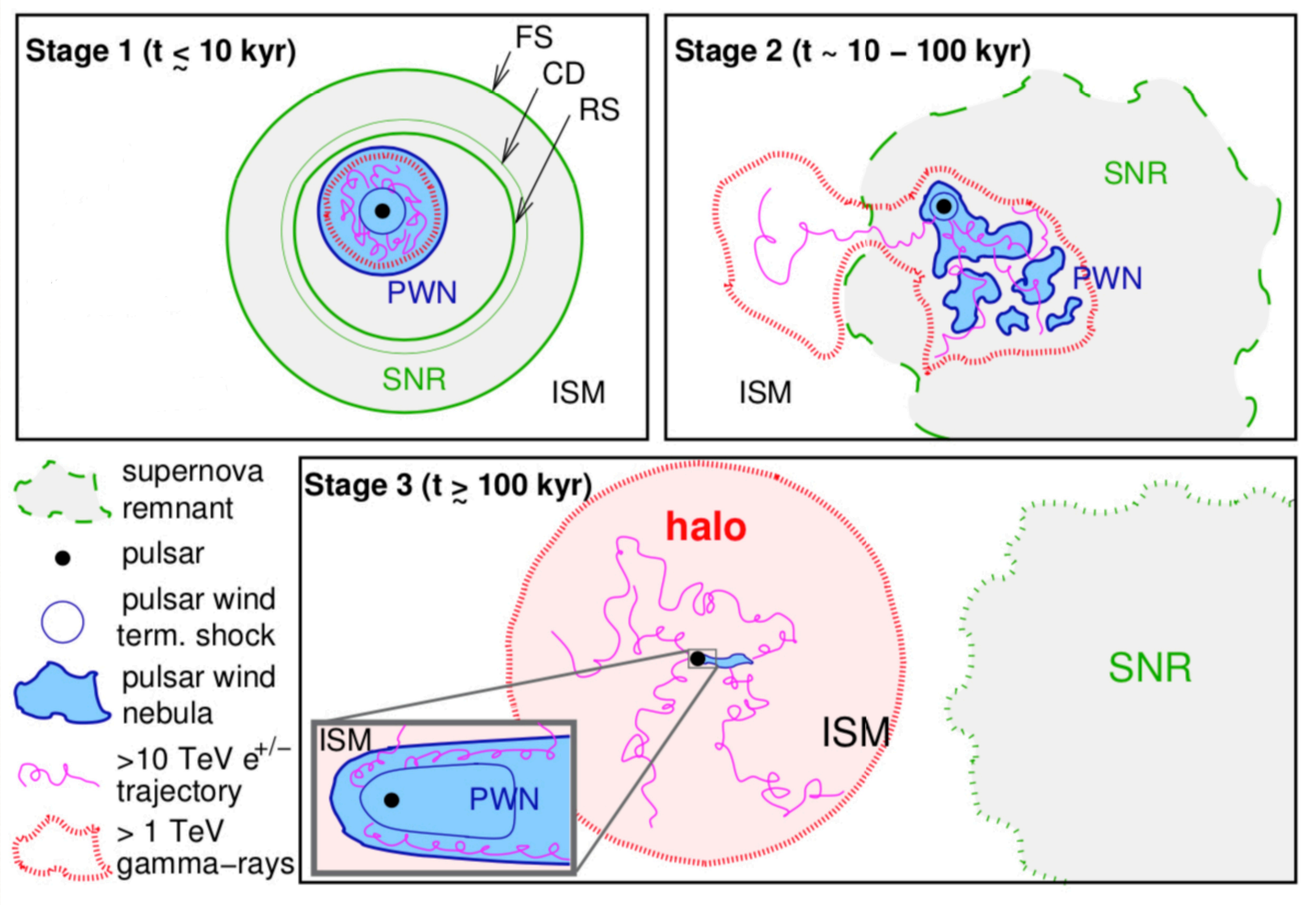
Di Mauro et al. 2020

Phenomenology of halos can describe many **pulsar-related sources**

For many sources **R_{TeV}>10pc** up to 40pc $\gtrsim R_{SNR} > R_{PWN}$

Significant **particle escape** at all ages ?

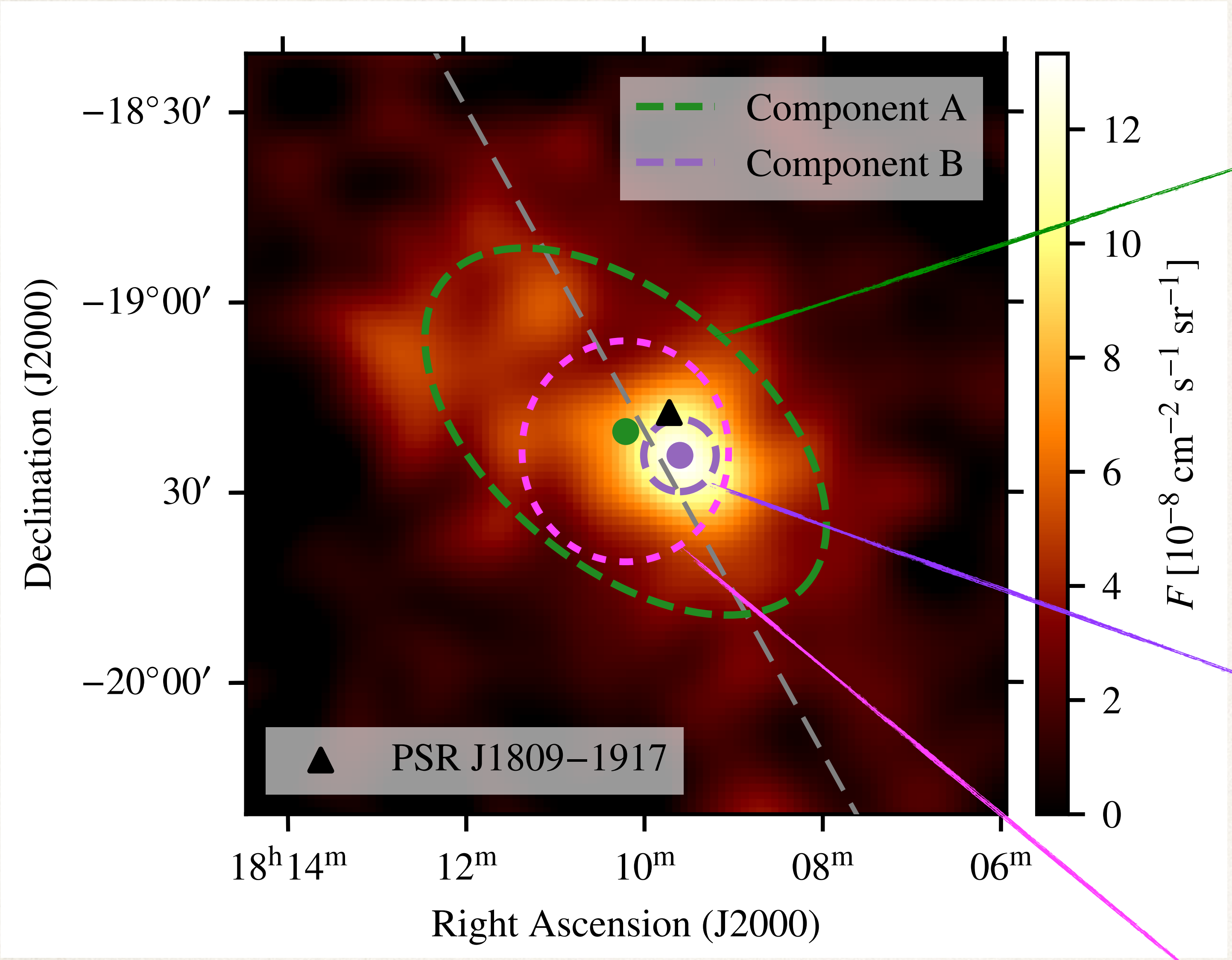
Particle escape in pulsars/PWNe: halos



Giacinti et al. 2020

Significant **particle escape** at all ages, as **early** as stage I ?
Gamma-ray halos around more **classical PWNe** ?
A probe of turbulence/transport in/around **younger systems** ?

A case study: HESS J1809-193



extended TeV component A
0.6° x 0.3°→2-σ extent = **70pc**
nearly **aligned** with Galactic plane
large for PWN or even for SNR !

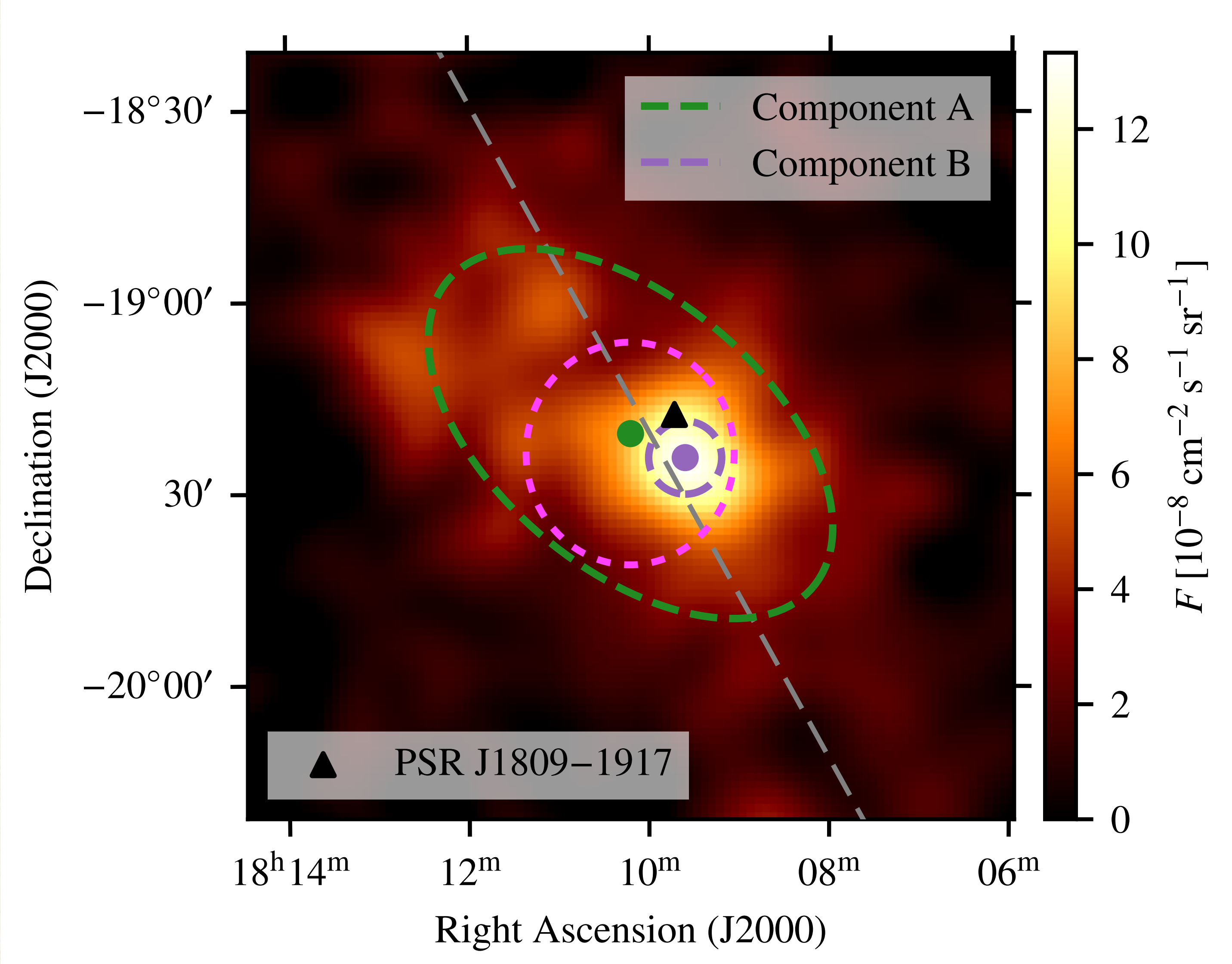
compact TeV component B
0.1°→2-σ extent = 12pc
offset south of pulsar
like X-ray elongated PWN
reverse-shock interaction

H.E.S.S. collaboration 2023 (plot: Lars Mohrmann)

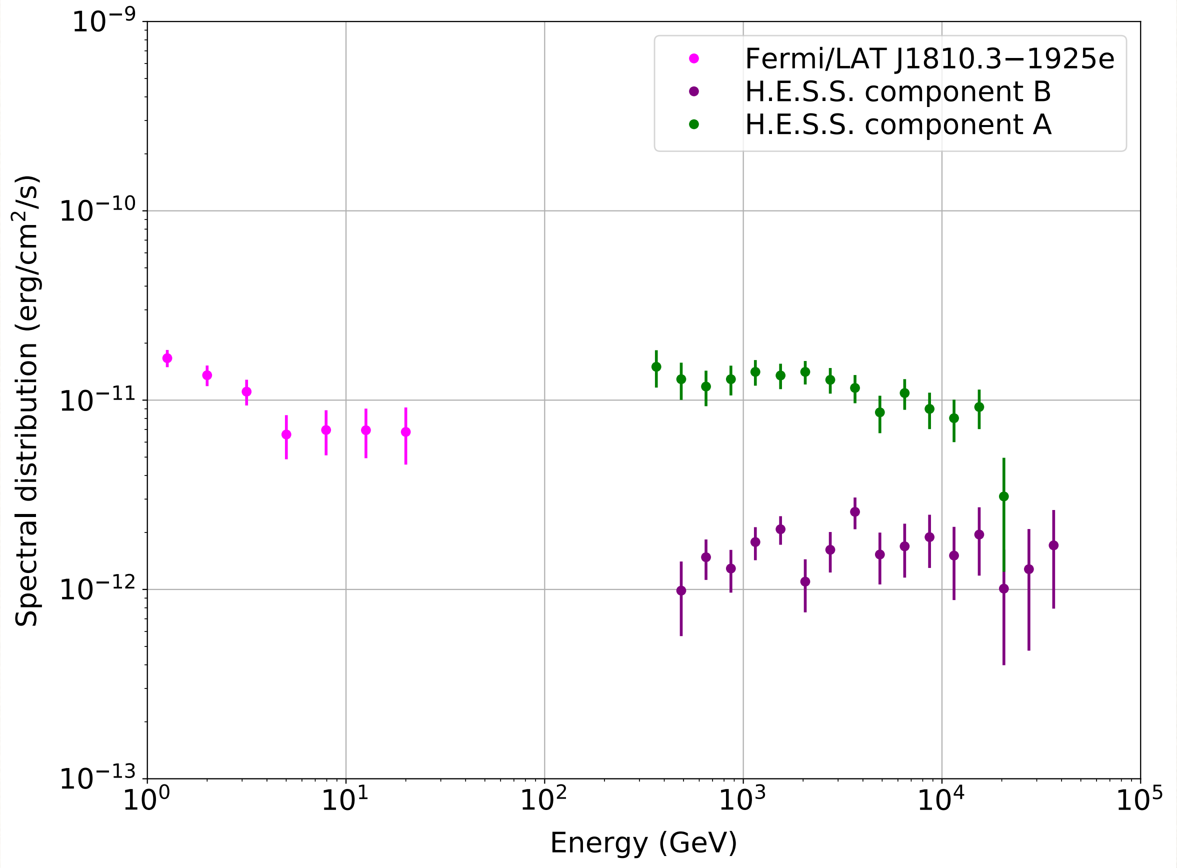
GeV component
4FGL 1810.3−1925e
intermediate in size

PSR J1809-1917: P=0.083s
$\dot{E}$=1.8 x10^{36} erg/s
τ_c=5.1 x10^{4} yr
d=3.3 kpc

A case study: HESS J1809-193



H.E.S.S. collaboration 2023 (plot: Lars Mohrmann)

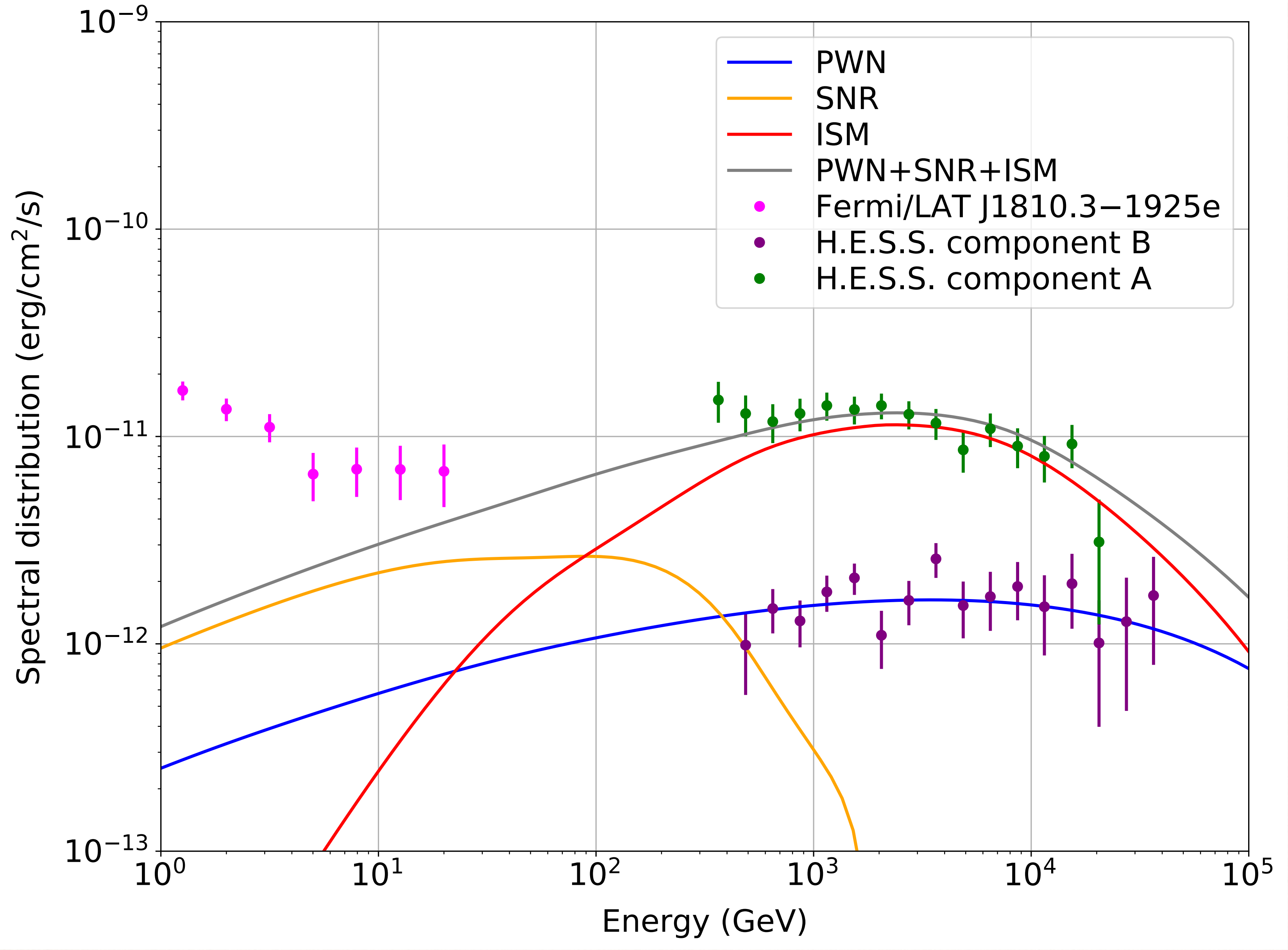


Spectrally distinct components

1) TeV signal dominated by extended component with cutoff at 13TeV
2) TeV surface brightness dominated by flat-spectrum compact component
3) GeV steep then flattening spectrum

Multi-component ?

Application to HESS J1809-193



Martin et al. (submitted)

Best-fit obtained on TeV data only
from typical pulsar-SNR-PWN parameters

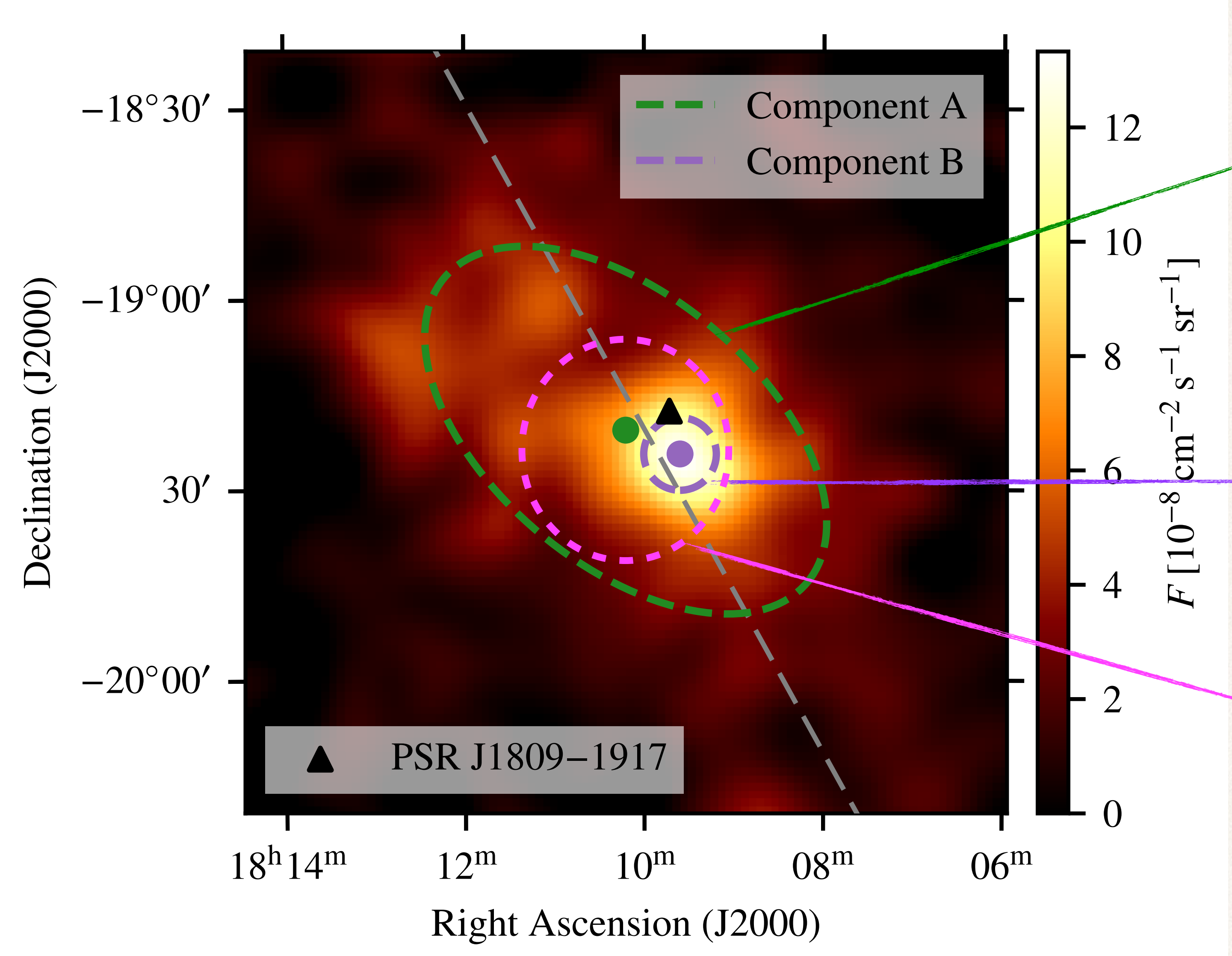
Extended TeV component from >0.1TeV particles escaped in ISM

Compact TeV component from particles trapped in PWN with predicted R_{PWN}=13pc

GeV component partially explained from SNR+ISM with predicted R_{SNR}=23pc

1-10GeV steep part from CRs in SNR ?

A case study: HESS J1809-193



Extended TeV component from >0.1TeV particles escaped in ISM

Observed extent should tell us something about propagation !

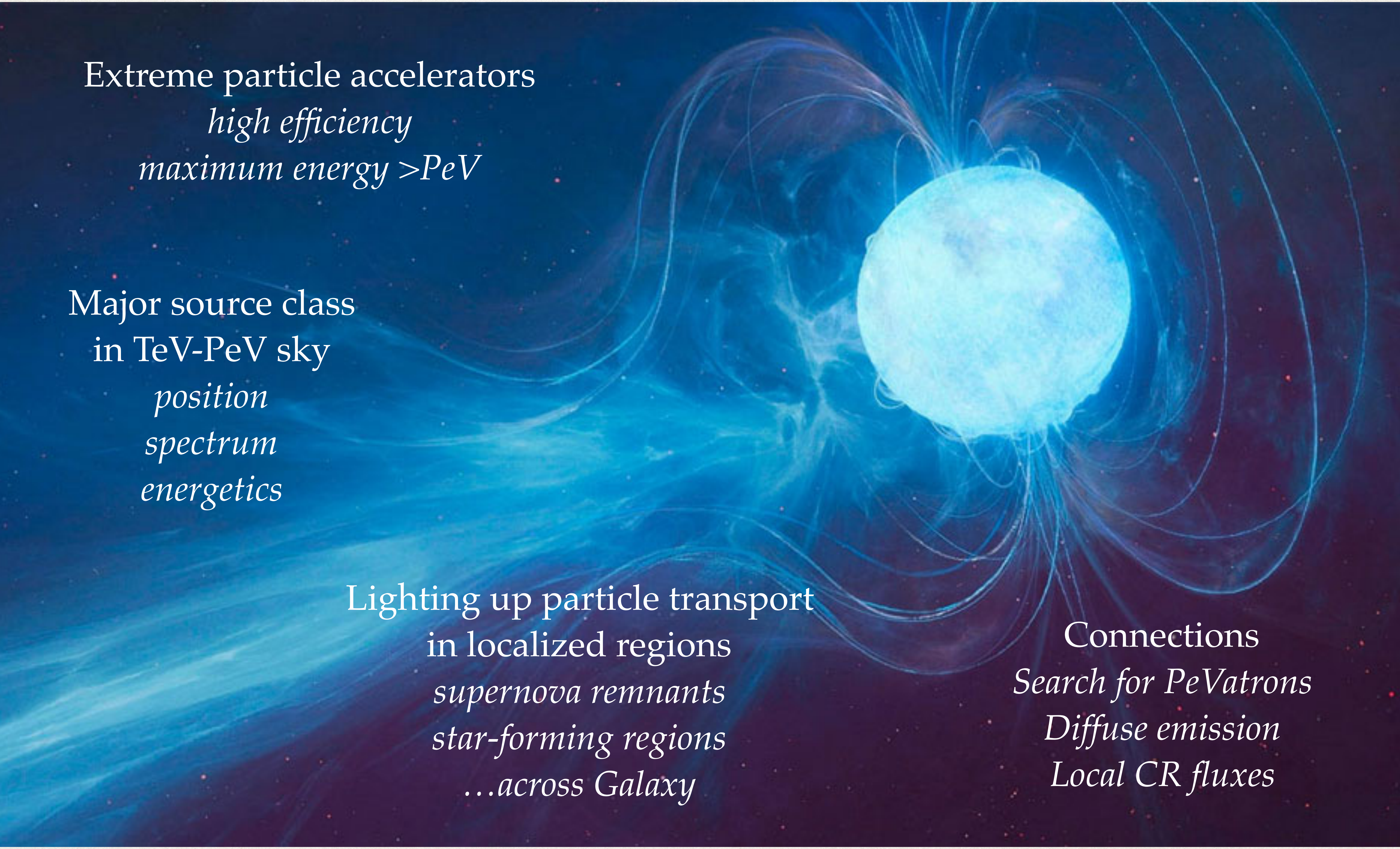
Compact TeV component from particles trapped in PWN

GeV component partially explained from SNR+ISM

H.E.S.S. collaboration 2023 (plot: Lars Mohrmann)

Strong escape losses after ~1kyr in many turbulence setups
GeV-TeV: **SNR+ISM** dominates PWN → extended H.E.S.S. sources
TeV-PeV: **ISM** dominates SNR+PWN → extended LHAASO sources

Summary and perspectives



Extreme particle accelerators
high efficiency
maximum energy >PeV

Major source class
in TeV-PeV sky
position
spectrum
energetics

Lighting up particle transport
in localized regions
supernova remnants
star-forming regions
…across Galaxy

Connections
Search for PeVatrons
Diffuse emission
Local CR fluxes

Credit: M. Rebisz

Summary and perspectives

- Pinning down the astrophysical context
  - *Multi-wavelength approach, novel probes of turbulence,…*
- Making the most of theoretical developments
  - *Cosmic-ray acceleration/transport, SNR/PWN simulations,…*
- Testing models at (gamma-ray) data level
  - *Combined broadband analyses, open tools and data*