THEORY OF HIGH ENERGY PHENOMENA IN THE UNIVERSE

Pasquale Blasi

Gran Sasso Science Institute

GRAN SASSO SCIENCE INSTITUTE

SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

WHAT'S OUR RESEARCH ABOUT?

INNER WORLD — OUTER WORLD

(D.N. Schramm)

The understanding of the universe on large scales requires the investigation of the microphysics, and in turn the big scales tell us about microphysics

While the initial statement was specialised to the connection between cosmology and particle physics, its meaning is much more pronounced and widely applicable

Whether we talk about cosmic rays or neutrinos, of non-thermal phenomena in NS mergers or in clusters of galaxies, we observe phenomena on very large scales, whose interpretation lies in the microscopic scales of either particle physics or plasma physics, or both.
Such microphysics is basically the same despite the variety of manifestations on large scales

WE INVESTIGATE SUCH MICROPHYSICS, ITS IMPLICATIONS FOR THE UNDERSTANDING OF NATURE, AND WHAT NATURE TELLS US ABOUT SUCH MICROPHYSICS

NON THERMAL PARTICLES AND COSMIC RAYS

SNRs

Sun

μQSO

NON THERMAL PARTICLES ARE UBIQUITOUS IN THE UNIVERSE

AGN

PWNe

Star Clusters

Starburst galaxies

THESE PHENOMENA REQUIRE ACCELERATION MECHANISMS TO BE AT WORK...

...AND TRANSPORT MECHANISMS THAT TAKE PARTICLES FROM A TO B

SOMETIMES THE NON-THERMAL PARTICLES PRODUCED IN THESE SOURCES MAKE THEIR WAY TO THE EARTH— AT THAT POINT WE CALL THEM COSMIC RAYS

FOR ALL THESE PROBLEMS, THE CRUCIAL ISSUE IS STILL THE TRANSPORT OF CHARGED PARTICLES IN SPACE AND ENERGY

WHY?

THE RATE OF DISCOVERIES IN THE FIELDS OF COSMIC RAYS, GAMMA RAYS, NEUTRINOS AND NOW GRAVITATIONAL WAVES IS PROBABLY UNEQUALED BY ANY FIELD OF PHYSICS AT THIS TIME

- *DISCOVERY OF POSITRON EXCESS IN THE COSMIC RADIATION*
- *DISCOVERY OF UNEXPLAINED FEATURES IN THE SPECTRA OF COSMIC RAY ELEMENTS*
- *FIRST EVIDENCE EVER OF ASTROPHYSICAL HIGH ENERGY NEUTRINOS*
- *MYSTERIOUS HALOS OF TeV GAMMA RAY EMISSION AROUND SOURCES*
- *DETECTION OF SOME PUTATIVE PEV CR SOURCES*
- *ANTI HELIUM IN COSMIC RAYS AT ODDS WITH ALL STANDARD PICTURES*
- *PROMPT AND AFTERGLOW EMISSION IN GRB —> FINALLY SOME PHYSICS*
- *GW AND EM EMISSION FROM SHORT GRBs —> UNPRECEDENTED CHANCE*
- *EXTREME SOURCES: STARBURST GALAXIES AS SOURCES OF GAMMAs,neutrinos and UHECRs*
- *...*

SOME OF OUR MAIN RESULTS

- Acceleration and transport of UHECRs

- Particle acceleration to PeV energies in supernova explosions with self-generated CR driven instabilities

- CR transport in self-generated magnetic fields on Galactic scales

- Phenomenology of CR transport in the aftermath of AMS-02 data

- Pioneering investigation of the transport of CR around sources and role of self-generated perturbations

- Atmospheric neutrinos vs diffuse astrophysical neutrinos

- Transport of charged particles in synthetic and MHD turbulence

- Positron production in pulsar winds and the origin of CR leptons

- Starburst galaxies as sources of gamma rays, neutrinos and UHECRs

- CR acceleration in star clusters

PHENOMENOLOGY OF COSMIC RAYS ON GALACTIC SCALES

See presentation by Benedikt Schroer

SOME PILLAR CONCEPTS OF CR TRANSPORT
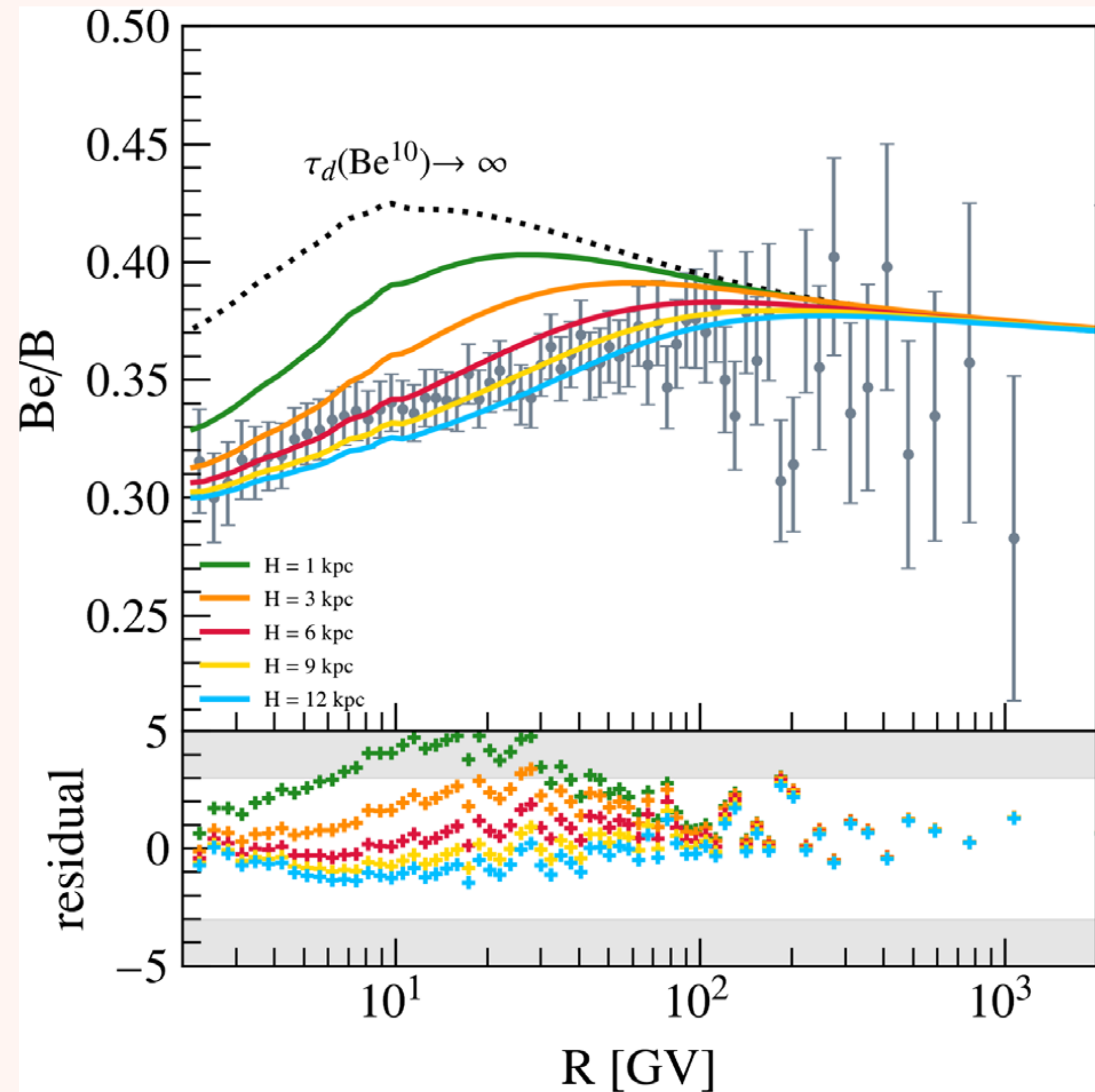## *(SEE PRESENTATION BY BENEDIKT SCHROER LATER...)*

› **THE TRANSPORT OF COSMIC RAYS IS WELL DESCRIBED BY A CONVECTION-DIFFUSION EQUATION, WITH LOSSES**

› **STATIONARITY ENSURED BY PROPER BOUNDARY CONDITIONS AT THE HALO BOUNDARY**

› **THE DIFFUSION COEFFICENT CONTAINS ALL THE PHYSICS OF RESONANT ABSORPTION AND EMISSION OF PLASMA WAVES BY CHARGED PARTICLES**

› **COSMIC RAYS ARE ASSUMED TO BE ACCELERATED AT SHOCK WAVES (PERHAPS IN SNRS) AND HENCE TO HAVE A POWER LAW SPECTRUM IN MOMENTUM IN THE ENERGY RANGE OF INTEREST**

$$-\frac{\partial}{\partial z}\left[D_a \frac{\partial f_a}{\partial z}\right] + v_A \frac{\partial f_a}{\partial z} - \frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{a,\text{ion}} f_a\right] + \frac{\mu v(p)\sigma_a}{m}\delta(z)f_a + \frac{f_a}{\hat{\tau}_{d,a}}$$

~80 couple partial differential equations

$$= 2h_d q_{0,a}(p)\delta(z) + \sum_{a'>a}\frac{\mu v(p)\sigma_{a'\to a}}{m}\delta(z)f_{a'} + \sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$
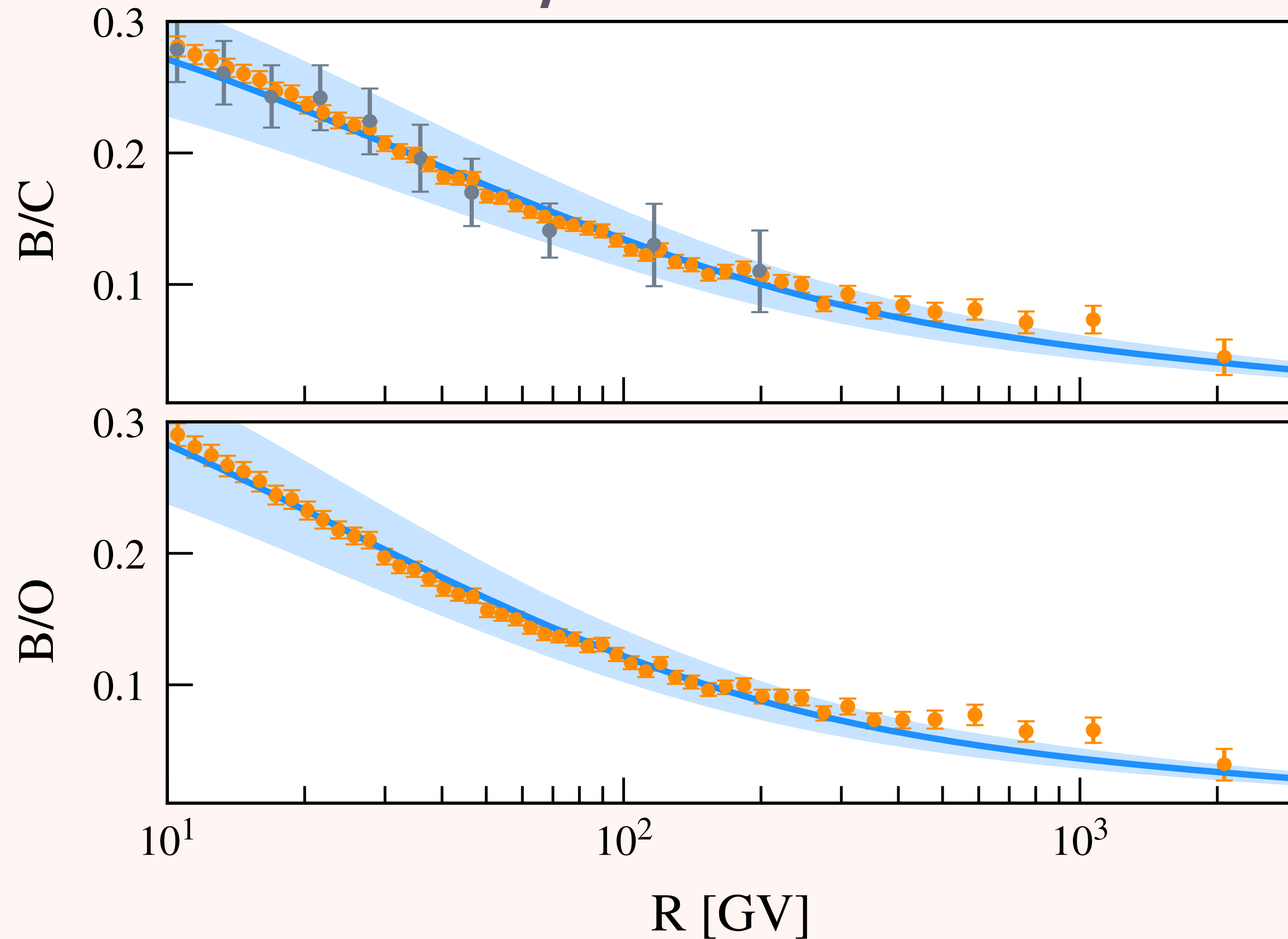
BERYLLIUM/BORON RATIO

The plot shows Be/B ratio versus R [GV]. Curves labeled:
- $\tau_d(Be^{10}) \to \infty$ (dotted line)
- H = 1 kpc (green)
- H = 3 kpc (orange)
- H = 6 kpc (red)
- H = 9 kpc (yellow)
- H = 12 kpc (cyan)

■ THE RATIO IS AFFECTED BY THE DECAY OF ^{10}Be BOTH BECAUSE OF DISAPPEARANCE OF BERYLLIUM AND PRODUCTION OF BORON

■ THE DOTTED LINE SHOWS THE LIMIT OF STABLE BERYLLIUM, IN WHICH THE BEHAVIOUR IS SIMILAR TO THAT OF C/O (DECLINING RATIO at >10GV)

■ THE DECAY OF ^{10}Be CHANGES THIS RESULT QUALITATIVELY AND QUANTITATIVELY, MAKING THE RATIO AN INCREASING FUNCTION OF RIGIDITY for R>few GV

■ THE FIT PREFERS A HALO SIZE H>6 kpc

ANTIMATTER FROM PULSARS

CR+ISM → e⁺+...

CR+ISM → e⁻+...

PAMELA e⁻
AMS02 e⁻
PAMELA e⁺
AMS02 e⁺
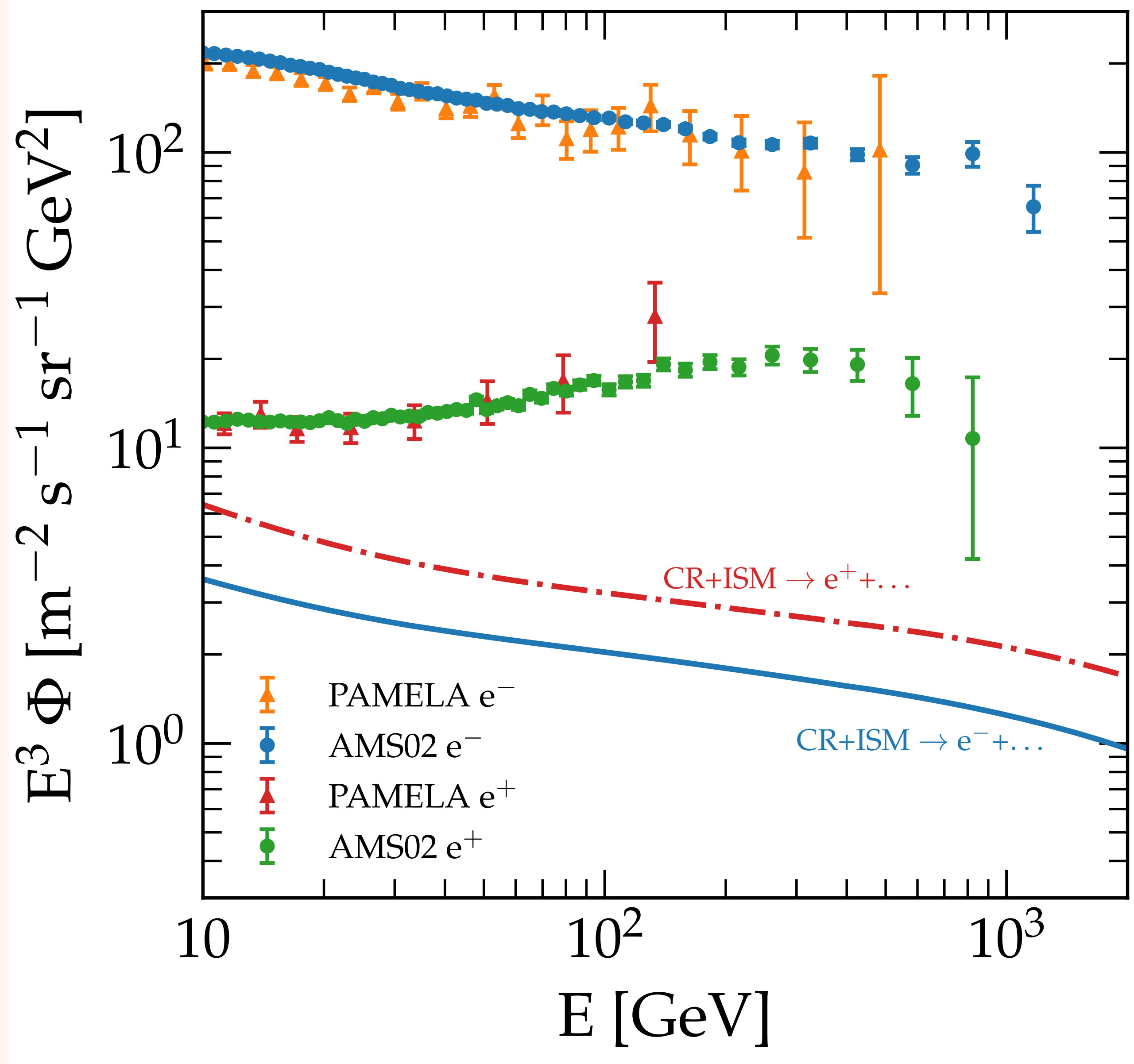
PULSAR WIND NEBULAE

IDEAL ELECTRON-POSITRON FACTORIES

Papers by: Hooper, PB & Serpico, 2008; Grasso et al. 2009; PB & Amato 2010, 2012, 2018

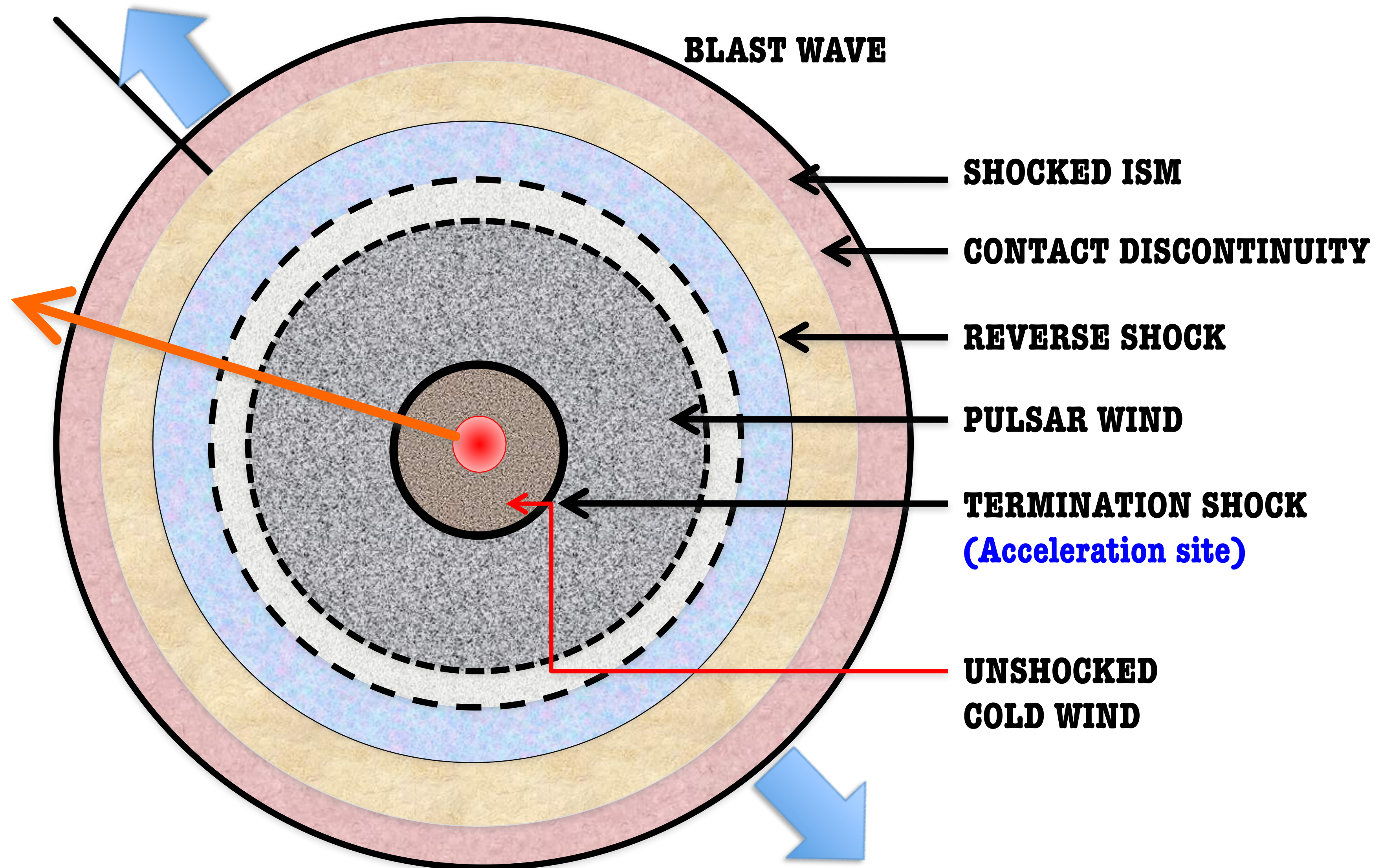# Pulsar wind launching
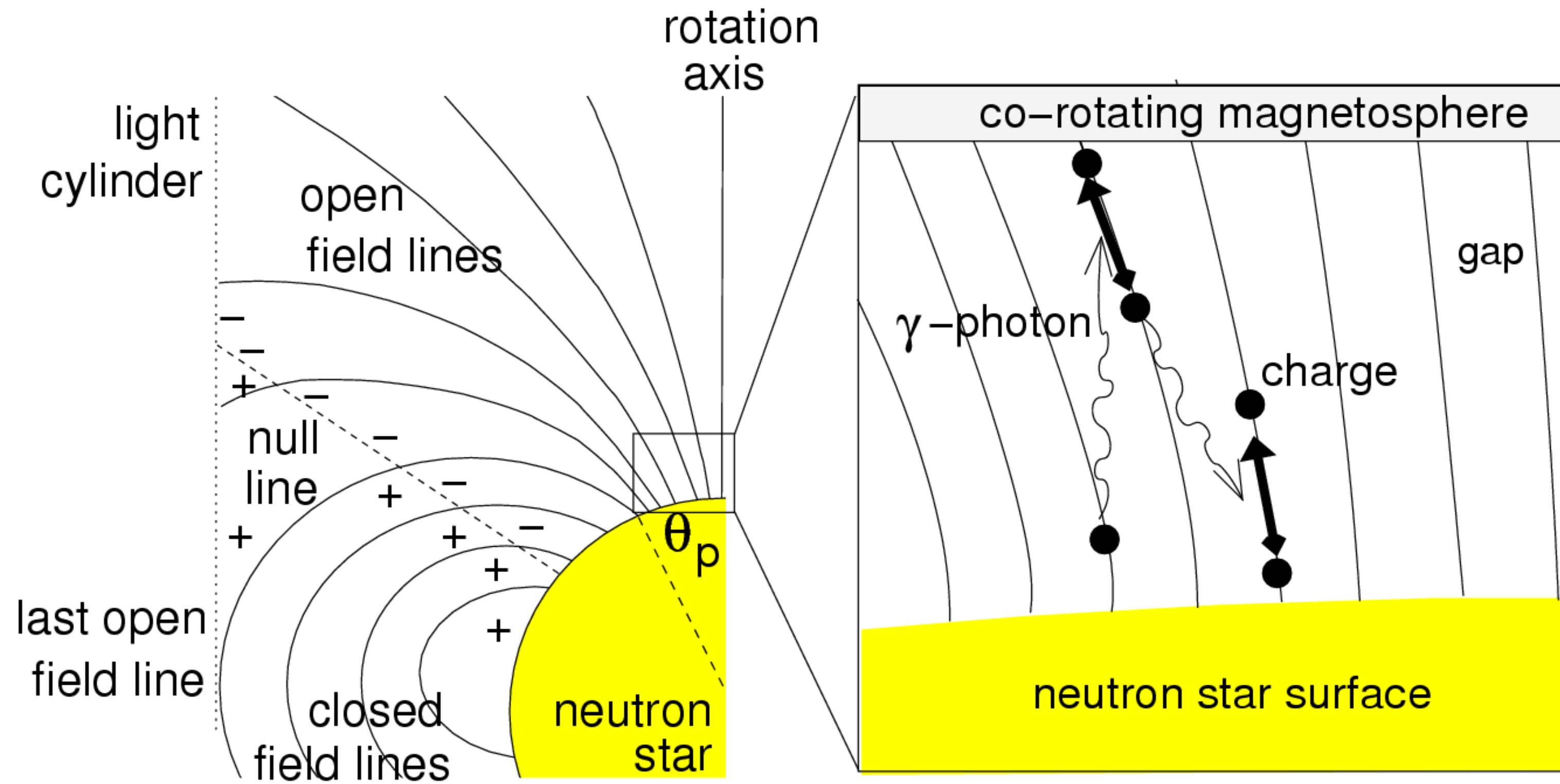
MORE ON THE MAGNETOSPHERE

open field lines

Ω

closed field lines

light cylinder

R_L
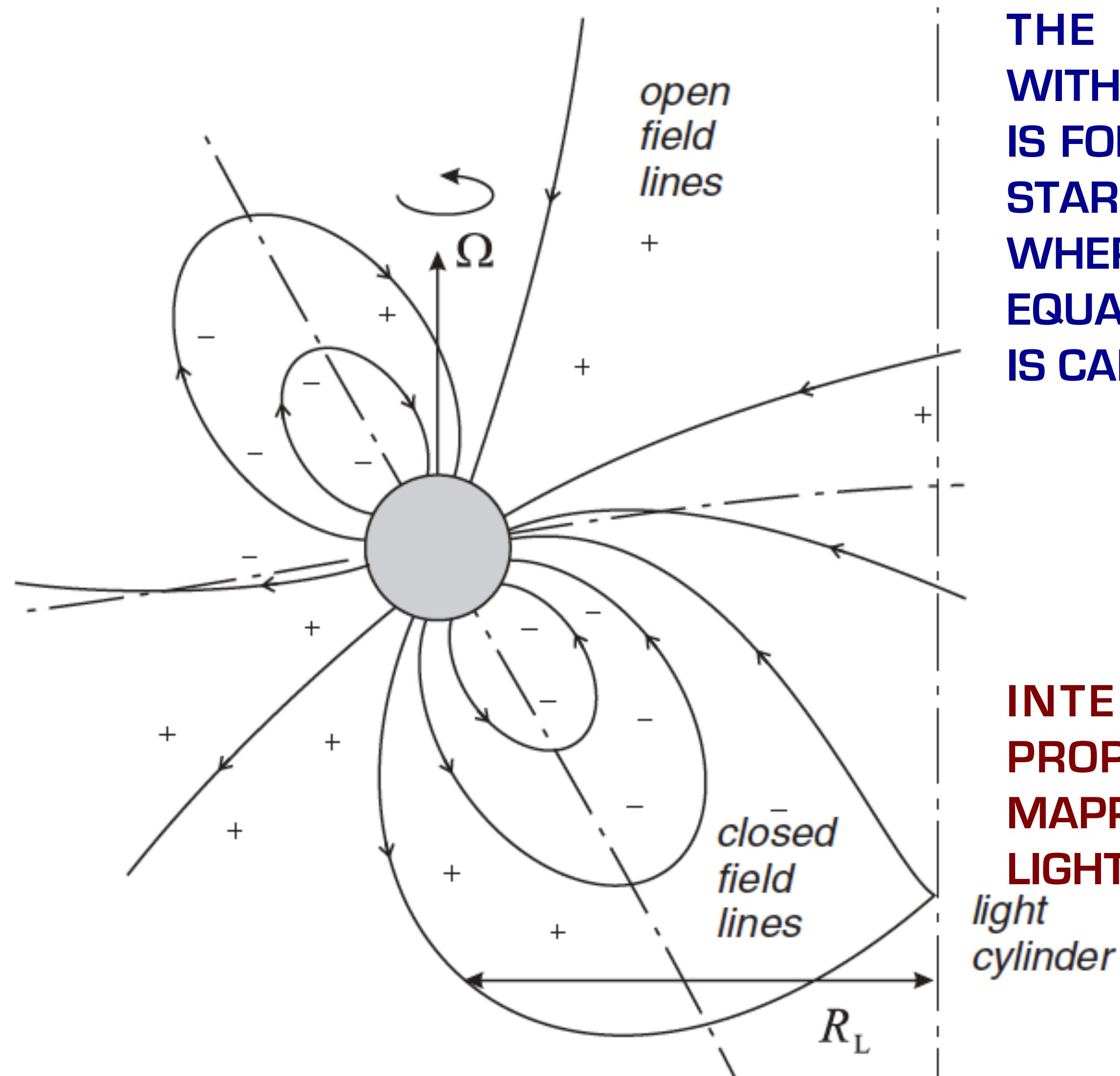
THE MAGNETOSPHERE, FILLED WITH ELECTRON-POSITRON PAIRS IS FORCED TO COROTATE WITH THE STAR, AT LEAST OUT TO THE POINT WHERE THE CO-ROTATION SPEED EQUALS THE SPEED OF LIGHT. THIS IS CALLED THE LIGHT CYLINDER:
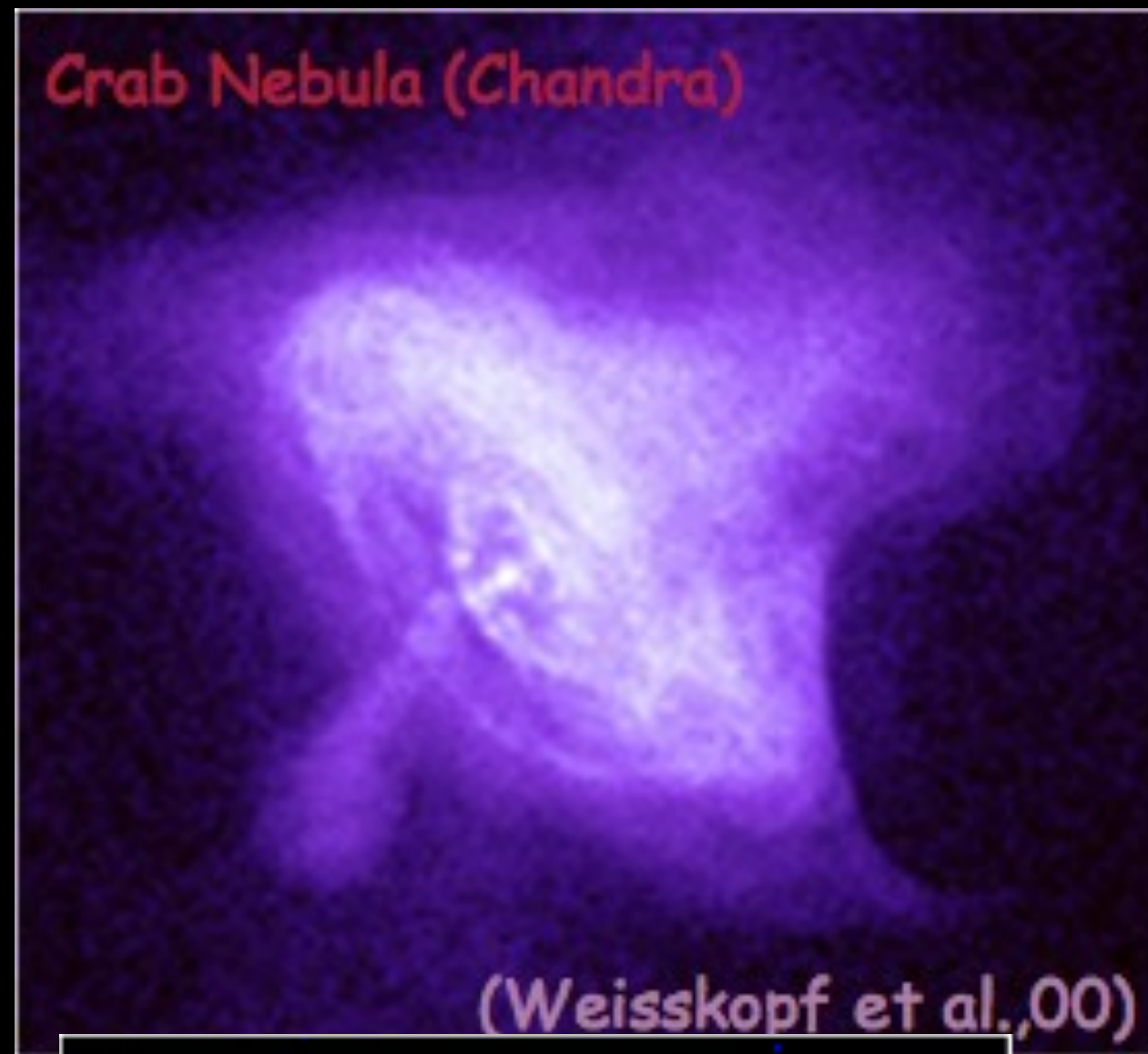
$$R_{\mathrm{L}} = \frac{c}{\Omega}$$

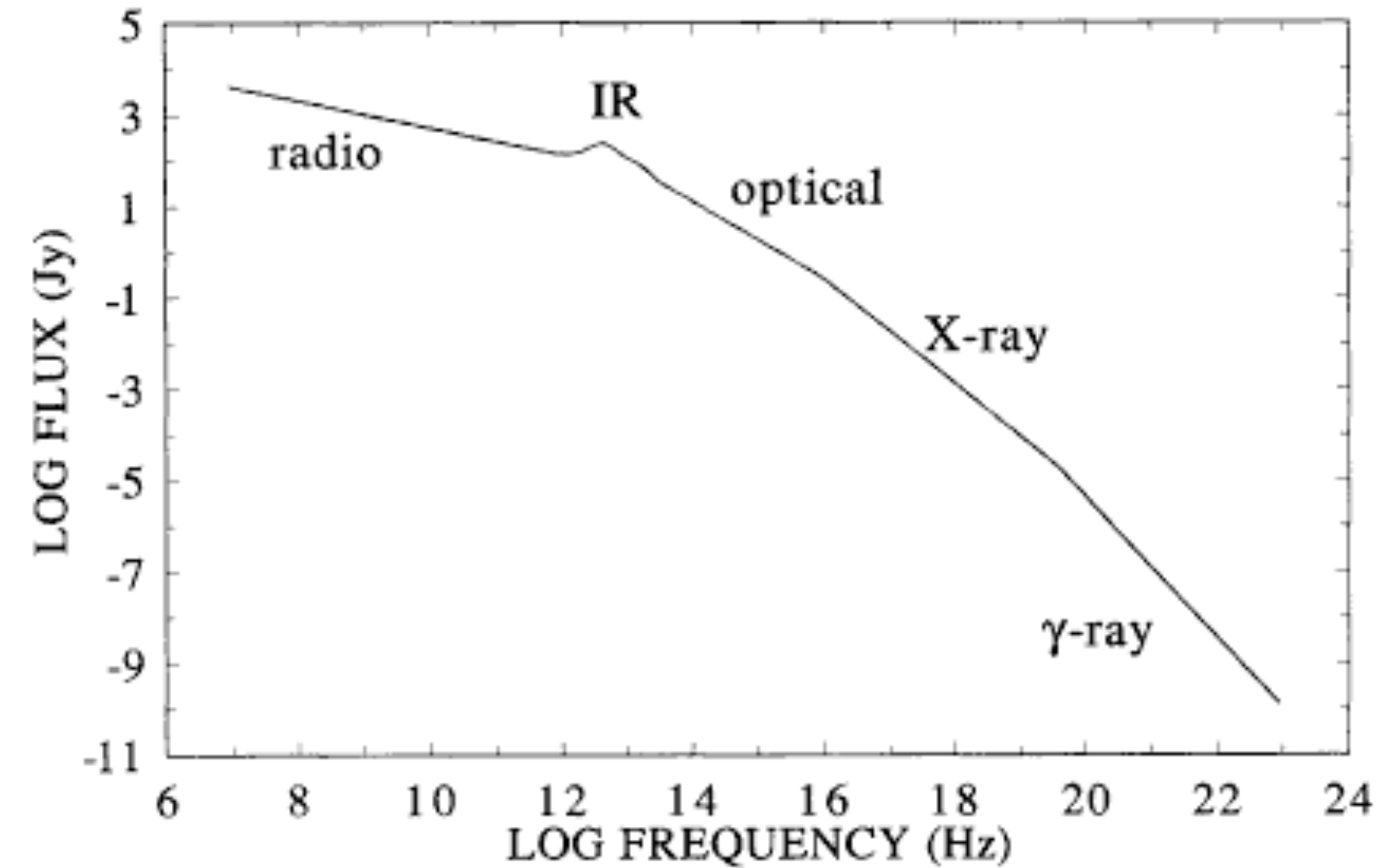INTERESTINGLY ENOUGH, ALL PROPERTIES OF THE PWN ARE MAPPED INTO PROPERTIES OF THE LIGHT CYLINDER

A SCHEMATIC VIEW OF A PWN

BLAST WAVE

SHOCKED ISM

CONTACT DISCONTINUITY

REVERSE SHOCK

PULSAR WIND

TERMINATION SHOCK
(Acceleration site)

UNSHOCKED
COLD WIND

COMPLEX MORPHOLOGIES

THE STEREOTYPICAL PWN

Combined IR, optical and X-ray data
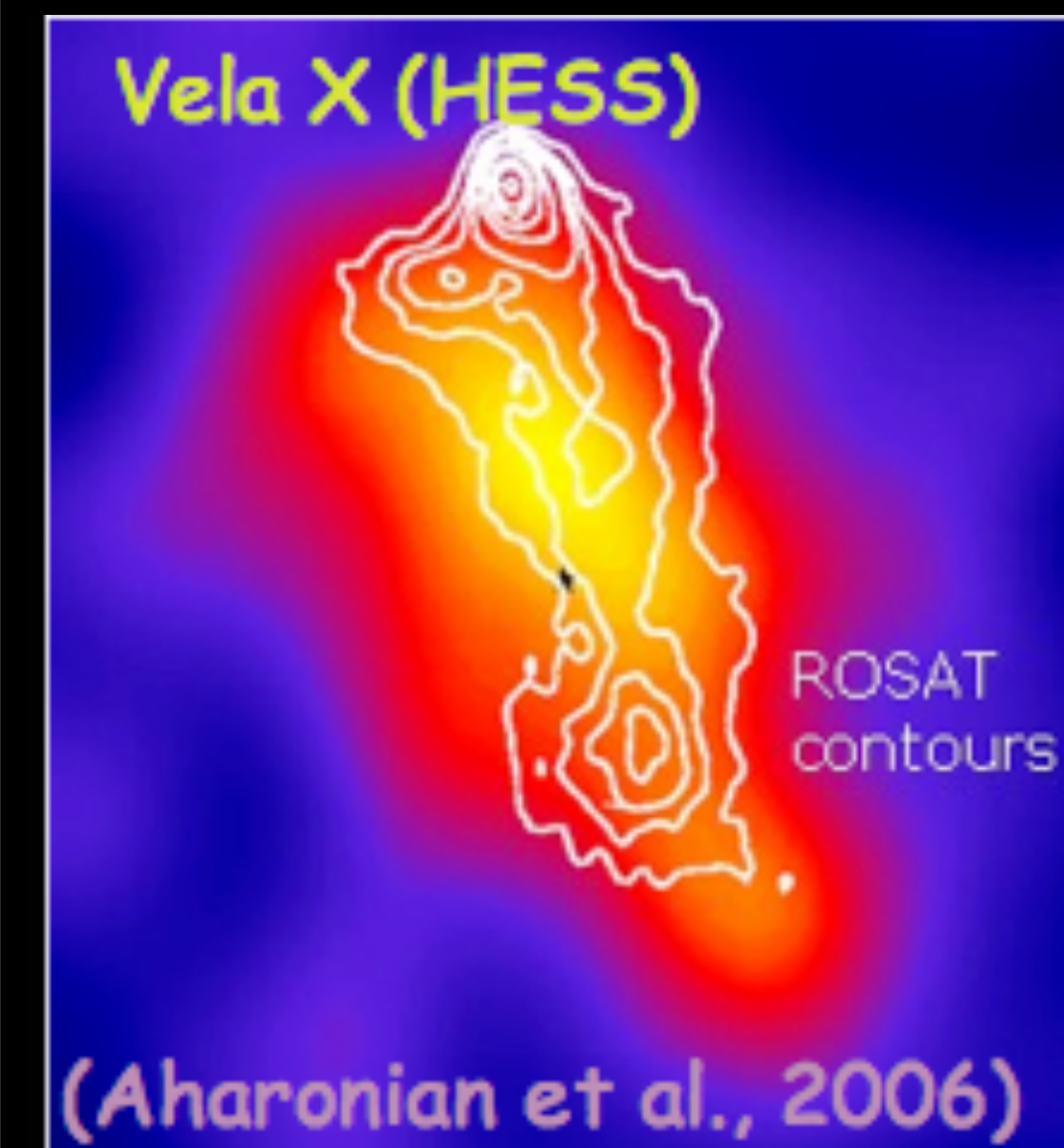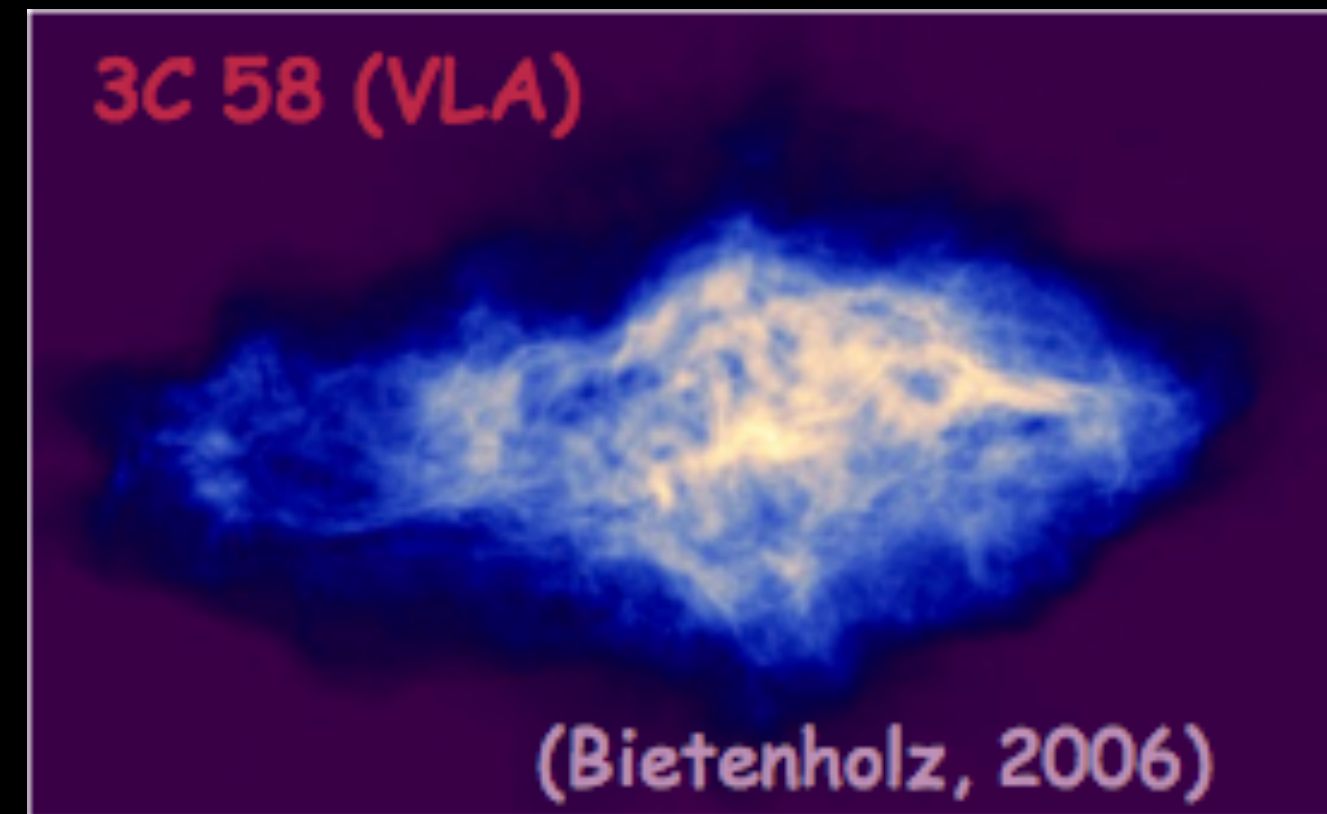
Primary emission mechanism is synchrotron radiation by relativistic particles in an intense (>few x 100 B_{ISM}) ordered (high degree of radio polarization) magnetic field

That a fast rotating Neutron Star could be the powering engine of the Crab was suggested before Pulsar discovery by Franco Pacini in 1967.

NS KICKS: ESCAPE THE REMNANT
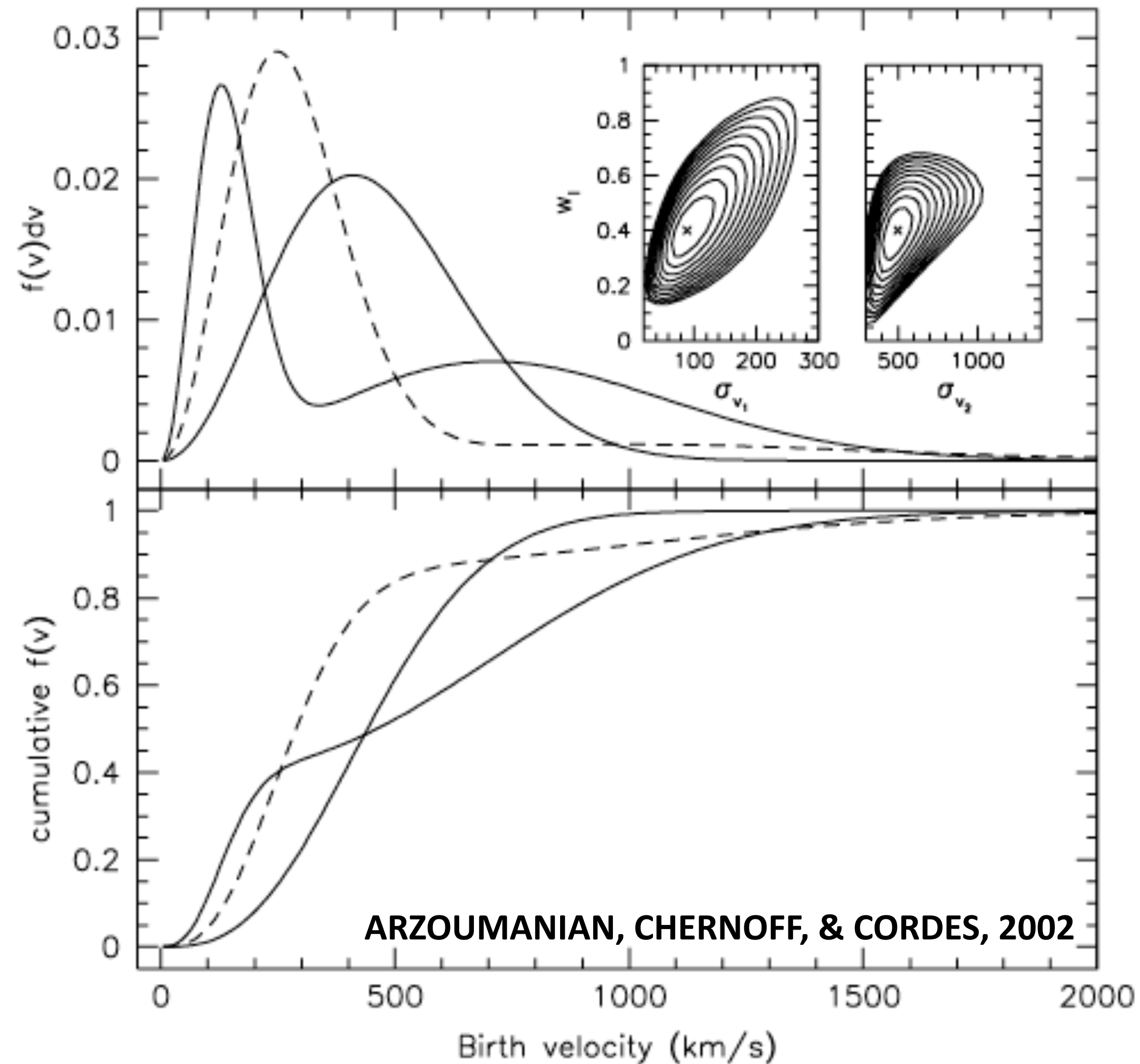
FOR TYPICAL VALUES OF PARAMETERS
THE NS LEAVES THE SNR ABOUT
40,000 years AFTER EXPLOSION

ARZOUMANIAN, CHERNOFF, & CORDES, 2002

Spectra in bow shock nebulae
Still spinning after escaping the SNR

IN THE TWO CASES of BSN OUTSIDE A SNR IN WHICH WE HAVE RADIO MEASUREMENTS WE INFER A SPECTRUM OF ACCELERATED PARTICLES WITH SLOPE ~-1.5

PSR J1509–5850
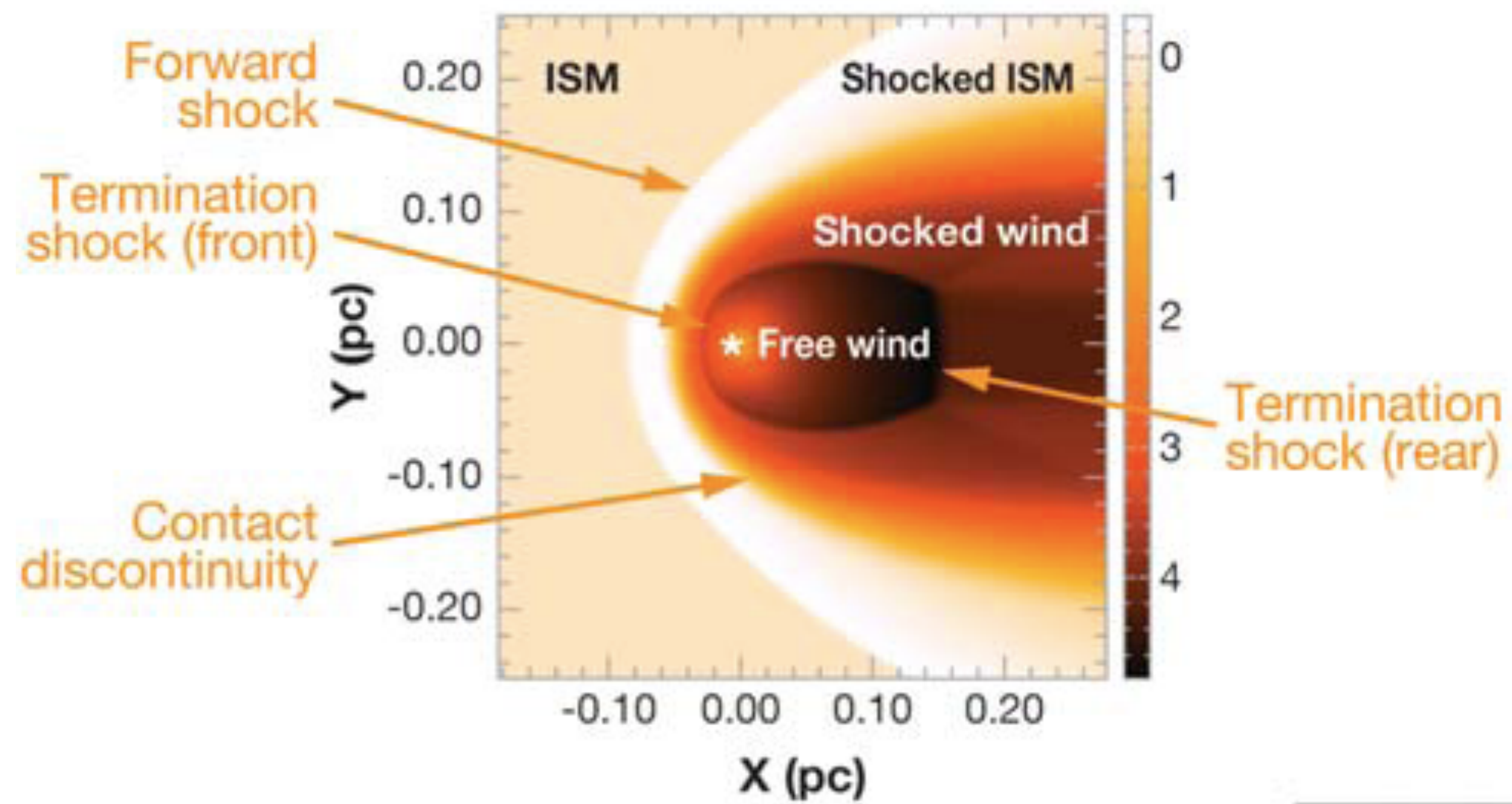**Slope radio: -0.26**
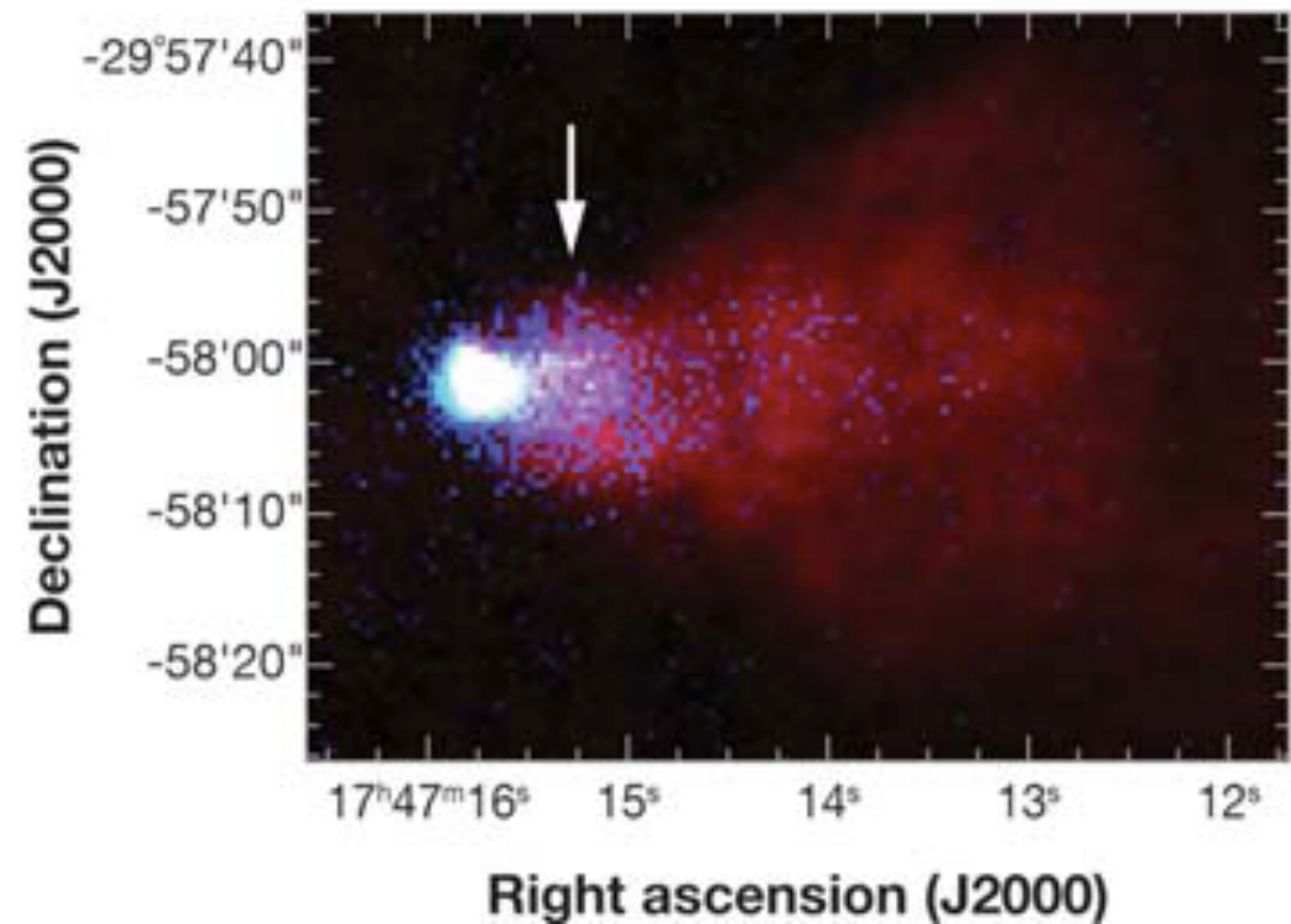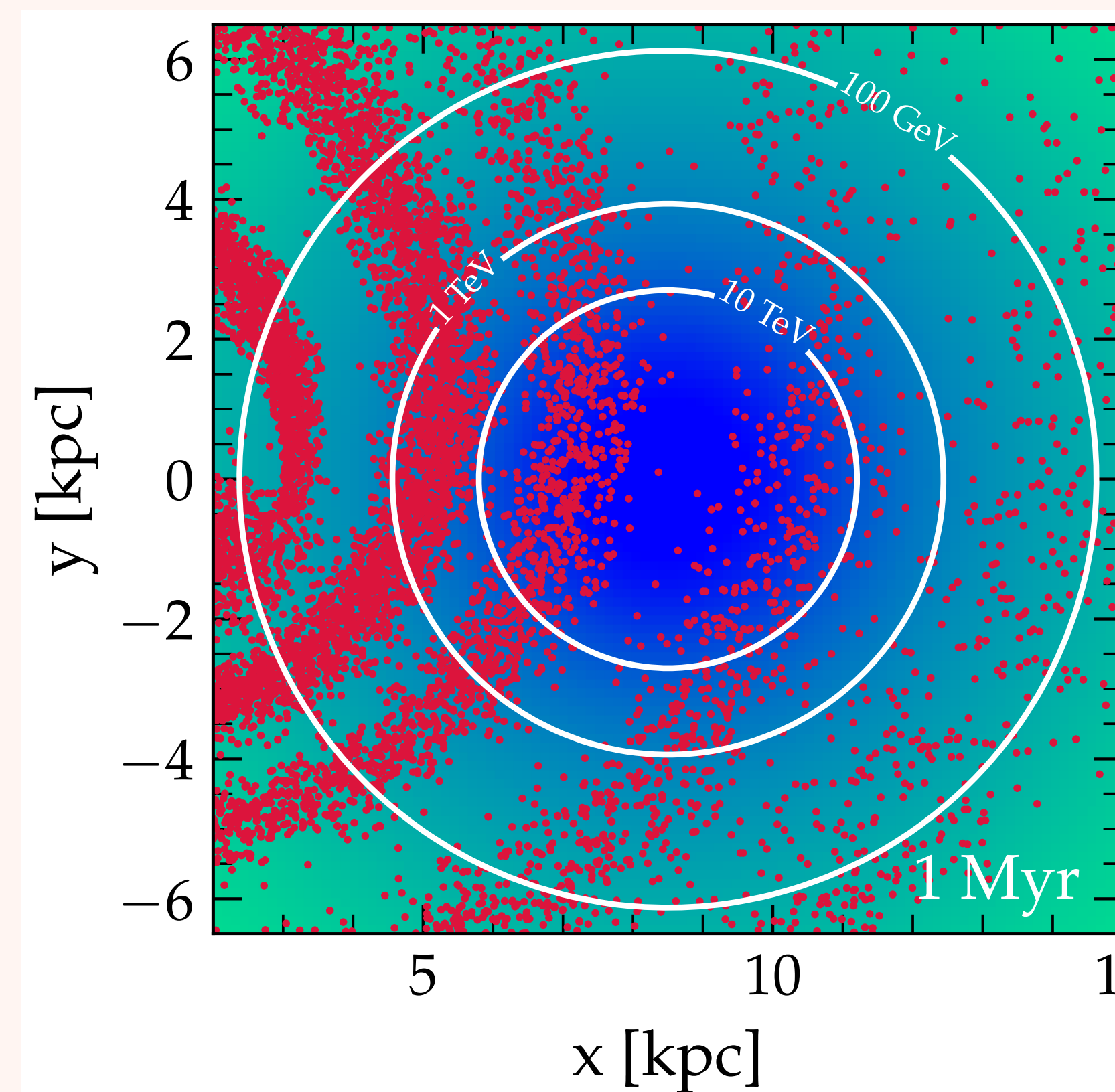**Slope Electrons: -1.52**
Ng et al. 2010

The Mouse
Slope radio: -0.3
Slope Electrons: -1.6
Gaensler et al. 2004

Forward shock
Termination shock (front)
Contact discontinuity
Termination shock (rear)

ISM
Shocked ISM
Shocked wind
Free wind

Y (pc)
X (pc)

Slane & Gaensler 2006

Declination (J2000)
Right ascension (J2000)

LEPTONS AND ENERGY LOSSES

Left panel: $E^3\Phi$ [$\mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,GeV^2}$] versus E [GeV].

Legend:
- SNR + secondary (red dashed)
- total (red solid)
- No KN ($\gamma = 2.38$) (green dash-dot)
- 2-σ (shaded)
- PAMELA e^-
- AMS-02 e^-

$H = 5$ kpc
$\mathcal{R}_{\mathrm{SN}} = 3/\mathrm{century}$
$\gamma_{\mathrm{SNR}} = 2.58$
$E_{\mathrm{C}} = 36$ TeV

Right panel: $e^+ / (e^+ + e^-)$ versus E [GeV].

Legend:
- 2σ (shaded)
- PAMELA
- AMS-02
- Fermi-LAT

Evoli et al. 2021
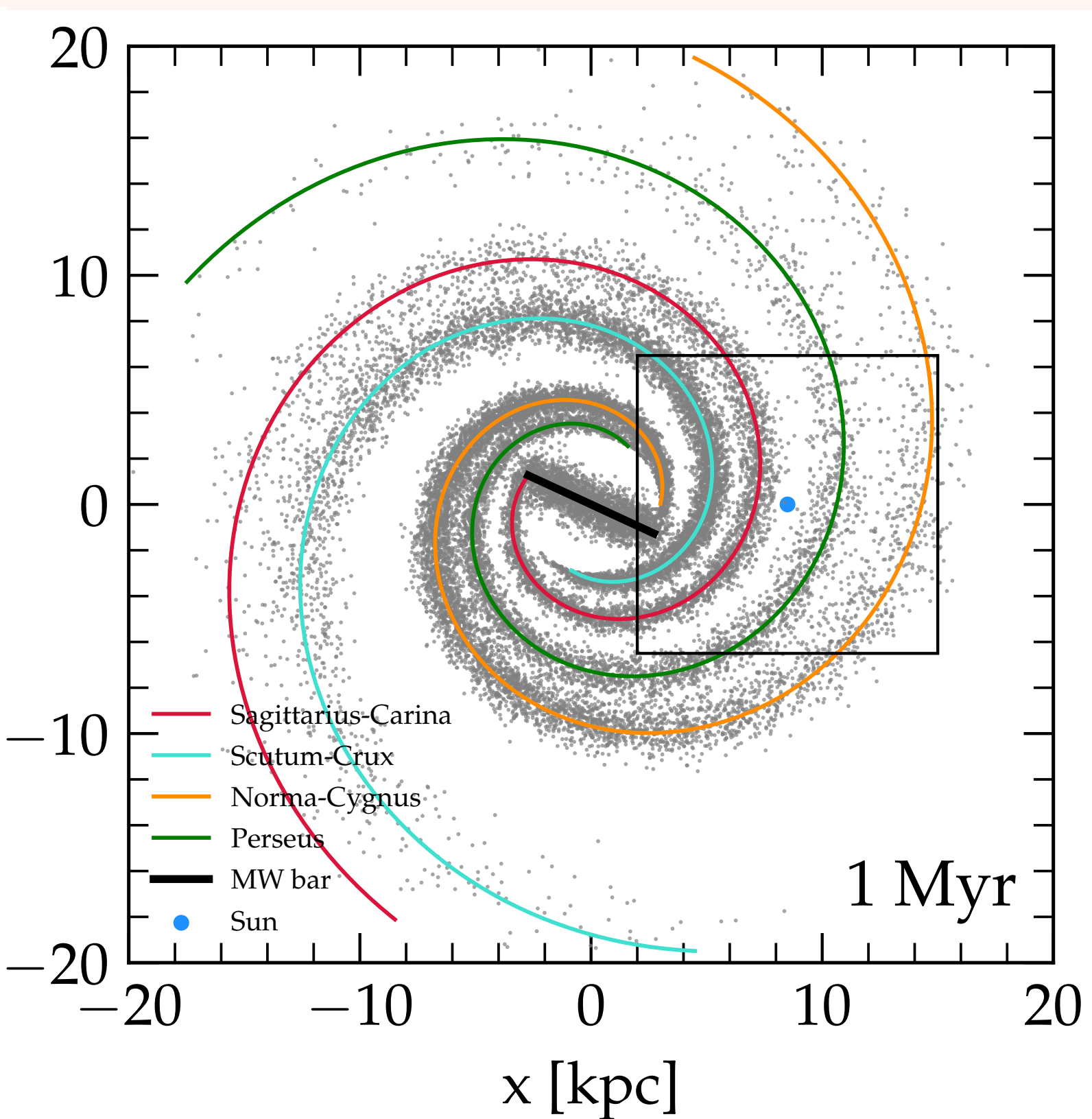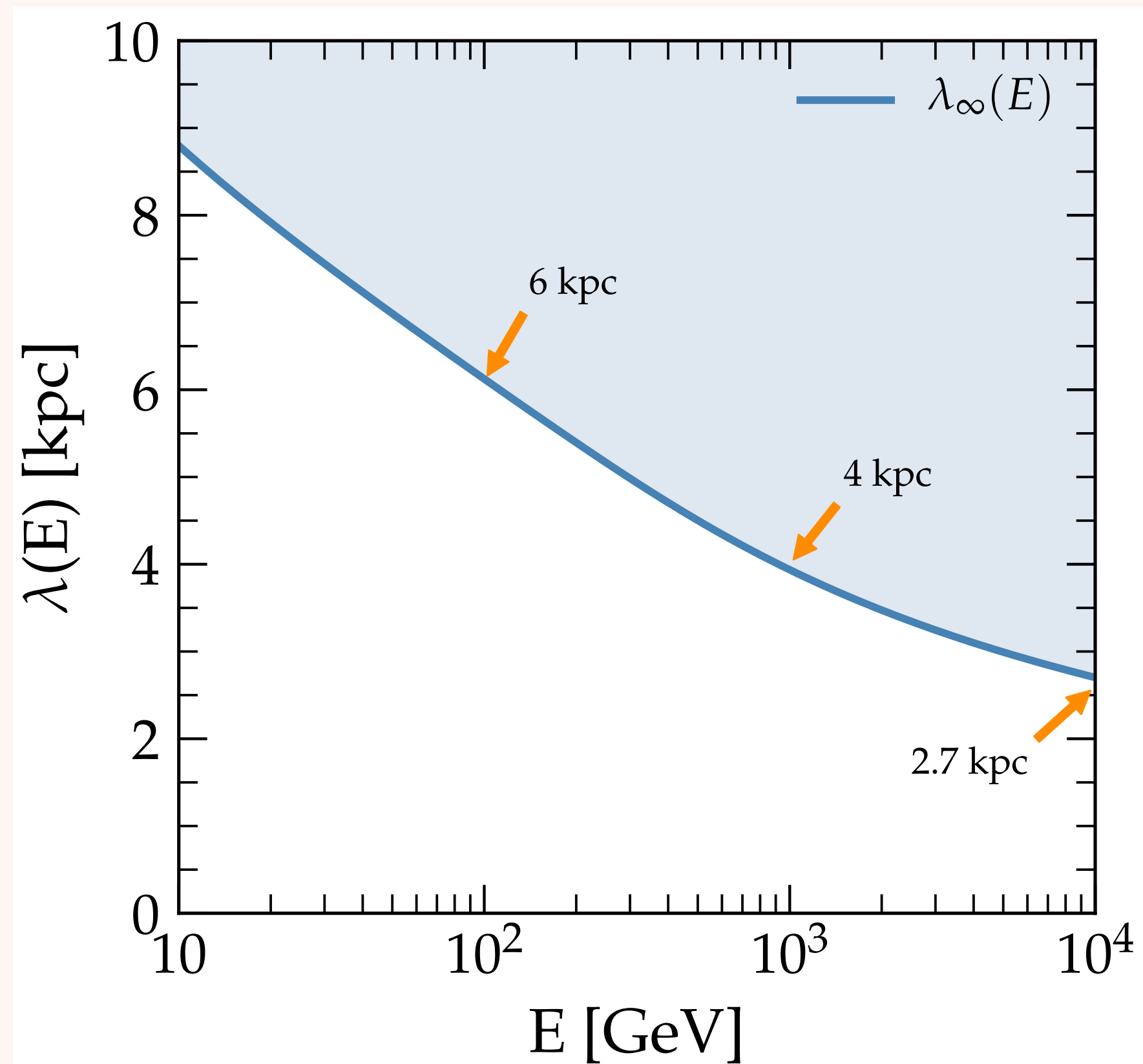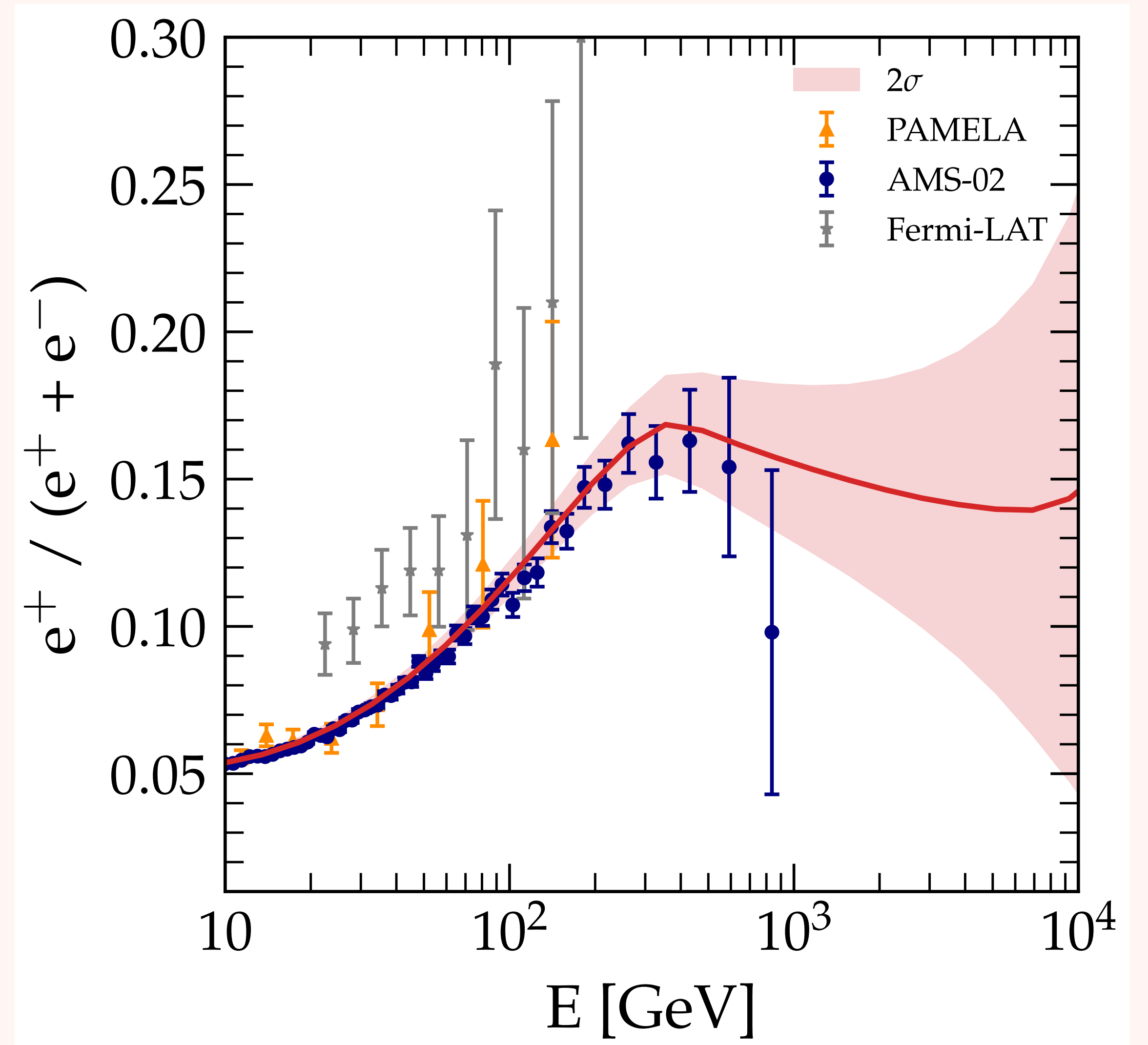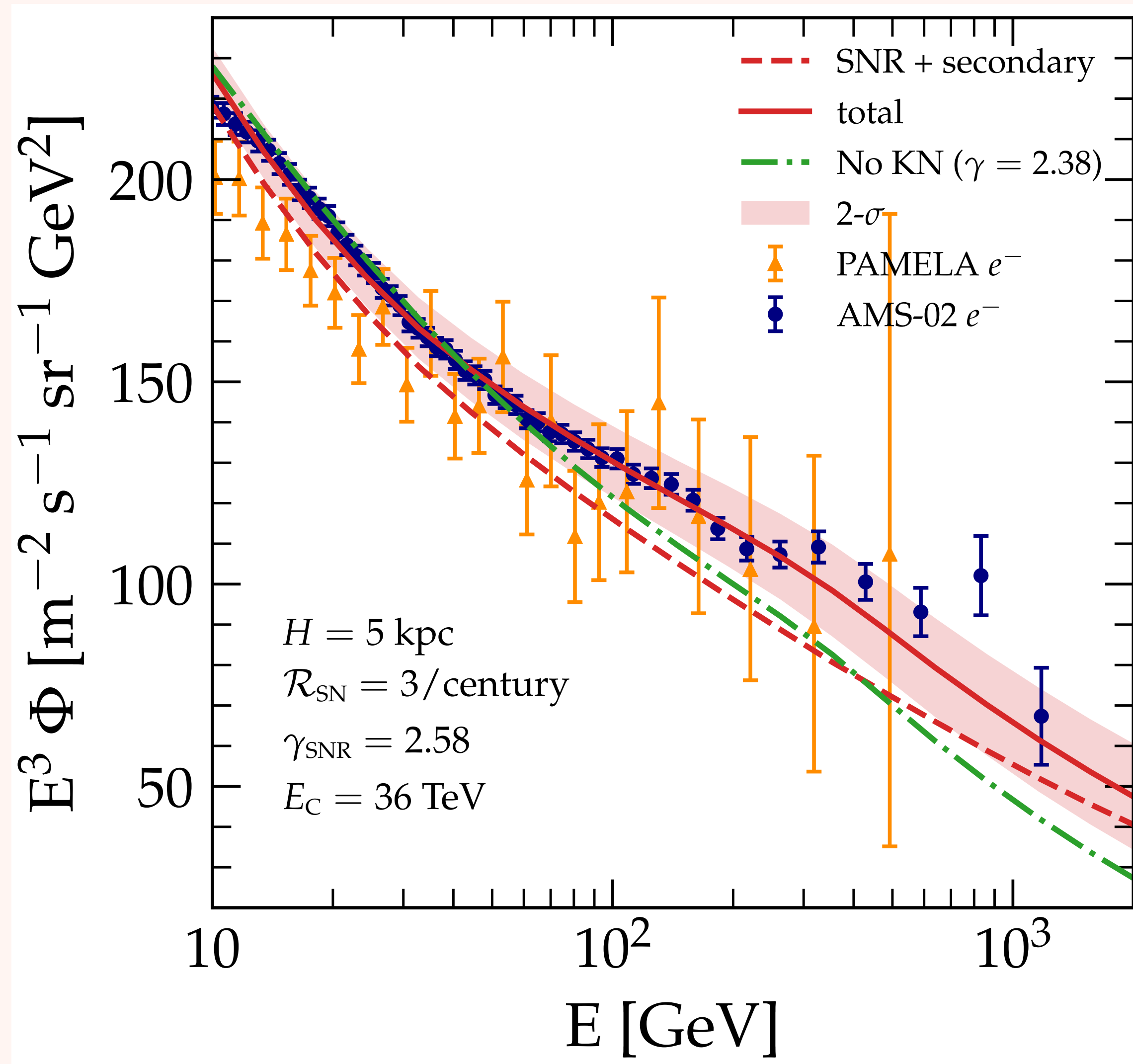
ACCELERATION IN THE WINDS OF STELLAR CLUSTERS

THE BUBBLE OF STELLAR CLUSTERS

Shocked ISM

ISM

Shocked stellar wind

Termination shock

u_2

u_1

R_c

R_s

$R_{cd} \simeq R_{fs} = R_b$
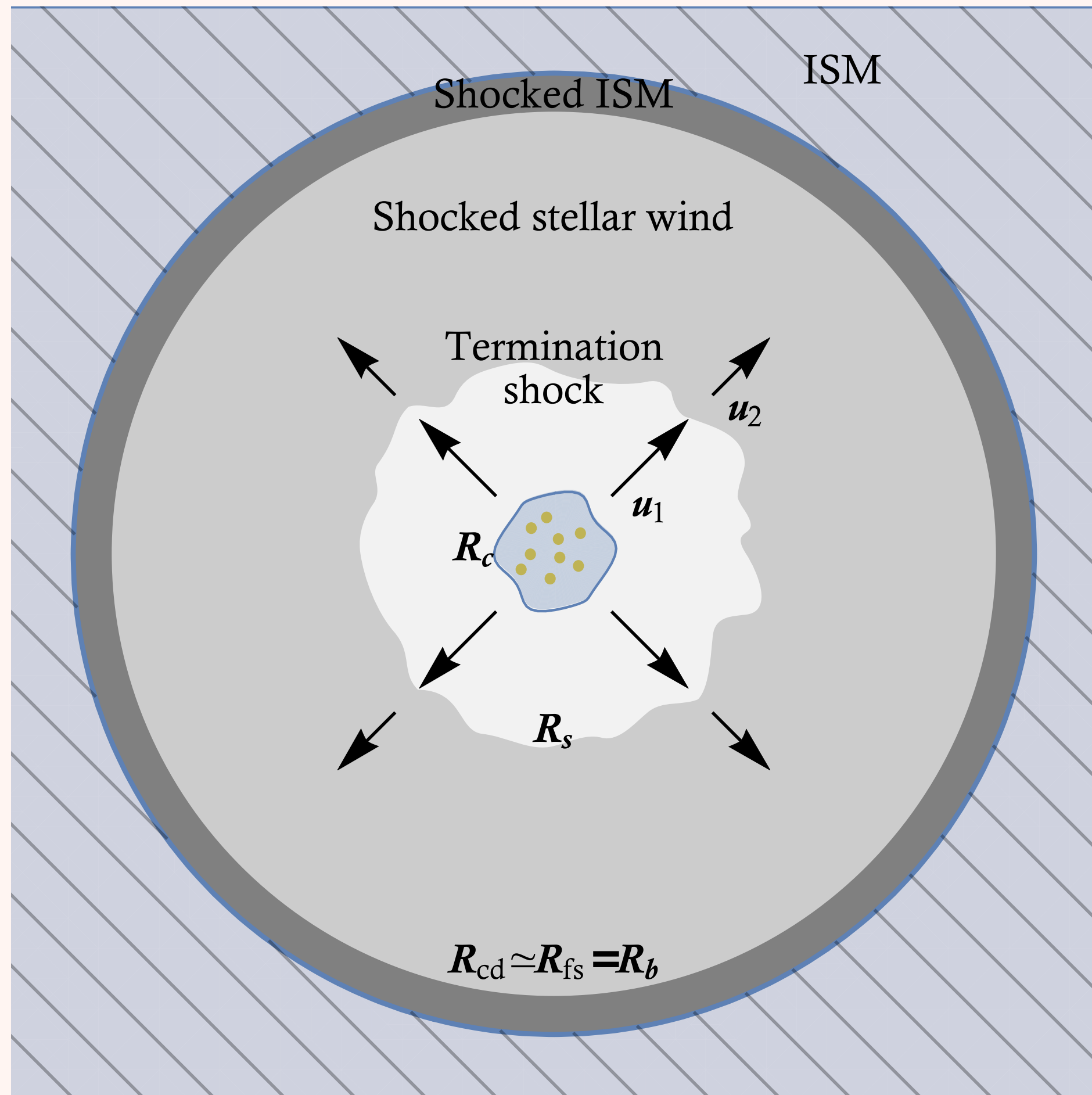
THE RAM PRESSURE OF THE COLLECTIVE WINDS OF A STAR CLUSTER EXCAVATES A BUBBLE OF ~100 pc

INSIDE THE BUBBLE A STANDING TERMINATION SHOCK IF FORMED WHERE PARTICLE ACCELERATION CAN TAKE PLACE

THE MAXIMUM ENERGY DEPENDS STRONGLY ON THE WIND VELOCITY

FOR SHOCKS WITH V>3000 Km/s PeV ENERGIES CAN BE REACHED

$$E_{\max} \approx 4 \times 10^{14} \, \eta_B^{1/2} \dot{M}_{-4}^{4/5} v_8^{13/5} \rho_1^{-3/10} t_{10}^{2/5} \left(\frac{L_c}{2\mathrm{pc}} \right)^{-1} \mathrm{eV}$$

THE MICROPHYSICS OF CR INTERACTIONS

See also presentation by O. Pezzi

A NOVEL VIEWPOINT

Whether we think about particle acceleration or transport in the Galaxy or on cosmological distances or near a gamma ray burst or a supernova the non thermal particles behave as a bunch of charged particles in motion —> A CURRENT propagating in a plasma which is made in turn of charged particles

This simple consideration, that our group here has championed in the last few years, leads to a flood of implications:

- *THESE PARTICLES EXCITE COLLECTIVE EFFECTS WHICH, UNDER CERTAIN CONDITIONS, BECOME UNSTABLE*

- *THE INSTABILITY CAN CREATE COLLECTIVE E-M FIELDS WHICH IN TURN AFFECT THE CURRENT*

- *THE PERTURBED DISTRIBUTION OF PARTICLES STARTS HAVING A DYNAMIC EFFECT ON THE SURROUNDING MEDIUM*

- *THESE INSTABILITIES ARE THE REAL REASON WHY PARTICLES GET ACCELERATED AND DIFFUSE IN ANY MEDIUM!*

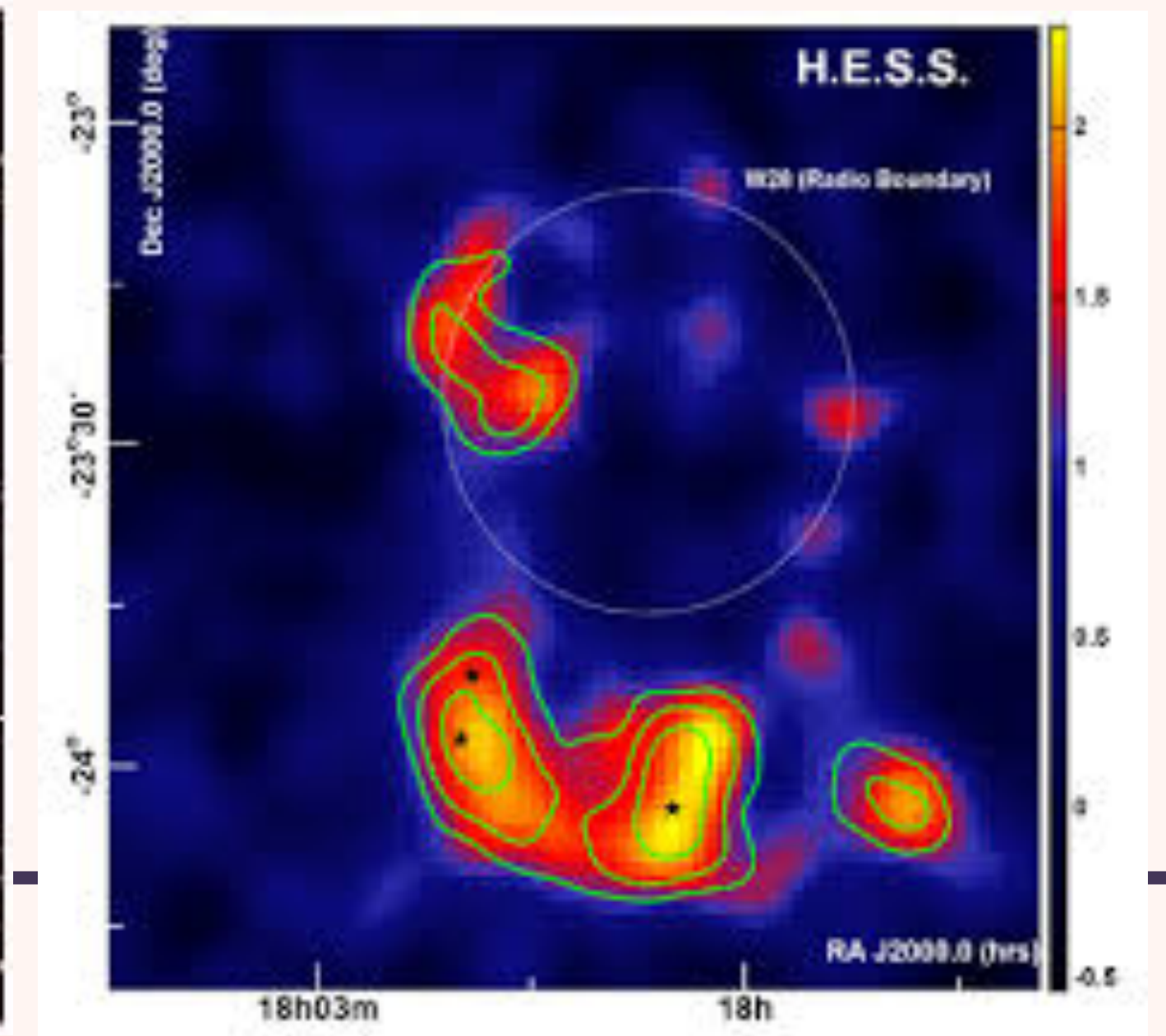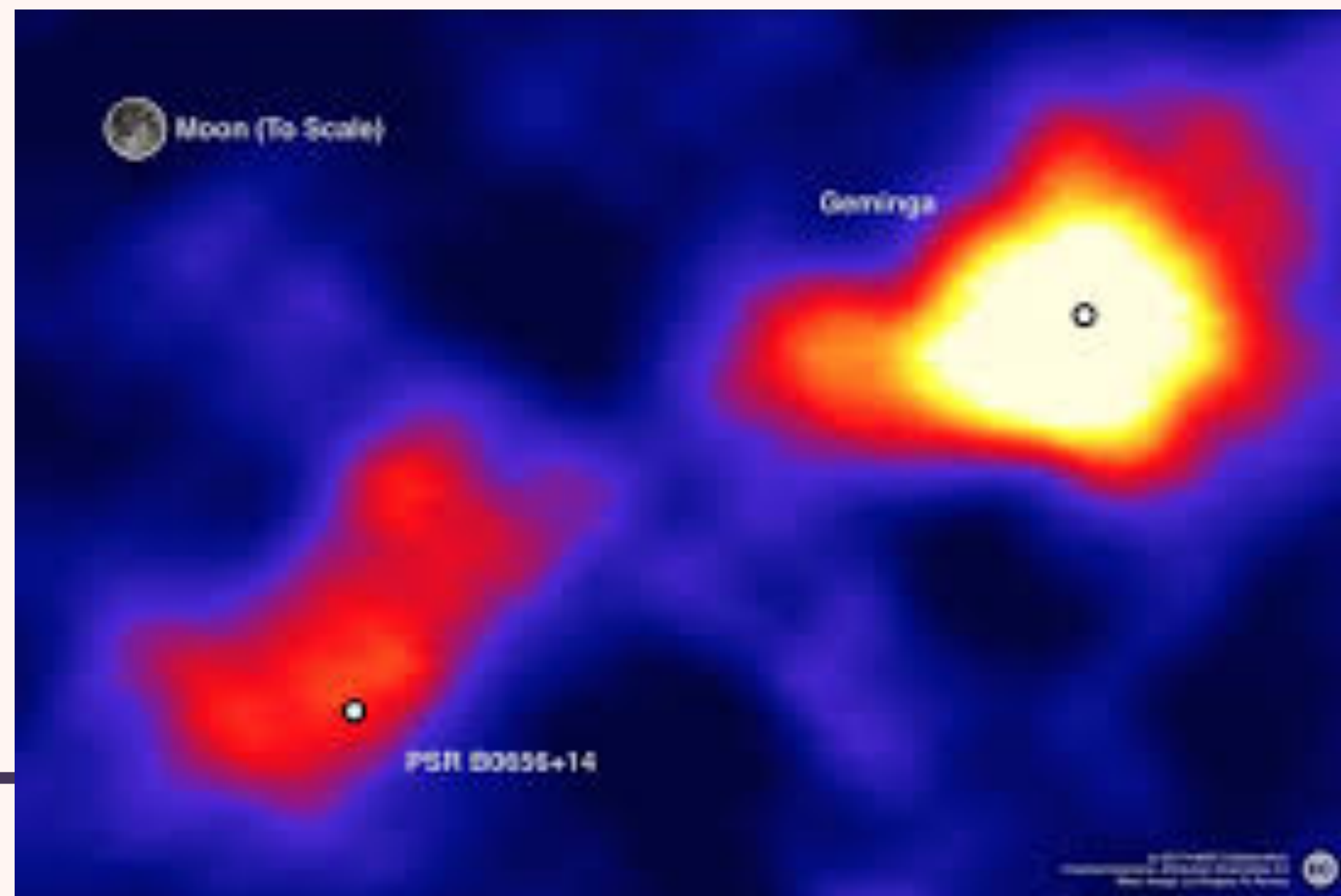- *CLOSE TO REGIONS WHERE THE CURRENTS ARE LARGER, DRAMATIC EFFECTS EXPECTED*

REDUCED DIFFUSIVITY AROUND SOURCES

INDEPENDENT SIGNATURES OR REGIONS OR REDUCED SENSITIVITY AOURND SOURCES (PULSARS, STAR CLUSTERS, SUPERNOVA REMNANTS)

PERHAPS COSMIC RAYS THEMSELVES ARE ABLE TO CAUSE THESE REGIONS

THE ACTION IS EASILY INDUCED BY THE STREAMING OF COSMIC RAYS THROUGH KINETIC INSTABILITIES **(D'angelo,PB&Amato+2015, 2016, 2018)**

OR A COMBINATION OF STREAMING AND HYDRODYNAMICS **(Schroer+2020, in preparation)**

A PICTORIAL VIEW

Local Magnetic Field

SOURCE

ELECTRIC CURRENT ASSOCIATED
WITH CR LEAVING THE SOURCE

If the energy density in CR escaping the source exceeds that in pre-existing magnetic field, a non resonant streaming instability gets excited

$$n_{CR}(> E)E \gtrsim \frac{B_0^2}{4\pi}$$

NR Instability

$$\gamma_{max}^{-1} \approx 1.1(\text{E}/2.5\text{TeV})^{-1} \text{ yr}$$

2D HYBRID SIMULATIONS OF THIS PHENOMENON
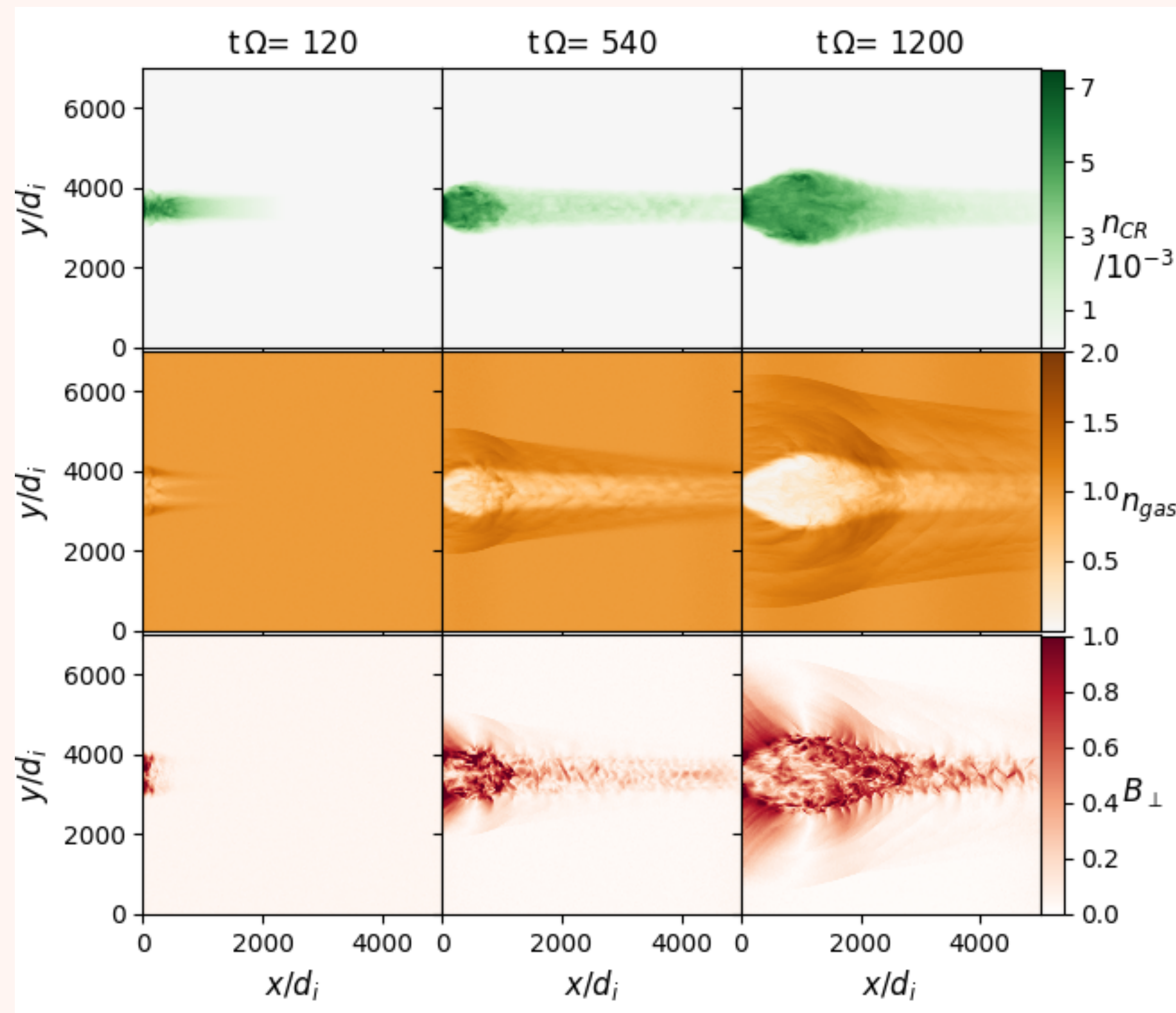
- THE EXCITATION OF THE INSTABILITY LEADS TO STRONG PARTICLE SCATTERING, WHICH IN TURN INCREASES CR DENSITY NEAR THE SOURCE

- THE PRESSURE GRADIENT THAT DEVELOPS CREATES A FORCE THAT LEADS TO THE INFLATION OF A BUBBLE AROUND THE SOURCE

- THE SAME FORCE EVACUATES THE BUBBLE OF MOST PLASMA

- THERE IS NO FIELD IN THE PERP DIRECTION TO START WITH, BUT CR CREATE IT AT LATER TIMES (**SUPPRESSED DIFFUSION, about 10 times Bohm)**

Schroer+, 2021, *Dynamical effects of cosmic rays leaving their sources*

2D HYBRID SIMULATIONS OF THIS PHENOMENON
STREAMING DOES INDEED SUPPRESS DIFFUSION
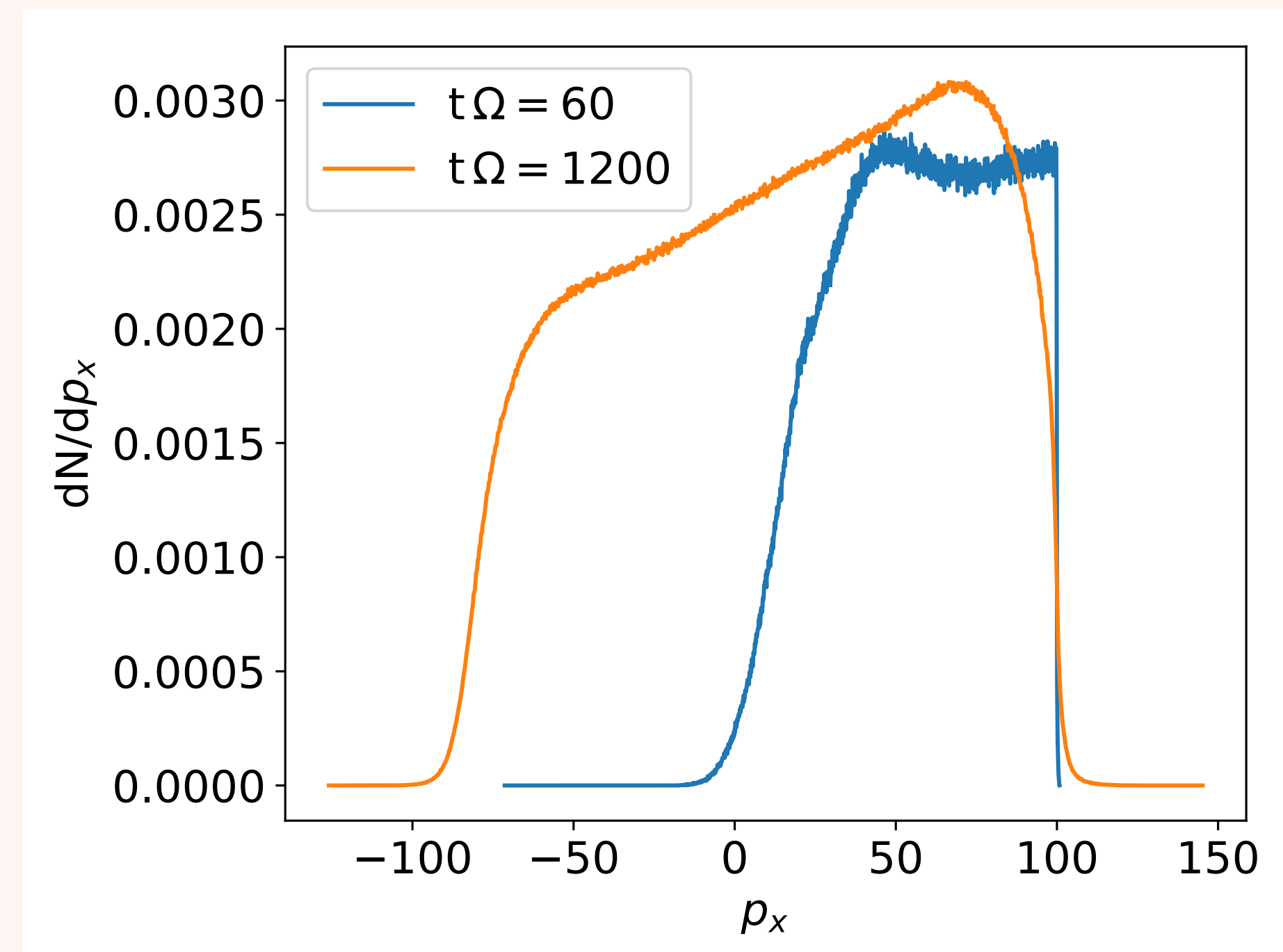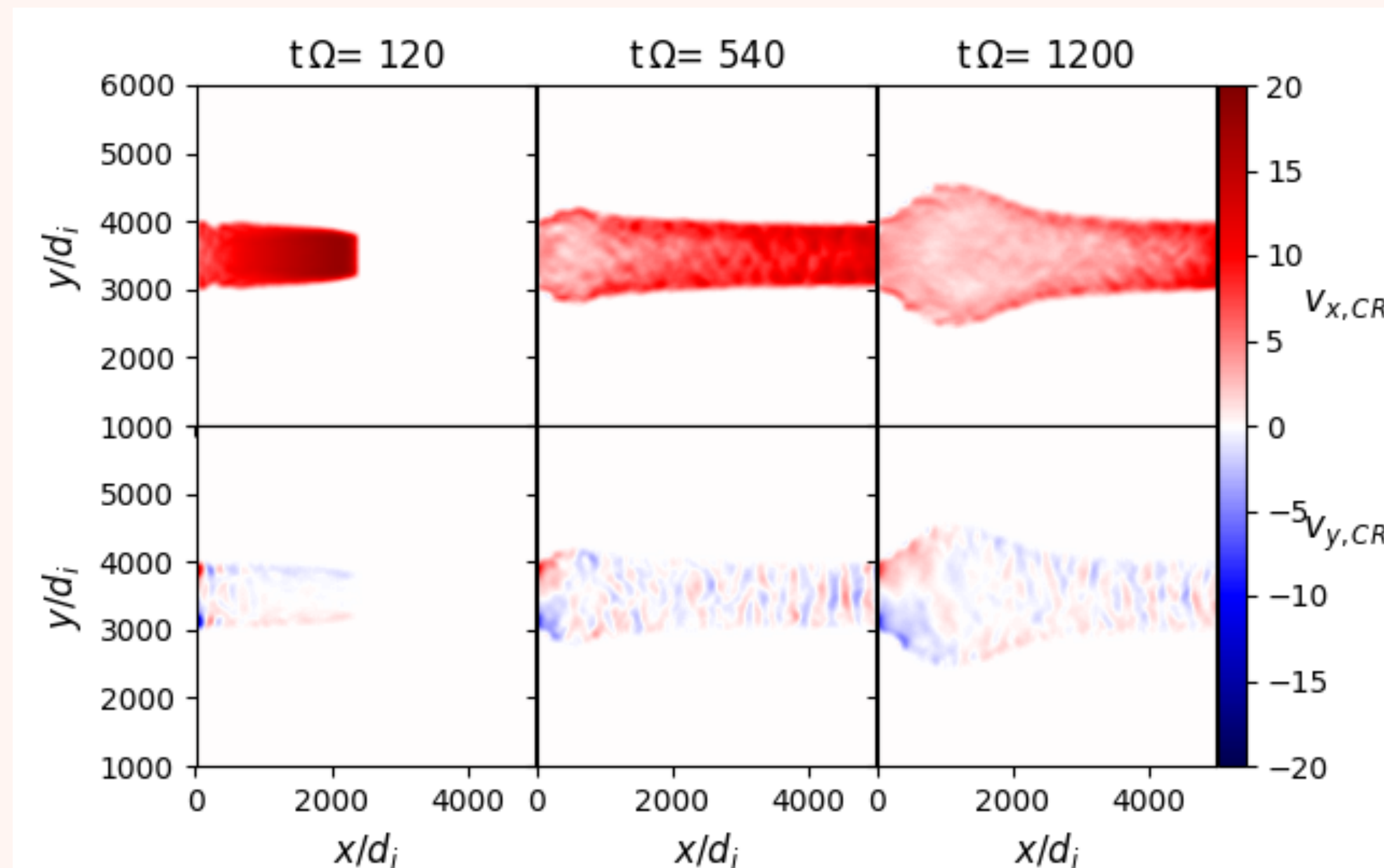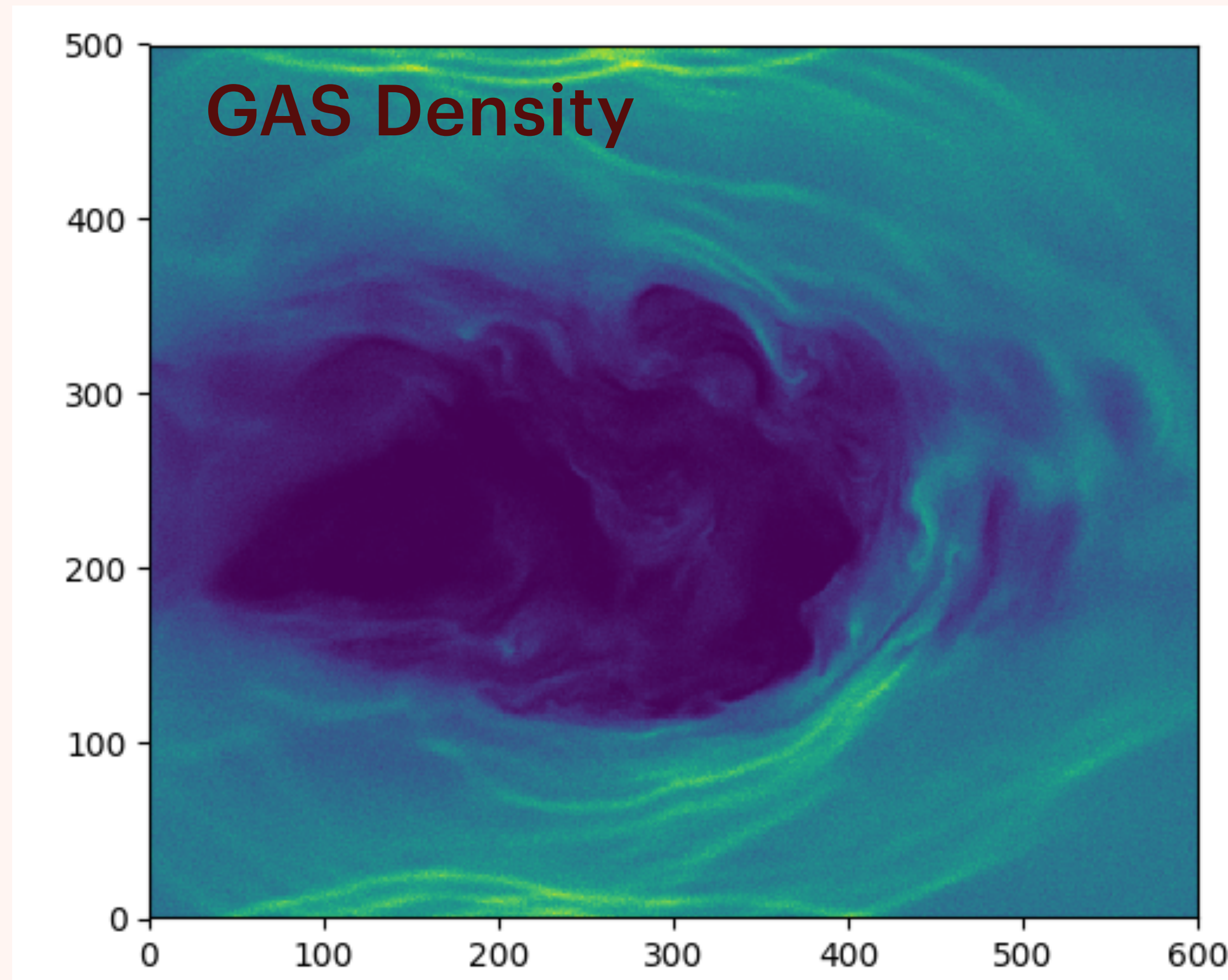
EXTENSION TO 3D SIMULATIONS
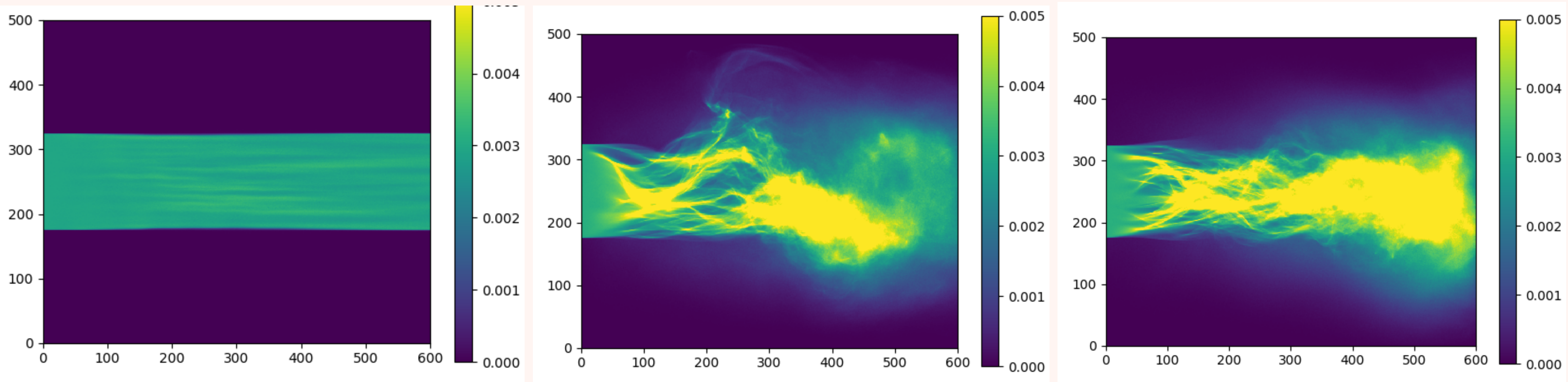
THE STREAM OF CR LEAVING THE CIRCUM-SOURCE REGION IS ABLE TO SELF-CONFINE ITSELF ON SHORT TIME SCALES

THE PRESSURE GRADIENT IN THE PERPENDICULAR DIRECTION MAKES THE STREAM EXPAND LATERALLY

THE REGION BECOMES OVERDENSE WITH CR AND SELF-PRODUCED MAGNETIC FIELDS
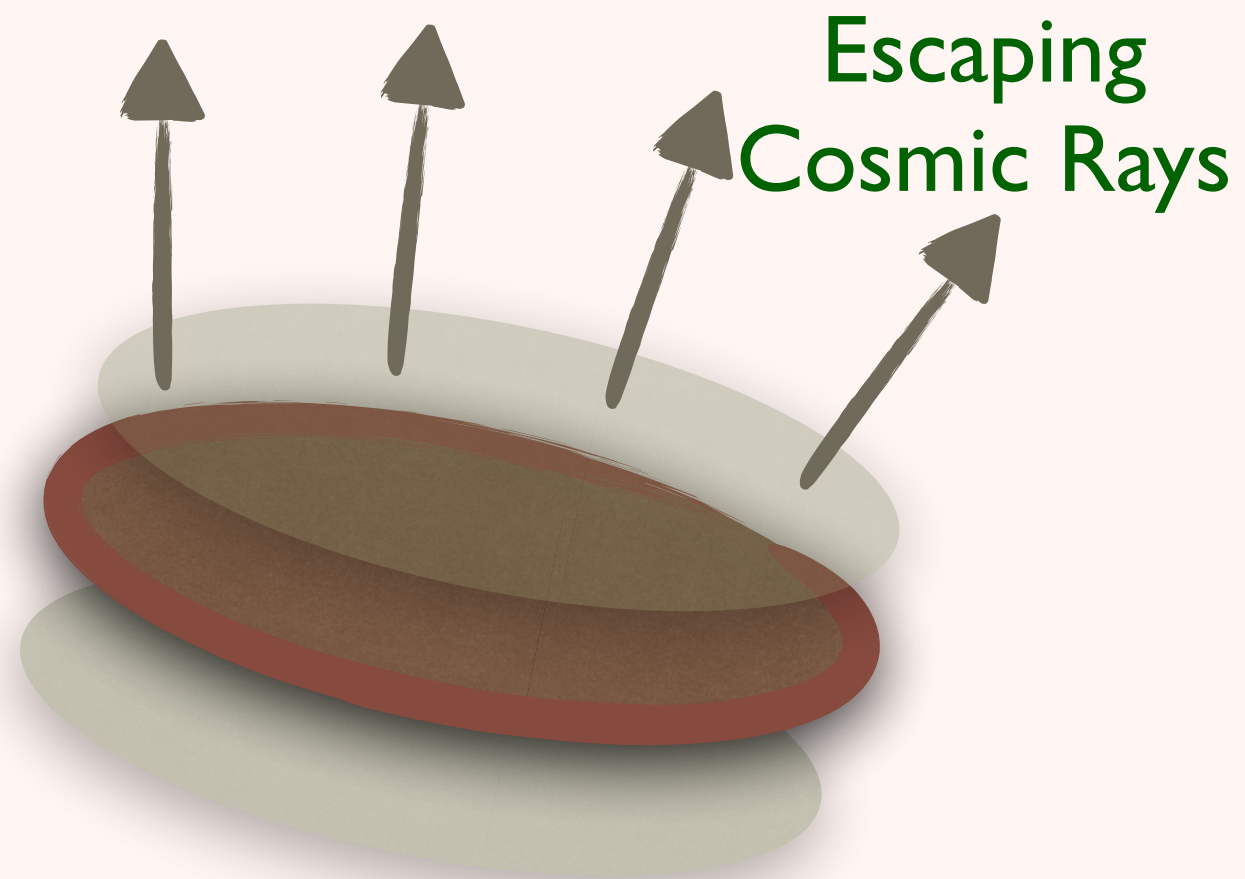
CR EXCAVATE MAGNETIZED BUBBLES AROUND SOURCES

GAS Density

Schroer + 2020

CR SELF CONFINE THEMSELVES DUE TO THE E-M PERTURBATIONS THEY GENERATE

AT THE SAME TIME THE PRESSURE GRADIENTS THAT DEVELOP INDUCE THE FORMATION OF CAVITIES AROUND SOURCES WHERE THE PLASMA DENSITY IS LOWERED

THE IMPLICATIONS OF THE EXISTENCE OF THESE CAVITIES FOR THE WHOLE PHENOMENOLOGY OF CR AND GAMMA RAY/ NEUTRINO PRODUCTION ARE GROUND BREAKING

DIFFERENT SCALES - SIMILAR PHENOMENON

Escaping Cosmic Rays

COSMIC RAYS ESCAPING THE GALAXY ON kpc SCALES CONSERVE THEIR CURRENT (CONSERVATION OF FLUX == LIOUVILLE THEOREM)

IF $\quad B_0 \leq B_{sat} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1}$ G
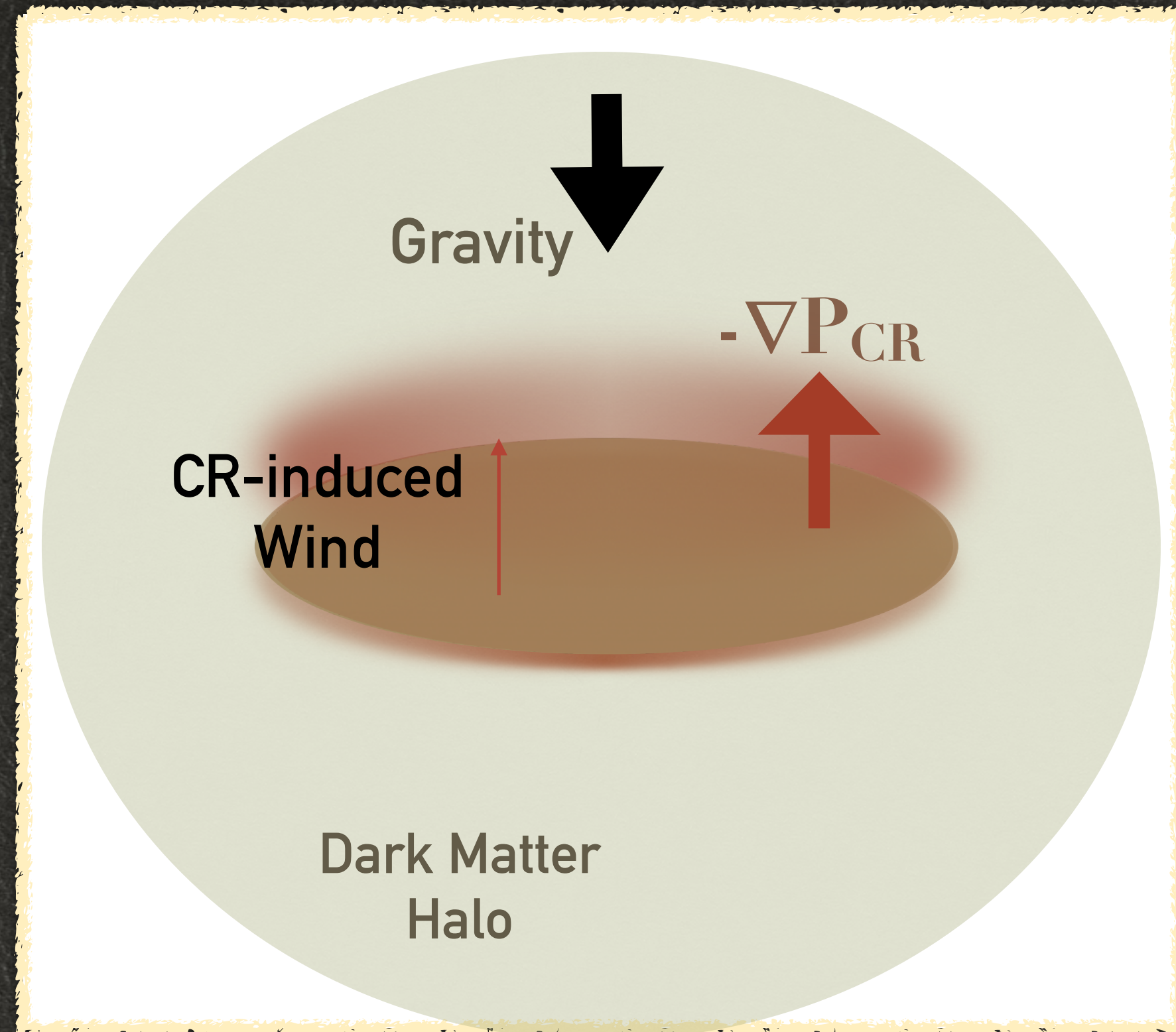
THEN THE SAME INSTABILITY GETS EXCITED AND LEADS TO GROWTH OF THE FIELD TO THIS VALUE

CR GET SELF-TRAPPED IN A BUBB;E AROUND THE GALAXY AND THEIR DENSITY GROWS. THIS PHENOMENON RESULTS IN ENHANCED NEUTRINO PRODUCTION
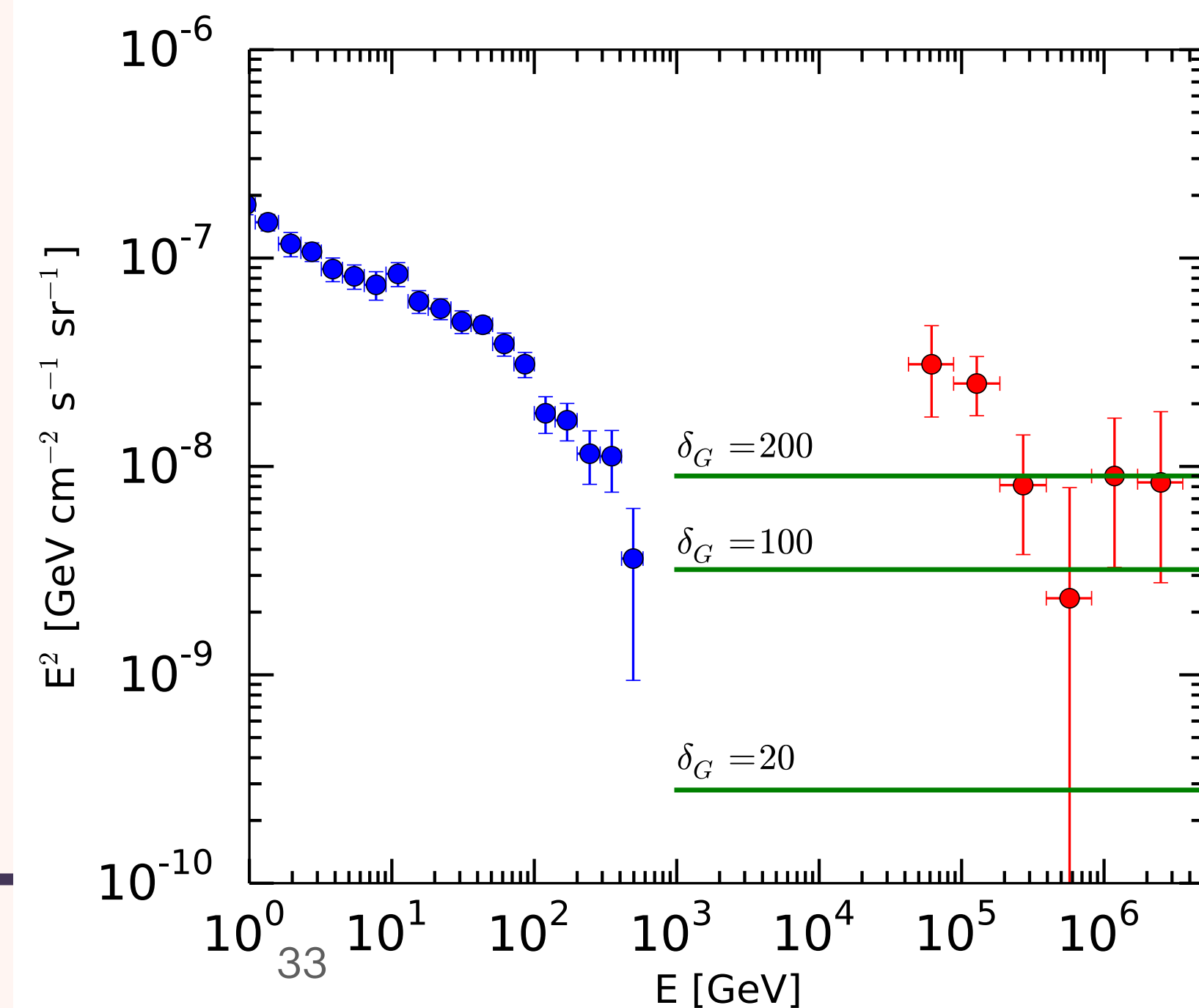
PB & Amato
Phys. Rev. Lett.122e1101B (2019)

CR DRIVEN WINDS

Cosmic Rays vs Gravity: CR driven winds

Aside from math, the Physics of the problem can be understood easily: There is a critical distance above (and below) the disc (which depends on particle energy) where diffusion turns into advection:

$$\frac{z^2}{D(p)} \simeq \frac{z}{u(z)} \rightarrow z_*(p) \propto p^{\delta/2} \qquad D(p) \sim p^{\delta}$$

Ptuskin et al. 1997

No fixed halo size H

$$f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{H}{D(p)} \sim E^{-\gamma-\delta} \qquad f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{z_*(p)}{D(p)} \sim E^{-\gamma-\delta/2}$$

STANDARD CASE   **CR-INDUCED WIND WITH SELF-GENERATION**

At high energy, the critical scale becomes larger than the size of the region where the geometry of the wind remains cylindrical, and a steepening of the spectrum should be expected

FUTURE

- UNPRECEDENTED RATE OF NEW AND OFTEN UNEXPECTED RESULTS IN THE FIELD

- IMPRESSIVE CONNECTION BETWEEN MICROPHYSICS AND LARGE SCALES

- AS DISCUSSED IN PREVIOUS PRESENTATIONS, MANY NEW EXPERIMENTAL AND OBSERVATIONAL FACILITIES ARE STARTING

- THE RECENT DETECTION OF GW FROM COMPACT SOURCES HAS SHOWN THE POWER OF THE SO-CALLED MM APPROACH, ADOPTED FOR DECADES IN THIS FIELD

- THE GROUP(S) AT GSSI OPERATE AT A STRATEGIC MOMENT AND WITH STRATEGIC CHOICES THEY SHOULD ALLOW THEM TO RETAIN THE ROLE OF LEADERSHIP THAT THEY CONQUERED