GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Cosmic Rays and their Messengers

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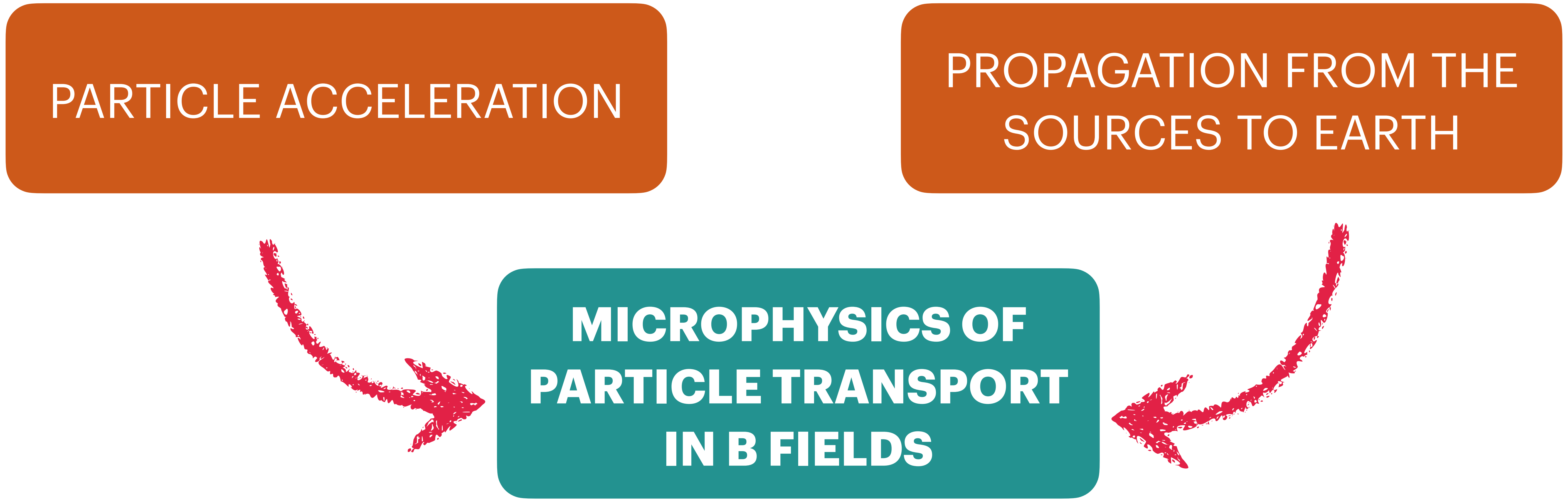
Cosmic Rays vs Non-thermal particles

Cosmic Rays (CR) consist of a small minority of particles that reach the Earth after being energised in sources, both Galactic and Extra-Galactic, and being transported through the Universe or the Galaxy

In this sense the physics of CR is the physics of all non-thermal particles that we see the radiation of, be it from AGN, GRB, SNR, muQSO, lightning, …

This Physics consists of



IN THE END MOST MULTI-MESSENGER ASTROPHYSICS OF NON-THERMAL PHENOMENA (WITH THE EXCLUSION OF GW) BOILS DOWN TO UNDERSTANDING TRANSPORT PLUS THE COMPLEXITY OF THE ENVIRONMENT

Cosmic Rays and MM/MW Astrophysics

The investigation of Cosmic Rays (CR) has always been based on Multi-Messenger and Multi-ν studies

What we know about CR transport through the Galaxy has been derived from observations of secondary stable nuclei and secondary unstable isotopes as well as positrons and antiprotons (many messengers)

The diffuse gamma ray emission from the Galaxy is a diagnostic tool of CR transport

Gamma ray emission from sources is routinely used to assess the role of such sources for CR origin

X-ray emission from SNR shocks has provided the first evidence ever of efficient CR acceleration

Radio emission is used to trace the non-thermal history of SNR

Neutrinos, both diffuse and from (many) sources, have been predicted long ago

GWs are the new addition to this long list… the type of sources detected (BH mergers and NS mergers) were not expected to have an obvious counterpart in either CR or high energy radiation relevant for particle acceleration to non-thermal energies … we will have to see…

A few examples of new trends inspired by MM

I will discuss two cases of observations, in gamma rays and neutrinos, that may deeply impact our ideas on Cosmic Rays

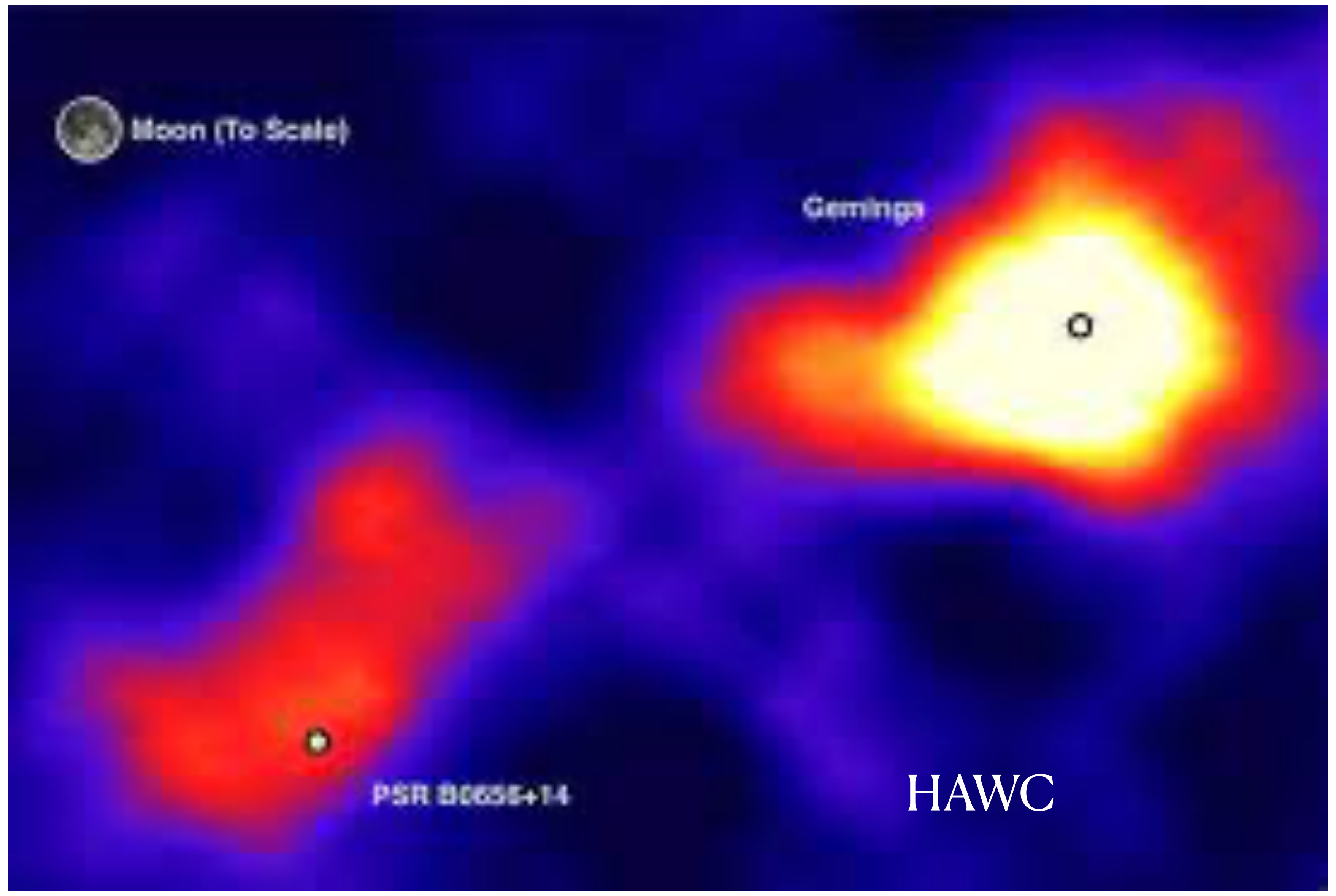
HALOS OF EXTENDED HIGH ENERGY GAMMA RAY EMISSION FROM AROUND SOURCES (HAWC, LHAASO)

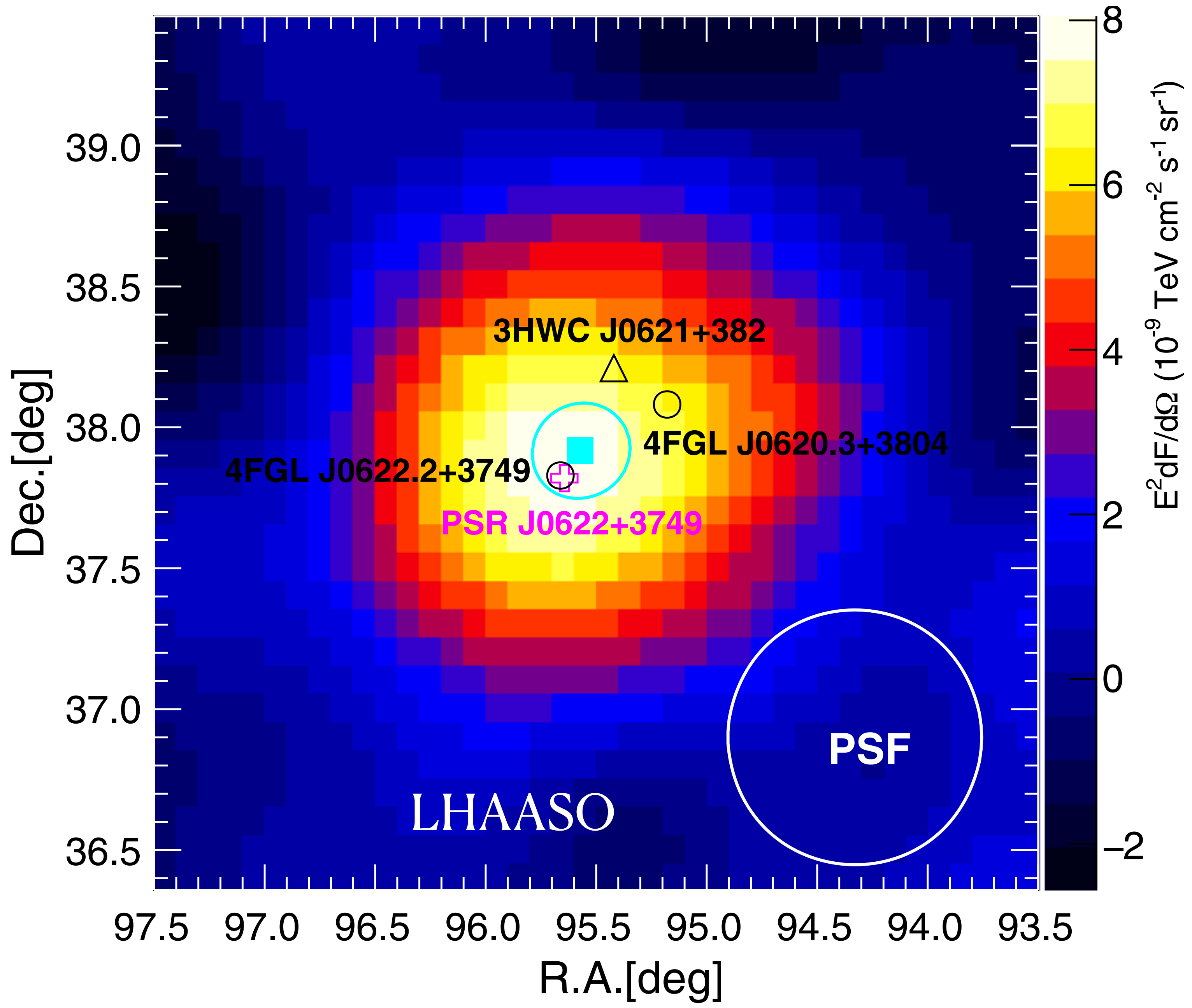
ISOTROPIC NEUTRINO FLUX (IceCube), POSSIBLY OF EXTRA-GALACTIC ORIGIN… COULD IT BE THE SIGNATURE OF CR ESCAPING OUR GALAXY?

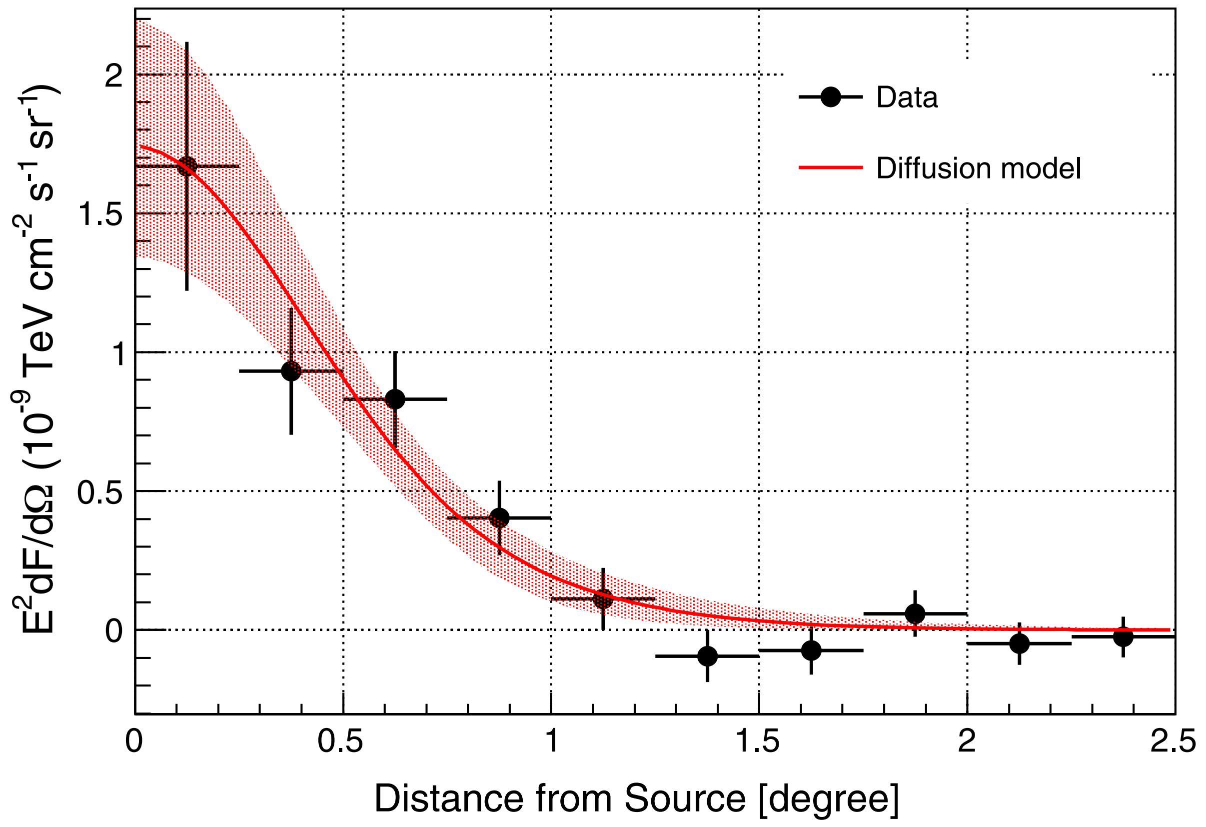
and then discuss one possible future development involving GW:

PRODUCTION OF UHECR NUCLEI IN NEWBORN NEUTRON STARS, POSSIBLE SOURCES OF GW

Extended γ-ray emission from around sources



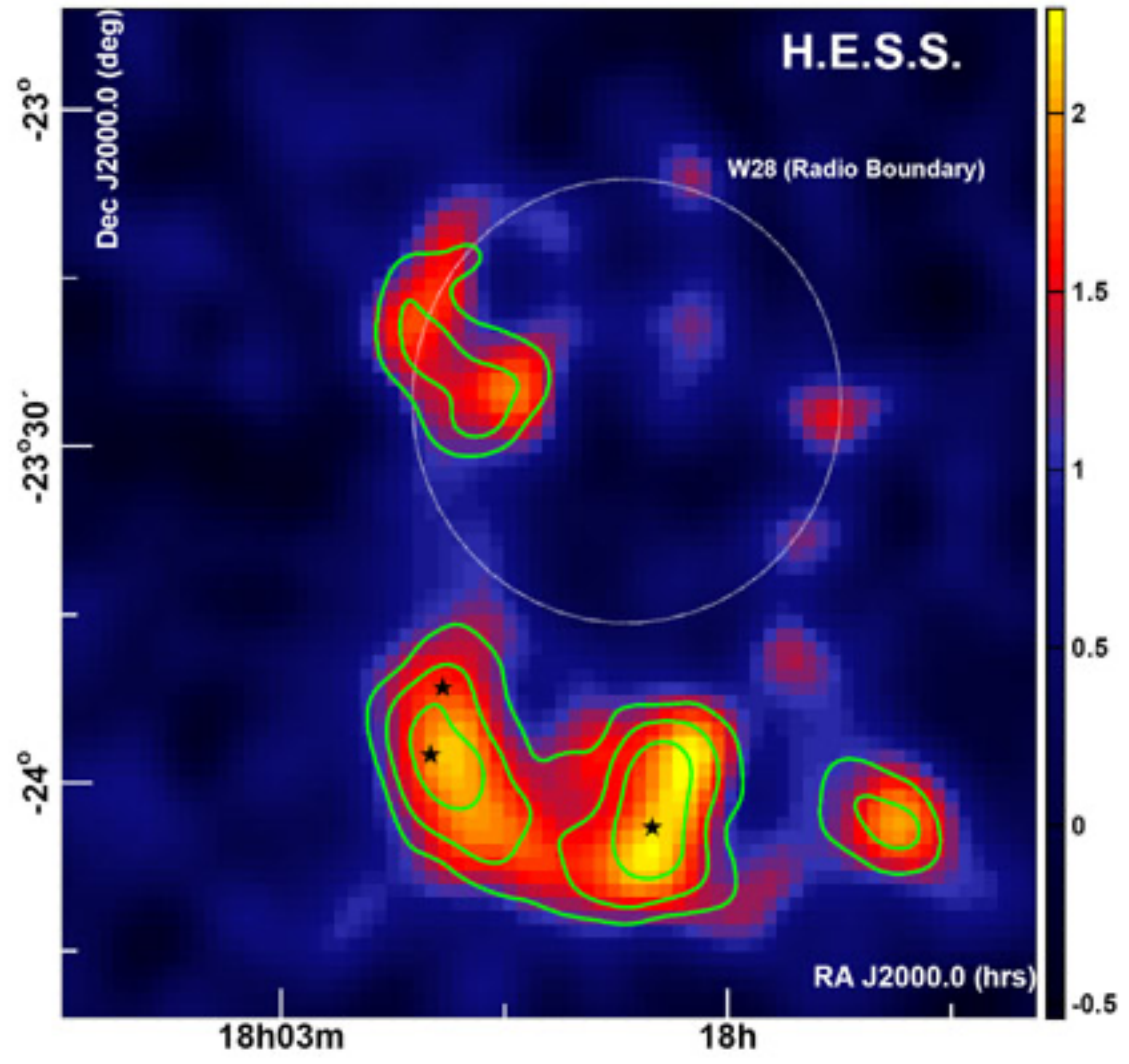




There are now several cases of extended gamma ray emission (halos) in the TeV range as seen with HAWC and LHAASO, around middle aged pulsars - the so-called **TeV halos**

The spatial extent of the emission, interpreted as the result of ICS of electrons and positrons from the pulsar, leads to the conclusion that the diffusion coefficient is $\sim 10^{-3}$-10^{-2} of the Galactic diffusion as inferred from Secondary/Primary ratios

Similar Phenomenon around SNRs?



THE SNR W28 IS SURROUNDED BY A SYSTEM OF MOLECULAR CLOUDS

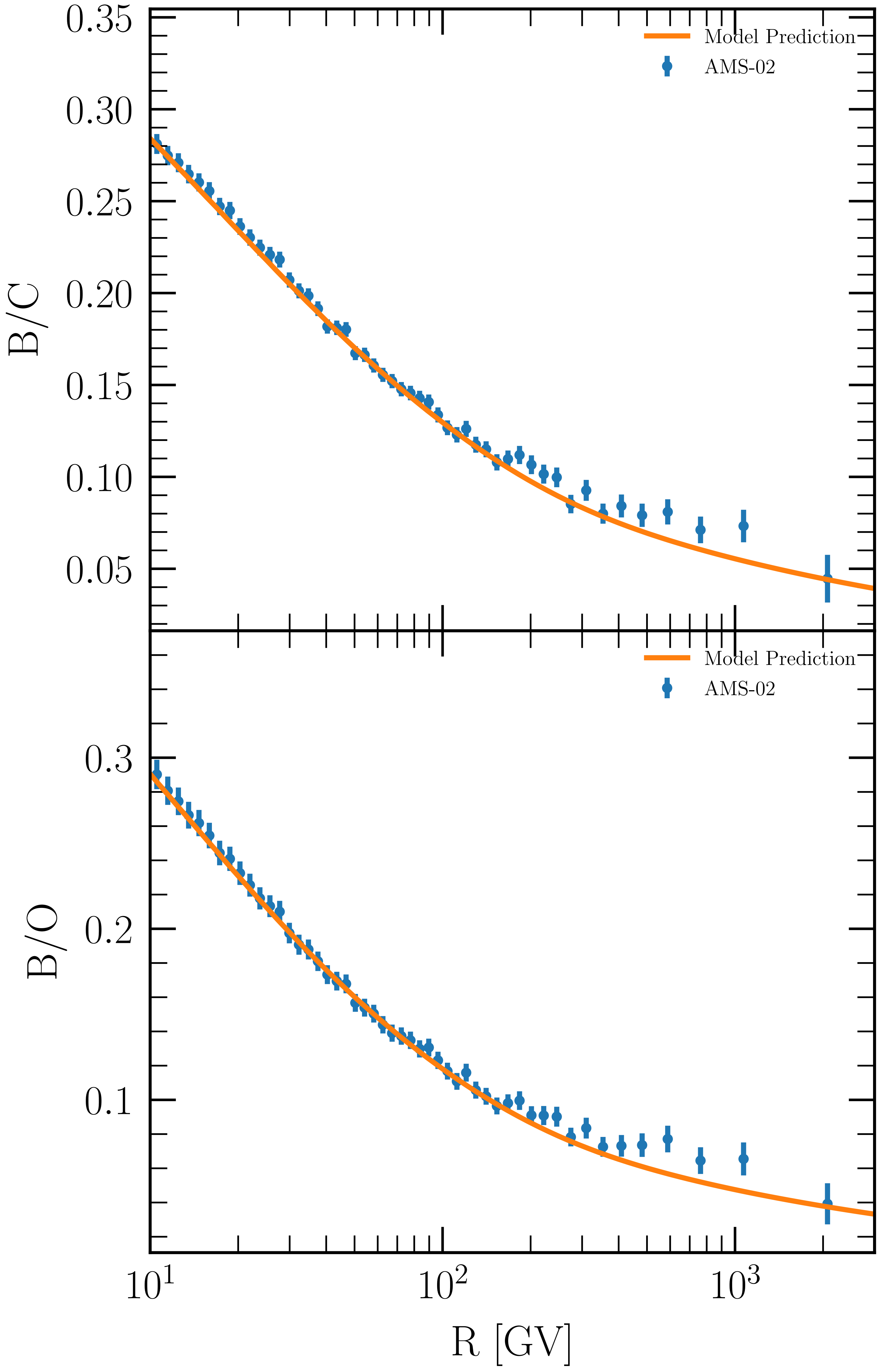
THE GAMMA RAY EMISSION FROM THESE CLOUDS ALSO PROVIDES PRECIOUS INFORMATION ABOUT CR TRANSPORT FROM THE SNR

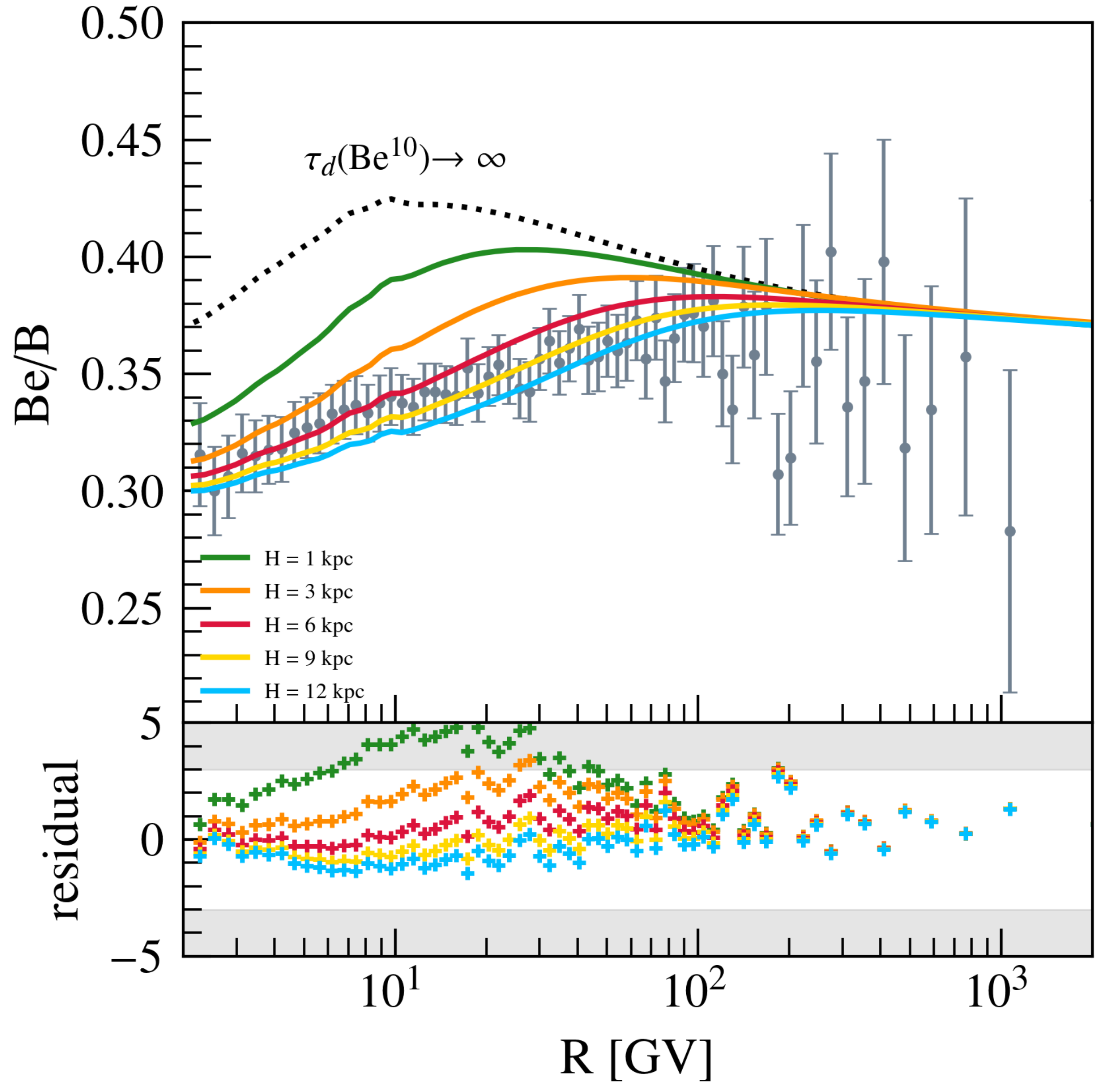
THIS EXERCISE ALSO LED TO THE CONCLUSION THAT THE DIFFUSION COEFFICIENT AROUND THE REMNANT IS ~40 TIMES SMALLER THAN THE GALACTIC D(E) [*Gabici et al 2010*]

- Is it possible that around sources of CR particles the diffusion coefficient is much smaller than on average?
- If so, what is the possible source of such phenomenon?
- Are there other implications that one could/should be looking for?

Basic indicators of CR diffusion

Evoli et al. 2020, 2021
Schroer, Evoli & PB 2021, PRD, in press





THESE RATIOS PLAY A CRUCIAL ROLE IN OUR UNDERSTANDING OF THE ORIGIN OF GALACTIC COSMIC RAYS

THEY FIX THE DIFFUSION COEFFICIENT OF CR IN THE GALAXY ON >> kpc SCALES AND THE SIZE OF THE GALACTIC HALO (H~5 kpc)

IS IT THE SAME D(E) AROUND SOURCES? IF NOT, WHY?

A Change of Paradigm?

- We are used to think of CR as individual charged particles (think for instance of the way we detect them!)

- But in fact CR behave as electric currents, propagating in a plasma (ISM, IGM)

- Electric currents in a plasma give rise to many interesting phenomena, such as the excitation of instabilities

- CR are very sensitive to the existence of these perturbations, produced by themselves

- Can it be that where there are lots of CR (near sources) these phenomena become important?

A PICTORIAL VIEW

$D(E) \simeq 3 \times 10^{28} E_{GeV}^{1/2} \longrightarrow \lambda(E) \simeq 1 \text{ pc } E_{GeV}^{1/2}$ **>Coherence scale for E> a few TeV!!!**

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

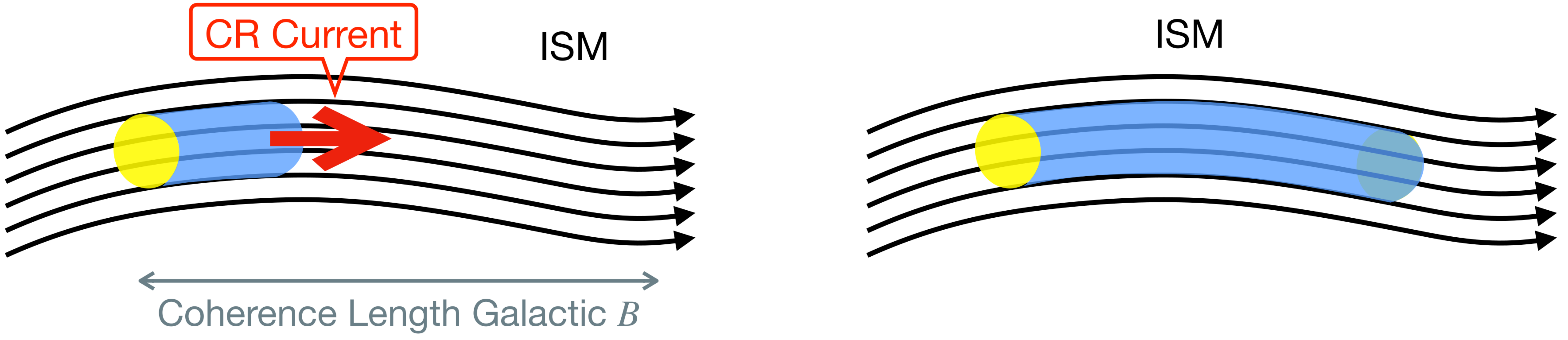
$$n_{CR}(>E)E \gtrsim \frac{B_0^2}{4\pi} \Longrightarrow$$

Non-Resonant Instability

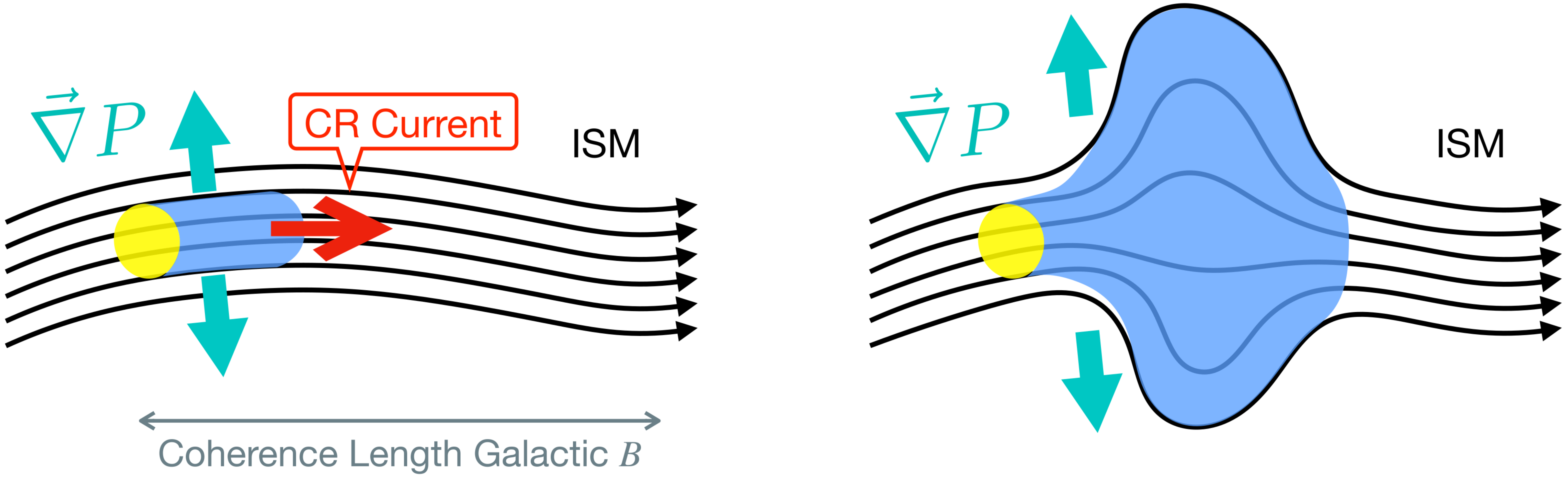
$$\gamma_{max}^{-1} \approx 1.1(\mathrm{E}/2.5\mathrm{TeV})^{-1} \ \mathrm{yr}$$

Early Time **Late Time**

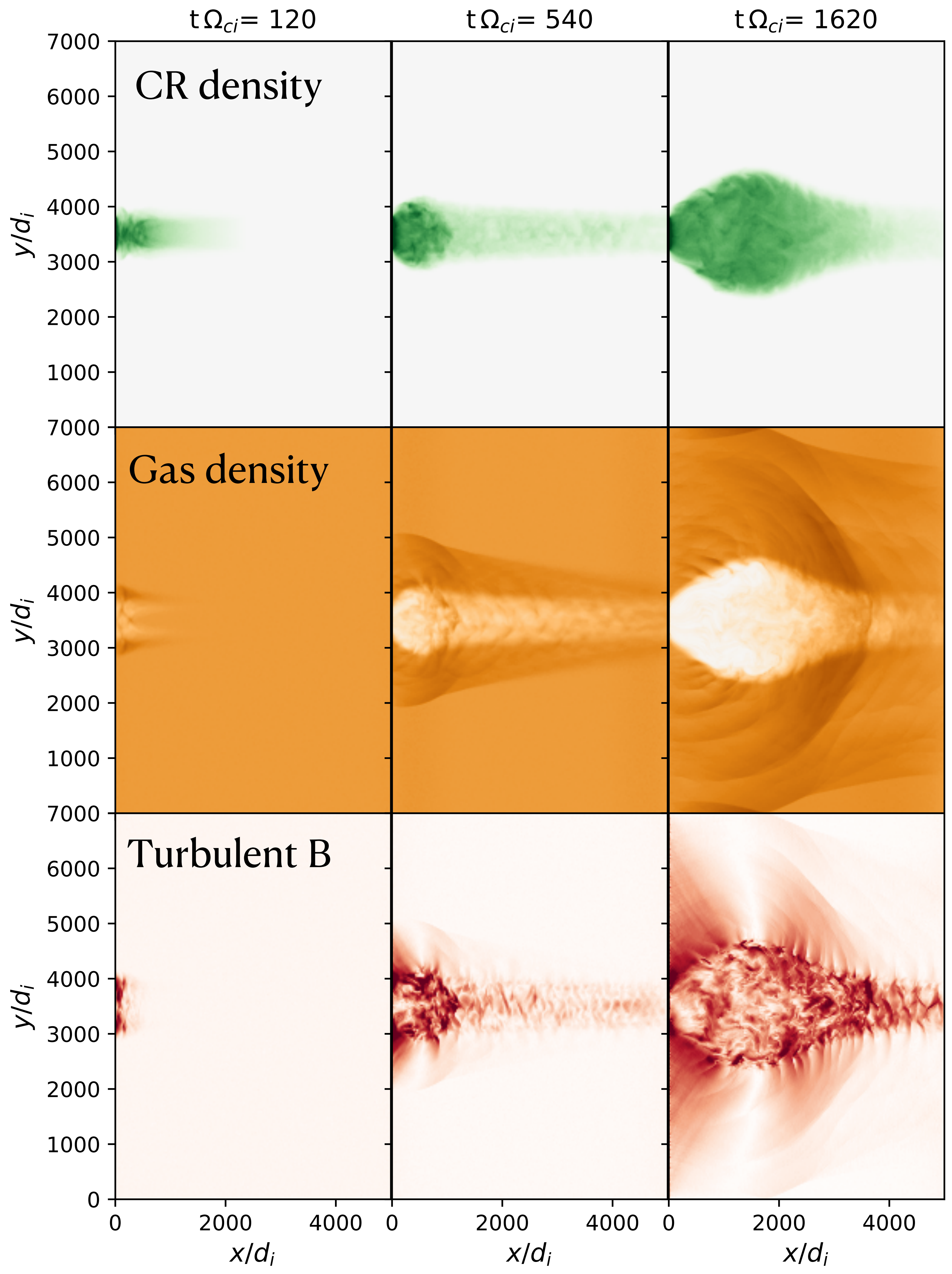
Flux Tube Scenario

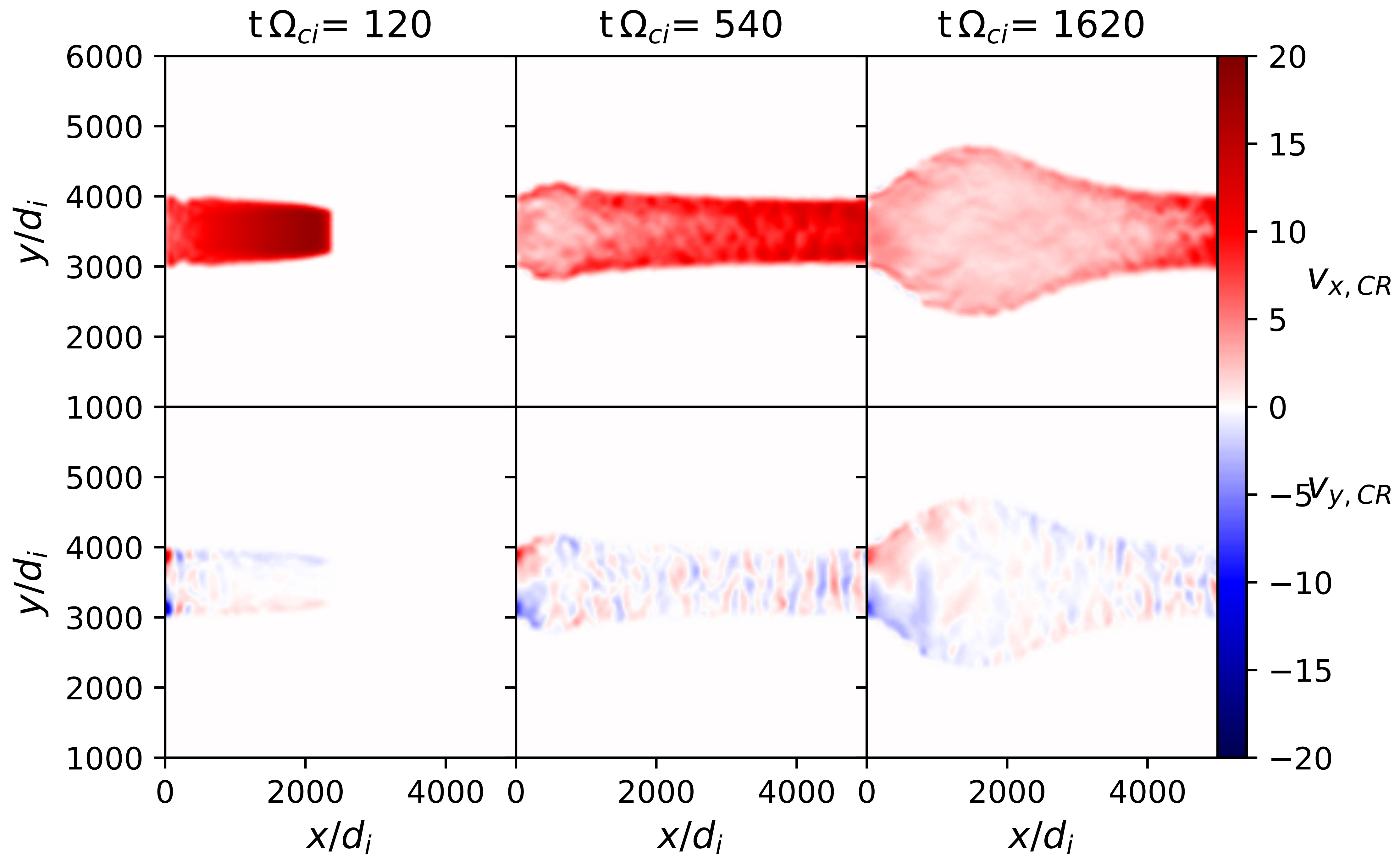


Bubble Scenario



Particle-in-Cell Simulations of particles becoming CR





Particles initially streaming freely in the x direction generate plasma fluctuations, and scatter off them, thereby drastically reducing the diffusion coefficient!

The induced D(E) is close to Bohm and much smaller than the one expected in the Galaxy

THIS IS DONE WITH PROTONS. THE CASE OF PAIRS FROM PWN IS MORE INTRICATE (AT ZERO ORDER CURRENT FREE) AND ONGOING...

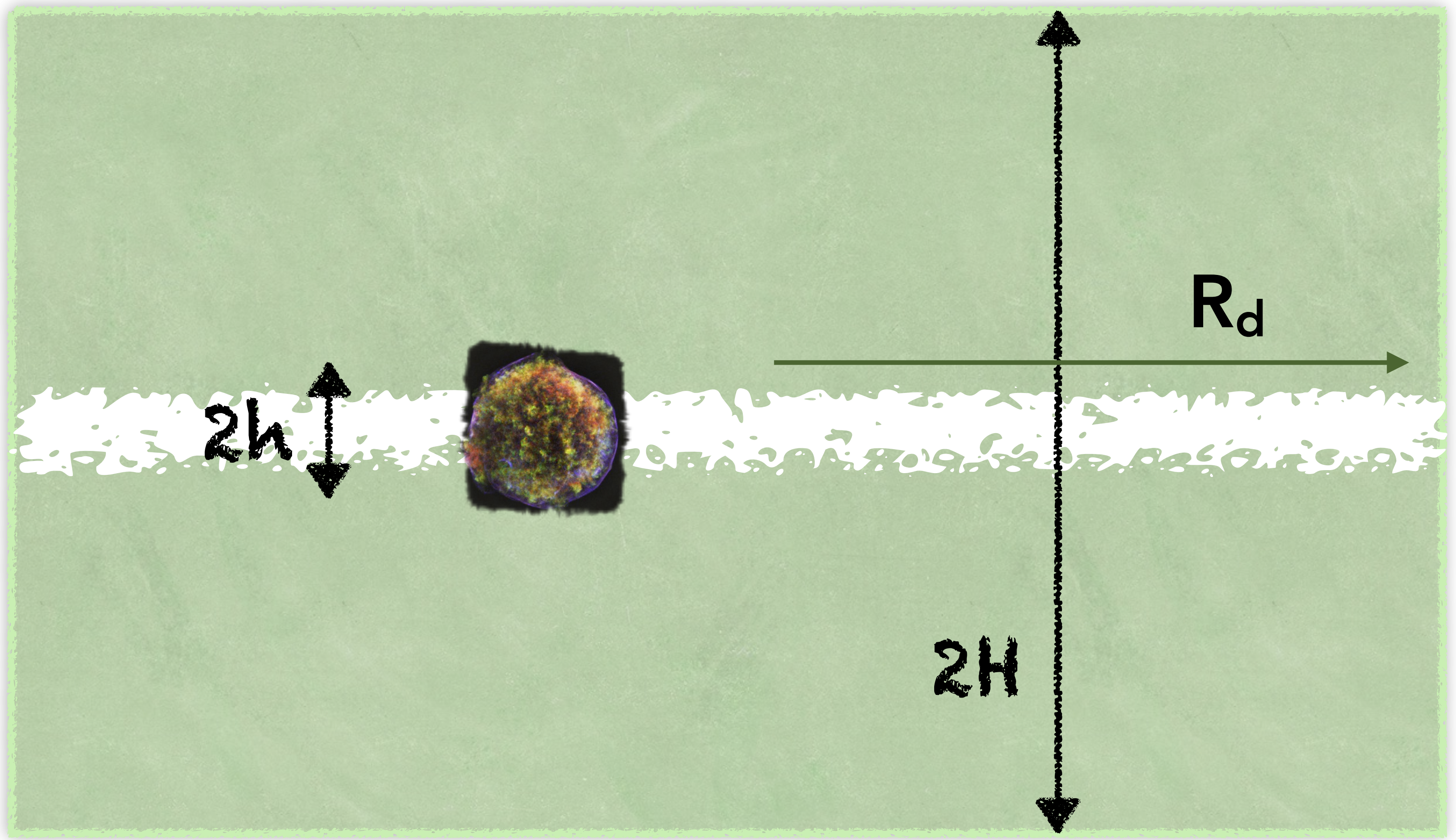
Schroer, et al. (2021), The Astrophysical Journal Letters, Volume 914, Issue 1, id.L13

Implications

- The self-generation of perturbations around sources seems to be a natural consequence of the excess current in those regions
- The effect should result in a reduction of D(E) and excavation of a bubble with reduced gas density and enhanced turbulence
- These bubbles are expected to be blown until pressure balance with the external ISM is reached (typical size of tens of pc) - perhaps the HAWC and LHAASO bubbles?
- CR confinement in these bubbles might lead to accumulation of excess grammage to be seen at some point in B/C and B/O (AMS-02 precision measurements crucial here)
- Small D(E) has very important for leptons
- Very rich phenomenology

Astrophysical neutrinos and the CR escape from the Galaxy

A TOY MODEL FOR OUR GALAXY



HALO ~ several kpc

DISC ~ 300 pc

Assumptions of the model:

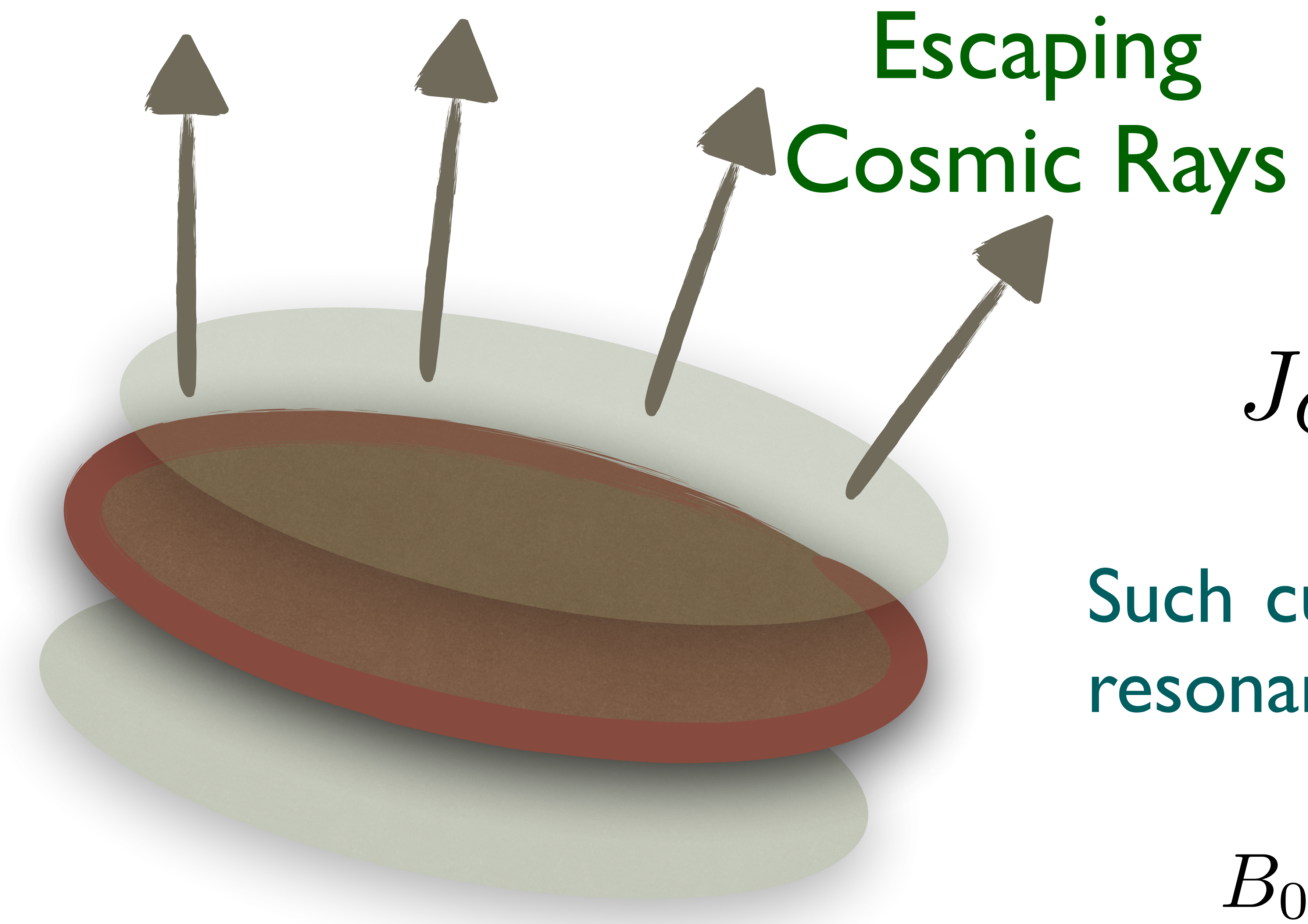
1. *CR are injected in an infinitely thin disc*
2. *CR diffuse in the whole volume*
3. *CR freely escape from a boundary*

Mathematically, the problem is faced by solving a set of (about 60, one per nucleus) second order coupled partial differential equations with free escape boundary conditions

In stationary regime, the flux injected by sources (for instance by supernova explosions or star clusters) is equal to the flux of CR escaping the Galaxy (not for heavy nuclei, because of fragmentation)

ESCAPING THE GALAXY

PB&Amato 2018



The current of escaping CRs is very well known

$$J_{CR}(p) = eD\frac{\partial f}{\partial z}|_{z=H} = \frac{eQ_0(p)}{2\pi R_d^2}$$

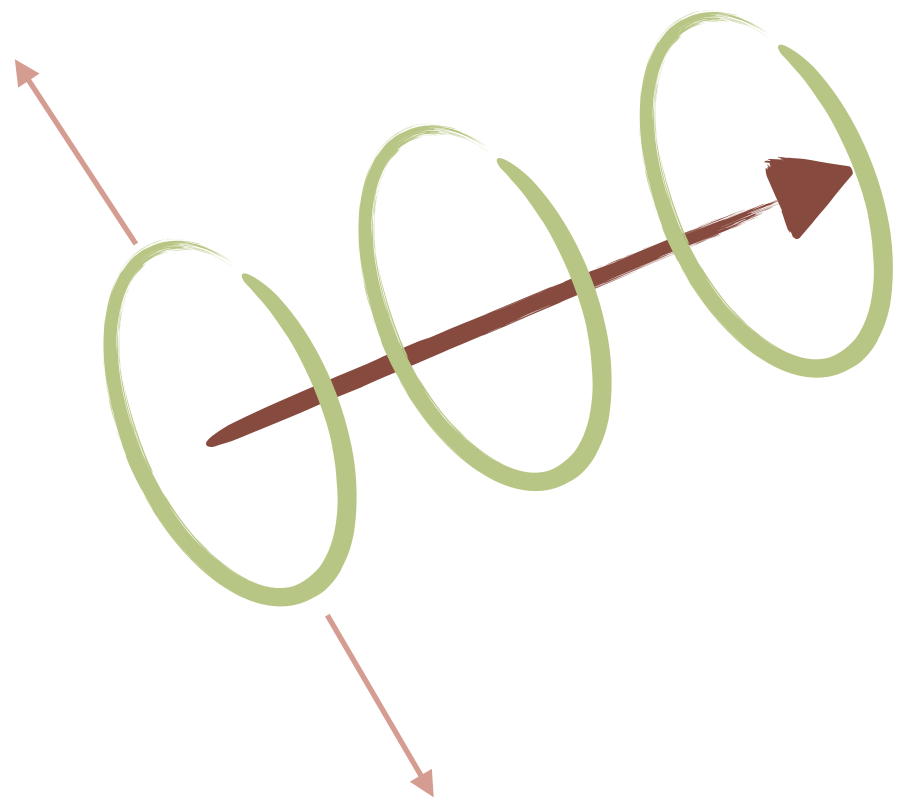
Such current in the typical IGM excites a non-resonant Bell-like instability provided:

$$B_0 \leq B_{sat} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1} \text{ G}$$

At a wavenumber $k_{max} = \frac{4\pi}{cB_0} J_{CR}$

and with a growth rate: $\gamma_{max} = k_{max} v_A \approx 0.5 \text{ yr}^{-1}\ \delta_G^{-1/2} E_{\text{GeV}}^{-1} L_{41} R_{10}^{-2}$

A PHYSICAL UNDERSTANDING OF SATURATION



The current exerts a force of the background plasma

$$\rho \frac{dv}{dt} \sim \frac{1}{c} J_{CR} \delta B$$

which translates into a plasma displacement:

$$\Delta x \sim \frac{J_{CR}}{c\rho} \frac{\delta B(0)}{\gamma_{max}^2} exp(\gamma_{max} t)$$

which stretches the magnetic field line by the same amount…

The saturation takes place when the displacement equals the Larmor radius of the particles in the field δB

$$\delta B \approx B_{\rm sat} \approx \sqrt{\frac{2 L_{CR}}{c\ R_d^2 \Lambda}} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1}\ {\rm G}$$

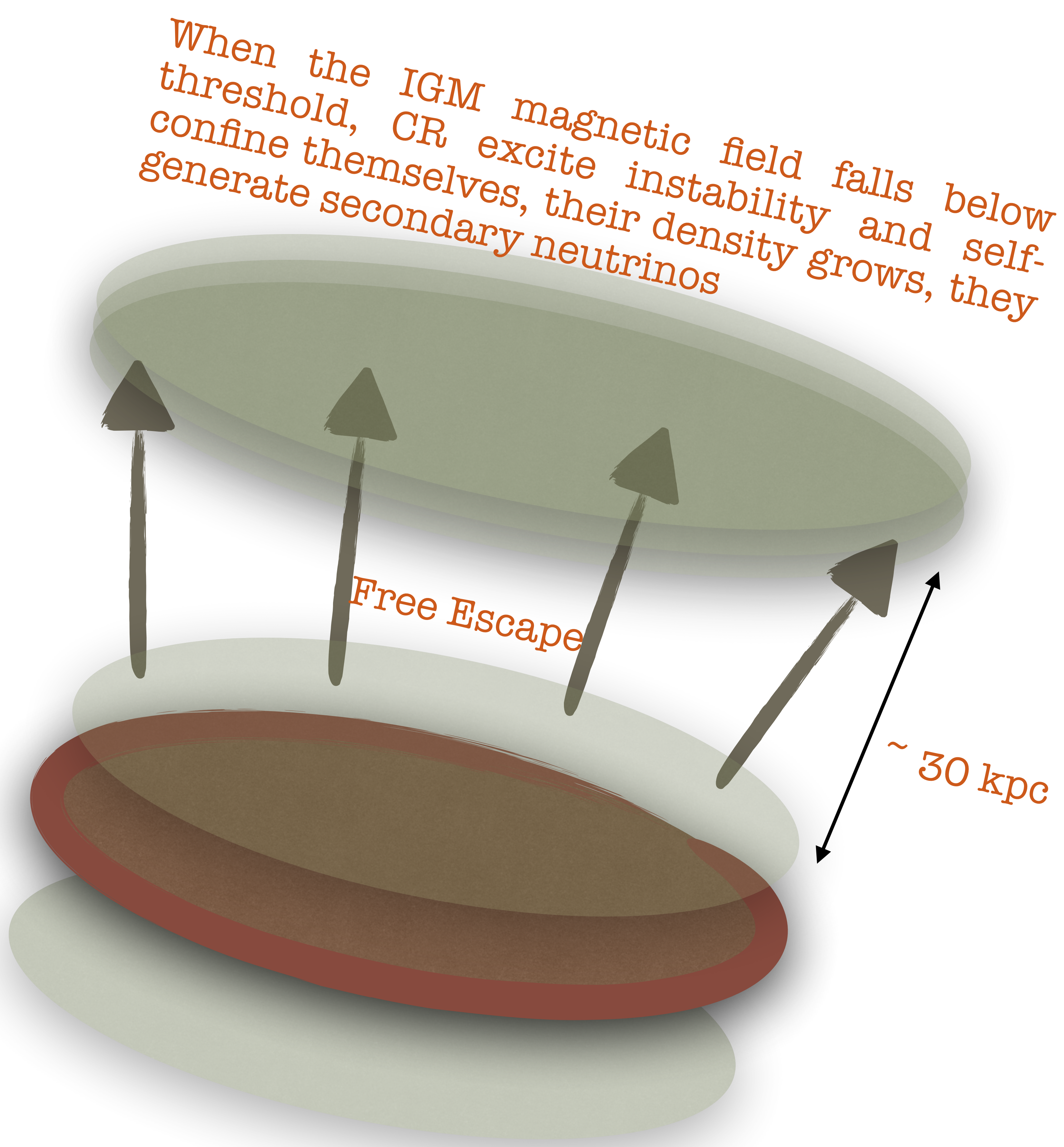
The Picture

When escaping CR reach a region where the field drops below ~10^{-8} G, they excite a non-resonant instability that sets the plasma in motion

Hence, their density is set by advection

$$n_{CR}(E) = \frac{\phi_{CR}}{\tilde{v}_A}$$

Instead of escaping at c they move at speed v_A so that their density is much higher around the Galaxy than in the case of free streaming

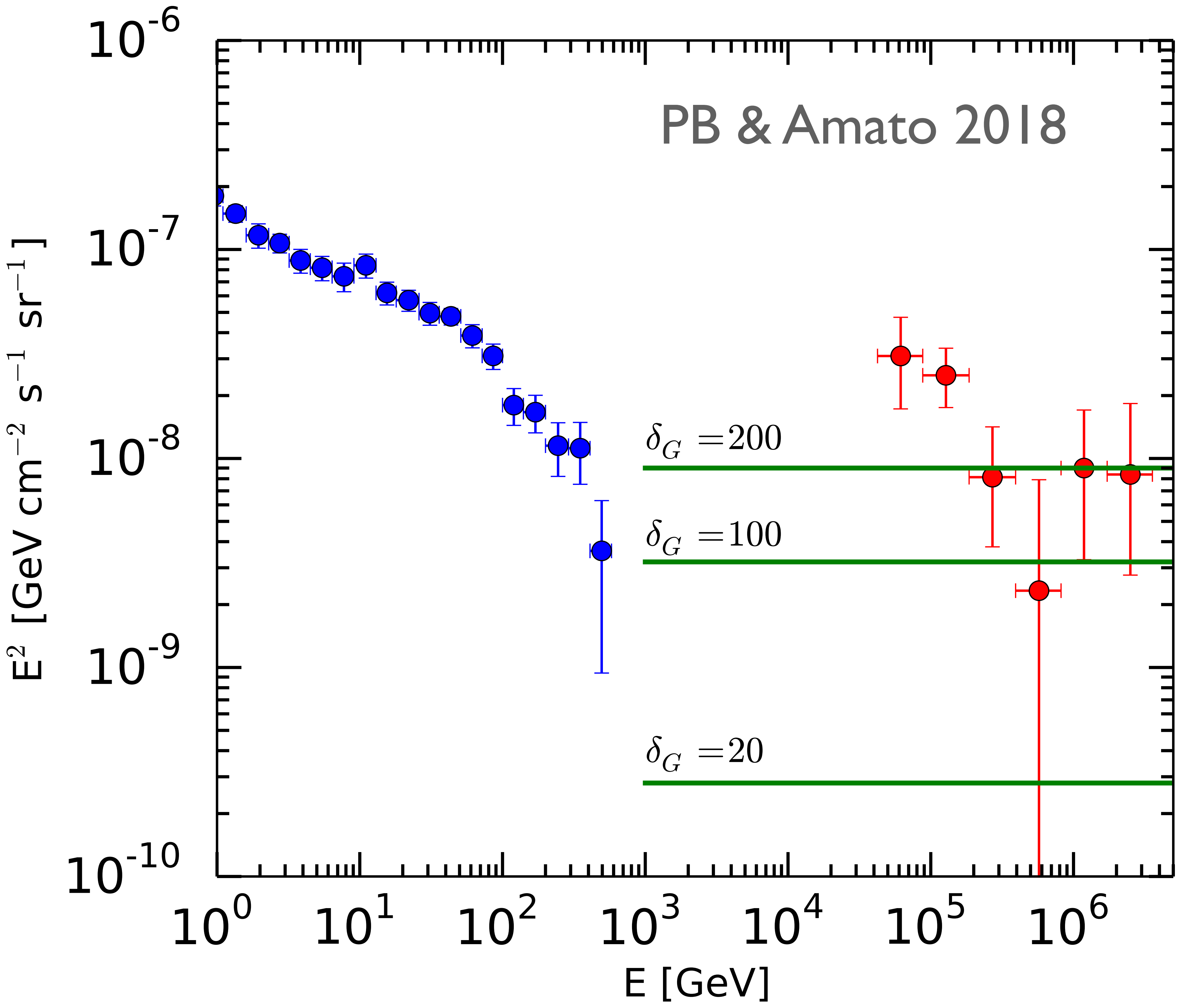


Implications for Neutrinos

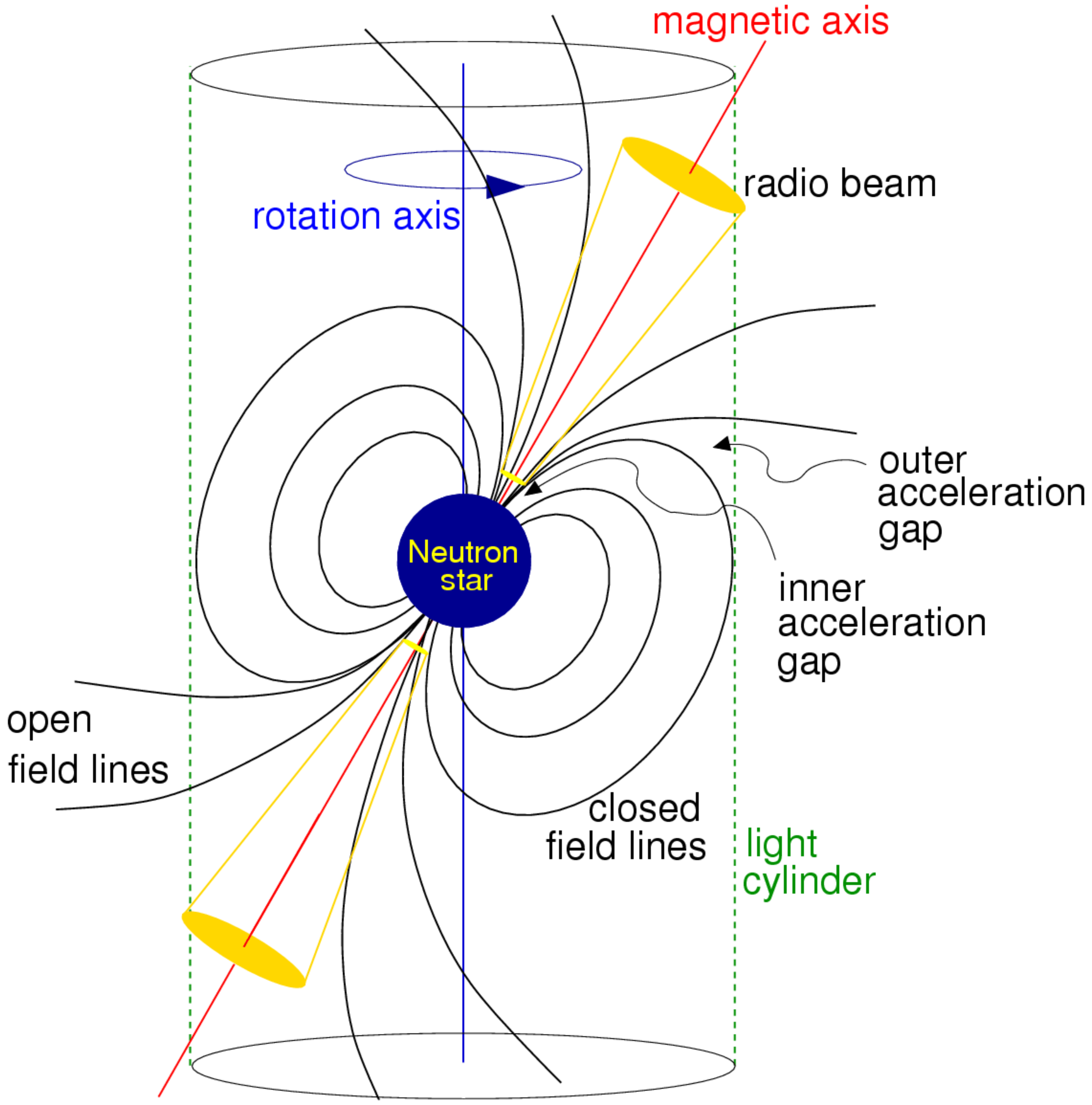
Around every galaxy there should be a region with B~$L_{CR}^{1/2}$ due to the action of escaping CR

The interaction of CR with the locally overdense intergalactic medium leads to production of a quasi-isotropic flux of secondary neutrinos

As seen from inside our Galaxy this phenomenon looks like an escape… conclusions unchanged for B/C



Newborn neutron stars



Courtesy: Lorimer & Kramer (2005)

A newly born neutron star is typically located in a very hostile environment for particle acceleration

The NS might still be acquiring its shape and getting rid of its quadrupole moment through emission of GW

The spinning of the NS results in a potential drop between the surface and infinity:

$$\Phi = \frac{2\pi^2 B R_\star^3}{P^2 c^2} \sim 6.6 \times 10^{19}\, B_{13} R_{\star,6}^3 P_{-3}^{-2}\,\mathrm{V}$$

Potential

$$\mathcal{E} = \frac{2\pi R_\star B}{Pc} \sim 6.3 \times 10^{14}\, B_{13} R_{\star,6} P_{-3}^{-1}\,\mathrm{V\,cm^{-1}}$$

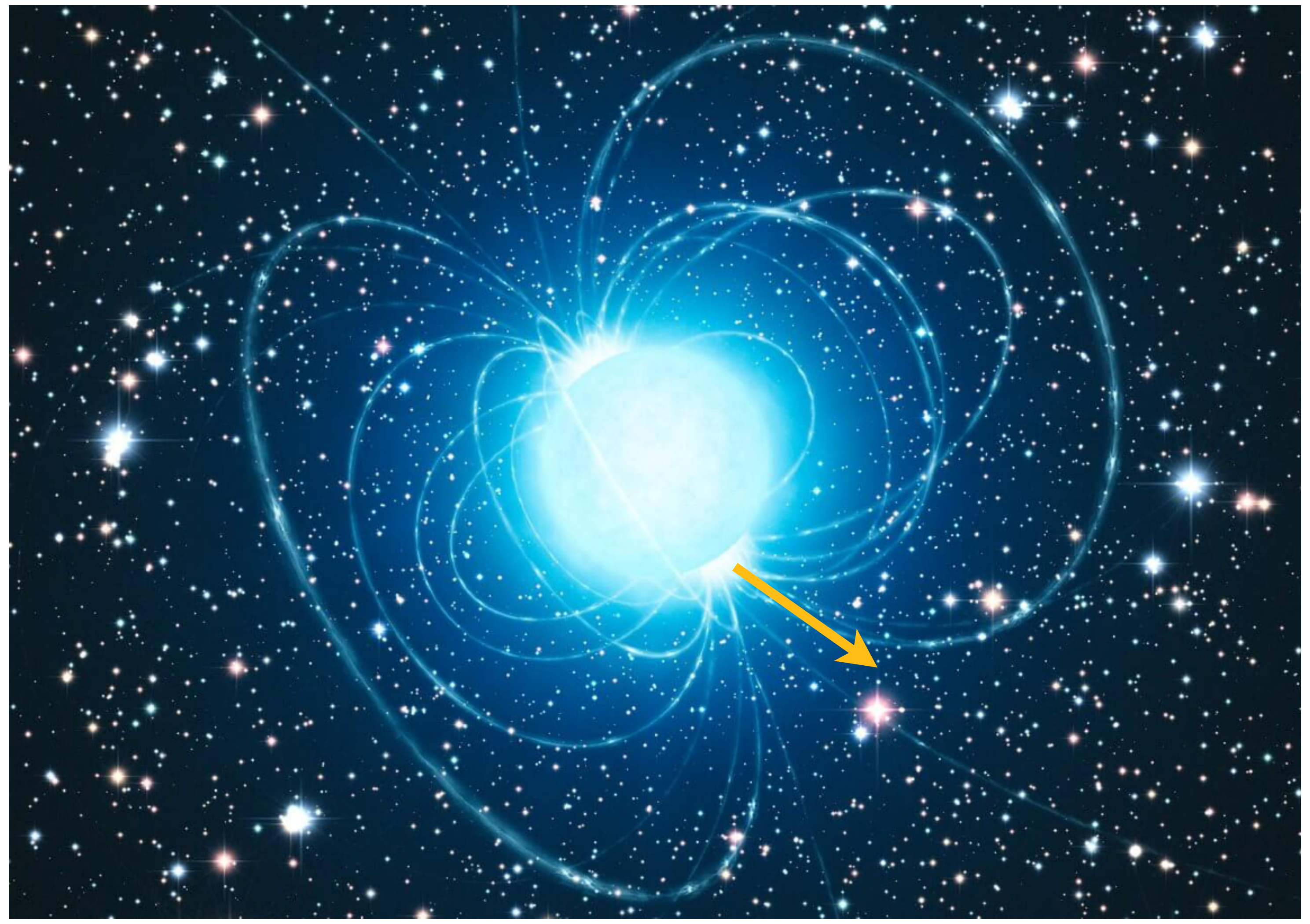
Electric field

The electric field at the surface may be large enough to extract Fe nuclei from the surface (requires $\mathcal{E}_0 = 14\,\mathrm{keV}/(Zel) \sim 5.4 \times 10^{11}\, Z_{26}^{-1} l_{-9}^{-1}\,\mathrm{Vcm^{-1}}$), with a maximum Lorentz factor:

$$\gamma_{\rm fpd} = \frac{Ze}{Am_p c^2}\Phi = 7 \times 10^{10}\,\frac{Z}{A}\,B_{13}\,P_{-3}^{-2}$$

the implications for UHECRS are quite impressive (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)

Newborn neutron stars

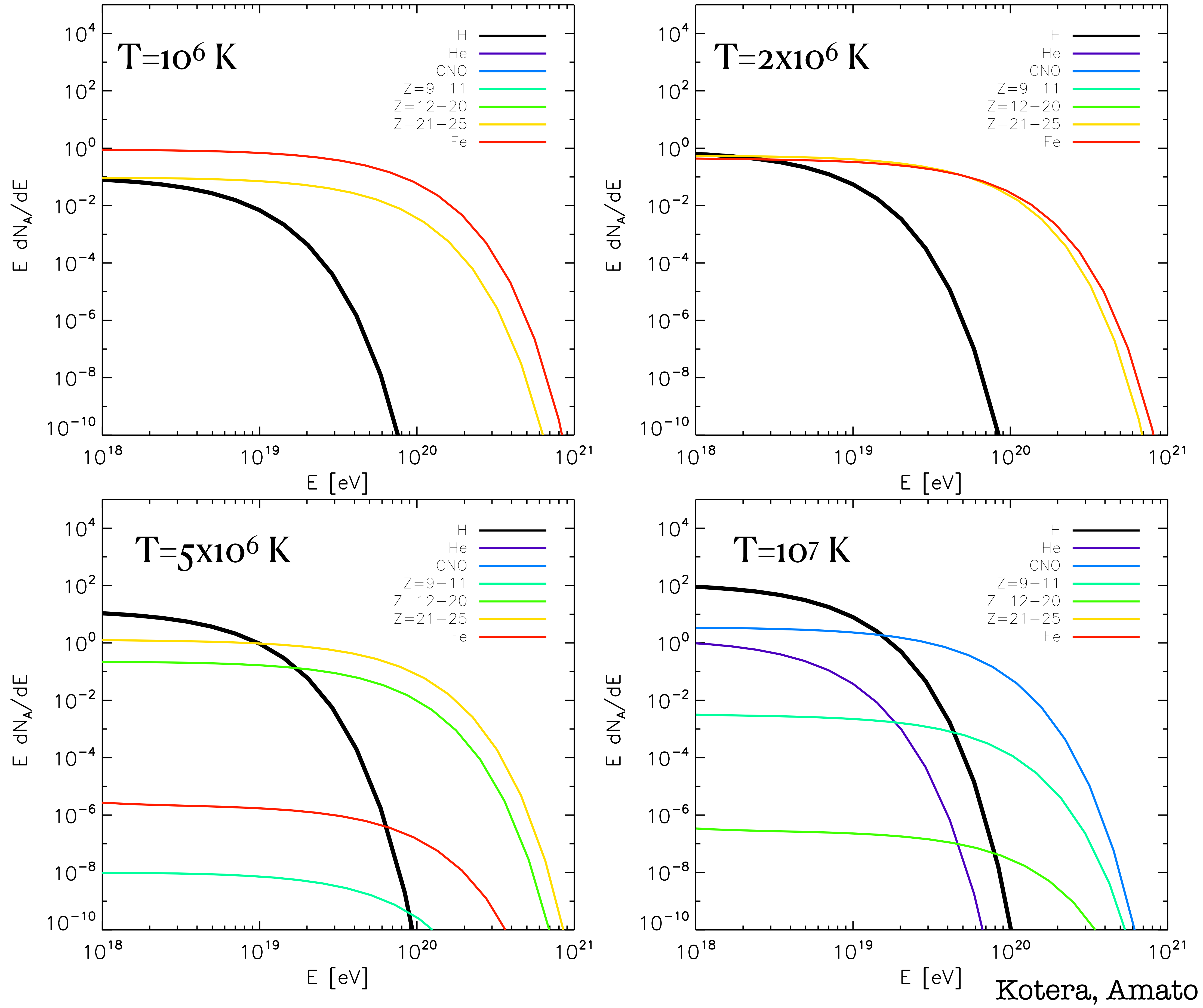


Credit: ESO/L. Calçada

Nuclei of Fe move along the B-field lines while being bombarded from below by thermal photons coming from the hot surface of the newborn neutron star

This phenomenon leads to photo-disintegration of nuclei

Magnetic dipole Spin-down of the pulsar leads to very hard spectra (~1/E) (PB, Epstein & Olinto 2000) and photo-disintegration leads to a mass composition that becomes mixed (Kotera, Amato & PB 2015). Both ingredients sit well with the findings of the Auger Observatory



Kotera, Amato & PB 2015

Conclusions

- ✓ RECENT DEVELOPMENTS IN GAMMA RAY AND NEUTRINO ASTROPHYSICS ARE FUELLING CONCEPTS WITH A PROFOUND EFFECT ON THE FIELD OF CR AND MORE IN GENERALE NON-THERMAL UNIVERSE
- ✓ PARTICULARLY IMPORTANT SEEMS TO BE THE DISCOVERY OF REGIONS OF REDUCED DIFFUSIVITY AROUND SNR AND PULSAR WIND NEBULAE (HAWC, LHHASO)
- ✓ THE ISOTROPIC NEUTRINO BACKGROUND MEASURED BY IceCube IS OPENING THE WAY TO A NEW BRANCH … TO BE STRENGTHENED BY FUTURE DETECTION FOR SOURCES, IF ANY…
- ✓ DATA ARE OVERFLOWING, THERE IS ROOM FOR DEEP THINKING, NOT JUST SAME OLD STUFF … BE BRAVE
- ✓ IT WILL GET EVEN BETTER WITH THE UPCOMING CTA (ESPECIALLY ON SOURCES SUCH AS SNR, STAR CLUSTERS, PWN…)
- ✓ GRAVITATIONAL WAVES HAVE PROBABLY NOT EXHAUSTED THEIR POTENTIAL OF DISCOVERY IN TERMS OF HIGH ENERGY UNIVERSE… INTERESTING WHAT THEY WILL TELL US ABOUT NEWBORN NEUTRON STARS