GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

THEORY OF HIGH ENERGY PHENOMENA IN THE UNIVERSE

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Gran Sasso Science Institute

OUR TOPICS OF INTEREST

- **FUNDAMENTAL PHYSICS OF PARTICLE ACCELERATION**
  - ***Particle acceleration at shocks and non-linear effects***
  - ***Plasma instabilities in the shock region and Emax***
  - ***Particle acceleration in MHD turbulence***
- **PHENOMENOLOGY OF PARTICLE ACCELERATION**
  - ***Cosmic ray acceleration at supernova remnant shocks and their escape***
  - ***CR acceleration at the termination shock of stellar clusters***
  - ***Acceleration of pairs at termination shocks of pulsar wind nebulae***

OUR TOPICS OF INTEREST

- **PLASMA PHYSICS OF COSMIC RAY ESCAPE FROM SOURCES**
  - *Non-linear effects of CR around their sources*
  - *Escape of electron-positron pairs from PWNe and their effects*
  - *TeV-halos as an implication of these phenomena*
- **COSMIC RAY TRANSPORT IN THE GALAXY**
  - *Phenomenology of CR transport and connection with observations (B/C,Be,Nuclei, gamma...)*
  - *Phenomenology of $e^{\pm}$ transport in the Galaxy and positron excess*
  - *Alternative models of positron excess (acceleration of secondary pairs and nuclei in sources)*
  - *CR driven winds and effects on global properties and observables*

OUR TOPICS OF INTEREST

- **COSMIC RAY ESCAPE FROM GALAXIES**
  - ***Self-trapping of CR around Galaxies of different luminosities***
  - ***Connection with HE gamma and neutrino emission***
  - ***Implications for the global magnetisation of the Universe***
  - ***Implications for protogalaxies at high redshift***
- **ULTRA-HIGH ENERGY COSMIC RAYS**
  - ***Global theory of UHECR propagation***
  - ***Models of UHECR based on pulsars***
  - ***Top-Down Models of UHECRs and implications of these new physics based models***

OUR TOPICS OF INTEREST

- **STARBURST GALAXIES**
  - ***CR transport in the cores and winds of SBG***
  - ***CR acceleration at the TS of SBG winds - HE gamma and neutrino emission and UHECR***
  - ***CR acceleration to UHE in UFO (UltraFast Outflows) around black holes***

NON THERMAL PARTICLES AND COSMIC RAYS


SNRs


Sun


µQSO


AGN

NON THERMAL PARTICLES ARE UBIQUITOUS IN THE UNIVERSE


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

COSMIC RAY TRANSPORT IN THE GALAXY - *See talk by* ***Benedikt Schroer***

ROLE OF TURBULENCE FOR PARTICLE TRANSPORT - *See talk by* ***Ottavio Fornieri***

HYBRID PIC SIMULATIONS OF CR AROUND SOURCES - *See talk by* ***Benedikt Schroer***

DIFFUSE GAMMA RAY EMISSION IN THE GALAXY - *See talk by* ***Vittoria Vecchiotti***

FUNDAMENTAL PHYSICS OF PARTICLE ACCELERATION AT SHOCKS

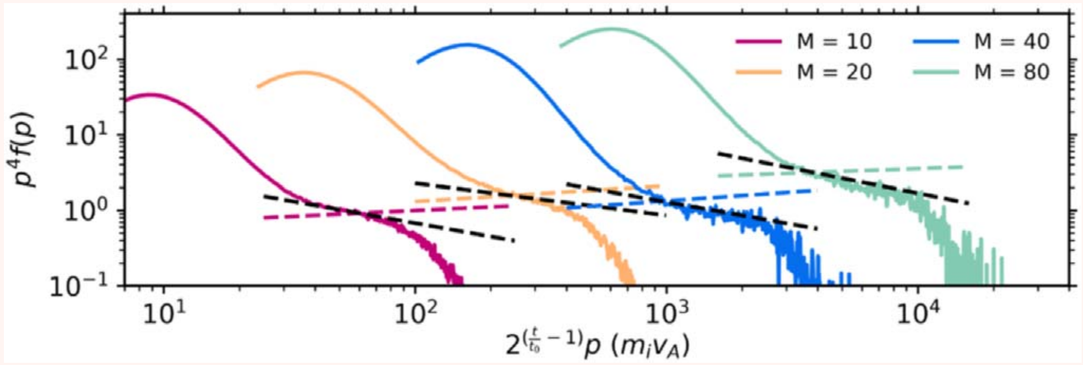
AN INTRINSICALLY NON LINEAR PHENOMENON

- **PARTICLES ACCELERATED AT A NEWTONIAN SHOCK CAN TAKE AWAY TENS OF PERCENT OF THE RAM PRESSURE** - they are not test particles
- **THE PLASMA INSTABILITIES THEY EXCITE ARE ABLE TO AMPLIFY SMALL PERTURBATIONS AND LEAD TO SUBSTANTIAL MAGNETIC FIELD AMPLIFICATION** - in the absence of this effect the maximum energy would have no practical interest
- **THE PARTICLES LEAVING THE SYSTEM ACT AS A BOOTSTRAPPING AGENT** - you need escape of some to trap all others
- **THE FLUCTUATIONS EVENTUALLY BECOME LARGE ENOUGH TO AFFECT THE SPECTRUM OF ACCELERATED PARTICLES** - it becomes steeper thereby solving one of the biggest mysteries behind DSA

NON LINEAR DSA

- **Amplified waves advected downstream of the shock lead to higher Alfven speed- hence smaller return probability from downstream**
- **This phenomenon leads to a steeper spectrum of accelerated particles, in general dependent upon the shock velocity**
- **Very steep spectrum for very fast shocks — milder steepening for historical SNR, as required by observations**

Caprioli, Haggerty and PB 2021



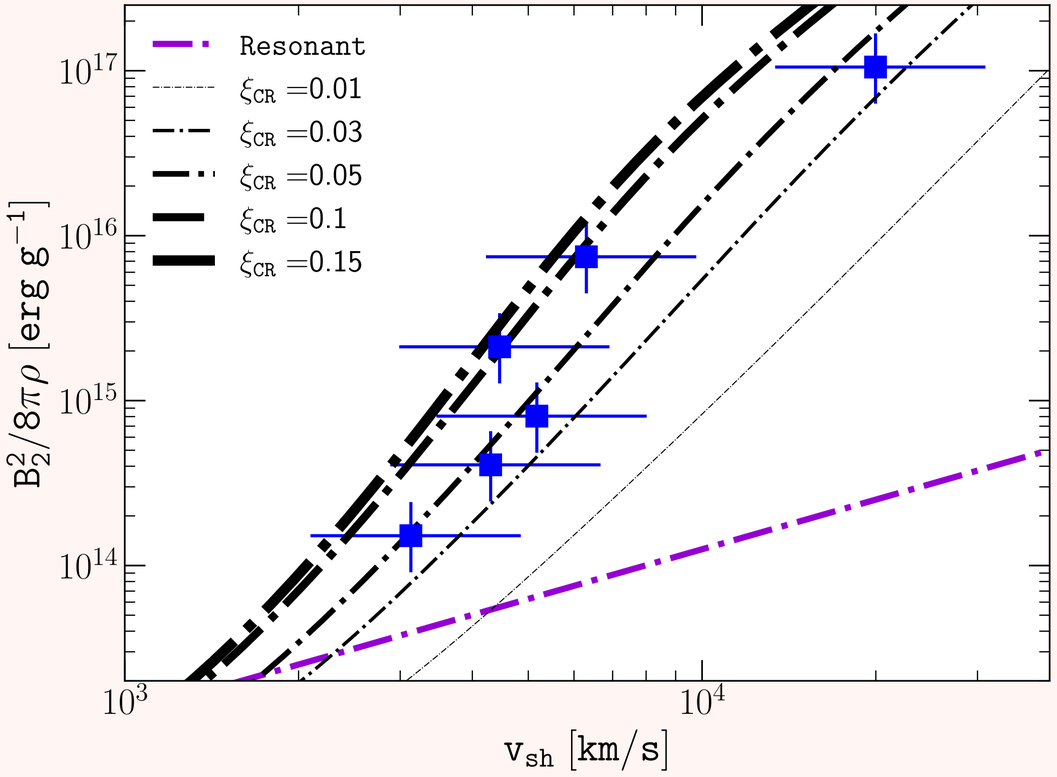
$$q = \frac{3r}{r - 1 - \alpha + \lambda(p)}; \quad \lambda(p) \equiv \frac{\alpha}{\alpha - 1} \frac{D_2(p)}{u_2 L}$$

$$\alpha \simeq 5 \times 10^{-3} \frac{B_2}{\mu\mathrm{G}} \frac{1000\ \mathrm{km\ s^{-1}}}{v_{\mathrm{sh}}} \left(\frac{R_{\mathrm{tot}}}{5} \frac{\mathrm{cm^{-3}}}{n_0} \right)^{\frac{1}{2}}$$

NON LINEAR DSA

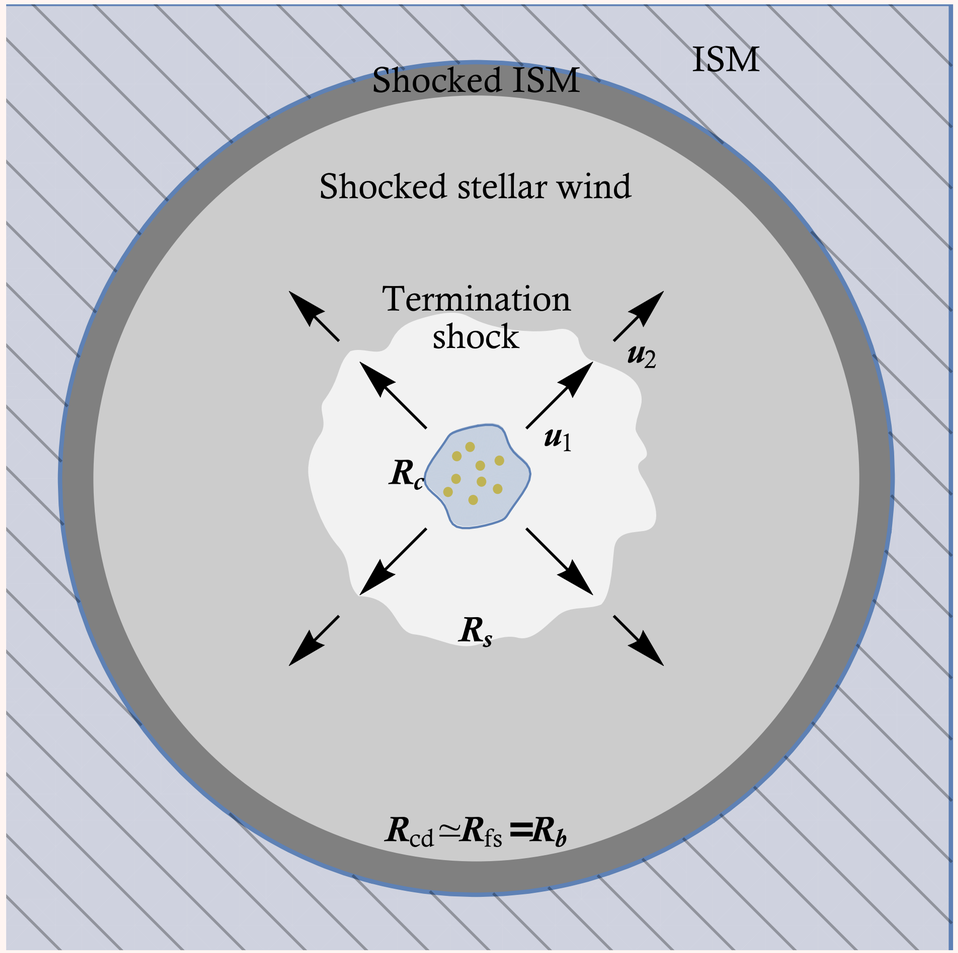
- **The effect seems to be confirmed by the observed dependence of the downstream magnetic field (X-ray observations) on the shock speed**
- **Both the magnetic field and the steep spectrum agree for both historical SNR and so-called radio SNR**

Cristofari, PB & Caprioli 2022 - in prep



ACCELERATION IN THE WINDS OF STAR CLUSTERS

THE BUBBLE OF STELLAR CLUSTERS



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

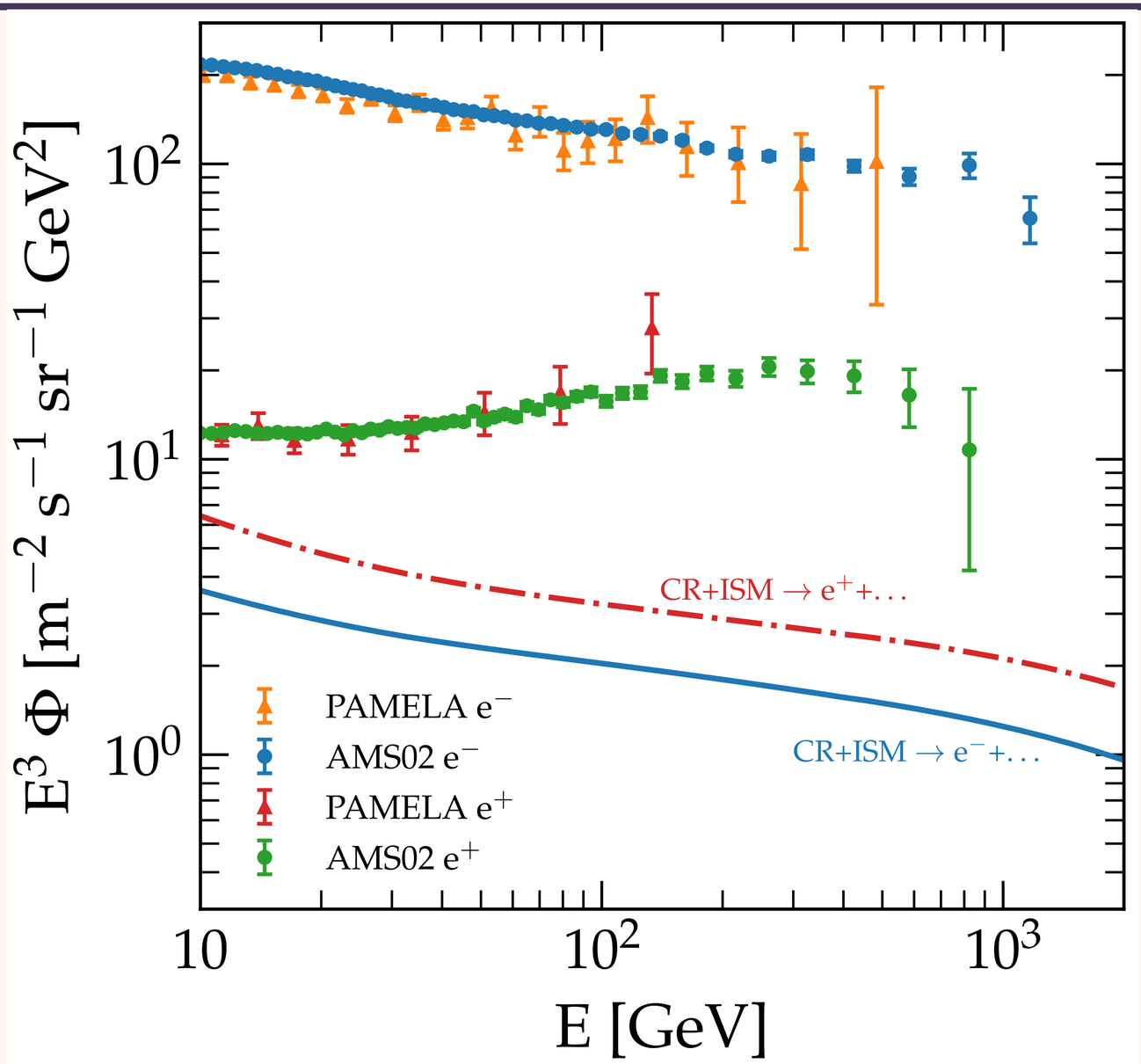
THE MAXIMUM ENERGY DEPENDS STRONGLY ON THE WIND VELOCITY

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

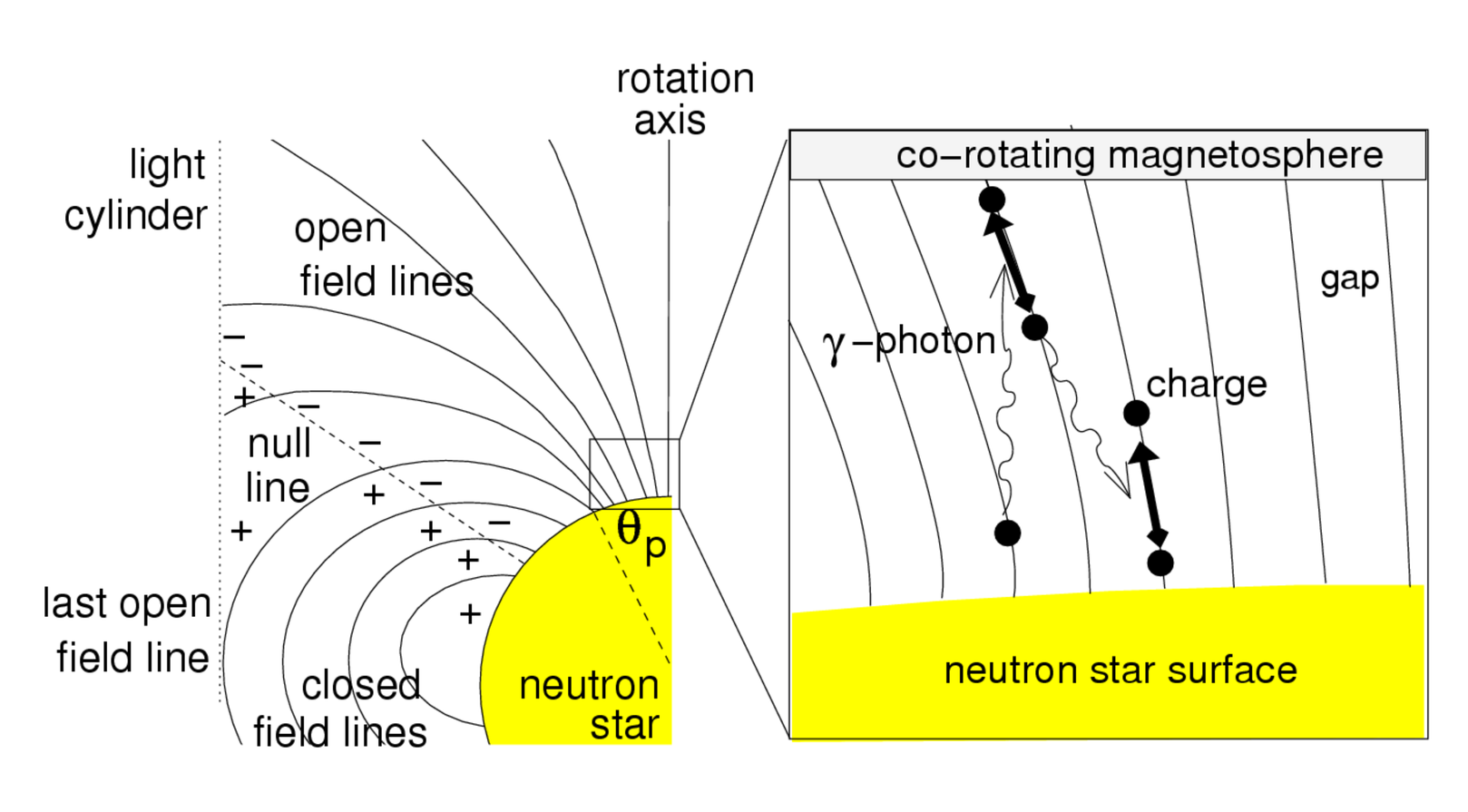
$$E_{\rm max} \approx 4\times10^{14}\,\eta_B^{1/2}\,\dot{M}_{-4}^{4/5}\,v_8^{13/5}\,\rho_1^{-3/10}\,t_{10}^{2/5}\left(\frac{L_c}{2{\rm pc}}\right)^{-1}\ {\rm eV}$$

Morlino, PB, Peretti & Cristofari 2021

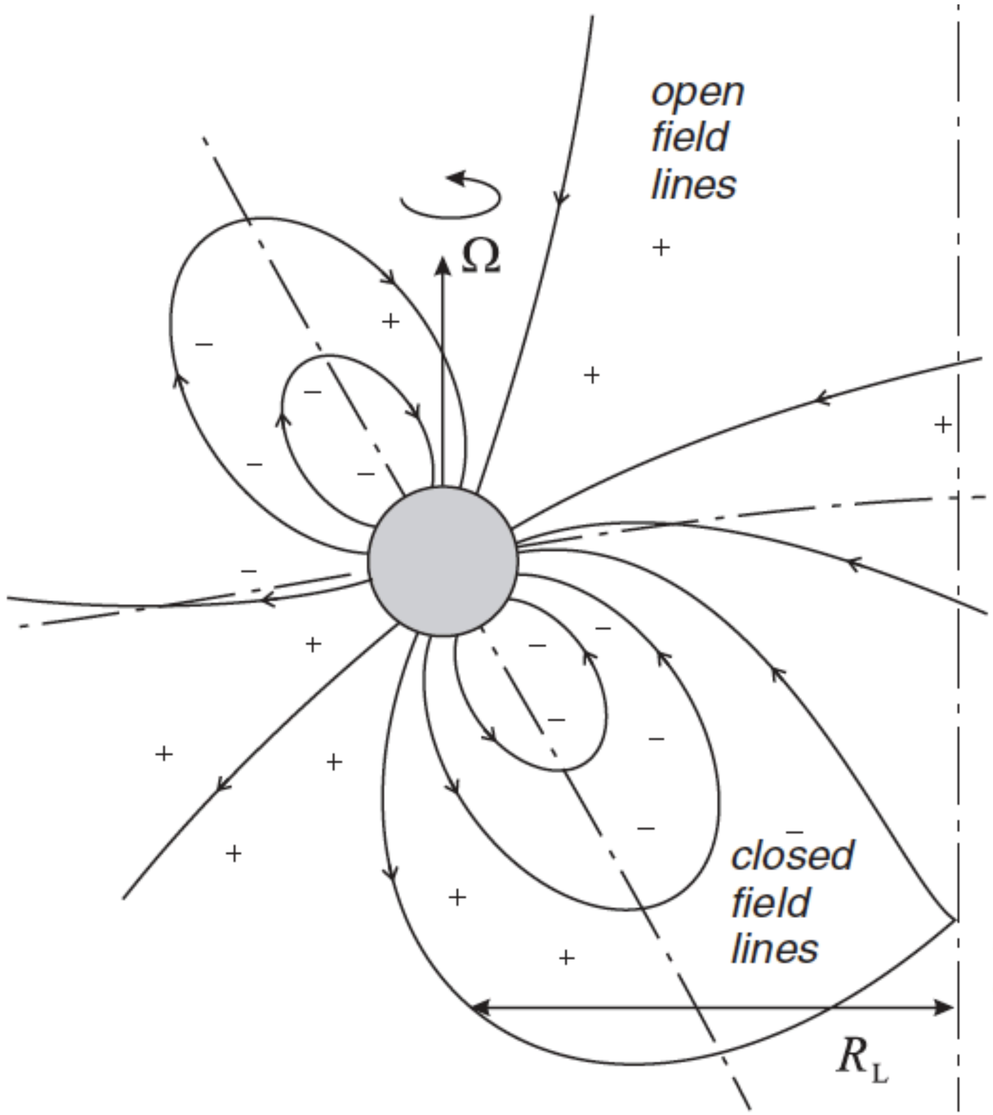
ANTIMATTER FROM PULSARS


$E^3\,\Phi\,[m^{-2}\,s^{-1}\,sr^{-1}\,GeV^2]$
10^2
10^1
10^0
10
10^2
10^3
E [GeV]
PAMELA e^-
AMS02 e^-
PAMELA e^+
AMS02 e^+
CR+ISM $\rightarrow e^+ + \ldots$
CR+ISM $\rightarrow e^- + \ldots$

PULSAR WIND LAUNCHING



MORE ON THE MAGNETOSPHERE

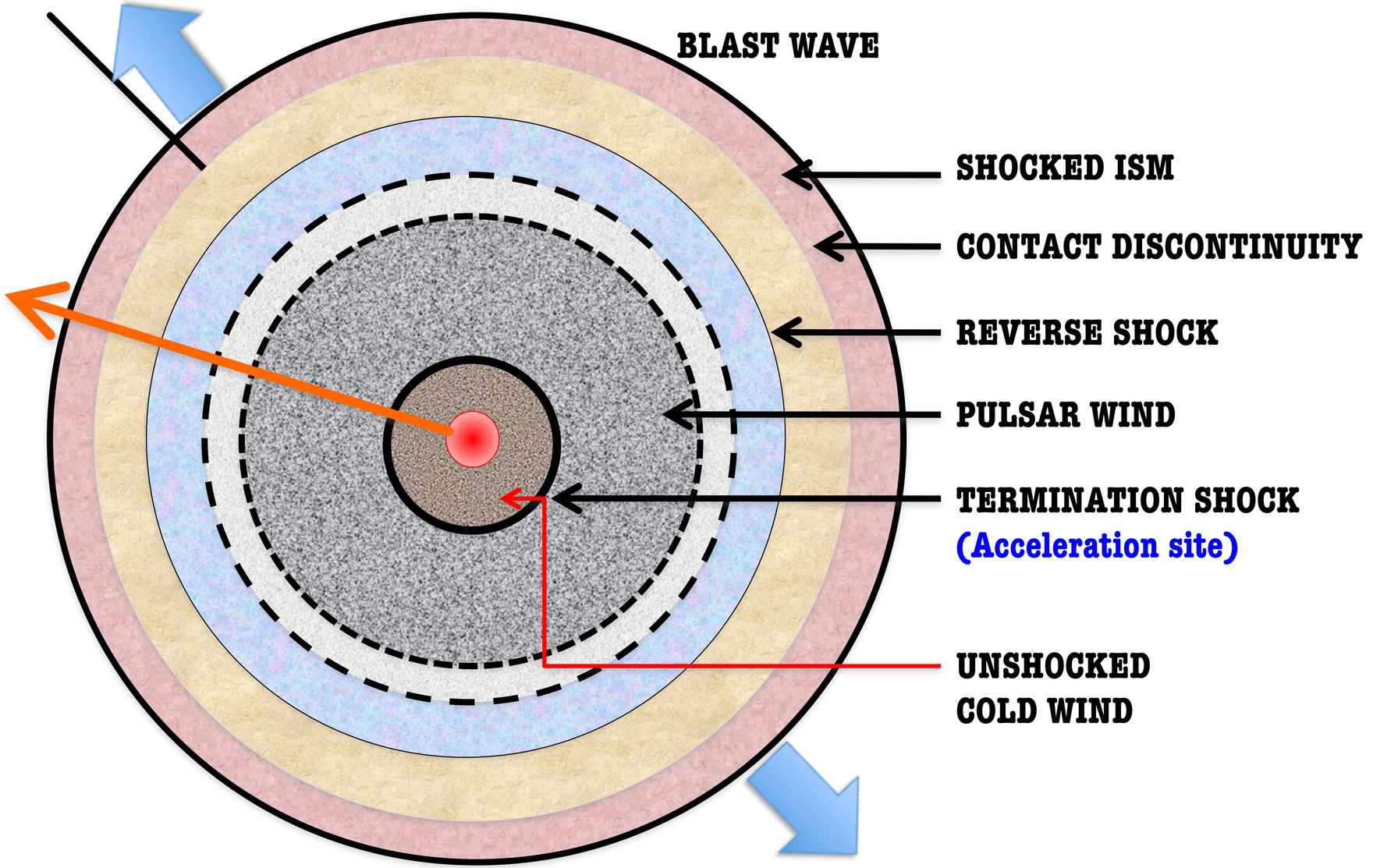


THE MAGNETOSPHERE, FILLED WITH ELECTRON-POSITRON PAIRS IS FORCED TO COROTATE WITH THE STAR, AT LEAST OUT TO THE POINT WHERE THE CO-ROTATION SPEED EQUALS THE SPEED OF LIGHT. THIS IS CALLED THE LIGHT CYLINDER:

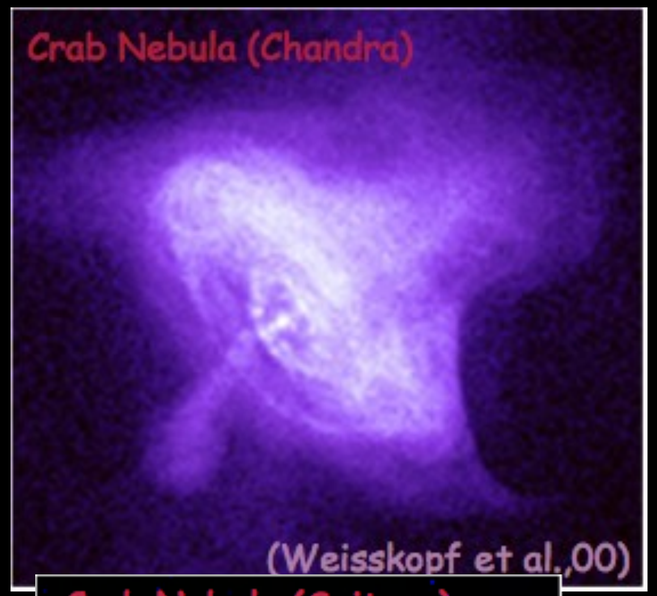
$$R_L = \frac{c}{\Omega}$$

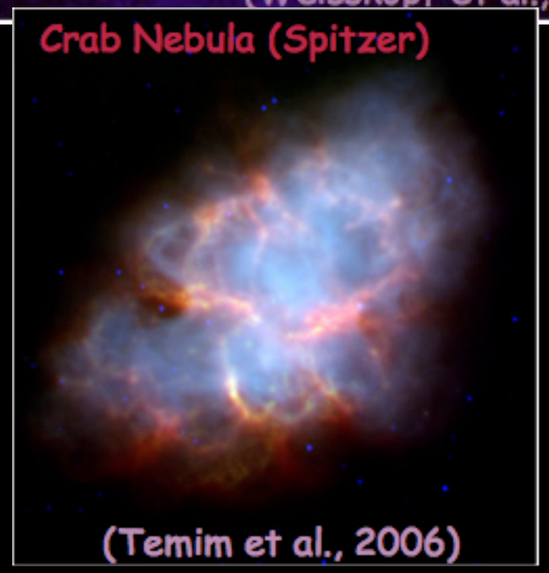
INTERESTINGLY ENOUGH, ALL PROPERTIES OF THE PWN ARE MAPPED INTO PROPERTIES OF THE LIGHT CYLINDER

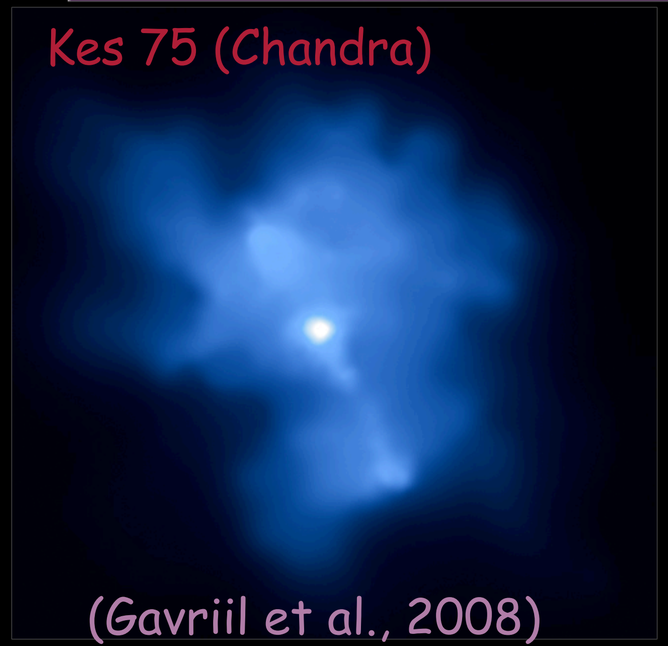
A SCHEMATIC VIEW OF A PWN

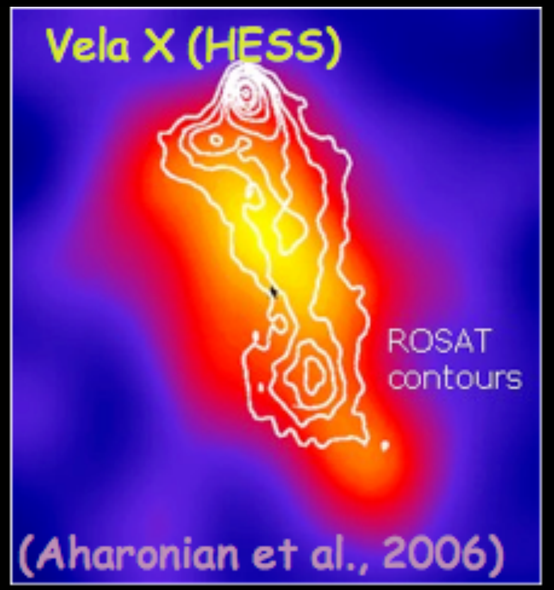


COMPLEX MORPHOLOGIES

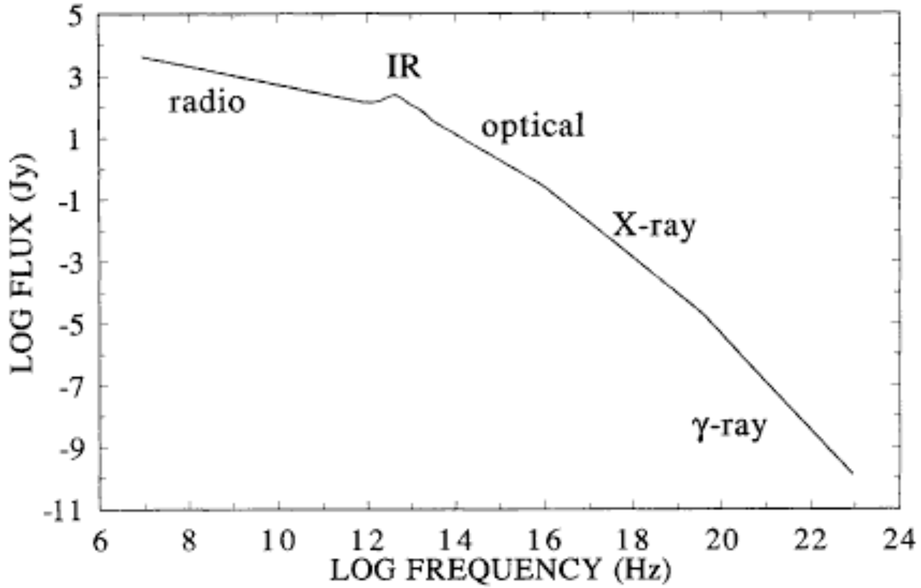








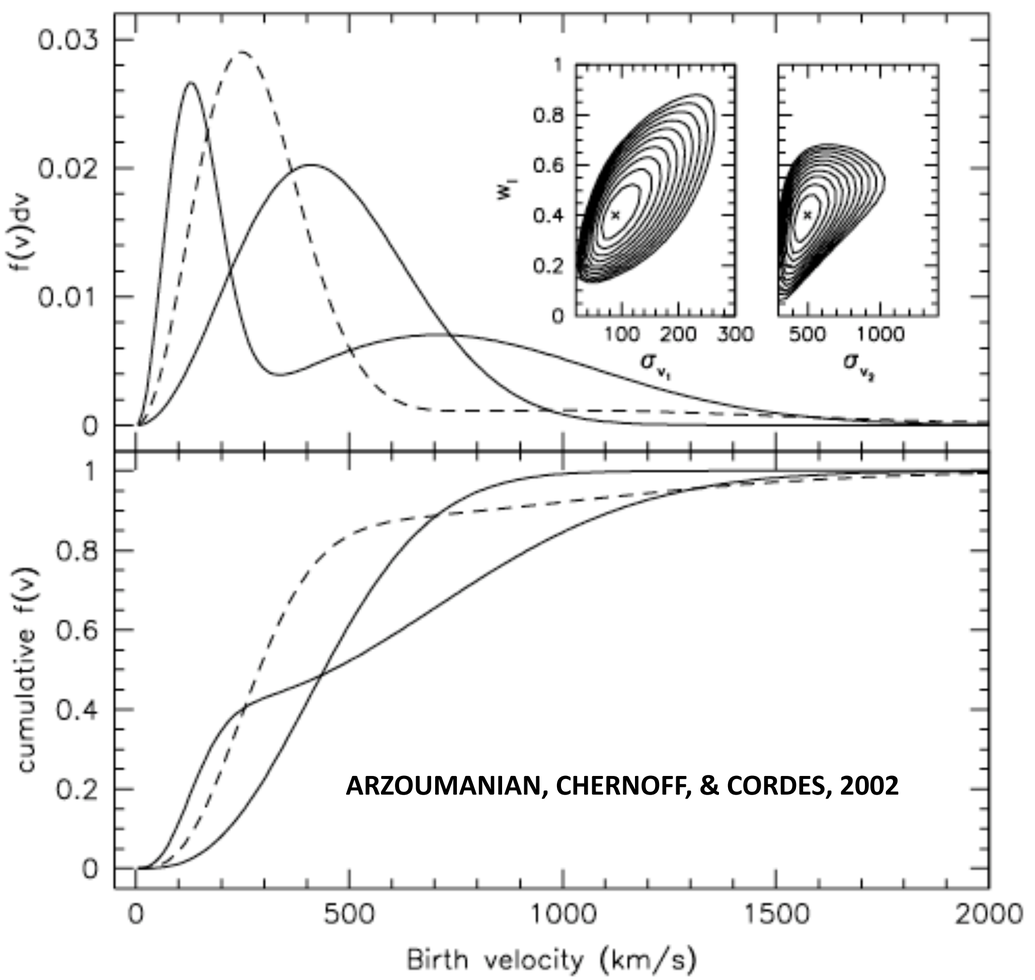
THE STEREOTYPICAL PWN



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.

NEUTRON STAR BIRTH KICK AND ESCAPING THE PARENT SNR

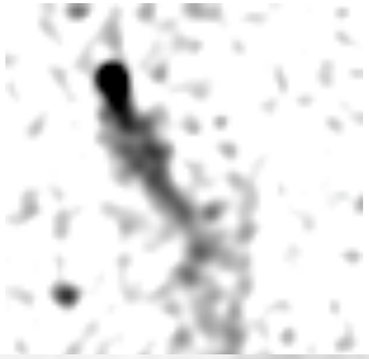


FOR TYPICAL VALUES OF PARAMETERS THE NS LEAVES THE SNR ABOUT 40,000 years AFTER EXPLOSION

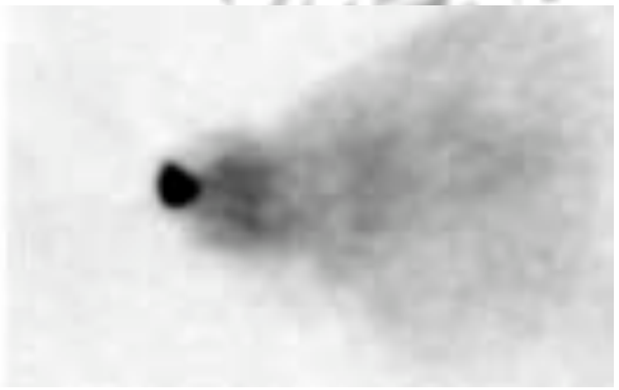
Spectra in bow shock nebulae

Still spinning after escaping the SNR

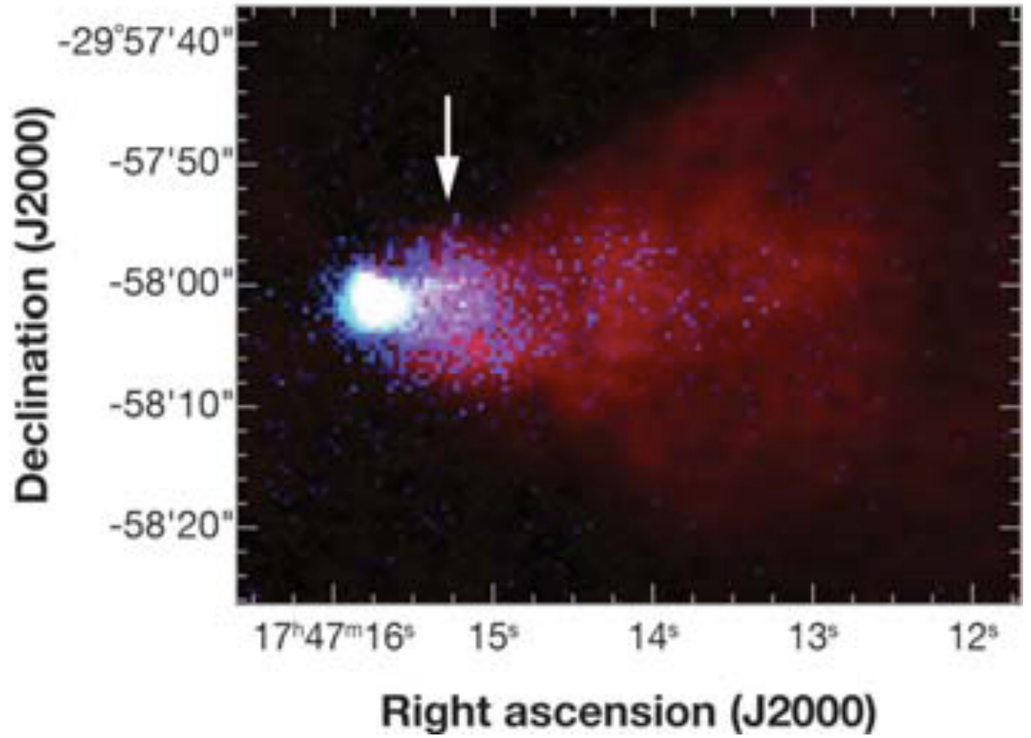
IN THE TWO CASES of BSN OUTSIDE A SNR IN WHICH WE HAVE RADIO MEASUREMENTS WE INFER A SPECTRUM OF ACCELERATED PARTICLES WITH SLOPE ~-1.5



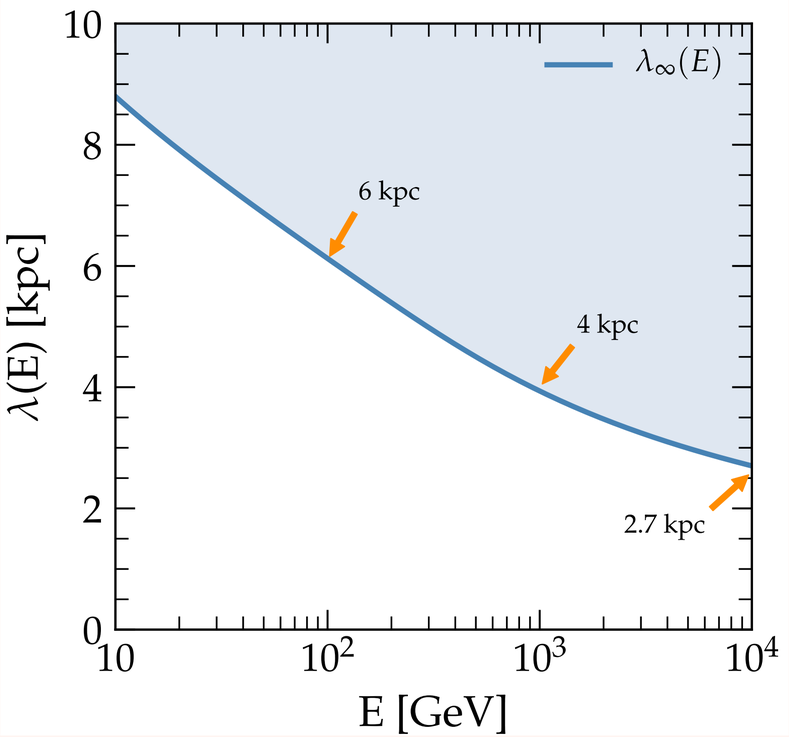
PSR J1509–5850
Slope radio: -0.26
Slope Electrons: -1.52
Ng et al. 2010

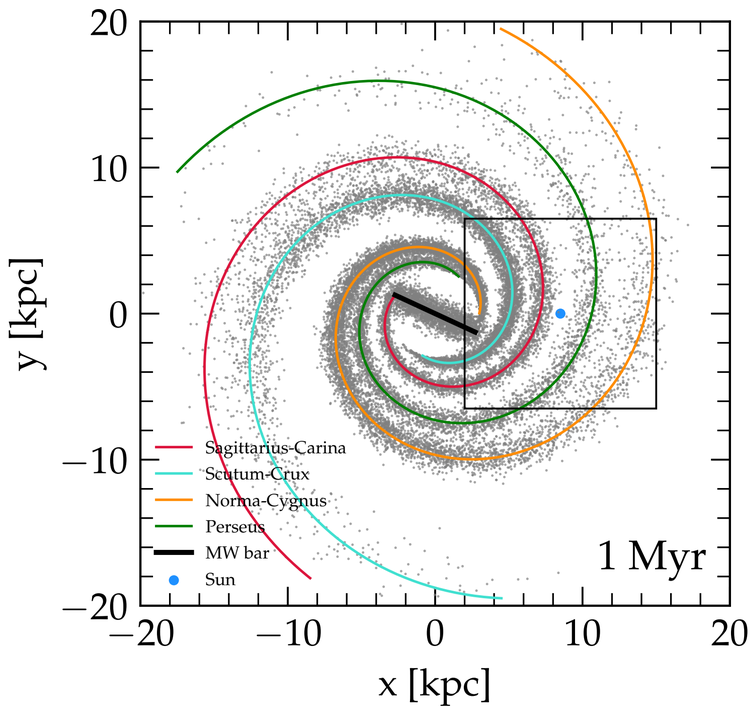


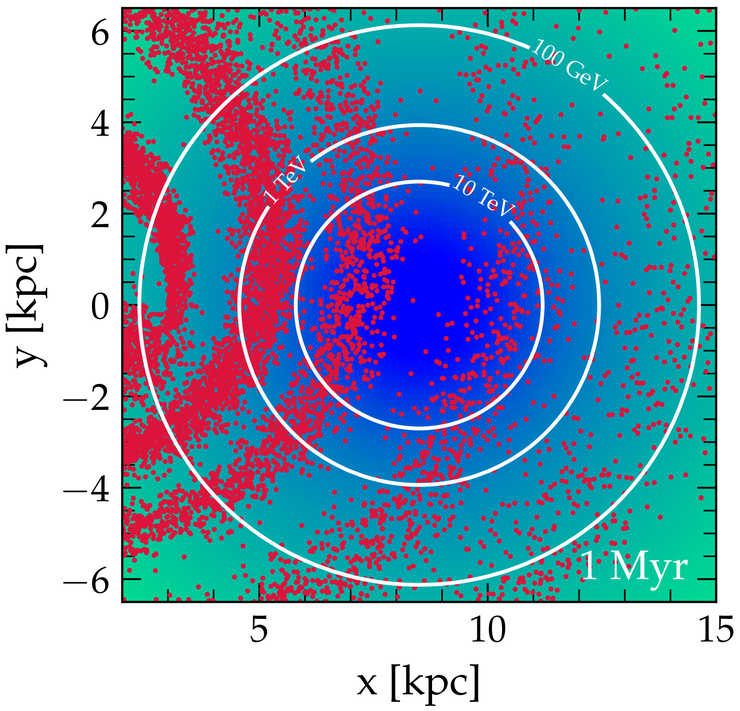
The Mouse
Slope radio: -0.3
Slope Electrons: -1.6
Gaensler et al. 2004



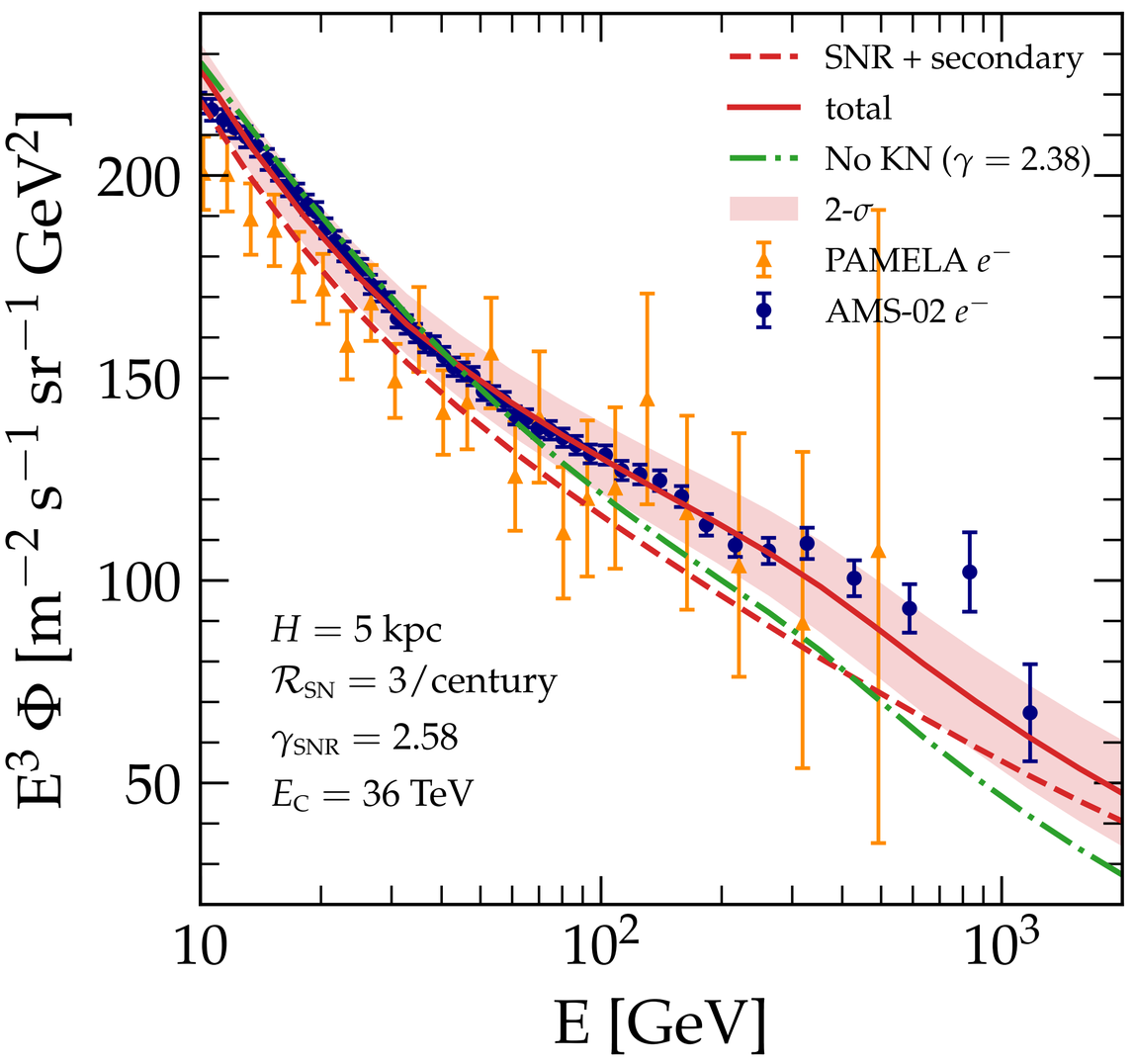
LEPTONS AND ENERGY LOSSES

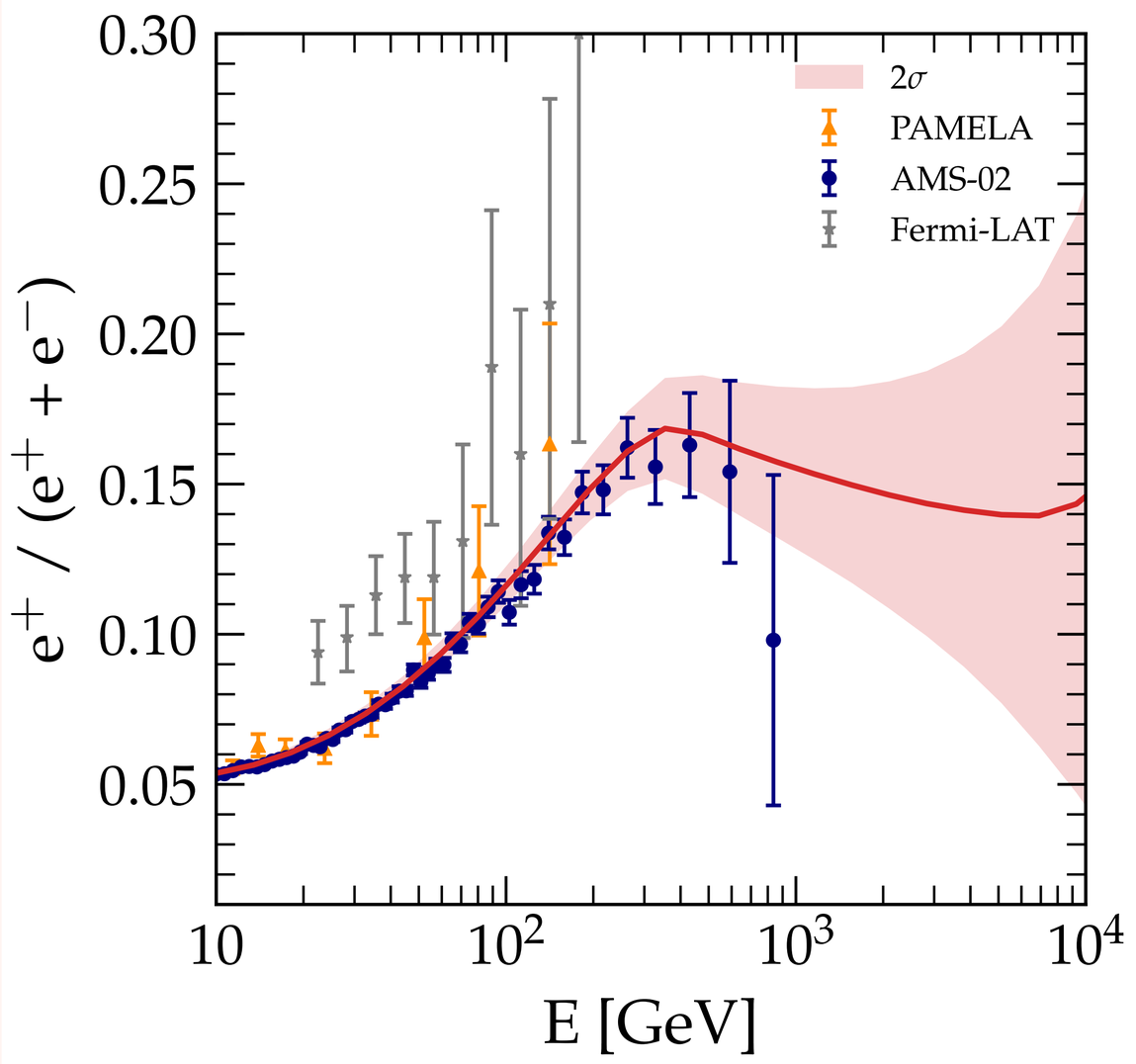




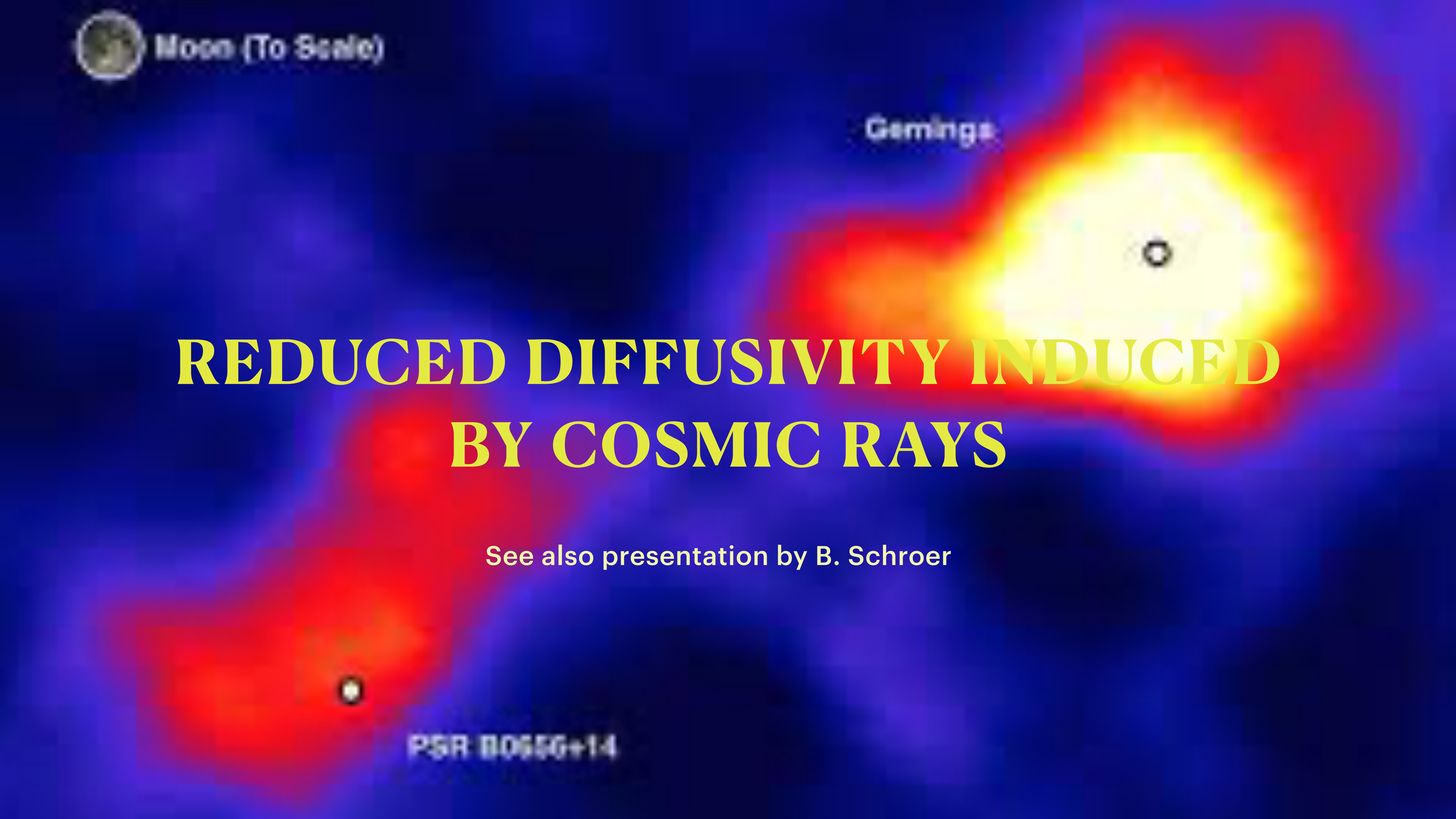


Evoli et al. 2020, 2021





Evoli et al. 2021



REDUCED DIFFUSIVITY INDUCED BY COSMIC RAYS

See also presentation by B. Schroer

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*

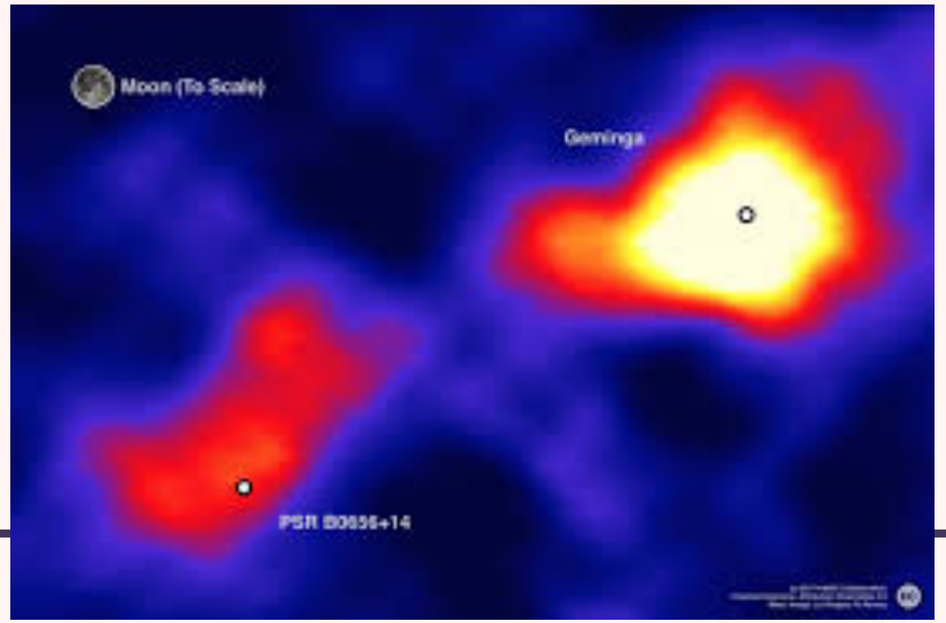
REDUCED DIFFUSIVITY AROUND SOURCES

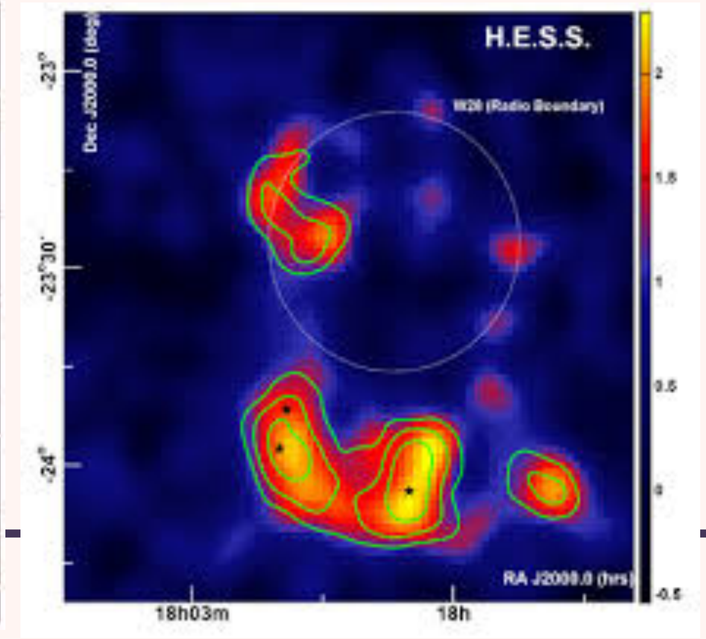
INDEPENDENT SIGNATURES OR REGIONS OR REDUCED SENSITIVITY AOURND SOURCES (PULSARS, STAR CLUSTERS, SUPERNOVA REMNANTS)

PERHAPS COSMIC RAYS THEMSELVES ARE ABLE TO CAUSE THESE REGIONS

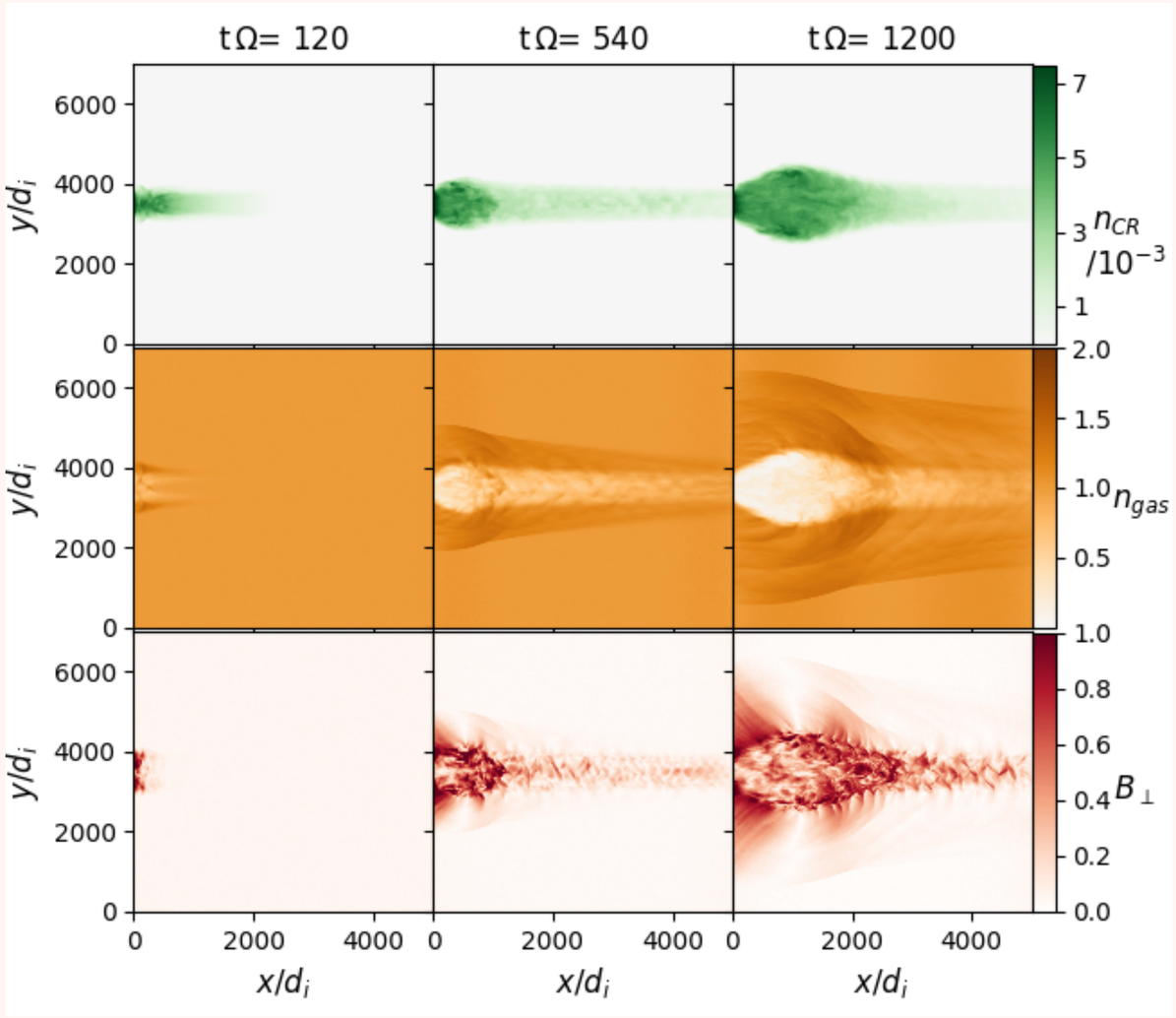
THE ACTION IS EASILY INDUCED BY THE STREAMING OF COSMIC RAYS THROUGH KINETIC INSTABILITIES **(D'angelo,PB&Amato+2015, 2016, 2018)**

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





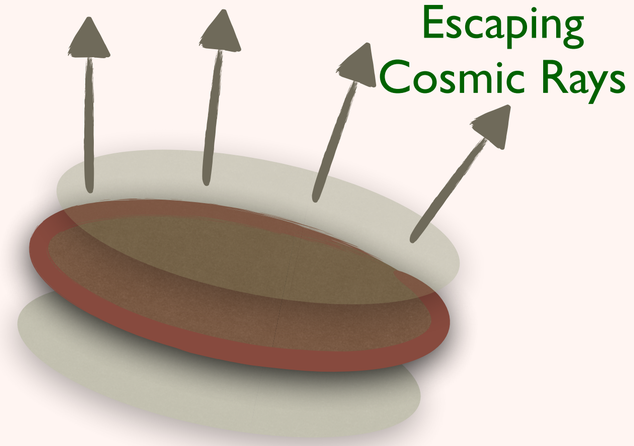
2D HYBRID SIMULATIONS OF THIS PHENOMENON



- 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*

ESCAPE OF CR FROM THE GALAXY

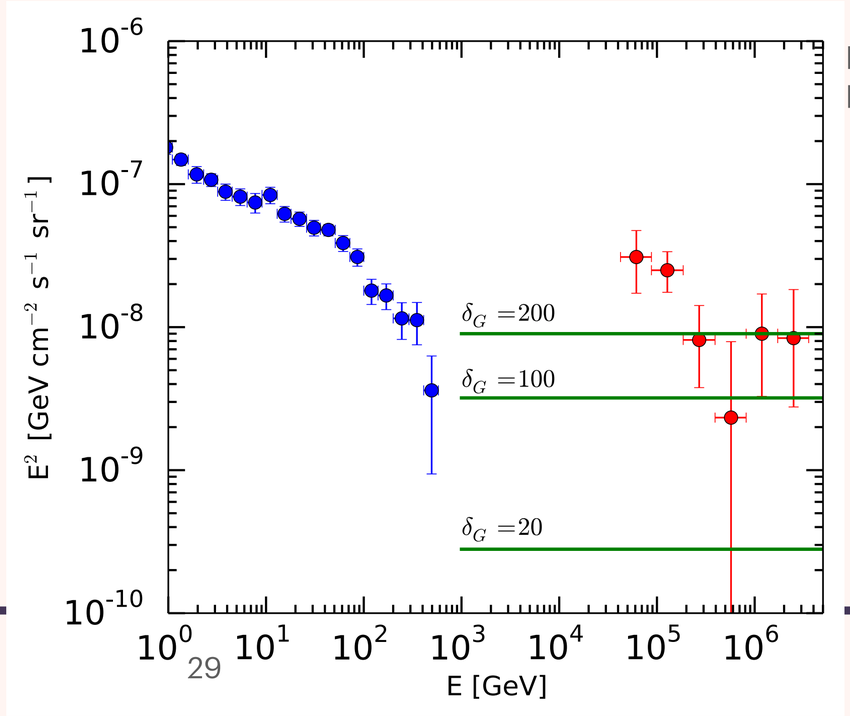


COSMIC RAYS ESCAPING THE GALAXY ON kpc SCALES CONSERVE THEIR CURRENT (CONSERVATION OF FLUX == LIOUVILLE THEOREM)

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

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 - NO LACK OF RICH SCIENCE CASES
- 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 CAN RETAIN THE ROLE OF LEADERSHIP THAT THEY CONQUERED