Astroparticle Physics

Cosmic Rays and related issues

P. Blasi

(INAF/Arcetri and Gran Sasso Science Institute/INFN)

What is Astroparticle Physics?

Astroparticle Physics: experimental and theoretical research papers in the interacting fields of **Cosmic Ray Physics**, **Astronomy** and **Astrophysics**, **Cosmology** and **Particle Physics** focusing on new developments in the following areas:

- High-energy cosmic-ray physics and astrophysics;
- Particle cosmology;
- Particle astrophysics;
- Related astrophysics: supernova, AGN, cosmic abundances, dark matter etc.;
- High-energy, VHE and UHE gamma-ray astronomy;
- High- and low-energy neutrino astronomy;
- Instrumentation and detector developments related to the above-mentioned fields.

In other words, Astroparticle Physics is, with good approximation, all what we will be discussing about in these two days…

It would not be a bad idea to conform to what everybody else means by the term Astroparticle Physics, so that we can avoid hearing people say that INAF is not too involved in it…

It is, after all, one of the wealthiest fields in terms of rate of observational stimuli and challenges

Cosmic Rays & *Sons*

Cosmic Rays are only the electrically charged and neutral particles impinging upon the Earth Atmosphere, but…

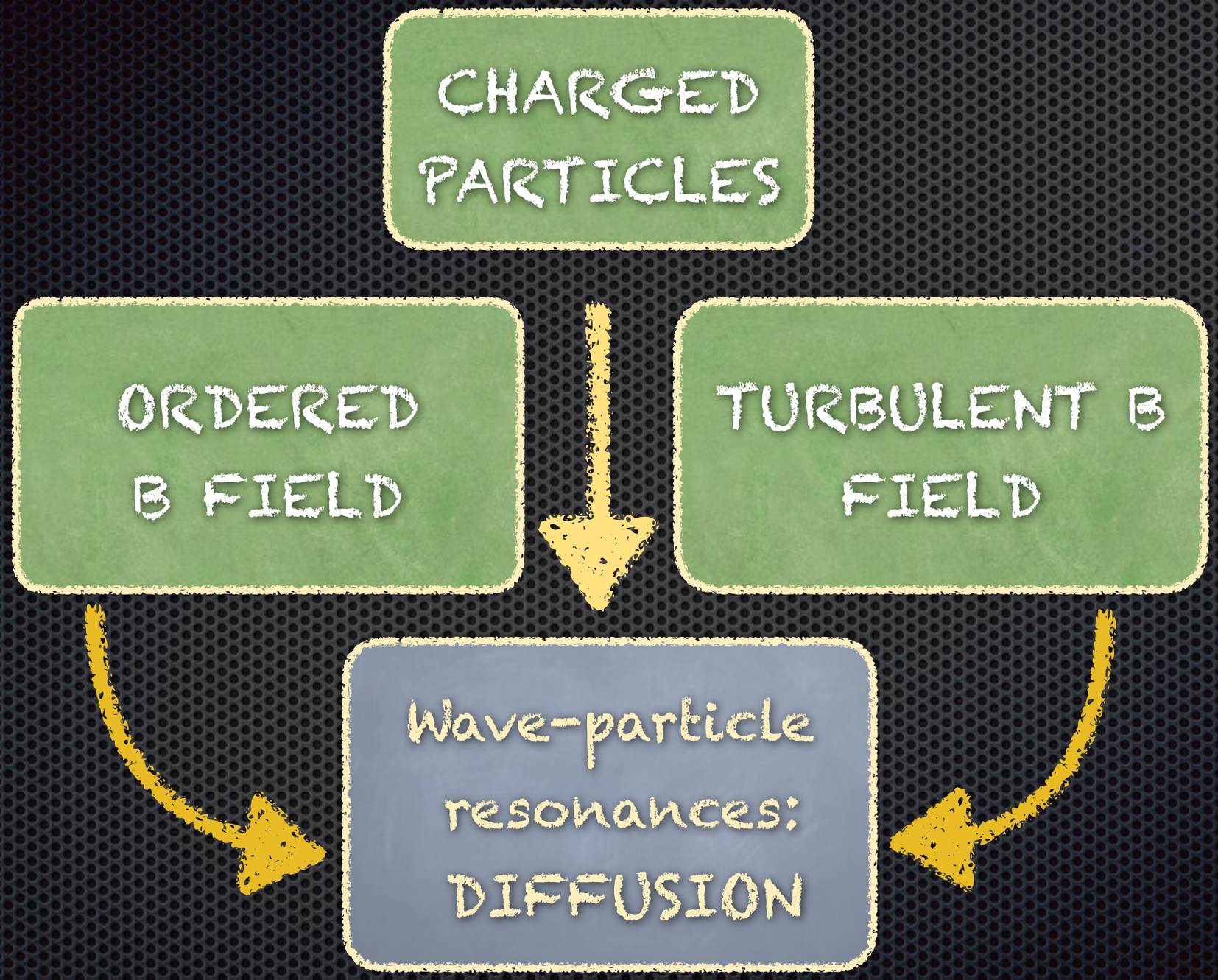
this field is involved in understanding the physics of origin and propagation also of those **accelerated particles** that do not make it to the Earth and still are responsible for the non-thermal emission we observe

We see this as:

Diffuse Galactic Emission
Emission from Galactic SNR, PWN, MicroQSO, neutrons stars, … (radio, gamma, …)
Emission from extragalactic sources (AGN, clusters, GRBs, starbursts, …)
Diffuse extragalactic emission (gamma rays, X-rays, radio…)

The Galactic diffuse emission is also an irreducible background for searches of DM annihilation/decay, for searches of CMB fluctuations, …

It's all about describing acceleration and transport as a whole...



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CHARGED PARTICLES → PLASMA INSTABILITIES

ORDERED B FIELD

TURBULENT B FIELD

Wave-particle resonances: DIFFUSION

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CHARGED PARTICLES

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Wave-particle resonances: DIFFUSION

RECALL THAT RESONANCE OCCURS ON SCALES (1/3) A.U. E_{GeV} /Bμ

(Some) Open issues with CRs

- Main sources of Galactic CRs
- Capability of SNRs reaching 10^{15} eV
- Modes of CR propagation in the Galaxy
- Transition from Galactic to extragalactic CRs
- Origin of UHECRs (sources, mass composition)
- Interaction between CRs and their environment
- Particle acceleration in extreme conditions
  - *Active Galactic Nuclei*
  - *Gamma ray bursts*
  - *Progenitors of merging black holes?*
- Indirect search for dark matter (radio, gamma, …)
- Tests of validity of Special Relativity

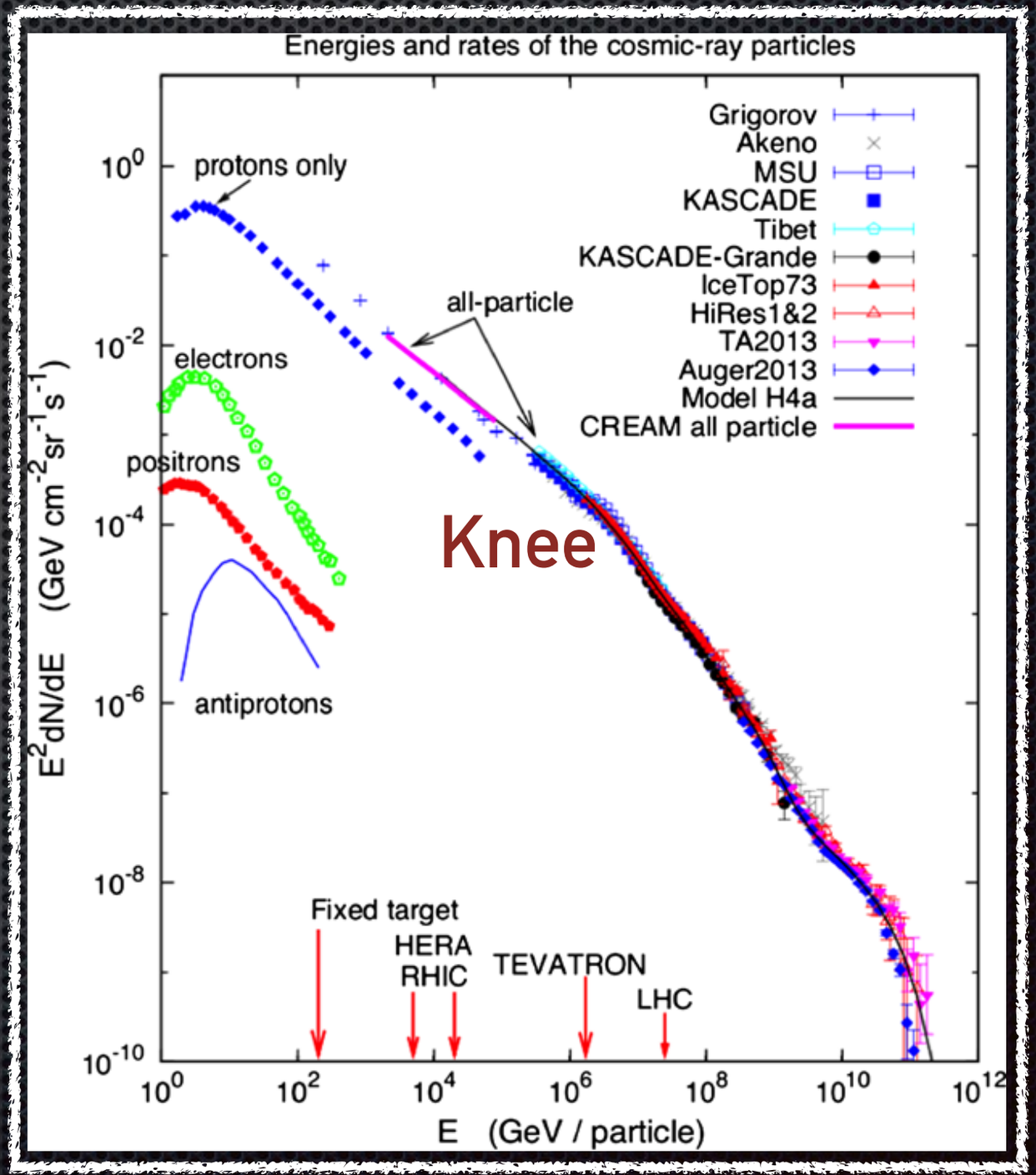
CR SPECTRUM

- From afar the spectrum looks like a power law

- power laws -> No Scales

- Broken power laws more interesting (scale->physics)

- After knee and ankle, first evidence of scales also in the spectra of individual elements



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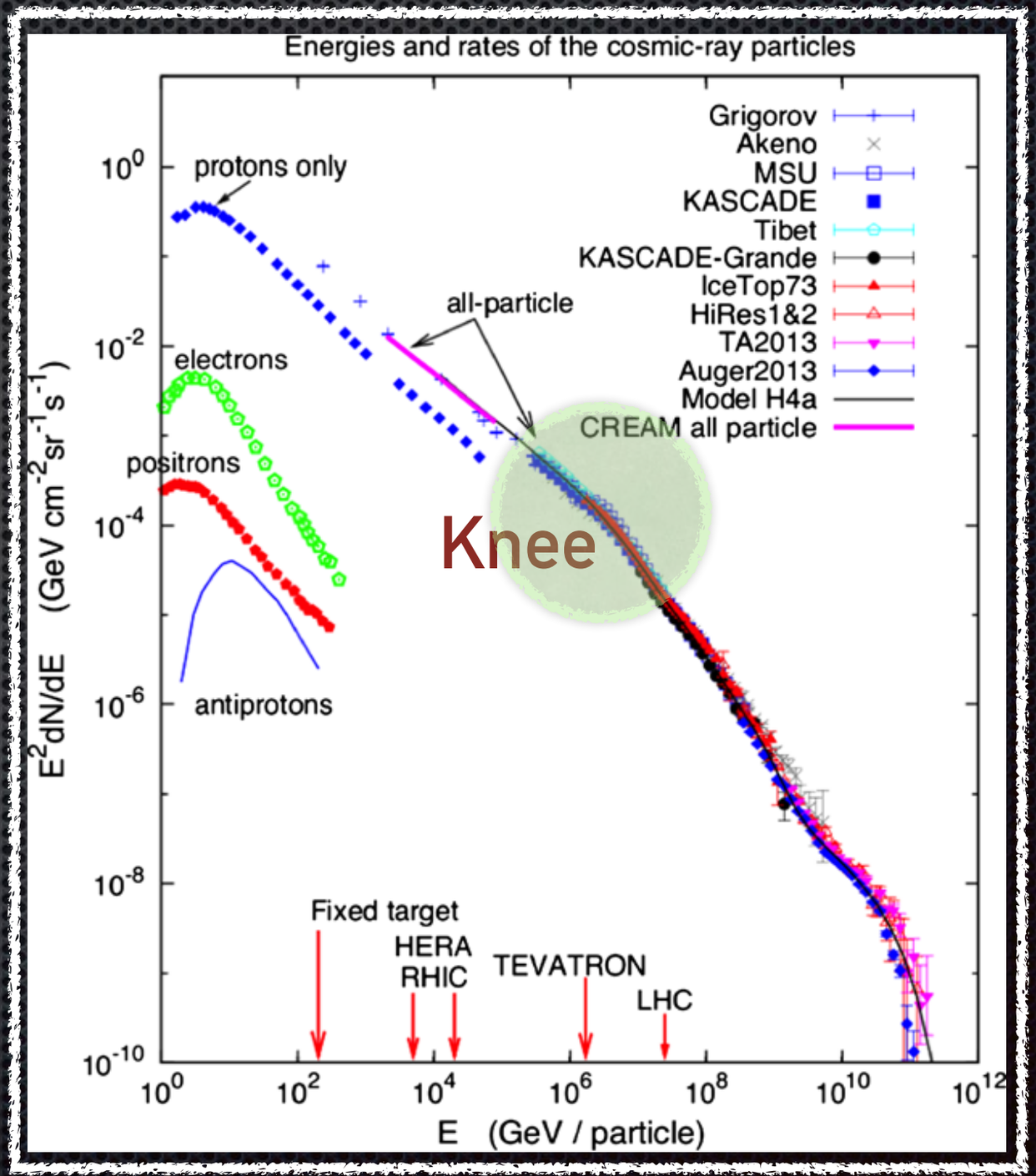

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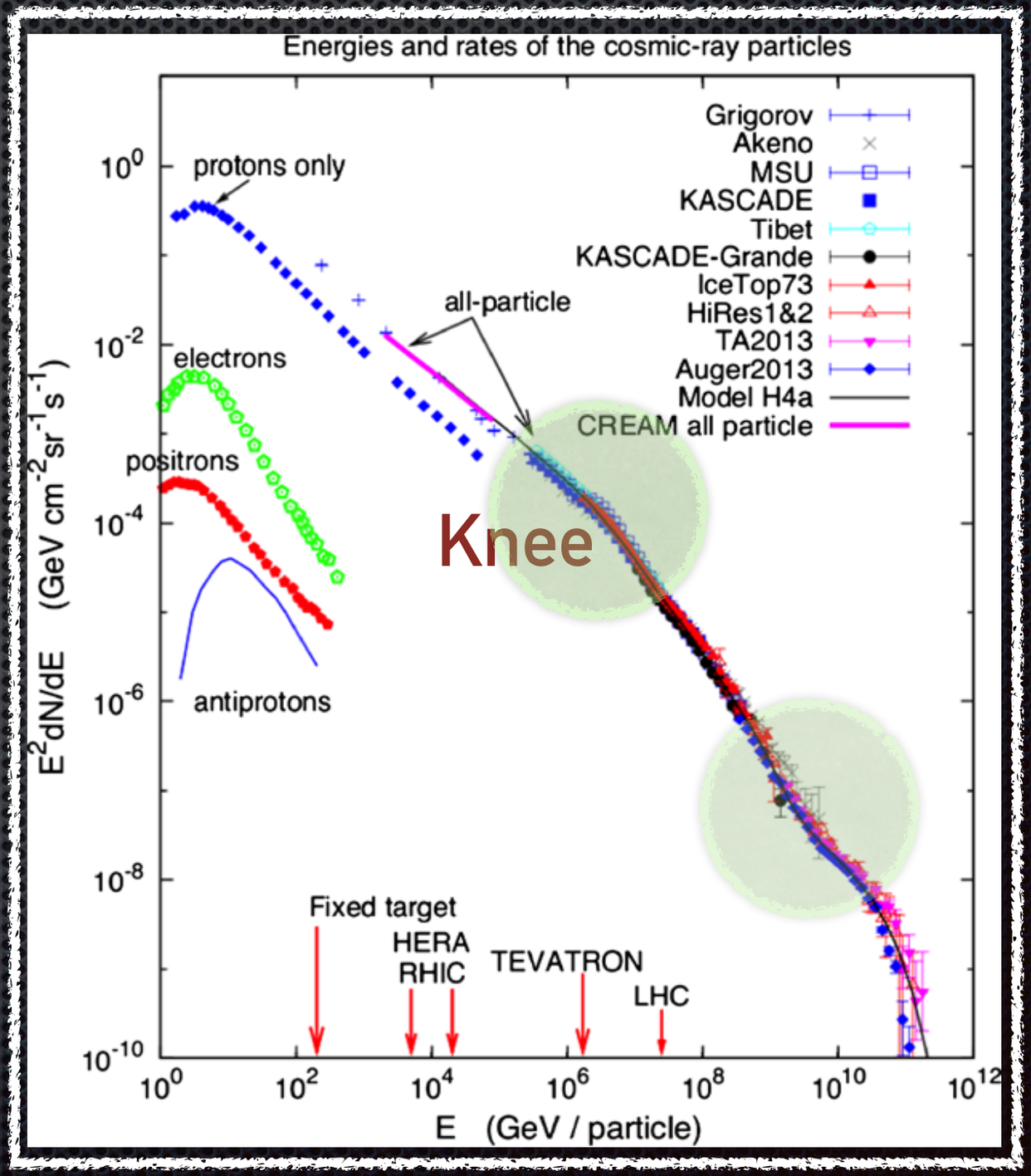

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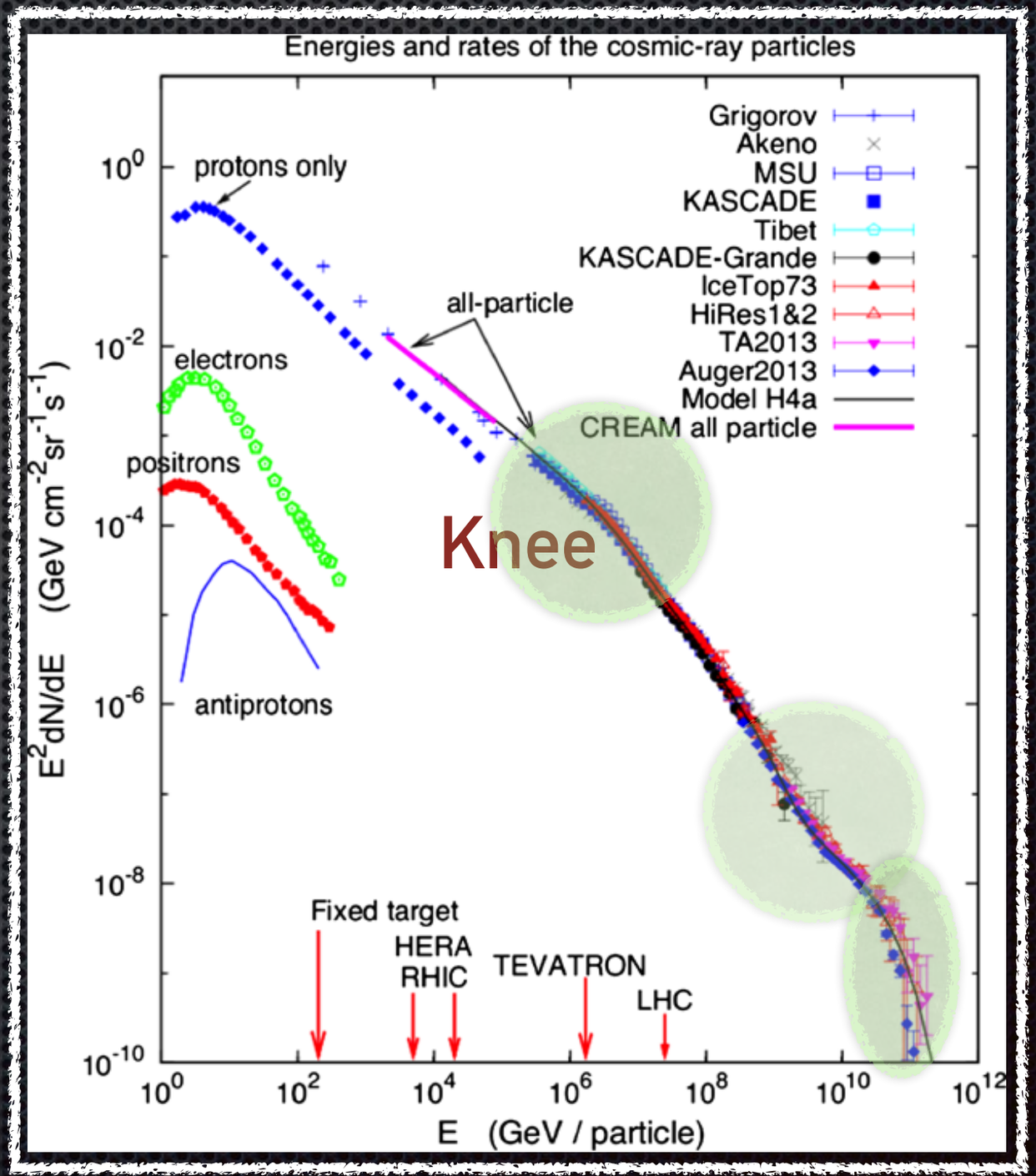
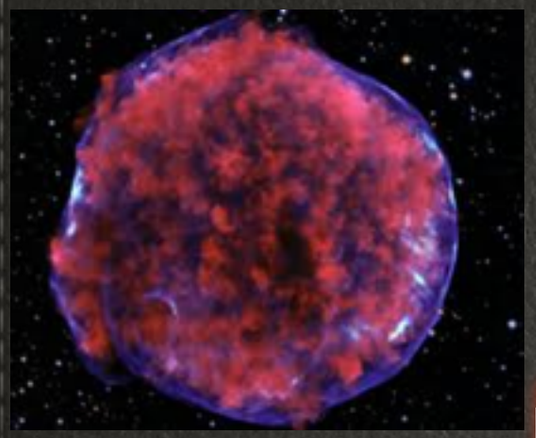


X-ray filaments and amplified B fields

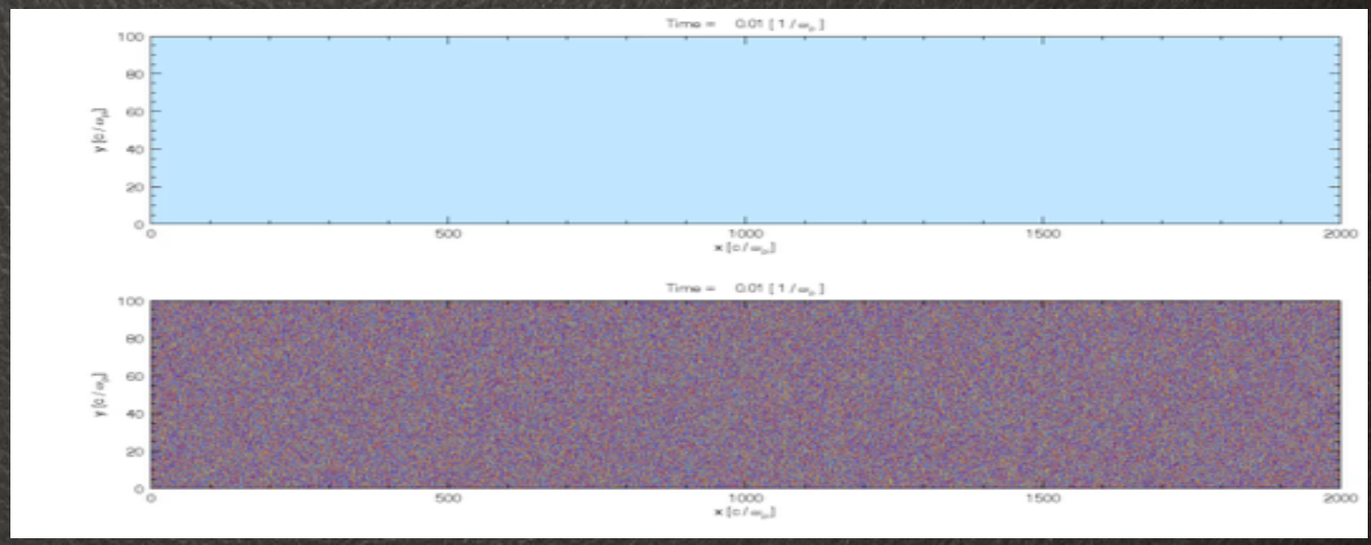


Virtually all young SNRs show evidence of thin non-thermal X-ray filaments (XMM, Chandra)

They are the result of synchrotron emission of high energy electrons accelerated at the shock

$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

B~100 B_{galaxy}



Caprioli & Spitkovsky 2013

Bell & Schure 2013
Cardillo, Amato & PB 2015

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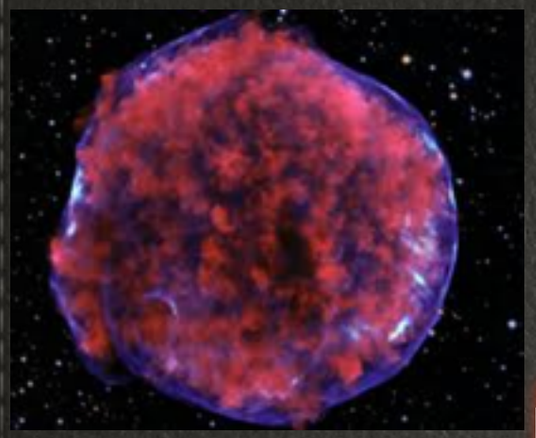

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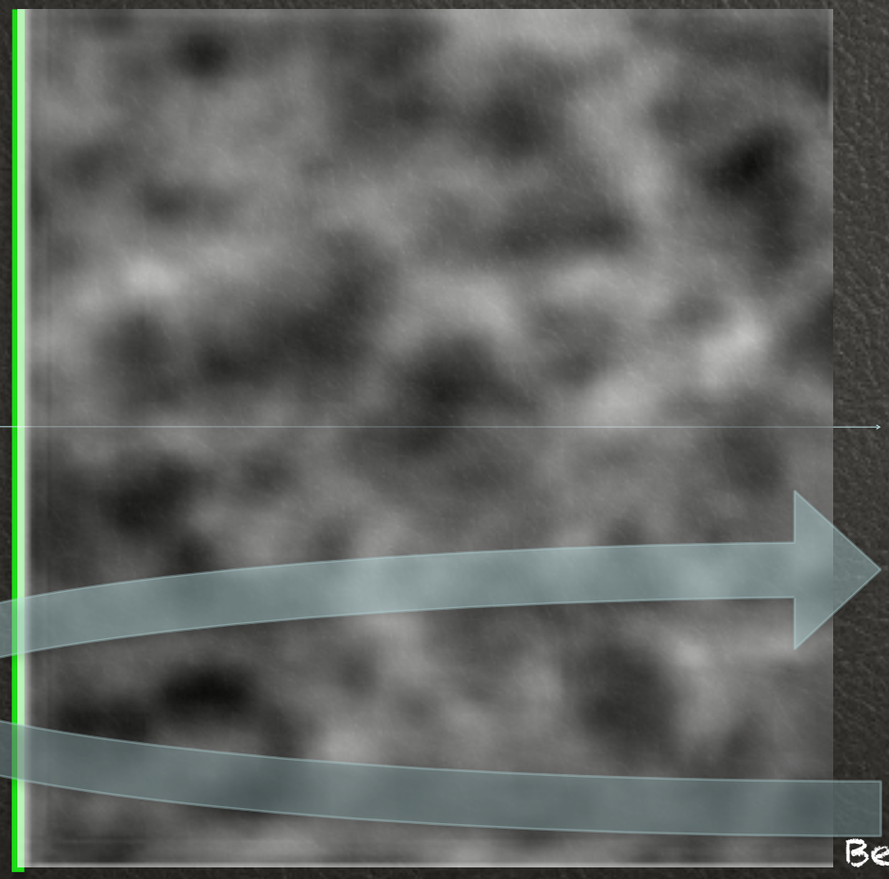

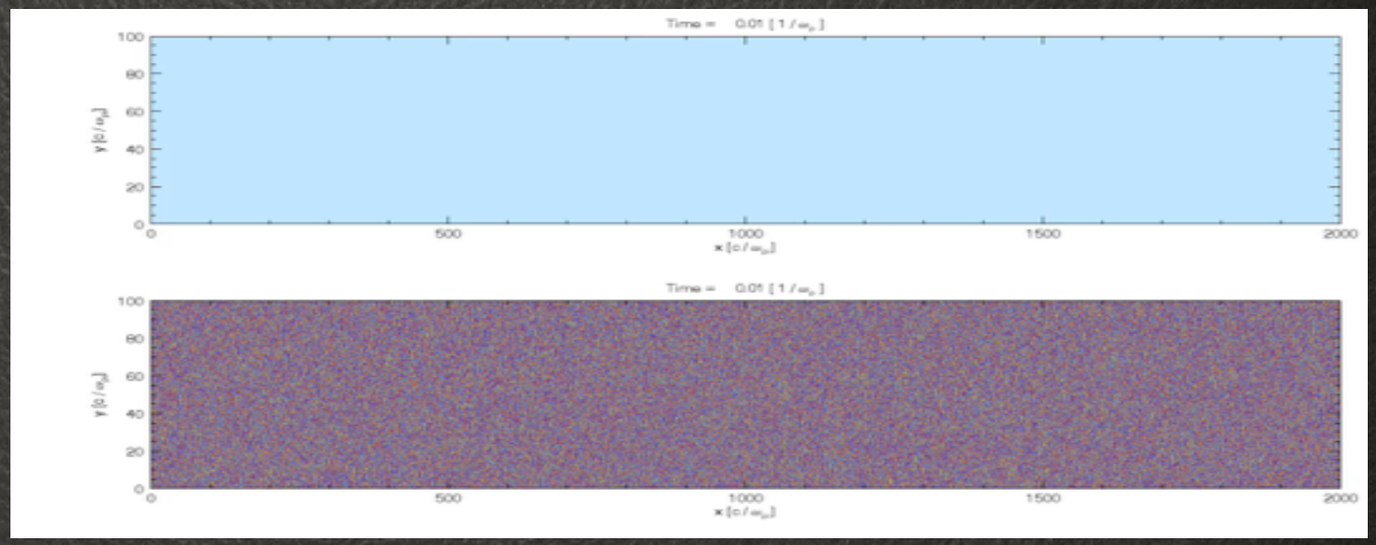

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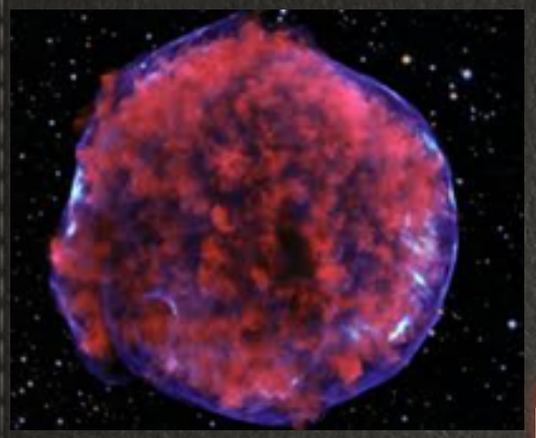

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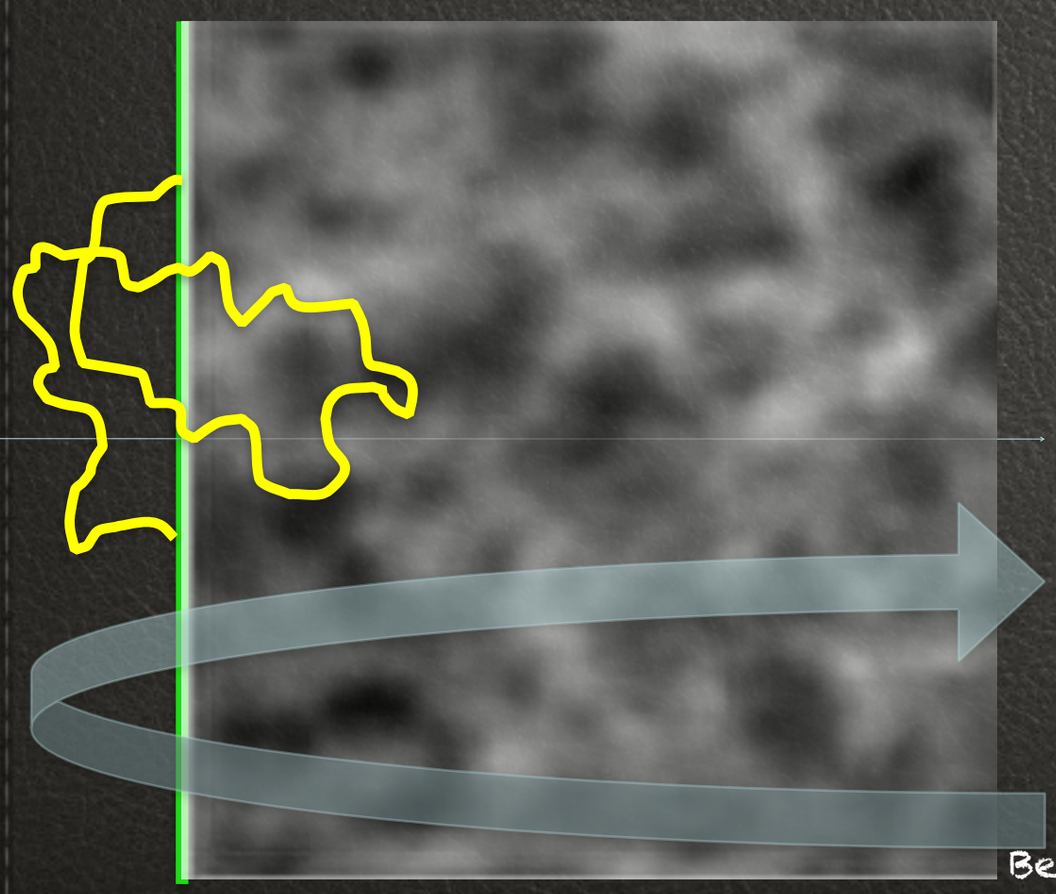

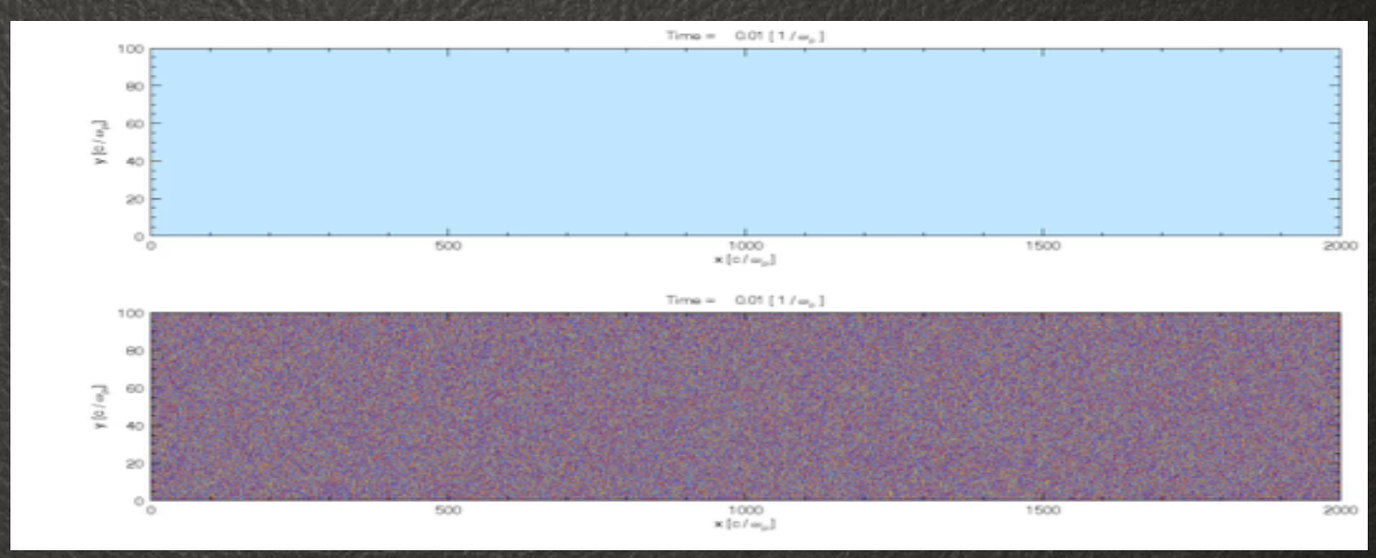

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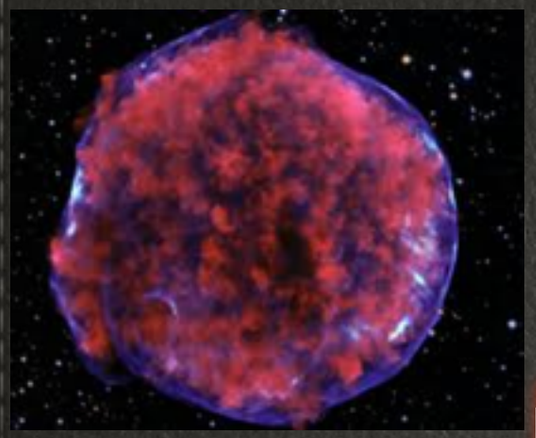

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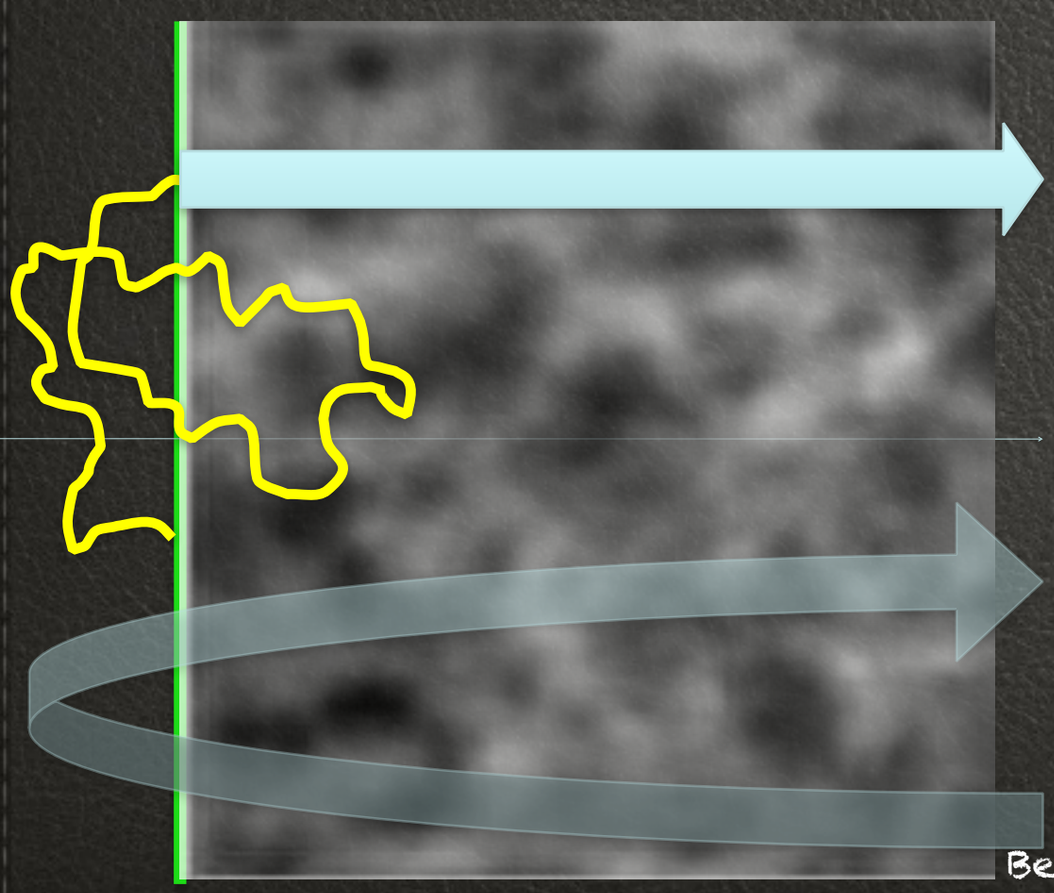

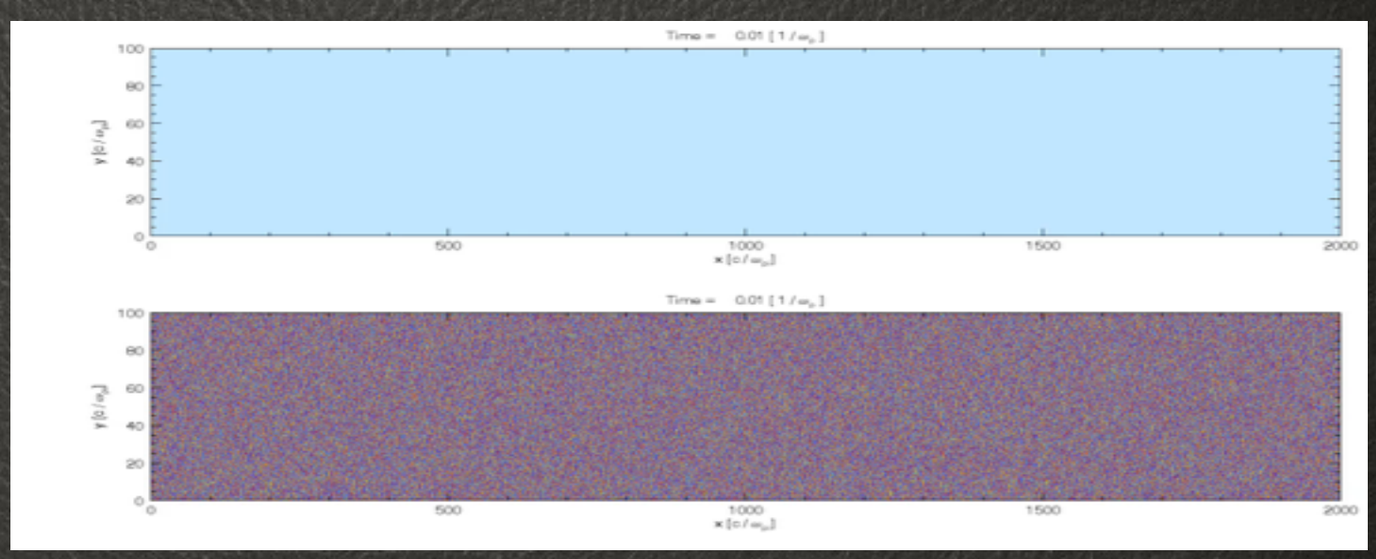

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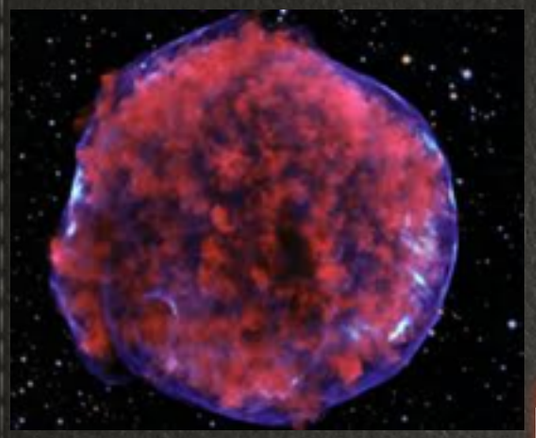

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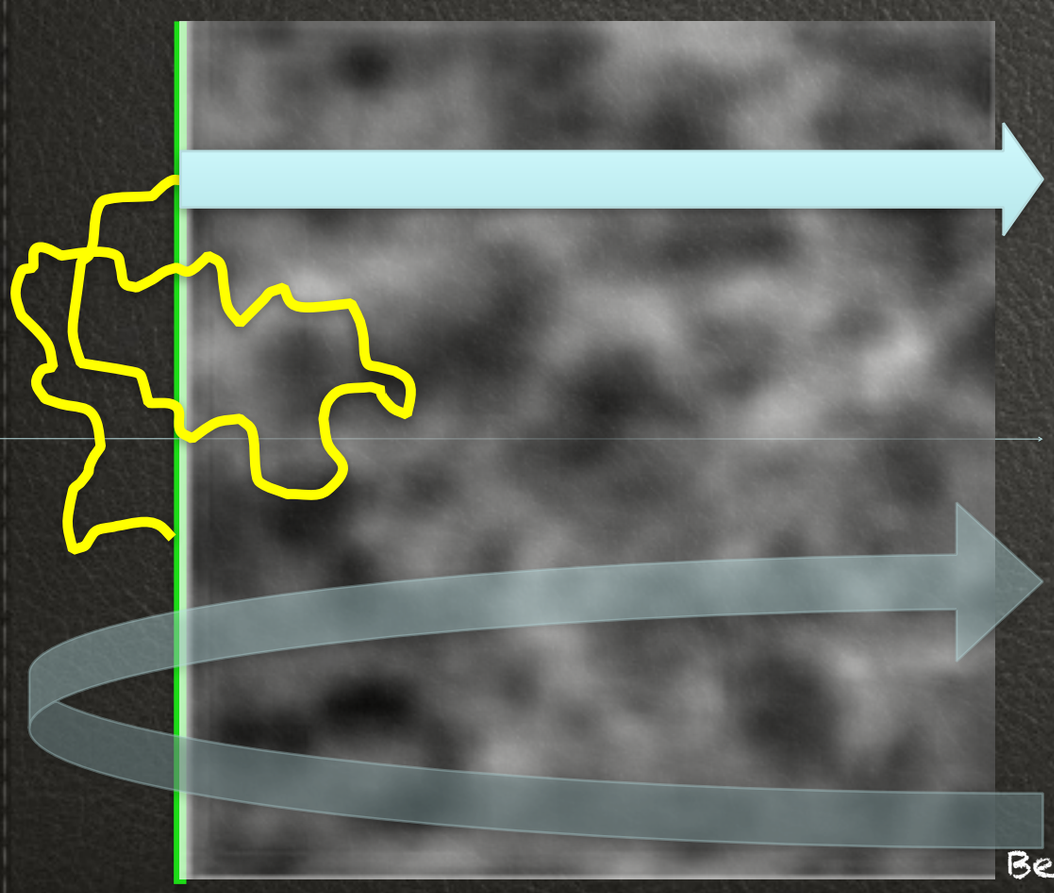

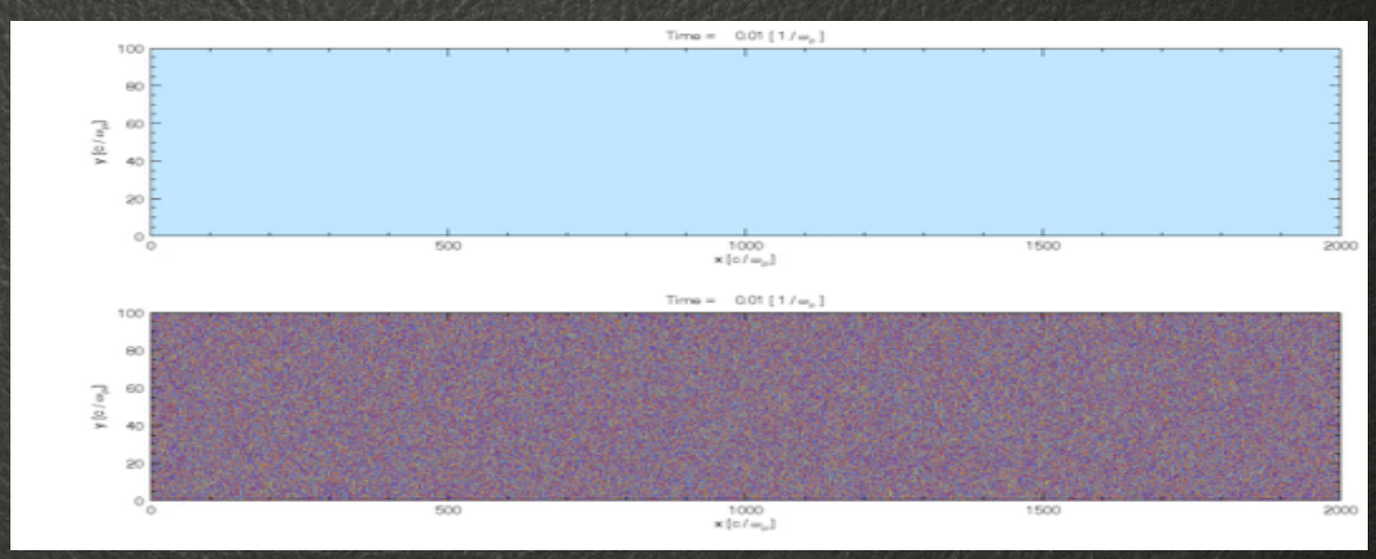

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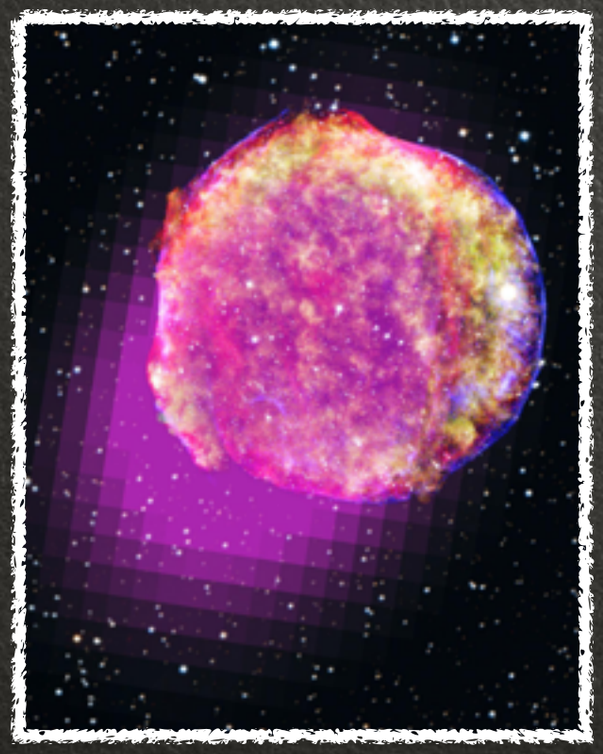
IMPLICATIONS FOR MAXIMUM ENERGY

Supernovae of type Ia

Explosion takes place in the ISM with spatially constant density

$$E_{max} \approx 130\ TeV \left(\frac{\xi_{CR}}{0.1}\right) \left(\frac{M_{ej}}{M_\odot}\right)^{-2/3} \left(\frac{E_{SN}}{10^{51} erg}\right) \left(\frac{n_{ISM}}{cm^{-3}}\right)^{1/6}$$



Supernovae of type II

IMPLICATIONS FOR MAXIMUM ENERGY

Supernovae of type Ia

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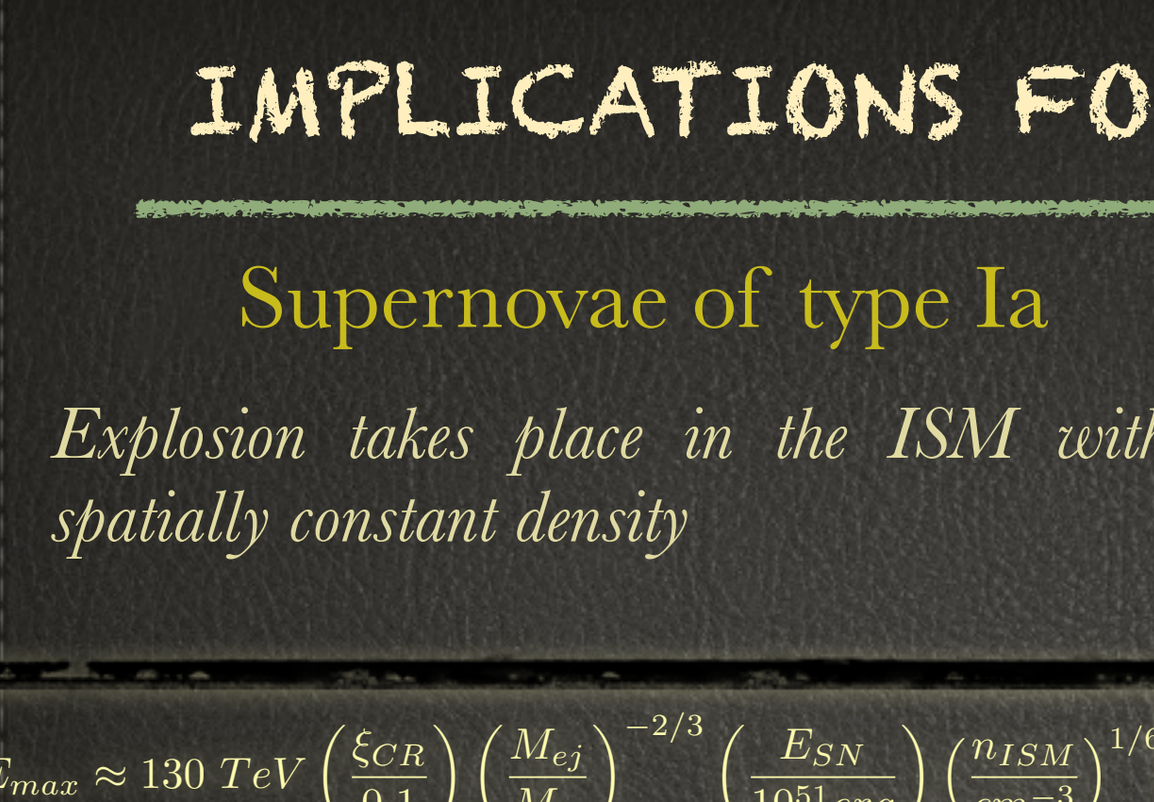

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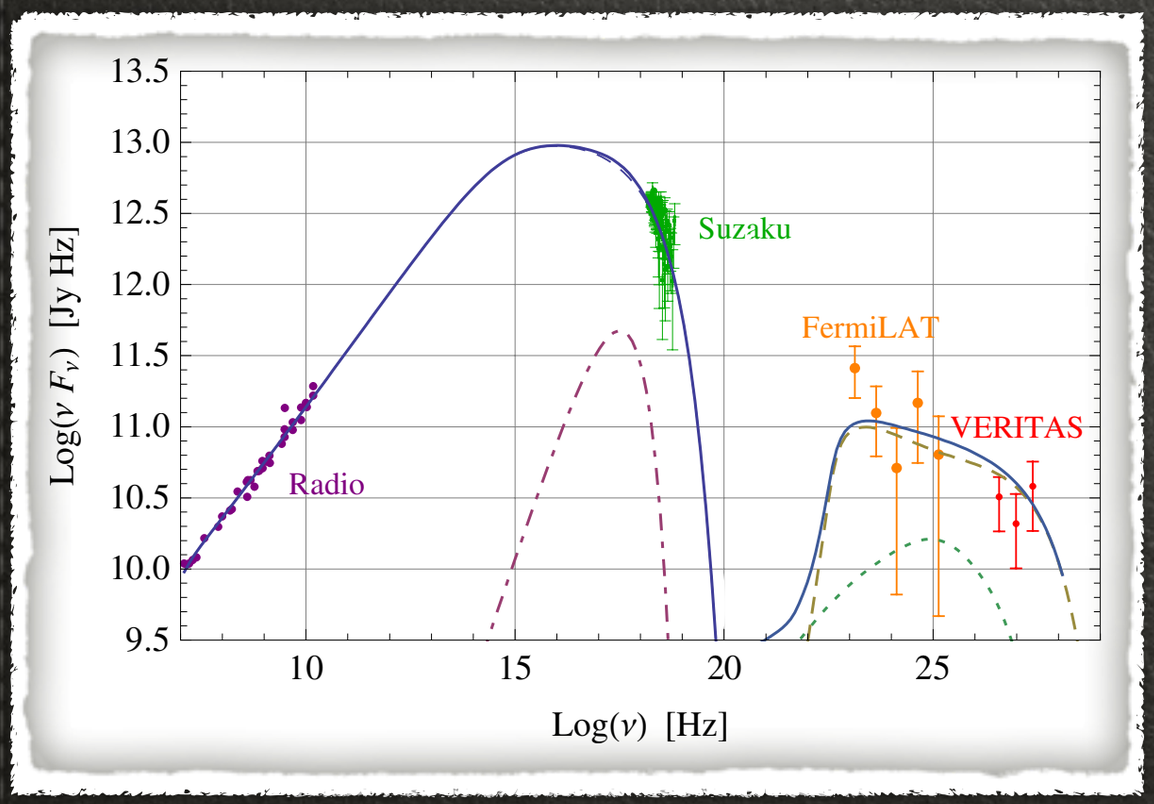


Supernovae of type II

In most cases the explosion takes place in the dense wind of the red super-giant progenitor

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_W}$$

The Sedov phase reached while the shock expands inside the wind

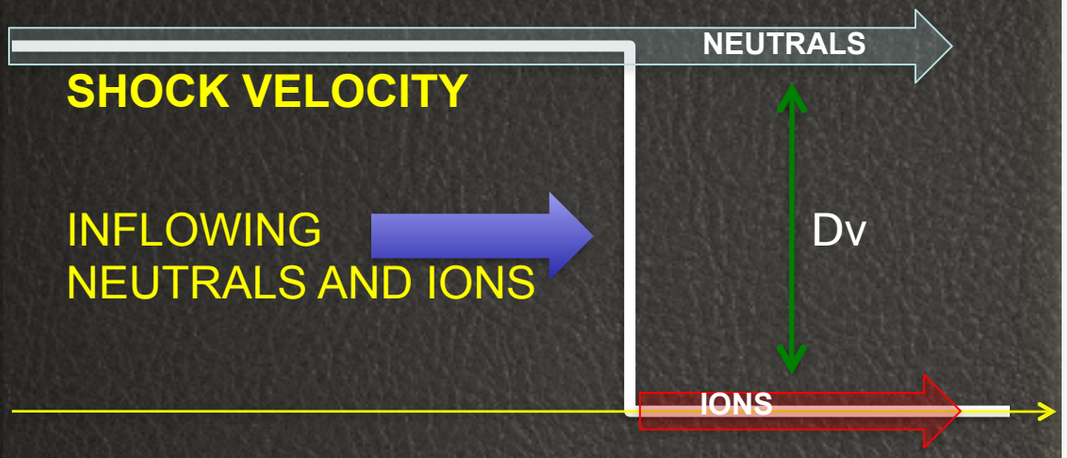
$$R = M_{ej} v_W / \dot{M}$$

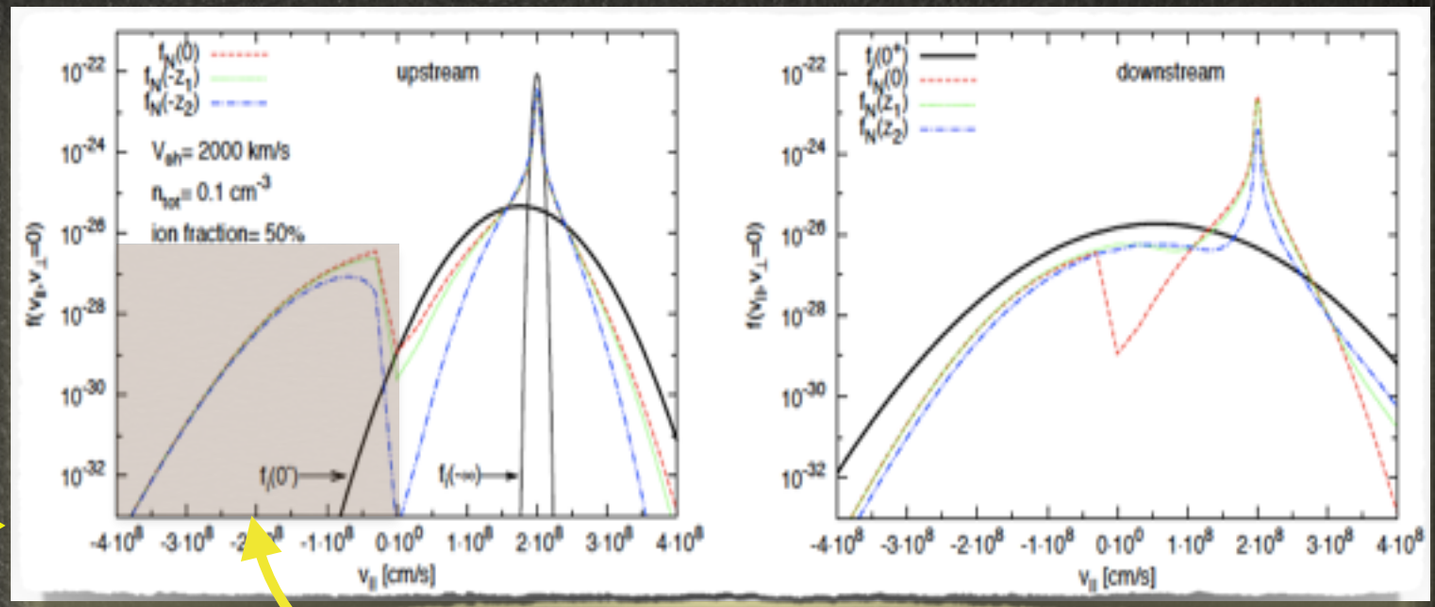
This corresponds to typical times of few tens of years after the SN explosion !!!

$$E_{max} \approx 1\ PeV \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-1}\left(\frac{E_{SN}}{10^{51}erg}\right)\times \left(\frac{\dot{M}}{10^{-5}M_\odot yr^{-1}}\right)^{1/2}\left(\frac{v_{wind}}{10km/s}\right)^{-1/2}$$

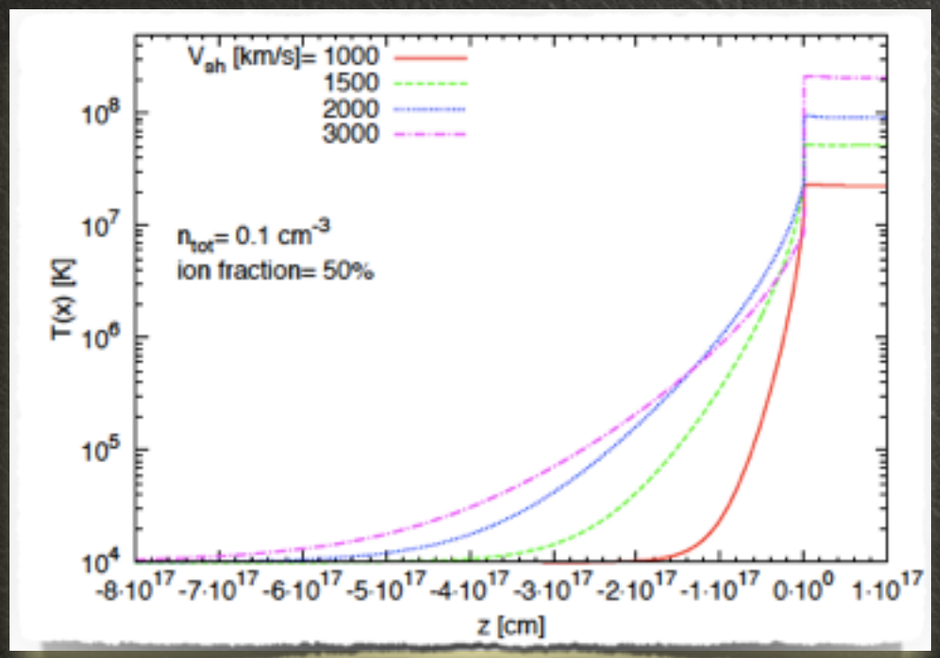
BALMER DOMINATED SHOCKS

PB et al. 2012

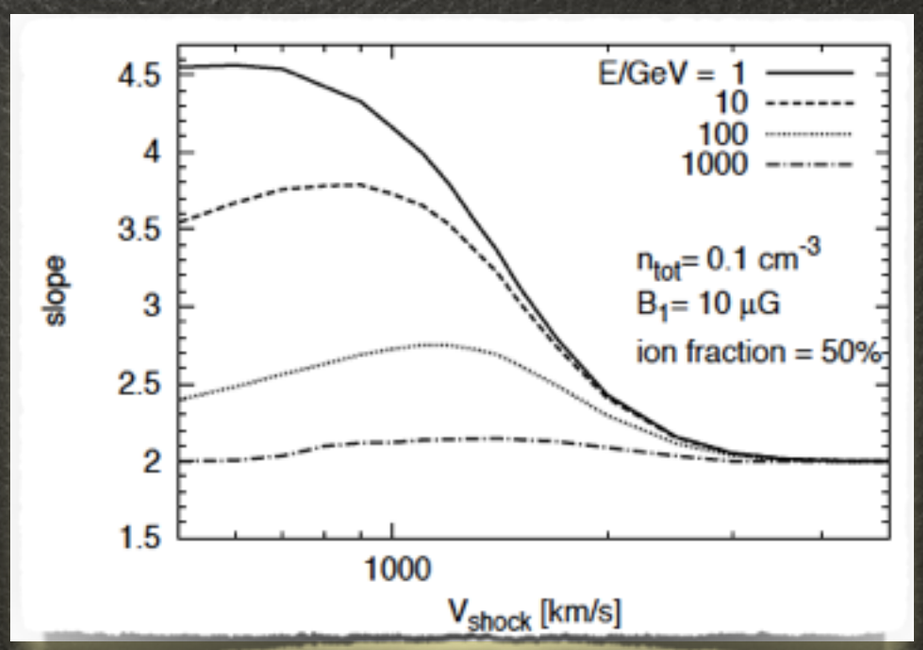




Neutral induced precursor

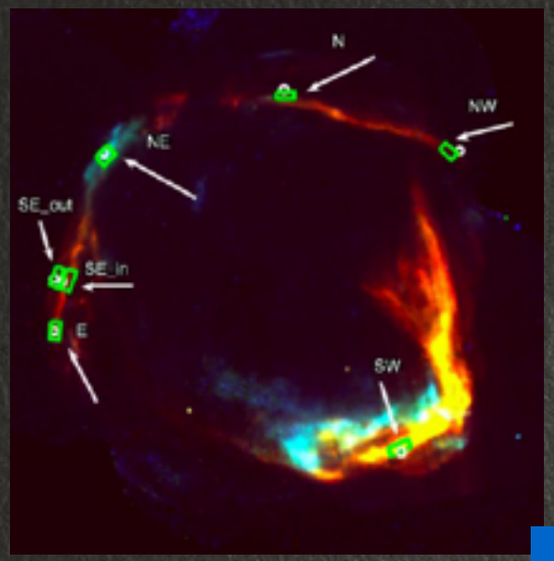


Neutral Return Flux



THE CASE OF RCW86

Helder, Vink and Bassa 2011



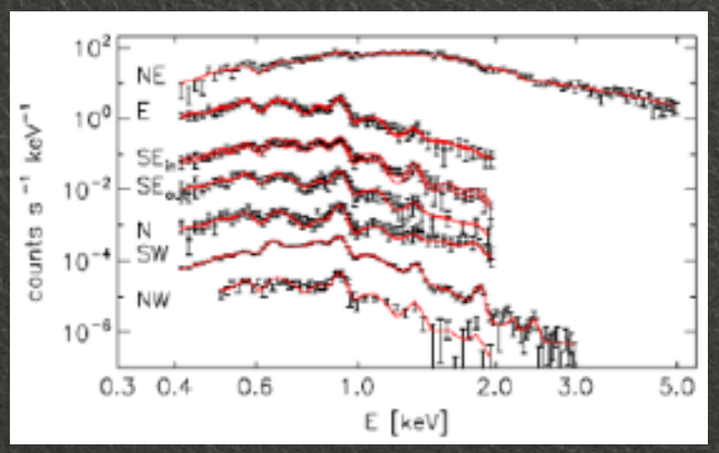
Balmer line + proper motion

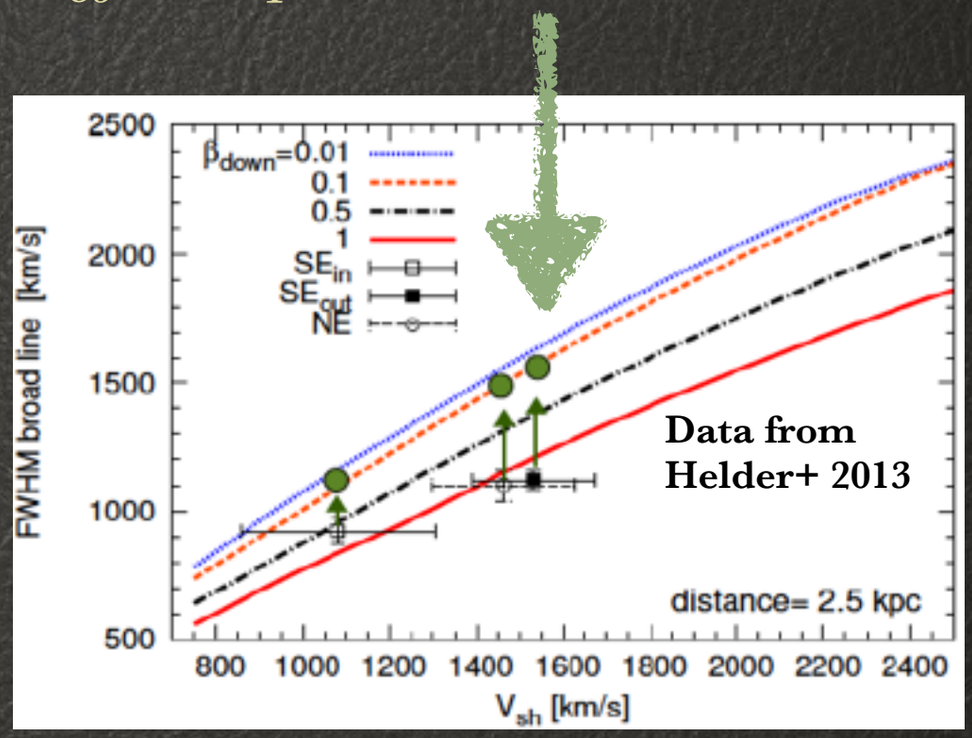
Thermal X-ray spectrum

In selected regions of the remnant there are X-ray measurements of the electron temperature… and measurements of the width of the broad Balmer line

If taken at face value —> efficient particle acceleration

	NE	SE_{in}	SE_{out}
T_e (keV)	37^{+29}_{-19}	0.9±0.1	0.6±0.1





Morlino et al. 2013

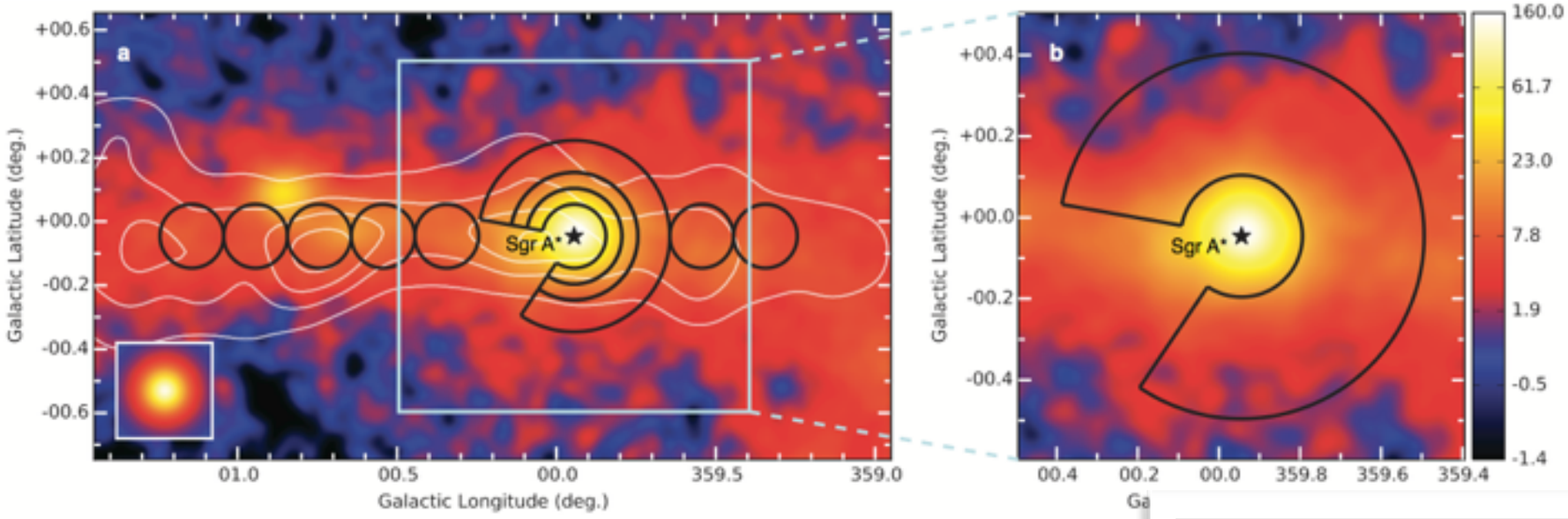
In general, particle acceleration in partially ionized plasmas leads to:

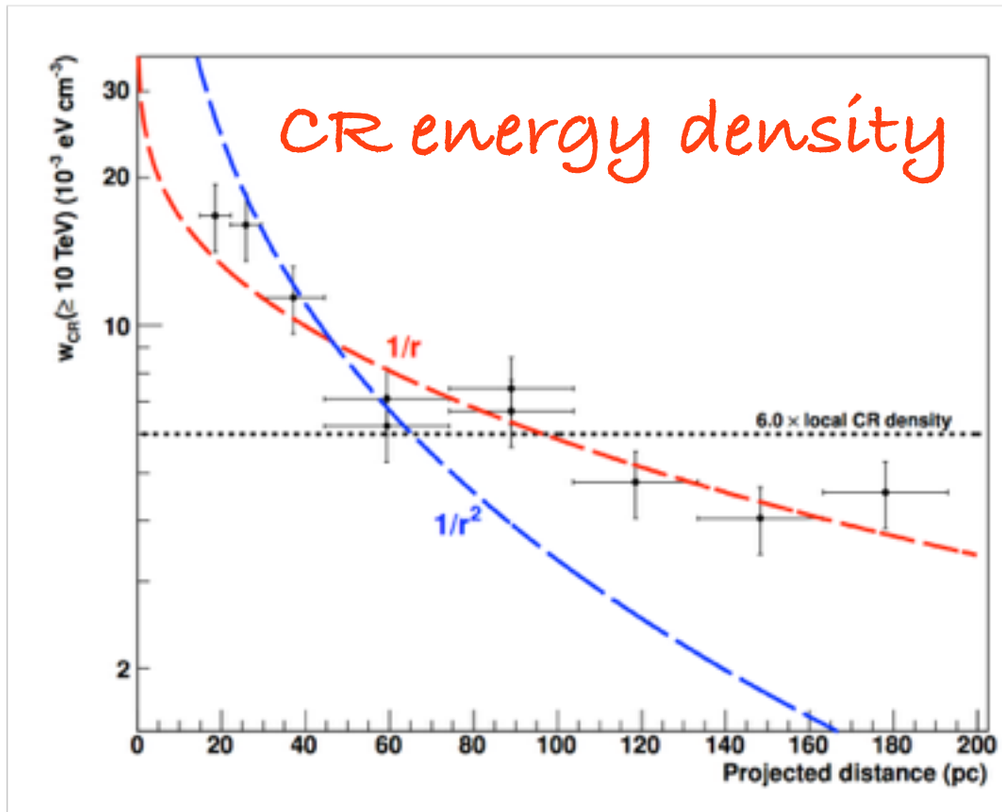
1) *Narrower broad Balmer line —— cooler ions as a result of CR acceleration*
2) *Broader Narrow Balmer line —— charge exchange in the CR induced precursor*
3) *Intermediate line with typical widths few hundred km/s —— charge exchange in the neutral induced precursor*

A PeVatron at the galactic center?

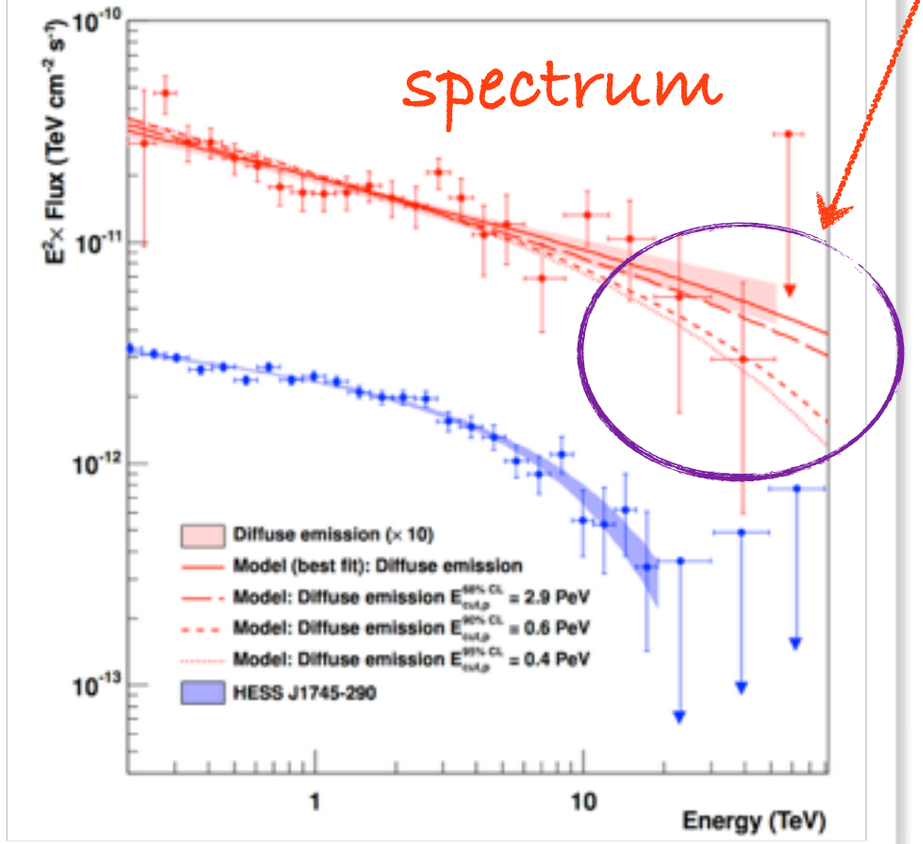
NEW

HESS Coll., 2016



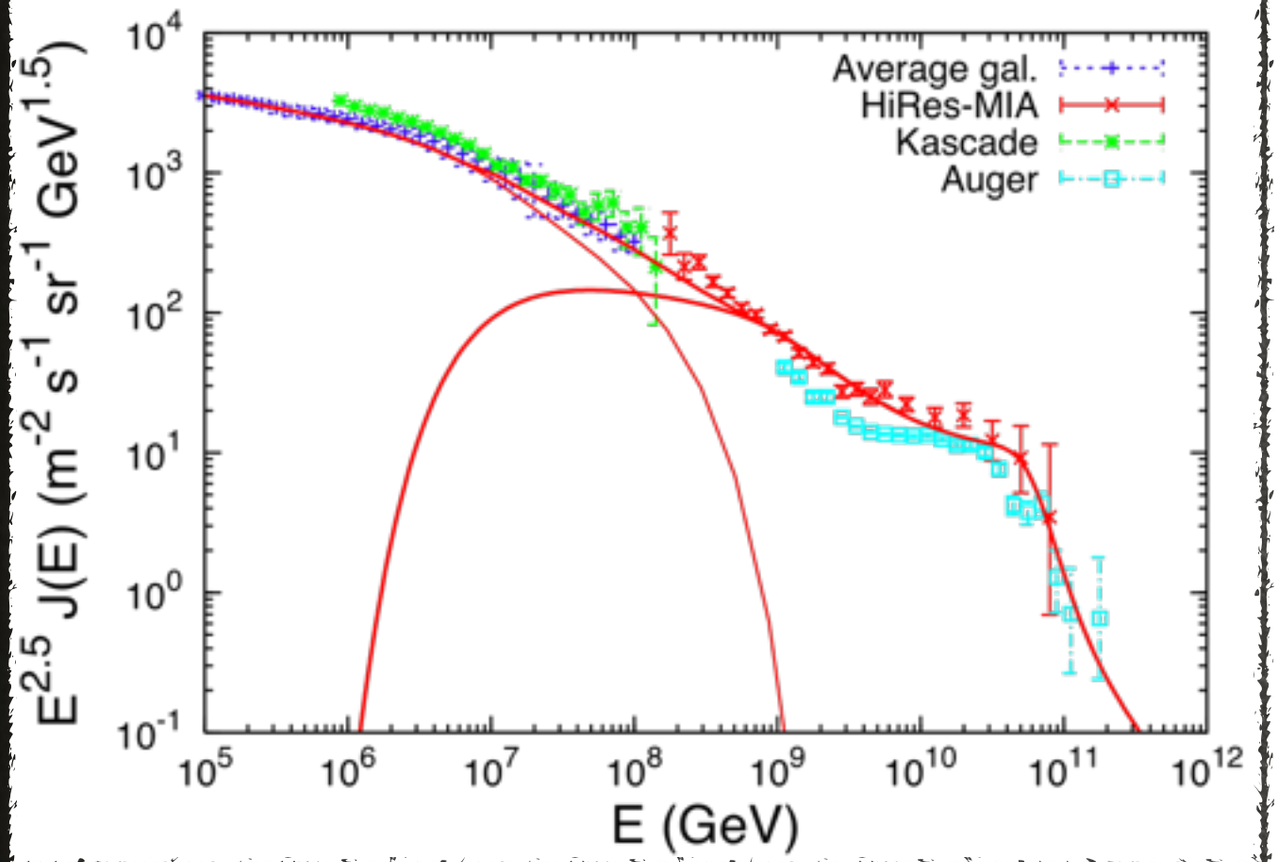


SST



From Talk by Tavecchio & PB, SAIT 2016

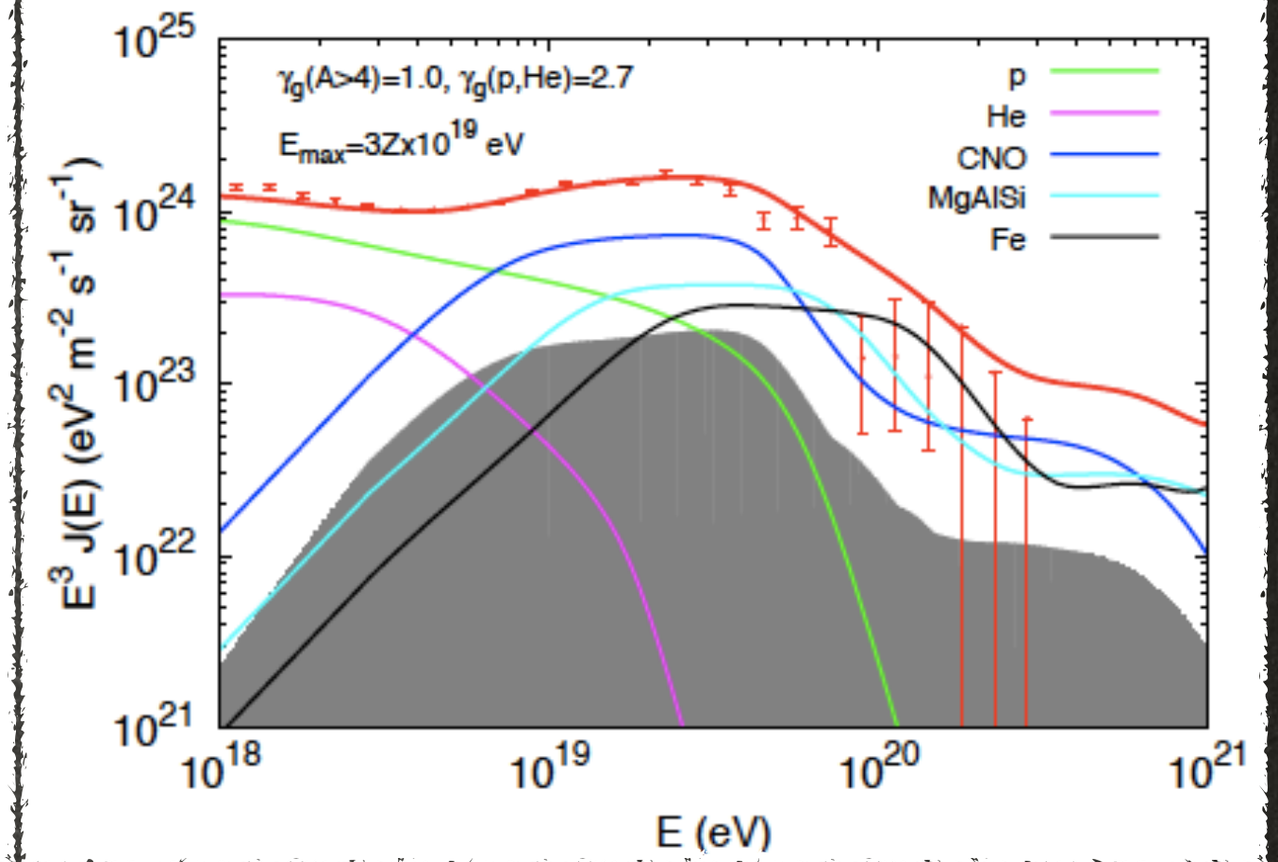
Transitions



Dip

Berezinsky et al.

chemical composition incompatible with Auger data



Mixed Compositions

Allard et al.; Aloisio et al.

Mixed composition with
E_{max}~5 10^{18} eV

Additional extra-gal protons

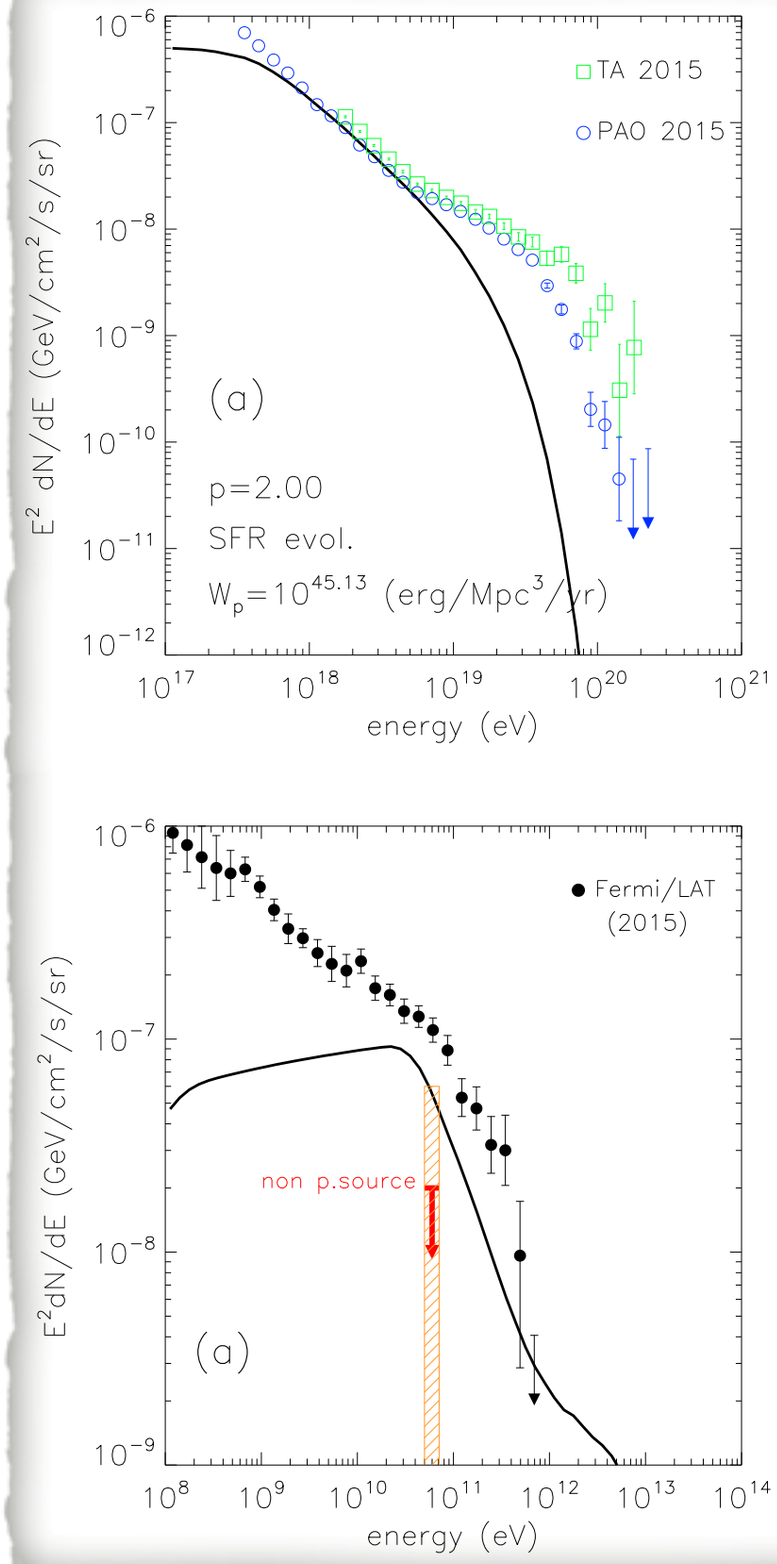
The gamma ray cascade limit

PROTONS WITH ENERGY ABOVE THRESHOLD FOR BETHE-HEITLER PRODUCE PAIRS

THE PAIRS INITIATE AN ELECTROMAGNETIC CASCADE

THE SPECTRUM OF THE CASCADE PHOTONS IS QUASI-UNIVERSAL [Berezinsky & Smirnov 1975]

IT CARRIES CRUCIAL INFORMATION ABOUT THE SOURCES OF UHECR PROTONS [local sources? Negative evolution with redshift?]



Liu et al. 2016

Main Nodes in INAF

Arcetri (Theory + Science Support Astri + CTA, Auger, Fermi-LAT)

Palermo (Theory + X/radio observations SNRs)

Trieste (Theory + Science support gamma ray observations)

Torino (Experiments, Auger)

Milano (LI violation, search for new physics)

About 10 people (Permanent researchers) + postdocs + Students

150 refereed publications (with **3000** citations) in the last 5 years

Main INAF results

Theory of non linear diffusive shock acceleration

Amplification of magnetic field induced by CRs

Development of the theory of Balmer dominated shocks

Acceleration at SNR shocks and its phenomenology (e.g. gamma, radio, obliquity, …)

Pulsars and old SNRs as sources of the positron excess

Non -linear transport and Galactic winds induced by cosmic rays

Chemical composition in the transition region to extragalactic CRs

CR confinement in clusters of galaxies

Numerous pivotal results by the Auger Collaboration

Study of phenomenological implications of breaking Lorentz invariance

Experimental effort

So far, main observational inputs from

Fermi-LAT
AGILE
HESS/MAGIC/Veritas

AMS-02
KASKADE-Grande
Auger
IceCUBE

Future:
ASTRI - CTA
CALET, IceCREAM, HAWK, Gamma400(?), EUSO(?)
Lofar (CR showers, chemical composition)