COSMIC RAY ACCELERATION AND TRANSPORT

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CR Spectrum

From afar the spectrum looks like a power law

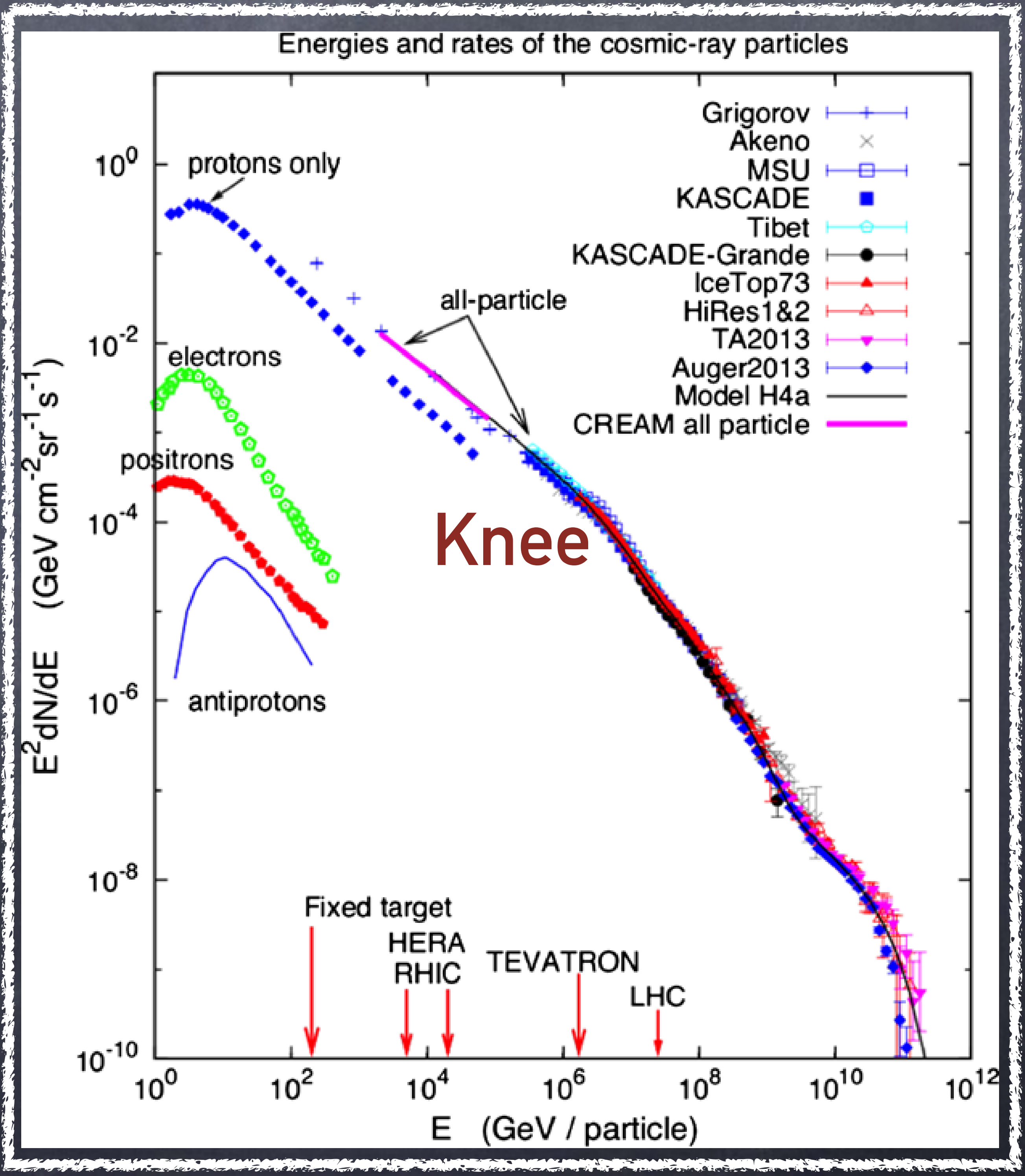
power laws -> No Scales

Broken power laws more interesting (scale->physics)

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

Substantial change in mass composition at the knee

Mass composition at the ankle unclear



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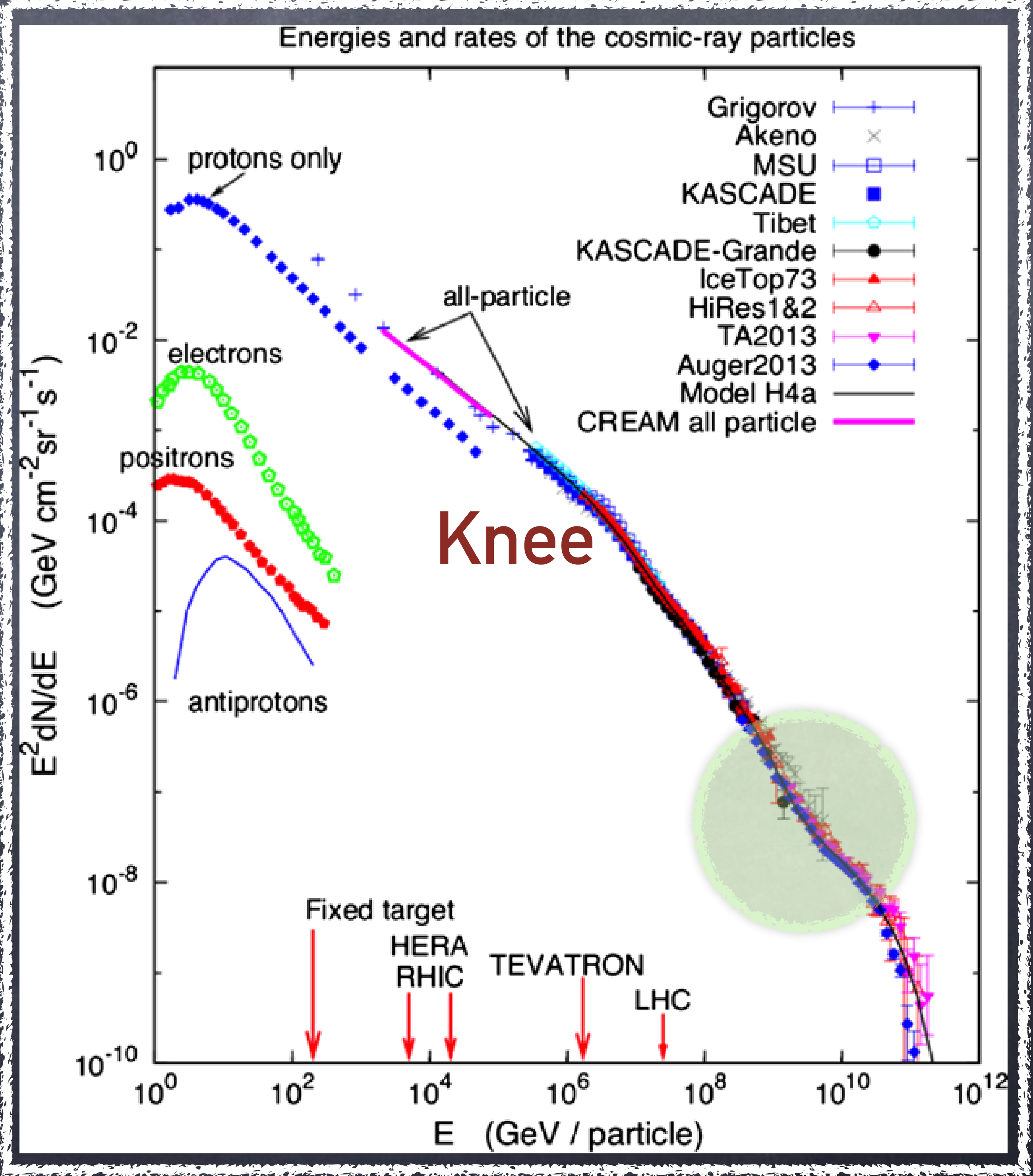

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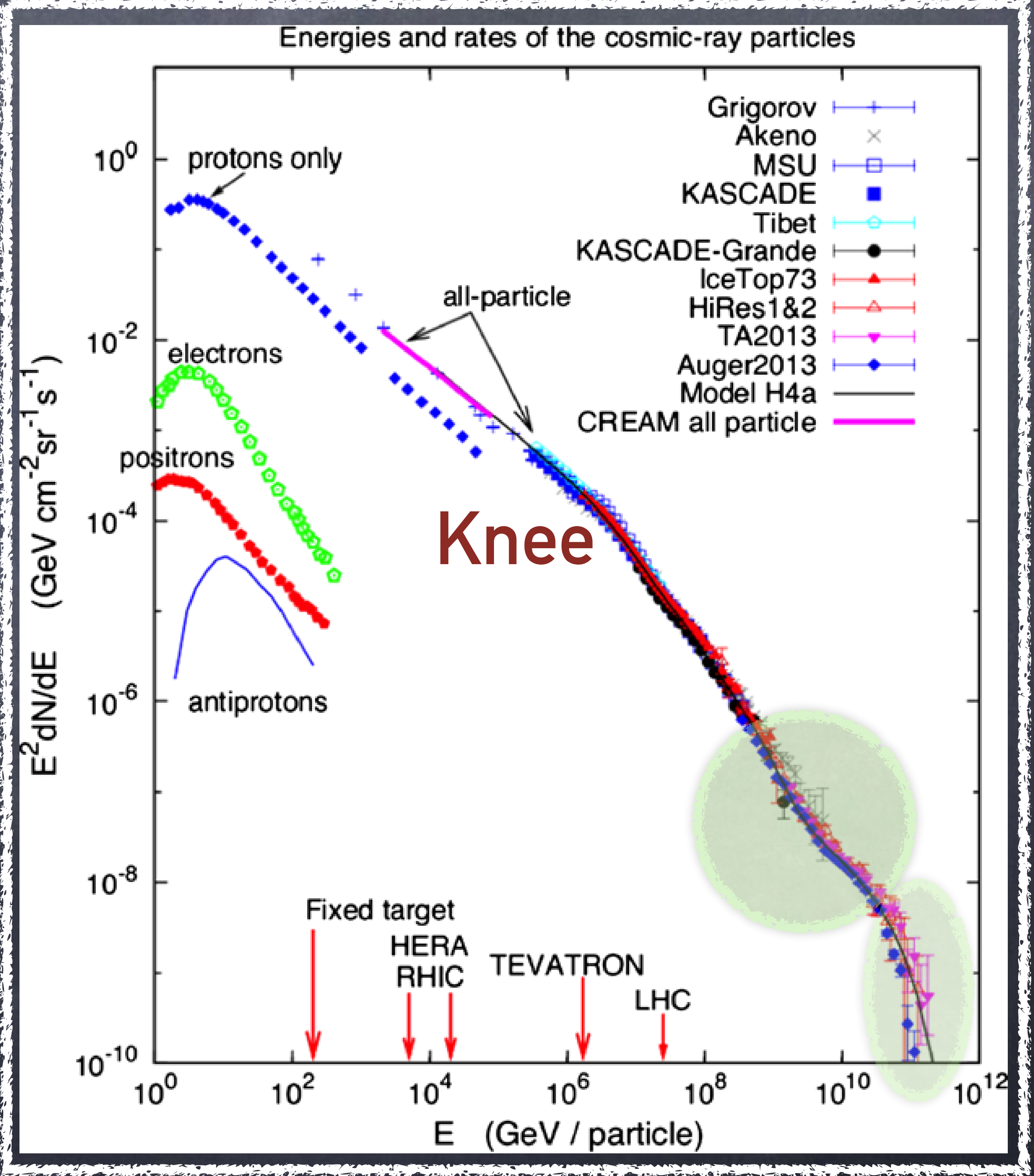
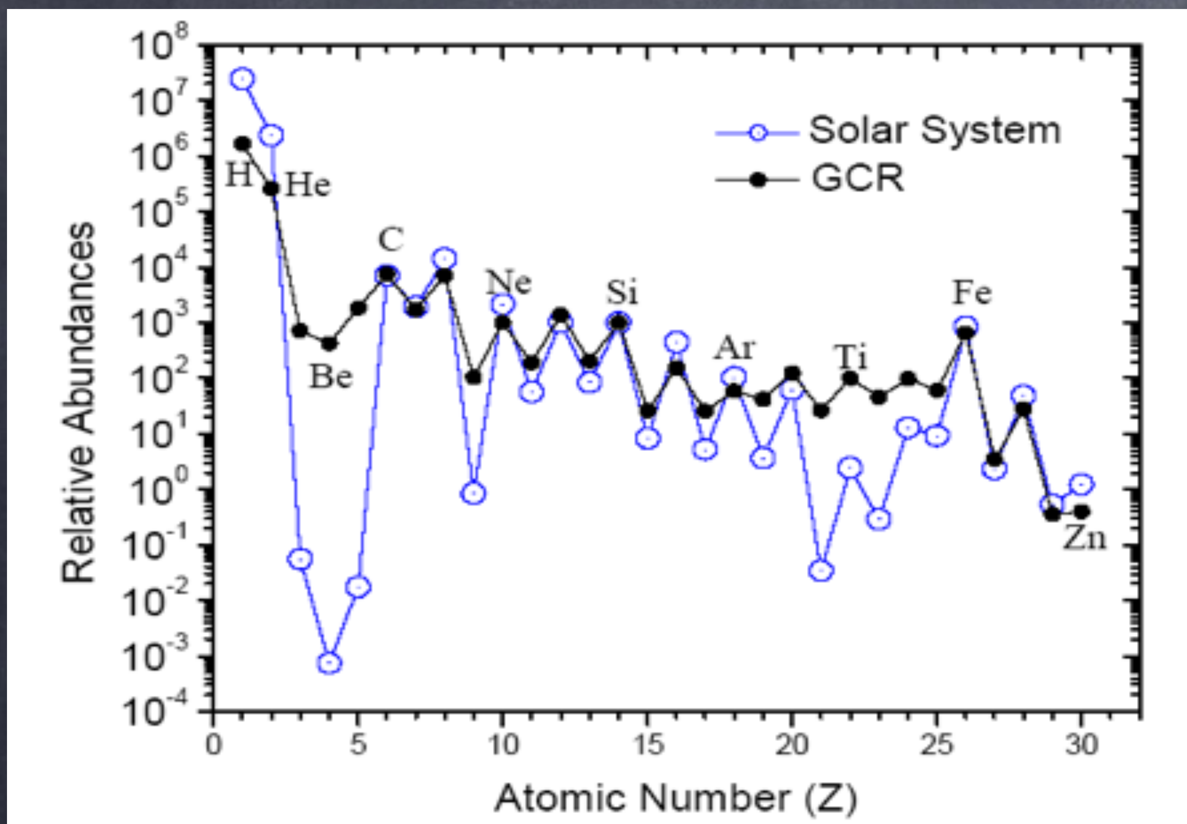


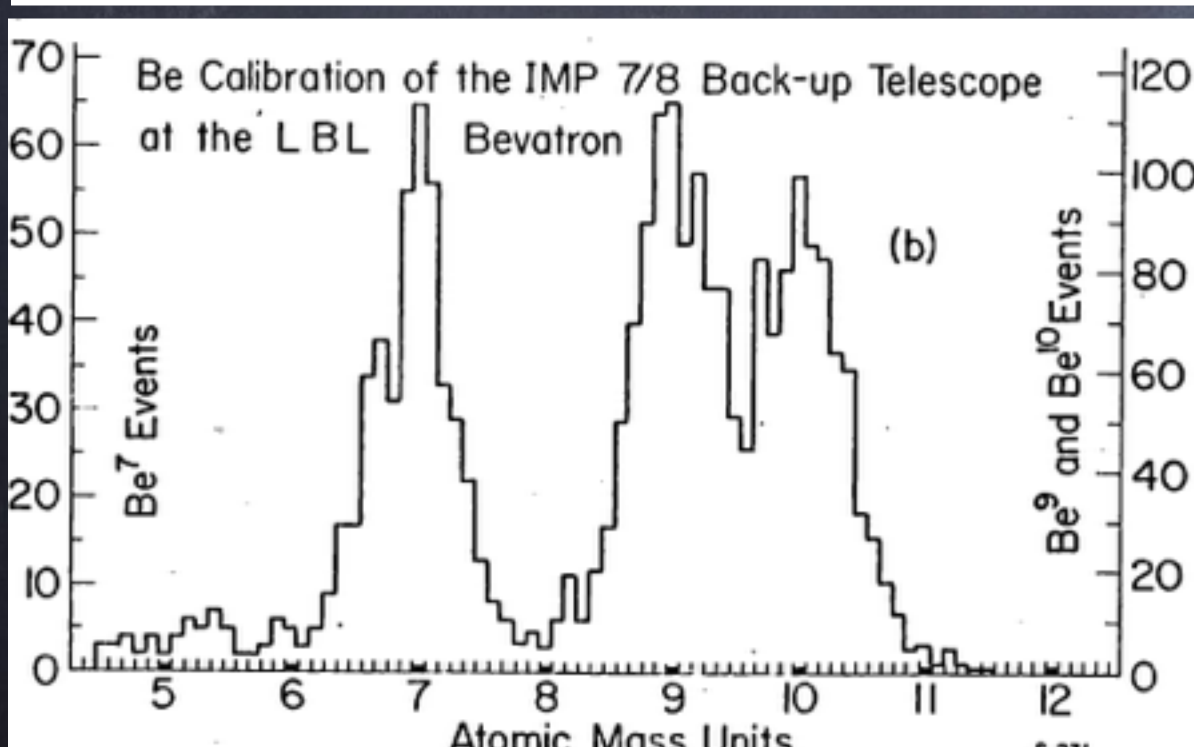
Basics of CR Physics

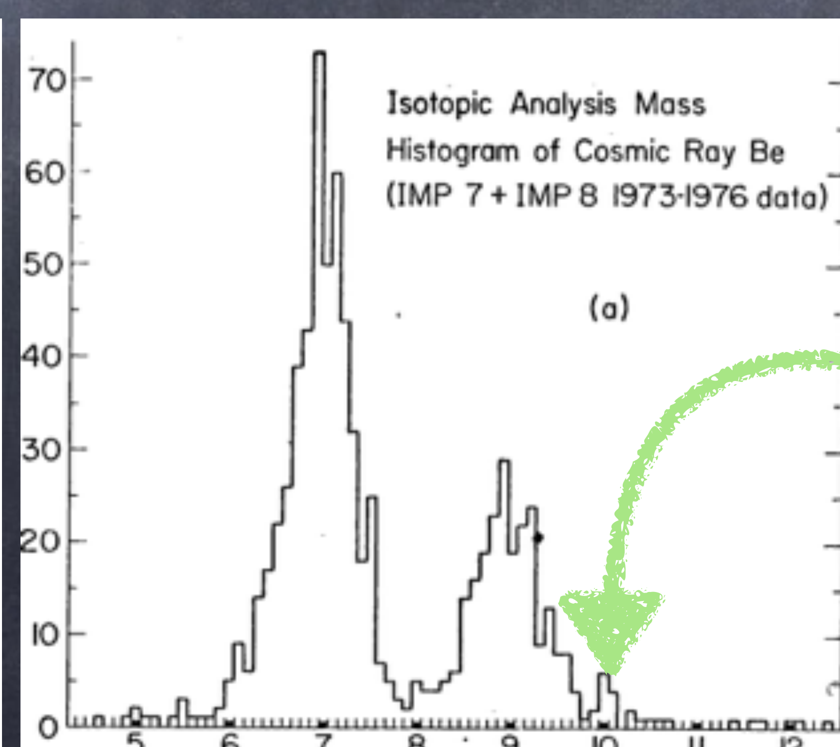


Measurements of the B-Li-Be in CRs show that CR live for tens of million years in the Galaxy

DIFFUSIVE TRANSPORT

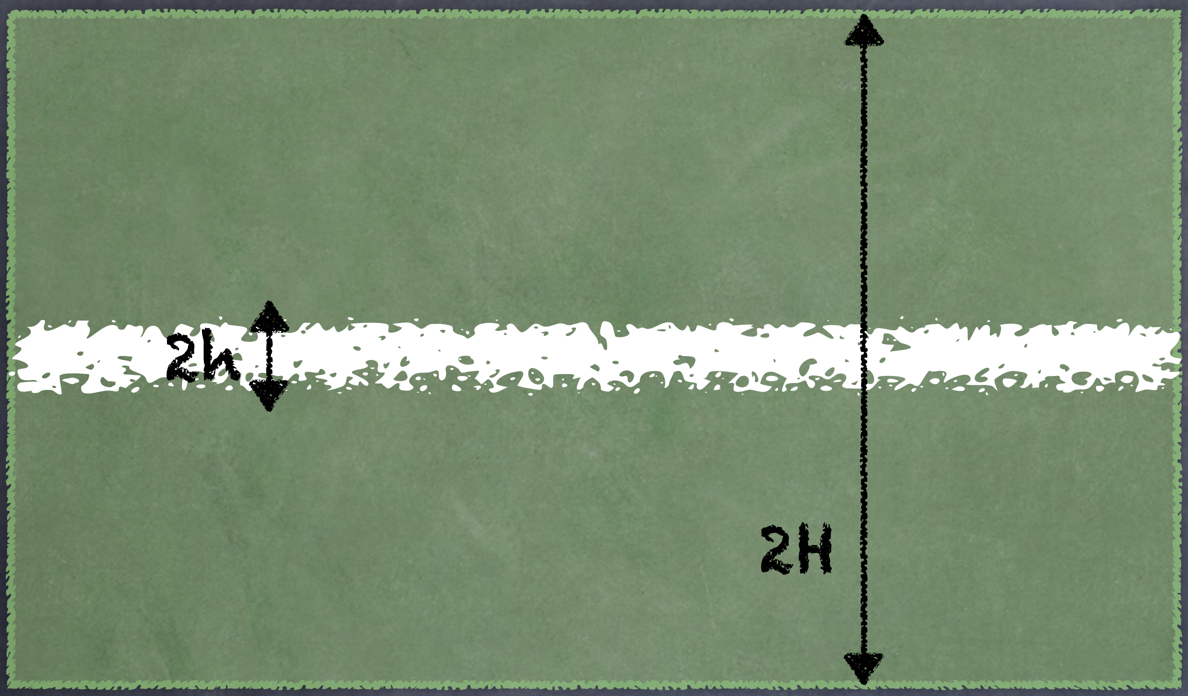
Garcia-Munoz et al. 1977





^{10}Be

Basics of CR Physics



$$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q_0(p)\delta(z)$$

$p^{-\gamma}$ p^{δ}

$$f_0(p) = \frac{N_{inj}(p)R_{SN}}{\pi R^2_{disc}\ 2H}\frac{H^2}{D(p)} \sim p^{-\gamma-\delta}$$

$$D\frac{\partial f}{\partial z} = Constant \rightarrow f(z) = f_0\left(1 - \frac{z}{H}\right)$$

PARTICLES ESCAPE AT |Z|=H -> FREE ESCAPE BOUNDARY !

Basics of CR Physics

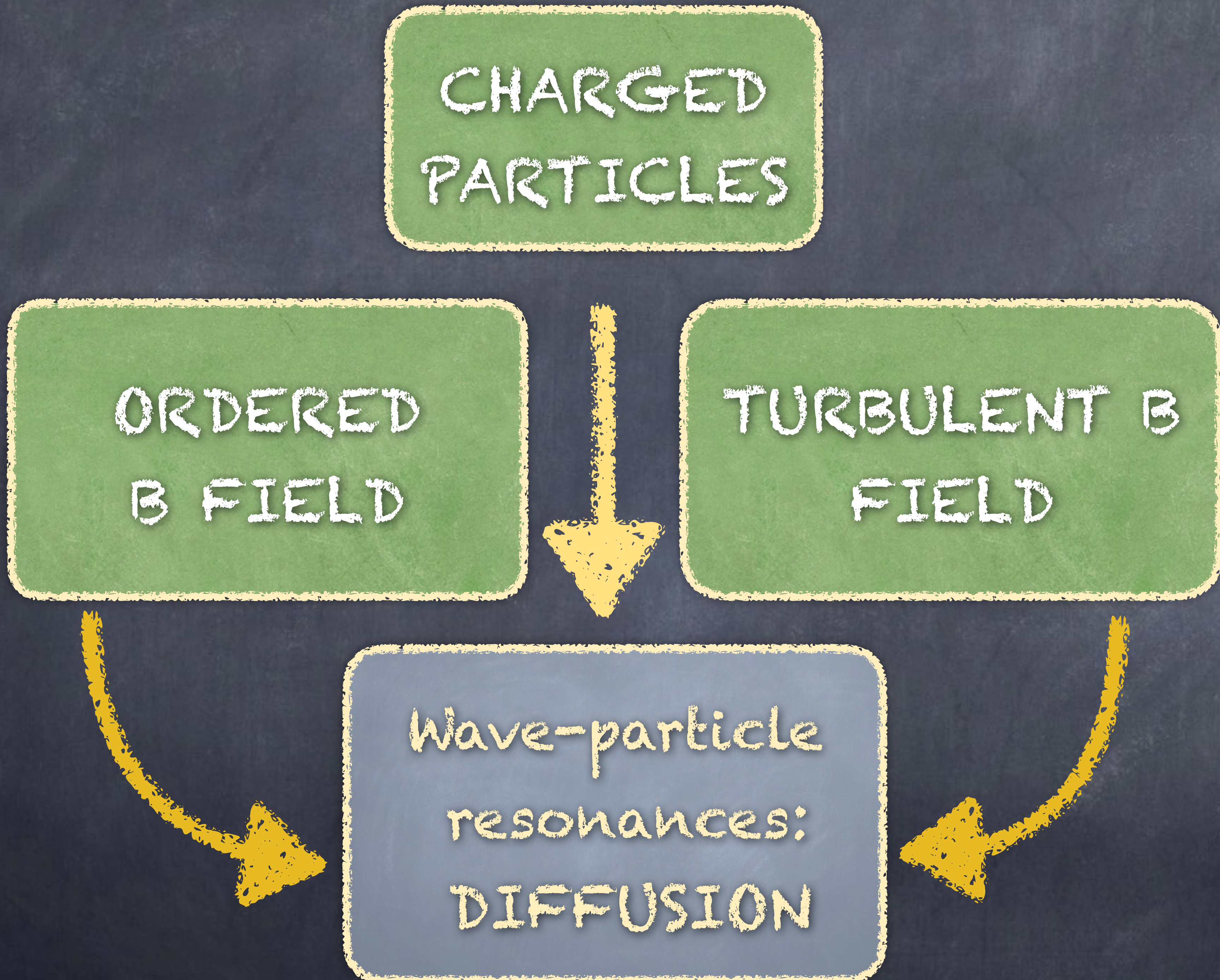
The Physics of the origin of CRs is mainly in the injection term (sources) and in the diffusion term (transport).

Both are often assumed –

far from being realistic...

PARTICLES ESCAPE AT |Z|=H –> FREE ESCAPE BOUNDARY !

Inner Space - Outer Space



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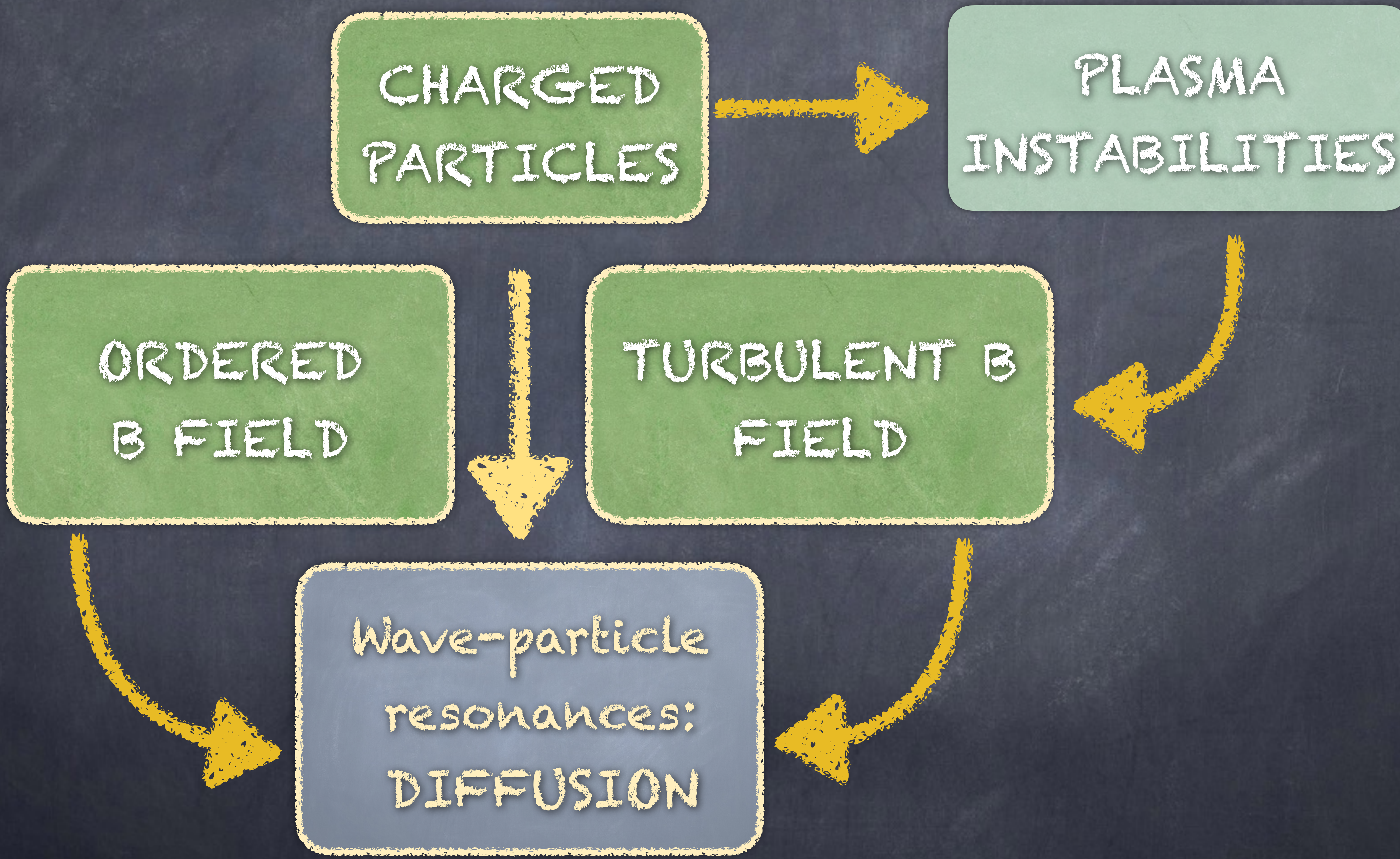

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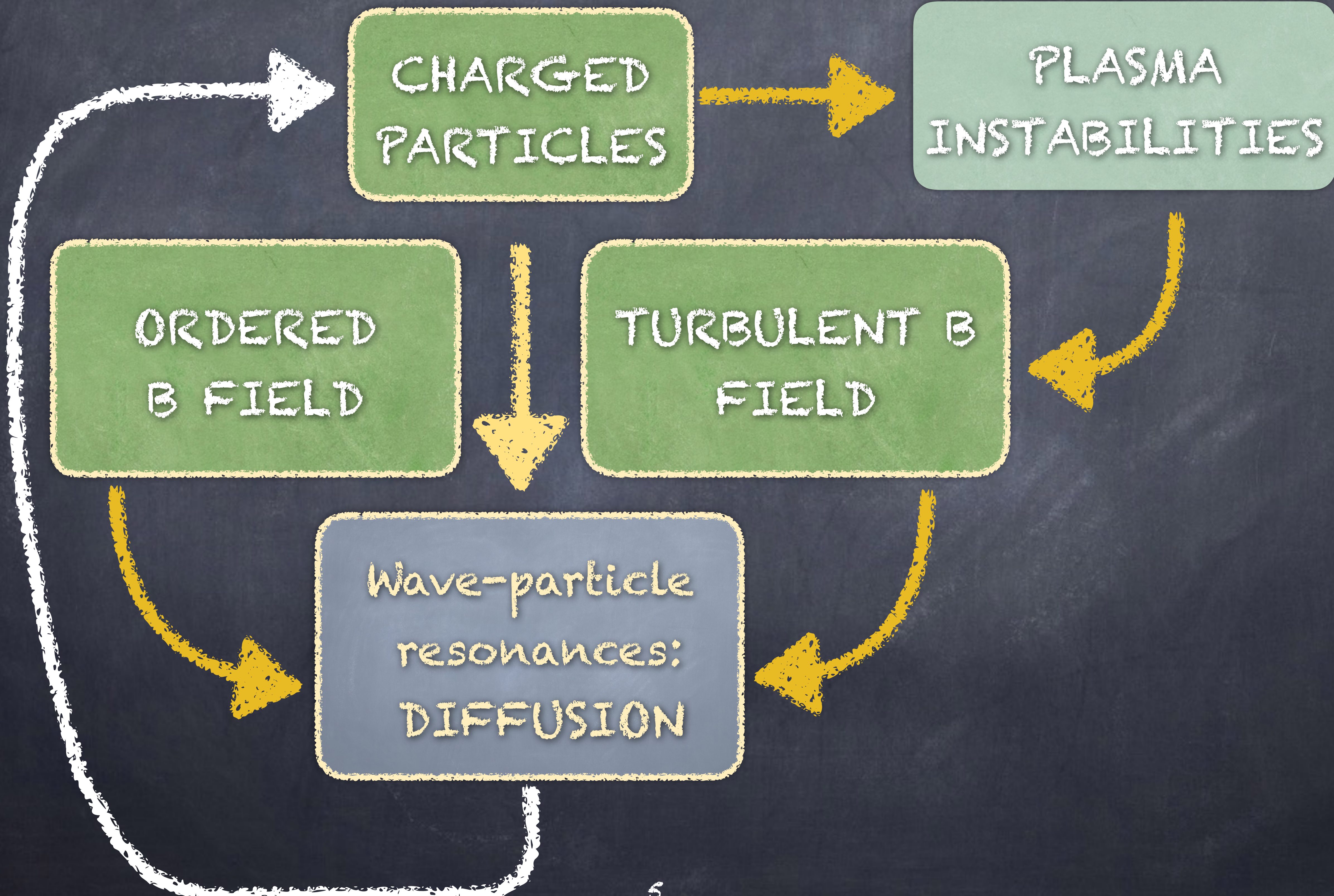

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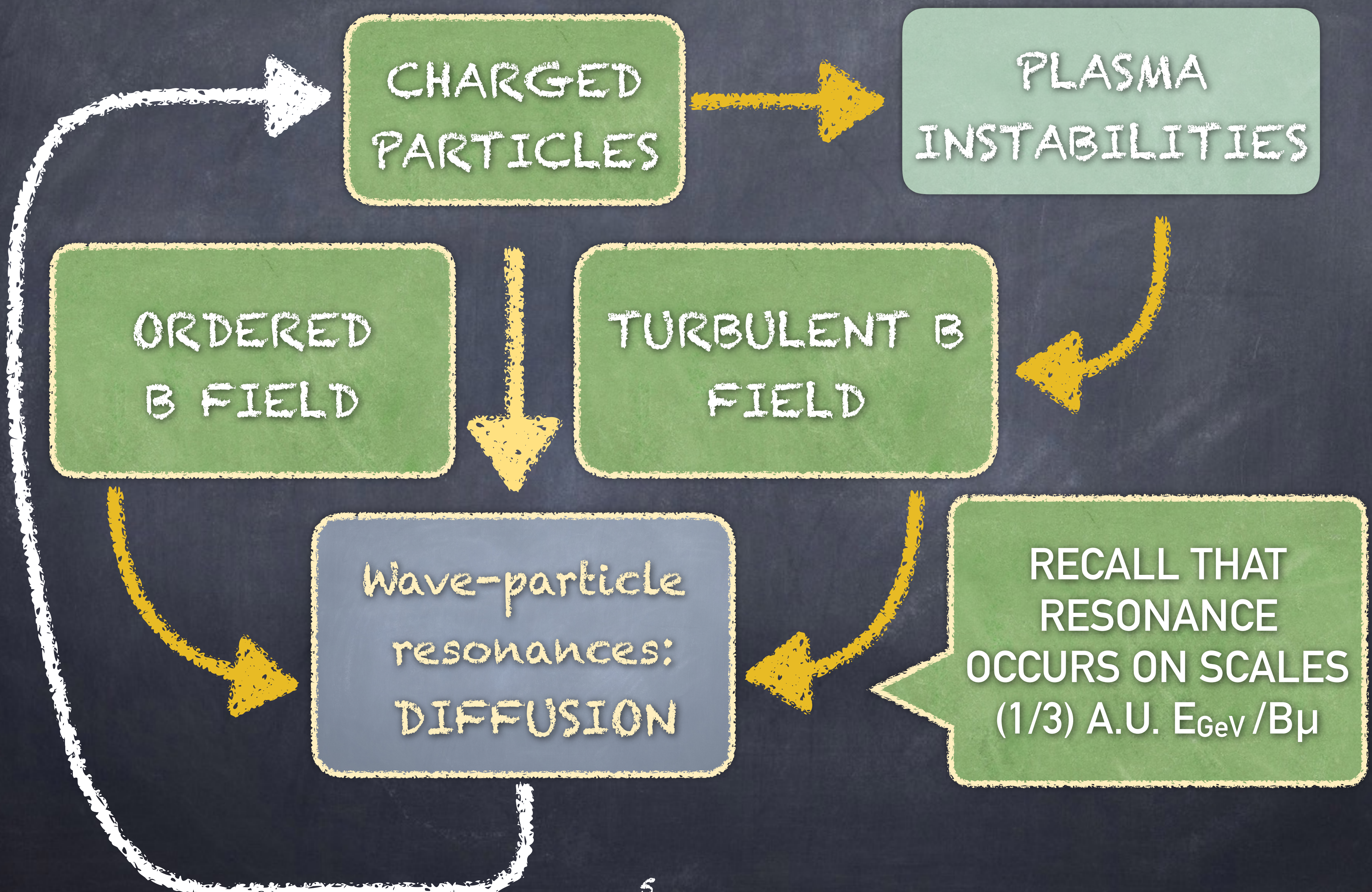
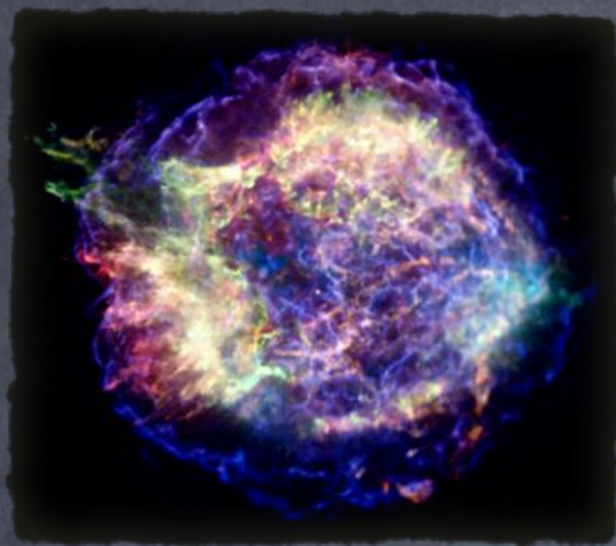
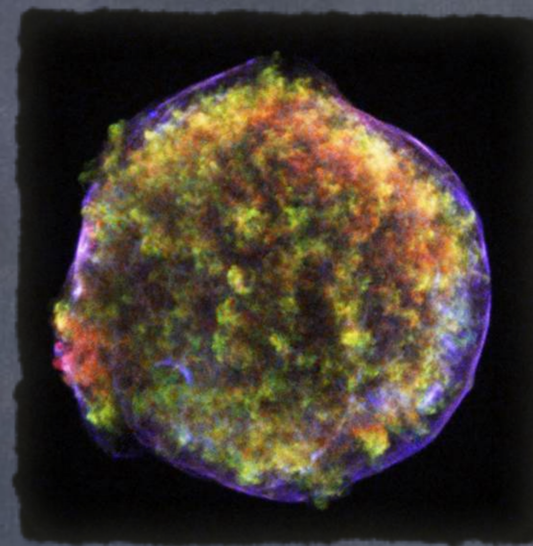


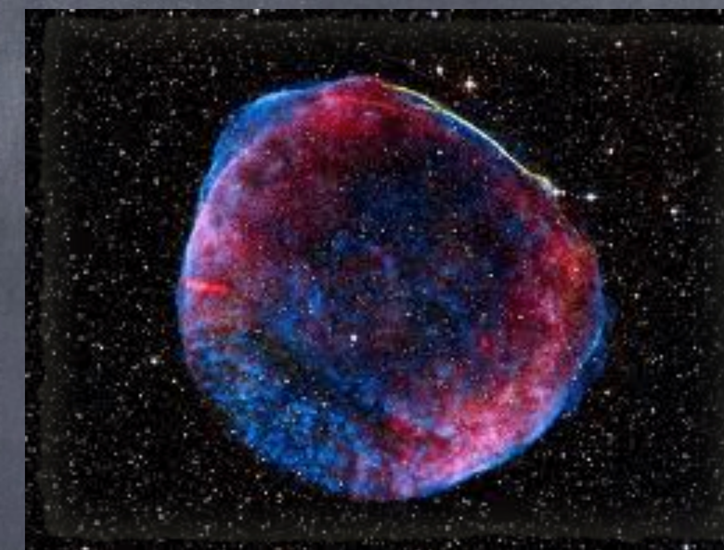
Sources of Galactic Cosmic Rays

- Despite some efforts to work in different directions, SNR still remain the main candidate sources of Galactic CRs
- They may be of different types, esplode in different environments, have different energetics, but…
- They all lead to the formation of strong collisionless shocks
- The main process of particle acceleration is diffusive shock acceleration (DSA) at such shocks
- But… many loose ends… as for any good theory, its weaknesses are proof if its testability

SUPERNOVA BLAST WAVES







FREE EXPANSION VELOCITY: $V_s = \sqrt{\frac{2E_{ej}}{M_{ej}}} = 10^9\ E_{51}^{1/2}\ M_{ej,\Theta}^{-1/2}$ cm/s

THE EXPANSION SPEED DROPS DURING THE SEDOV-TAYLOR PHASE BUT THE MACH NUMBER STAYS >10-100

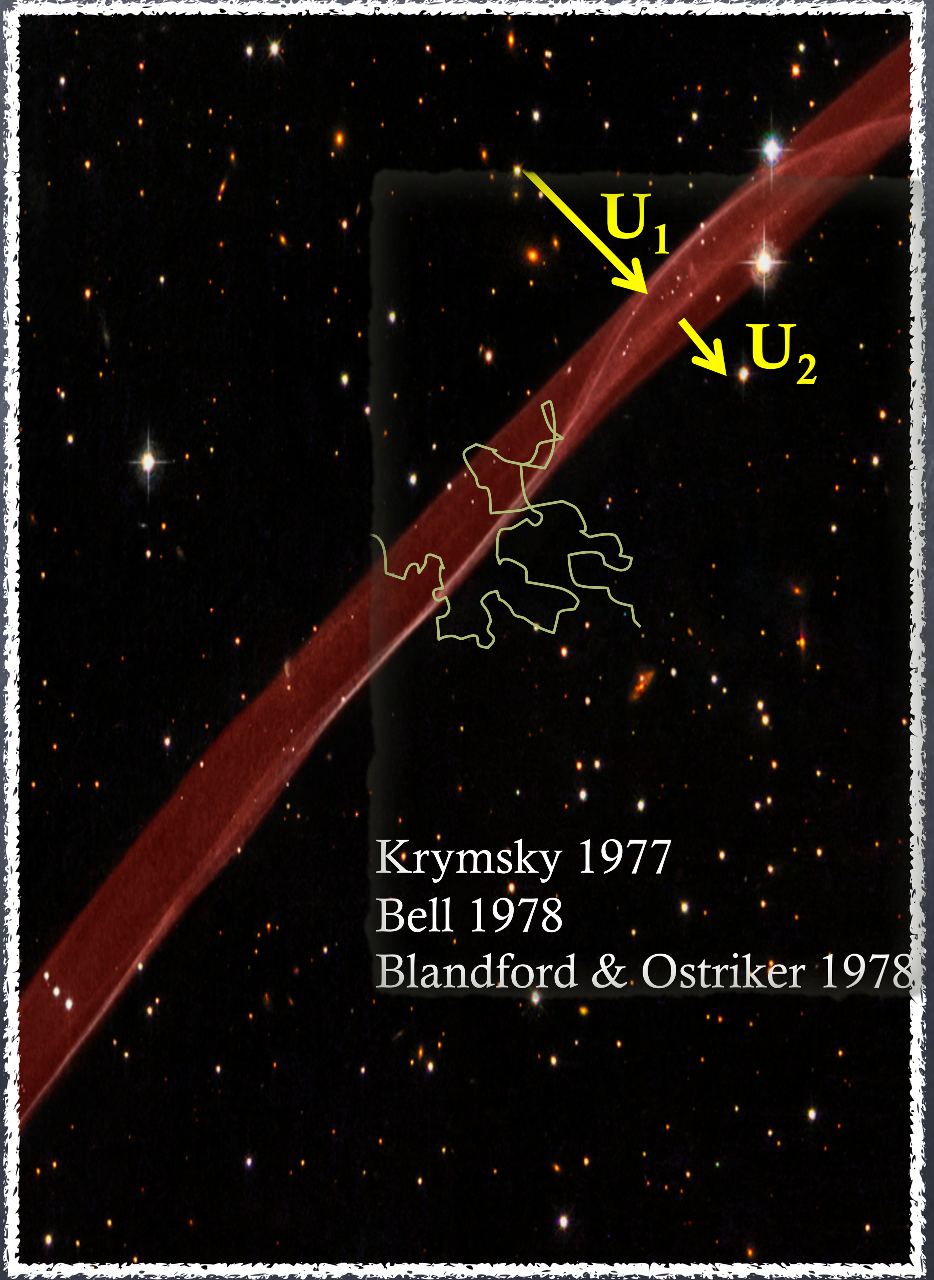
STRONG COLLISIONLESS SHOCK WAVE

DIFFUSIVE SHOCK ACCELERATION
Test Particle Approach

- Diffusion of charged particles back and forth across the shock leads to

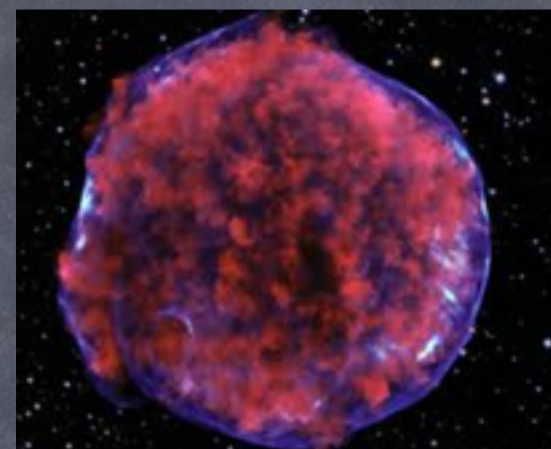
$$\frac{\Delta E}{E} = \frac{4}{3}(U_1 - U_2)$$

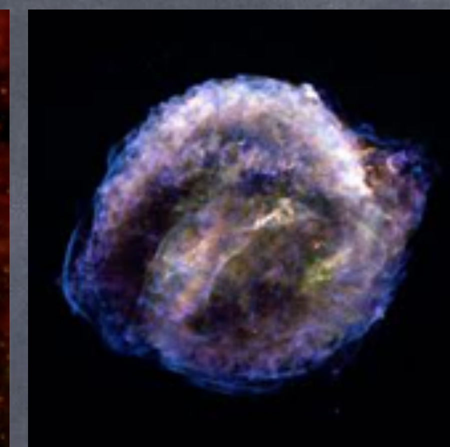
  - POWER LAW SPECTRUM
  - THE SPECTRAL SLOPE ONLY DEPENDS ON SHOCK COMPRESSION
  - INDEPENDENT OF THE DIFFUSION COEFFICIENT
  - FOR STRONG SHOCKS: E^{-2}

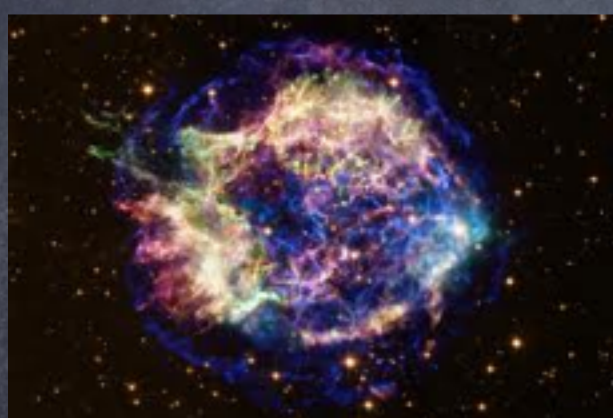


THE EFFICIENCY REQUIRED PER SNR ~10%: TEST PARTICLES?
FIRST NEED FOR A NON-LINEAR THEORY

X-ray filaments





Virtually all young SNRs show evidence of thin non-thermal X-ray filaments

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

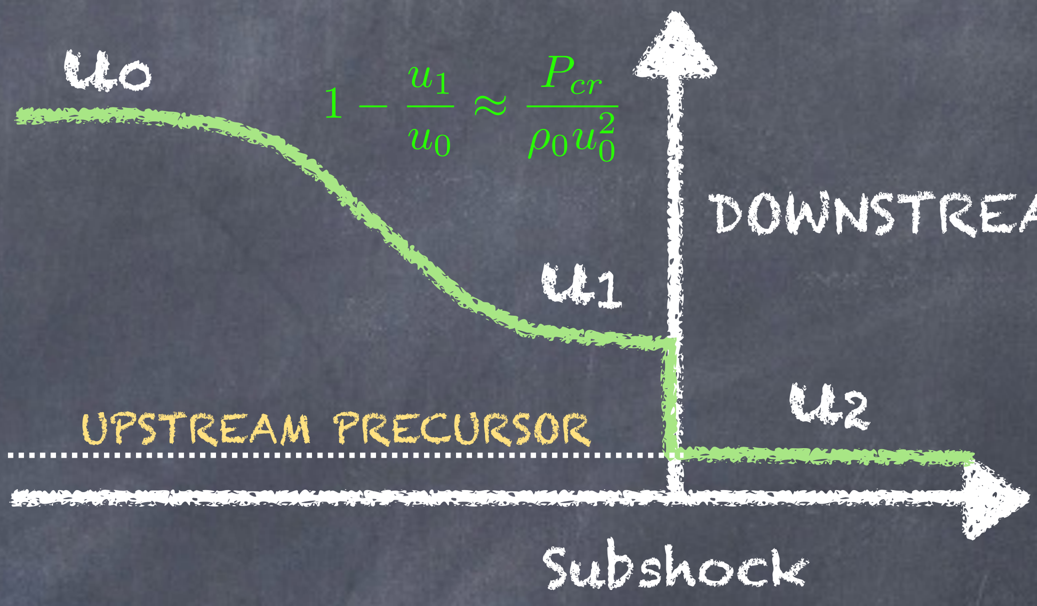
$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

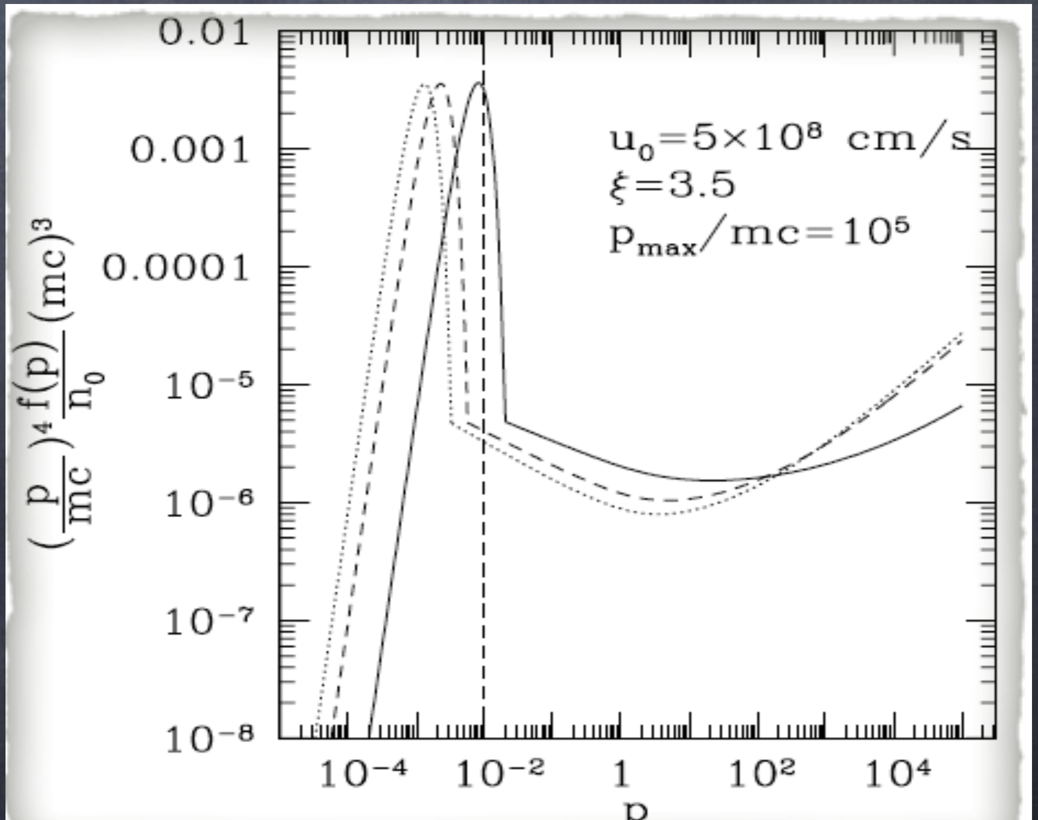
→ $B \sim 100\ B_{galaxy}$

SECOND NEED FOR A NON-LINEAR THEORY

Basic predictions of NLDSA

- COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY
- SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)
- GAS BEHIND THE SHOCK IS COOLER WHEN PARTICLE ACCELERATION IS EFFICIENT
- RAPID GROWTH OF B-FIELD IF ACCELERATION EFFICIENT





PB, Gabici and Vannoni 2005

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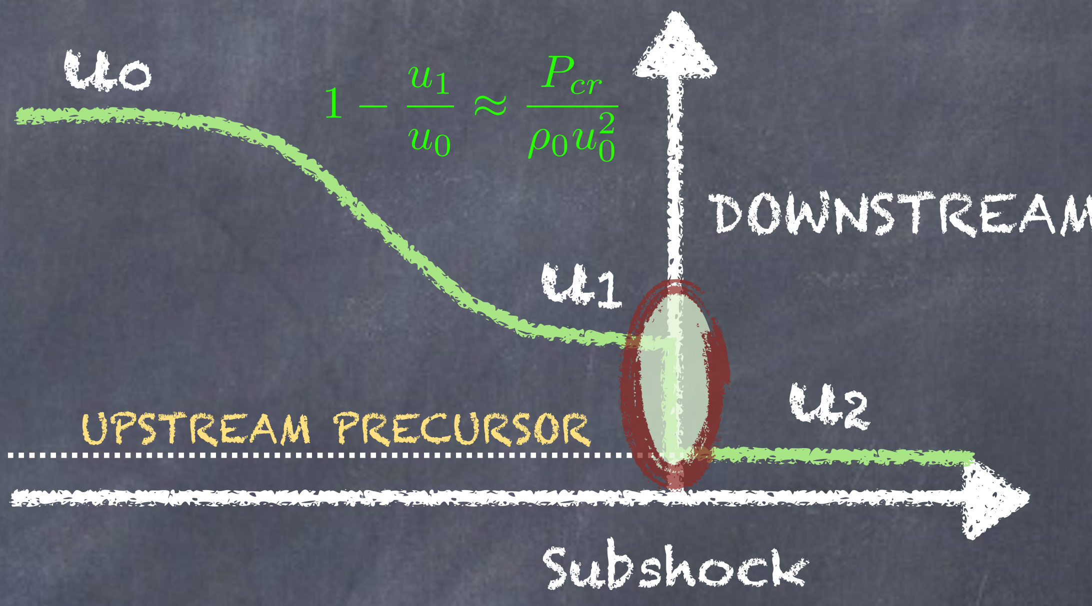

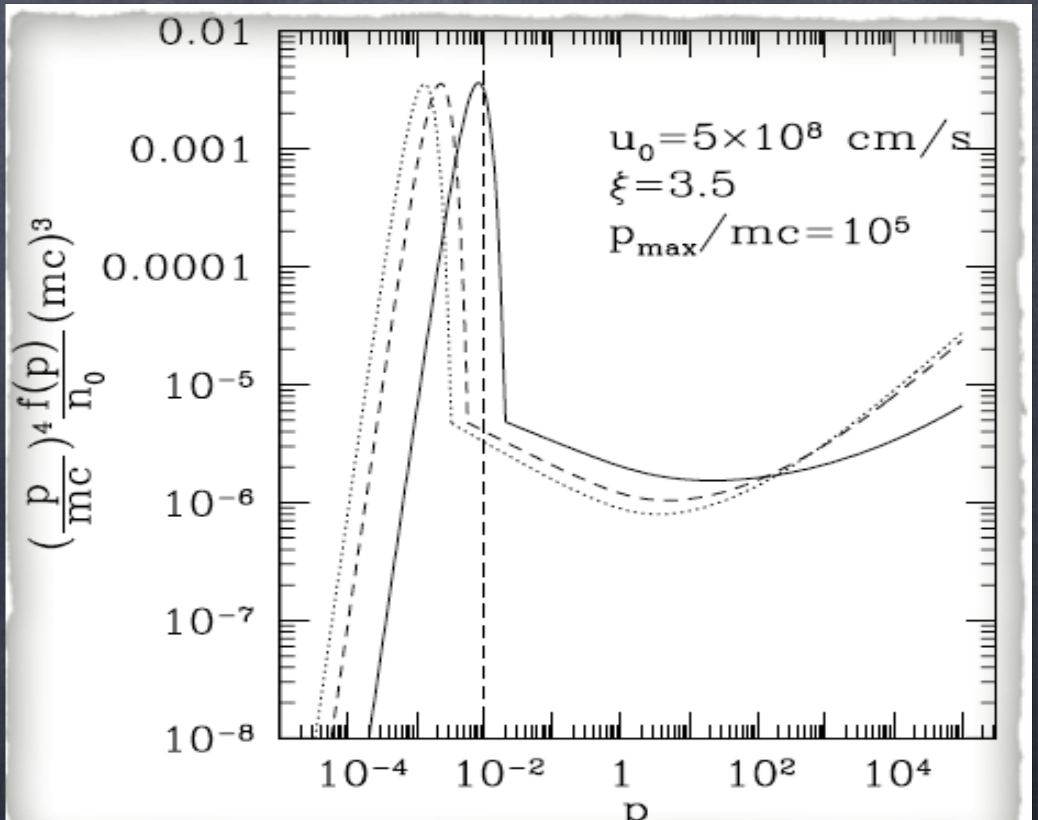

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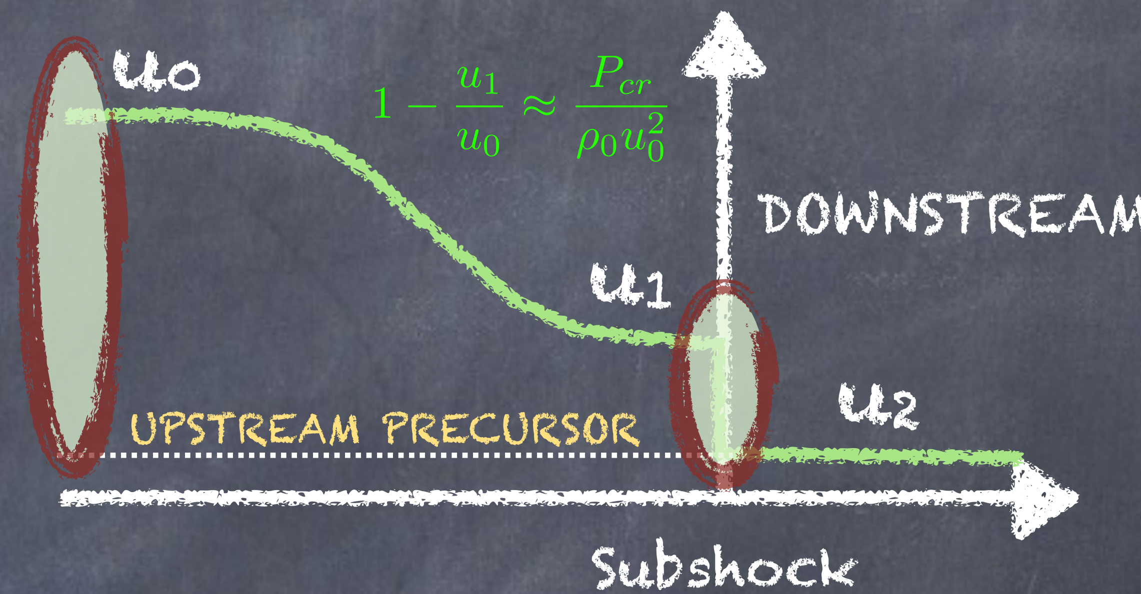
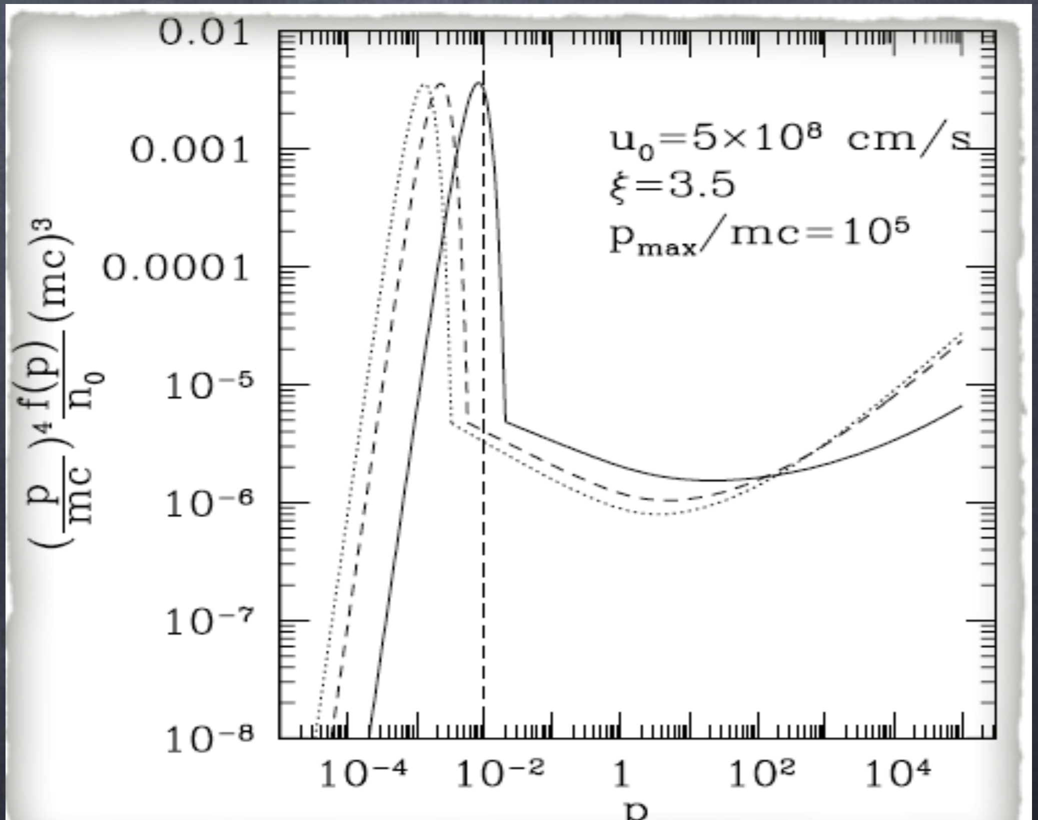




PB, Gabici and Vannoni 2005

THE QUEST FOR E_{MAX}

Maximum energy fixed by:

$$\tau_{accel}(E_{max}) = Min\left[Age, \tau_{losses}(E_{max})\right]$$

$$\sim \frac{D(E_{max})}{v_s^2} \sim \frac{E^\delta}{B^\alpha}$$

With D(E) derived from B/C: E_{max}~ GeV

With D(E) = Ec/eB [Bohm diffusion]: E_{max}~ 10^{4-5} GeV

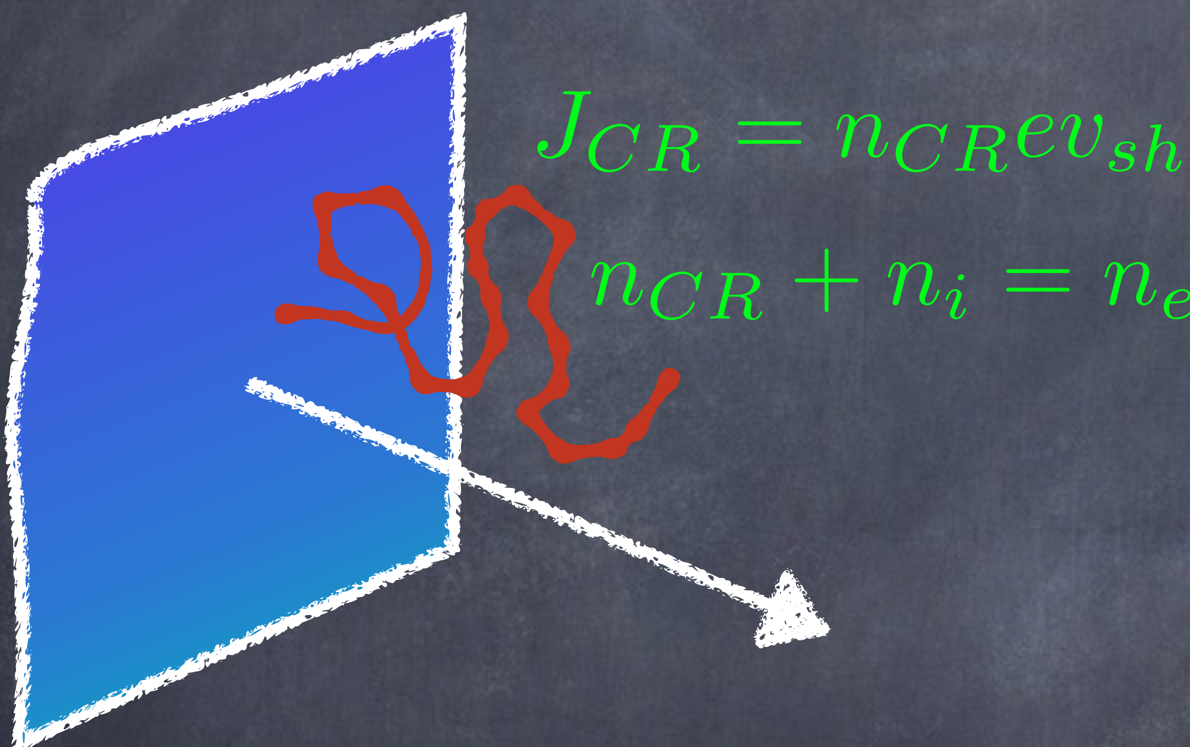
Lagage & Cesarsky 1983

TURBULENT MAGNETIC FIELD NEEDS TO BE STRONGLY AMPLIFIED IF TO REACH KNEE

Basics of magnetic field amplification

The ever-lasting quest for E_{max}

Particle acceleration at shocks is basically a problem of electro-dynamics, just very complex

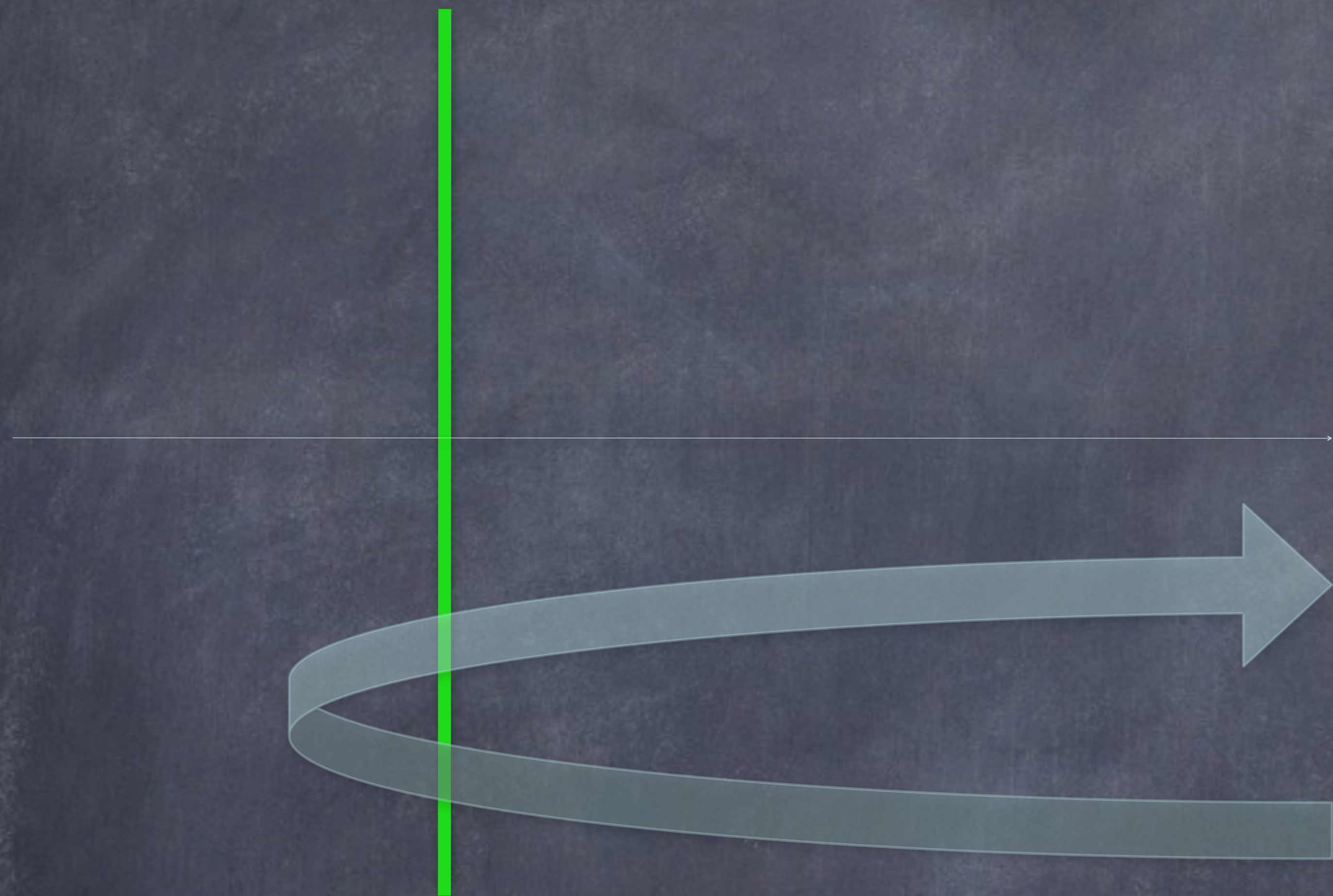


The background plasma reacts to the presence of CR by creating a return current

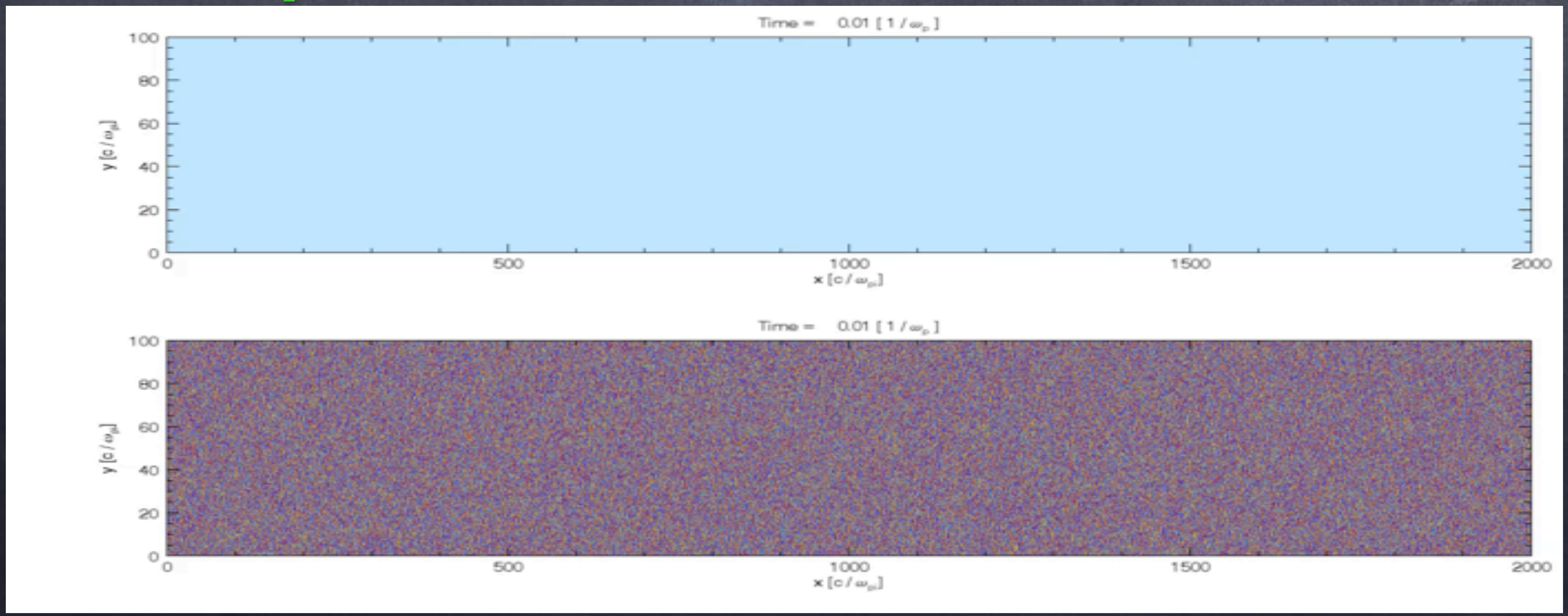
It is this RETURN CURRENT that induces the plasma instabilities responsible for magnetic field amplification and regulates the MAXIMUM ENERGY [Bell 2004]

THE CRUCIAL ROLE OF ESCAPING CR

Bell & Schure 2013
Cardillo, Amato & PB 2015



Escaping particles
Generating seed
turbulence



Caprioli & Spitkovsky 2013

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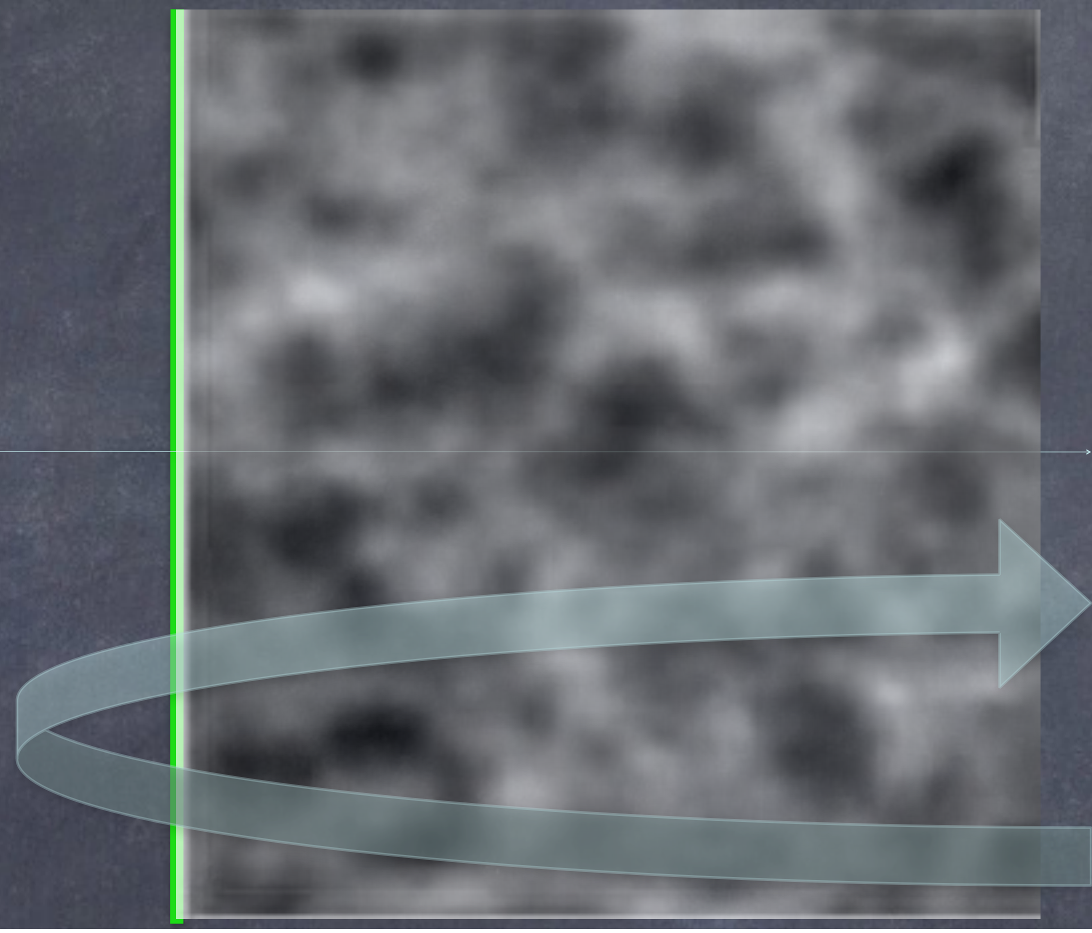

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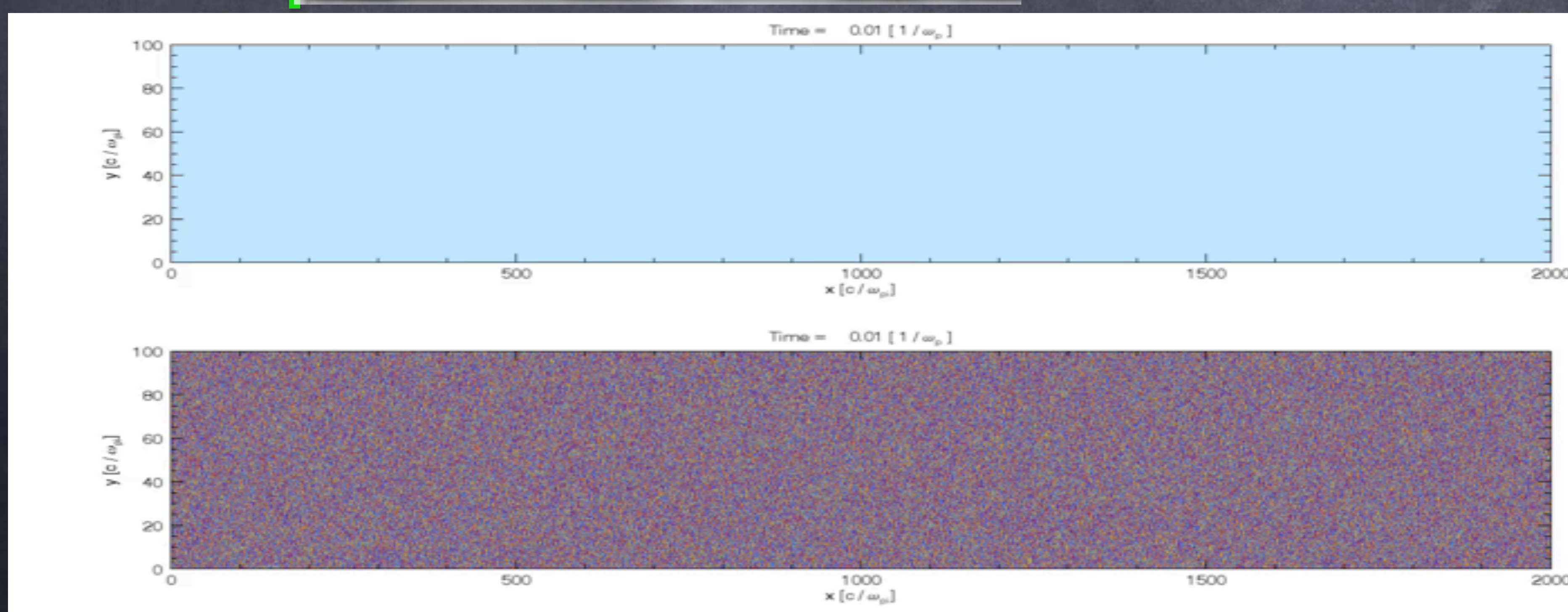

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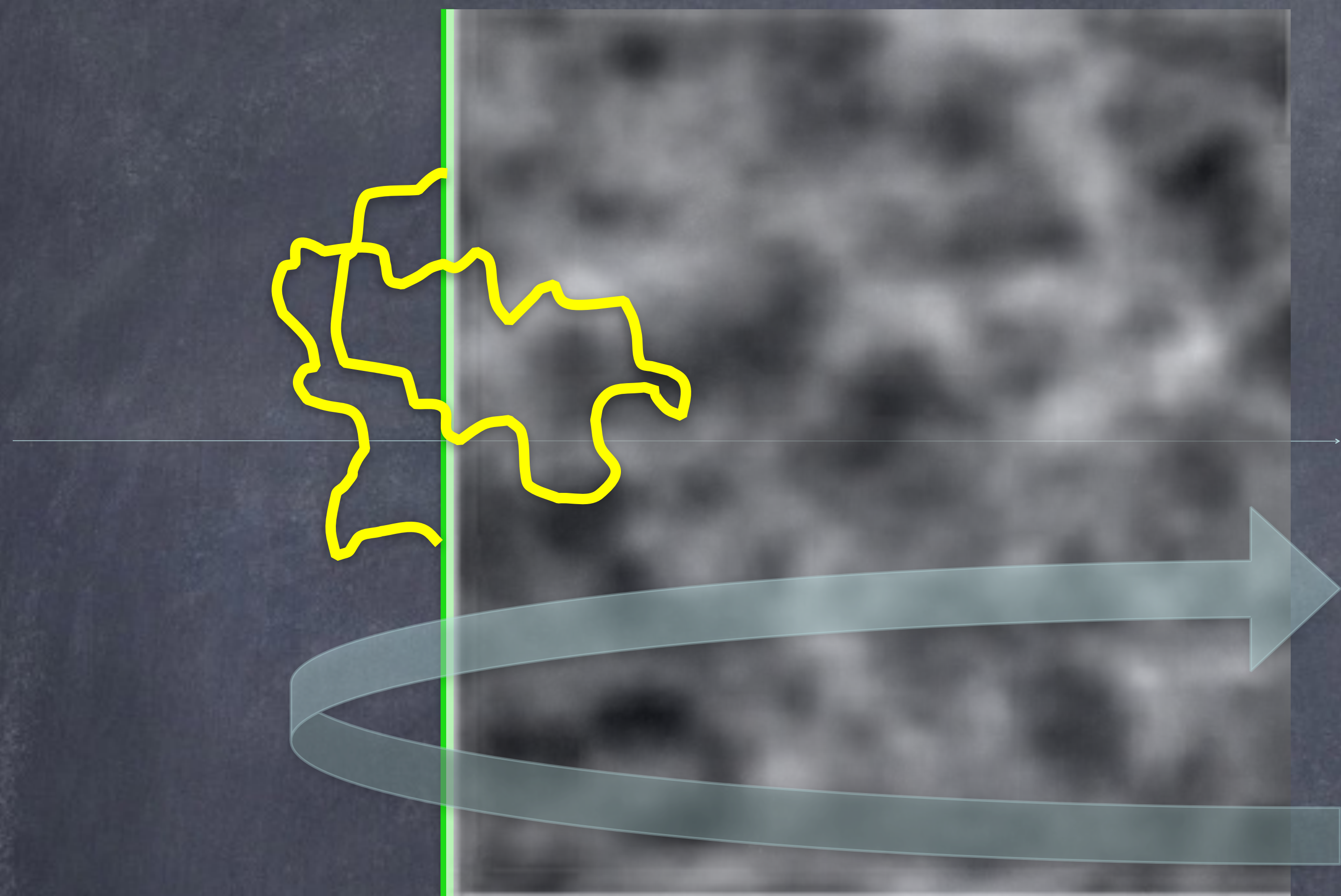
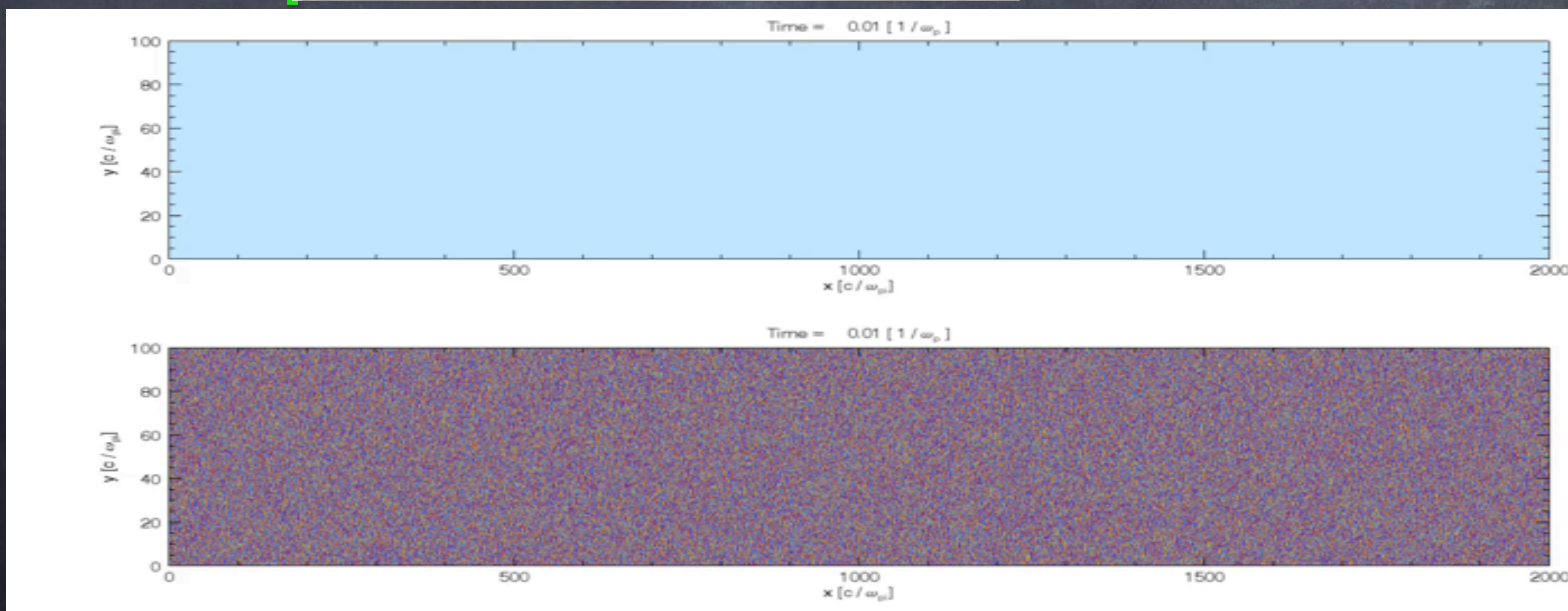


Escaping particles Generating seed turbulence



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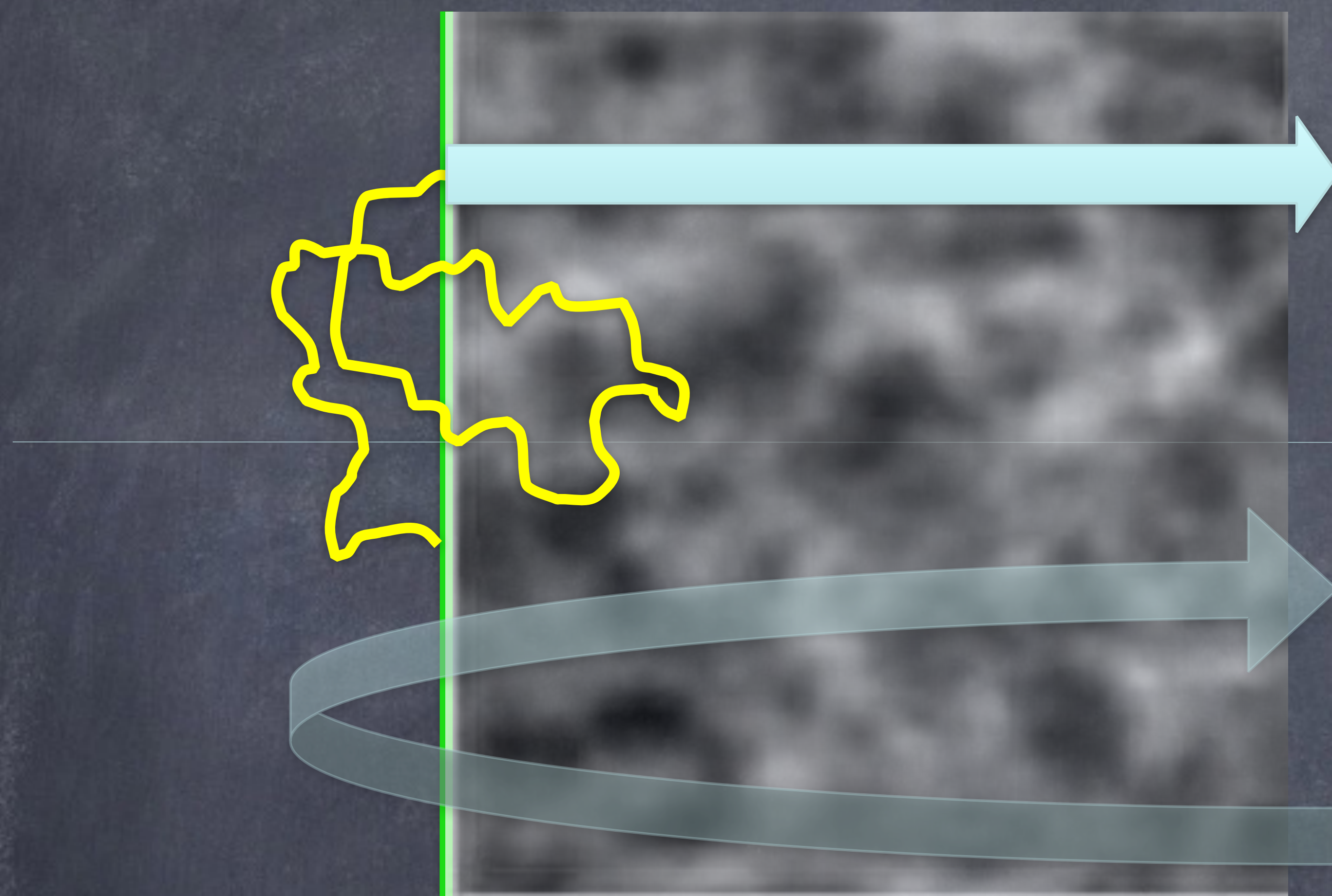

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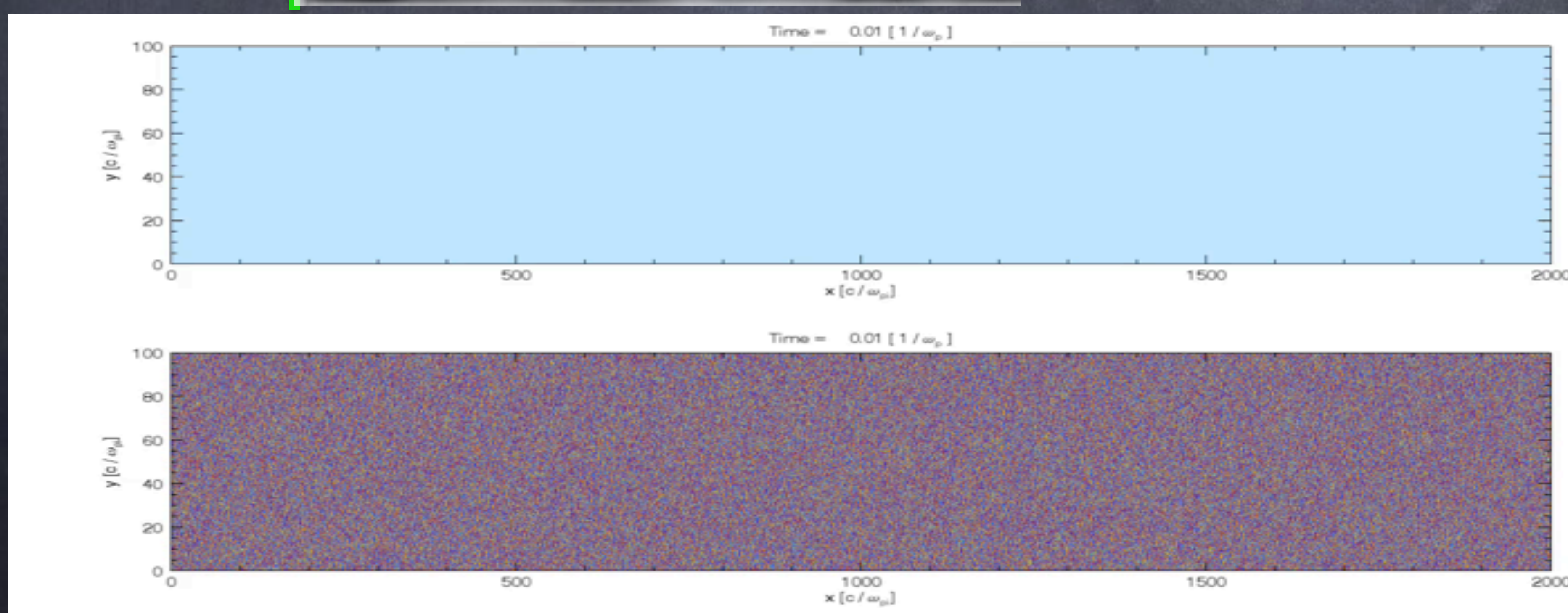

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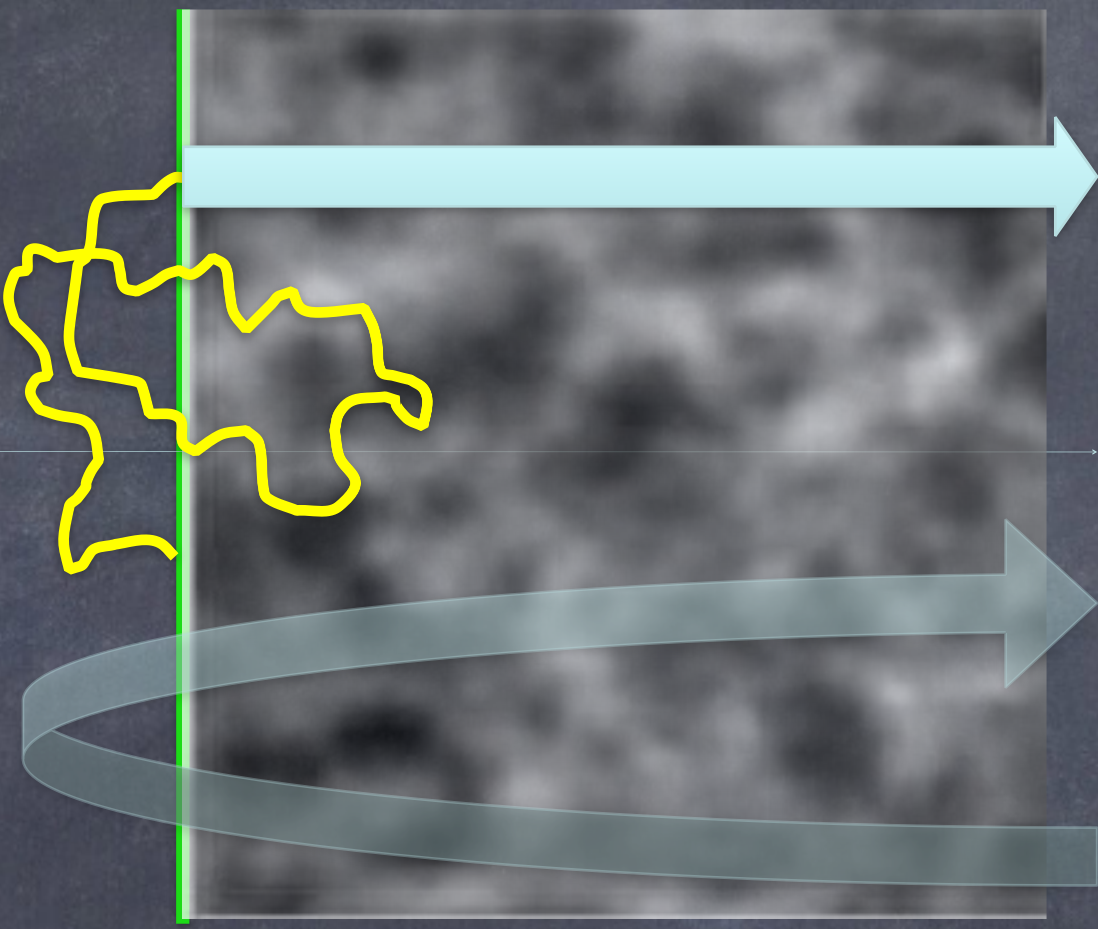

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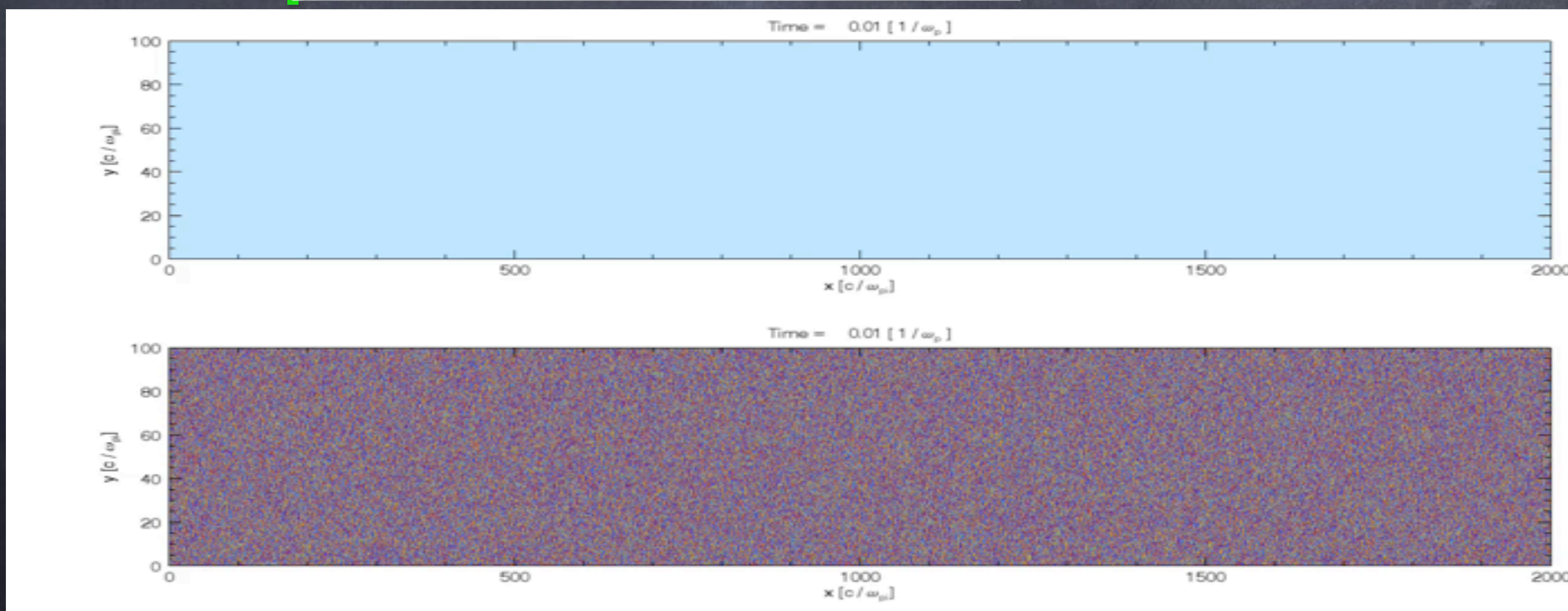


Caprioli & Spitkovsky 2013

The fastest growing modes

quasi purely growing non-resonant modes

Bell (2004): for parameters of a young SNR - new instability when

$$n_{CR}(>E)E\frac{v_s}{c} > \frac{B_0^2}{4\pi} = U_{mag}$$

Energy density of escaping CRs

$$\gamma_{max} = k_{max} v_A \qquad k_{max} B_0 = \frac{4\pi}{c} J_{CR}^{esc}$$

Growth rate $\quad k_{max} \gg 1/r_L(E)$

The instability grows on non-resonant scales -> current not affected

Force on fluid element -> scale of the field increases

$$\rho \frac{dv}{dt} \approx J_{CR} \delta B(t) \rightarrow \frac{\delta B^2}{4\pi} \approx n_{CR}(>E)E\frac{v_s}{c}$$

THE FIELD SATURATION -> EQUIPARTITION BETWEEN MAGNETIC ENERGY AND ENERGY OF ESCAPING CR -> TYPICALLY SEVERAL HUNDRED MICROGAUSS AFTER COMPRESSION, FOR A YOUNG SNR

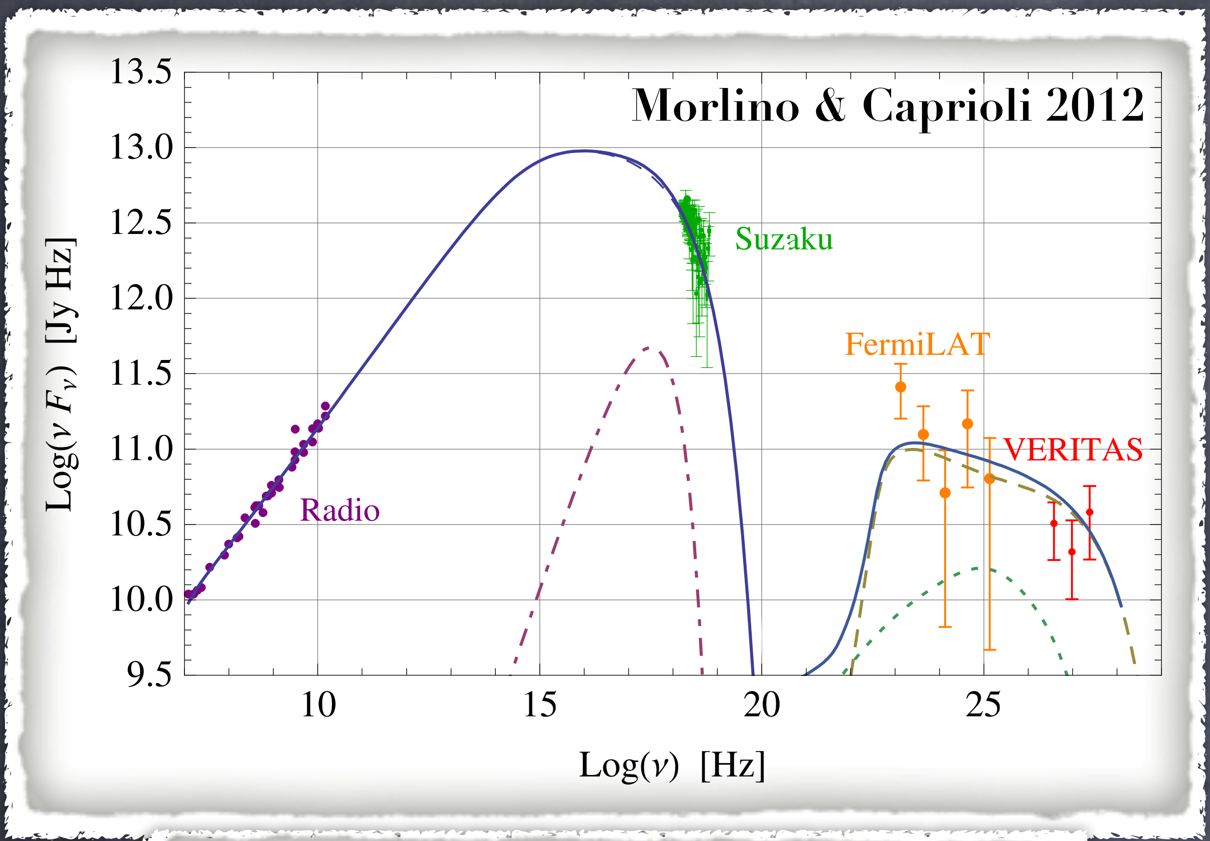
IMPLICATIONS FOR MAXIMUM ENERGY
Supernovae Type Ia

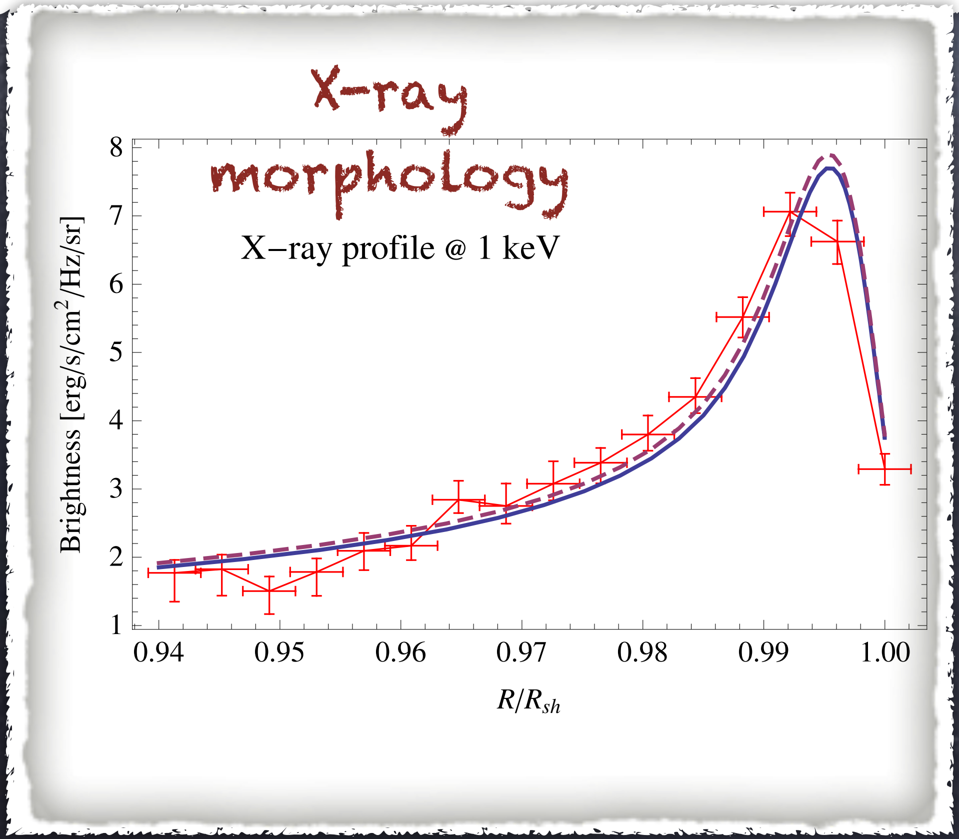
FOR A SN TYPE Ia EXPLODING IN THE ISM THE MAXIMUM ENERGY CAN BE ESTIMATED AS:

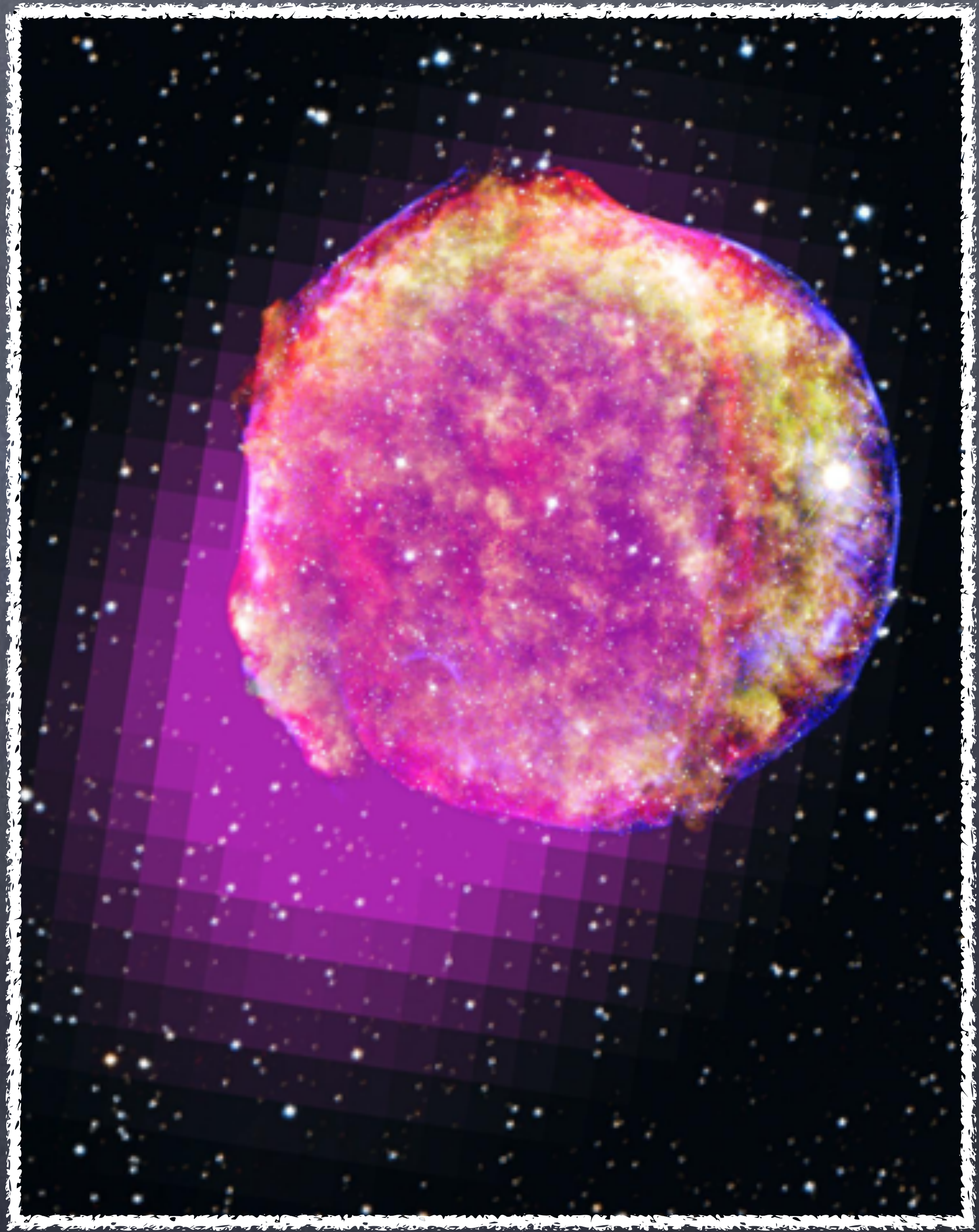
$$E_M \cong \frac{2e}{10c}\xi_{CR} v_0^2 \sqrt{4\pi\rho R_0^2} = 130 \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-\frac{2}{3}}\left(\frac{E_{SN}}{10^{51}\mathrm{erg}}\right)\left(\frac{n_{ISM}}{\mathrm{cm}^{-3}}\right)^{\frac{1}{6}} \; TeV$$

FOR TYPICAL VALUES OF THE PARAMETERS THE MAXIMUM ENERGY REACHABLE IS WELL BELOW THE KNEE

The case of Tycho



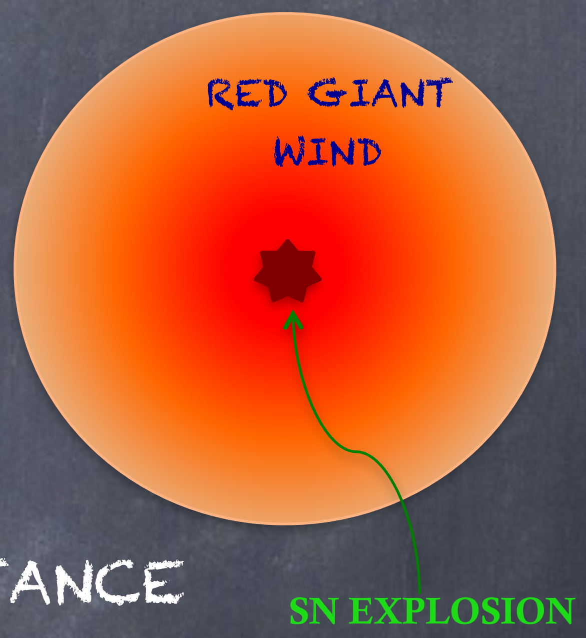




MAXIMUM ENERGY FOR A CORE COLLAPSE SN IN A RED SUPERGIANT WIND

CORE COLLAPSE SN OFTEN EXPLODE IN THE WIND OF THE GIANT PROGENITOR. THE GAS DENSITY IN THE WIND IS

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



IN THE DENSE WIND THE SEDOV PHASE IS REACHED AT DISTANCE

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

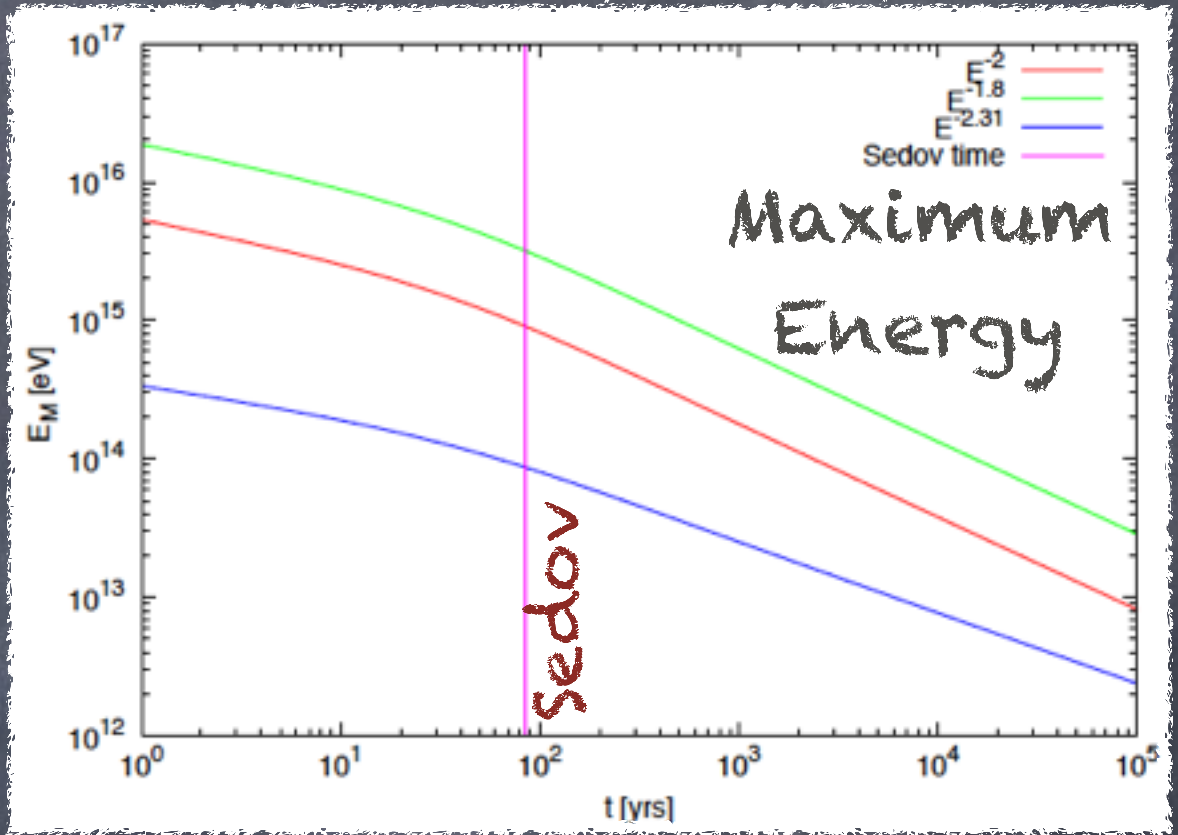
(About 30 years after explosion)

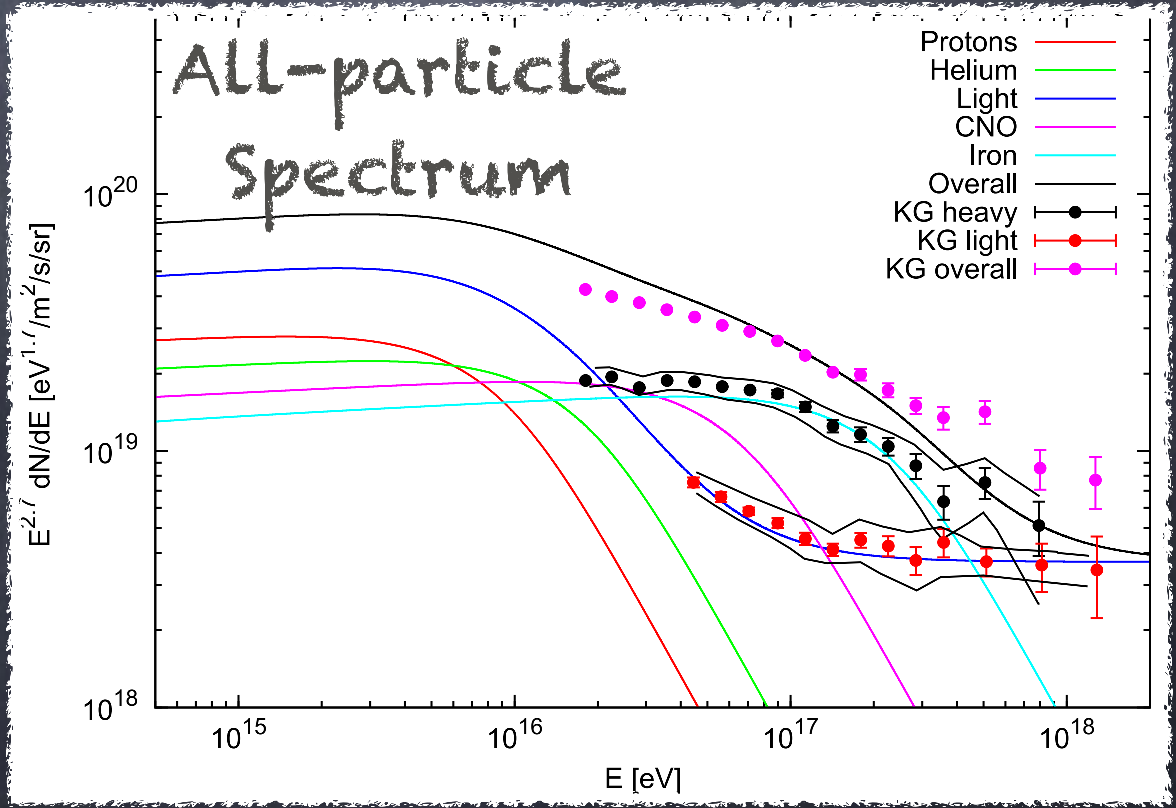
$$E_M \simeq \frac{2e}{5c}\xi_{CR} v_0^2 \sqrt{4\pi\rho R_0^2} \approx 1 \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-1}\left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)\left(\frac{\dot{M}}{10^{-5}\,M_\odot \mathrm{yr}^{-1}}\right)^{\frac{1}{2}}\left(\frac{V_w}{10\,\mathrm{km\,s^{-1}}}\right)^{-\frac{1}{2}} PeV$$

Some points...

Cardillo, Amato & PB 2015

- Effective max energy at the beginning of Sedov phase (~30 years...) - not easy to catch Pevatrons with gamma rays...
- No exponential cutoff at Emax (broken power law)
- Overall spectrum of galactic CRs should end around 10^{17} eV<<Ankle
- Mass composition should become heavy at the transition
- Transition to what?





GALACTIC COSMIC RAY PROPAGATION

Aside from phenomenological approaches, the Physics is in the understanding of the two-ways connection between CR and the scattering they suffer (diffusion, winds...)

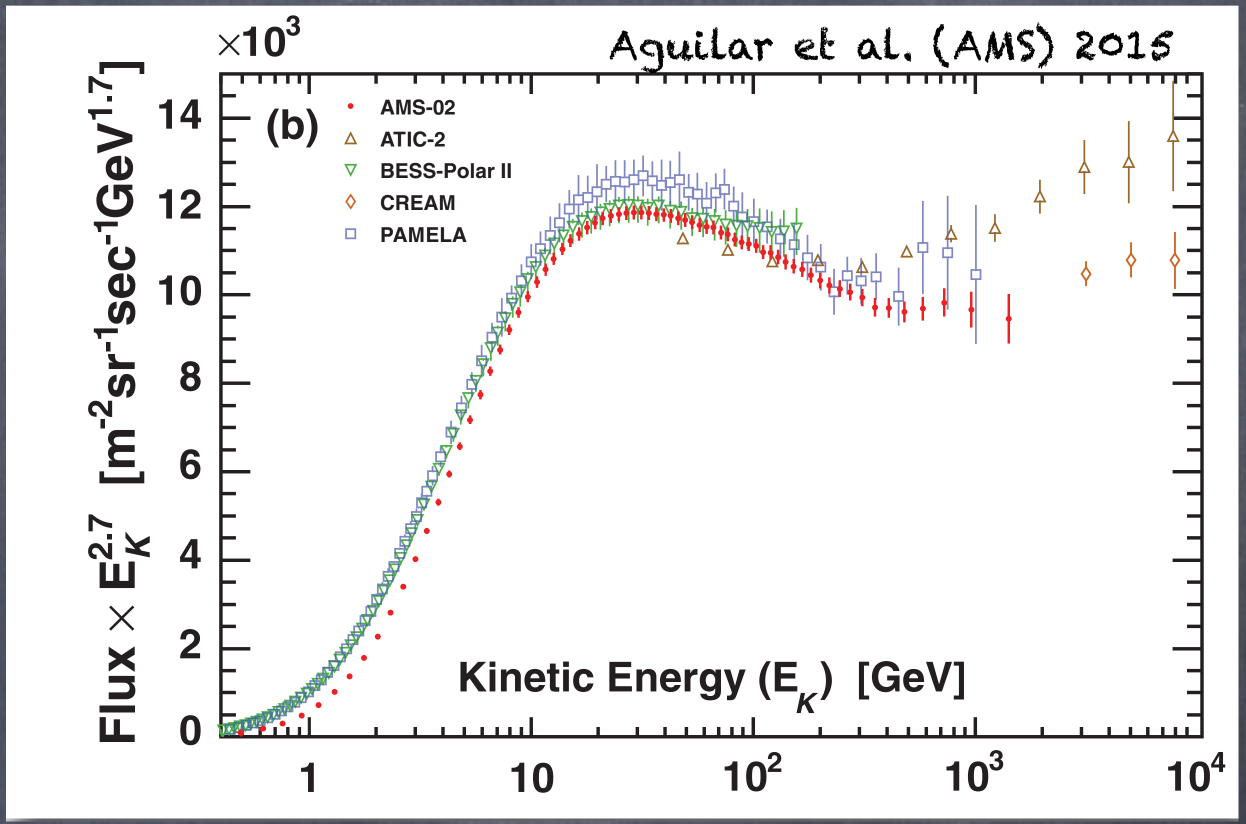
Turbulence on scales resonant with particle gyration is the cause for DIFFUSION

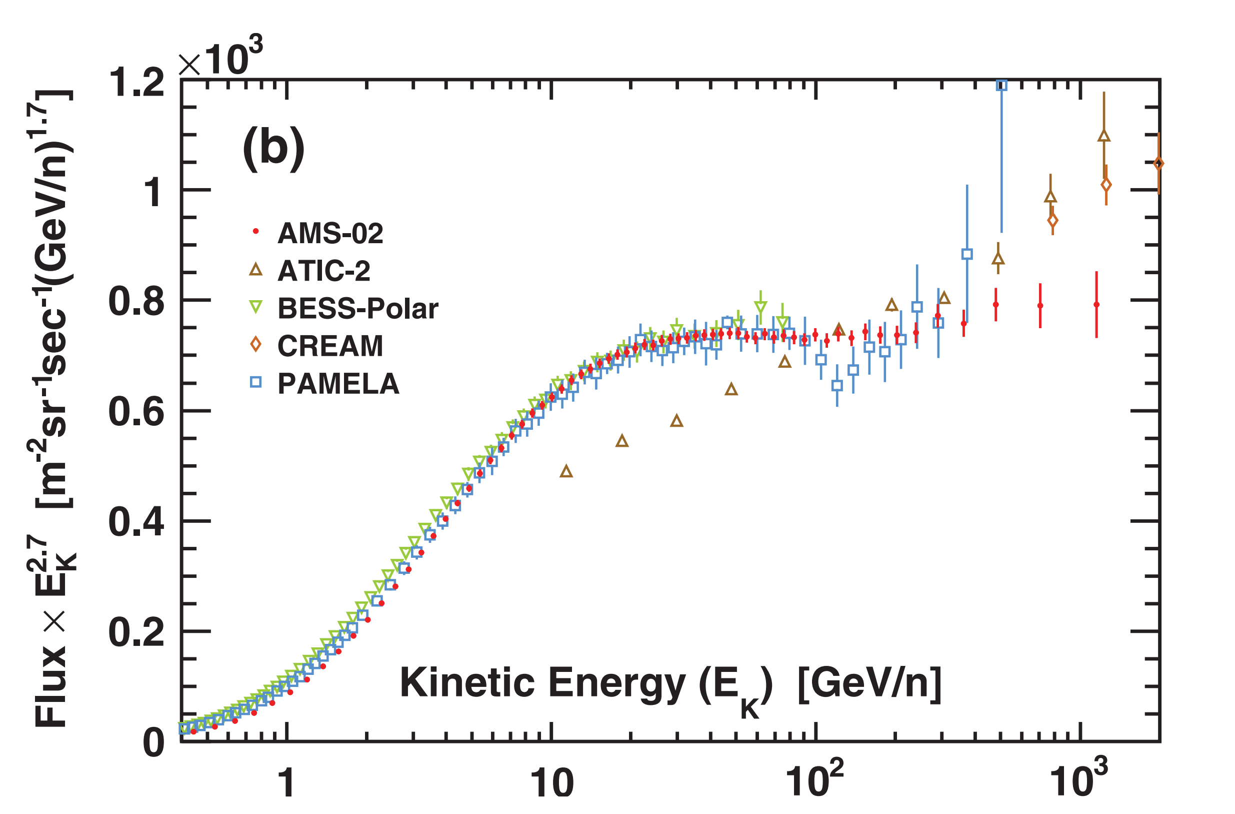
WAVES INJECTED ON LARGE SCALES AND CASCADING TO SMALLER SCALLER SCALES (Kolmogorov)

WAVES ARE GENERATED BY CR THEMSELVES AT THE RESONANT SCALE (STREAMING INSTABILITY)

Proton and He spectral breaks

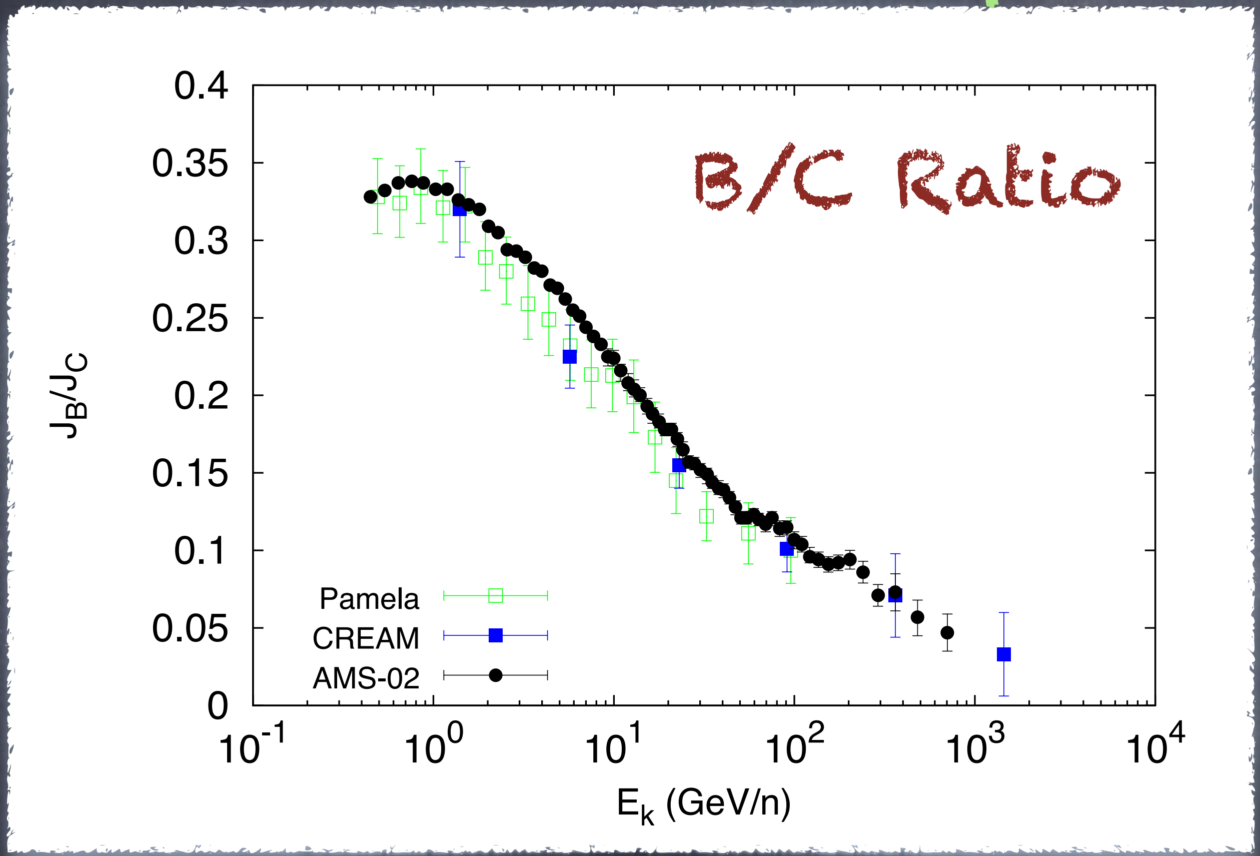
- Both protons and helium spectra show a break @~200-300 GV (PAMELA and AMS-02)
- The He spectrum is slightly harder than that of protons
- There is some indication that a similar break exists for heavier nuclei (CREAM)





Secondary/Primary: B/C

Evidence for CR diffusive transport



primary equilibrium

$$n_{pr}(E/n) \propto Q(E/n)\tau_{diff}(E/n)$$

secondary injection

$$q_{sec}(E/n) \approx n_{pr}(E/n)\sigma v n_{gas}$$

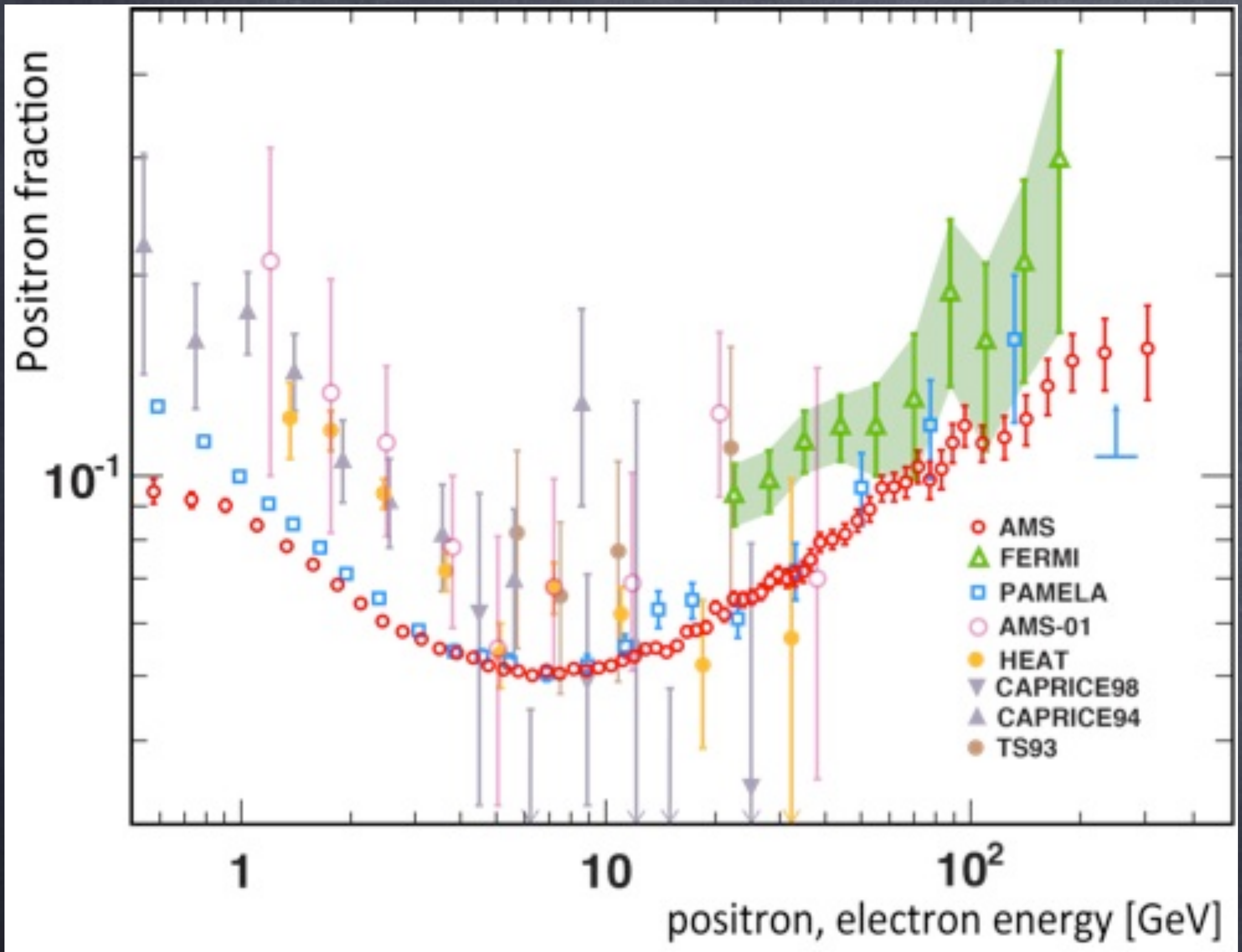
secondary equilibrium

$$n_{sec}(E/n) \approx q_{sec}(E/n)\tau_{diff}(E/n)$$

$$\frac{n_{sec}}{n_{pr}} \approx \frac{\sigma}{m_p}[v n_{gas} m_p \tau_{diff}]$$

GRAMMAGE: $X(E/n) \propto \tau_{diff}(E/n) \sim 1/D(E/n)$

Secondary/Primary: $e^+/(e^- + e^+)$



AMS-02 Coll. 2013

Reacceleration of secondary Pairs in old SNRs

PB 2009, PB & Serpico 2009

Mertsch & Sarkar 2009

Pulsar Wind Nebulae

Hooper, PB & Serpico (2009)

PB & Amato 2010

Dark Matter Annihilation

Difficult: high annihilation Cross section, leptophilia, Boosting factor [Serpico (2012)]

Non-linear diffusion

The CR gradient excites Alfven waves at a rate:

$$\Gamma_{CR}(k) = \frac{16\pi^2}{3}\frac{v_A}{B^2\mathcal{F}}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{k=k_{res}}$$

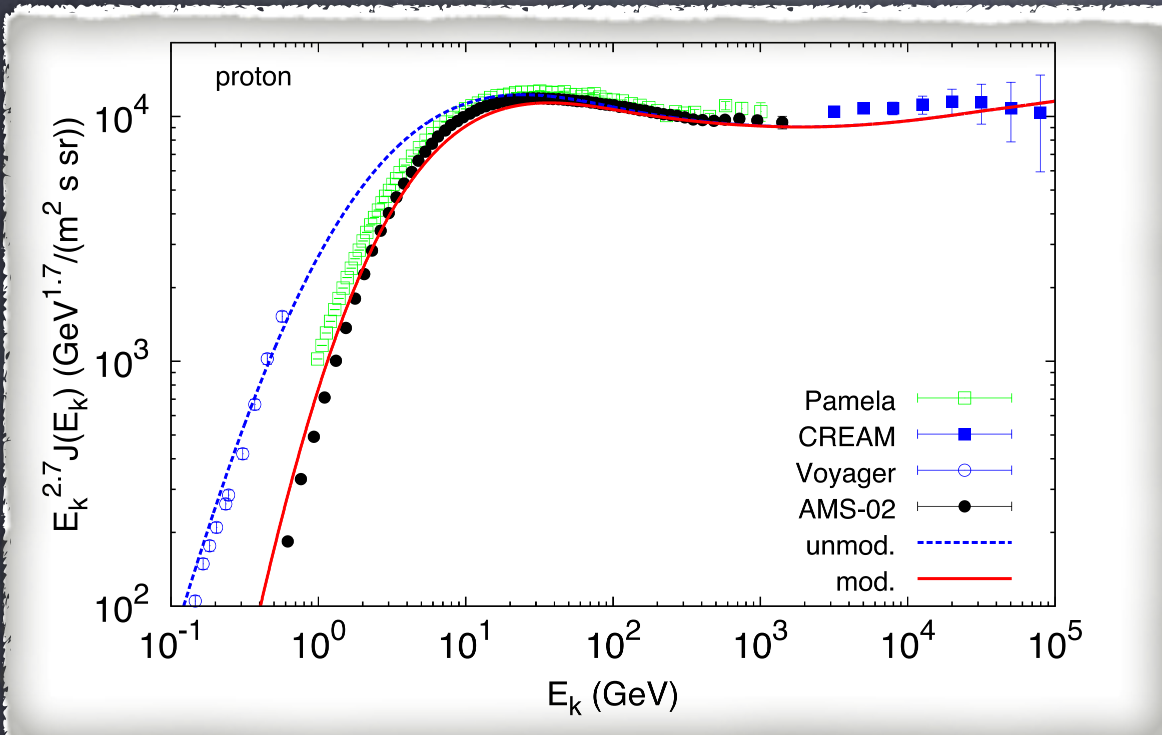
$$D(p) = \frac{1}{3} r_L(p) v \frac{1}{\mathcal{F}}$$

~f_0/H

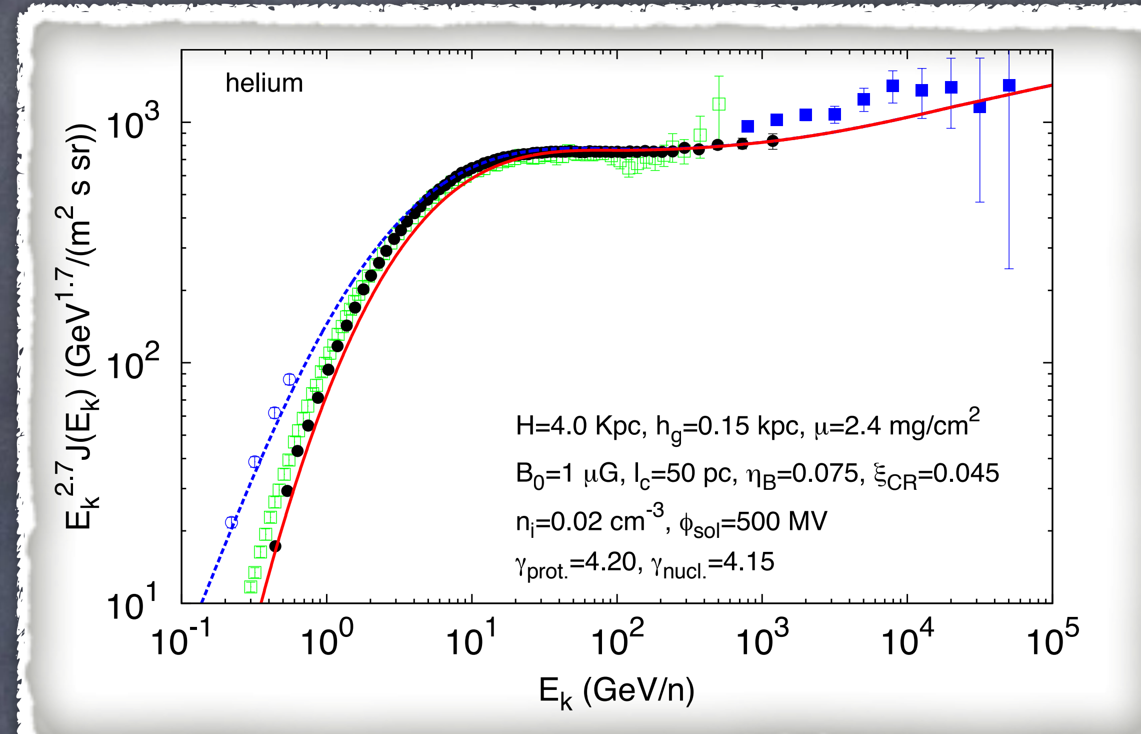
In Nature we expect that f(p,z) and D(p,z) determine each other... THEY ARE NOT INDEPENDENT QUANTITIES!

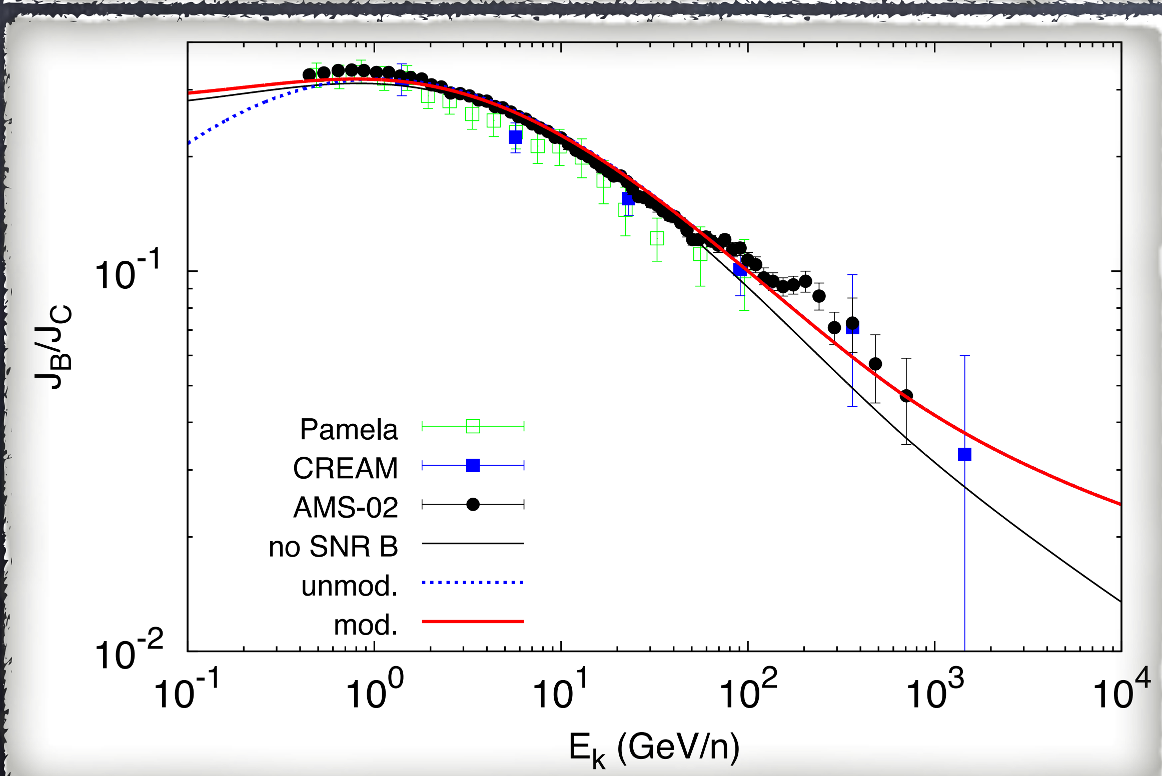
Interesting: WHEN REQUIRING $p^2 f(p) \sim p^{-2.7}$ one gets for free $D(p) \sim p^{0.7}$

Spectral Breaks: self-generation and cascade



Aloisio, PB & Serpico 2015





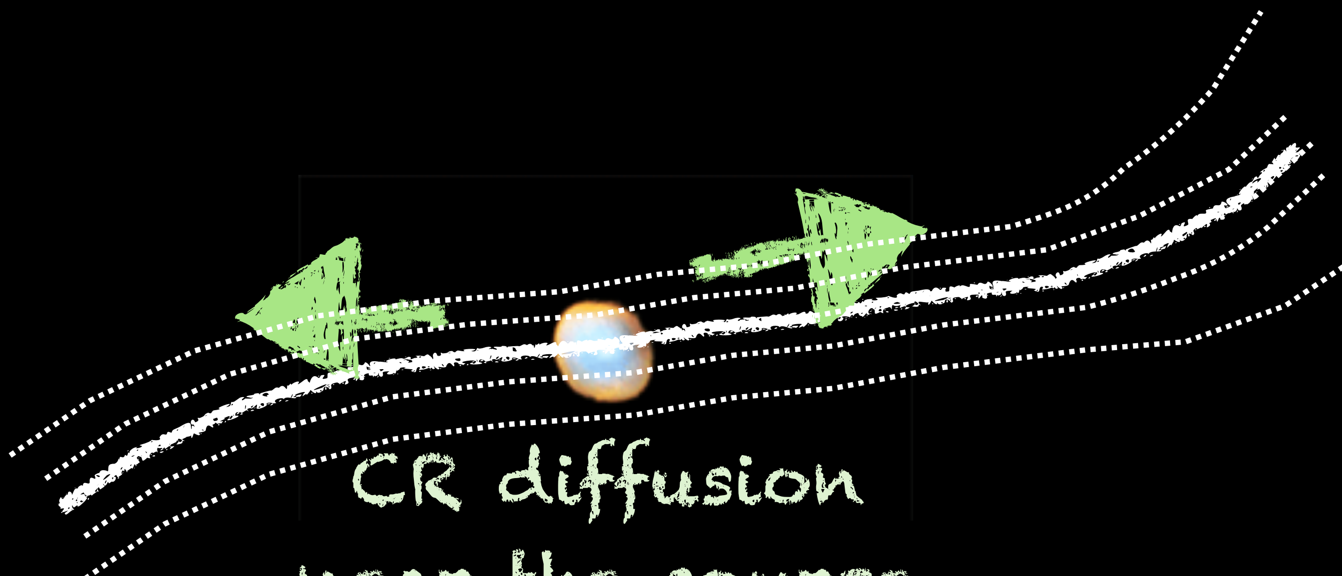
PAMELA and AMS-02 data — combination of self-generated and pre-existing waves

Voyager data are automatically fitted with no additional breaks… advection with self-generated waves at E<10 GeV?

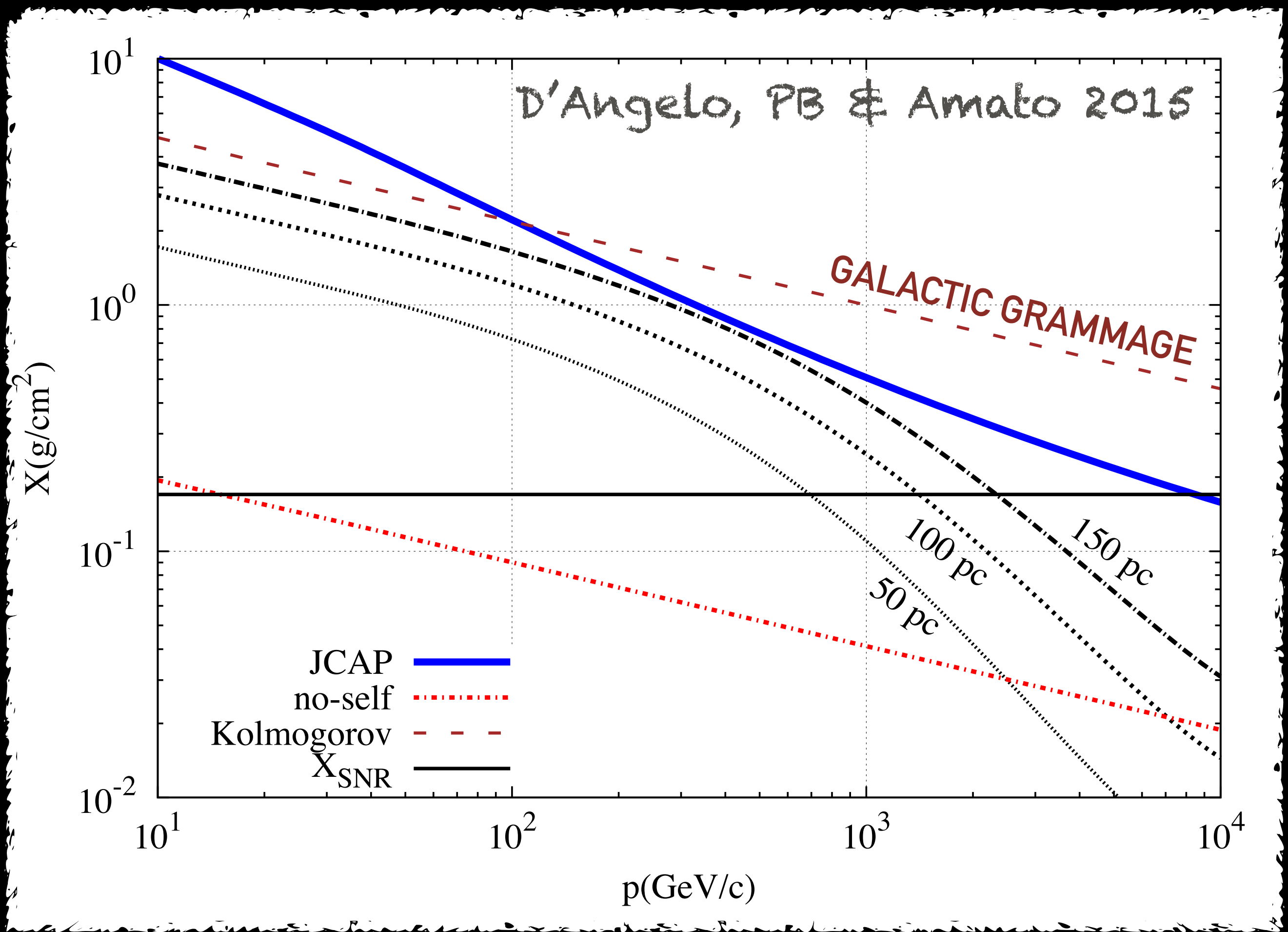
AMS-02 B/C shows an excess at E>100GeV, compatible with the grammage inside sources:

$$X_{\rm SNR} \approx 1.4 r_s m_p n_{\rm ISM} c T_{\rm SNR} \approx 0.17\,{\rm g\,cm^{-2}} \frac{n_{\rm ISM}}{\rm cm^{-3}} \frac{T_{\rm SNR}}{2\times 10^4 {\rm yr}}$$

Near-source grammage?



Both CR density and gradients near a source are huge for quite some time after explosion



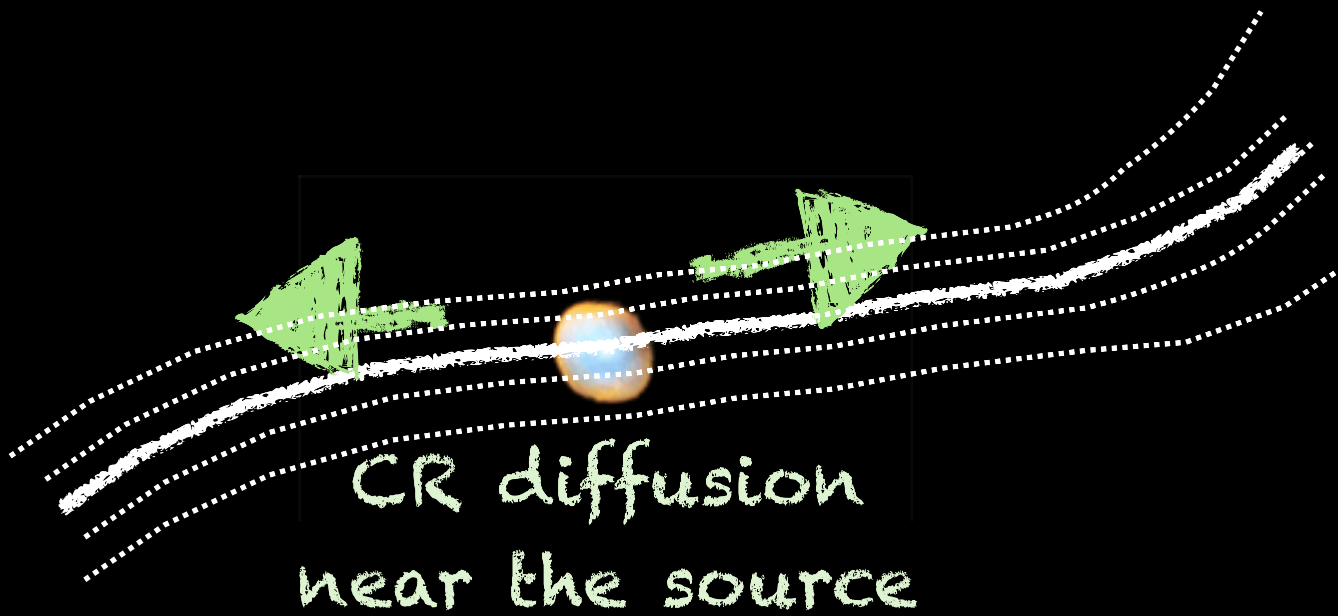
D'Angelo, PB & Amato 2016

NON LINEAR DIFFUSION CHANGES GRAMMAGE

X(E) close to sources important below ~TeV

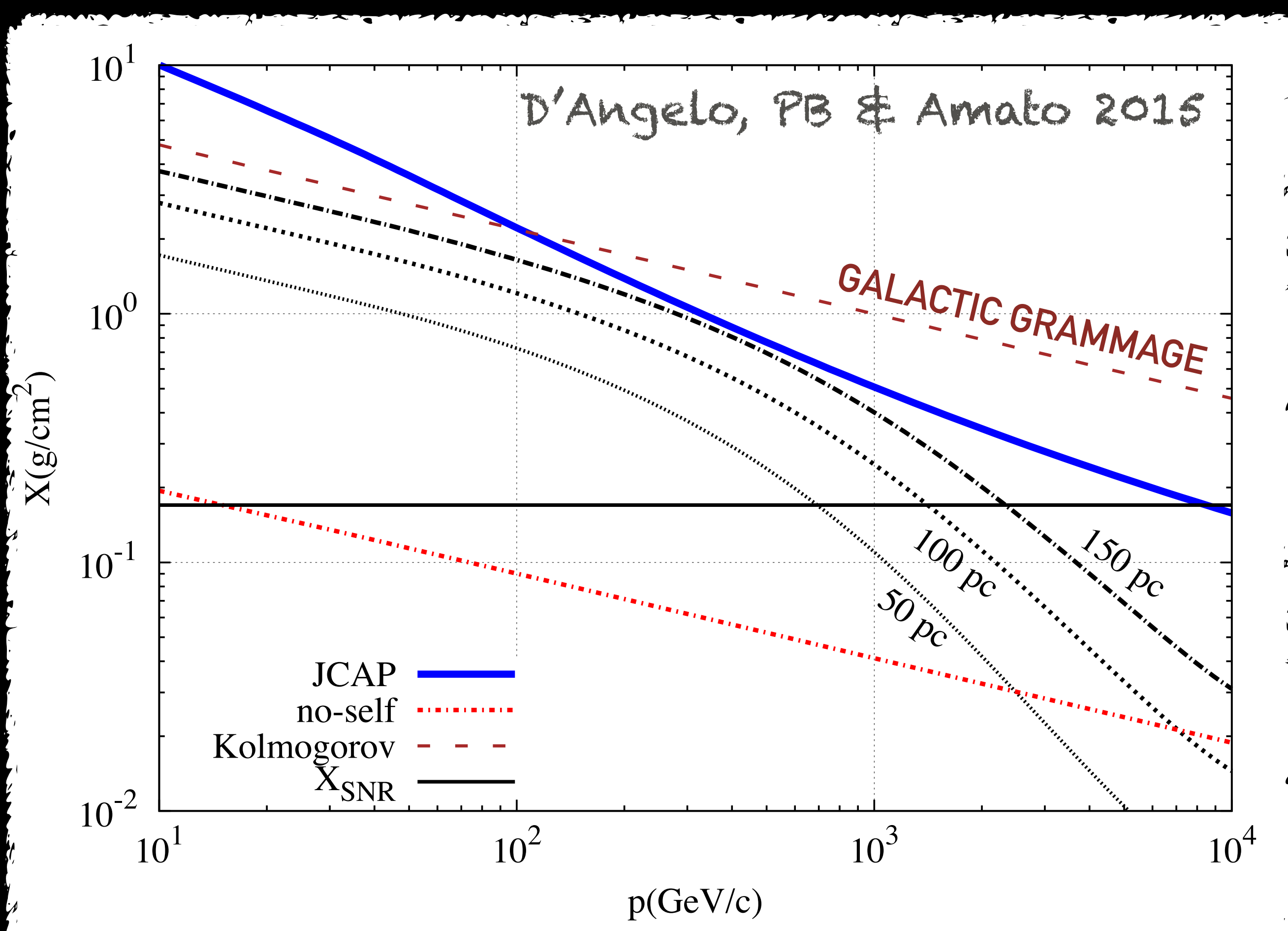
X(E) inside sources important > TeV

Near-source grammage?



Both CR density and gradients near a source are huge for quite some time after explosion

NON LINEAR DIFFUSION CHANGES GRAMMAGE

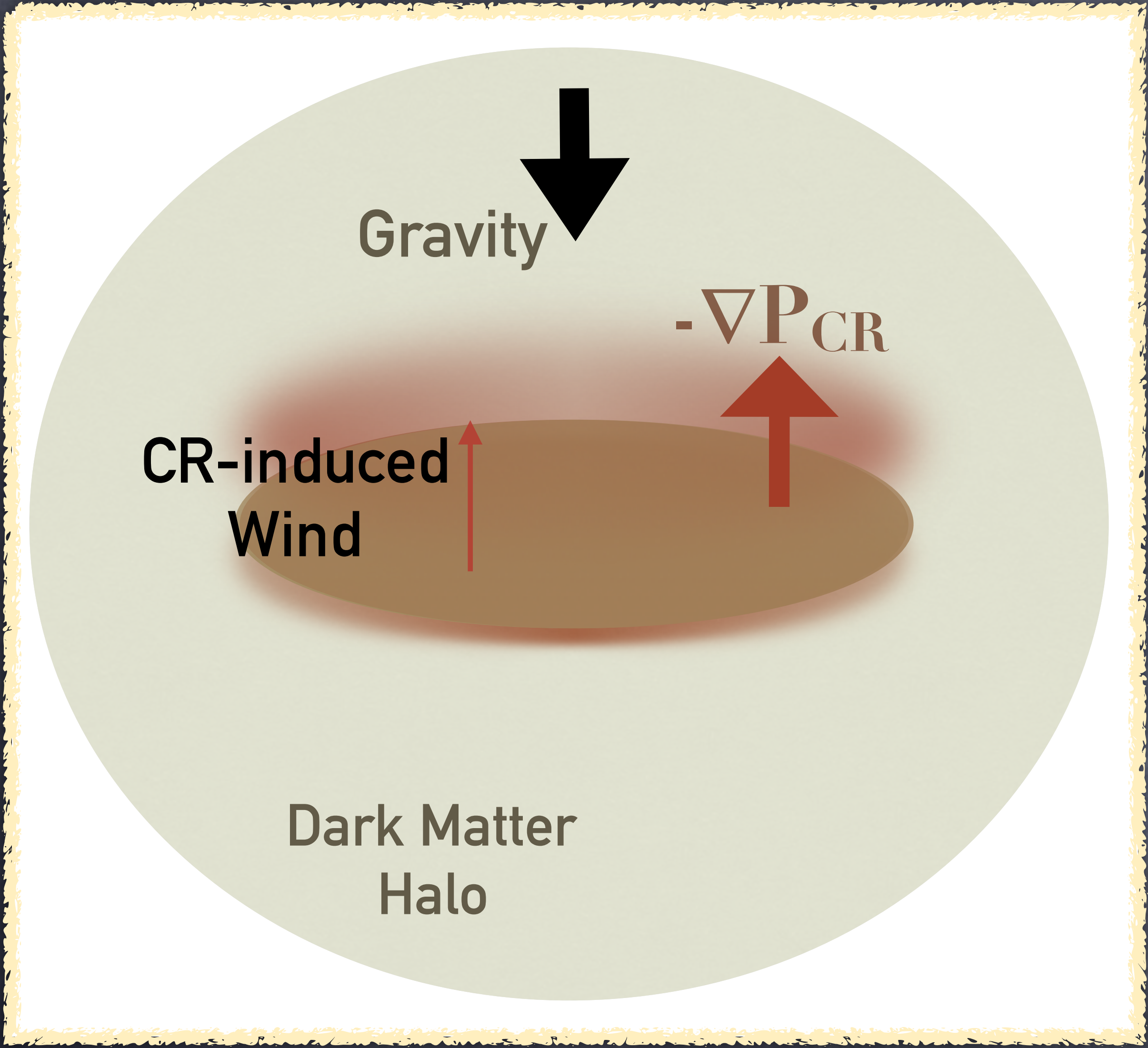


D'Angelo, PB & Amato 2016

X(E) close to sources important below ~TeV

X(E) inside sources important > TeV

Cosmic Rays vs Gravity



The force exerted by CR may wins over gravity and a wind may be launched

Close to the Galaxy: Diffusion
Farther away: Advection with wind

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

No effective halo size H

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

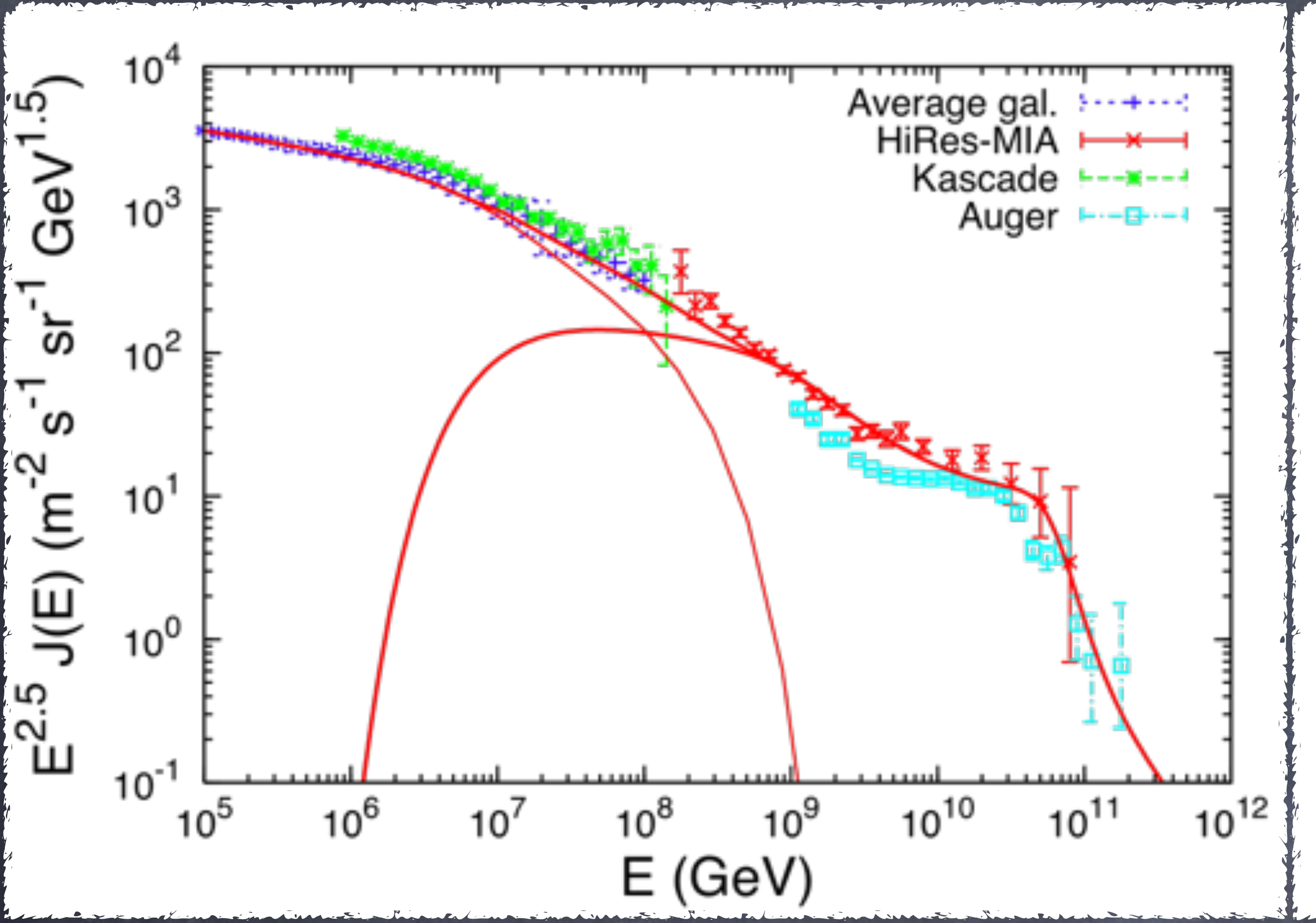
STANDARD CASE

CR-INDUCED WIND WITH SELF-GENERATION

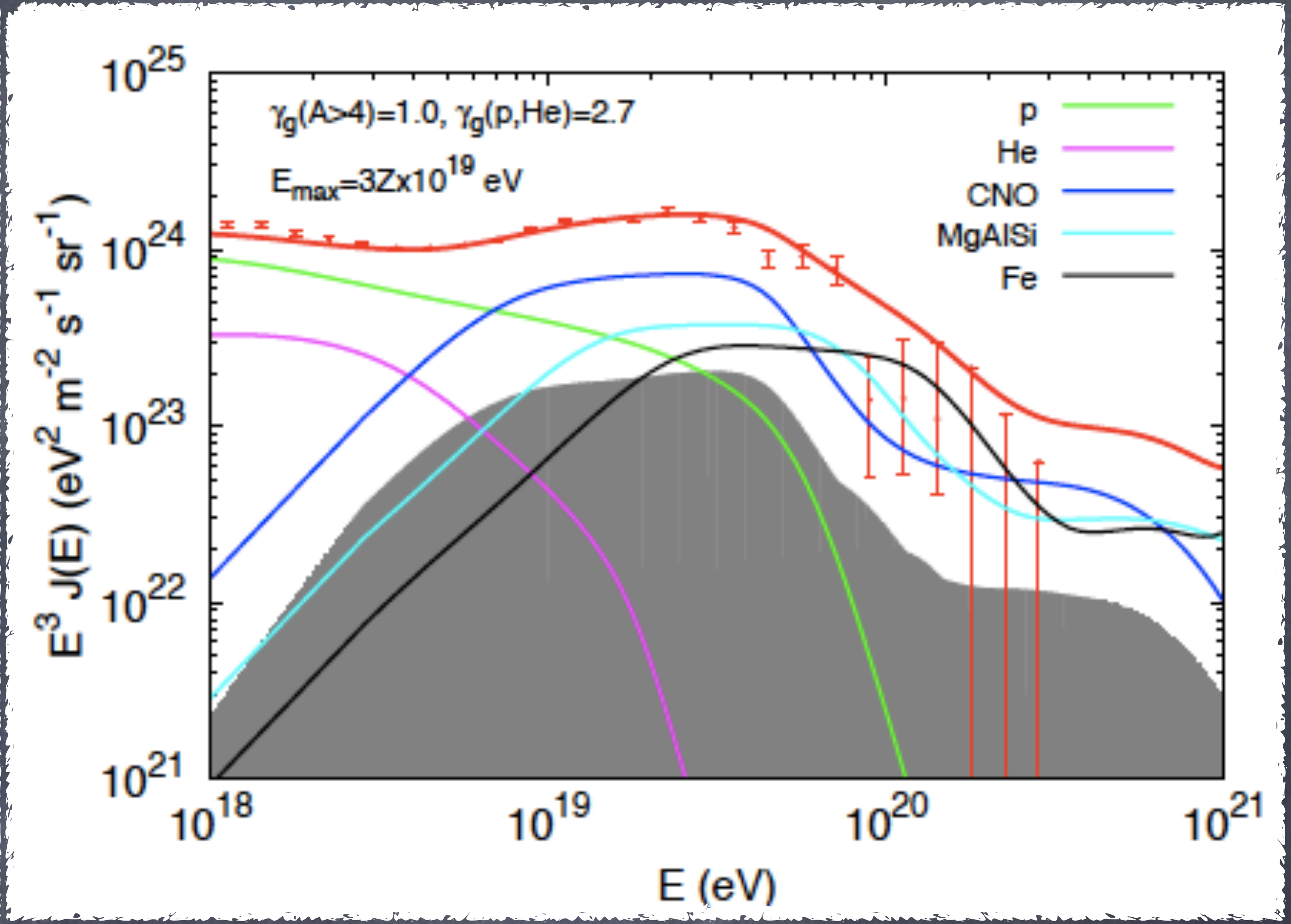
Ends and Beginnings

- The end of Galactic CRs (GCRs) should be around 10^{17} eV
- Observationally ~ second knee
- GCR end with heavy composition
- At 1 EeV TA and Auger agree on light composition!
- Yet, at >10 EeV mixed composition (Auger)

Transitions



Dip



Mixed Compositions

Berezinsky et al.

chemical composition incompatible with Auger data

Allard et al.; Aloisio et al.

Mixed composition with $E_{max} \sim 5\ 10^{18}$ eV

Additional extra-gal protons

SUMMARY (I)

- Microphysics of CRs (inner space) determines what we see on large scales (outer space) and even the electrodynamics of the plasmas where CRs move

- This simple concept is crucial to understand both acceleration and transport

- Even accounting for such effects SNIa only reach few 100 TeV. For SN II E_{max}~PeV

- But only ~20-30 years after bang (not so good news for gamma ray observations)

- CR transport in the Galaxy still poorly understood: NL effects generate many surprises – e.g. grammage

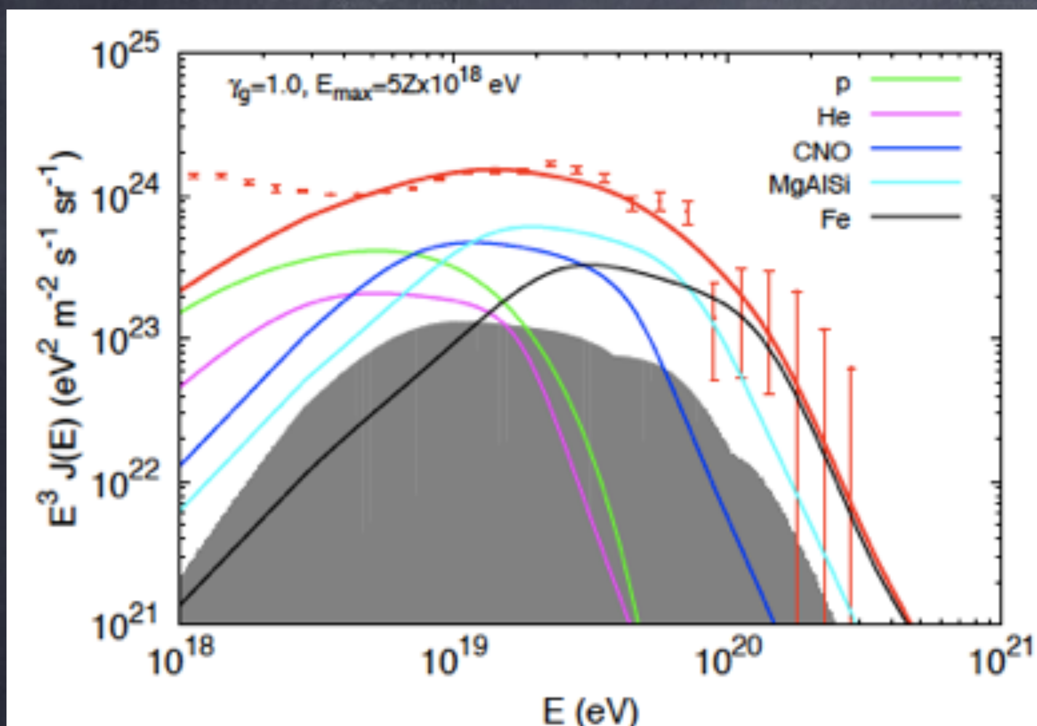
SUMMARY (II)

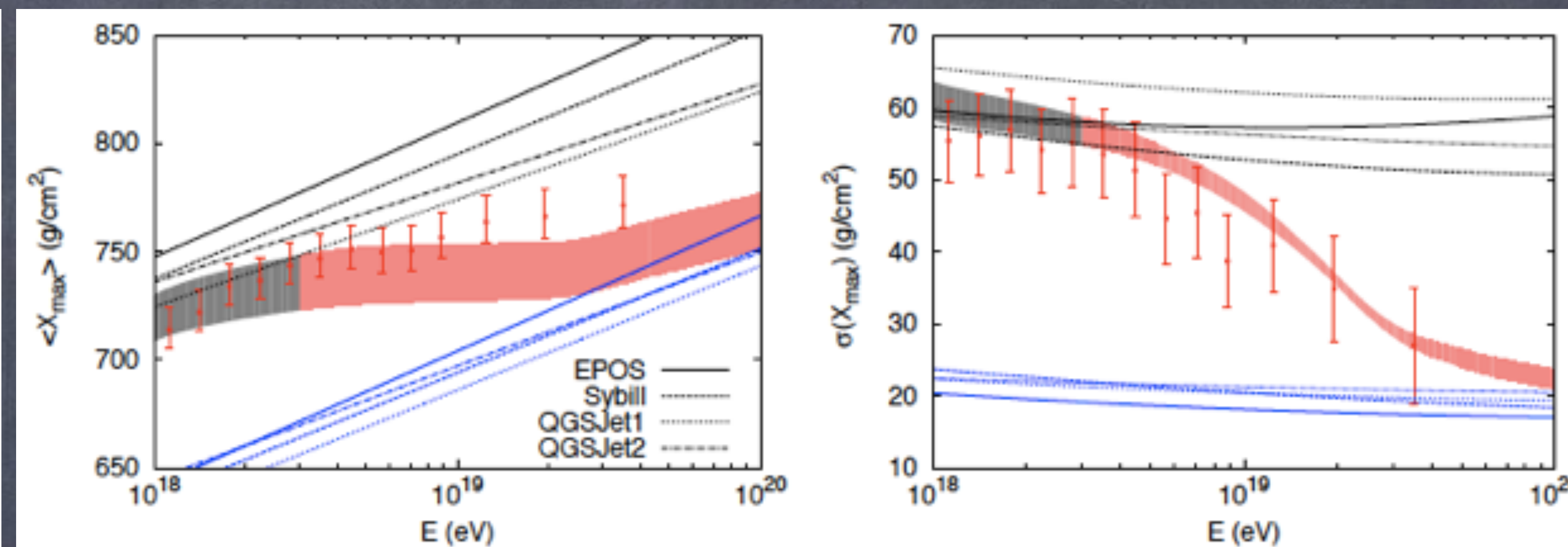
- Interplay between NL effects and gravity --> CR induced winds
- Galactic CR are expected to end at 0.1 EeV (second knee?) ... with a heavy composition
- Yet at 1 EeV we have mainly light elements again
- Transition to extragalactic CRs? Also anisotropy changes phase (Auger)
- At higher E Mixed mass composition (hard injection)
- Extragalactic CR sources: $E_{max} \sim 5\ 10^{18}$ eV !!!

Supplementary Slides

TRANSITION AND UHECR

Aloisio, Berezinsky & PB 2014





VERY HARD INJECTION SPECTRA REQUIRED IF SOURCES GENERATE NUCLEI (Allard 2011, Taylor 2014, Aloisio et al. 2014)

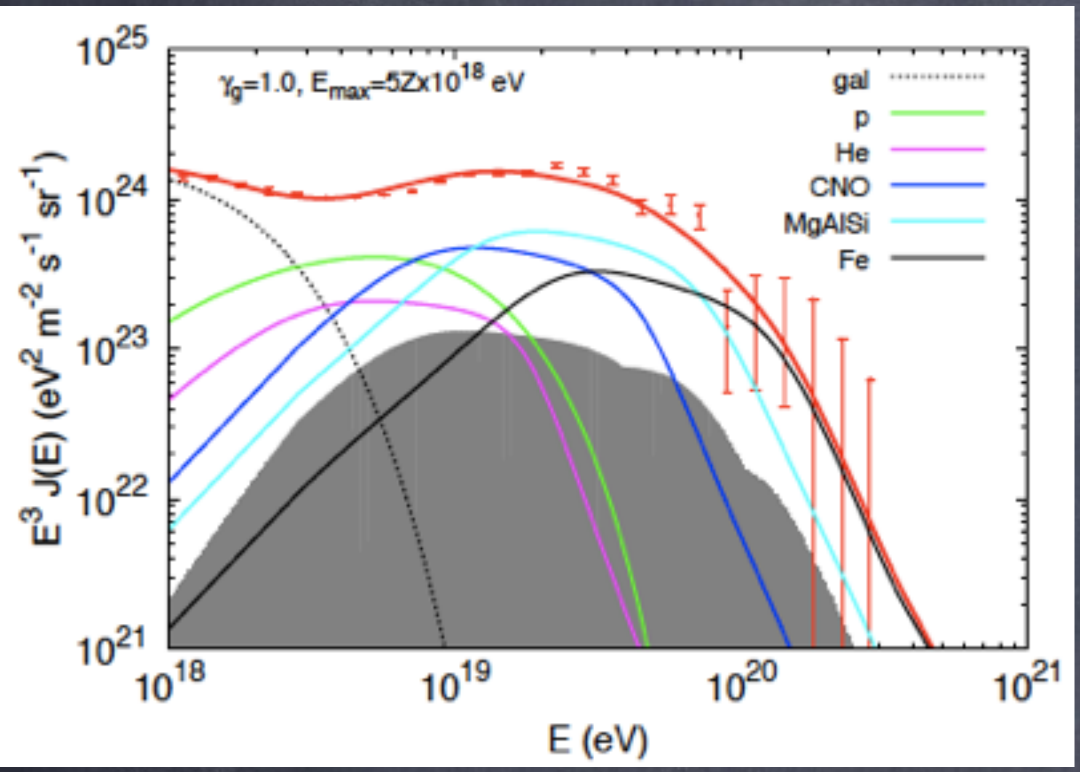
...AND LOW VALUE OF E_{MAX}~5 10^{18} eV...

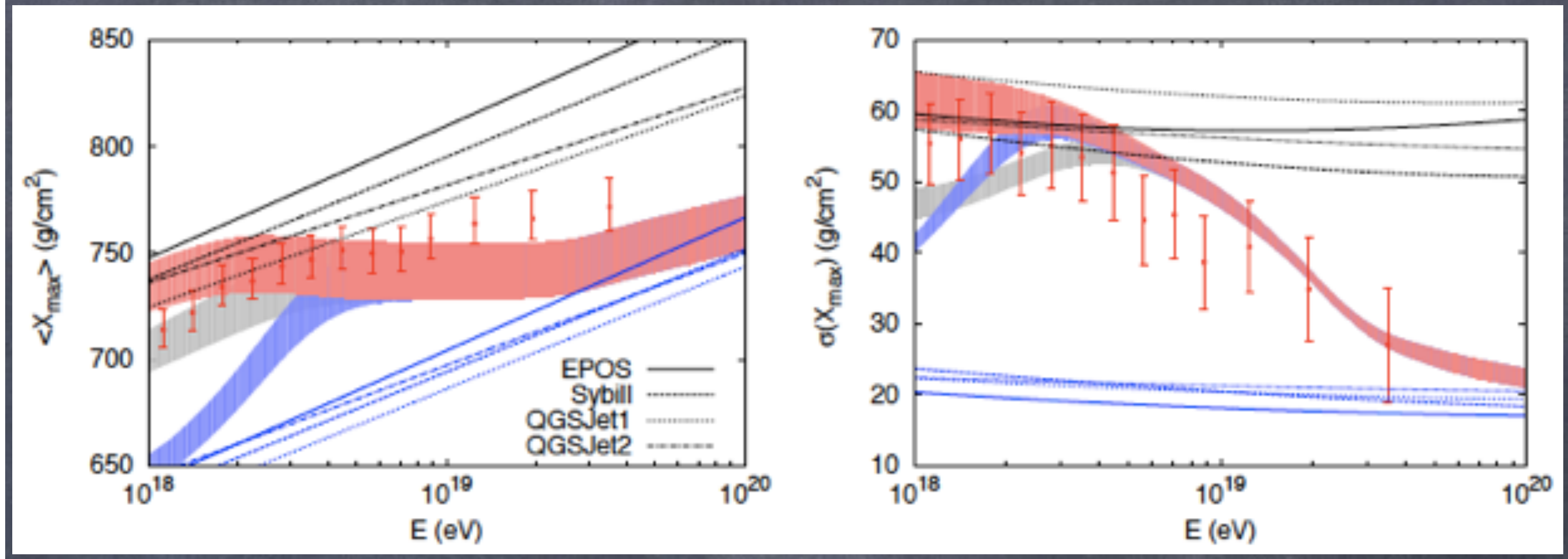
QUITE A CHANGE OF PARADIGM

TRANSITION AND UHECR

Additional Galactic Component

Aloisio, Berezinsky & PB 2014

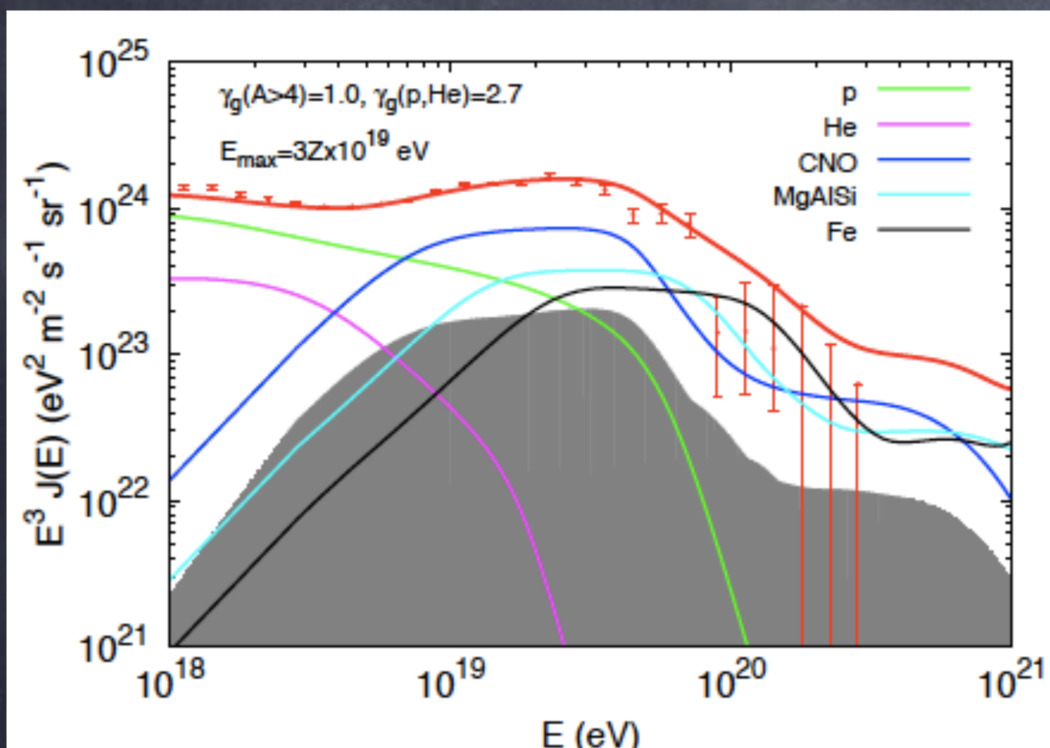




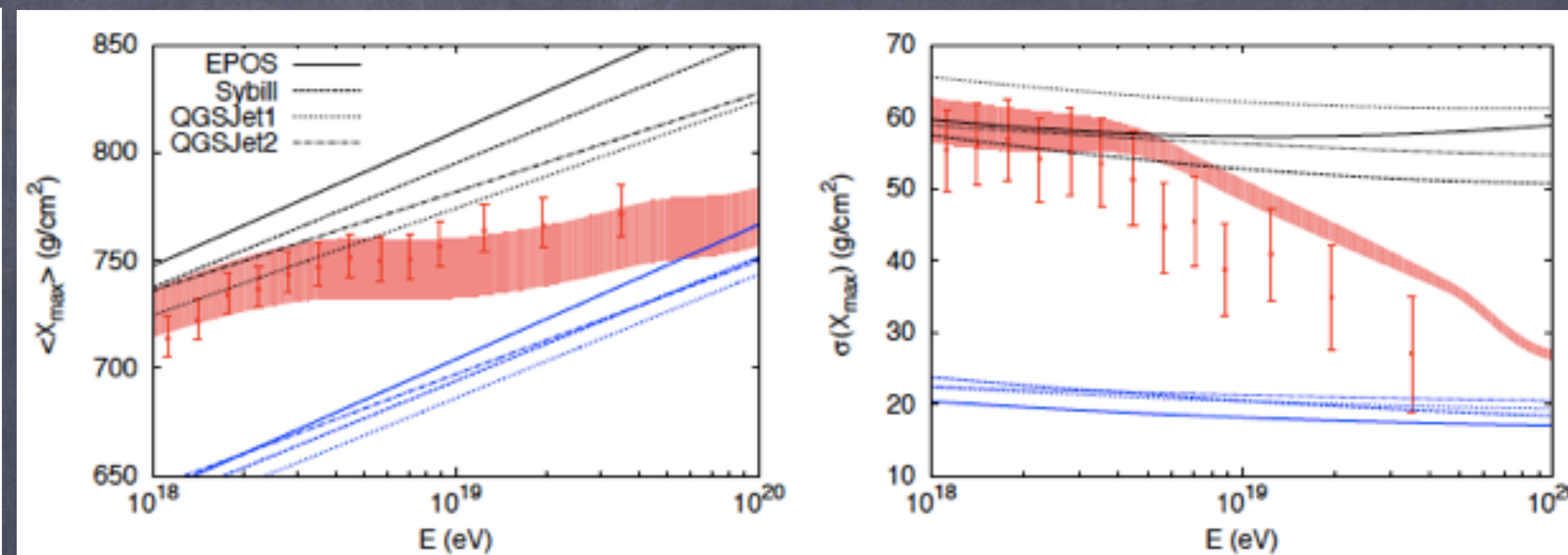
IF THE REQUIRED ADDITIONAL COMPONENT IS GALACTIC IN ORIGIN, IT HAS TO BE LIGHT. BUT THIS IS NOT CONSISTENT WITH THE ANISOTROPY MEASURED BY AUGER AT 10^{18} eV

TRANSITION AND UHECR

Additional Extragalactic Component



Aloisio, Berezinsky & PB 2014

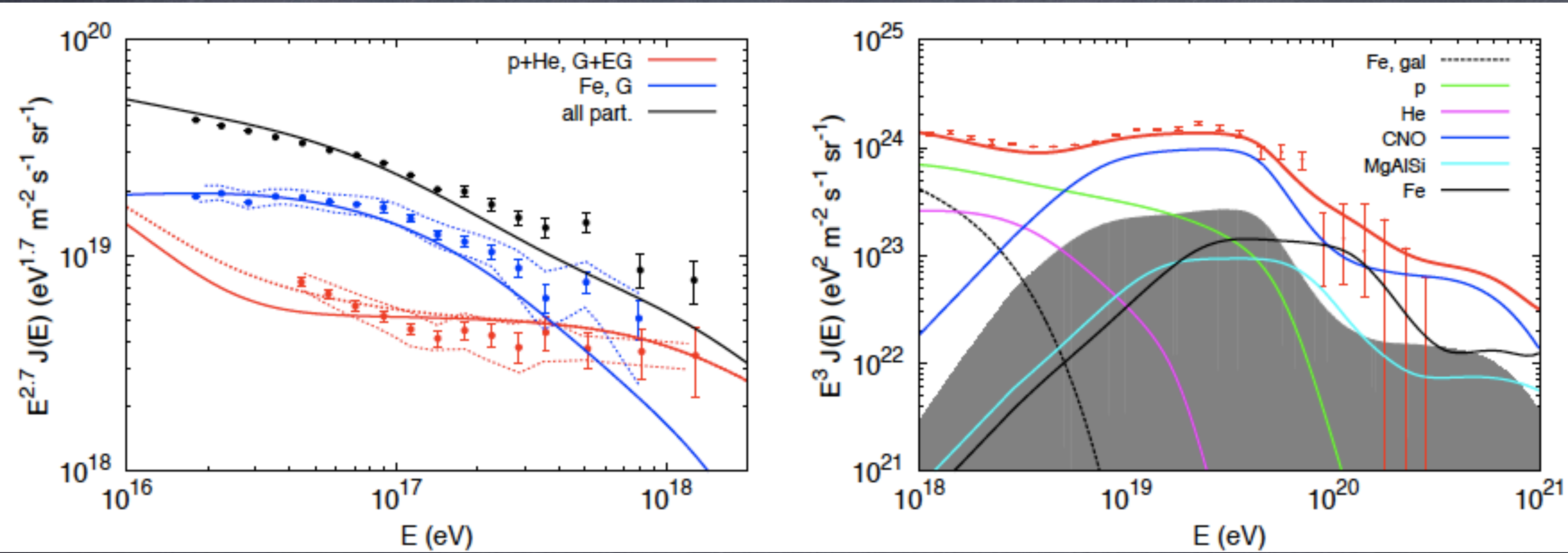


THE REQUIRED ADDITIONAL LIGHT COMPONENT MUST HAVE A STEEP SPECTRUM AND A CUTOFF AT ~10^{19} eV

TRANSITION AND UHECR

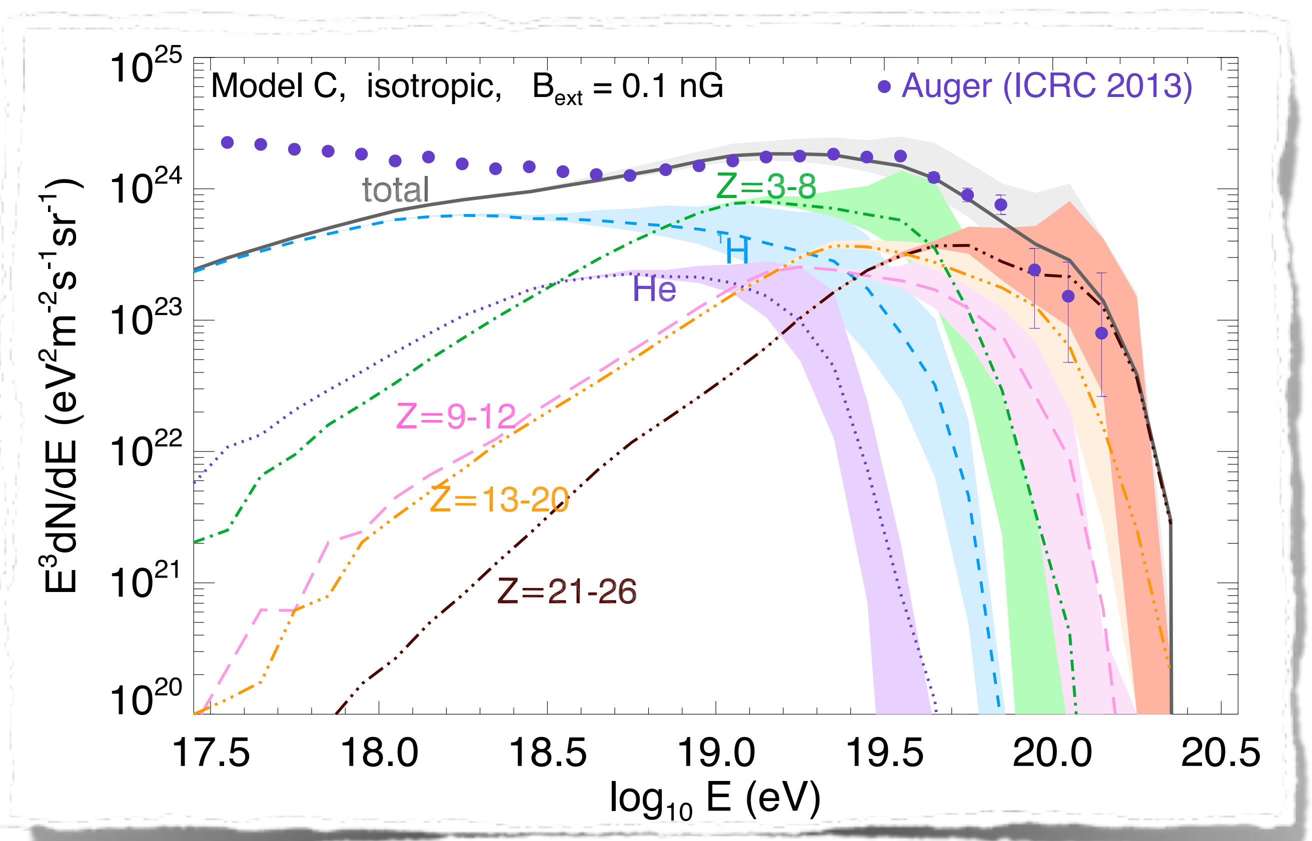
Additional Extragalactic Component and KASCADE-Grande

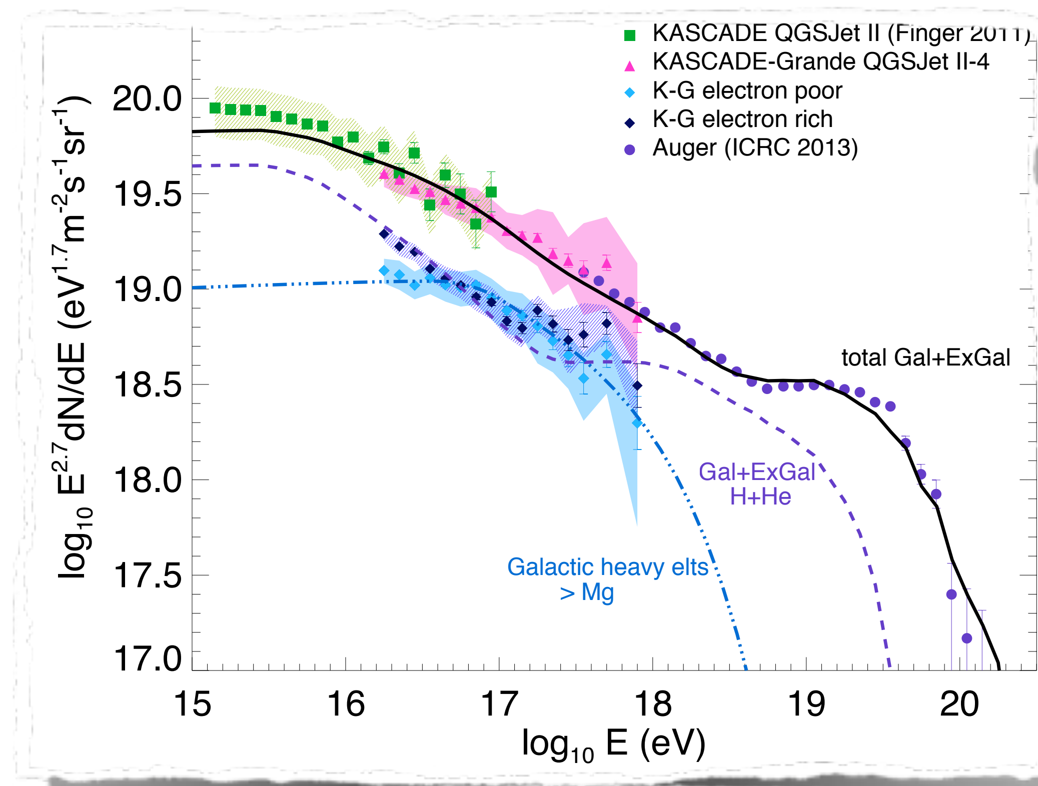
Aloisio, Berezinsky & PB 2014



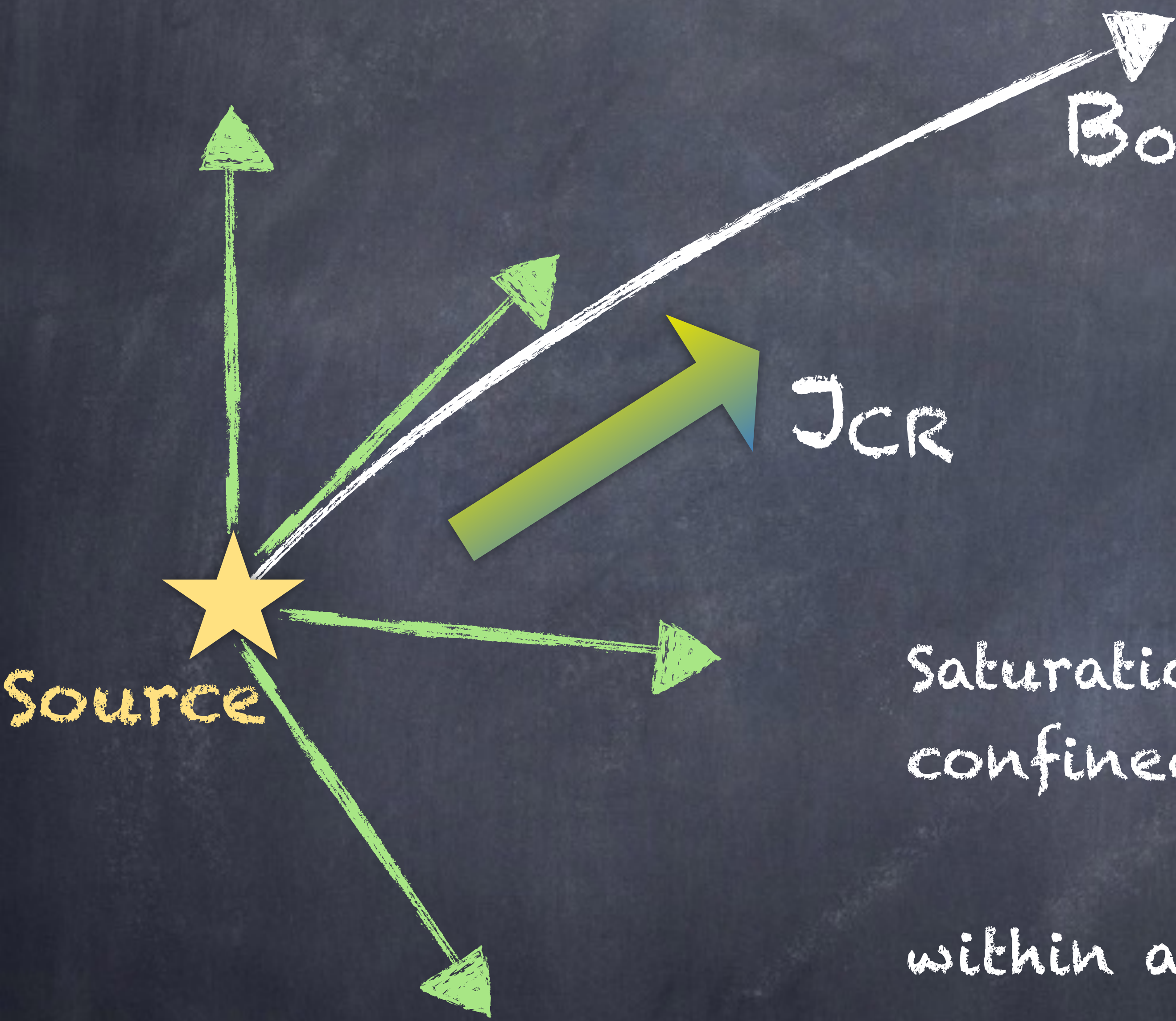
A physical model

Globus et al. and Unger et al. (2015) propose a similar idea: spectra of nuclei appear hard because at low energies photo disintegration inside sources has been at work





CR self-confinement



The electric current due to escaping CR leads to excitation of a non-resonant instability

[PB+, 2015, Phys. Rev. Lett. 115, 121101]

Saturation of the instability -> CR self-confined around the source if

$$E<E_c \sim 10^7 \text{ GeV } L_{44}^{2/3}$$

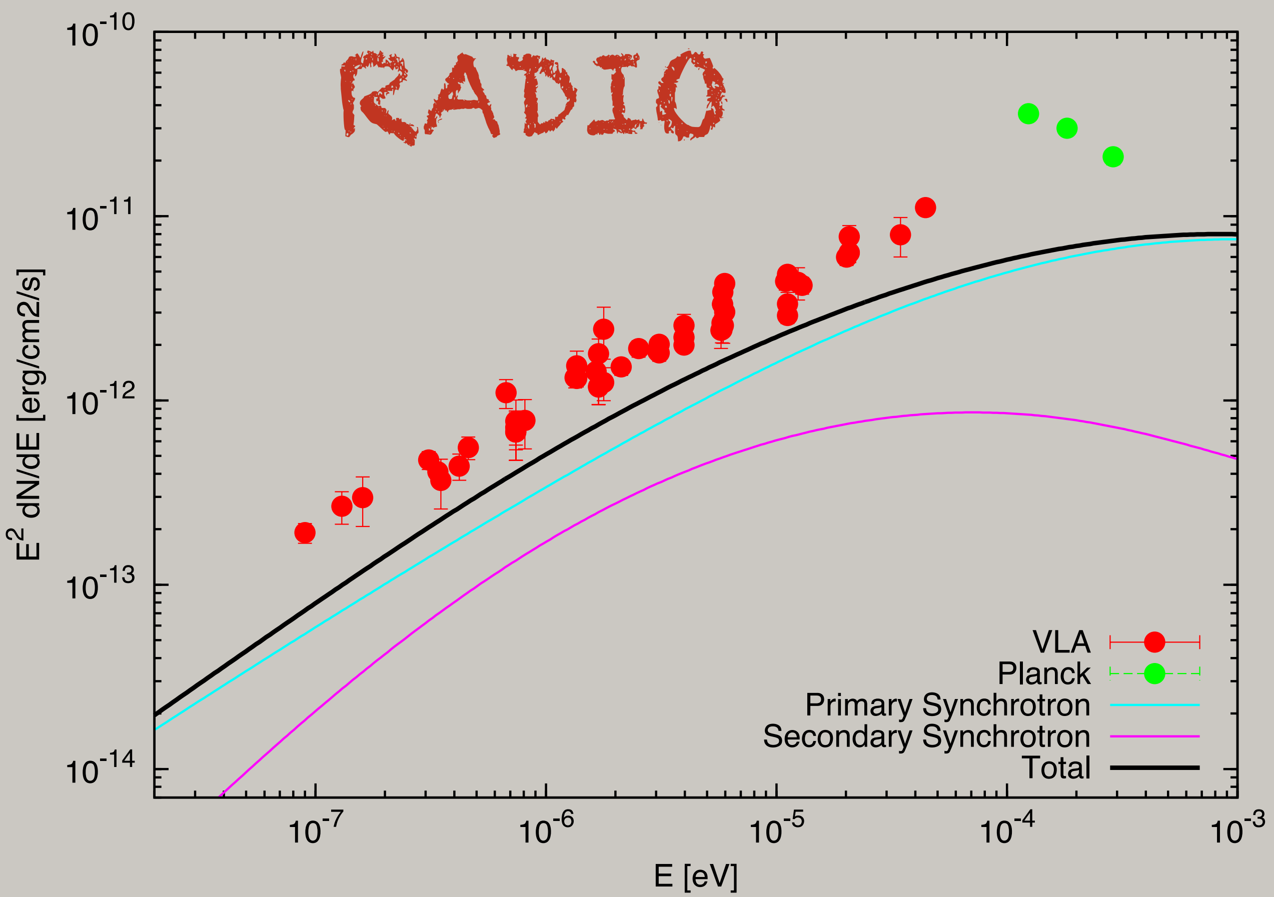
within a distance

$$r_{max} \sim 3.8 \text{ Mpc } L_{44}^{1/6}$$

THESE CR DO NOT REACH THE EARTH AND MORE SO IF THE SOURCE IS BRIGHT

The case of W44

New calculation of CR reacceleration and compression using Voyager+AMS-02 CR data for H and He (Cardillo et al. 2015)



Cardillo, PB & Amato 2015

Both radio and gamma ray data appear to be perfectly well fitted if Galactic CRs are reaccelerated and compressed (Blandford & Cowie 1982)… The same conclusion previously reached by Uchiyama et al. 2010 and Lee et al. 2015, though with CR spectrum not normalised to Voyager and with no He + ad hoc steepening