CR SOURCES AND PROPAGATION MODELS

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PROLOGUE

This workshop is dedicated to discussions on the data and physics of cosmic ray composition between the knee and the ankle in the view of theoretical models for the transition from galactic to extragalactic origin of cosmic rays.

The reason we are here is that we can't make sense of some pieces of observations

... because observations see things that require theory to go beyond the obvious

... and because observations provide conflicting info, which raises the problem of systematic uncertainties

BUT ESPECIALLY, WE REALIZED THE STRONGLY INTERCONNECTED NATURE OF THE PROBLEM (YOU CAN'T DO UHECR WITHOUT UNDERSTANDING GALACTIC CR)

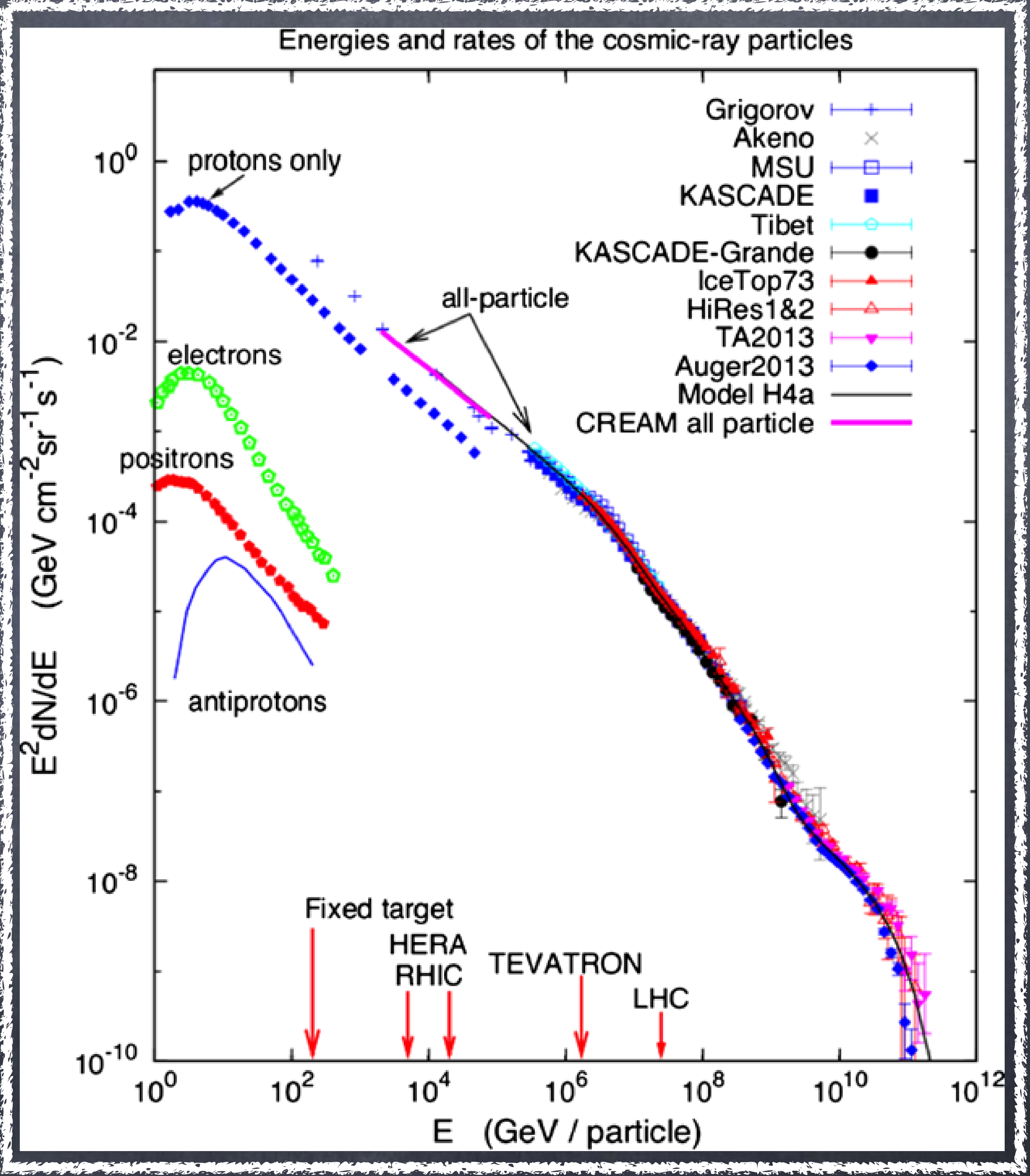
CR Spectrum

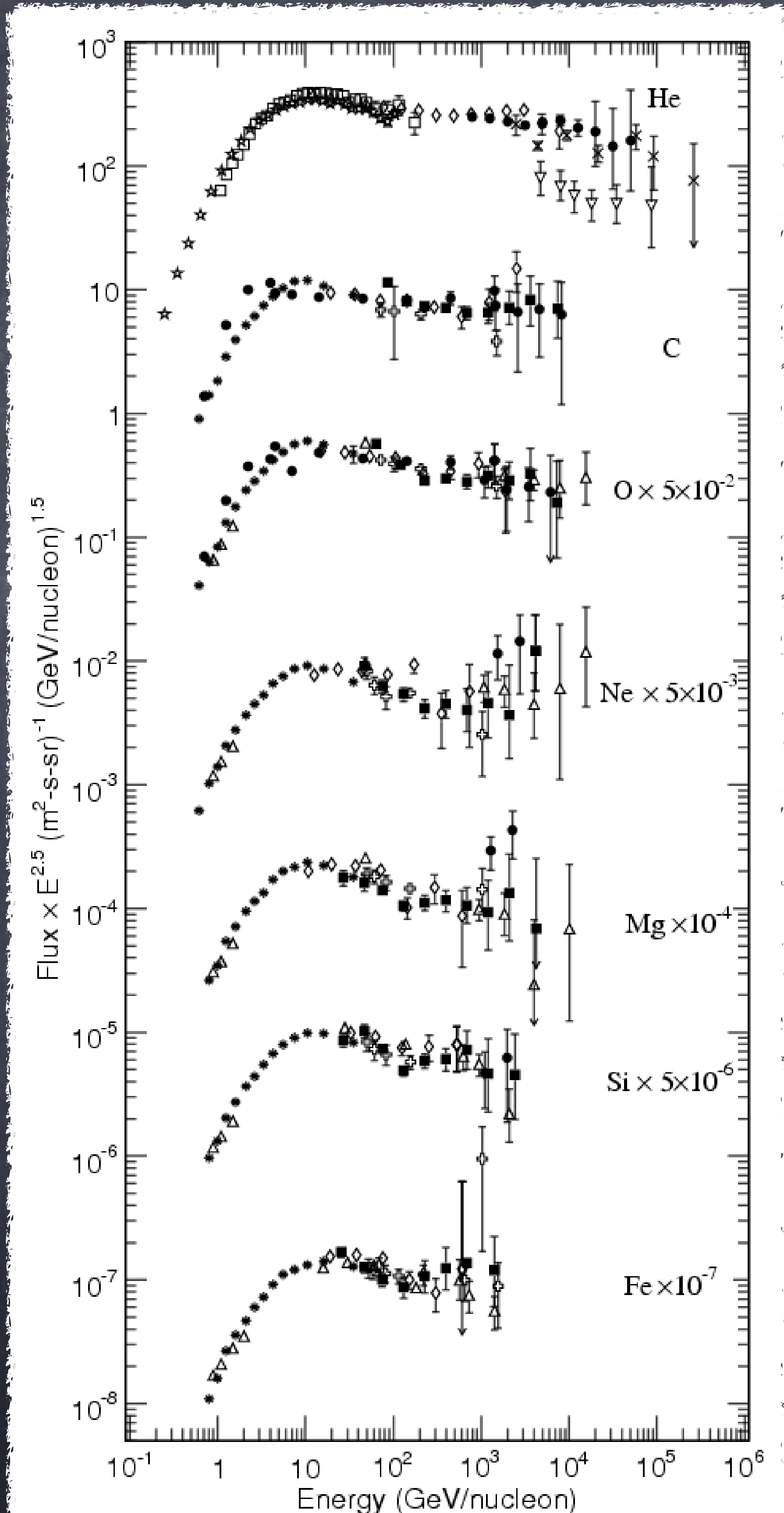
From afar the spectrum looks like a power law

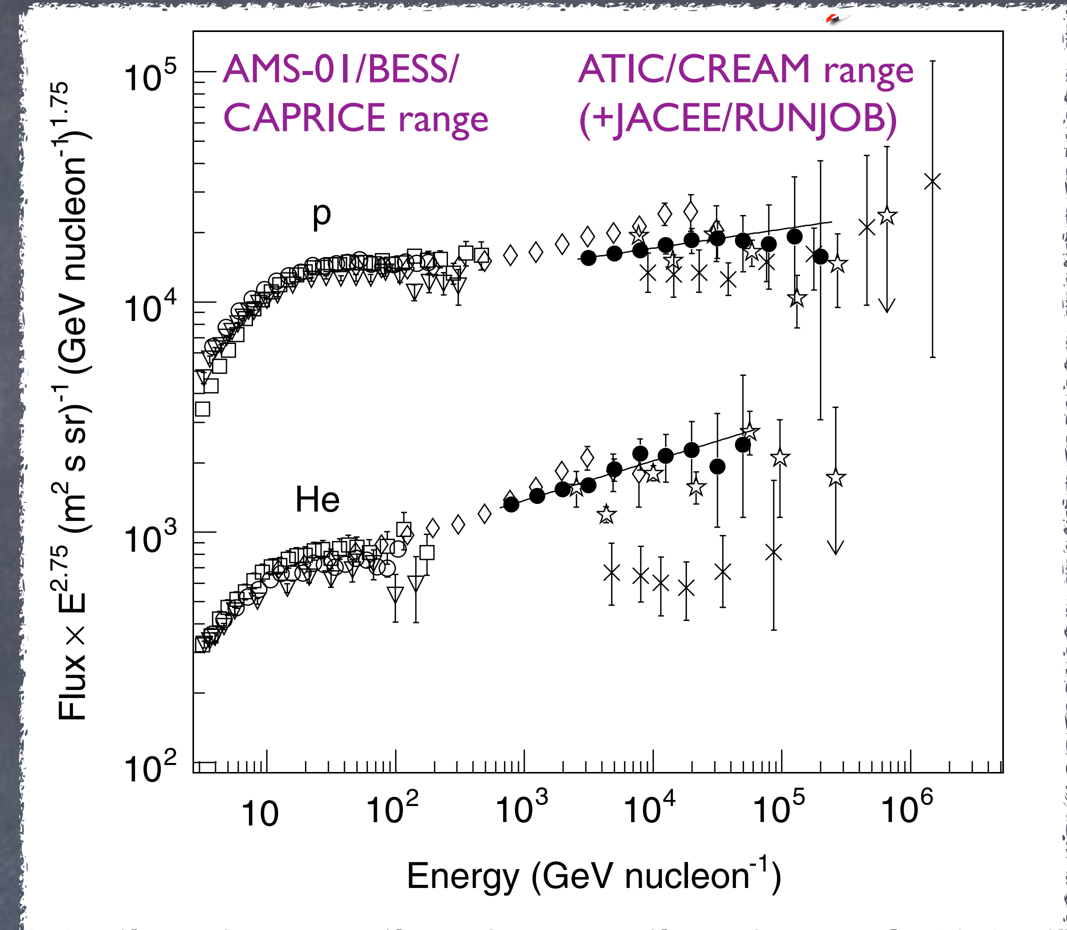
Scale free physics ?

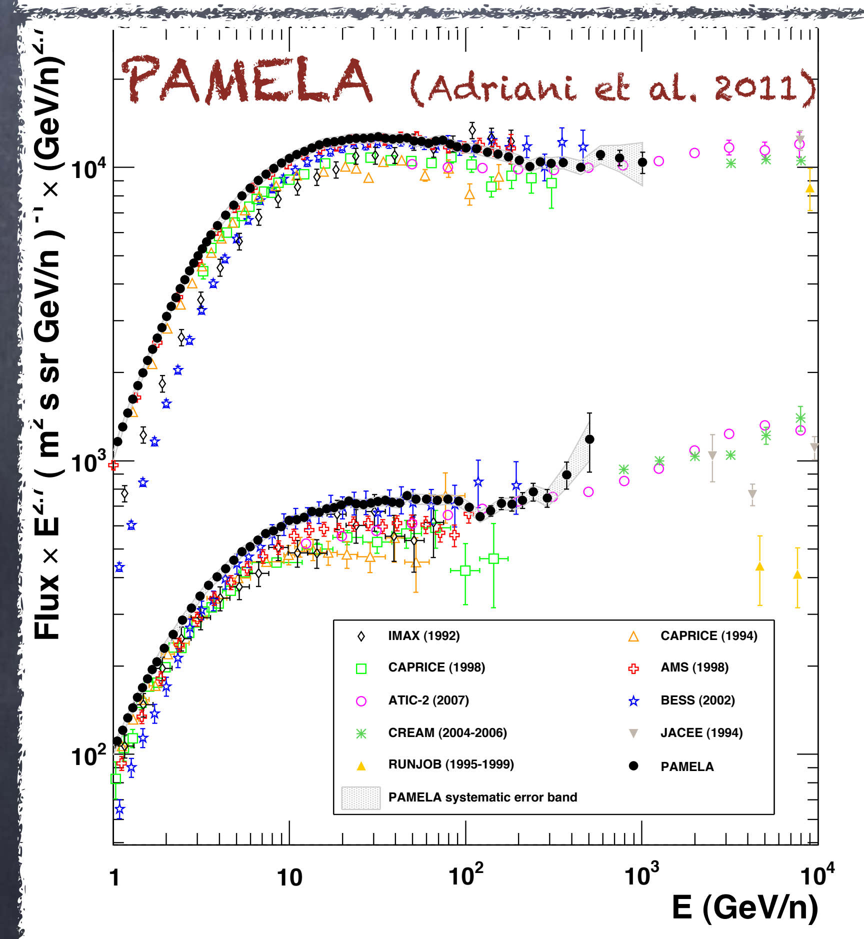
Broken power laws more interesting (scale->physics)

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



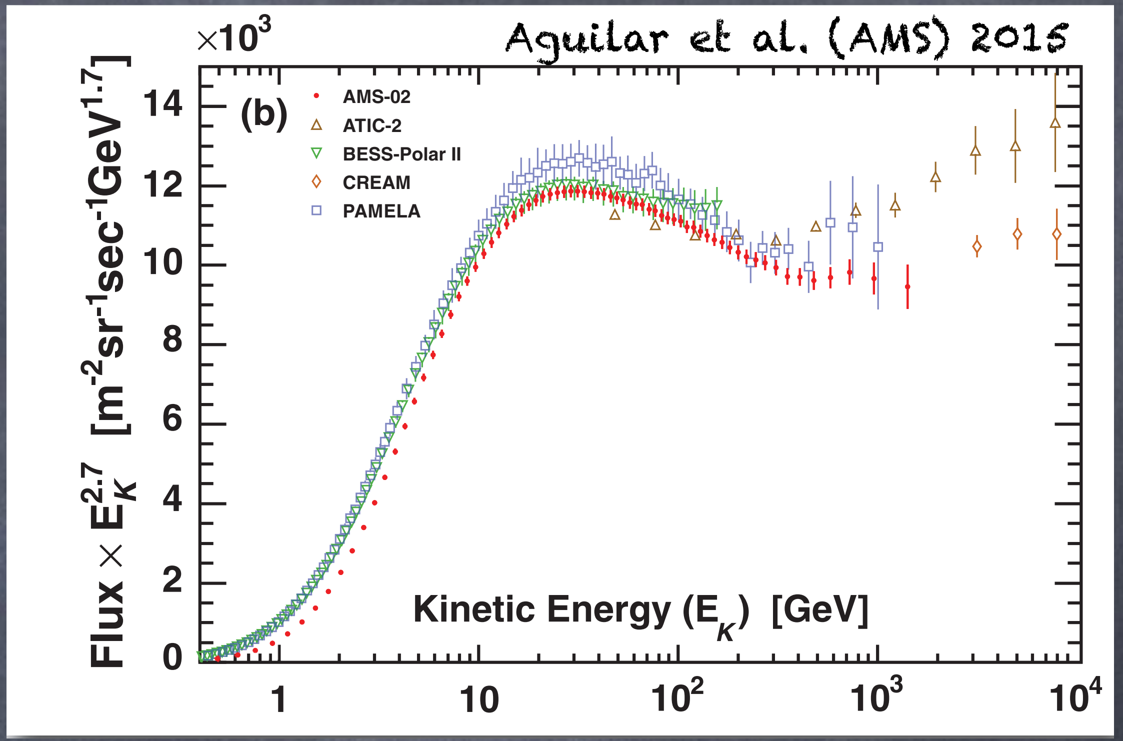

He
C
O × 5×10⁻²
Ne × 5×10⁻³
Mg ×10⁻⁴
Si × 5×10⁻⁶
Fe ×10⁻⁷
Flux × E^2.5 (m²-s-sr)⁻¹ (GeV/nucleon)^1.5
Energy (GeV/nucleon)

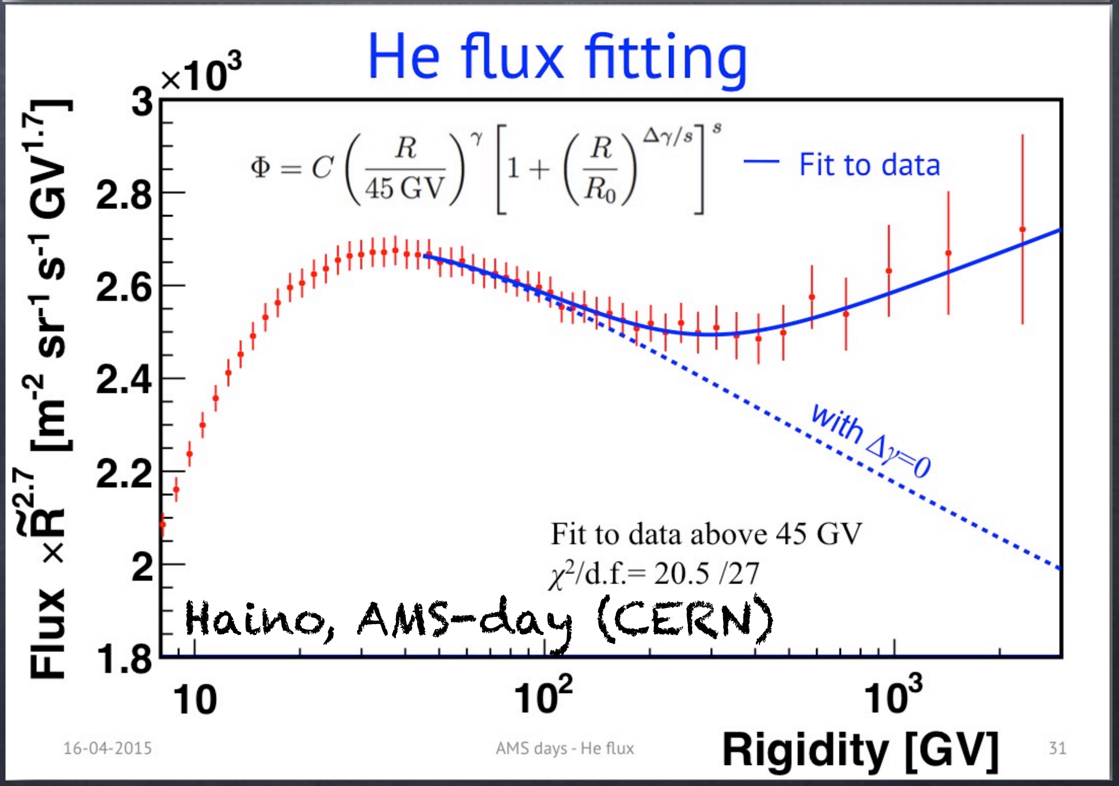

AMS-01/BESS/
CAPRICE range
ATIC/CREAM range
(+JACEE/RUNJOB)
p
He
Flux × E^2.75 (m² s sr)⁻¹ (GeV nucleon⁻¹)^1.75
Energy (GeV nucleon⁻¹)


PAMELA (Adriani et al. 2011)
IMAX (1992)
CAPRICE (1994)
CAPRICE (1998)
AMS (1998)
ATIC-2 (2007)
BESS (2002)
CREAM (2004-2006)
JACEE (1994)
RUNJOB (1995-1999)
PAMELA
PAMELA systematic error band
E (GeV/n)

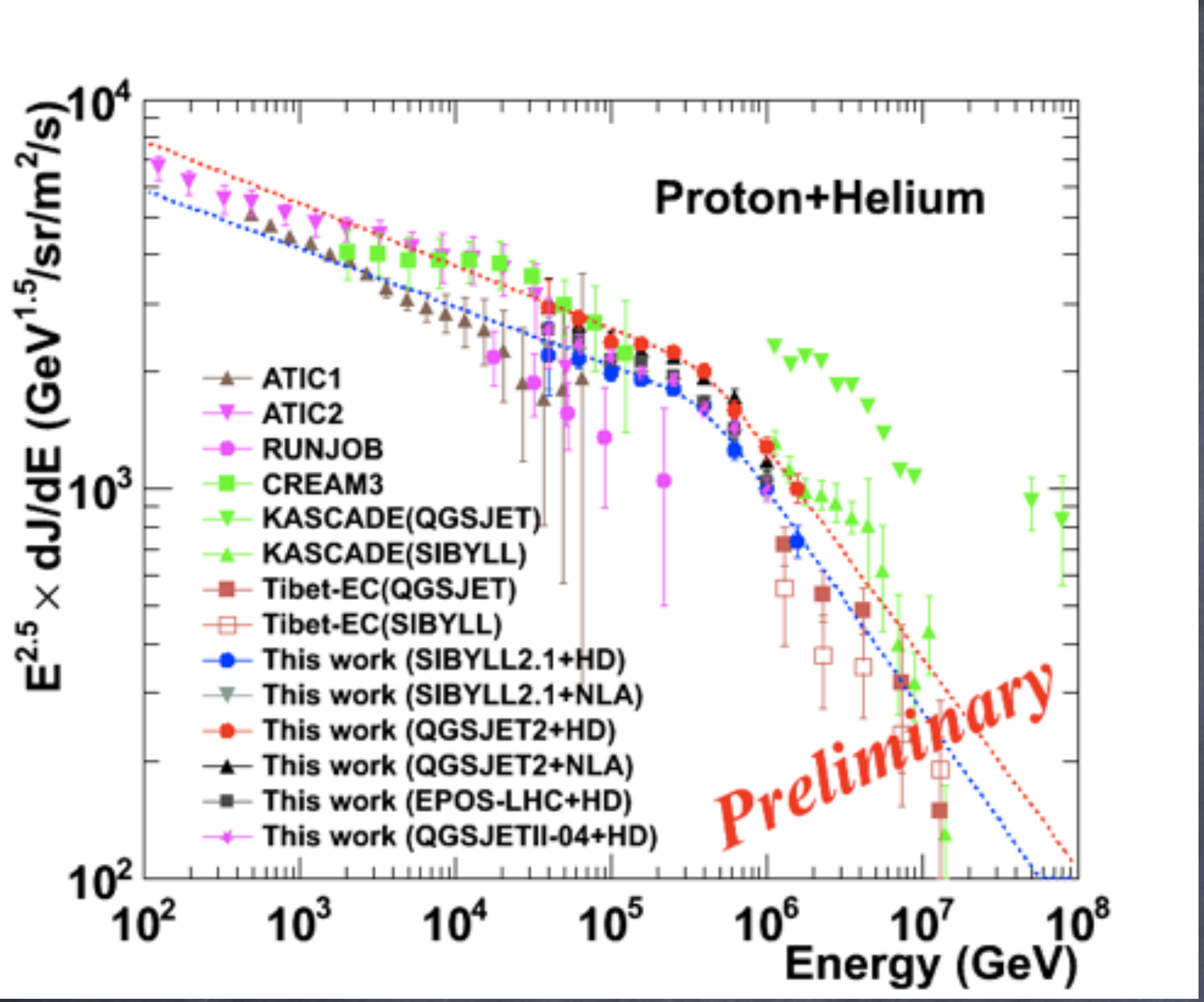
AMS-02 confirmation

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

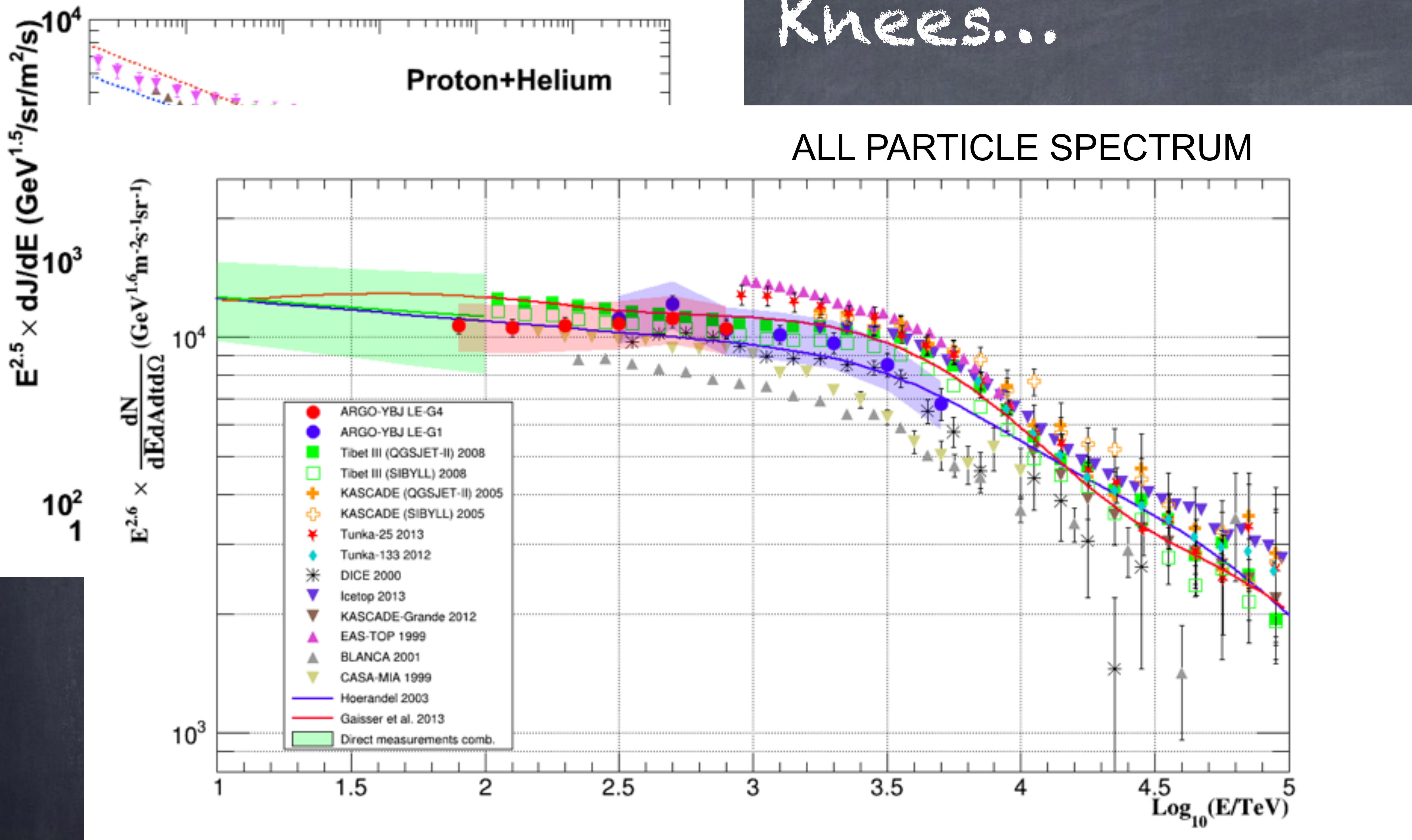




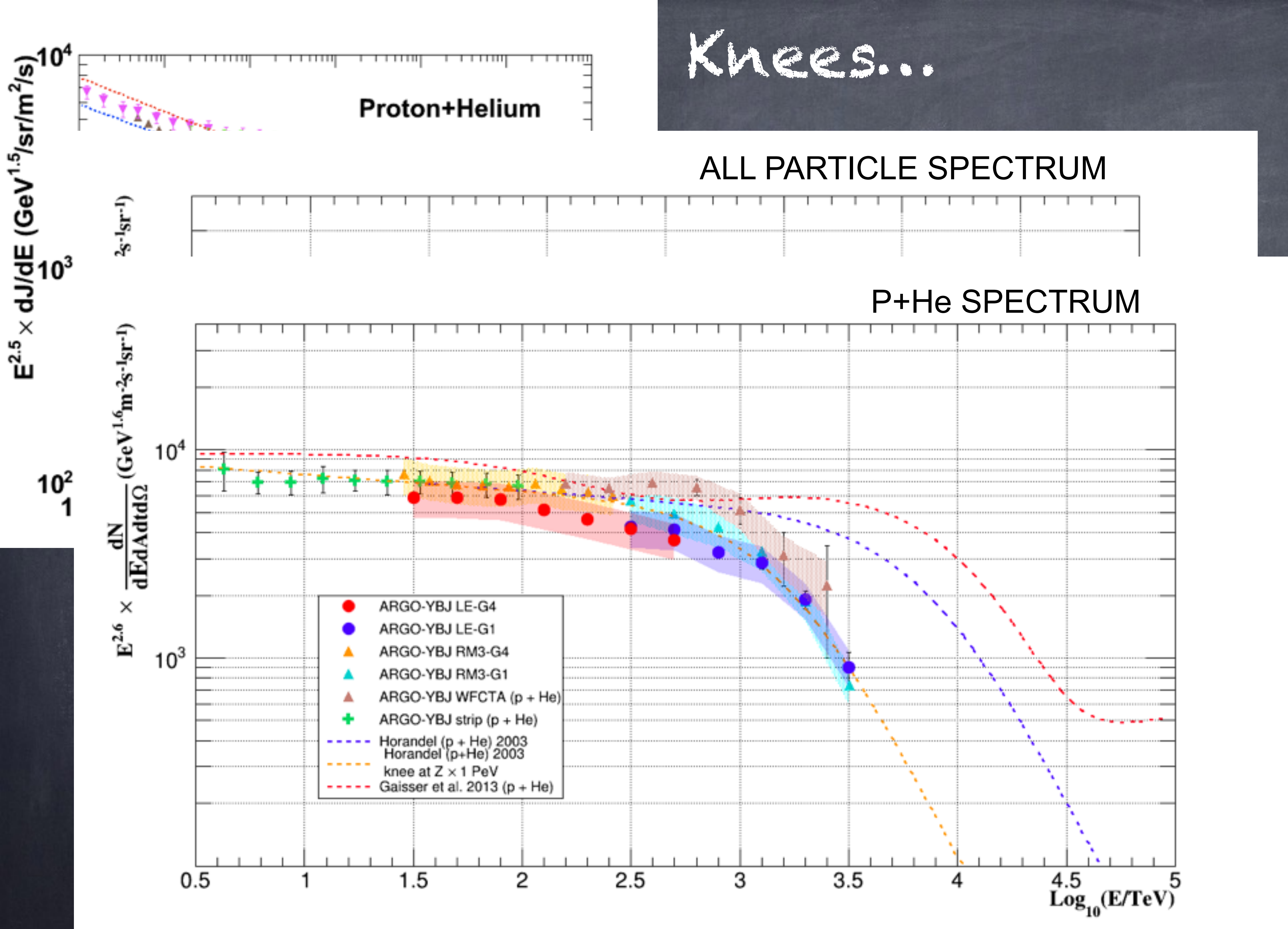
Knees...


Proton+Helium
ATIC1
ATIC2
RUNJOB
CREAM3
KASCADE(QGSJET)
KASCADE(SIBYLL)
Tibet-EC(QGSJET)
Tibet-EC(SIBYLL)
This work (SIBYLL2.1+HD)
This work (SIBYLL2.1+NLA)
This work (QGSJET2+HD)
This work (QGSJET2+NLA)
This work (EPOS-LHC+HD)
This work (QGSJETII-04+HD)
Preliminary
$E^{2.5} \times dJ/dE$ (GeV$^{1.5}$/sr/m^2/s)
Energy (GeV)

Knees...

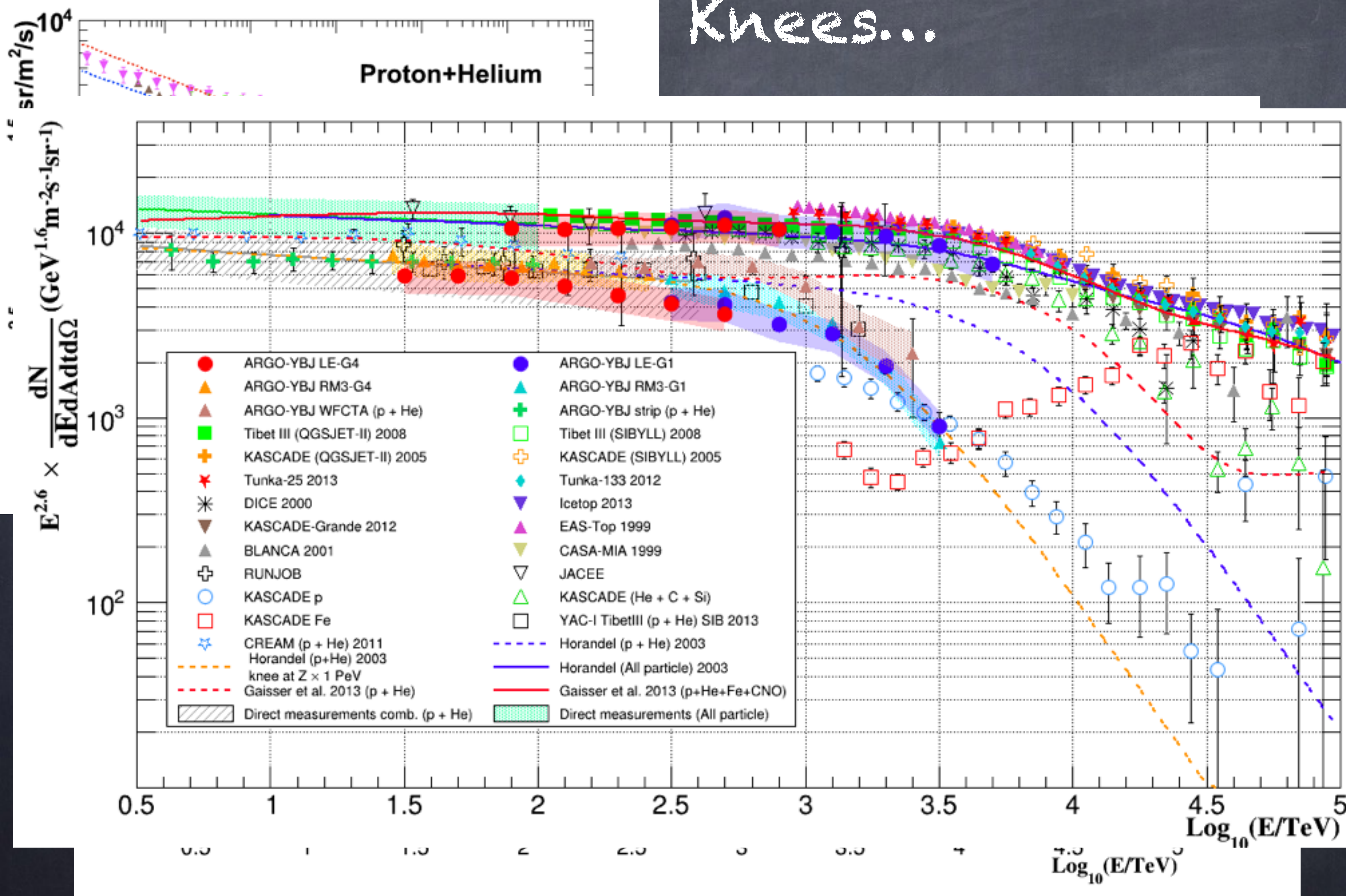

Proton+Helium
$E^{2.5} \times dJ/dE$ (GeV$^{1.5}$/sr/m^2/s)
10^4
10^3
10^2
1
ALL PARTICLE SPECTRUM
$E^{2.6} \times \frac{dN}{dEdAdtd\Omega}$ (GeV$^{1.6}$m^{-2}s^{-1}sr^{-1})
10^4
10^3
1
1.5
2
2.5
3
3.5
4
4.5
5
Log$_{10}$(E/TeV)
ARGO-YBJ LE-G4
ARGO-YBJ LE-G1
Tibet III (QGSJET-II) 2008
Tibet III (SIBYLL) 2008
KASCADE (QGSJET-II) 2005
KASCADE (SIBYLL) 2005
Tunka-25 2013
Tunka-133 2012
DICE 2000
Icetop 2013
KASCADE-Grande 2012
EAS-TOP 1999
BLANCA 2001
CASA-MIA 1999
Hoerandel 2003
Gaisser et al. 2013
Direct measurements comb.

Knees...



Proton+Helium
$E^{2.5} \times dJ/dE$ (GeV$^{1.5}$/sr/m^2/s)
10^4
10^3
10^2
1
ALL PARTICLE SPECTRUM
P+He SPECTRUM
$E^{2.6} \times \frac{dN}{dEdAdtd\Omega}$ (GeV$^{1.6}$m^{-2}s^{-1}sr^{-1})
ARGO-YBJ LE-G4
ARGO-YBJ LE-G1
ARGO-YBJ RM3-G4
ARGO-YBJ RM3-G1
ARGO-YBJ WFCTA (p + He)
ARGO-YBJ strip (p + He)
Horandel (p + He) 2003
Horandel (p+He) 2003
knee at Z × 1 PeV
Gaisser et al. 2013 (p + He)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Log_{10}(E/TeV)

Knees...

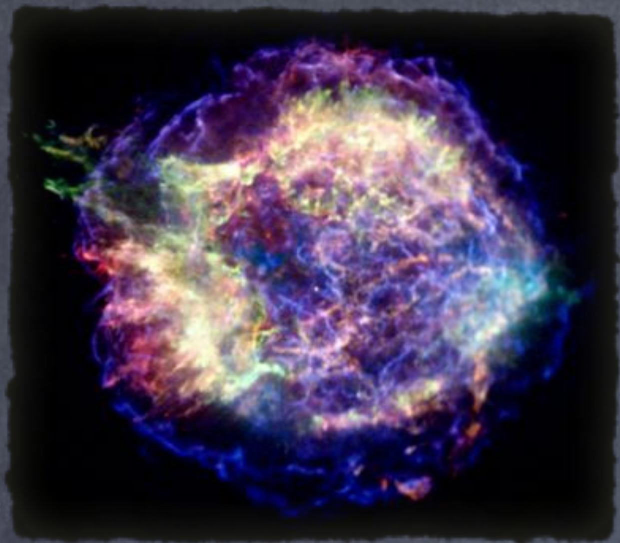


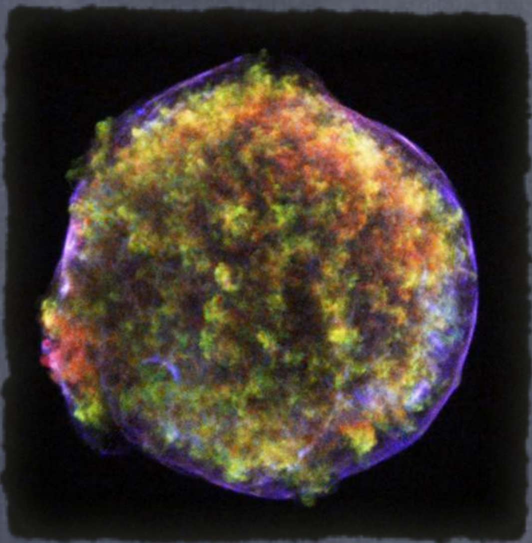
Proton+Helium
$E^{2.6} \times \frac{dN}{dEdAdtd\Omega}$ (GeV$^{1.6}$m^{-2}s^{-1}sr^{-1})
10^4
10^3
10^2
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Log$_{10}$(E/TeV)
ARGO-YBJ LE-G4
ARGO-YBJ LE-G1
ARGO-YBJ RM3-G4
ARGO-YBJ RM3-G1
ARGO-YBJ WFCTA (p + He)
ARGO-YBJ strip (p + He)
Tibet III (QGSJET-II) 2008
Tibet III (SIBYLL) 2008
KASCADE (QGSJET-II) 2005
KASCADE (SIBYLL) 2005
Tunka-25 2013
Tunka-133 2012
DICE 2000
Icetop 2013
KASCADE-Grande 2012
EAS-Top 1999
BLANCA 2001
CASA-MIA 1999
RUNJOB
JACEE
KASCADE p
KASCADE (He + C + Si)
KASCADE Fe
YAC-I TibetIII (p + He) SIB 2013
CREAM (p + He) 2011
Horandel (p + He) 2003
Horandel (p+He) 2003 knee at Z × 1 PeV
Horandel (All particle) 2003
Gaisser et al. 2013 (p + He)
Gaisser et al. 2013 (p+He+Fe+CNO)
Direct measurements comb. (p + He)
Direct measurements (All particle)

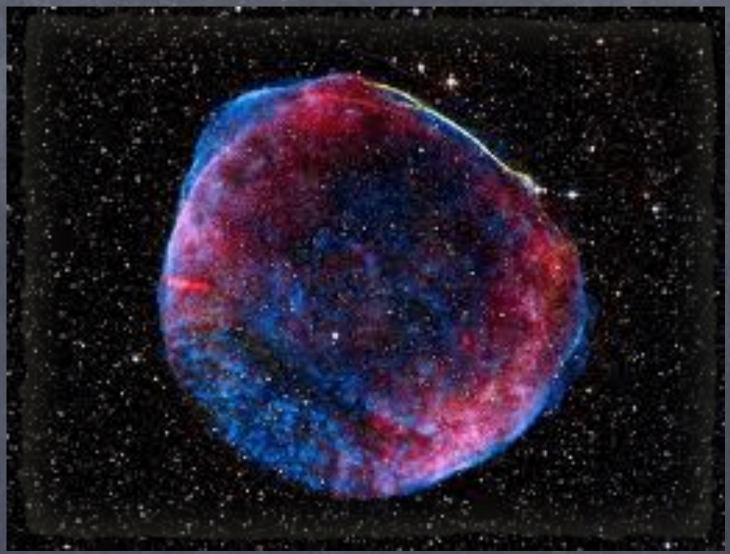
Sources of Galactic Cosmic Rays

- 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 a 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

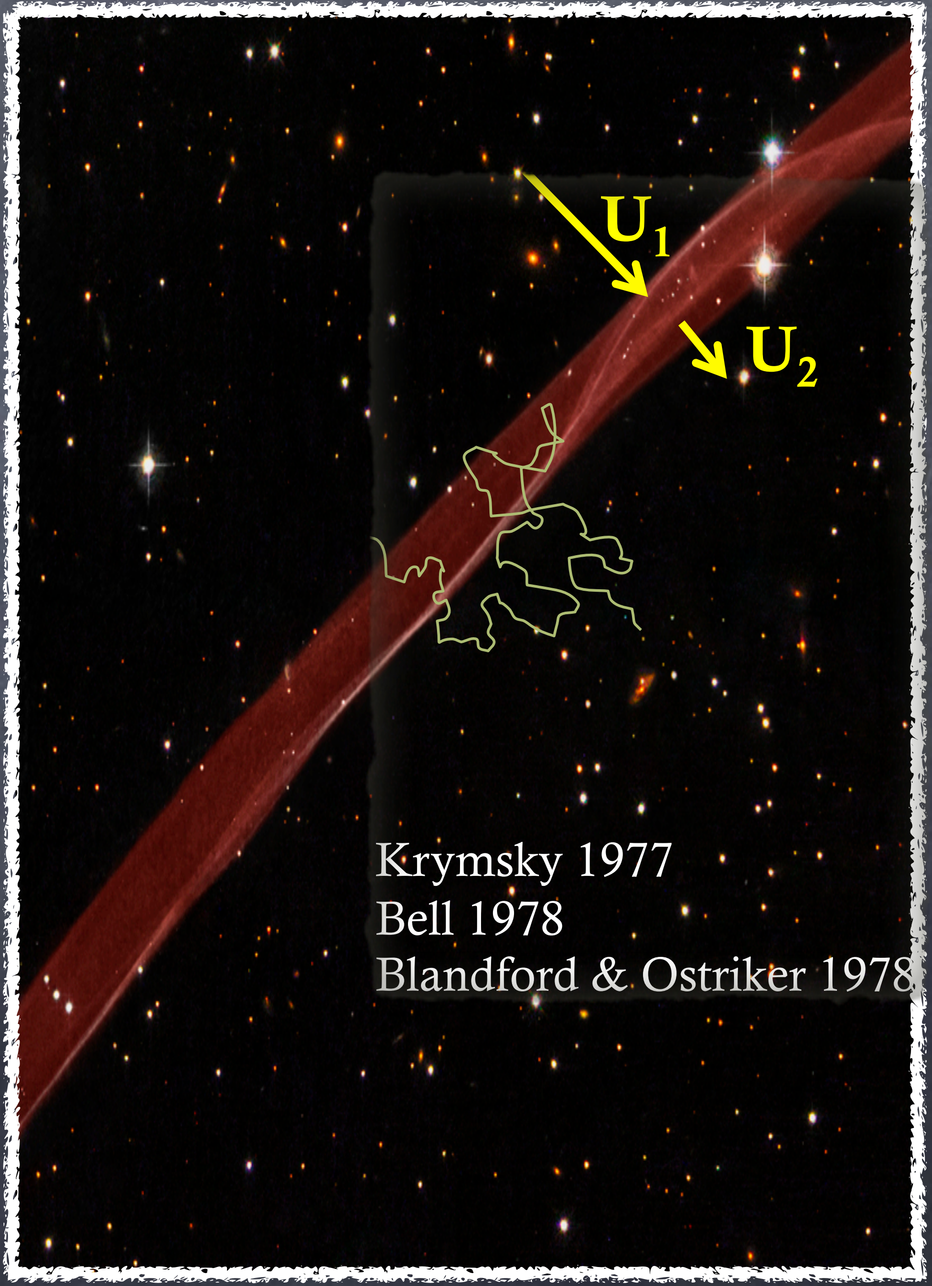
STRONG COLLISIONLESS SHOCK WAVE

DIFFUSIVE SHOCK ACCELERATION
Test Particle Approach

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

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

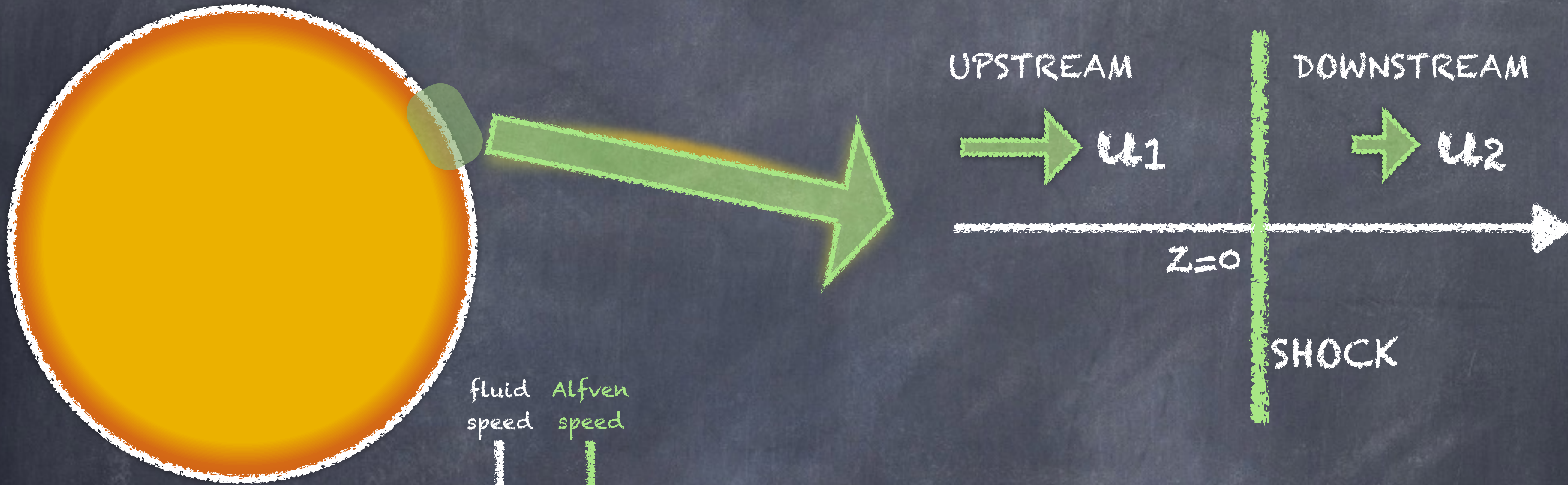
  - POWER LAW SPECTRUM
  - THE SPECTRAL SLOPE ONLY DEPENDS ON SHOCK COMPRESSION
  - INDEPENDENT OF THE DIFFUSION COEFFICIENT
  - FOR STRONG SHOCKS: E^{-2}



THE EFFICIENCY REQUIRED PER SNR ~10%: TEST PARTICLES?

FIRST NEED FOR A NON-LINEAR THEORY

TRANSPORT EQUATION AND DSA



fluid speed — Alfven speed

$$-\frac{\partial}{\partial z}\left[D(E)\frac{\partial f}{\partial z}\right] + (u + v_A)\frac{\partial f}{\partial z} + \frac{1}{3}\left(\frac{d(u+v_A)}{dz}\right)p\frac{\partial f}{\partial p} = A\delta(p - p_{inj})\delta(z)$$

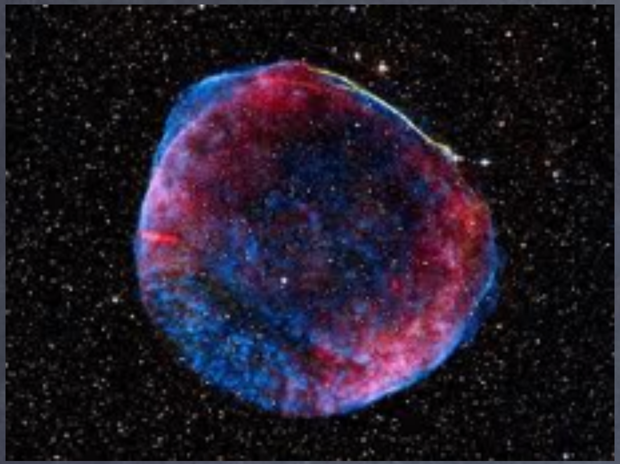
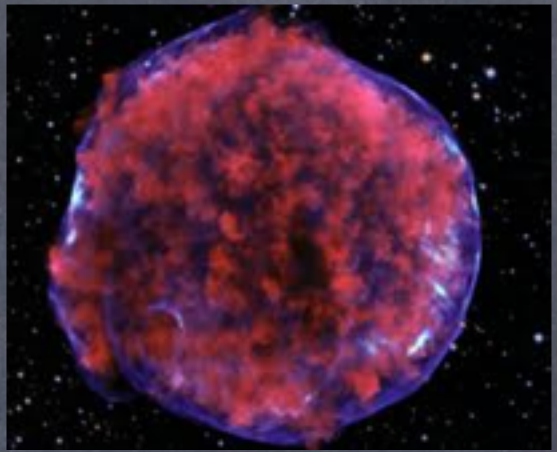
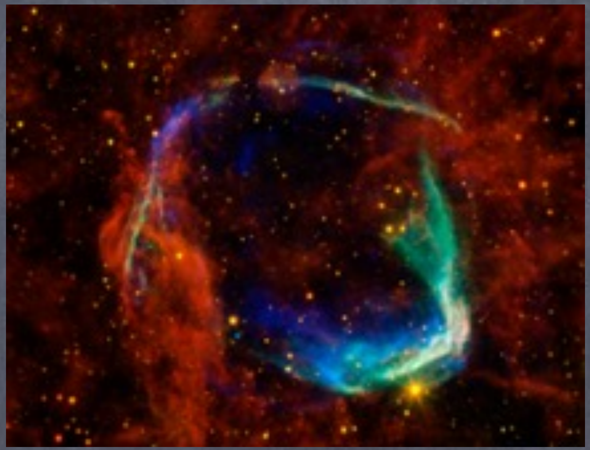
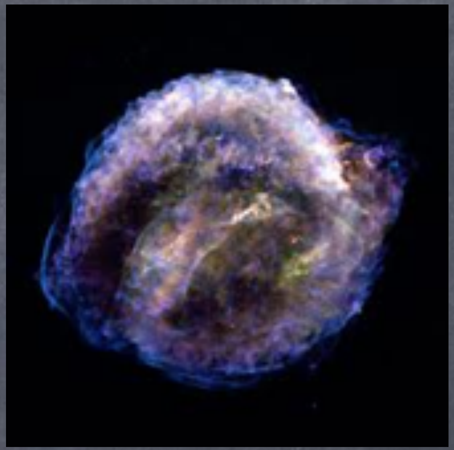
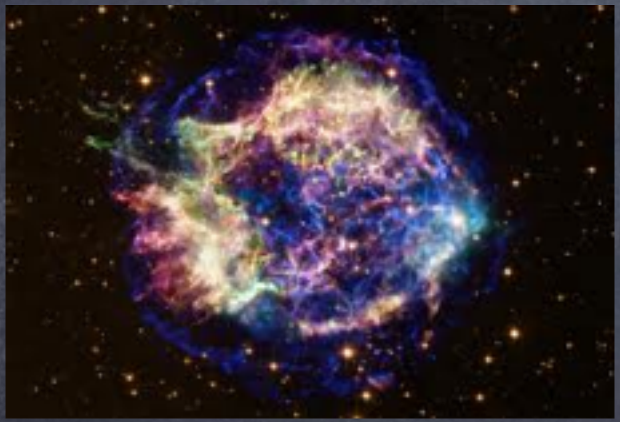
Integrating between 0^- and 0^+ and between $-\infty$ and z=0, one finds the usual result:

$$f_0(p) \propto p^{\frac{3r}{r-1}} \qquad r = \frac{u_1 - v_{A,1}}{u_2 + v_{A,2}} \approx \tilde{r}\left(1 - \frac{1}{M_A}\right)$$

COMPRESSION OF THE SCATTERING CENTERS → SPECTRUM

10 IF v_{A2}~0

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

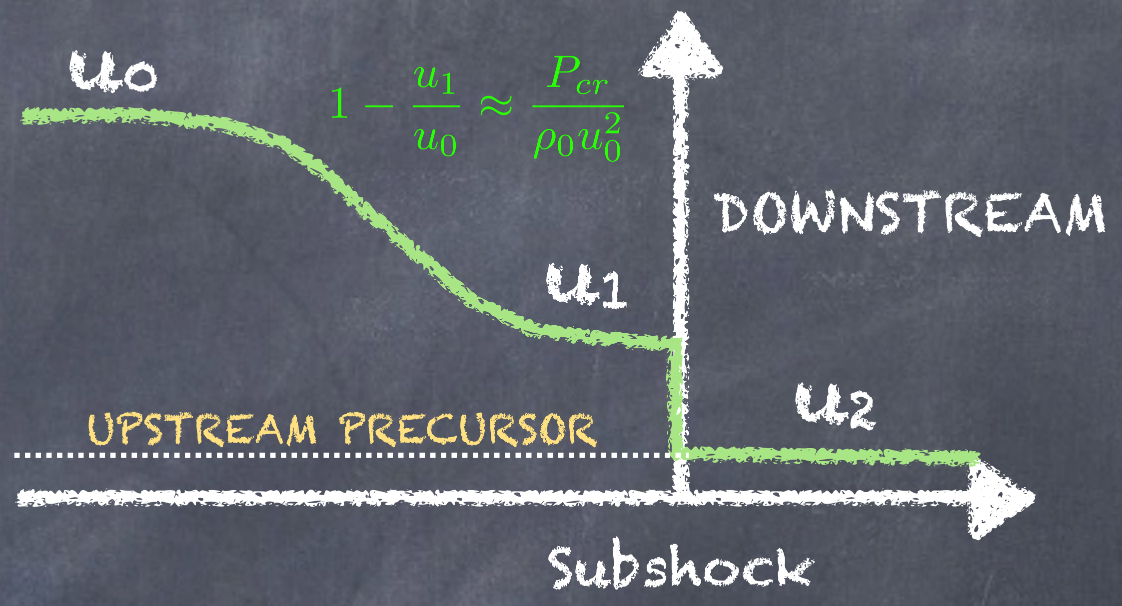
$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

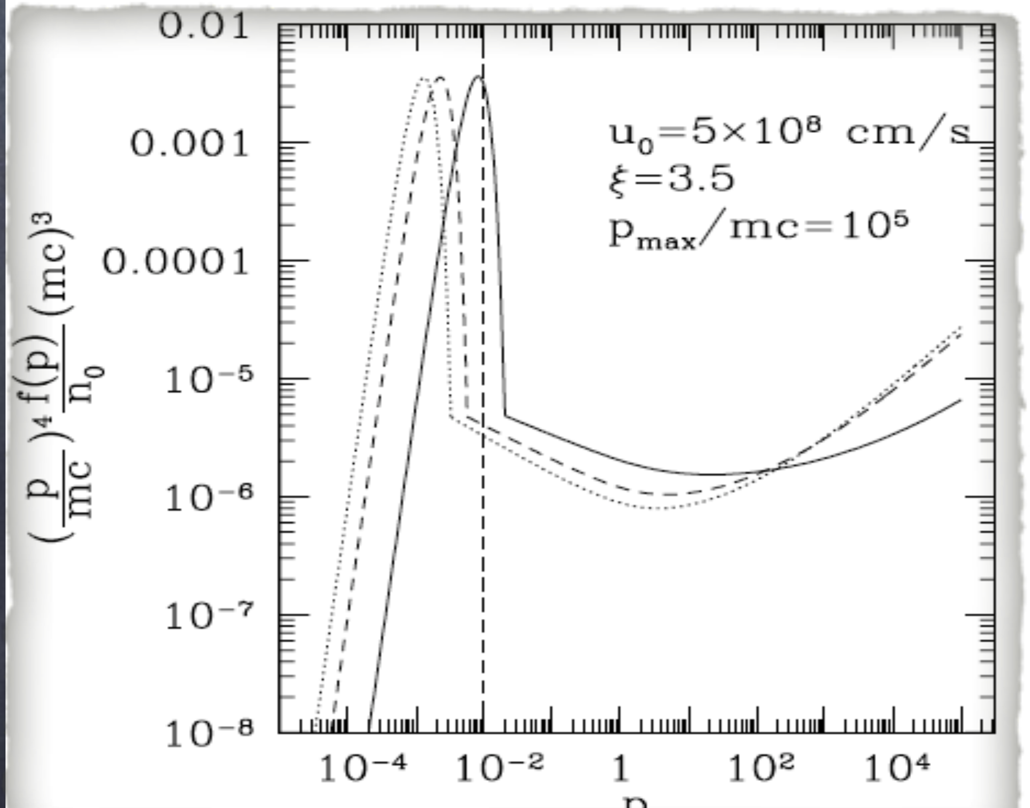
→ $B \sim 100\ B_{galaxy}$

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 FOR EFFICIENT SHOCK ACCELERATION
- EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT





PB, Gabici and Vannoni 2005

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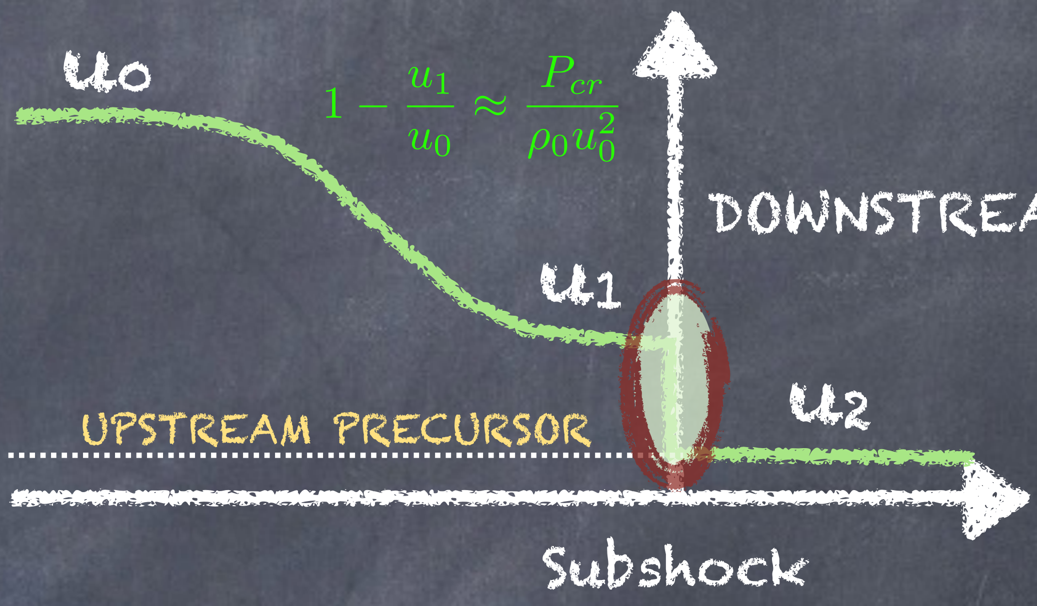

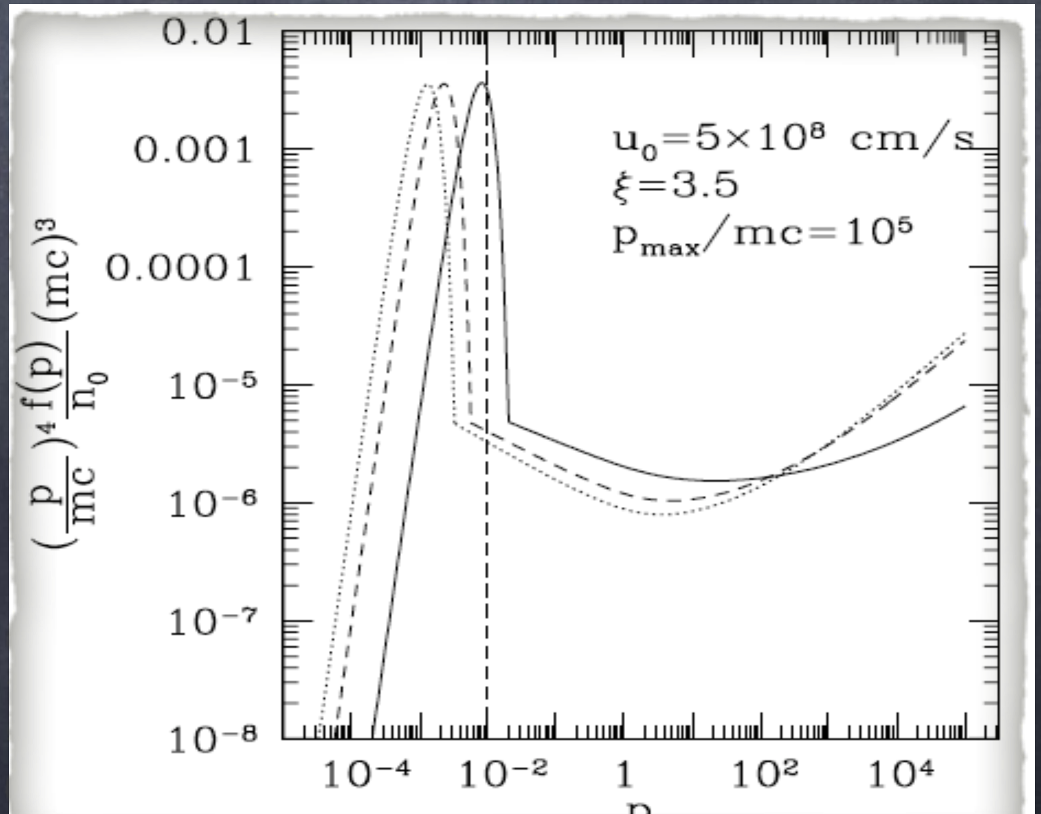

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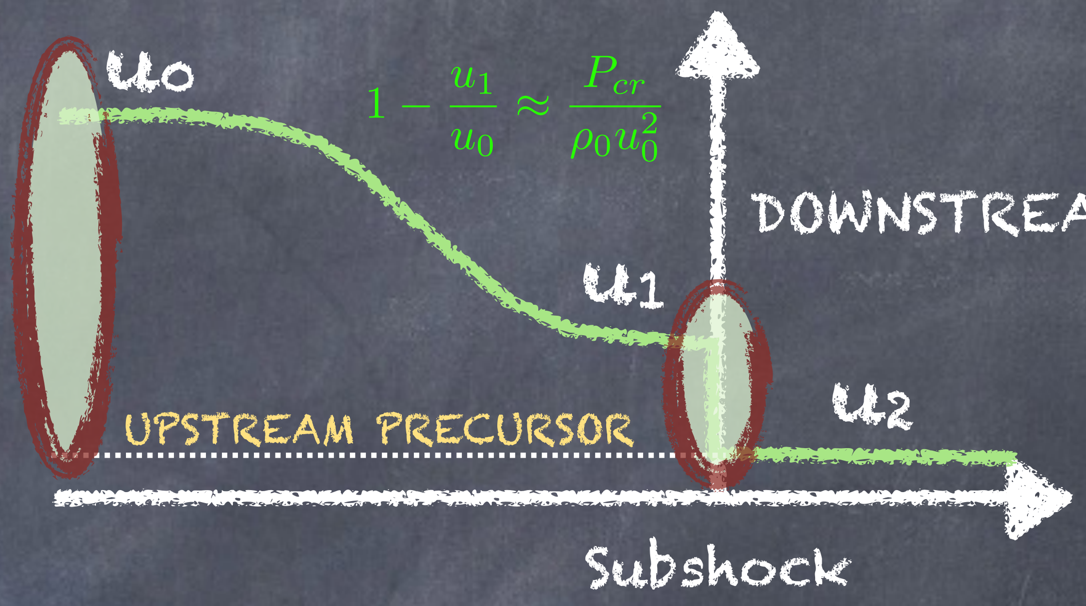

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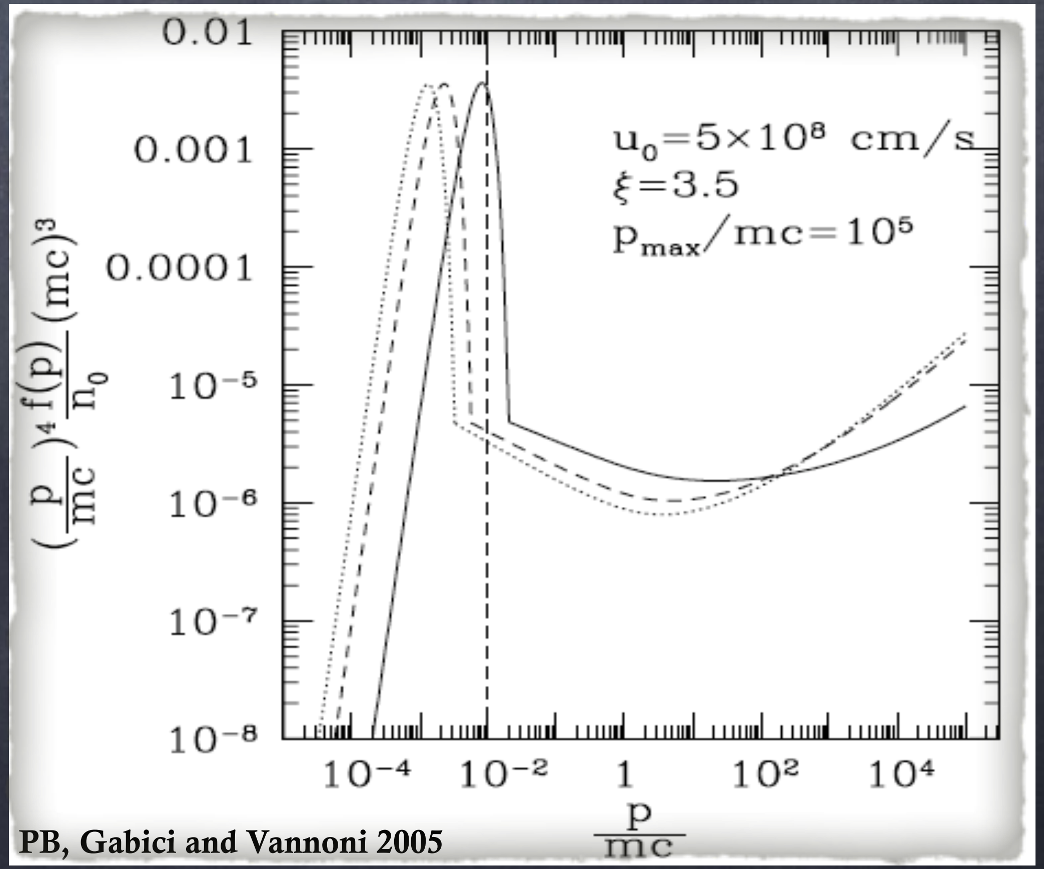
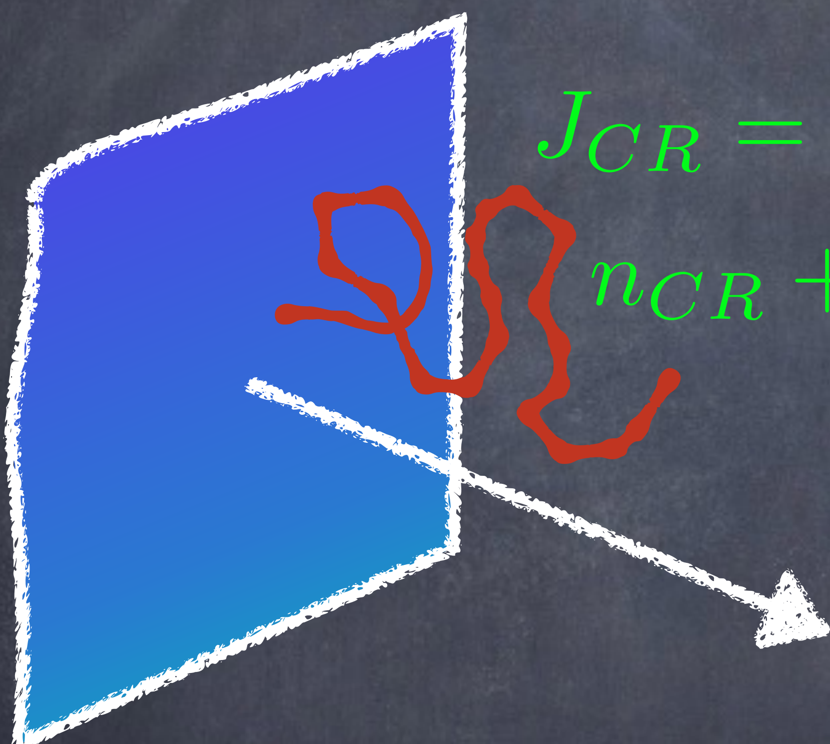


Basics of magnetic field amplification

The ever-lasting quest for E_{max}

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



$$J_{CR} = n_{CR} e v_{sh}$$

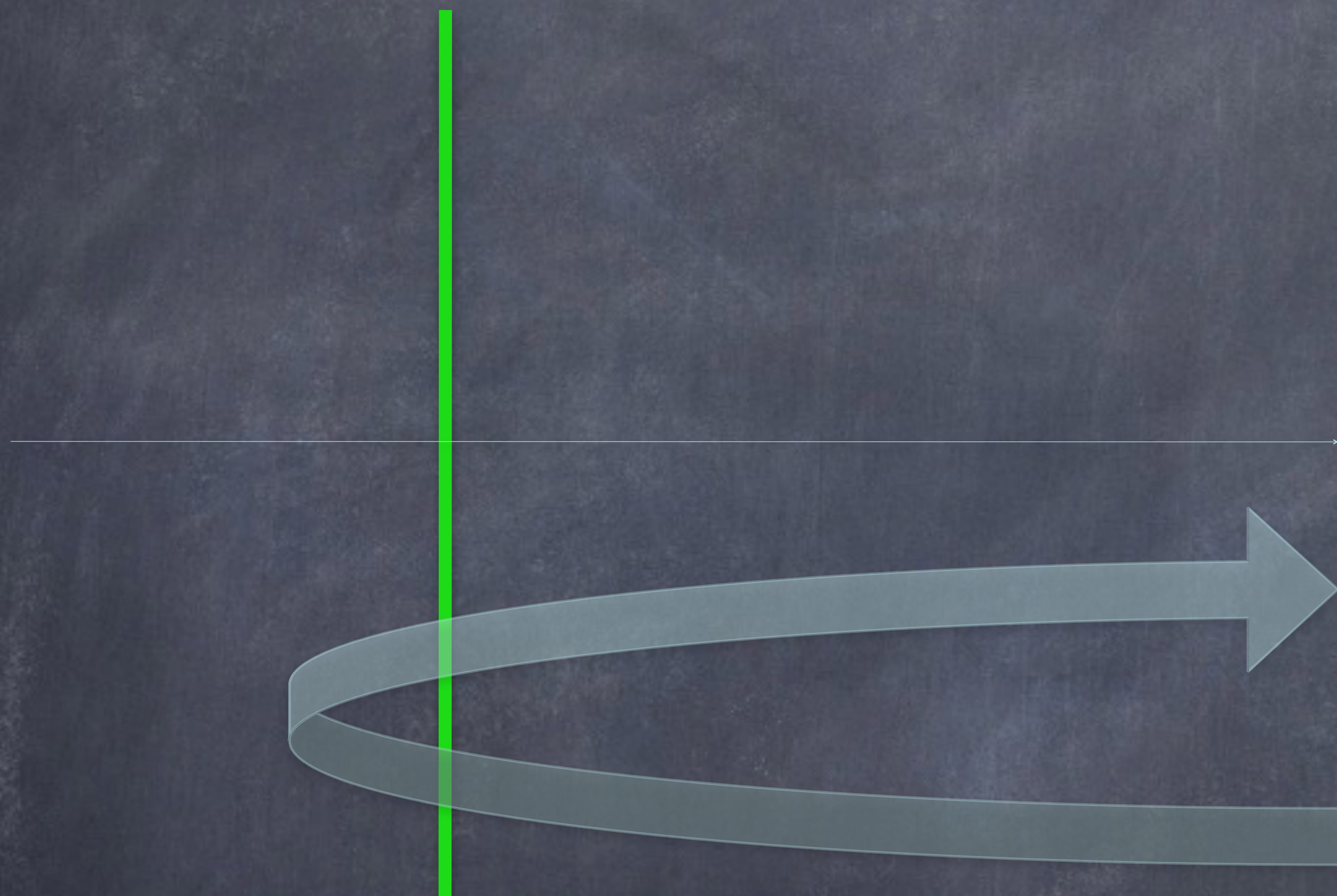
$$n_{CR} + n_i = n_e$$

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

THE CRUCIAL ROLE OF ESCAPING CR

Bell & Schure 2013
Cardillo, Amato & PB 2015



Escaping particles
Generating seed
turbulence

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Bell & Schure 2013
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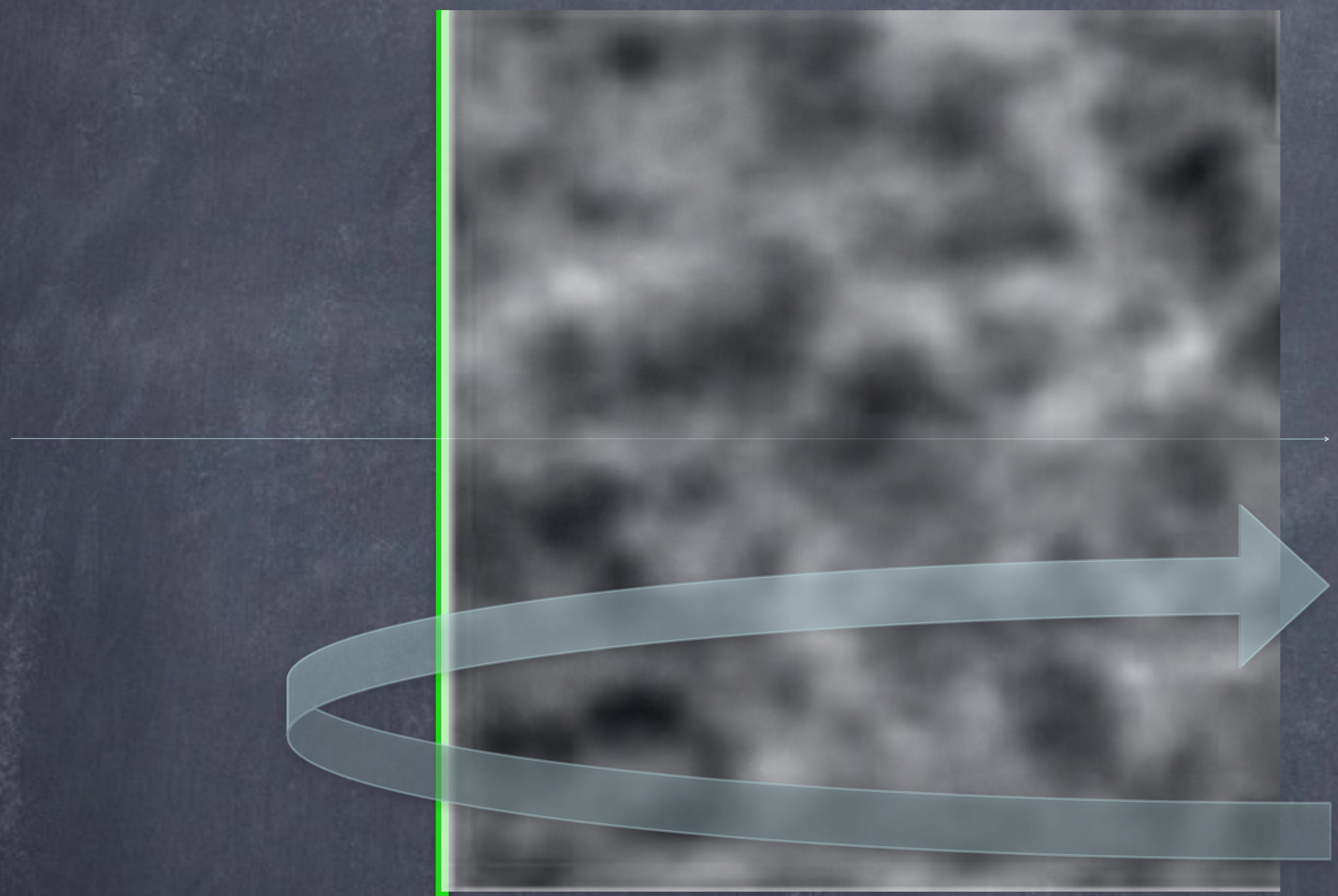

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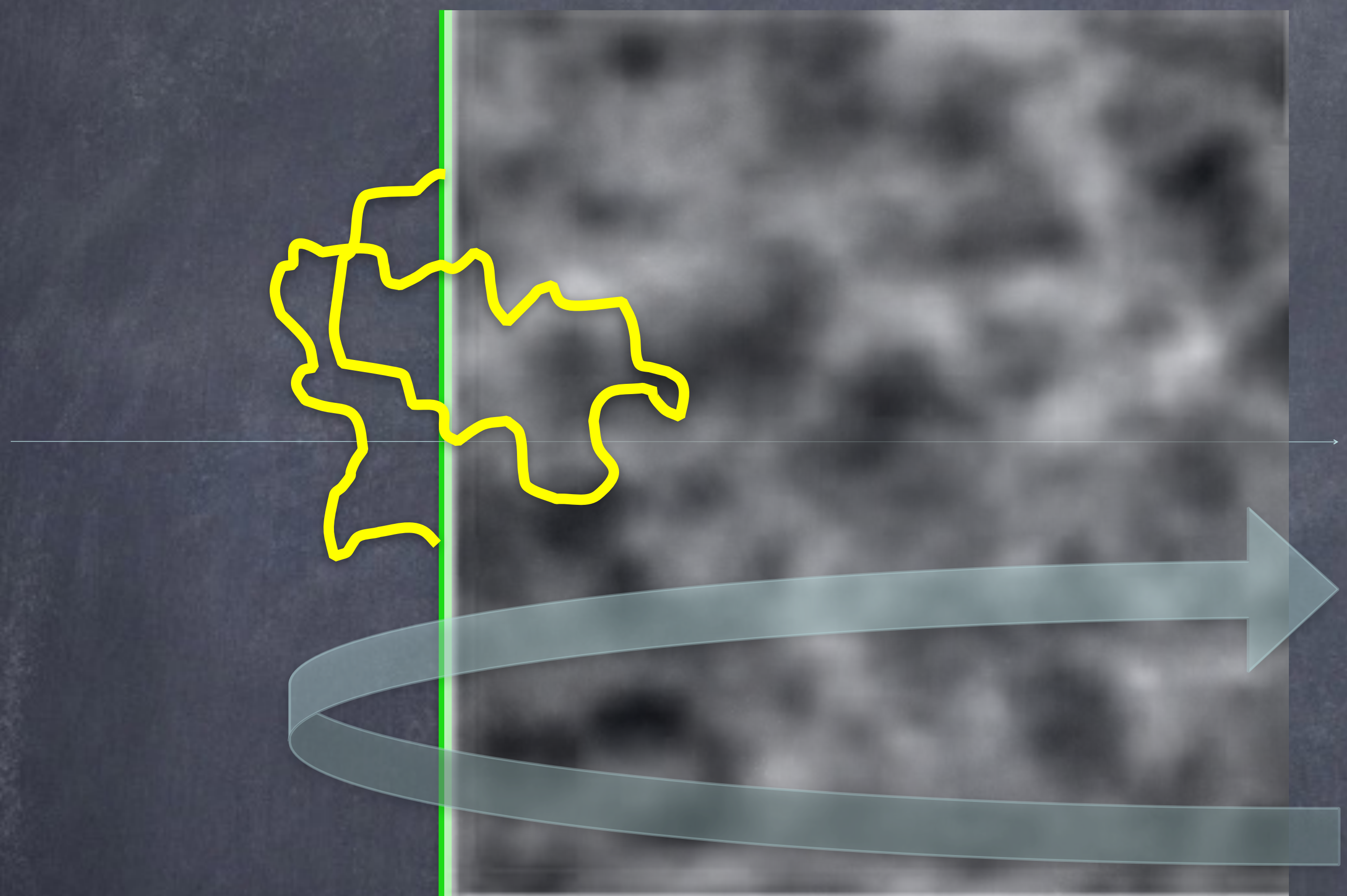

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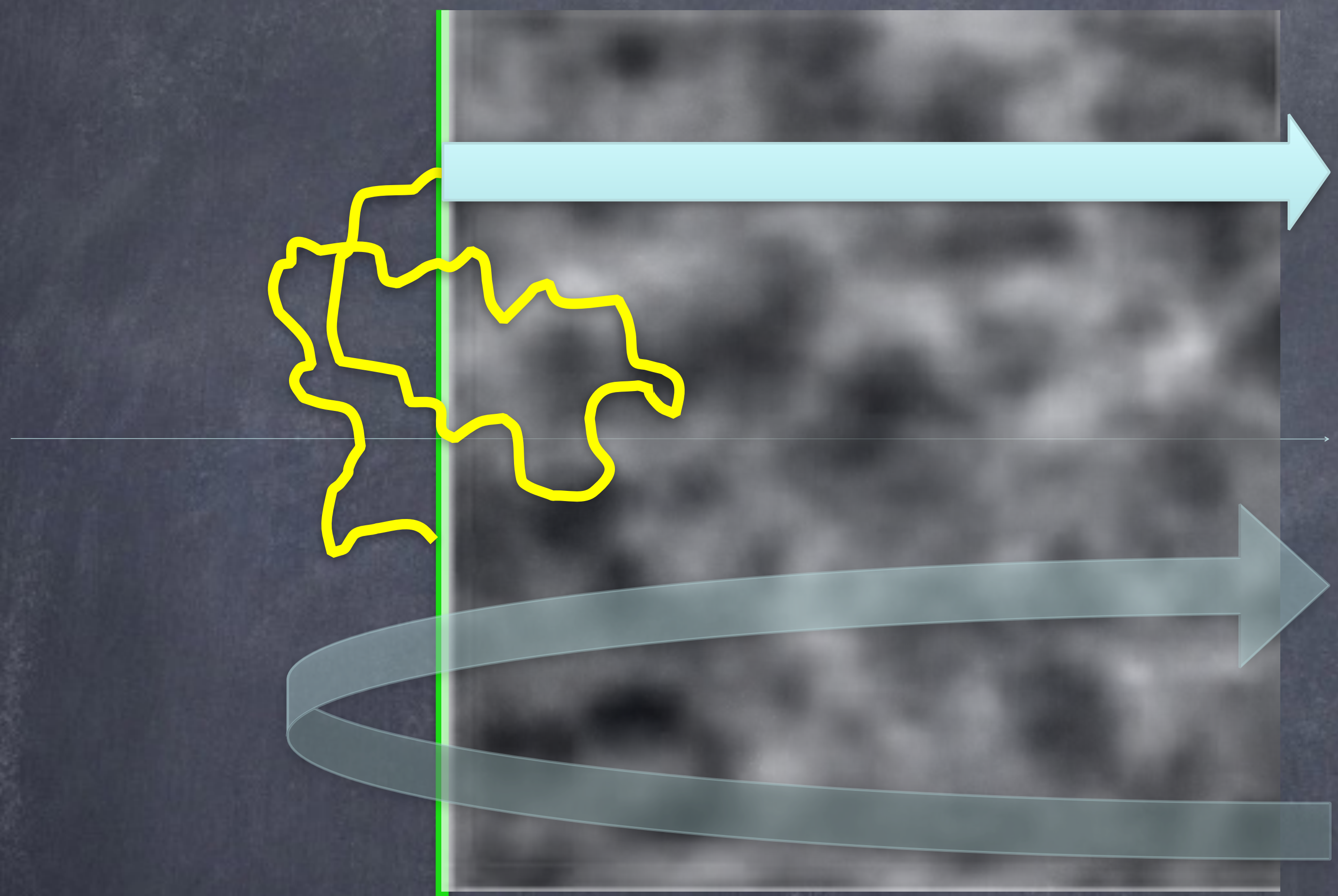

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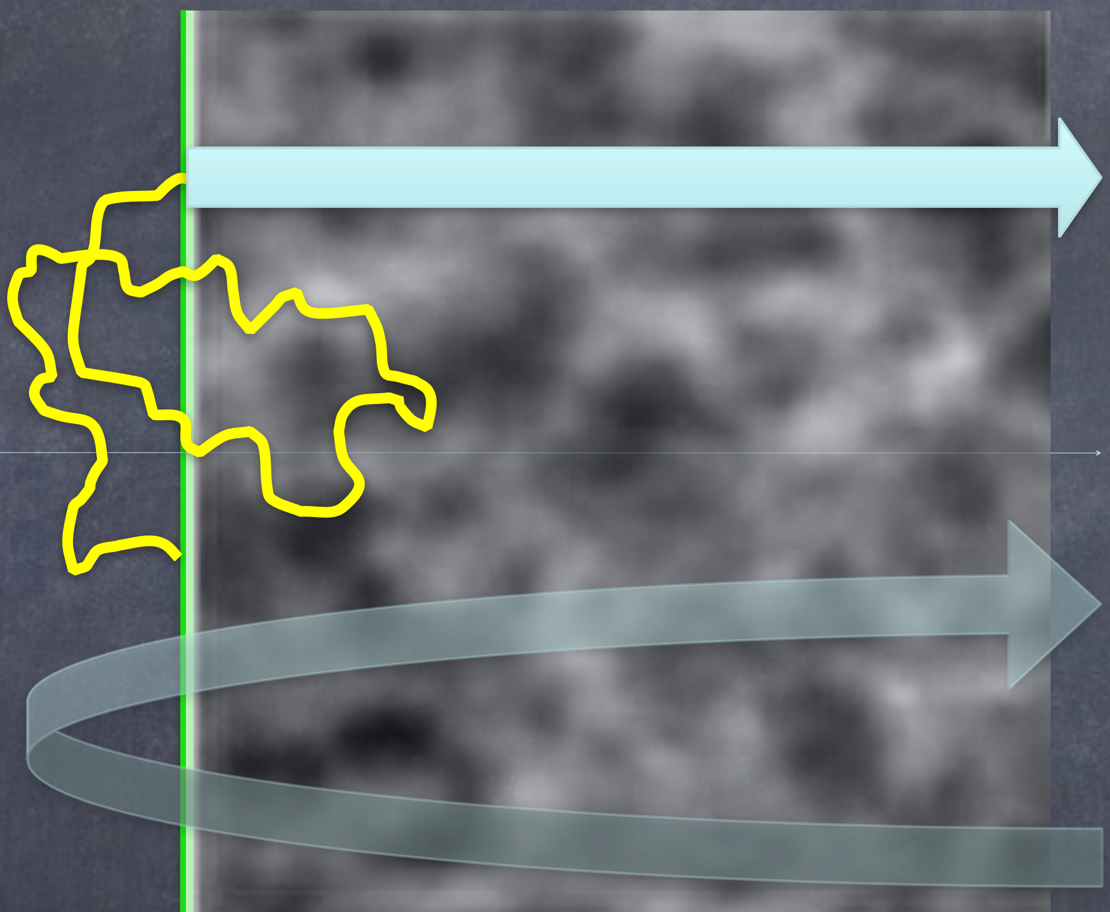


Escaping particles
Generating seed
turbulence

CALCULATING THE SPECTRUM OF PARTICLES ESCAPING A SNR DURING THE LIFE OF THE REMNANT IS ONE OF THE BIGGEST CHALLENGES FACED BY STUDIES OF THE ORIGIN OF CR

The fastest growing modes

The growth rate can be written as (Bell 2004)

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

but the modes exist only is $k_{max}>1/r_L$ (they do not affect the current)

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

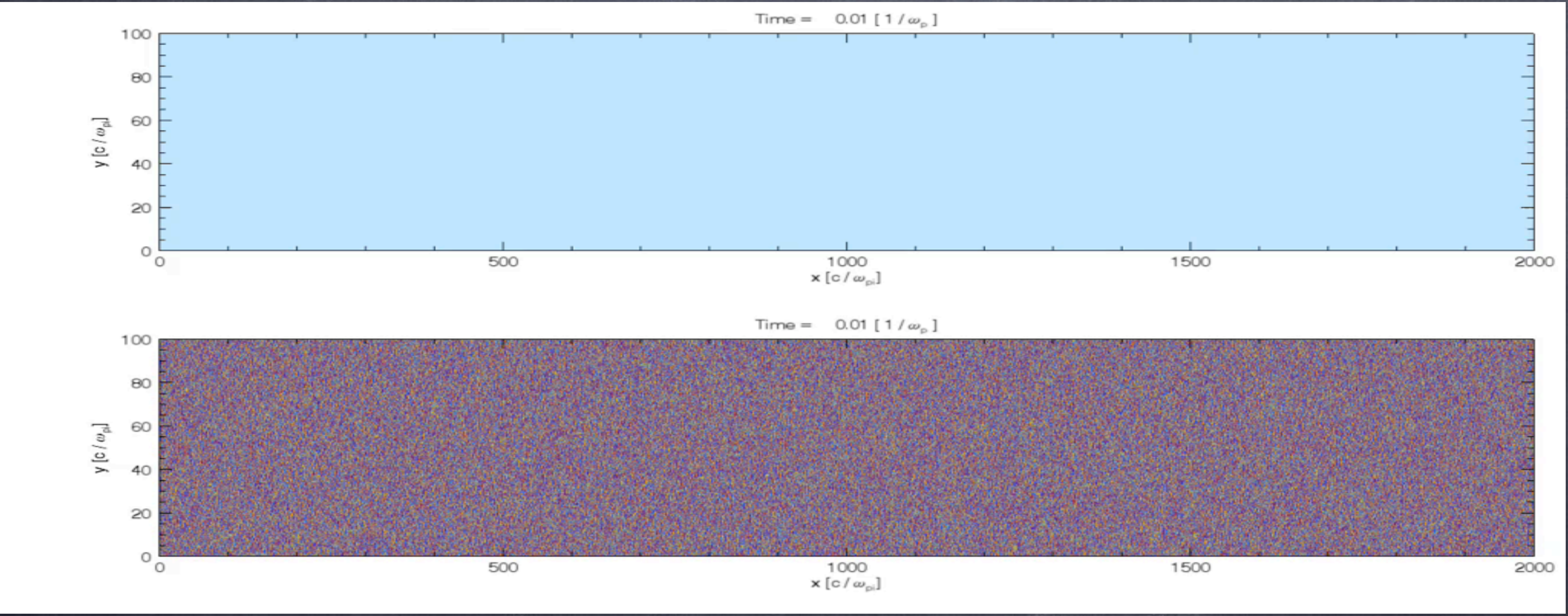
Energy density of escaping CRs

a fluid element gets subject to a force, the scale of the amplified field increases

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

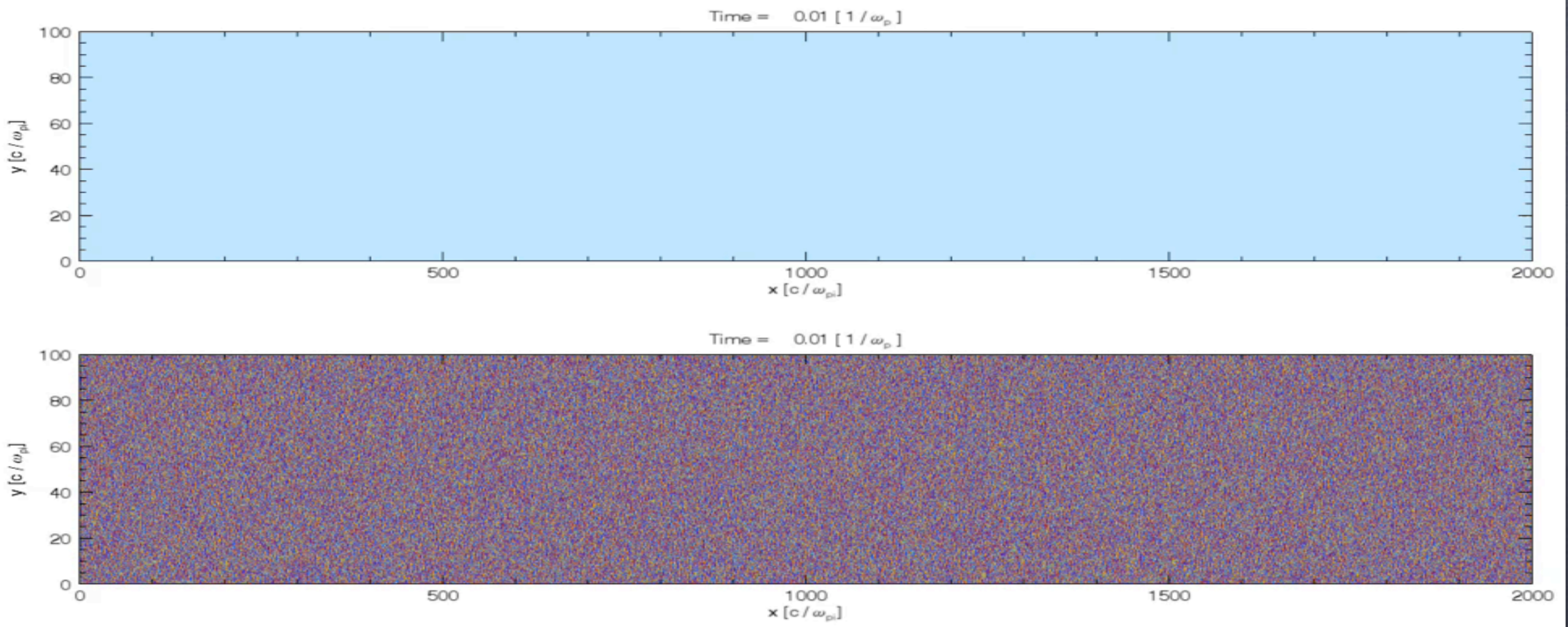
IN OTHER WORSD THE FIELD SATURATES AT ROUGLY EQUIPARTITION BETWEEN MAGNETIC ENERGY AND ENERGY OF ESCAPING CR,TYPICALLY SEVERAL HUNDRED MICROGAUSS AFTER COMPRESSION

THE CRUCIAL ROLE OF ESCAPING CR



Caprioli & Spitkovsky 2013

THE CRUCIAL ROLE OF ESCAPING CR



Caprioli & Spitkovsky 2013

IMPLICATIONS FOR MAXIMUM ENERGY
Supernovae Type Ia

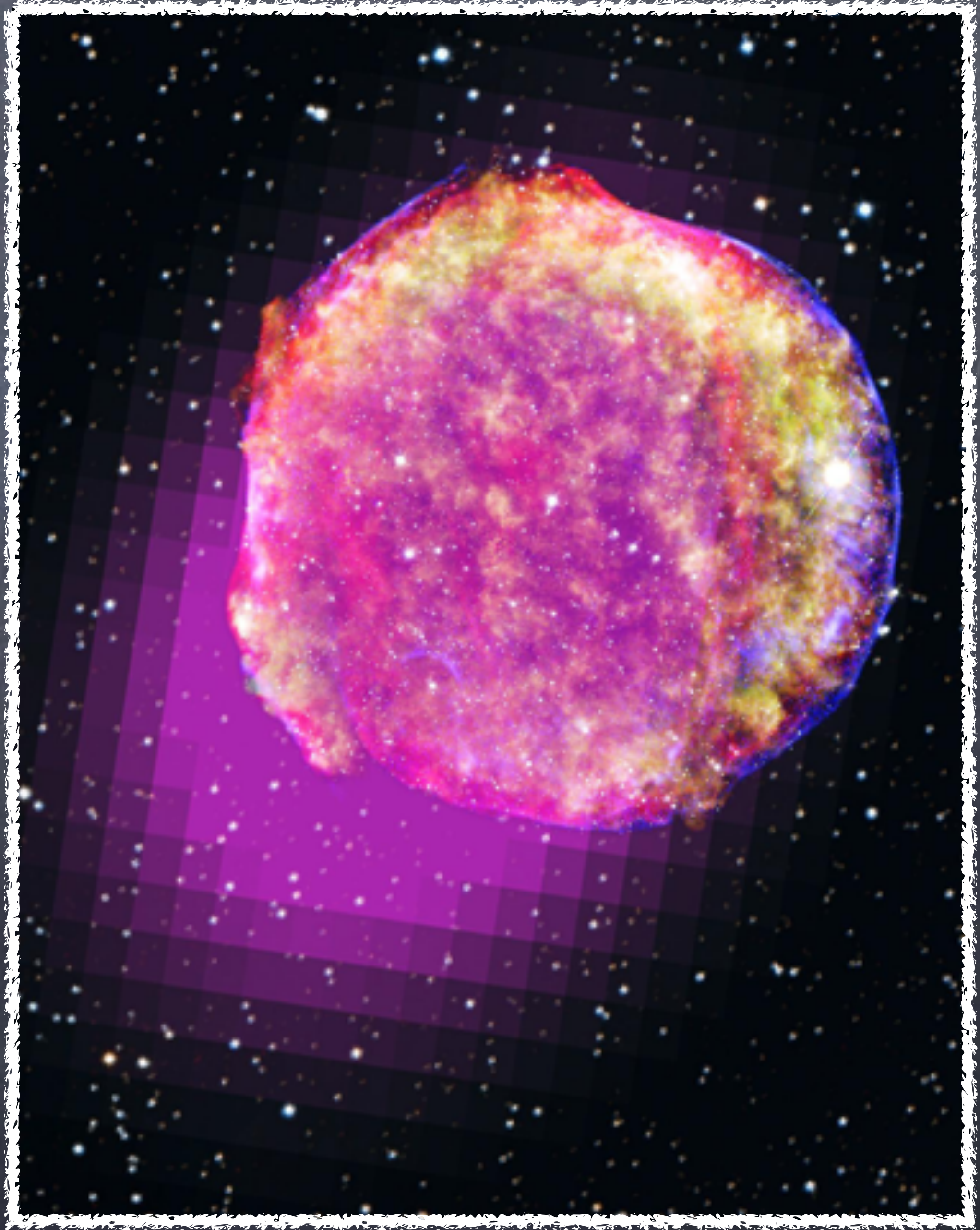
FOR A SN TYPE Ia EXPLODING IN THE ISM THE MAXIMUM ENERGY CAN BE ESTIMATED AS:

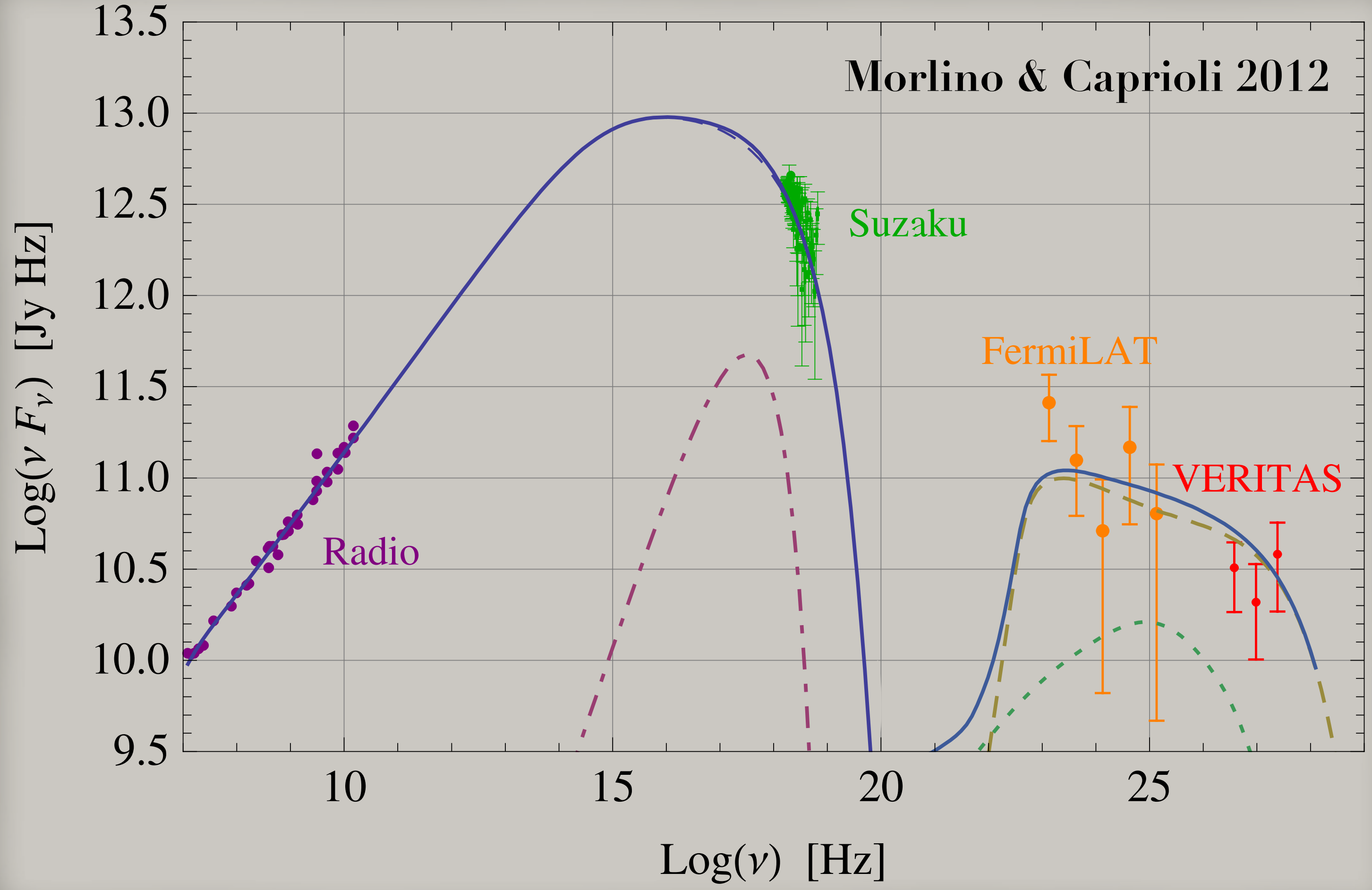
$$E_M \cong \frac{2e}{10c}\xi_{CR} v_0^2 \sqrt{4\pi\rho R_0^2} = 130 \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-\frac{2}{3}}\left(\frac{E_{SN}}{10^{51}\mathrm{erg}}\right)\left(\frac{n_{ISM}}{\mathrm{cm}^{-3}}\right)^{\frac{1}{6}} TeV$$

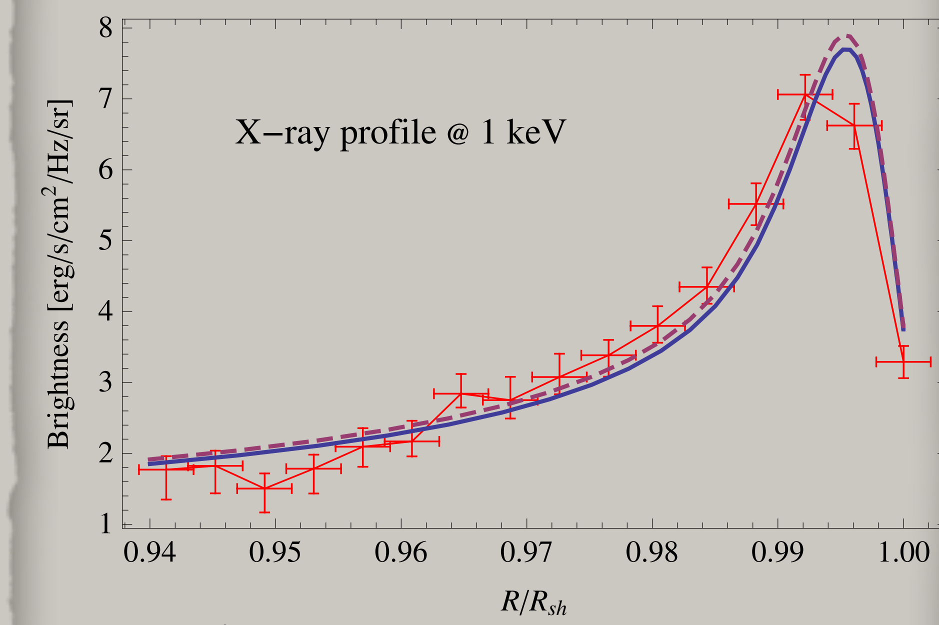
FOR TYPICAL VALUES OF THE PARAMETERS THE MAXIMUM ENERGY REACHABLE IS WELL BELOW THE KNEE

The case of Tycho

- Type Ia SN, exploded 1572 (age: 443 years)
- Very regular shape
- Strong evidence for X-ray filaments
- Radio—> e spectrum $E^{-(2.2-2.3)}$
- Detected in gamma rays by Fermi-LAT and VERITAS

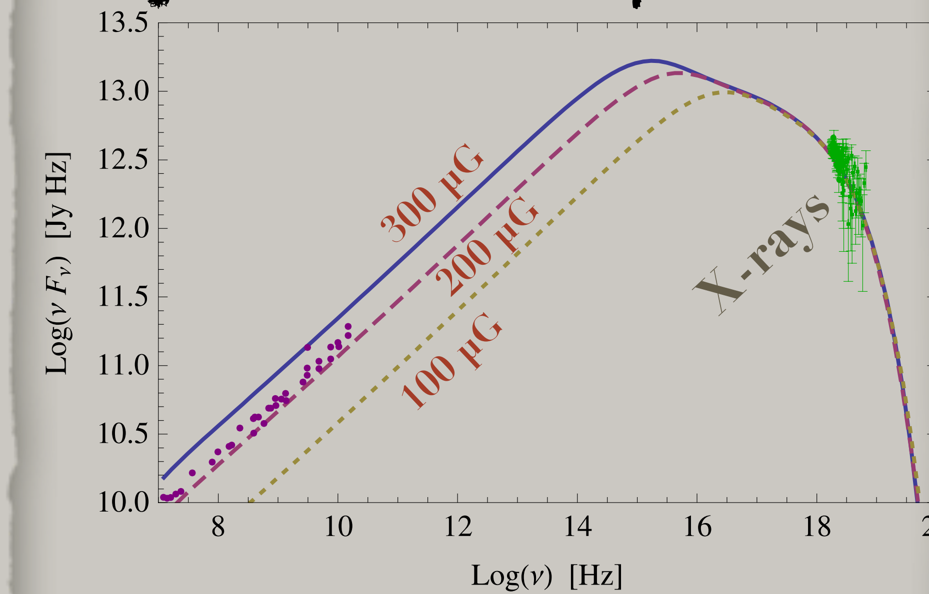






X-Ray Morphology

Synchrotron spectra



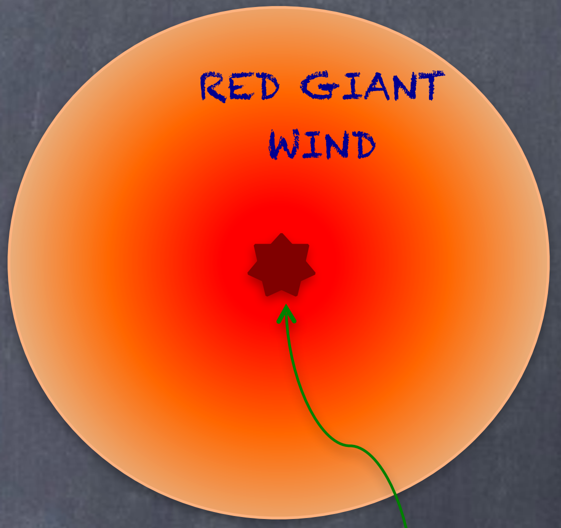
SPECTRUM AND MORPHOLOGY APPEAR TO BE WELL DESCRIBED BY EFFICIENT CR ACCELERATION

THE MAXIMUM ENERGY IS IN THE RANGE OF A FEW HUNDRED GeV

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

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



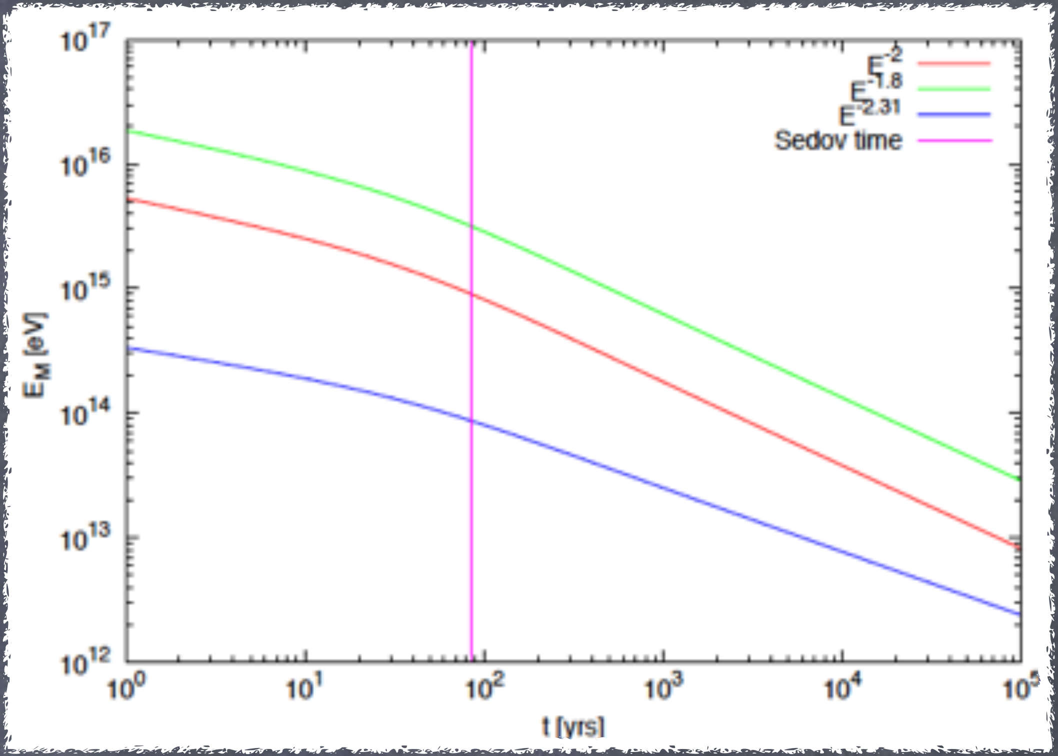
IN THE DENSE WIND THE SEDOV PHASE IS REACHED AT DISTANCE

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

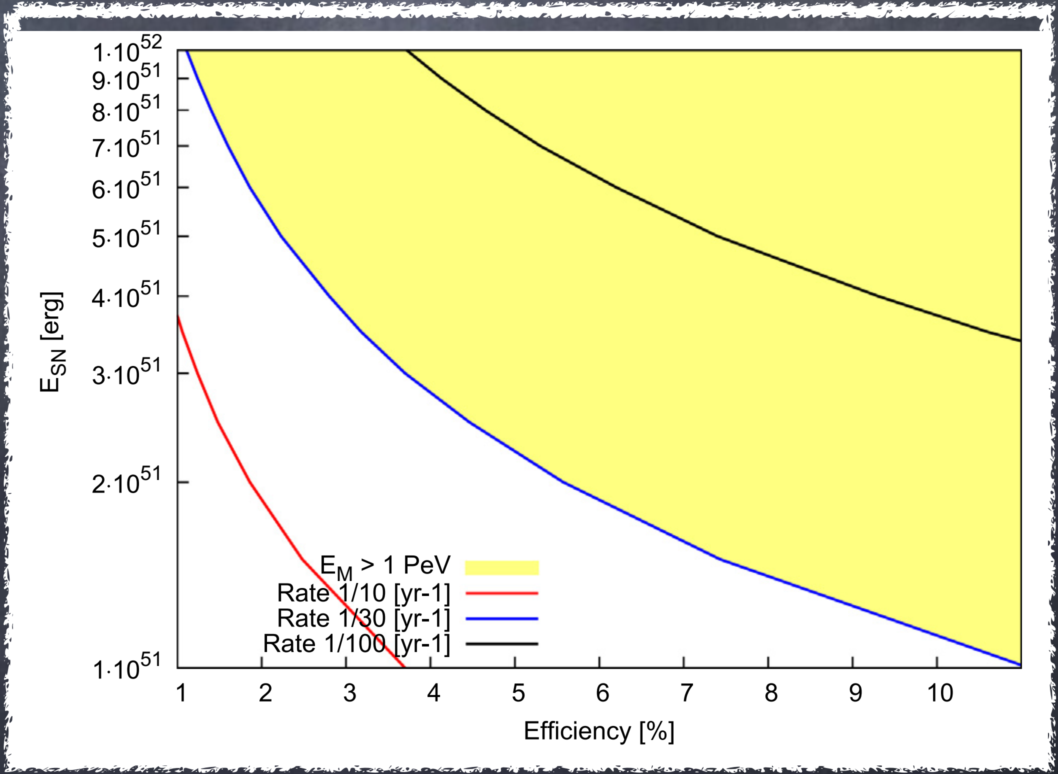
(About 30 years after explosion)

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

- The effective max energy is reached at the beginning of the ST phase
- The escape flux is non zero even during ejecta dominated→ no exp cutoff at E_{max}
- SNe cannot be too rare otherwise too high efficiency to reach the knee
- Overall spectrum of galactic CRs should end around 10^{17} eV



Cardillo, Amato & PB 2015



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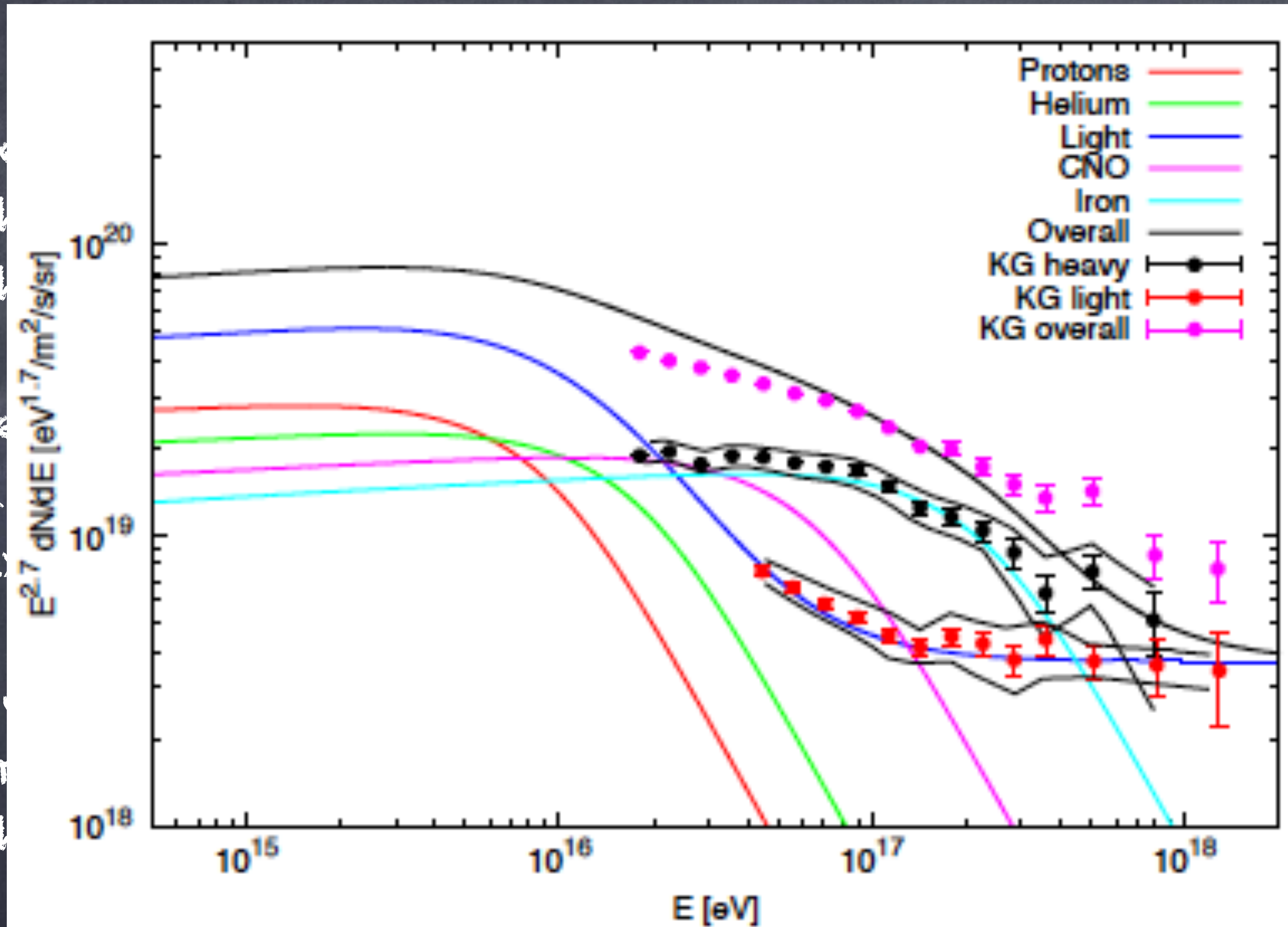
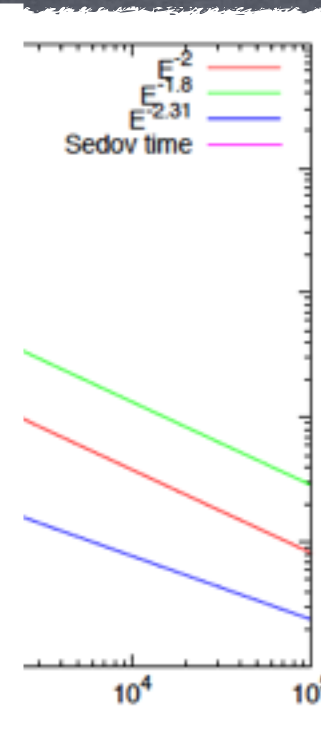
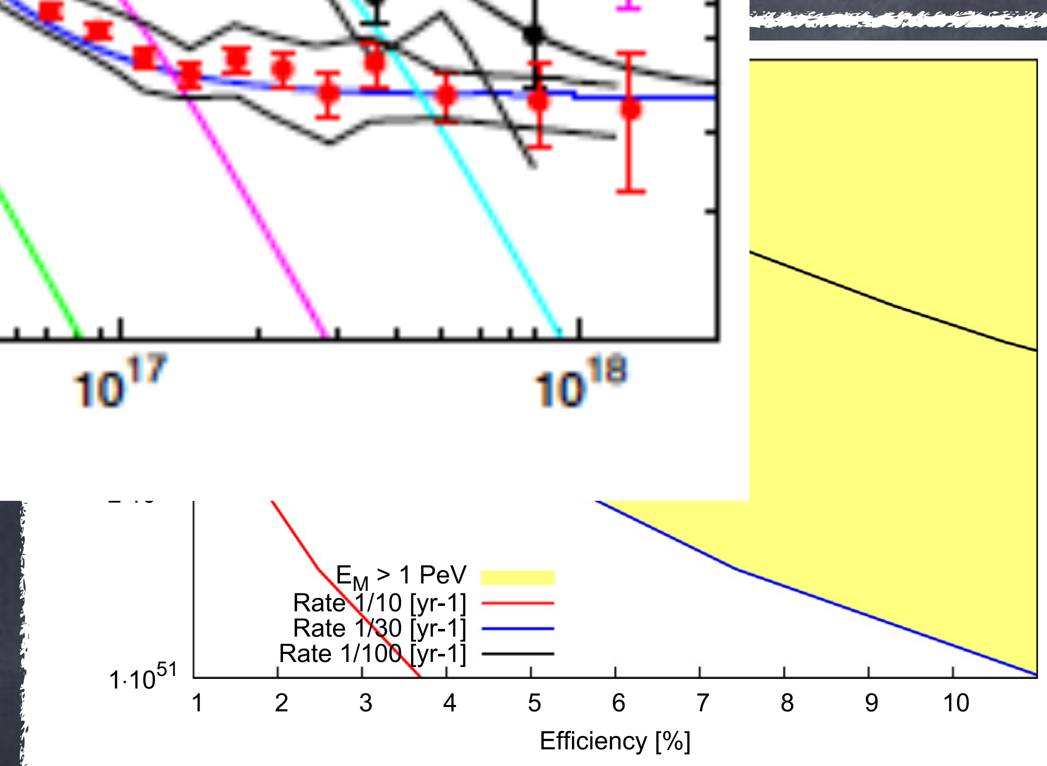




& PB 2015



- Overall spectrum of galactic CRs should end around 10^{17} eV

GALACTIC COSMIC RAY PROPAGATION

Simple Transport Equation

Things can get really complex, but the essential Physics is caught by the simplest transport equation (for protons):

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

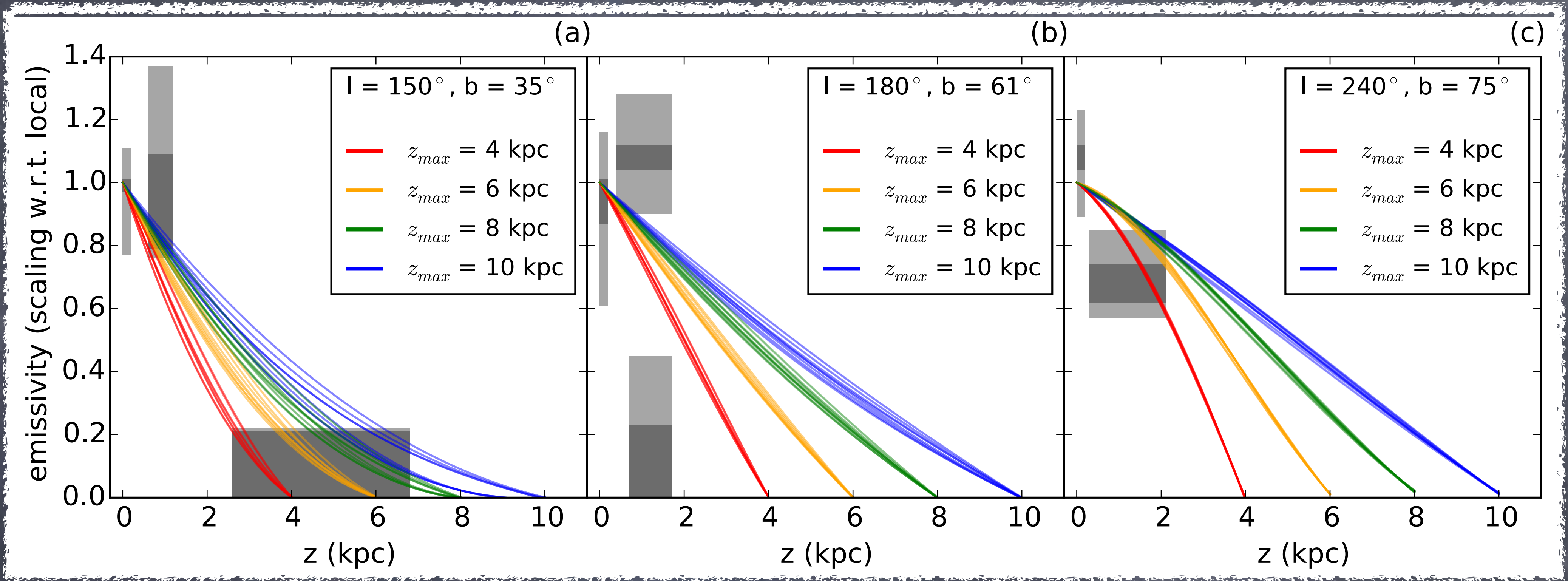
For z>0 (or <0) one has:

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

where we used the definition of a Halo [f(z=H)=0]

This simple approach contains most of the diffusion Physics that can be found in more complex approaches (one can even introduce advection, D(z,p), ...)

First measurement of z-dependence



Tibaldo et al. (2015)

- Using HVC one can measure the emissivity per atom as a function of z (proportional to f)
- Indications of a halo with H~4-6 kpc
- ...and here is where we got to be careful... what physical meaning should we attribute to H???

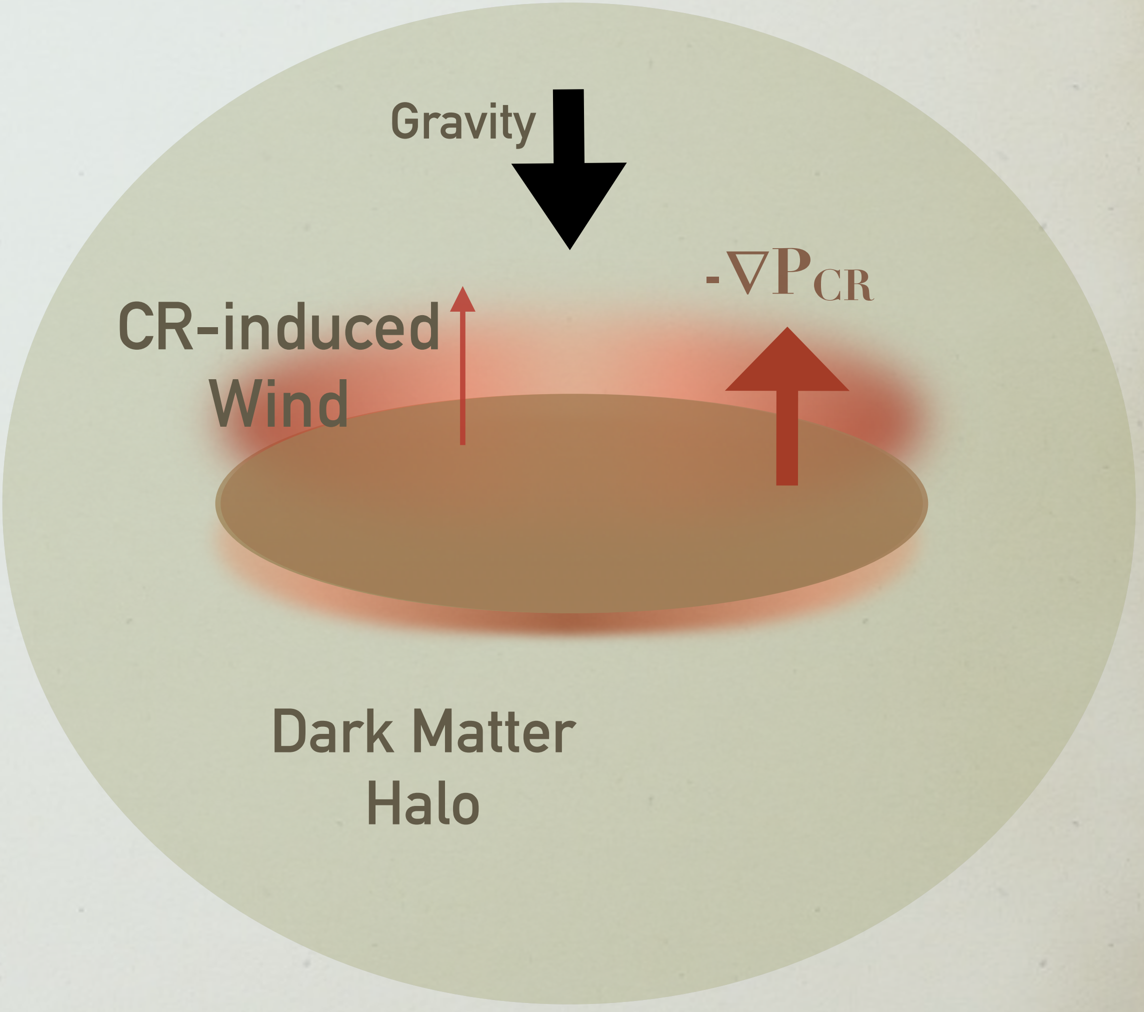
The halo size H

- Assuming f(H)=0 reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because B goes to zero, or because turbulence vanishes
- Vanishing turbulence may reflect the lack of sources… but the only source up there is CRs themselves
- What if there is no H at all? Or it is dependent on particle E?

CR blown winds with self-generation of waves

[Breitschwerdt et al. 1991; Ptuskin et al. 1997]

- Wherever the force $-\nabla P_{CR}$ becomes larger that the gravitational force, plasma can be lifted into a wind
- In turn $-\nabla P_{CR}$ is determined by diffusion which occurs on self-generated waves
- The situation is such that there is no H (the wind extends to infinity) but at some distance advection takes over diffusion



CR blown winds with self-generation of waves

The hydrodynamical problem typically leads to u_W+v_A that grows linearly with z (in a NFW DM profile), hence a transition from diffusion to advection occurs when

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

The typical solution that one gets is a simple generalisation of the trivial case:

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

STANDARD CASE

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

CR-INDUCED WIND WITH SELF-GENERATION

DIFFERENT SCALINGS AND NO REAL BOUNDARY H AT FINITE DISTANCE

Diffusion as a physical process

Although we think of D(E) as a coefficient that we can tune to fit the data, it actually contains most of the physics we are trying to describe

$$f(p,z) \longleftrightarrow D(p,z)$$

The gradient in f induces waves generation:

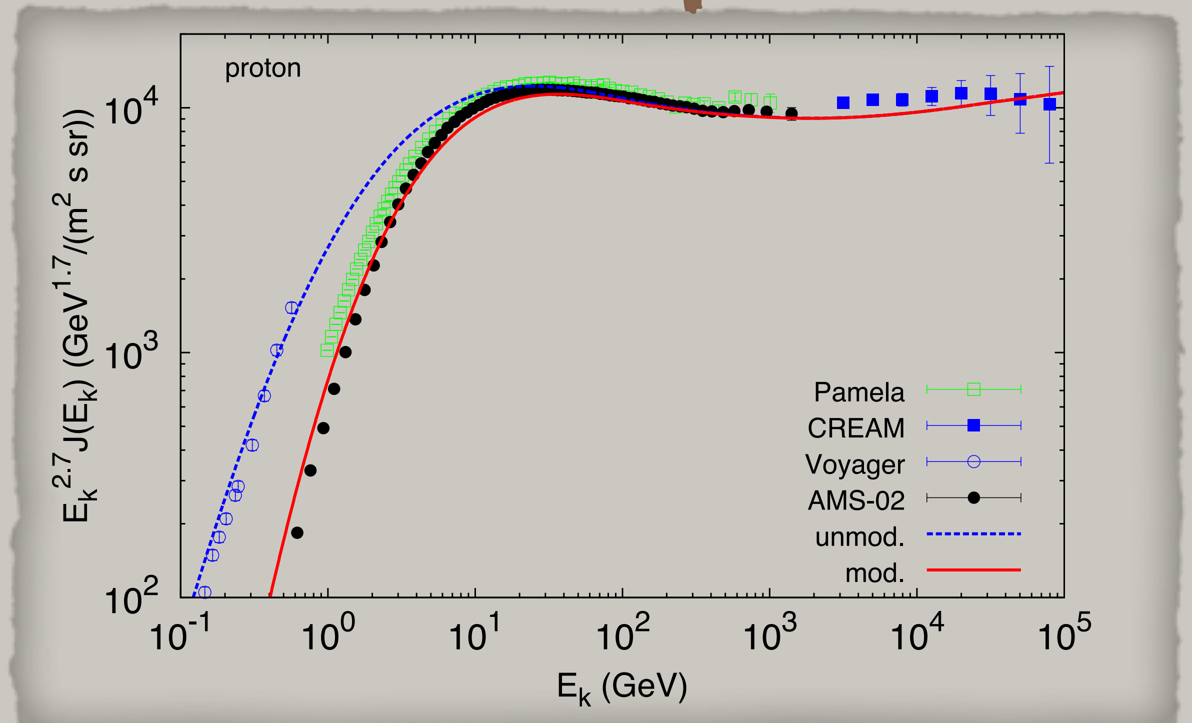
$$\Gamma_{CR}(k) = \frac{16\pi^2}{3}\frac{v_A}{B^2\mathcal{F}}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{k=k_{res}}$$

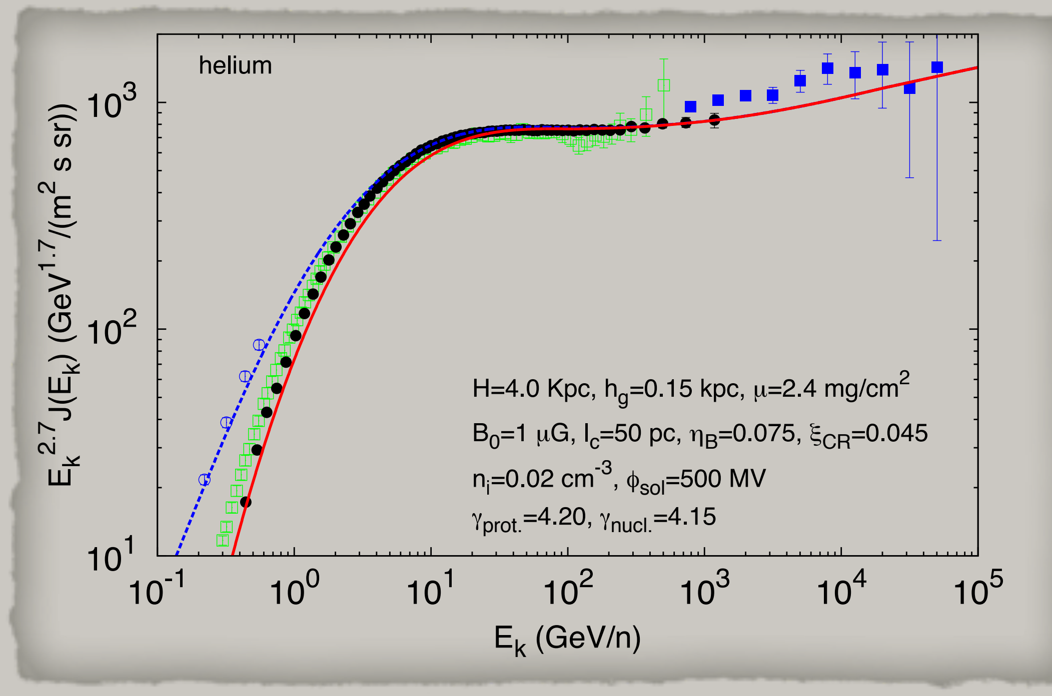
which get damped (ion-neutral, non-linear Landau, ...).
The balancing between the two leads to the determination of D

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

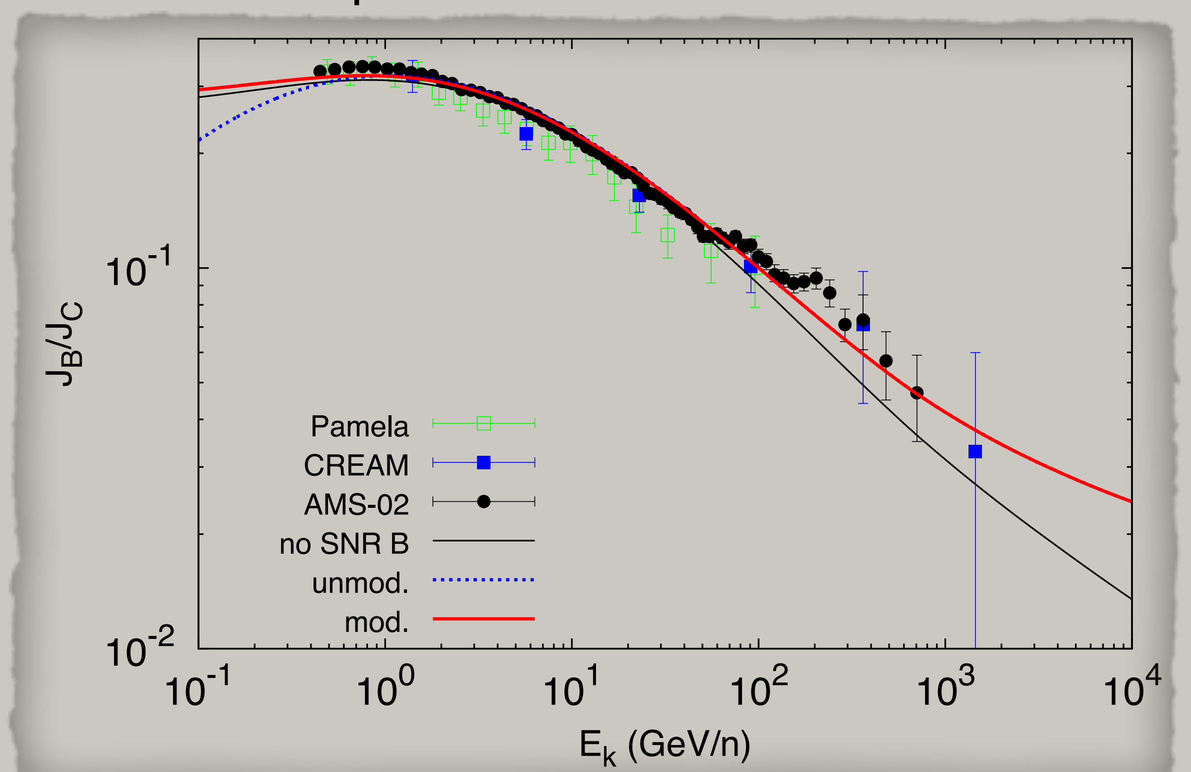
PB, Amato & Serpico 2012
Aloisio & PB 2014
Aloisio, PB & Serpico 2015

Spectral Breaks





Aloisio, PB & Serpico 2015



PAMELA and AMS-02 data are well described by a 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:

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

CONCLUSIONS ON GALACTIC CR

- SNR of type II exploding in red giant winds can reach the knee, type Ia are not...
- At E_{max} no exponential cutoff but change of slope
- No indication (e.g. gamma) that other objects can reach higher energies
- The knee is most easily explained in terms of E_{max}
- But if $E_{max}>10^{17}$ eV, the knee could signal a change in transport (Ginzburg 1963, De Marco&PB2007, Giacinti et al. 2014, 2015)

$$D(E) \sim E^{\delta} \qquad r_L(E) < L_c$$

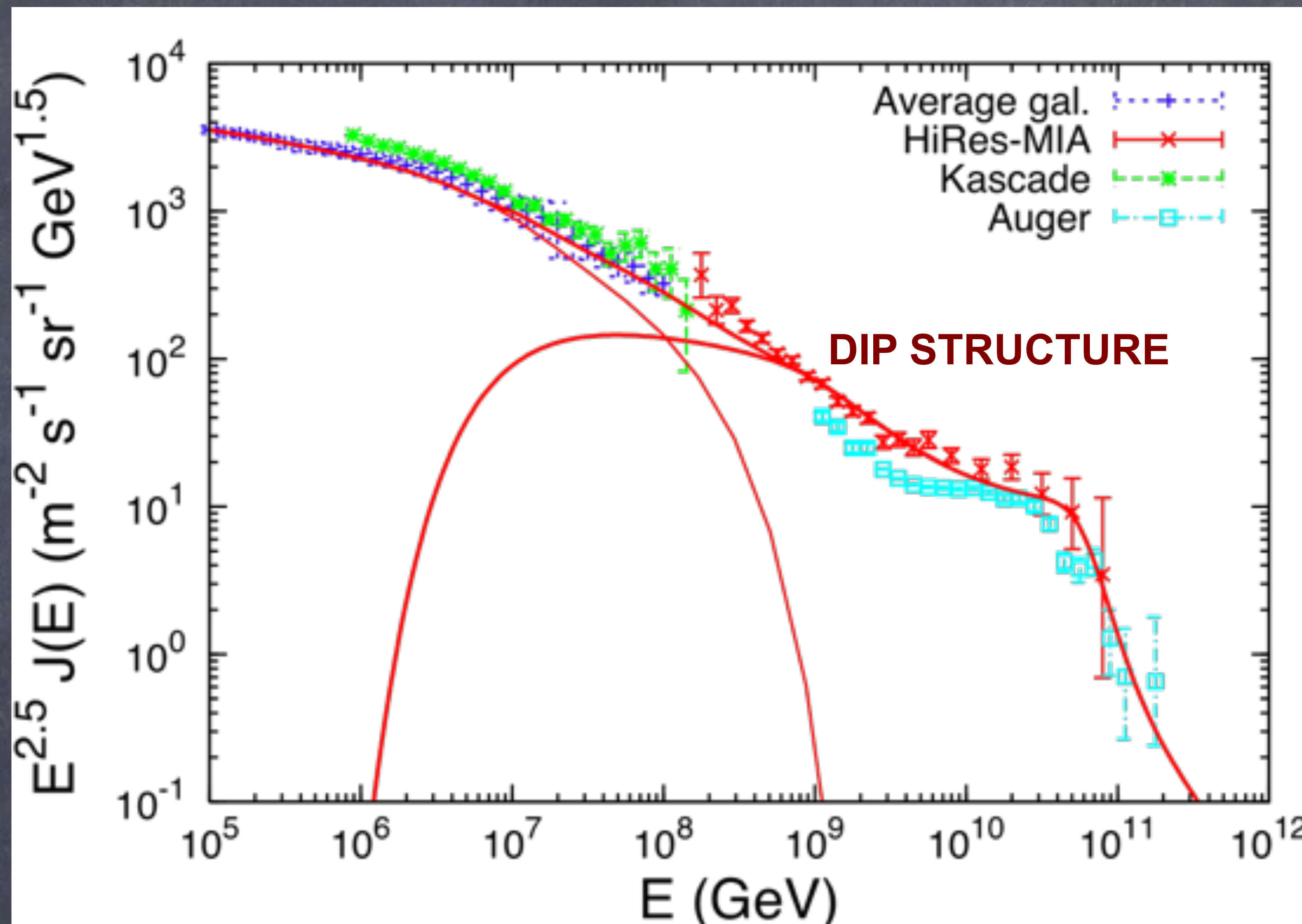
$$D(E) \sim E^{2} \qquad r_L(E) > L_c$$

For Lc~10 pc the transition energy is ~ knee

End of Galactic CRs and transition

- If the knee flags the sources running out of steam, then GCRs should end around 0.1 EeV with a heavy composition
- If the knee is due to propagation, the transition has very similar characteristics to the previous case (transition over at 2 EeV) BUT very high E_{max} and small L_c required
- Transition could be at the ankle, but very severe requirements on the sources and not easy to accommodate Auger
- IN ANY CASE THE TRANSITION IS COMPLEX: IT RETAINS INFO ON BOTH THE WAY GALACTIC CR SPECTRUM ENDS AND EGCR PROPAGATE

THE DIP

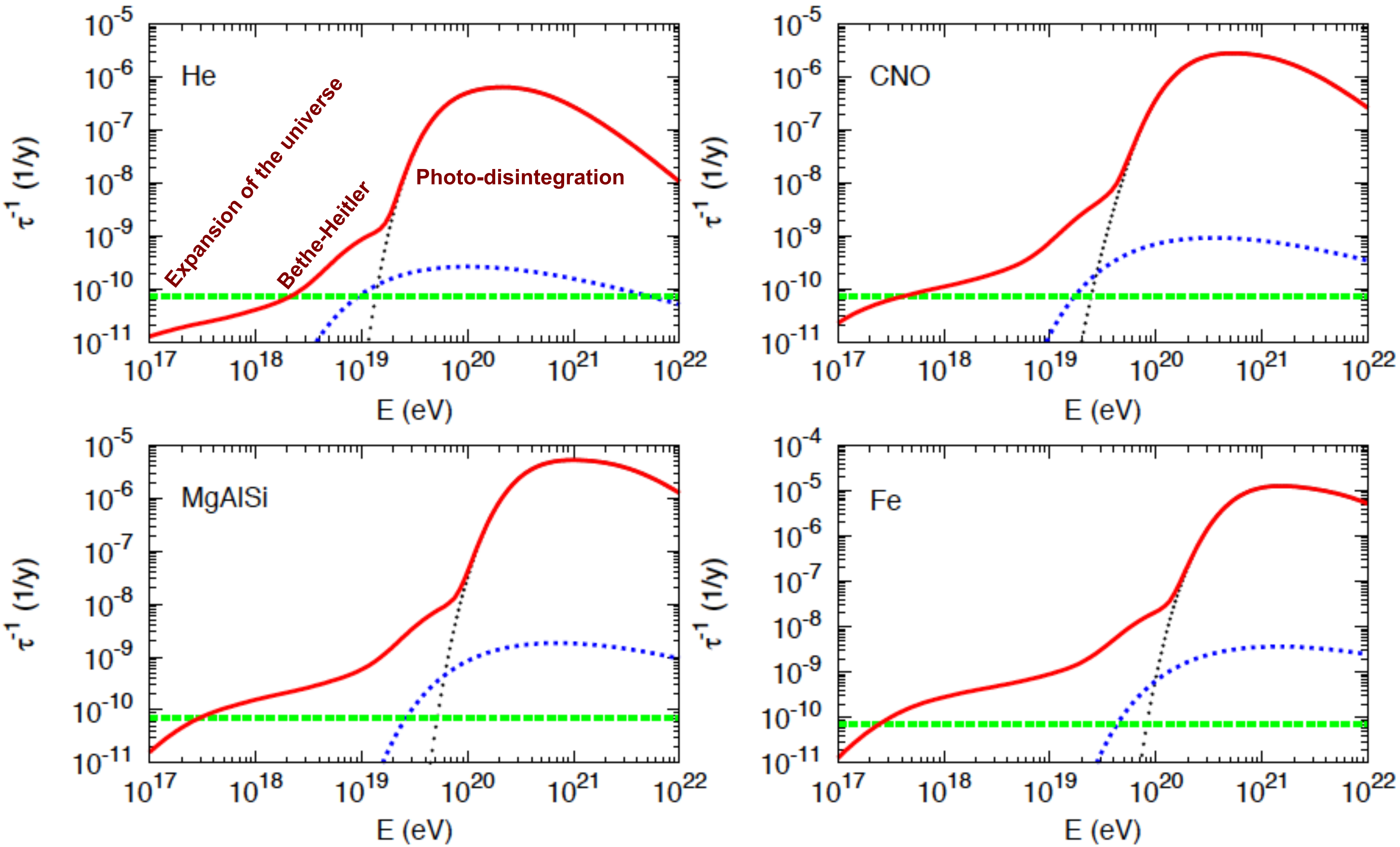


THE BALANCE BETWEEN BETHE-HEITLER PAIR PRODUCTION AND EXPANSION OF THE UNIVERSE NATURALLY CREATES A DIP IN THE CR SPECTRUM

THE DIP IS VISIBLE ONLY IF COMPOSITION IS LIGHT (<15% He)

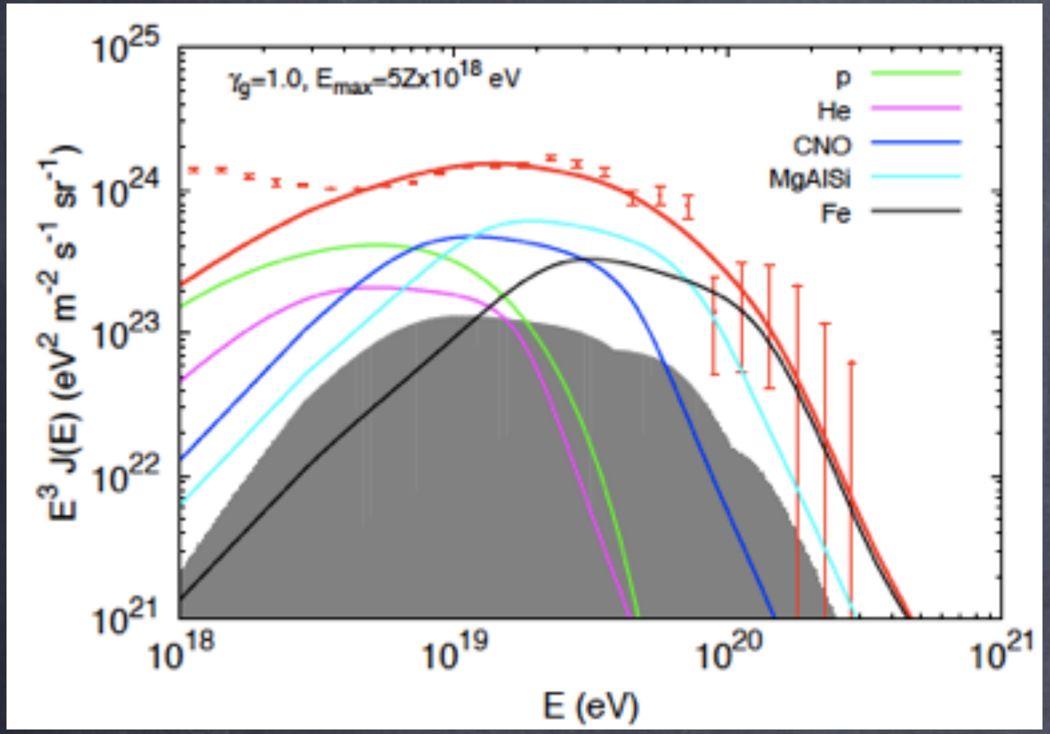
LOSSES OF NUCLEI

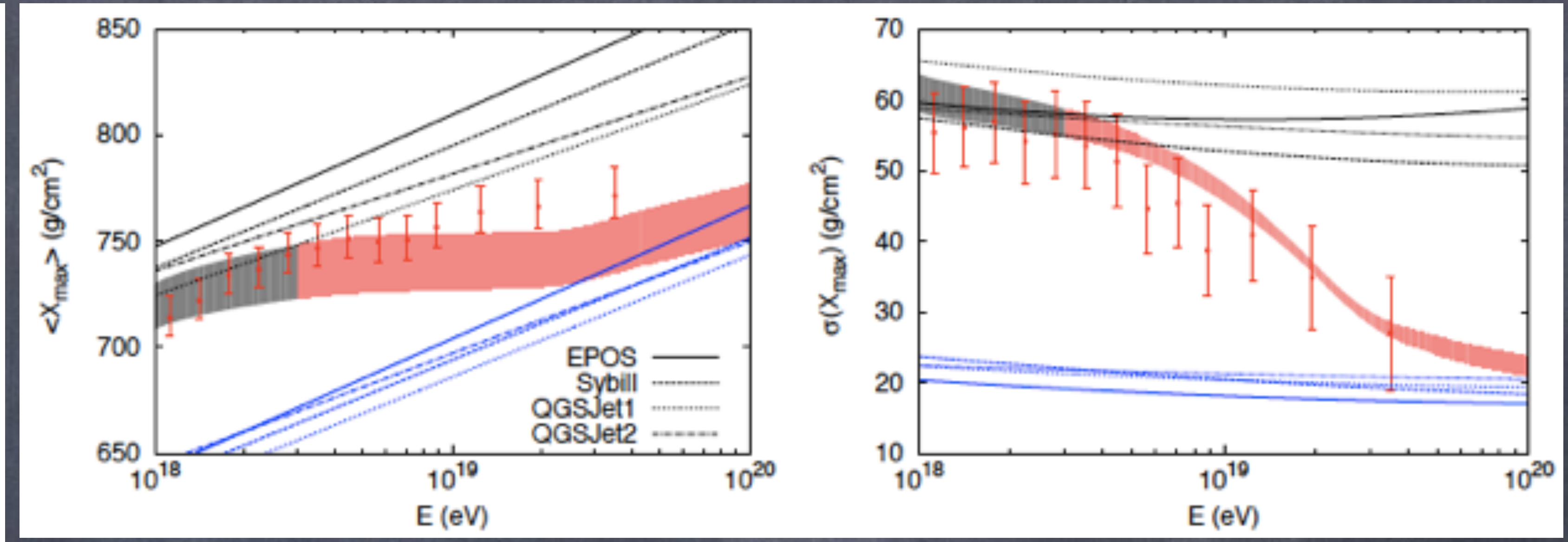
Aloisio et al. 2014



TRANSITION AND UHECR

Aloisio, Berezinsky & PB 2014





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

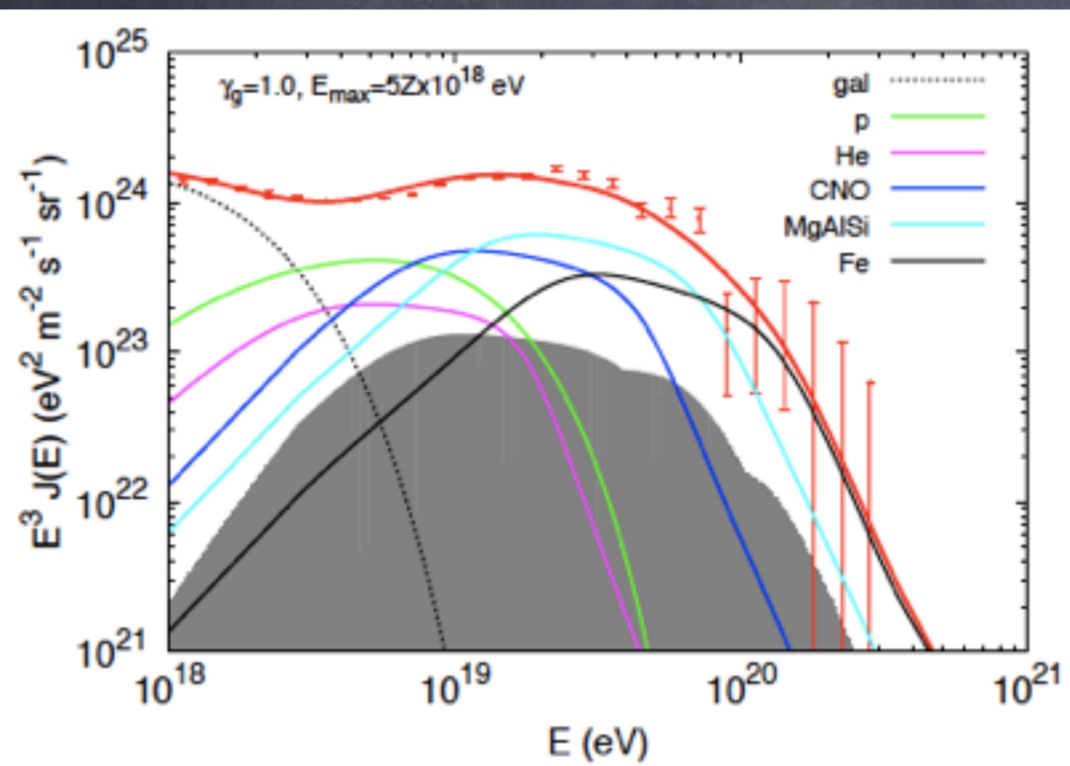
...AND LOW VALUE OF E_{MAX}~5 10^{18} eV...

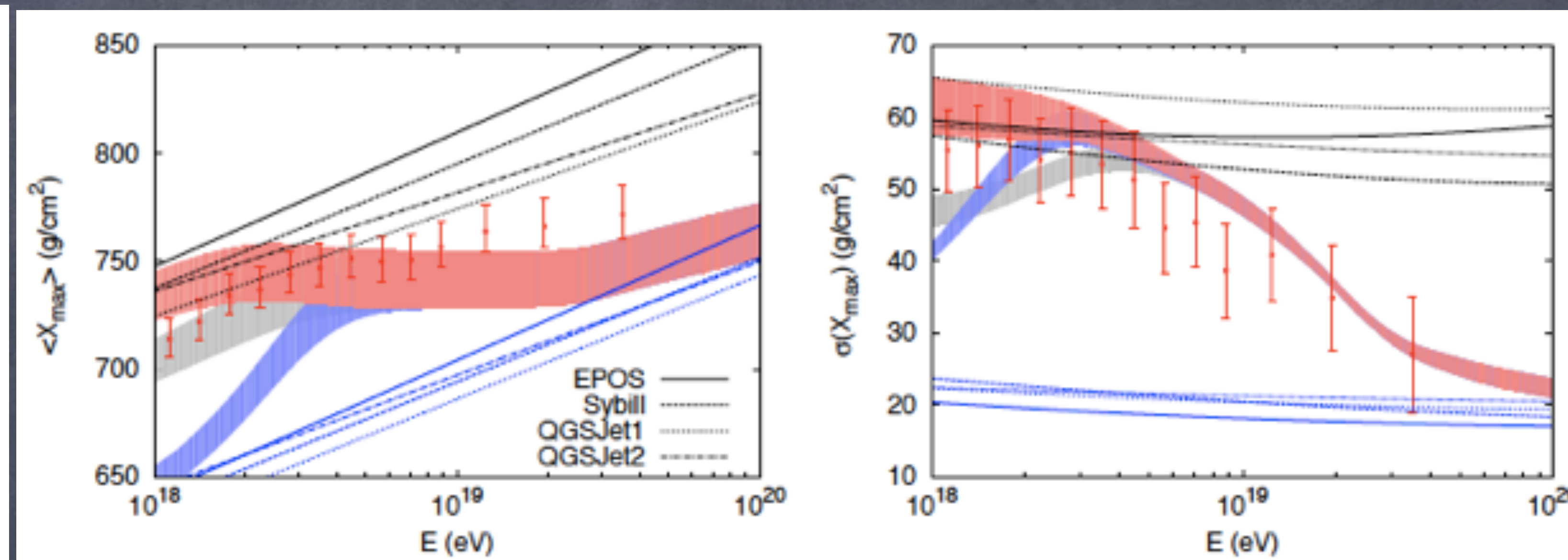
QUITE A CHANGE OF PARADIGM

TRANSITION AND UHECR

Additional Galactic Component

Aloisio, Berezinsky & PB 2014

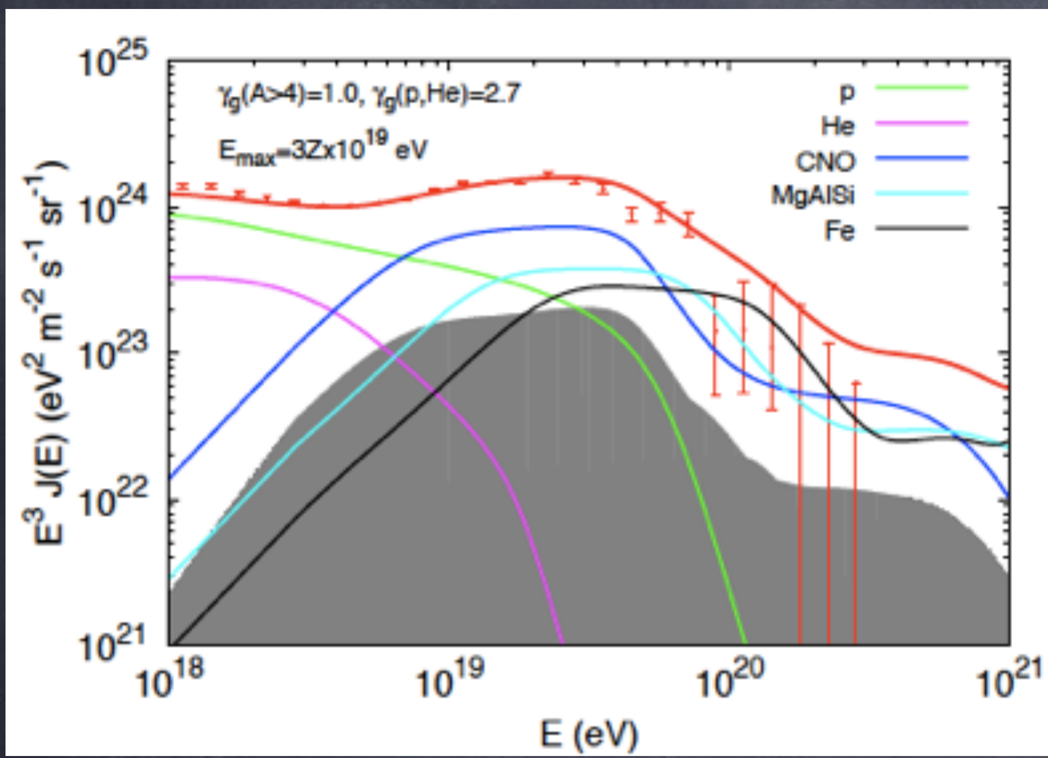




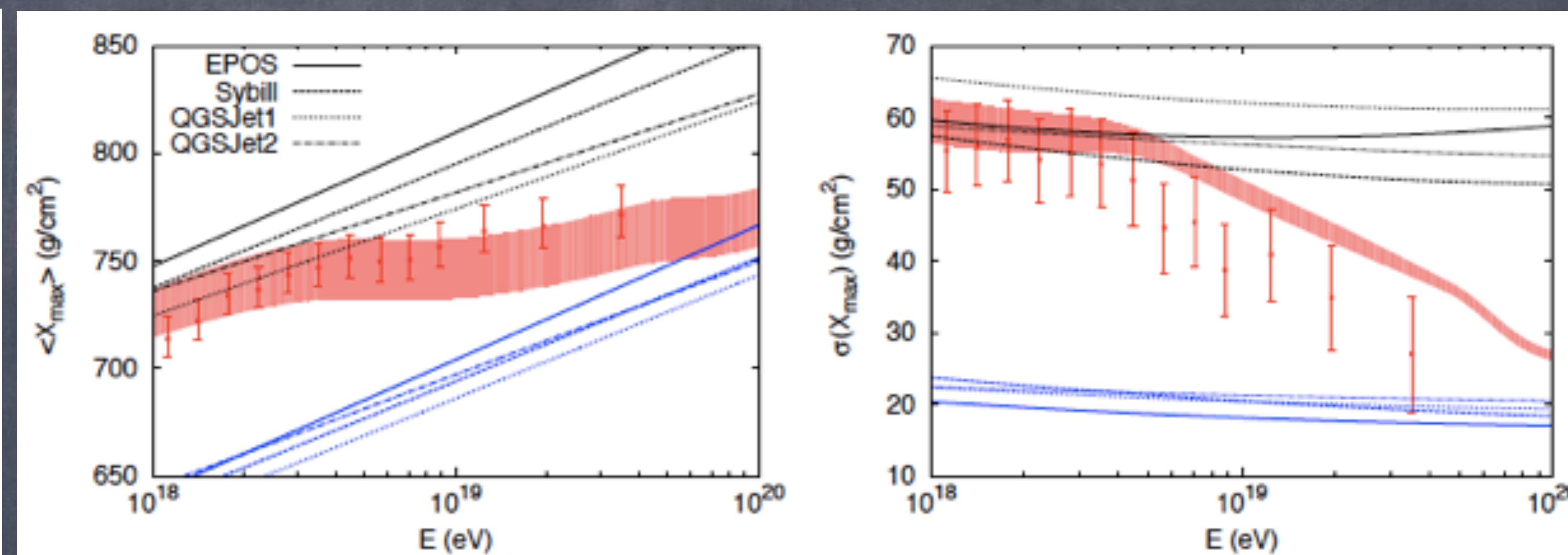
IF THE REQUIRED ADDITIONAL COMPONENT IS GALACTIC IN ORIGIN, IT HAS TO BE LIGHT. BUT THIS IS NOT CONSISTENT WITH THE ANISOTROPY MEASURED BY AUGER AT 10^{18} eV

TRANSITION AND UHECR

Additional Extragalactic Component



Aloisio, Berezinsky & PB 2014

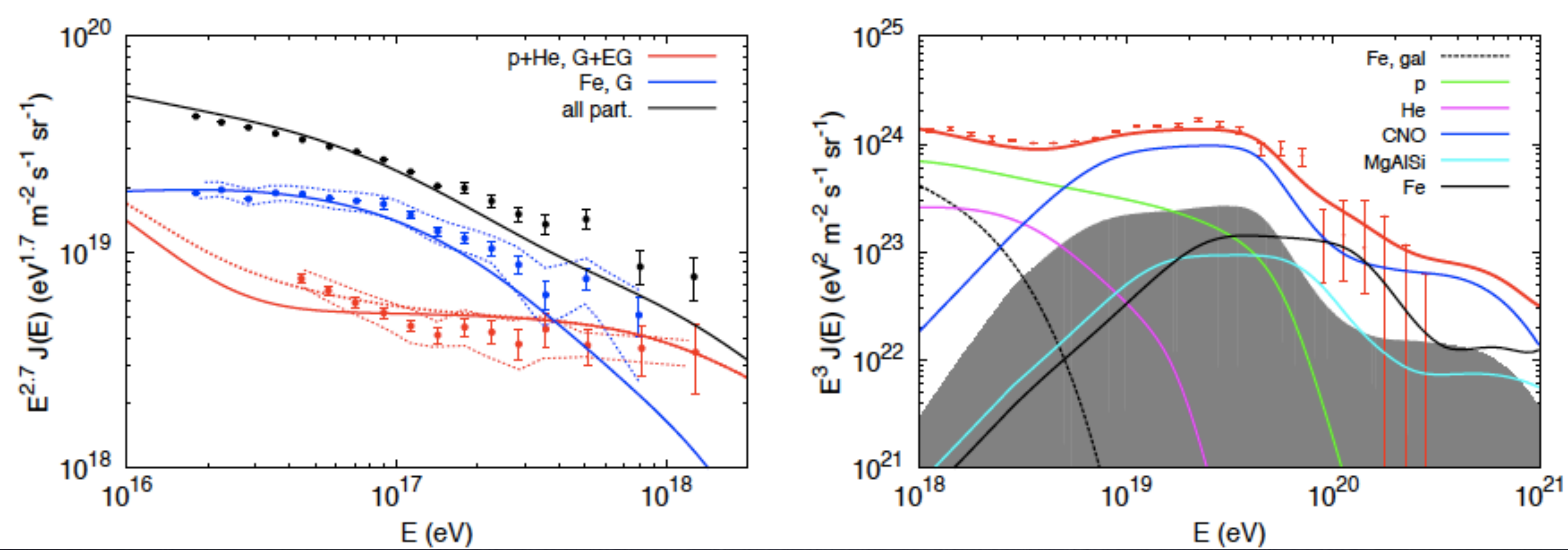


THE REQUIRED ADDITIONAL LIGHT COMPONENT MUST HAVE A STEEP SPECTRUM AND A CUTOFF AT ~10^{19} eV

TRANSITION AND UHECR

Additional Extragalactic Component and KASCADE-Grande

Aloisio, Berezinsky & PB 2014

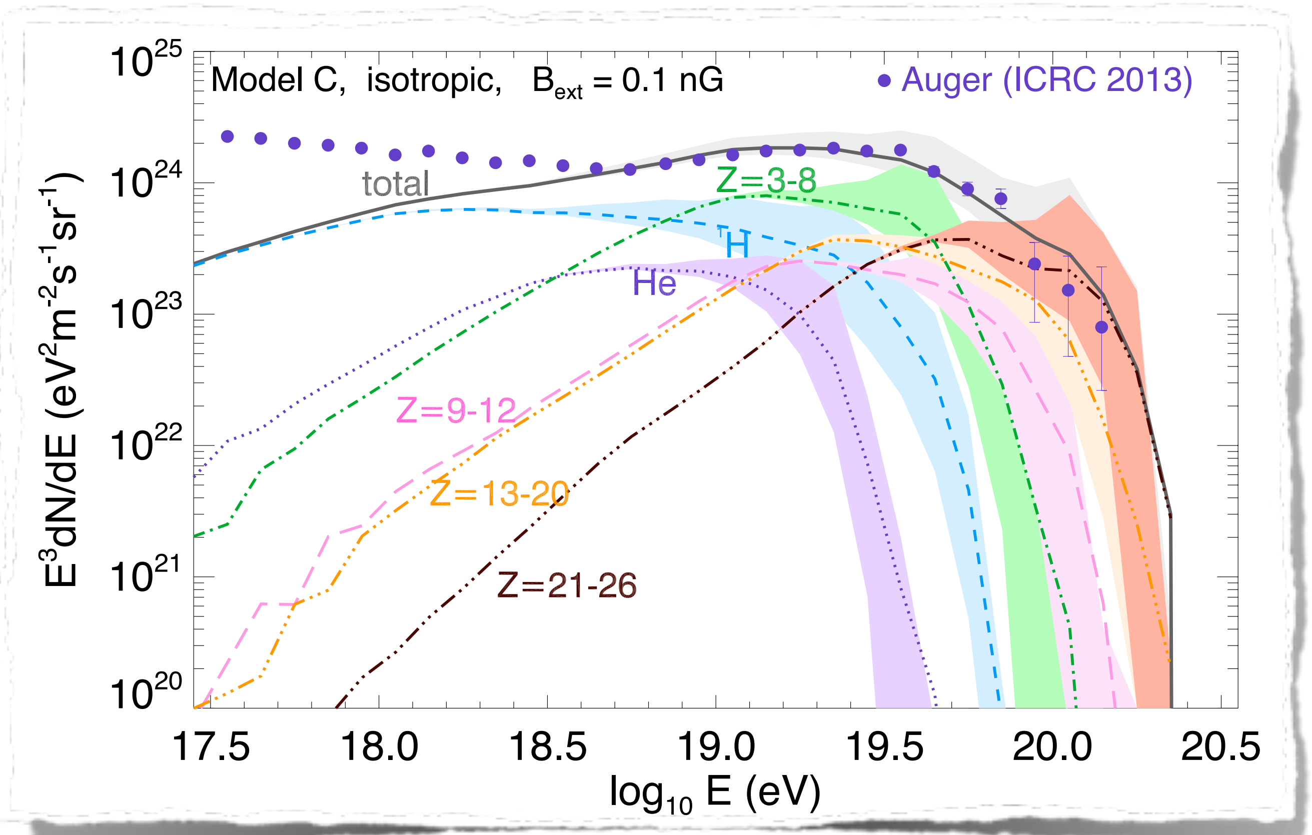


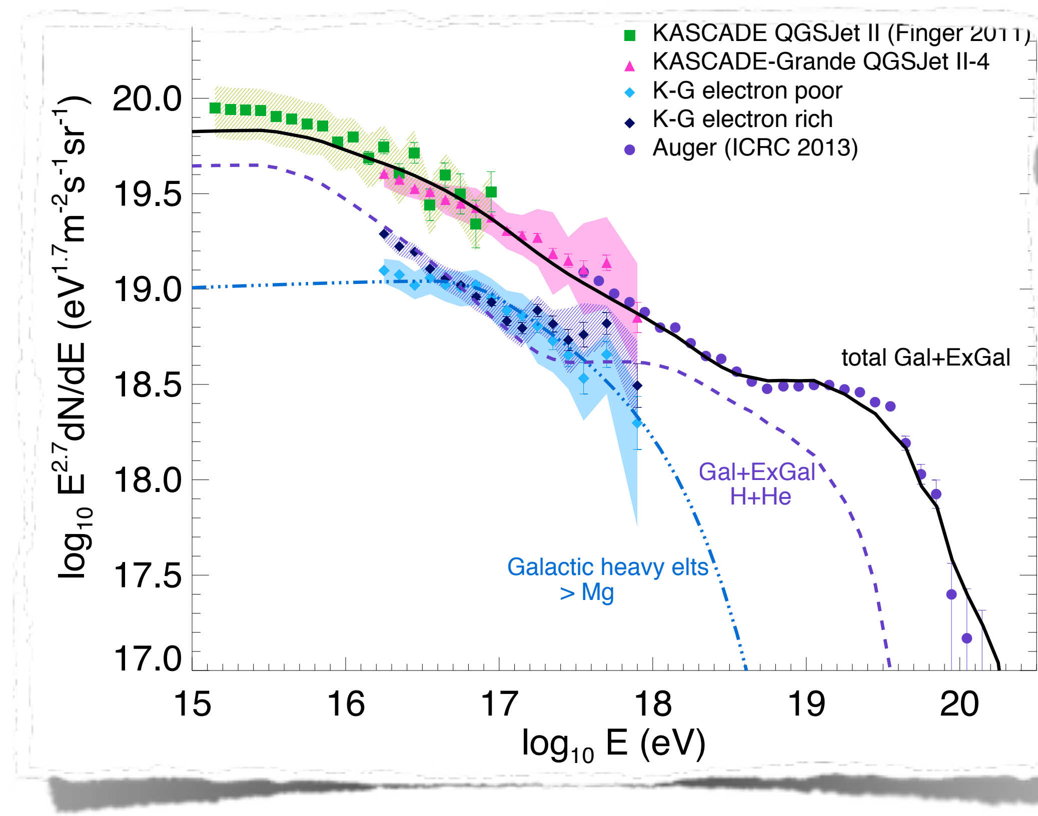
An attempt to go beyond phenomenology

- Existence of peculiar sources? e.g. pulsars can generate very hard spectra of mixed nuclei (Kotera et al. 2015)
- Sources with peculiar (negative) cosmological evolution (Taylor et al. 2015)
- Injection spectra already modified by losses INSIDE the sources (Globus et al. 2015, Unger et al. 2015)
- Magnetic trapping near sources, possibly self-generated by UHECRs themselves (PB et al. 2015) or not (Aloisio+, 2011; Mollerach & Roulet 2013)
- Or may be data do not make sense...

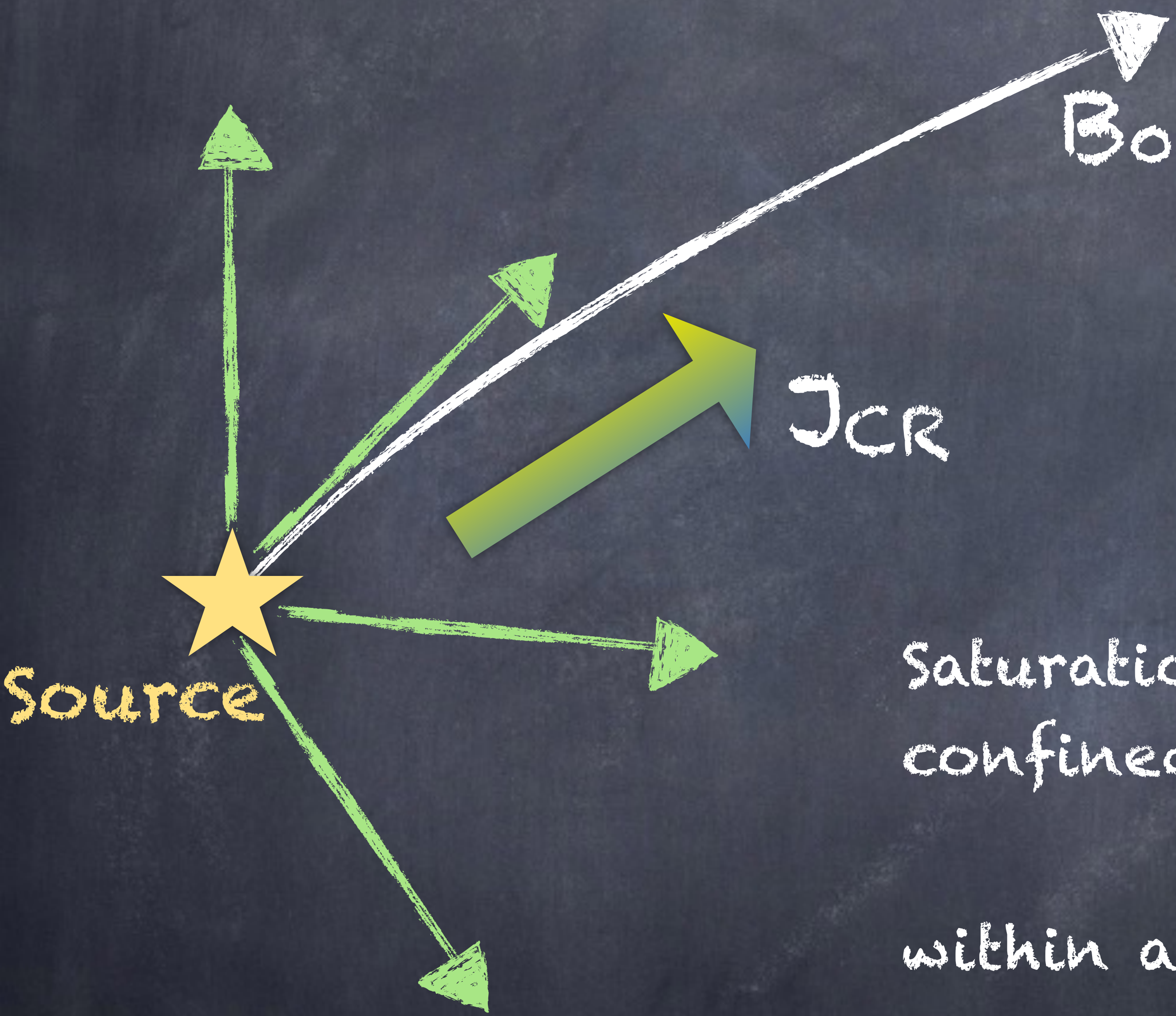
A physical model

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

Summary - I

- GCR start showing interesting features (in addition to the knee) —> Physics?
- Acceleration in SNRs <—> recent understanding… PeV only in special conditions and cutoff not exponential
- At present it is not easy to envision a way to reach >>PeV energies in SNRs (while retaining the same spectrum)
- Hence, GCR should end around 10^{17} eV with an Fe dominated chemical composition

Summary - II

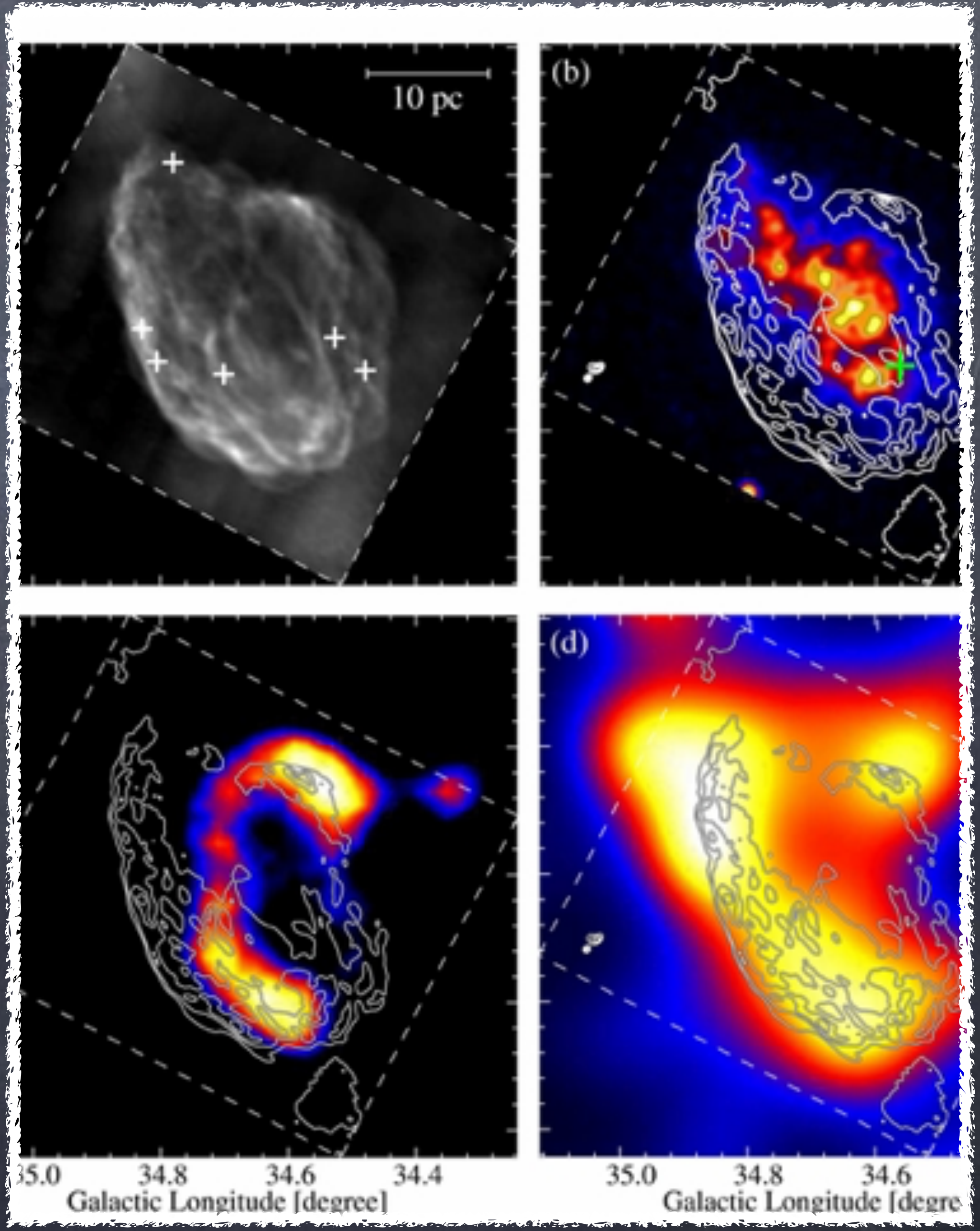
- Auger data force to require
  - Mixed composition
  - Hard spectra
  - E_{max}~5 EeV
  - Extra light-component with steep spectrum

- These could be manifestations of either unusual sources (pulsars) or losses in sources
- Transition region is complex with important Galactic and extragalactic contributions

Additional slides

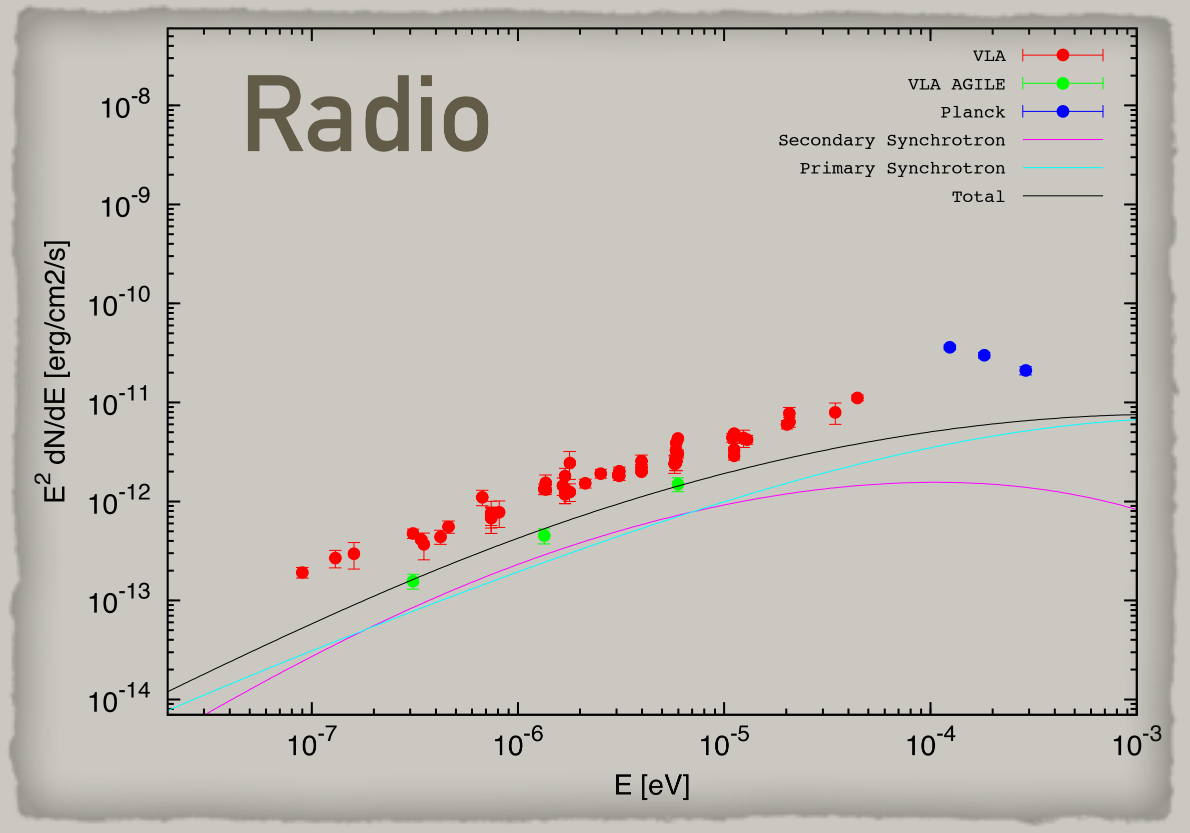
SNRs close to Molecular Clouds

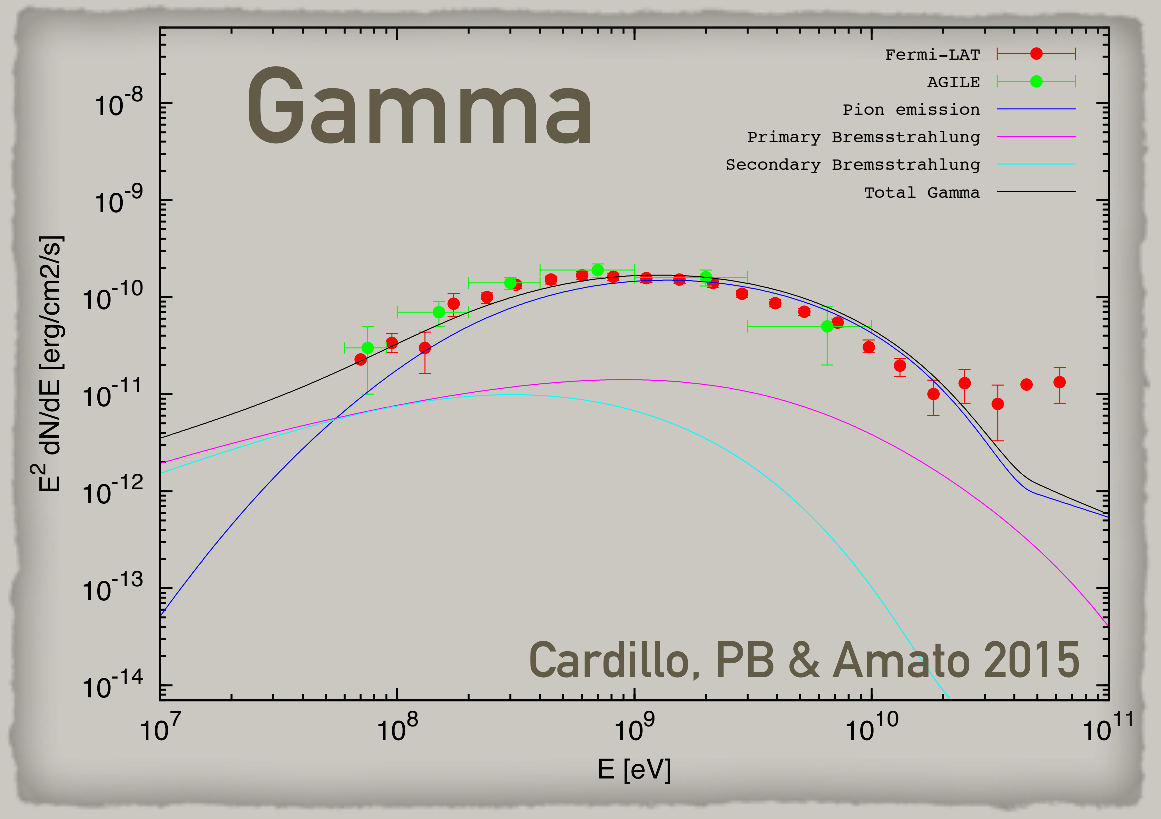
- γ-ray emission is hadronic
- Cases of W44 and IC443 very interesting
- Middle aged SNRs - Not much acceleration expected
- But lots of target material (pp)
- Propagation SNR -> cloud (W28)



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)

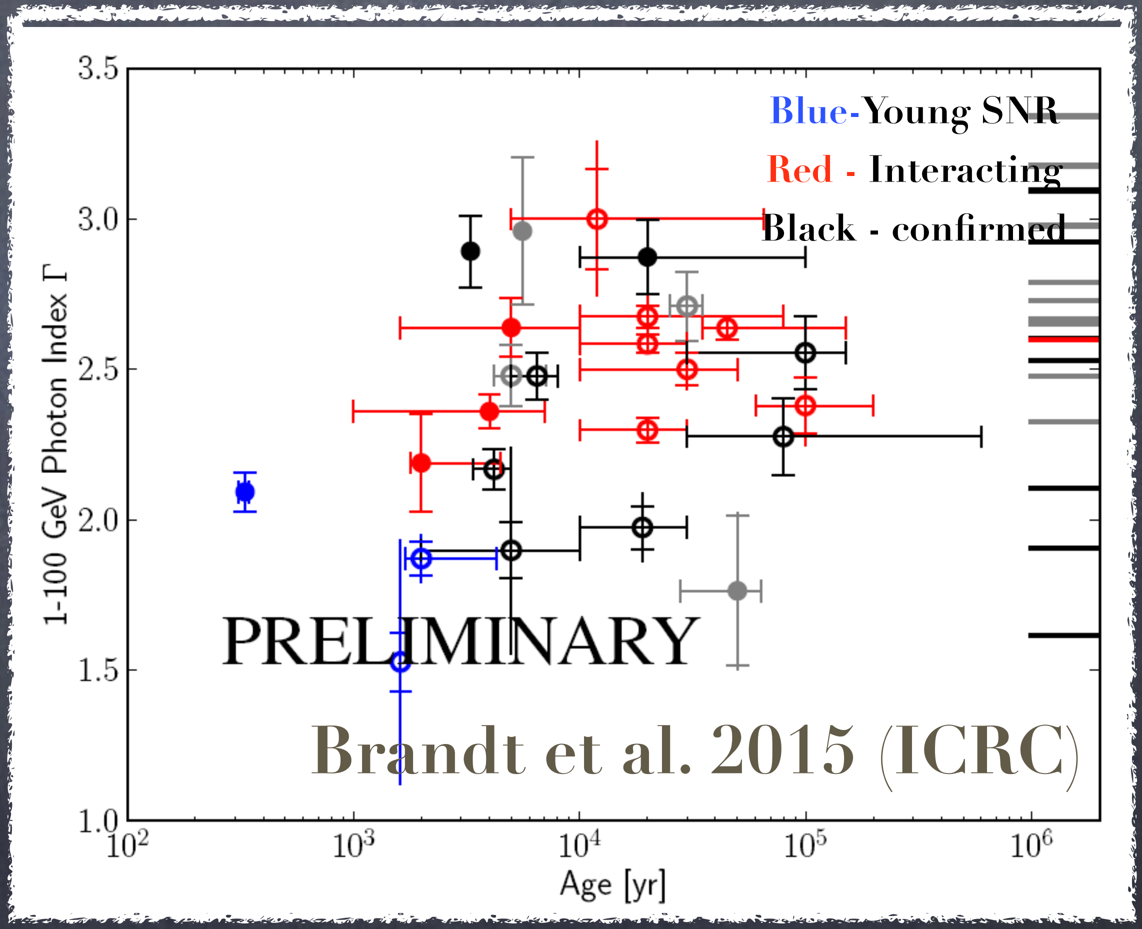




Both radio and gamma ray data appear to be perfectly well fitted if Galactic CRs are reaccelerated and compressed (Blandford & Cowie 1982)… The same conclusion previously reached by Uchiyama et al. 2010 and Lee et al. 2015, though with CR spectrum not normalised to Voyager and with no He + ad hoc steepening

Puzzling spectra?

- There are indications of spectra steeper than E^{-2} especially in older SNRs
- Steeper spectra are definitely a hint of hadronic origin, but not easy to reconcile with DSA
- They are even more at odds with NLDSA
- Very interesting the case of Tycho for which slope~2.3 (see above)



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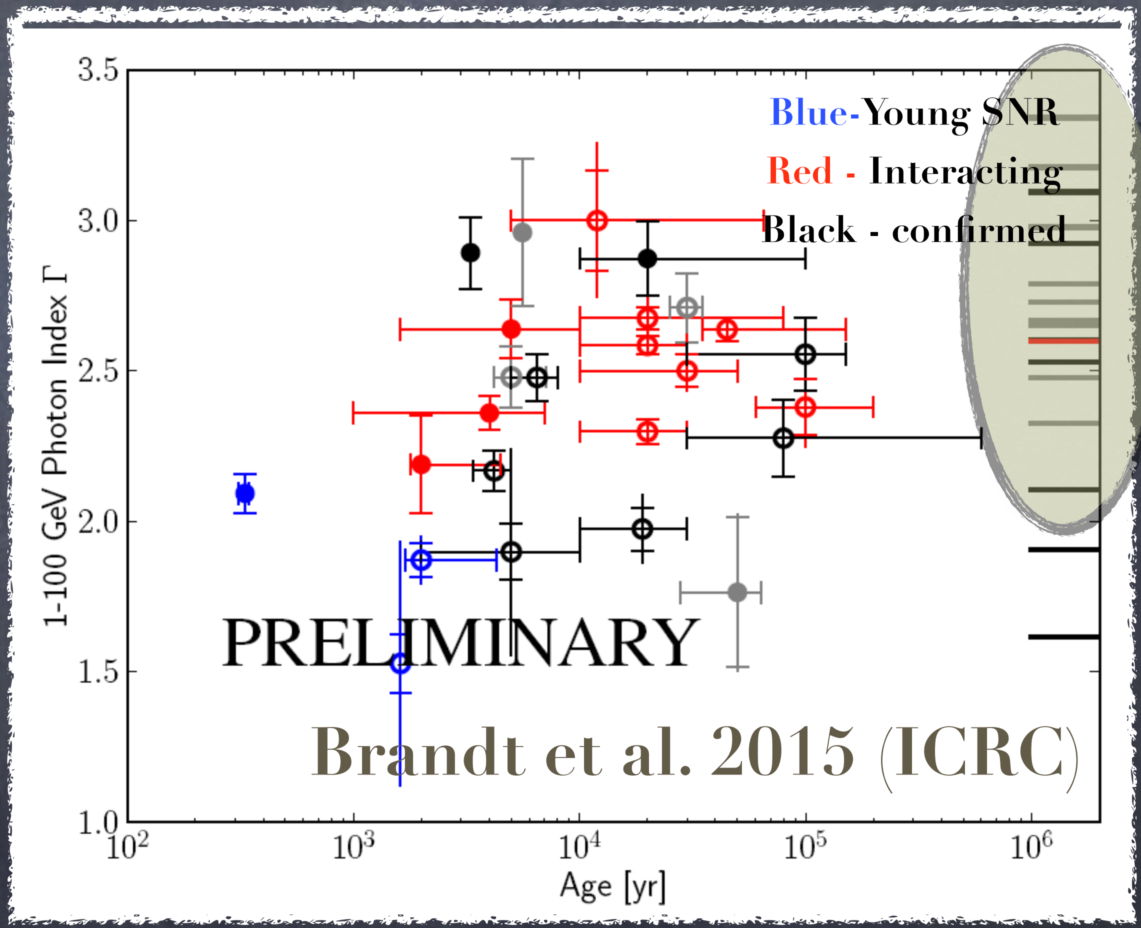
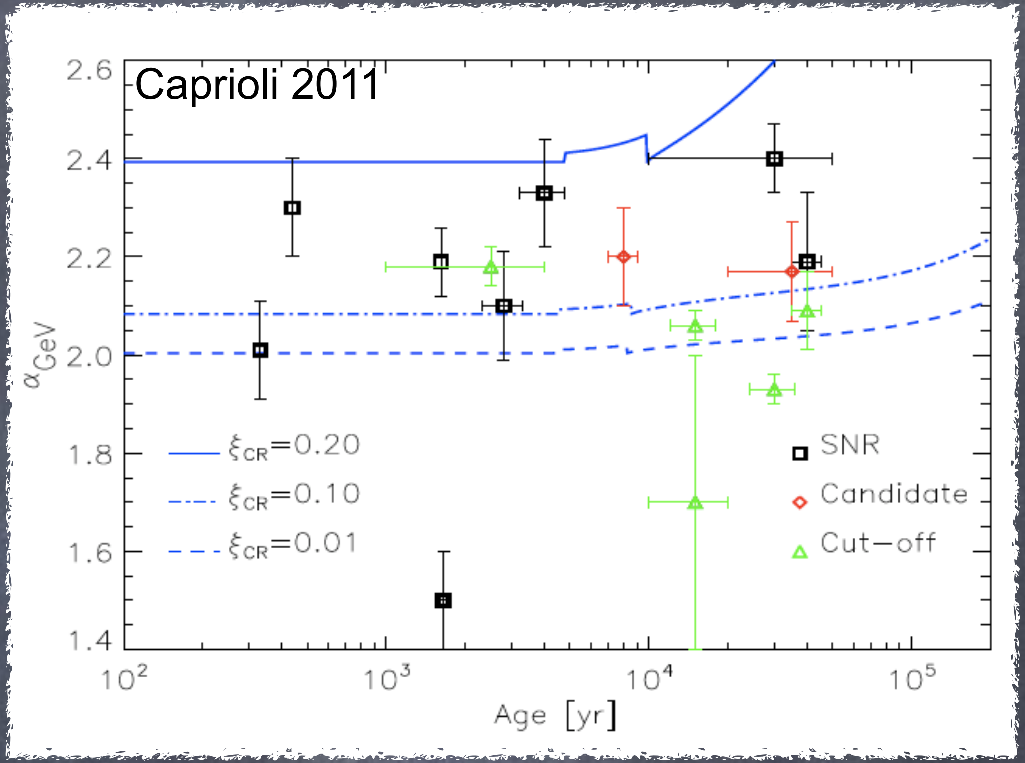
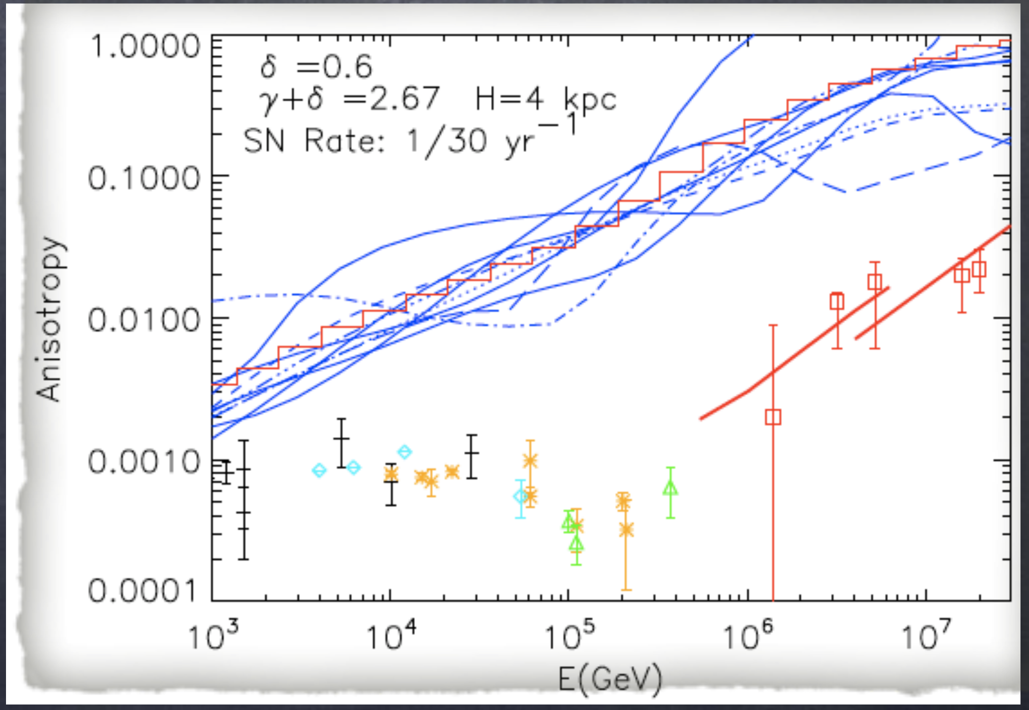


Puzzling spectra?

- ✓ Steeper spectra might be due to velocity of scattering centers (model dep)[Caprioli 2011]
- ✓ They also may be due to the presence of neutral hydrogen [PB + 2012]
- ✓ Again, be aware of morphology: even in type Ia there may be more neutrals on one side...
- ✓ On the other hand harder spectra are incompatible with anisotropy
- ✓ But recall that spectra of escaping CRs are different from inside...





PB & Amato 2012

Knee as a propagation effect

IT REQUIRES VERY HIGH E_{MAX} AND RARE SOURCES (HIGH EFFICIENCY)