

GAMMA RAYS AS A TOOL TO UNVEIL THE ORIGIN OF COSMIC RAYS

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OUTLINE

- **GAMMA RAYS FROM SUPERNOVA REMNANTS**
 - Acceleration of Galactic CR and local propagation around sources
- **GAMMA RAYS FROM CLOUDS IN THE GOULD BELT**
 - Propagation of Galactic CR
- **GAMMA RAYS FROM DISTANT AGN**
 - Effect of intergalactic magnetic fields
- **GAMMA RAYS AND UHECR**
 - Sources of UHECR

GAMMA RAYS FROM SNR

**ACCELERATION OF CR AND
PROPAGATION AROUND SOURCES**

BASICS OF PARTICLE ACCELERATION IN SNR

SNR SHOCKS ARE COLLISIONLESS → ONLY IONIZED GAS FEELS THE SHOCK AND ONLY IONS GET ACCELERATED

PARTICLES GAIN ENERGY THROUGH REPEATED PASSAGES ACROSS THE SHOCK THE SHOCK SURFACE

THE DYNAMICAL REACTION OF ACCELERATED PARTICLES ON THE SHOCK CHANGE THE SHOCK STRUCTURE → **THE ACCELERATION PROCESS TURNS NON-LINEAR**

THE TRANSPORT OF ACCELERATED PARTICLES WITH THE SHOCK CREATES A CURRENT WHICH INDUCES CR-INDUCED PLASMA INSTABILITIES → **MAGNETIC FIELD AMPLIFICATION**

THE AMPLIFIED B-FIELD EXERTS A NON-LINEAR DYNAMICAL REACTION ON THE SHOCK



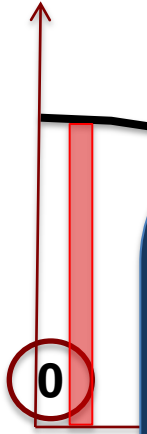
ACCELERATED PARTICLES CHANGE THE CONDITIONS IN WHICH THEY GET ENERGIZED

NON LINEAR THEORY: BASIC PREDICTIONS

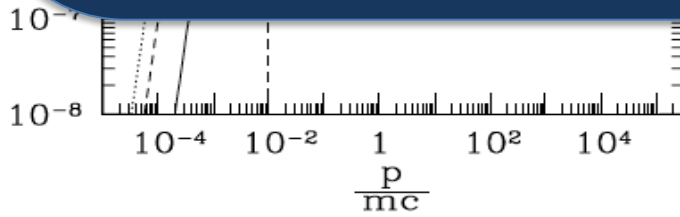
VELOCITY
PROFILE

CHALLENGES:

1. DIFFICULT TO REACH VERY HIGH ENERGIES
2. SPECTRA ARE TYPICALLY VERY HARD... POSSIBLE PROBLEM WITH ANISOTROPY



$$\left(\frac{p}{mc}\right)^4 \frac{f(p)}{n_0} (mc)^3$$



R BECOMES

FECT
(E)

K IS
SHOCK

B-FIELD
ICIENT

TES !!!

X-RAY RIMS AND B-FIELD AMPLIFICATION

TYPICAL THICKNESS OF FILAMENTS: $\sim 10^{-2}$ pc

The synchrotron limited thickness is:

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



$$B \approx 100 \mu\text{Gauss}$$

$$E_{max} \approx 10 B_{100}^{-1/2} u_8 \text{ TeV}$$

$$\nu_{max} \approx 0.2 u_8^2 \text{ keV}$$

In some cases the strong fields are confirmed by time variability of X-rays
Uchiyama & Aharonian, 2007

MAXIMUM ENERGY

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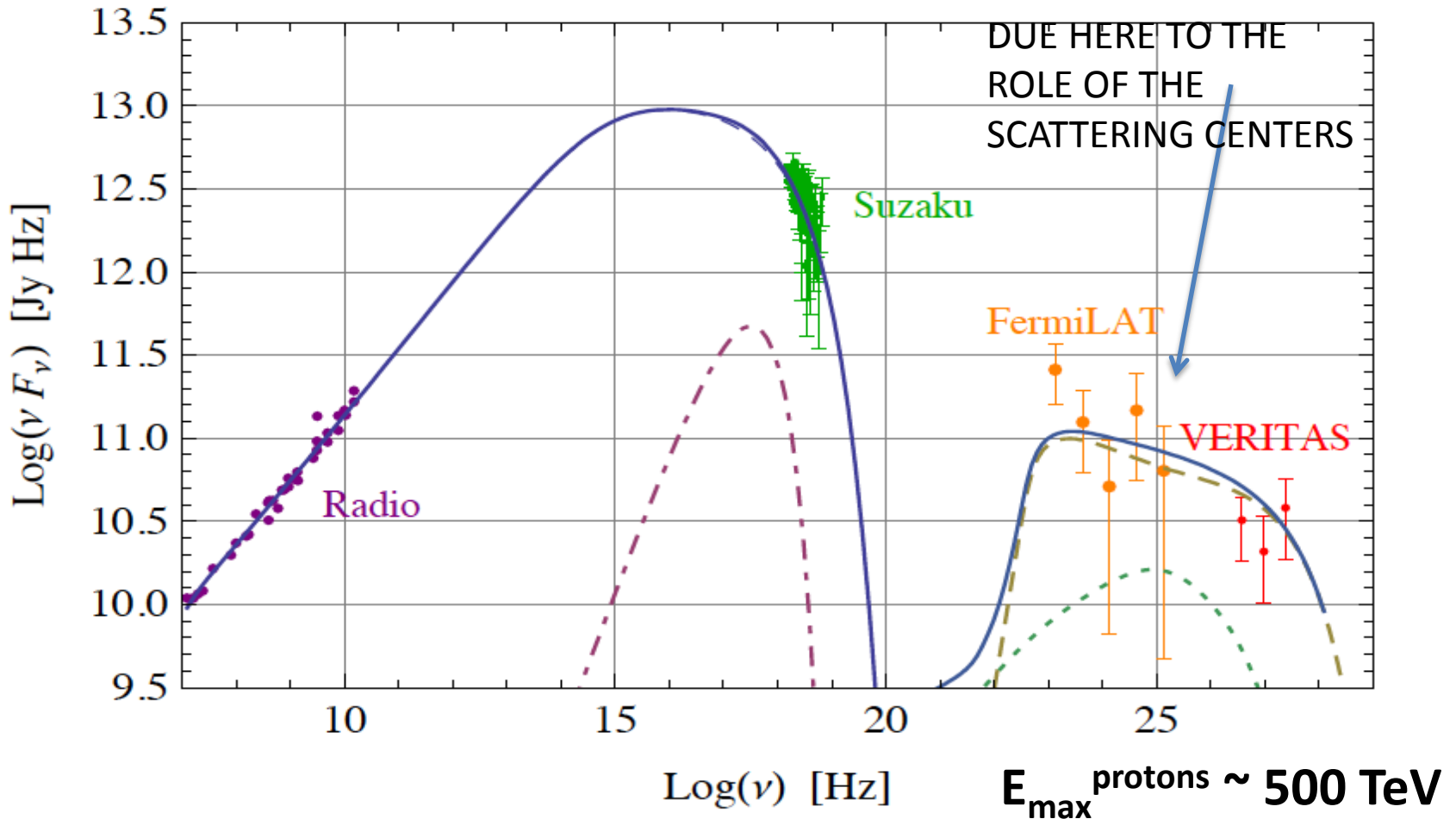
**EFFICIENT CR ACCELERATION IN SNR
REQUIRES GENERATION OF TURBULENCE
INDUCED BY THE SAME ACCELERATED
PARTICLES THROUGH CR DRIVEN
STREAMING INSTABILITY**

LENCE

THE CASE OF TYCHO

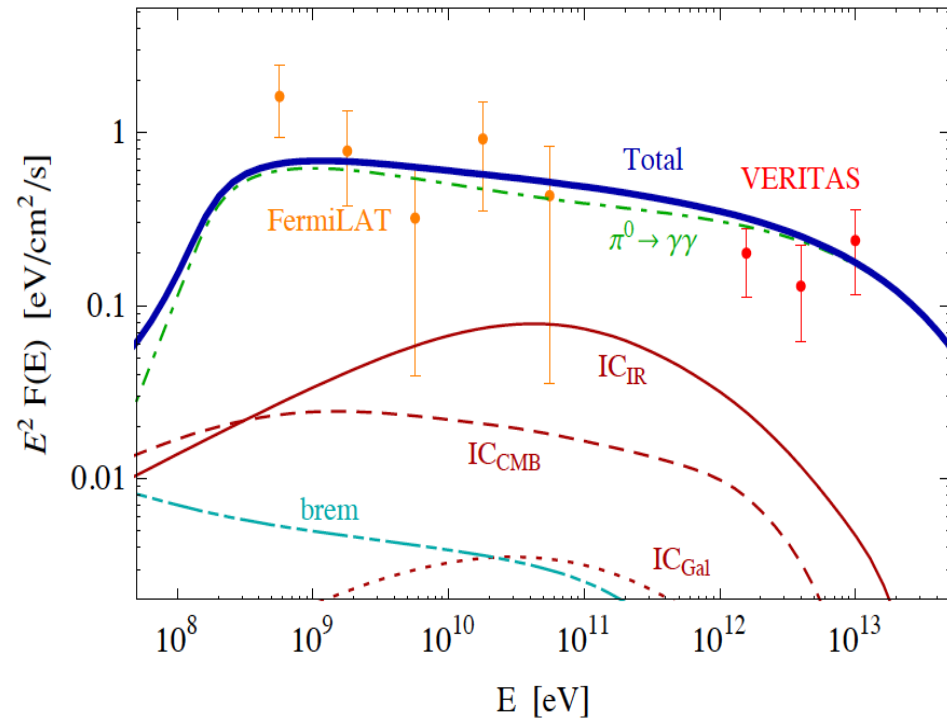
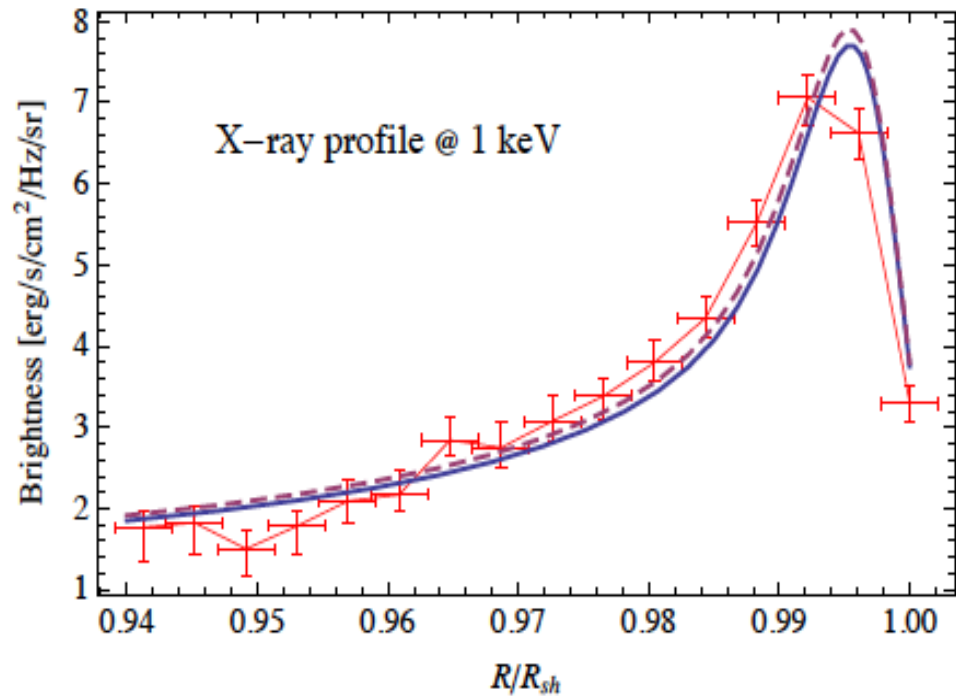
Morlino&Caprioli 2011

**STEEP SPECTRUM HARD
TO EXPLAIN WITH LEPTONS**



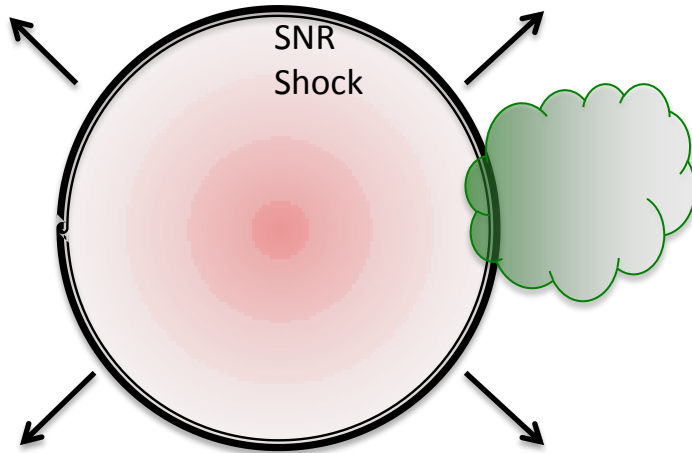
THE CASE OF TYCHO

Morlino&Caprioli 2011



THE CASE OF MOLECULAR CLOUDS

Scenario n. 1: shock enters the cloud



THE SHOCK BECOMES COLLISIONAL ON SCALES:

$$\lambda \approx \frac{1}{n_{cloud}\sigma_{mol}} \sim 10^{10} \left(\frac{n_{cloud}}{10^4 cm^{-3}} \right)^{-1} \left(\frac{\sigma_{mol}}{10^{-14} cm^2} \right)^{-1} cm$$

THIS IMPLIES THAT THE SHOCK SLOWS DOWN SINCE IT FEELS THE LOAD OF THE GAS IN THE CLOUD (CONFIRMED BY OH MASER OBSERVATIONS)

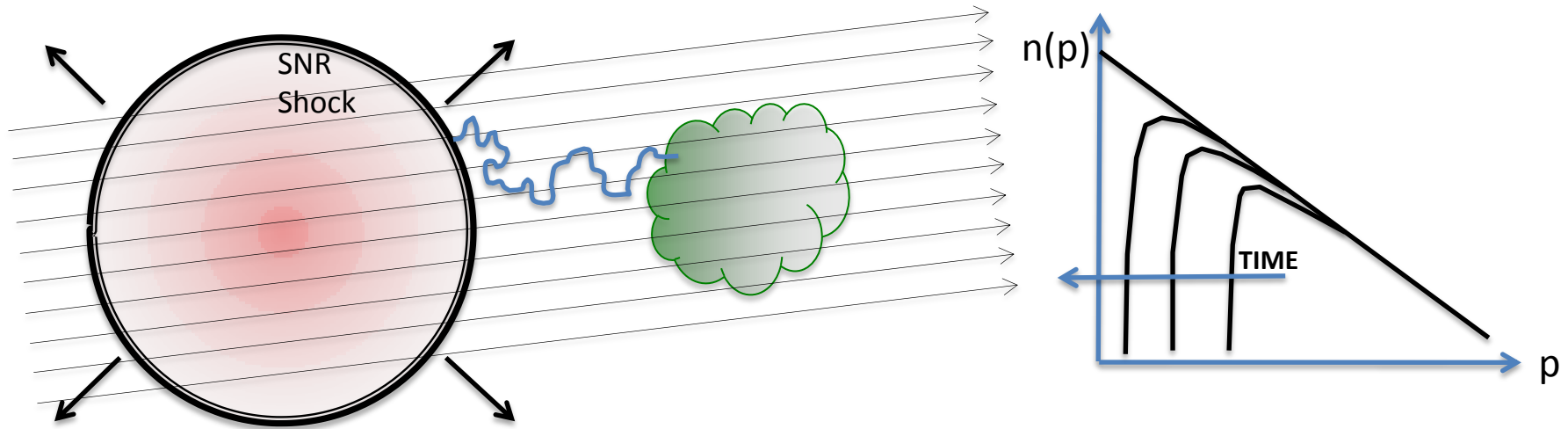
THE LARGE DENSITY OF NEUTRALS (LARGE TARGET DENSITY FOR pp) CAUSES EFFICIENT ION-NEUTRAL DAMPING

WAVES ARE HARD TO EXCITE INSIDE THE CLOUD, THEREFORE ACCELERATION IS LIKELY TO BE SUPPRESSED AND PARTICLE SHOULD STREAM AWAY EASILY

GAMMA RAY EMISSION FROM PARTICLES ACCELERATED AT PREVIOUS TIMES AND TRYING TO LEAVE

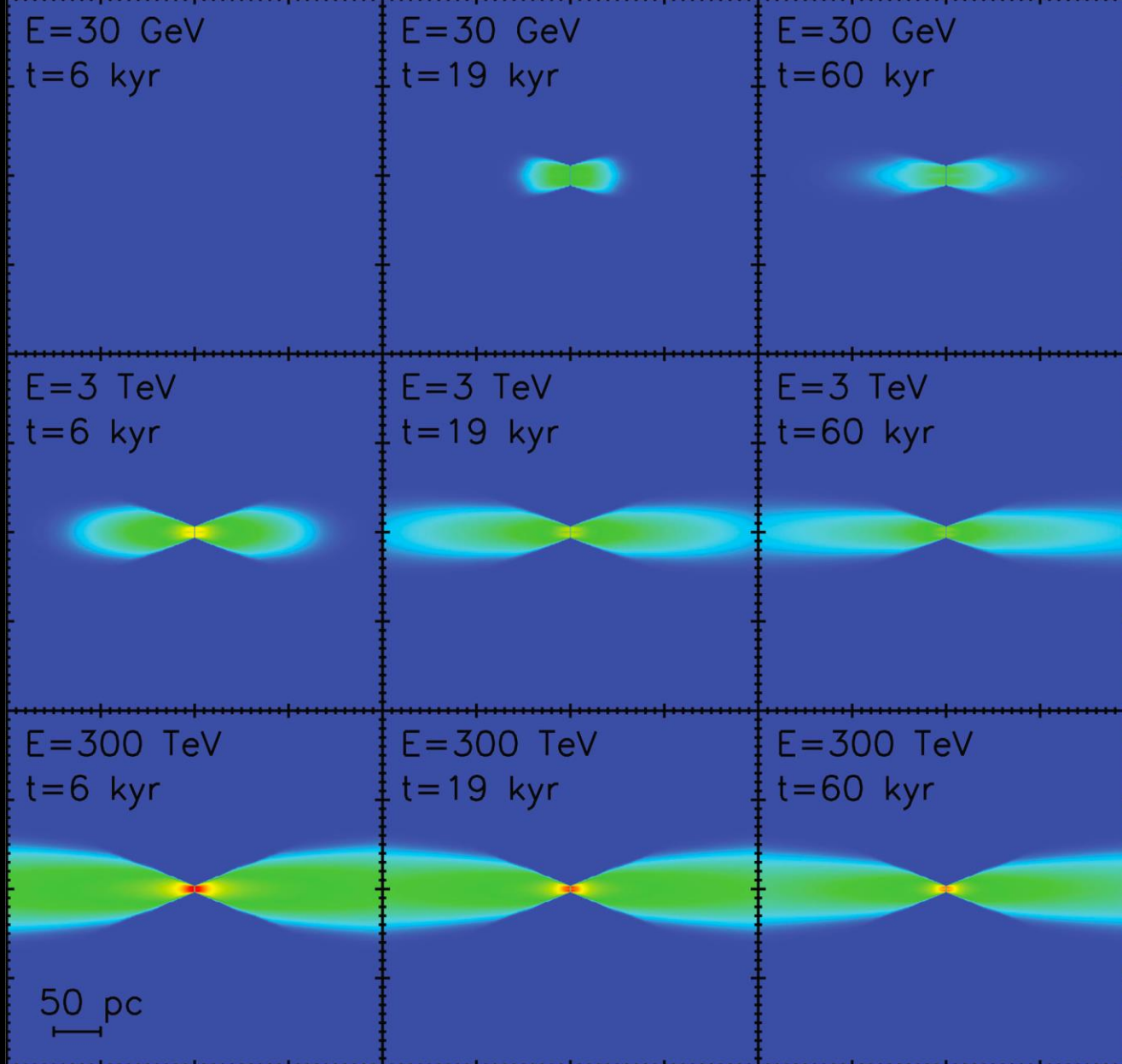
THE CASE OF MOLECULAR CLOUDS

Scenario n. 2: shock away from the cloud

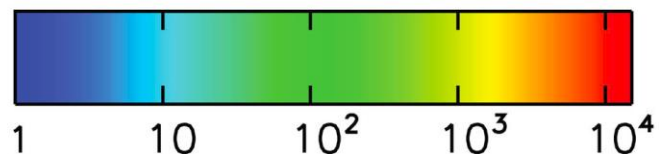


THE SPECTRUM OF PARTICLES THAT REACHES THE CLOUD IS A FUNCTION OF THE AGE OF THE SNR AND AT ANY GIVEN TIME IT HAS A LOW ENERGY CUTOFF AT THE MAXIMUM ENERGY REACHED AT THAT GIVEN TIME

THESE SITUATIONS ARE IDEAL TO INVESTIGATE PROPAGATION OF CR CLOSE TO THEIR SOURCES, WHICH ARE MOST LIKELY AFFECTED BY STRONG CR FEEDBACK!



Nava & Gabici 2013

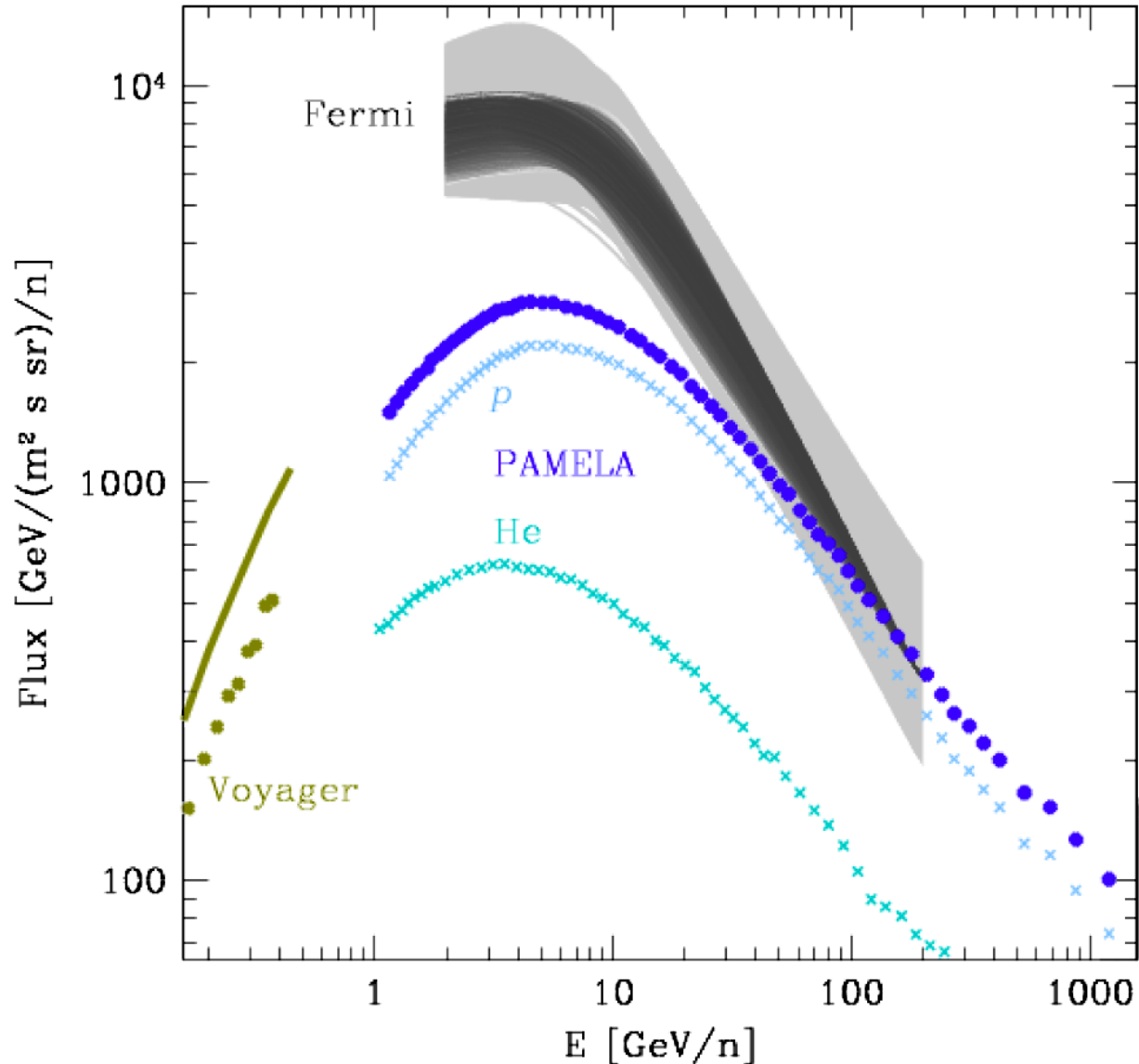


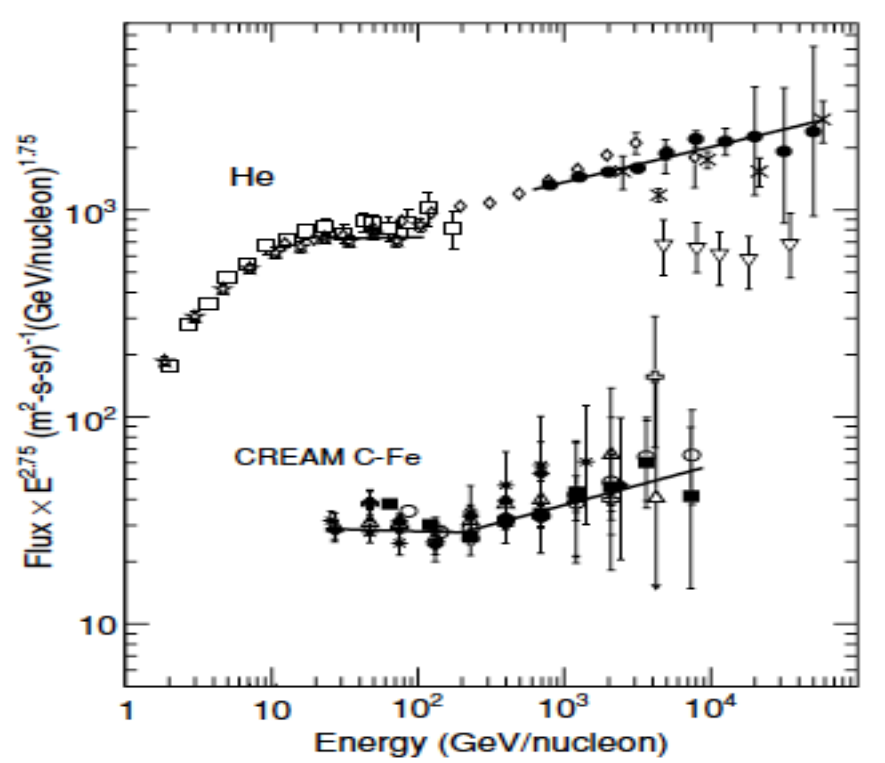
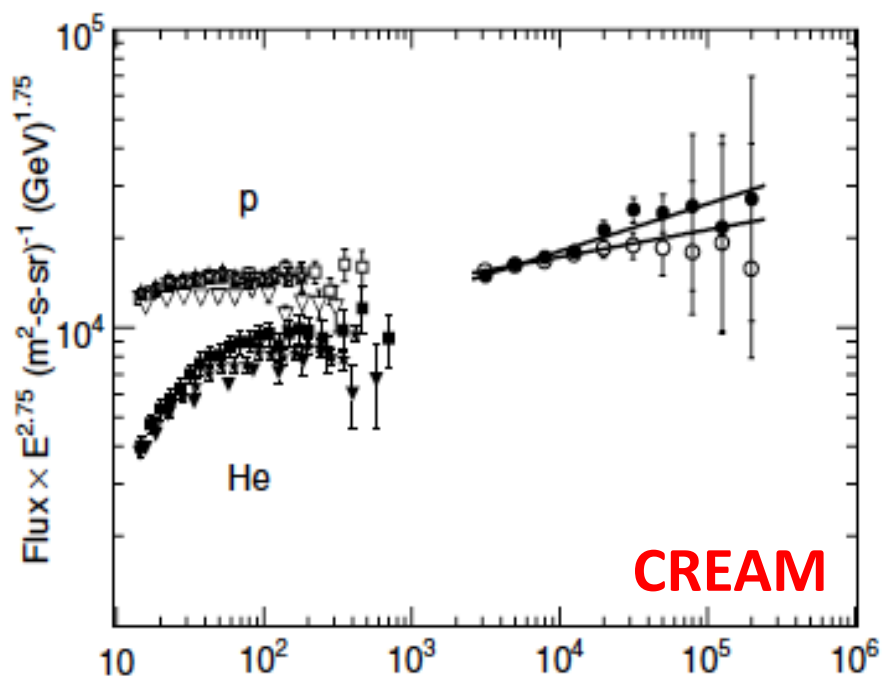
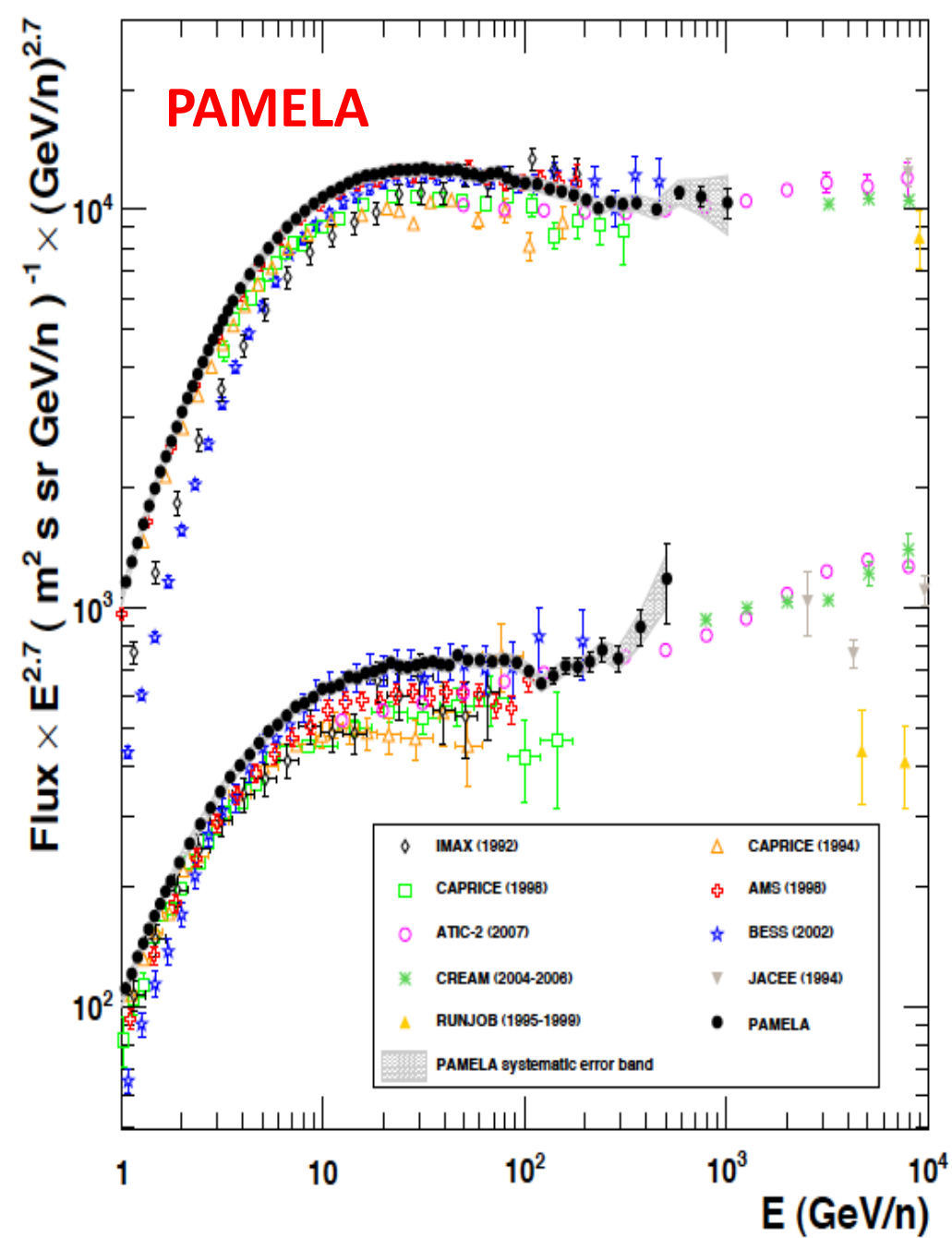
GAMMA RAYS FROM MOLECULAR CLOUDS FAR FROM SOURCES

PROPAGATION OF GALACTIC COSMIC RAYS

GAMMA RAYS FROM CLOUDS IN THE GOULD BELT

Neronov et al. 2012, Kachelriess & Ostapchenko 2012





CR FEEDBACK ON PROPAGATION

SIMILAR TO WHAT HAPPENS INSIDE THE ACCELERATION ZONE, CR GENERATE WAVES IN THE ISM WHILE PROPAGATING IN A DIFFUSIVE MANNER, DUE TO STREAMING INSTABILITY, WITH GROWTH:

$$\Gamma_{CR} = \frac{16\pi^2}{3} \frac{v_A}{B_0^2 \mathcal{F}(k_{res})} \left[p^4 v(p) \frac{\partial f}{\partial z} \right]_{p_{res}(k)}$$

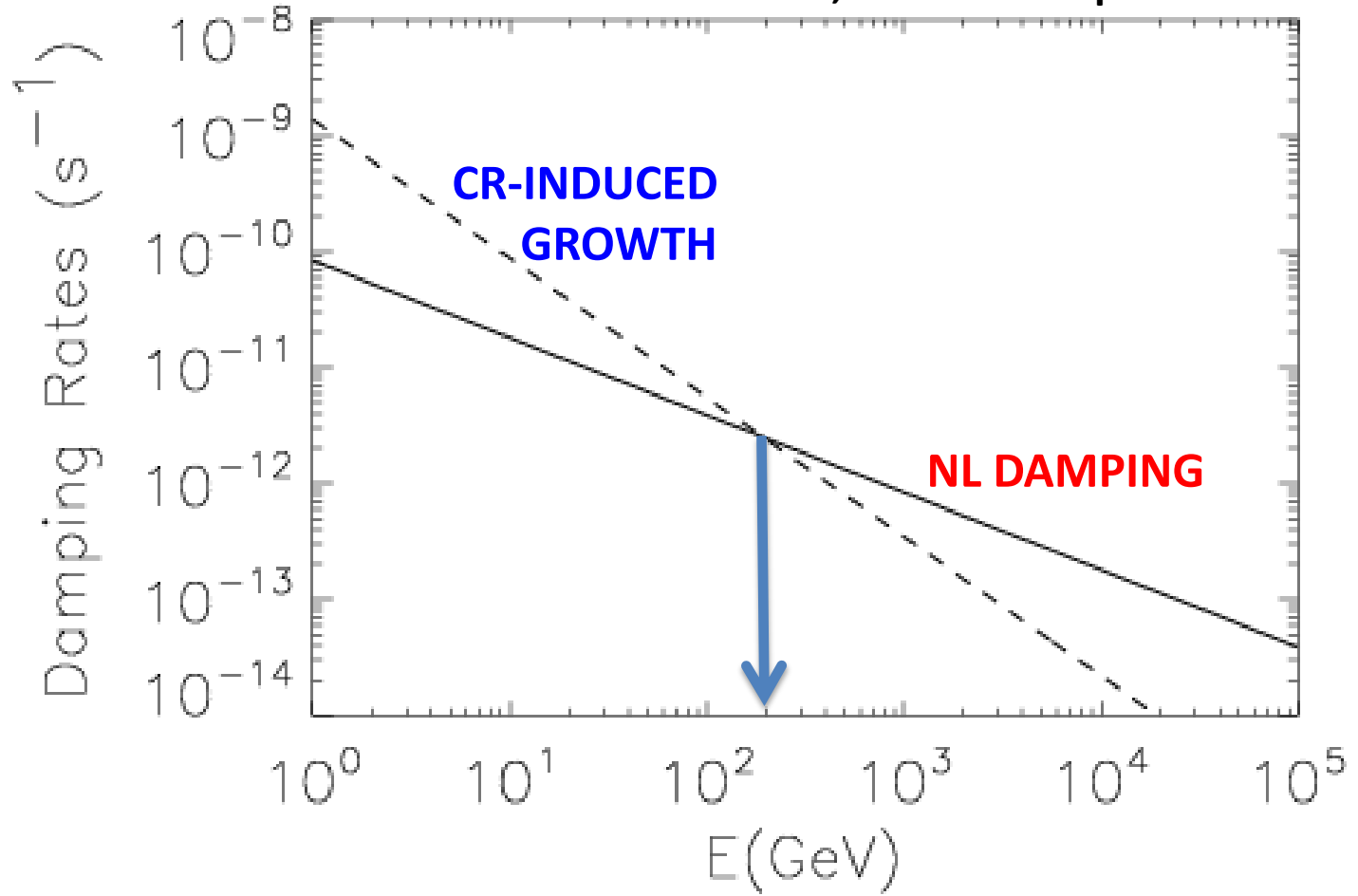
WHICH ACCOUNTS FOR DIFFUSION COEFFICIENT:

$$D(p) \approx \frac{1}{3} r_L v(p) \frac{1}{\mathcal{F}(k_{res})}$$

WAVES FIGHT AGAINST DAMPING...

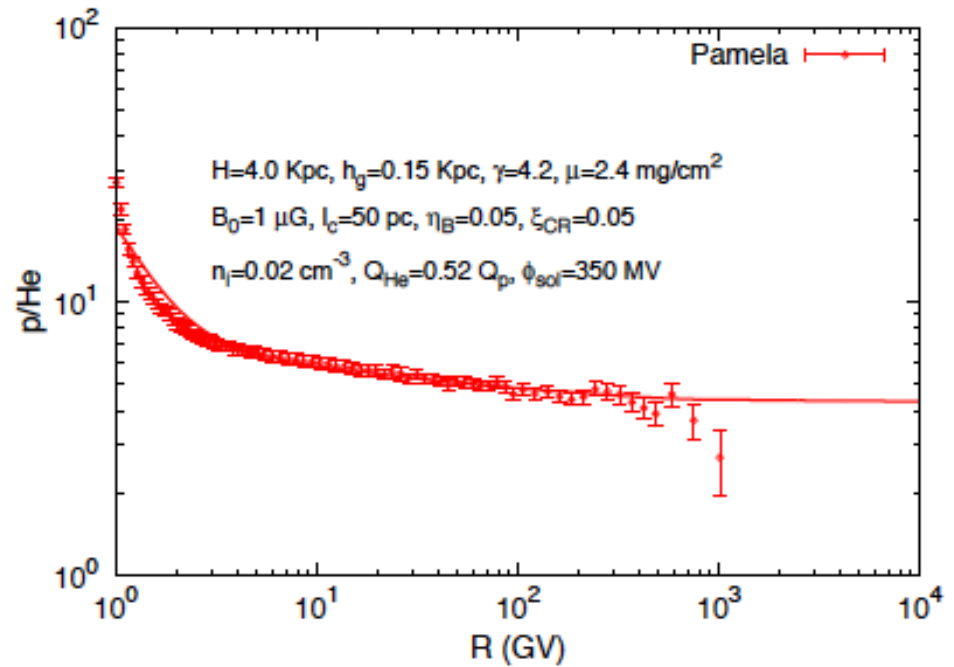
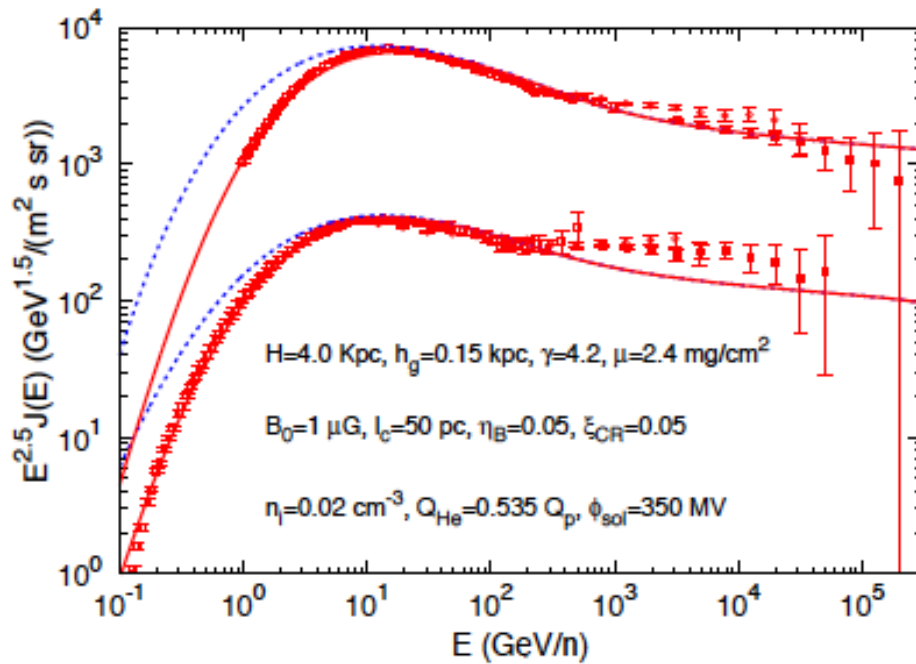
DAMPING vs CR-INDUCED GROWTH

PB, Amato & Serpico 2013



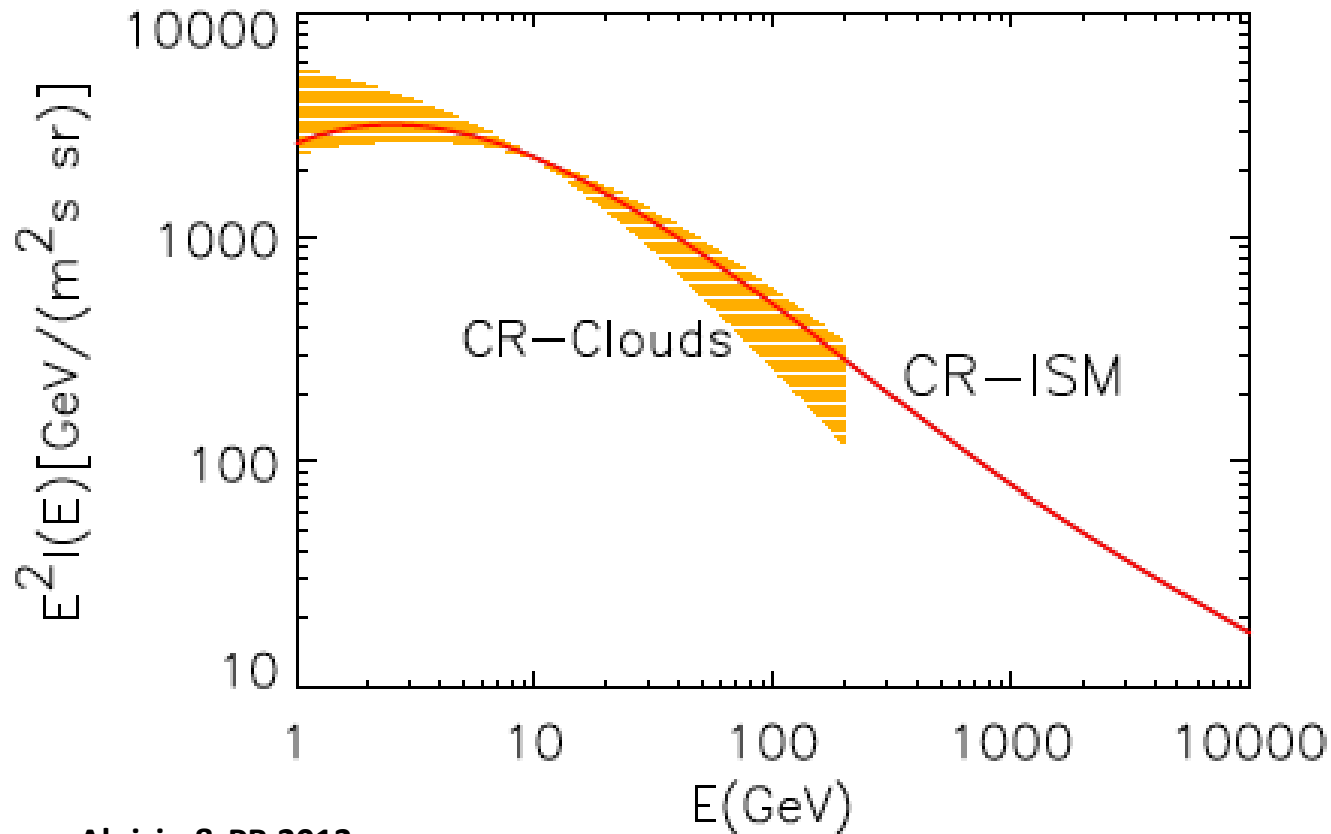
AT ENERGIES BELOW 200 GeV THE WAVES GROW FASTER THAN THEY ARE DAMPED AND THE QUESTION OF THE SELF-GENERATED D(E) IS WELL POSED.

PROTONS AND HELIUM NUCLEI



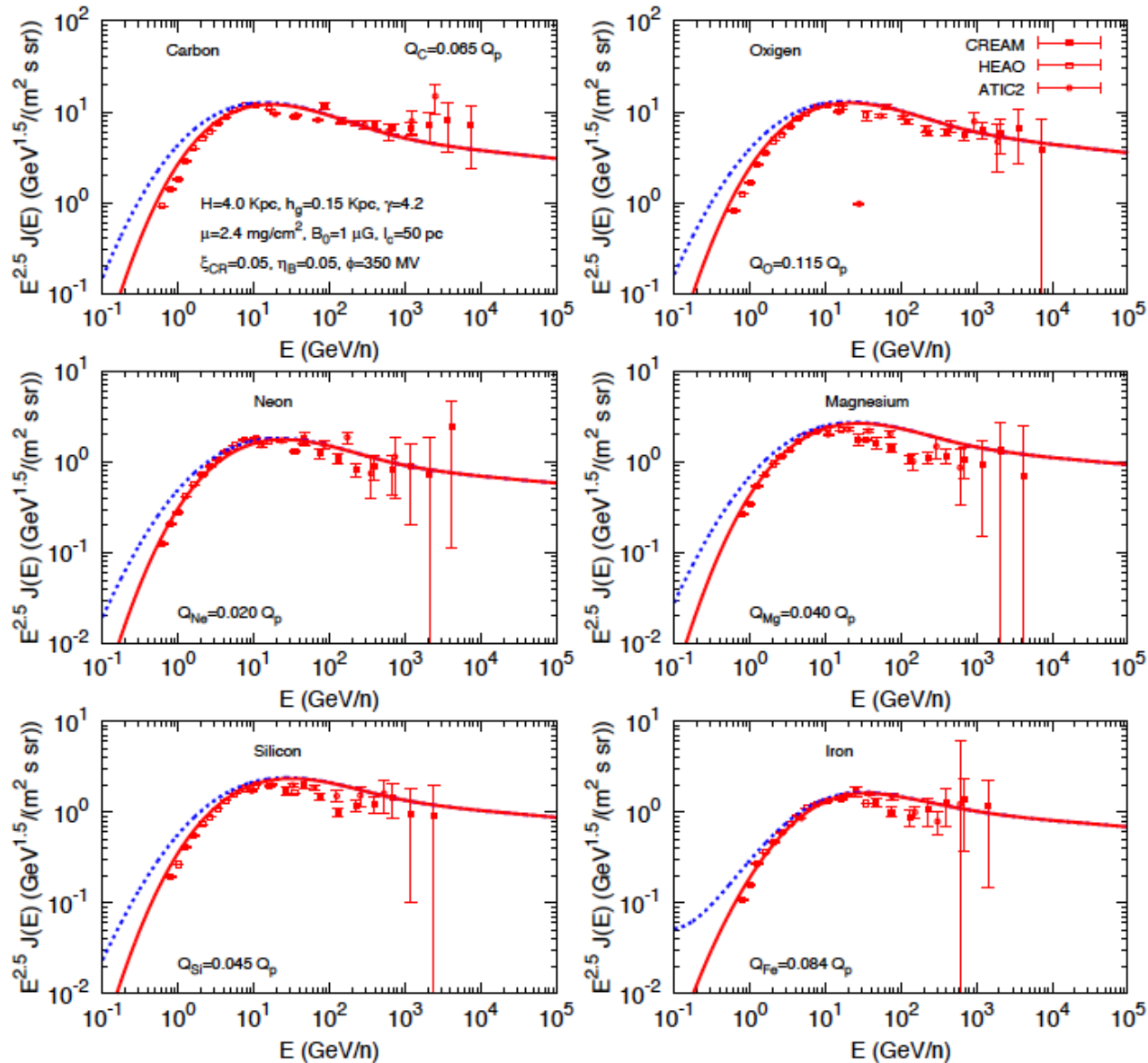
GAMMA RAYS FROM CLOUDS IN THE GOULD'S BELT

(Neronov et al. 2012, Kachelriess & Ostapchenko 2012)

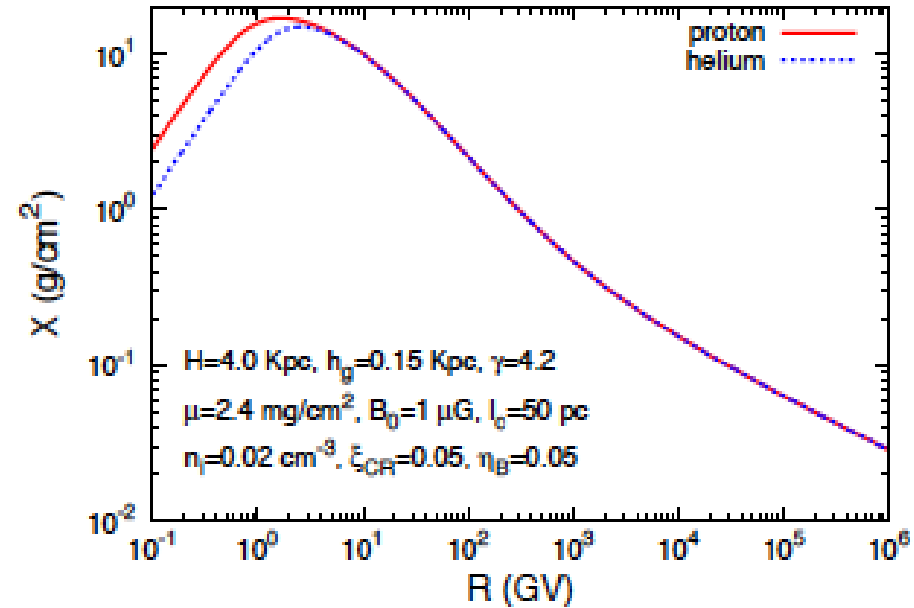
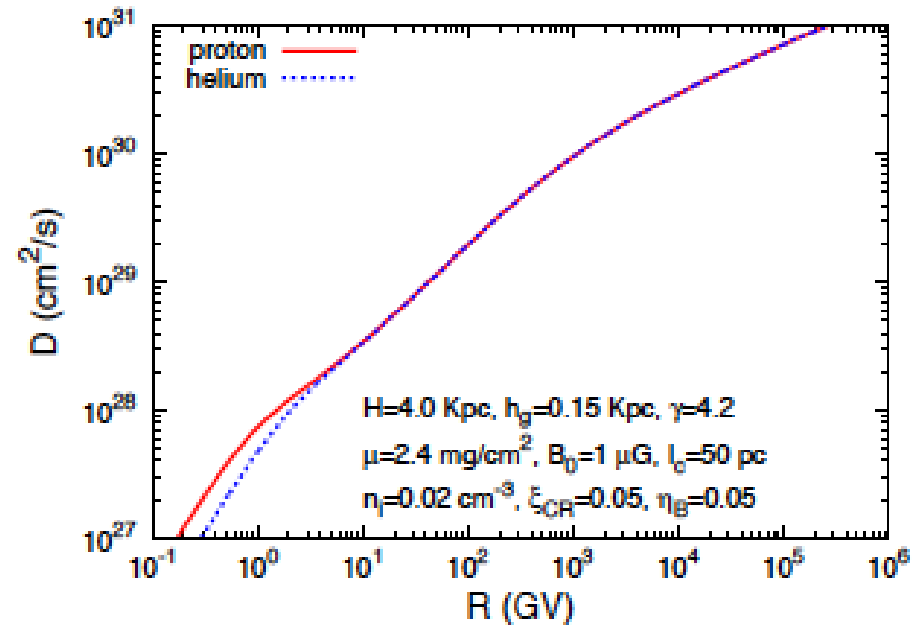


Aloisio & PB 2013

SPECTRA OF HEAVIER NUCLEI

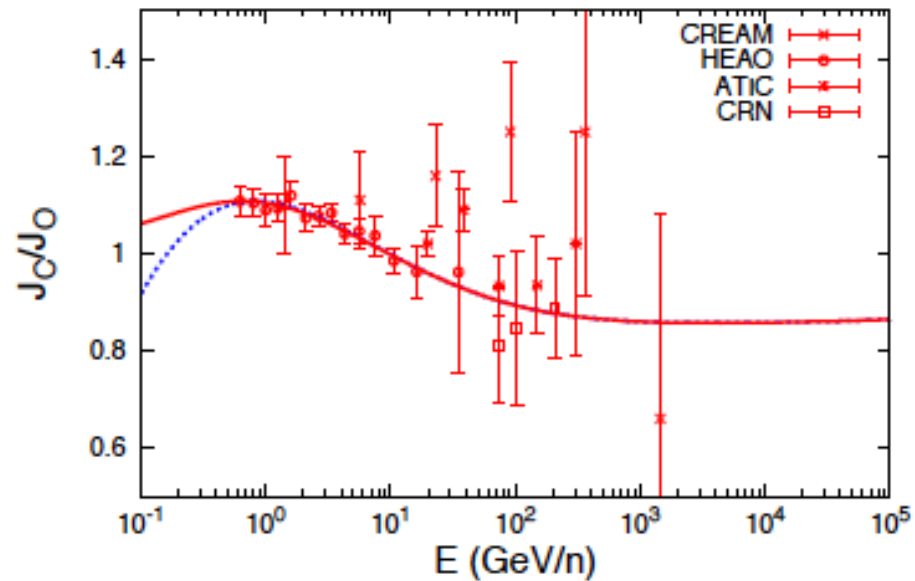
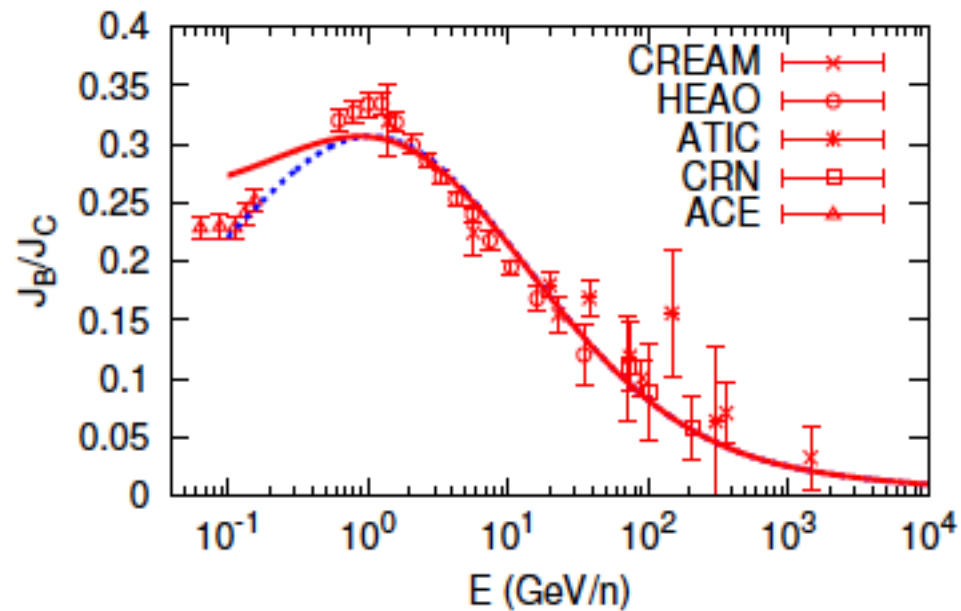


GRAMMAGE AND DIFFUSION



SECONDARY/PRIMARY AND PRIMARY/PRIMARY

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GAMMA RAYS AND CASCADING

MAGNETIC FIELD IN THE IGM

EM CASCADE

THE UNIVERSE IS OPAQUE TO VERY HIGH ENERGY PHOTONS DUE TO THE PROCESS OF PAIR PRODUCTION IN EBL

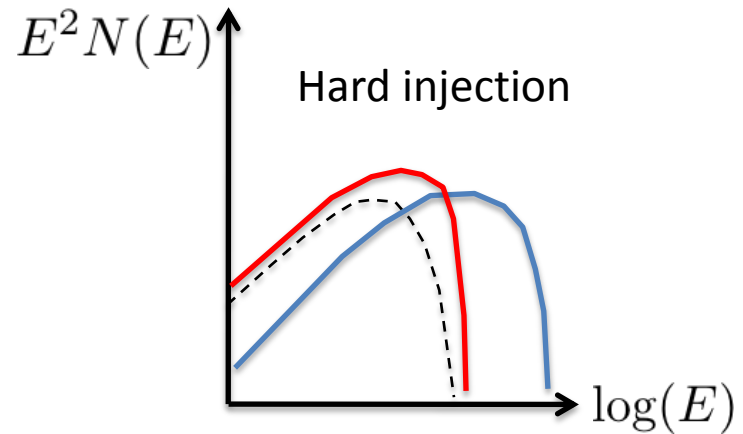
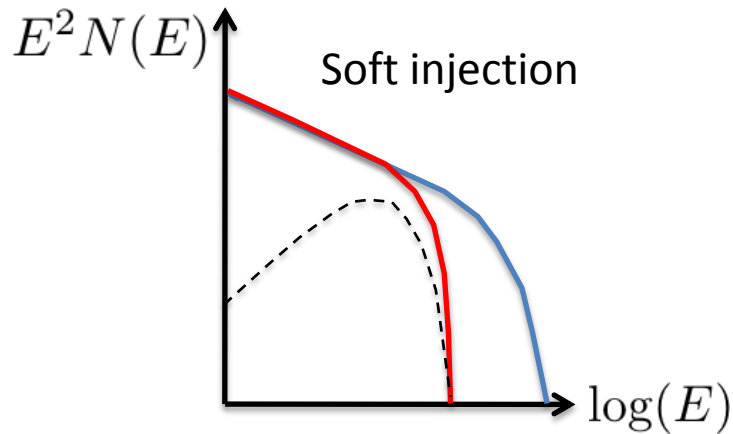
$$E_{\gamma} \epsilon_{EBL} = m_e^2 \rightarrow E_{\gamma} = 26 \text{ TeV} \left(\frac{\epsilon_{EBL}}{0.01 \text{ eV}} \right)^{-1}$$

THE ELECTRONS AND POSITRONS PRODUCED IN THIS PROCESS MAY LOSE ENERGY THROUGH ICS IN THE KLEIN-NISHINA REGIME AND THE PHOTONS MAY STILL BE ABOVE THRESHOLD FOR PAIR PRODUCTION... AND SO ON

AN E.M. CASCADE IS GENERATED THAT PROCEEDS THROUGH STANDARD ICS IN THE THOMPSON REGIME AT LOW ENERGY...

THE CASCADE GENERATES A ROUGHLY UNIVERSAL $E^{-3/2}$ GAMMA RAY SPECTRUM AT LOW ENERGIES

SOFT vs HARD



THE ENERGY IN THE FORM OF GAMMA RAYS ABOVE THRESHOLD FOR PAIR PRODUCTION IS RECYCLED INTO LOWER ENERGY PHOTONS

FOR HARD INJECTION SPECTRA THE SECONDARY GAMMA RAYS HAVE A FLUX THAT DOMINATES ABOVE THE PRIMARY FLUX

LOW ENERGY FLUX AFFECTED HOWEVER BY TIME DELAYS AND DEFLECTION OF ELECTRONS DUE TO B-FIELD

B-FIELD MODIFIED CASCADE

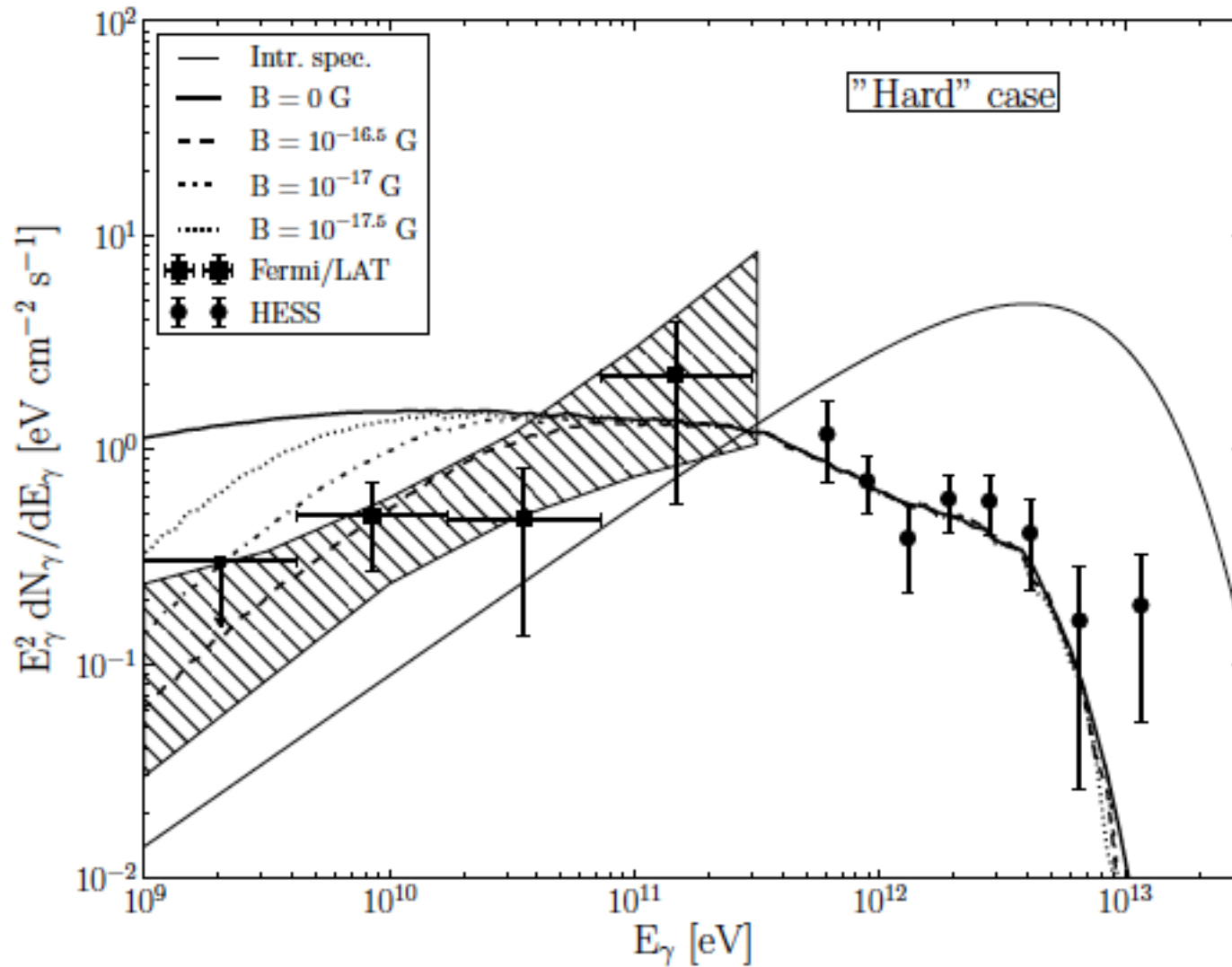
AFTER THE INITIAL PRODUCTION OF A PAIR ON THE OPTICAL/IR EBL, PAIRS PROPAGATE UNDER THE ACTION OF CS IN THE THOMPSON REGIME

$$\lambda_{ICS}(E) \approx 0.4 \text{ Mpc } E_{TeV}^{-1}$$

$$r_L(E) \approx 10 \text{ Mpc } E_{TeV} B_{-16}^{-1}$$

THE EFFECT OF THE MAGNETIC FIELD ON A ICS PHOTON WITH ENERGY 2 GeV E_{TeV}^2 BECOMES RELEVANT WHEN

$$\theta \sim \frac{\lambda_{ICS}}{r_L} \sim 2^\circ B_{-16} E_{TeV}^{-2} \sim PSF(E)$$

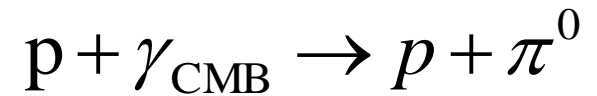
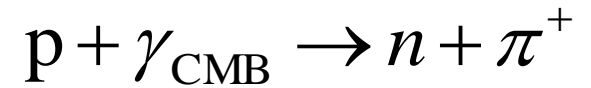
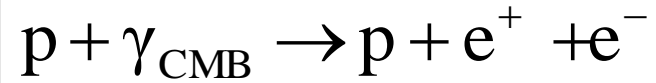
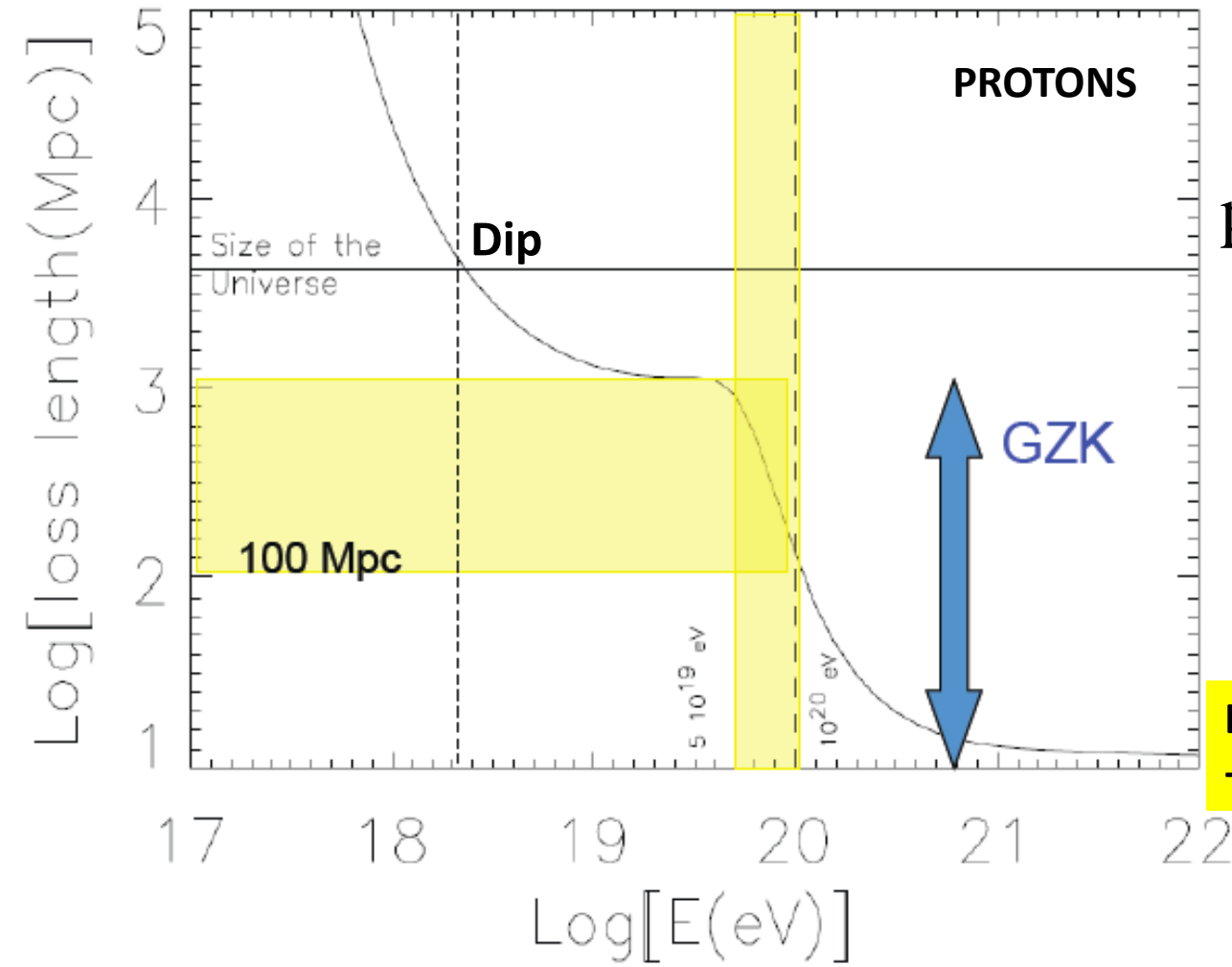


THE SYSTEMATIC DETECTION OF THESE EFFECTS WOULD REPRESENT A TERIFIC PROOF OF A IGM WITH SMALL LEVEL OF MAGNETIZATION WITH HUGE IMPLICATIONS FOR CR PHYSICS

GAMMA RAYS FROM CASCADES INITIATED BY UHECRs

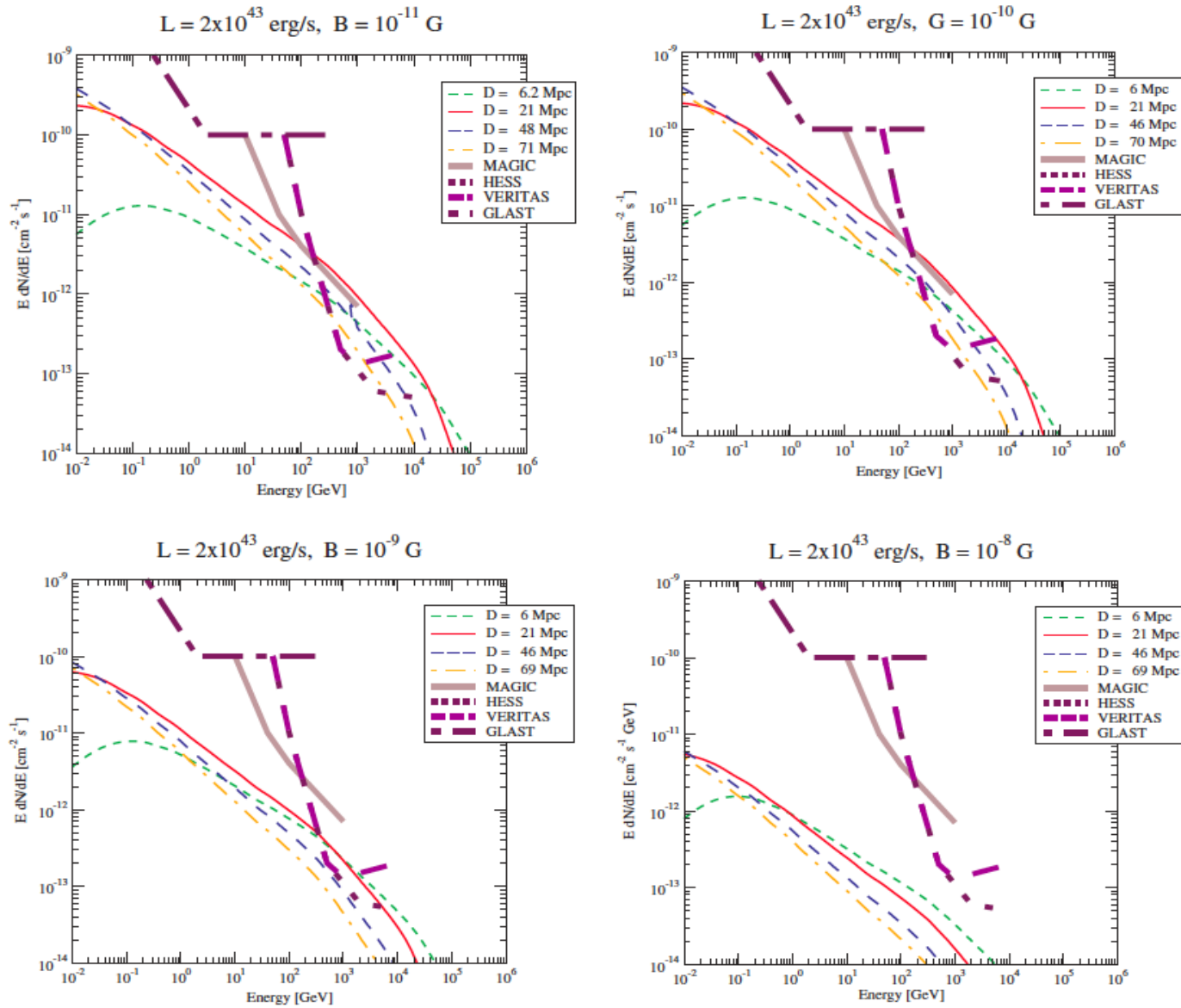
**SOURCES OF UHECRs, MAGNETIC FIELDS
IN THE IGM, CHEMICAL COMPOSITION**

UHECR LOSSES

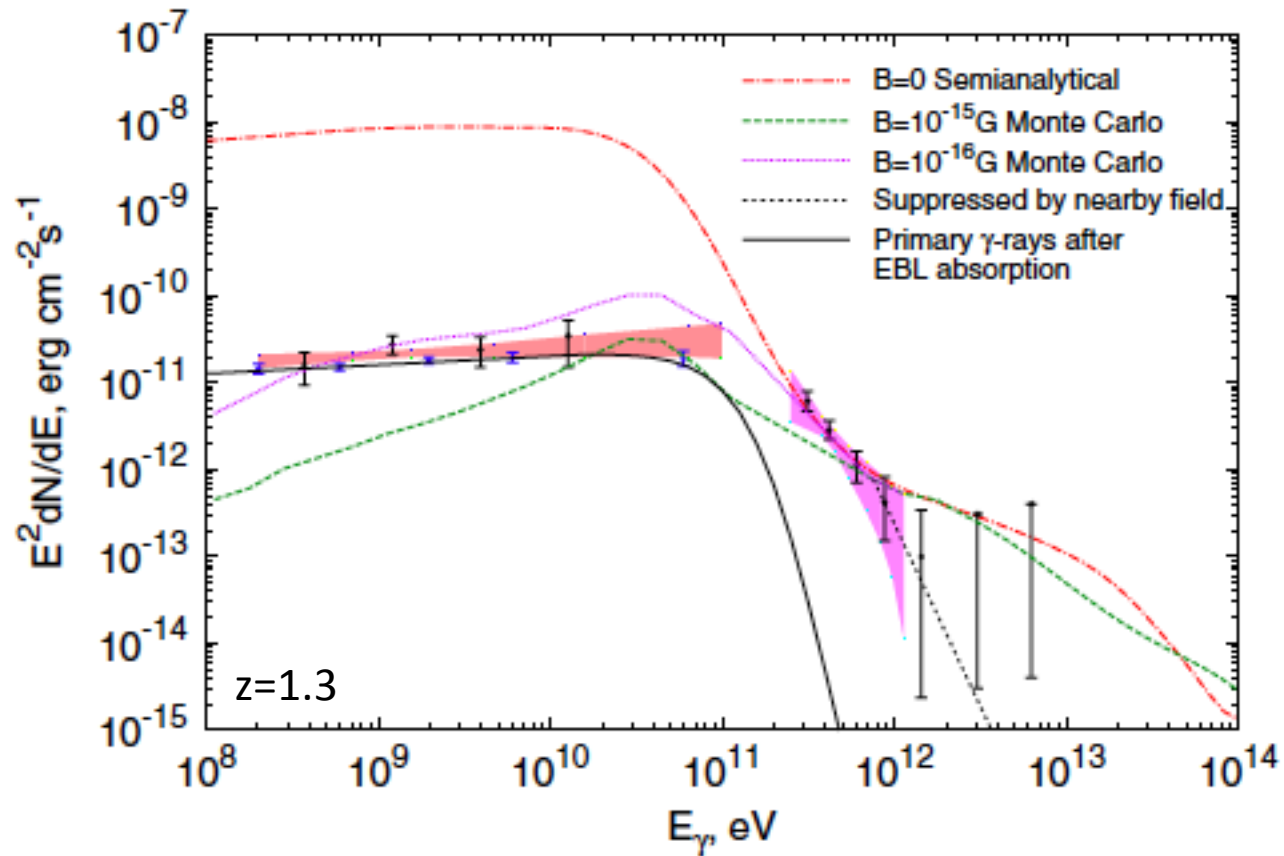


EM CASCADE ON RADIO + CMB
+ IR/OPTICAL LIGHT

UHECR-INDUCED E.M. CASCADES



UHECR-INDUCED E.M. CASCADES



Aharonian et al. 2013

SUMMARY

★ THE DETECTION OF GAMMA RAYS FROM YOUNG SNR PROVIDES EVIDENCE OF CR HADRONIC ACCELERATION ONLY IN VIRTUALLY ONE CASE (OTHERS COMPLICATED)

★ THE DETECTION OF GAMMA RAYS FROM MOLECULAR CLOUDS AROUND MATURE SNR PROVIDES REACH PHENOMENOLOGY → PROPAGATION OF ESCAPING CR

★ GAMMA RAYS ARE FINALLY ALSO SHEDDING SOME LIGHT ON THE ORIGIN OF EXTRAGALACTIC CR, THROUGH THE DEVELOPMENT OF E.M. CASCADES

★ THE REGION THAT STILL REMAINS SOMEWHAT HIDDEN IS THE TRANSITION REGION FROM GALACTIC TO EXTRAGALACTIC CR