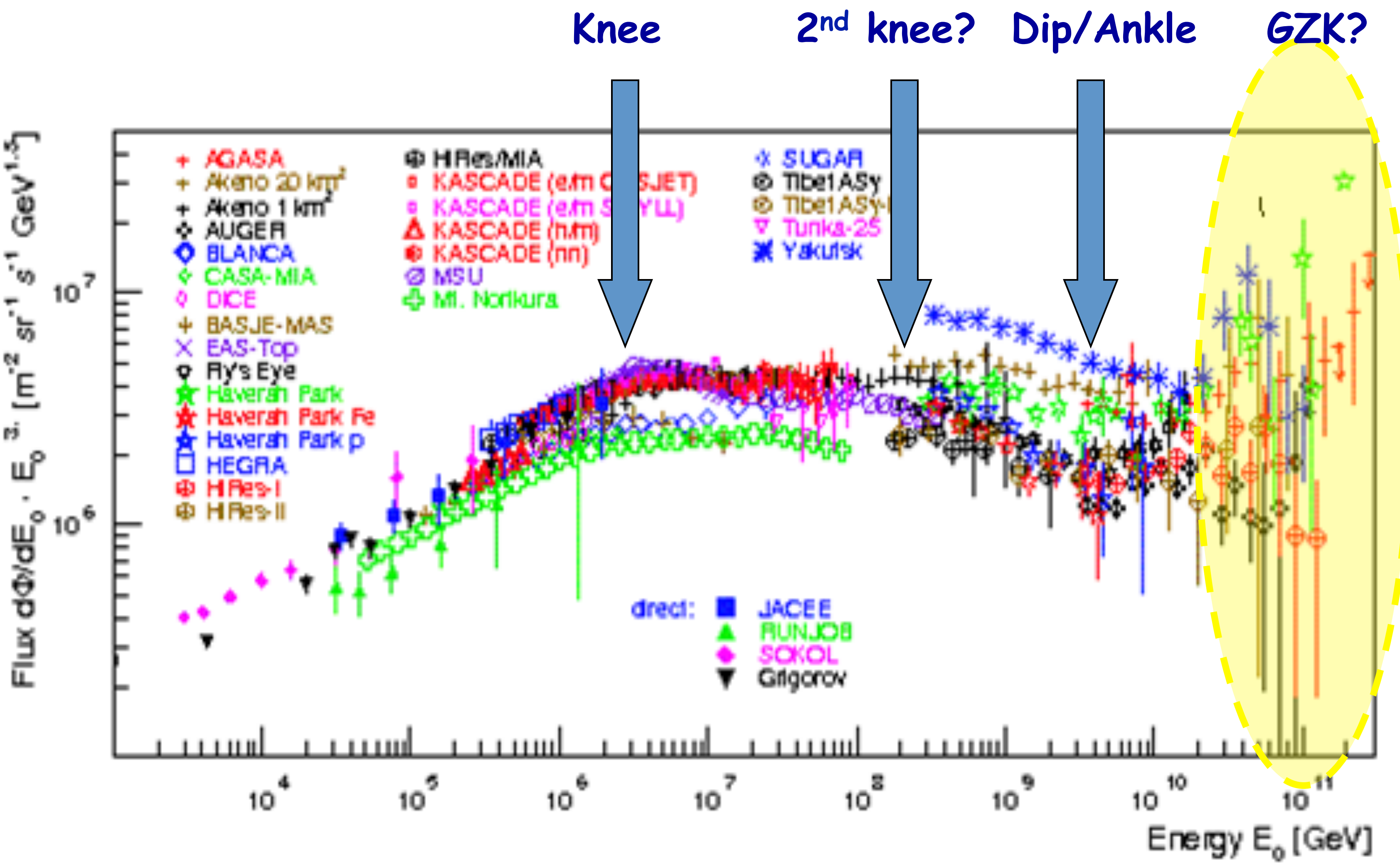
Lecture 5:
EXTRAGALACTIC CR ACCELERATION AND PROPAGATION

Pasquale Blasi

INAF/Arcetri Astrophysical Observatory

1. THE END OF GALACTIC CR AND THE BEGINNING OF UHECR
2. WHAT IS SPECIAL ABOUT UHECR
3. PARTICLE ACCELERATION IN EXTRAGALACTIC SOURCES
4. FERMI ACCELERATION AT RELATIVISTIC SHOCKS
5. MAY BE NEUTRON STARS?
6. SOME NOTES OF LARGE SCALE STRUCTURES

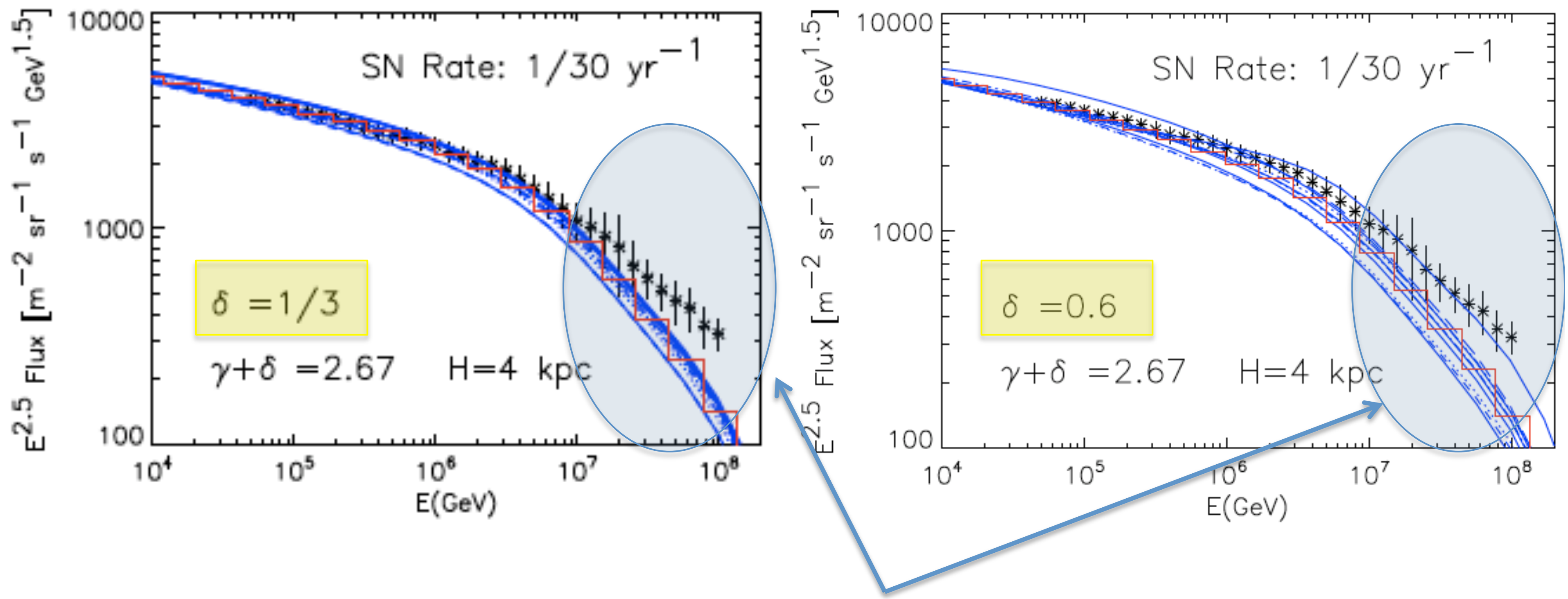
The Spectrum of Cosmic Rays



140 GeV   2.5 TeV   20 TeV   100 TeV   450 TeV

EFFECT OF RANDOMNESS IN SNRs

Blasi & Amato 2012



DEFICIT POSSIBLY INDICATING THAT HERE IS WHERE EXTRAGALACTIC CR KICK IN

PROPAGATION OF EXTRAGALACTIC COSMIC RAYS

ON COSMOLOGICAL TIME SCALES THERE ARE THREE PROCESSES THAT ARE RELEVANT FOR PROPAGATION

ADIABATIC LOSSES DUE TO THE EXPANSION OF THE UNIVERSE

BETHE-HEITLER PAIR PRODUCTION

$$\mathrm{p} + \gamma_{\mathrm{CMB}} \to \mathrm{p} + \mathrm{e}^{+} + \mathrm{e}^{-}$$

PHOTOPION PRODUCTION

$$\mathrm{p} + \gamma_{\mathrm{CMB}} \to n + \pi^{+}$$

$$\mathrm{p} + \gamma_{\mathrm{CMB}} \to p + \pi^{0}$$

SOME KINEMATICS

FOR BOTH PROCESSES ONE HAS THAT THE MAXIMUM INVARIANT MASS OF THE SYSTEM (HEAD-ON COLLISION) IS:

$$s = (p_p + p_\gamma)^2 = m_p^2 + 2E_p\epsilon_\gamma(1+\beta_p) \approx m_p^2 + 4E_p\epsilon_\gamma$$

FOR PAIR PRODUCTION THE MINIMUM VALUES OF s IS THE ONE IN WHICH ALL PRODUCTS OF THE INTERACTION ARE AT REST IN THE FINAL STATE:

$$s = (p_p + 2p_e)^2 = (m_p + 2m_e)^2$$

IT FOLLOWS THAT THE REACTION IS KINEMATICALLY ALLOWED WHEN:

$$m_p^2 + 4E_p\epsilon_\gamma = m_p^2 + 4m_e^2 + 4m_pm_e \rightarrow E_{p,min} = \frac{m_e(m_p+m_e)}{\epsilon_\gamma}$$

FOR THE CMB PHOTONS KT~2.7K THAT CORRESPONDS TO e_g~6 10^{-4} eV, THEREFORE THE THRESHOLD IS AROUND 10^{18} eV.

FOR THE REACTION OF PHOTOPION PRODUCTION ONE HAS A MINIMUM INVARIANT MASS WHEN THE PION IS AT REST IN THE FINAL STATE, THEREFORE:

$$s = (m_p + m_\pi)^2$$

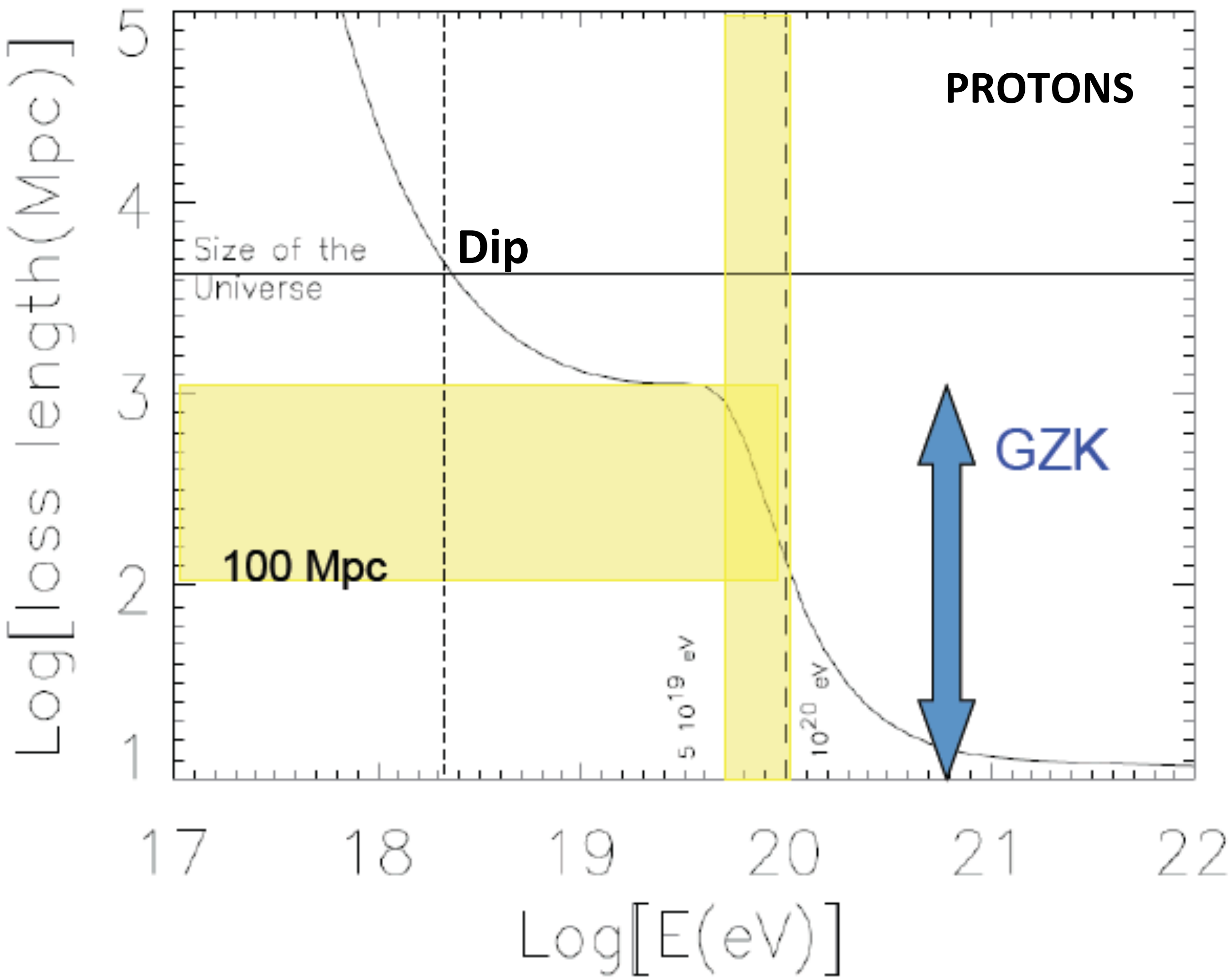
IT FOLLOWS THAT THE REACTION IS KINEMATICALLY ALLOWED WHEN:

$$m_p^2 + 4E_p\epsilon_\gamma = m_p^2 + m_\pi^2 + 2m_p m_\pi \rightarrow E_{p,min} = \frac{m_\pi^2 + 2m_p m_\pi}{4\epsilon_\gamma}$$

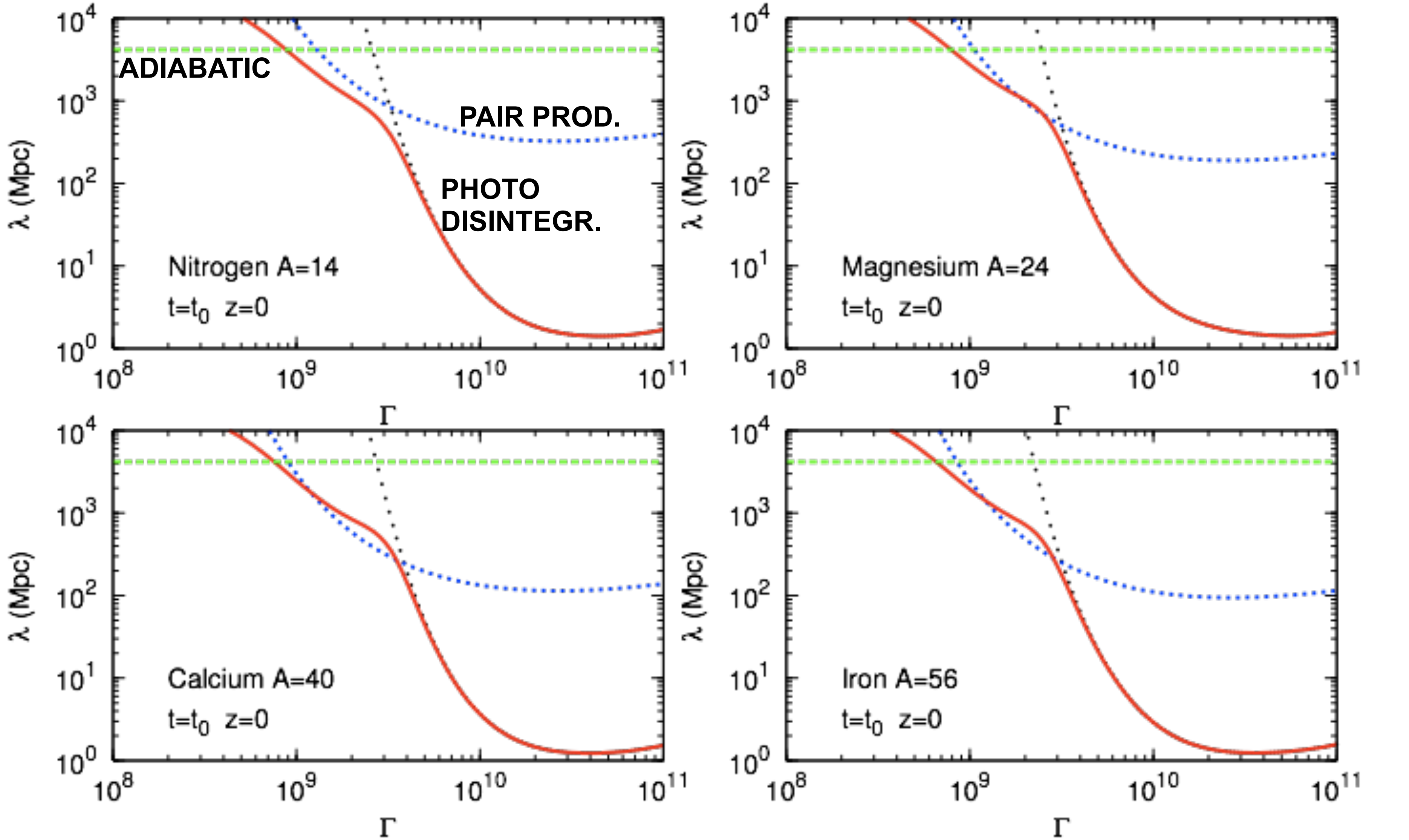
AGAIN, FOR e_g~6 10^{-4} eV, ONE DERIVES A THRESHOLD AT: 1.3 10^{20} eV.

ONE MUST BE CAREFUL THOUGH THAT THE REACTION STARTS BECOMING EFFICIENT ON THE TAIL OF THE BLACKBODY DISTRIBUTION OF PHOTONS IN THE CMB. THIS IS THE REASON FOR THE SHAPE OF THE LOSS CURVES THAT WE WILL SEE.

PROPAGATION OF EXTRAGALACTIC CR PROTONS



PROPAGATION OF EXTRAGALACTIC CR NUCLEI



ENERGY LOSSES

THE RATE OF ENERGY LOSSES FOR PHOTOPION PRODUCTION AND PAIR PRODUCTION AT REDSHIFT ZERO CAN BE WRITTEN AS:

$$\beta_0(E) = -\frac{1}{E}\frac{dE}{dt} = \frac{cT}{2\pi^2\Gamma^2}\int_{\varepsilon_{th}}^{\infty} d\varepsilon_r \sigma(\varepsilon_r) f(\varepsilon_r) \varepsilon_r \times \left\{ -\ln\left[1 - \exp\left(-\frac{\varepsilon_r}{2\Gamma T}\right)\right]\right\}.$$

WHERE AT THRESHOLD:

$$f_{\rm pair} = \frac{2m_e}{2m_e + m_p}, \qquad f_{\rm pion} = \frac{m_\pi}{m_\pi + m_p}$$

IN TERMS OF REDSHIFT DEPENDENCE:

$$\beta(E, z) = (1 + z)^3 \beta_0[(1 + z)E],$$

THE SPECTRUM

CONSERVATION OF THE NUMBER OF PARTICLES IN THE COMOVING VOLUME READS:

$$n_p(E)dE = \int_{t_{\min}}^{t_0} dt Q_{\text{gen}}(E_g, t) dE_g$$

IMPLYING THAT THE FLUX IS:

$$J_p(E) = \frac{c}{4\pi} \mathcal{L}_0 K \int_0^{z_{\max}} dz \left| \frac{dt}{dz} \right| (1+z)^m q_{\text{gen}}(E_g) \frac{dE_g}{dE}$$

WHERE E_g IS THE GENERATION ENERGY, OBTAINED FROM E BY SOLVING THE EQUATION FOR LOSSES OUT TO A REDSHIFT Z

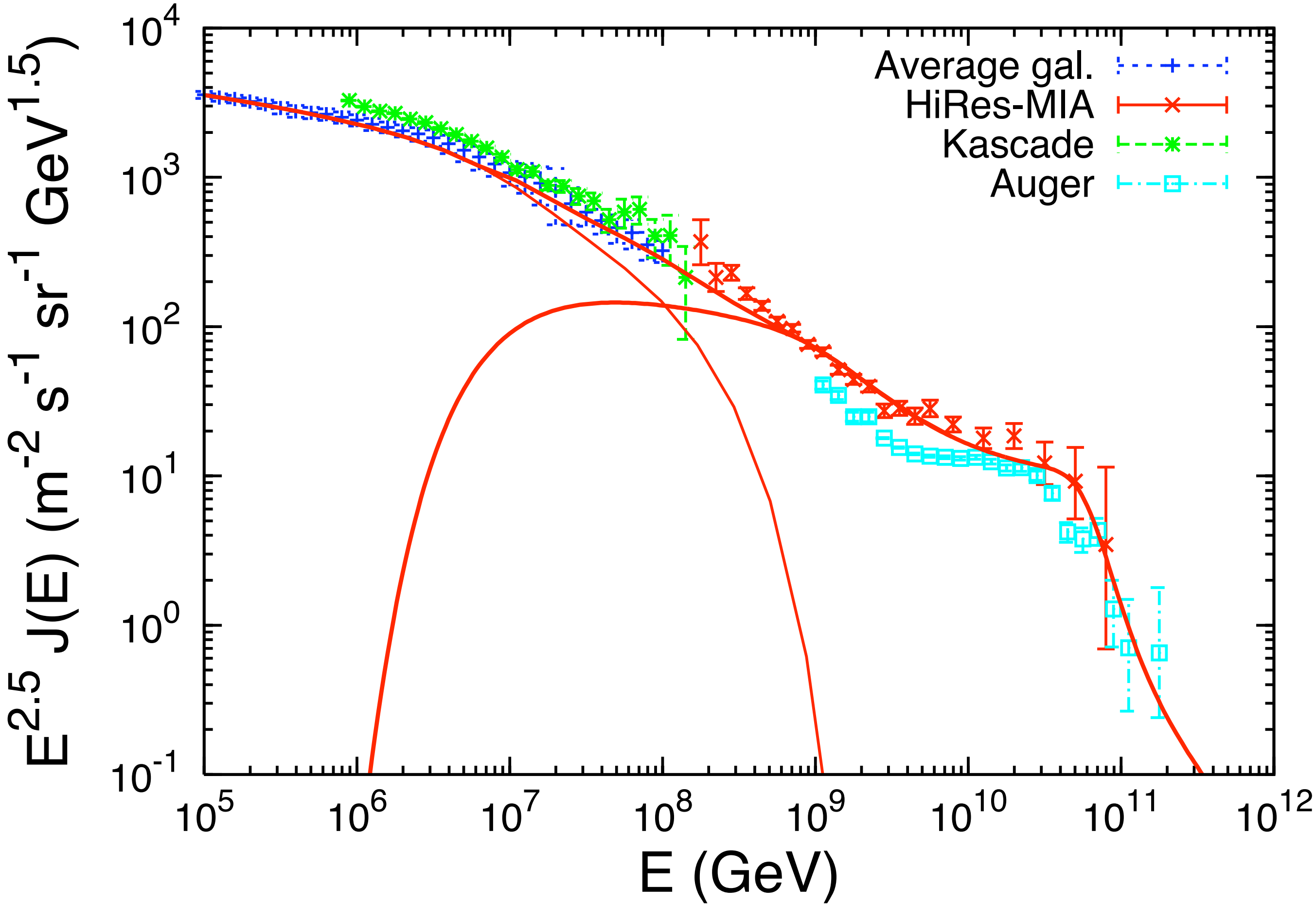
MODELS OF THE TRANSITION

1. DIP MODEL: THE TRANSITION IS AT THE SECOND KNEE AND IT IS ASSOCIATED WITH THE OCCURRENCE OF BETHE-HEITLER PROCESS (DIP). THE EXTRAGALACTIC CR ARE PROTONS

2. MIXED COMPOSITION MODEL: THE TRANSITION IS AROUND 10^{18} eV AND IT IS DUE TO A TRANSITION TO A COMPLEX (MIXED) CHEMICAL COMPOSITION.

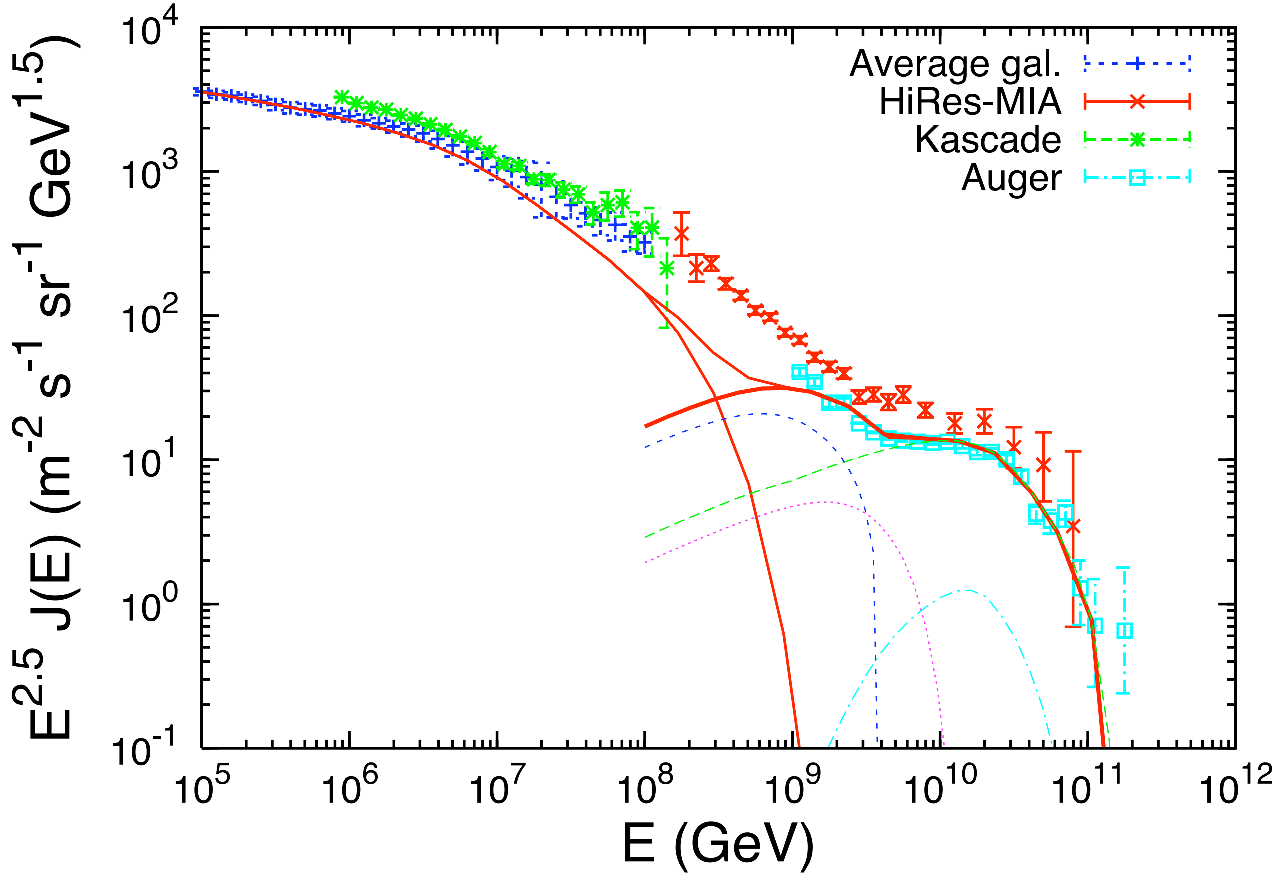
3. ANKLE MODEL: THE TRANSITION IS AT 10^{19} eV, EXTRAGALACTIC CR ARE PROTONS. GALACTIC COMPONENT MUST EXTEND TO VHE

DIP MODEL



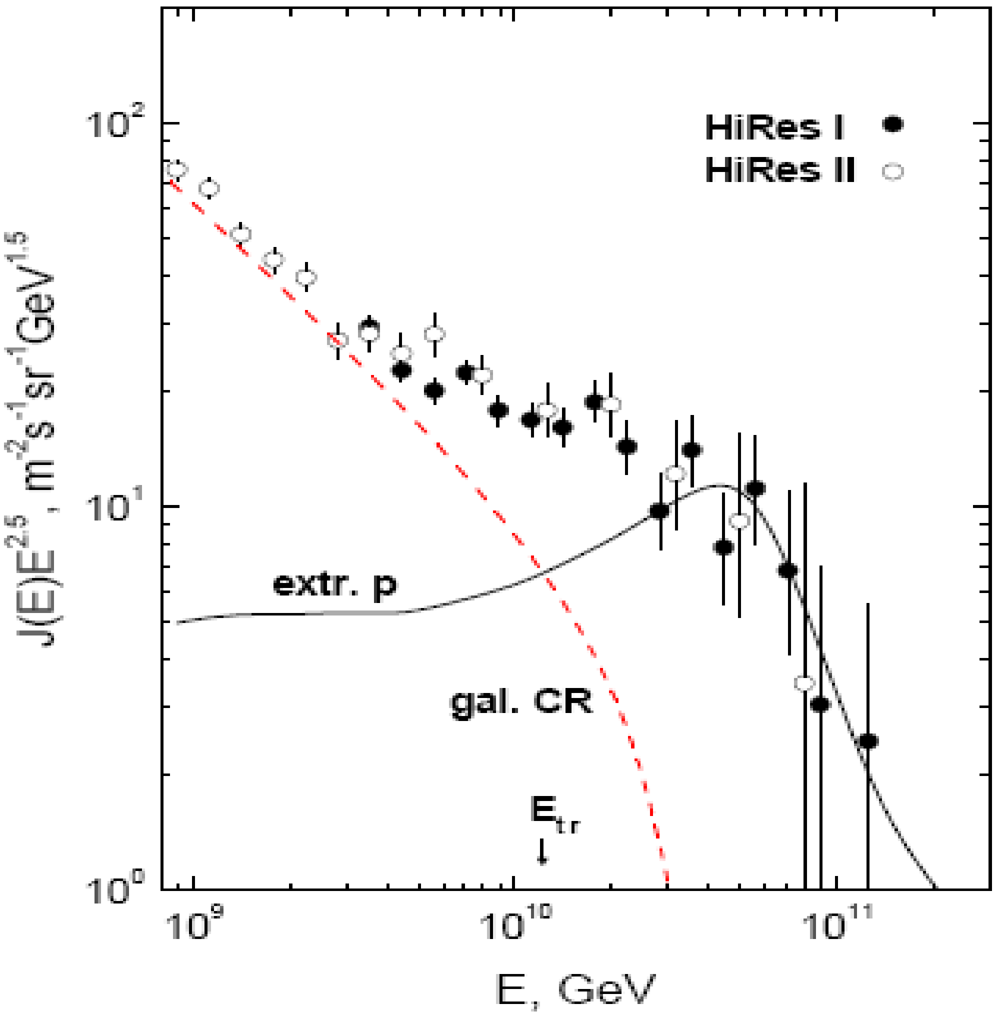
- Galactic CR end compatibly with the SNR paradigm (Fe and Emax~$26 * 3 * 10^{15}$ eV)
- Extra-Gal CR are protons (not more than 15% He)
- Transition is at the second knee

MIXED COMPOSITION MODEL



1. LOTS OF PARAMETERS (RELATIVE ABUNDANCES AND SPECTRA)
2. TRANSITION AT ~10^{18} eV, CHEMICAL COMPOSITION IN THE TRANSITION REGION IS MIXED

THE ANKLE MODEL



1. TRANSITION AT 10^{19} eV
2. GALACTIC CR REQUIRED TO EXTEND TO SUCH ENERGIES
3. EXTRAGALACTIC CR MAINLY PROTONS

GLOBAL ENERGETICS

THE FLUX AT E>10^{19}eV IS ~1.5 10^{-28} cm^{-2}s^{-1}sr^{-1}GeV^{-1}

A SIMPLE ESTIMATE OF THE FLUX CAN BE WRTTEN AS

$$J(E) = \frac{c}{4\pi}\dot{n}(E)\tau_{loss}(E)$$

WHICH LEADS TO AN ENERGY INJECTION RATE PER UNIT VOLUME OF

$$\dot{E} \approx 3 \times 10^{45} erg\ Mpc^{-3} yr^{-1}$$

Limits on Accelerators of UHECRs

IN THE NON RELATIVISTIC CASE ONE CAN WRITE A GENERIC EXPRESSION:

$$\frac{1}{3}\frac{E(eV)}{300ZB}\frac{c}{u} = \xi R \quad \xi < 1$$

THIS IMPLIES THAT:

$$\epsilon_B = \frac{B^2}{4\pi} > 9.8 \times 10^{-8}\frac{E(eV)^2}{Z^2\beta^2\xi^2 R^2}$$

THE SOURCE ENERGETIC MUST BE AT LEAST AS LARGE AS THE MAGNETIC ONE:

$$L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.8 \times 10^{46} erg/s \left(\frac{E}{Z10^{20}eV}\right)^2 \left(\frac{\xi}{0.1}\right)^{-2} \beta^{-1}$$

PROBABLY THE ONLY NON RELATIVISTIC SOURCES THAT MAY SATISFY THIS BOUND ARE LARGE SCALE STRUCTURE FORMATION SHOCKS AND ONLY MARGINALLY, ALTHOUGH NOTICE THE ROLE OF Z

Caveat on definitions

THE SO-CALLED HILLAS CRITERION FOR THE MAXIMUM ENERGY IS SOMEWHAT DIFFERENT:

$$\frac{E(eV)}{300B} < R \qquad \xi < 1$$

WITH THIS DEFINITION THE CONDITION ON LUMINOSITY BECOMES LESS SEVERE:

$$L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.6 \times 10^{45} erg/s \left(\frac{E}{Z10^{20}eV}\right)^2 \beta$$

BUT LESS CLOSE TO WHAT IS FOUND IN ACTUAL CALCULATIONS. THE 'TRUE' CASE IS SOMEWHERE IN BETWEEN…

CLEARLY THIS DISTINCTION IS IMMATERIAL IN THE CASE OF RELATIVISTIC ACCELERATORS

THIS RESULT CAN BE GENERALIZED TO THE CASE OF RELATIVISTIC SOURCES WITH LORENTZ FACTOR G (Waxman 2005)

B' → MAGNETIC FIELD IN THE COMOVING FRAME

E' =E/G → PARTICLE ENERGY IN THE COMOVING FRAME

THE CONDITION FOR MAXIMUM ENERGY IS:

$$\frac{2\pi}{c}\frac{E'}{ZeB'} = \frac{2\pi}{c}\frac{E}{ZeB'\Gamma} < T_{dyn} \approx \frac{r}{c\Gamma}$$

WHICH IMPLIES:

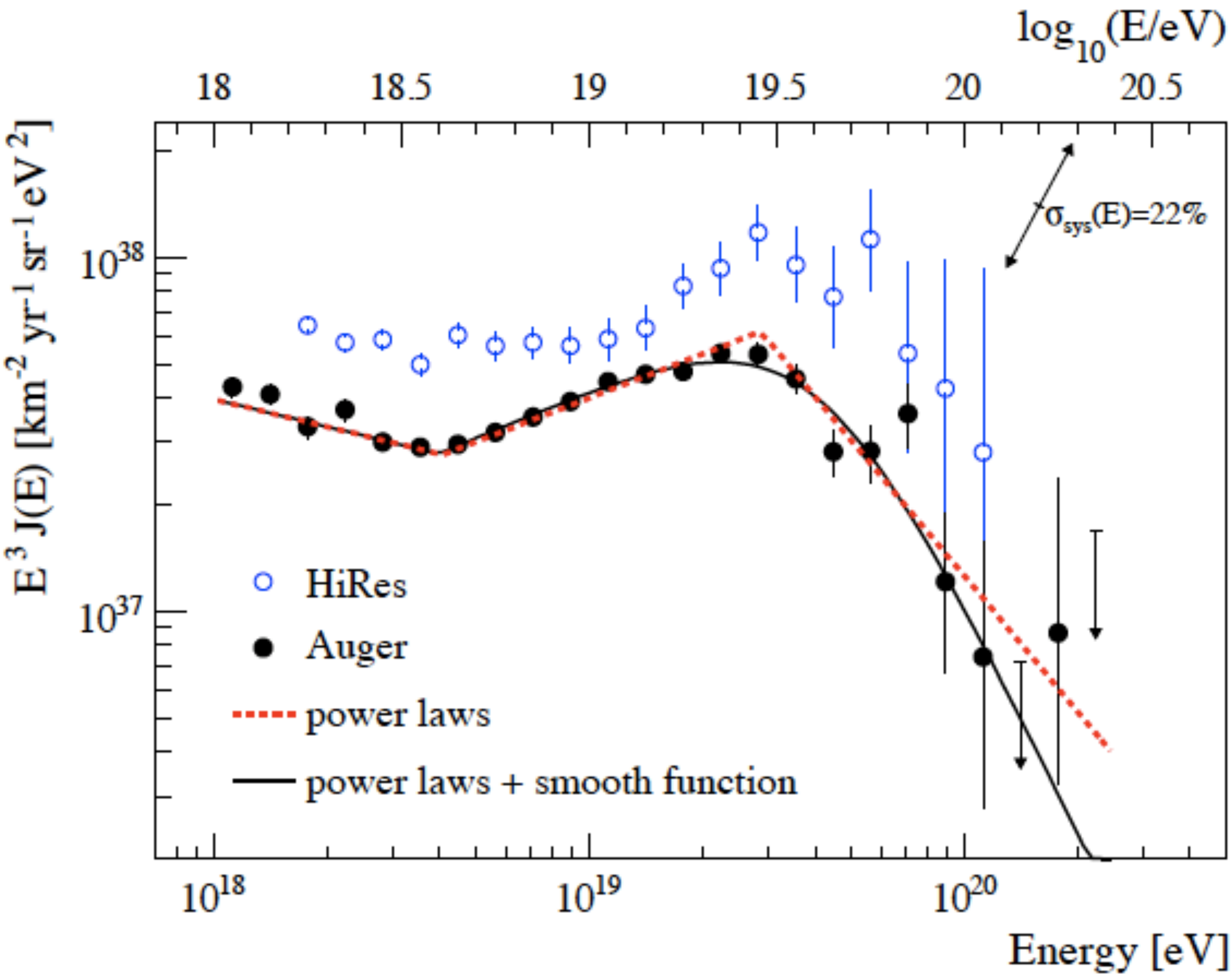
$$B' > \frac{2\pi E}{Zer} \to \epsilon'_B = \frac{B'^2}{4\pi} > \left(\frac{2\pi E}{Zer}\right)^2 /(4\pi)$$

AND FINALLY THE SOURCE ENERGY INPUT MUST SATISFY:

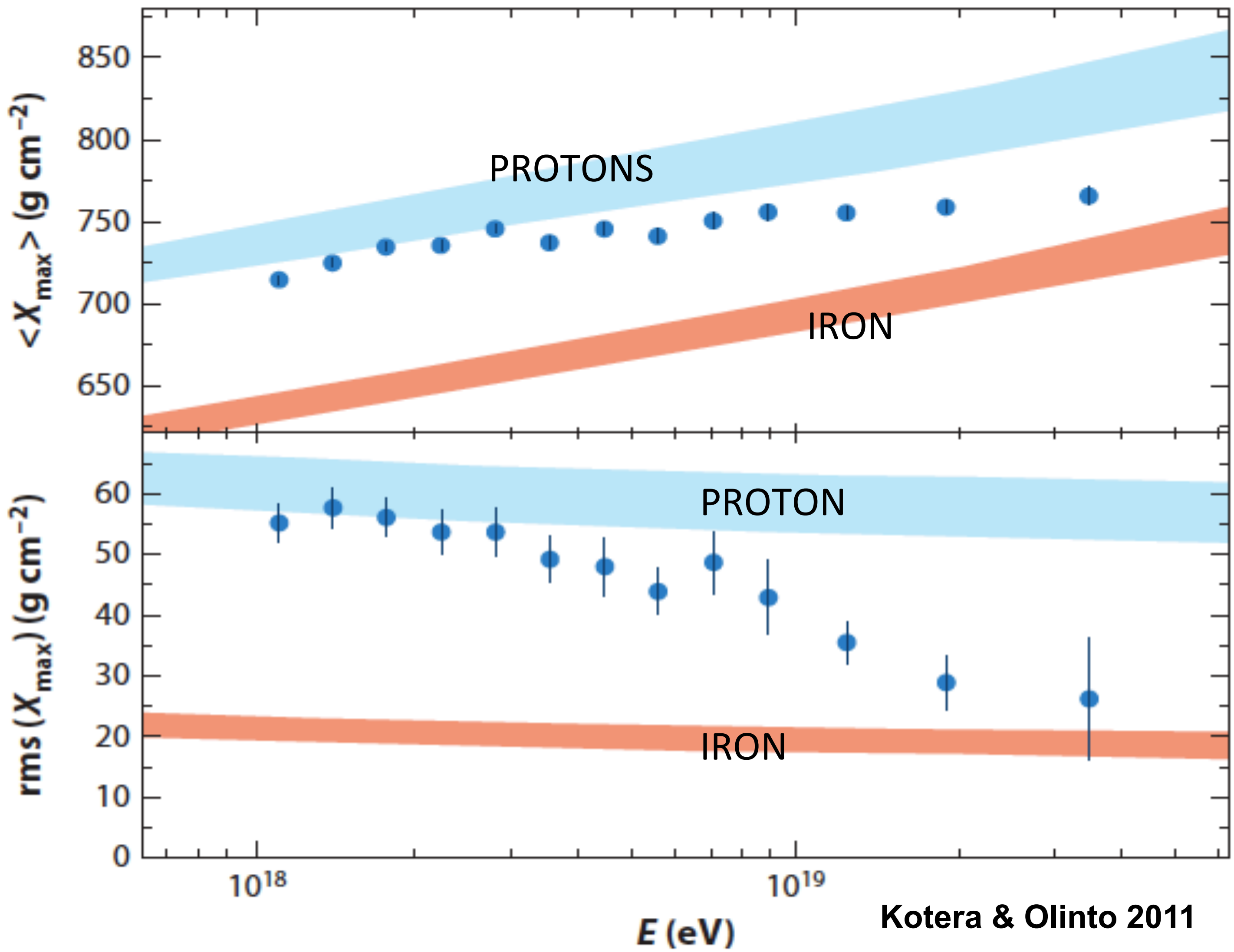
$$L > 4\pi r^2 c\Gamma^2 \epsilon'_B = c\Gamma^2 (2\pi E/Ze)^2 \approx 10^{47}\Gamma^2 \left(\frac{E}{Z\ 10^{20} eV}\right)^2 erg/s$$

THIS IS HUGE AND ONLY THE UPPER END OF THE AGN AND GRB APPEAR TO SATISFY THIS BOUND, ALTHOUGH NOTICE THE ROLE OF Z

SPECTRUM OF UHECRs



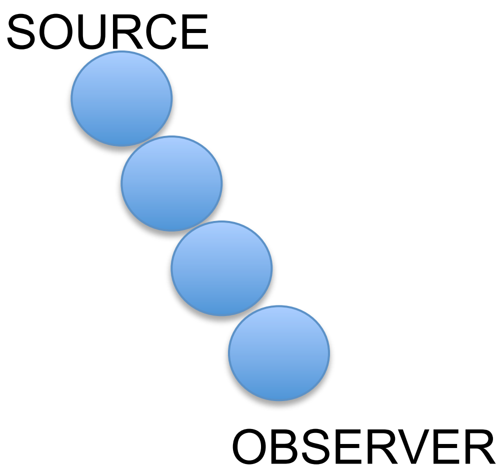
CHEMICAL COMPOSITION



Kotera & Olinto 2011

UHECR ASTRONOMY?

CR PROPAGATING IN THE INTERGALACTIC MEDIUM MIGHT NOT FIND ANY MAGNETIC FIELD THERE, OR MIGHT FIND A WEAK MAGNETIC FIELD B THAT FLIPS DIRECTION EACH LENGTH L.



IF $L/R_L(E)<<1$ ONE CAN SAY THAT IN EACH BUBBLE THE DEFLECTION IS

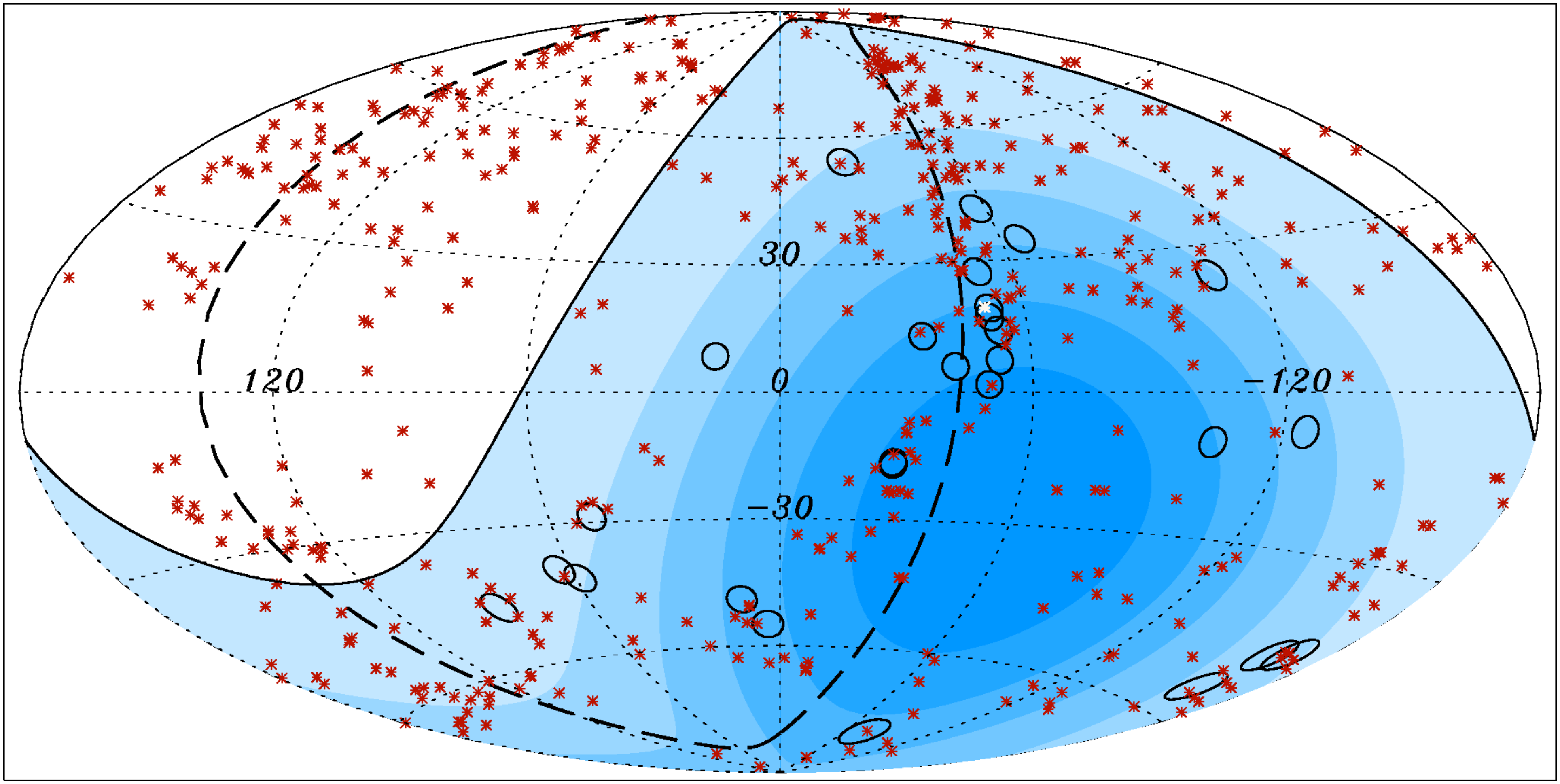
$$\theta \simeq \frac{L}{r_L(E)} \approx \frac{300BL}{E(eV)}$$

THIS IS ANOTHER EXAMPLE OF DIFFUSION (IN ANGLE) AND AFTER CROSSING N BUBBLES THE DEFLECTION ON AVERAGE SUMS UP TO ZERO BUT ITS FLUCTUATION DEOES NOT:

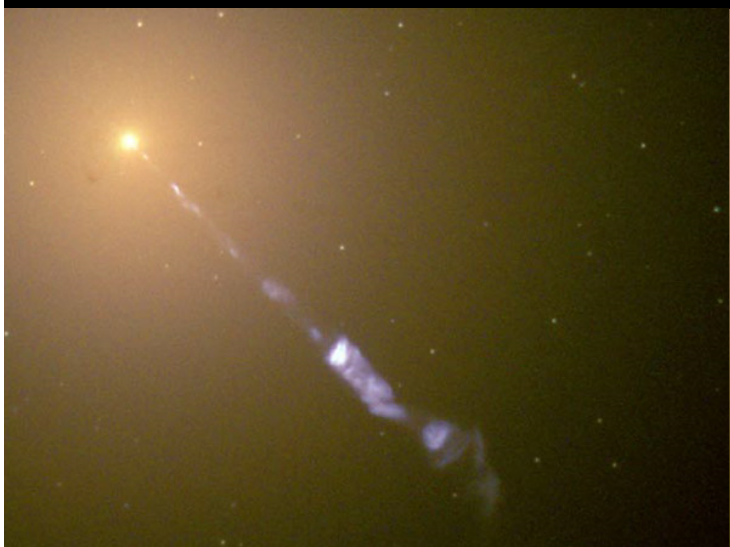
$$\theta_{obs} \simeq \theta N^{1/2} = \theta \left(\frac{D}{L}\right)^{1/2} \approx 0.5 \text{ degrees } \mathrm{E}_{20}^{-1} \mathrm{D}_{100\mathrm{Mpc}}^{1/2} \mathrm{L}_{\mathrm{Mpc}}^{1/2} \mathrm{B}_{-10}$$

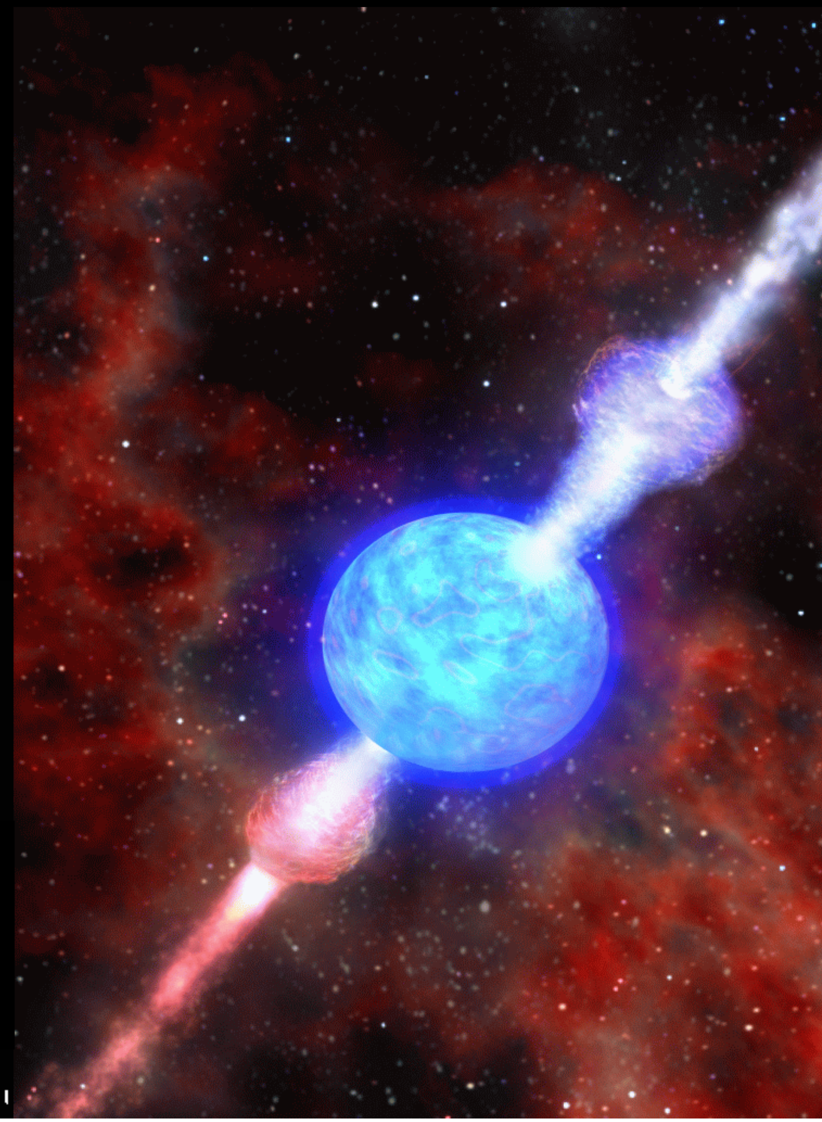
BUT MUCH LARGER DEFLECTIONS FOR NUCLEI!!! MOREOVER THE MAGNETIC FIELD OF THE GALAXY ADDS TO THE DEFLECTIONS.

Anisotropy



ACCELERATION AT RELATIVISTIC SHOCKS





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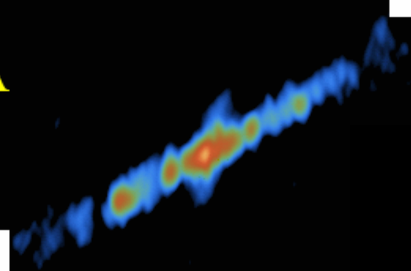


BASICS OF ACCELERATION AT RELATIVISTIC SHOCKS

$$\gamma_1\beta_1 n_1 = \gamma_2\beta_2 n_2$$

$$\gamma_1^2\beta_1(\varepsilon_1 + p_1) = \gamma_2^2\beta_2(\varepsilon_2 + p_2)$$

$$\gamma_1^2\beta_1^2(\varepsilon_1 + p_1) + p_1 = \gamma_2^2\beta_2^2(\varepsilon_2 + p_2) + p_2$$

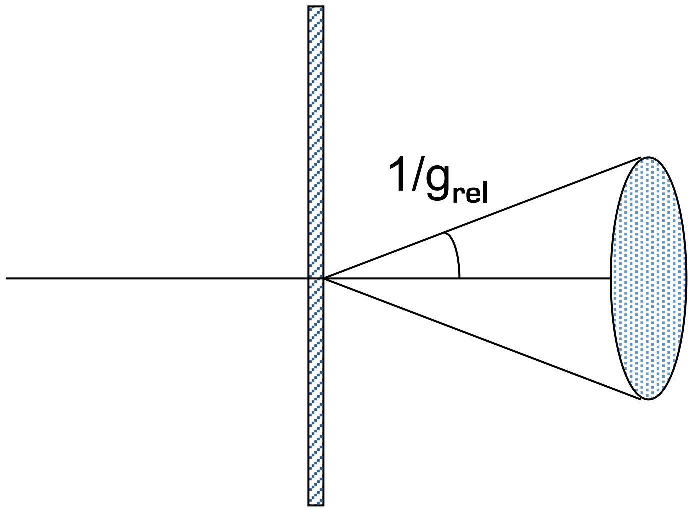
IN THE ASSUMPTION THAT:

$\frac{B_1^2}{4\pi} \ll (\varepsilon_1 + p_1)$	$\gamma_1 \gg 1$	$p_1 = 0$
No equipartition	ultrarelativistic	pressureless

WE FIND THAT:

$$p_2 = \frac{1}{3}\varepsilon_2 \qquad \beta_2 = \frac{1}{3}$$

BASICS



THE IDEA WE WANT TO EXPLORE IS SIMILAR TO THE STANDARD SHOCK ACCELERATION WE HAVE ALREASDY SEEN IN LECTURE 2. BUT HERE LIFE IS MUCH MORE COMPLICATED BECAUSE OF RELATIVISTIC BEAMING.

FIRST INTERACTION:

$$E_i \Rightarrow E_d = \gamma_{rel} E_i (1+\beta_{rel}) \Rightarrow E_f = \gamma_{rel}^2 E_i (1+\beta_{rel})^2 \approx 4\gamma_{rel}^2 E_i$$

FURTHER INTERACTIONS:

$$E_f \approx 2\ E_i$$

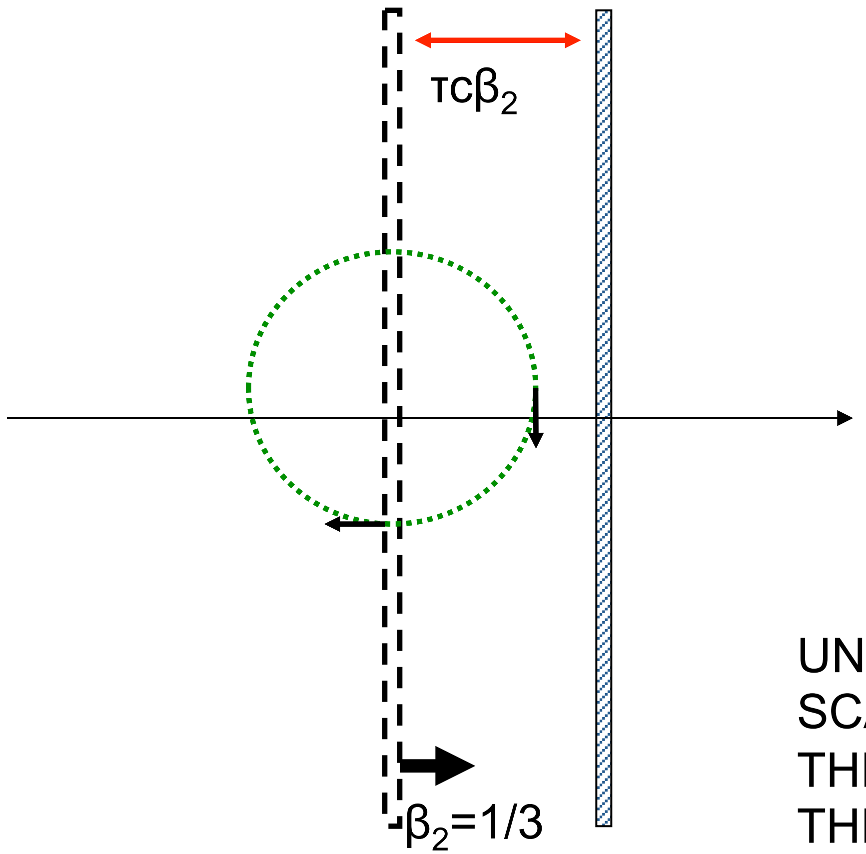
DETAILS MATTER

WHEN MAGNETIC FIELD CROSSES A SHOCK FRONT THE PERPENDICULAR COMPONENT OF THE FIELD GETS COMPRESSED BY THE SQUARE OF THE LORENTZ FACTOR. THIS IMPLIES THAT THE FIELD BEHIND THE SHOCK BECOMES ALMOST PERPENDICULAR (NAMELY PARALLEL TO THE SHOCK SURFACE).

THE ONLY WAY TO AVOID THIS IS IF THE FIELD UPSTREAM IS PARALLEL WITHIN 1/ g_{rel}.

THIS COMMENT APPLIES EVEN IF THE FIELD UPSTREAM IS TURBULENT...

EVEN THE EQUATION OF STATE OF THE PLASMA DOWNSTREAM IS IMPORTANT (EP VS PAIRS, EQUIPARTITION B-FIELD, THERMALIZATION BETWEEN ELECTRONS AND PROTONS, ...)



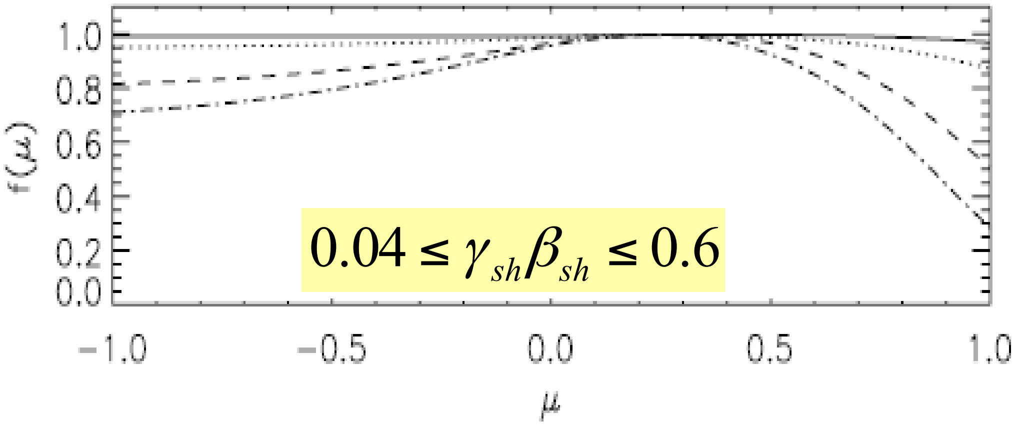
$$\tau \approx \frac{3}{4}\frac{2\pi\, r_L}{c}$$

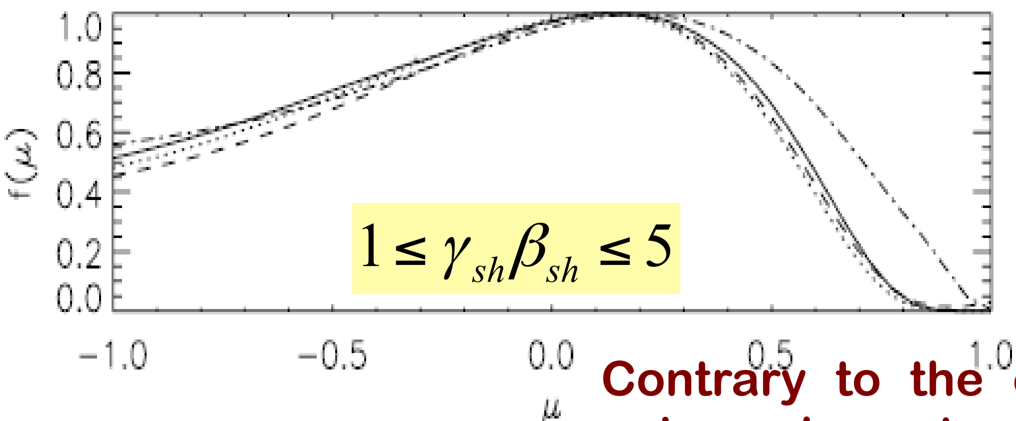
$$\Delta x = \frac{1}{3}c\,\tau = \frac{\pi}{2} r_L > r_L$$

UNLESS THERE IS STRONG SCATTERING DOWSNTREAM THE PARTICLES ARE TRAPPED THERE

THE RETURN PROBABILITY FROM DOWNSTREAM IS EXPECTED TO BE SMALLER THAN FOR NEWTONIAN SHOCKS: STEEPER SPECTRA

EFFECTS OF ANISOTROPY





PARTICLE SLOPES FOR SHOCKS IN THE SPAS LIMIT

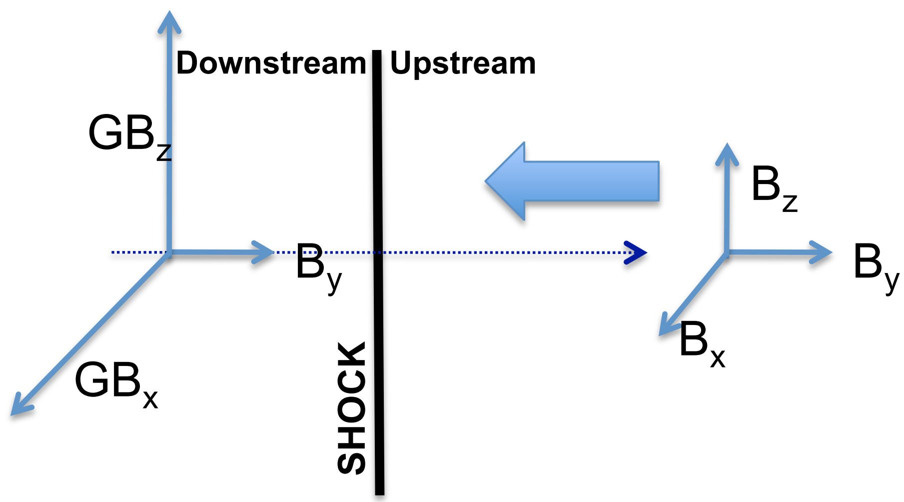
$\gamma_{sh}\beta_{sh}$	u	u_d	Slope
0.04........................	0.04	0.01	4.00
0.2..........................	0.196	0.049	3.99
0.4..........................	0.371	0.094	3.99
0.6..........................	0.51	0.132	3.98
1.0..........................	0.707	1.191	4.00
2.0..........................	0.894	0.263	4.07
4.0..........................	0.97	0.305	4.12
5.0..........................	0.98	0.311	4.13

Contrary to the case of non relativistic shocks, no universal spectrum of accelerated particles exist

In the small pitch angle scattering (SPAS) assumption, one obtains $E^{-2.23}$ at high energy, but this result neglects many complications

PB & Vietri 2005

ACCELERATION AT RELATIVISTIC SHOCKS



EVEN IF THE TURBULENT FIELD UPSTREAM WERE ISOTROPIC, THE SHOCK COMPRESSION WOULD MAKE THE SHOCK QUASI-PERP

ACCELERATION IS INHIBITED AND THE SPECTRA OF ACCELERATED PARTICLES ARE TYPICALLY VERY STEEP **(Lemoine and Ravenue 2006)**

DESPITE THE SIMPLE PREDICTIONS OF SPAS CALCULATIONS, THE COMPRESSION OF THE B-FIELD LEADS TO TYPICAL SPECTRA $E^{-2.7}$ RATHER THAN $E^{-2.23}$

ACCELERATION AT RELATIVISTIC SHOCKS

THE CONCEPT OF SMALL OR LARGE ANGLE SCATTERING IS RELATIVE TO THE CRITICAL PARTICLE DEFLECTION 1/G

THE REGIME OF SPAS CAN BE BROKEN AND THIS LEADS TO SPECTRA THAT ARE IN GENERAL FLATTER (HARDER) THAN IN THE SPAS LIMIT

MAGNETIC FIELD PRESSURE AND EQUATION OF STATE OF THE PLASMA BEHIND THE SHOCK (FOR INSTANCE DUE TO DIFFERENT LEVELS OF THERMALIZATION OF PROTONS AND ELECTRONS) ALSO LEAD TO CHANGES IN THE SPECTRAL SLOPE

WHERE ARE THESE RELATIVISTIC SHOCKS?

CERTAINLY GRBs AND AGN ARE THE BEST SUSPECTS…

BUT THE LIMITS DERIVED ABOVE ON LUMINOSITY LEAD TO CONCLUDE THAT ONLY THE AGN IN THE UPPER PART OF THE LUMINOSITY FUNCTION COULD WORK (UNLESS Z>>1, IN WHICH CASE THE REQUIRED L BECOMES MUCH SMALLER!)

IN AGN THE FASTEST SHOCKS HAVE G~10-30

IN GRB THE NECESSARY CONDITIONS APPEAR TO BE FULFILLED…
AND G~200.

THE ISSUES THAT RISE ARE ABOUT ACCELERATION

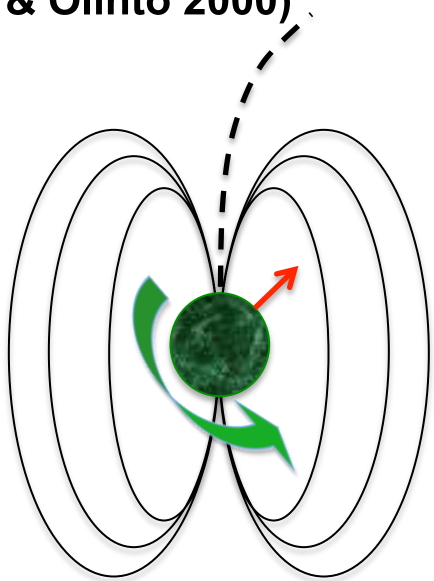
LARGE SCALE OR WITH LARGE COHERENCE SCALE
The shock is quasi-perp, steep spectra, inefficient acceleration but in principle high E_{max}

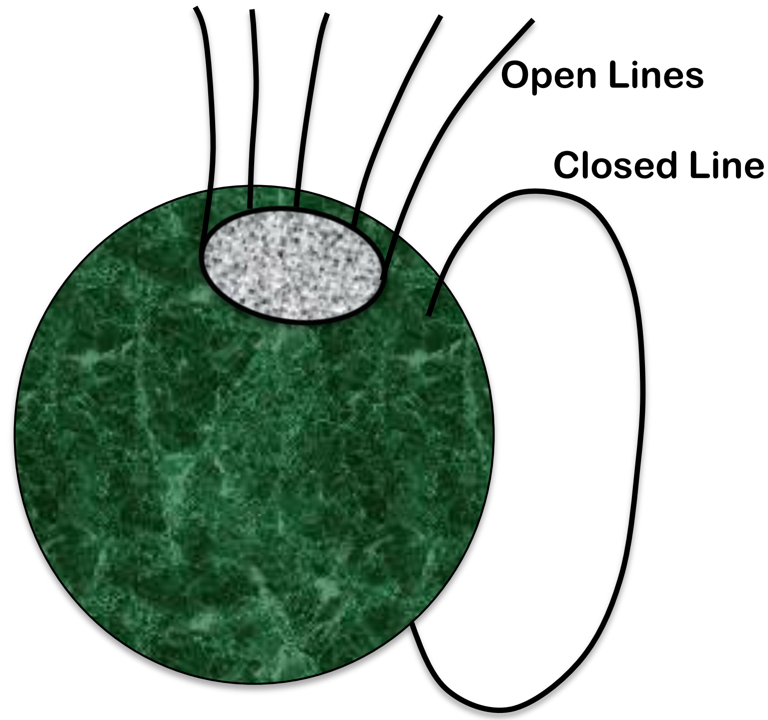
B-FIELD

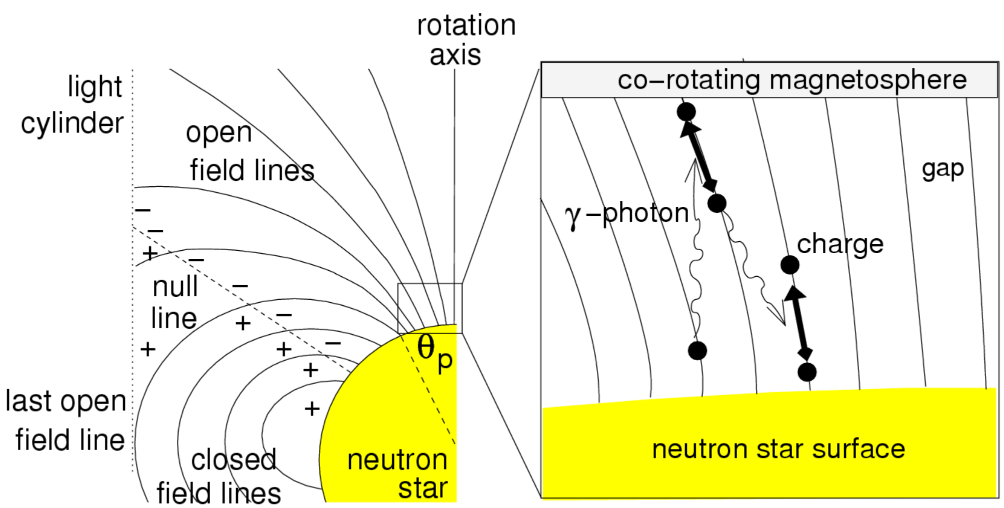
SMALL SCALE (SKIN DEPTH)
Canonical spectra, but slow return→ low E_{max}

NEUTRON STARS AND MAGNETARS

PB, Epstein & Olinto 2000)
Arons 2003







THE ELECTROMOTIVE FORCE DUE TO THE ROTATING B-FIELD LEADS TO EXTRACTION OF ELECTRONS FROM THE STAR'S SURFACE

$$\dot{\Omega} = -a\Omega^n \qquad \dot{E} = I\Omega\dot{\Omega} = aI\Omega^{n+1}$$

MAX ENERGY AND SPECTRUM

THE MAXIMUM POTENTIAL DROP IN A NEUTRON STAR MAGNETOSPHERE IS BASICALLY DETERMINED BY THE MAGNETIC FIELD AT THE LIGHT CYLINDER

$$V \approx \frac{\Omega R_L}{c} B_s \left(\frac{R_s}{R_L}\right)^3 R_L = \frac{1}{c^2} R_s^3 B_s \Omega^2 \approx 9 \times 10^{20} \left(\frac{\Omega}{3000 s^{-1}}\right)^2 \left(\frac{B_s}{10^{13} s^{-1}}\right) V$$

BUT IT IS HARDLY USABLE, BECAUSE OF ENERGY LOSSES (CURVATURE ESPECIALLY). HOWEVER, IT IS WELL KNOWN THAT PARTICLES MAY BE SLING SHOT IN THE WIND TO A LORENTZ FACTOR

$$\Gamma = \frac{B_L^2}{8\pi n_{GJ}} \frac{1}{A m_p c^2}$$

$$n_{GJ} = 1.7 \times 10^{11} Z^{-1} \left(\frac{B_s}{10^{13} G}\right) \left(\frac{\Omega}{3000 s^{-1}}\right)^4 cm^{-3}$$

$$E_{max}(t) \approx 10^{21} \left(\frac{\Omega}{3000 s^{-1}}\right)^2 \left(\frac{B}{10^{13} G}\right) eV$$

$$\dot{N} = 4\pi R_L^2 c n_{GJ}(R_L) \propto \Omega^2$$

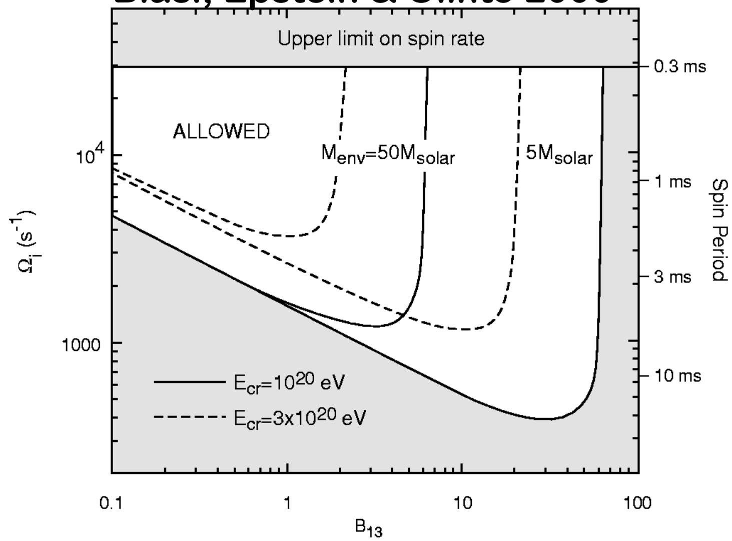
$$N(E) dE = \dot{N} \frac{dt}{d\Omega} \frac{d\Omega}{dE} dE = \frac{\dot{N}}{\dot{\Omega}} \frac{d\Omega}{dE} dE$$

$$N(E) \propto \Omega^{1-n} \propto E^{\frac{1-n}{2}}$$

IN GENERAL VERY FLAT SPECTRA

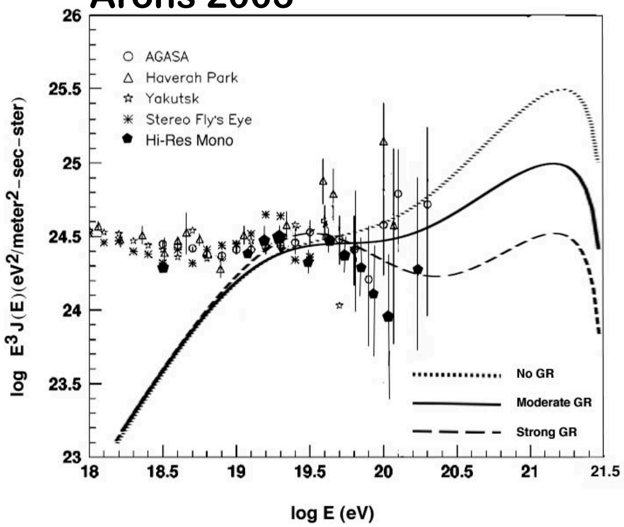
Galactic Fe vs extragalactic p

Blasi, Epstein & Olinto 2000



Fe nuclei can be accelerated in the wind of Galactic neutron stars to UHE
Open issues:
1)Anisotropy probably low but check
2)Very flat spectra (Galactic CR must extend to VHE)
3)How many NS with the useful features?

Arons 2003



Protons may be accelerated to UHE in the winds of extragalactic Magnetars
Open Issues:
1)The conditions required appear to be possible only in very young Magnetars, still surrounded by the star→ unbearable losses
2)Very flat spectra (Galactic CR must extend to VHE)

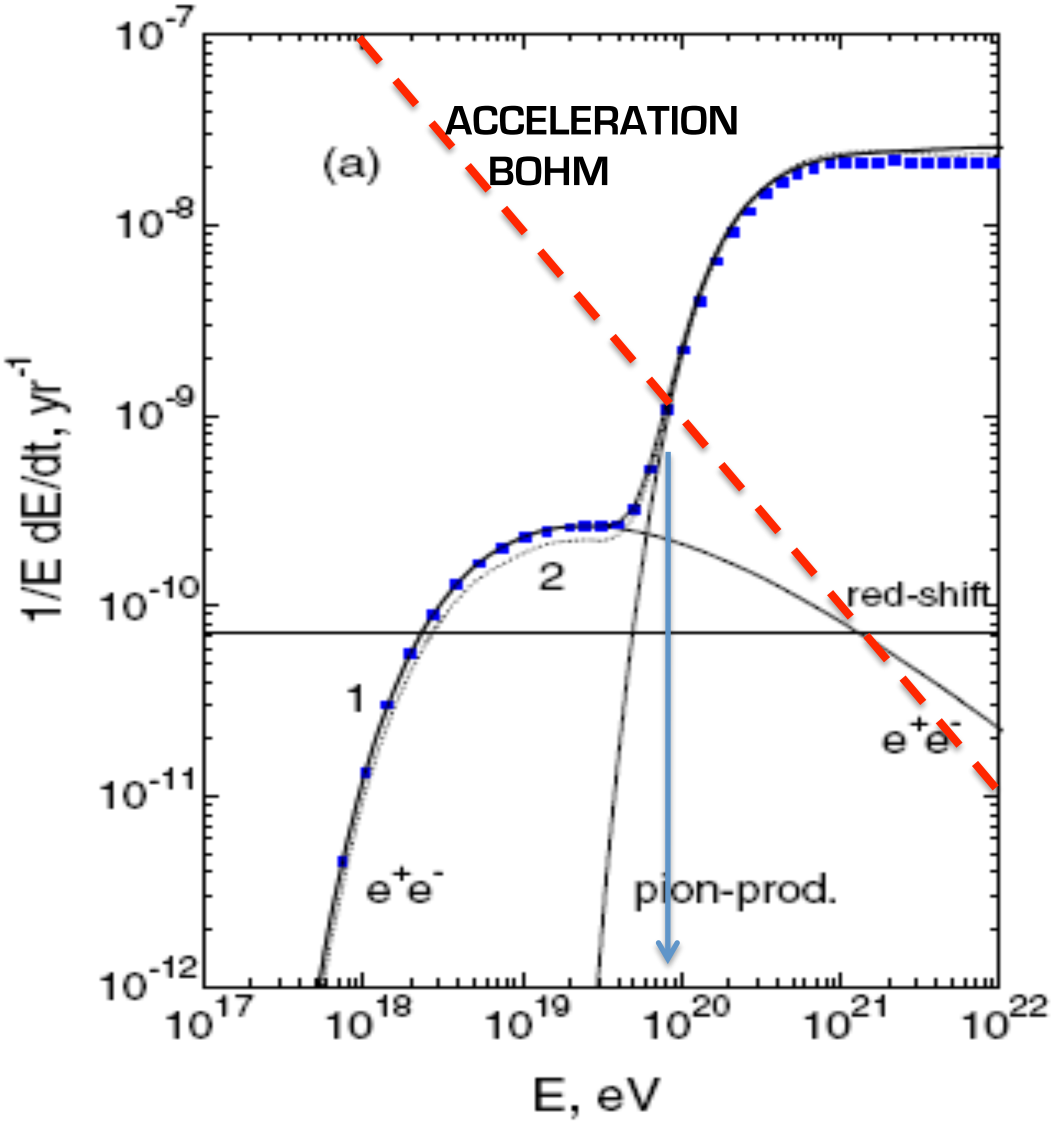
LARGE SCALE STRUCTURES

BARYONIC GAS FALLS ON THE POTENTIAL WELLS FORMED BY DARK MATTER AND FORMS STRUCTURES (CLUSTERS) THAT EVENTUALLY VIRIALIZE

GAS ACCRETING ON A CLUSTER HAS A FREE-FALL VELOCITY THAT IS 100-1000 TIMES LARGER THAN THE SOUND SPEED IN THE INTERGALACTIC MEDIUM: THIS PHENOMENON FORMS THE SO-CALLED ACCRETION SHOCKS (FILAMENTS)-these shocks are strong!

CLUSTERS OF GALAXIES CAN ALSO COLLIDE AND EVENTUALLY MERGE ON TIME SCALES ON SEVERAL BILLION YEARS. THE RELATIVE VELOCITY OF MERGERS IS ONLY MILDLY SUPERSONIC → WEAK MERGER SHOCKS-these shocks are weak!

BEST CASE SCENARIO



INTERESTING SIDE ASPECTS

Berezinsky, PB and Ptuskin (1997) and Voelk et al. (1996) independently found out that clusters of galaxies behave as storage rooms of CRs

COSMIC RAYS ARE CONFINED IN THE ICM FOR TIMES EXCEEDING THE AGE OF THE CLUSTER

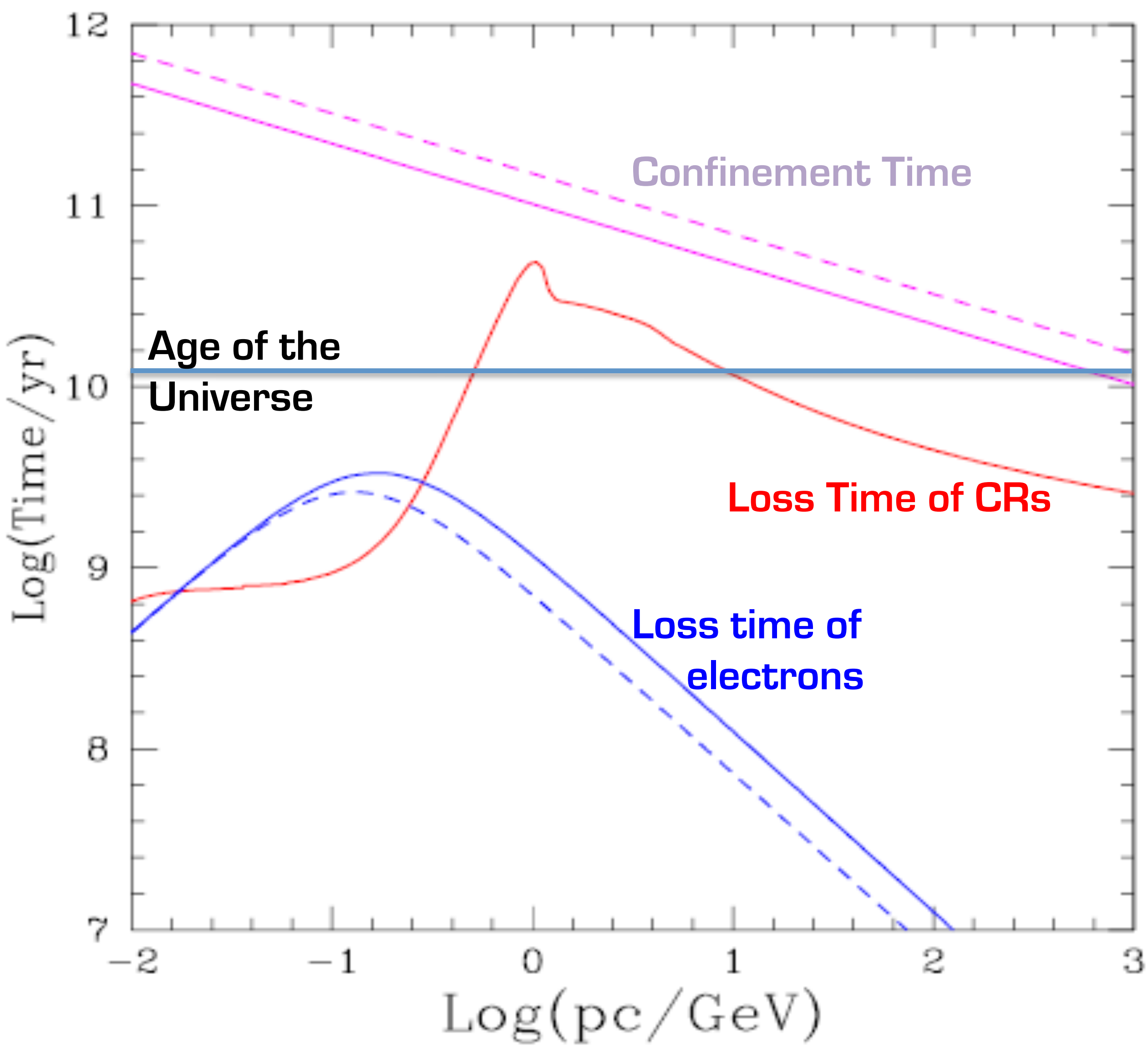
COSMIC RAY CONFINEMENT

$$D(p) = \frac{r_L(p)v(p)}{3\mathcal{F}(k(p))} = \frac{1}{3} r_L c \frac{B^2}{\int_{2\pi/r_L}^{\infty} dk P(k)}$$

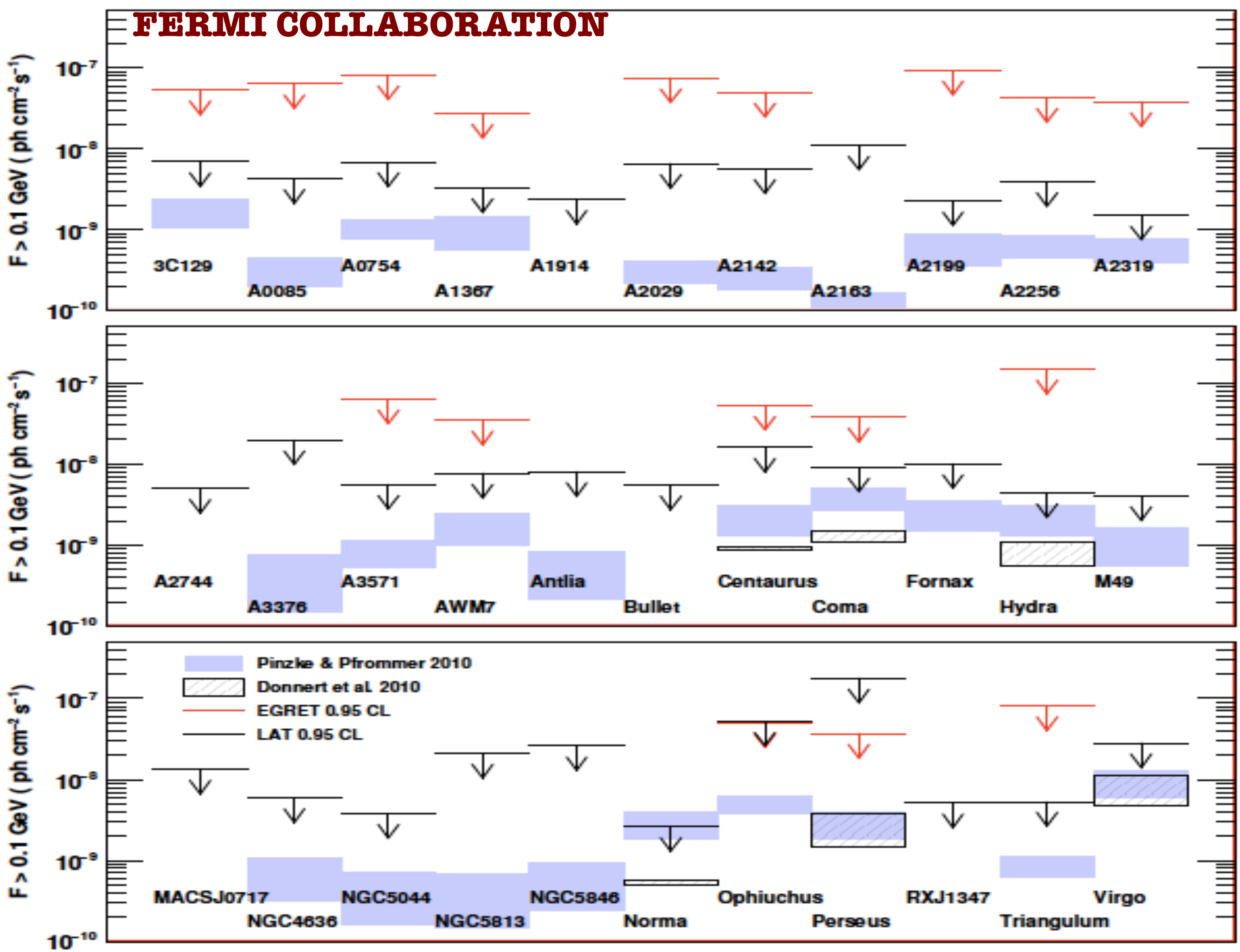
$$D(E) \approx 7 \times 10^{29} E(GeV)^{1/3} \xi^{-1} B_{\mu}^{-1/3} L_{100}^{2/3} \ \mathrm{cm}^2 \mathrm{s}^{-1}$$

CONFINEMENT TIME

$$\tau_{conf} = \frac{R_{cluster}^2}{4D(E)} >> \text{Age of the cluster}$$



PB, Gabici & Brunetti 2007


FERMI COLLABORATION
F > 0.1 GeV (ph cm^{-2}s^{-1})
10^{-7}
10^{-8}
10^{-9}
10^{-10}
3C129
A0085
A0754
A1367
A1914
A2029
A2142
A2163
A2199
A2256
A2319
A2744
A3376
A3571
AWM7
Antlia
Bullet
Centaurus
Coma
Fornax
Hydra
M49
Pinzke & Pfrommer 2010
Donnert et al. 2010
EGRET 0.95 CL
LAT 0.95 CL
MACSJ0717
NGC4636
NGC5044
NGC5813
NGC5846
Norma
Ophiuchus
Perseus
RXJ1347
Triangulum
Virgo

Epilogue From "COSMIC RAYS", by Bruno Rossi, 1964

The last pages of this book are written in August, 1962. A few days ago it was the fiftieth anniversary of Hess's flight, with which my story began. The half century covered by this story has been a revolutionary period for science. And cosmic rays, as I have tried

It is particularly appropriate at this time to pause and look back on the history of cosmic rays, not so much because the fiftieth anniversary of their discovery calls for some sort of celebration, but because, curiously enough, the anniversary comes at a critical moment for cosmic-ray physicists, if not for cosmic-ray physics itself. The interest in cosmic rays is certainly not waning; on the contrary, it is steadily growing. But cosmic-ray research has

the solution of their problems. It is quite possible that future historians of science will close the chapter on cosmic rays with the fiftieth anniversary of Hess's discovery. However, they will undoubtedly note that in renouncing its individuality and merging with the main stream of science, cosmic-ray research continued to perform a vital role in advancing man's understanding of the physical world.