GRAPPA seminar

Supernova remnants in gamma rays and acceleration of Galactic cosmic rays

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Outline

Why supernovae?

Energy scale

Supernovae can release 10^{53}ergs $\triangleq 10^{46}$J, one of the most energetic processes in the known universe

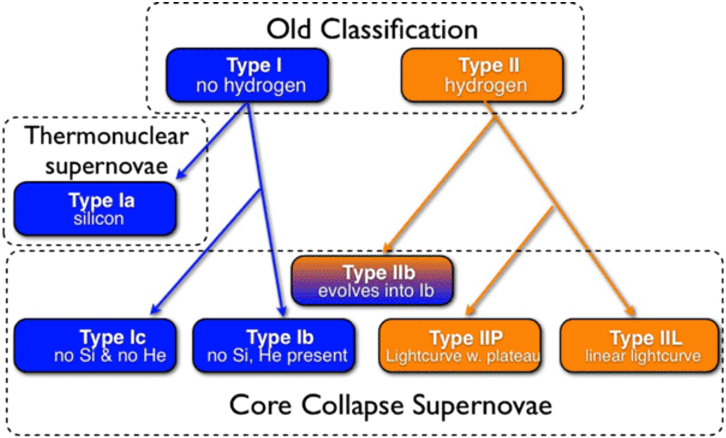
Rate

More energetic events (e.g. gamma-ray bursts) are too rare

Proof

Only proven source so far . . .

Types of supernovae



[Vink(2012)]

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Hydrogen	11 Myrs	H	He
Helium	2 Myrs	He	C,O
Carbon	2000 yrs	C	Ne,Mg
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  - ^{56}Fe most stable element, no energy to be gained from fusing it $\rightarrow$ star builds up an iron core

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  2. Free electrons supporting the core (electron degeneracy) are captured by heavy nuclei and free protons from photodisintegration, e.g.:

     $$p^{+} + e^{-} \rightarrow n + \nu_e \quad (2)$$

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- End result: star loses so much energy, it can no longer support itself $\to$ core collapses under its own gravity

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- However, photodisintegration creates expanding neutrinosphere which impacts the accretion shock, causing it to expand again

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  - DD Detonation, deflagration or delayed detonation

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3. Pressure driven: radiative losses are significant
4. Merging: remnant mixes with the interstellar medium

Acceleration mechanisms

- Many different acceleration mechanisms for galactic particles.
- Acceleration generally assumed in or near the source.
- We discuss 6 plausible mechanisms.

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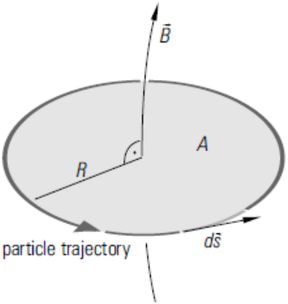
$$\phi = \int B \cdot dA = B\pi R^2$$



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- Generation / decay of magnetic fields cause electric fields.
- Electric fields cause accelerations of protons / electrons.

Energy gained after one orbit is equel to eU.

$$R = 10^7 \text{ m} \qquad \frac{dB}{dt} = 0.2 \text{ Tesla/day}$$

$$eU = 0.73 \text{ GeV}$$

1 - Cyclotron

The Cyclotron mechanism provides the right energies (particles up to 100 GeV).

But stable circular orbits require additional forces!

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Sunspots often come in pairs with opposite magnetic polarity. They approach each other and then merge.

Electric field $E \sim v \times B$ up to 10 V/m.

- Distance of 10^7 m
- B = 0.2 T
- $v = 10^7$ m/day

can give energies in GeV range for protons.

2 - Sunspot Pairs

Conclusion:

Same energies as Cyclotron, but doesn't require additional forces!

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$$\Delta E = \frac{1}{2}m(v + (u_1 - u_2)^2 - \frac{1}{2}mv^2$$

Linearly: $\frac{\Delta E}{E} \sim 2\frac{u_1 - u_2}{v}$

Relativistically: $\frac{\Delta E}{E} \sim \frac{4}{3}\frac{u_1 - u_2}{c}$

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Colliding with outer front: $\Delta E \sim \frac{1}{2}m(u_1^2 - 2vu_1)$
On average: $\Delta E \sim mv(u_2 - u_1)$
$\frac{\Delta E}{E} \sim 2\frac{u_2 - u_1}{v}$

3 - Shock Acceleration

Energies up to $\sim$ 100 TeV can be explained!

(Linear shock acceleration mechanisms are also called Fermi mechanism of first order.)

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If v and u anti-parallel: $\Delta E \sim \frac{1}{2}m(-2uv + u^2)$
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Magnetic clouds have higher gas density and therefore higher interaction probability.

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This minimum energy could be provided by head on collision mechanism (Fermi mechanism of first order).

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$$v_{pulsar} = \frac{2\pi R_{pulsar}}{T_{pulsar}} \sim 4 \cdot 10^6 \text{ m/s}$$

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Assuming magnetic flux is conserved:

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Single charged particles can gain 1000 TeV per meter!!

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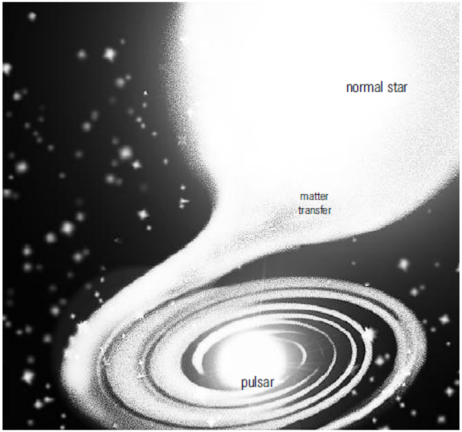
Works out to energy density of 1.1 eV/cm^3 from cosmic/gamma rays. ($\sim$ 1 eV/cm^3 observed)

6 - Binaries

Binaries consisting of a normal star and a pulsar are an acceleration candidate as well.



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The particles obtain an energy from this force $E = \int F \cdot ds = evB\Delta s$ up to $\sim 10^{19}$ eV.

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As a consequence of this, high-energy neutrinos are created in the decays of charged pions. Detections can presumably be made only if the jets are directed at us.

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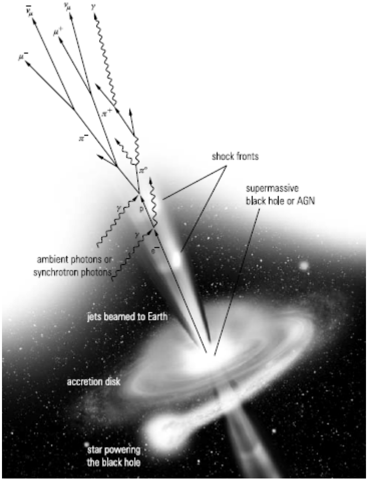

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6. Accretion disks of binary systems

Gamma Ray Production (Omer)

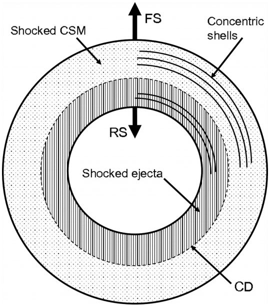
γ Ray Production Mechanisms Review

γ Rays from Supernova Remnants

- γ-ray astronomy is important for determining the CR content of astrophysical sources
- In γ-rays one can observe photons emitted as a result of hadronic CRs, which make up 99% of the CRs observed on Earth
- Three different particle radiation processes are considered most dominent in the supernova spectrum at γ-ray energy scales:
    - nuclear pion-production interactions
    - nonthermal electron bremsstrahlung
    - Compton scattering

Model of Suprenova Explosion

The supernova explosion is modeled as an expanding spherical shell of material that sweep up matter from the surrounding interstellar medium (ISM)



$$E_{ke} = \frac{1}{2}[M_0 + M_{su}(t)]v^2 \tag{3}$$

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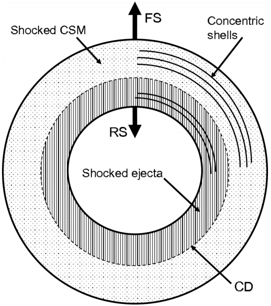


$$\frac{dE_{ke}^{su}(t)}{dt} = \frac{d}{dt}\left[\frac{1}{2}M_{su}v^2\right] = \frac{1}{2}\dot{M}_{su}v^2 + M_{su}v\dot{v} \tag{4}$$

Density of the target particles for interactions

There are three targets available for particle-particle interactions

- Explosion mass : $n_{ex}(t) = M_0/m_p V_{sh}(t)$
- Swept-up mass : increased by the comprassion ratio, for strong shock the shell of swept-up mass has density $n_{su} \cong 4n_0$
- ISM gas - n_0

Nuclear pion-production interactions

Rate of change of the Lorentz factor

$$\boxed{-\dot{\gamma}_{pp} = K_p c \sigma_{pp} n(t) \gamma_p}$$

Energy-loss time scale

$$\boxed{t_{pp} = |\gamma_p / \dot{\gamma}_{pp}| = [K_p c \sigma_{pp} n(t)]^{-1} \cong 2.2 \times 10^{15} / n(t)\ s}$$

Expected luminosity

$$\boxed{L_{pp}(t) \cong \frac{\eta_{pp} E_{su}(t)}{3 t_{pp}(t)}}$$

Nonthermal electron bremsstrahlung

Rate of change of the Lorentz factor

$$\boxed{-\dot{\gamma}_{ff} = k_{ff}\alpha_f c\sigma_{\mathrm{T}}[\Sigma n_Z Z(Z+1)]\gamma_e}$$

Energy-loss time scale

$$\boxed{t_{ff}(t) = |\gamma_e/\dot{\gamma}_{ff}| \cong 8.0 \times 10^{14}/n(t)\ s}$$

Expected luminosity

$$\boxed{L_{ff}(t) \cong \frac{\eta_{ff}\, E_{su}(t)}{t_{ff}(t)}}$$

Compton scattering

Rate of change of the Lorentz factor

$$-\dot{\gamma}_C = (4/3) c \sigma_{\mathrm{T}} U_\gamma \gamma_e^2 / m_e c^2$$

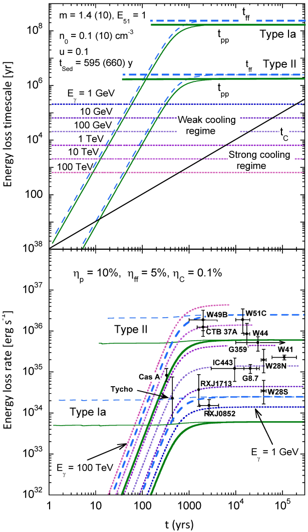
Energy-loss time scale

$$t_C(\mathrm{s}) = |\gamma_e / \dot{\gamma}_C| = 7.7 \times 10^{19} / \gamma_e \ s$$

Expected luminosity

$$L_C(t) \cong \frac{\eta_C \, E_{su}(t)}{t_C(t)}$$

Energy-loss time scales and γ-ray luminosities



SNR seen on Earth in γ-Rays

- Q_0^{π}, Q_0^{brem}, and Q_0^{IC} gamma ray emissivities ($\mathrm{cm}^{-3}\ \mathrm{s}^{-1}\ \mathrm{GeV}^{-1}$)
- Then the gamma ray flux observed at Earth, a distance d from the SNR, is given by -

$$F_{\gamma}(E_{\gamma}, \alpha) = \frac{n_1 A_1 V}{4\pi d^2} \left[Q_0^{\pi}(E_{\gamma}, \alpha) + R_e Q_0^{\mathrm{brem}}(E_{\gamma}, \alpha) + \frac{R_e}{n_1} Q_0^{\mathrm{IC}}(E_{\gamma}, \alpha) \right] \tag{5}$$

Coffee Break and Discussion

Propagation Through Space

- Cosmic Rays
- Gamma Rays

Cosmic rays (CRs)

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- galactic magnetic field amplification $\rightarrow$ efficient CRs scatter back and forth the SNR shock
- self-consistent model:
  efficient CRs acceleration $\rightarrow$ magnetic field amplification
  feedback from amplified fields $\rightarrow$ efficient CR acceleration

general procedure

- specify the CRs sources
- define the CRs halo shape and boundary conditions (CRs freely exit into intergalactic space)
- account for energy loss or gain processes in interstellar medium (ISM)
- nuclear fragmentation
- radioactive decay of unstable nuclei

Galactic CRs diffusion model

- steady state transport equation in ISM

$$-\nabla D \nabla \Psi + \nabla(\mathbf{u}\Psi) - \frac{\partial}{\partial p}\left[p^2 K \frac{\partial}{\partial p}(p^{-2}\Psi)\right] - \frac{\partial}{\partial p}\left(p\frac{\nabla \mathbf{u}}{3}\Psi\right) + \frac{\partial}{\partial p}\left(\dot{p}_{loss}\Psi\right) + \frac{\Psi}{\tau} = q \quad (6)$$

- diffusion equation

$$D = \frac{v r_g B^2}{12\pi k_{res} W(k_{res})} = \frac{v r_g^a}{3(1-a)k_L^{1-a}} \frac{B^2}{\delta B_L^2} \quad (7)$$

- GALPROP code for numerical simulation: solves (1) for nuclei, $\bar{p}, e^-, e^+$; computes γ-rays and synchrotron emission

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- two proposed spectra

MHD turbulence spectrum

- Kolmogorov spectrum $W(k) \propto k^{-\frac{5}{3}}$
  - accounts for reacceleration of CRs by MHD
  - leads to $D \propto v(p/Z)^{1/3}$
- Iroshnikov-Kraichnan spectrum $W(k) \propto k^{-\frac{3}{2}}$
  - reacceleration with wave damping
  - leads to $D \propto v(p/Z)^{1/2}$

secondary-to-primary ratio

- key information on CRs propagation from the abundance of light elements: ^{2}H, ^{3}H, Li, Be, B
- produced by spallation of heavier primary with ISM
- estimate secondary-to-primary ratio $\rightarrow$ B/C
- allows to infer the MHD turbolence spectrum

B/C ratio

instabilities and plasma effects

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- both lead to amplification of magnetic fields at the supernova shock $\rightarrow$ integral part of CRs acceleration
- Galactic gas halo might not be static (galactic wind) $\rightarrow$ CRs exiting the Galaxy increase the MHD turbulance $\rightarrow$ self-consistently determines diffusion-convection of CRs

Photon propagation

- γ-rays propagate freely propagate through ISM
- their path might be deflected by gravitational lensing
- they "feel" the ISM magnetic field through the Faraday Effect

Observations

Space-born detectors:
Fermi- Large Area Telescope (LAT)
Astro-rivelatore Gamma a Immagini Leggero (AGILE) AGILE and Fermi-LAT investigate complementary energy bands

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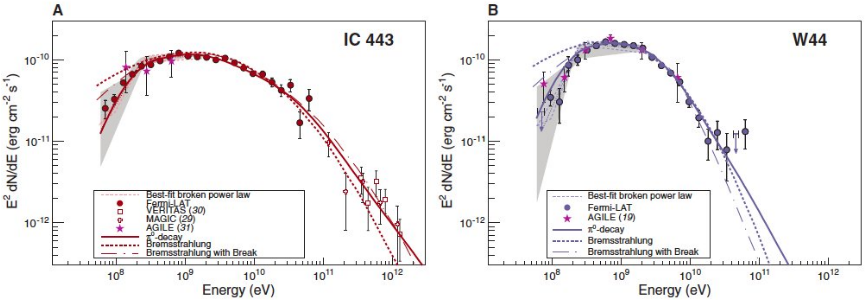
- no leptonic model $\rightarrow$ hadronic model (π^0 decay)

Tycho SNR

SNRs and Molecular clouds interaction



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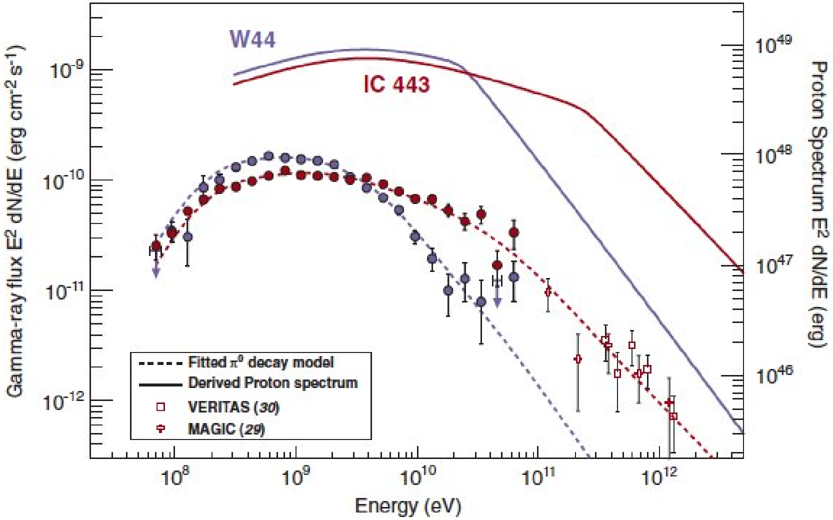
- fit the Fermi-LAT and AGILE data with π^0 decay spectrum

W44 and IC443

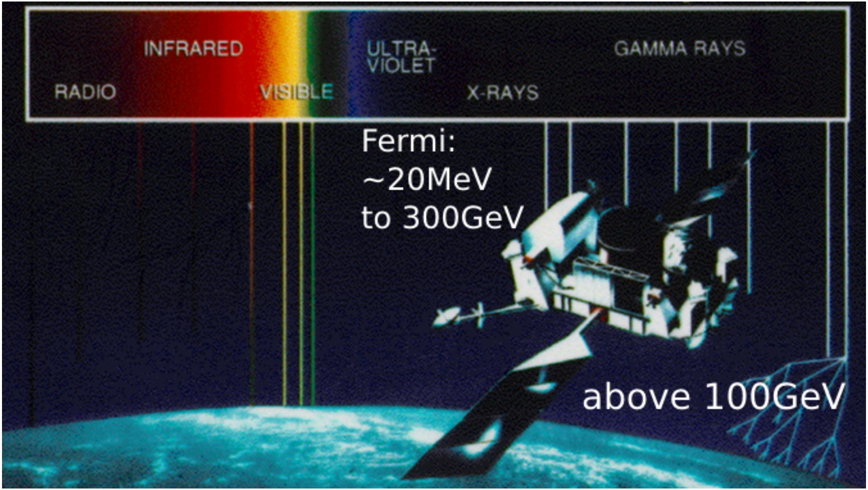


first detections of SN

date	length of visibility	remnant	Historical Records Chinese	Japanese	Korean	Arabic	European
AD1604	12 months	G4·5+6·8	few	–	many	–	many
AD1572	18 months	G120·1+2·1	few	–	two	–	many
AD1181	6 months	3C58	few	few	–	–	–
AD1054	21 months	Crab Nebula	many	few	–	one	–
AD1006	3 years	SNR327.6+14.6	many	many	–	few	two
AD393	8 months	–	one	–	–	–	–
AD386?	3 months	–	one	–	–	–	–
AD369?	5 months	–	one	–	–	–	–
AD185	8 or 20 months	–	one	–	–	–	–

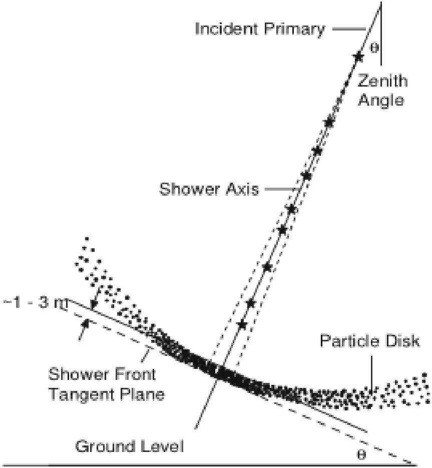
We will take another look at the remnants of the highlighted supernovas at the end of this presentation.

the electromagnetic spectrum observed so far



characterization of airshowers

- amount of particles
- direction of main axis
- spacial structure
- spread in time
- hadron content
- fluctuations in development
- muon content

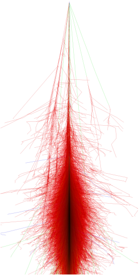


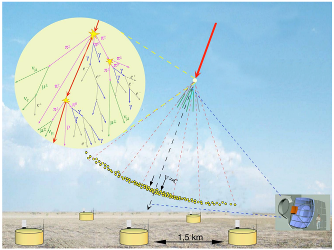
different signatures

- Cherenkov light
- particles reaching the ground
- radio emission (as well from interaction with the geomagnetic field)
- air fluoresence
- acoustic effects

particle detector arrays

- sampling on arrival at ground level
- some information on the state of the shower from the arrival sequence of the current particle generation
- direction information from the charge separation of the magnetic field and the geometry / arrival times of the signal





example: Akeno Grand Air Shower Array in Japan

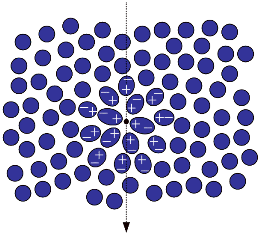
- takeing data since 1991
- 111 detectors
- approx 1km spacing
- measured gamma rays above the GZK-cutoff

fly's eyes: air fluoresence detectors

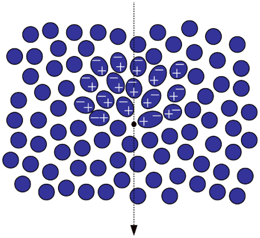
- shower excites nitrogen in the atmosphere
- isotropic emission of fluoresence light (300-400 nm band)
- detection by PMTs
- advantage: able to monitor large areas and therefore aimed to detect rare ultra high gamma ray events

HiRes detector in Utah

Cherenkov telescopes: review of Cherenkov light



$\beta < \frac{1}{n}$



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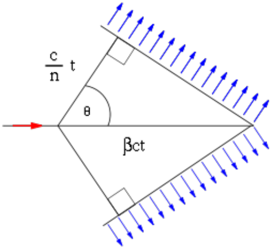
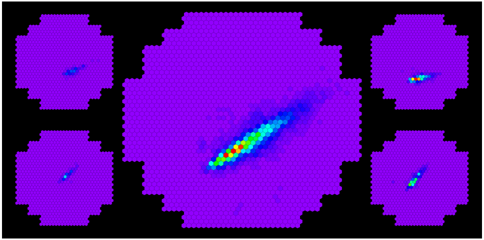


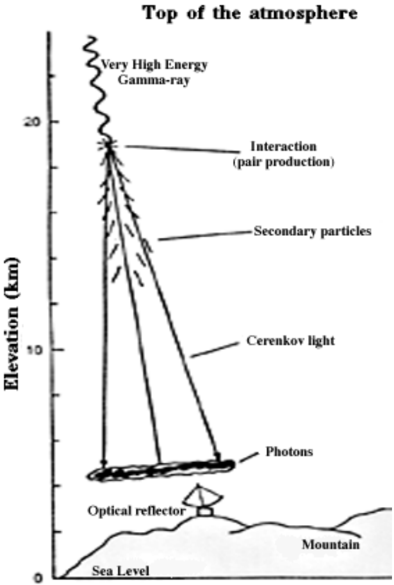
$cos(\Theta) = \frac{1}{\beta \cdot n}$

Cherenkov telescope: H.E.S.S.

goal: restruct energy, species and direction of the initial particle



Cosmic Ray Simulations for Kascade



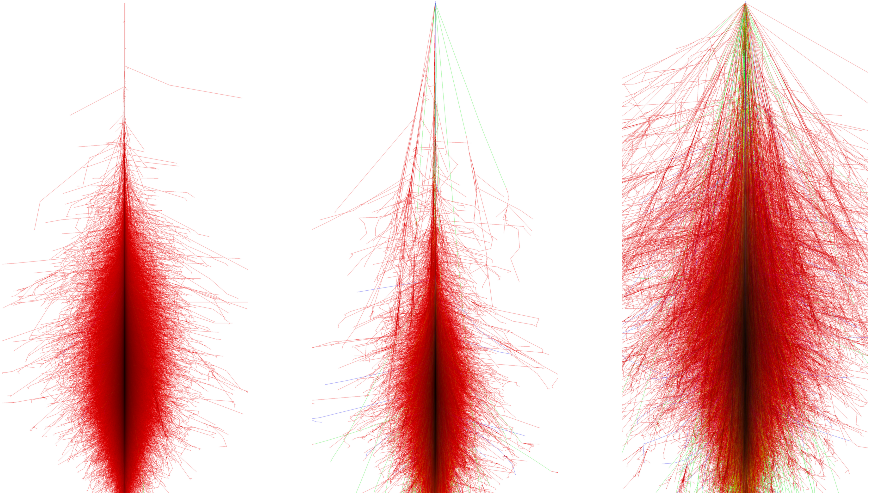
The CORSICA code:

- interactions and cross-sections
- decay and propagation (ionization of the atmosphere, energy loss)
- (seasonal) composition of atmoshere, different layers
- earth magnetic field

A word of caution:

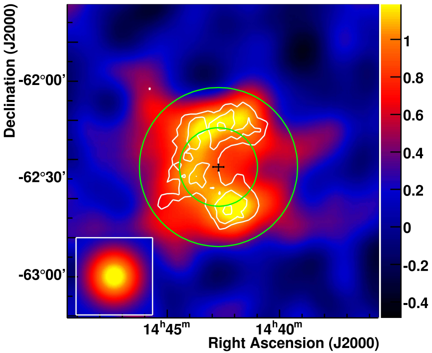
- knowledge of high energy interactions incomplete
- extreme forward direction not accesible at colliders

simulation results - photon, proton and iron at 10^{13}eV

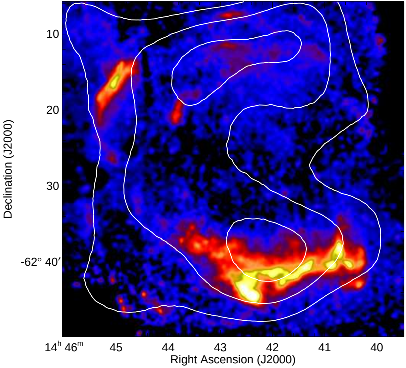


CORSIKA simulation 100TeV gamma ray

RCW86 possibly the remnant of SN AD185

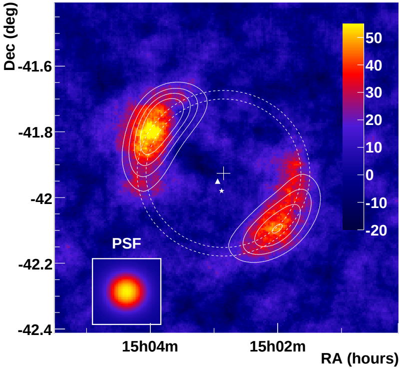


excess counts of gamma rays (with energy above 100GeV)

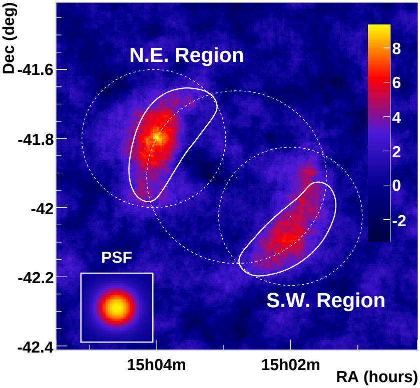


gamma ray map (here in white) in comparison with the background subtracted X-ray map

SN AD1006 remnant morphology

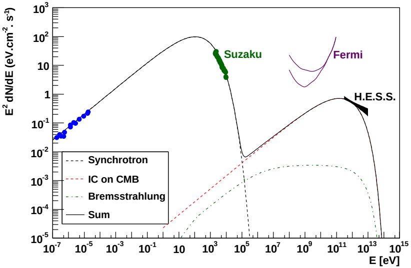


excess counts of gamma rays (with energy above 260 GeV)
white region shows the earlier measured X-ray distribution

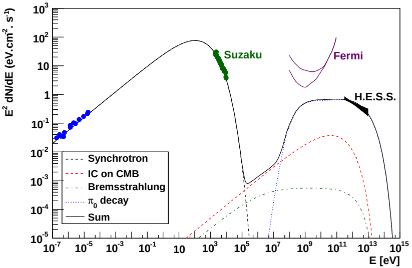


significance in standard deviations
white region contains 80% of the respective X-ray energy

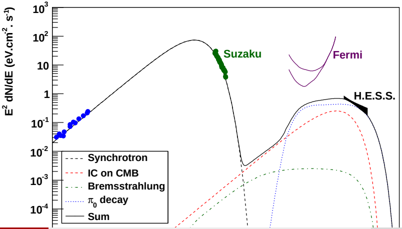
SN AD1006 remnant gamma source



leptonic scenario



hadronic scenario



SHALL WE DO ONE SLIDE WITH ALL CONCLUSIONS FROM THE SECOND PART FOR THE DISCUSSION?

Another Coffee? And Discussion..

References

- NASA FERMI Gamma Ray Space Telescope site
- Dermer, C. D., & Powale, G. 2013, 553, A34
- Ackermann, M., Ajello, M., Allafort, A., et al. 2013, Science, 339, 807
- Vink, J. (2012)

The End