Astroparticle Physics

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IEEC-CSIC, Barcelona

Taller de Altas Energias 2013
Centro de Ciencias de Benasque Pedro Pascual

General

1. Physical processes relevant in astroparticle physics (EdOW / 1h)
2. Instruments and experimental techniques in gamma-ray astronomy (Javier Rico / 1h)
3. Experimental results (EdOW /1h)
4. Instruments and experimental techniques in cosmic-ray astronomy (Javier Rico / 1h)
5. Tutorial: Q&A

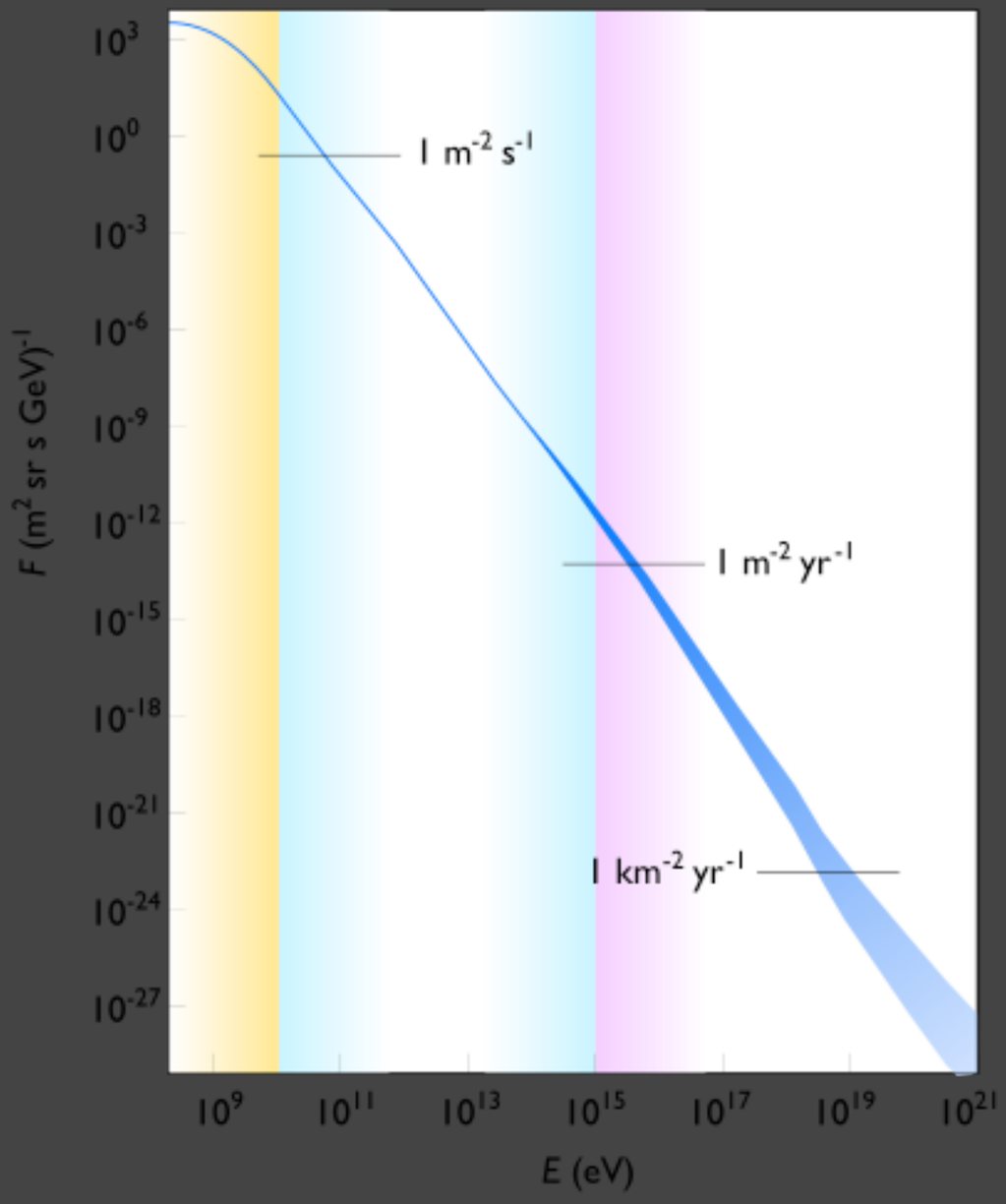
Q & A

Method: Choose one of this questions and discuss it in the group (30').
The results of the discussion will be presented by one of the group members to be discussed in the lasting part of the tutorial time.

- What are the advantage and disadvantages of placing an astro-particle detector on the Moon surface?
- Which astrophysical source might be able to accelerate particles to VHE beside the one discussed?
- New ideas to improve a detector (HAWK, CTA or/and Auger). Could you think in a different kind of detector beside the ones discussed here?

What is Astroparticle Physics?

- Study of elementary particles of astronomical origin and their relation to astrophysics and cosmology
- "Particle Physics without accelerators!"
- Particle Physicist had to use astrophysics scenario to perform comparable experiments to those found in nature going to energies up to $E=10^{20}$ eV
- Investigation of non-thermal processes in the Universe in the most energetic, extreme and violent forms
- Through different messengers: gamma-rays, neutrinos, and cosmic rays



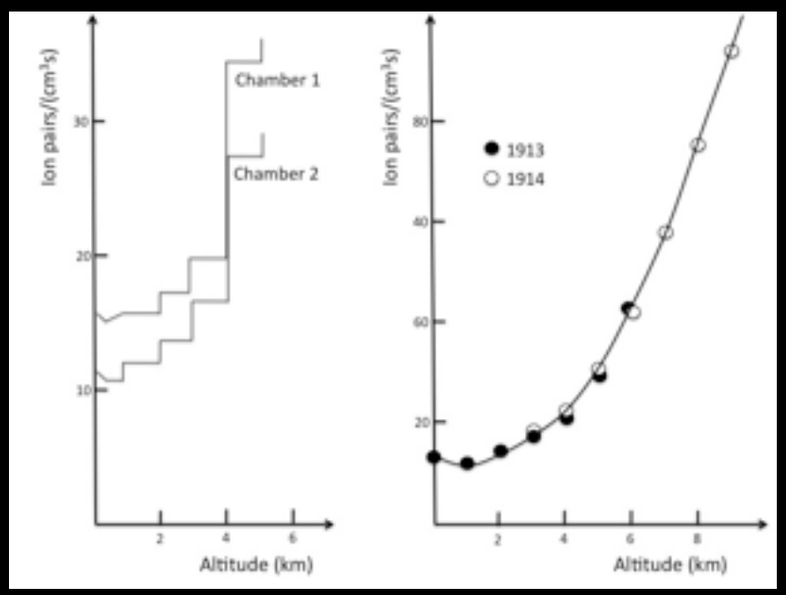
Historical approach

Victor Hess experiment:

>Measure the ionization of the atmosphere at different altitude, using a ballon

>During sun eclipse, no change was observed:

it comes from the space



The first photographies of particles

>Supersaturated vapor of water or alcohol to trace de trajectories

>Application of a uniform magnetic field

August 12, 1912

1913

1914

The first theoretical ideas:

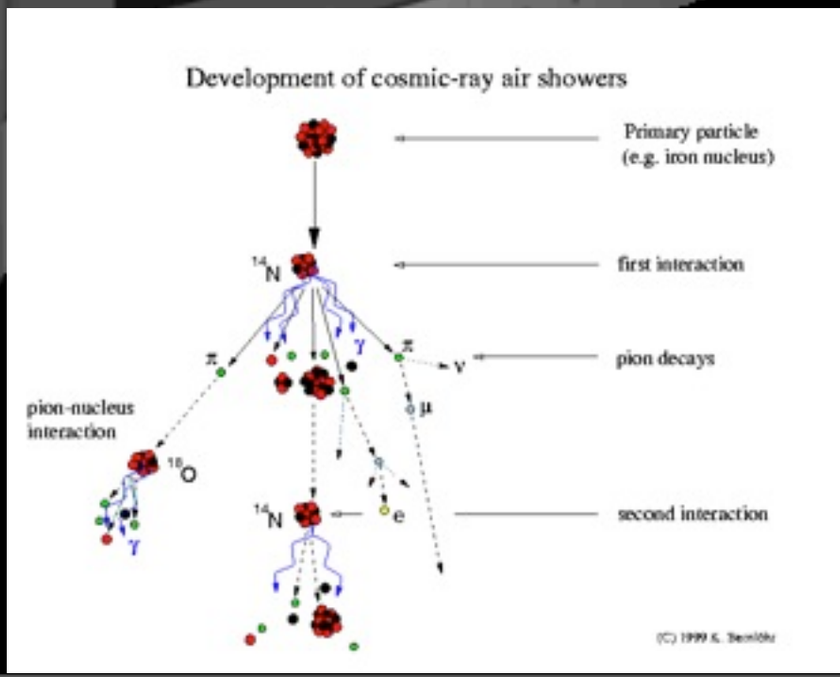
>Cosmic ray origin in SNRs

>Neutrinos

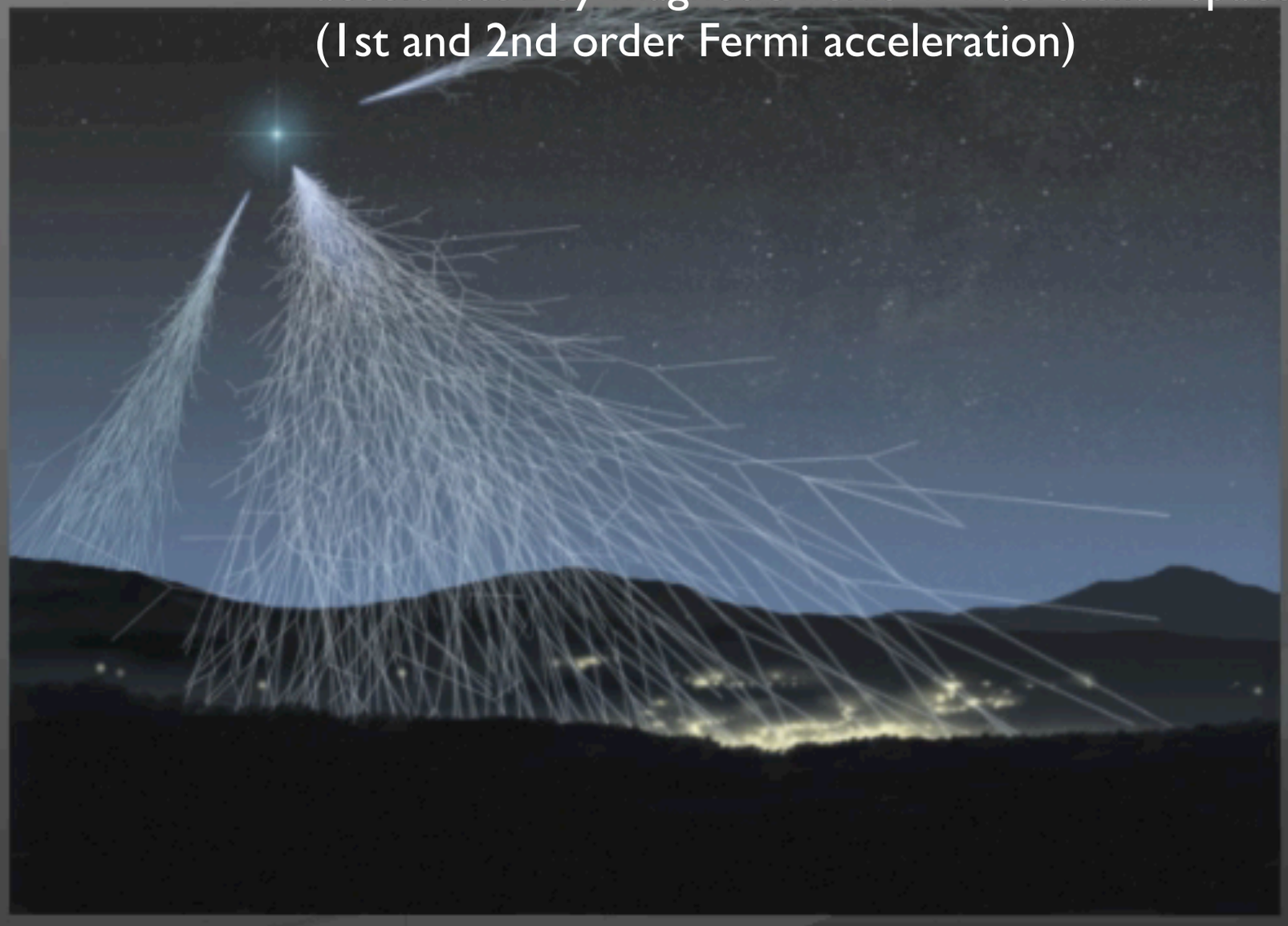
>Dark Matter

>....

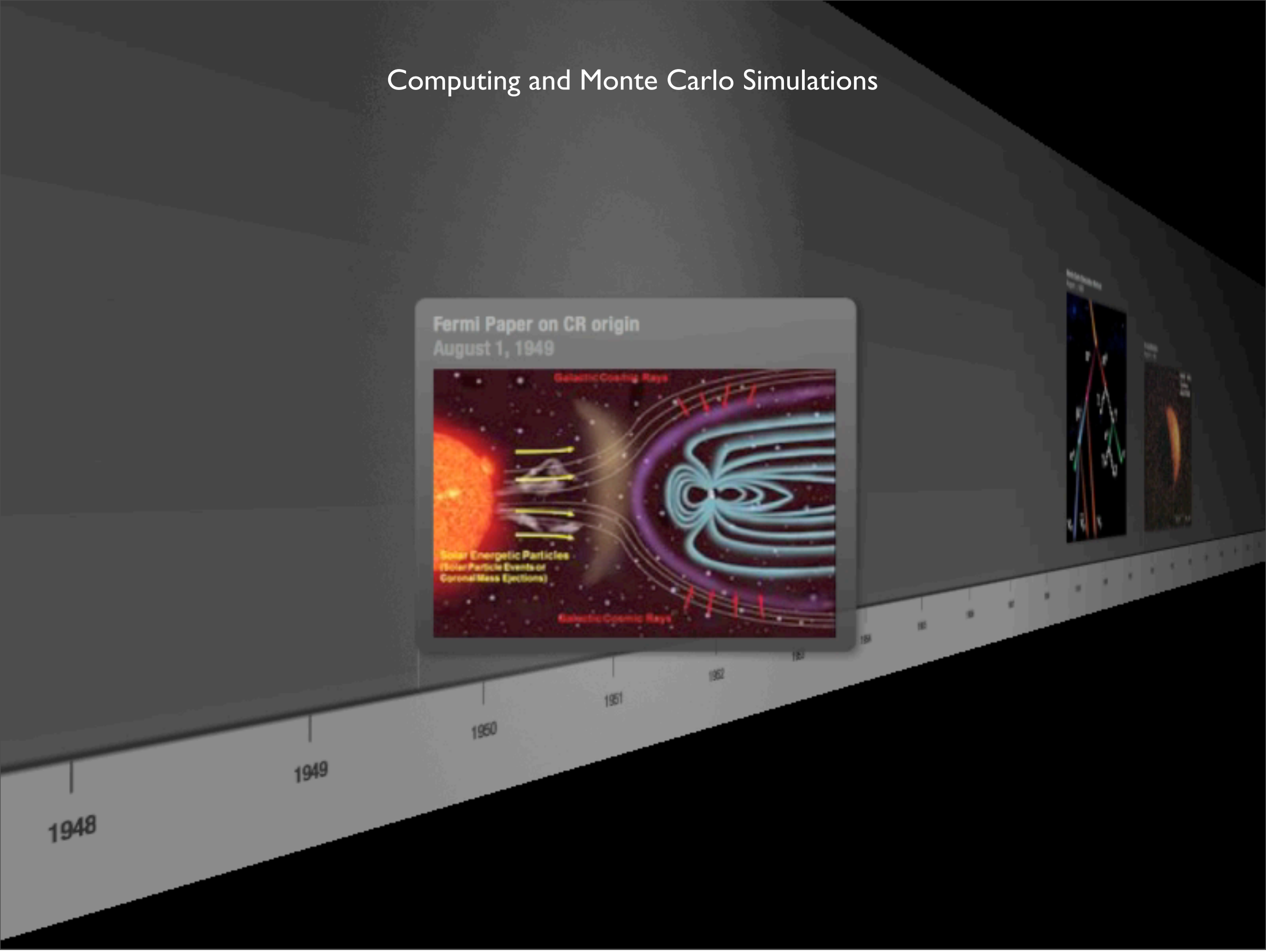
Not all the ionizing particles were the original (or primary) but product of their decay



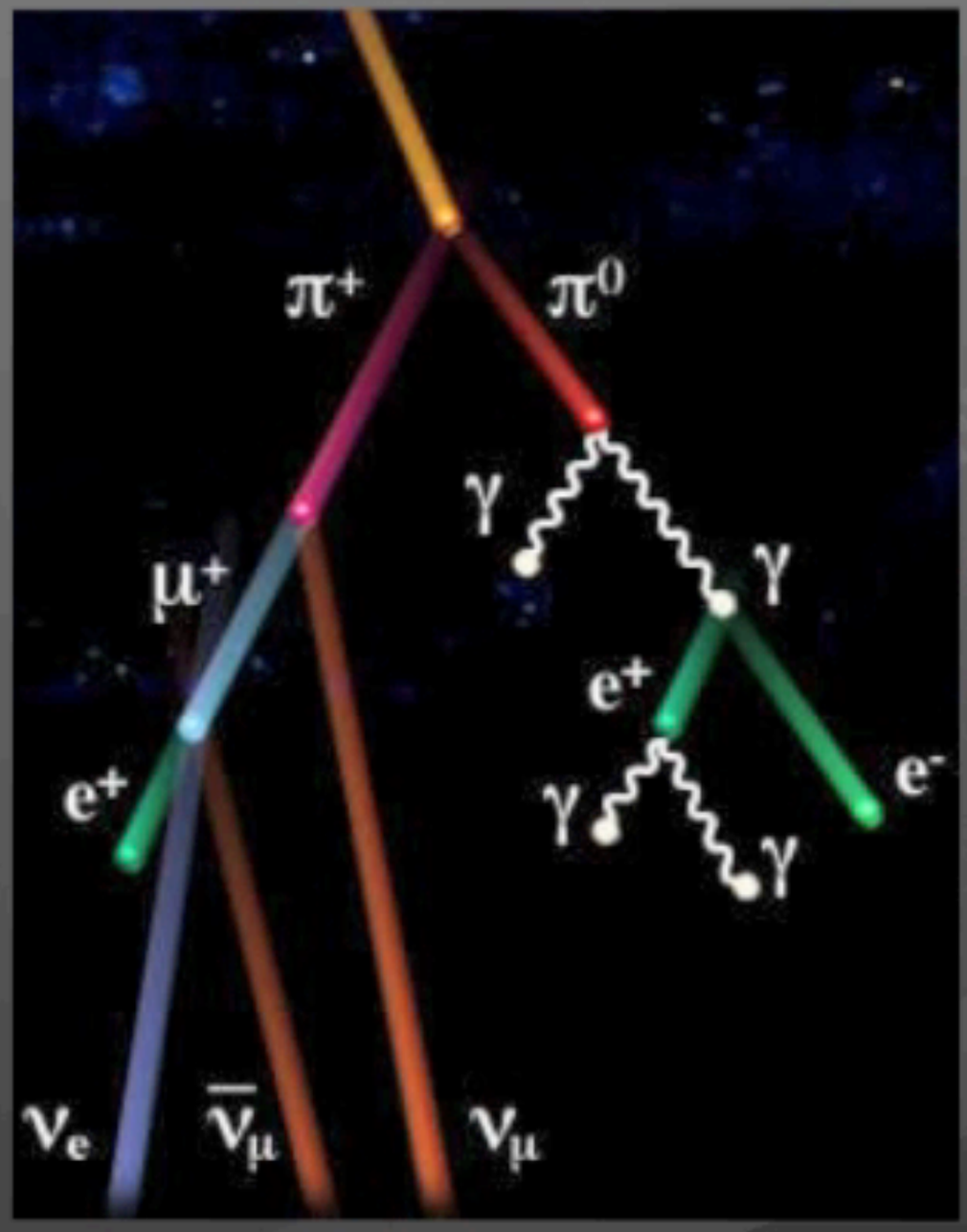
cosmic rays arose through material being accelerated by magnetic fields in interstellar space (1st and 2nd order Fermi acceleration)



Computing and Monte Carlo Simulations

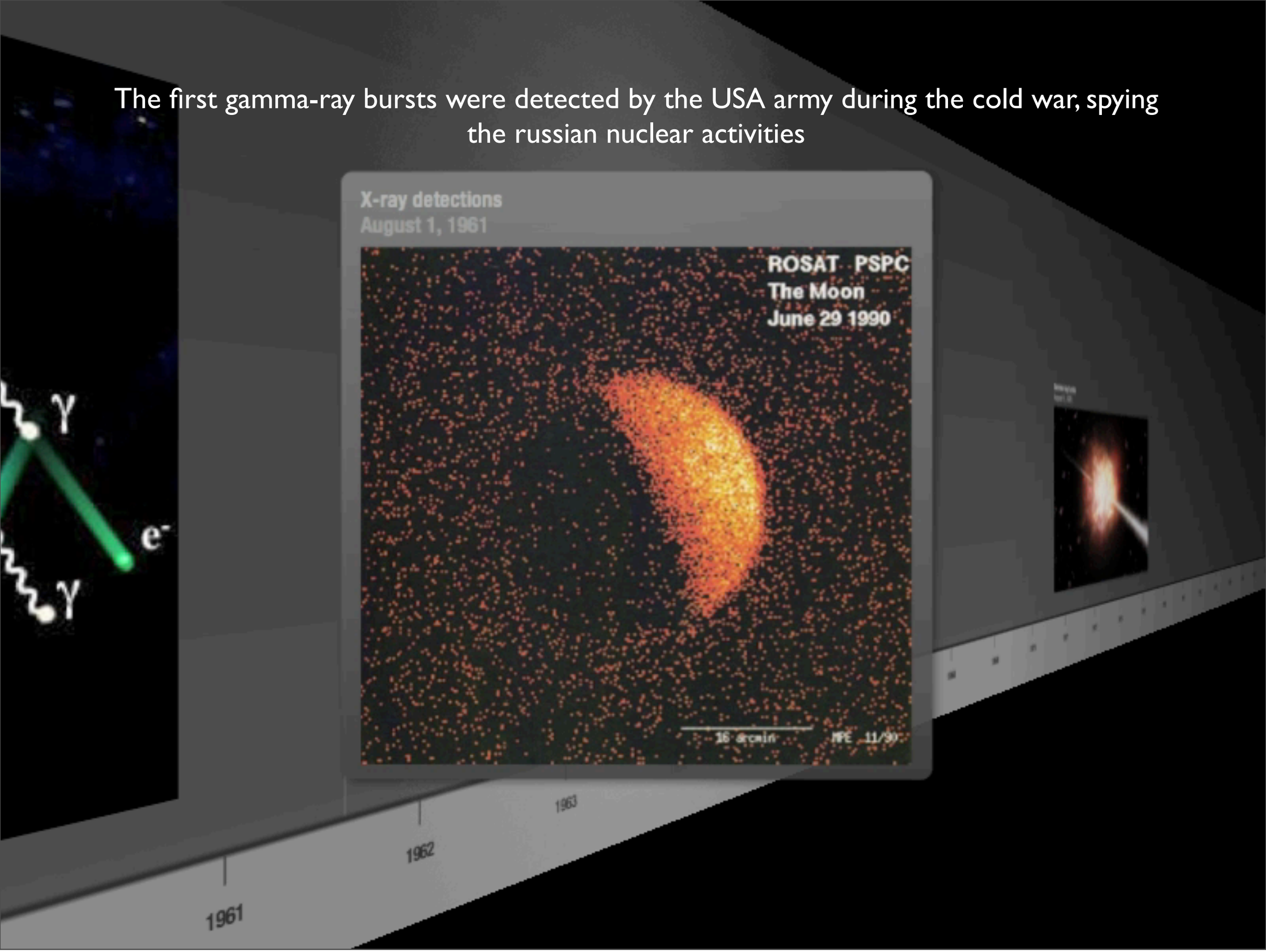


Monte Carlo Simulation Method
August 1, 1958



1959
1960

The first gamma-ray bursts were detected by the USA army during the cold war, spying the russian nuclear activities



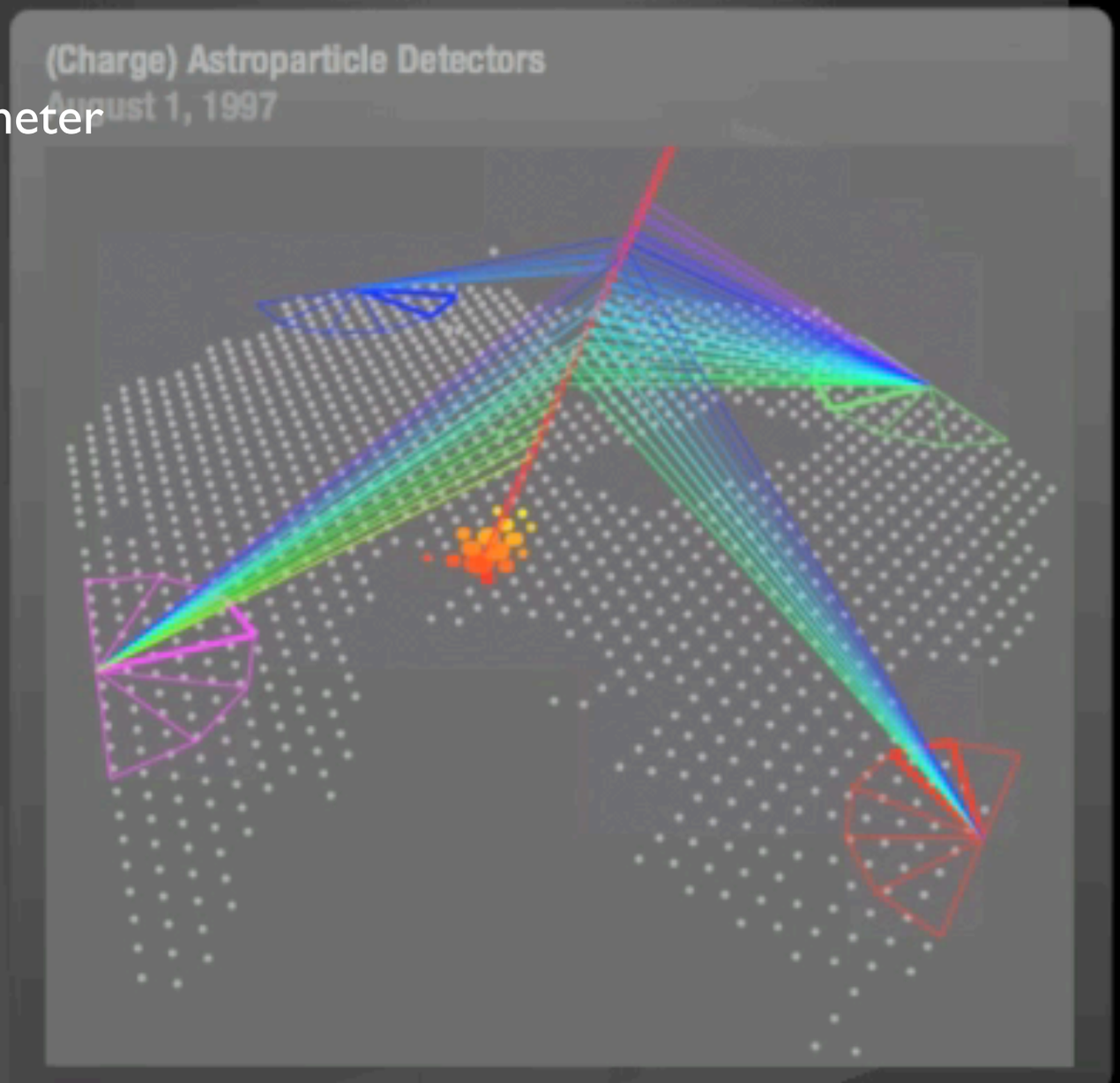
Gamma-ray bursts
August 1, 1970

1971

1972

(Charge) astro-particle detectors reconstruct particle showers until the primary interacting particle

Neutrino Experiments:
Using the Earth as calorimeter



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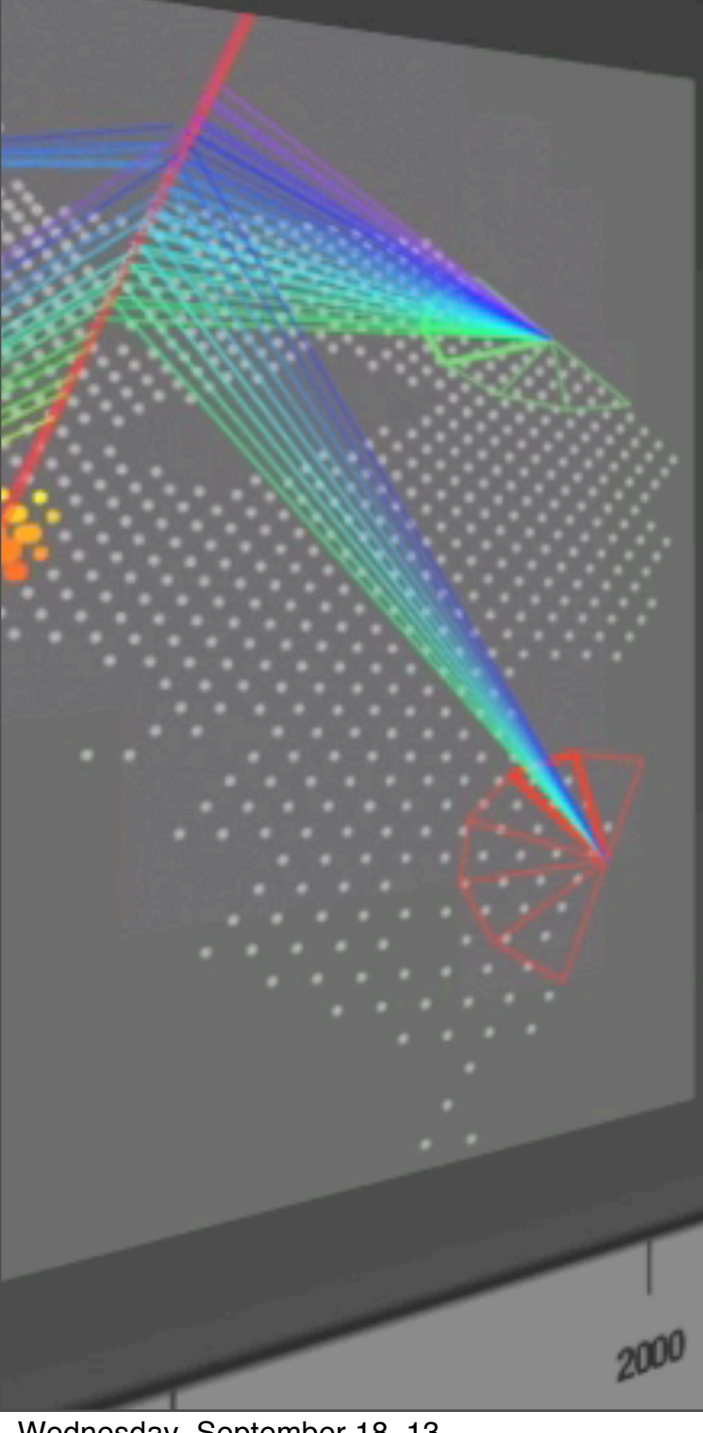
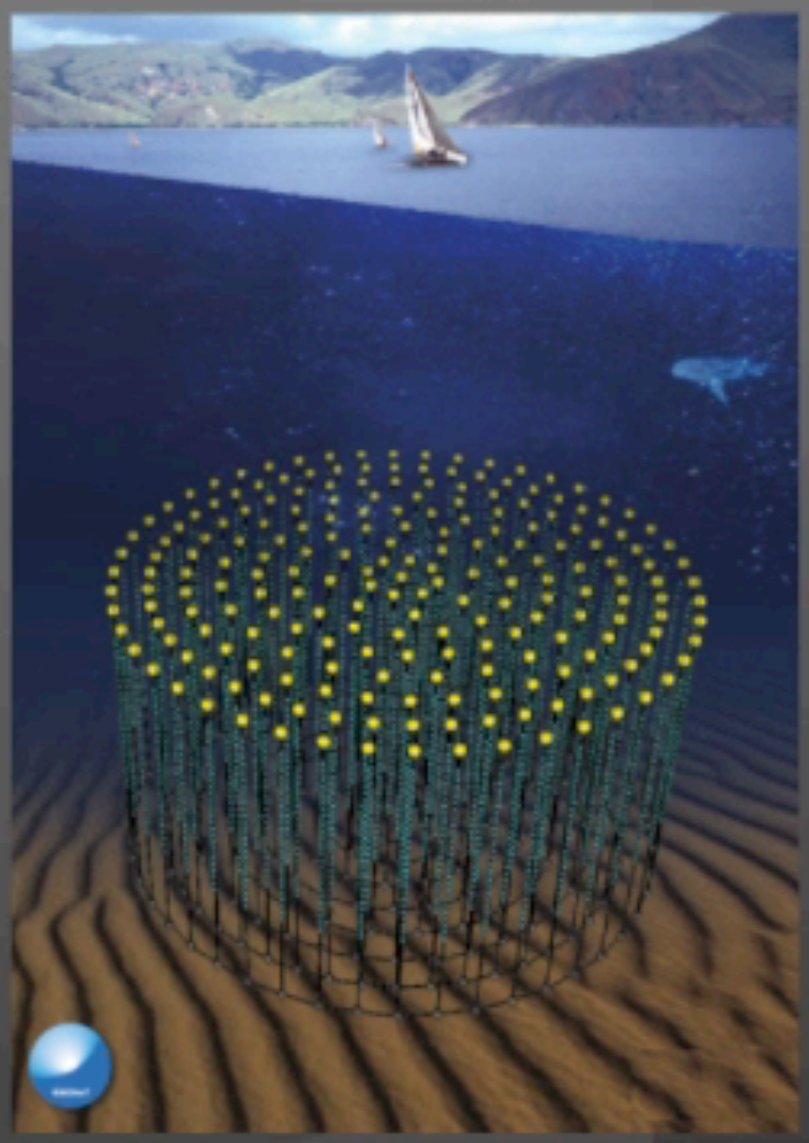


Neutrino detectors
August 1, 2000

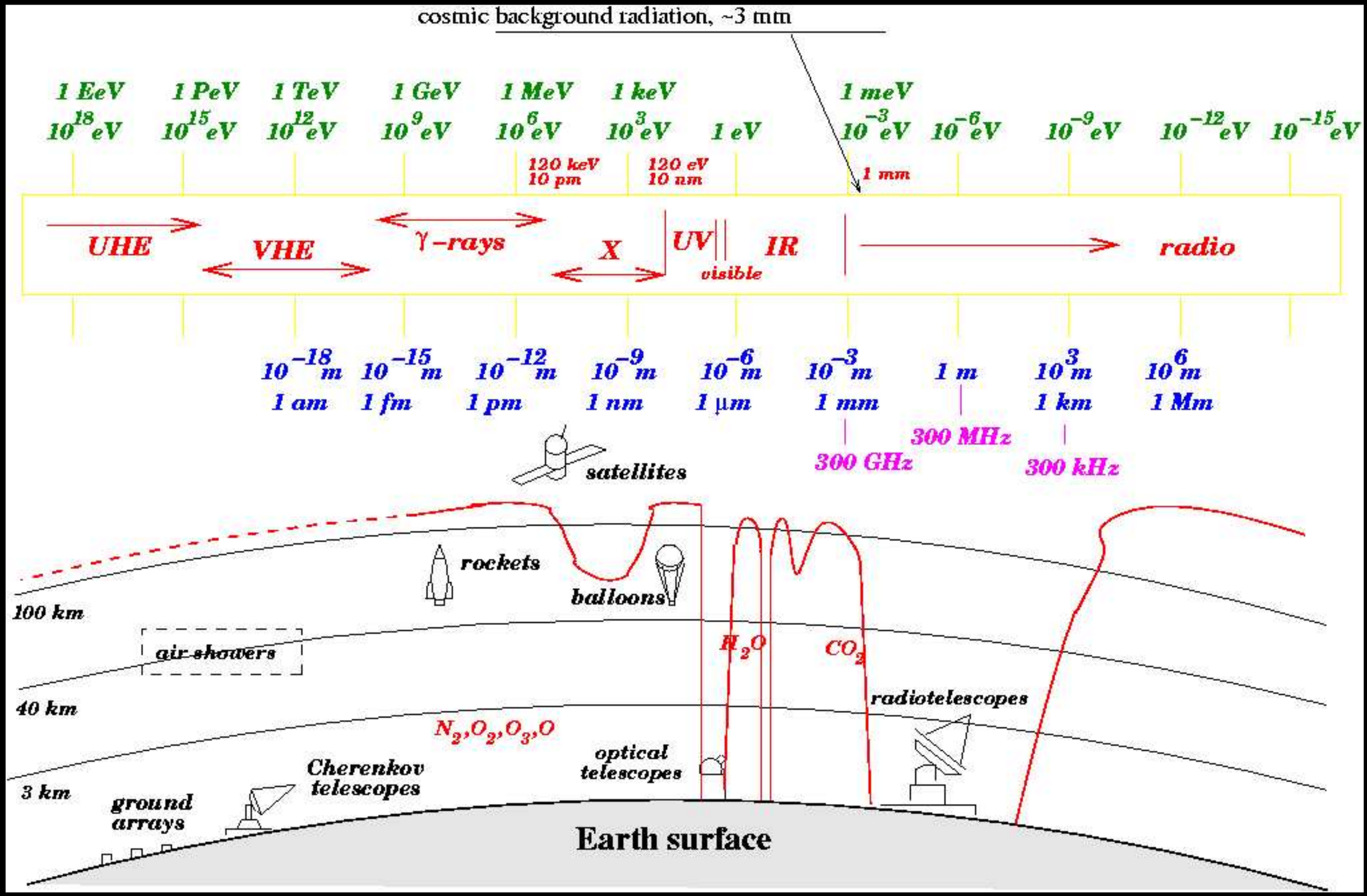


2000

2001

2002

‘the last window’ in the E-M spectrum



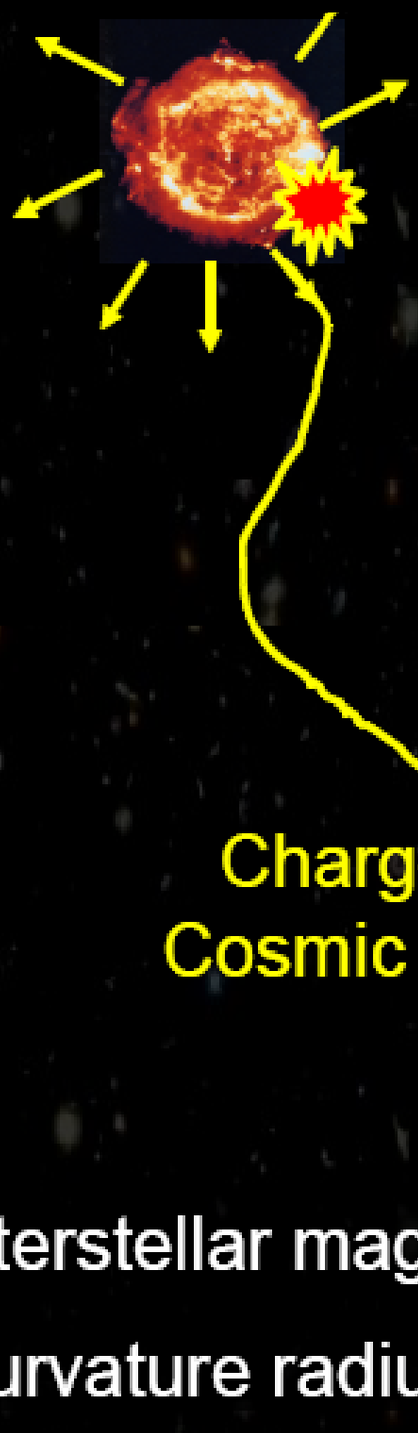
Relevant Physics Processes

generally the phenomena relevant to HEA proceed under extreme physical conditions in environments characterized by

- huge gravitational, magnetic and electric fields
- very dense background radiation
- relativistic bulk motions (black hole jets and pulsar winds)
- shock waves, highly excited (turbulent) media, etc...

Messengers

astronomical messengers should be neutral & stable
photons and neutrinos fully satisfy these conditions
partially also ultra-high energy neutrons and protons

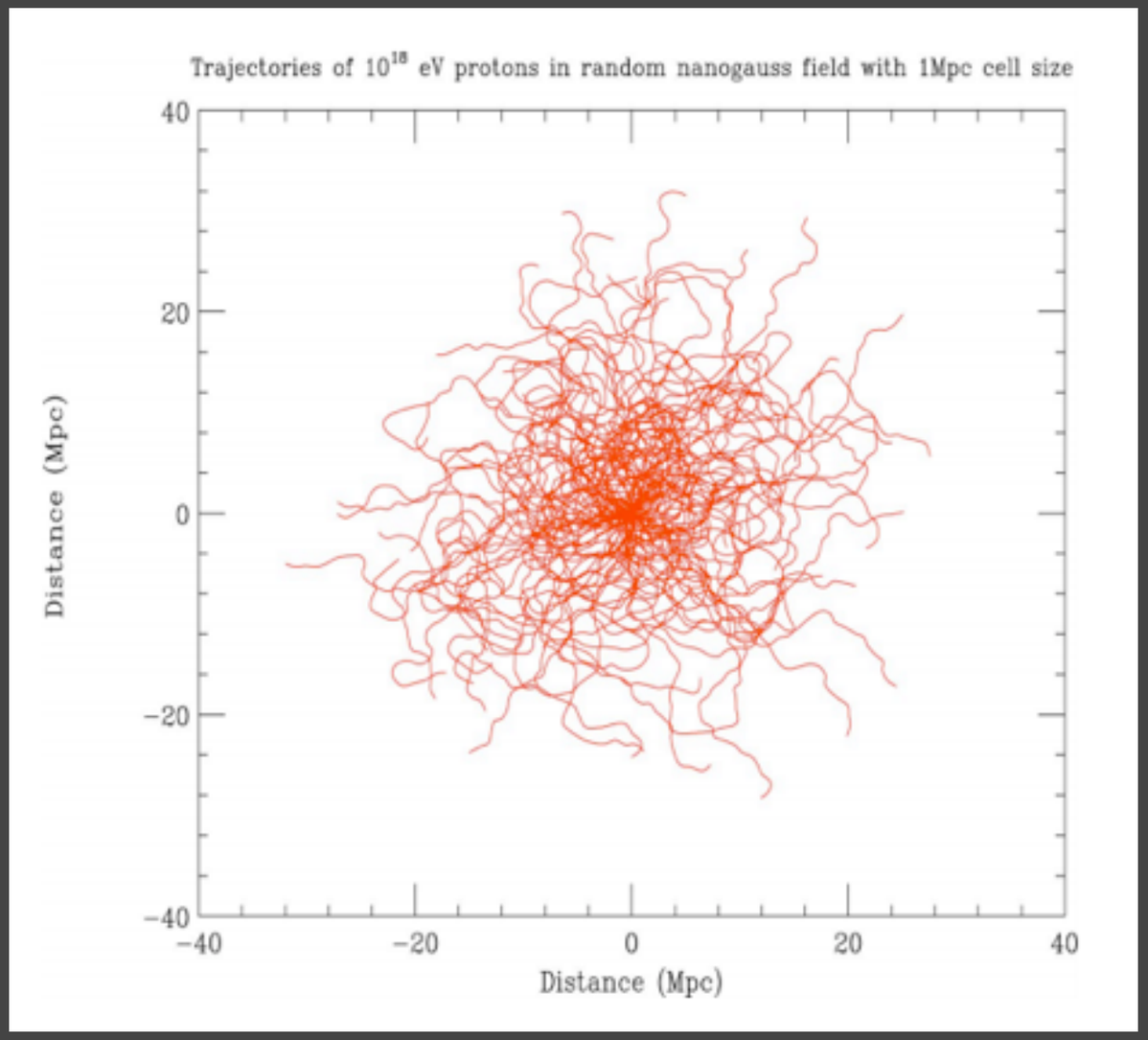


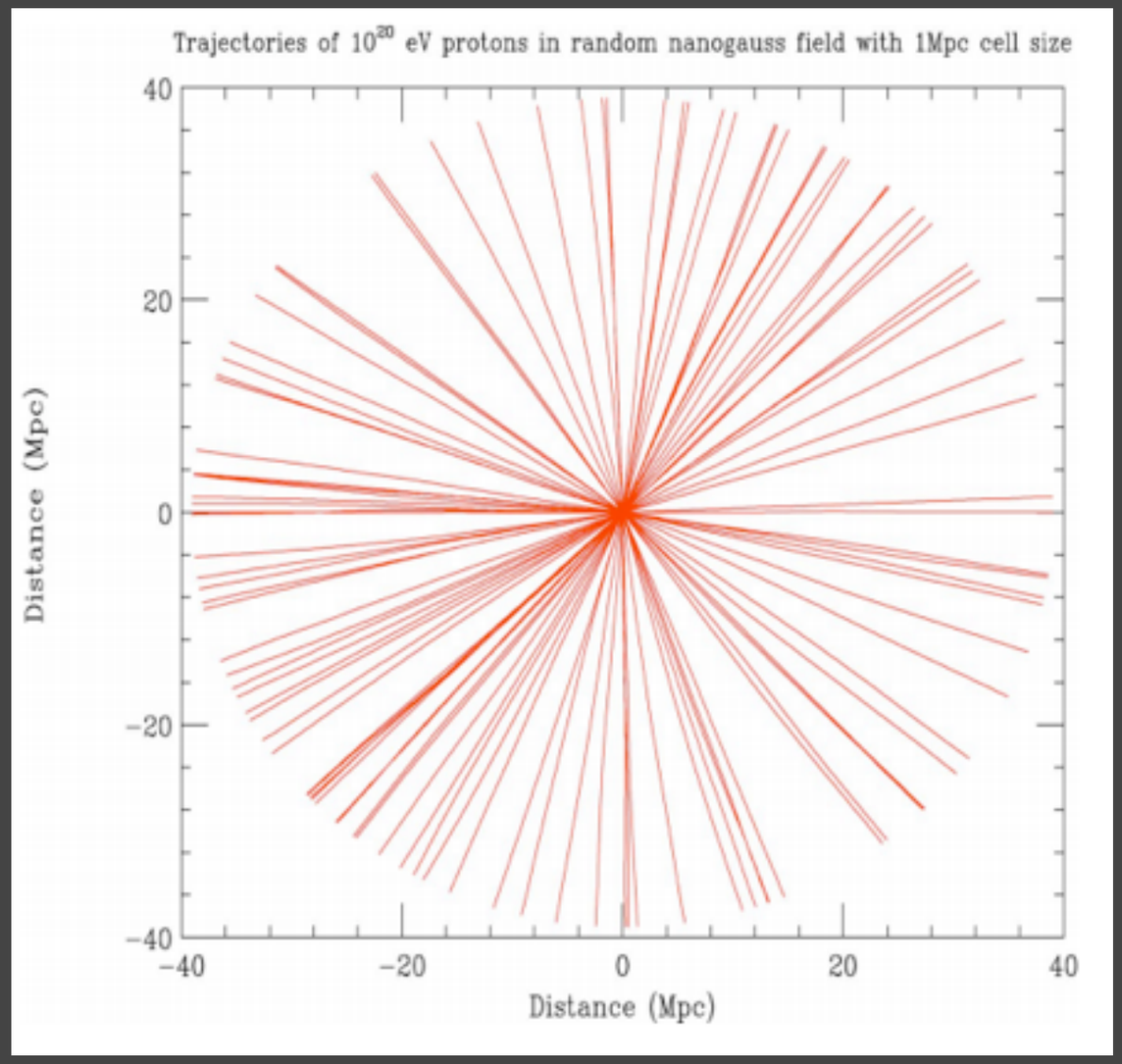
- **neutrons:**
  $d < (E_n/mc^2)\, c\, \tau \Rightarrow E_n > 10^{17}$ (d/1 kpc) eV

  Galactic astronomy with $E>10^{17}$ eV neutrons

- **protons:**
  $\Phi \sim 1^\circ$ if $E>10^{20}$ eV for IGMF $B<10^{-9}$ G
  Extragalactic astronomy with $E>10^{20}$ eV protons

Astrophysics with protons





J. Cronin

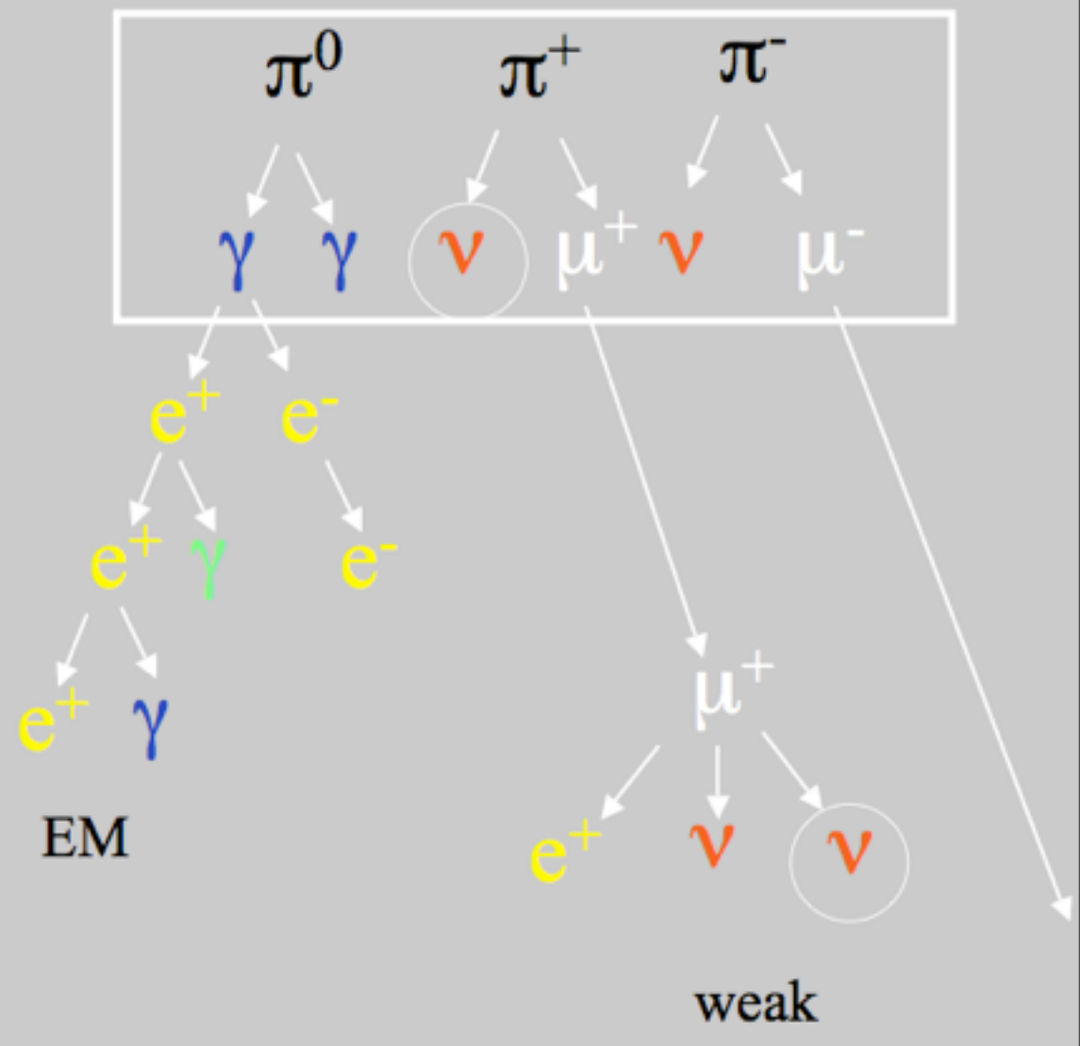
Gamma-ray and Neutrinos

- **gamma-rays:**
  produced in hadronic and E-M interaction
- **neutrinos:**
  produced only in hadronic interactions

Hadronic interaction

$p + p \Rightarrow \pi^0, \pi^+, \pi^-$

(and synchrotron emission in X-ray and radio in presence of B)



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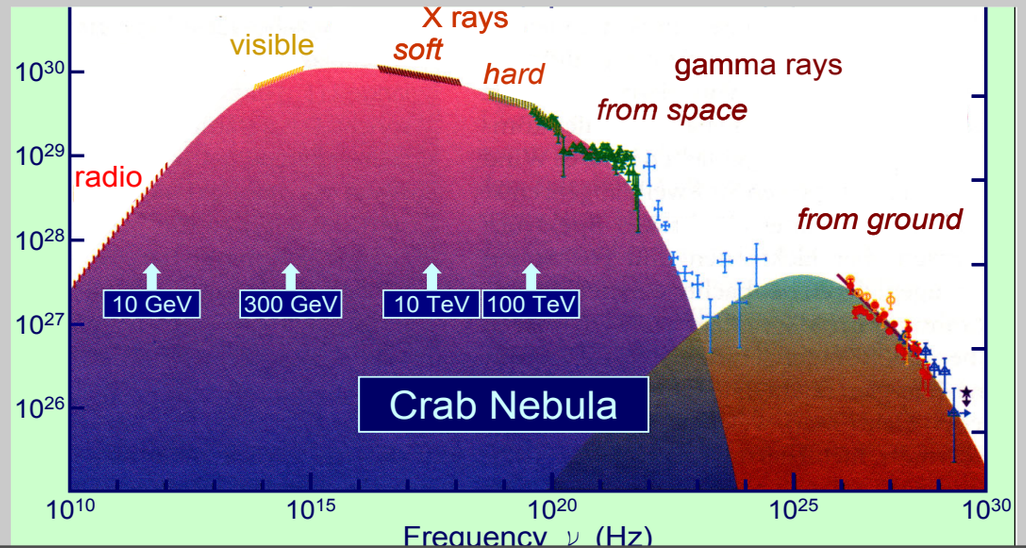
E-M interaction

$e_{HE} + \gamma_{LE} \Rightarrow e_{LE} + \gamma_{HE}$ Inverse Compton on CMB, dust & starlight

$e_{LE} + B \Rightarrow e_{LowerE} + \gamma_{LE}$ Synchrotron emission in X-ray and radio



Radiation and Absorption Processes

> Interaction with matter:

E-M:

> bremsstrahlung: e N(e) => e' γ N (e) * $E\gamma \sim 1/2E_e$

> pair production: γ N(e) => e^+e^- N (e)

> e+e- annihilation: e^+e^- => γ γ (511 keV line)

Strong/week: pp (A) => π, K, Λ, ... * $E\gamma \sim 1/10E_p$

π, K, Λ => γ, ν, e, μ

μ => ν

Radiation and Absorption Processes

> Interaction with radiation and B-fields

Radiation field

E-M:

inverse Compton: e γ (B) => e **γ** $E\gamma \sim \varepsilon(Ee/mc^2)^2$ (T) to ~Ee (KN)

γγ pair production: γ γ (B) => e^+e^-

Strong/week $p\gamma \Rightarrow \pi, K, \Lambda, \ldots$ $E\gamma \sim 1/10 Ep$

$\pi, K, \Lambda \Rightarrow$ **γ**, ν, e, μ

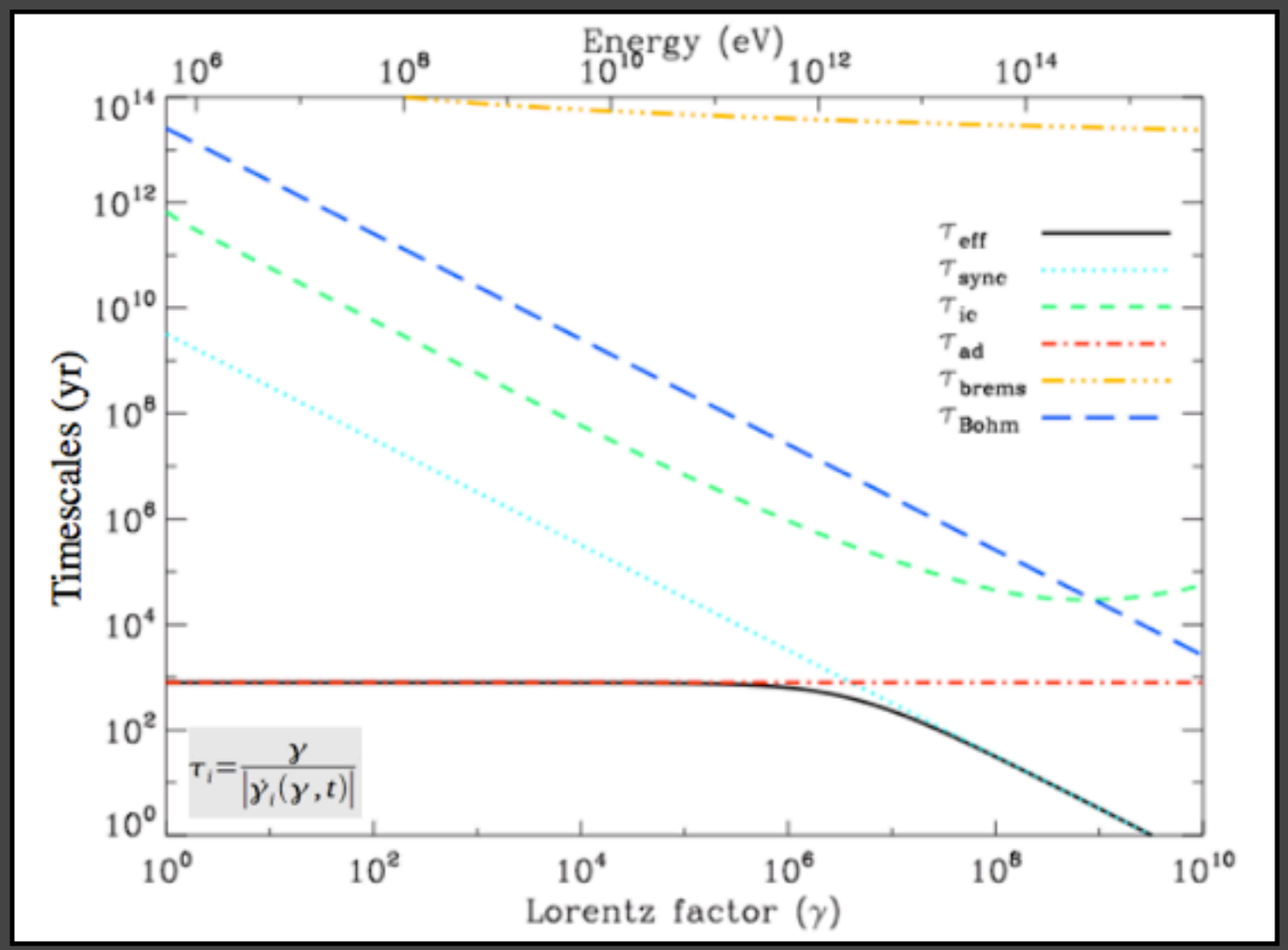
$\mu \Rightarrow \nu$

B-field

synchrotron e (p) B => **γ** $E\gamma \sim BE_e^2$; $h\nu_{max} \sim \alpha^{-1} mc^2$

pair production **γ** B => e+e-

Acceleration Sites



$$t_{acc} \propto EB^{-1}$$
$$t_{syn} \propto B^{-2}E^{-1}$$
$$t_{IC} \propto u^{-1}E_e^{-1}$$
$$E^e_{max} \propto sqrt(B)$$
$$E^\gamma_{max} = h\nu \propto BE^2$$

- Jets, relativistic bulk motions
- Shocks, relativistic winds
- Fermi acceleration to reach those energies

Fermi acceleration

Fermi acceleration (or DSA) is the acceleration of charged particles when multiple reflected in magnetic mirrors. This results of a gain of no-thermal energy of the particles (collisionless)

- First order:
  - when the magnetic inhomogeneities both precede and follow the particles
  - results on a power-law spectrum
  - energy gain per bounce proportional to v_{shock}/c
  - In solar and SNRs shocks

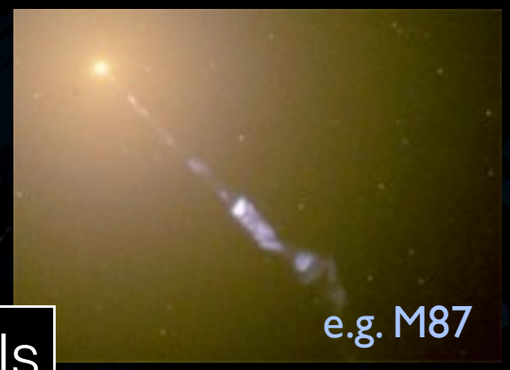
- Second order:
  - energy gained during the motion of particles in the presence of randomly
  - moving "magnetic mirrors"
  - used to explain the formation of Cosmic-rays (interstellar magnetized clouds)
  - energy gain per bounce proportional to $(v_{shock}/c)^2$

(inspired in J. Hinton talk)

Galaxy

Active Nuclei?

yes



AGNs

(...)

Blazars, radio Galaxies, Halos...

no

very massive stars?

yes

very high formation rate?

yes

Starburst Galaxy

no

In a cluster?

no

no

Extreme events?

yes

no

yes

Galaxy Clusters

no

Inside the Galaxy...

GRBs

(inspired in J. Hinton talk)

Galaxy

Active Nuclei?

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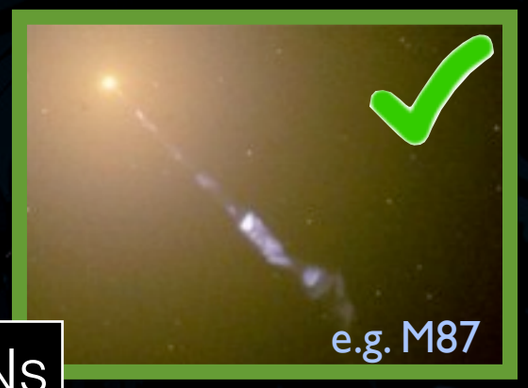

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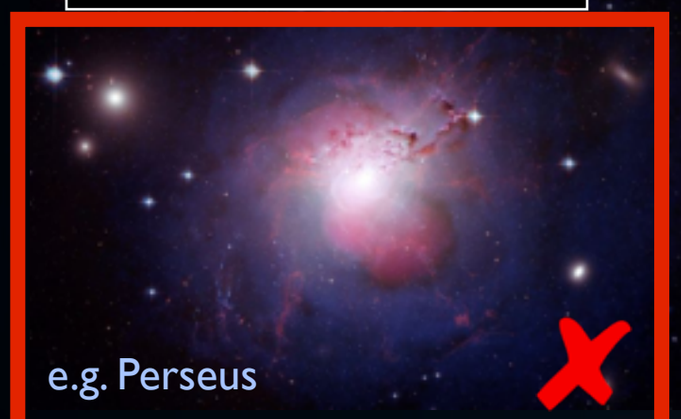

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Inside the Galaxy...

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(inspired in J. Hinton talk)

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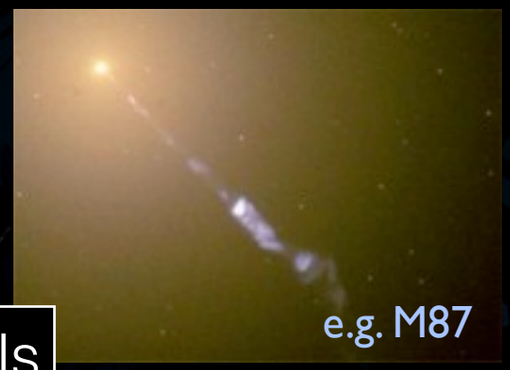

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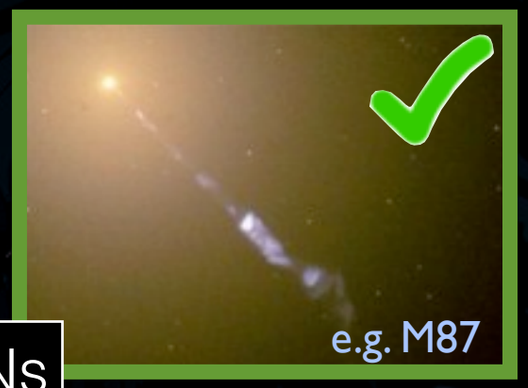

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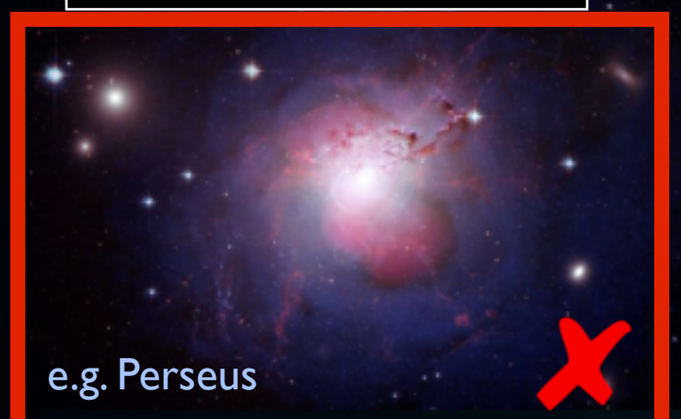


no

Inside the Galaxy...

no

(inspired in J. Hinton talk)

Inside the Galaxy...

F. Acero & H. Gast

(J. Hinton)

Molecular Cloud

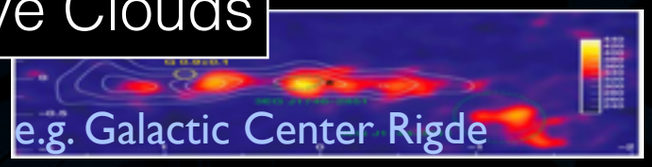
(J. Hinton)

Molecular Cloud

Nearby accelerator

yes

Active Clouds



e.g. Galactic Center Rigde

no

Passive Clouds

e.g. Fermi clouds

(J. Hinton)

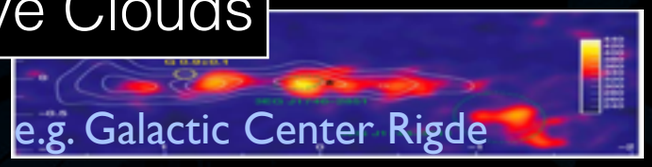
Molecular Cloud

Massive Star

Nearby accelerator

yes

Active Clouds



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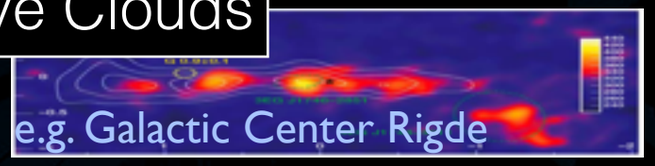


e.g. Galactic Center Rigde

no

Passive Clouds

e.g. Fermi clouds

In cluster?

yes

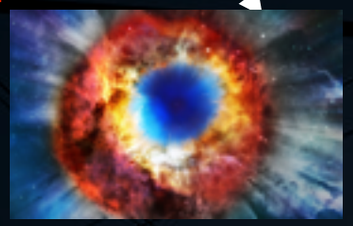
Collective interactions

no

No VHE expected until...

e.g. Westerlund 1

Supernova



(J. Hinton)

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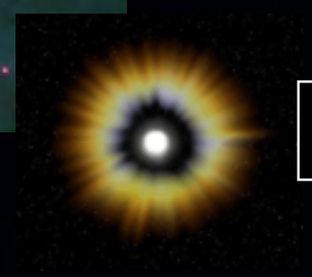


Massive Star

Binary?

yes

Compact companion?

yes

Neutron star?

yes

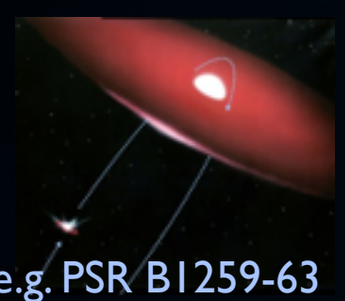
Binary PWNe

no

radio jets?

yes

Microquasars



e.g. PSR B1259-63

e.g. Cyg X-1

no

Massive companion?

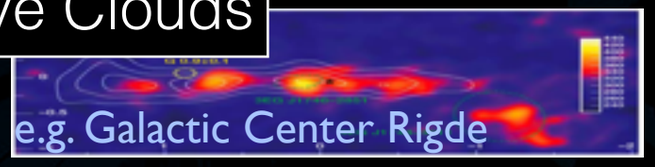
Colliding wind sys.

e.g. Eta Carina

Nearby accelerator

yes

Active Clouds



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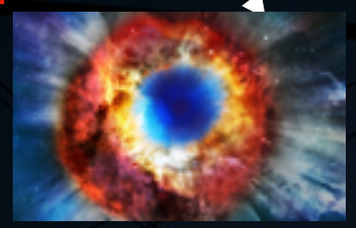

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(J. Hinton)

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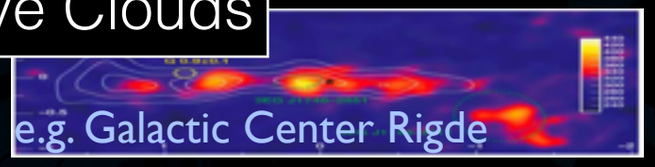

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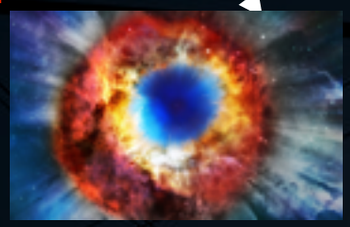


Neutron star remains?

yes

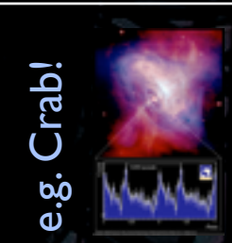
Neutron star?

Massive companion?

no

yes

no



Binary PWNe

radio jets?

Colliding wind sys.

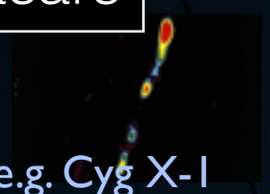
yes

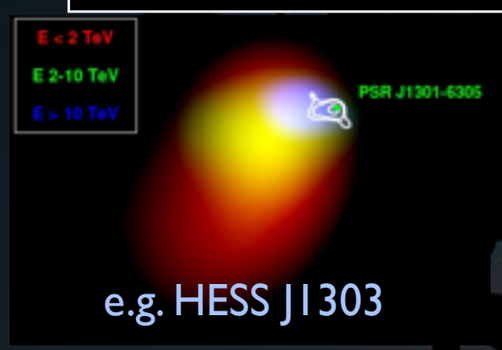
SNR Shell

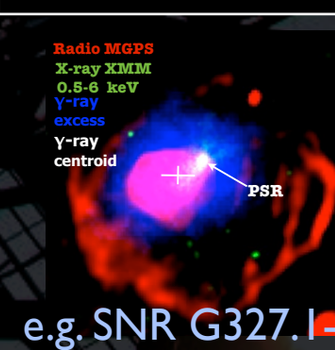
PWN outlasts or escapes SNR

Composite SNR

Microquasars







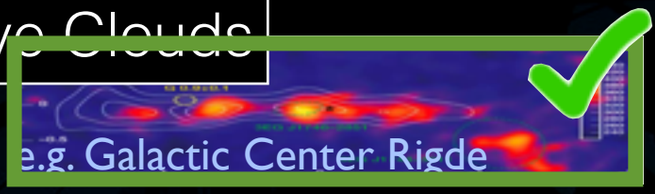
(J. Hinton)

Molecular Cloud

Nearby accelerator

yes

Active Clouds



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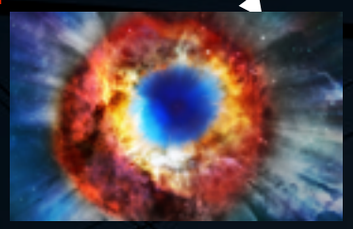

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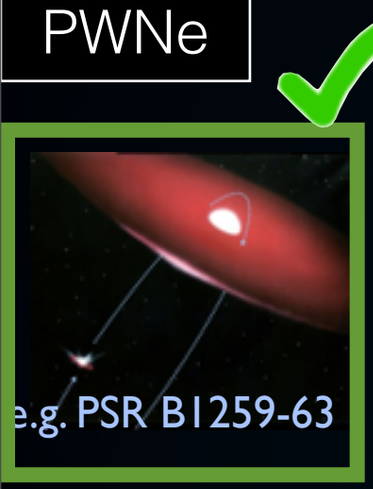
radio jets?

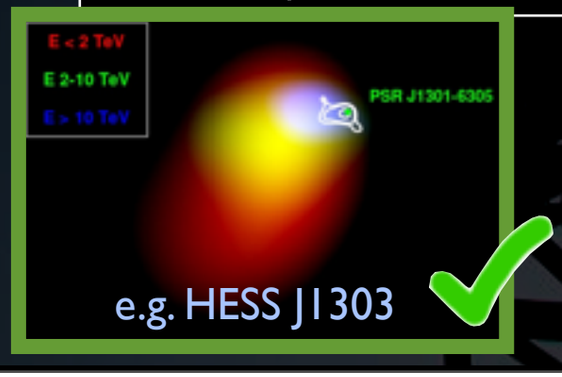
Colliding wind sys.



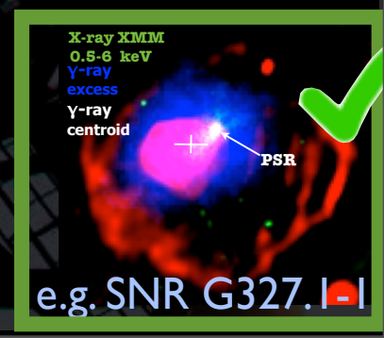
Microquasars

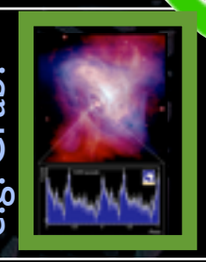
SNR Shell

PWN outlasts or escapes SNR



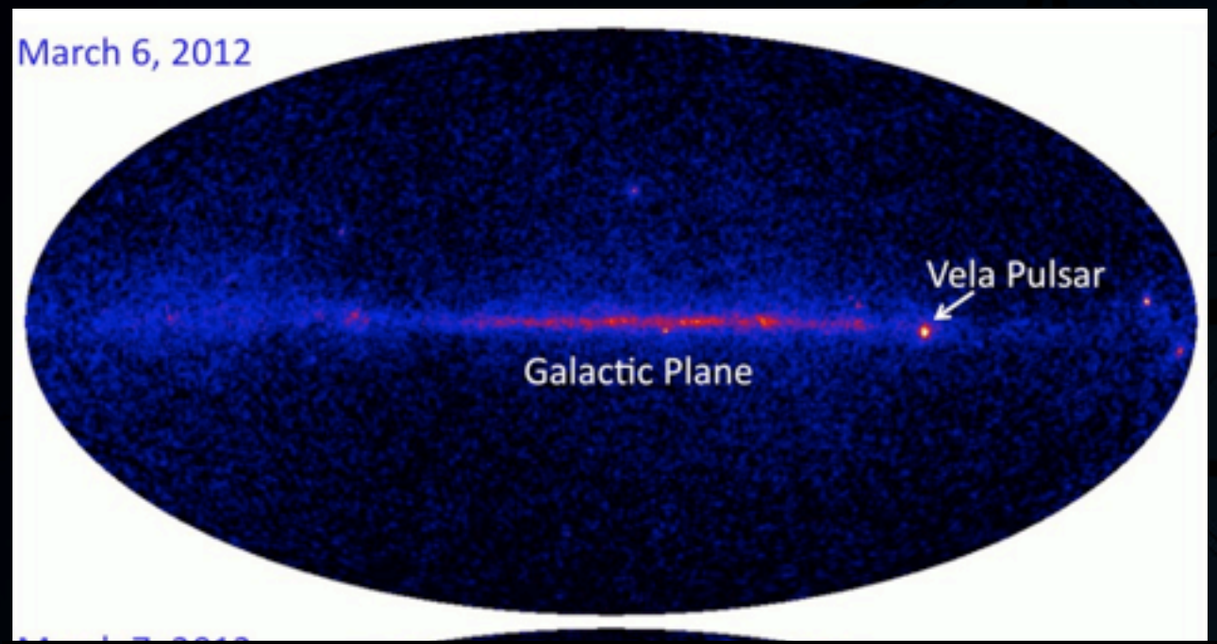
Composite SNR

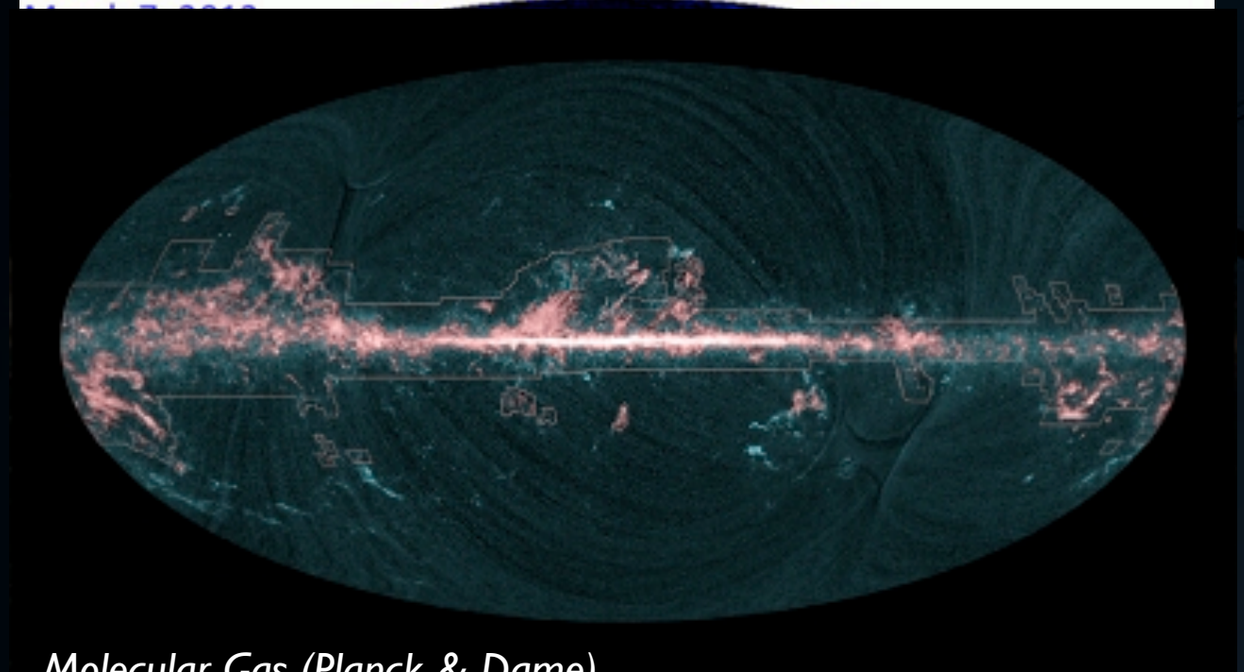




Astropaticles with gamma-rays: Heavy Cosmic Rays

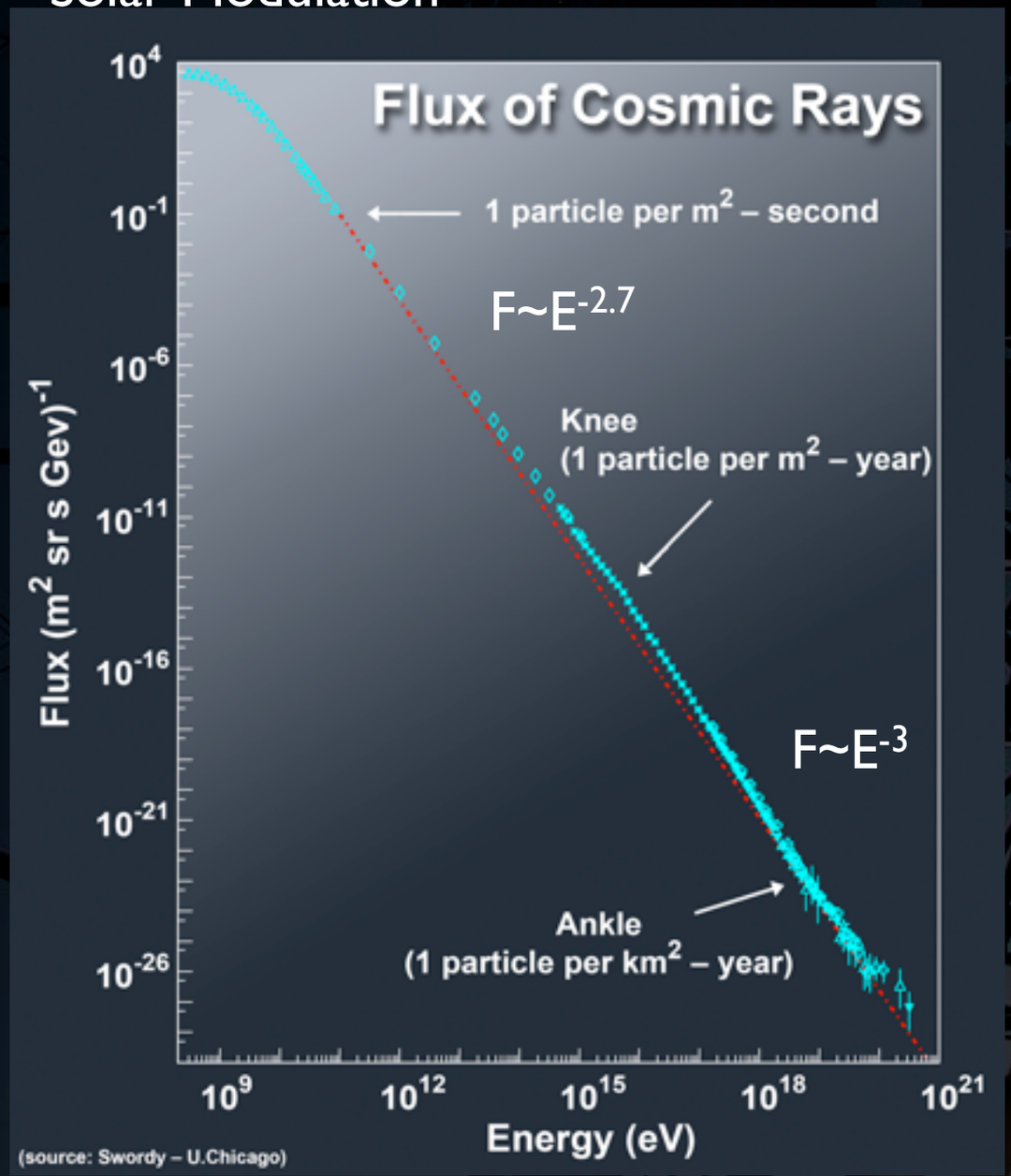
The Fermi LAT experiment





Molecular Gas (Planck & Dame)

Solar Modulation



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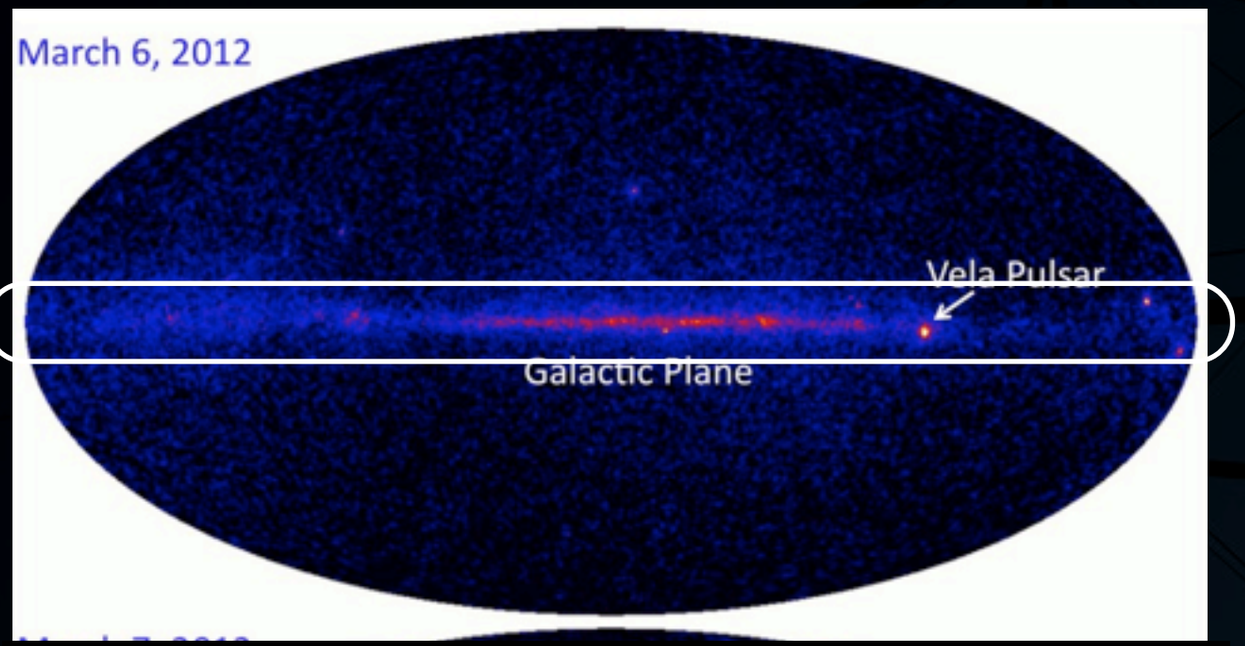

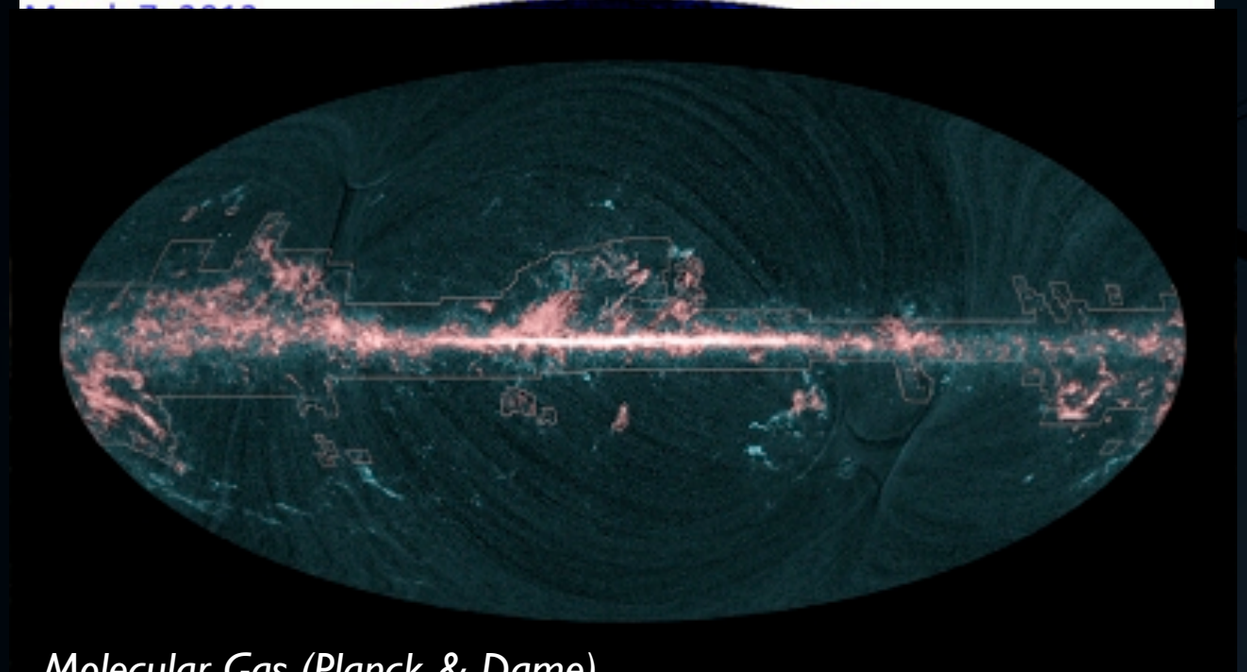

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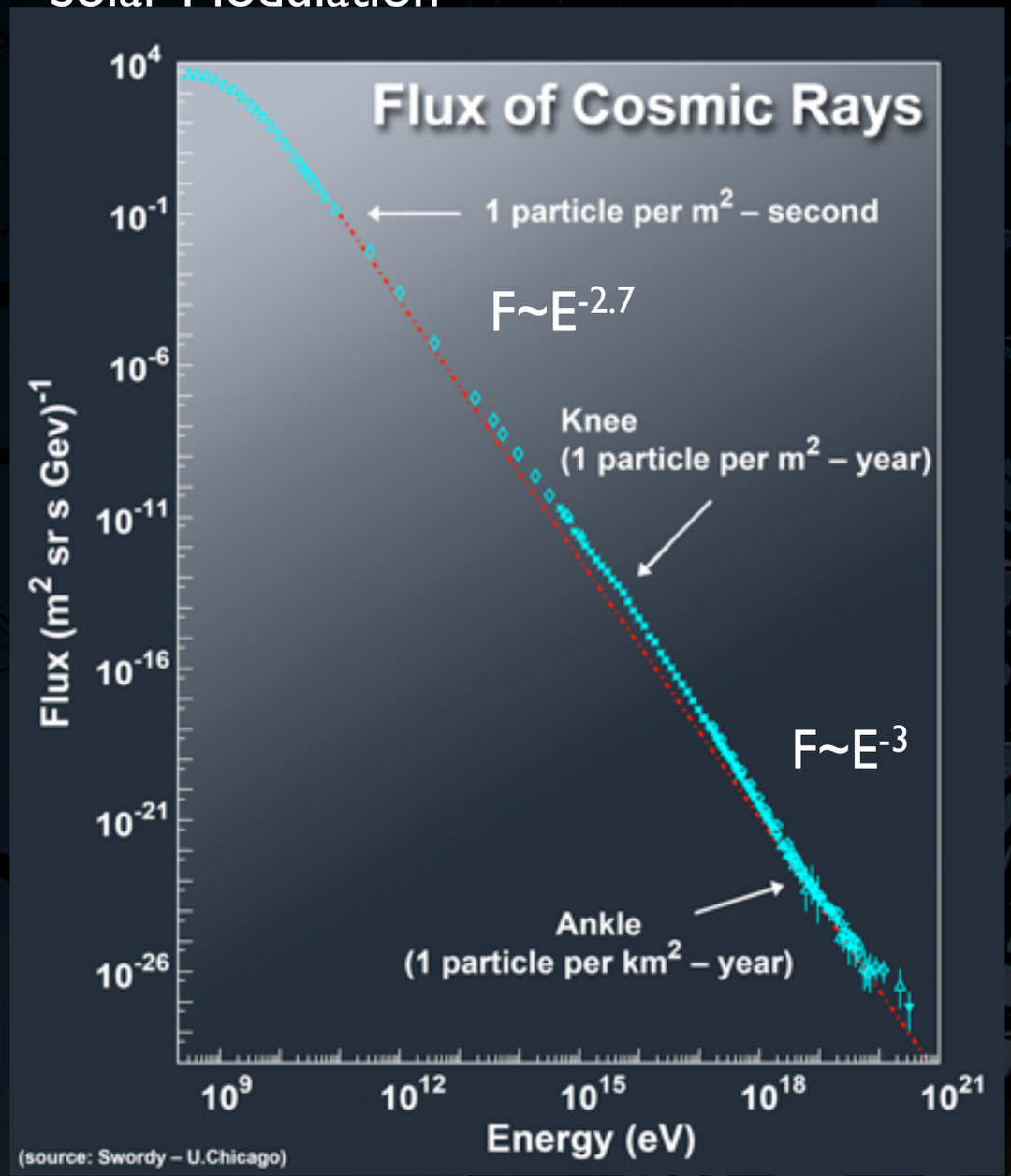

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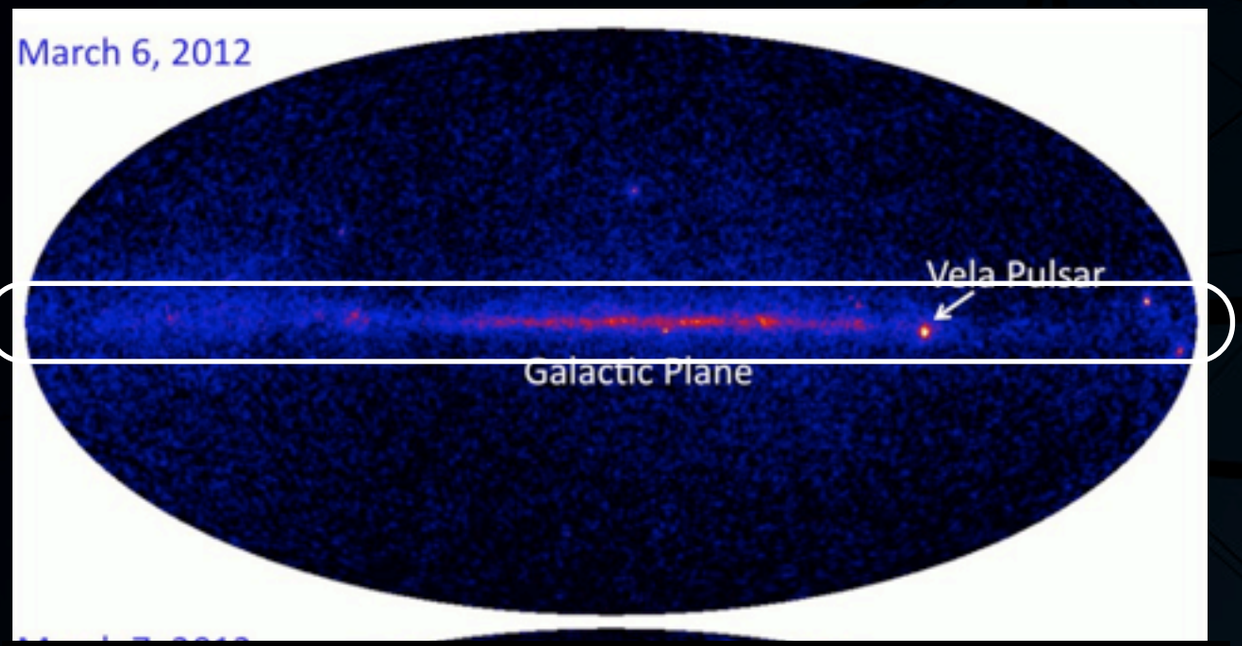

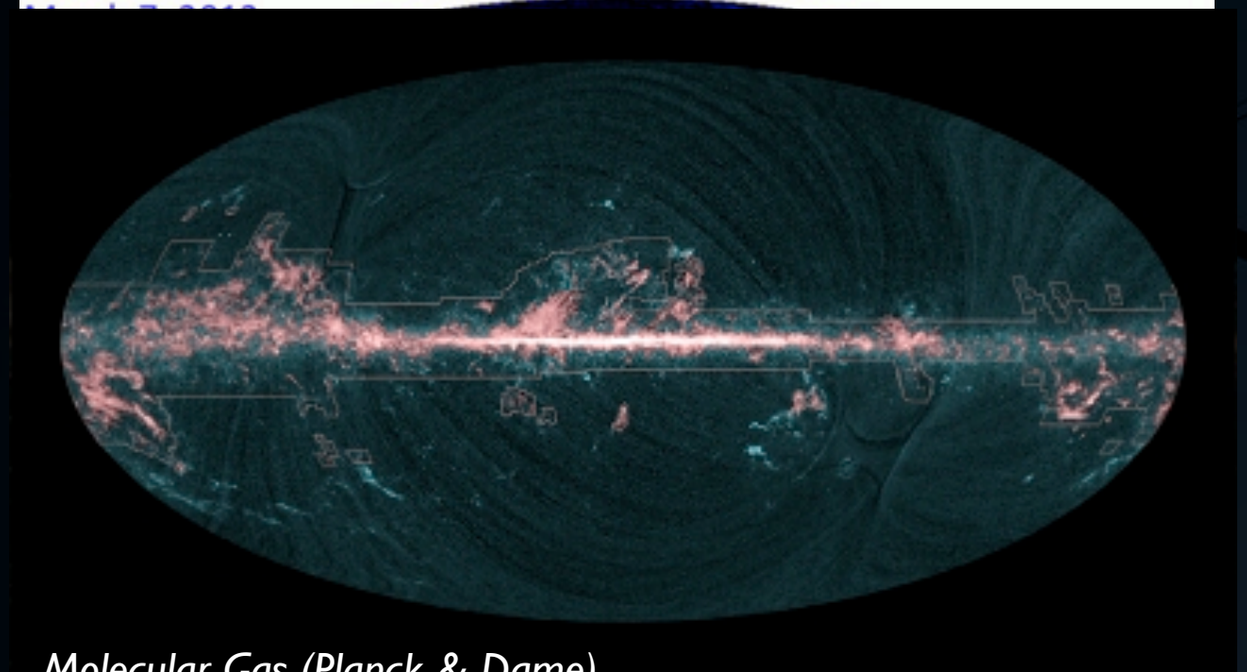

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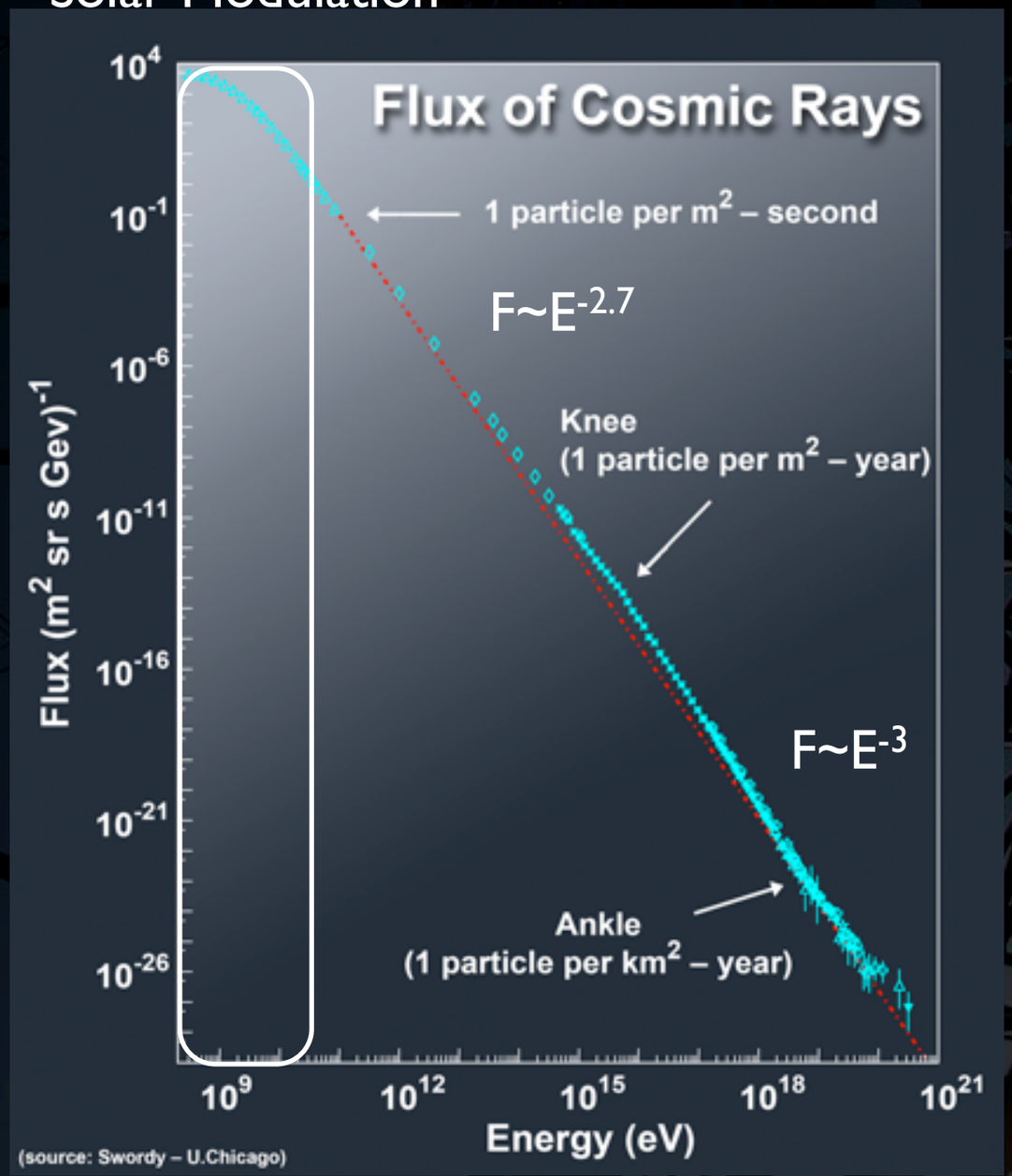

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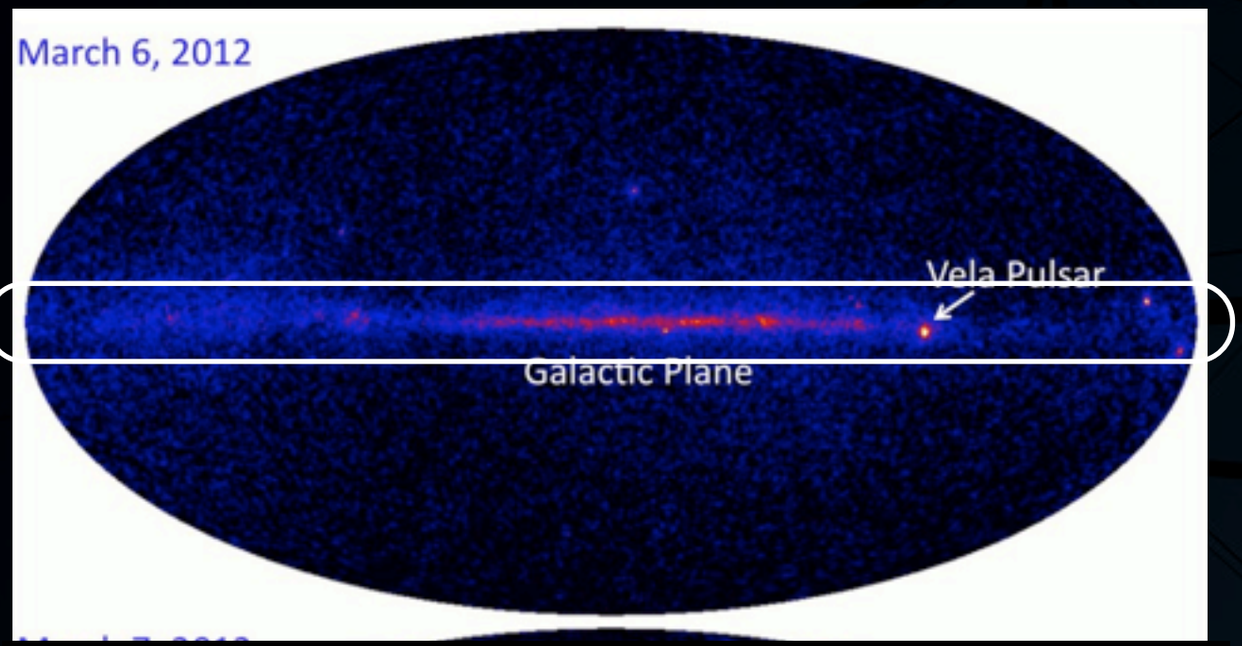
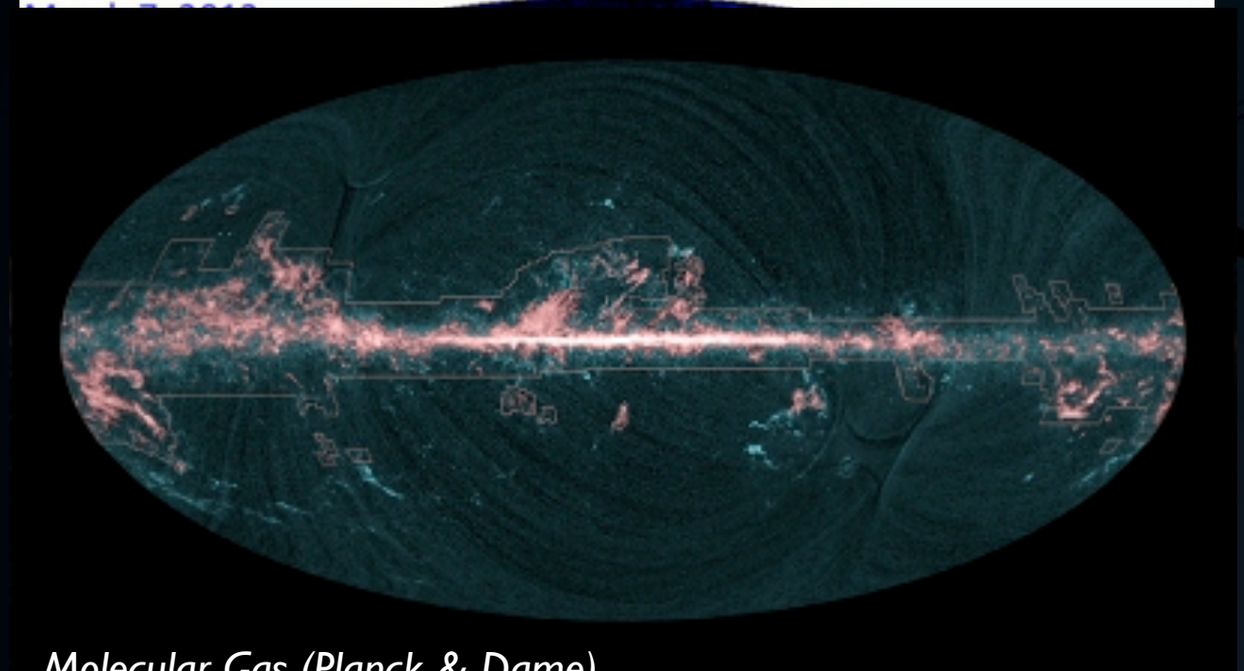


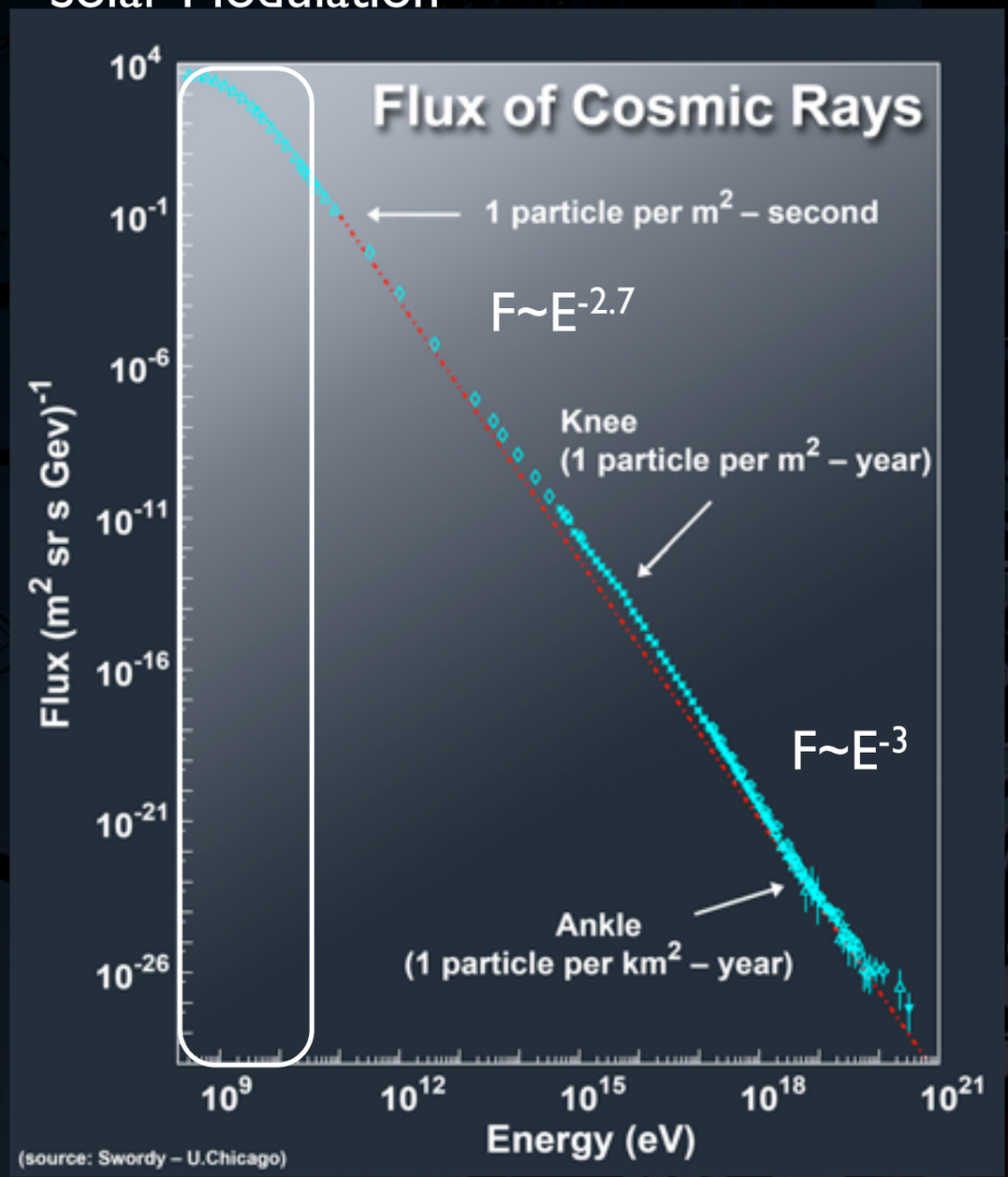


Molecular Gas (Planck & Dame)

$pp\ (A) \Rightarrow \pi, K, \Lambda, \ldots \quad * \quad E\gamma \sim 1/10 E_p$

$\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$

Solar Modulation



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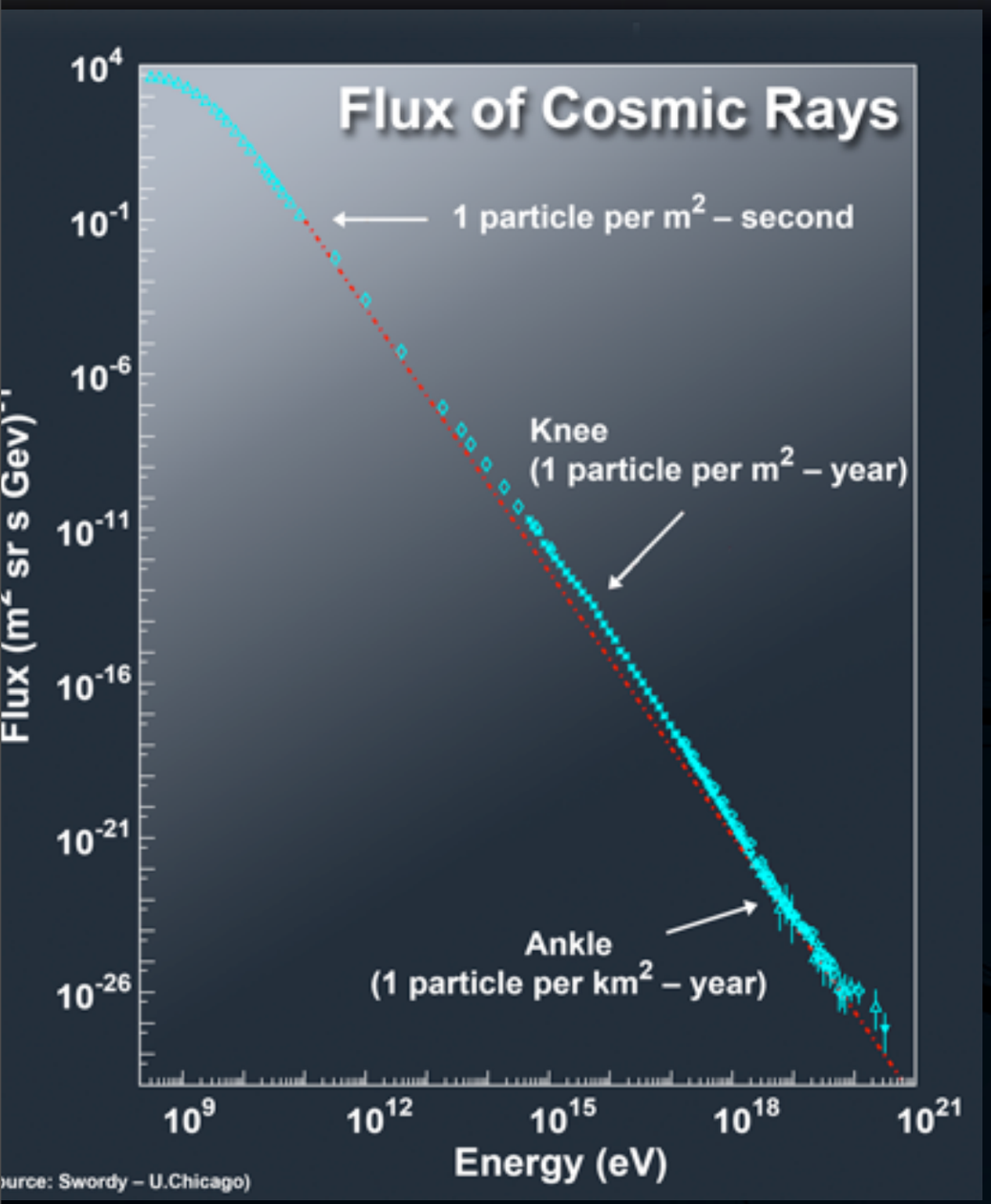

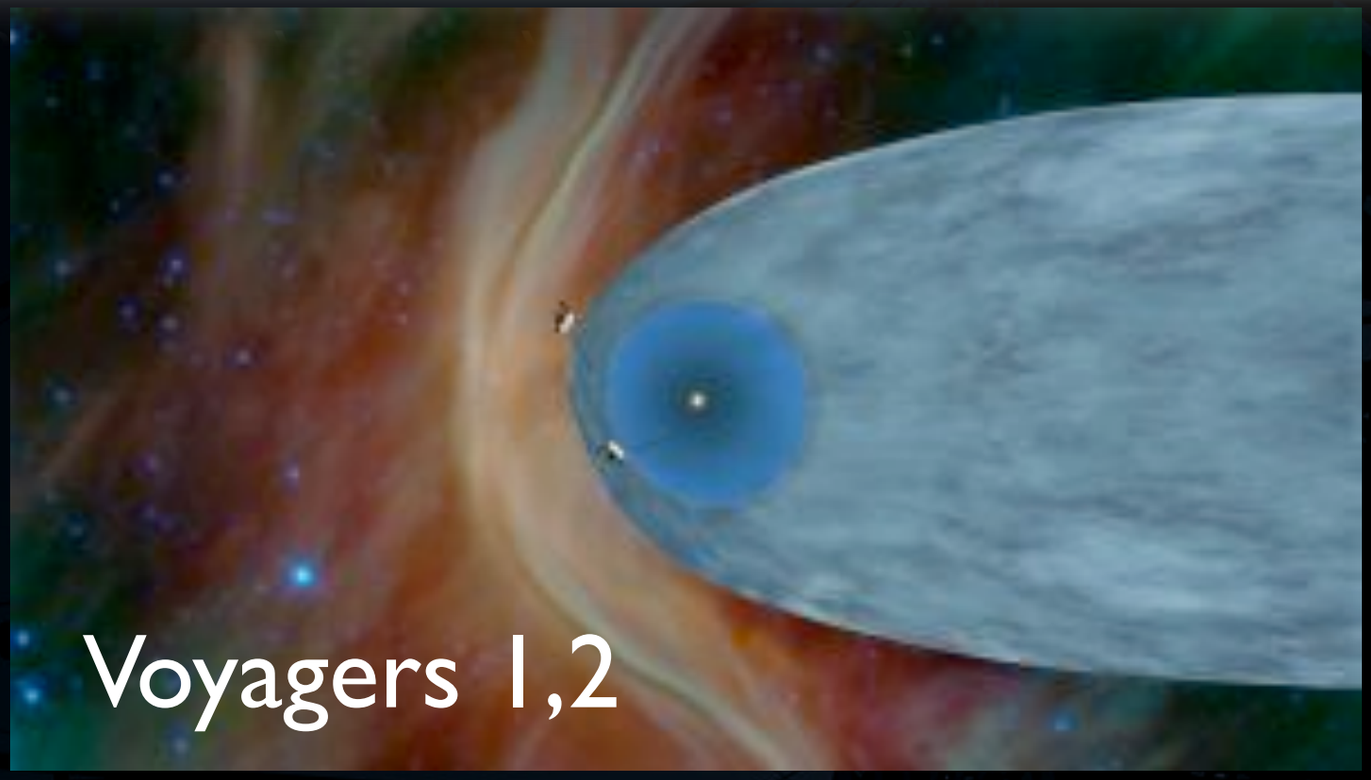

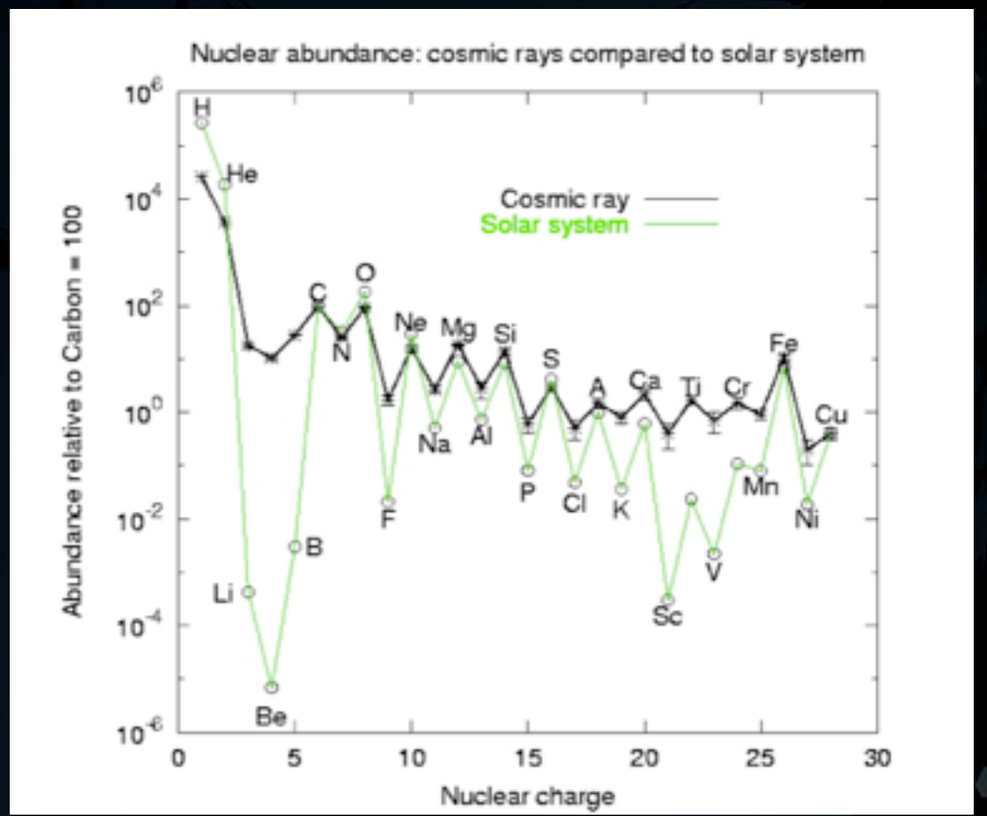

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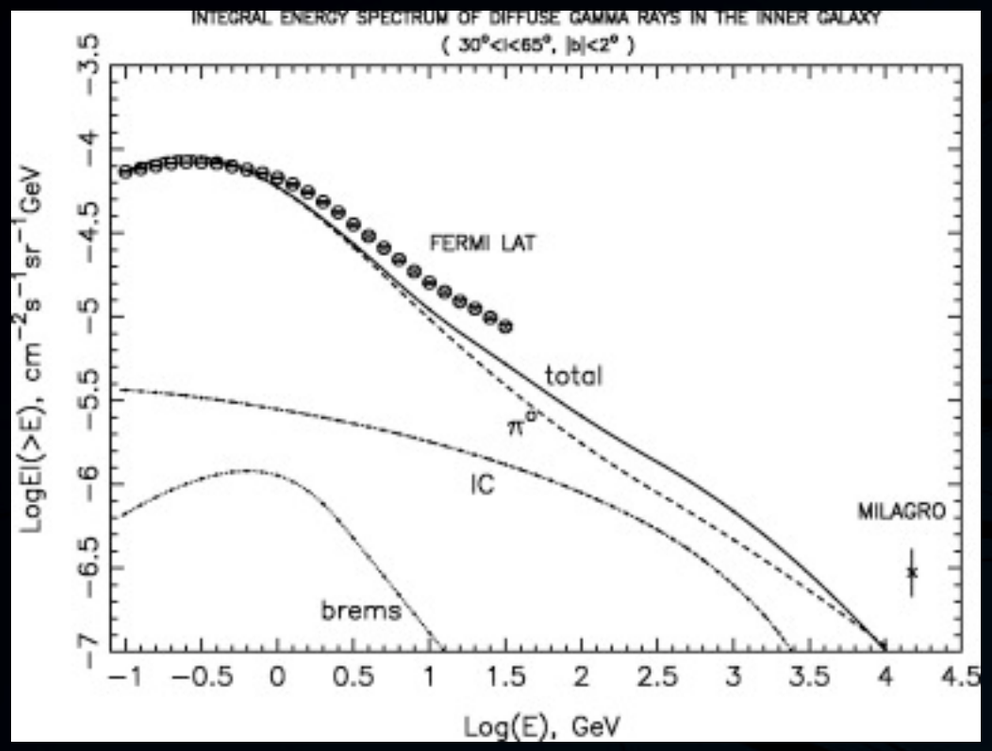
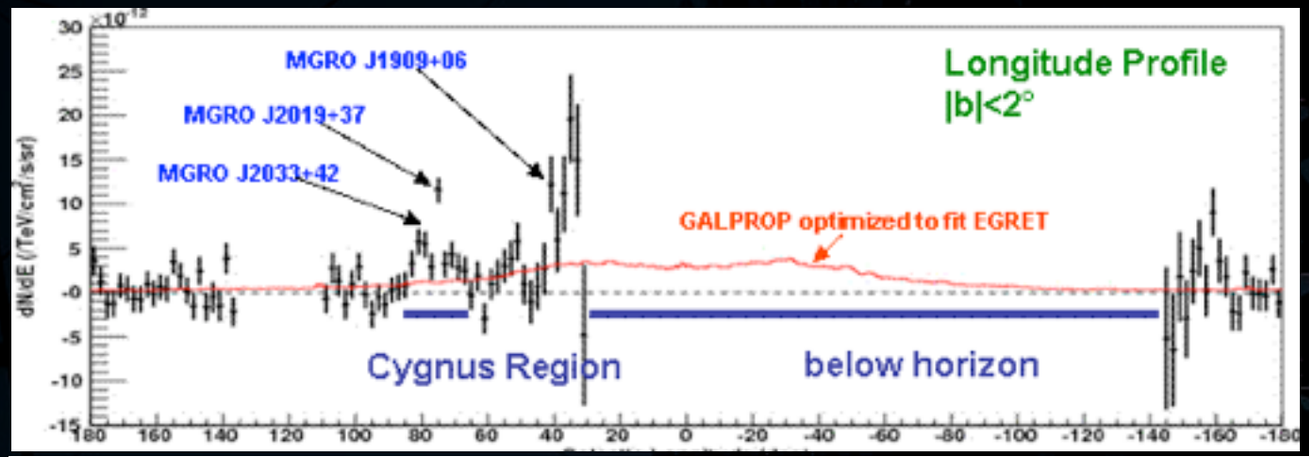
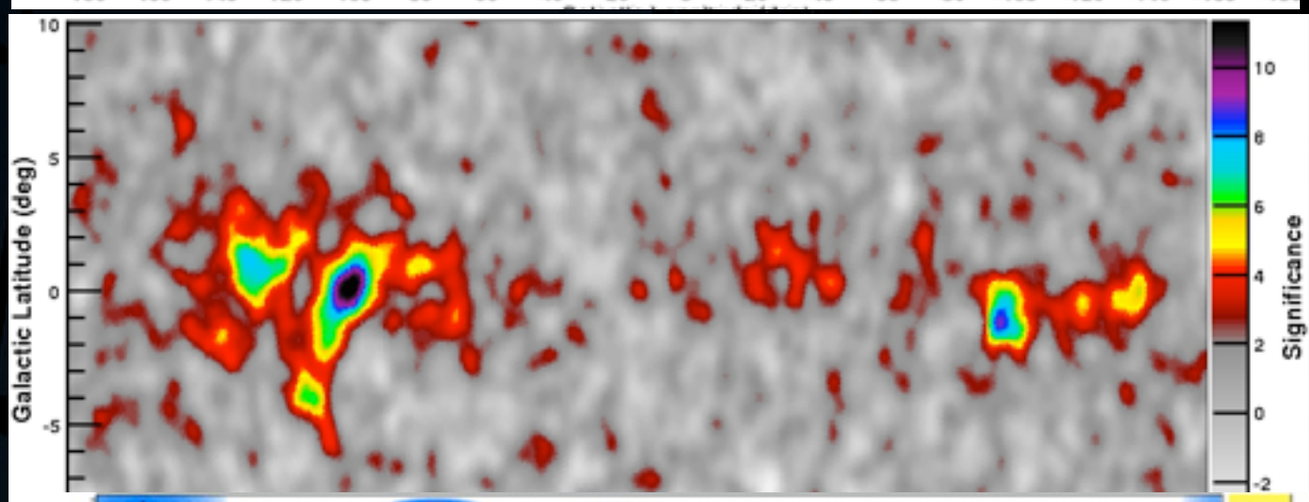


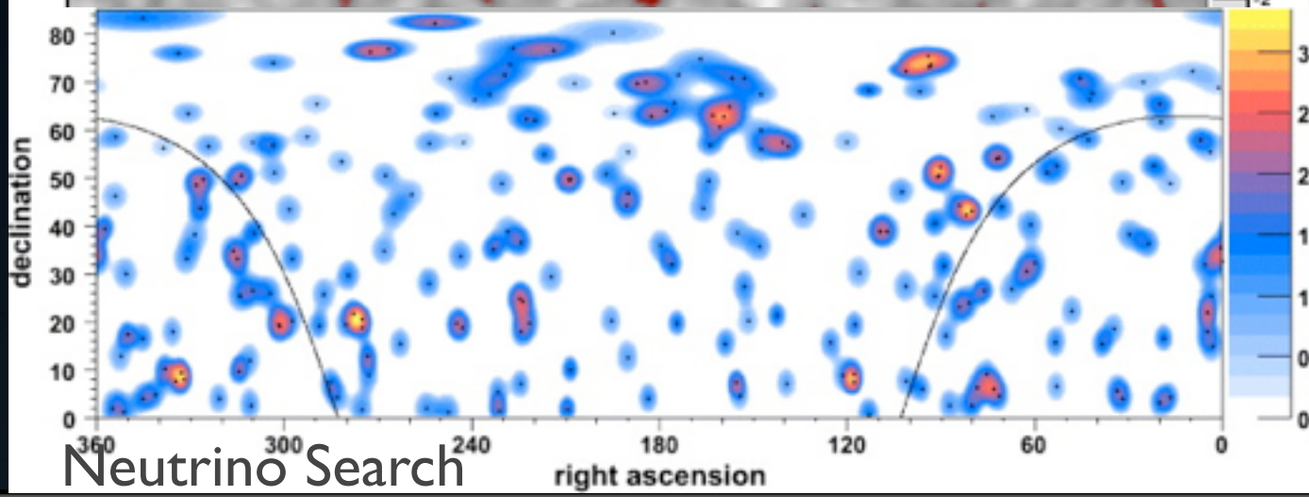
Particle/Water Cherenkov Detectors

Energy range **1-100 TeV**
Area **> 10^4 m^2**
Background Rejection **> 95%**
Angular Resolution **~0.3-0.7°**
Aperture **> 2 sr**
Duty cycle **90%**

MILAGRO



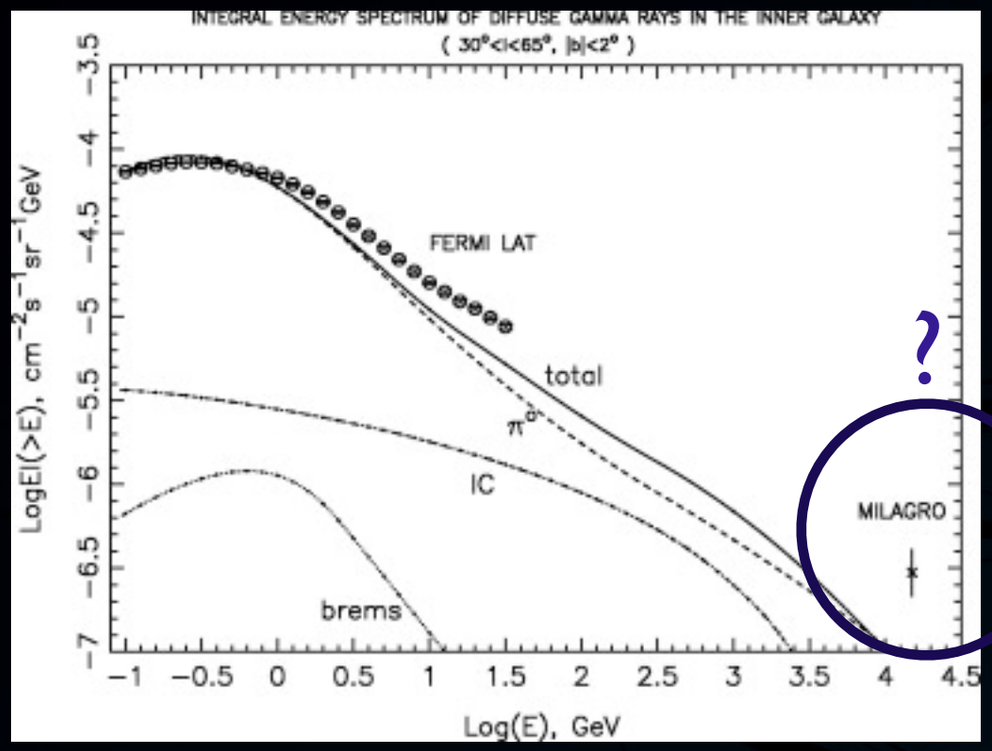




Neutrino Search

Astropaticles with gamma-rays: Heavy Cosmic Rays

The Fermi LAT experiment



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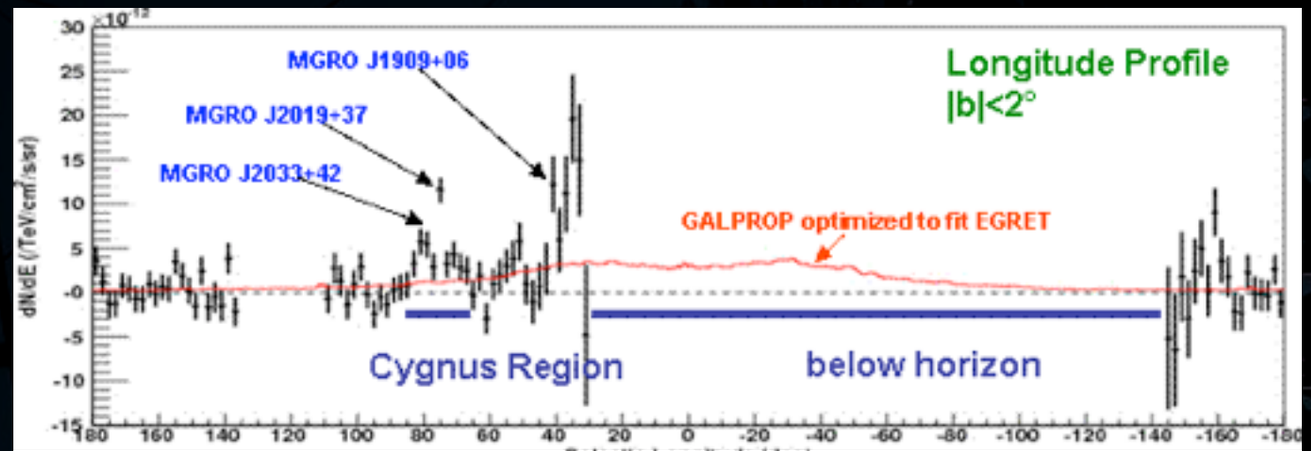
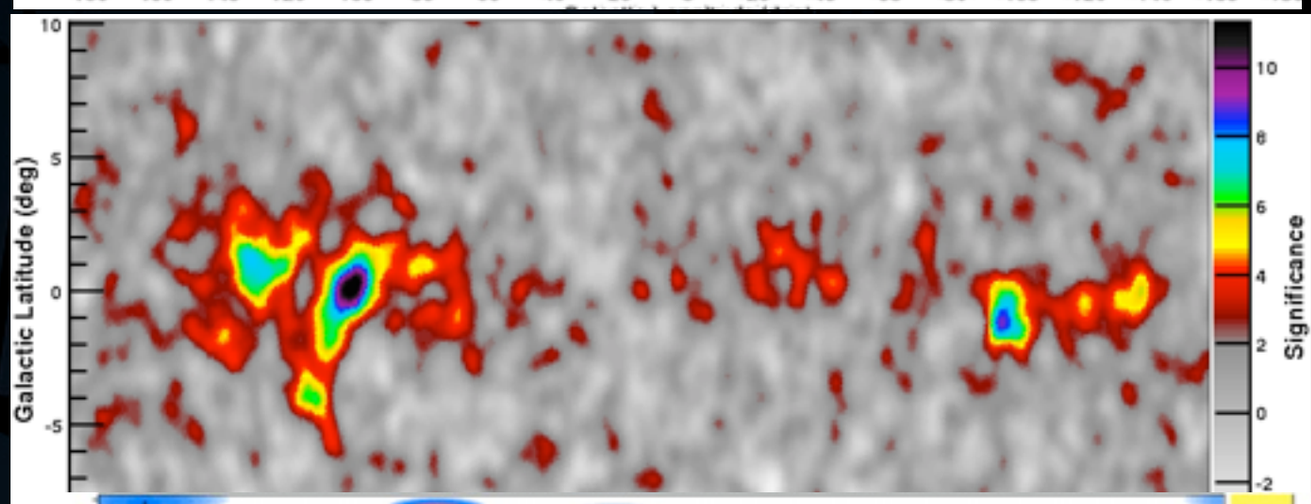
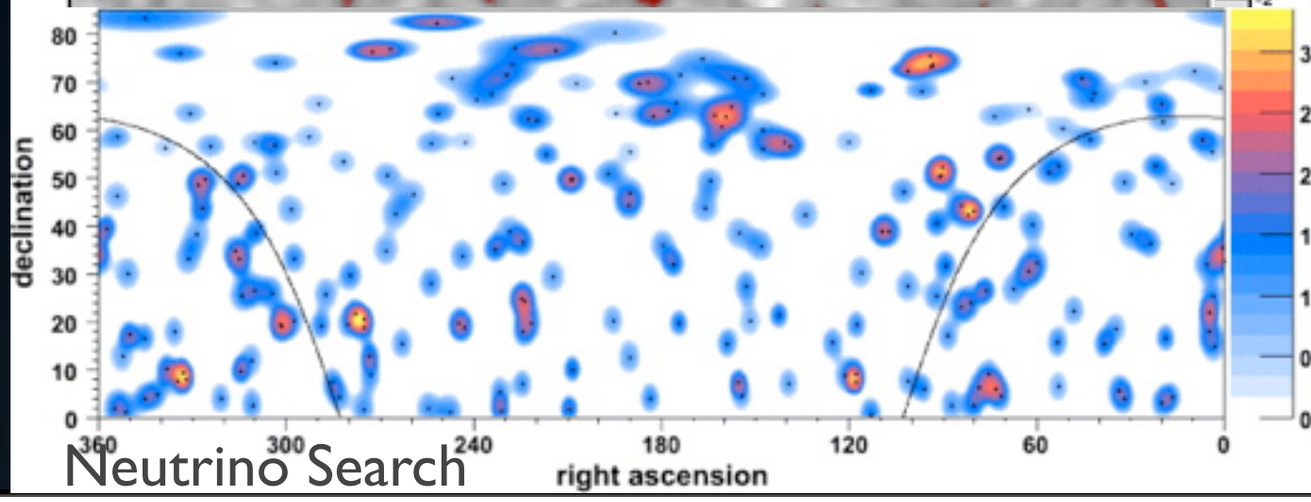






Neutrino Search

TeV Galactic Surveys

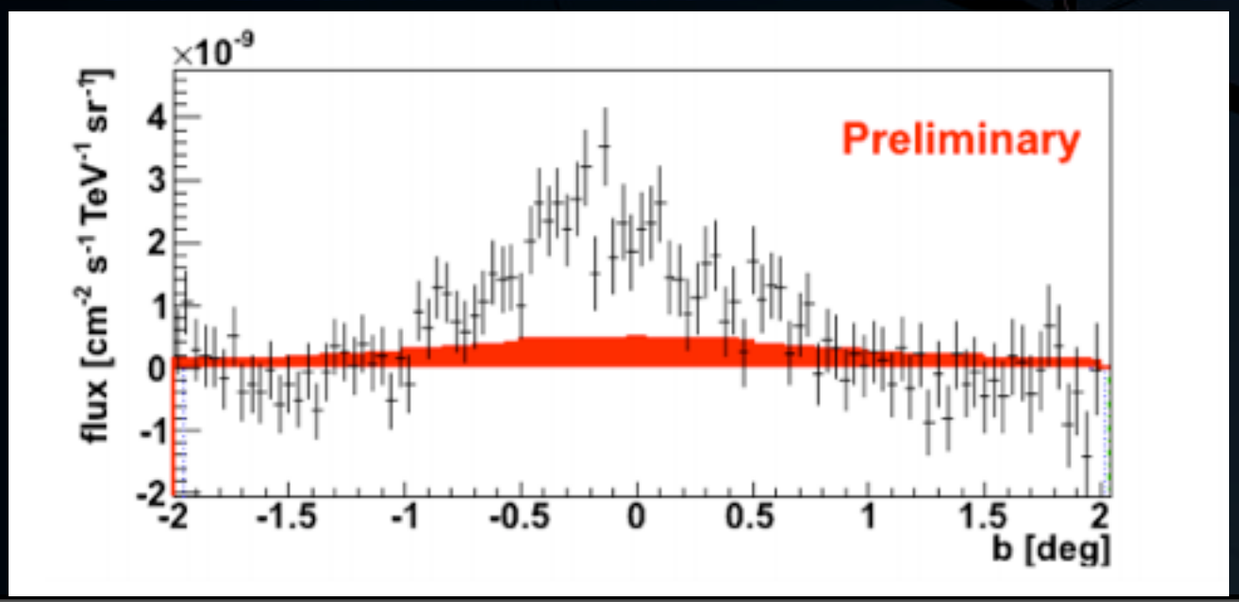
Air Cherenkov Telescopes

Energy range **0.05-50 TeV**
Area **> 10^4 m²**
Background Rejection **> 99**
Angular Resolution **~0.05°**
Aperture **0.003 sr**
Duty cycle **10%**

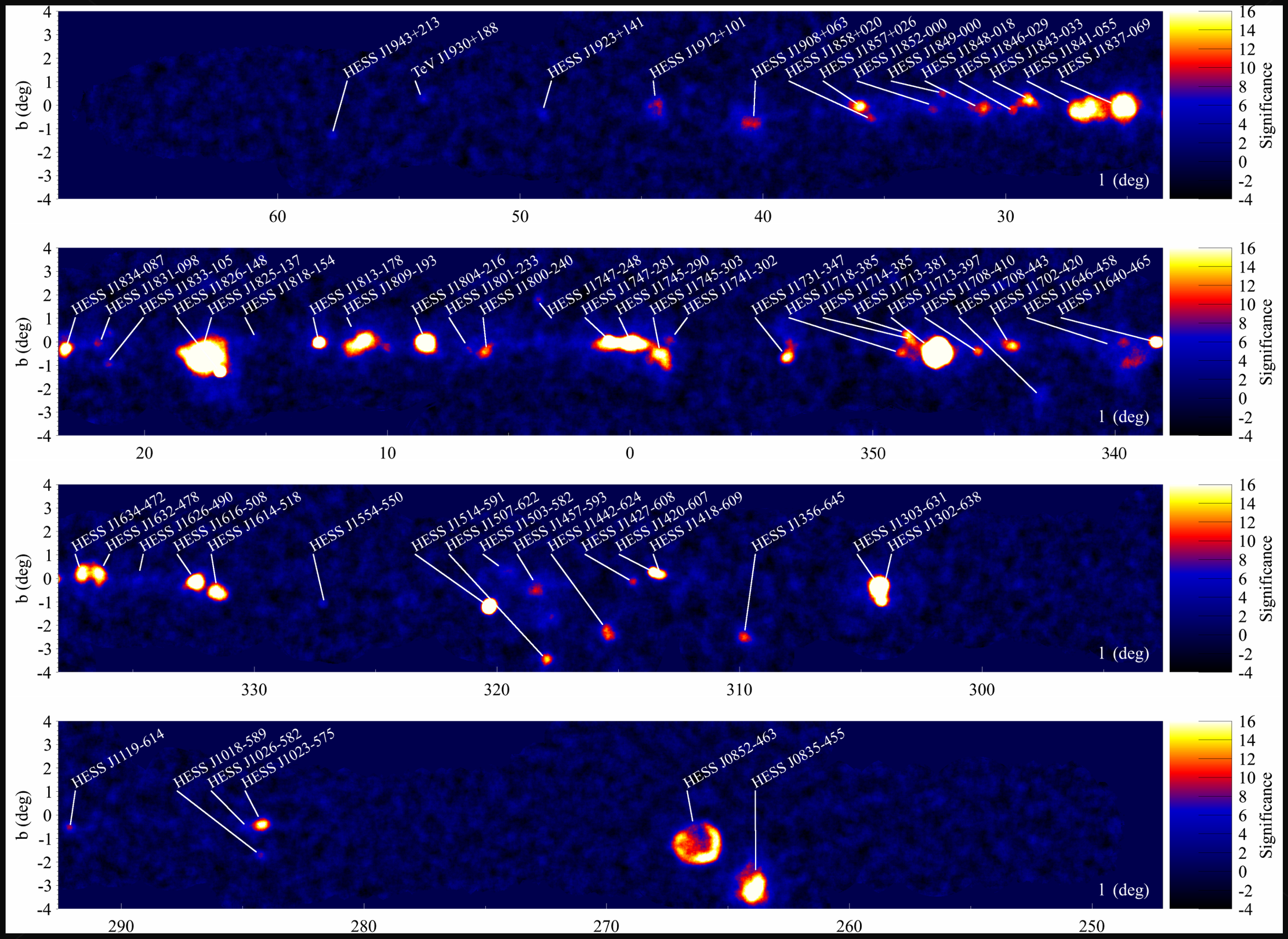
Maier et al (VERITAS) 2012

Cygnus Survey

HESS Survey



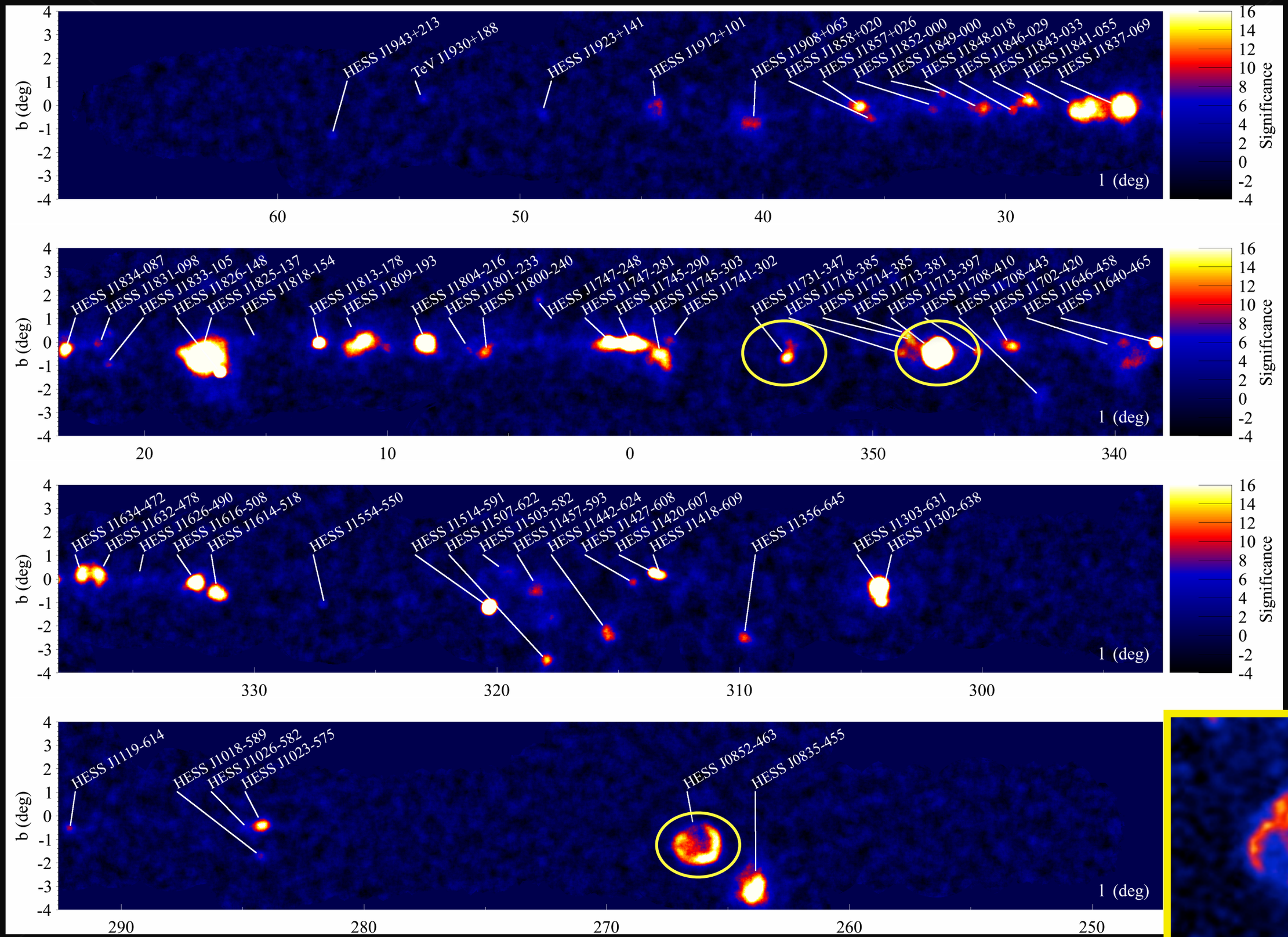
The Inner Galaxy



H.E.S.S. Collaboration 2011

Gast et al, 2011

The Inner Galaxy



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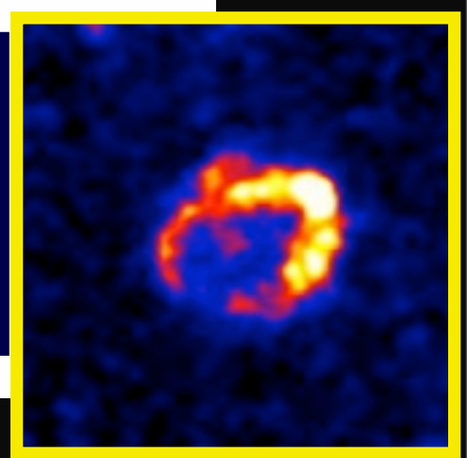
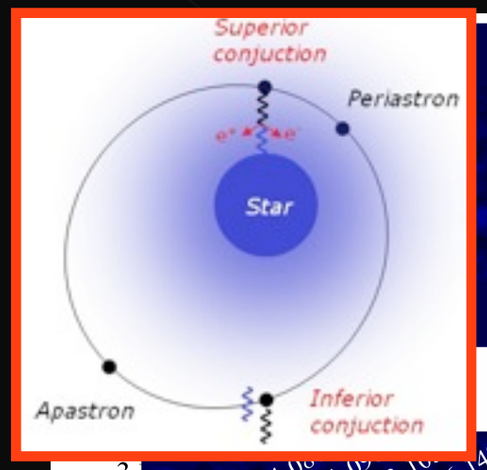


SNR

The Inner Galaxy

Binaries



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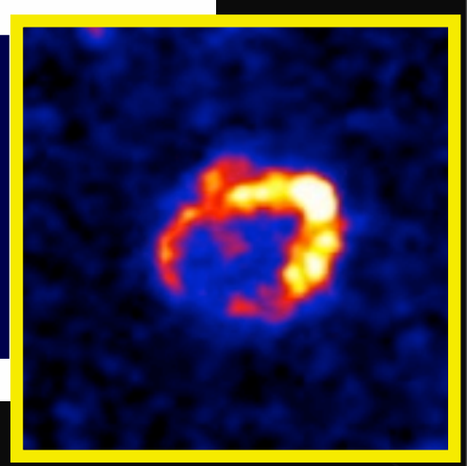

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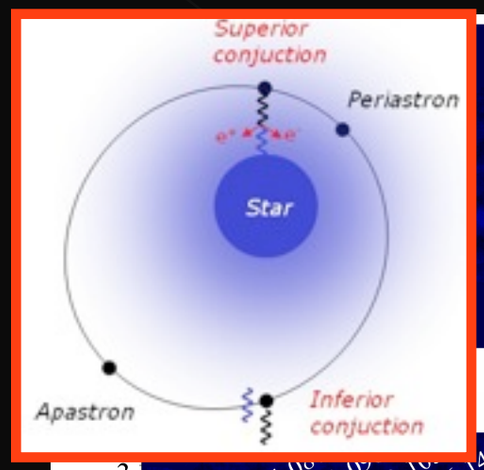

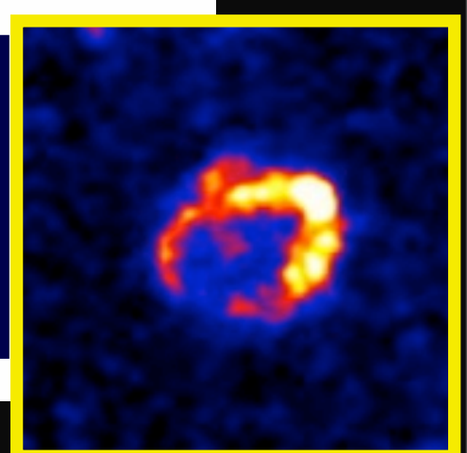

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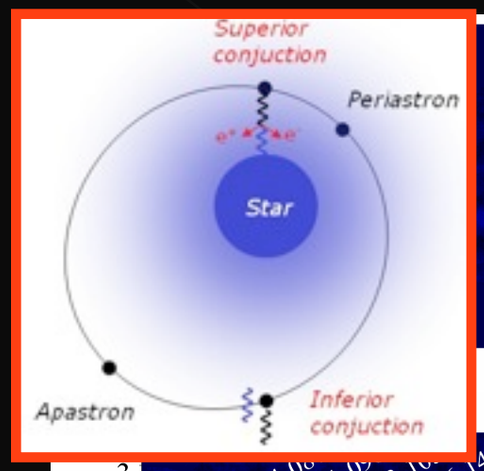

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The Inner Galaxy

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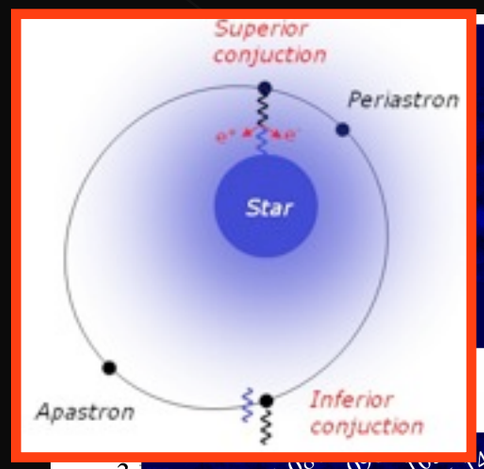
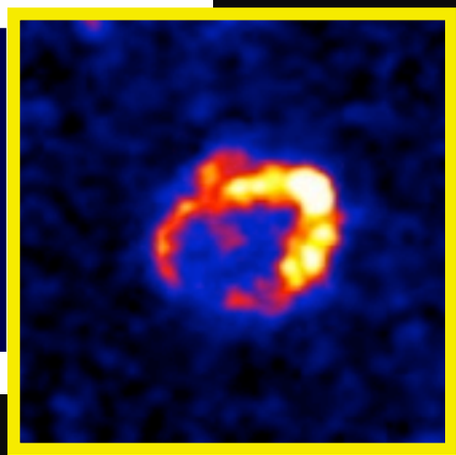


Plerions/Dark



SNR

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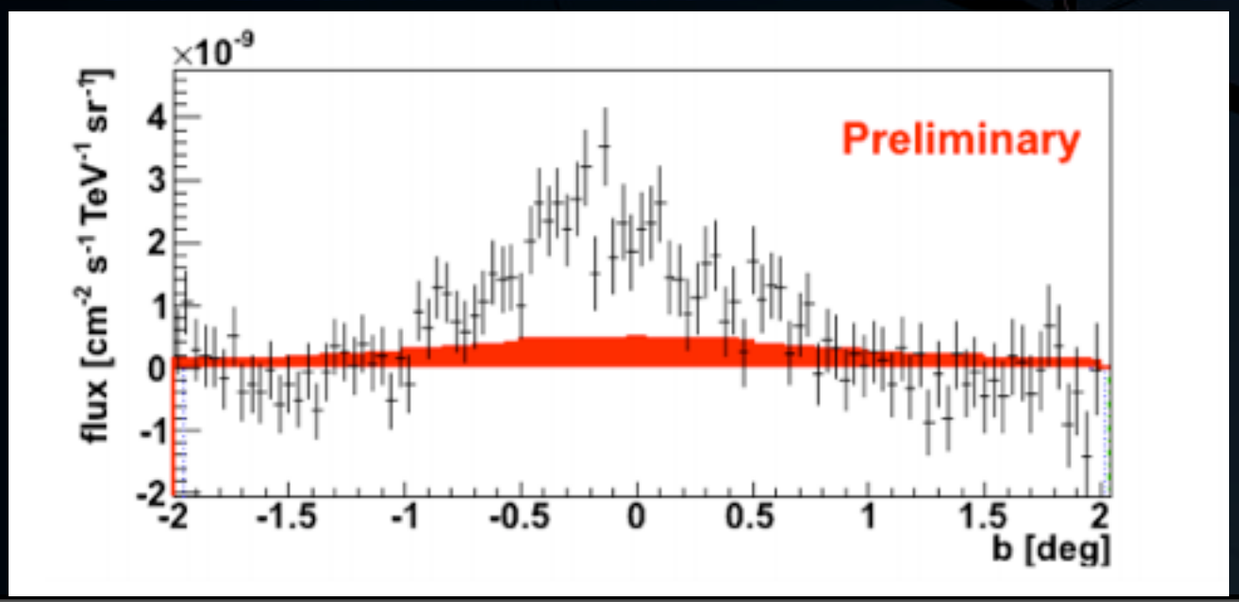
Maier et al (VERITAS) 2012

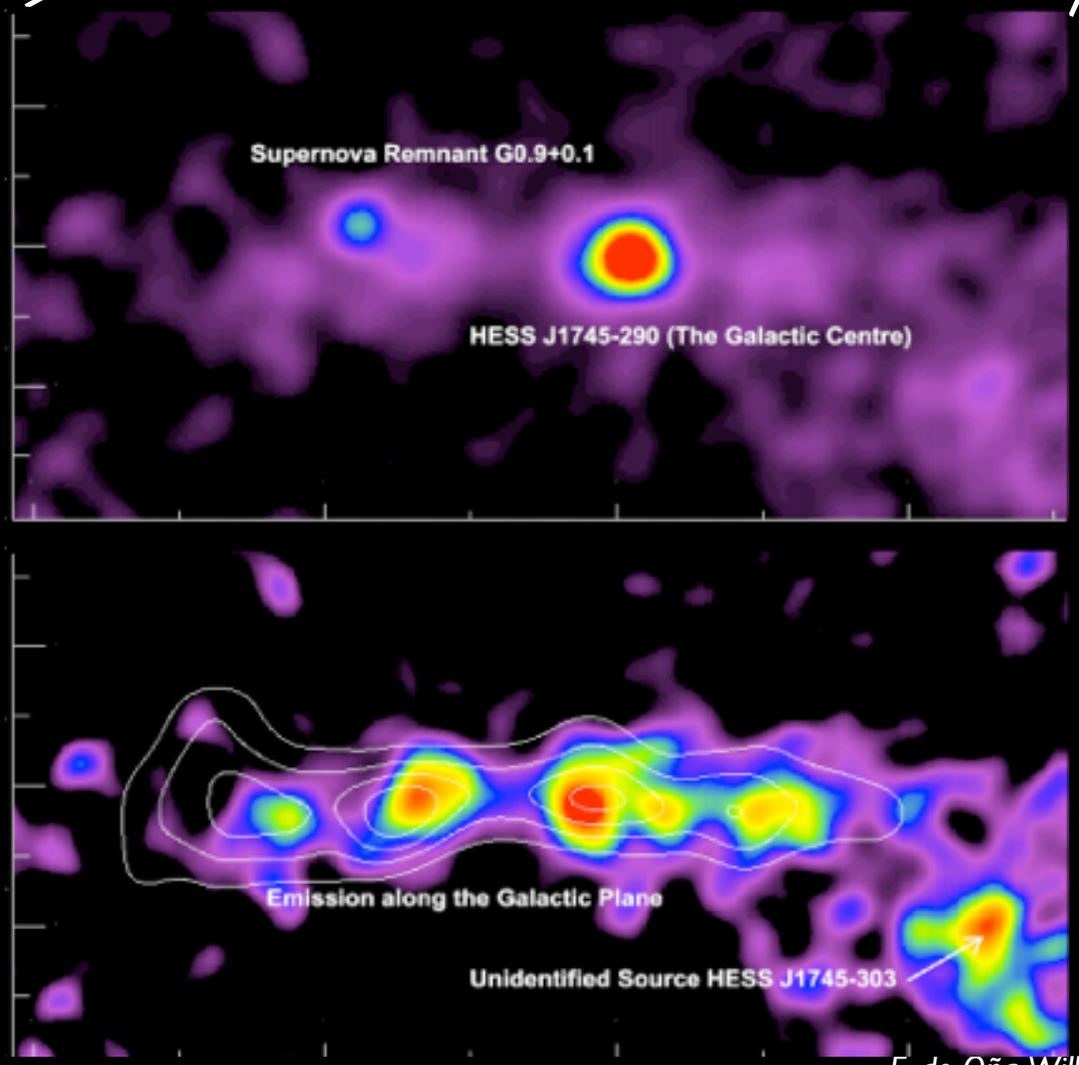
Cygnus Survey

HESS Survey

Substracting all point-like sources in the HESS Galactic Survey:



VHE γ-rays



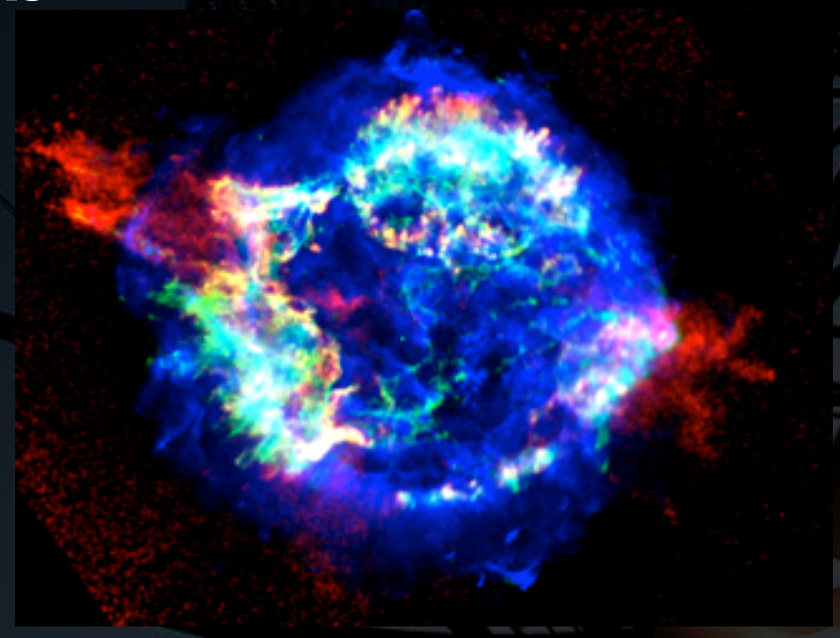
- $F_\gamma \propto F_{cr} \times \rho_{target}$
- Correlation with Molecular Clouds
- Central Source + diffusion ~ 10 Kyrs ➙ propag. 100 pc

- Measured flux implies higher CR density and harder spectrum

Shell-Type Supernova Remnants

- Many SNRs detected and well-study at lower energy ranges
 (evolution, magnetic fields, composition, etc....)

- Why is it important to observe SNRs at VHE
  > VHE trace the particle distribution, independently of the magnetic field
  > Origin of Cosmic Rays! -> direct evidence for GeV-PeV (e,p) being accelerated at front shocks

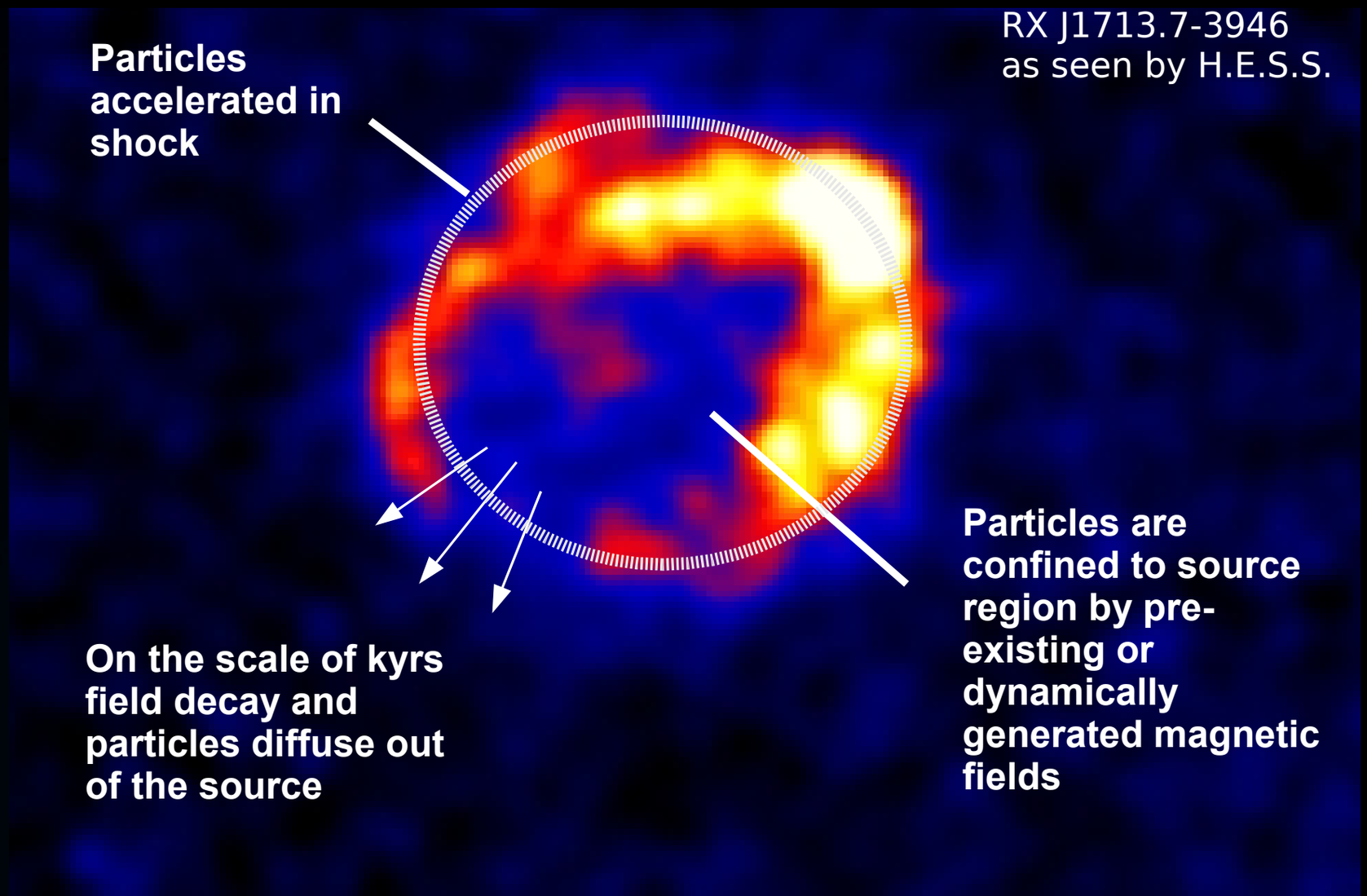


Cas A - J.Vink 2004

SNRs as Cosmic Ray Origin

Galactic CR luminosity = $L_{CR} \sim 10^{41}$ erg/s → $\eta_{CR} \sim 0.1 \times (R_{SN}/0.03\ yr^{-1}) \times (10^{51}\ erg/E_{SN})$

- Non-linear diffuse shock acceleration theory in shells provides the right spectral index, high P_{CR}, magnetic field amplification and $E_{max} \sim E_{knee}$ *(Helder et al 2012, 2009, Völk et al 2005, Bamba et al*



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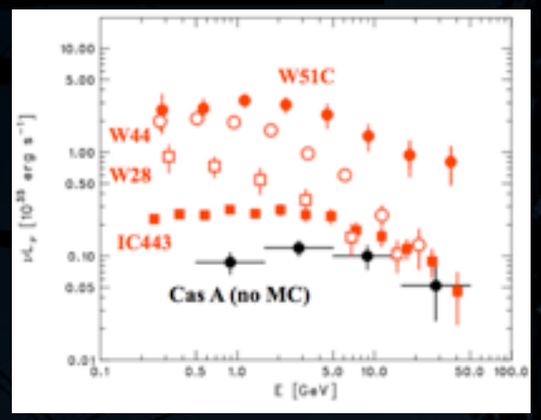
GeV-hard TeV-bright SNRs
(RX J1713, Vela Jr, RCW 86, HESS J1731?) :
Leptonic-like shape ⌦ not an efficient CR source

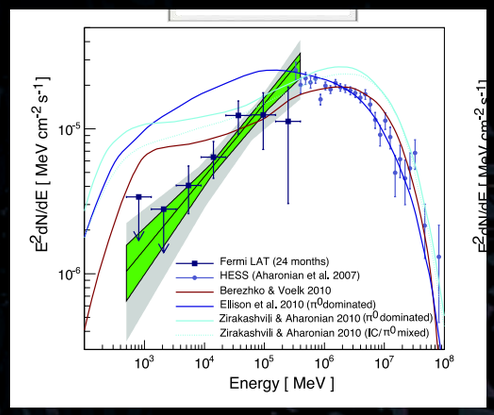
GeV/TeV-faint SNRs
(Cas A, Tycho, SN 1006?) :
Hadronic-like shape ⌦ efficient CR source

GeV bright TeV-soft SNRs, interacting with MC
(W44, W51C, IC443, W49B...) :
Hadronic-like shape ⌦ efficient CR source

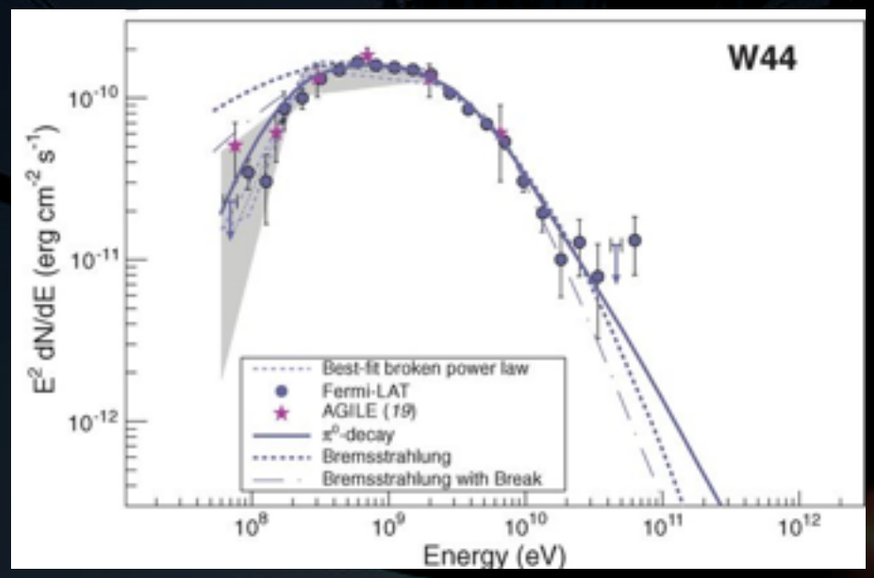
... although detection of "π^0-decay peak"!!!!



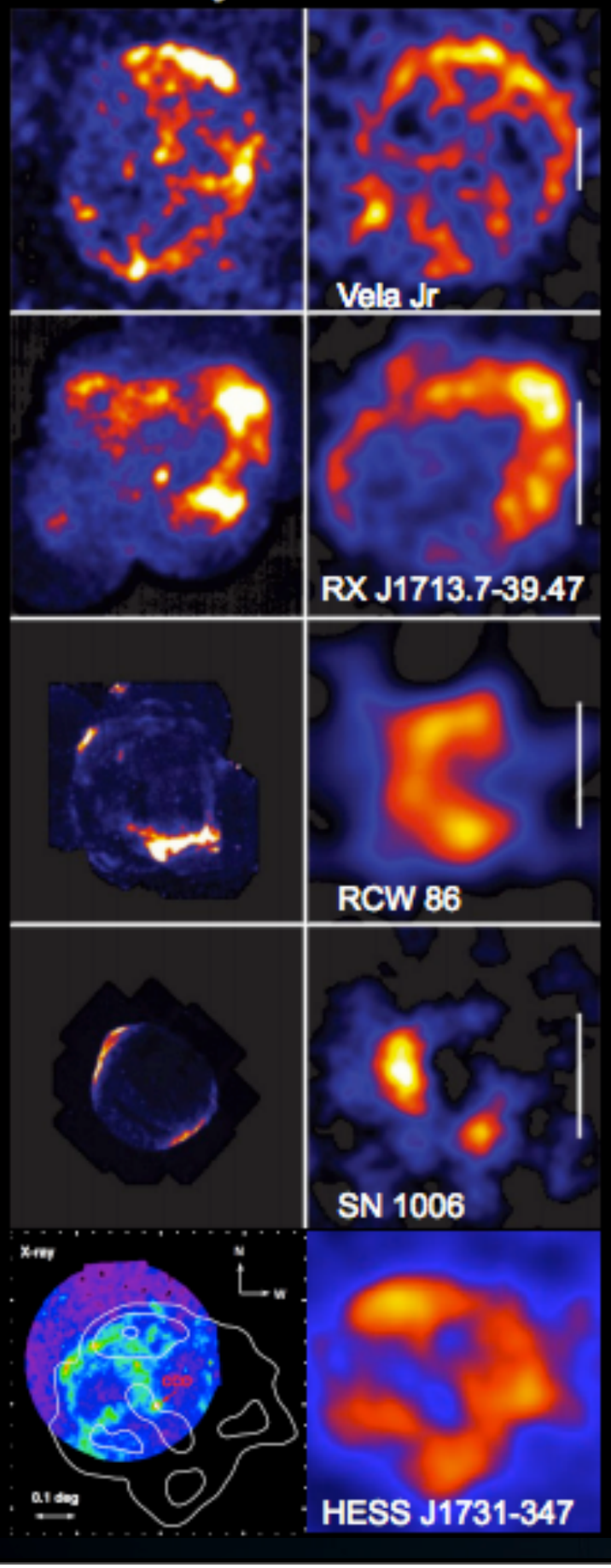
Uchiyama et al 2011



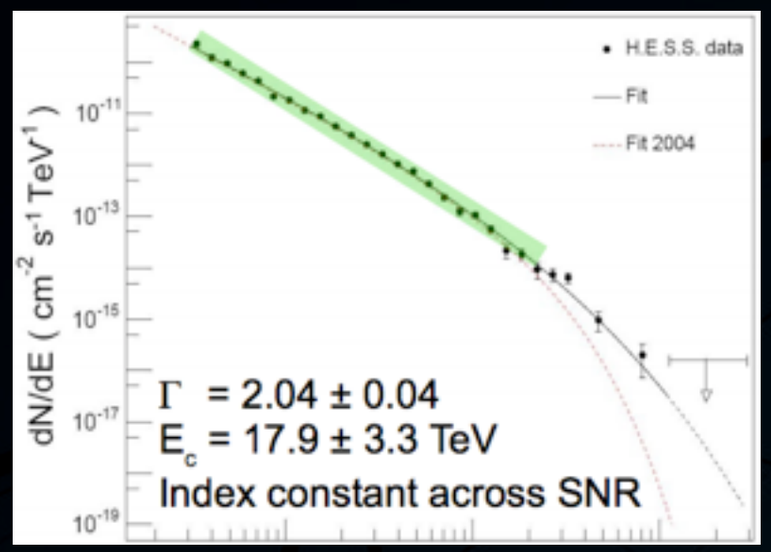
Abdo et al 2011



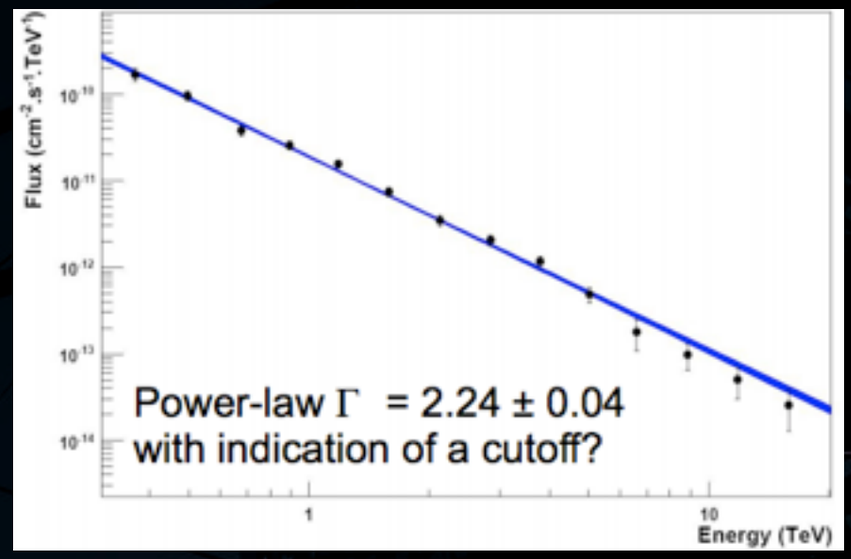
Ackermann et al 2013



Vela Jr



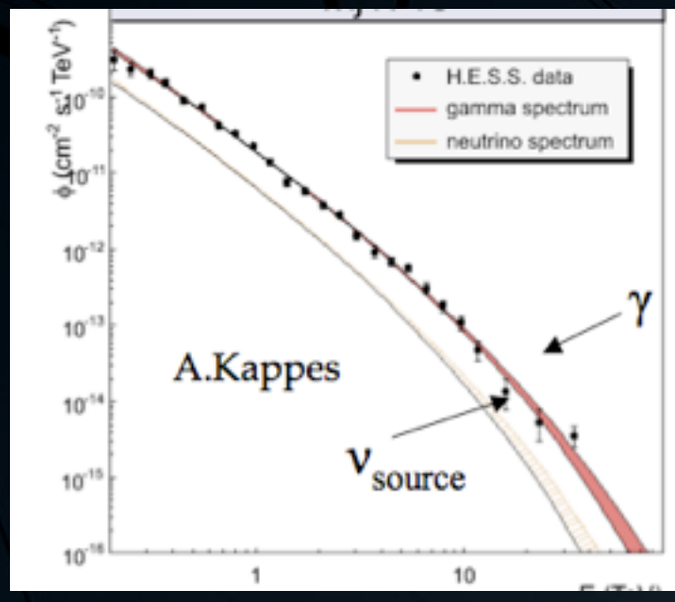
RX J1713.7-3947

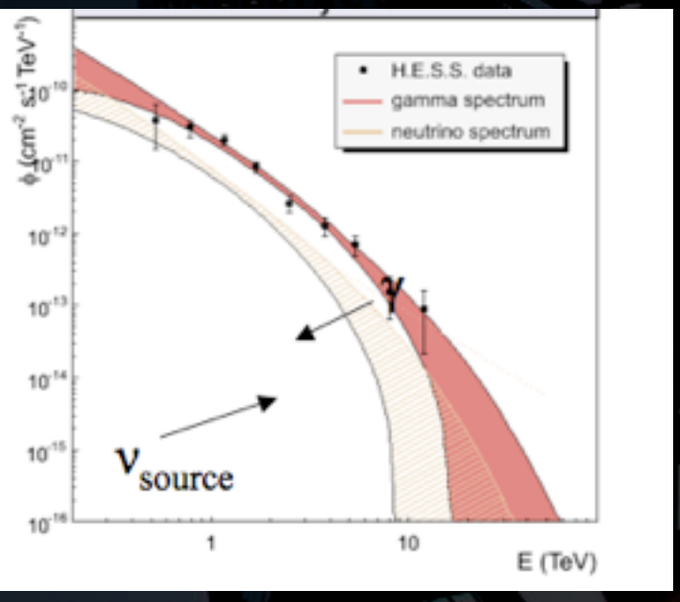


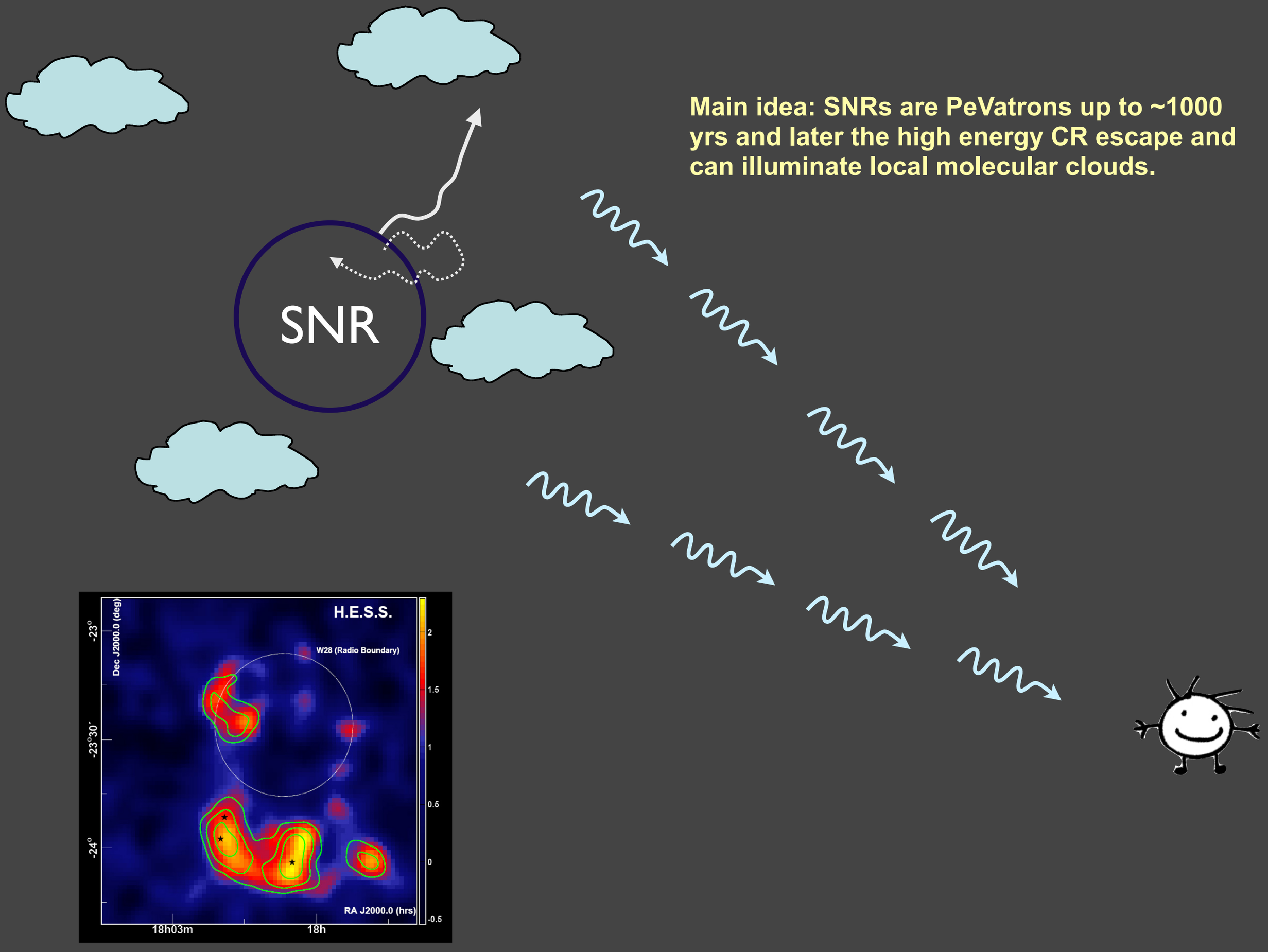
The 2 brightest SNRs show a cutoff at 10-20 TeV

BUT! PeV particles are accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high!

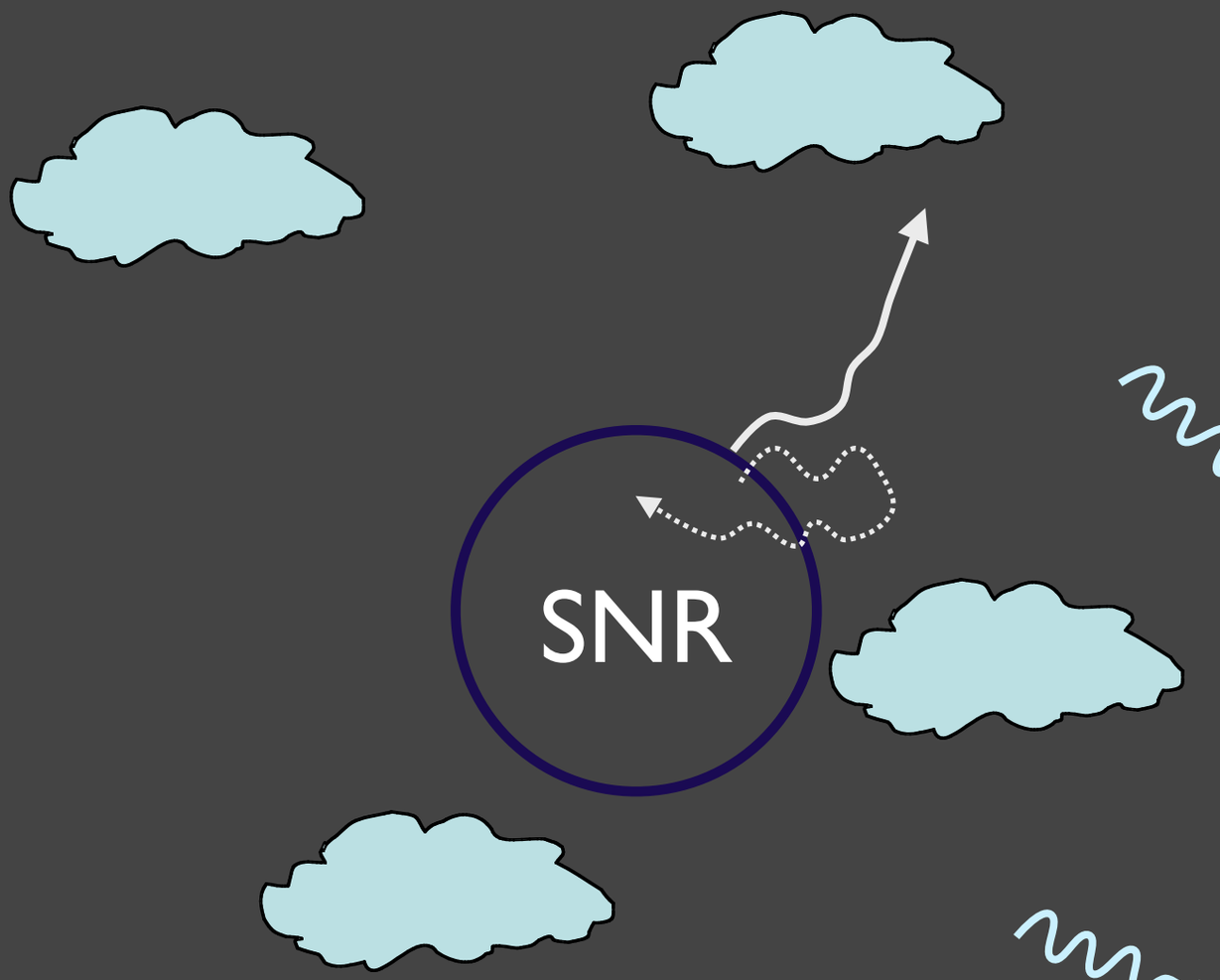
Look at the surroundings







Main idea: SNRs are PeVatrons up to ~1000 yrs and later the high energy CR escape and can illuminate local molecular clouds.



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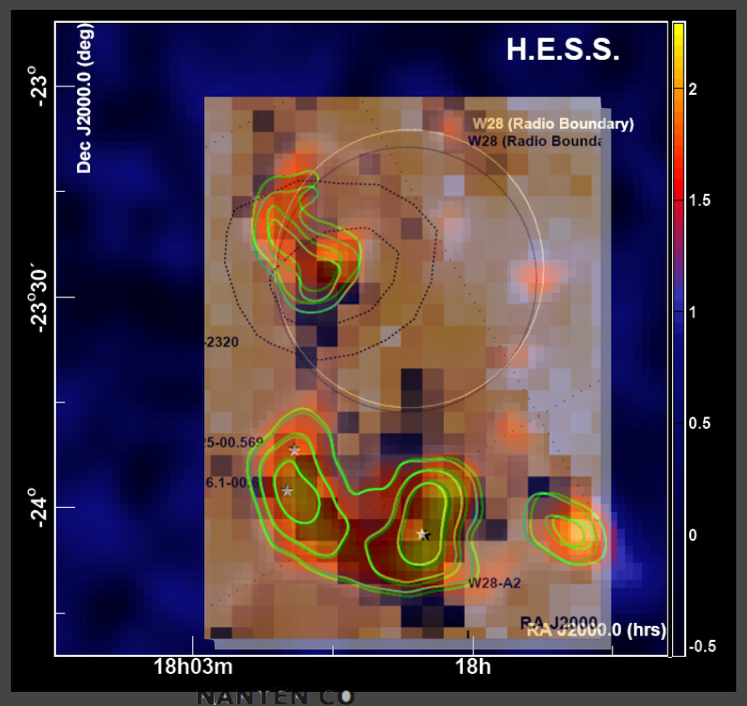

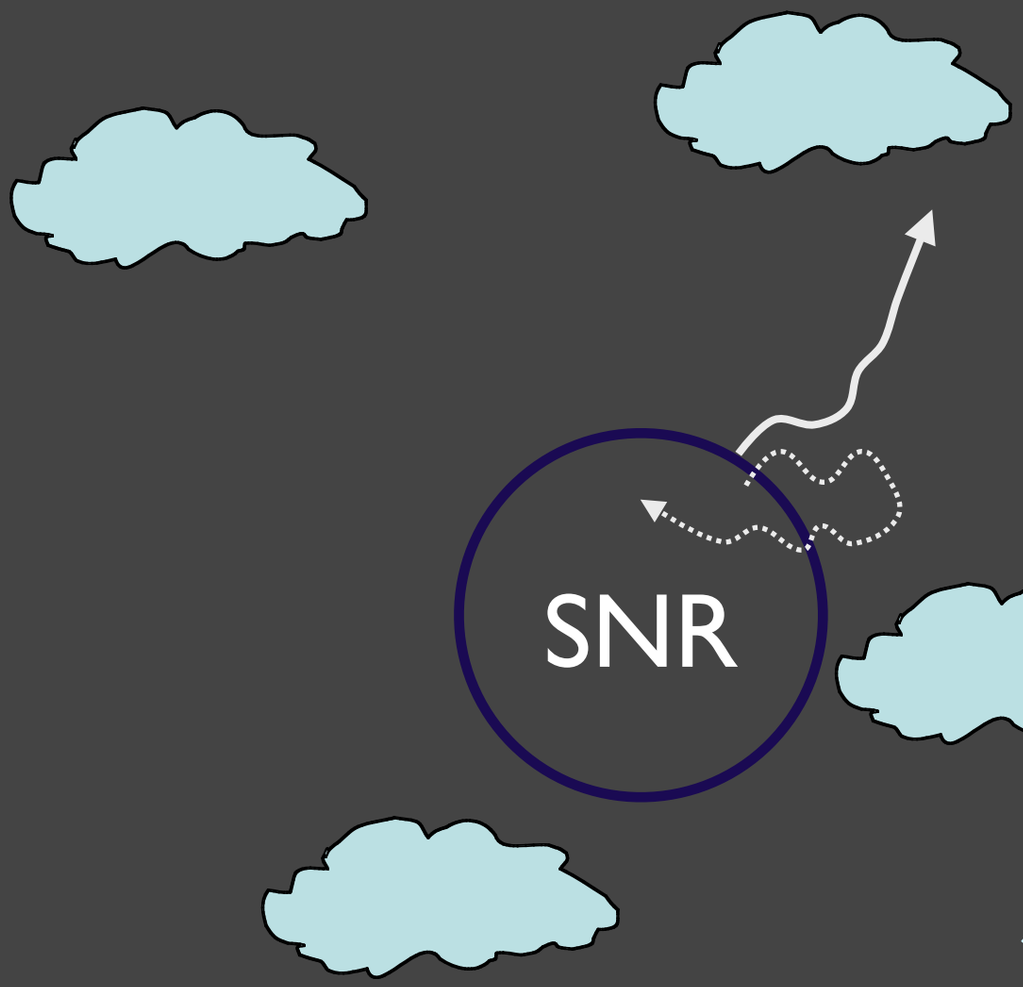

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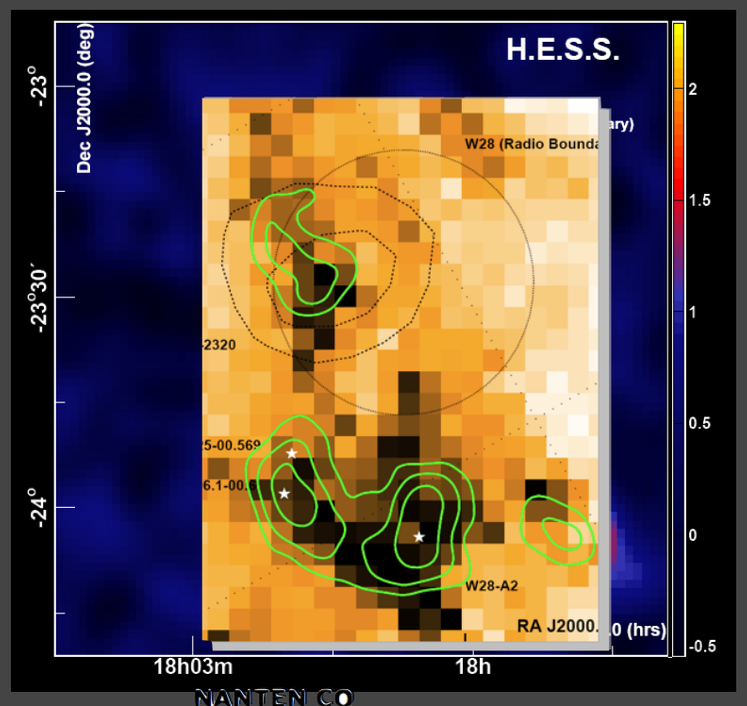
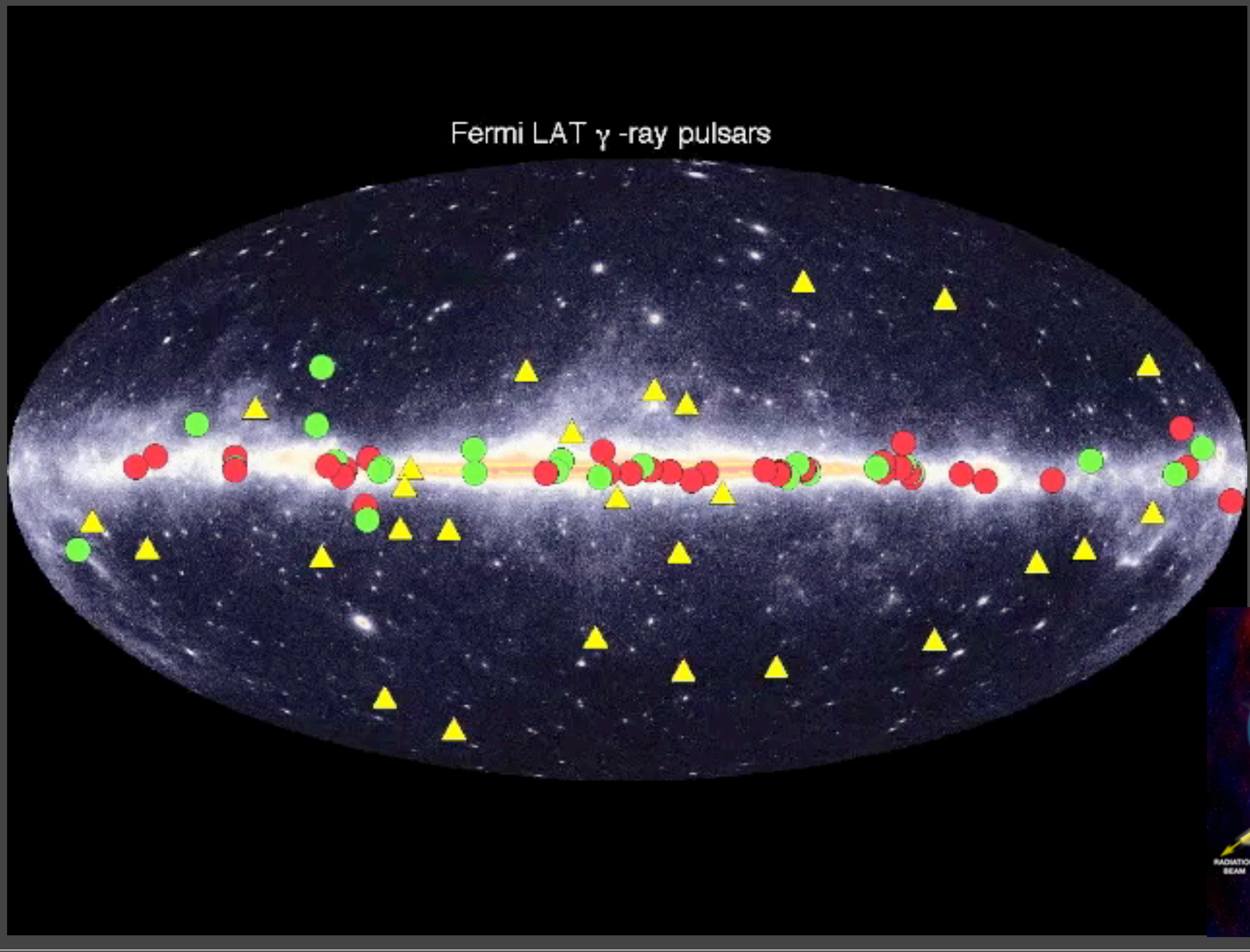
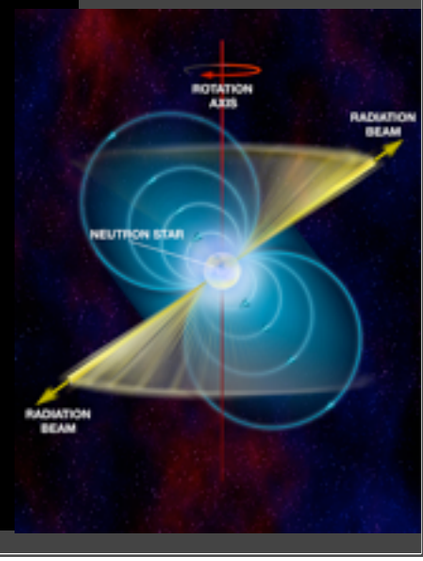


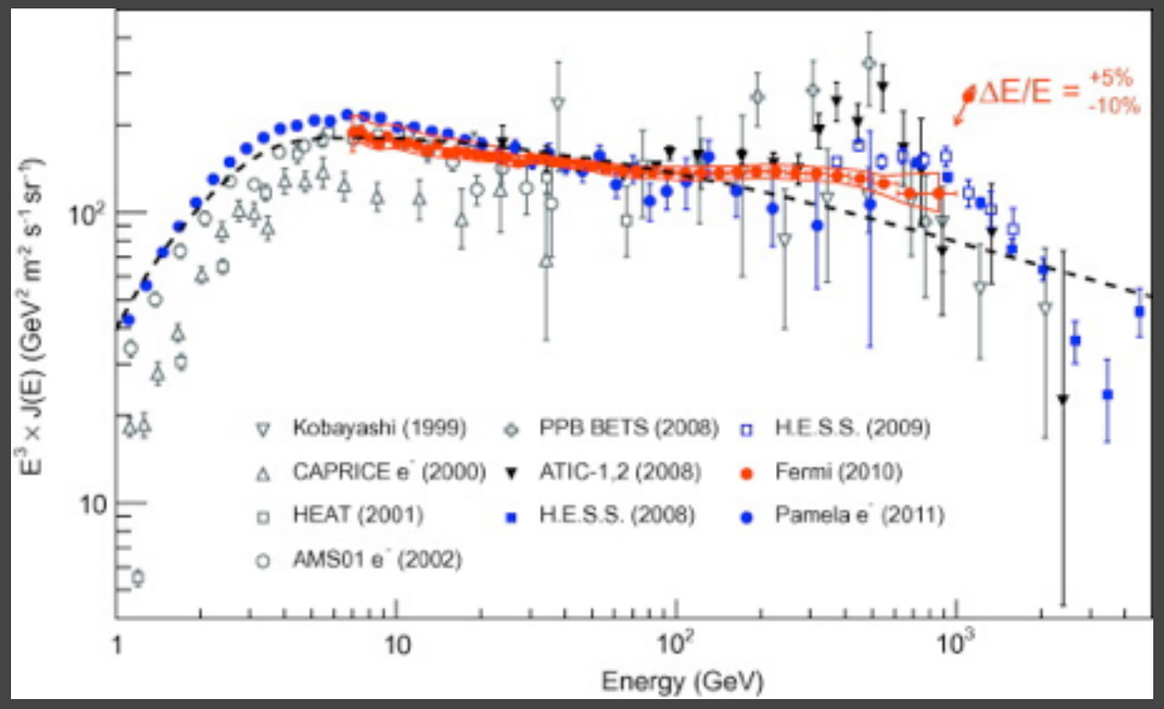
Astropaticles with gamma-rays: Electrons Cosmic Rays

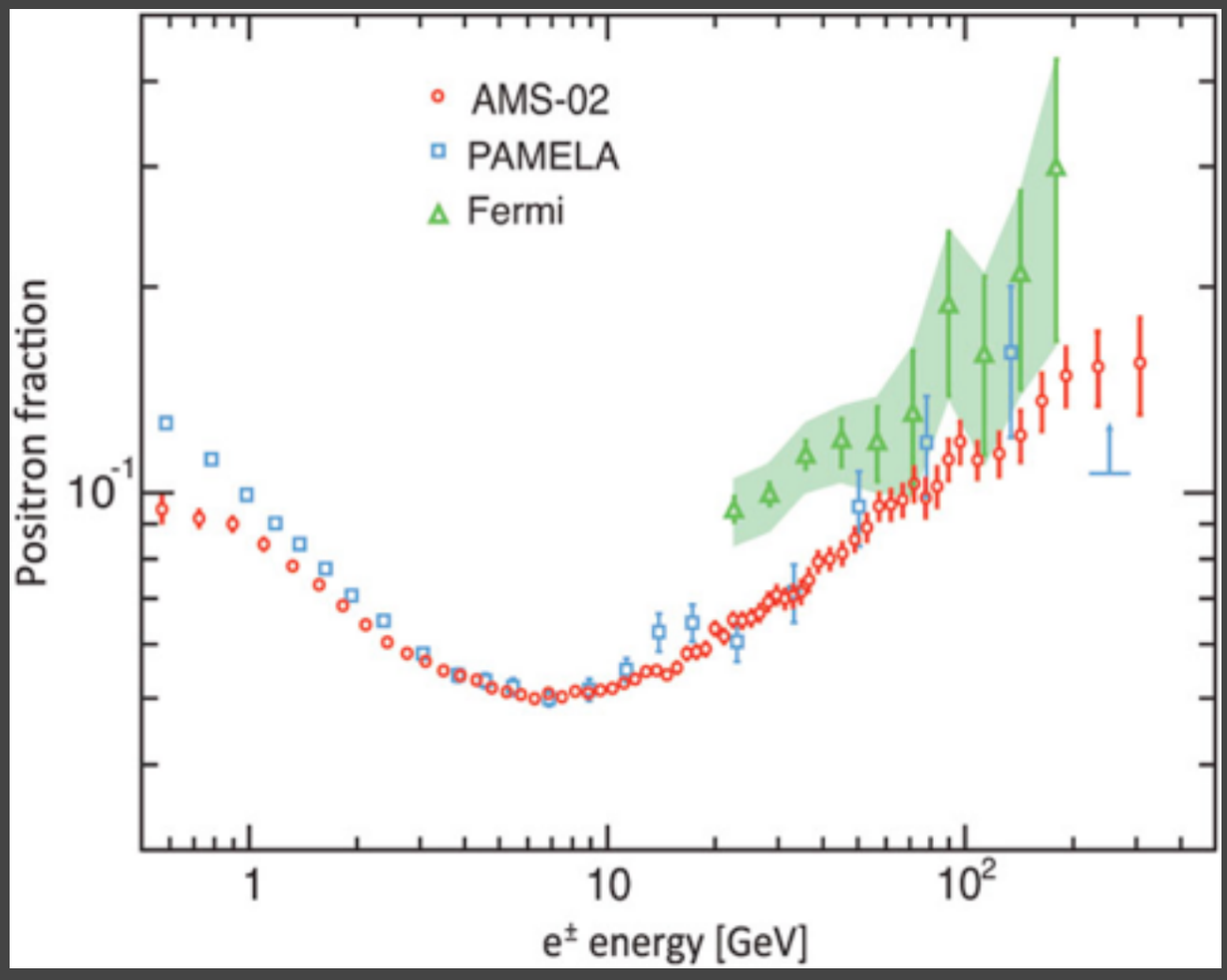




Astropaticles with gamma-rays: Electrons Cosmic Rays

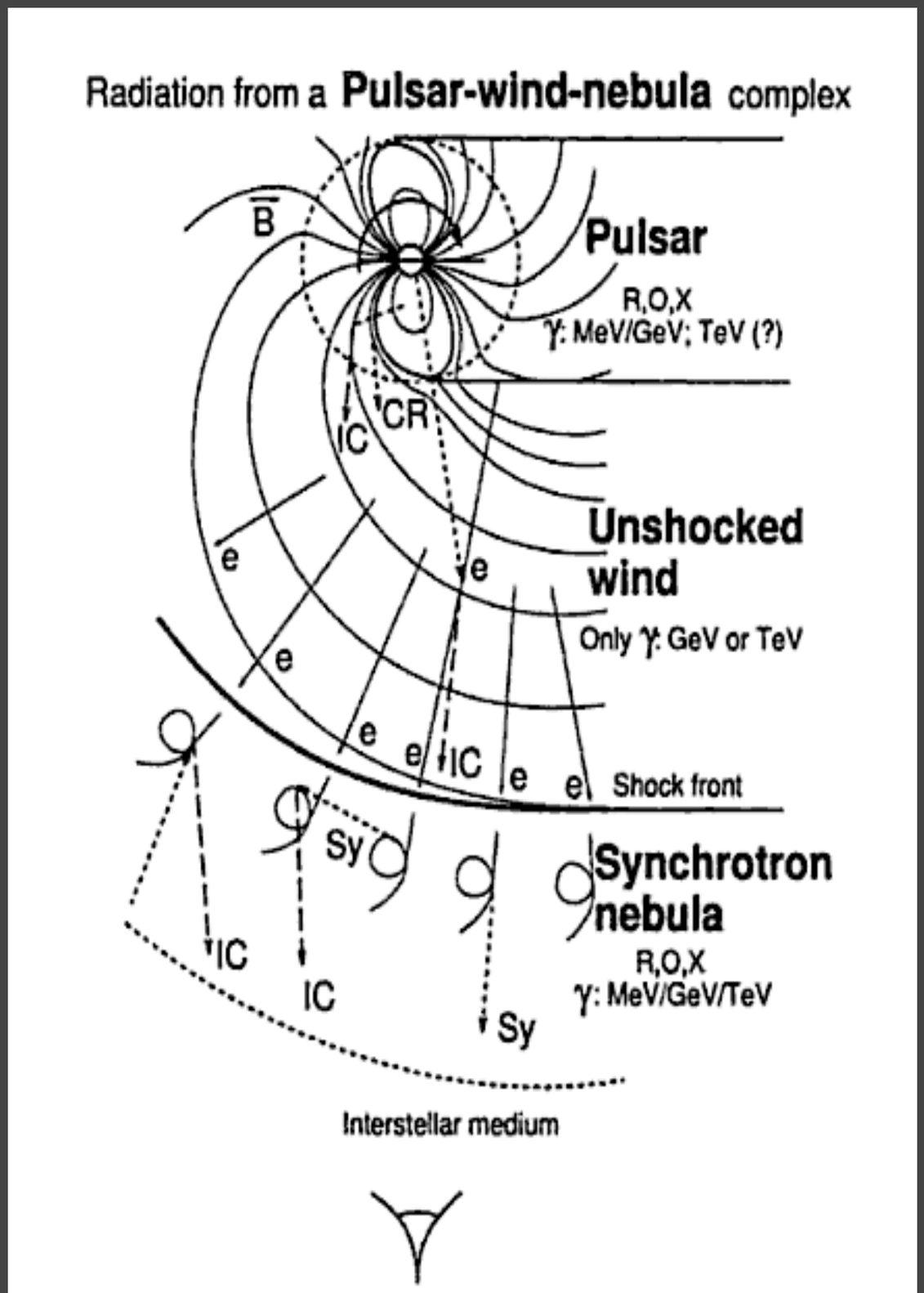
Fermi LAT + Pamela + AMS + Cherenkov Telescopes





The number of positrons increases with energy:
1) Dark Matter ...
2) Astrophysical origin (i.e. pulsars)

The electron factory



Aharonian 2008

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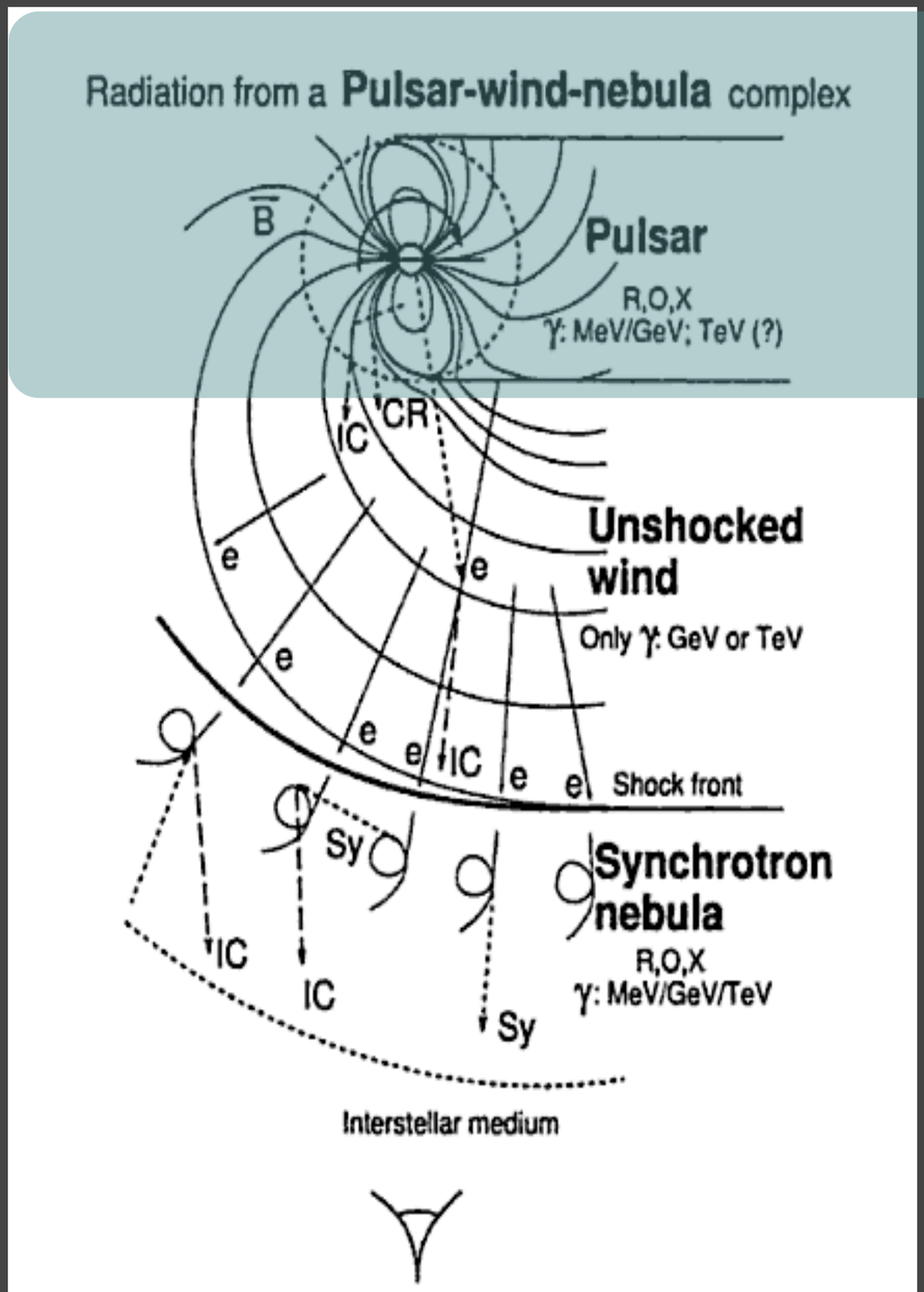

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  - Cascading of secondary particles

Aharonian 2008

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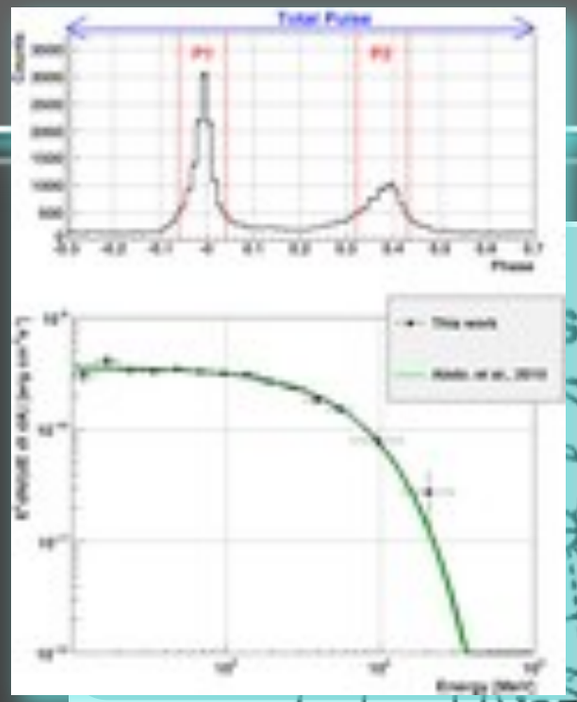

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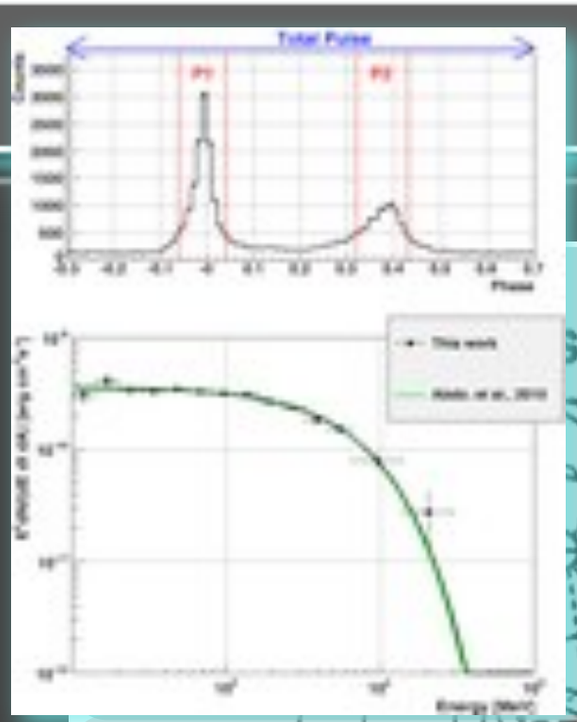

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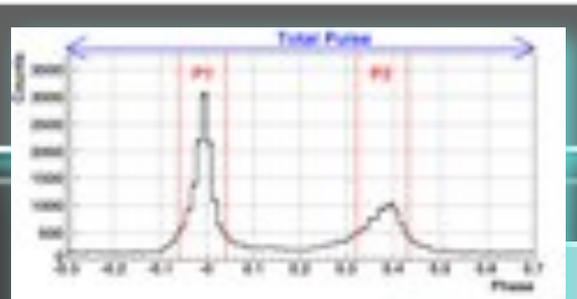

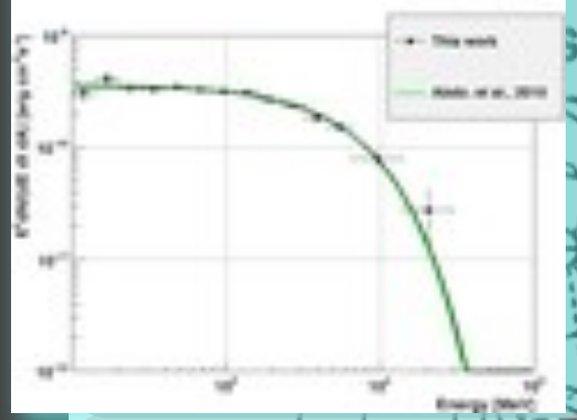

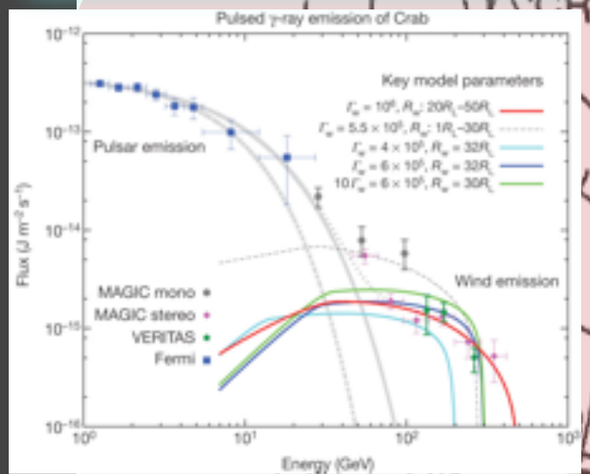

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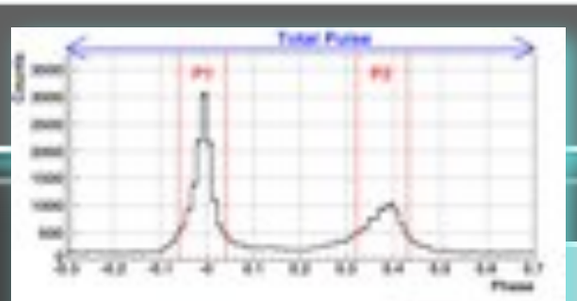

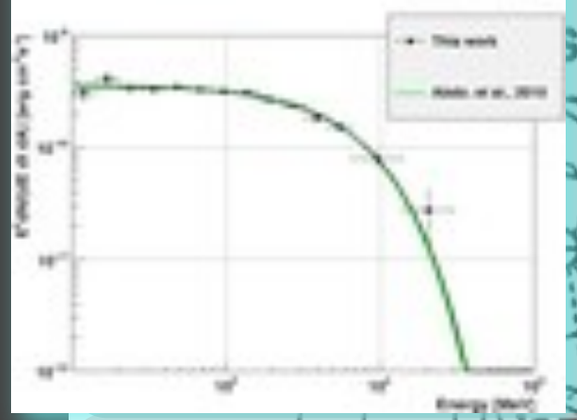

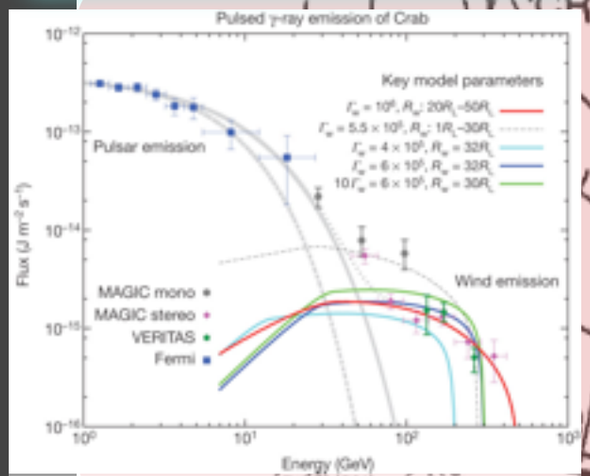

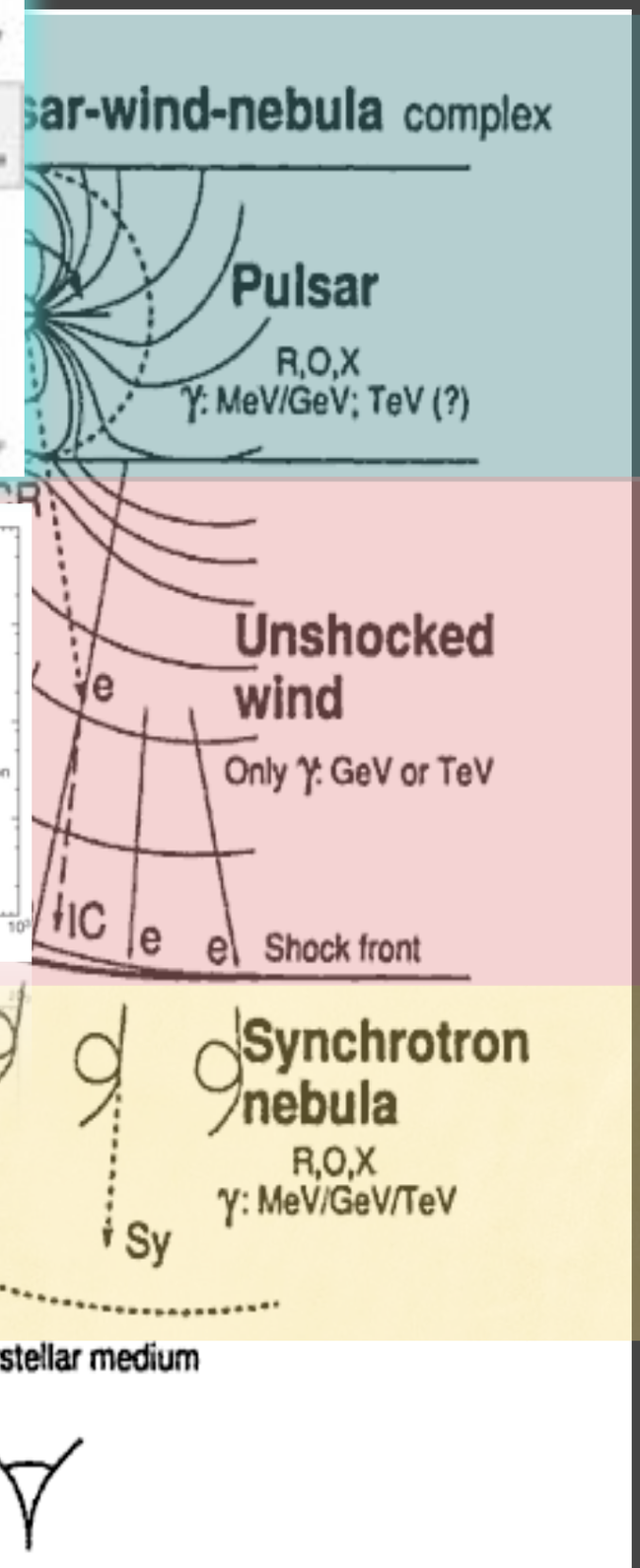

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Aharonian 2008

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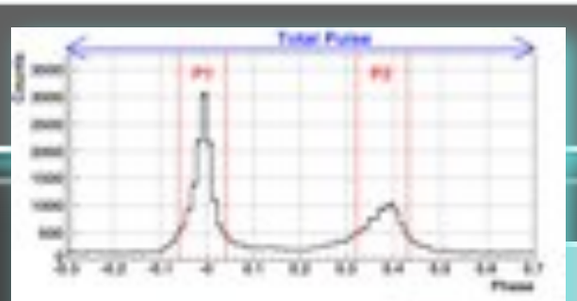

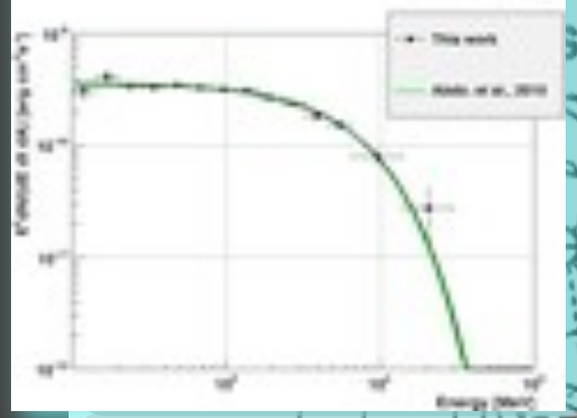

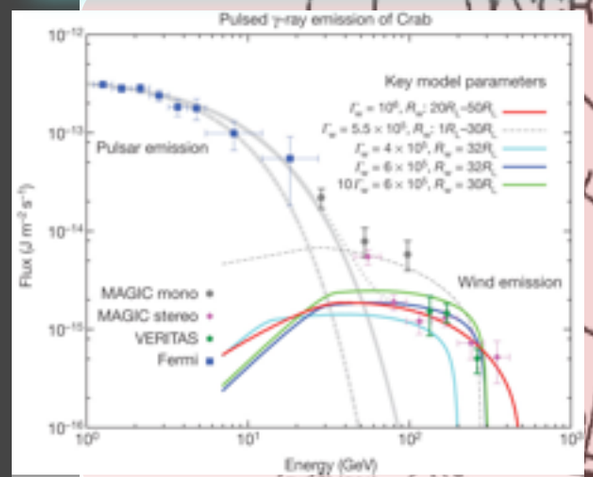

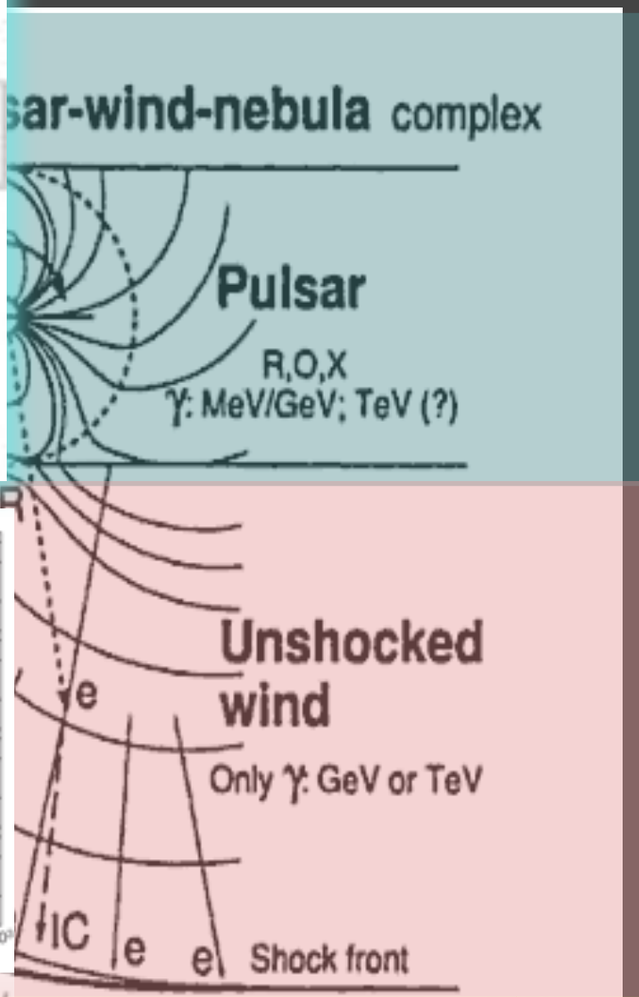

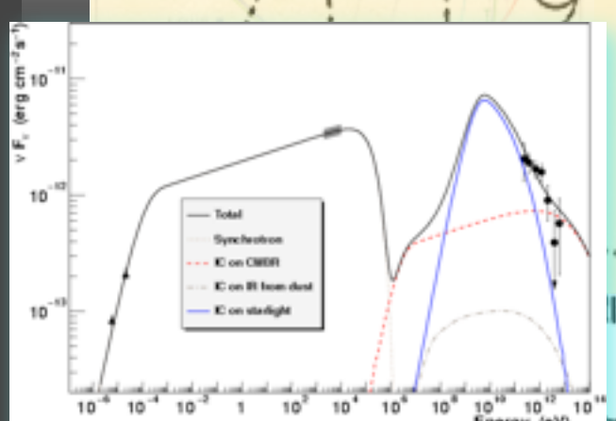

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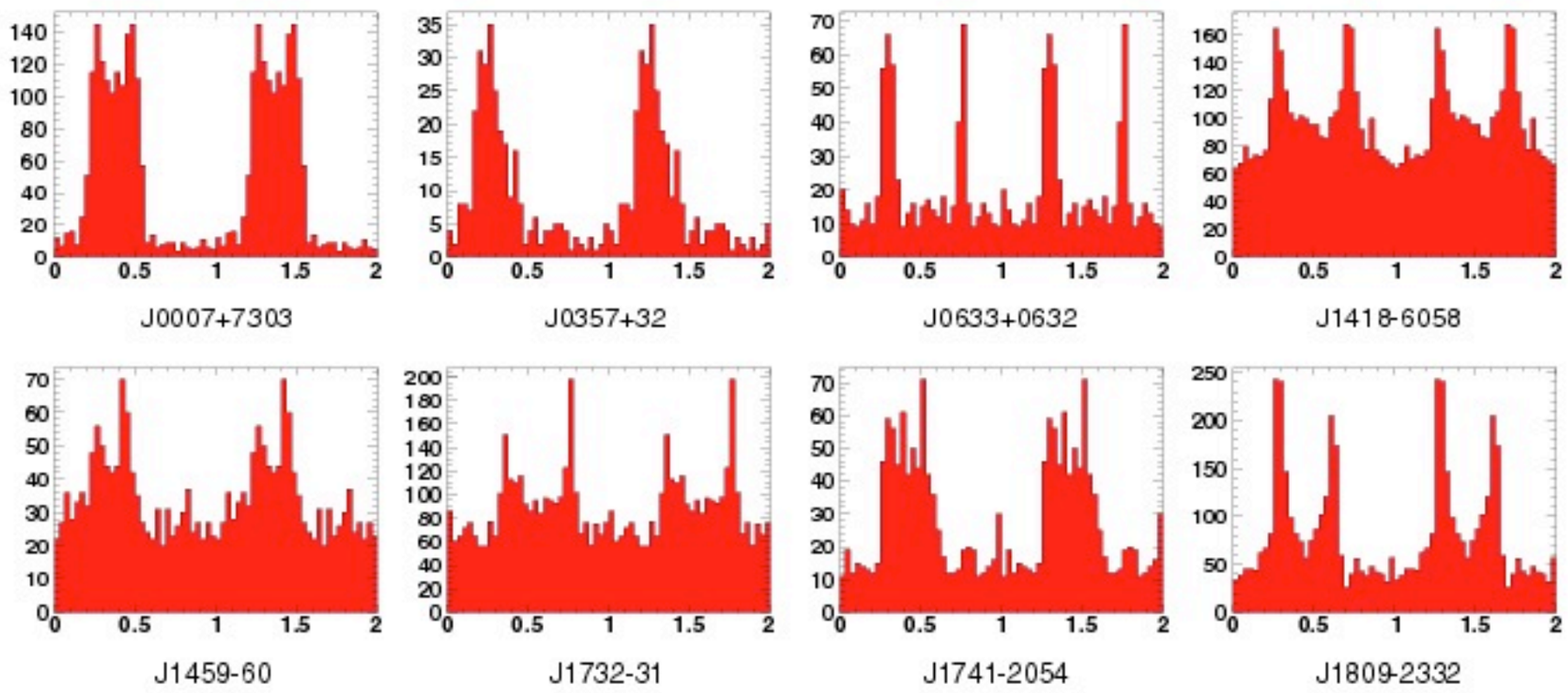
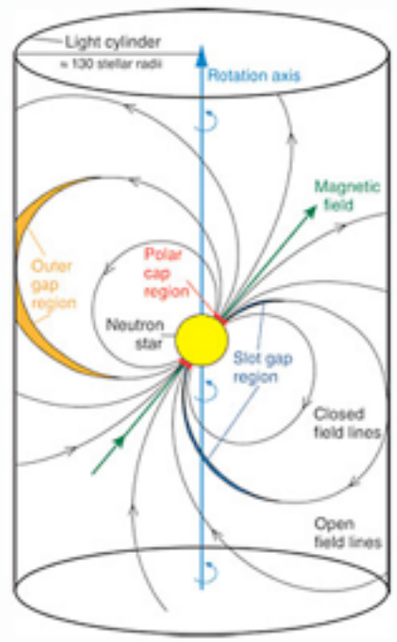
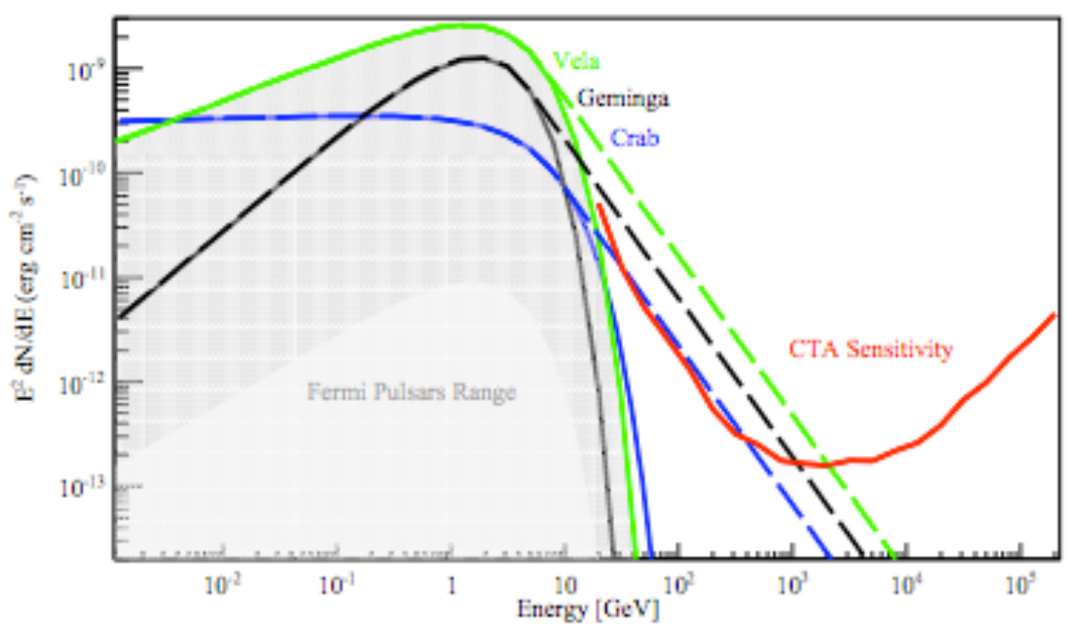
Pulsars with Fermi LAT



Identified by the light-curve
Sharp cutoff at ~few GeV
Tails at high energies?



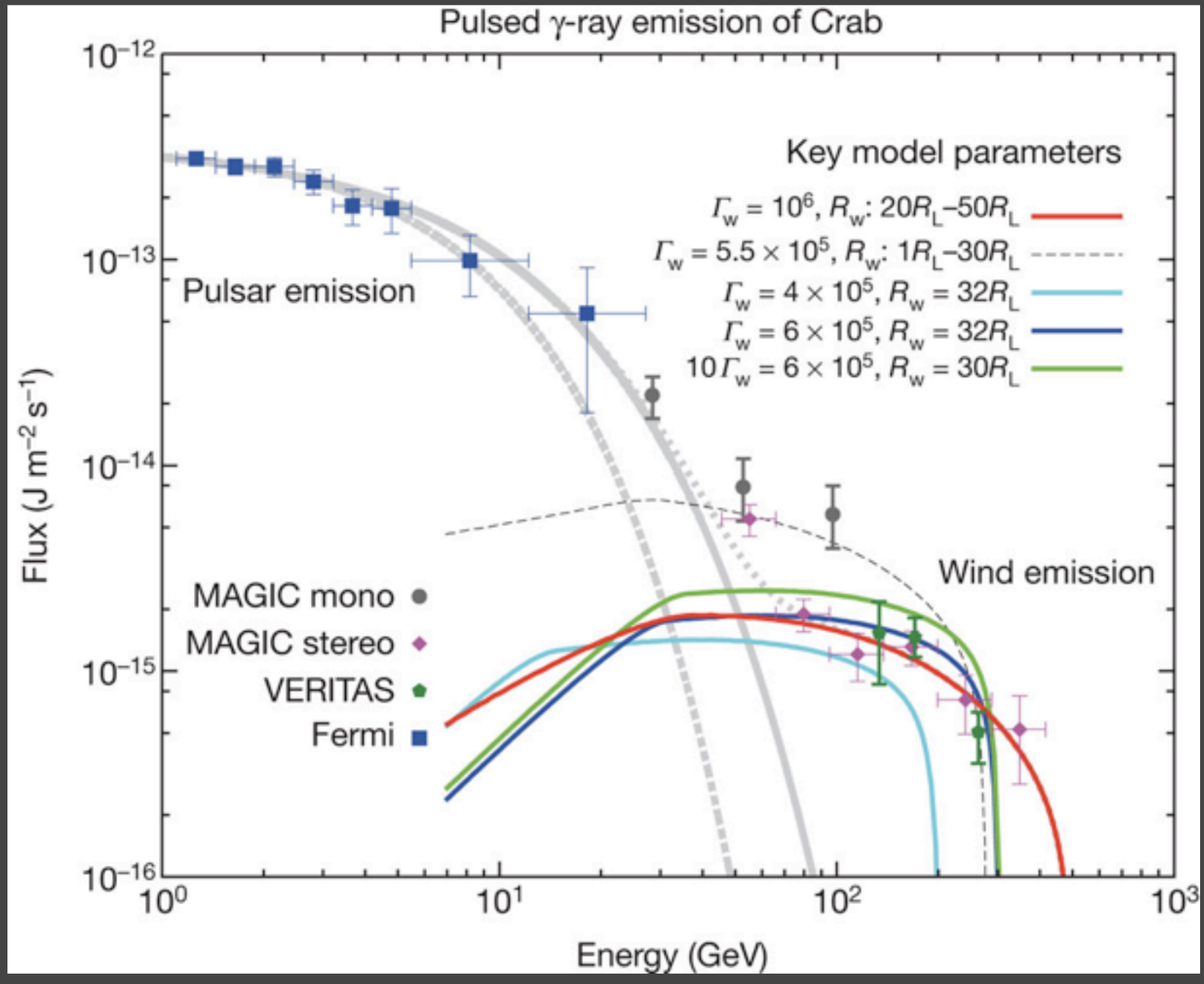


Pulsars at VHE

- Two explanation proposed:
  - SSC from secundary electron-positron pairs created in the magnetosphere
  - IC of the relativist wind with pulsed low-energy (X-ray) emission

Hirotani, 2012

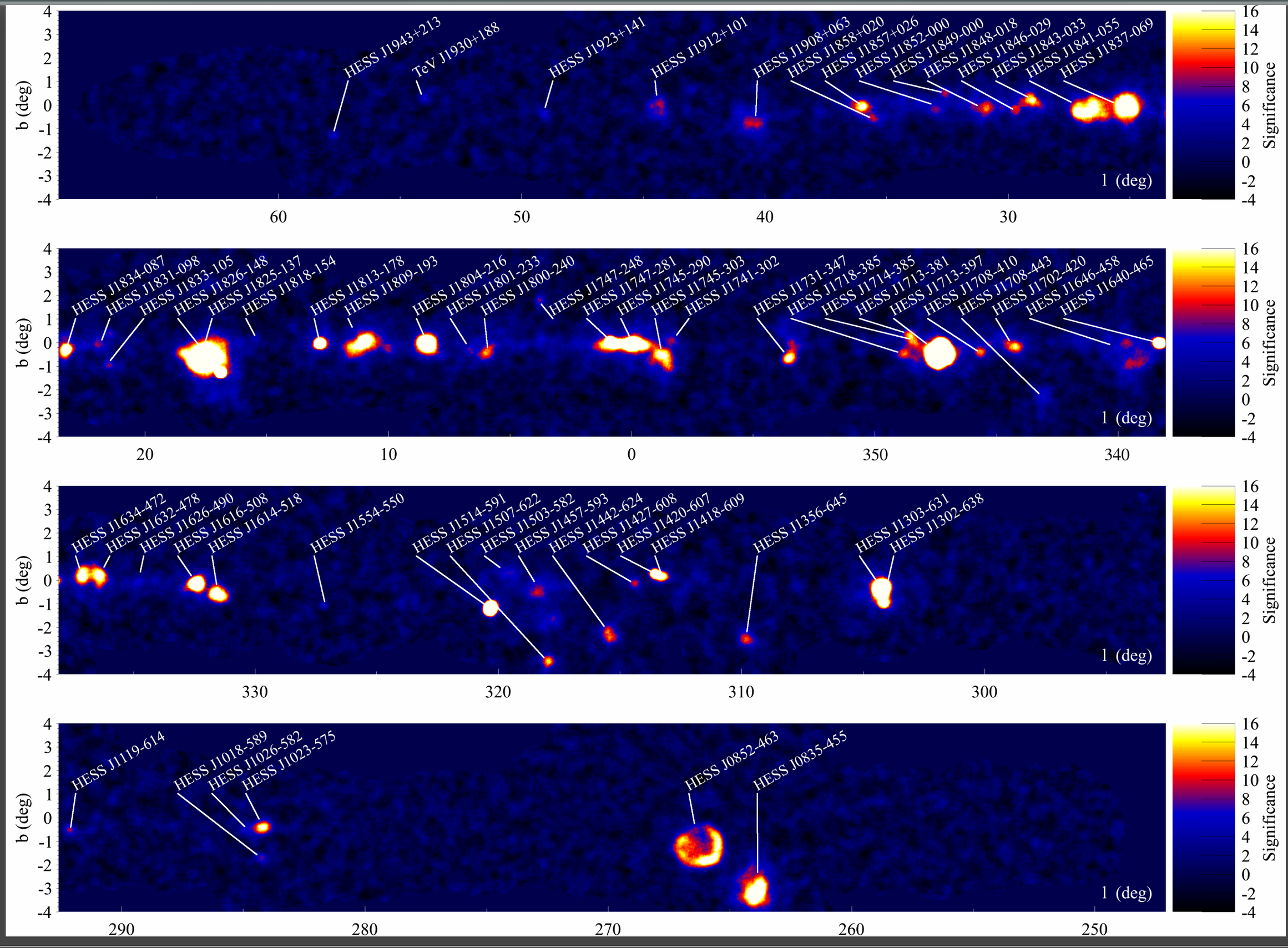
Aharonian, 2012



Aharonian et al. *Nature* **482**, 507–509, 2012

Veritas & MAGIC Collaborations, 2011

Pulsars Winds



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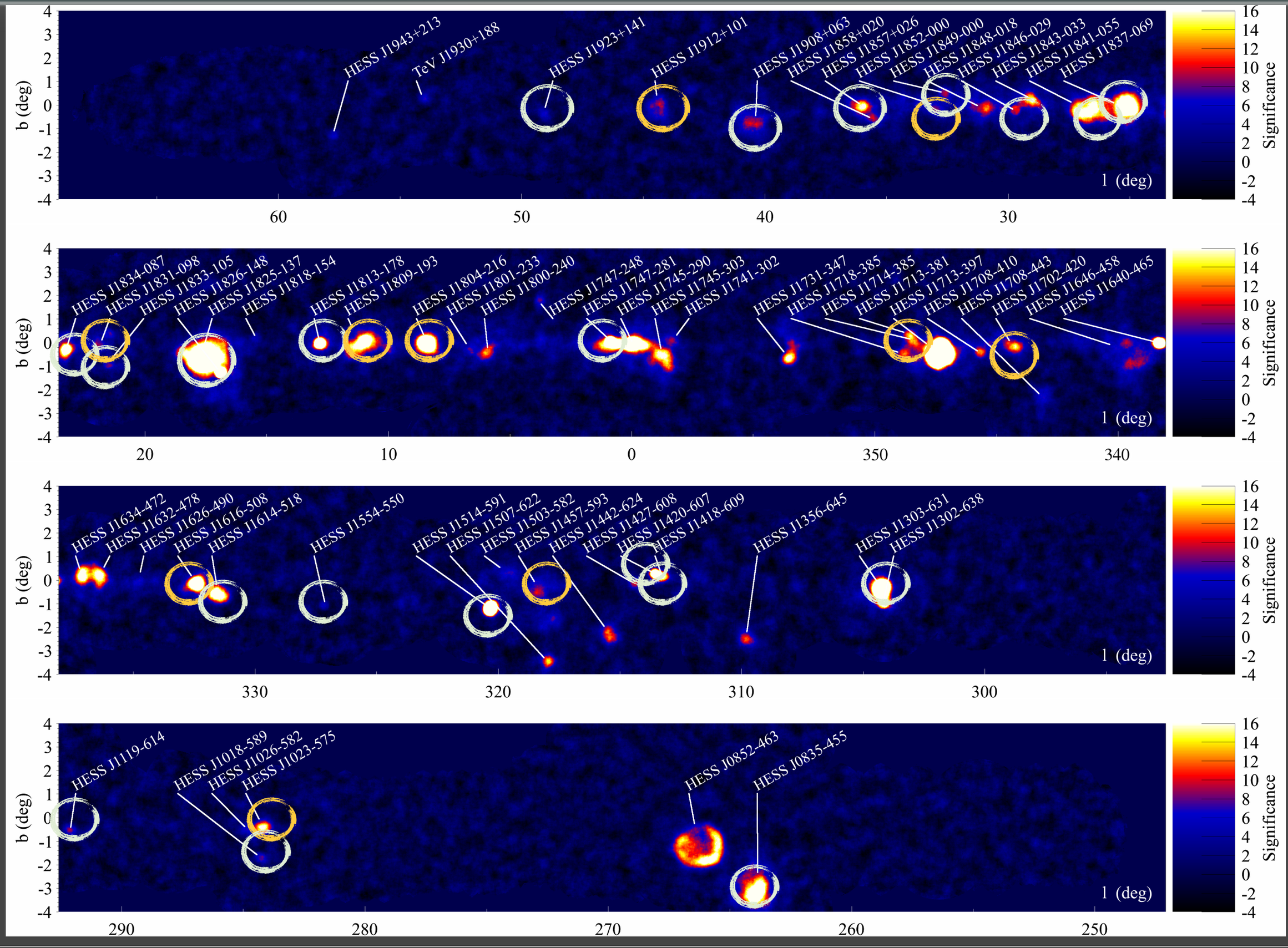

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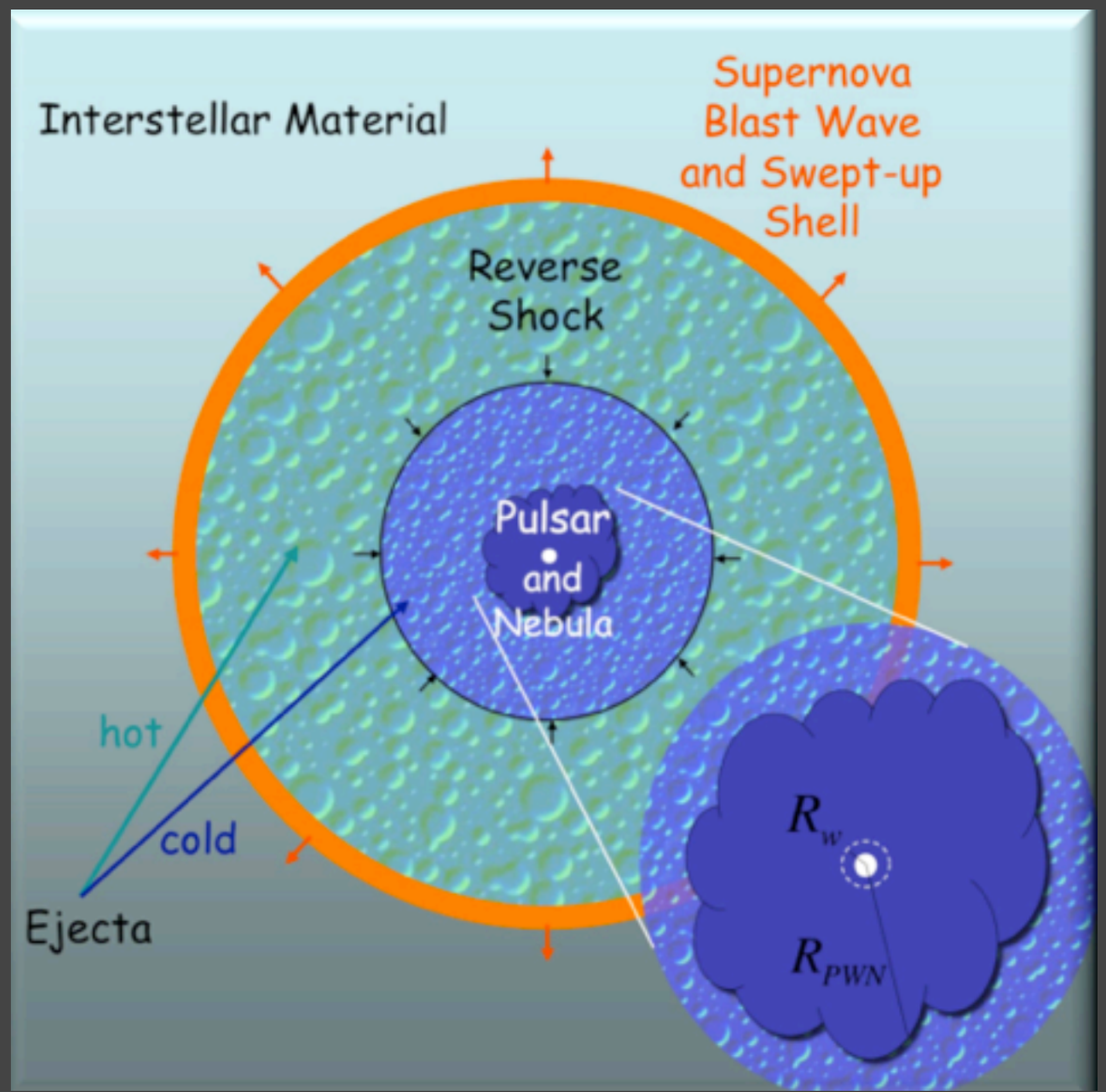
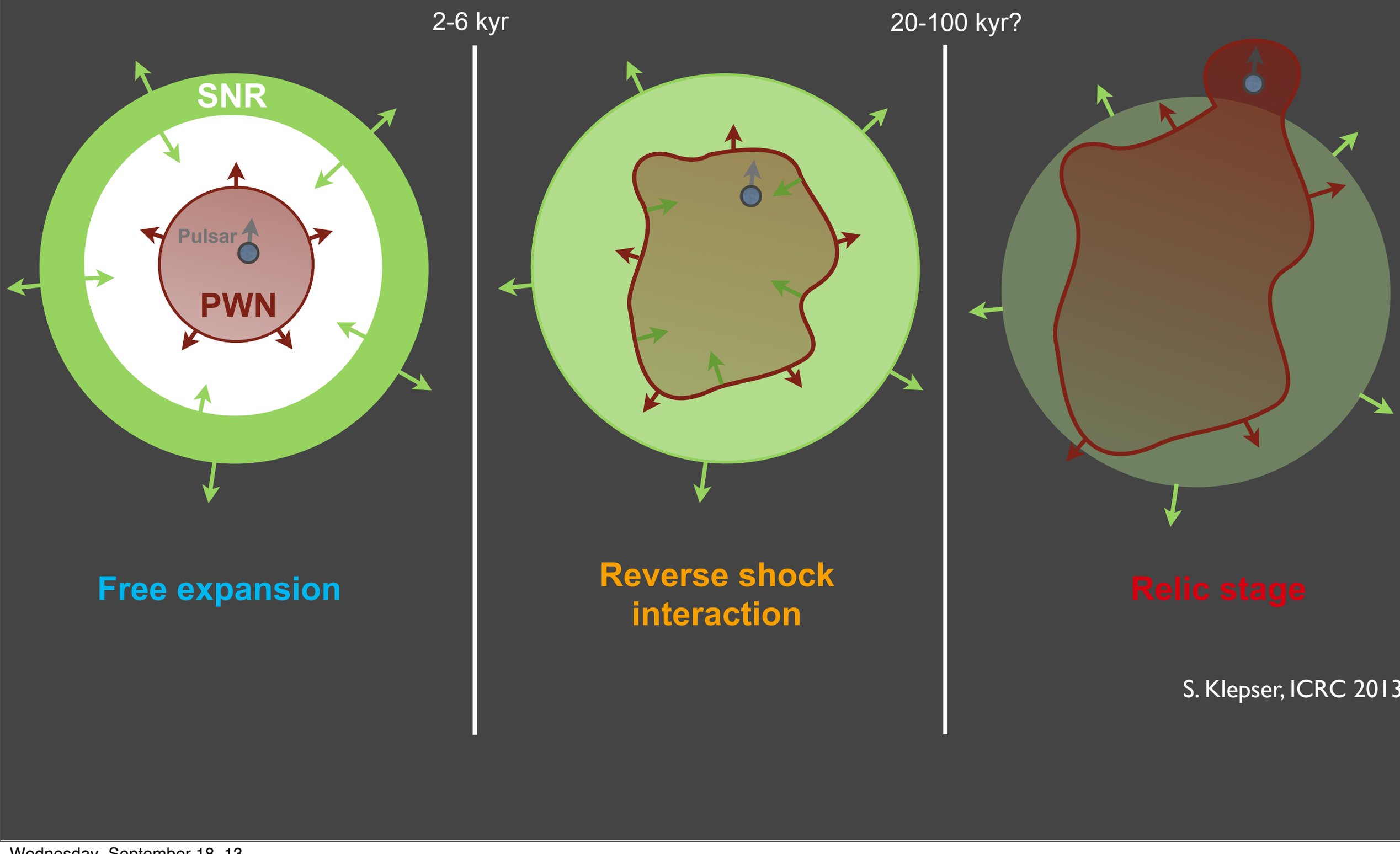


—Pulsar Wind sweeps up the ejecta; the shock decelerates the flow & accelerate particles; PWN form

PWN: hot bubble of particles and magnetic field, emitting non-thermal radiation (via synchrotron - IC) from radio to TeV gamma-rays

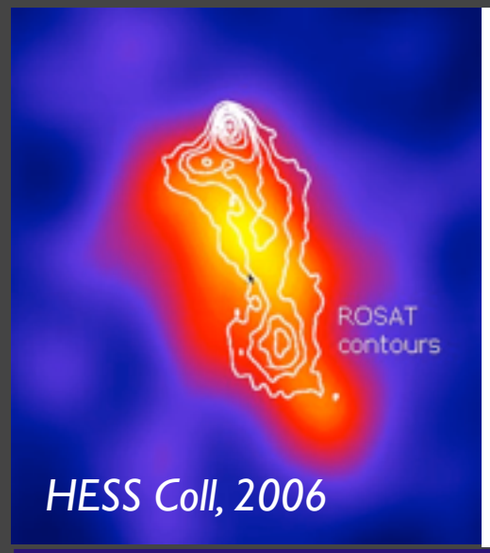
—Supernova Remnant sweeps up the ISM; reverse shock heats ejecta; for old PWNe, ultimately compresses it

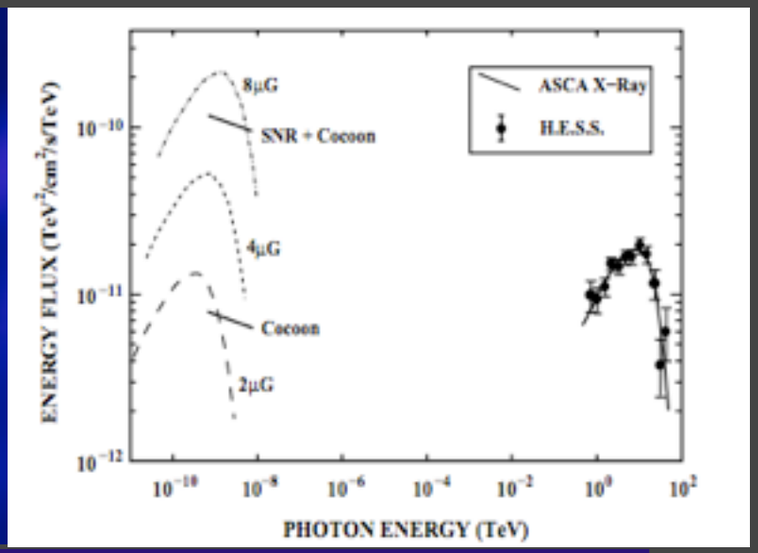
Pulsars Winds



S. Klepser, ICRC 2013

Pulsars Winds





Required Ee to radiate synchrotron keV photons:

$E_e = (70\ \text{TeV})\ B^{-1/2}_{-5}\ E^{1/2}_{\text{keV}}$

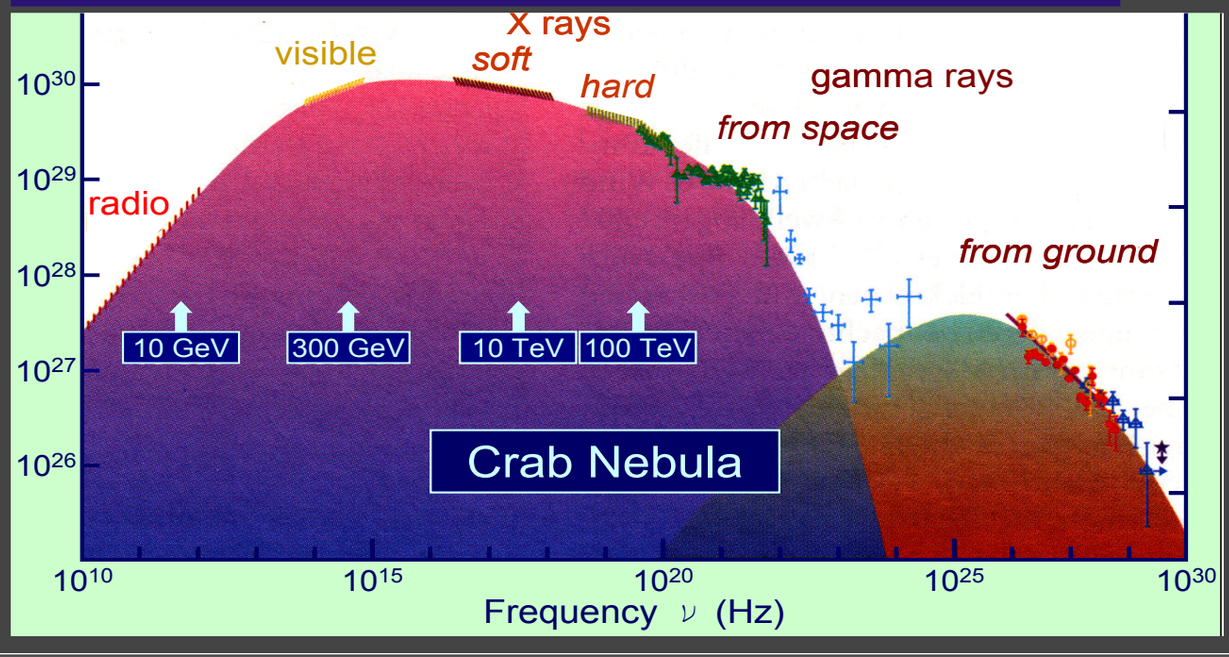
Mean Ee to IC scatter CMB to TeV photons:

$E_e = (18\ \text{TeV})\ E^{1/2}_{\text{TeV}}$

$(E_{\text{keV}}=0.06\ B_{-5}E_{\text{TeV}})$

Distribution of the Energy Budget

$L_x/L_\gamma \sim B^{-2}$



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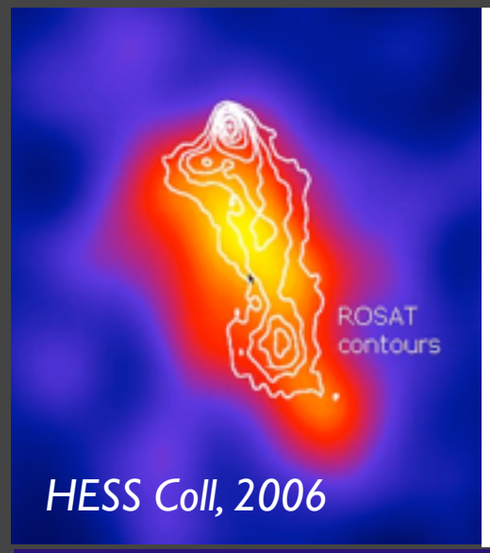

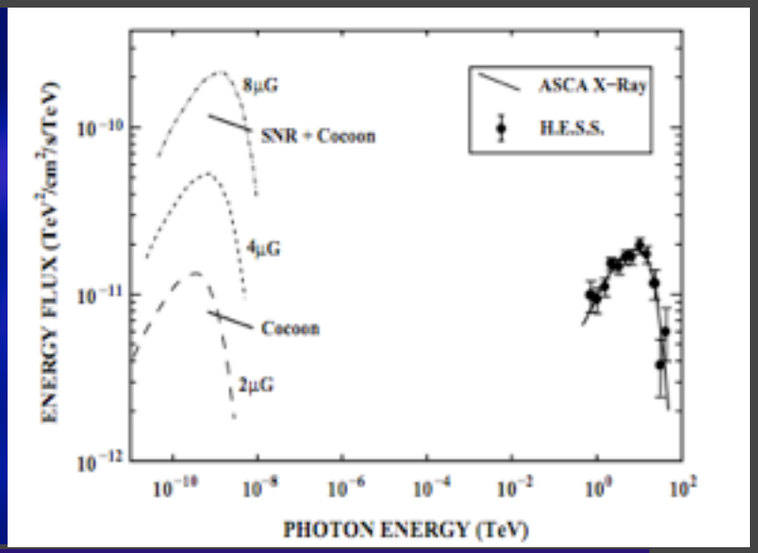

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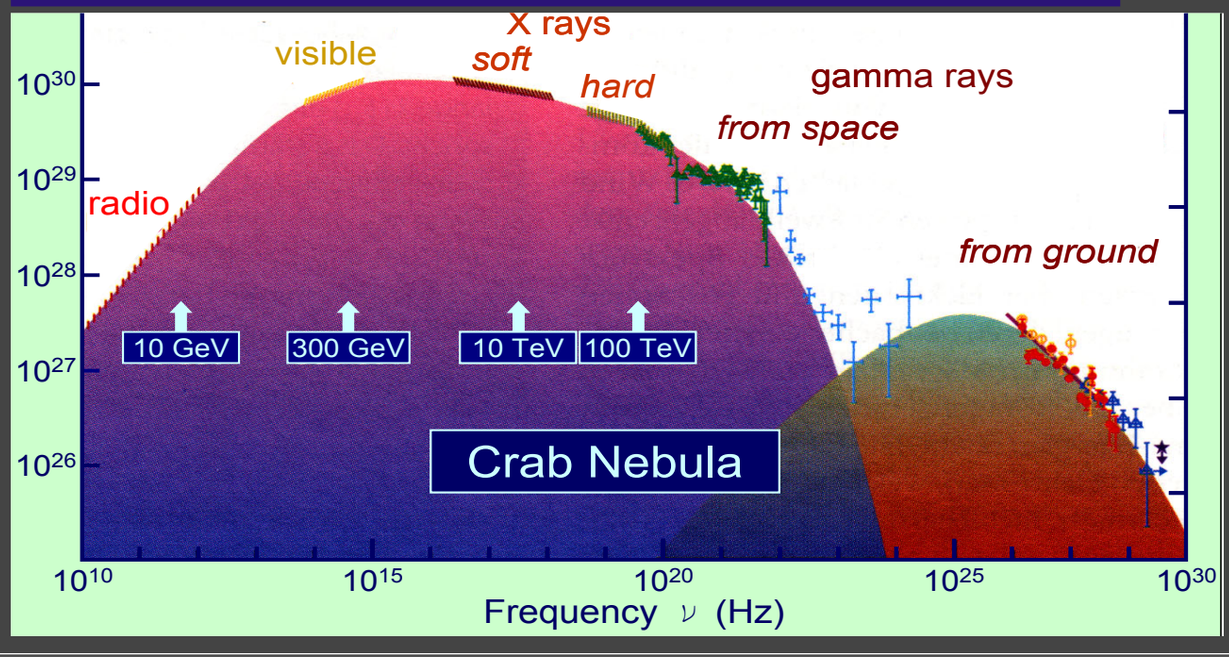

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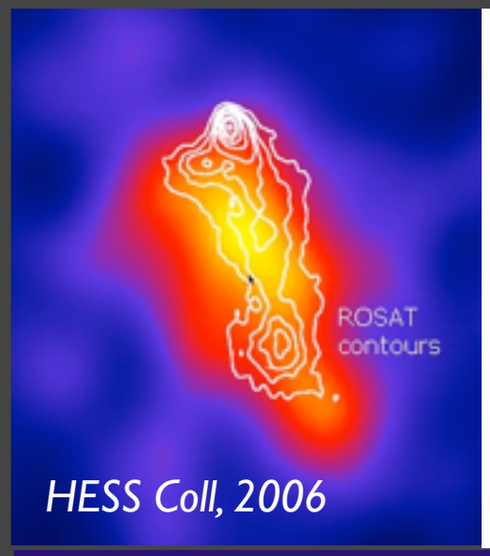

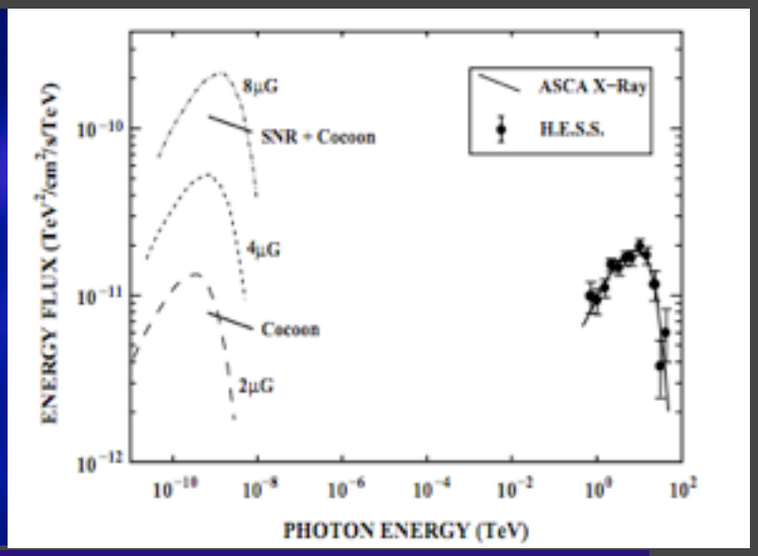

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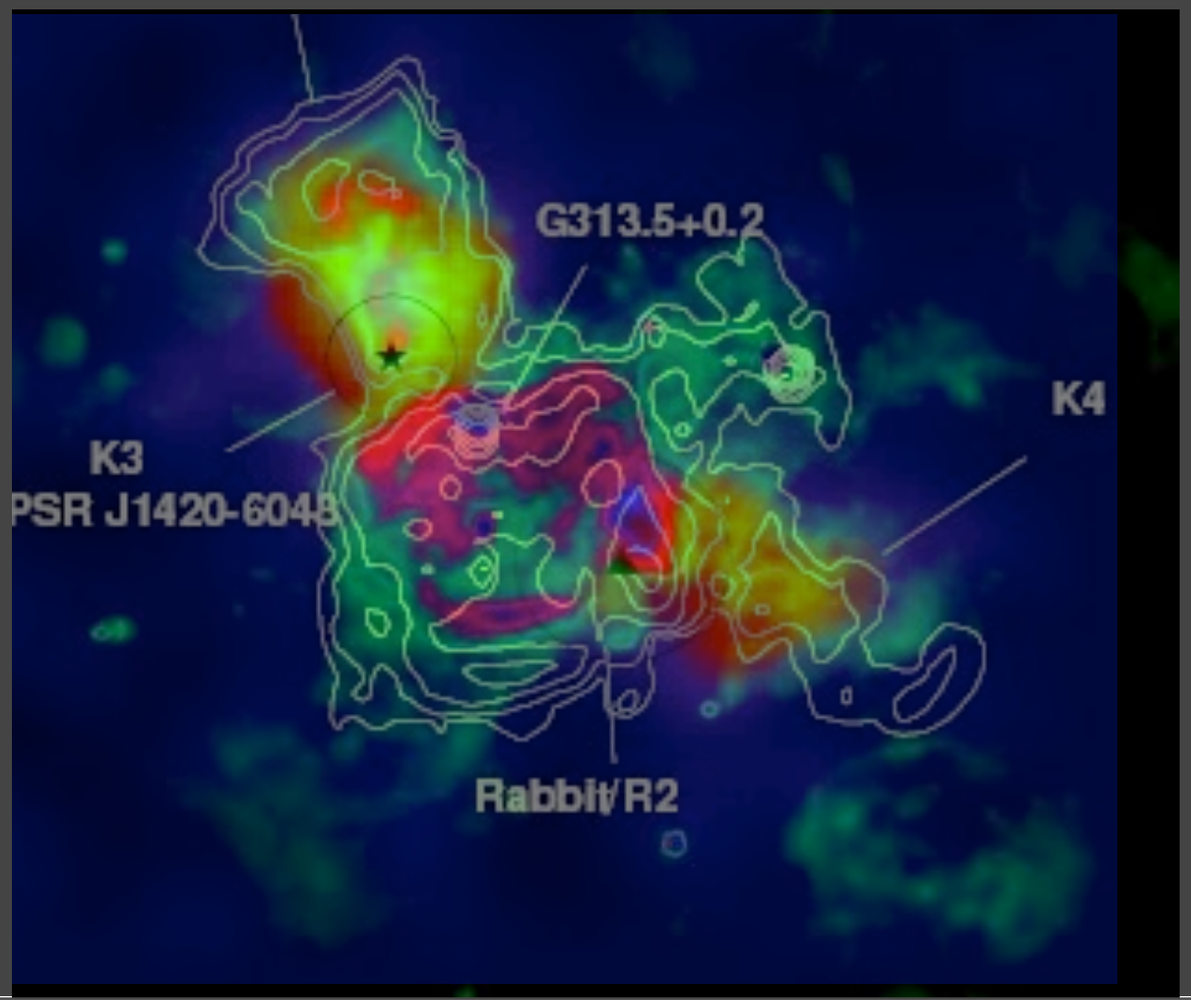

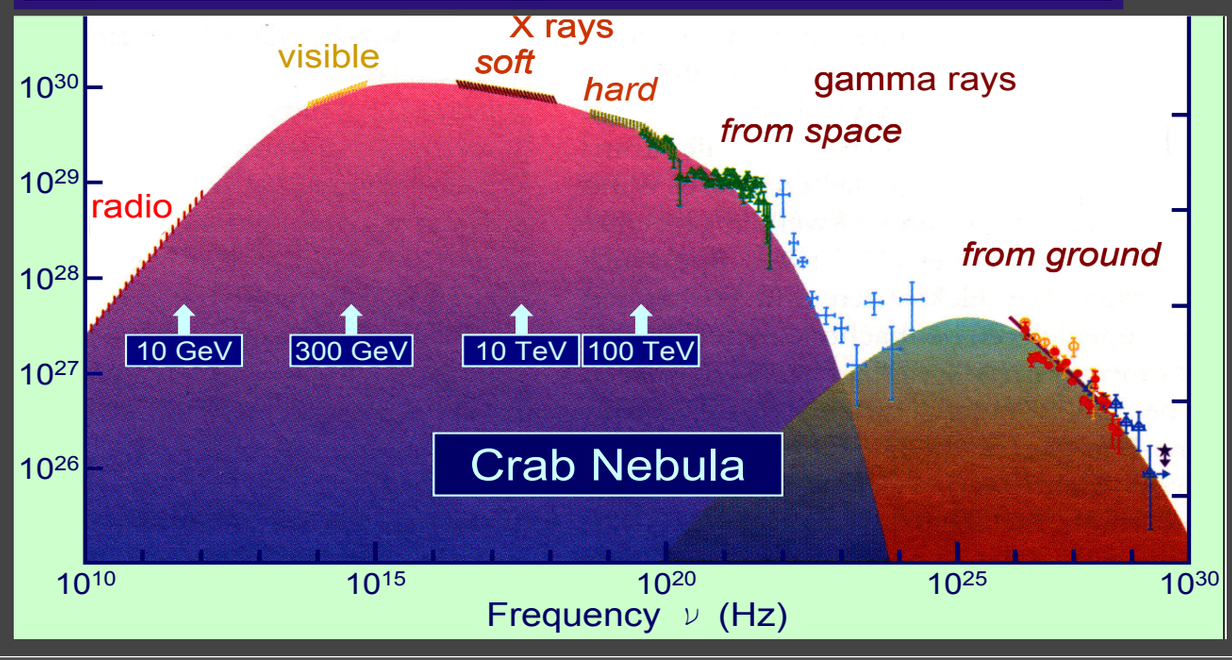

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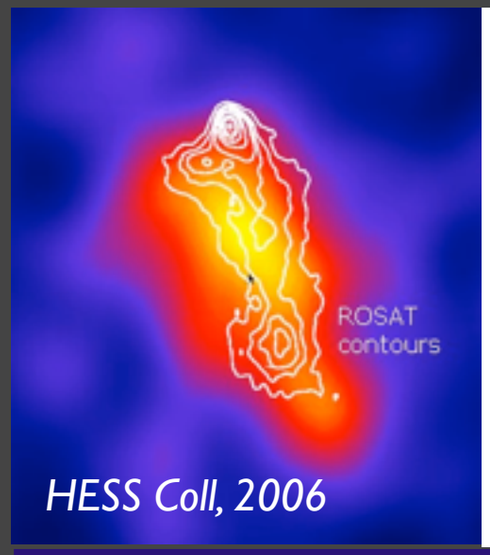

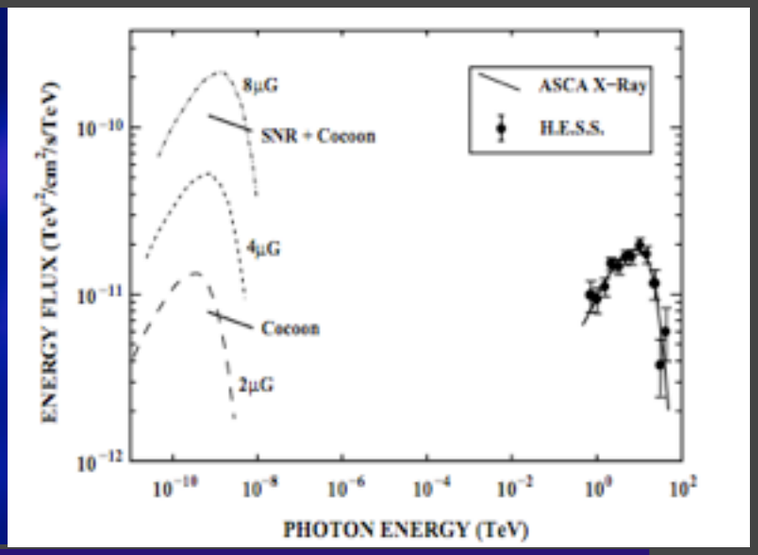

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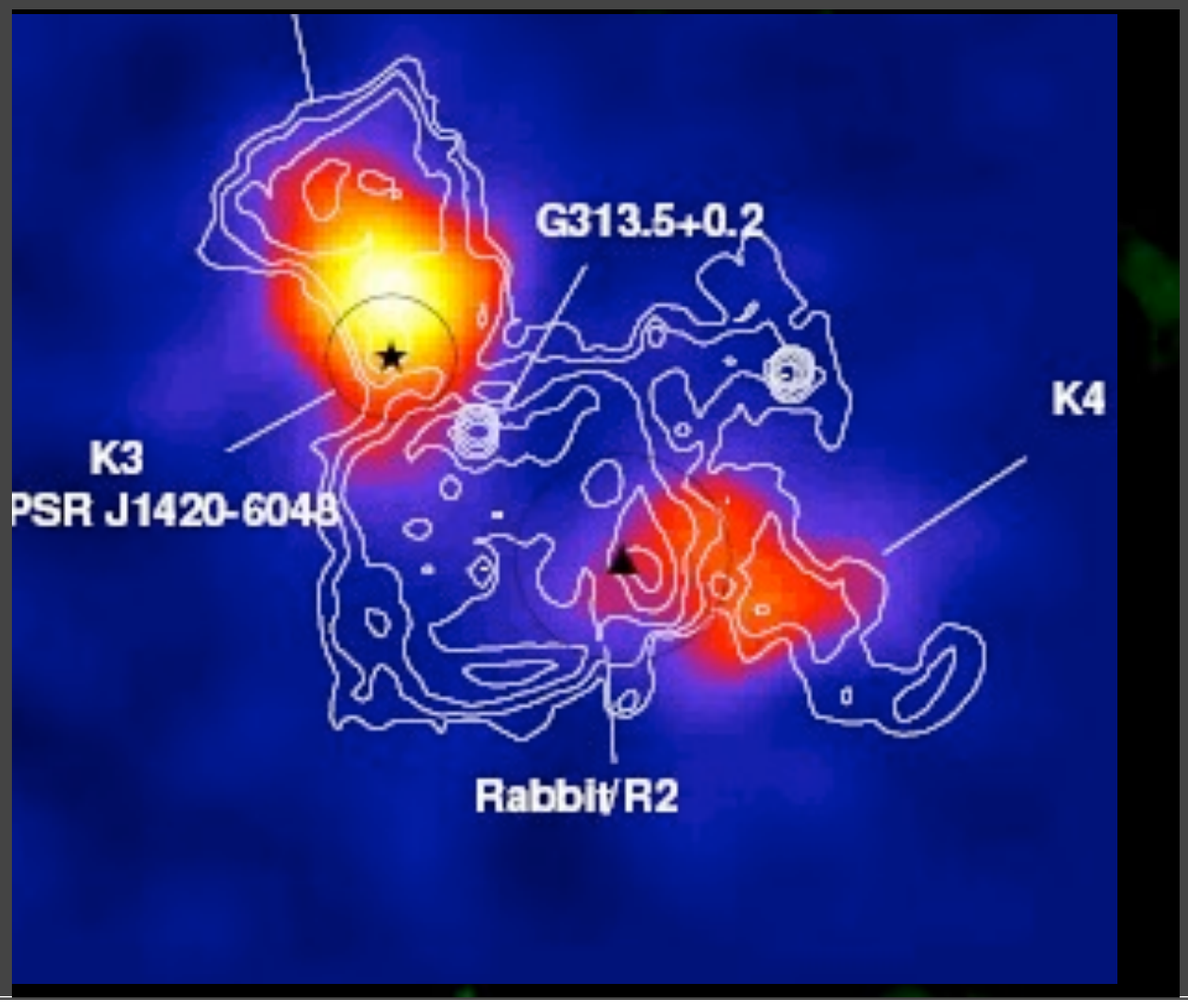

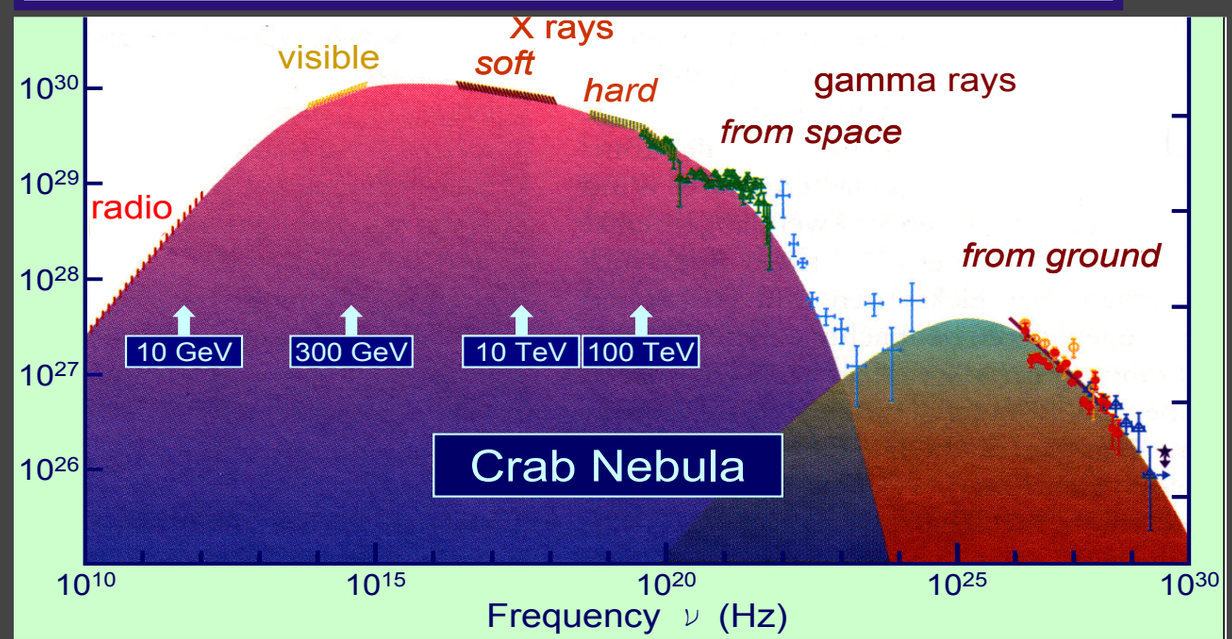

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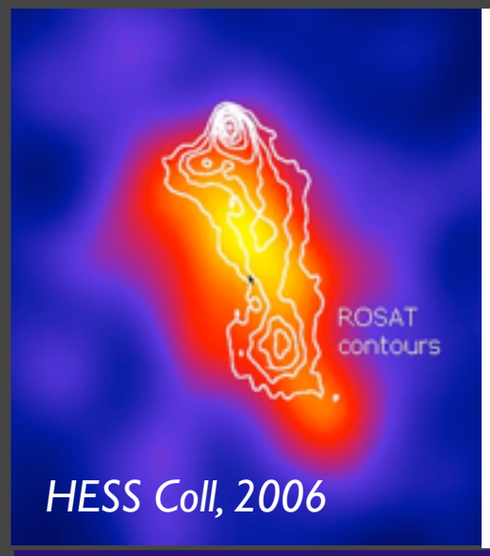

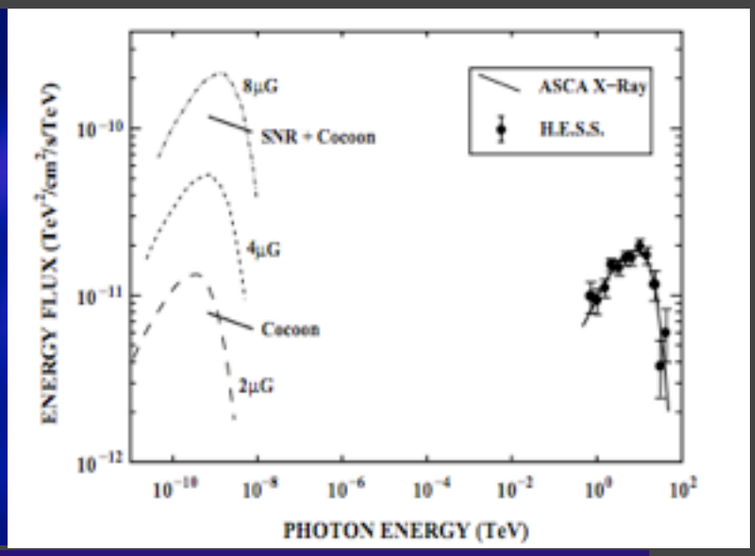

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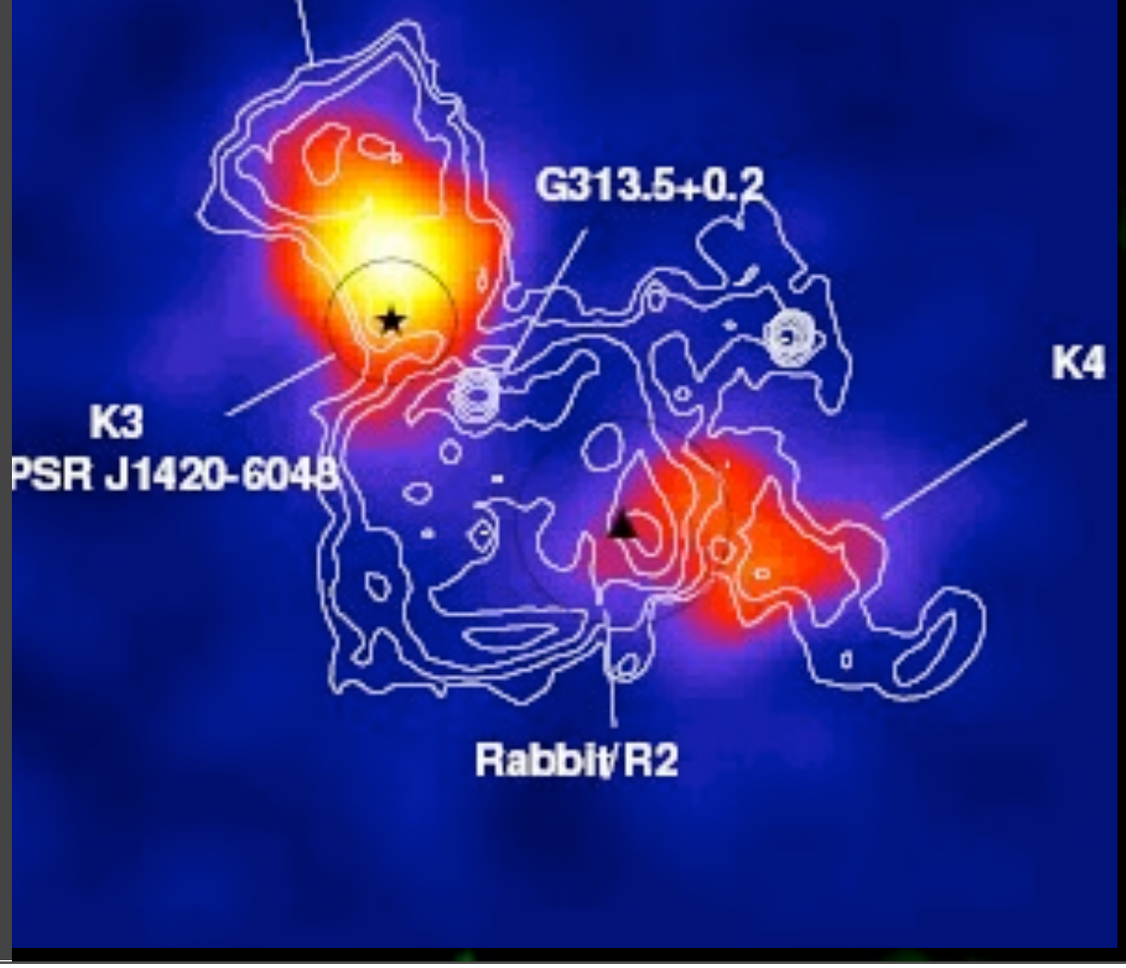
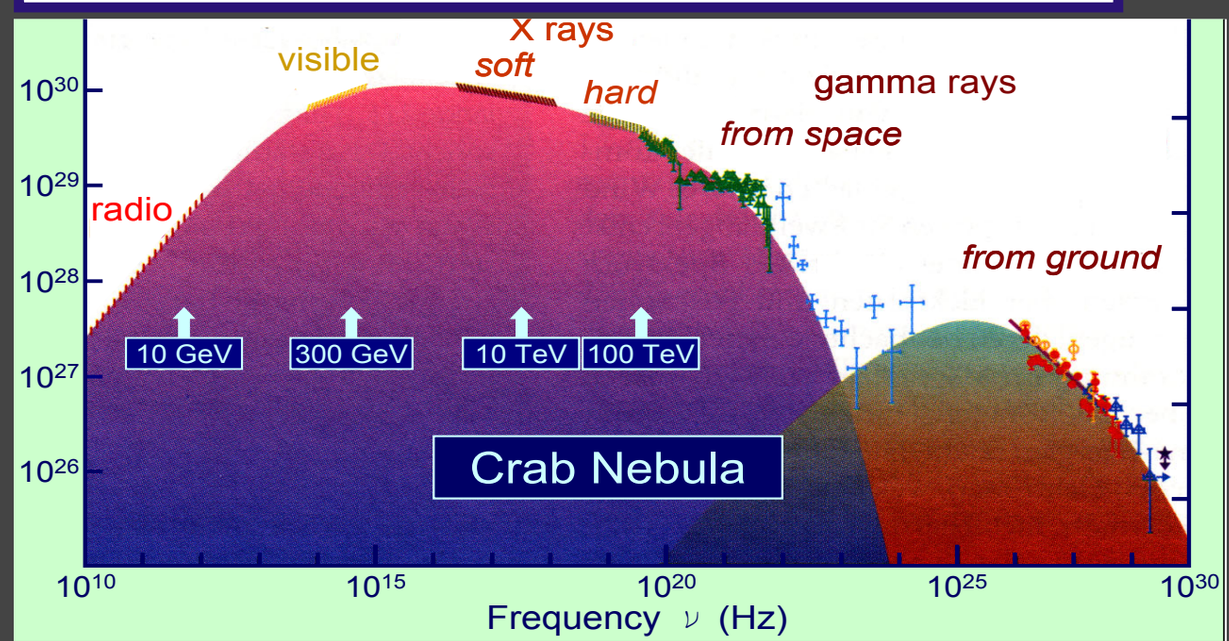
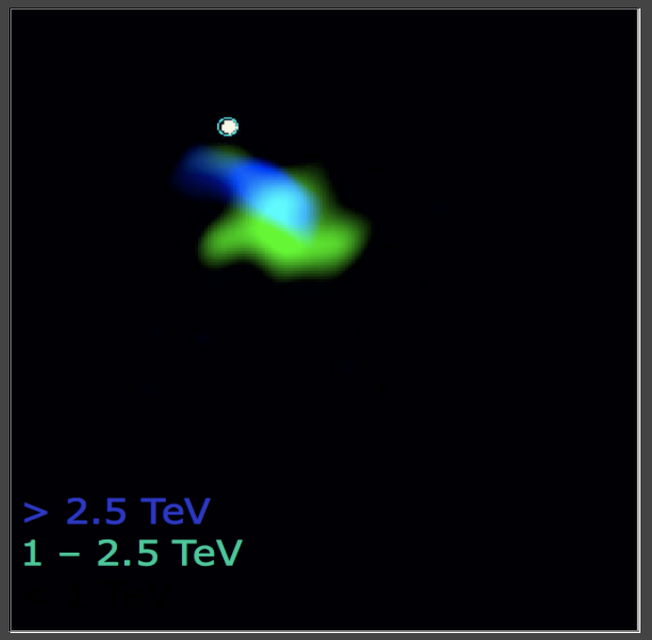
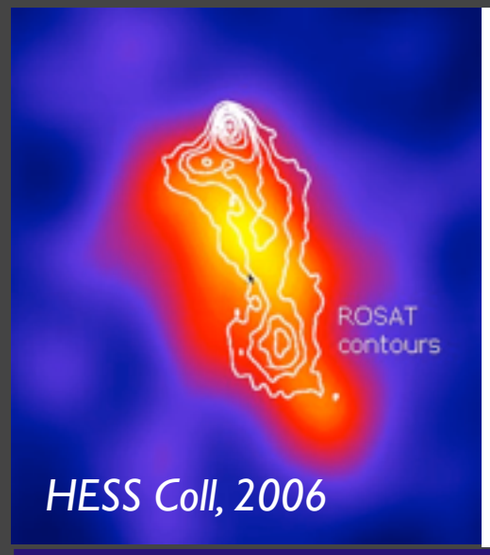
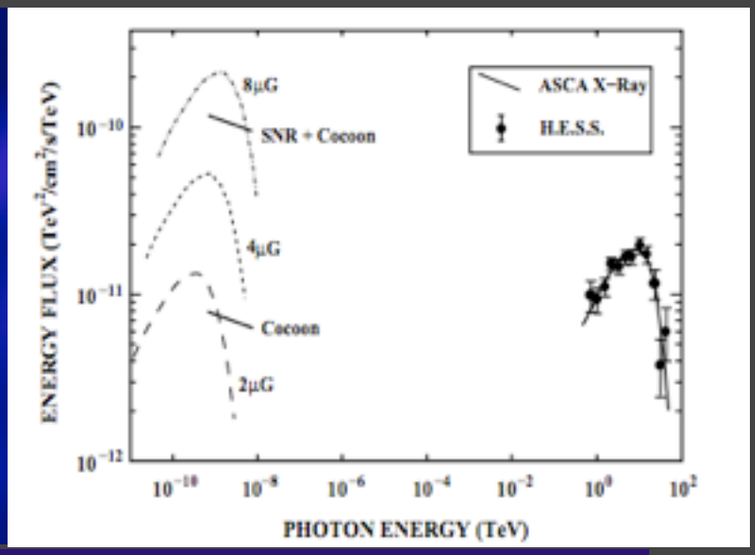




Pulsars Winds







Required Ee to radiate synchrotron keV photons:

$E_e = (70\ \text{TeV})\ B^{-1/2}_{-5}\ E^{1/2}_{\text{keV}}$

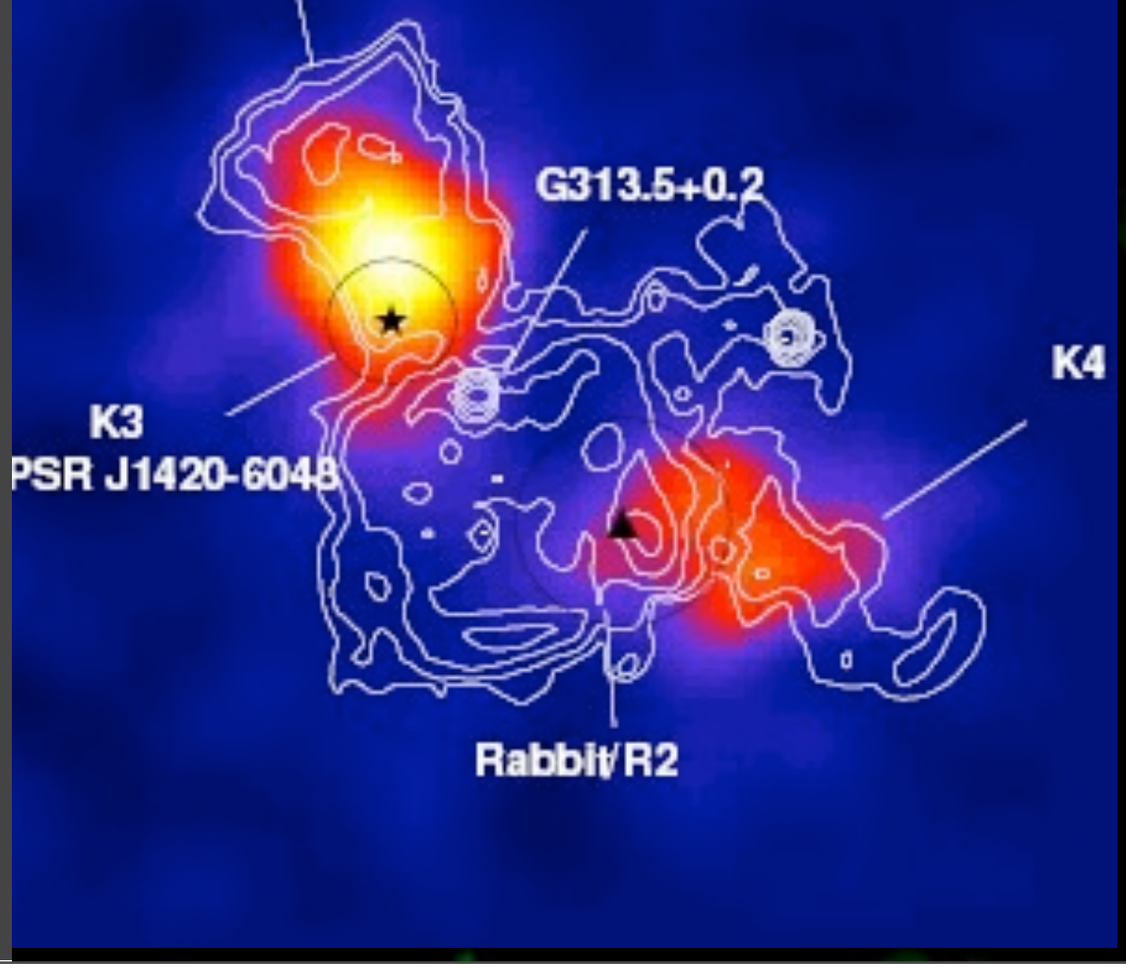
Mean Ee to IC scatter CMB to TeV photons:

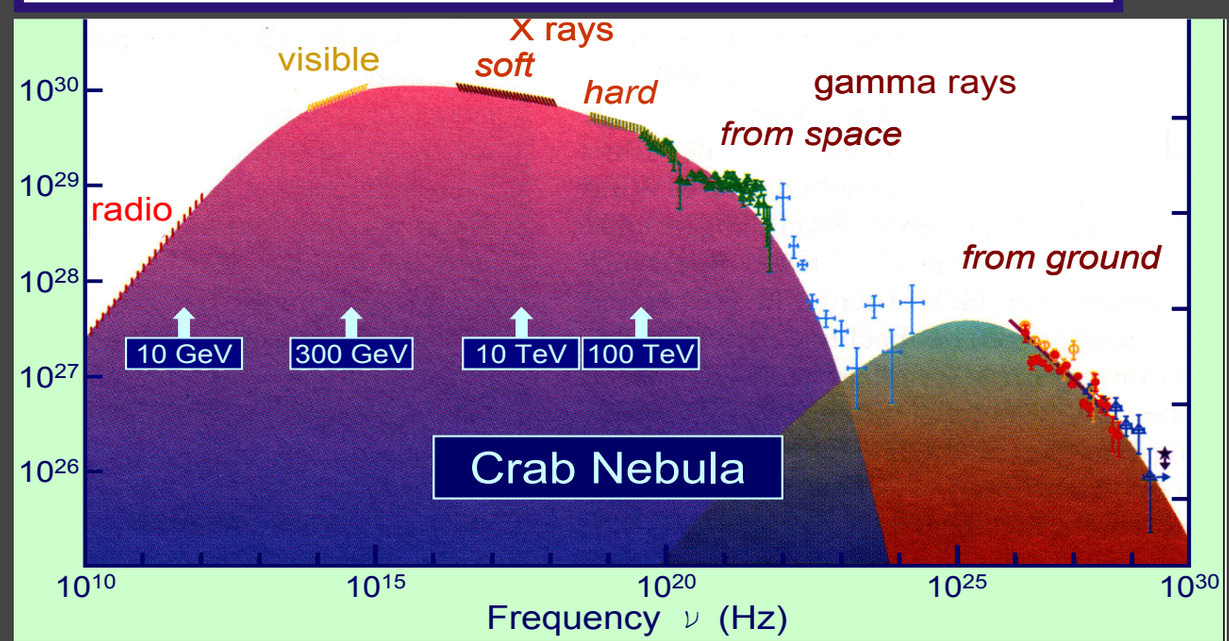
$E_e = (18\ \text{TeV})\ E^{1/2}_{\text{TeV}}$

$(E_{\text{keV}}=0.06\ B_{-5}E_{\text{TeV}})$

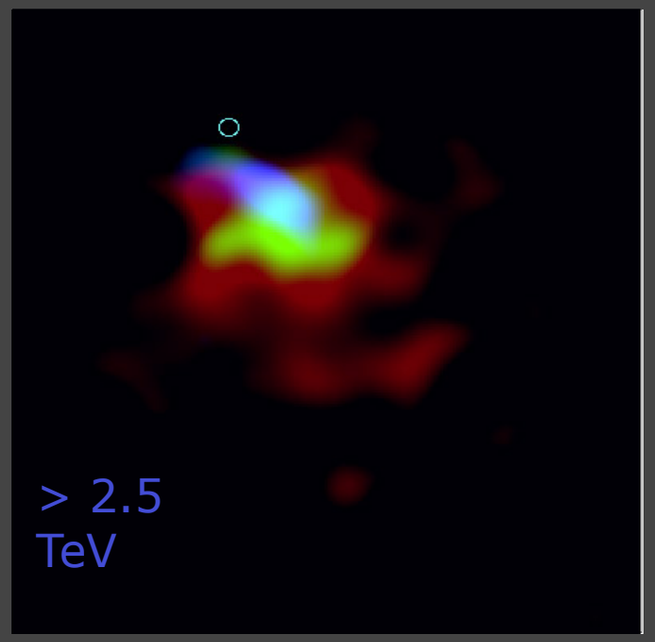
Distribution of the Energy Budget

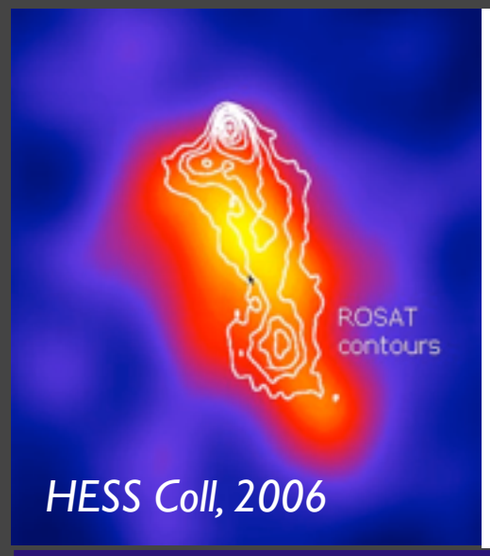
$L_x/L_\gamma \sim B^{-2}$

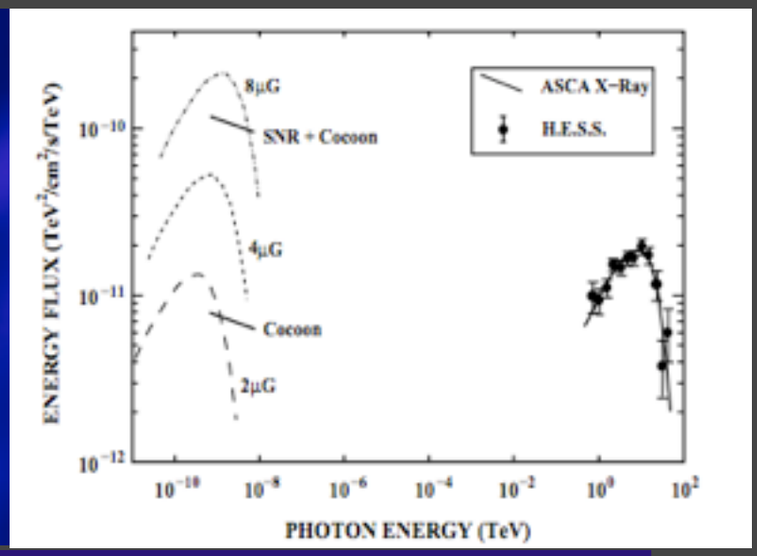




Pulsars Winds







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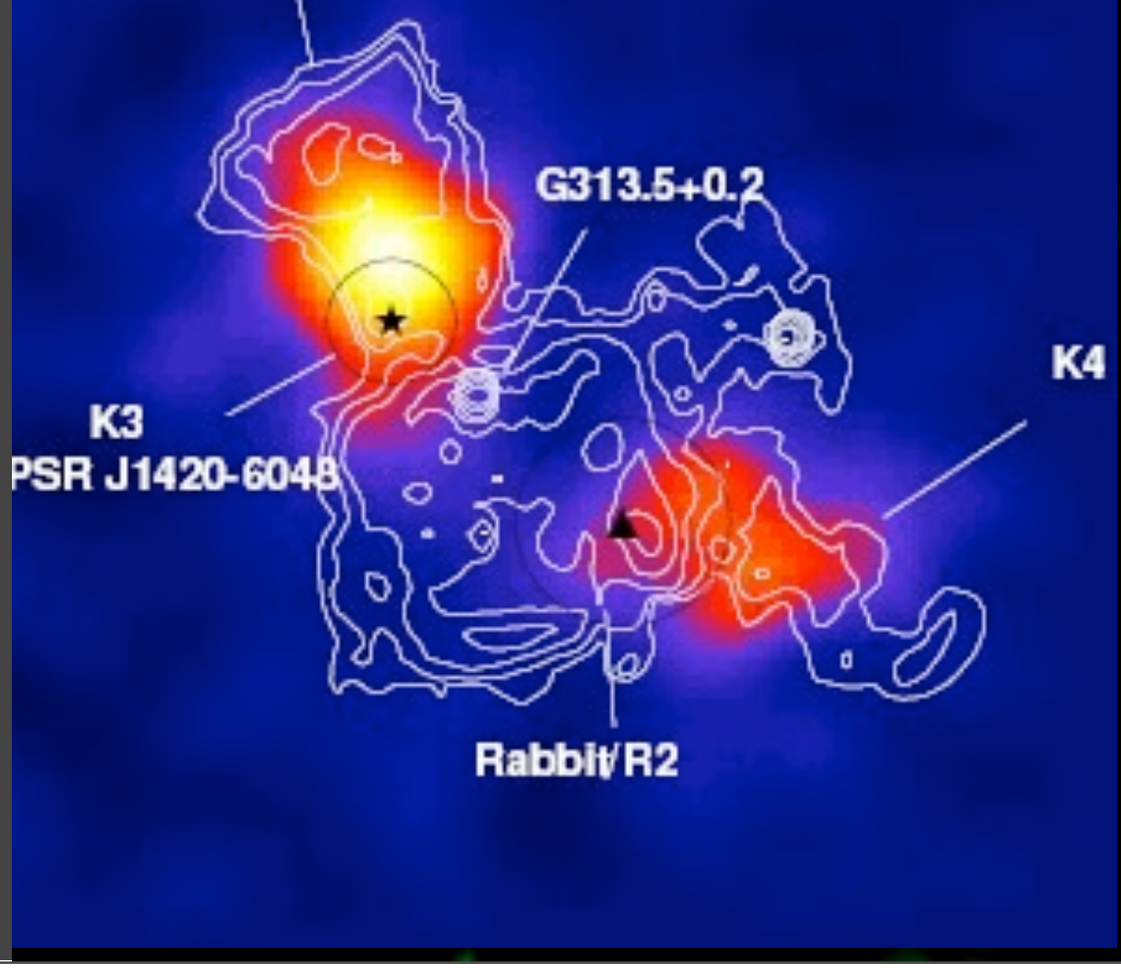
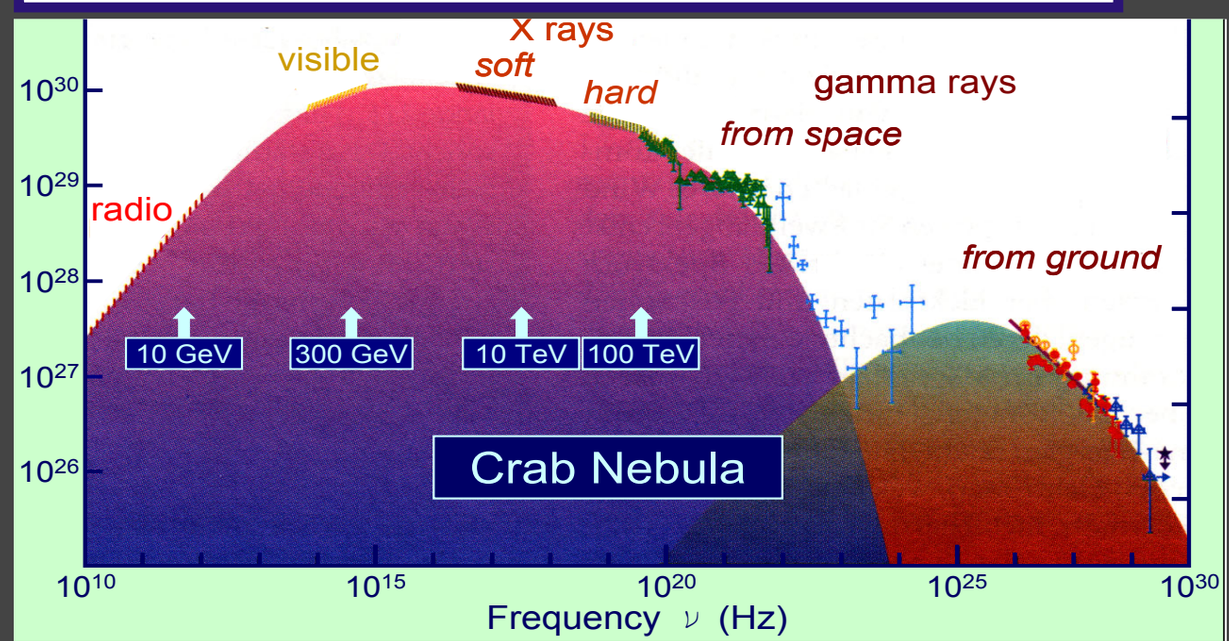
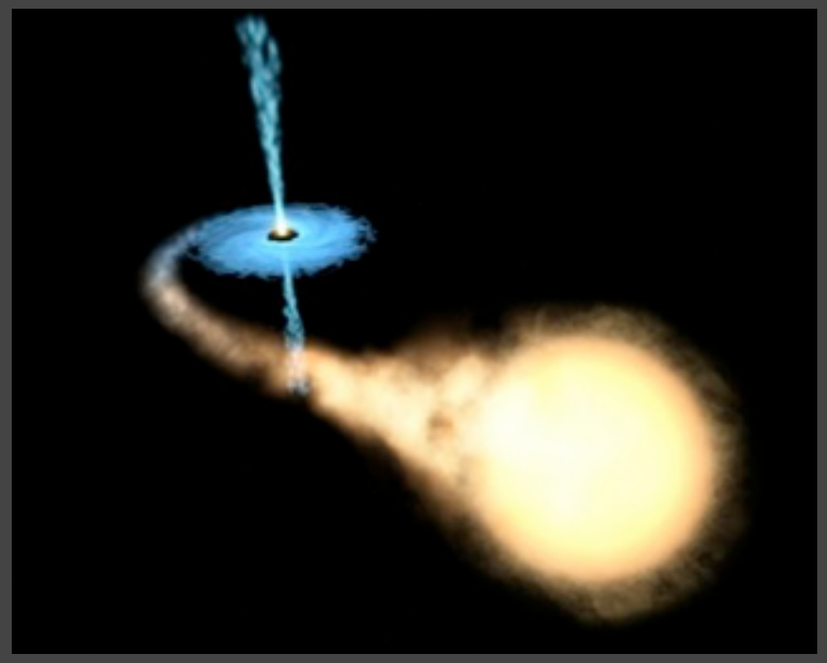
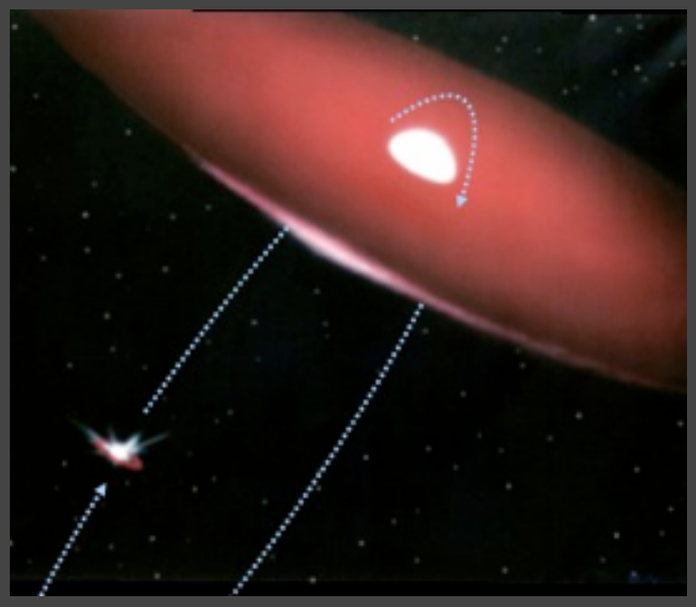




Pulsars in Binary Systems o microquasars

- Compact sources:
  neutron star or black hole + massive companion
- Modulation of the radiation due to their interaction
  Observed in radio, X-ray, HE and VHE
- Difficult to reconcile all observations





	Flux (% Crab)	D (Kpc)	Flux variability (HE/VHE)	Periodic
LSI +61 303	0-15	2	yes/yes	yes (~1 month)
LS 5039	5-15	2.5	yes/yes	yes (~4 days)
PSR B1259-63	0-10	1.5	yes/yes	yes (~3.4 years)
HESS J0632+057	0-3	1.5	no/yes	yes (~300 days)
Cyg X-1	0-10	2.2	yes/yes(?)	no
1FGL J1018.6-589	5-15	5	yes/?	yes (~16 days)

Pulsars in Binary Systems o microquasars

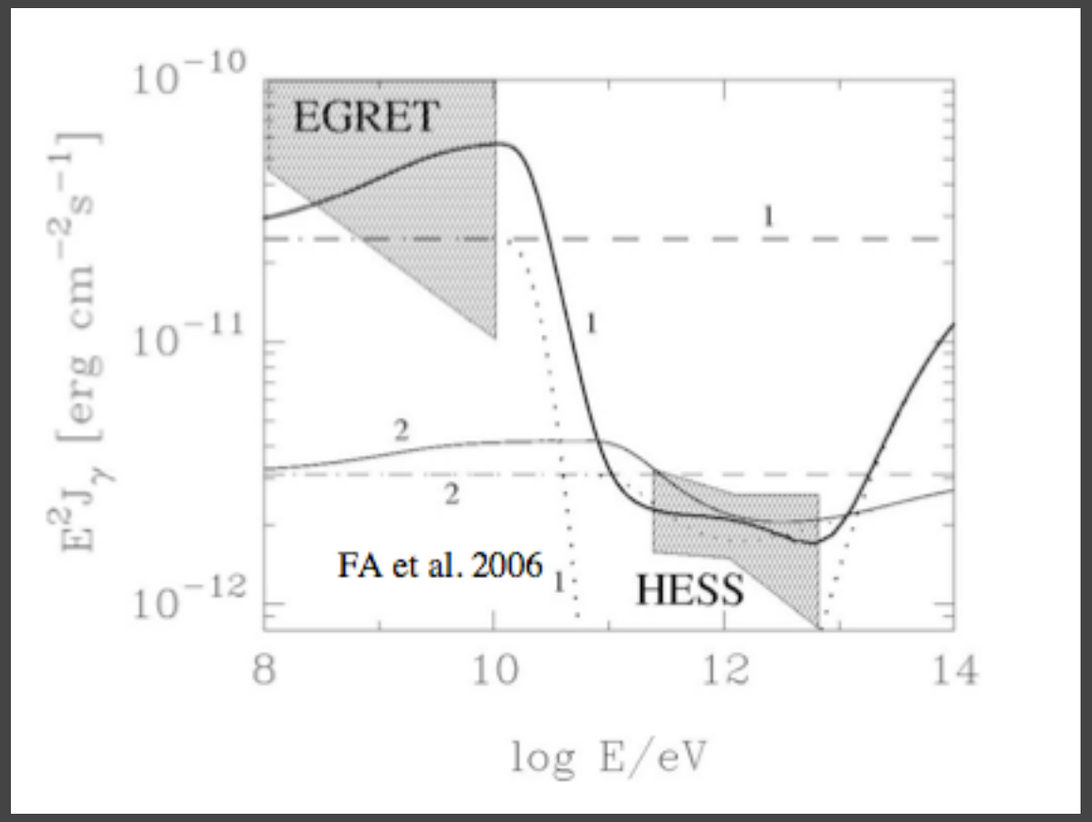
—Can they produce neutrinos?

If the TeV gamma-ray detected is produced within the binary system R<12 cm

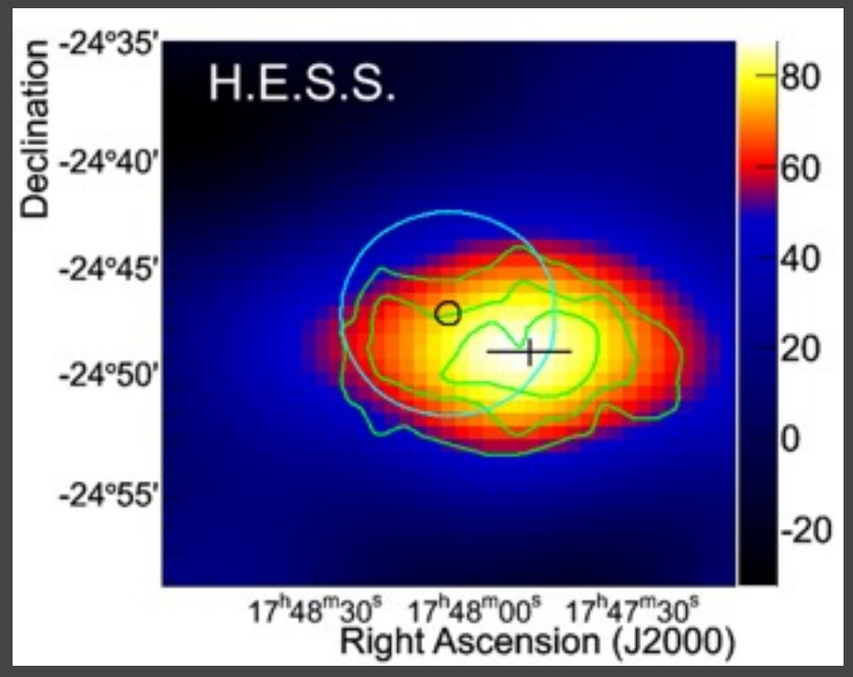
- Severe absorption of >100 GeV gamma-rays
  (γ+starlight→e+e-)
  Up to a factor of 10 to 100 higher luminosity

- Severe radiative losses
  Acceleration of electron to multi-TeV difficult

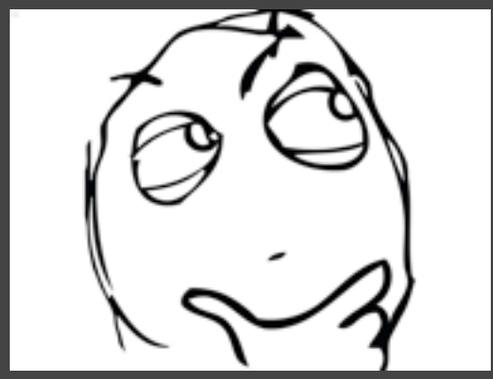
Consequence: The origin of the gamma-ray emission is hadronic and neutrino fluxes should be high

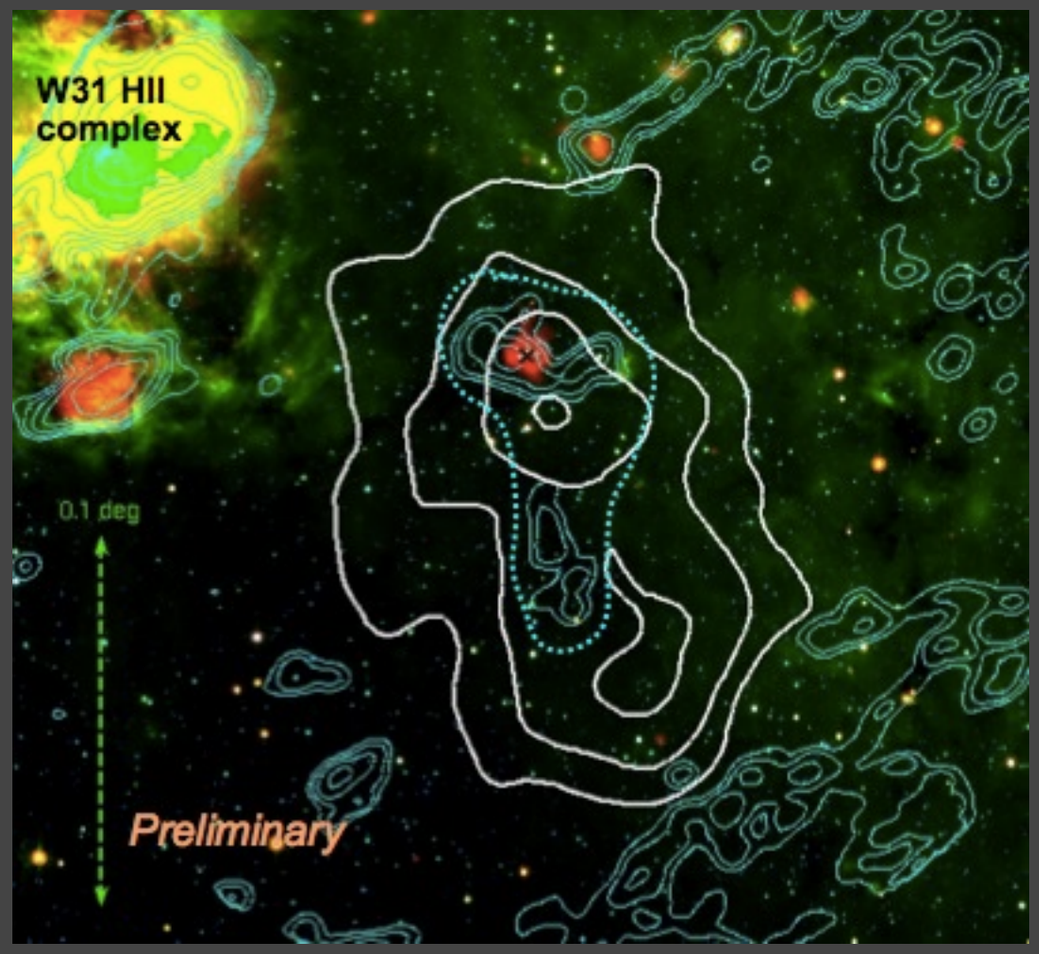


Other type of accelerators?



globular clusters

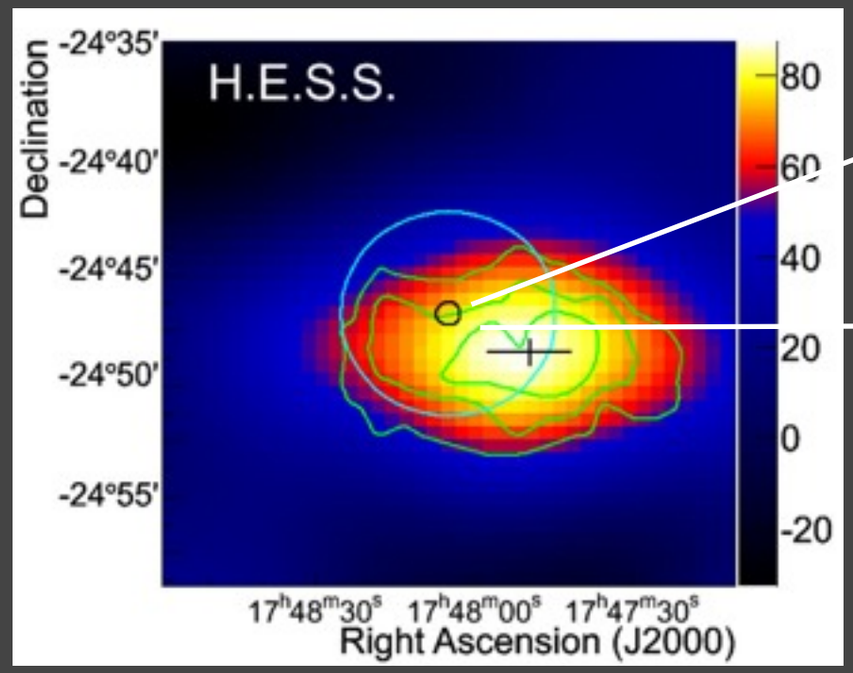




strong stellar winds

magnetars

Other type of accelerators?



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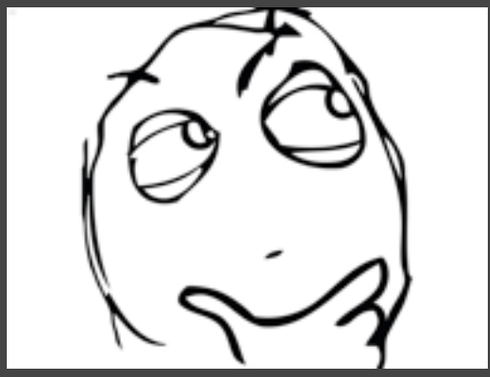
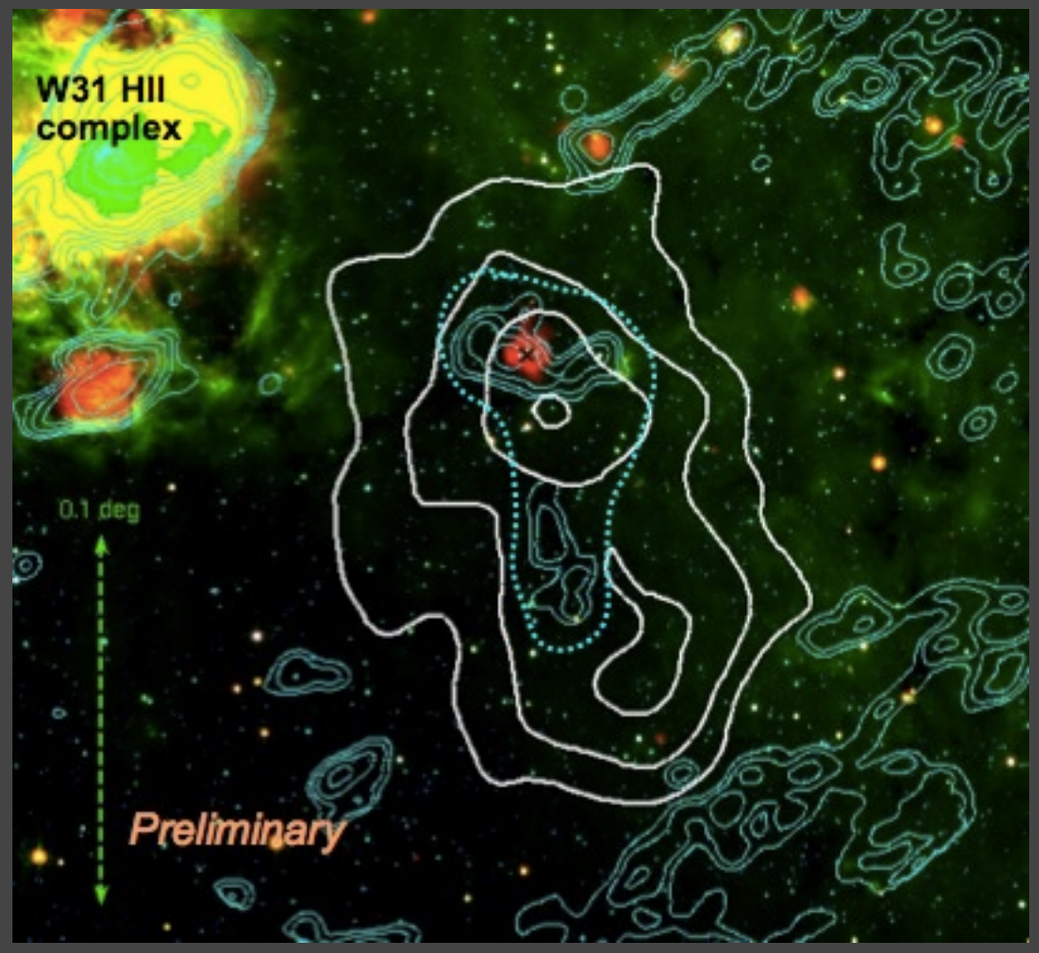


strong stellar winds

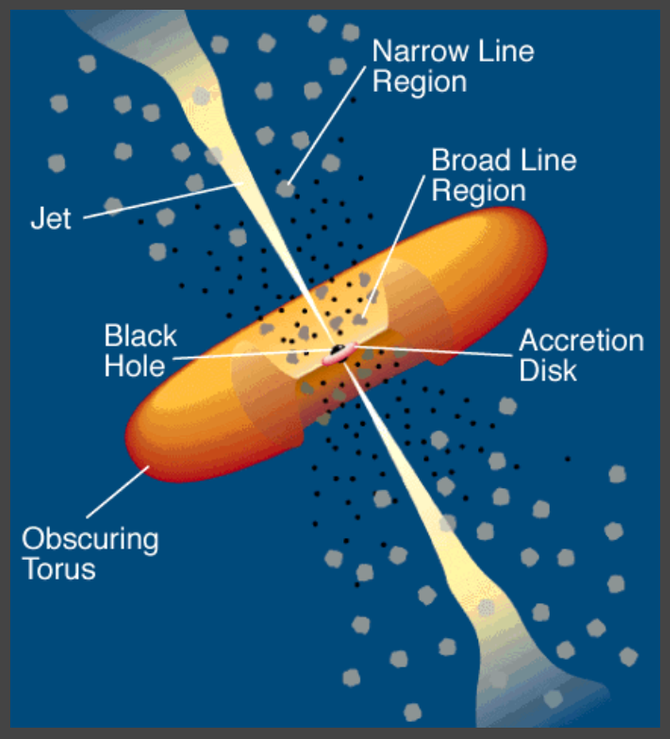


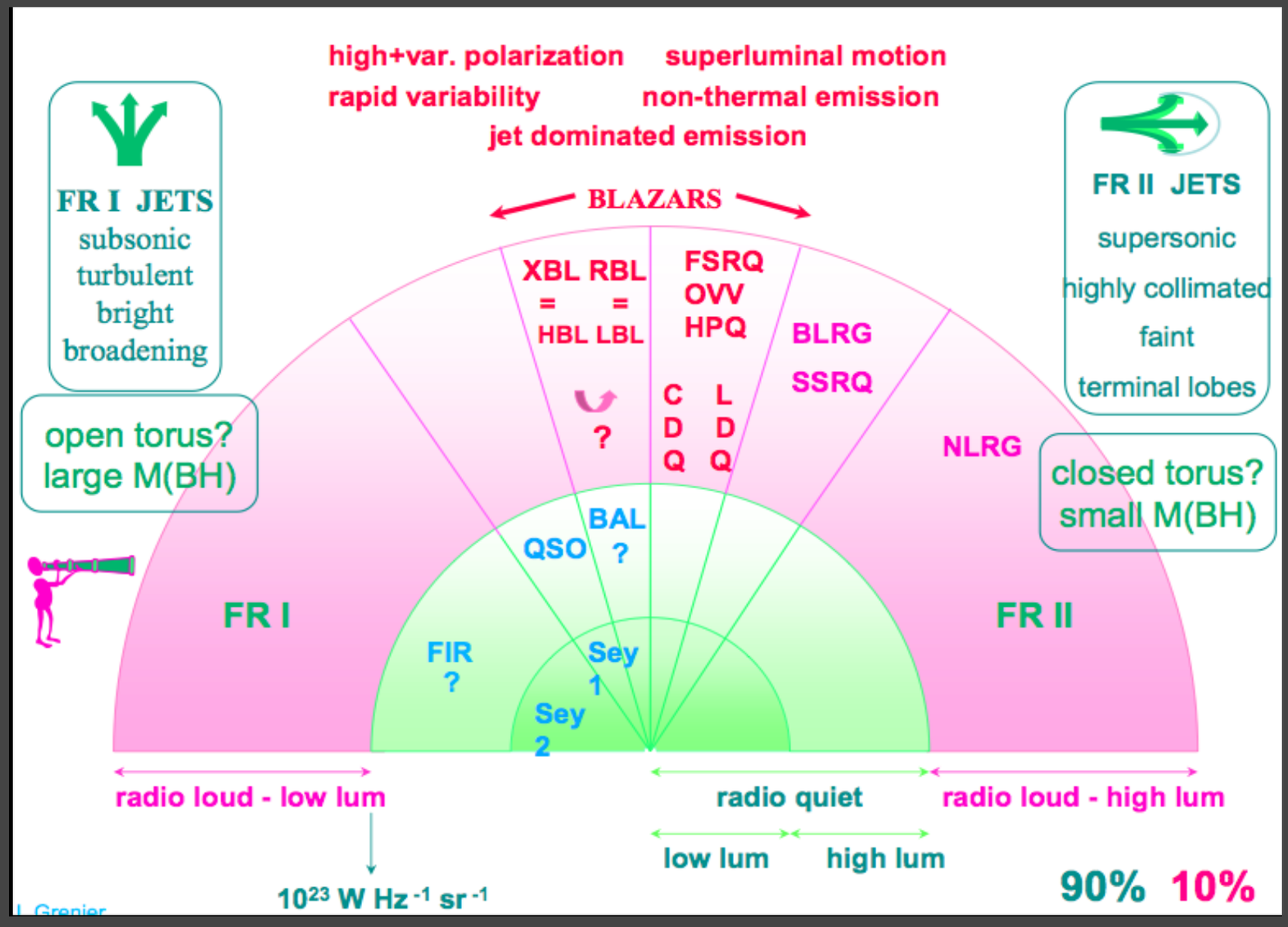
magnetars

OUTSIDE OUR GALAXY

RELATIVIST JETS IN ACTIVE GALACTIC NUCLEUS GALAXIES

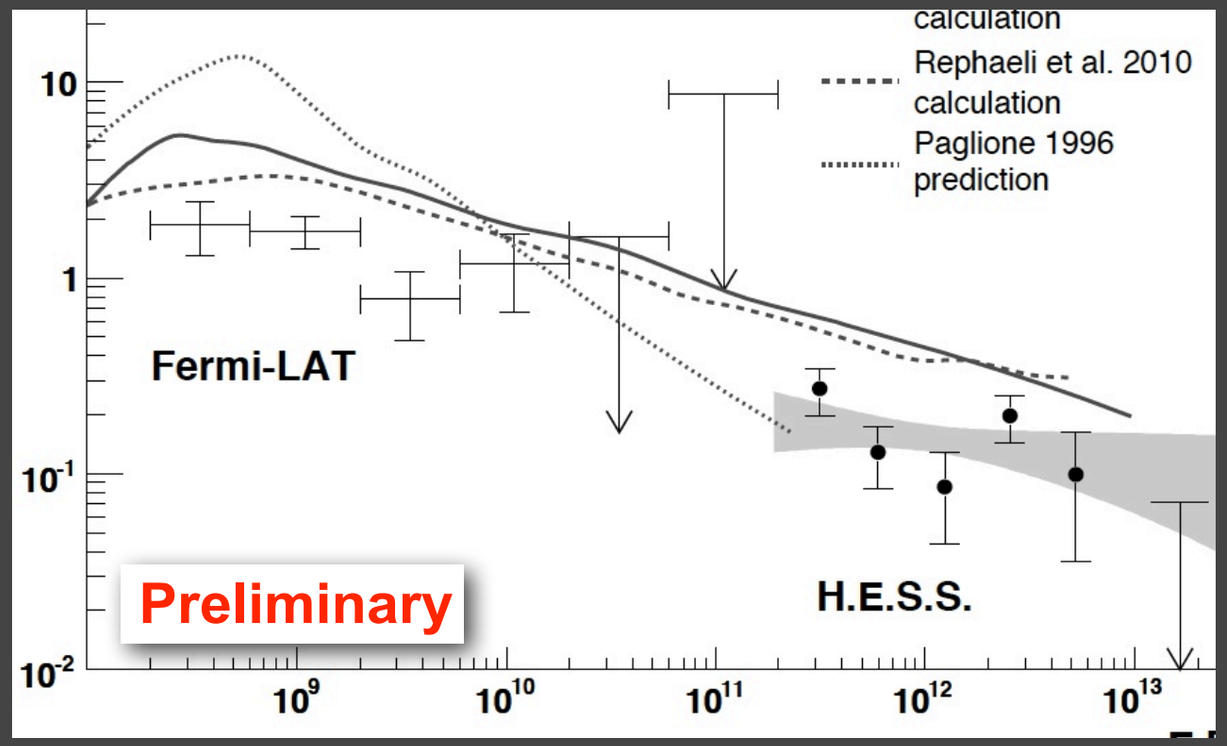
- Very far away objects
- Blazars (AGNs)
- Clusters of Galaxies
- Gamma-ray Burst
- EBL studies

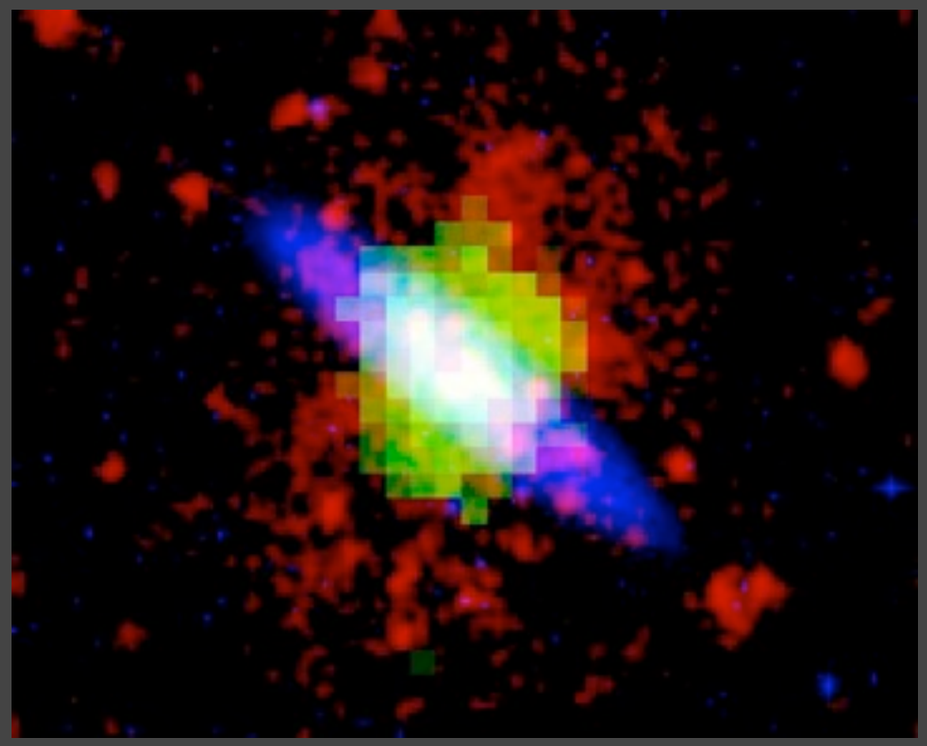




RELATIVIST JETS IN ACTIVE GALACTIC NUCLEUS GALAXIES

Starburst Galaxy: Cosmic rays? but then, where are the neutrinos?





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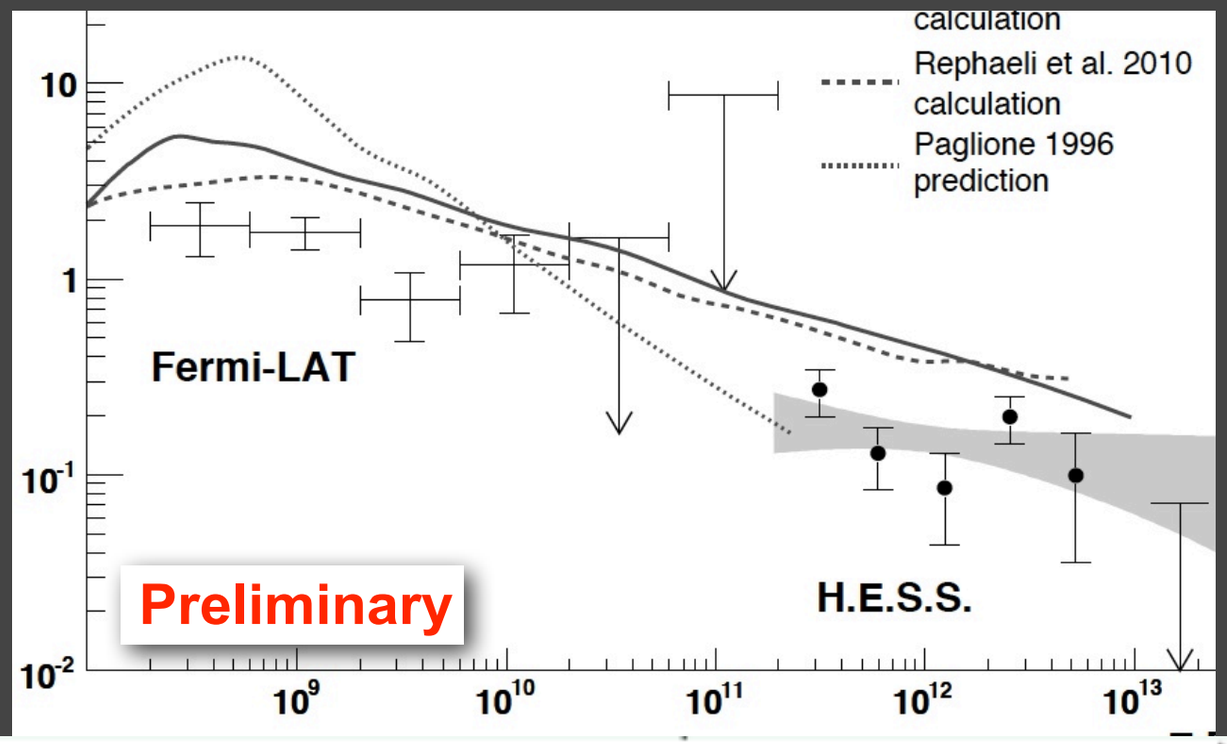

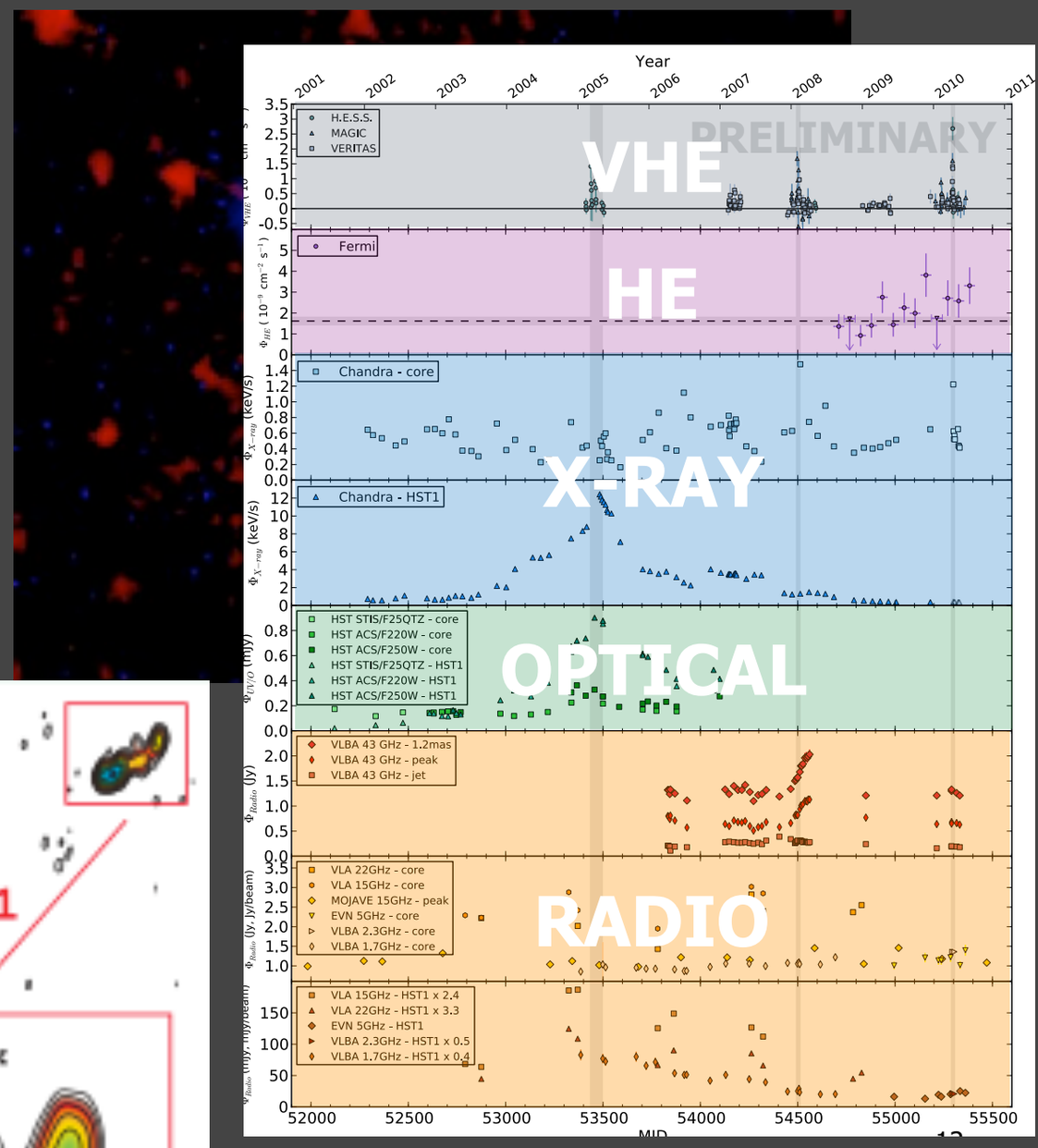

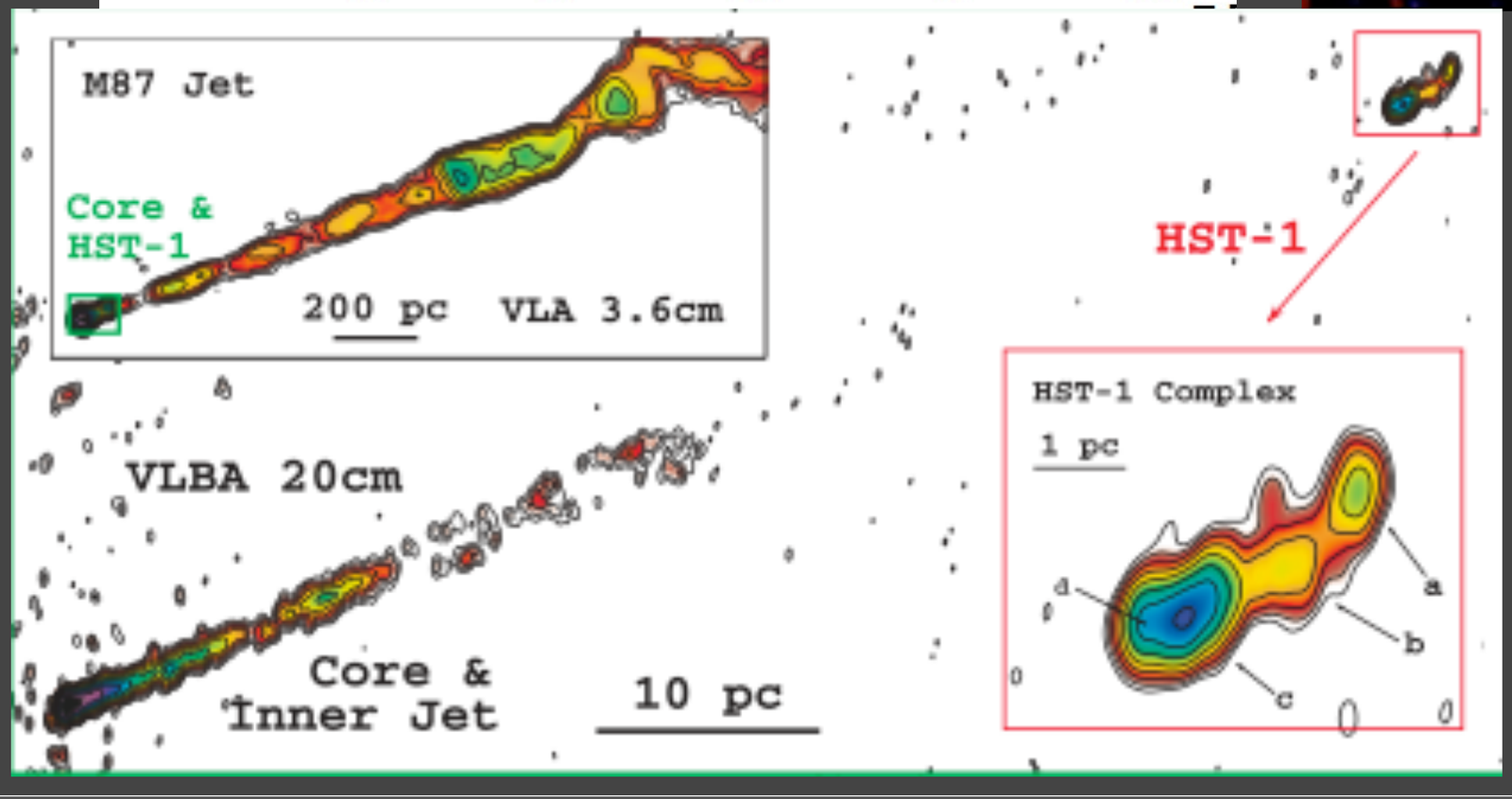

Radio Galaxies
Where is the acceleration happening?

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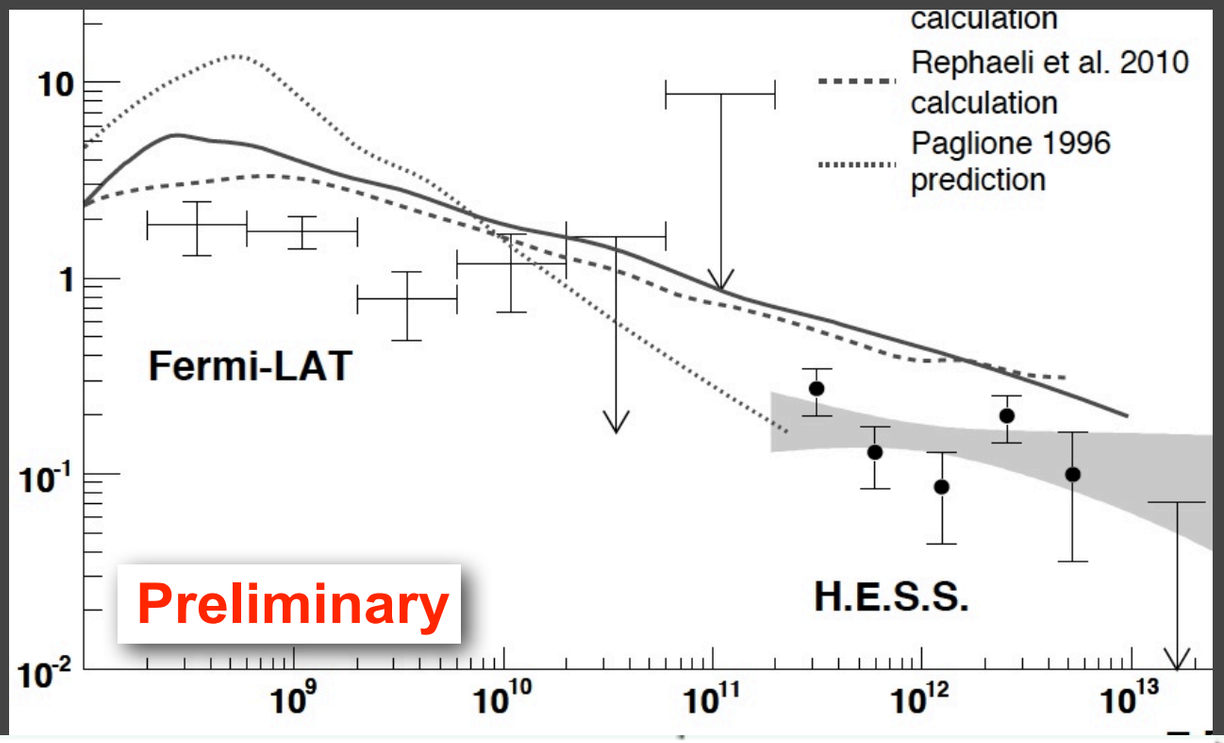
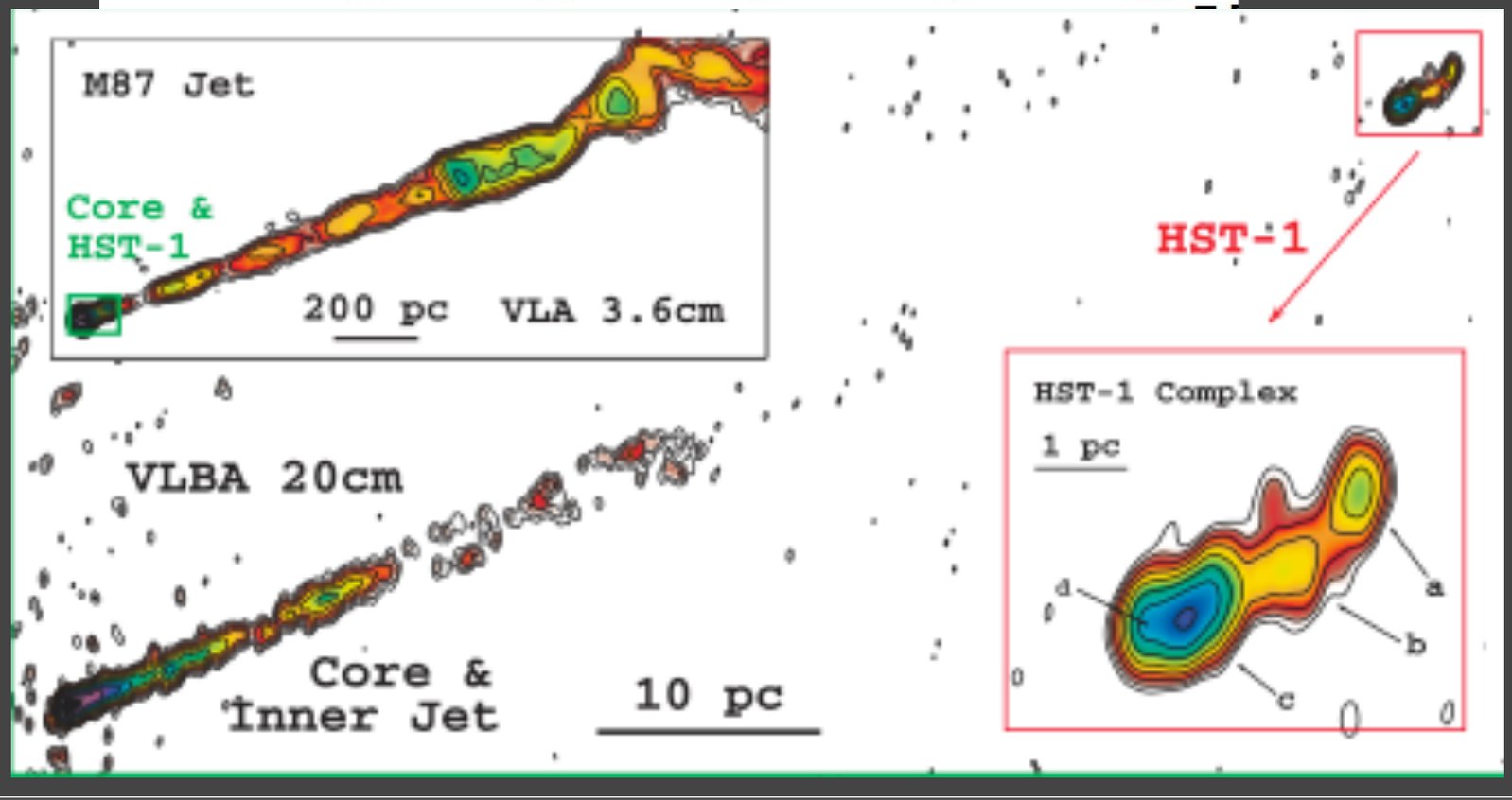
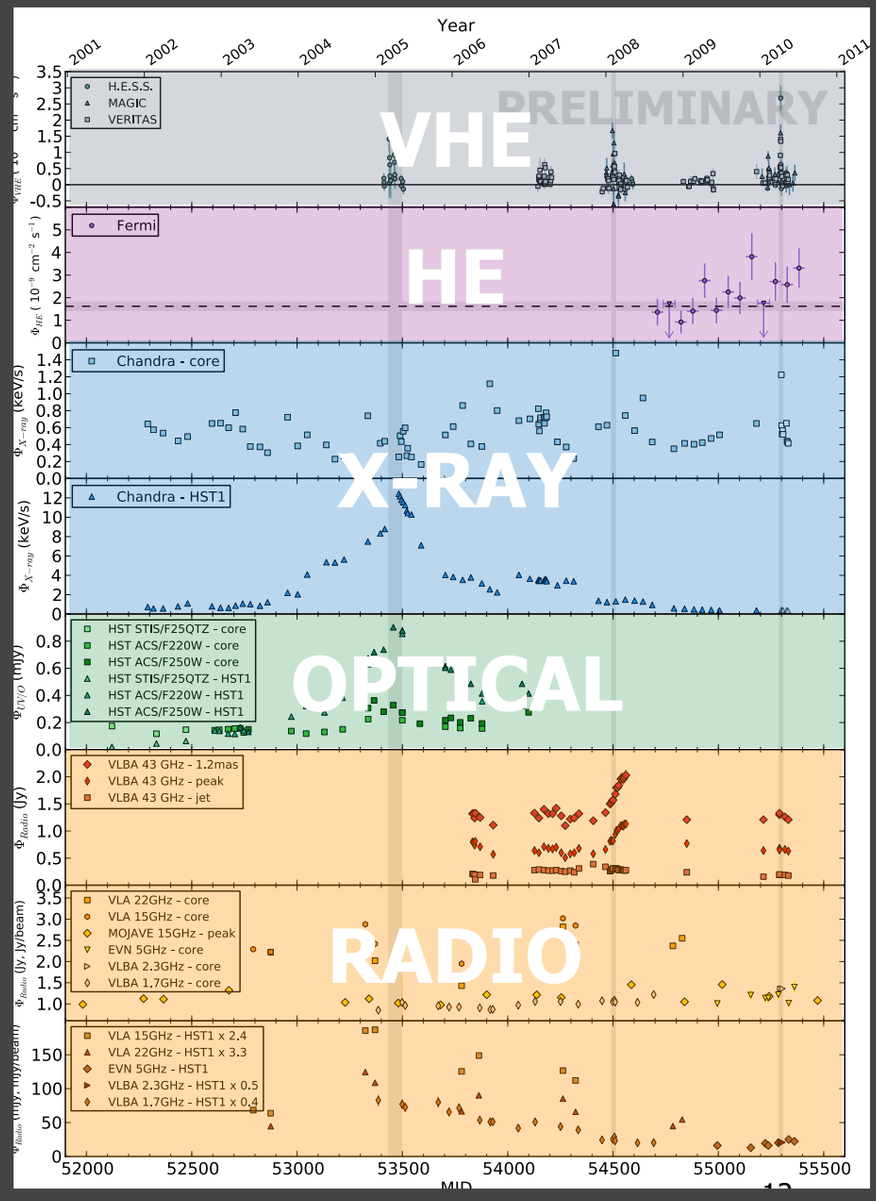
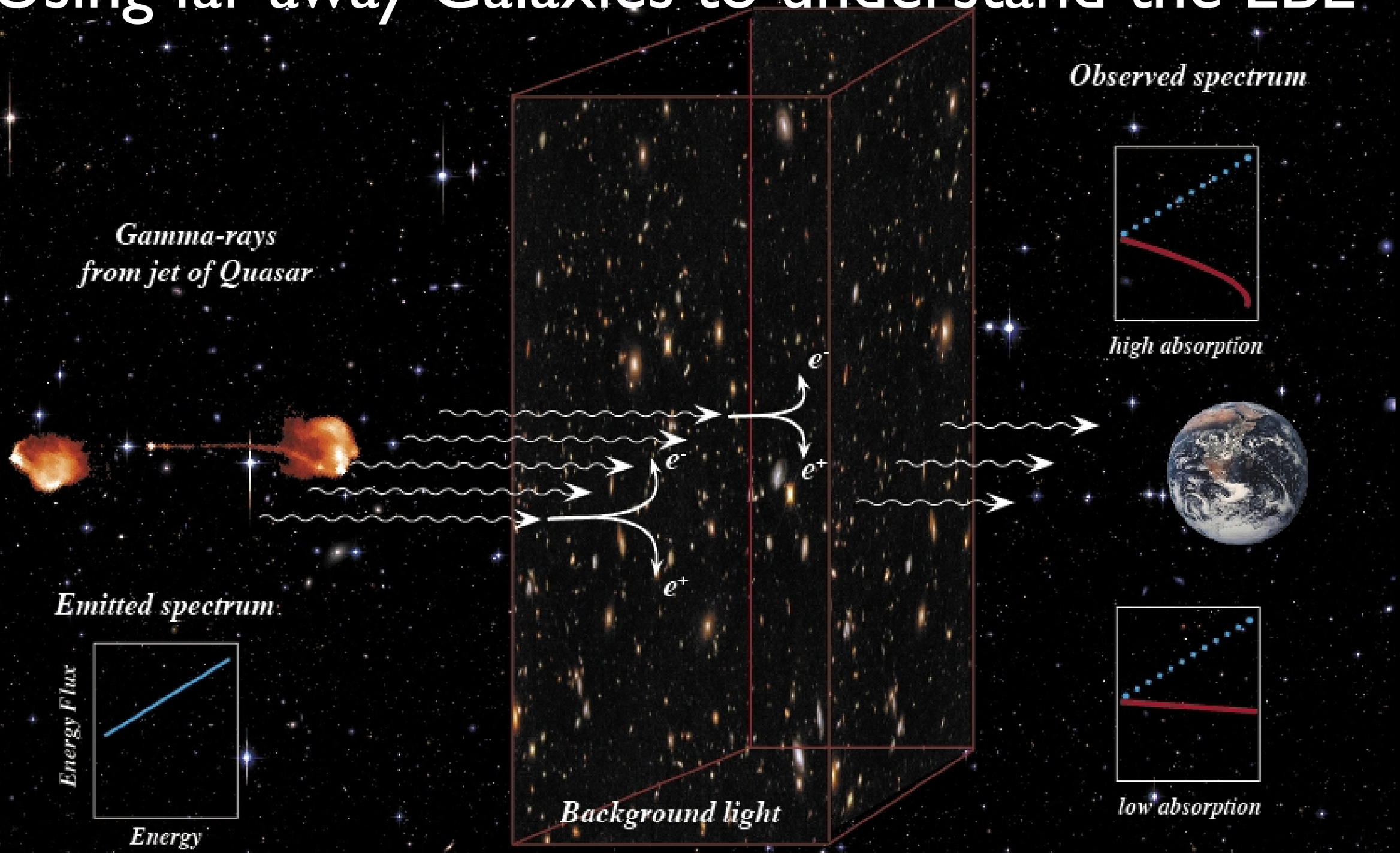






Radio Galaxies
Where is the acceleration happening?

Using far-away Galaxies to understand the EBL



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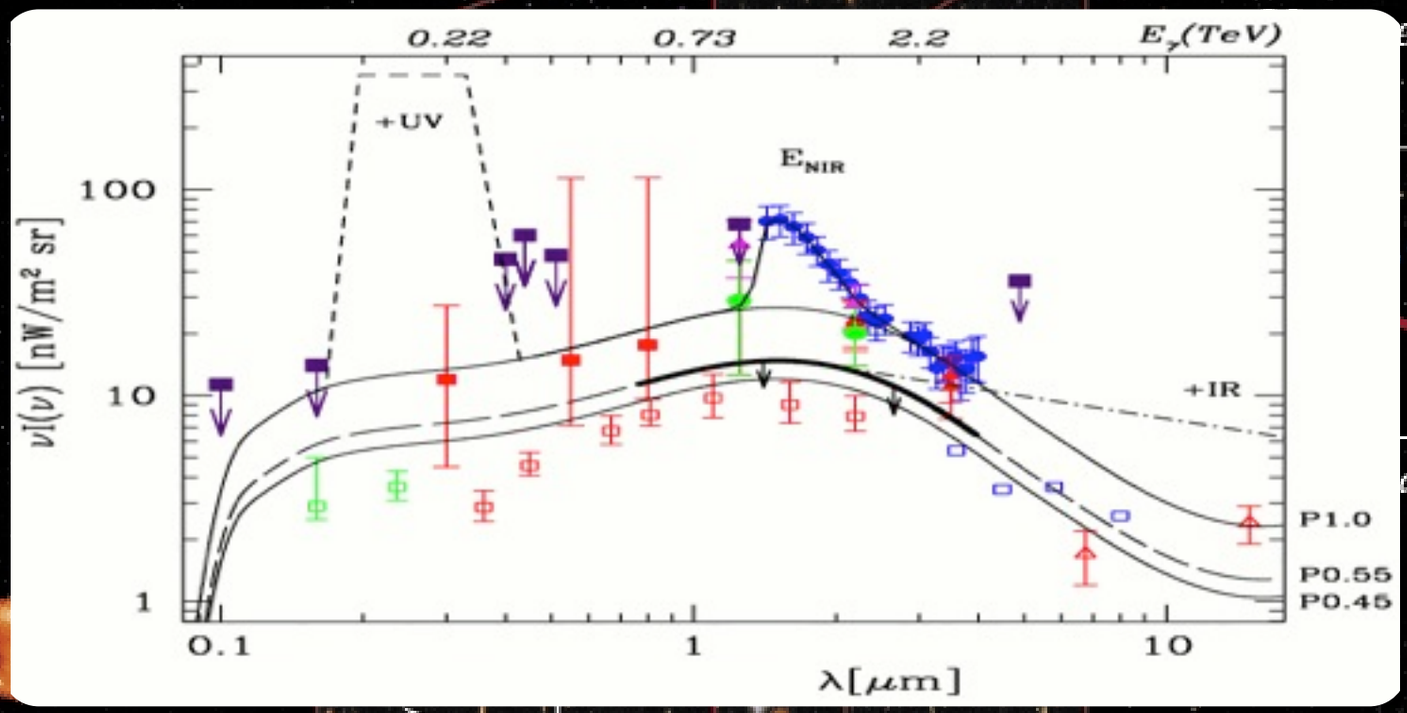
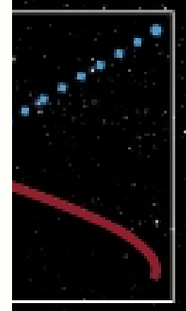
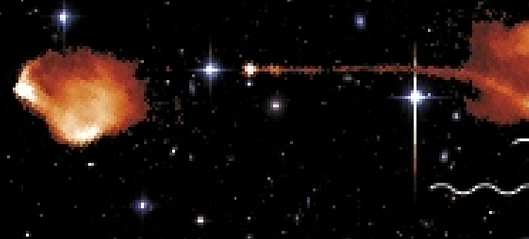


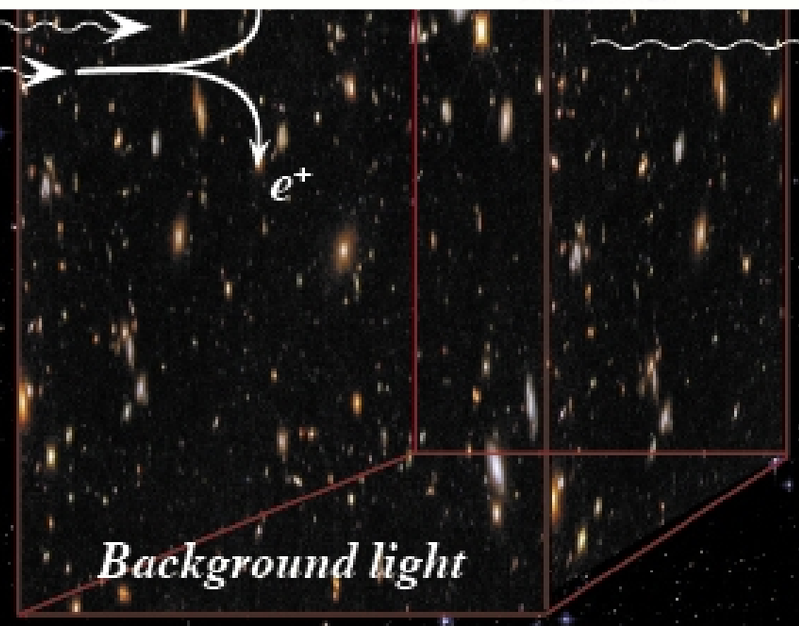
Gamma-rays from jet of Quasar

ed spectrum

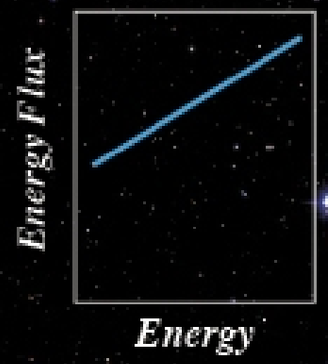


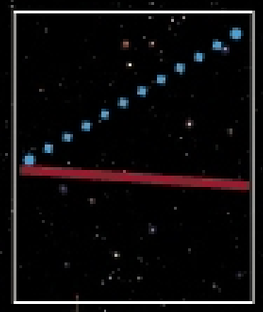
absorption





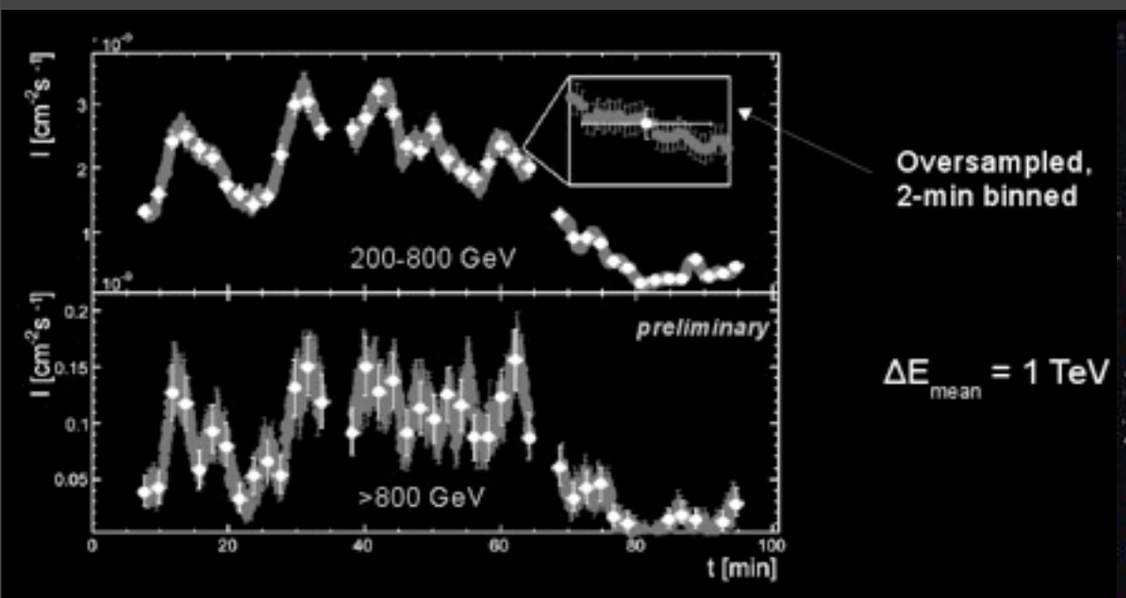
Emitted spectrum

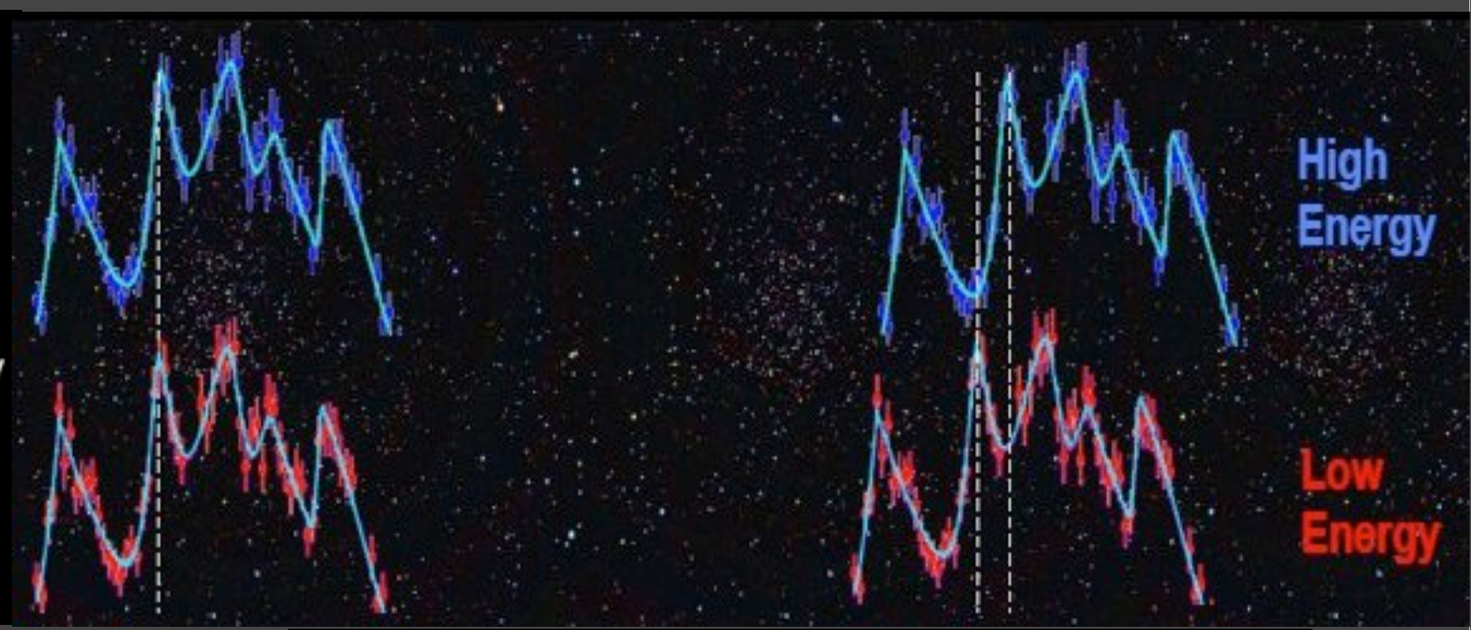




low absorption

Probing quantum gravity



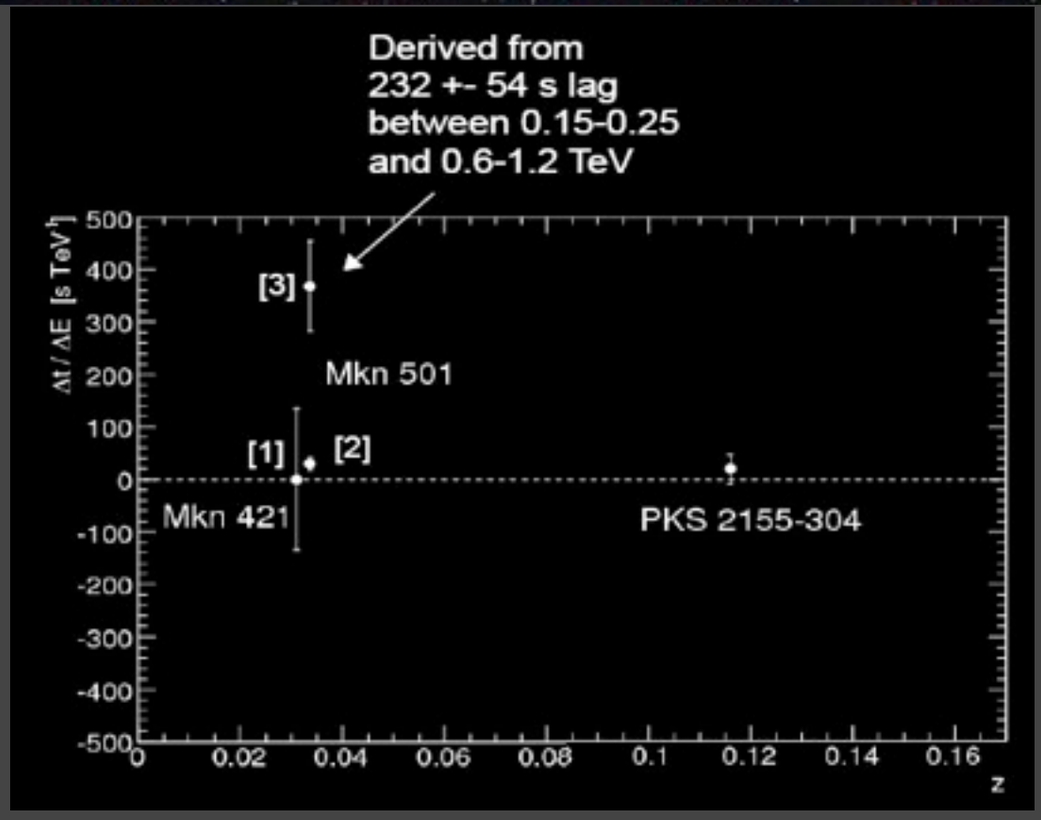


Best measured risetime: 173 +- 28 s

Two orders of magnitude brighter than typical state

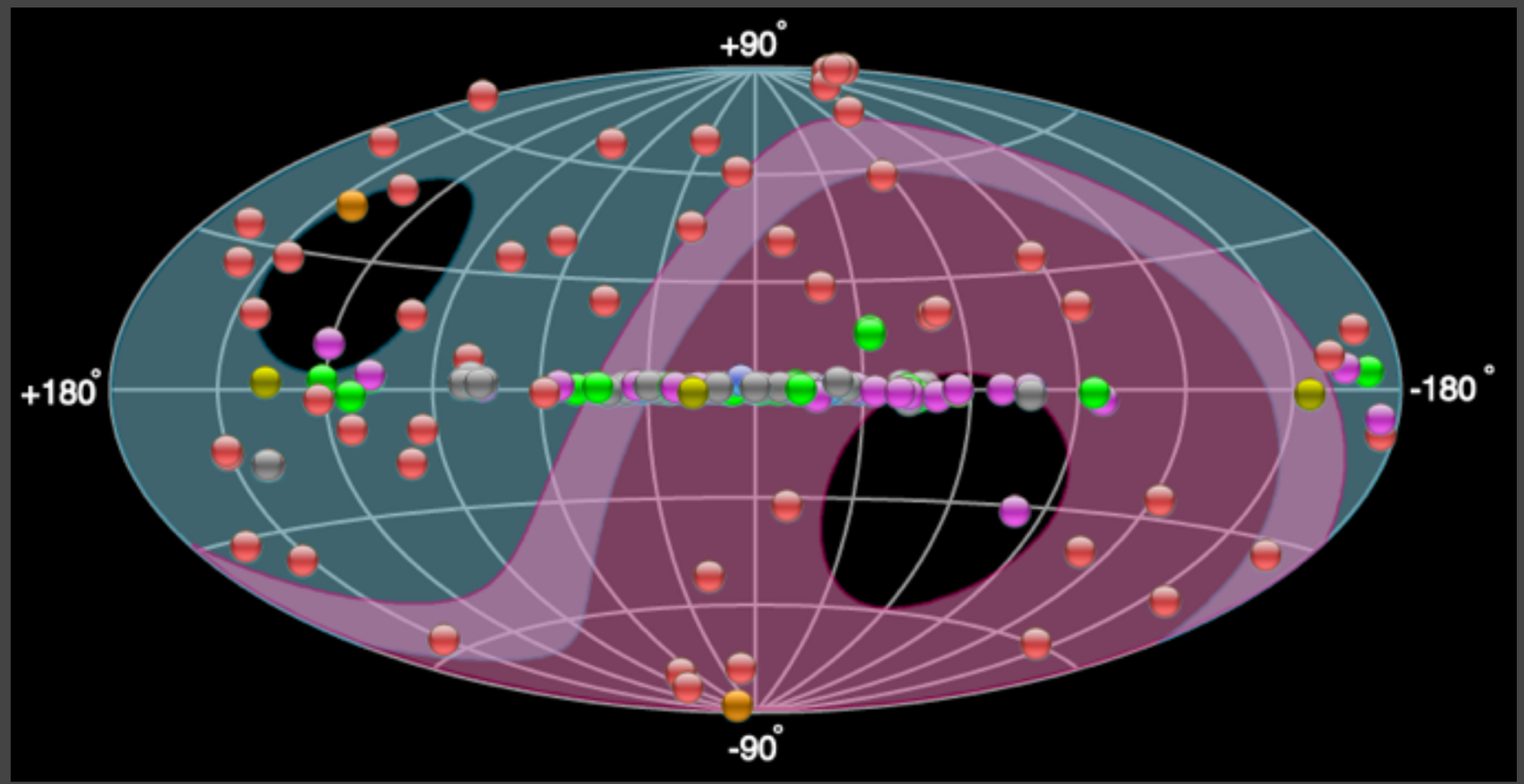
Quantum Gravitiy models predicted energy dependence of the speed of light

$$c' = c\left(1 \pm \xi\frac{E}{E_{\mathrm{P}}} \pm \zeta^2\frac{E^2}{E_{\mathrm{P}}^2}\right)$$



Conclusions

- New and exciting results in the recent times
- Astro-particle physics provide a window to the most violent and energetic events in the Universe
- Gamma-ray astronomy has been stablished as a discipline on its own
- Neutrino astronomy shows very promising results
- Particle detectors like Auger reveals the ultra-high energy particles



F. Aharonian, Saas-Fee Course 2010
Aspera network 2013