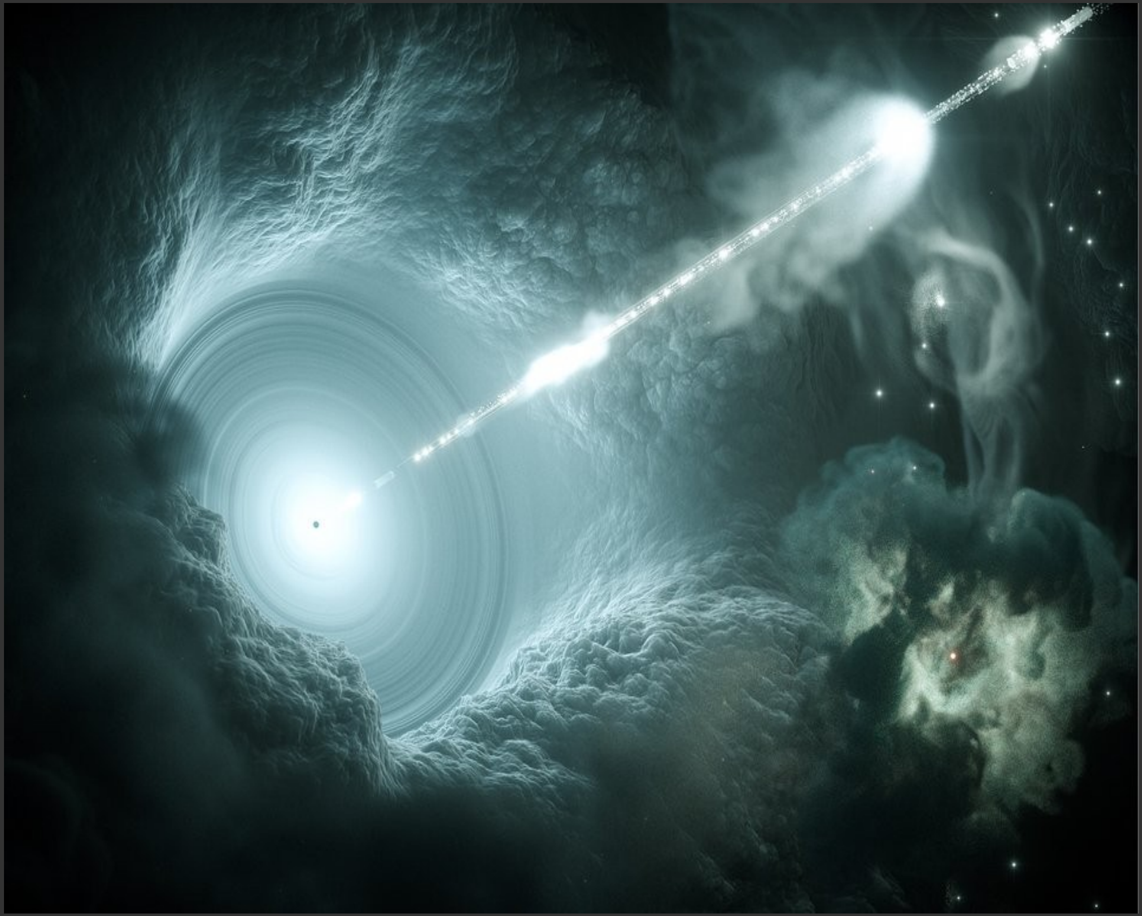
Astronomia de Multicores e Multimensagens



Juan Carlos Rodríguez-Ramírez

Astronomia ao meio dia

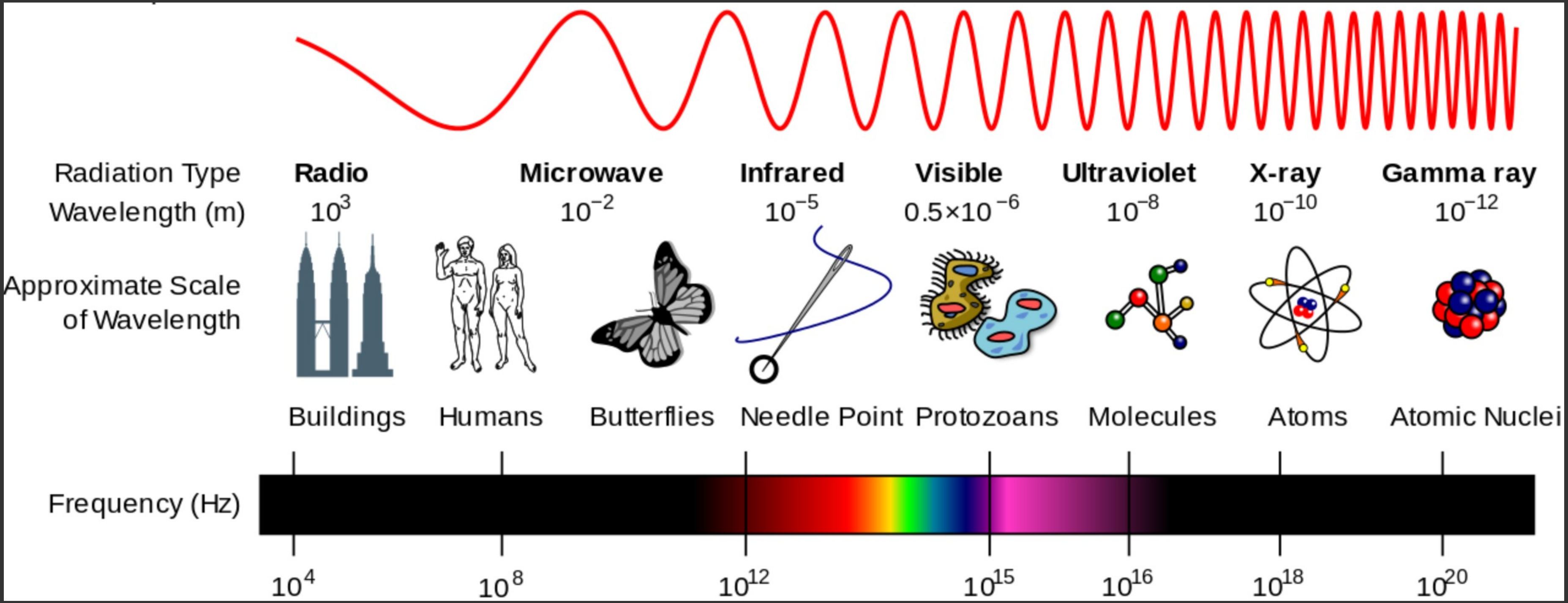
Instituto de Astonomia Geofísica e Ciências Atmosféricas
Universidade de São Paulo
IAG-USP

Outubro, 2019

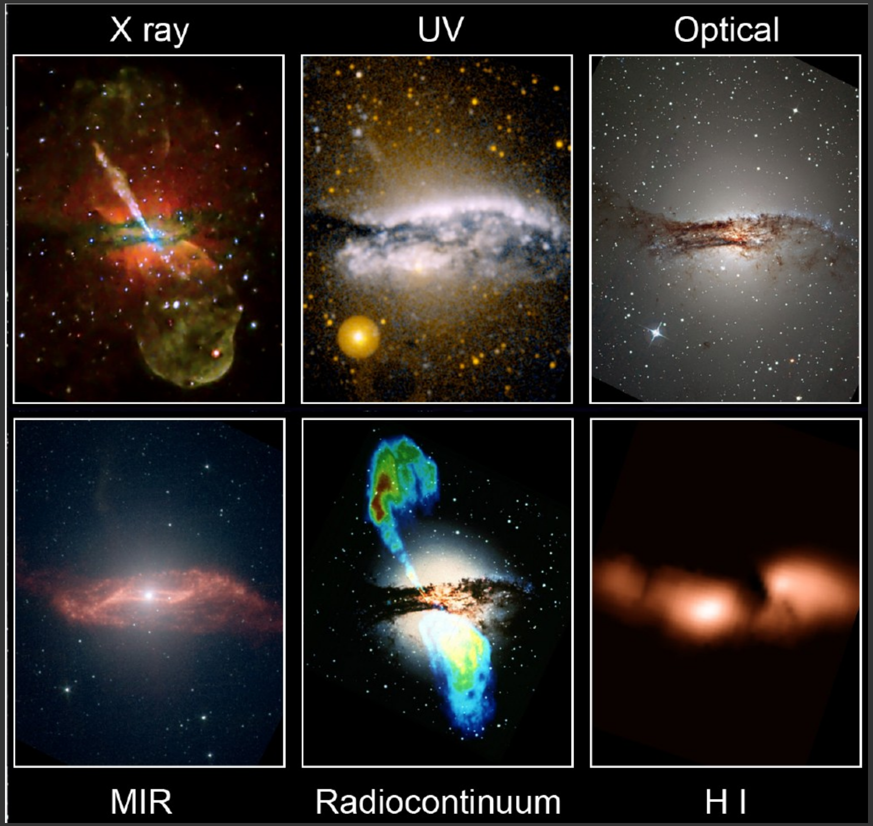
OVERVIEW

- Introduction
- Detection of very high energy radiation and neutrinos
- Particle acceleration and non-thermal emission
- CR emission from BH systems
- Conclusions

Electromagnetic Spectrum

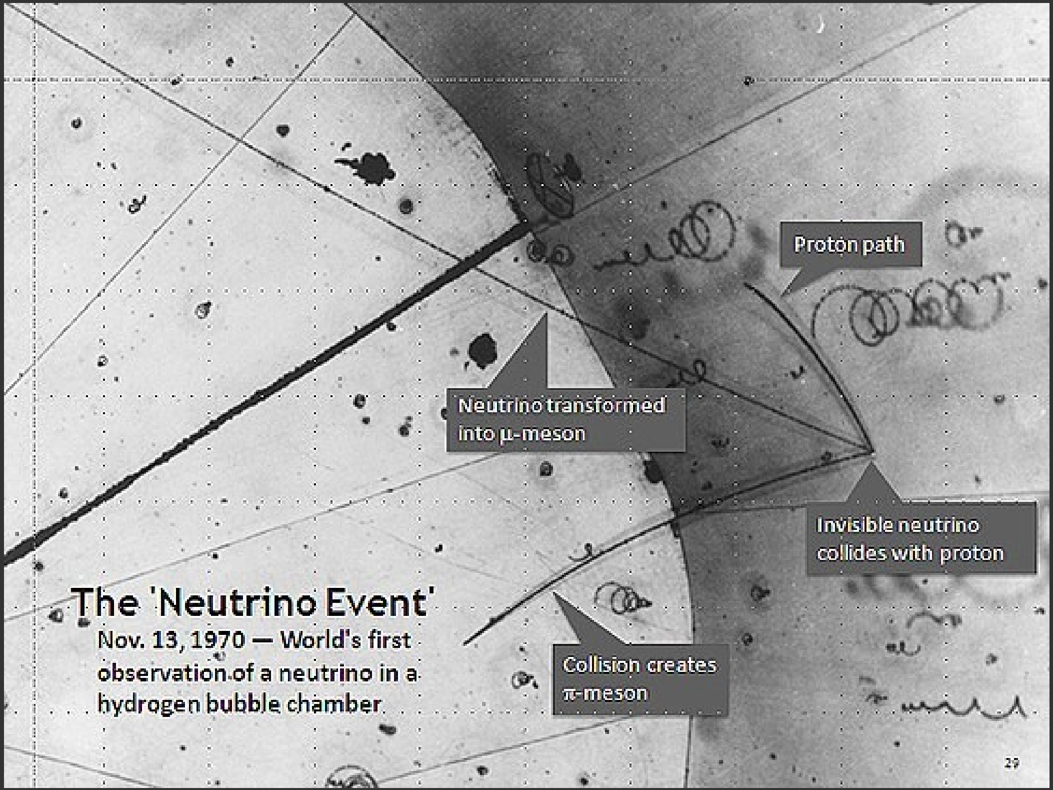


Unvailing different information by *looking* at different wavelengths

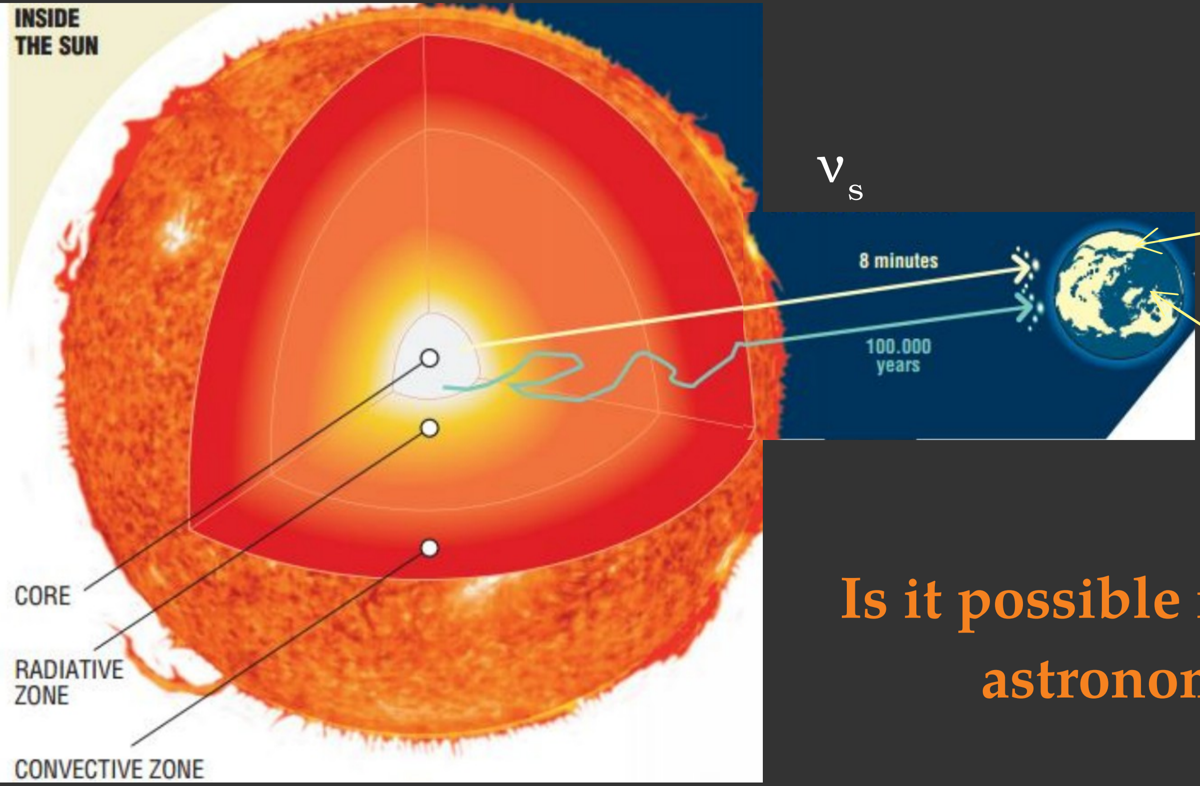


Centaurus A

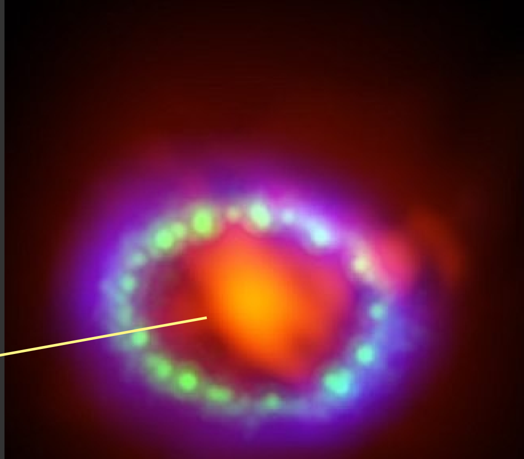
Neutrino (ν): neutral, lightest, subatomic particle



Neutrino (ν): neutral, lightest, subatomic particle



ν_s



ν_s

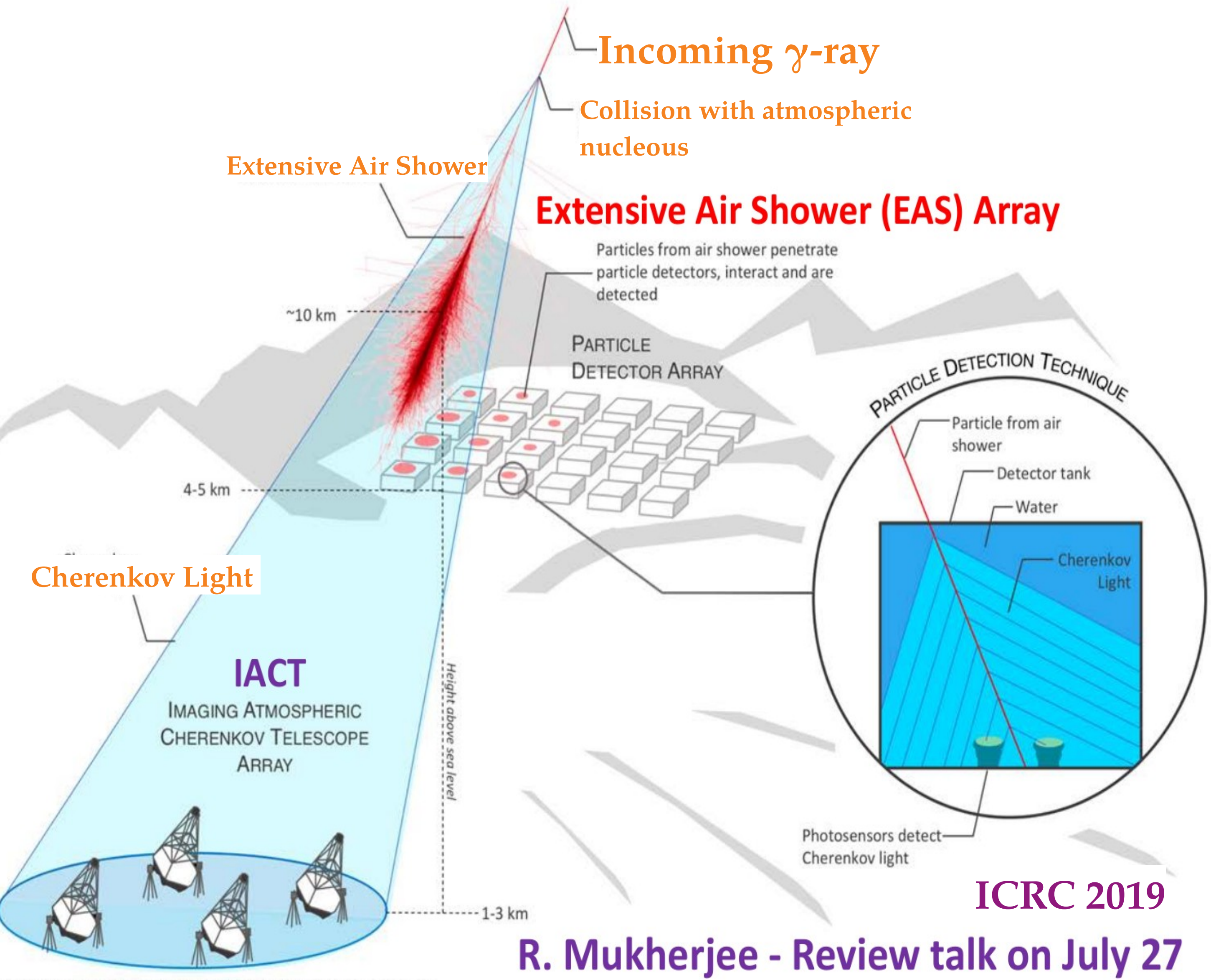
Supernova explosion 1987A: Neutrinos detected three hours before light detection

Is it possible neutrino astronomy?

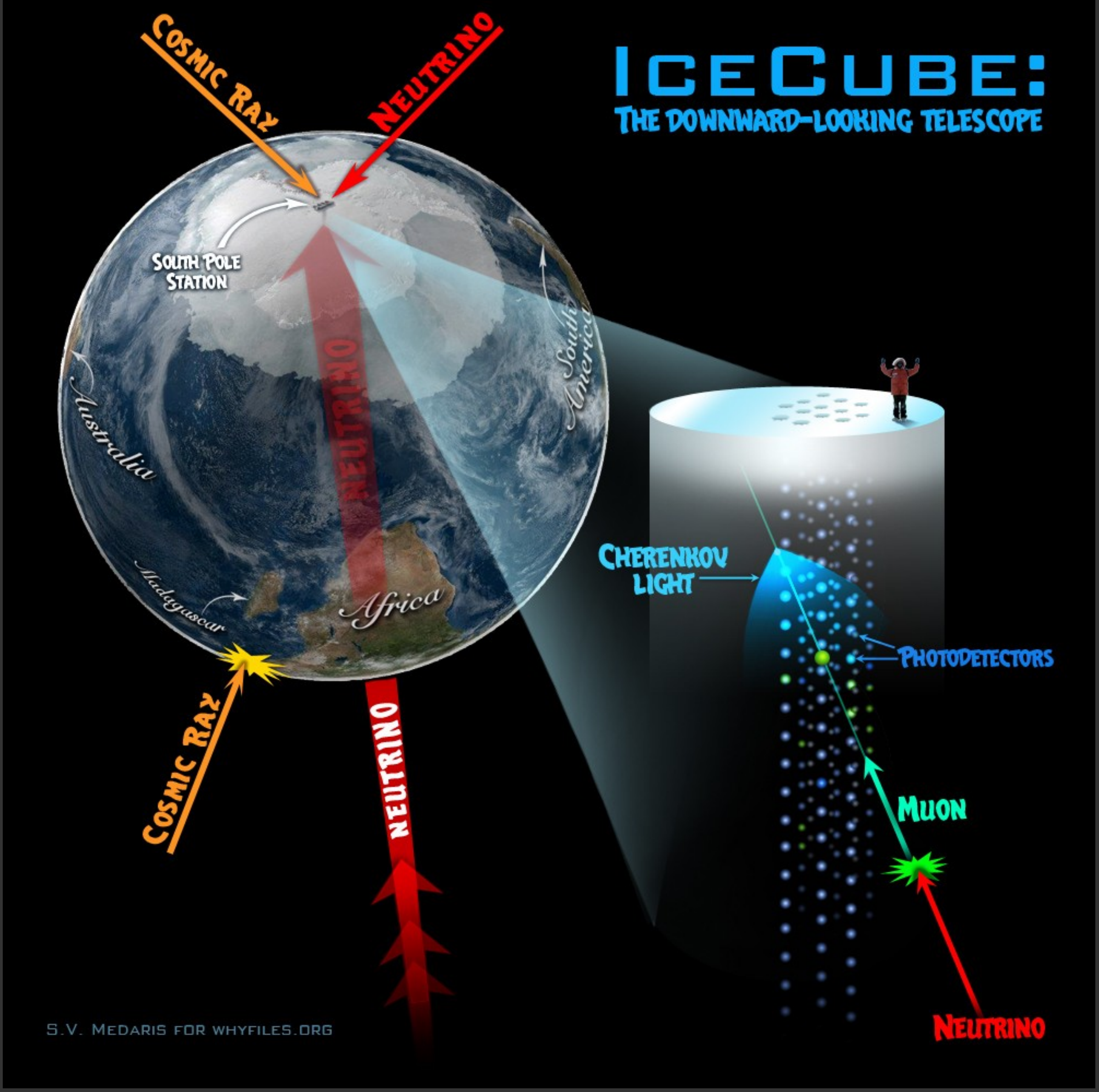
ν_s

Blazar TXS 0506+056: Simultaneous Neutrino and γ-ray event

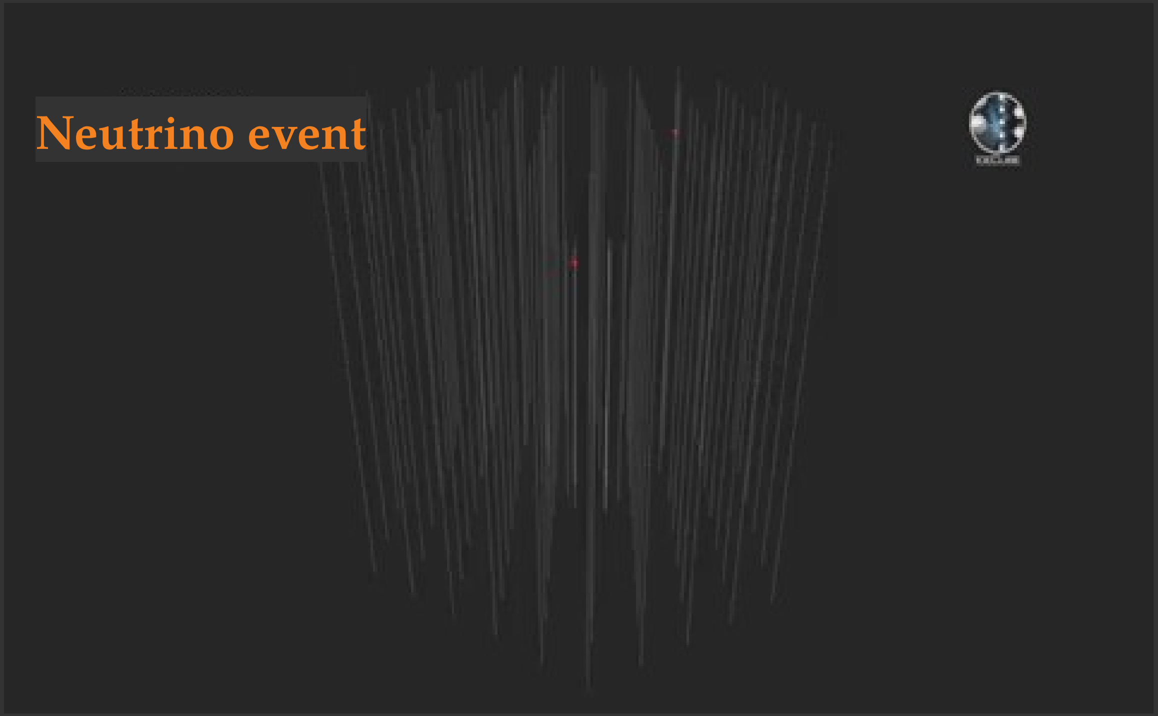
Detection of Very High Energy Radiation and Neutrinos



- Indirect γ-ray detection
- Reconstruction of the initial γ-ray direction, energy, etc.



- Cosmic neutrinos interacting with water molecules in ice produce HE muons, taus and electros.
- *Cherenkov light* of charged particles is used to reconstruct the neutrino parameters.


Neutrino event

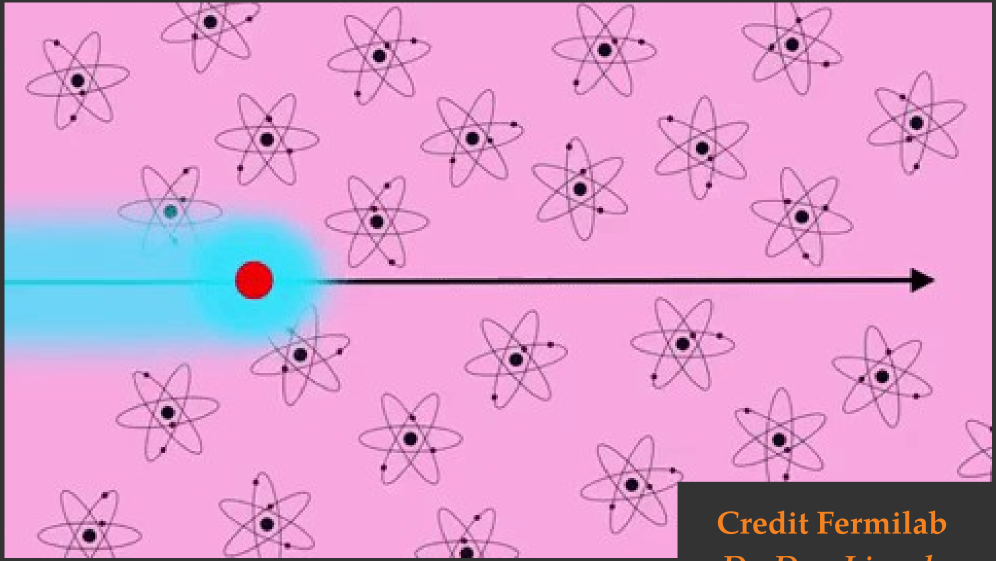
Credit: IceCube Collaboration

- Cosmic neutrinos interacting with water molecules in ice produce HE muons, taus and electros.

- *Cherenkov light* of charged particles is used to reconstruct the neutrino parameters.

Cherenkov Radiation

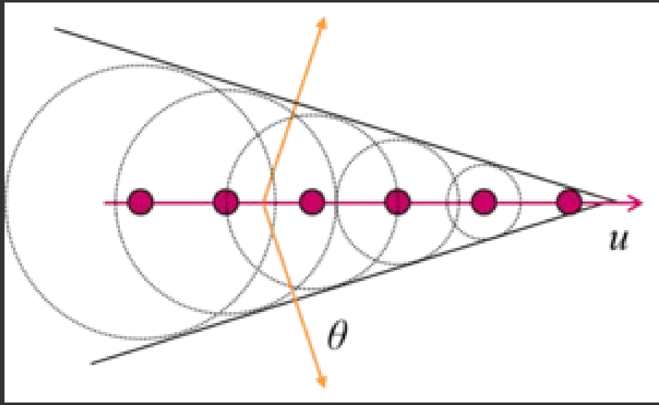
- A charged particle is travelling ***faster than the speed of light*** within a dielectric a medium (e.g. air, water, ice).



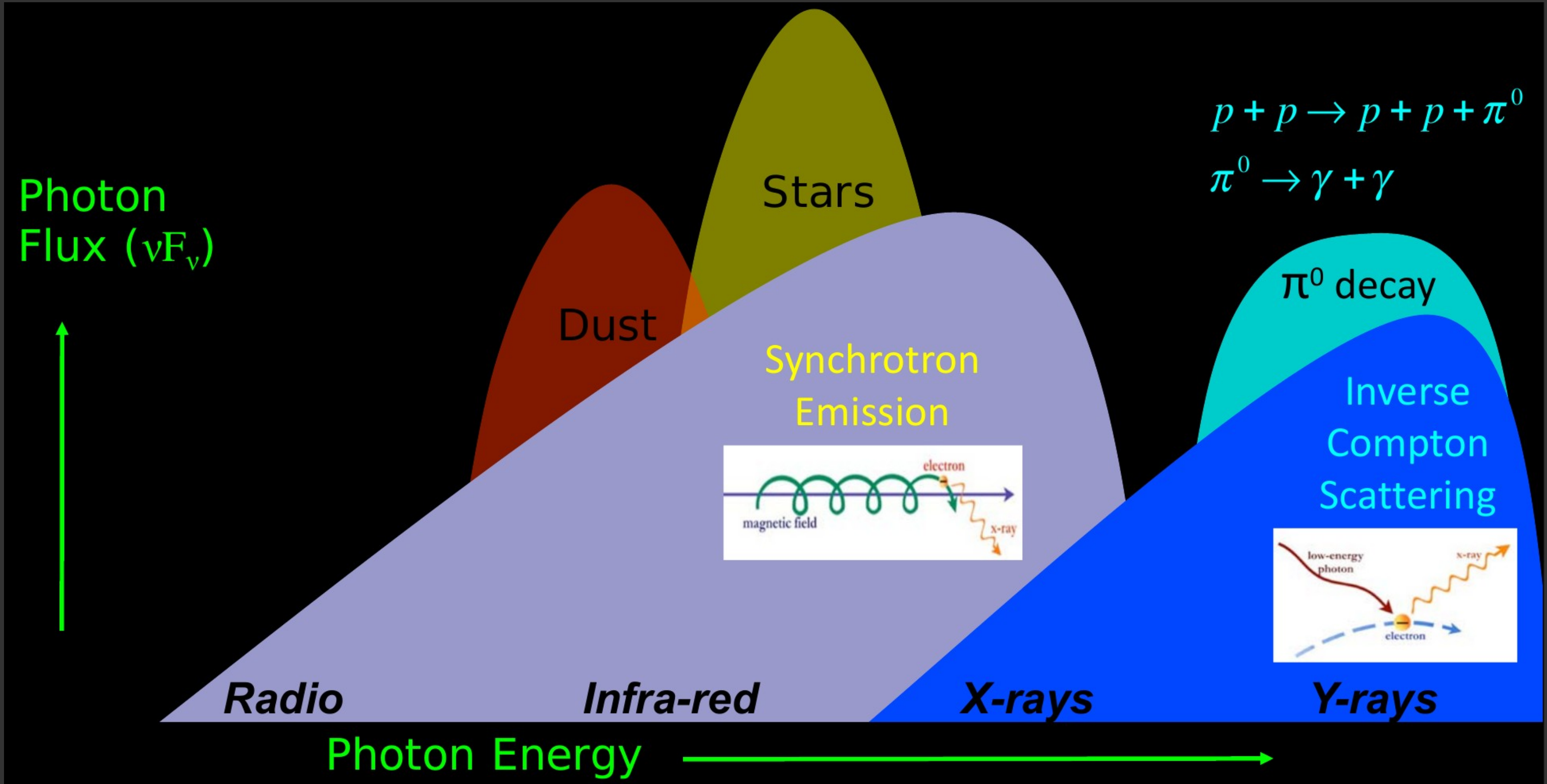
Credit Fermilab
Dr. Don Lincoln

- An electric field distrubance is created, which propagates througout the medium.

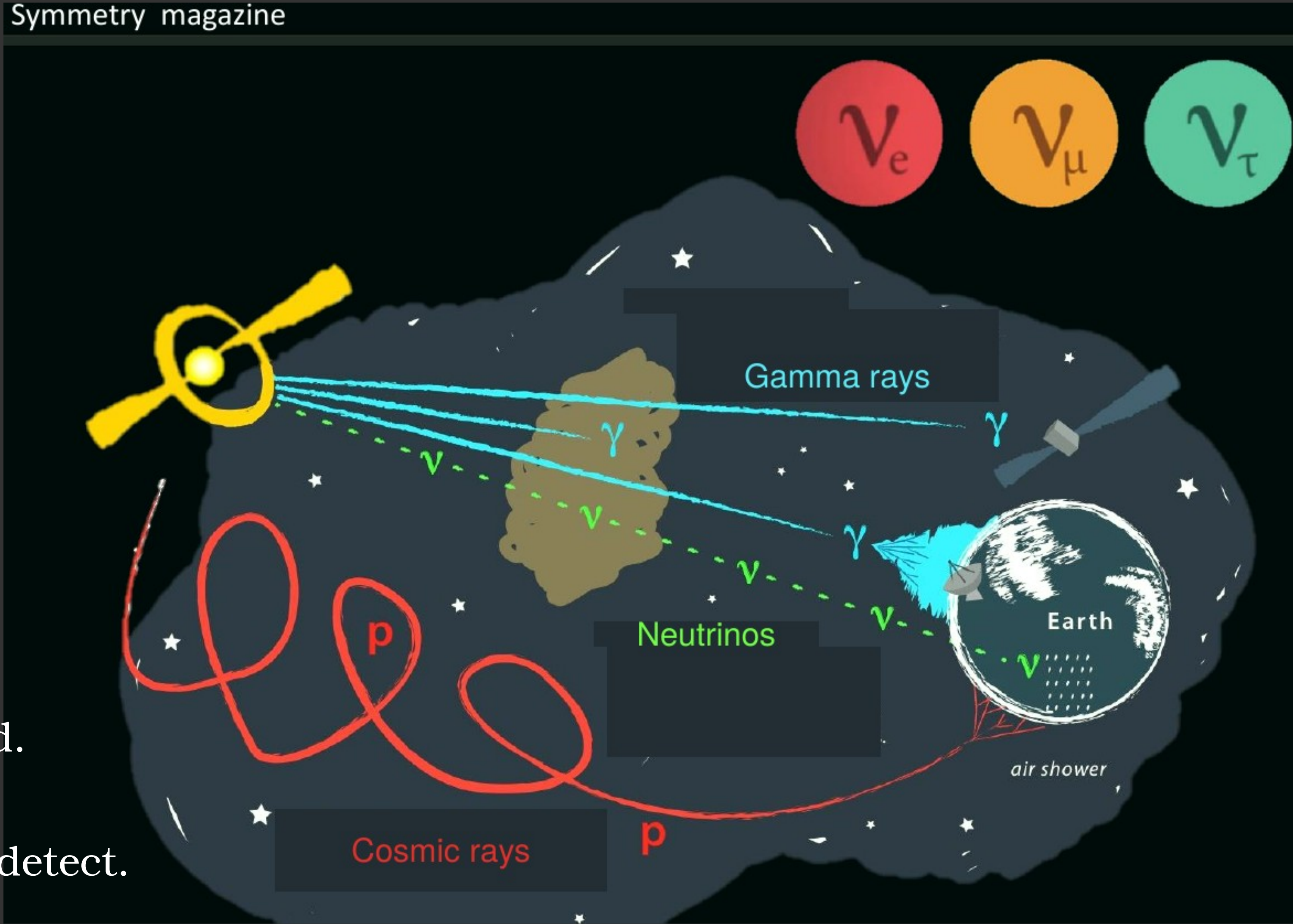
- A ***shock front*** of Cherenkov light is fromed.



HE photons and ν_s are only produced by non-thermal relativistic particles



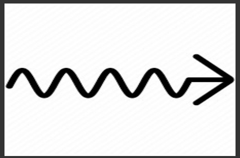
Relativistic protons produce ɣ-rays and ν_s



Challenges for interpretation:

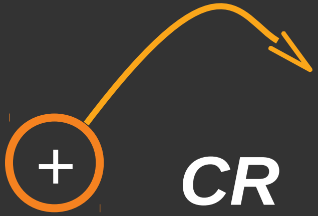
- CRs, deflected.
- gamma-rays, absorbed.
- Neutrinos, difficult to detect.

Cherenkov detection techniques are employed to detect:



Ɣ-rays

ν



e.g. CTA

e.g. IceCube

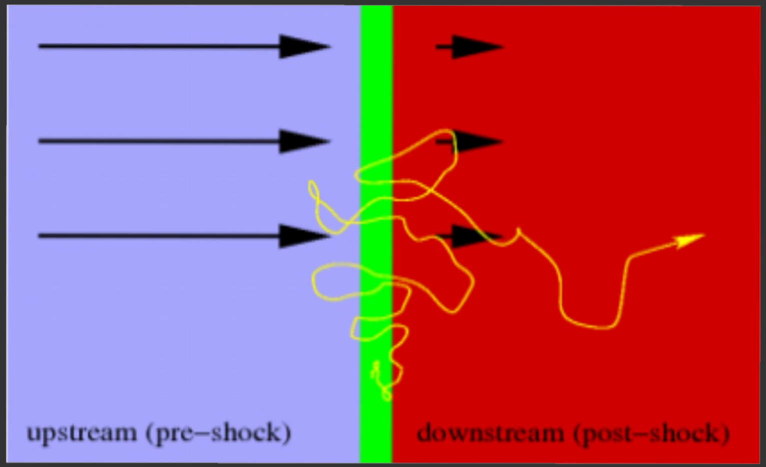
e.g.

PIERRE AUGER OBSERVATORY

Acceleration of Relativistic Particles

1st ORDER FERMI ACCELERATION

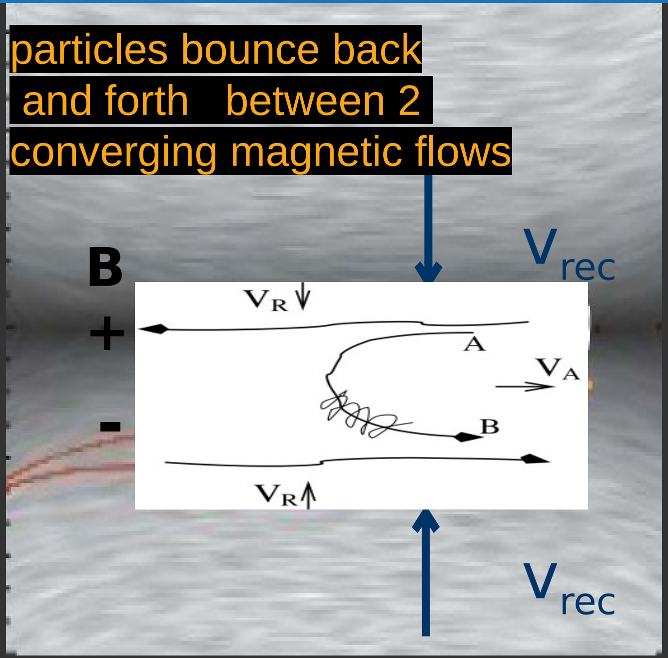
Shock acceleration



Bell (1978); Begelman & Eichler (1997):

$<\Delta E/E> \sim v_{sh}/c$

Reconnection acceleration



de Gouveia Dal Pino & Lazarian, A&A (2005):

$<\Delta E/E> \sim v_{rec}/c$

PARTICLE ACCELERATION

- Astrophysical Scenarios
  - Shock acceleration
    - Supernova remnants (SNR)
    - Astrophysical jets
    - Stellar winds
  - Magnetic Reconnection
    - Solar Flares
    - Earth magneto-tail
    - Magnetised accretion flows
    - Magnetised jets

Shock waves

- They are formed when the source travels ***faster than the speed of perturbations*** in the local medium.

- ***A sharp discontinuity*** in the properties of the medium (ρ, T, v) is formed.

- Shock waves are common in astrophysical environments.

Shock waves

Stellar wind of LL Orionis

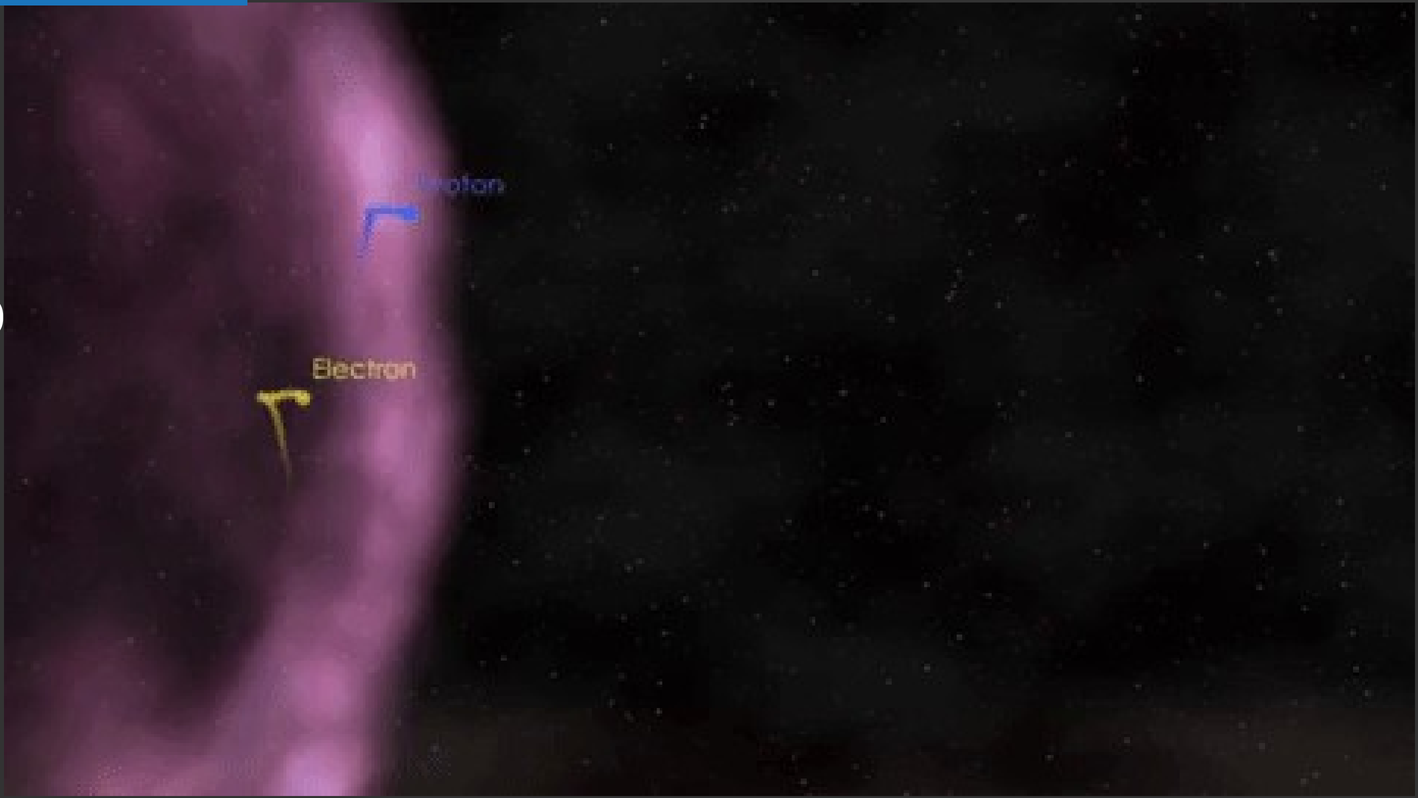
- They are formed when the source travels faster than the local perturbations' speed.
- A sharp discontinuity in the properties of the medium (ρ, T, v) is formed.
- Shock waves are common in astrophysical environments.

Credit: NASA and the Hubble Heritage Team (STScI/AURA)

PARTICLE ACCELERATION

Astrophysical shockwaves

- Supernova remnants
- Jets (AGNs, GRBs, YSOs)
- Massive star wind-wind collision



PARTICLE ACCELERATION

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PARTICLE ACCELERATION

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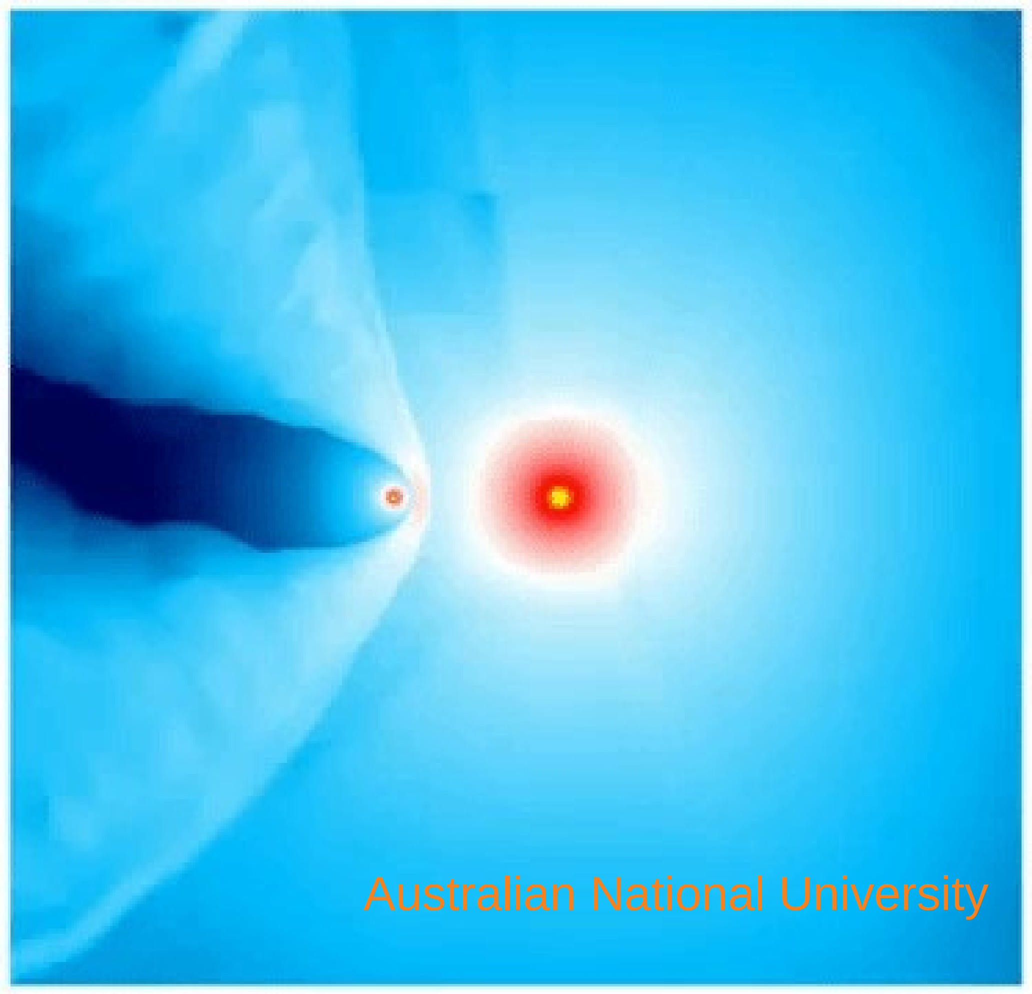
PARTICLE ACCELERATION

Astrophysical shockwaves

- Supernova remnants
- Jets (AGNs, GRBs, YSOs)
- Massive star, wind-wind collision

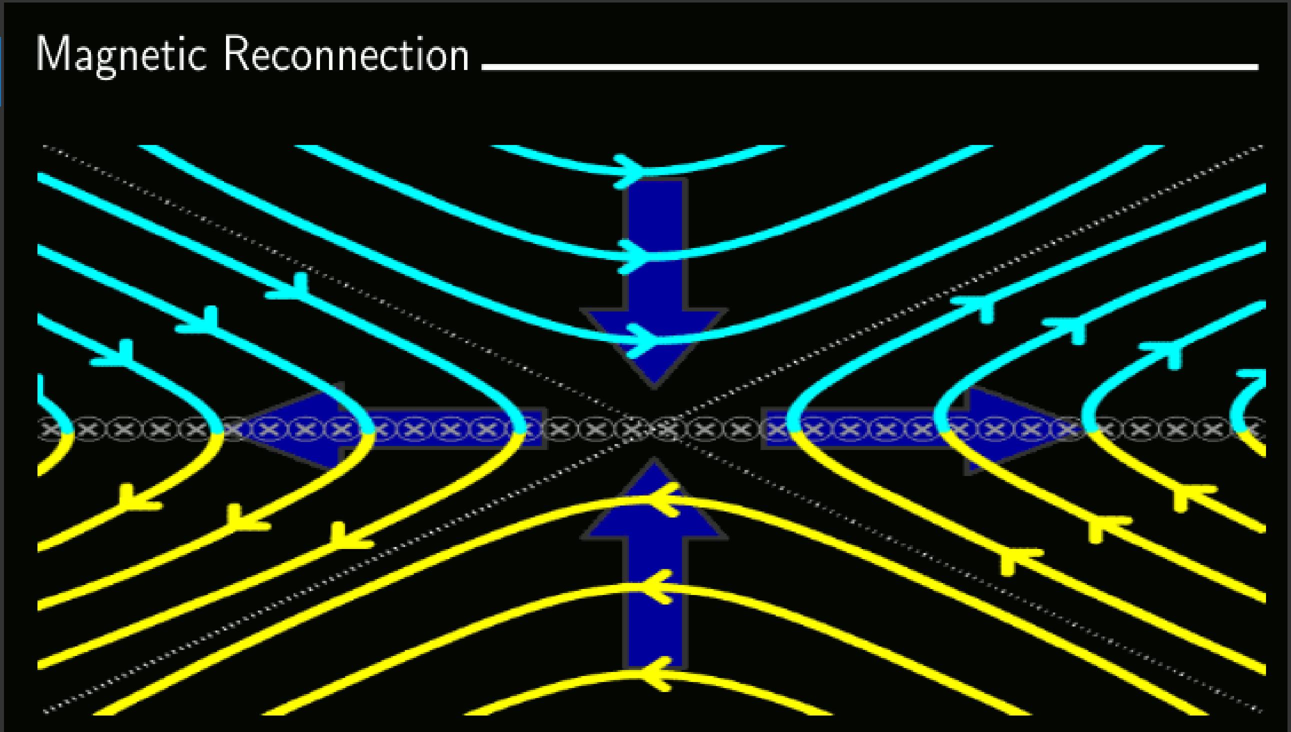


PARTICLE ACCELERATION

Magnetic reconnection

MAGNETISED PLASMAS

- Solar corona
- Earth magneto-tail
- Magnetised astrophysical jets
- Turbulent and magnetised accretion flows



(wikipedia)

PARTICLE ACCELERATION

Magnetic reconnection

MAGNETISED PLASMAS

- Solar corona
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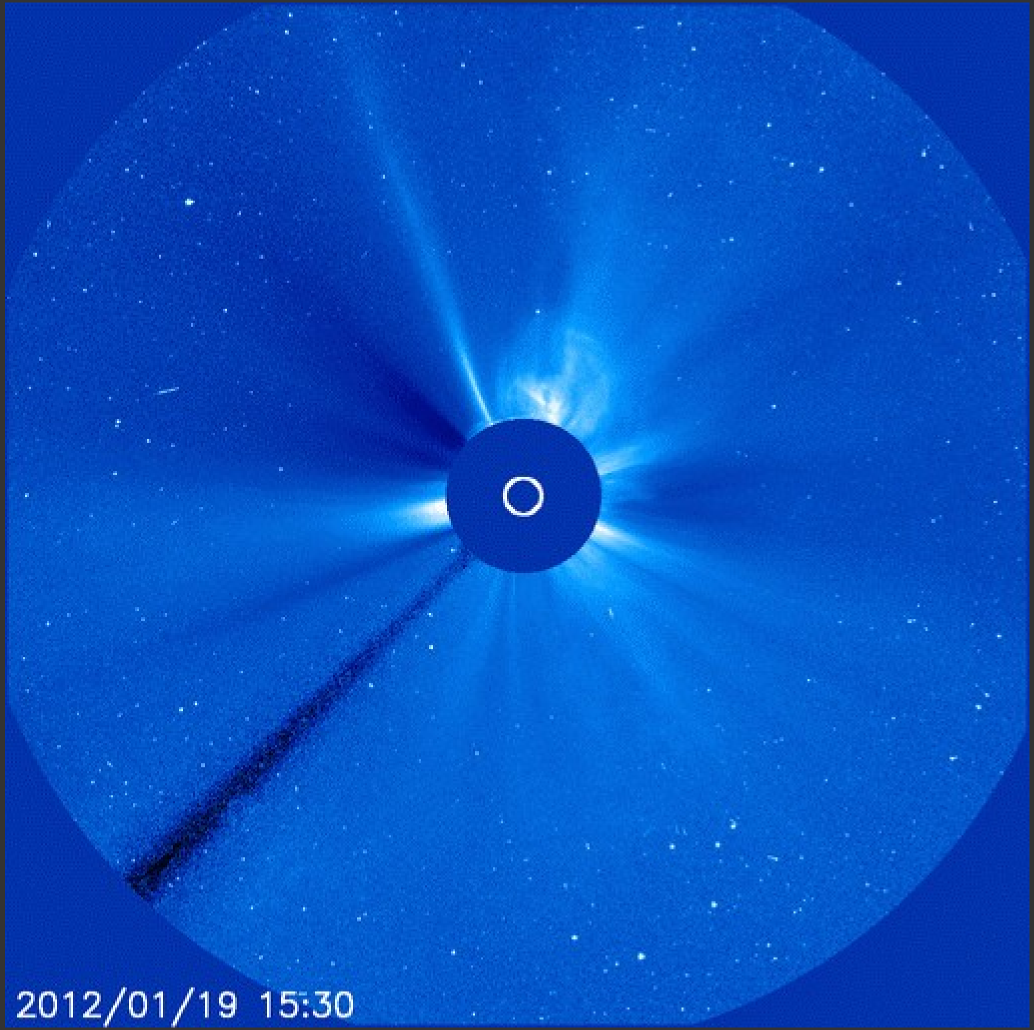

PARTICLE ACCELERATION

Magnetic reconnection

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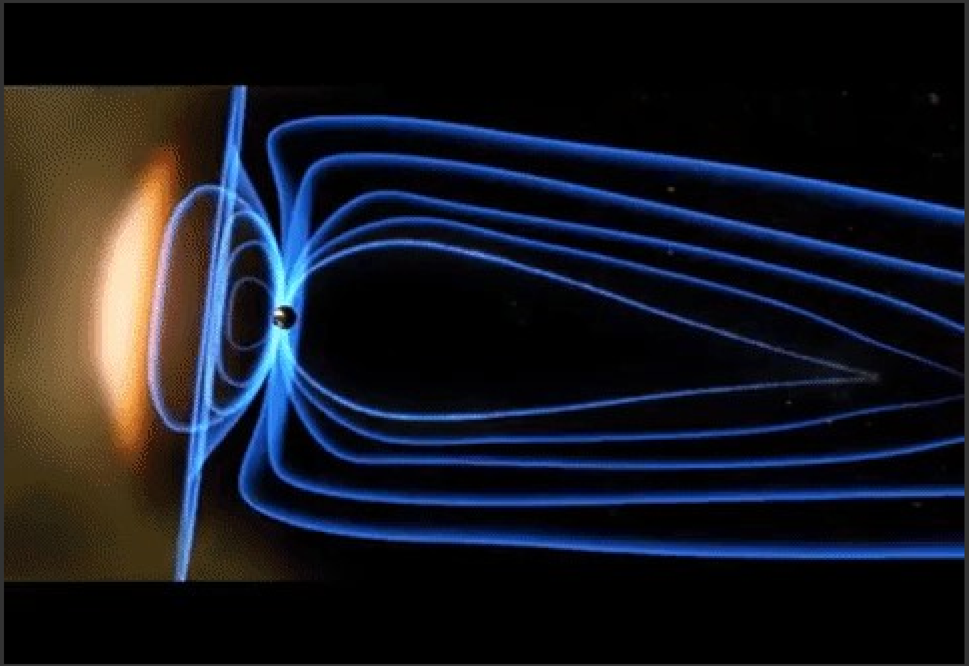
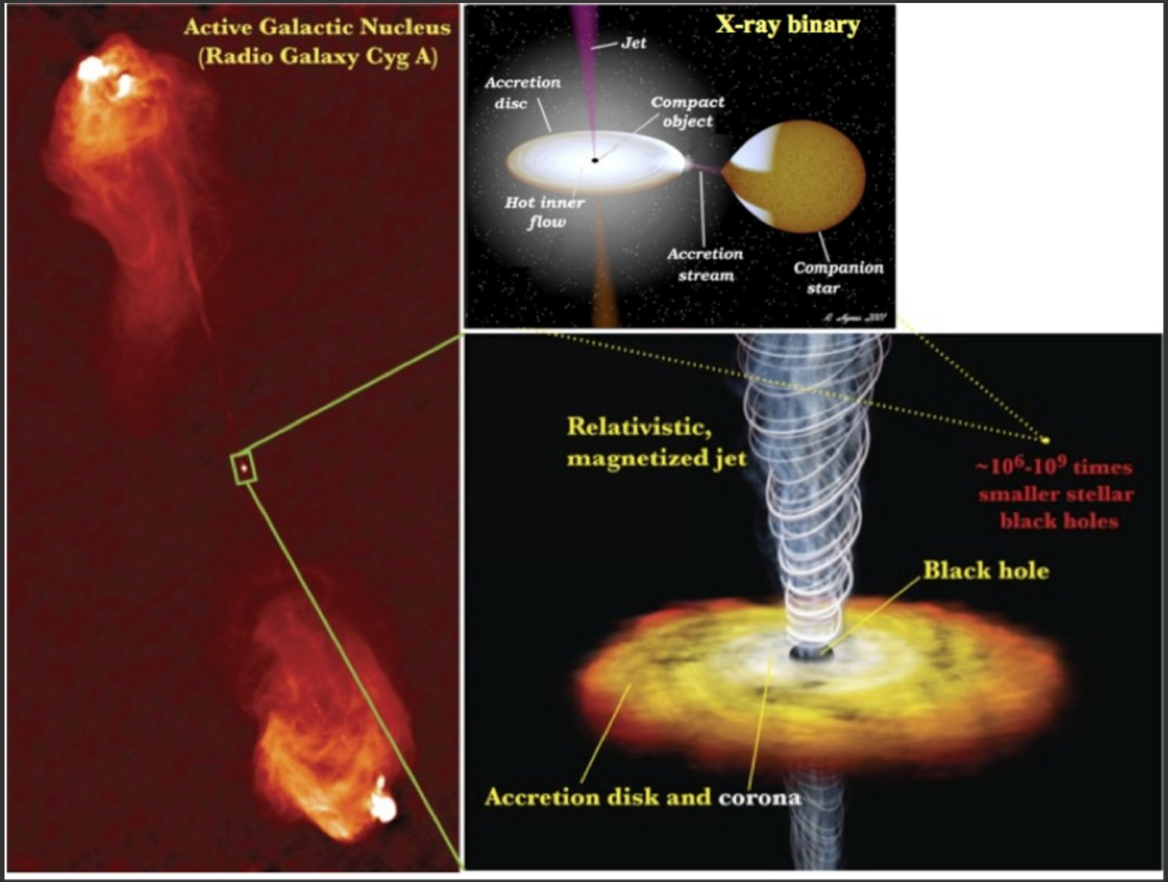


PARTICLE ACCELERATION

Magnetic reconnection

MAGNETISED PLASMAS

- Solar corona
- Earth magneto-tail
- Magnetised astrophysical jets (AGNs, GRB)
- Turbulent and magnetised accretion flows



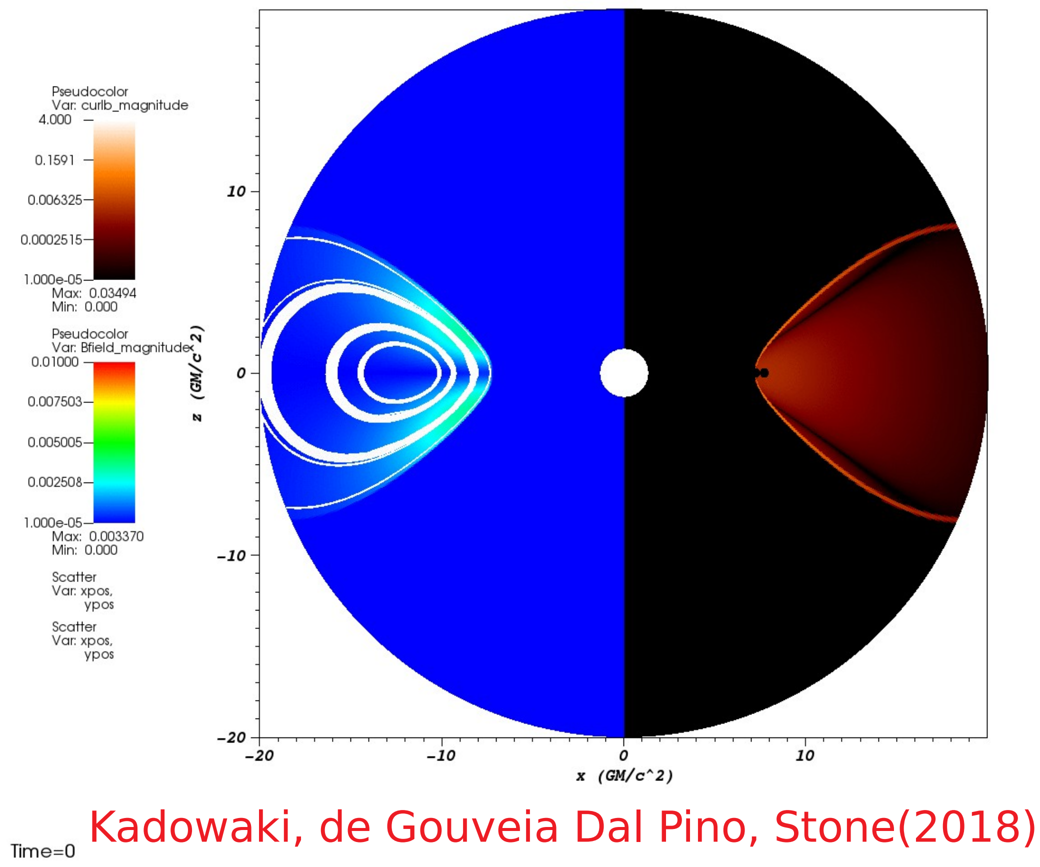
PARTICLE ACCELERATION

Magnetic reconnection

MAGNETISED PLASMAS

- Solar corona
- Earth magneto-tail
- Magnetised astrophysical jets
- Turbulent and magnetised accretion flows

Fast magnetic reconnection current-sheet-search algorithm



Kadowaki, de Gouveia Dal Pino, Stone(2018)

de Gouveia Dal Pino et al. (2019)

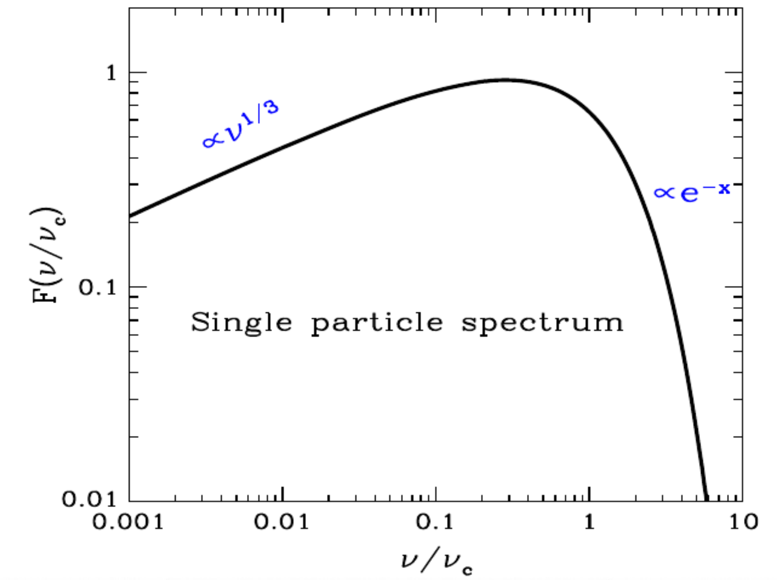
How can we test/trace sources of relativistic particles?

NON-THERMAL EMISSION OF RELATIVISTIC PARTICLES

- Leptonic emission: electrons, positrons. E.g:
  - Electron synchrotron
  - Inverse Compton (IC)

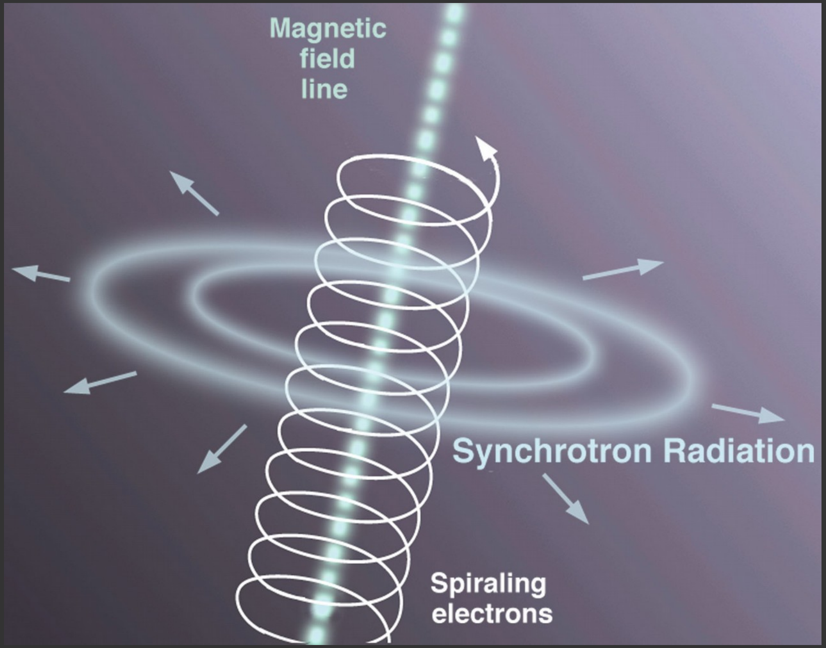
- Hadronic emission: ions, nuclei. E.g.:
  - Photo-pion production
  - Proton-proton interaction
  - Bethe-Heitler pair production

Synchrotron emission



$$\boxed{\frac{dW}{d\omega dt} = \frac{\sqrt{3}q^3 B \sin(\alpha)}{4\pi m_e c^2} \times F(x)},$$

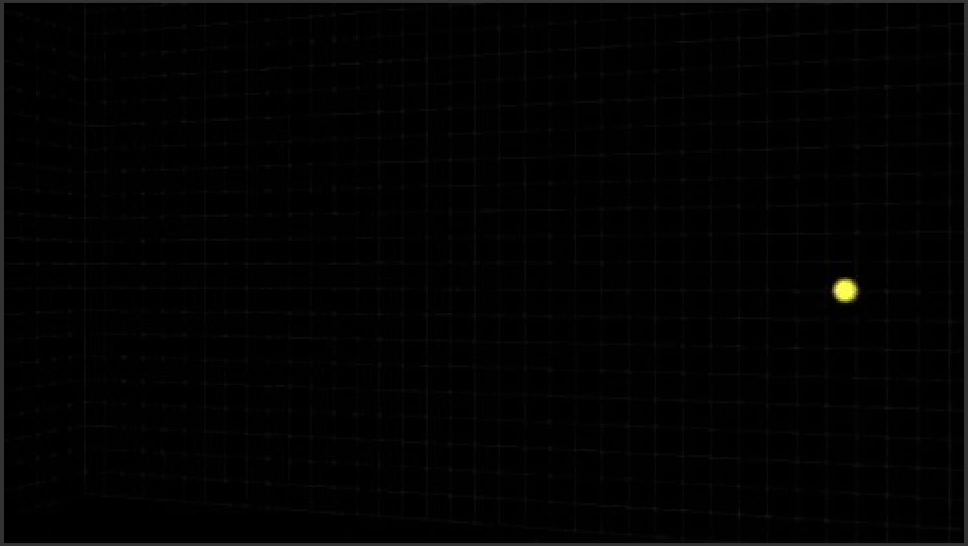
$$F(x) = x \int_x^\infty K_{5/3}(u)du\ , x = \frac{\omega}{\omega_c}\ , \omega_c = \frac{3qB\sin(\alpha)\gamma^2}{2m_e c}.$$



- Ghisellini, G. 2013, *Radiative Processes in High Energy Astrophysics,* Spriger.
- Longair, M.,S. 1981 *High Energy Astrophysics,* Cambridge University Press.

Inverse Compton Scattering

$$\frac{dE_e}{dt} = \frac{4}{3}\sigma_{\mathrm{T}} c \gamma^2 \beta^2 U_{\mathrm{r}}$$

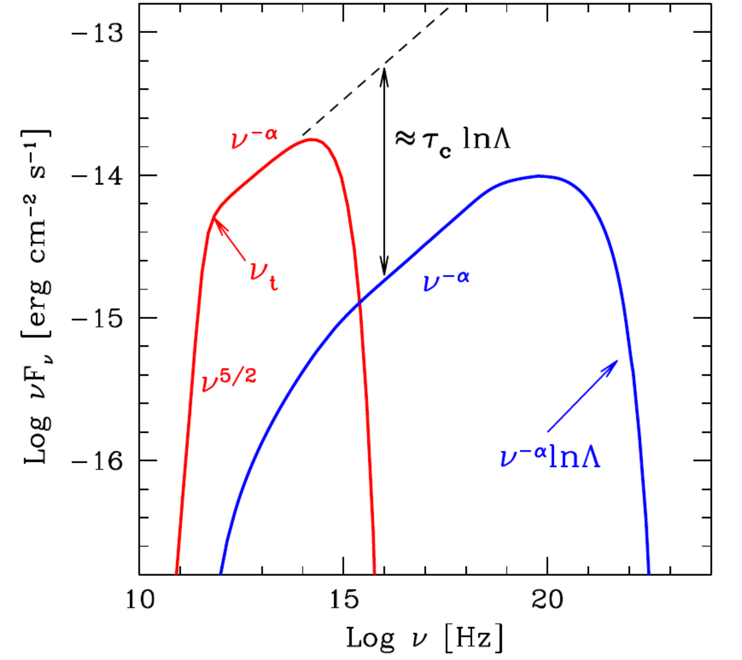


Total emission power of a single electron interacting with a radiation field with energy density U_r .

- Ghisellini, G. 2013, *Radiative Processes in High Energy Astrophysics*, Spriger.
- Longair, M.,S. 1981 *High Energy Astrophysics*, Cambridge University Press.

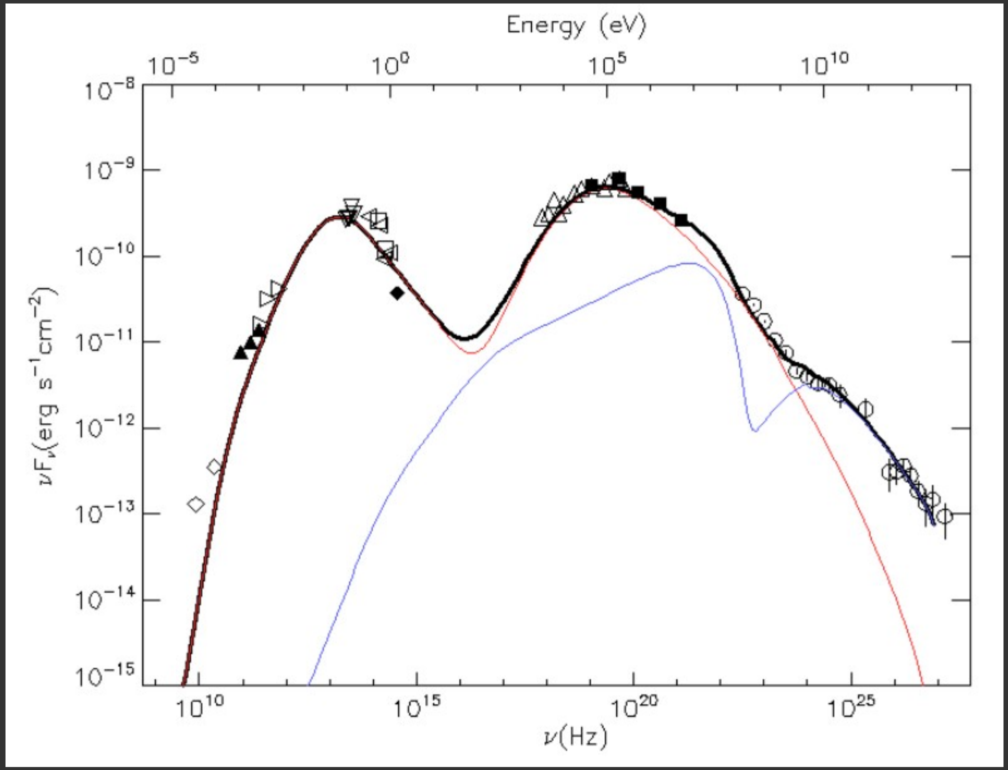
Synchrotron Self-Compton (SSC)

Typical example of SSC spectrum in the νF_ν representation.



- Ghisellini, G. 2013, *Radiative Processes in High Energy Astrophysics,* Spriger.
- Longair, M.,S. 1981 *High Energy Astrophysics,* Cambridge University Press.

Example: SED of Centaurus A



Centaurus A (Cen A):

The closest active radio galaxy at 3.8 Mpc.

Two-zone SSC model, or hadronic emission component?

H.E.S.S. Collaboration (2018).

NON-THERMAL EMISSION OF RELATIVISTIC PARTICLES

- Leptonic emission: electrons, positrons. E.g:
  - Electron synchrotron
  - Inverse Compton (IC)

- Hadronic emission: ions, nuclei. E.g.:
  - Photo-pion production
  - Proton-proton interaction
  - Bethe-Heitler pair production

Hadronic interactions

- Proton-proton interaction: $p + p \rightarrow p + p + n_1(\pi^+ + \pi^-) + n_2\pi^0 \,,$

- Photo-pair production (Bethe-Heitler process): $p + \gamma \rightarrow p + e^- + e^- \,.$

- Photo-pion production:

$$
\begin{aligned}
p + \gamma &\rightarrow p + \pi^0 \,, \\
p + \gamma &\rightarrow p + \pi^+ + \pi^- \,.
\end{aligned}
$$

$$
\begin{aligned}
\pi^\pm &\rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu \,, \\
\pi^0 &\rightarrow 2\gamma \,, \\
\mu^\pm &\rightarrow e^\pm + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu \,.
\end{aligned}
$$

Hadronic interactions

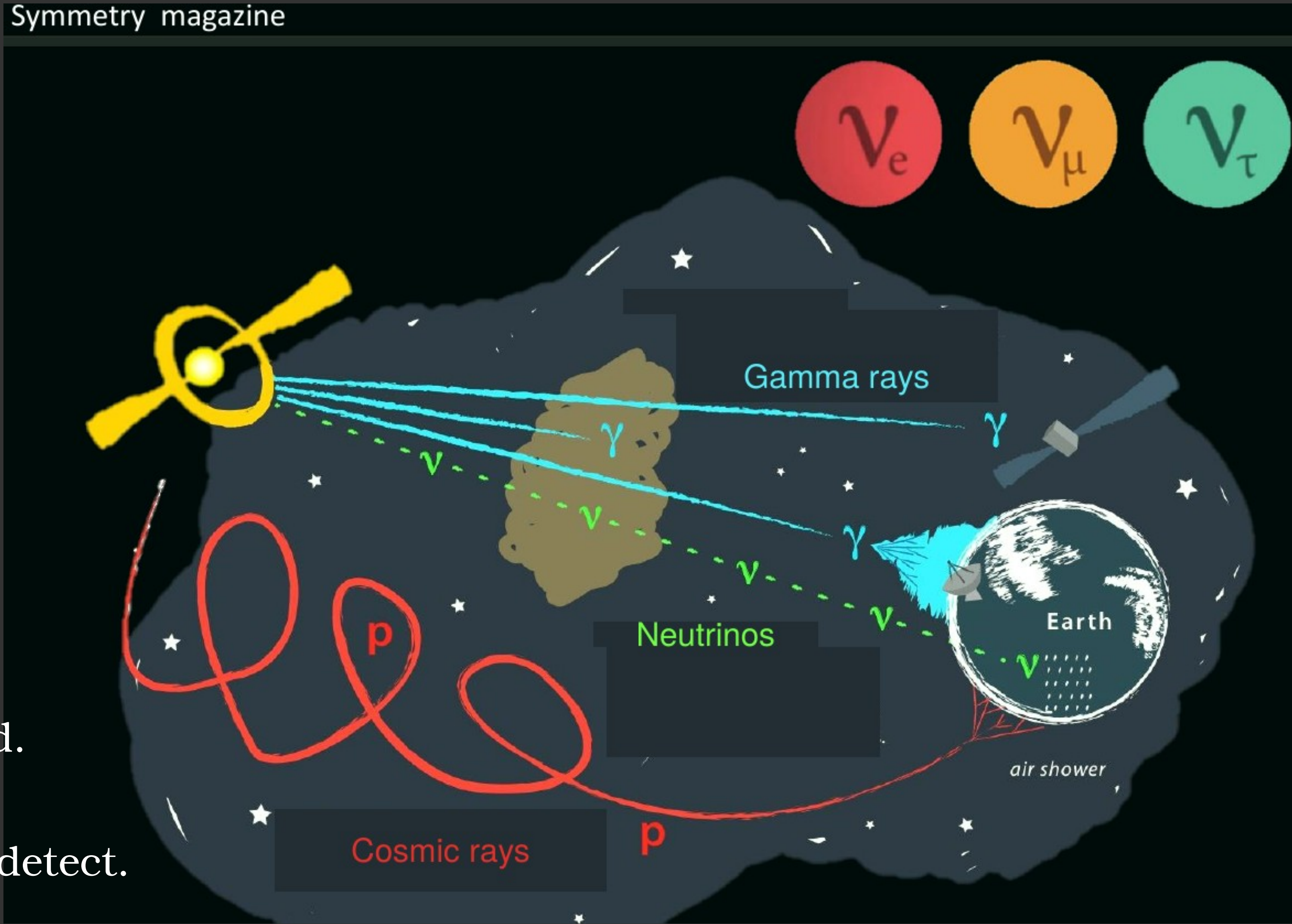
- Proton-proton interaction: $p + p \rightarrow p + p + n_1(\pi^+ + \pi^-) + n_2\pi^0$,
- Photo-pair production (Bethe-Heitler process): $p + \gamma \rightarrow p + e^- + e^-$.
- Photo-pion production:

$$\begin{aligned} p + \gamma &\rightarrow p + \pi^0 \, , \\ p + \gamma &\rightarrow p + \pi^+ + \pi^- \, . \end{aligned}$$

Multi-messenger processes

$$\begin{aligned} \pi^\pm &\rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu \, , \\ \pi^0 &\rightarrow 2\gamma \, , \\ \mu^\pm &\rightarrow e^\pm + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu \, . \end{aligned}$$

Relativistic protons produce ɣ-rays and ν_s

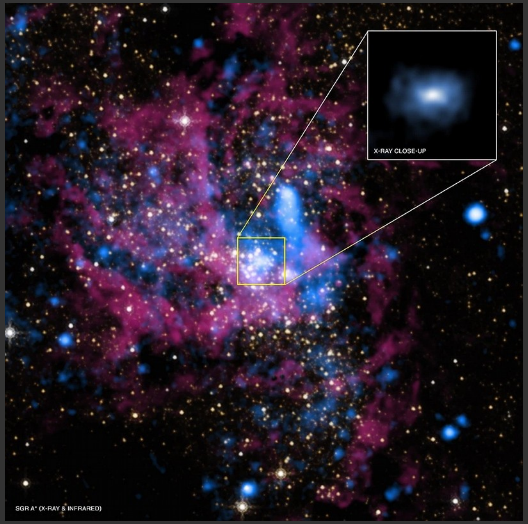


Challenges for interpretation:

- CRs, deflected.
- gamma-rays, absorbed.
- Neutrinos, difficult to detect.

CR emission from the core of Low-Luminosity Active Galactic Nuclei (LLAGNs)

- Sagittarius A* (Sgr A*): LLAGN at the GC

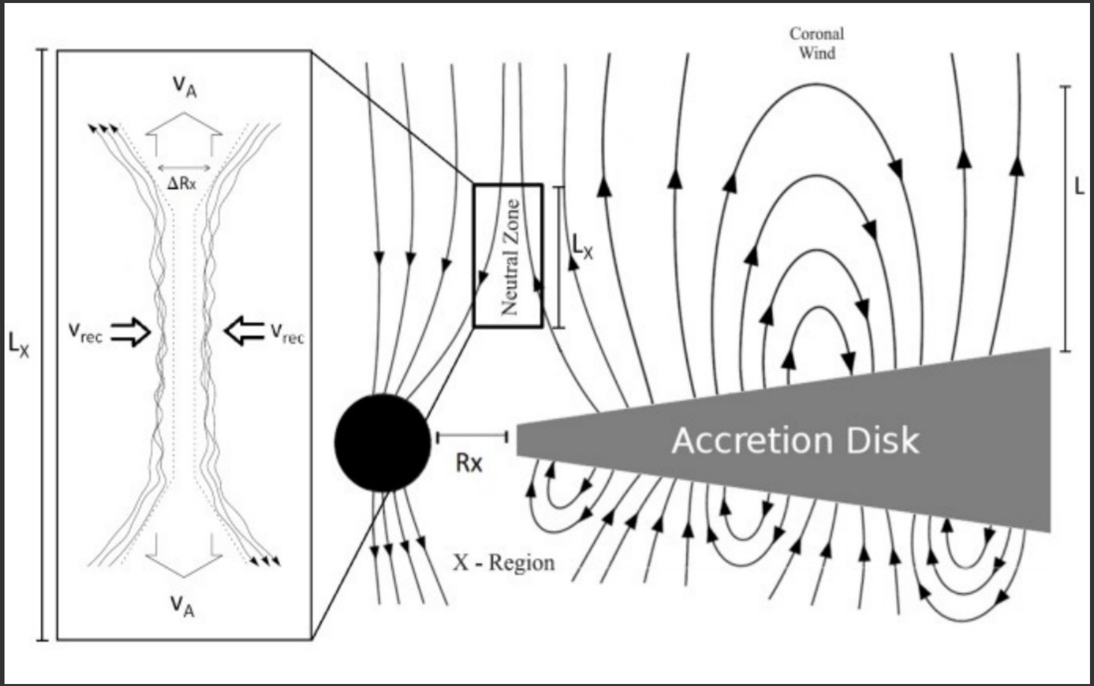


- Associated with VHE γ-ray emission

- Centaurus A (Cen A): The closest active radio galaxy at 3.8 Mpc

- Difficult to explain with SSC scenario.

CR acceleration by turbulent magnetic reconnection



- de Gouveia dal Pino & Lazarian (2005)
- Kowal, de Gouveia Dal Pino & Lazarian (2011,12)
- Kadowaki, de Gouveia Dal Pino & Singh (2015)
- Singh, de Gouveia Dal Pino & Kadowaki (2015)
- Kimura, Tomida & Murase (2019)

General Relativistic Magneto-hydrodynamics

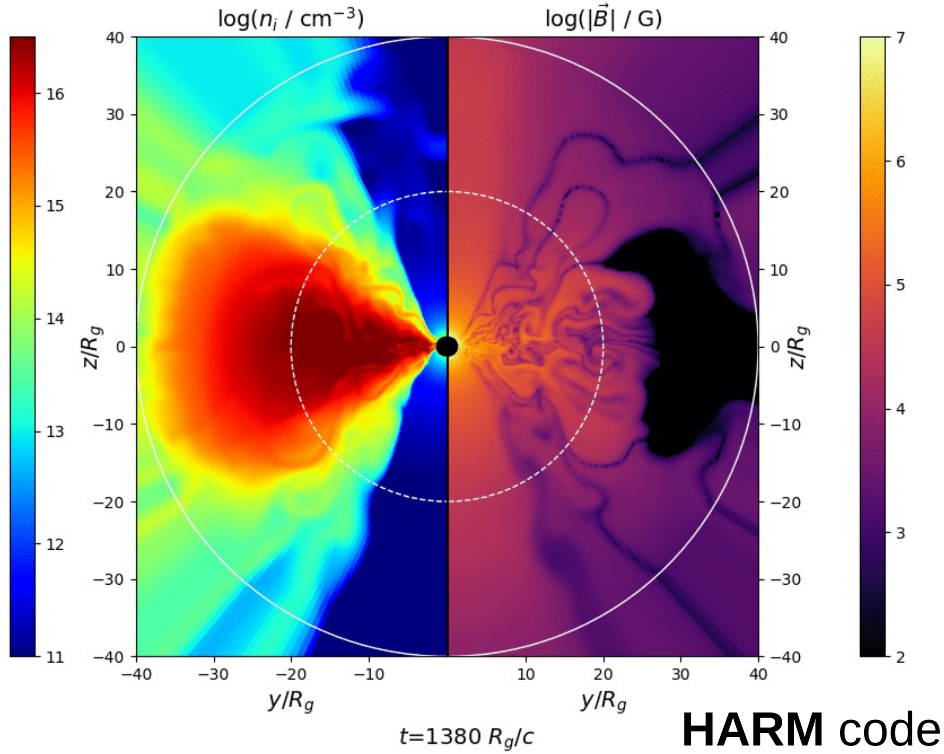
$$T^{\mu\nu}_{\mathrm{MHD}} = (\rho + u + p + b^2)u^\mu u^\nu + (p + \frac{1}{2}b^2)g^{\mu\nu} - b^\mu b^\nu$$

$$\frac{1}{\sqrt{-g}}\partial_\mu(\sqrt{-g}\,\rho u^\mu) = 0$$

$$\partial_t\left(\sqrt{-g}\,T^t{}_\nu\right) = -\partial_i\left(\sqrt{-g}\,T^i{}_\nu\right) + \sqrt{-g}\,T^\kappa{}_\lambda\,\Gamma^\lambda{}_{\nu\kappa}$$

$$\partial_t(\sqrt{-g}B^i) = -\partial_j(\sqrt{-g}\,(b^j u^i - b^i u^j))$$

$$\frac{1}{\sqrt{-g}}\partial_i(\sqrt{-g}\,B^i) = 0,$$



HARM code

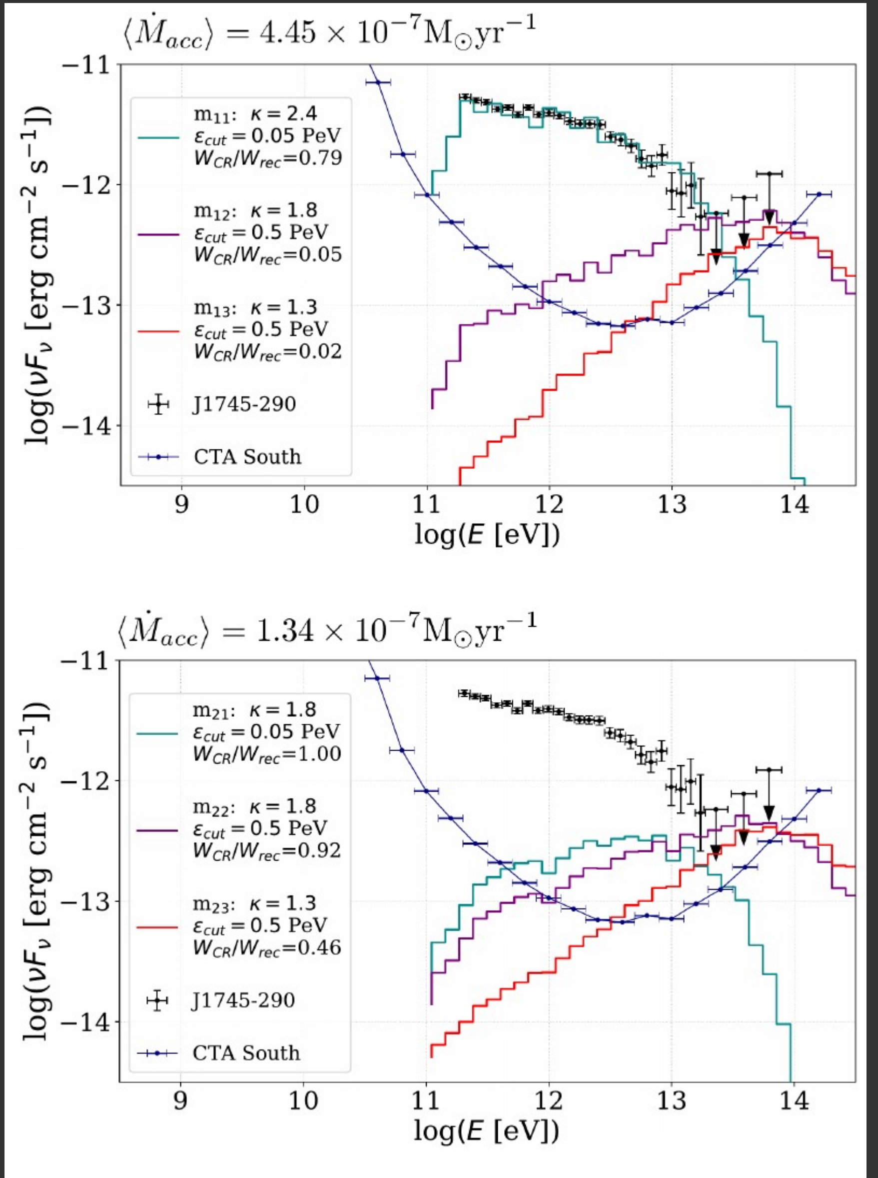
CR emission model for the accretion flow of SgrA*.

CR injection parametrised as:

$$\frac{dN_{CR}}{d\epsilon} \propto \epsilon^{-\kappa} \exp\{-\epsilon/\epsilon_{cut}\}$$

$$W_{rec} = 1.52 \times 10^{42} f \left(\frac{\dot{M}_{acc}}{\mathrm{M}_{\odot}\mathrm{yr}^{-1}}\right) \left(\frac{T_p}{T_e}\right) \mathrm{erg\ s}^{-1}$$

- Rodríguez-Ramírez et al. ApJ (2019a)

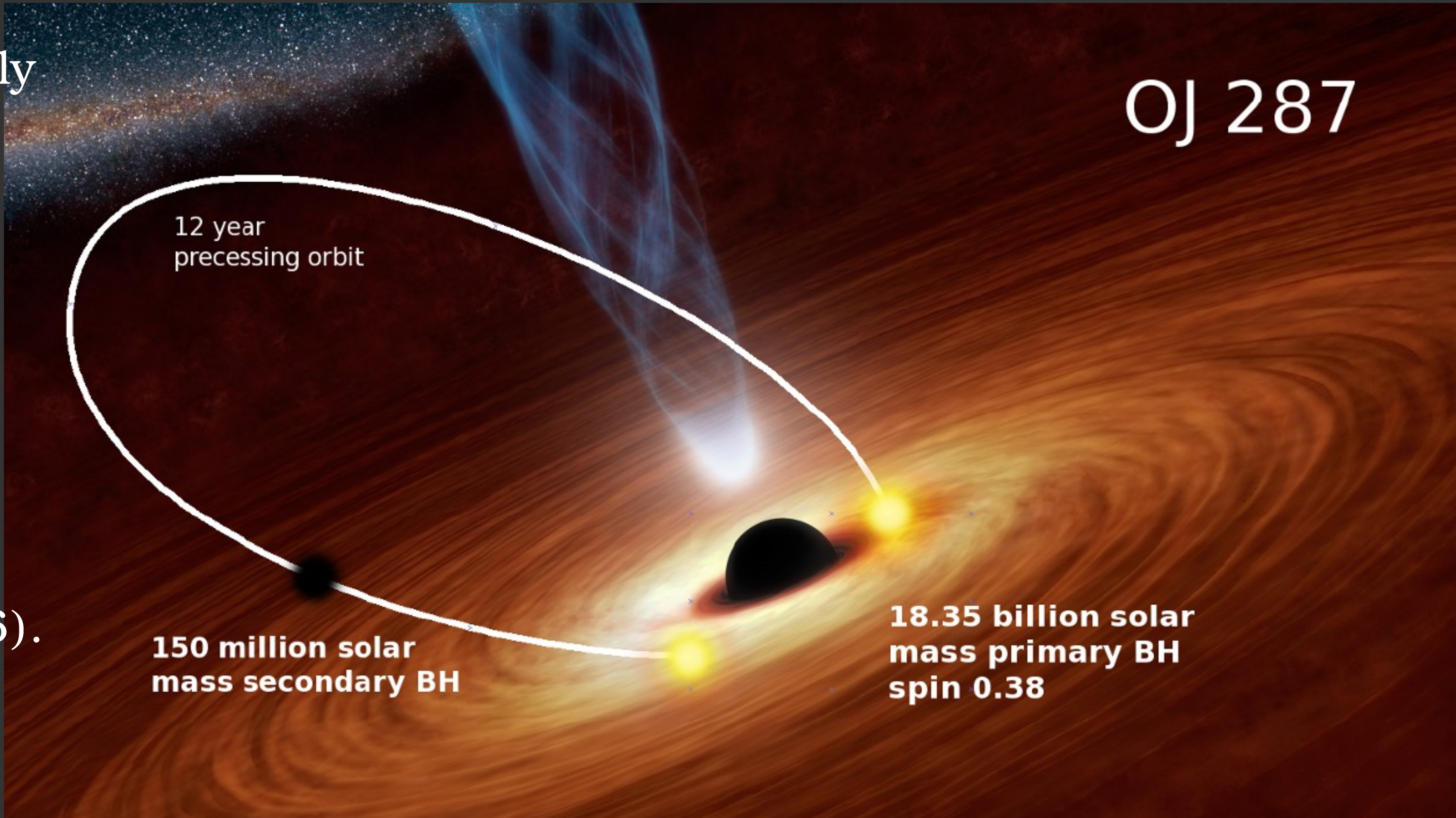


Particle Acceleration in Black Hole - disc impacts

The unique blazar OJ 287

- Located at ~ 3.5 billion ly (z=0.306).
- Remarkable ~12 yr double peaked optical variations.
- Claimed to be a SMBH binary:

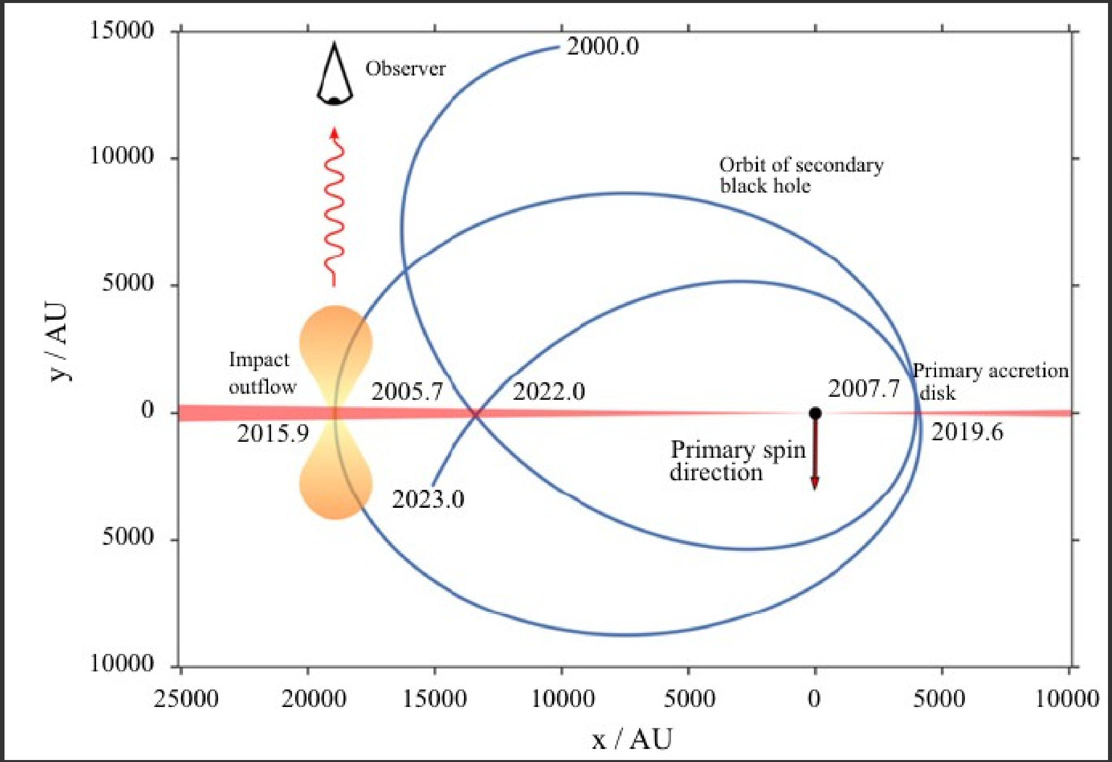
  Sillanpaa et al. (1988)
  Lehto & Valtonen (1996).



The unique blazar OJ 287

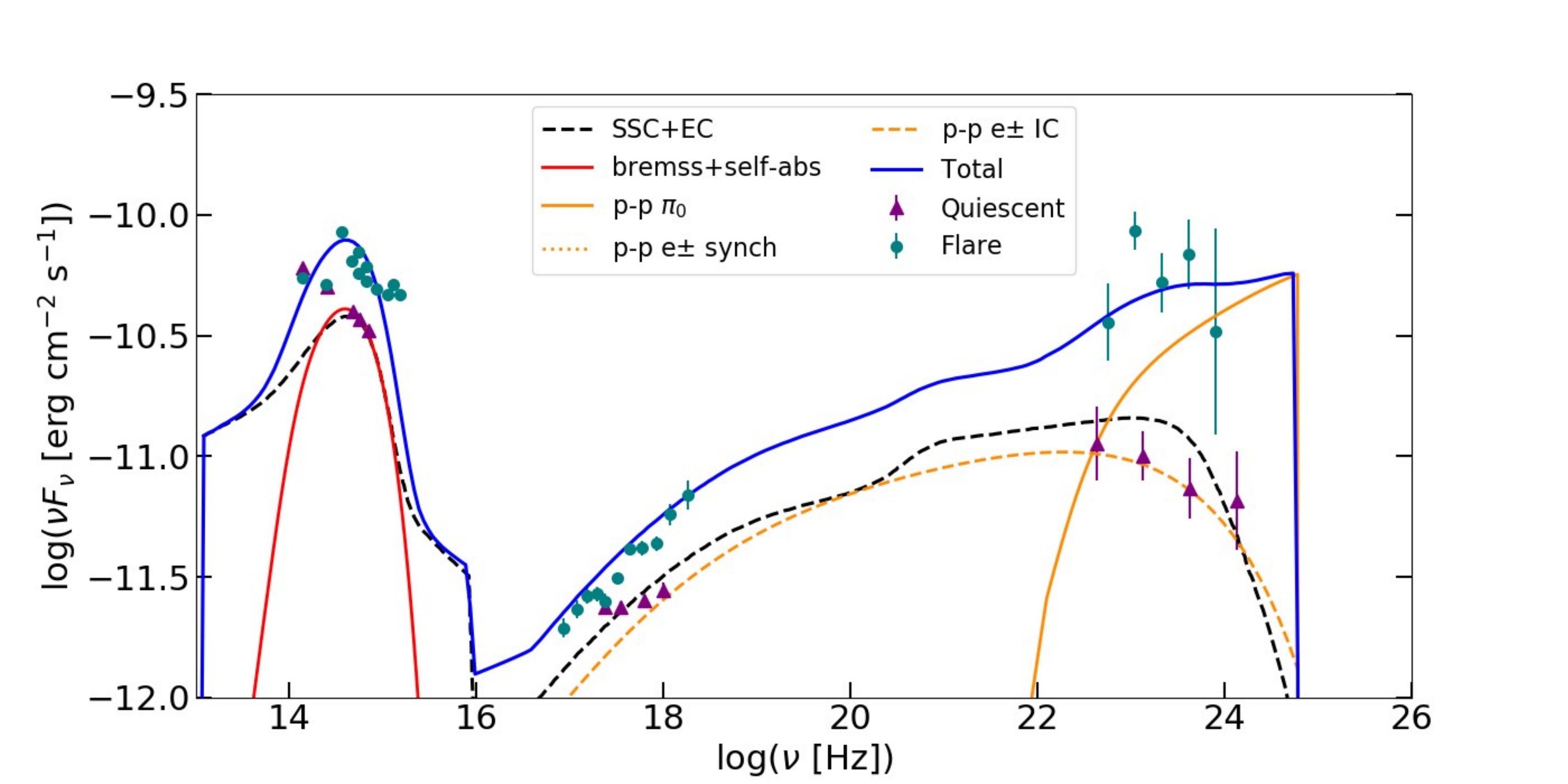
- Is the high energy SED of hadronic origin?
- Detectable neutrino fluxes?

To investigate this, we explore a *blast wave-like,* non-thermal emission model.



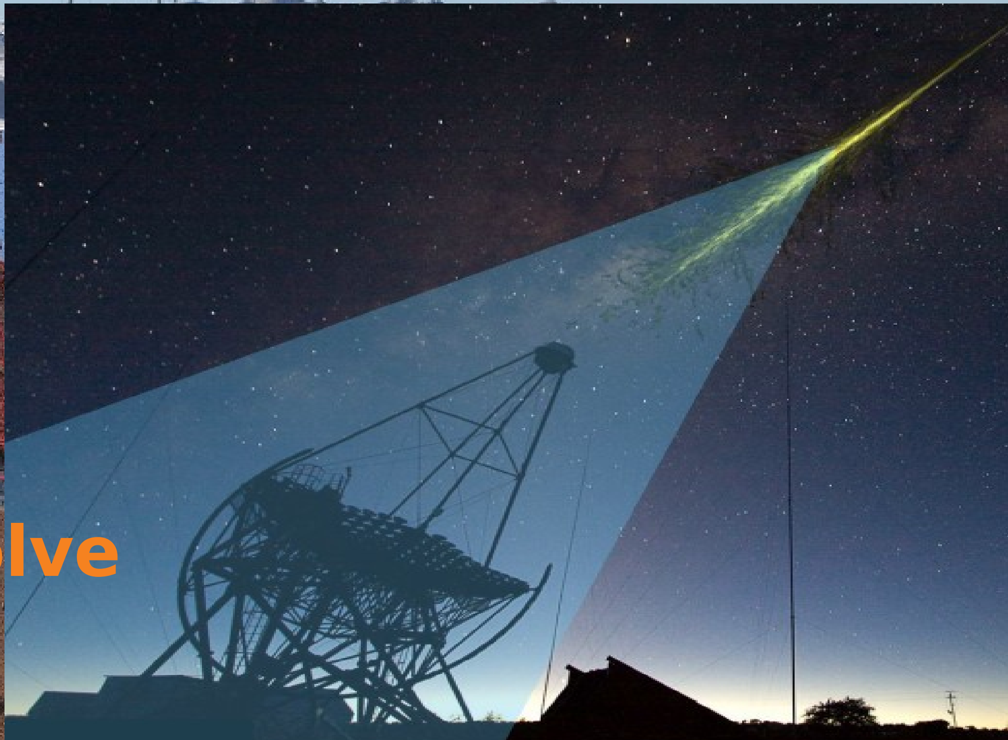
Valtonen et al. (2016)

The unique blazar OJ 287



- Rodríguez-Ramírez, Kushwaha & de Gouveia Dal Pino *in prep.*

Cherenkov Telescope Array



Exploring the Universe at the Highest Energies: will solve some of these puzzles

Summary

- Nonthermal emission allow us to unvail our universe in extreme conditions.
- Hadronic emission models are mandatory to interpret observations in forthcoming multi-messenger era.
- Forthcoming new instruments with umprecedent sensitivity will give us new surprises.
- Theoretical models and data analysis are highly requiered.

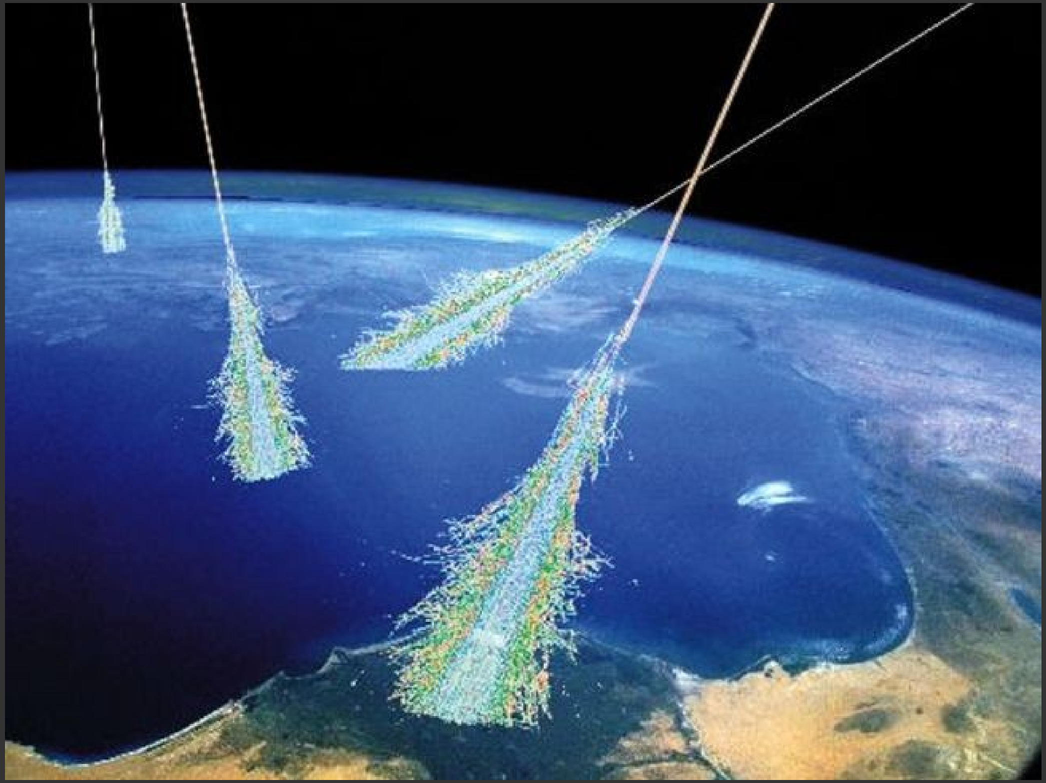
Backup slides

Cosmic-ray spectrum

Charge energetic particles, producing particle cascades in the atmosphere

- Where are they comming from?

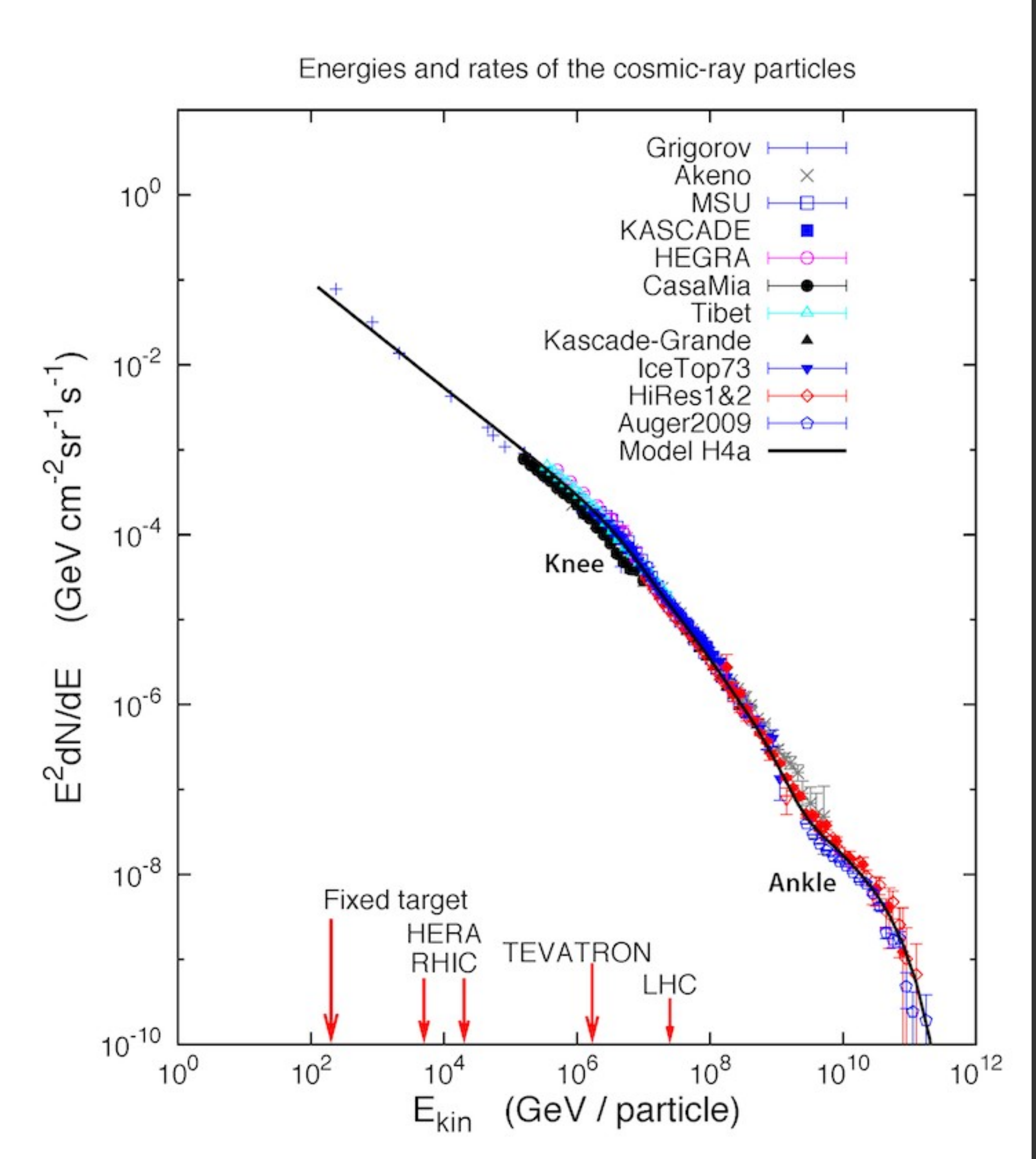
- How are they accelerated?

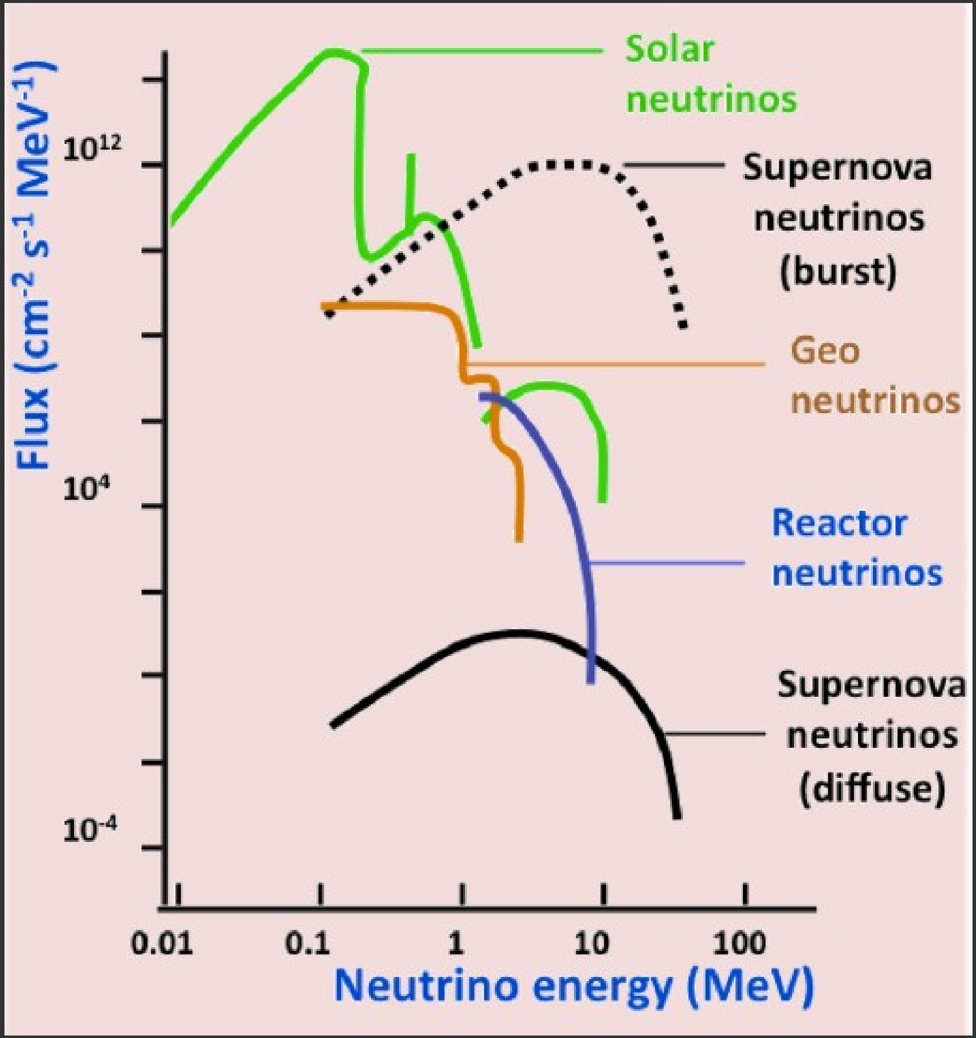


Cosmic-ray spectrum

Charge energetic particles, producing particle cascades in the atmosphere

- Where are they coming from?
- What is the acceleration mechanism?




Solar neutrinos
Supernova neutrinos (burst)
Geo neutrinos
Reactor neutrinos
Supernova neutrinos (diffuse)
Flux (cm-2 s-1 MeV-1)
10^12
10^4
10^-4
0.01
0.1
1
10
100
Neutrino energy (MeV)