PULSARS, PULSAR WIND NEBULAE and AGNs

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LECTURE V

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The Gran Sasso Science Institute (GSSI), founded in 2012 in L'Aquila (Italy) as Center for Advanced Studies of the National Institute for Nuclear Physics (INFN) and then established in March 2016 as a new university providing post-graduate education, offers 41 PhD fellowships for the academic year 2016/17.

OUTLINE

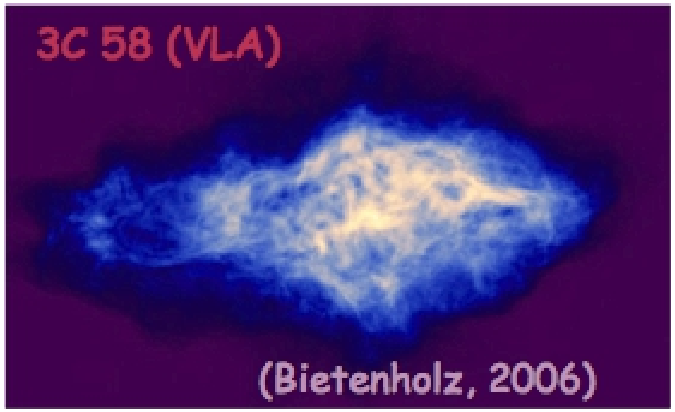
- **Pulsars & Pulsar wind nebulae**
  - *The unipolar inductor*
  - *Relativistic perpendicular shocks*
  - *Magnetic reconnection*
  - *A possible explanation for the positron fraction*
- **Active Galactic Nuclei**
  - *The jet-disk connection*
  - *The mechanism of Blandford-Znajek*
- **Electromagnetic cascade induced from UHECR**
  - *Effect on the diffuse extragalactic gamma-ray emission*

PULSAR WIND NEBULAE

What makes PWNe interesting

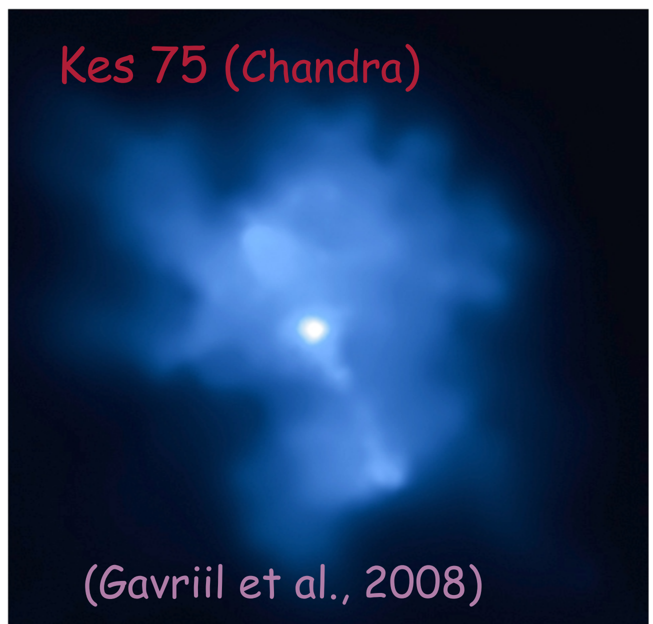
- The most numerous class of galactic TeV sources
- They enclose most of the pulsar spin-down energy
- Best-suited laboratories for the physics of relativistic astrophysical plasmas
- As many positrons as electrons
- Particle acceleration at the highest speed shocks in Nature ($10^4 < \gamma < 10^7$)
- **Only sources showing direct evidence for PeV particles**

PWNe at a glance



Plerions:

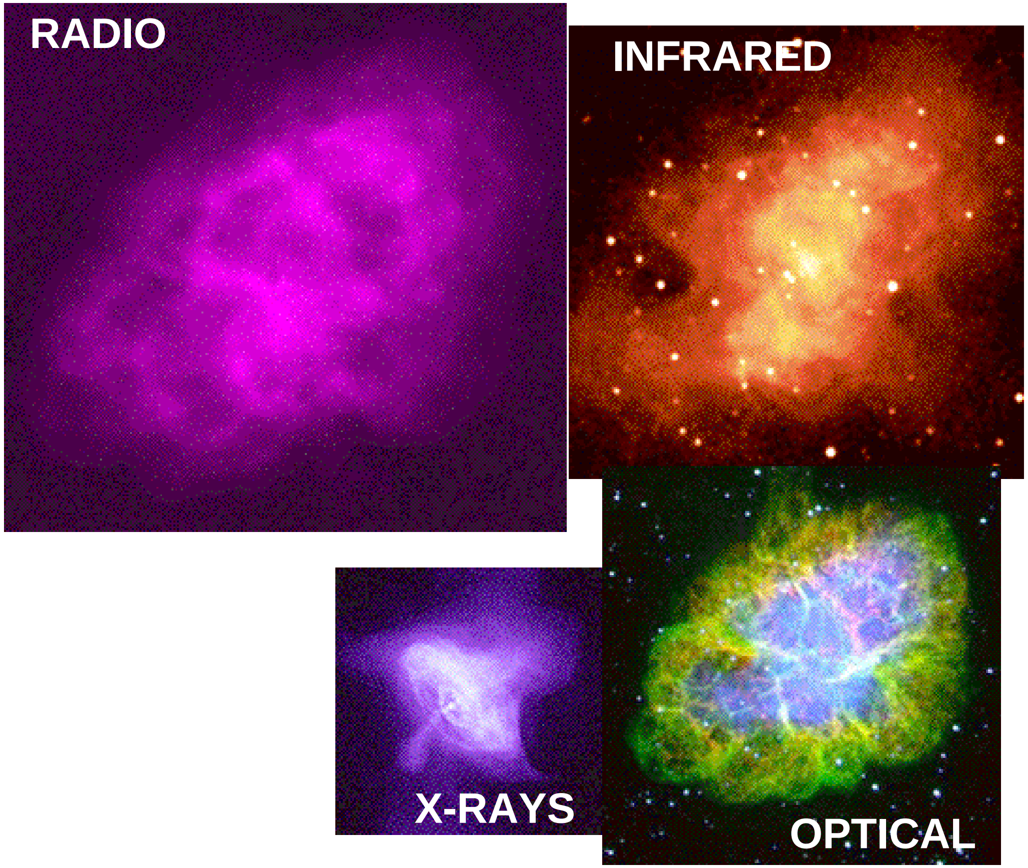
- ✓Supernova Remnants with a center filled morphology
- ✓Flat radio spectrum ($\alpha_R<0.5$)
- ✓Very broad non-thermal emission spectrum (from radio to multi-TeV γ-rays)

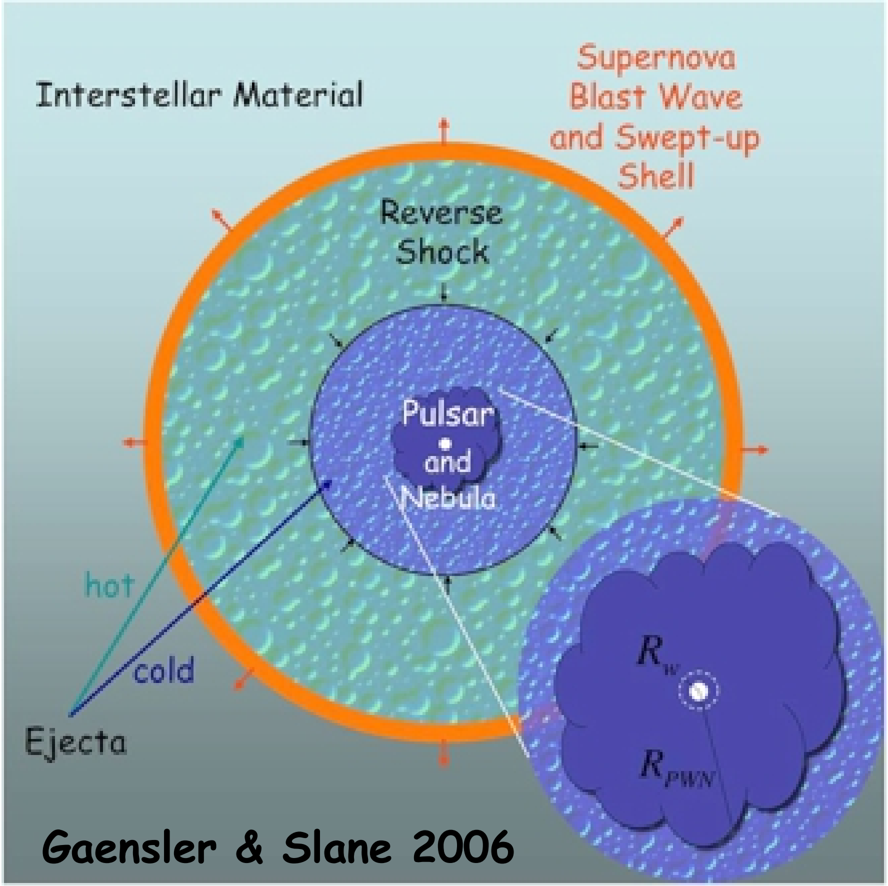


THE BASIC PICTURE

e.m. braking of fast-spinning magnetized NS → Magnetized relativistic wind

If wind efficiently confined
↓
Star rotational energy *visible* as non-thermal emission of the magnetized relativistic plasma

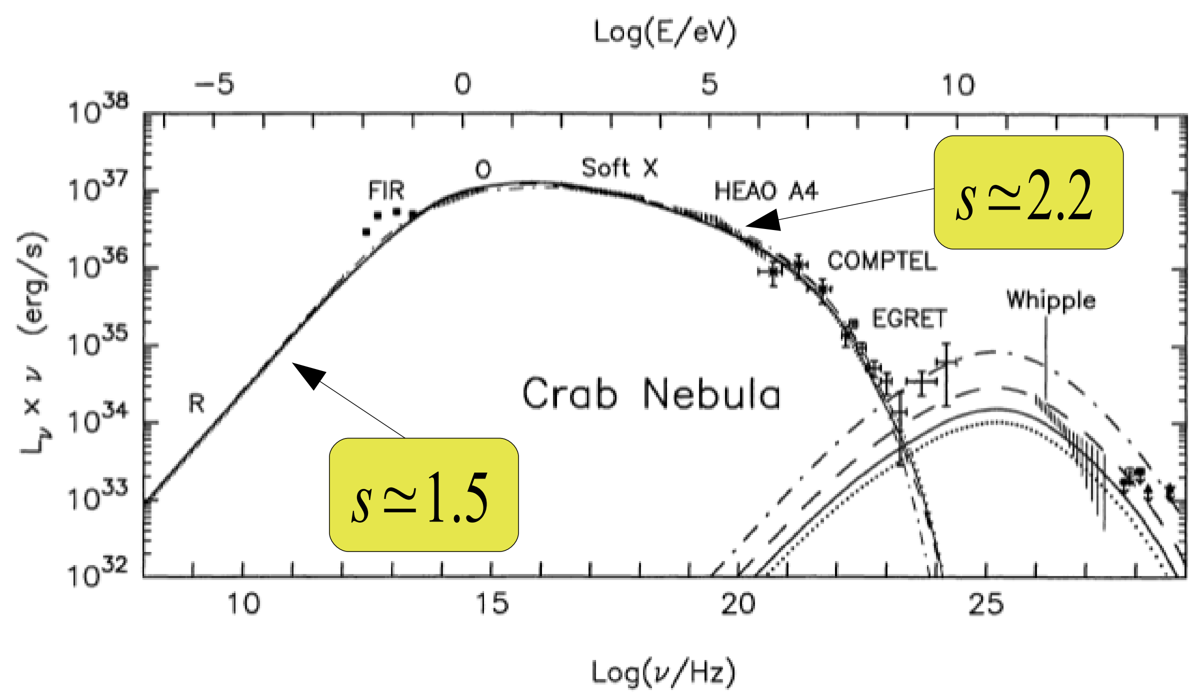




The Crab nebula
(where we have learnt most of what we know)

Primary emission mechanism:
synchrotron radiation by
relativistic particles in a
intense (>few x 100 B_{ISM}) *ordered*
(high degree of polarization, in radio, optical and even γ-rays, Dean et al. 08)
magnetic field

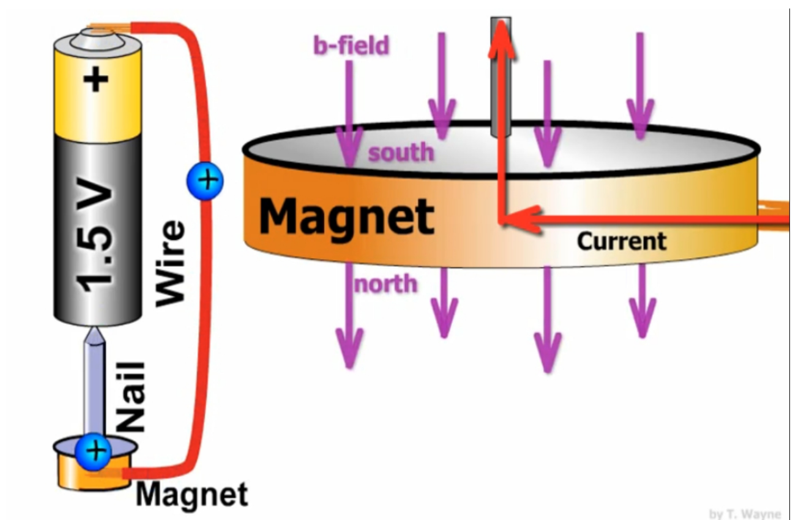
Source of B field and particles:
NS suggested before pulsar discovery
(Pacini '67)

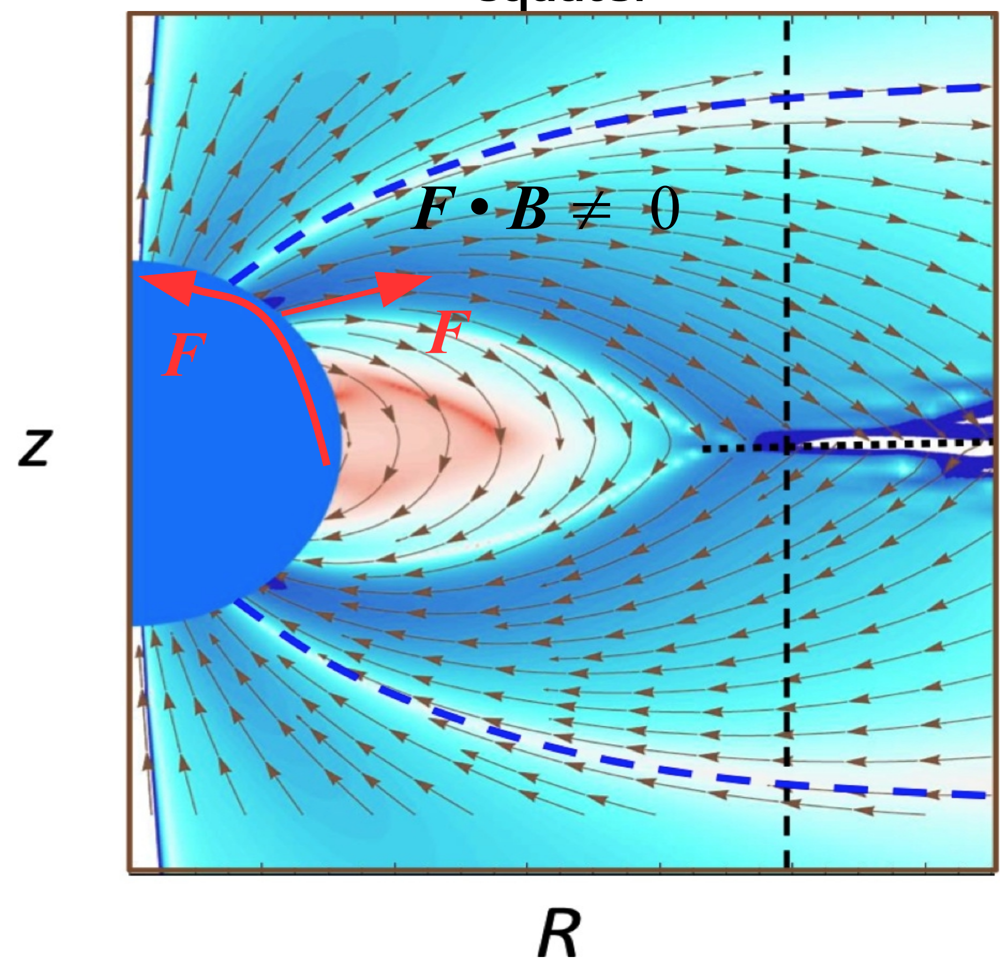


UNIPOLAR INDUCTOR

A magnetized conductor rotates if there is a potential difference between the pole and the equator

A magnetized conductor which rotates produces a potential difference between the poles and the equator





THE MAGNETOSPHERE

Electrons are stripped off the surface of the neutron star because of the strong electric field and drift along the direction of the magnetic field.

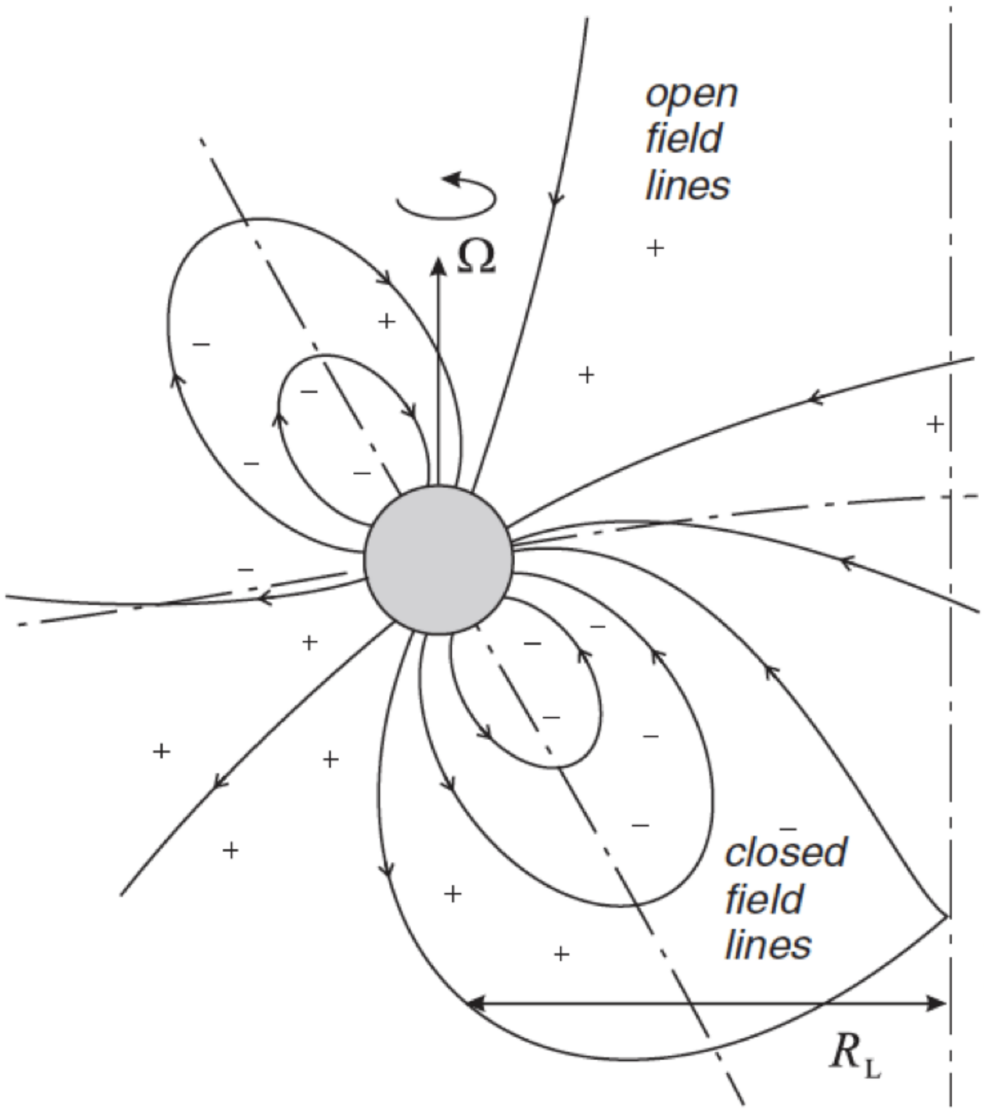
Any perpendicular momentum is rapidly dissipated through synchrotron emission

The combination of curvature radiation, pair production on the virtual photons of the magnetic field and ICS off the thermal photons leads to populate the magnetosphere with 10^4-10^6 pairs for each electron extracted from the surface.

The actual charge density is however fixed at the Goldreich-Julian value:

$$\rho_{\rm GJ} = \frac{1}{4\pi}{\rm div}\mathbf{E} \approx -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

THE MAGNETOSPHERE



THE MAGNETOSPHERE, FILLED WITH ELECTRON-POSITRON PAIRS IS FORCED TO COROTATE WITH THE STAR, AT LEAST OUT TO THE POINT WHERE THE CO-ROTATION SPEED EQUALS THE SPEED OF LIGHT. THIS IS CALLED THE LIGHT CYLINDER:

$$R_L = \frac{c}{\Omega}$$

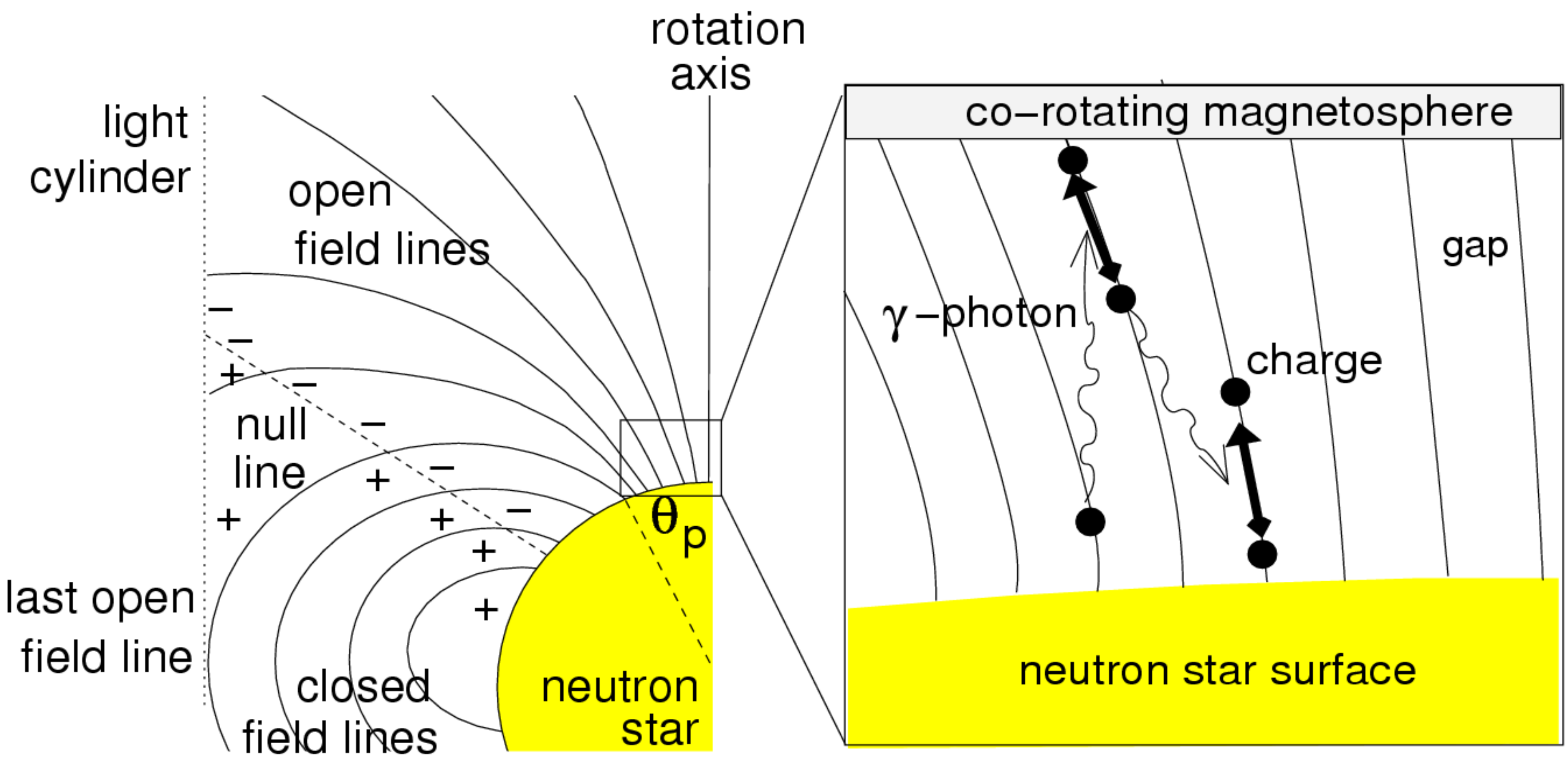
INTERESTINGLY ENOUGH, ALL PROPERTIES OF THE PWN ARE MAPPED INTO PROPERTIES OF THE LIGHT CYLINDER

PULSAR WIND LUNCHING

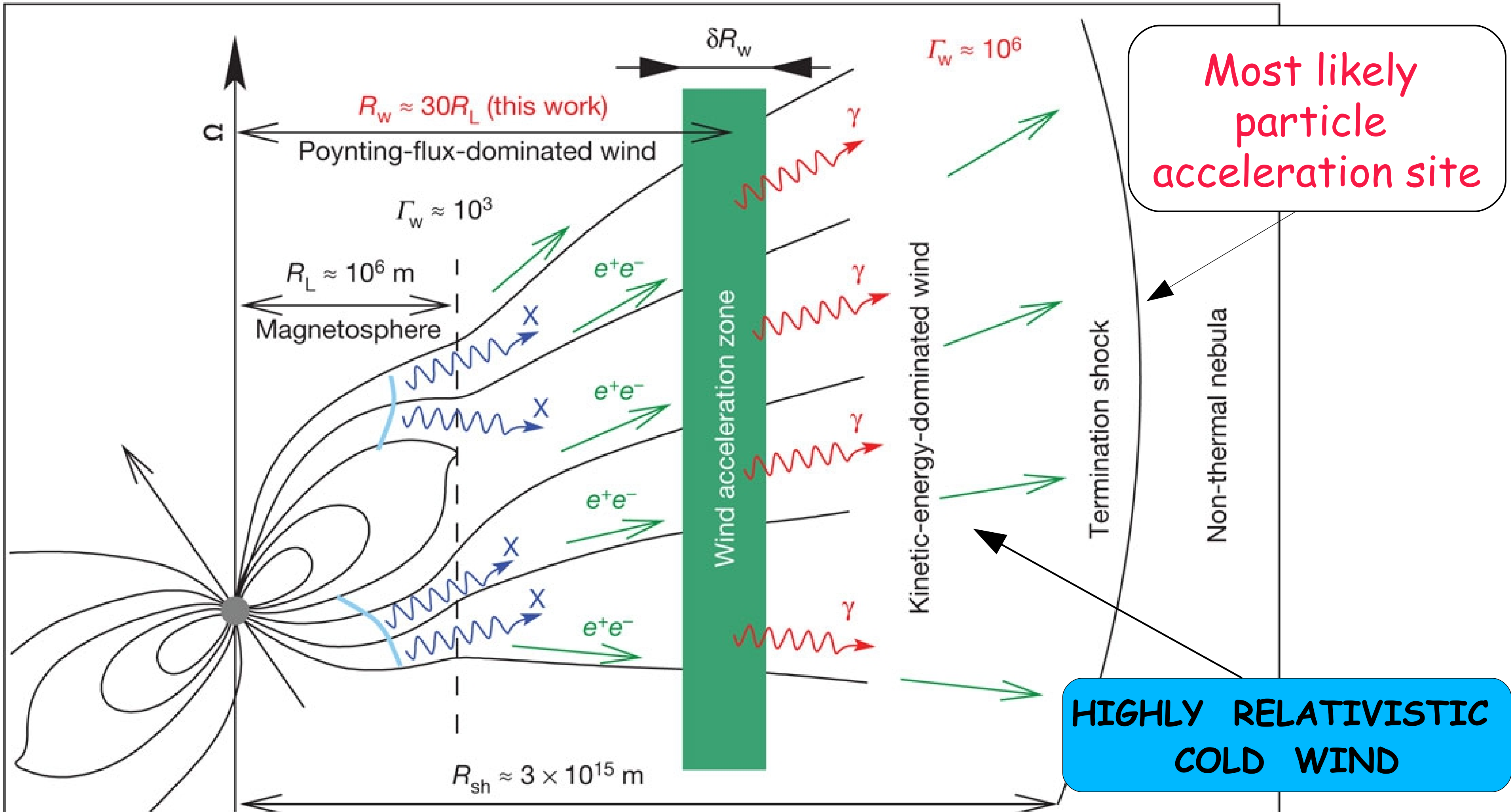
- Electrons located in open field lines can be accelerated producing photons due to the curvature radiation

- Photons start an electromagnetic cascade

- An pointing flux-dominated wind is lunched



THE BASIC PICTURE



F. A. Aharonian, S. V. Bogovalov & D. Khangulyan (2012)

In Crab R_{TS} ~0.1 pc
from pressure balance
(e.g. Rees & Gunn 74)

THE TERMINATION SHOCK

THE RADIUS OF THE TERMINATION SHOCK CAN BE DERIVED FROM THE PRESSURE BALANCE BETWEEN THE RELATIVISTIC WIND AND THE NON-RELATIVISTIC NEBULA: $R_{TS} \sim R_N (V_N/C)^{1/2} \sim 10^9\text{-}10^{10}\ R_{LC}$ (REES & GUNN 74) – HERE WE ASSUMED THAT THE MAGNETIC PRESSURE IS NEGLIGIBLE, NOT TRUE IN GENERAL – In the Crab R_{TS} ~0.1 pc

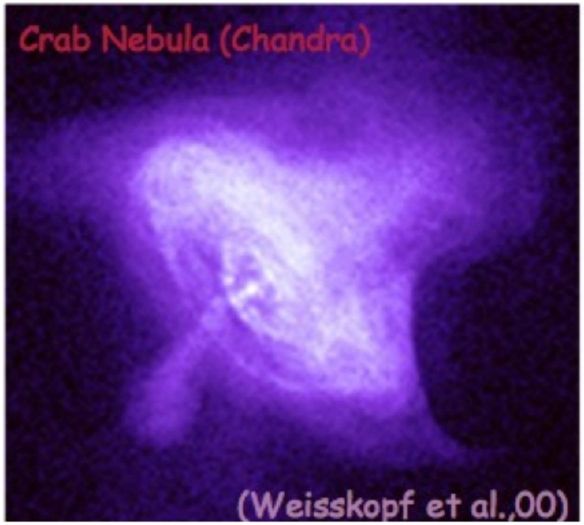
Composition: mainly pairs maybe a fraction of ions
Geometry: perpendicular where magnetized even if field not perfectly toroidal
Magnetization: $\sigma = B^2/4\pi n \Gamma m c^2 \rightarrow \sigma \sim V_N/c \ll 1$, a paradox

At $r \sim R_{LC}$: $\sigma \sim 10^4$ $\Gamma \sim 10^2$
(pulsar and pulsar wind theories)

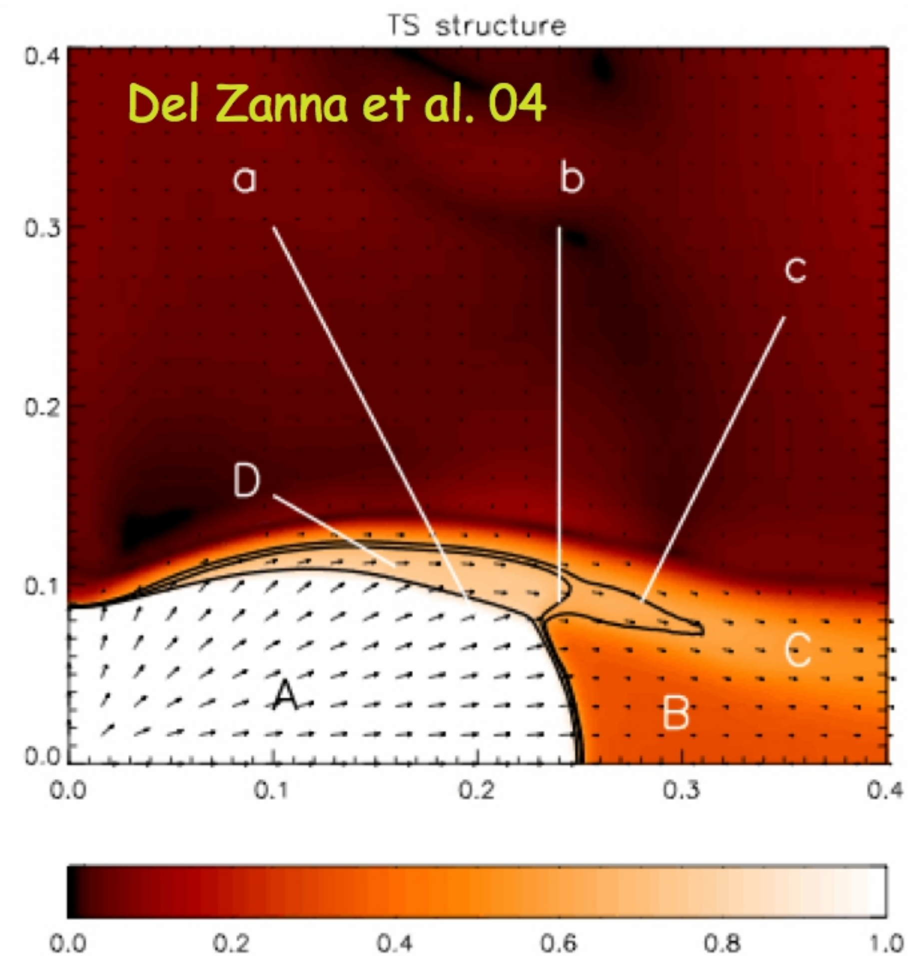
σ-paradox!

At R_{TS}: $\sigma \sim V_N/c \ll 1$(!?!) $\Gamma \in (10^4\text{-}10^7)$
(PWN theory and observations)

A MORE REALISTIC STRUCTURE OF THE TERMINATION SHOCK



The termination shock is not spherical

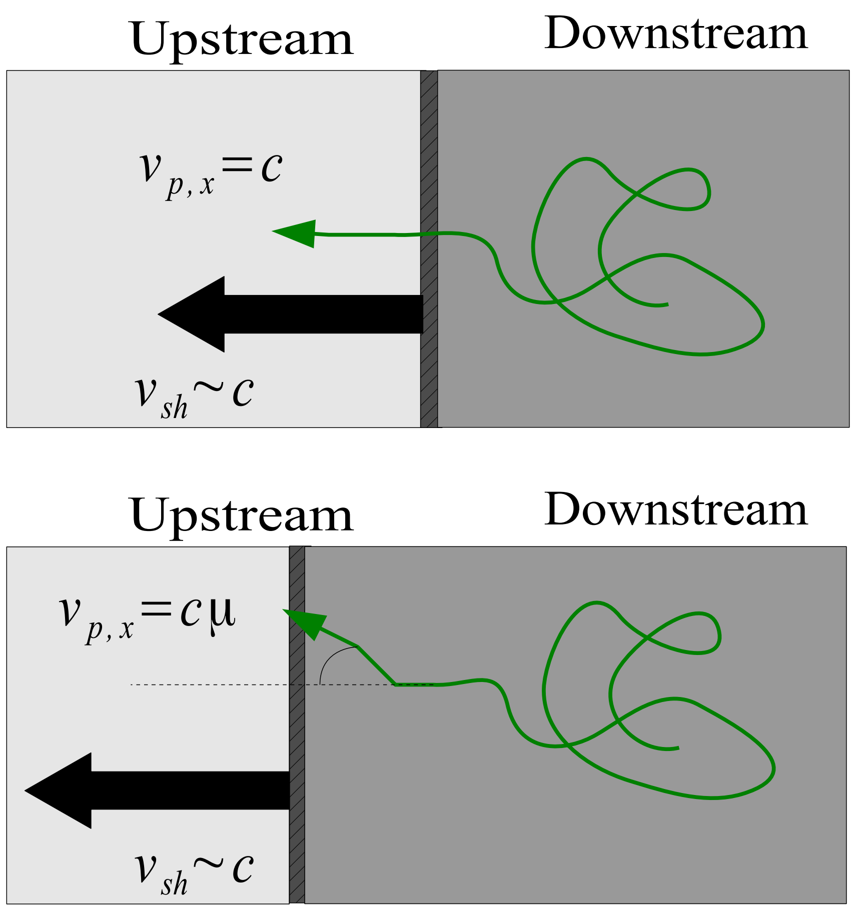


ACCELERATION AT THE TERMINATION SHOCK

Is the termination shock able to accelerate particles?

• Cold high relativistic wind: $\gamma > 10^5$
→ particles are catched by the shock as

$$\mu < 1/\gamma$$



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- High magnetization:

$$\sigma_1 = \frac{B_1^2}{4\pi\gamma_1 n_1 m_e c^2} > 1$$

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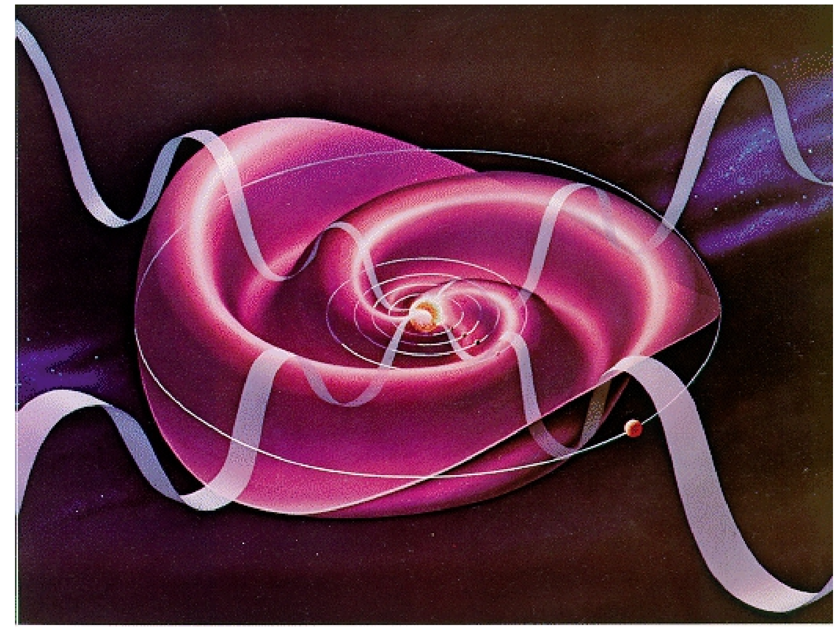
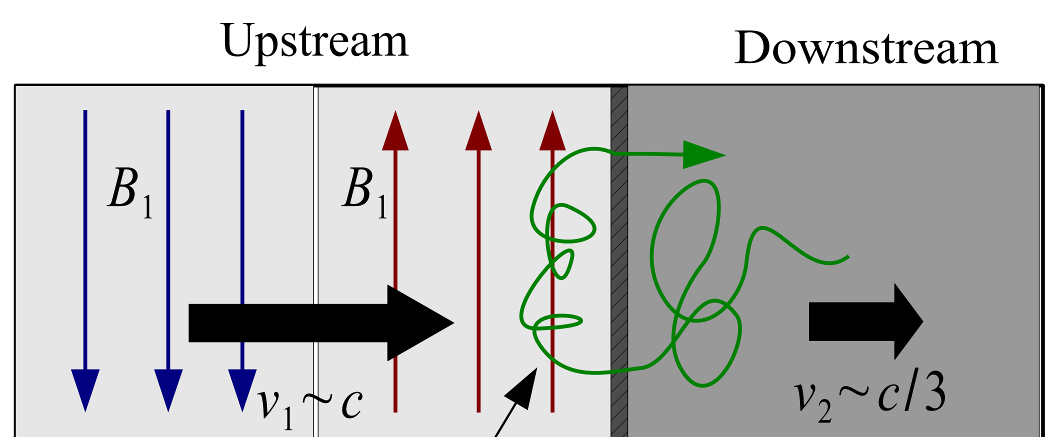
- Perpendicular shock configuration (Parker's spiral configuration)

Fermi-shock acceleration seems not suitable

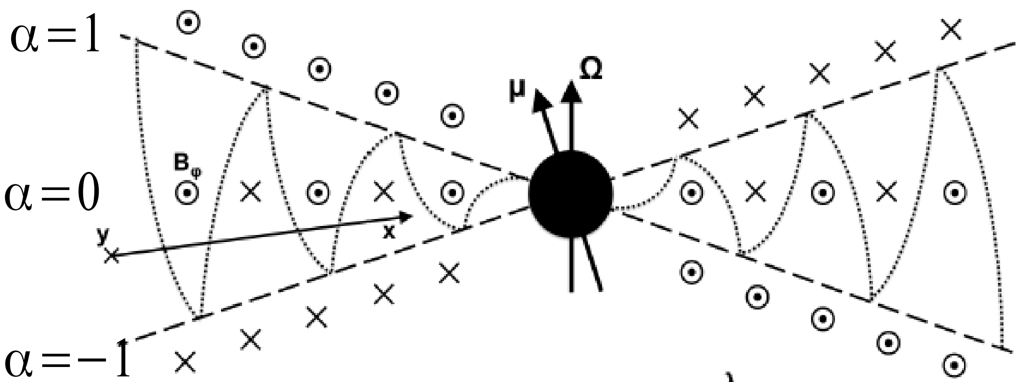


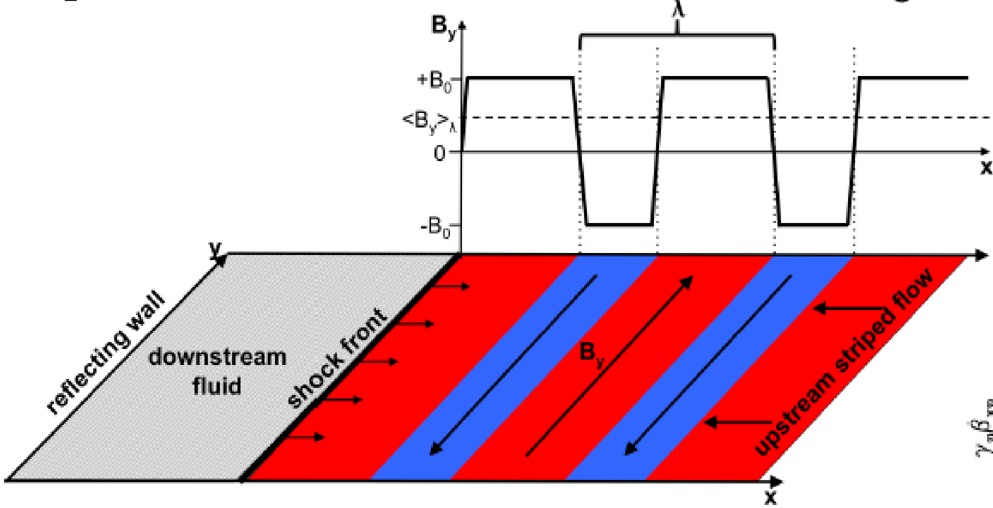


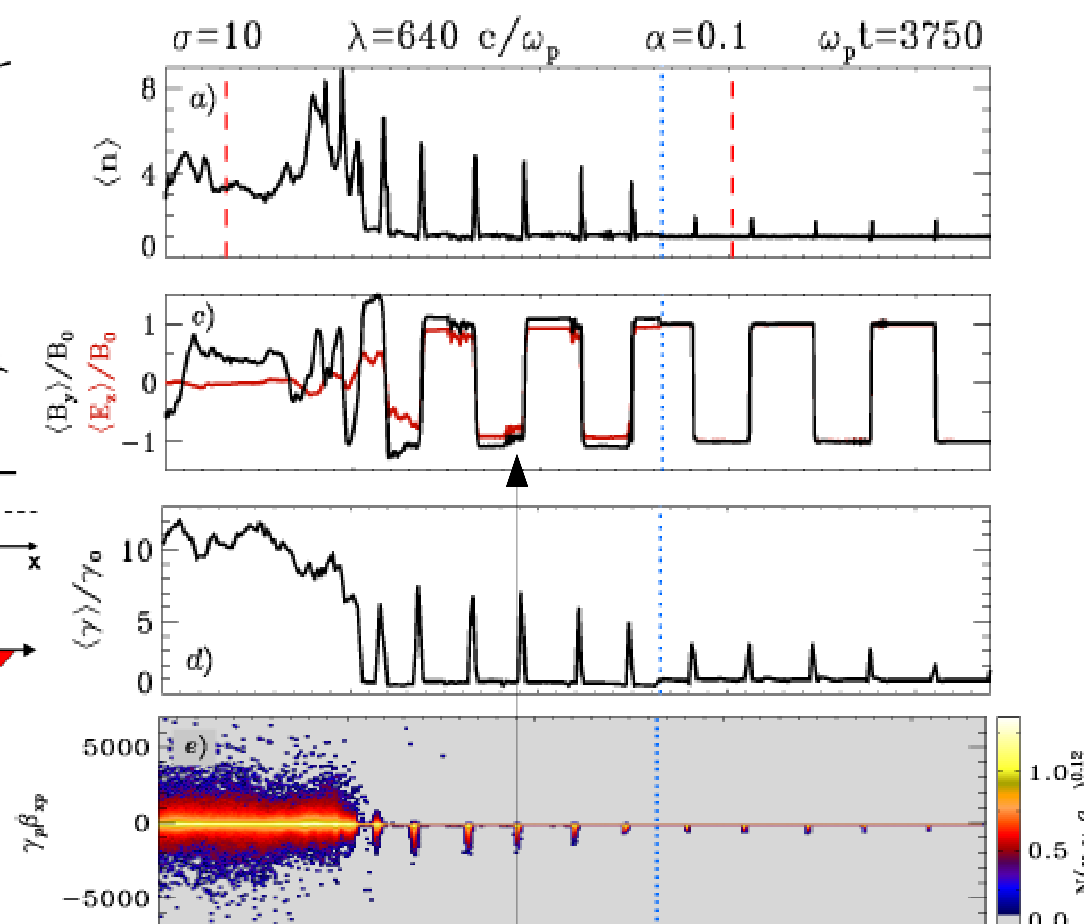
It is difficult for particles to diffuse upstream

STRIPED WINDS + TERMINATION SHOCK

From Sironi & Spitkovsky (2012)



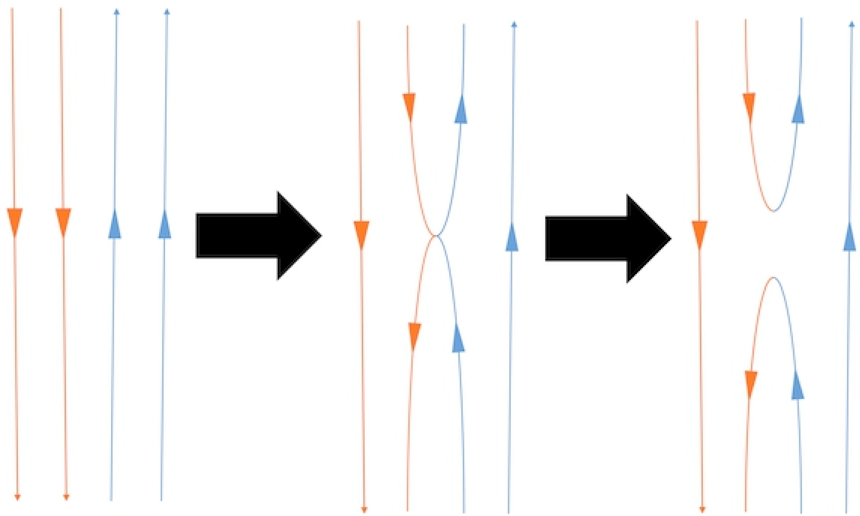




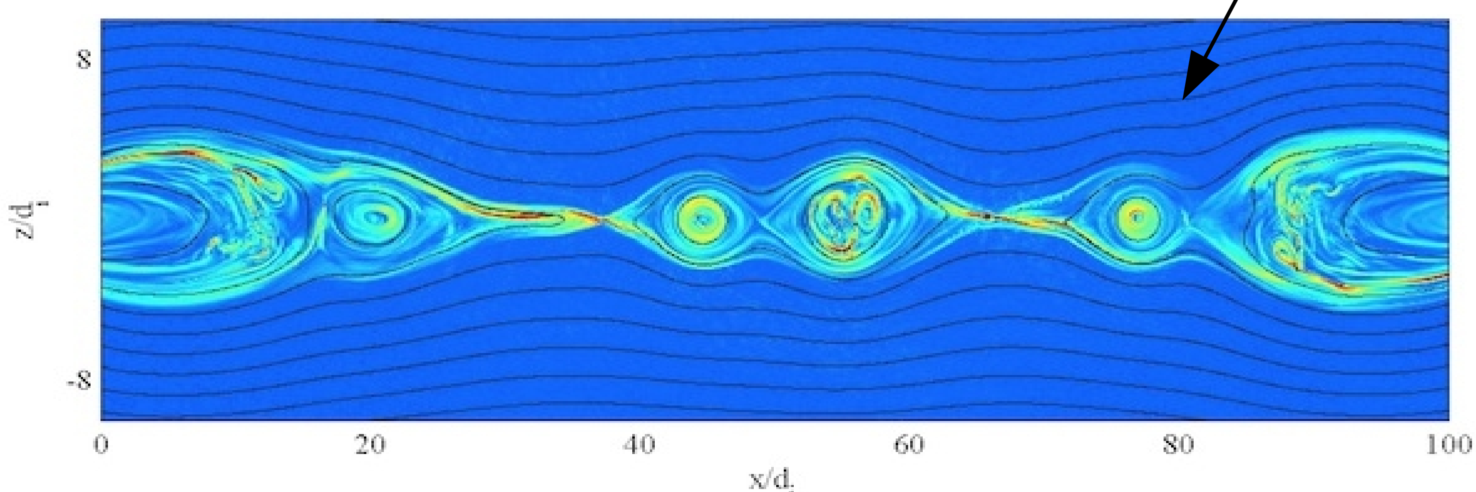
$$\frac{\langle B_y \rangle}{B_0} = \frac{\alpha}{2-|\alpha|} \rightarrow -1 < \alpha < 1$$

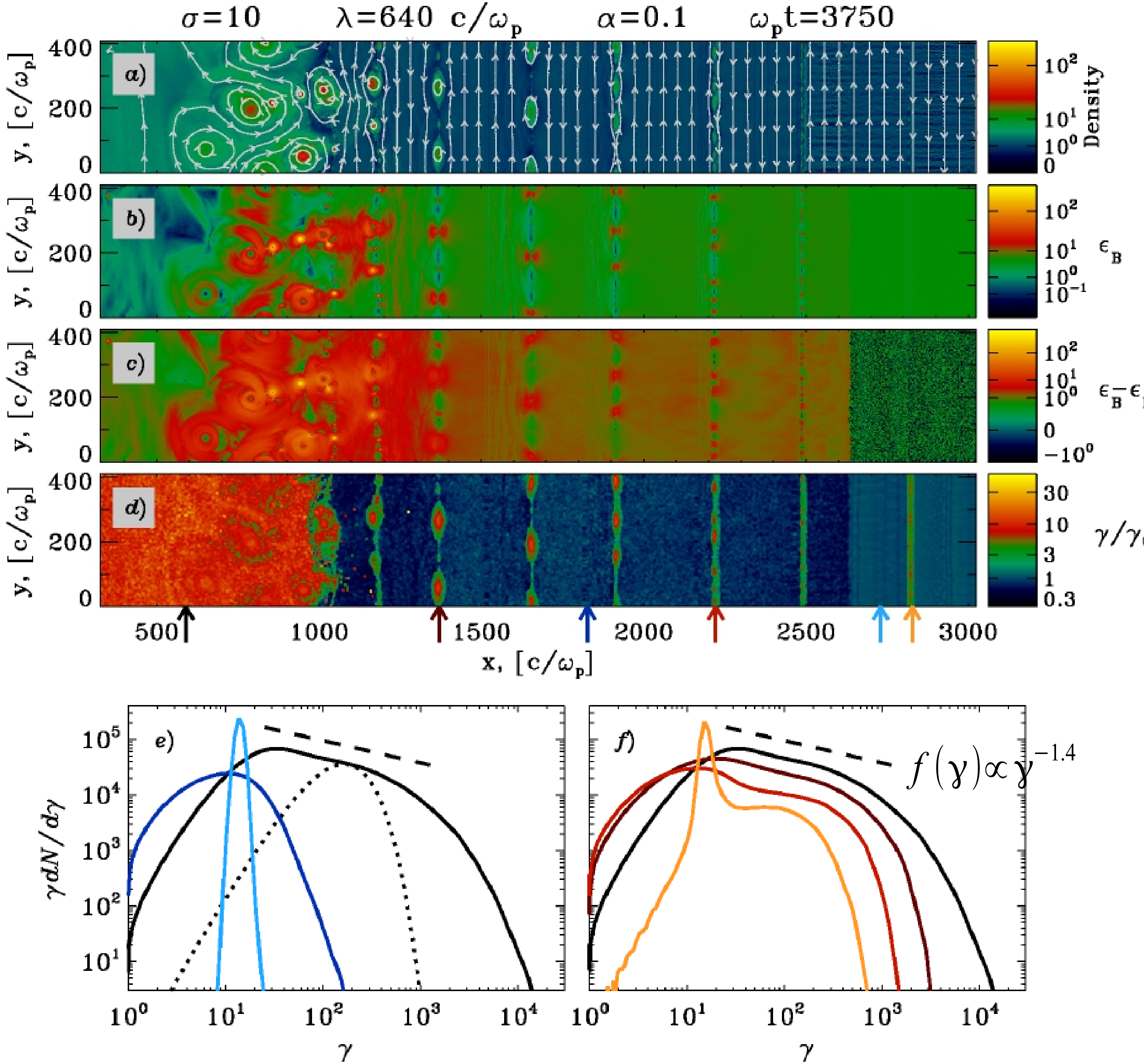
MHD shock drives the reconnection of magnetic field

MAGNETIC RECONNECTION IN ONE SLIDE



Magnetic hislands is where particles' energization occurs

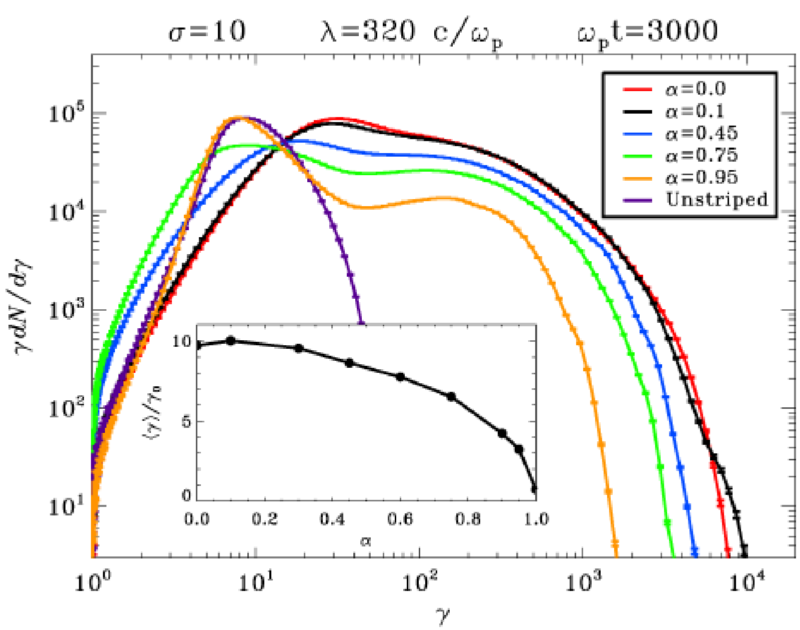


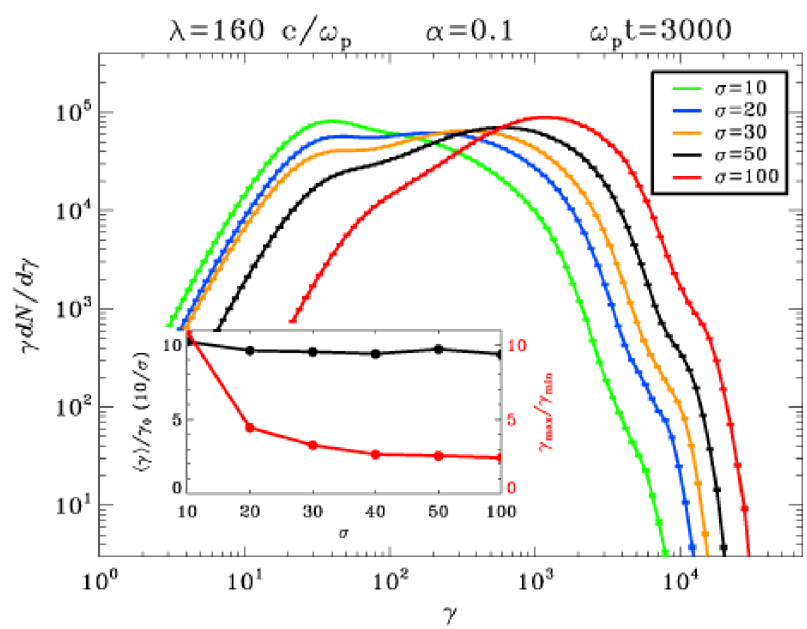


σ=10 λ=640 c/ωp α=0.1 ωpt=3750
a)
b)
c)
d)
y, [c/ωp]
x, [c/ωp]
500
1000
1500
2000
2500
3000
Density
εB
εB−εE
γ/γ0
e)
f)
γdN/dγ
γ
f(γ)∝γ−1.4

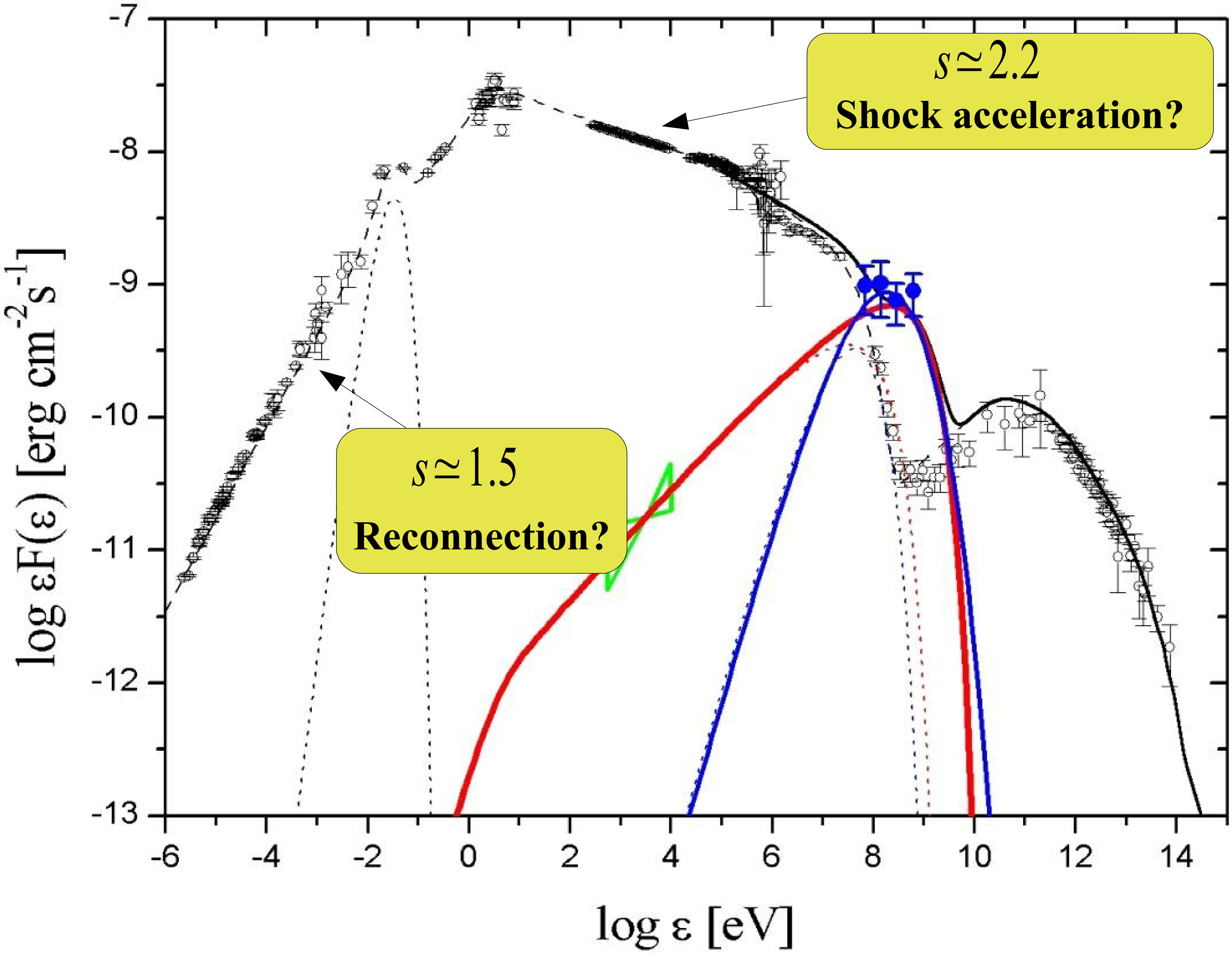
Particle spectrum from MF reconnection

- Slope of accelerated particles depends on magnetization σ
- For $\sigma \in$ [; : -; : :] $\rightarrow$ ***f(E) = E*** $^{-s}$ with ***s*** **∈ [1-2]**





SPECTRUM OF CRAB



THE POSITRON FRACTION

Life of an elctron within a SNR

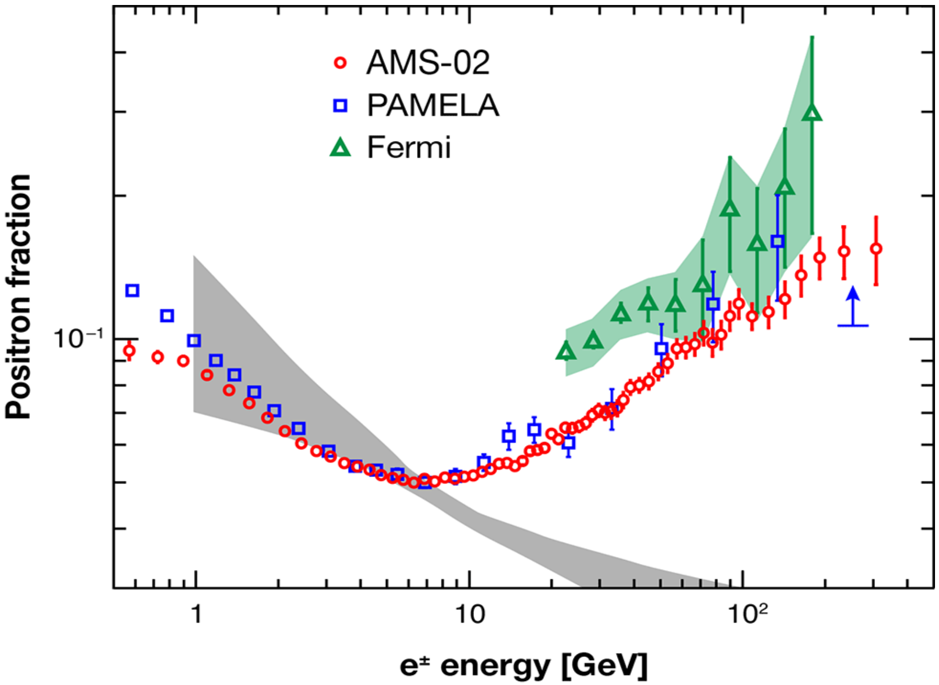
Pulsar are the primary astrophysical generators of positrons

If we want to explain the Pamela positron spectrum, pairs need to escape from the PWN and the SNR

The pairs inside the PWN try to expand against the ejecta adiabatic+ radiative losses

When the reverse shock of the blast wave reaches the center, some level of compression might occur
...but it could even displace the PWN (see case
electrons and positrons

In general however the electrons and positrons stay inside the remnant and keep losing energy both radiatively and adiabatically



BUT do we really need to retrieve these pairs from in there?

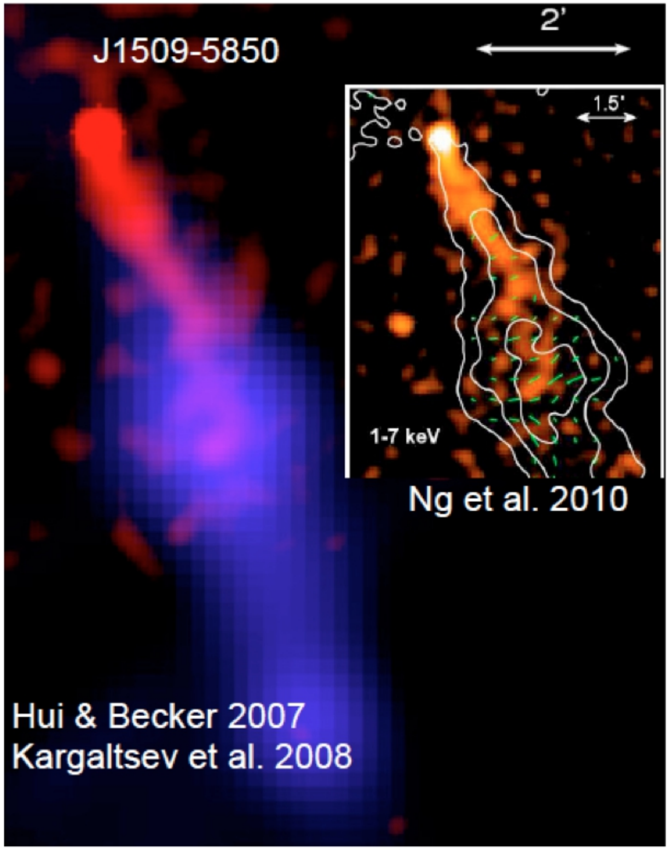
Pulsars escaping from the SNRs

Pulsars which born with high kick velocity can escape from the SNR in a relatively shocrt time when the pulsar is still energetic enough

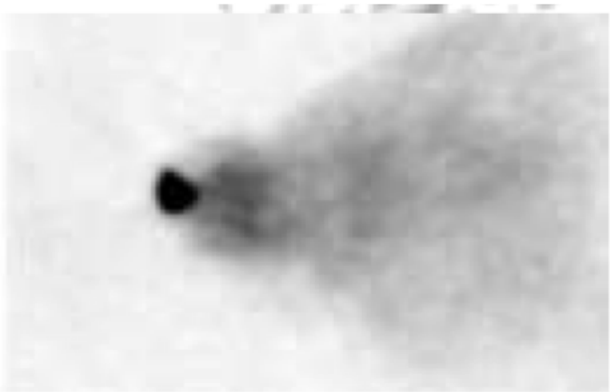
- We see escaping pulsars: bow shock PWNe

In two cases of bow shock PWN outside the SNR in which we have radio measurement, we infer a spectrum of accelerated particles with slope ~ -1.5

Those middle age PWN could be the primary sources od positrons in the Galaxy

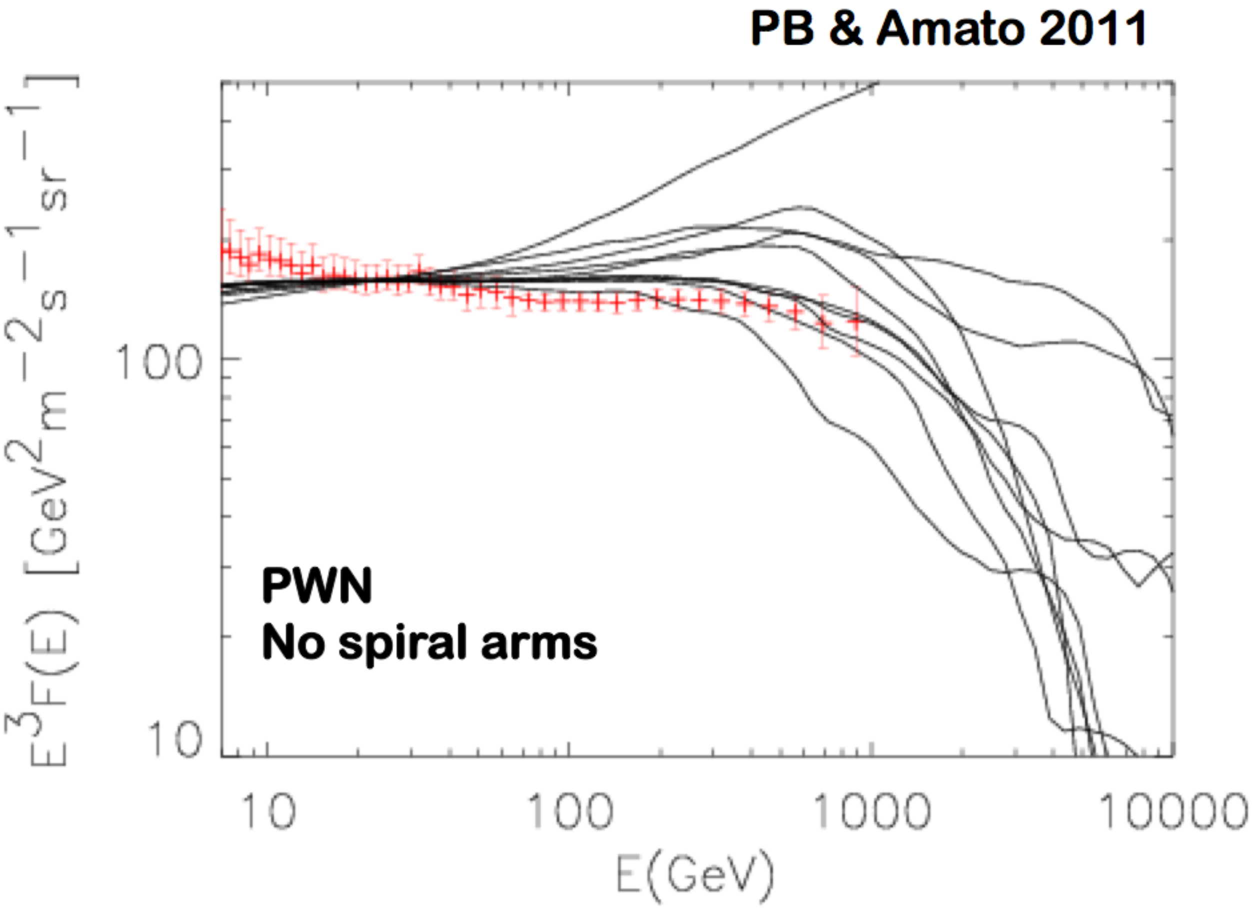


PSR J1509–5850
Slope radio: -0.26
Slope Electrons: -1.52
Ng et al. 2010

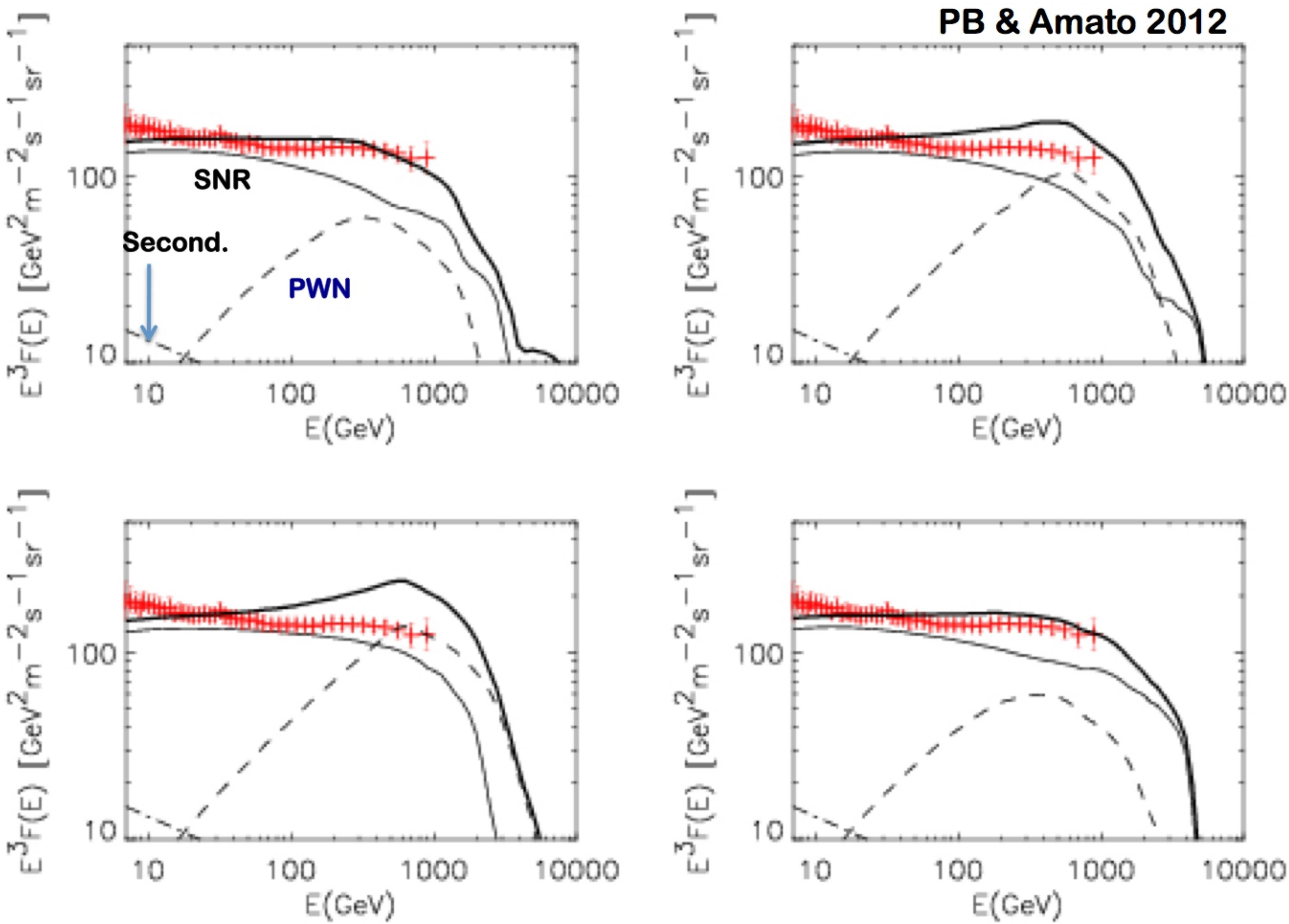


The Mouse
Slope radio: -0.3
Slope Electrons: -1.6
Gaensler et al. 2004

POSITRONS FROM PWNe

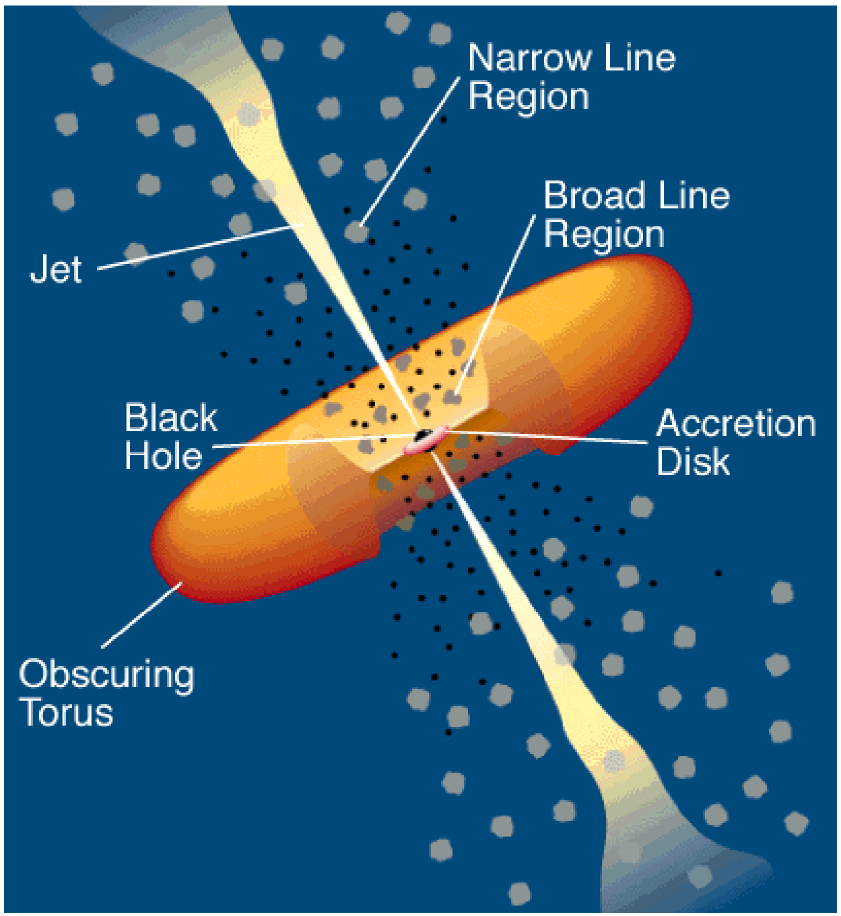


Including also SNRs



THE CENTRAL ENGINE OF AGNs

ACTIVE GALACTIC NUCLEI



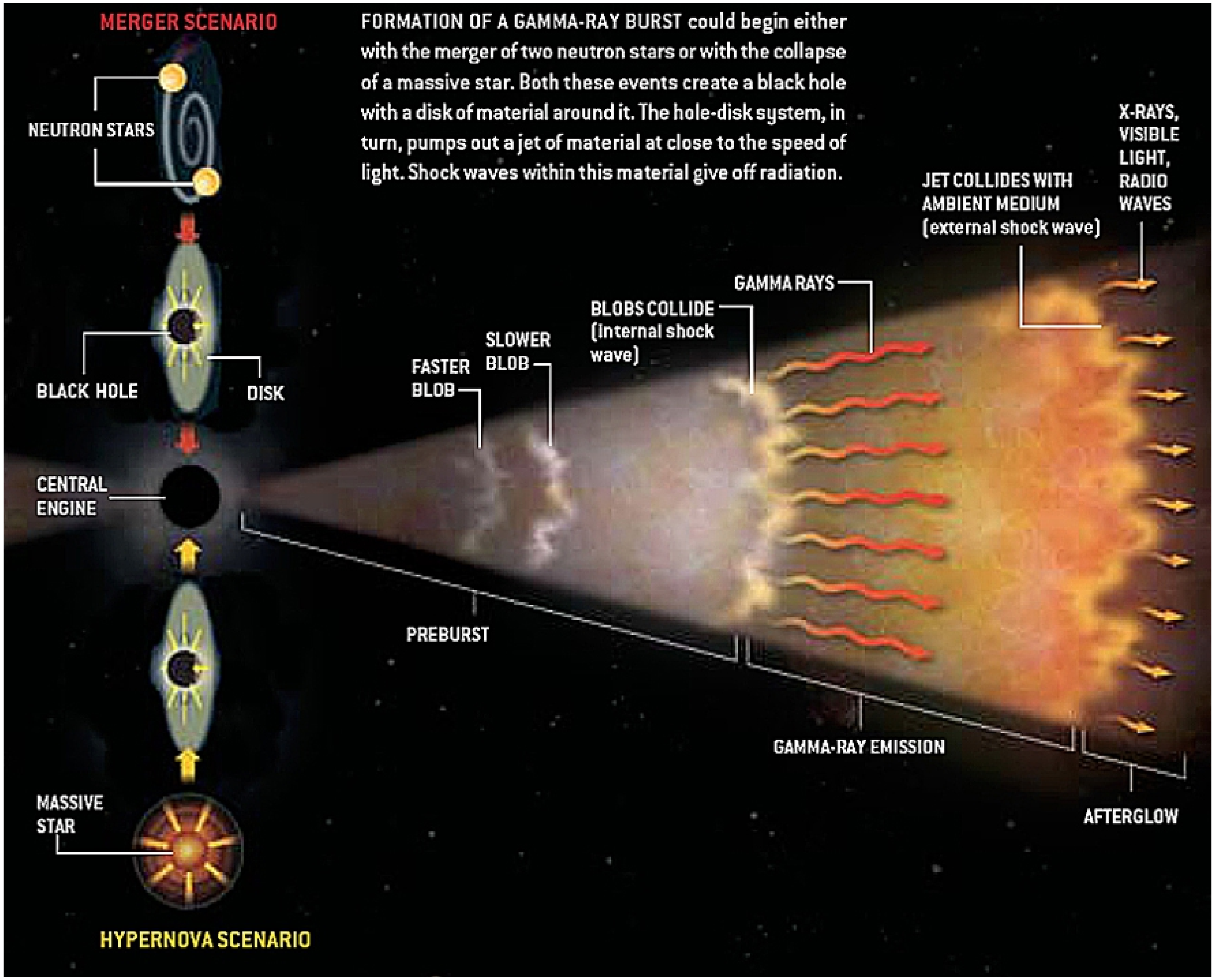
Just two basic questions:

1) Which is the process that energize particles inside the jet?

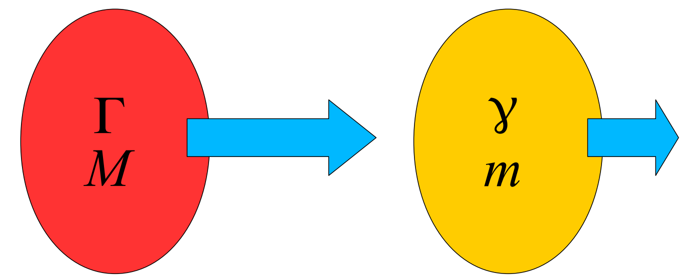
2) Which is the mechanism that power the jet?

Internal shocks

Particle energization in the jet: internal shocks?



Internal shocks



How much energy can be extracted from internal shocks?

Assuming two colliding blobs with lorentz factors Γ and γ and masses *M* and *m*

$$\begin{cases} \mathcal{E}_0/c^2 = M\Gamma + m\gamma = (M + m + \mathcal{E}/c^2)\,\Gamma_f \\ P_0/c = M\sqrt{\Gamma^2 - 1} + m\sqrt{\gamma^2 - 1} = (M + m + \mathcal{E}/c^2)\,\sqrt{\Gamma_f^2 - 1}. \end{cases}$$

Energy conservation

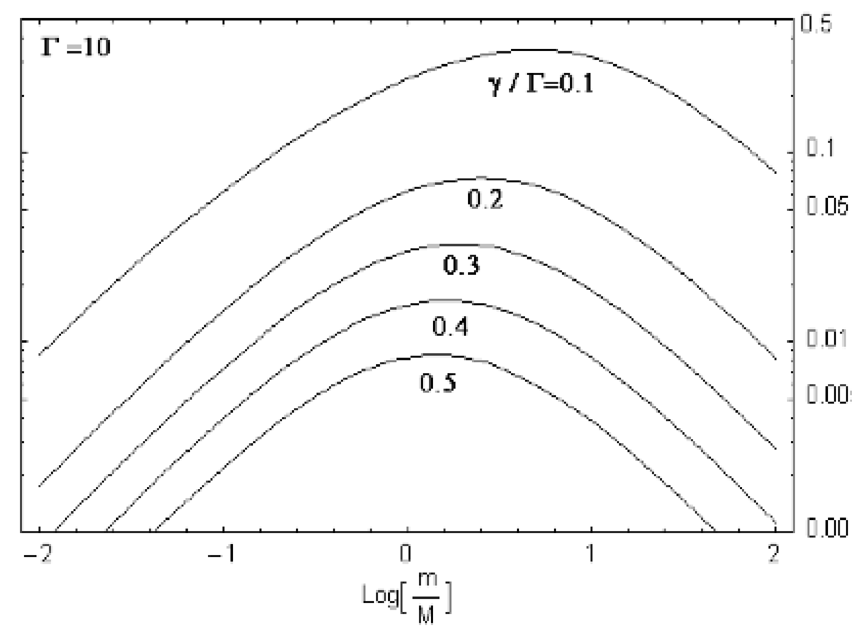
Momentum conservation

Solution:

$$\begin{cases} \mathcal{E} = \mathcal{E}_0/\Gamma_f - (M+m)c^2 \\ \Gamma_f = \mathcal{E}_0 \Big/ \sqrt{\mathcal{E}_0^2 - P_0^2 c^2}\,. \end{cases}$$

Efficiency:

$$\eta = \frac{\mathcal{E}}{\mathcal{E}_0} = \frac{1}{\Gamma_f} - \frac{1 + m/M}{\Gamma + \gamma m/M}.$$



The efficiency is high only if Γ >> γ
 relativistic shocks

Reconnection

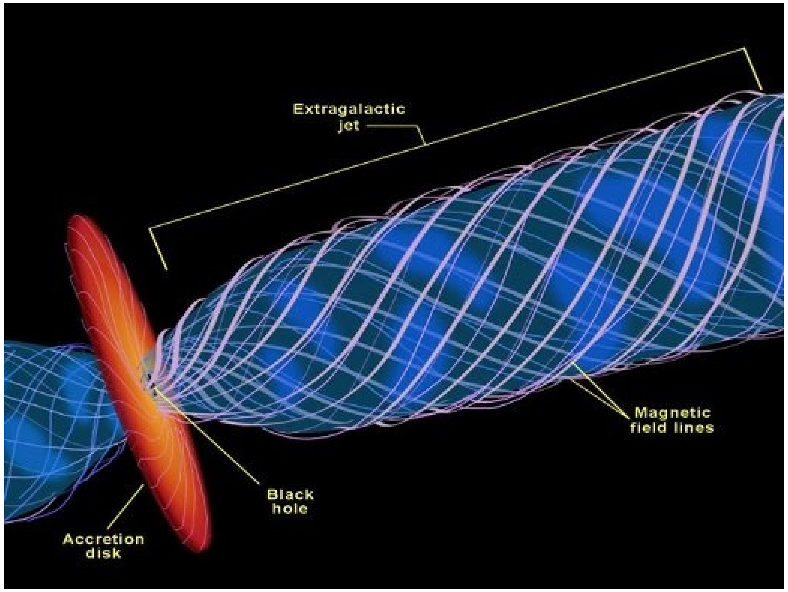
BUT: Fermi acceeration seems to be difficult at relativistic shocks

RECONNECTION?

We know that at some level it has to occur:

 from theory we know that when the jet is lunched it is pointing flux-dominated

 Few kpc away from the cente the magnetic energy is much smaller (probably in equipartition with mass energy)



ALSO: the spiral configuration of the magnetic field does not help the reconnection

Possible roles of:

- Instabilities
- Intermittency of the central engine

Power of jets vs. power of accreation disks: observations

From Ghisellini, Tavecchio et al., Nature 515, 376 (2014)

Disk lumisosity is inferred from the luminosity of the Broad Line Region:

$$L_{BLR} = \phi L_{disk} \quad with \quad \phi \approx 0.1$$

Jet luminosity is inferred using data from **Fermi-LAT** and assuming a leptonic 1-zone model:

$$P_{rad} = 2 f \; L_{jet}^{bol} \; \Gamma^{-2}$$

Two jets — Geometric factor — Bolometric luminosity

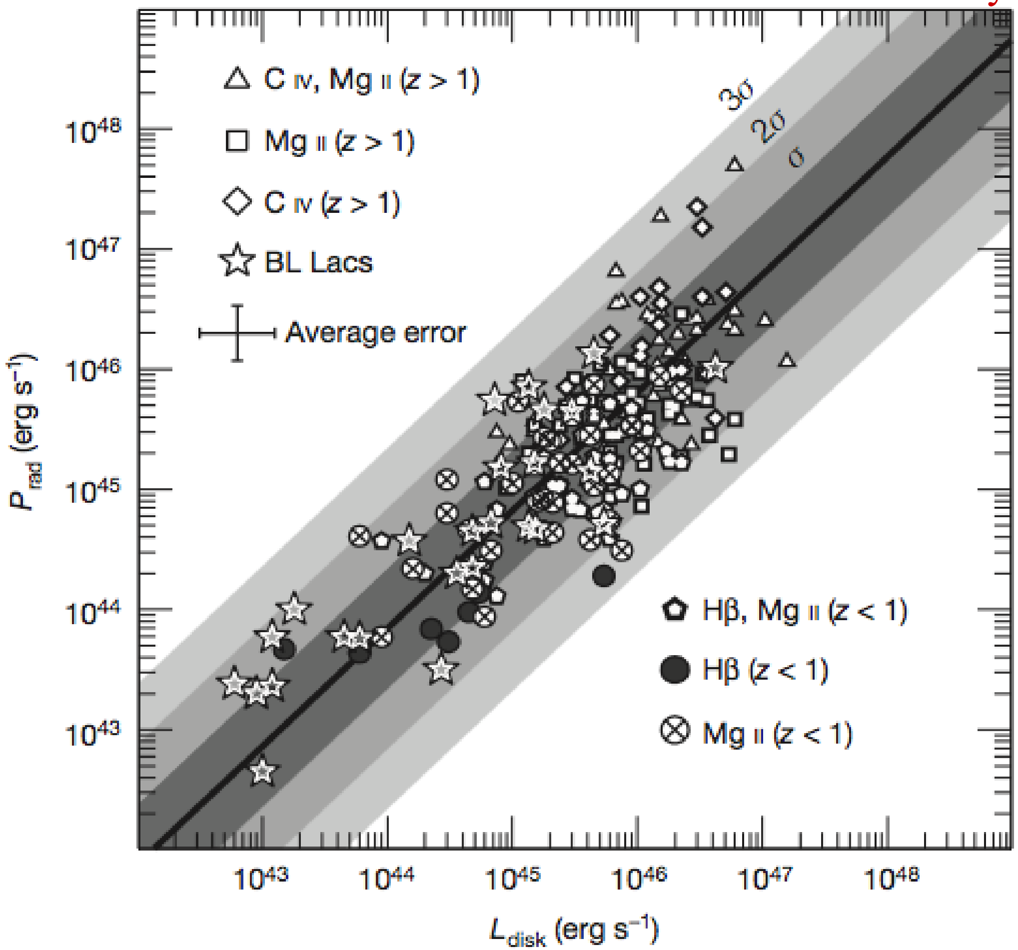
with $\Gamma \simeq 10$. The following correlation is found:

$$\log(P_{rad}) = 0.98 \; \log(L_{disk}) + 0.639$$

But P_{rad} is a lower limit to the jet power because it neglects completely the kinetic energy.

Relation between jet luminosity and disk luminosity fo 191 FSRQ and 26 BL Lac

Different symbols correspond to the different emission lines used to estimate the disk luminosity



Power of jets vs. power of accreation disks: observations

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Theoretical models gives:

$$P_{rad} \approx 0.1\, P_{jet}$$

For rapidly rotating black holes the maximum disk luminosity is

$$L_{disk} = \eta \dot{M} c^2 \quad with \quad \eta \simeq 0.30$$

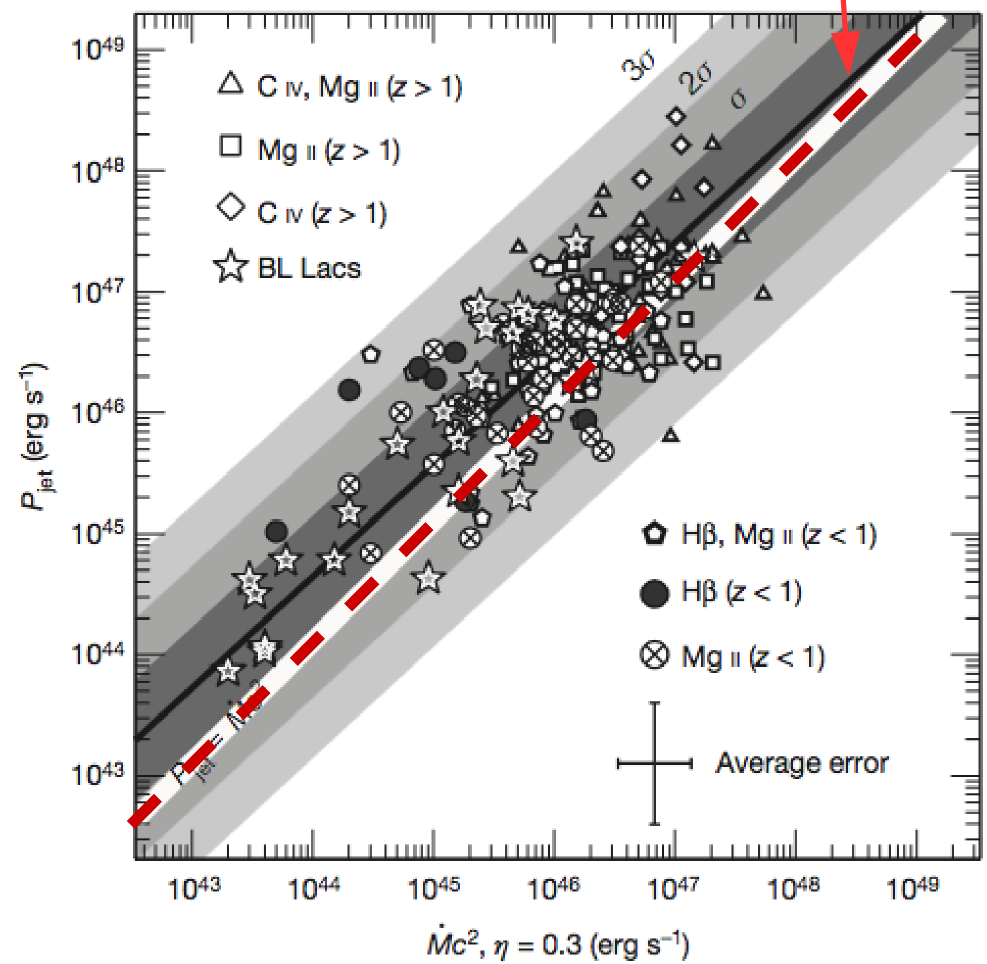
Assuming $\eta = 0.3$ it is possible to correlate the jet power with the accreated mass. They get:

$$\log(P_{jet}) = 0.92 \log(\dot{M} c^2) + 4.09$$

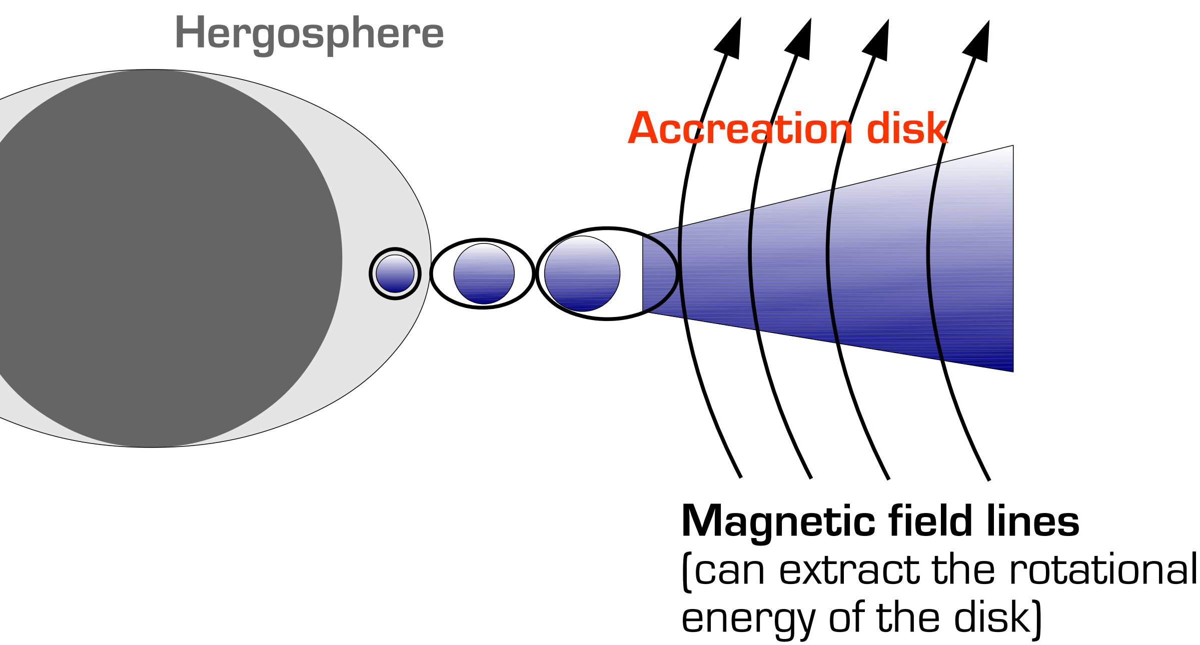
But P_{rad} is a lower limit to the jet power because neglect completely the kinetic motion.

From the data → $P_{jet} > \dot{M} c^2$

$$P_{jet} = \dot{M} c^2$$



Extracting energy from the black hole: unipolar inductor applied to the disk-BH system



Minimal rotating Black Hole

The last stable orbit is outside the hergosphere

$$r_H = M^2 + \sqrt{M^2 - a^2}$$
$$r_e = M^2 + \sqrt{M^2 - a^2 \cos(\theta)}$$
$$r_{LSO} = 6M$$

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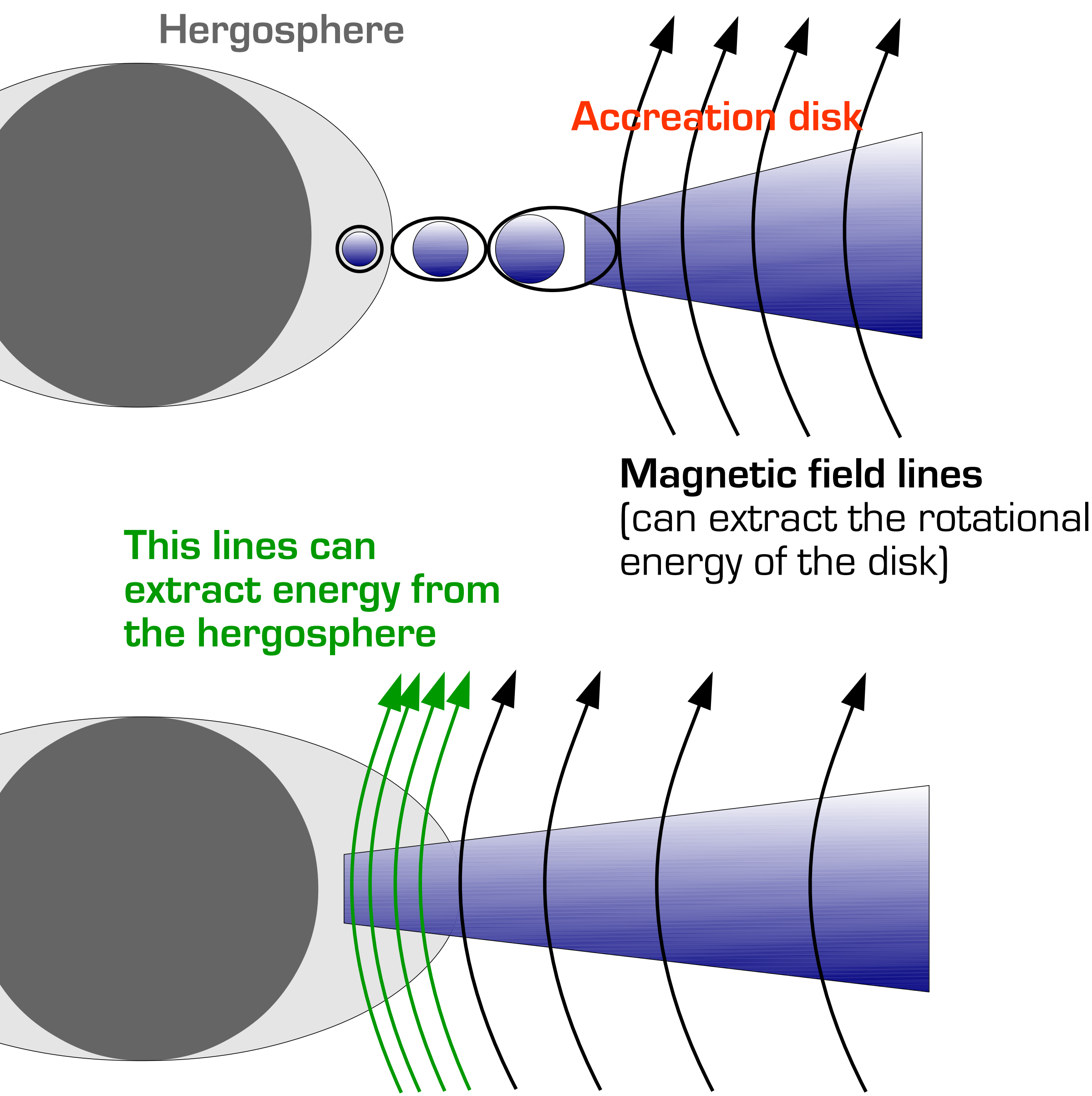

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$$r_{LSO} = 6\,M$$

Maximal rotating Black Hole

For $a \rightarrow M$ the last stable orbit is inside the hergosphere

$$r_H \rightarrow M$$
$$r_e \rightarrow 2\,M$$
$$r_{LSO} \rightarrow 1.45\,M < r_e$$

Jeneration of Jets in GR-MHD

From Tchekhovskoy, Narayan, McKinney, MNRAS 418, 79 (2011)

General Relativistic MHD siulation of Jet formation from a magnetically arrested accretion flow onto a prograde black hole, with dimensionless spin *a*.

Accreated mass:

$$F_M = \dot{M} c^2$$

Flux of escaping energy:

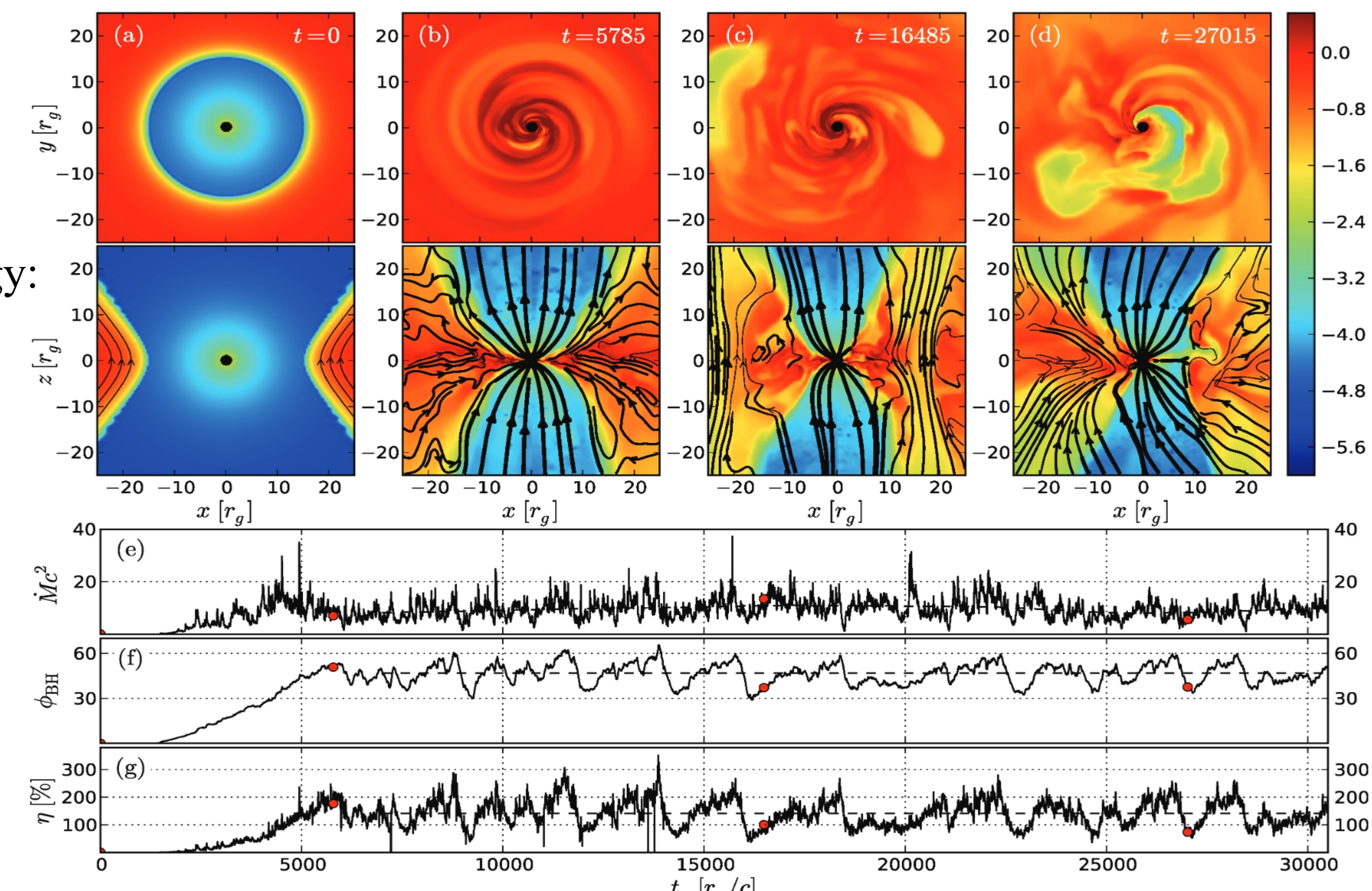
$$F_E$$

Efficiency:

$$\eta = \frac{F_E - F_M}{F_M}$$

$$a = 0.5 \rightarrow \eta = 0.30$$

$$a = 0.9 \rightarrow \eta = 1.40$$



Jeneration of Jets in GR-MHD

From Tchekhovskoy, Narayan, McKinney, MNRAS 418, 79 (2011)

Conclusion from simulations:

1) For small BH spin □ efficiency $\eta < 100\%$
- The energy could be preferencially extracted from the accreation disk

2) For large BH spin □ efficiency $\eta > 100\%$ (e.g a = 0.99 □ η = 140%)
- The energy is extracted from the black hole rotational energy
- The efficiency is very close the the one predicted by the Blandford-Znajek process

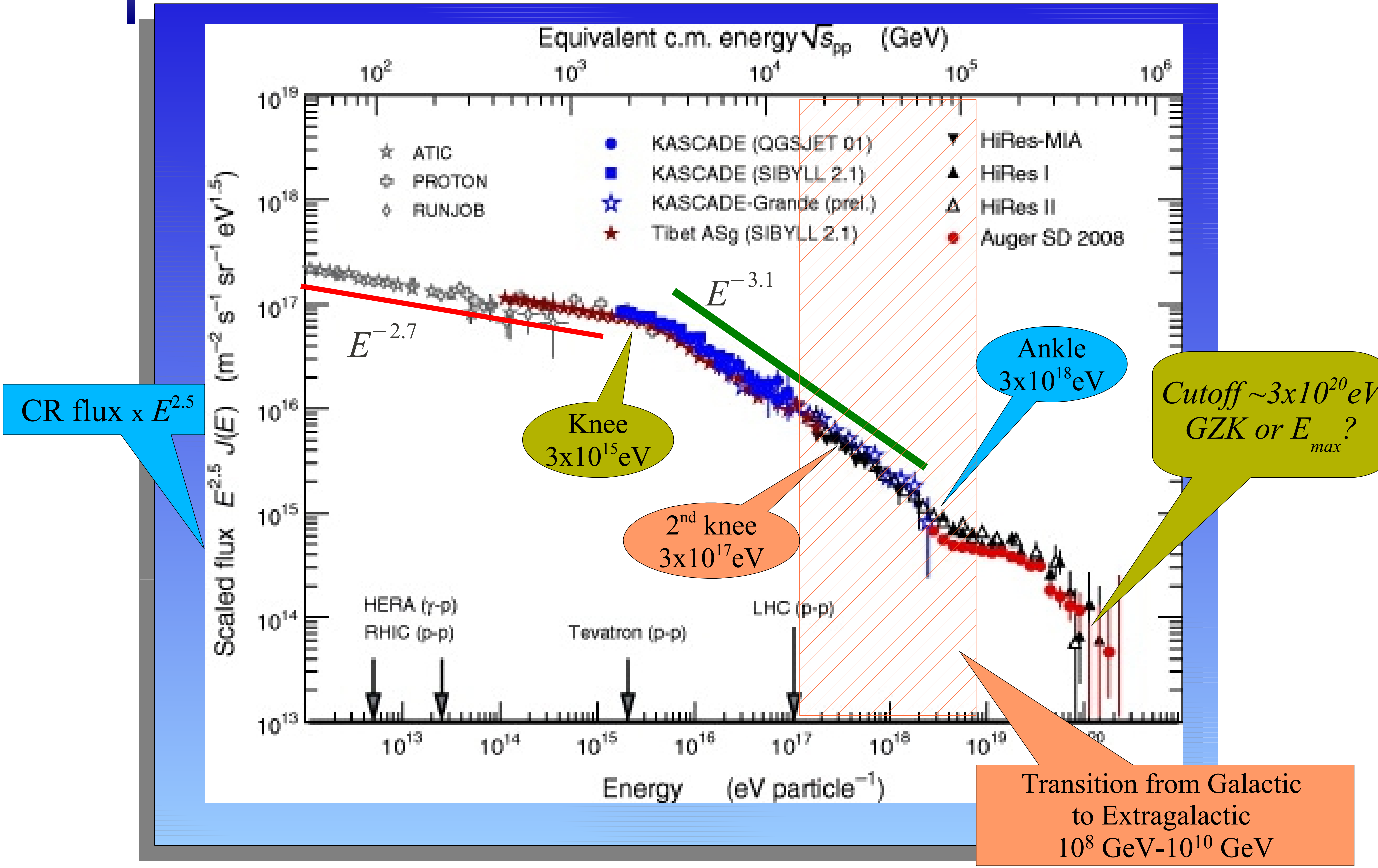
3) Prograd rotating black hole produces more energy than retrograde (for a =0.9 about 3 time more than a =-0.9)

4) Two different outflow:
- Relativistic collimated jet (connected to the Black Hole)
- Less collimated subrelativistic winds (Lovelace 1976; Blandford & Payne 1982) (connected to the innermost region of the accreation flow)

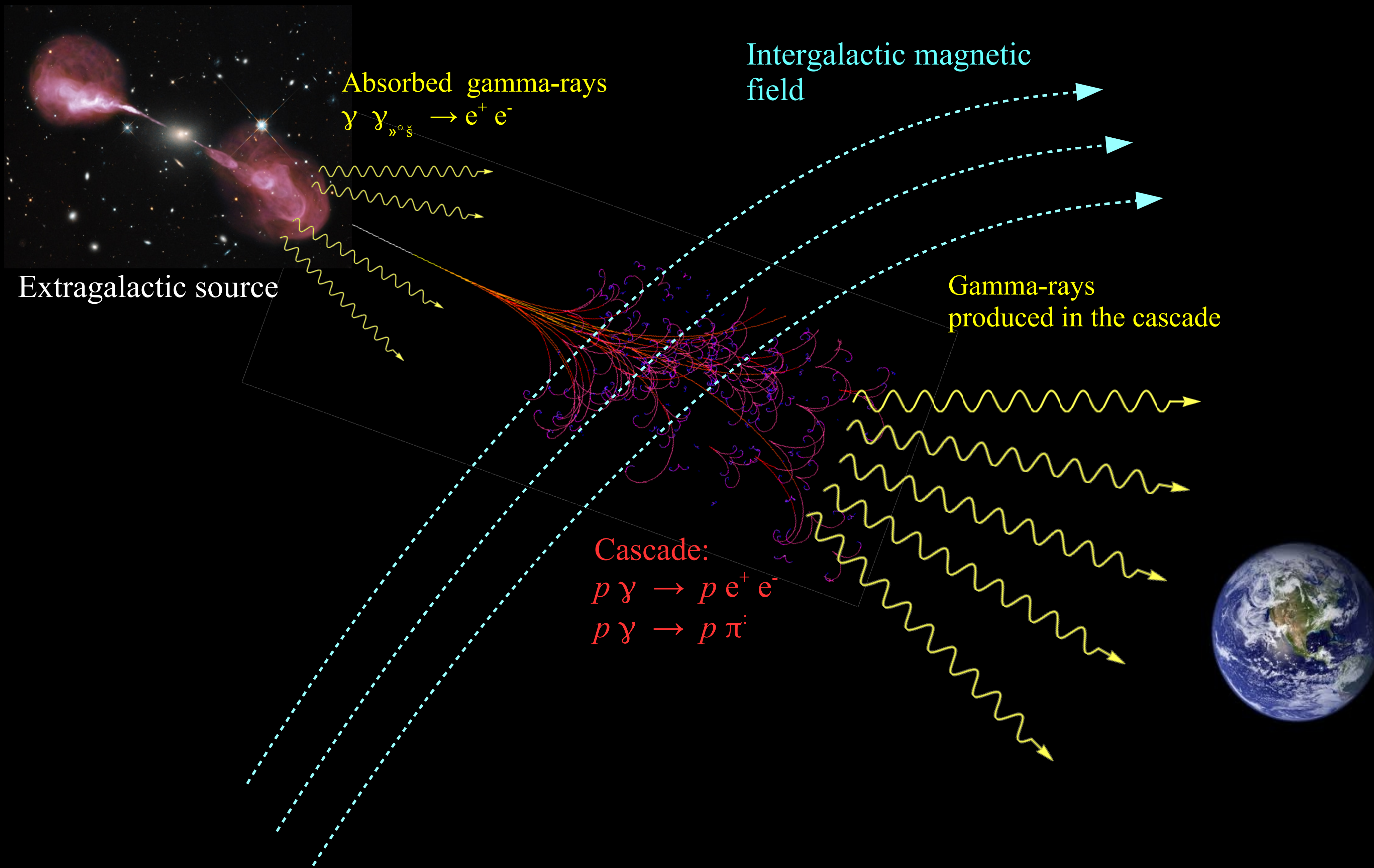
5) The subrelativistic wind could play an important role in the collimation of the relativistic jet

CR-iduced γ-rays from AGNs

Quick view on CR spectrum



CR induced γ-rays for AGN beyond z=1



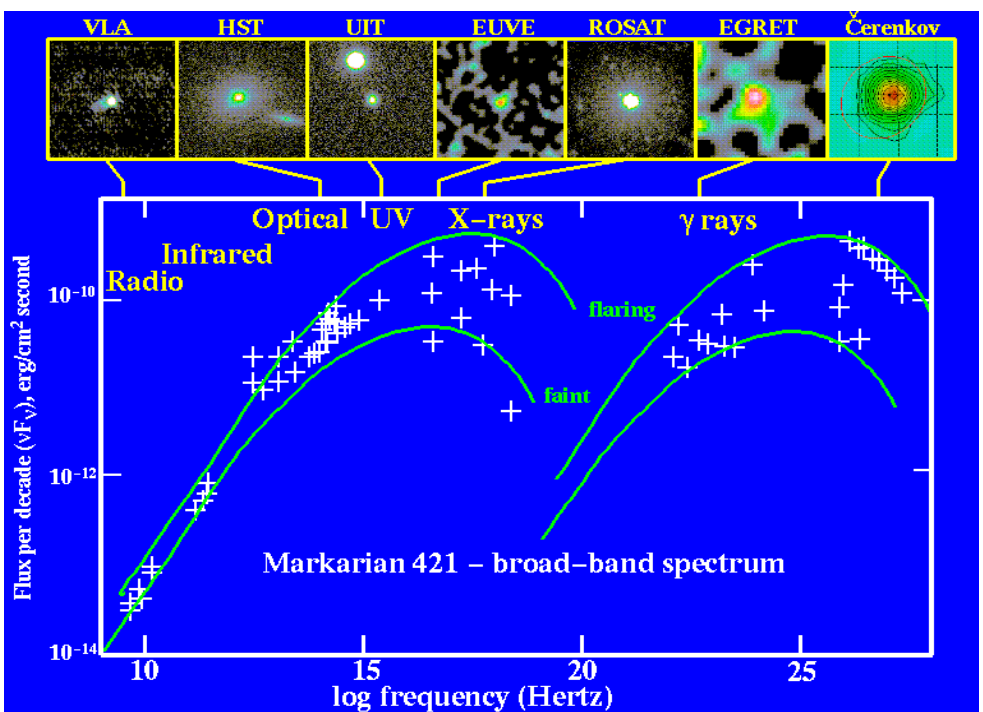
CR-induced gamma-ray from extragalactic sources at high redshift

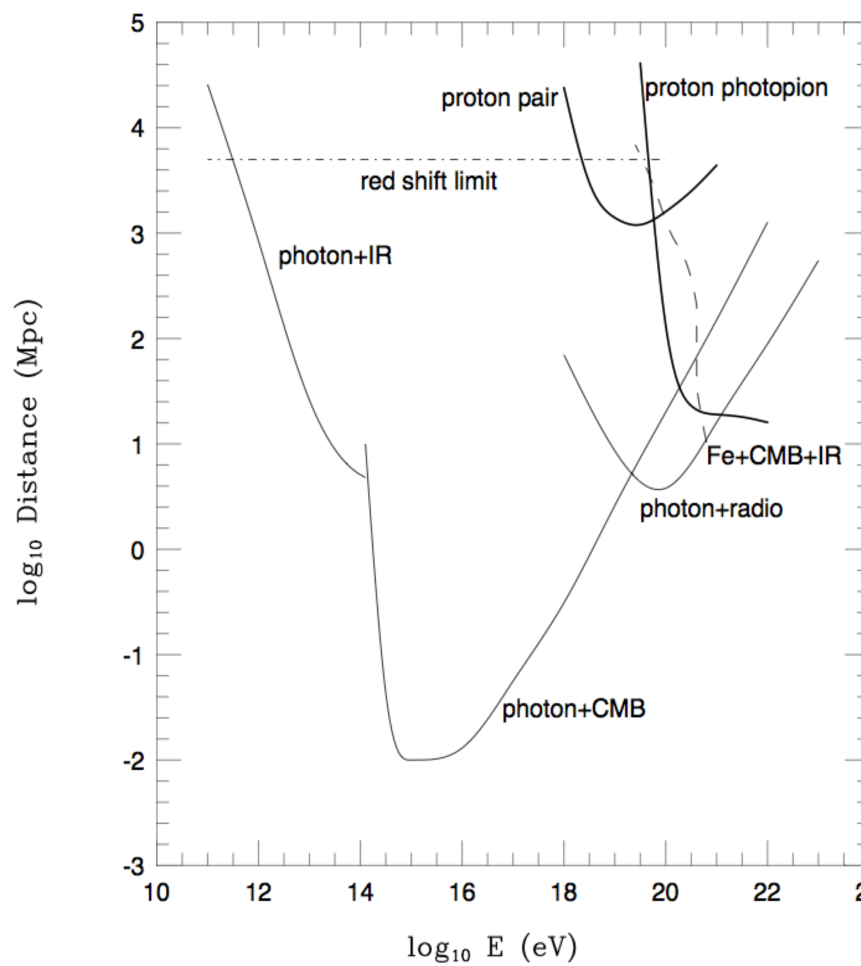
- **Active Galactic Nuclei are detected in GeV and TeV γ-rays**
- **Recently several AGN with z~0.5 have been detected in TeV γ-rays**
- **There are claims of TeV detection also for few**

AGN with z >~1

- **But for z > 1 (d > 1 Gpc) γ-ℑ ℝℒ are absorbed:**

γ

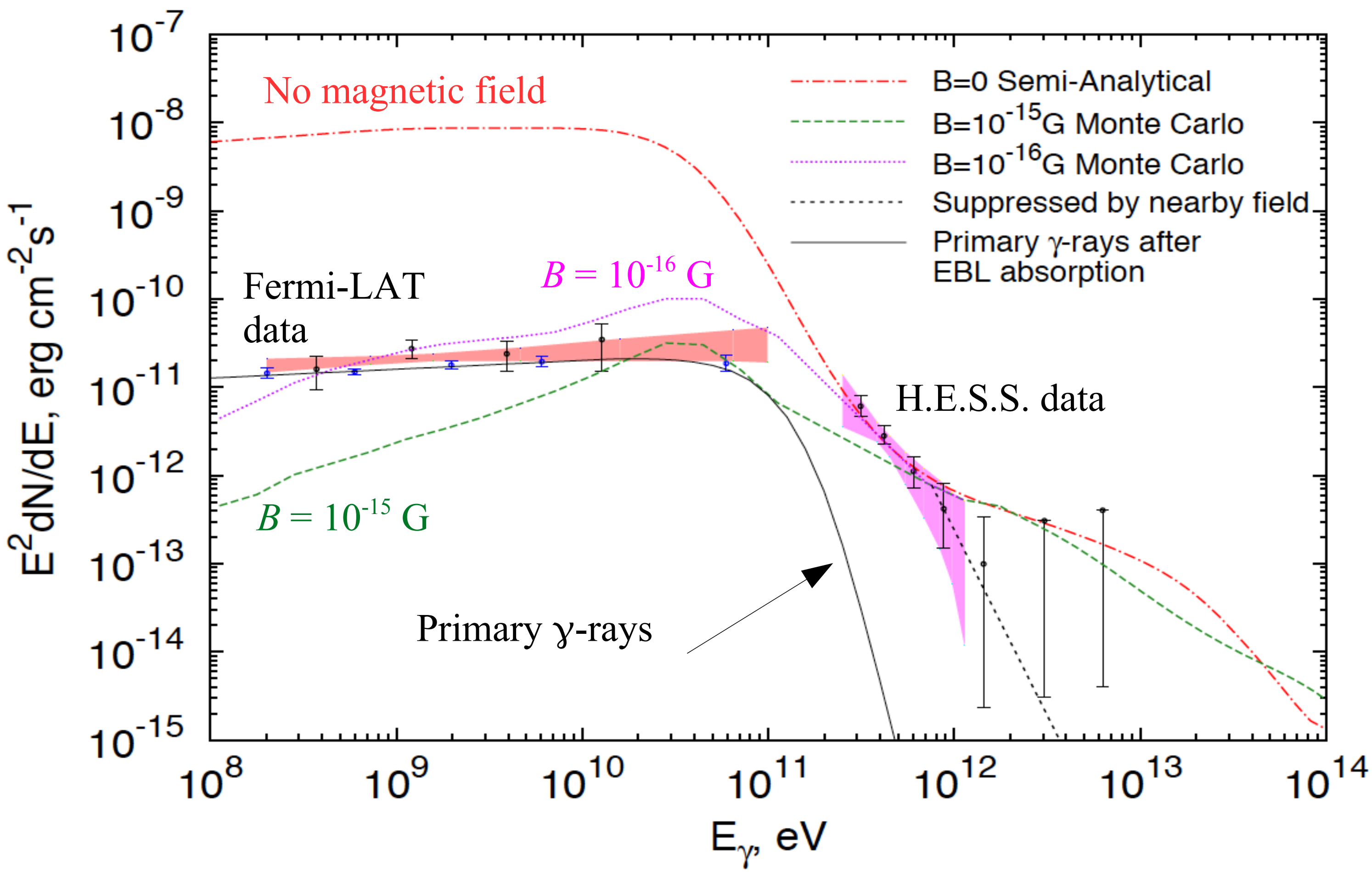




CR-induced gamma-ray from extragalactic sources at high redshift

Model prediction for PKS 0447-439 if $z = 1.3$ (???)
[Aharonian et al. 2013]

Assumed proton spectrum: $\frac{dN_p}{dE} \propto E^{-2} \quad for \quad 10^{17} < E < 10^{18}\, eV$



Extracting information on UHECRs from diffuse extragalactic emission

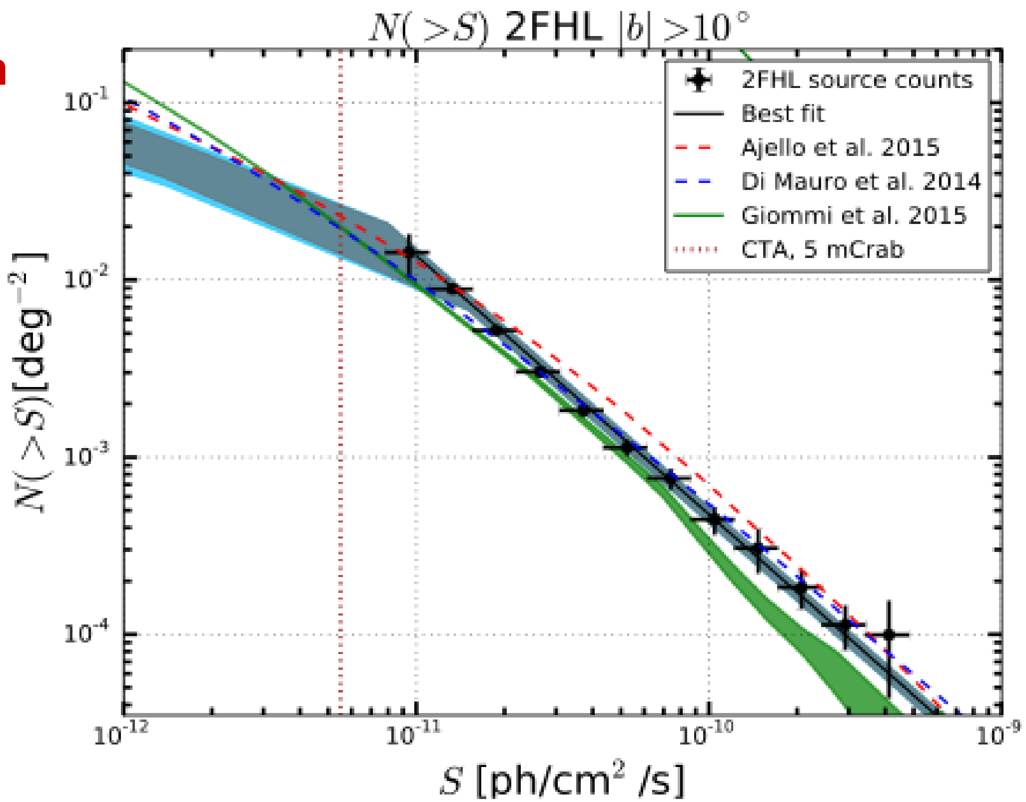
From Ackermann et al. PRL 116, 1105 (2016)

Integration of dN/dS shows that point sources account for at least 86% of the total extragalactic

 only about 14 % of the diffuse emission detected by Fermi-LAT can be really diffuse

Can we constrain the UHECR sources from this?

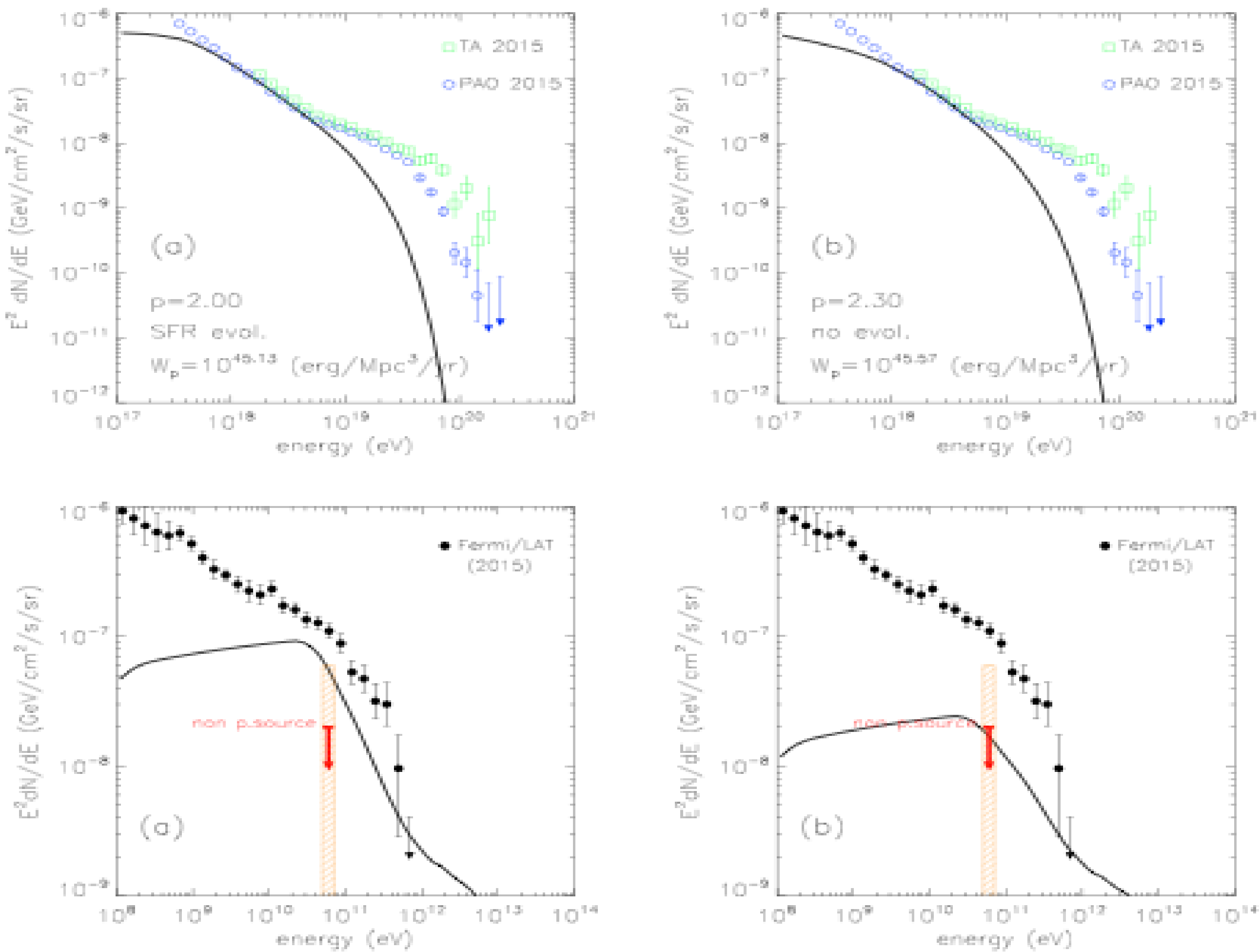
Number of point sources per photon flux above 50 GeV



Extracting information on UHECRs from diffuse extragalactic emission

From Liu et al. (2016) arXiv160303223

Sources evolving with the SFR | **No evolution**

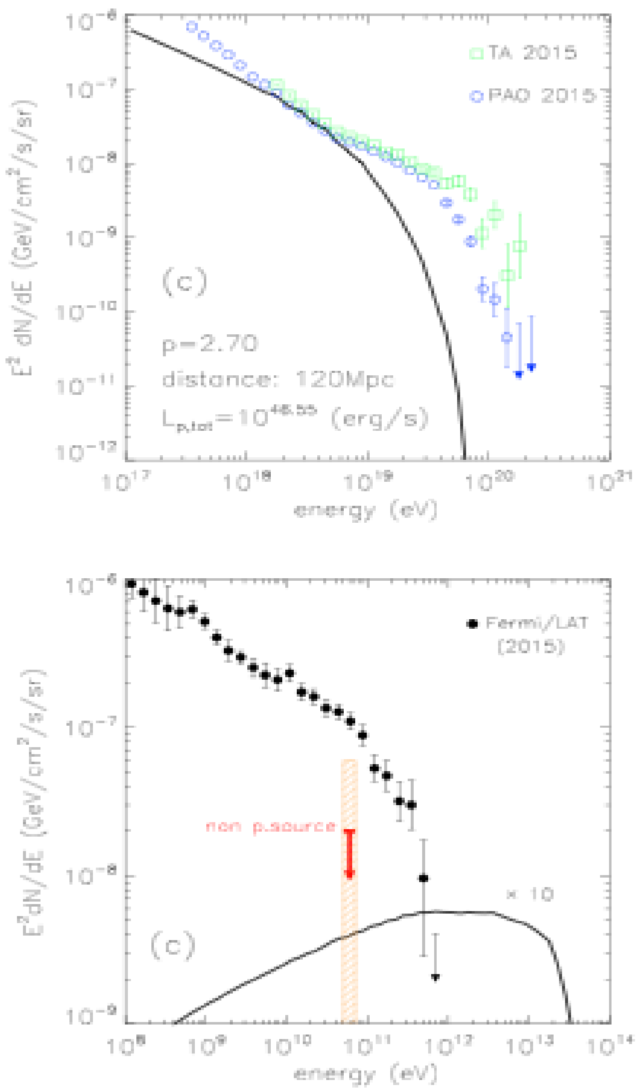


Fitting to UHECR spectrum below the ankle and the corresponding diffusive gamma-ray flux initiated by CR prop- agation with different source distributions

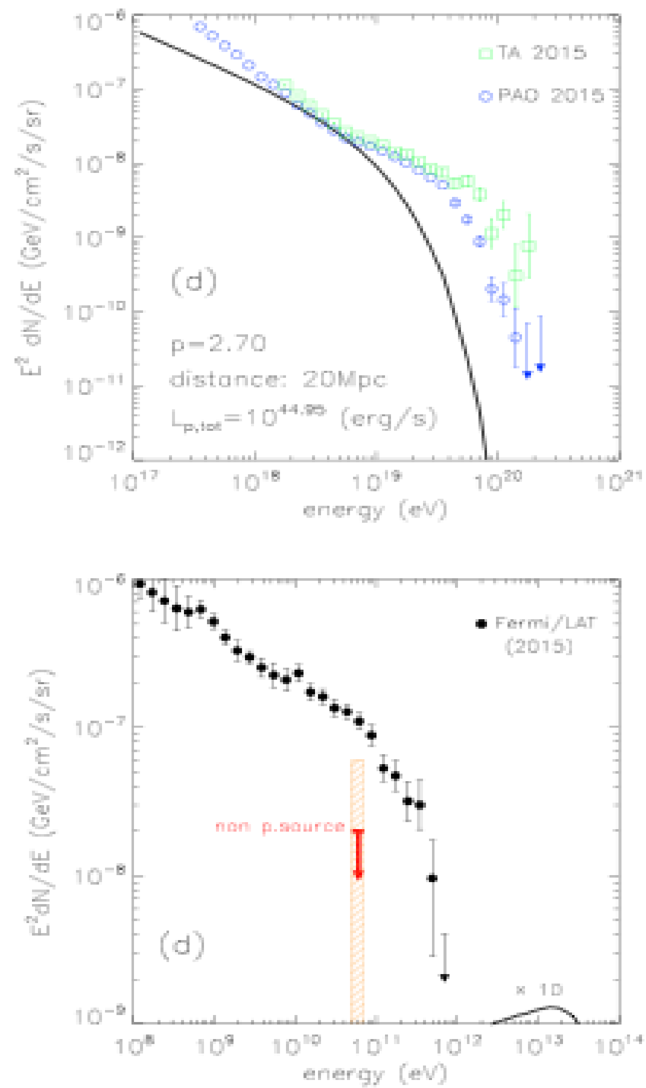
Extracting information on UHECRs from diffuse extragalactic emission

From Liu et al. (2016) arXiv160303223

Assuming all sources located within 120 Mpc



Assuming all sources located within 20 Mpc



CONCLUSIONS

Even sfter more than 100 yrs from their discovery CRs are teaching us a lot on

- Foundamental interactions
- Plasma physics
- Astrophysical processes

Even today CR physics is not an isolated field of study strong connection with other parts of Astrophysics.

1) CRs are an essential ingredient of the Interstellar Medium, their energy density being 1 eV cm^{-3}, comparable with the energy density of other components
 This simple fact suggests that CRs can play a relevant role in many Galactic processes including the long term evolution of the Galaxy.
2) In particular they are the only agent that can penetrate deep inside molecular clouds determining the cloud's ionization level and chemical evolution, hence, directly affecting the initial condition of the star formation process.
3) CRs can also be responsible for the generation of galactic winds which subtract gas from the Galactic plane, lowering the total star formation rate and polluting the inter-galactic medium with high metallicity gas.
4) The CR flux on Earth may ontribute to the variation of cloud cover important effects on the Earth climate

All these aspects represent open fields which promise interesting discovery in the near future.