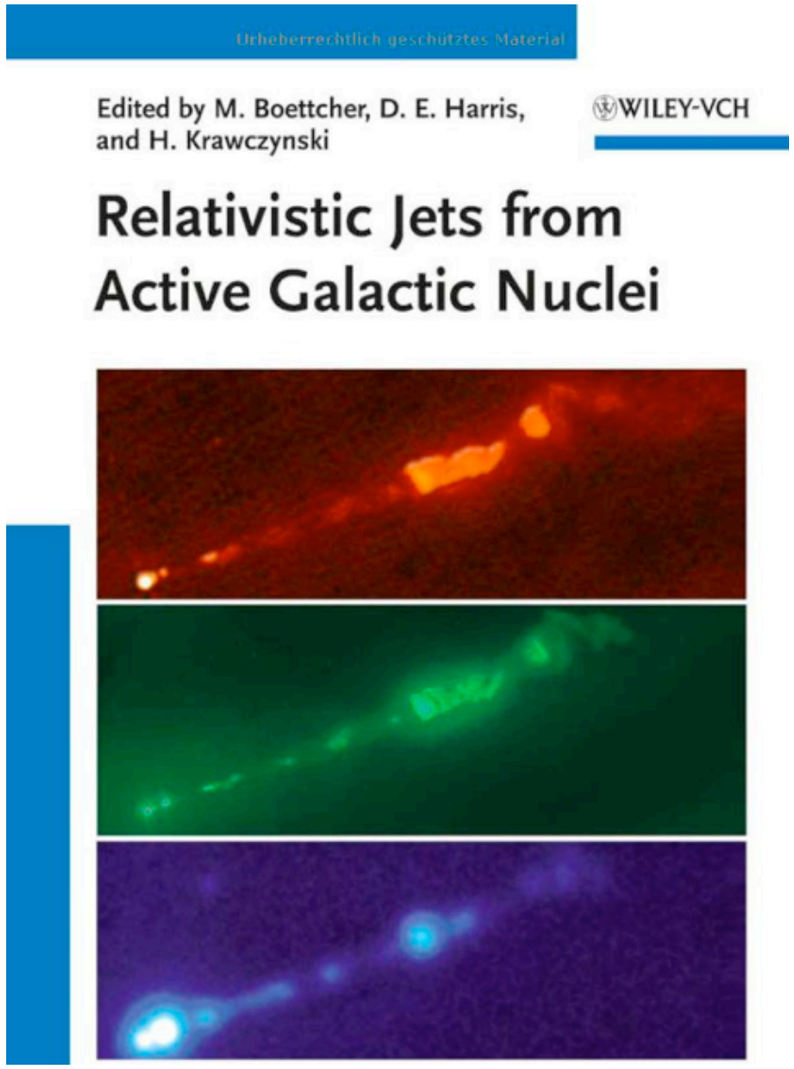
AGNs as Particle Accelerators

Henric Krawczynski, March 6, 2013

Washington University in St. Louis
McDonnell Center for the Space Sciences

- *Particle acceleration sites: from the black hole horizon to radio lobes.*
- *AGN observations with X-ray and gamma-ray telescopes.*
- *Theoretical Results.*
- *Summary and Conclusions.*

Related Books and Articles



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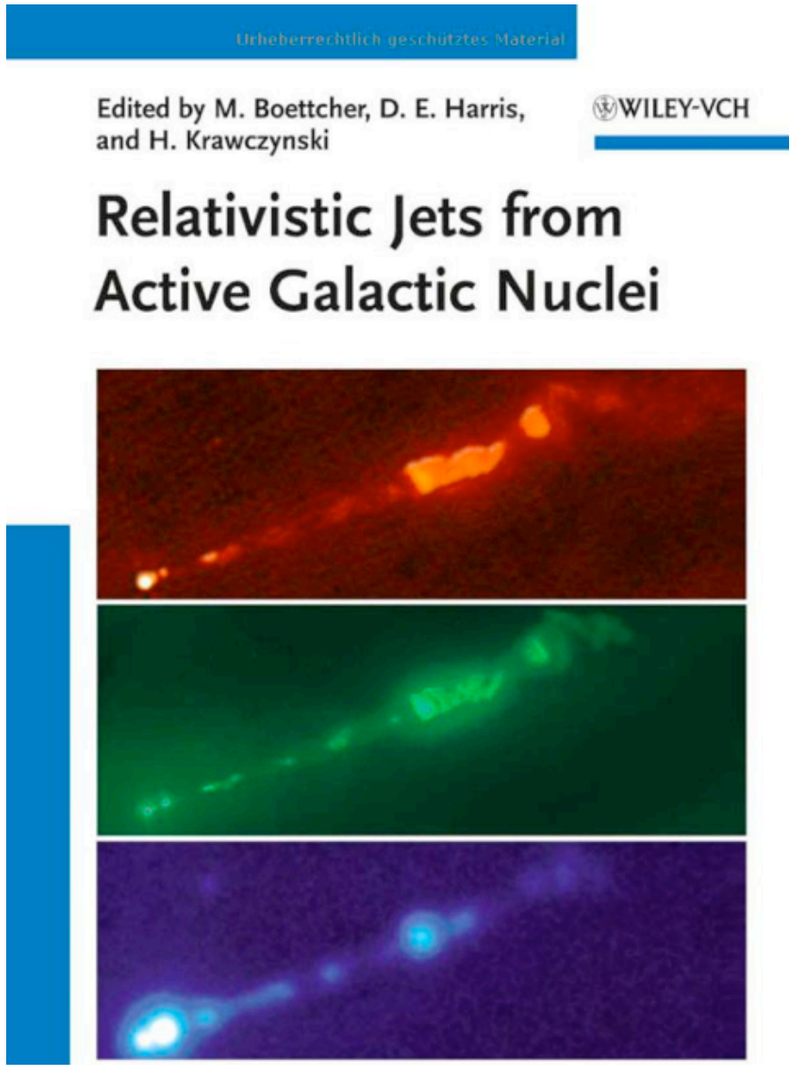

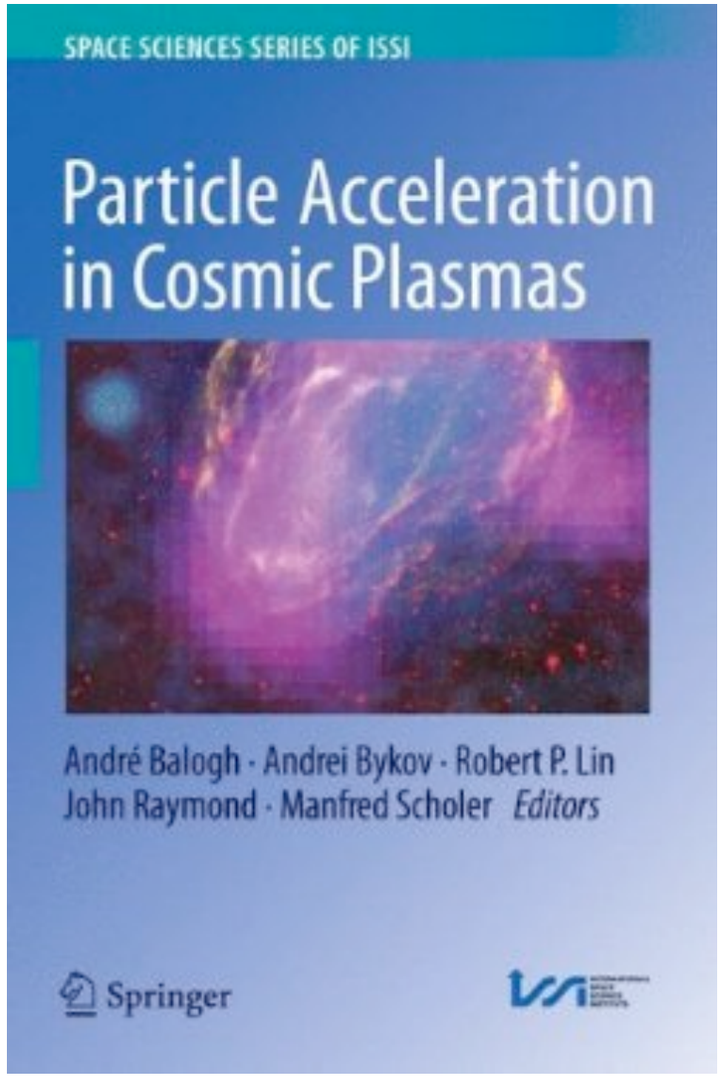

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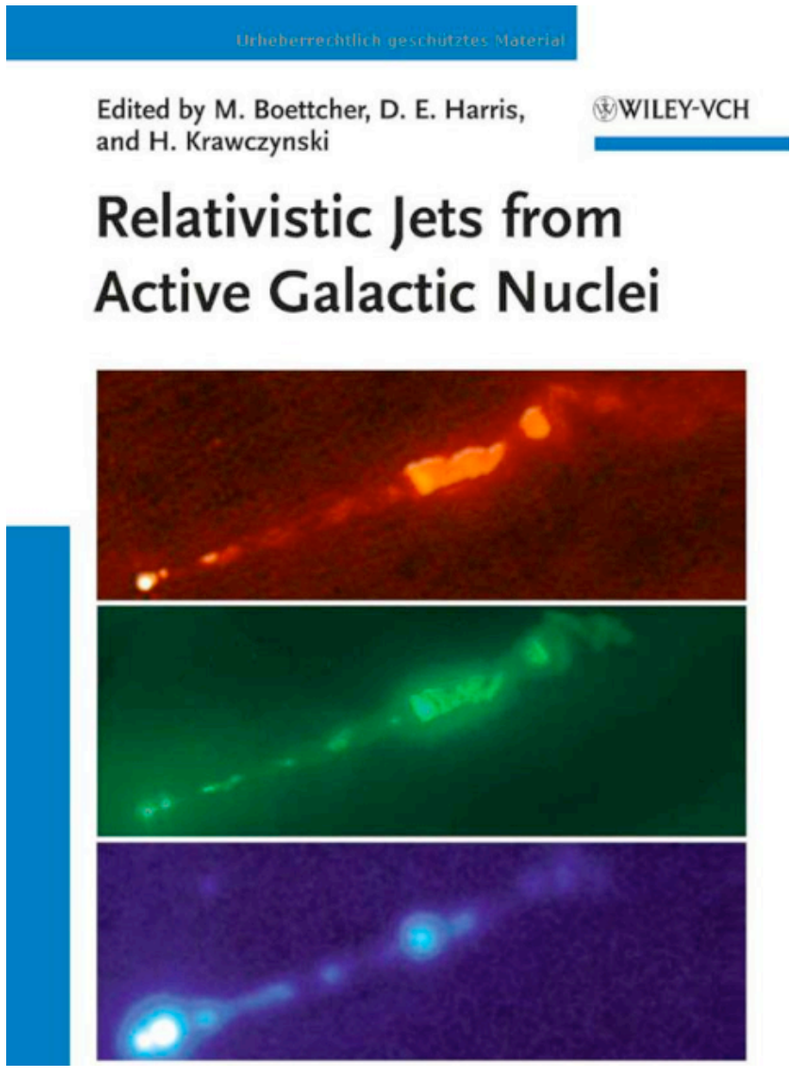

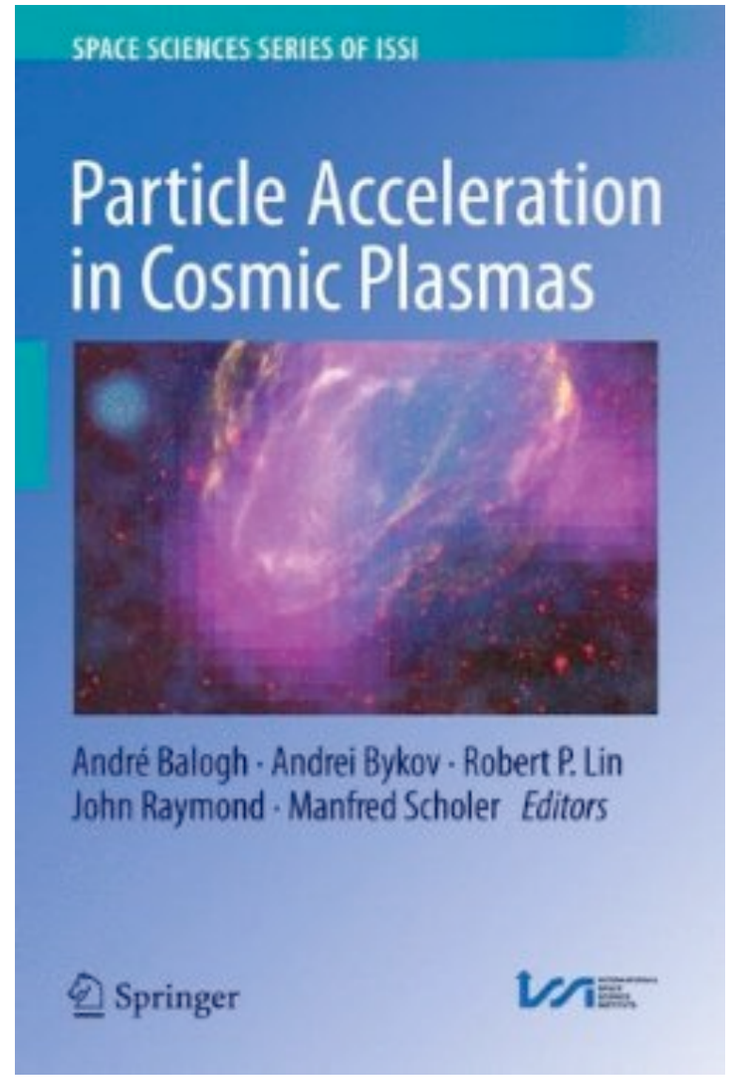

Particle acceleration in relativistic outflows

Andrei Bykov · Neil Gehrels · Henric Krawczynski · Martin Lemoine · Guy Pelletier · Martin Pohl

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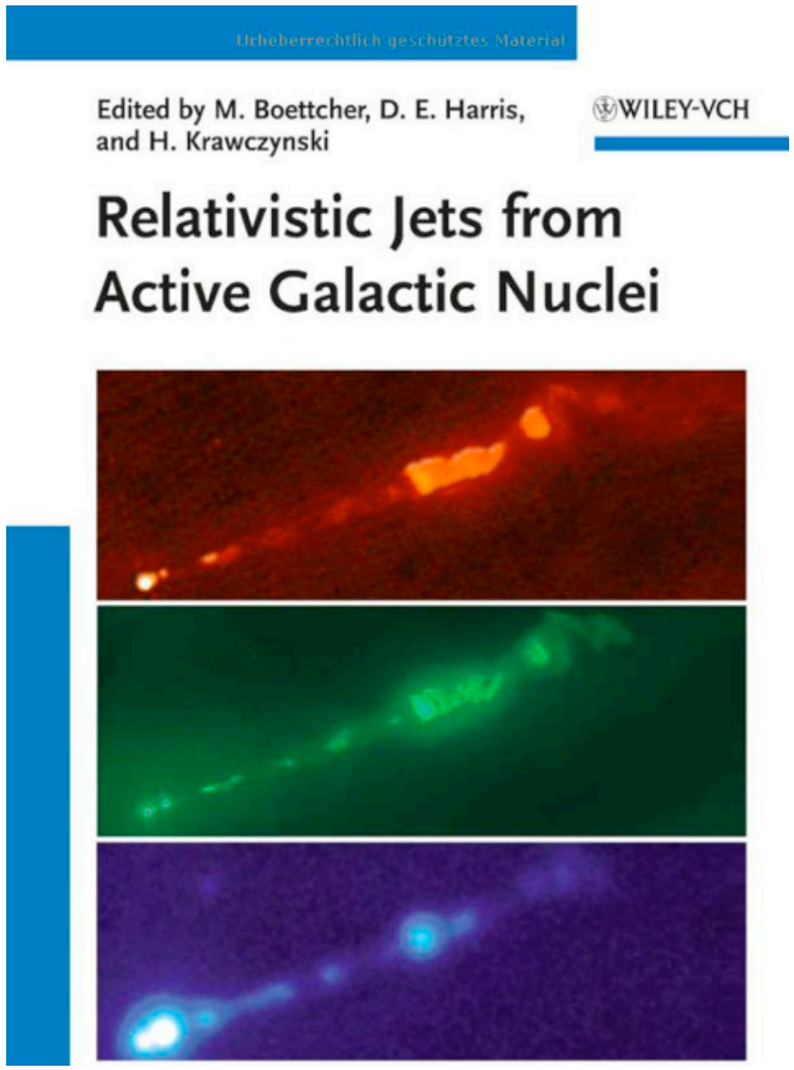

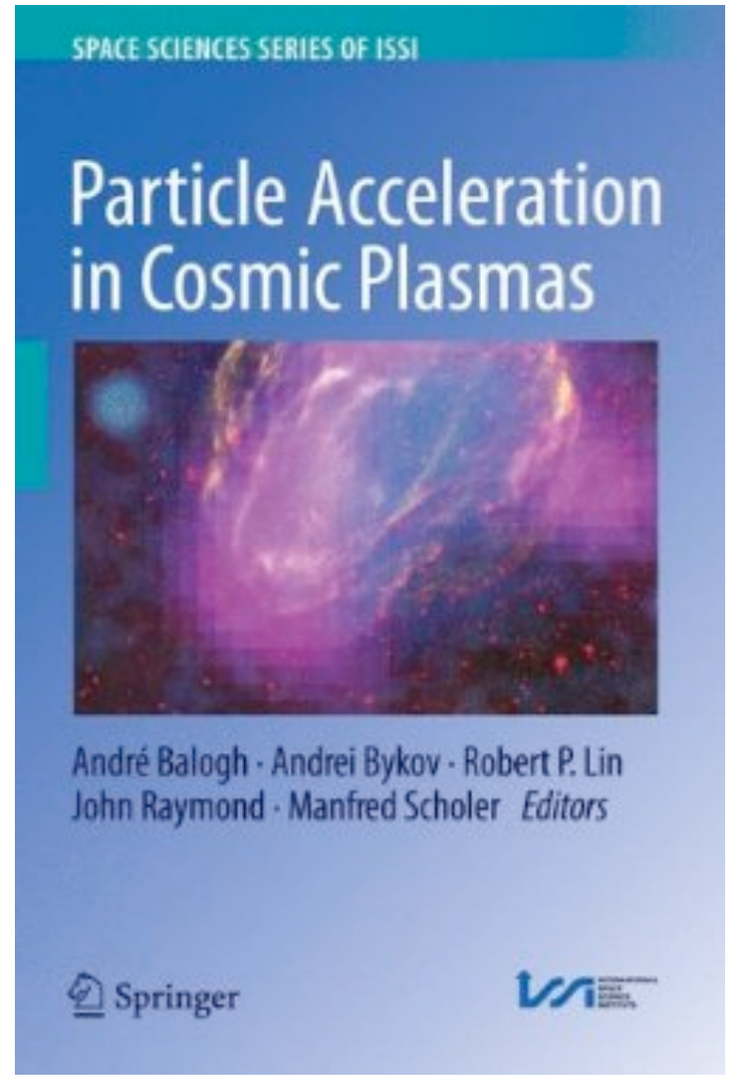

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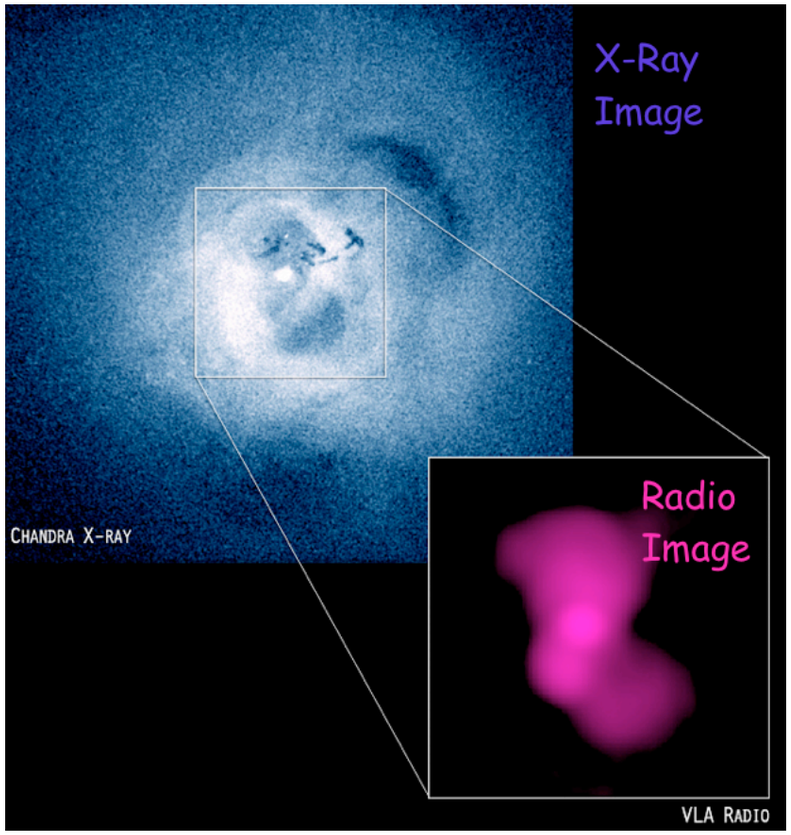
arXiv:1205.2208

Motivation for the Study of Particle Acceleration at AGNs



(Credit: NASA, CXO)

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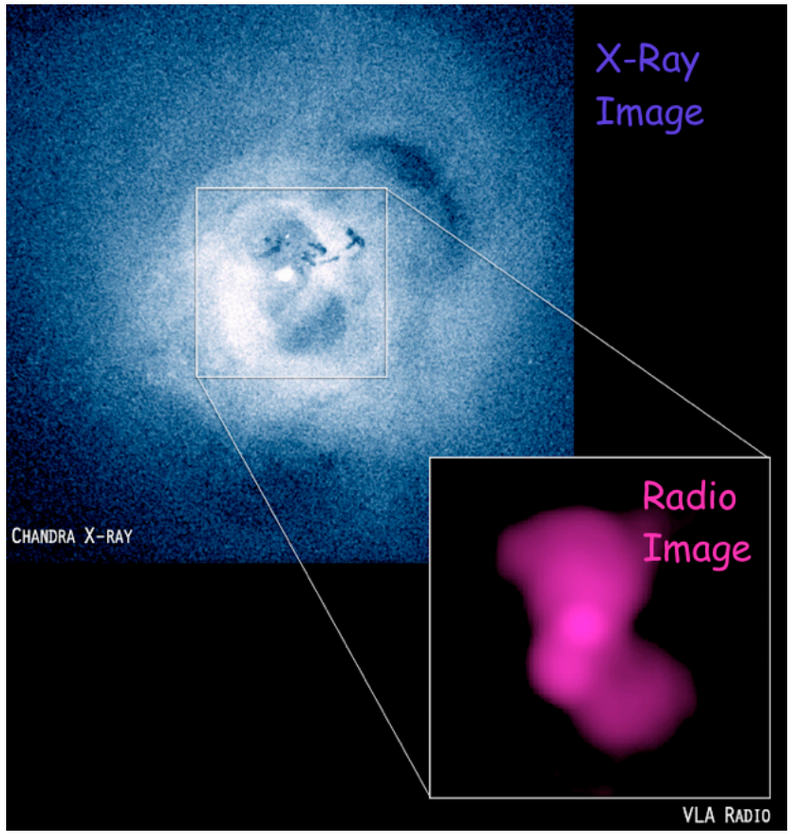
- Particle acceleration in cosmic plasmas.



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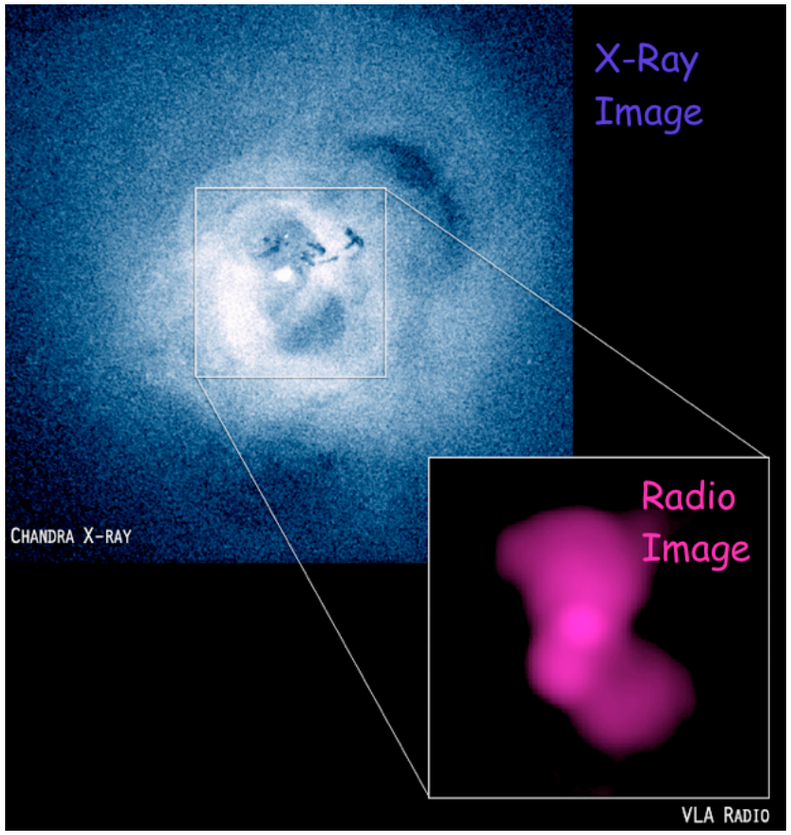

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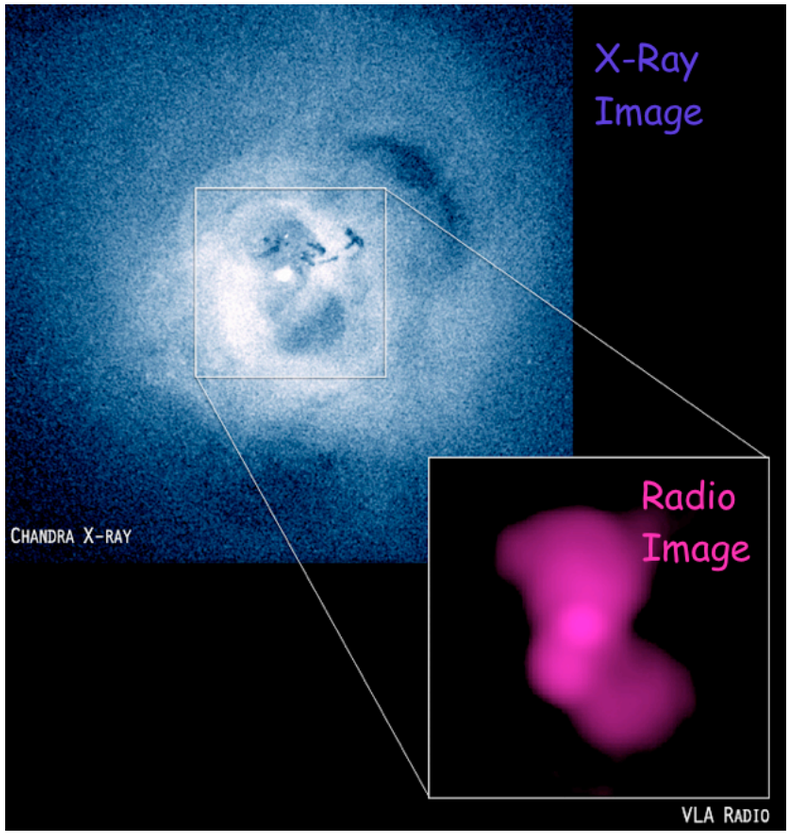

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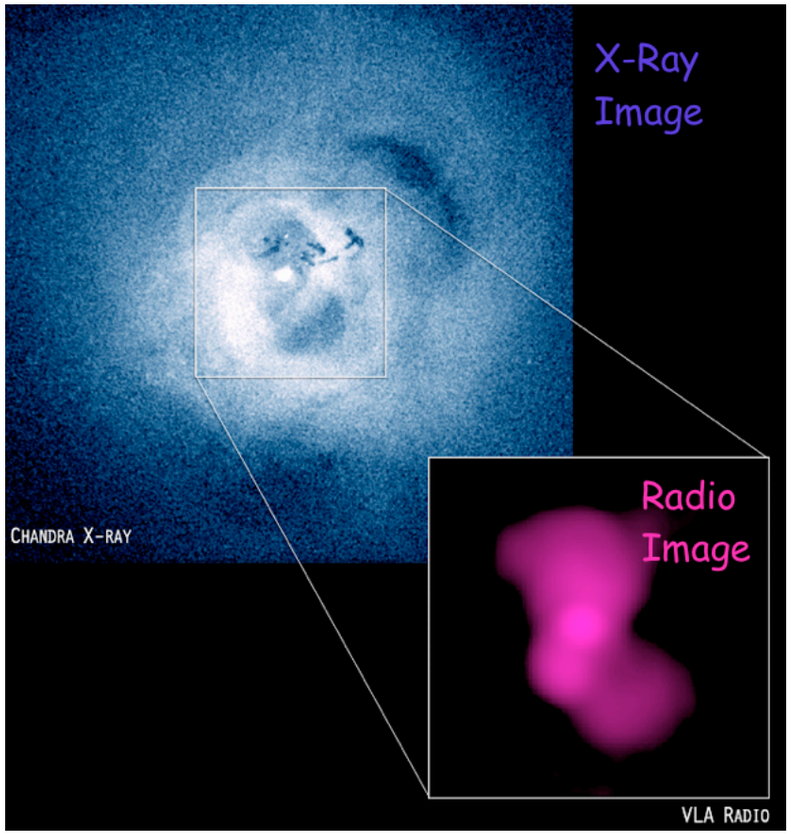

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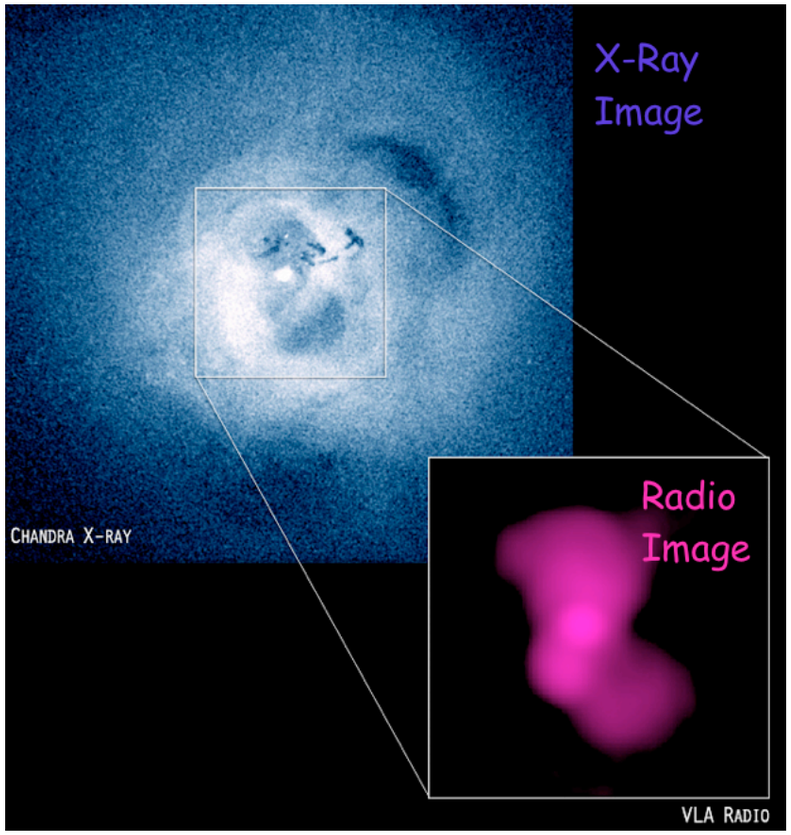

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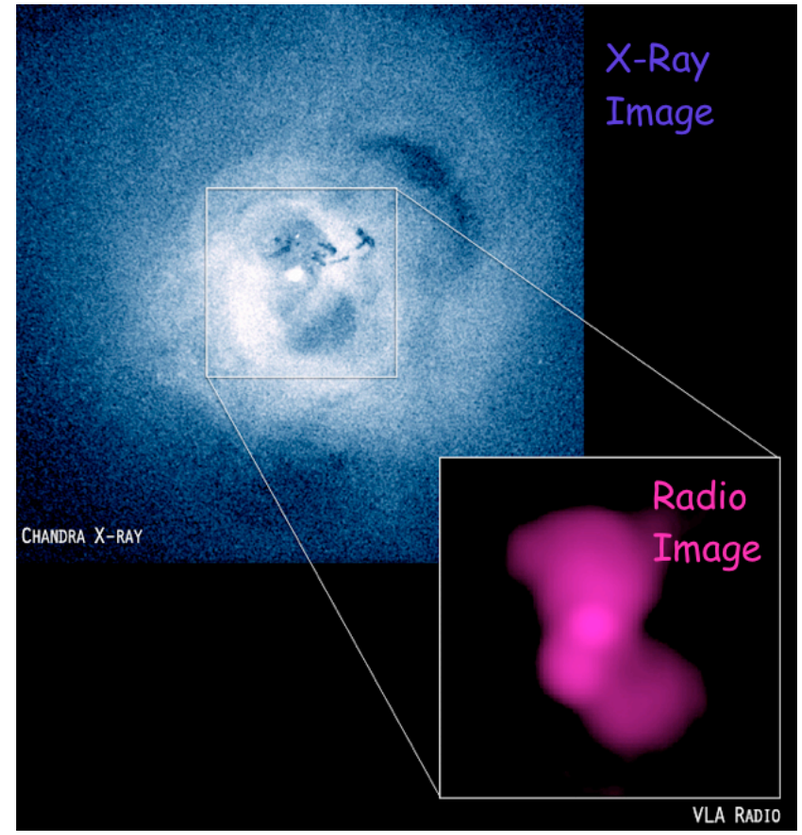

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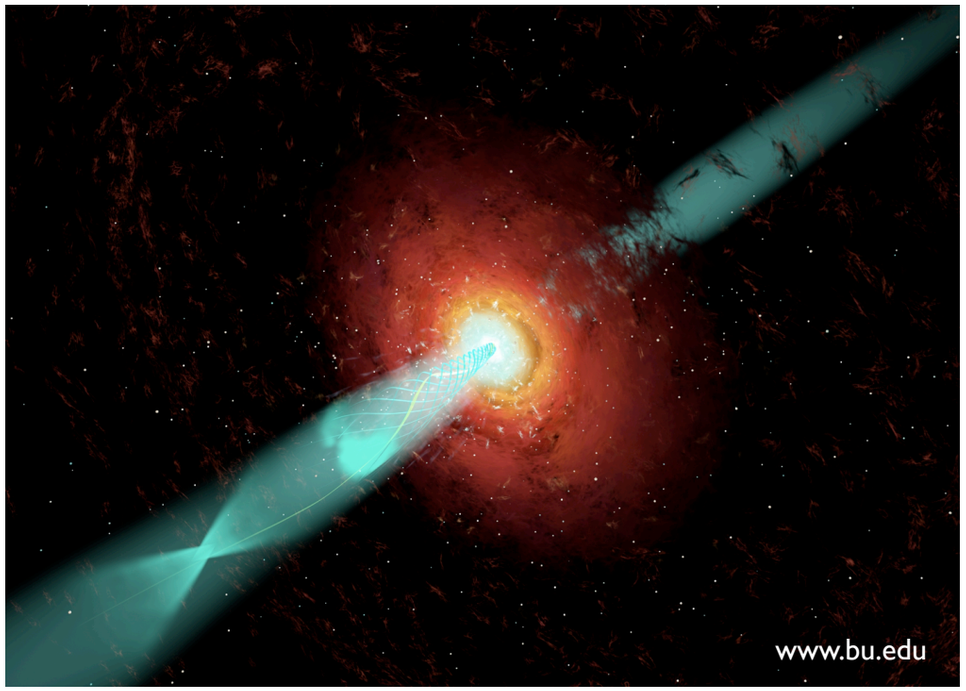
Added motivation: understand AGNs to perform background subtraction for DM searches.

Similar Systems

Active Galactic Nuclei:



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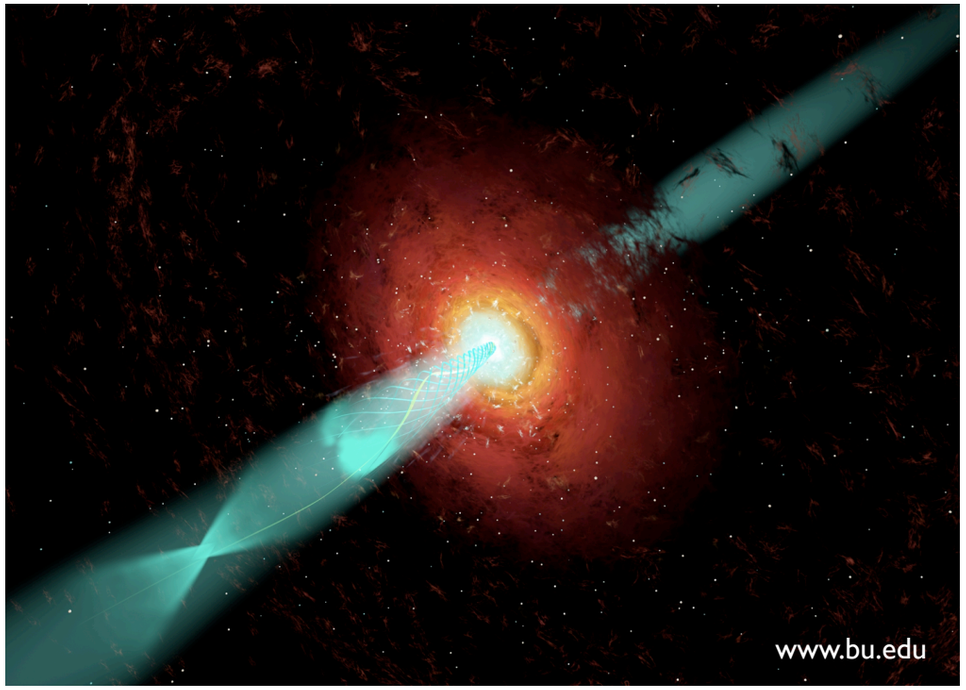
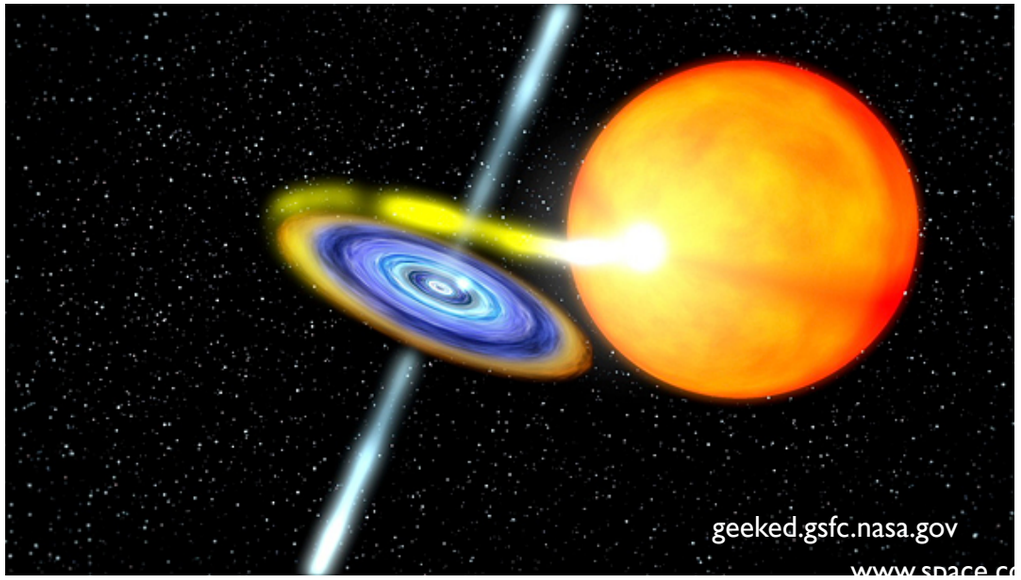


Black Holes in X-ray Binaries



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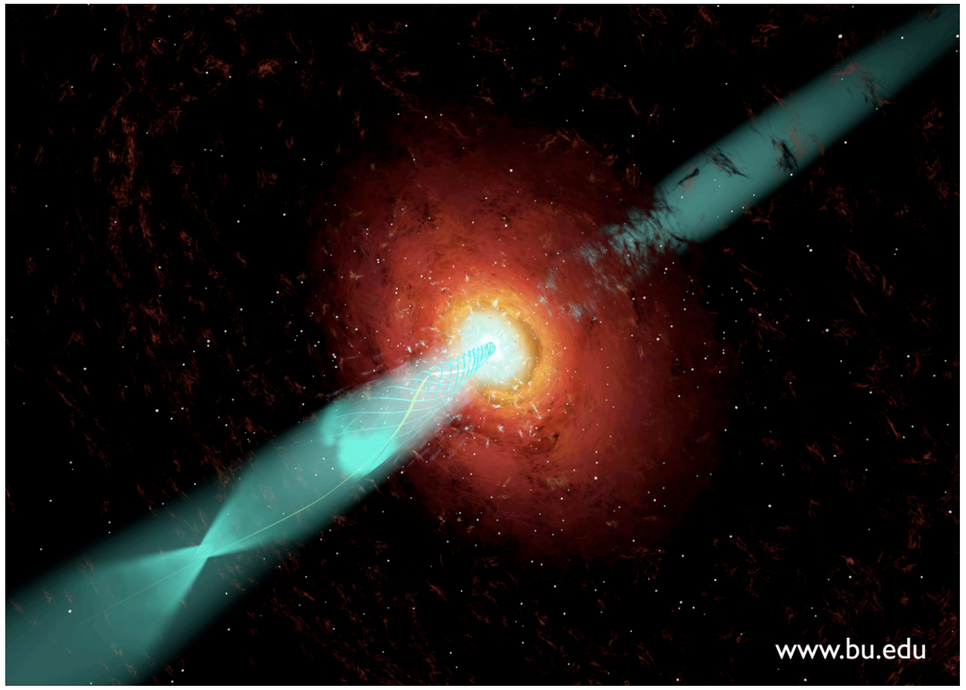

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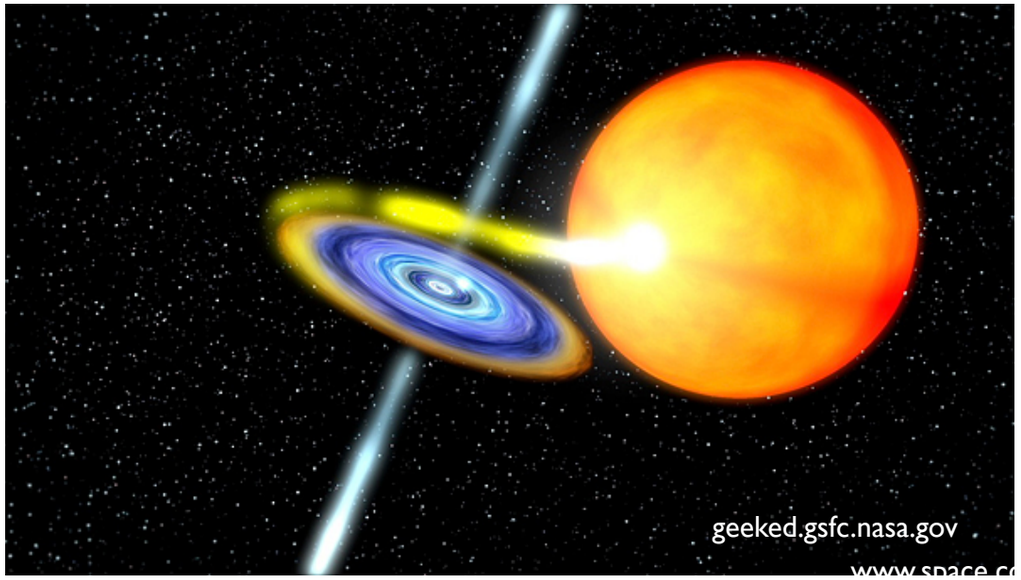

Gamma-Ray Bursts:

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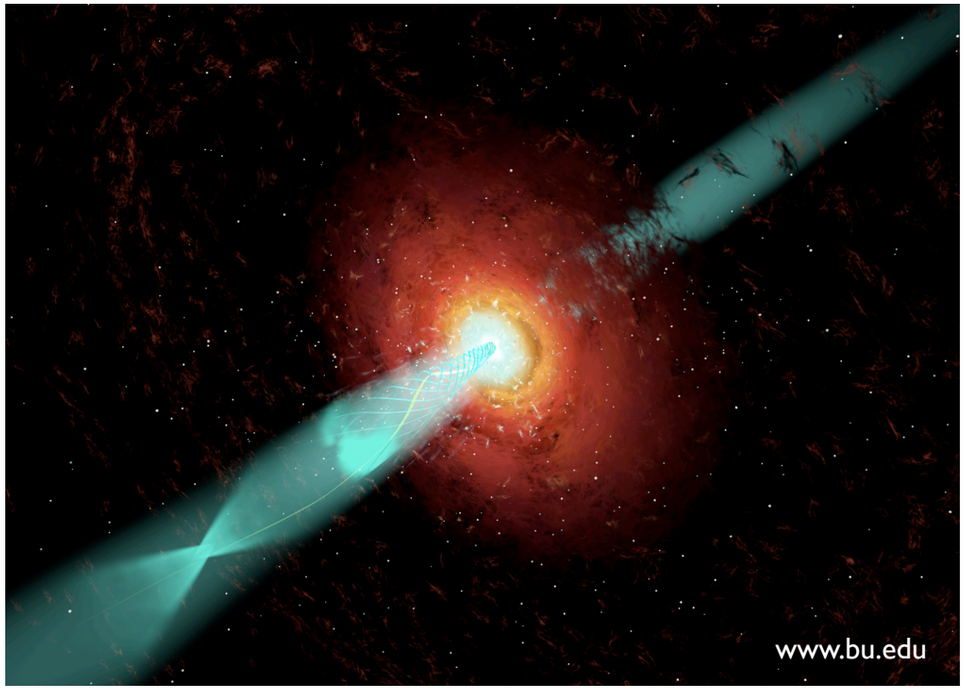

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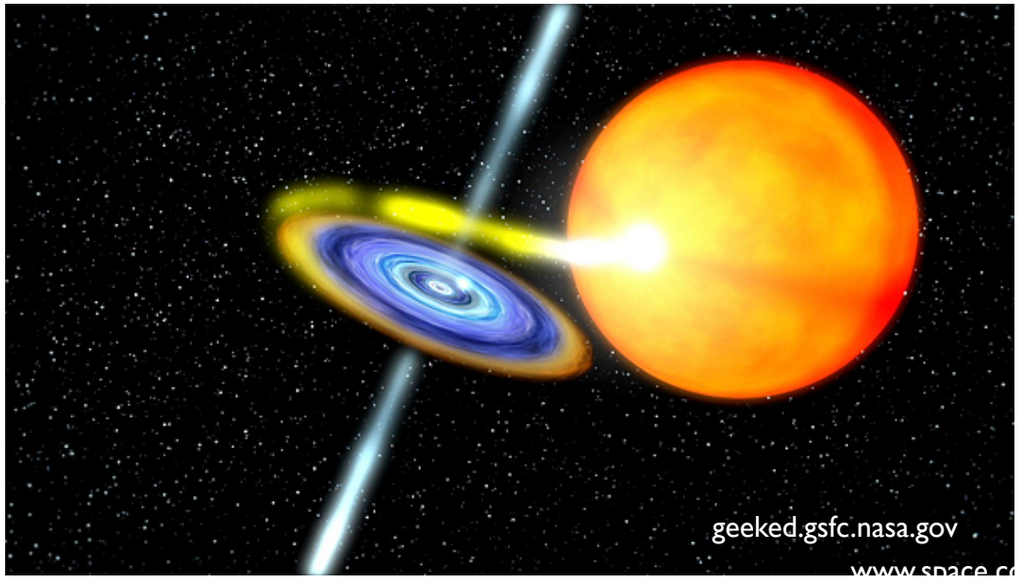
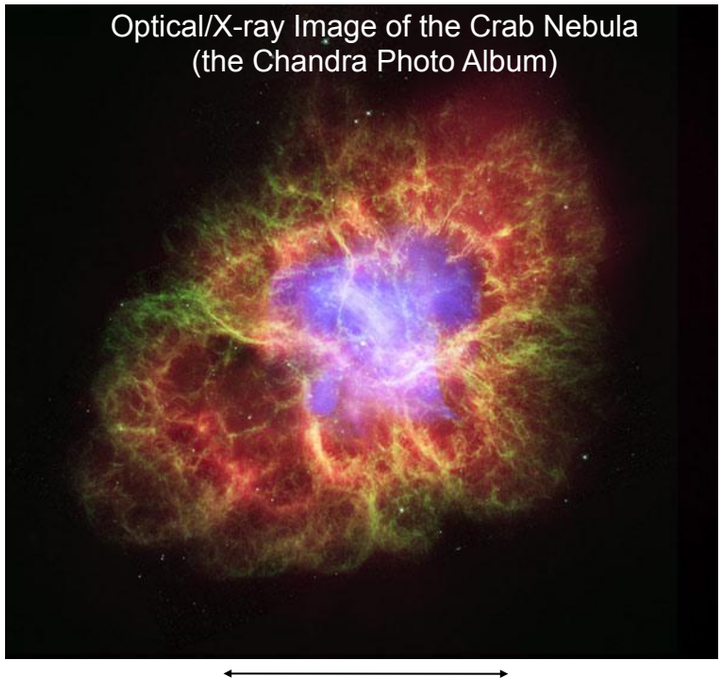


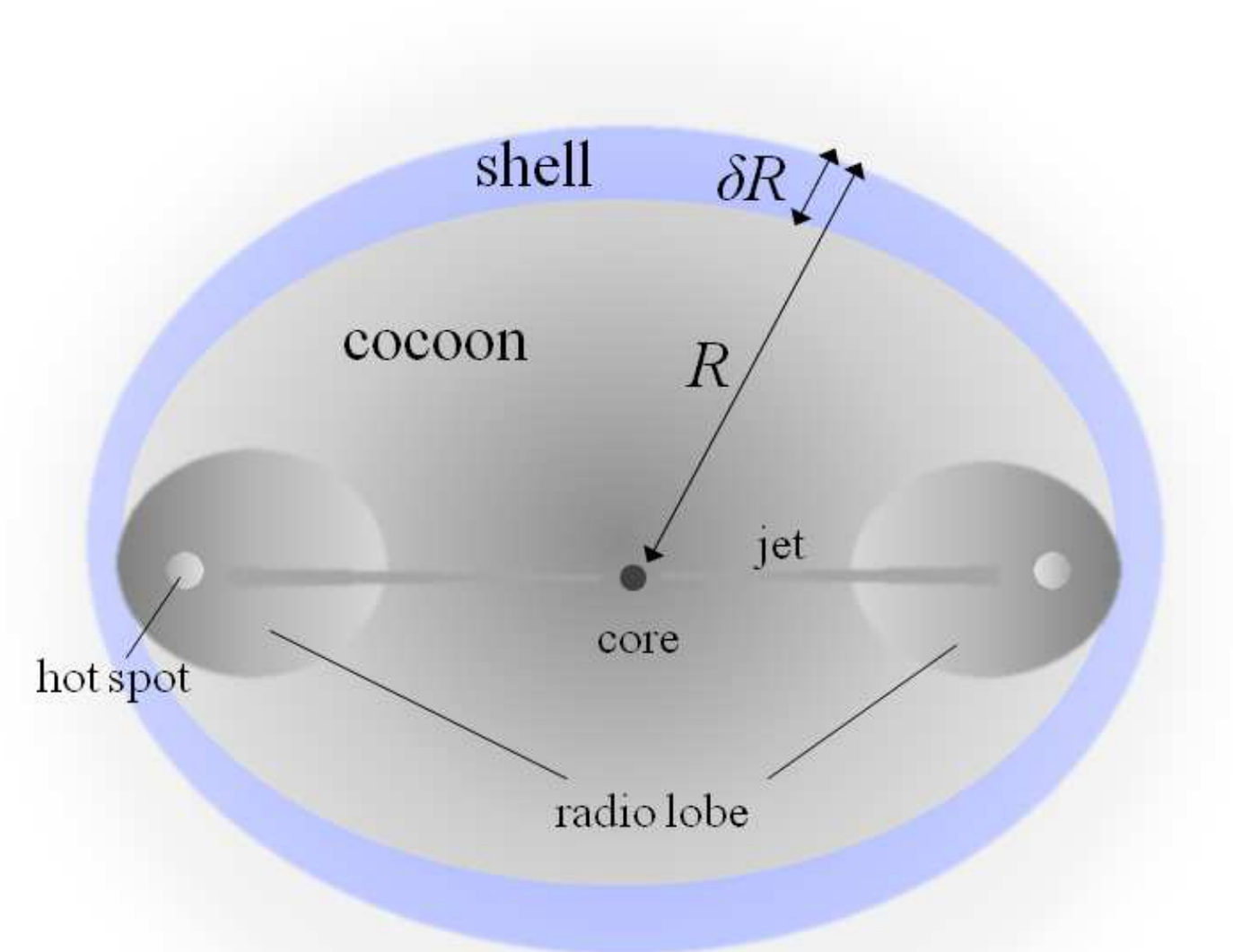
Gamma-Ray Bursts:

Pulsar Wind Nebulae



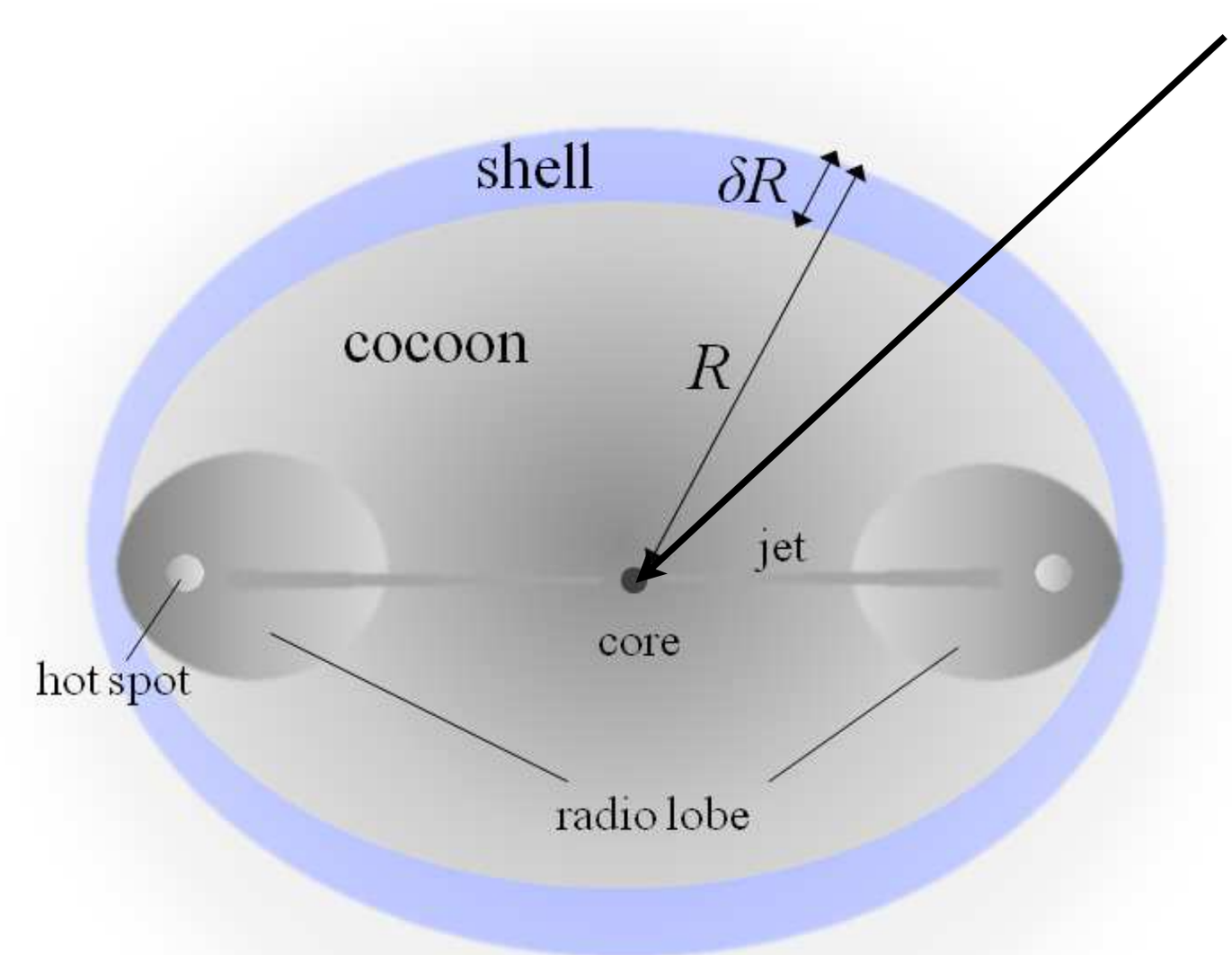
1.6 arcmin (~1 pc)

Particle Acceleration Sites



Kino et al. 2013

Particle Acceleration Sites



Kino et al. 2013

- Event Horizon
- Black Hole Magnetosphere

$$\sim r_g = GM / c^2 \sim 10^{-4} \text{ pc}$$

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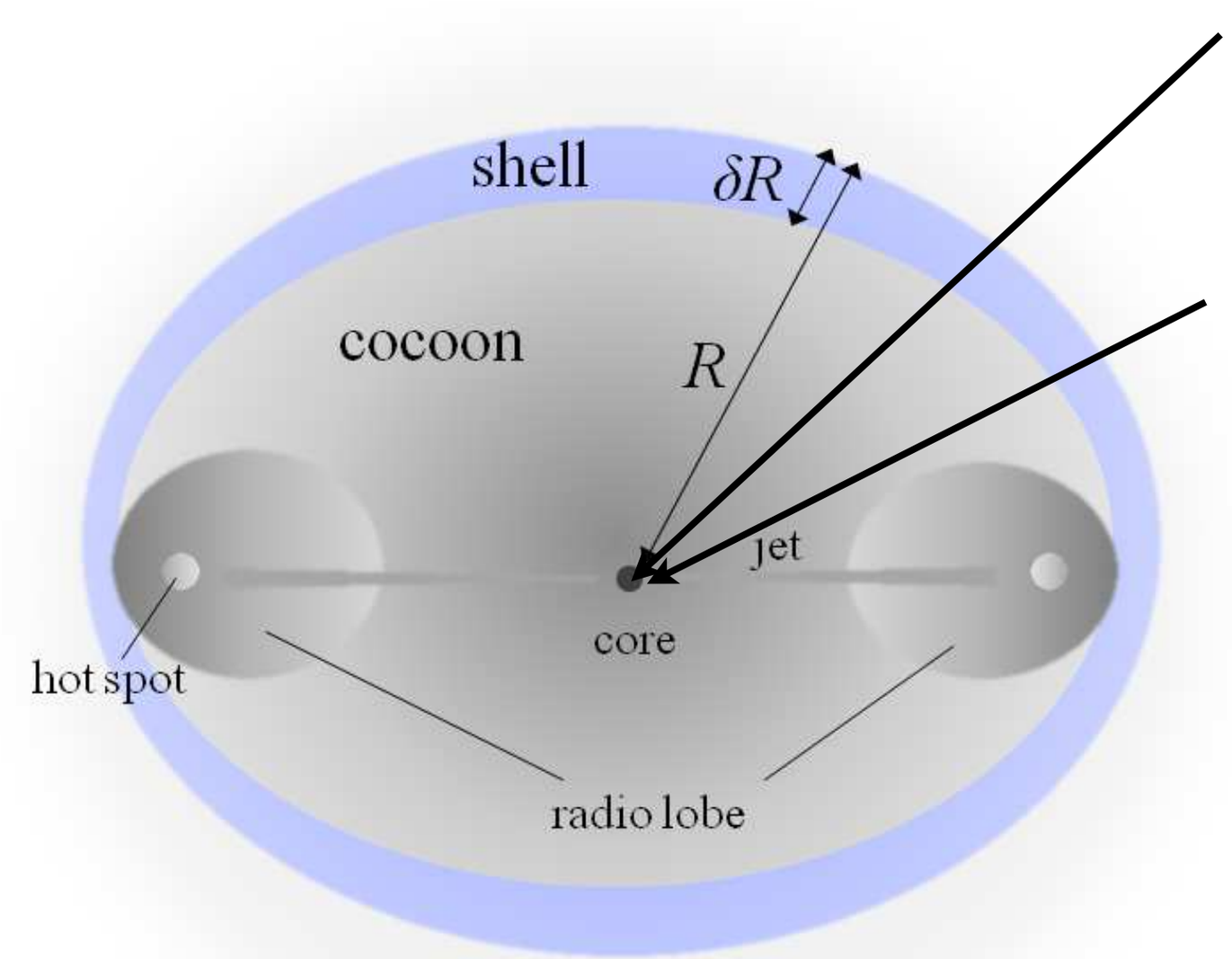

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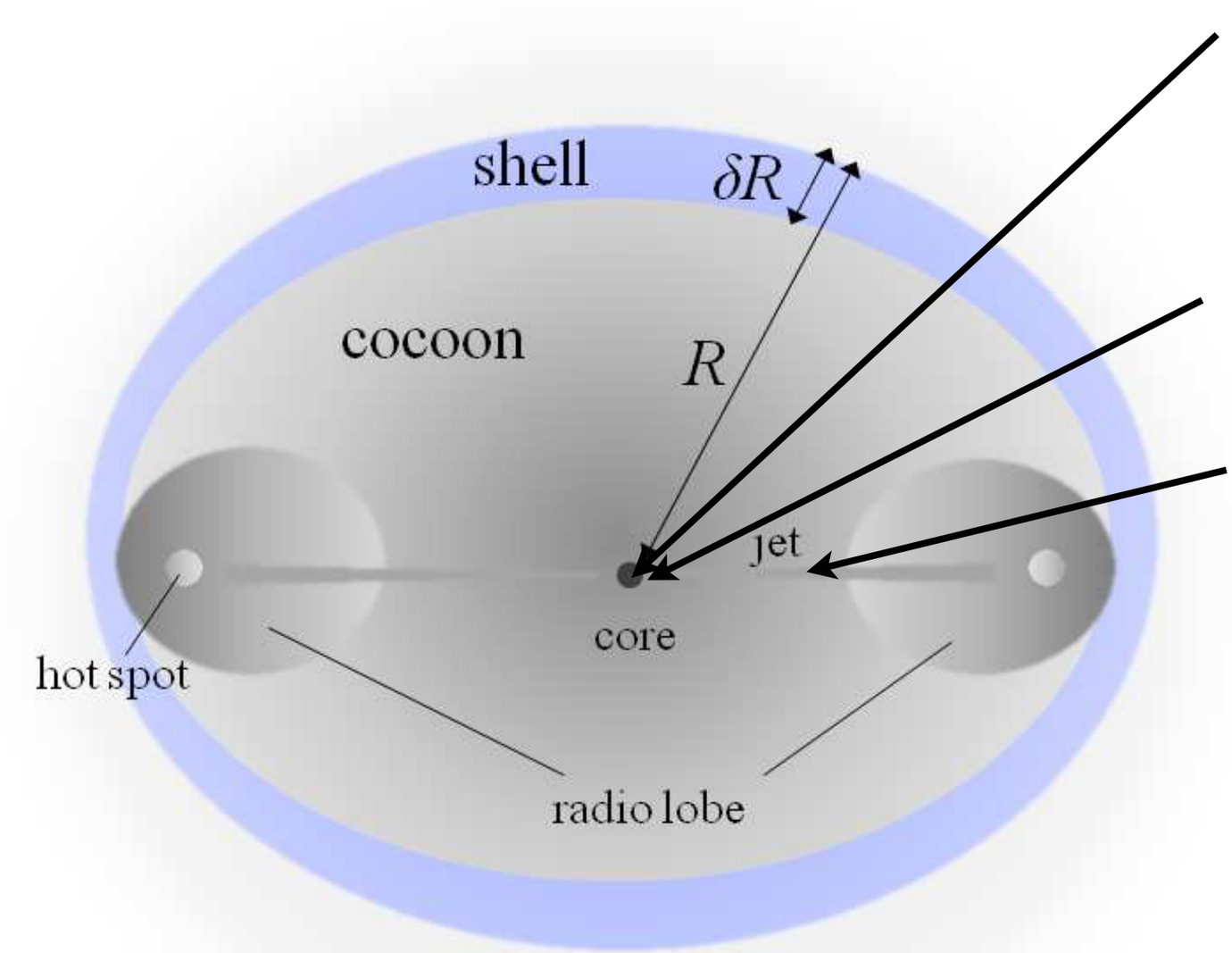

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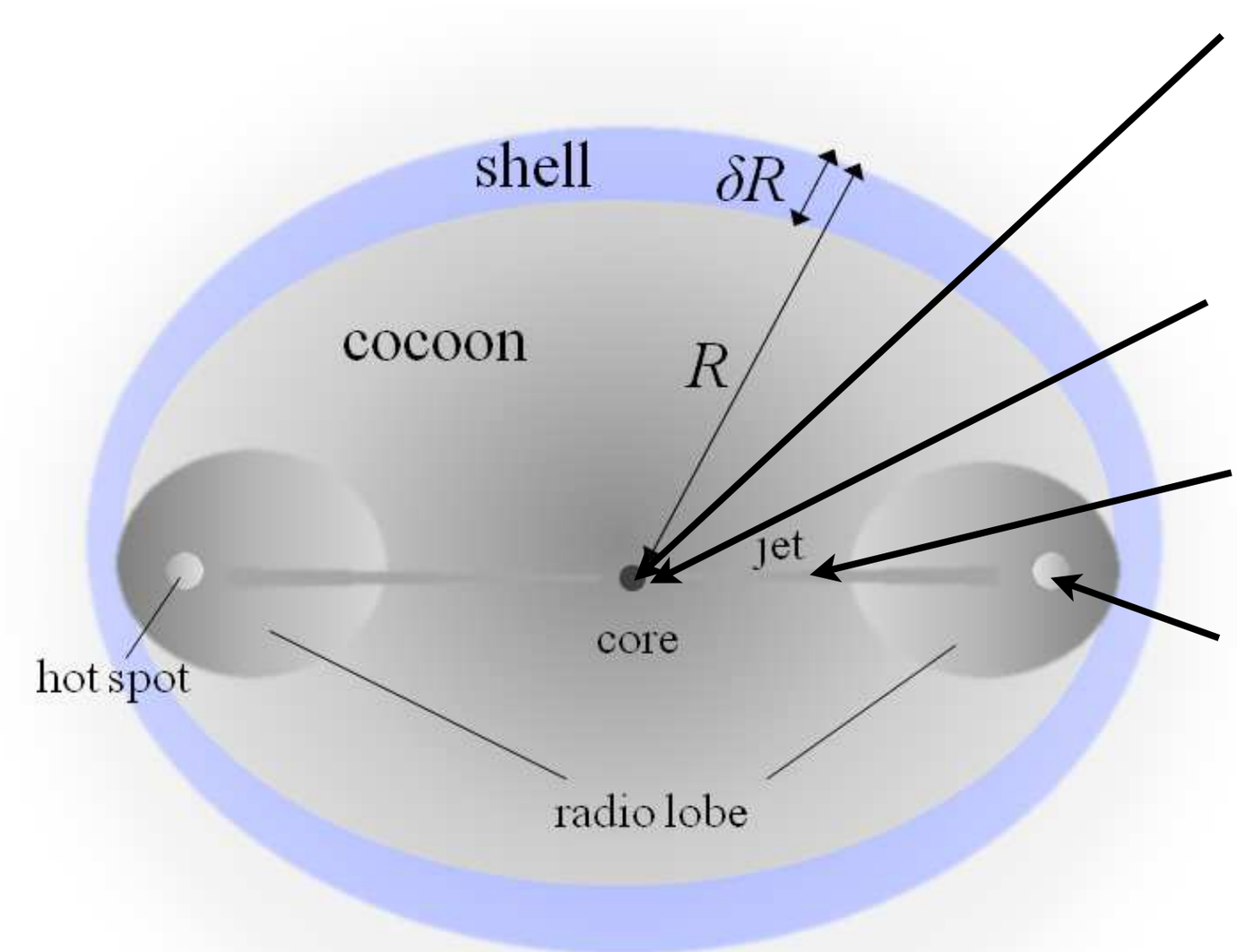

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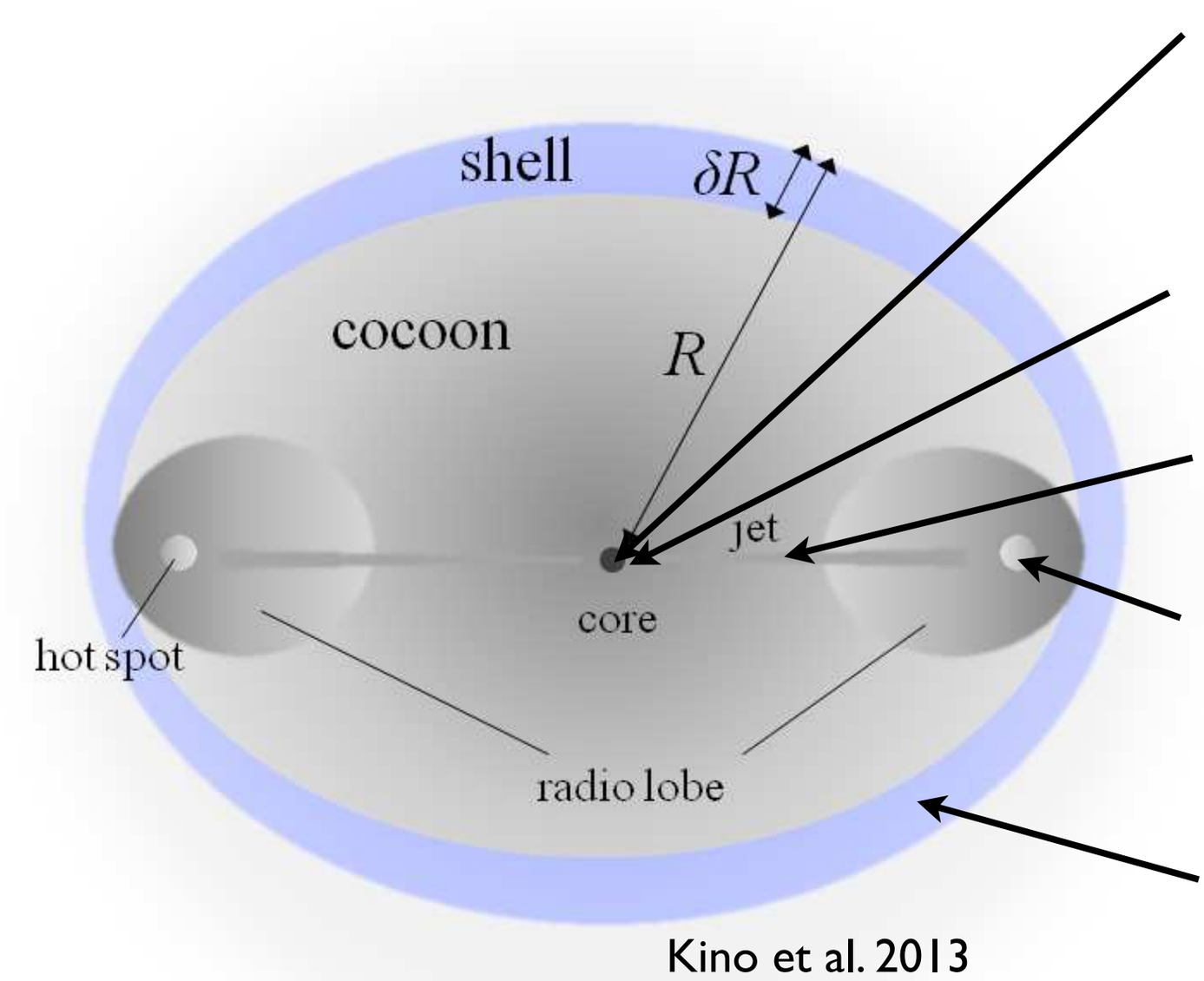

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  (e.g. Kino et al. 2013)

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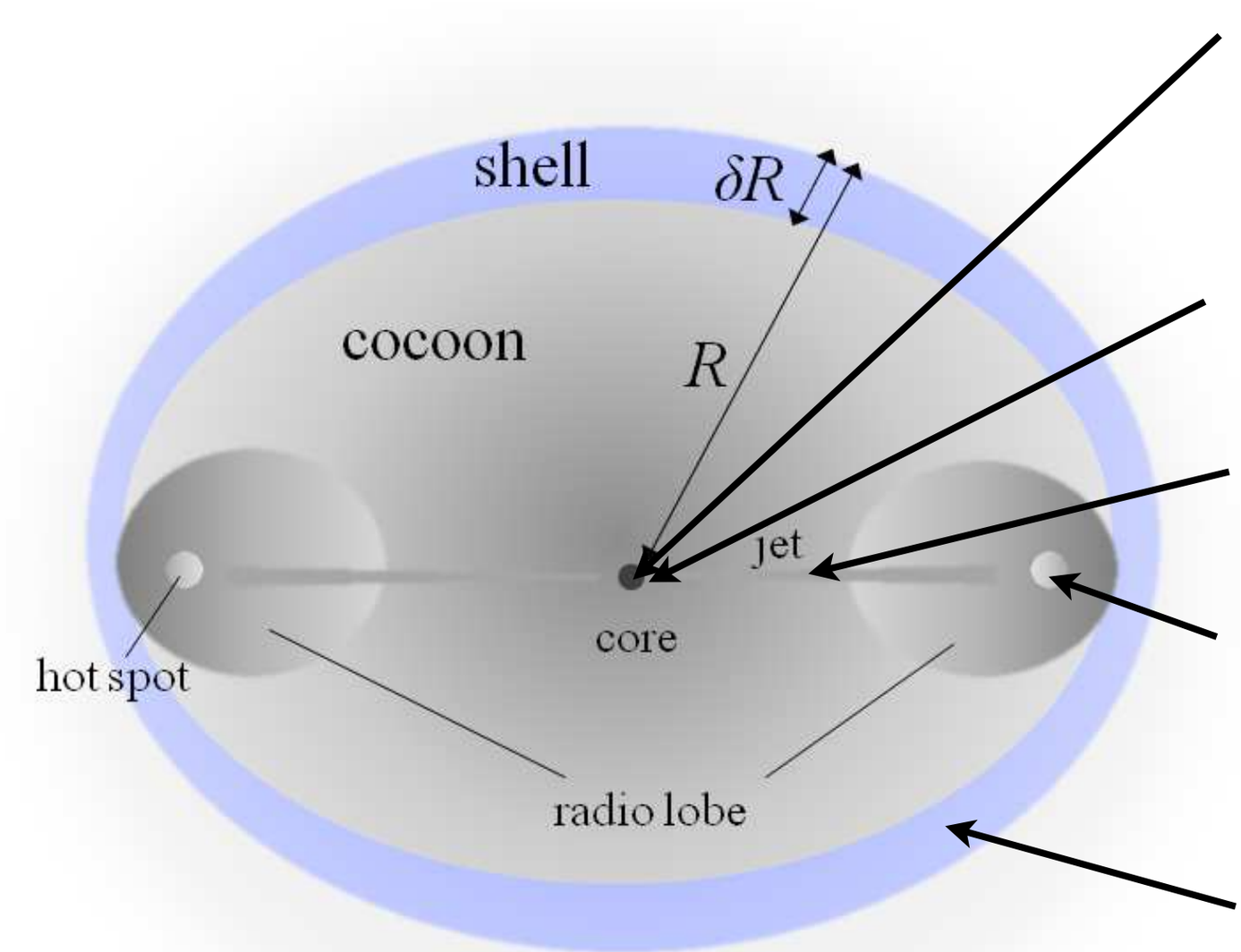

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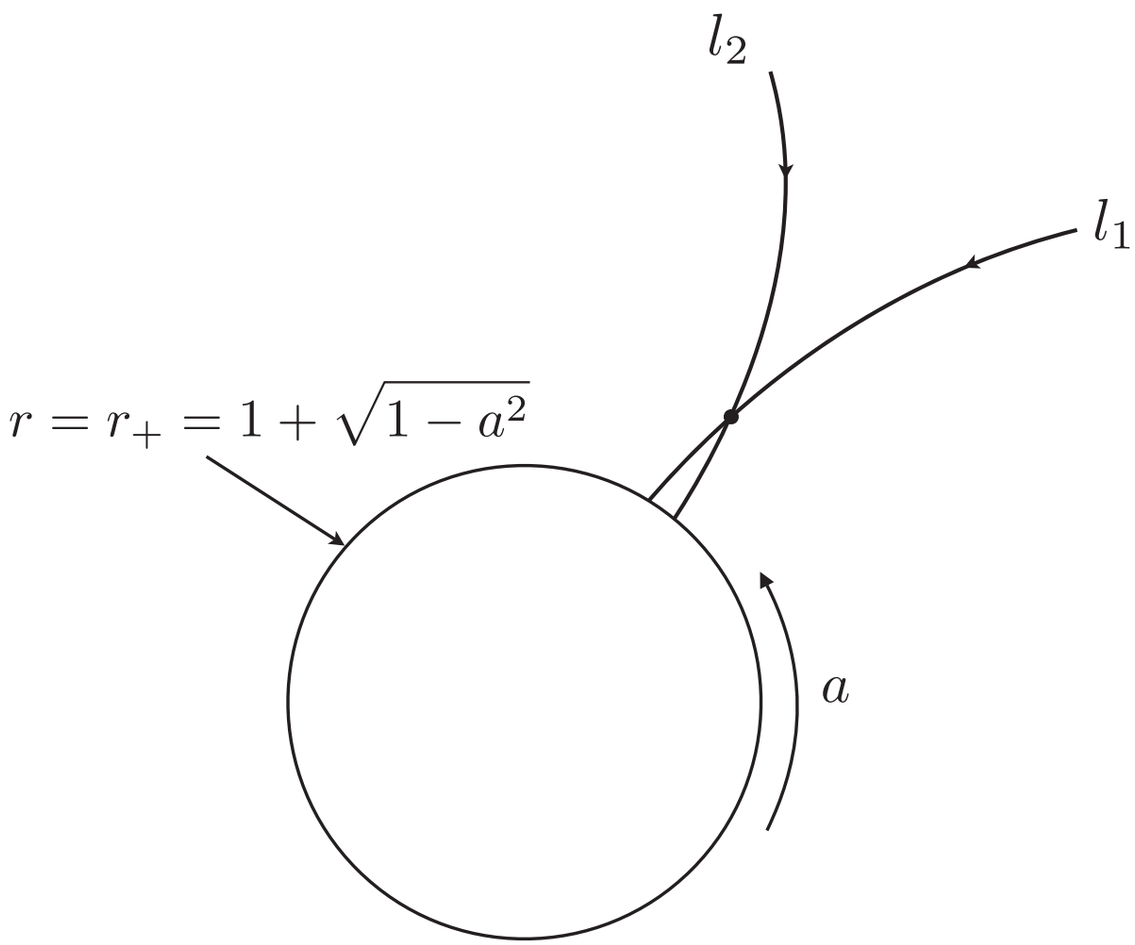
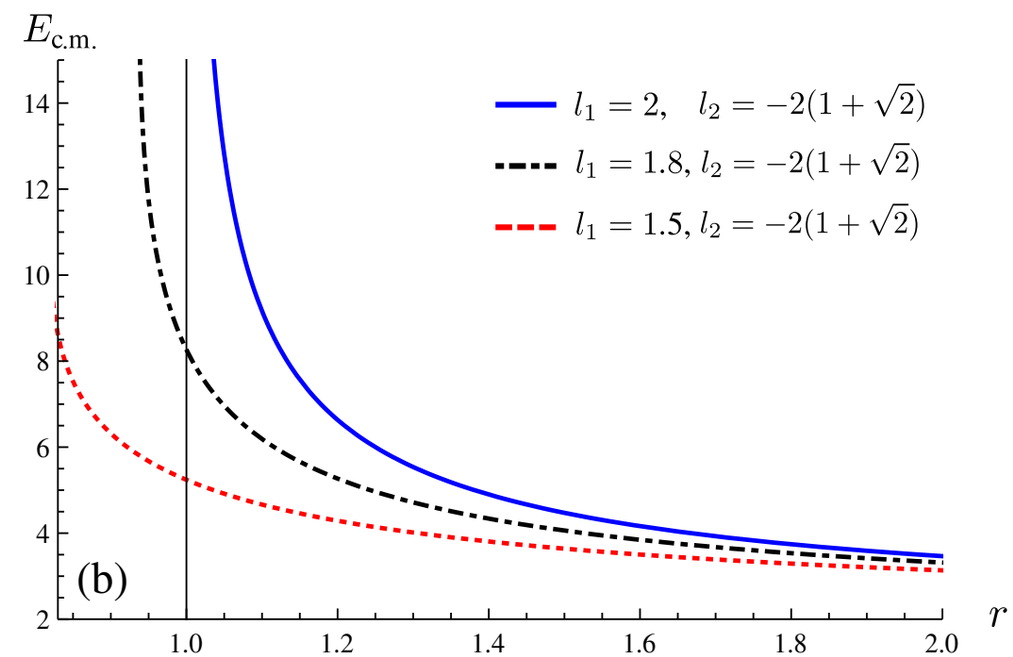
Role of P, $e^{\pm}$, B ?

The Event Horizon as Particle Accelerator?





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Bañados, Silk, West (2009)

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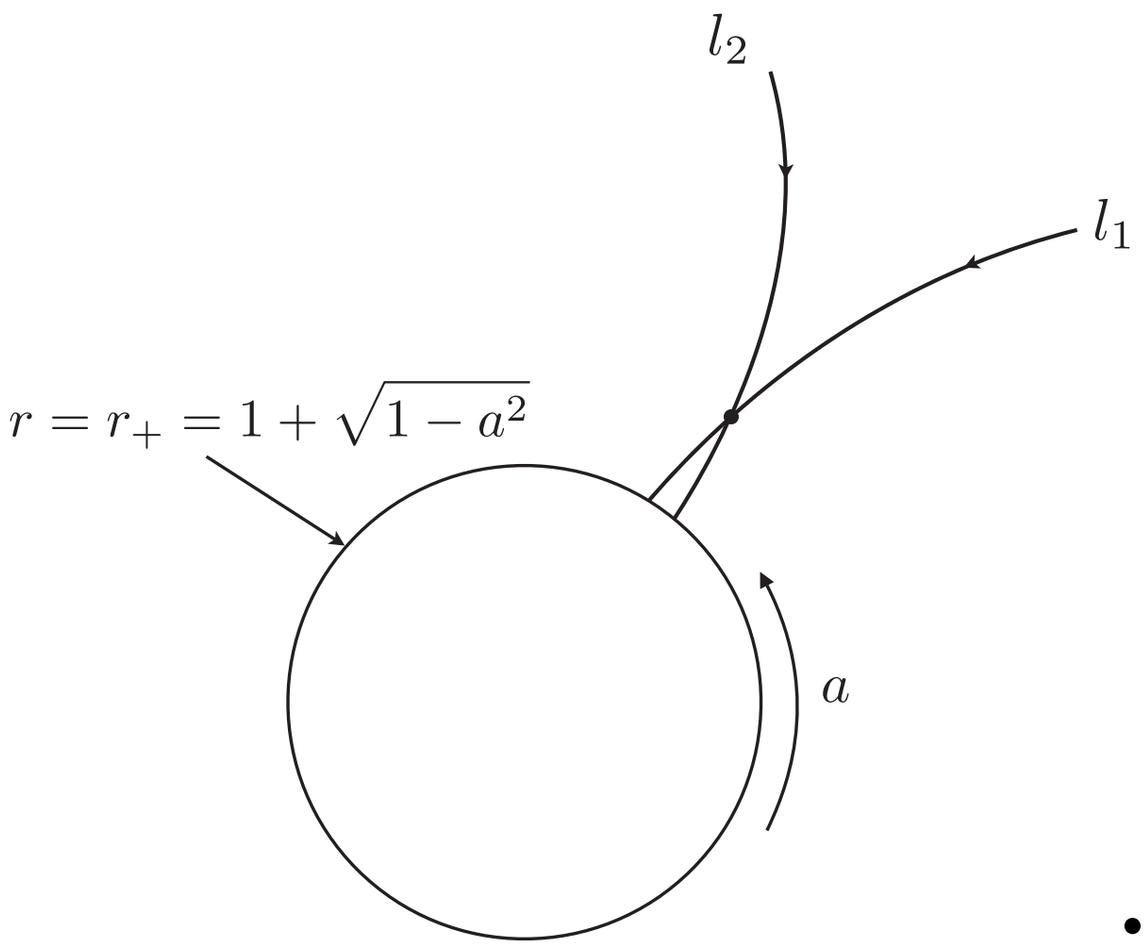

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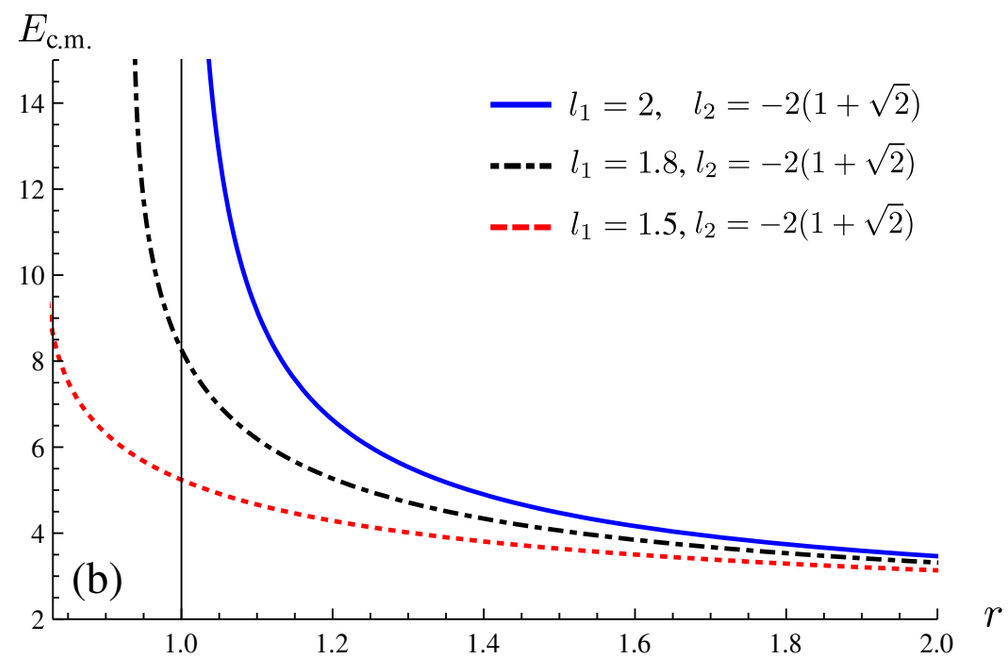

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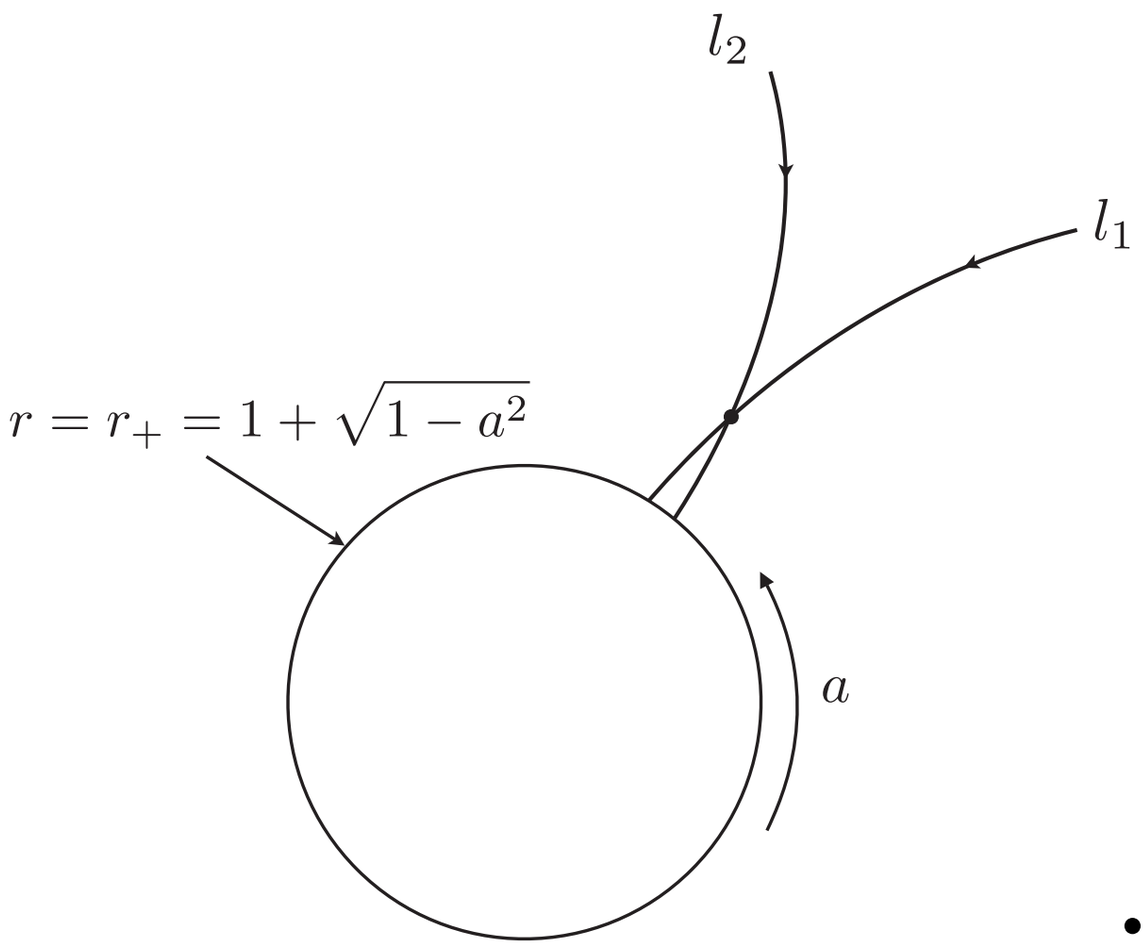

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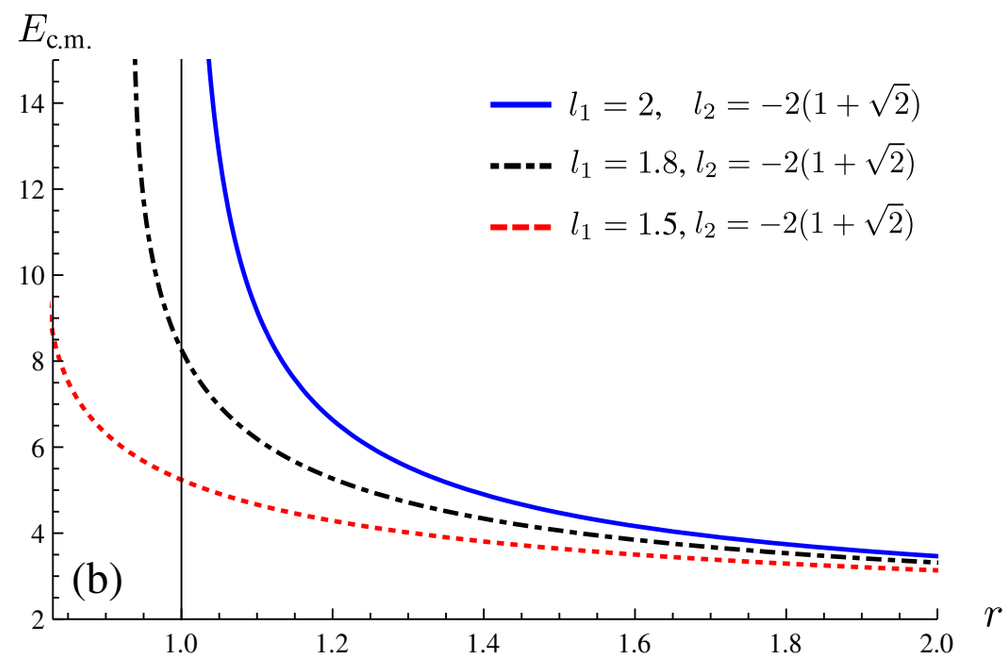

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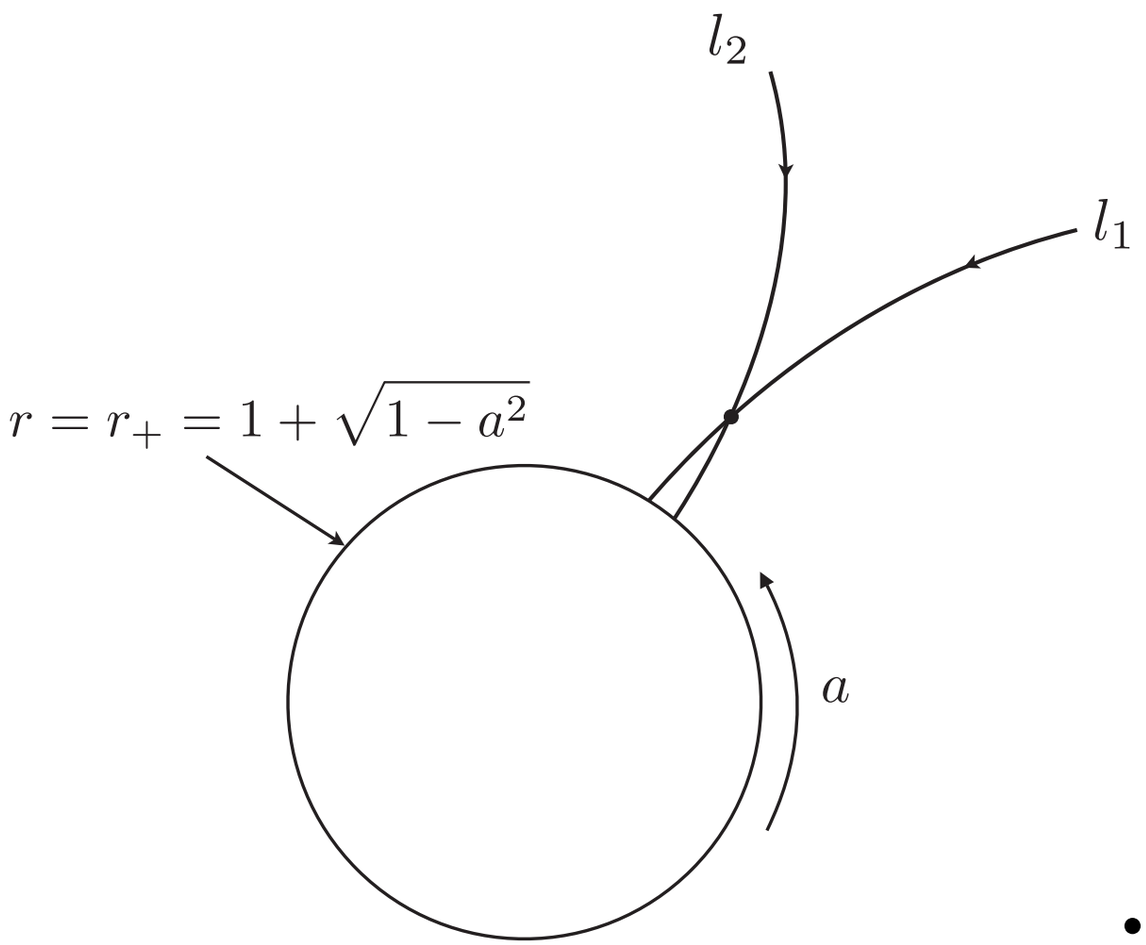

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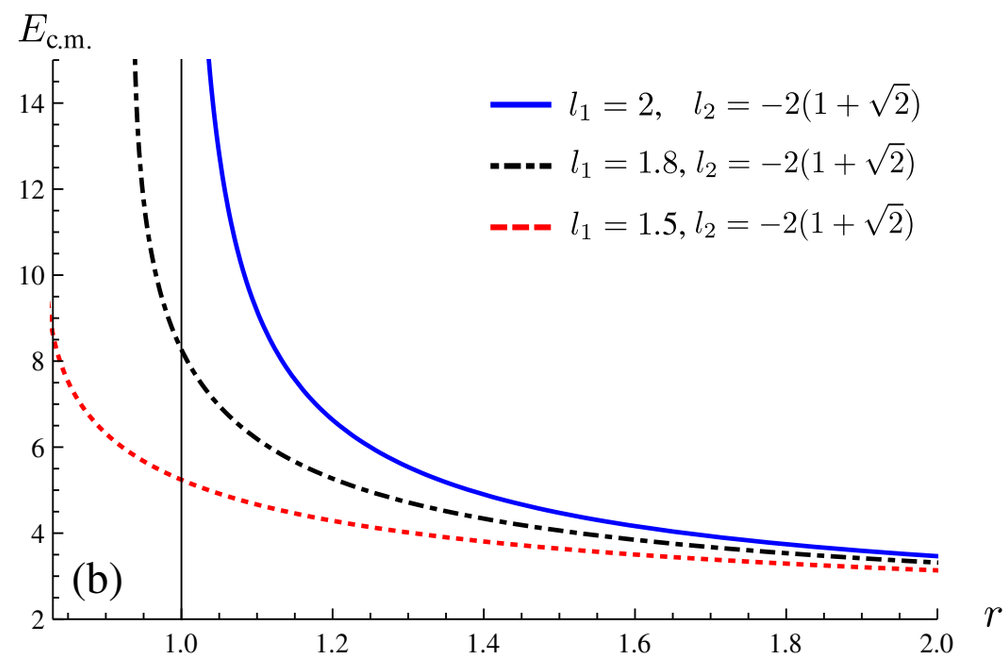

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- The center of mass energy is limited!
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- Dark matter annihilation close to black hole
  (Williams 2013).

Particle Acceleration in the BH Magnetosphere

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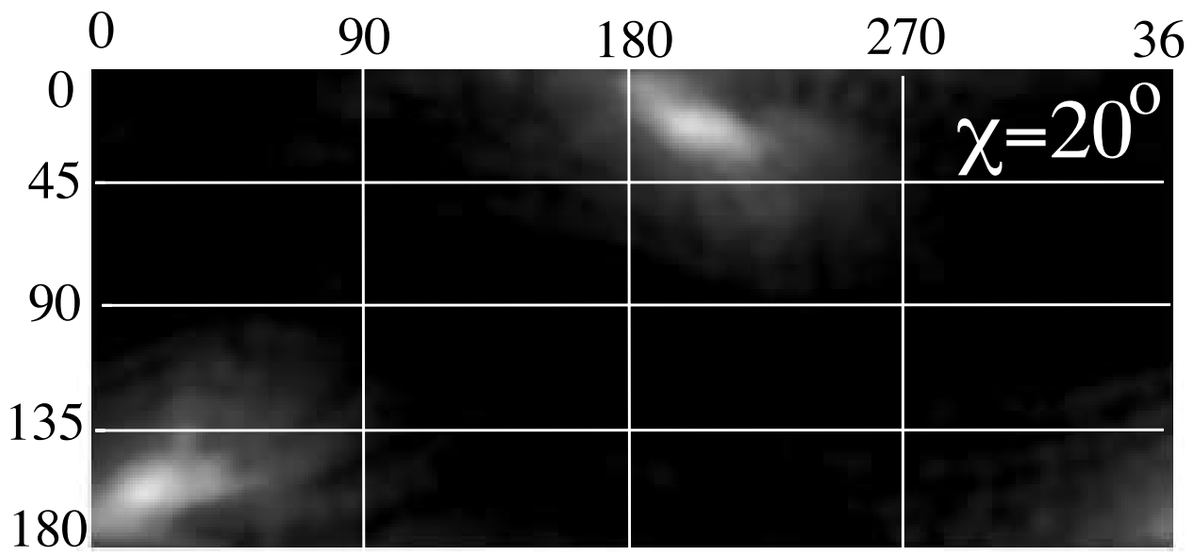

Pattern of synchrotron/IC emission from electrons accelerated in vacuum gaps.

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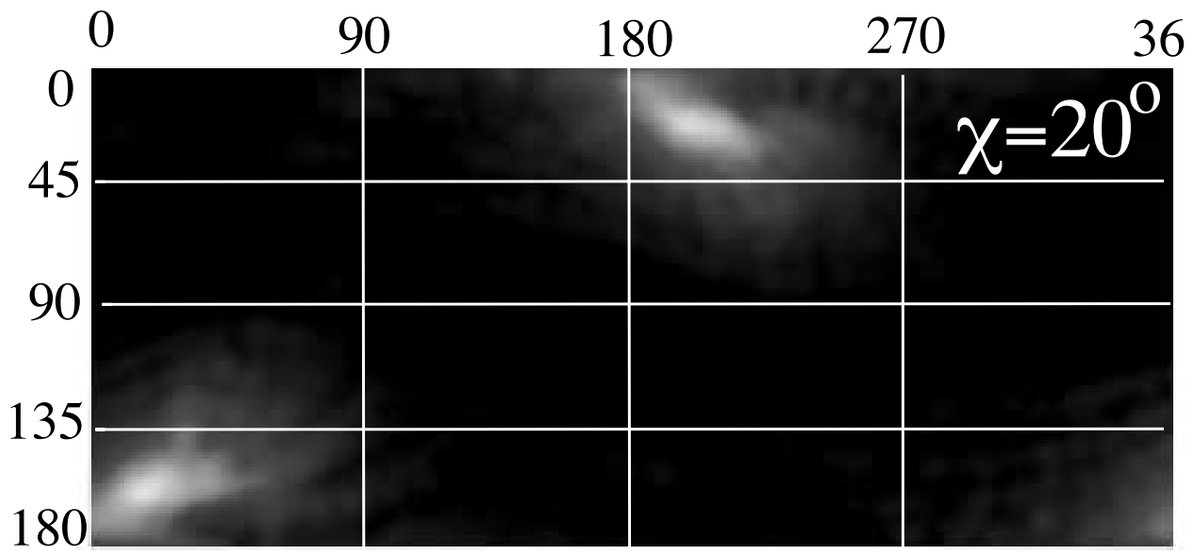

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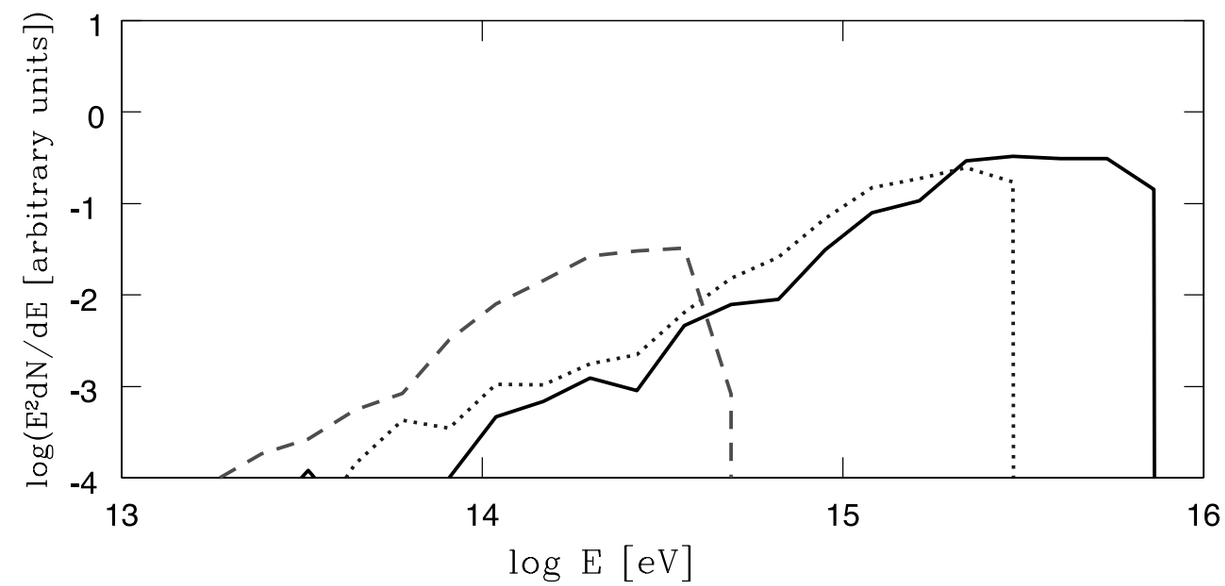

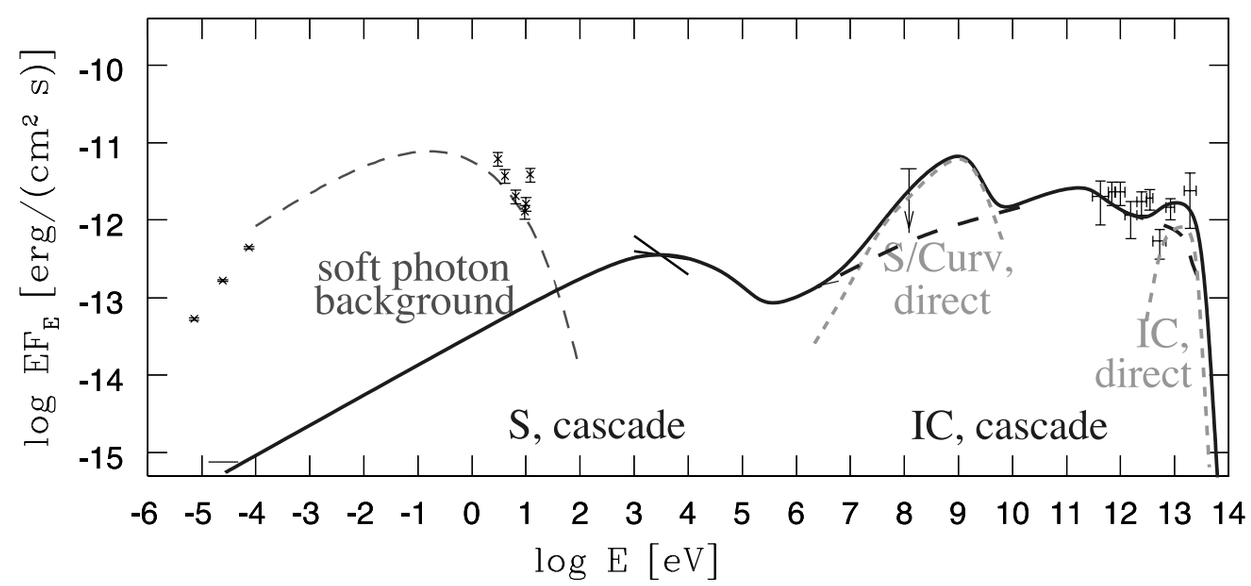

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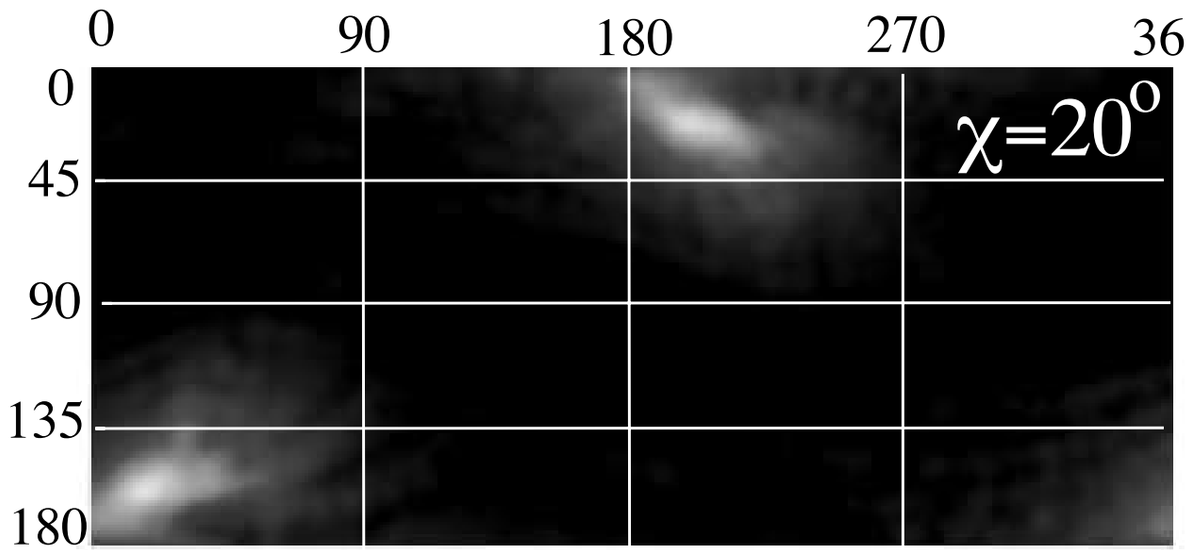

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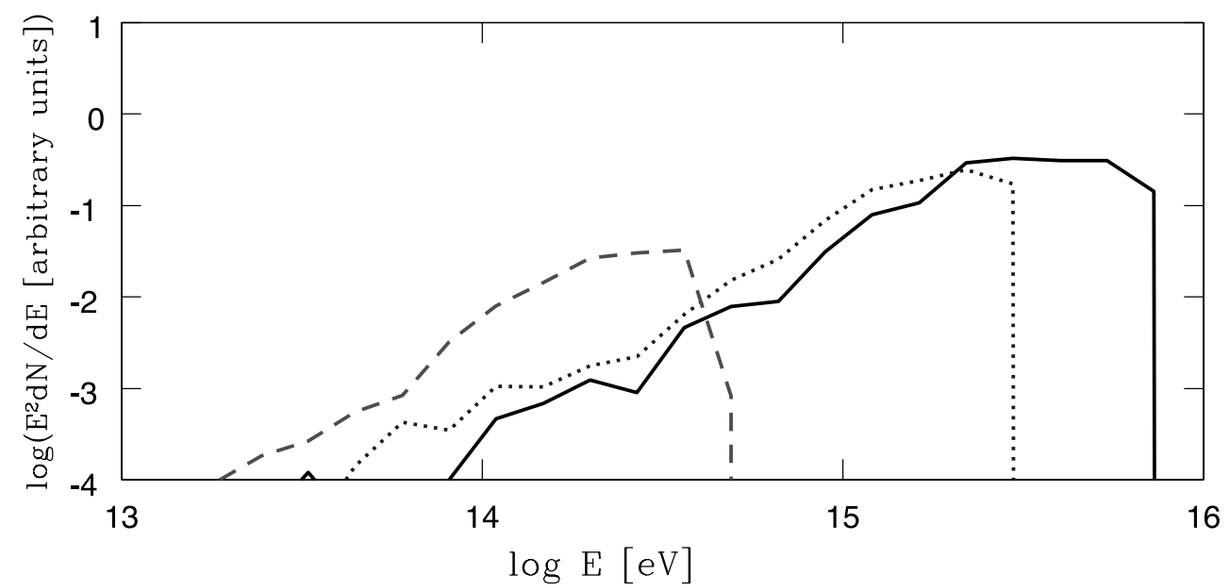
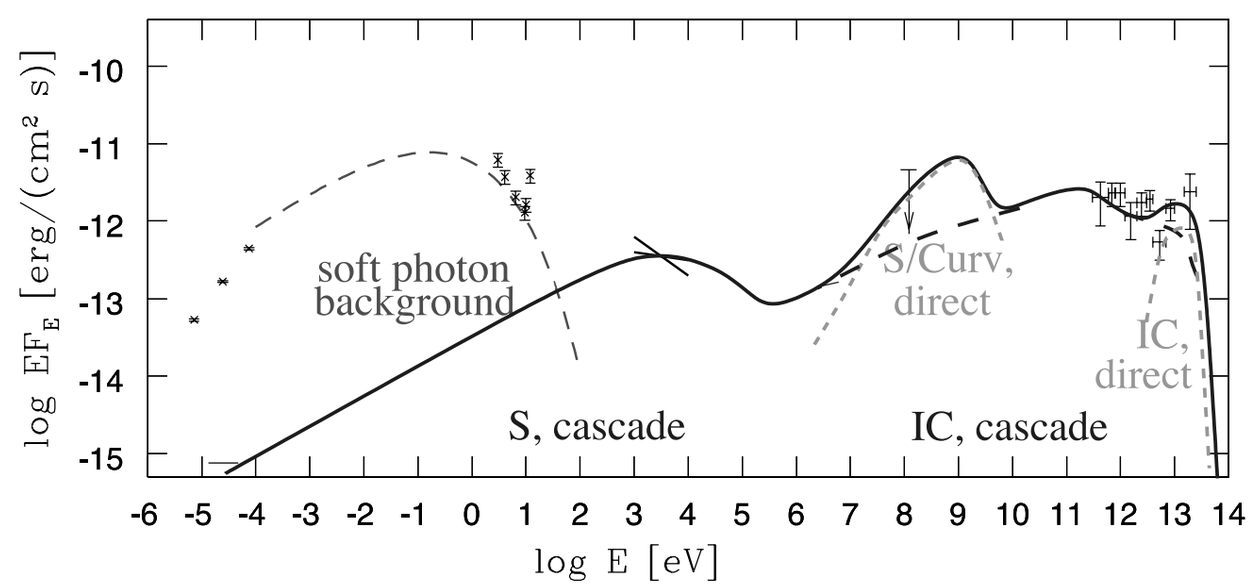
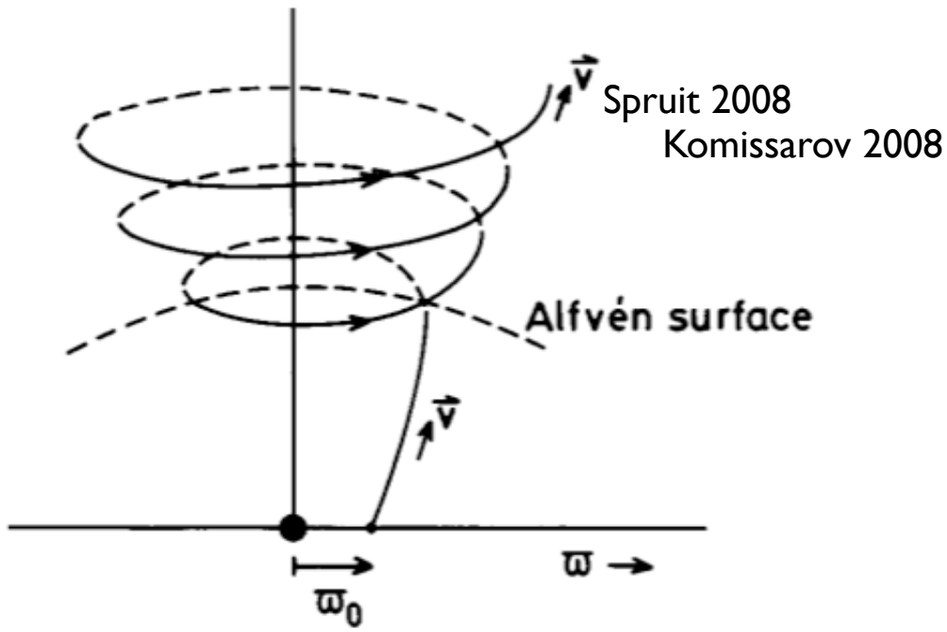


Model with similarities to particle acceleration pulsar vacuum gaps.



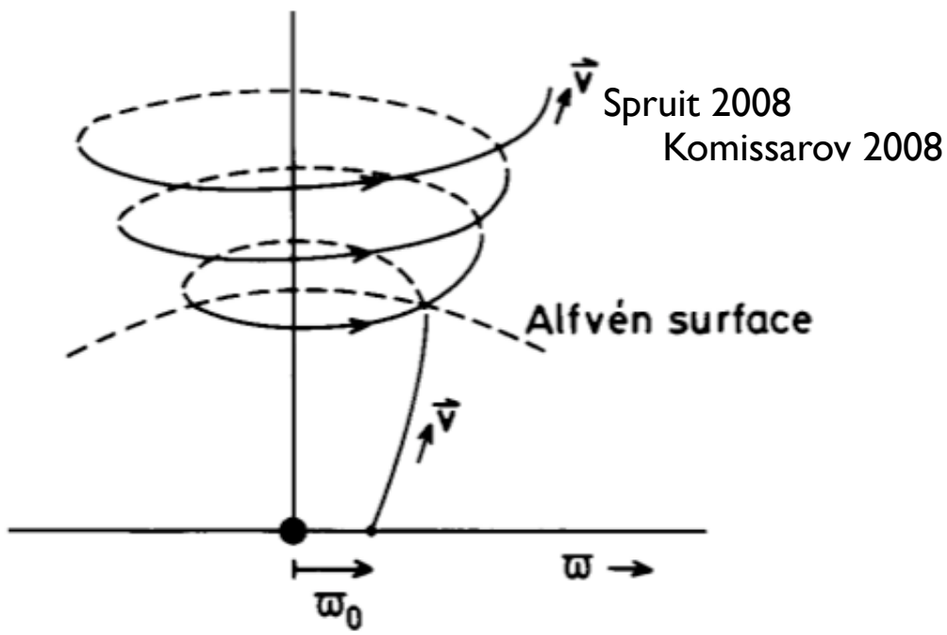
Magnetic Acceleration and Collimation of Jets

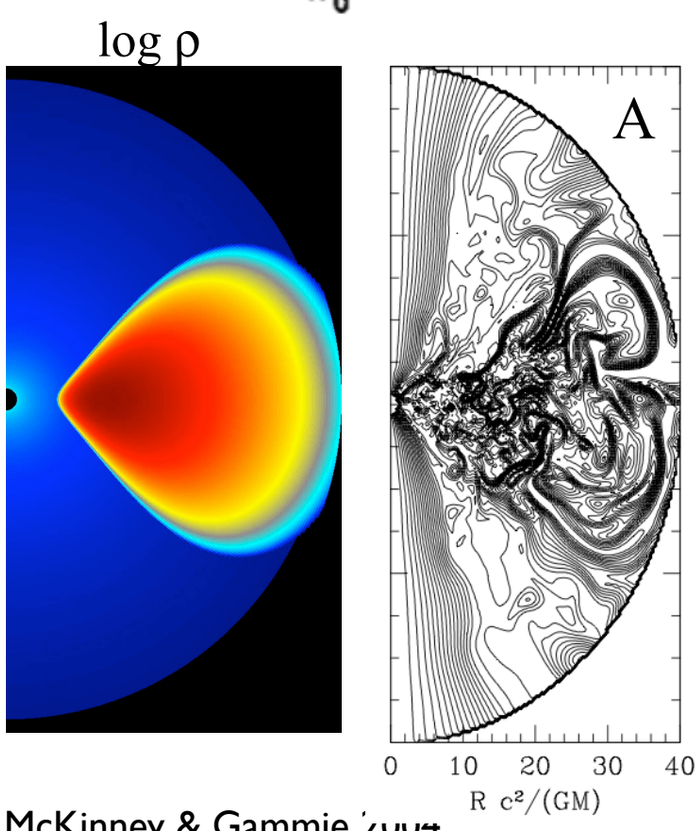


Basic Mechanisms:

- Magnetic acceleration and confinement (Blandford & Payne 1982, Li, Chiueh, Begelman 1992, Vlahakis & Königl, 2003, and others).
- Blandford-Znajek effect (Blandford & Znajek 1977).

Magnetic Acceleration and Collimation of Jets





McKinney & Gammie 2004, ApJ, 611, 977.

Basic Mechanisms:

- Magnetic acceleration and confinement (Blandford & Payne 1982, Li, Chiueh, Begelman 1992, Vlahakis & Königl, 2003, and others).
- Blandford-Znajek effect (Blandford & Znajek 1977).

Numerical results (De Villiers et al. 2005, McKinney 2006, Krolik, Hawley, Hirose, 2007, Komissarov 2007, and others):

- Possible jet structure: matter dominated funnel wall, electromagnetic core.
- Magnetic acceleration & collimation on scales of 10^{3}-10^{4} r_g.
- Asymptotic flow: ~50% of magnetic energy converted into kinetic energy.

$$\sigma = B^2/4\pi\Gamma\rho c^2$$

- Γ~10-1000 seems feasible.

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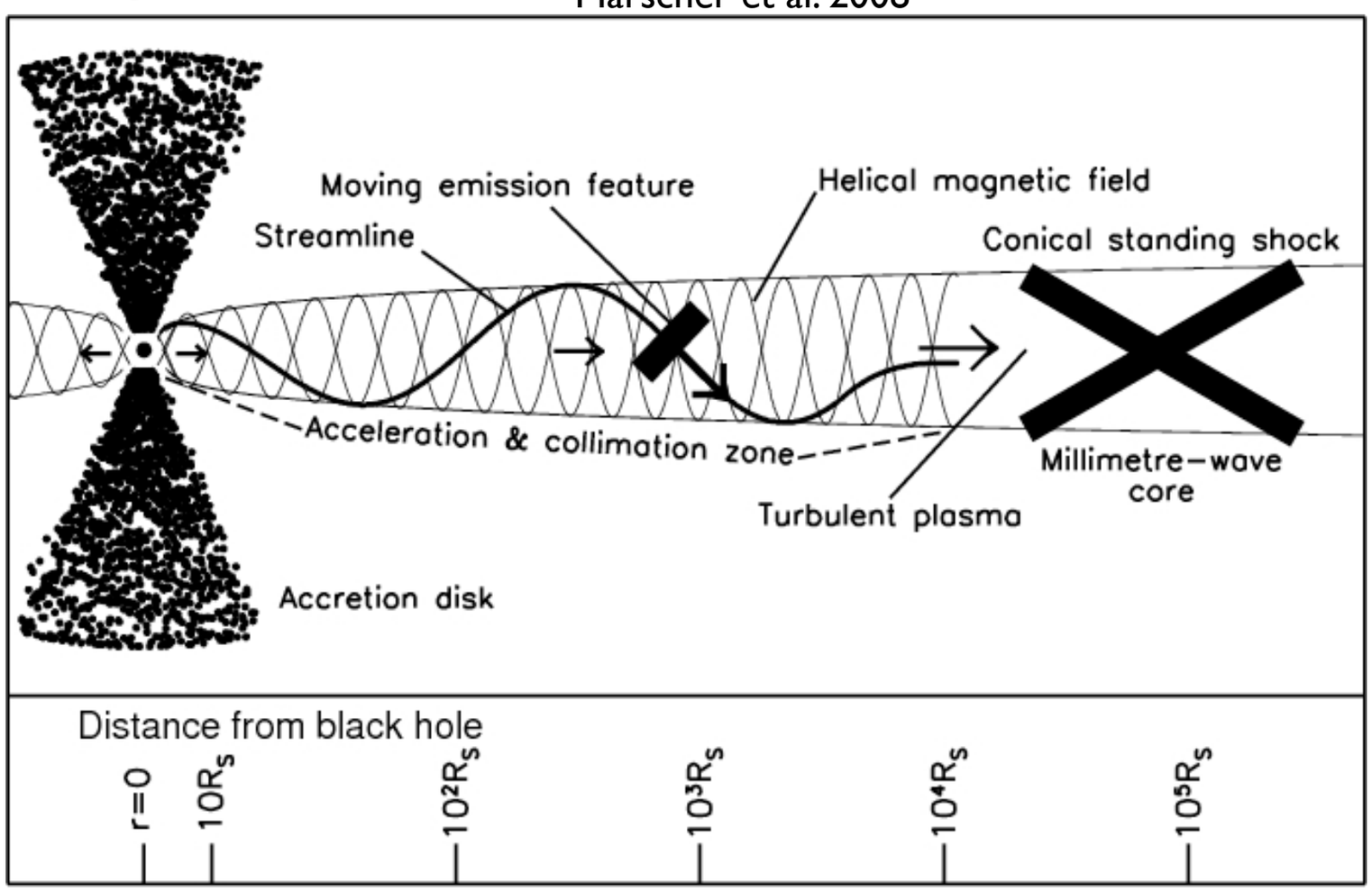

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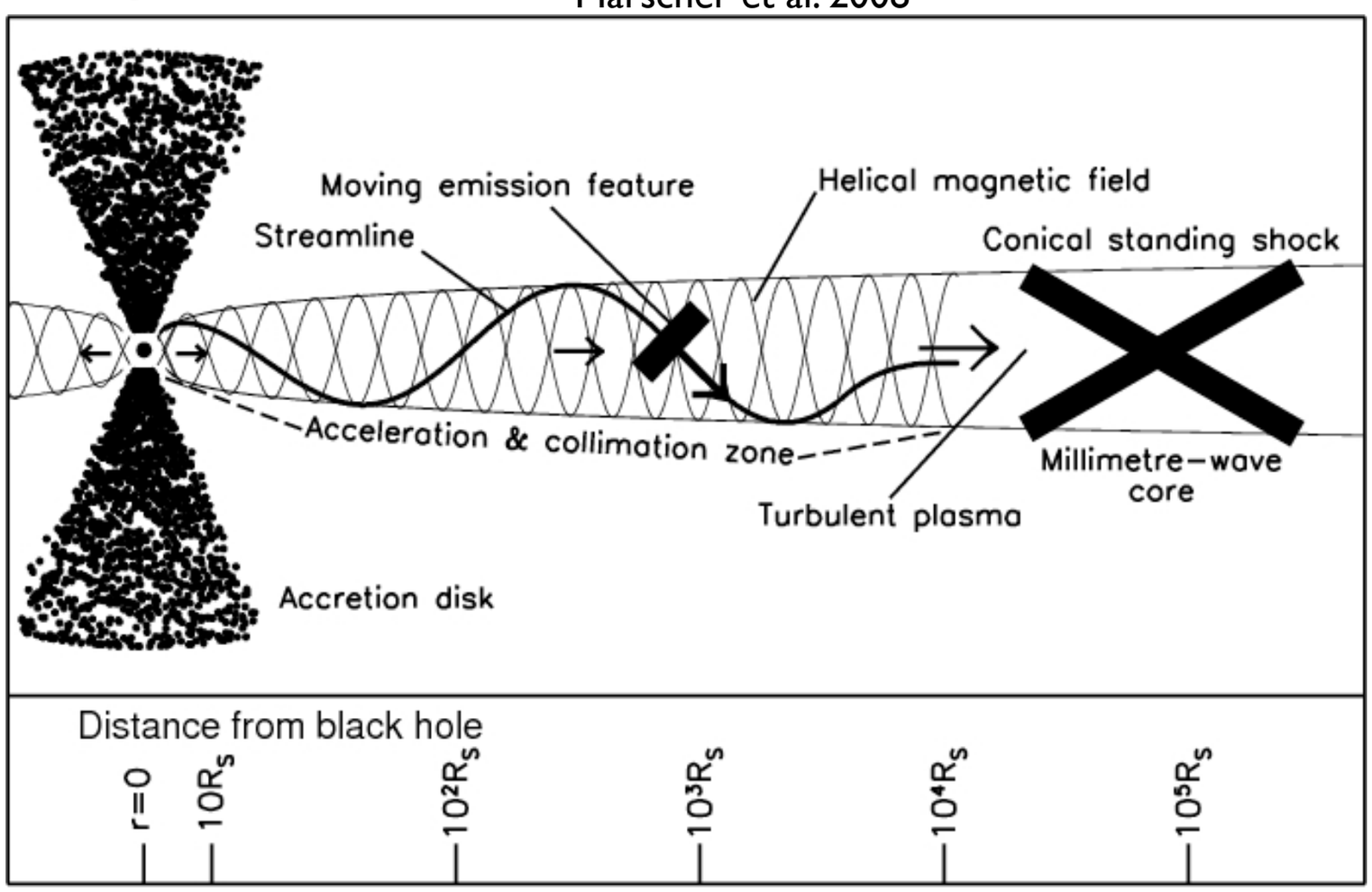

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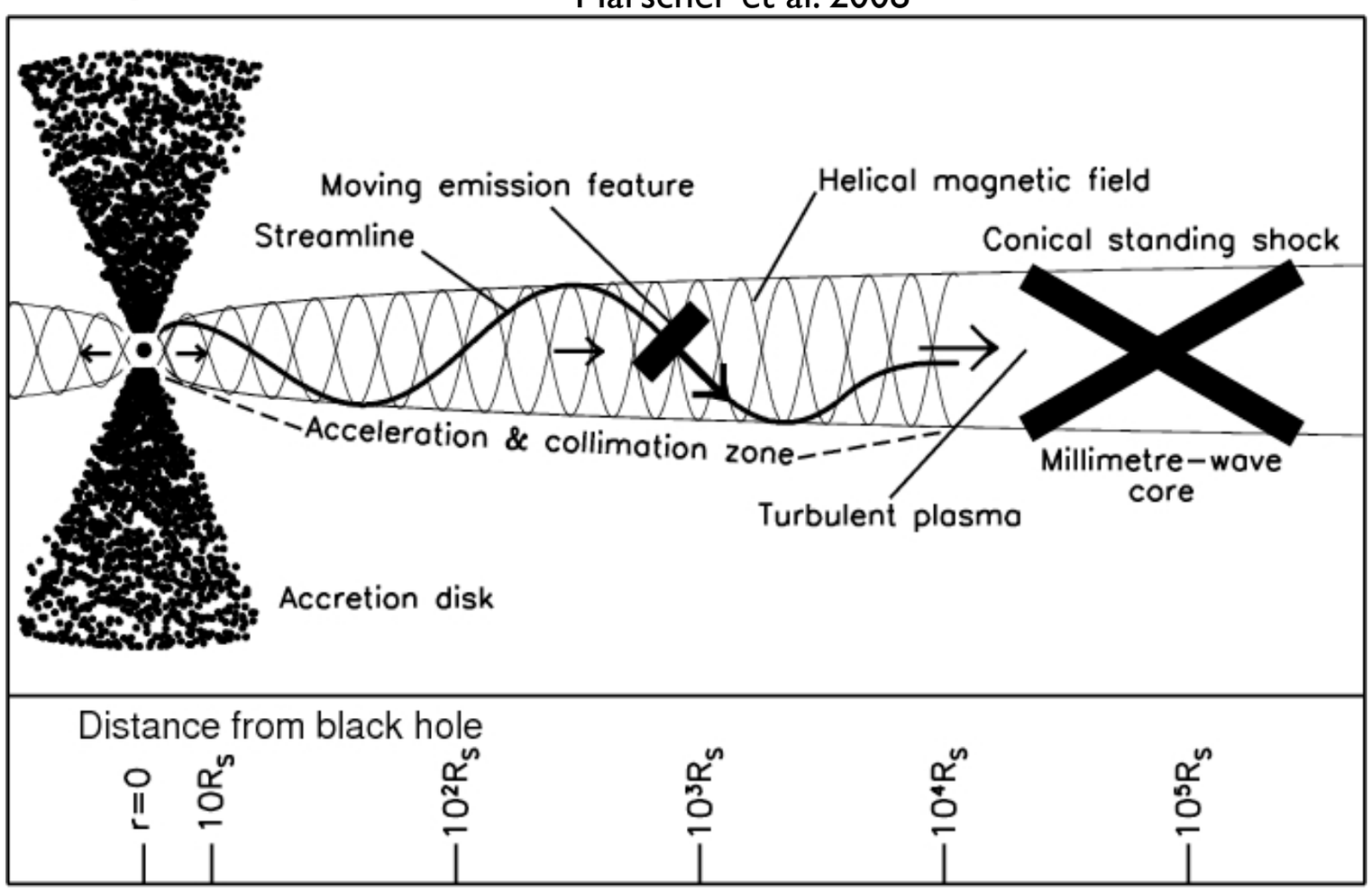
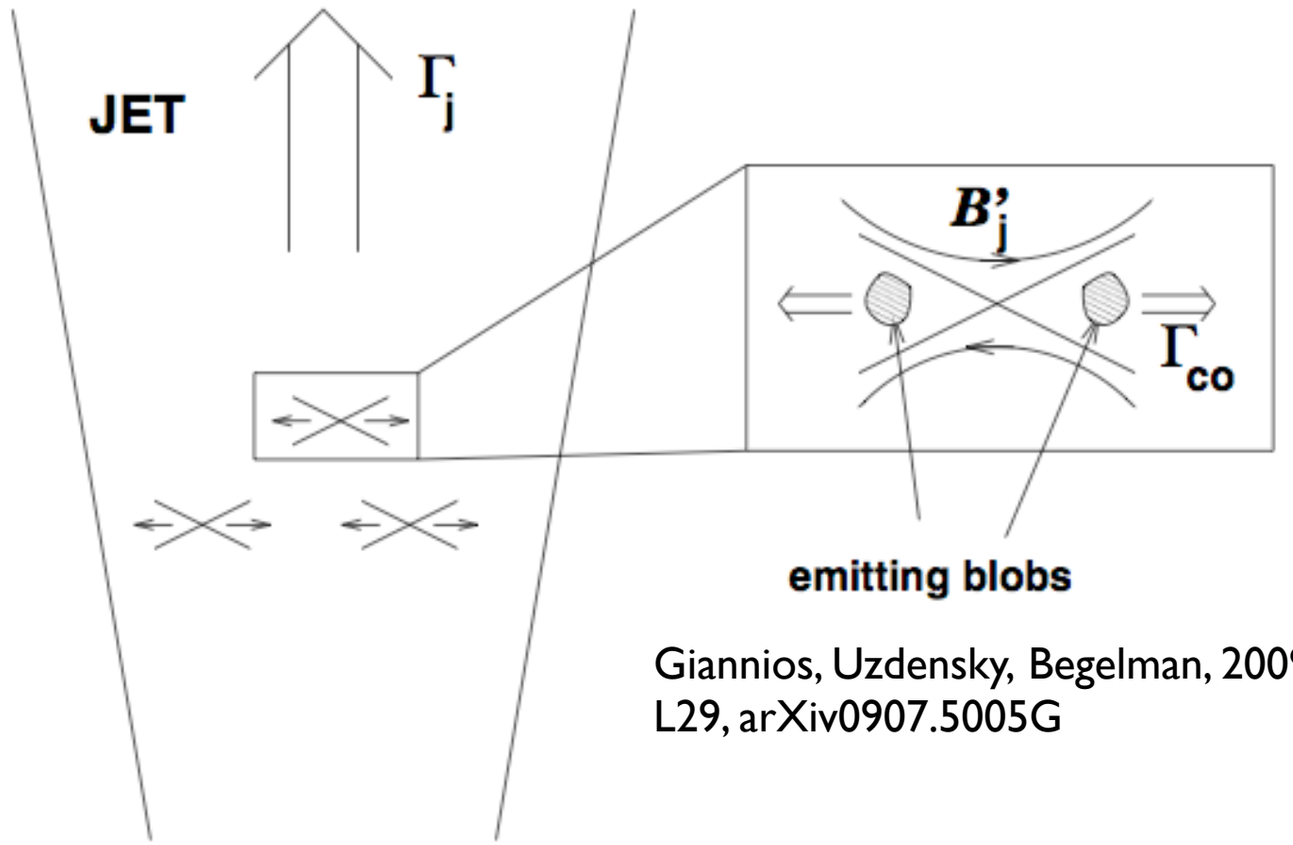


- External shocks.

$$\sigma = B^2/4\pi\Gamma\rho c^2 \ll 1$$

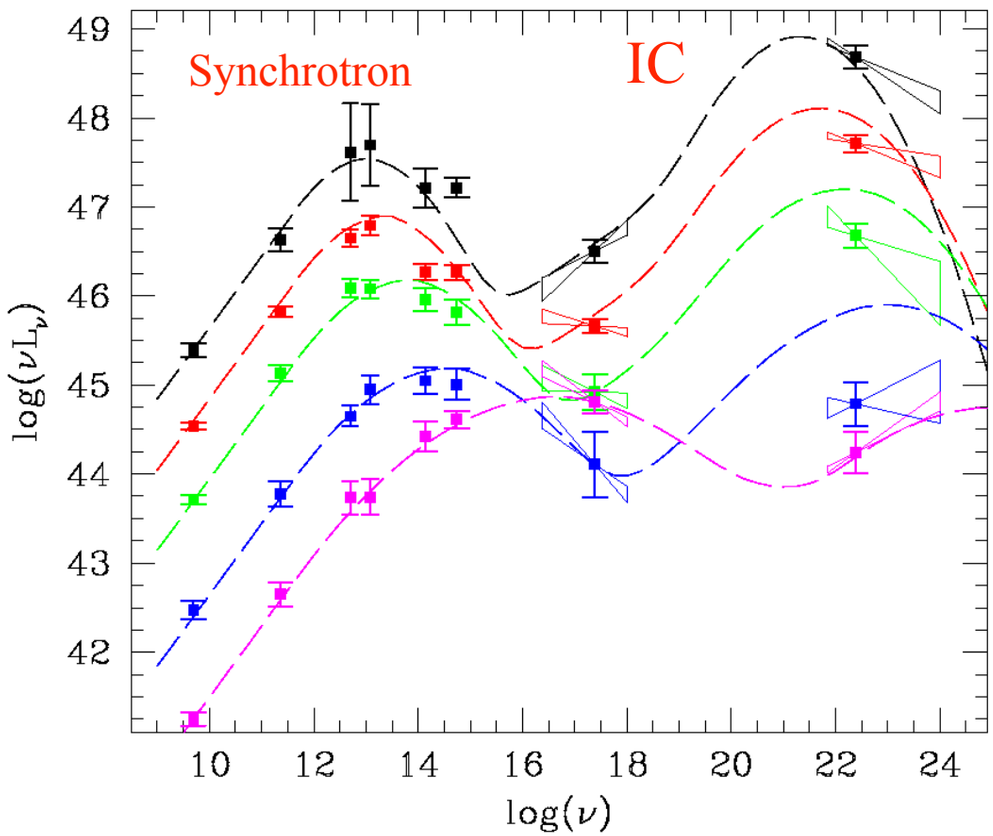
Acceleration through Magnetic Reconnection?



Giannios, Uzdensky, Begelman, 2009, MNRAS, 395, L29, arXiv0907.5005G

- Relativistic generalization of Petschek-type reconnection (Lyubarsky, 2005):
- Lorentz factor of minijets: $\Gamma_{co} = \sqrt{\sigma}$
- Thermal electron γ-factors are not high enough and particle acceleration is needed.
- Reconnection: kink instabilities or B-field reversals in BH magnetosphere.

Blazar Observations



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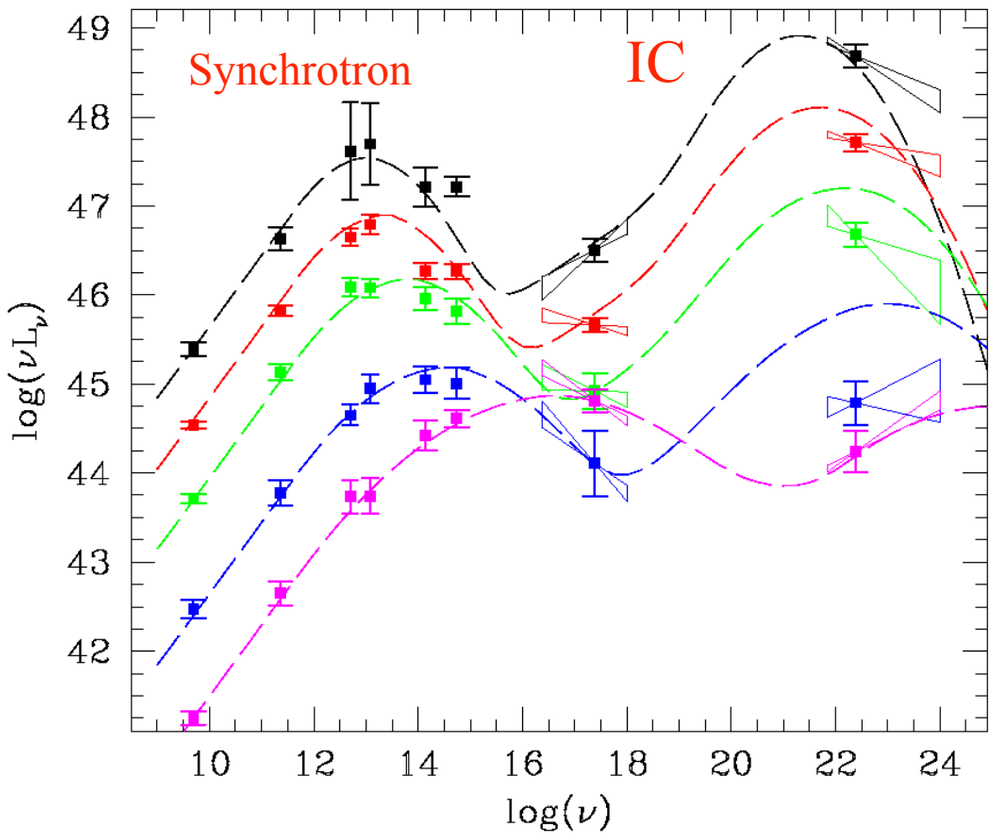
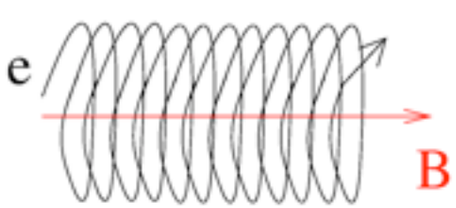


Synchrotron Emission:



dE/dt ~ B² E²

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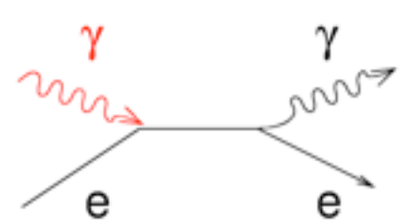

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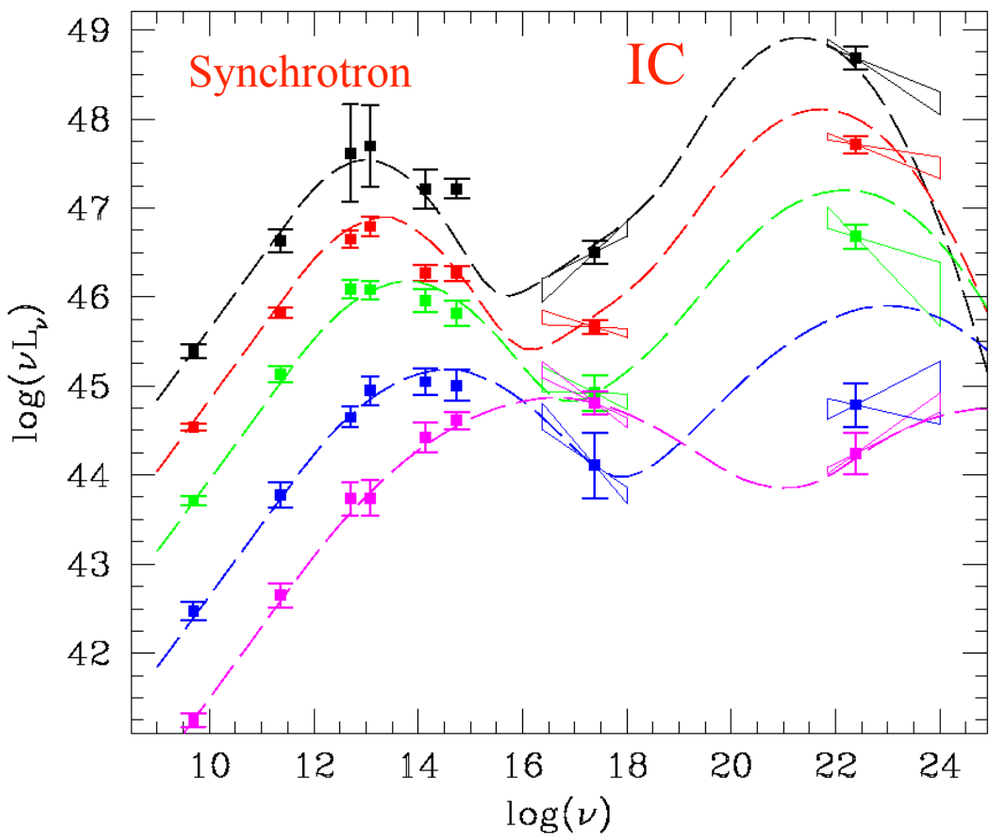

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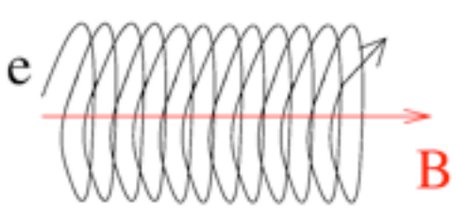

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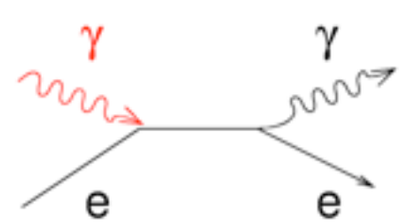

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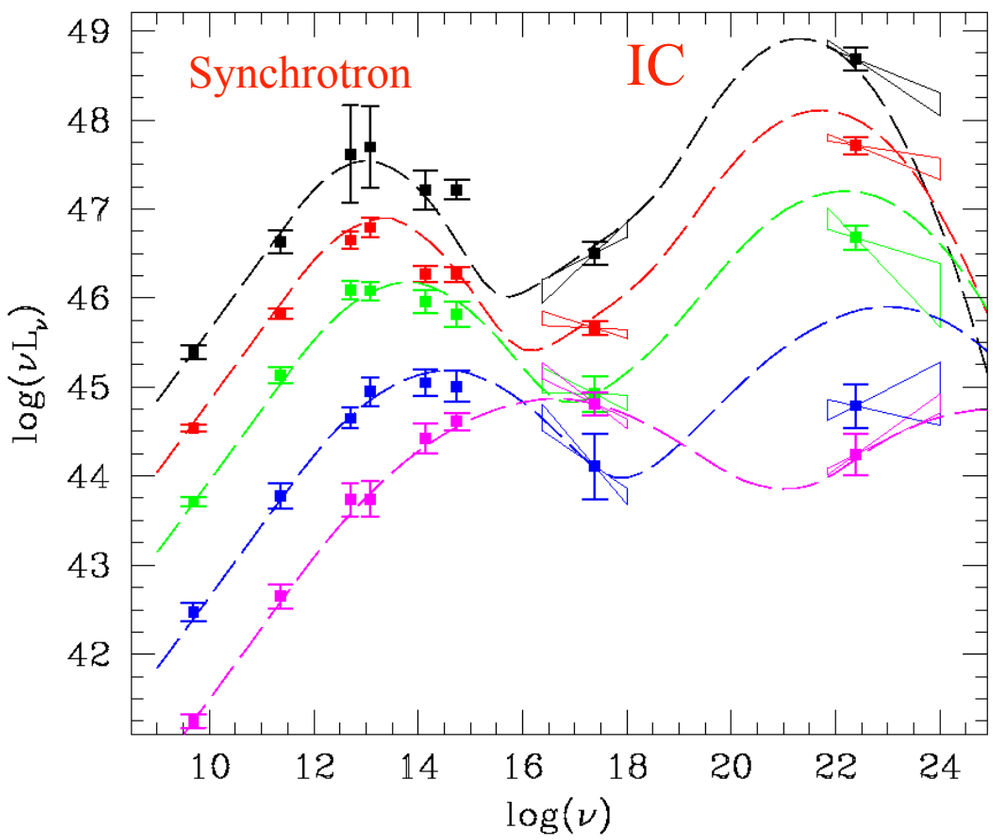

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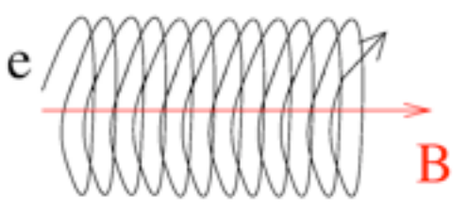

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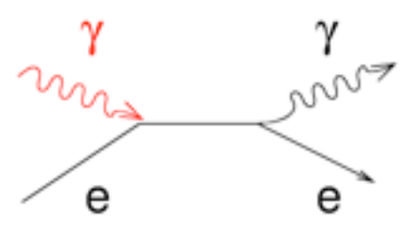

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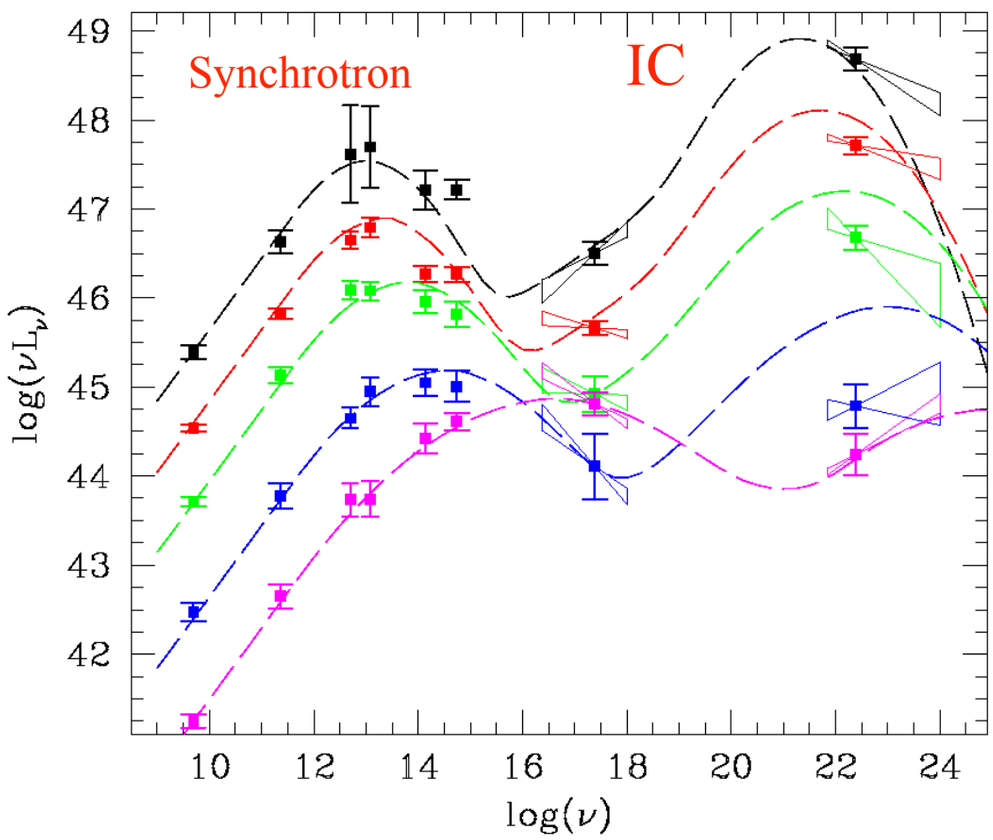

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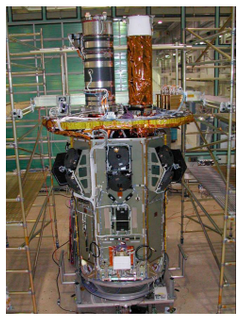


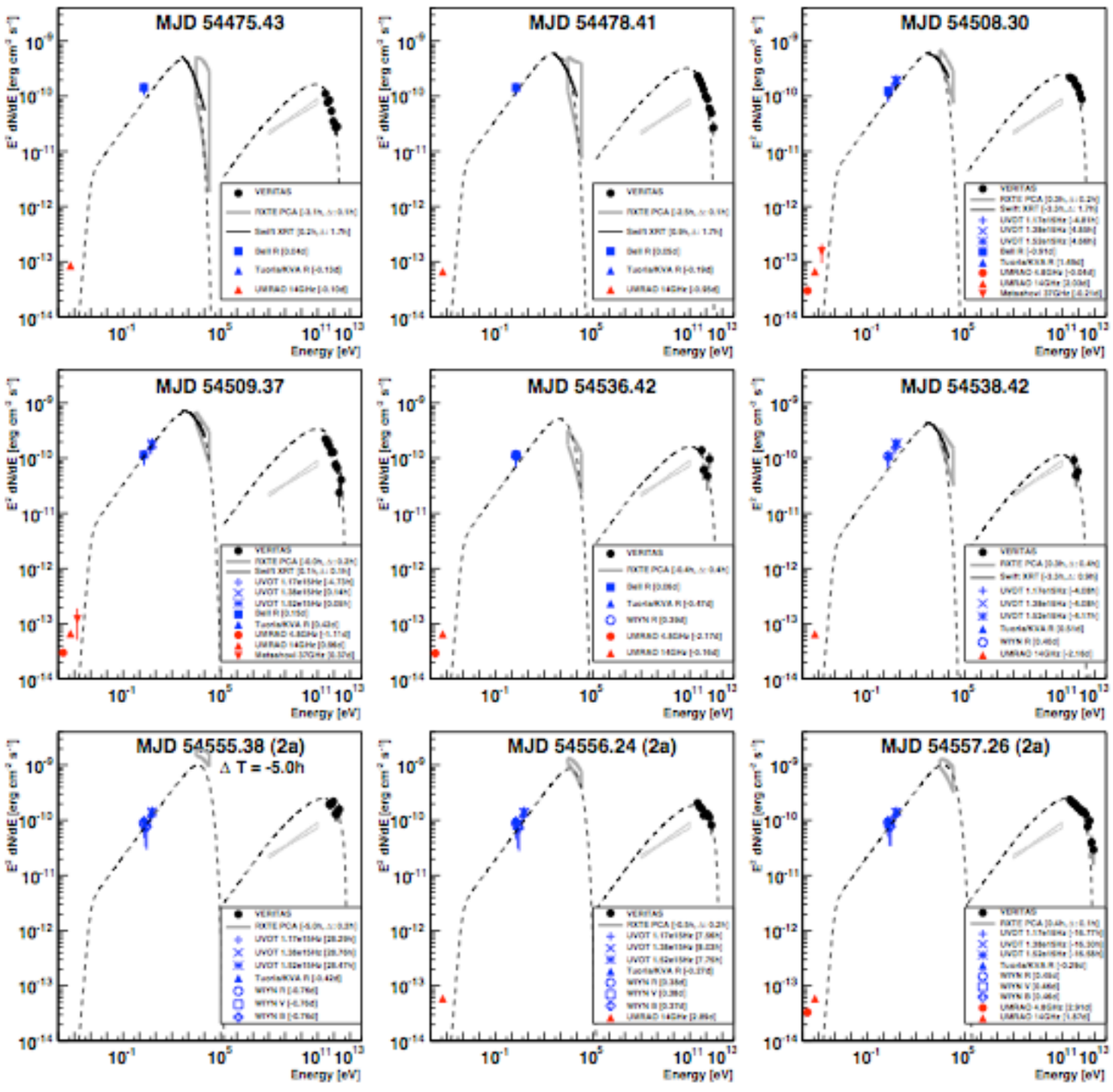
Swift

(Suzaku, NuSTAR!)

VERITAS (Fermi, H.E.S.S., MAGIC, **HAWC, CTA**)

X-Ray/γ-ray observations of Mrk 421 - 2008

Mrk 421 - Leptonic SSC Models of Diurnal SEDs:



Acciari et al. 2011

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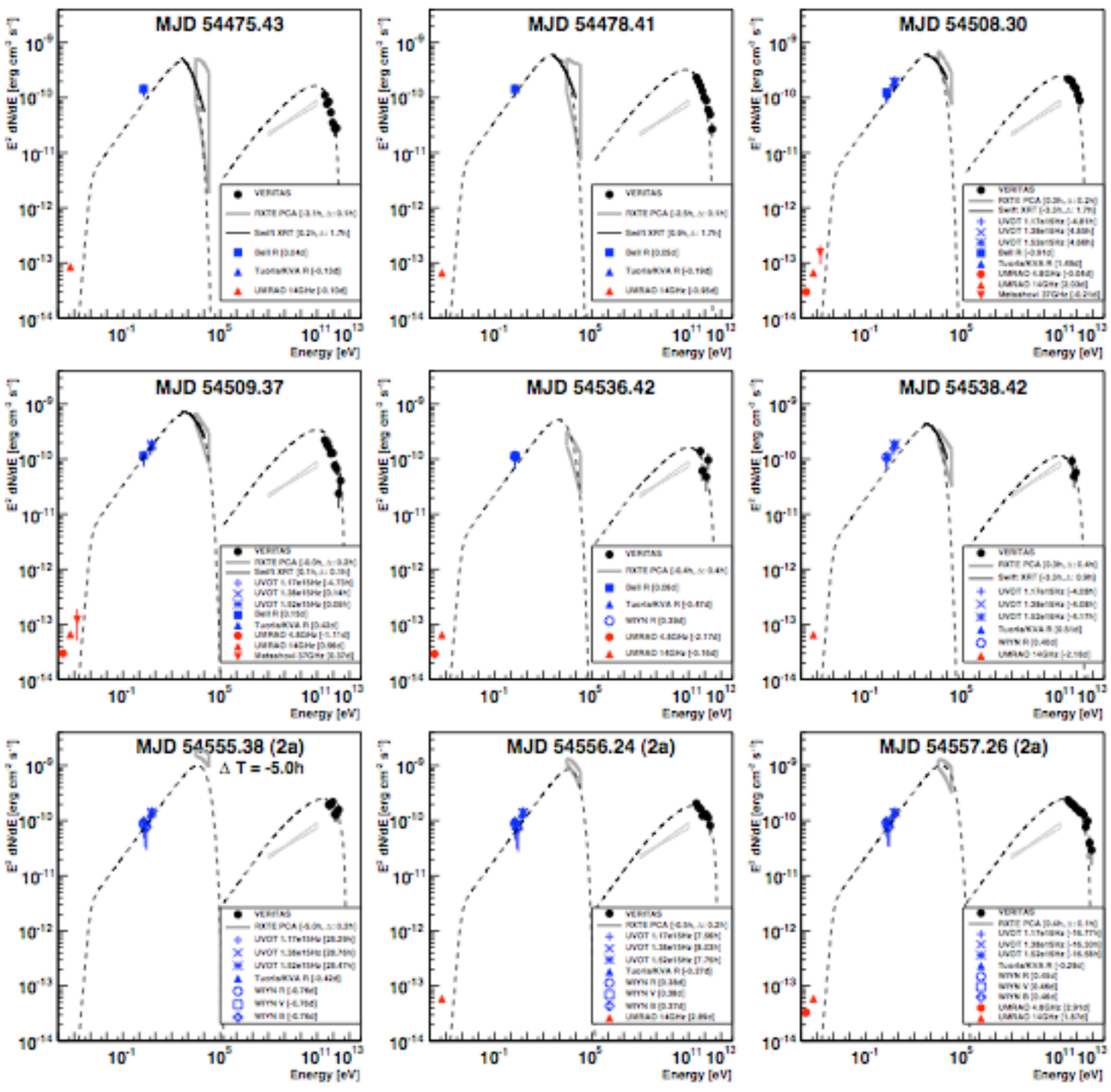

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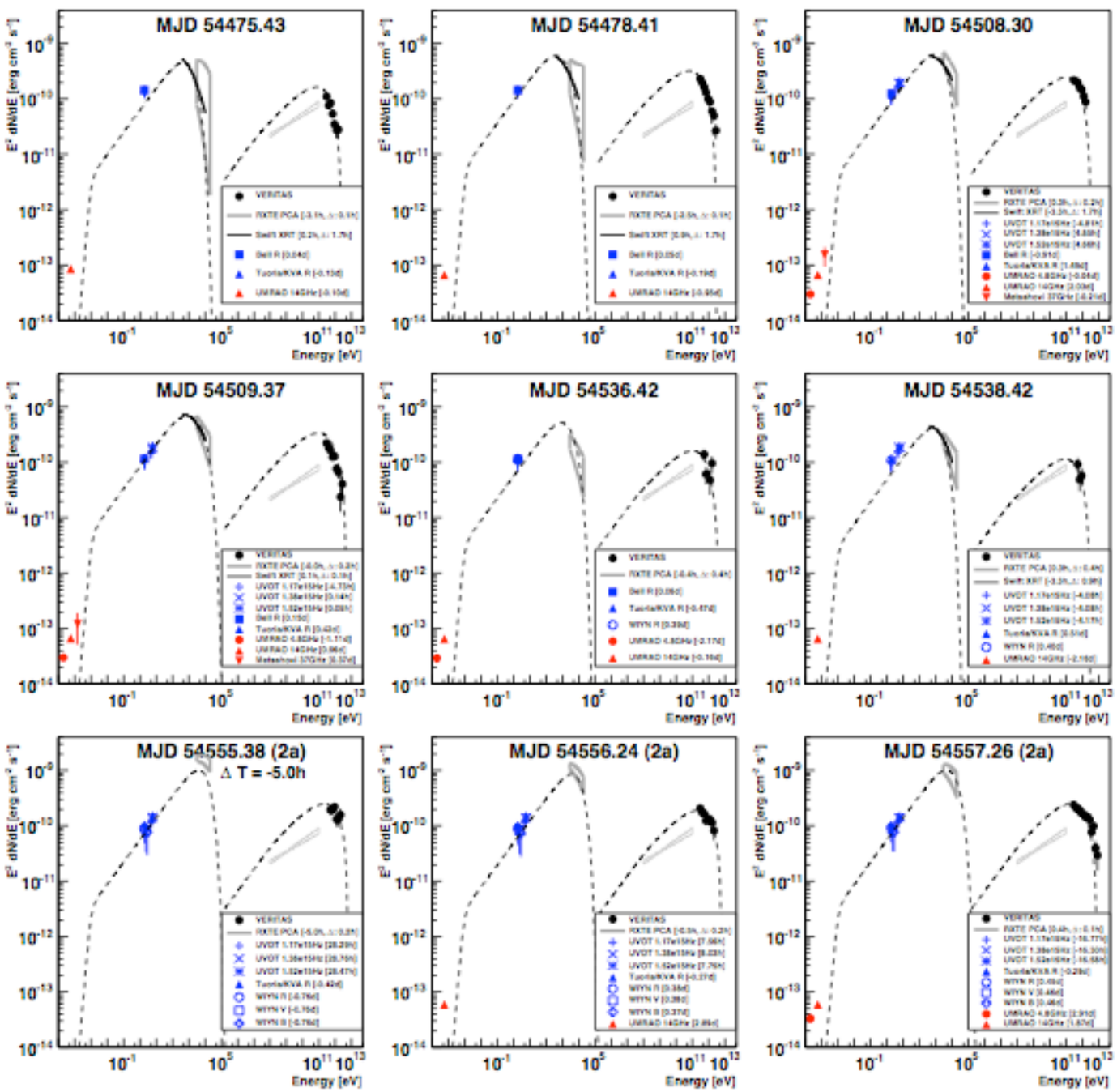

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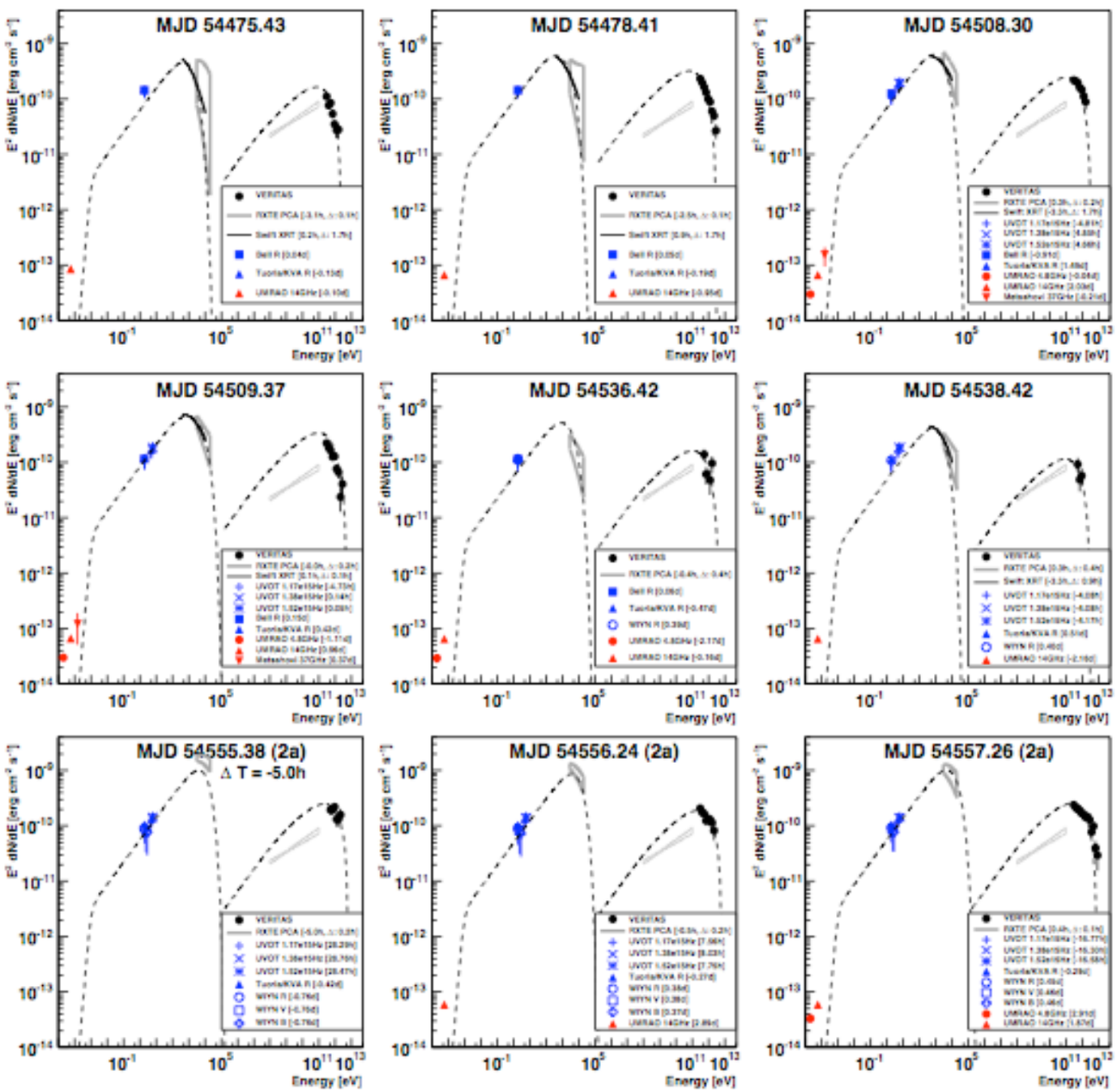

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- Absence of internal γ-γ abs.: $\delta_{\text{jet}} \geq 15$
  Celotti et al. 2000
- 5-min Flares & Causality: $\delta_{\text{jet}} \sim 50$
  Begelman et al. 2007

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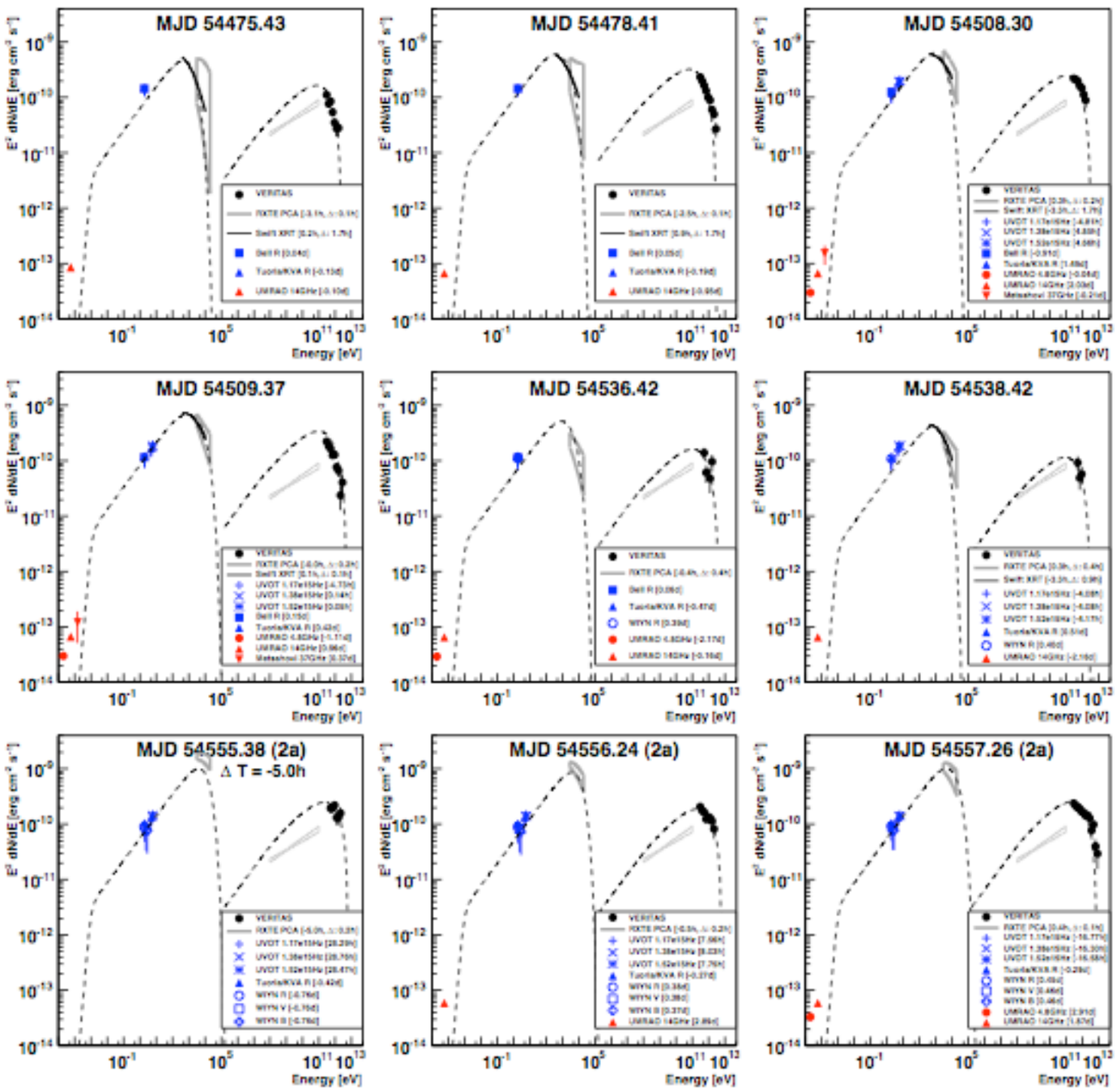

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54557.3	0.40	11.3	11.0	251
54559.2	0.40	11.4	10.8	251
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54564.2	0.40	11.4	10.7	251
54566.2	0.40	11.2	10.6	251
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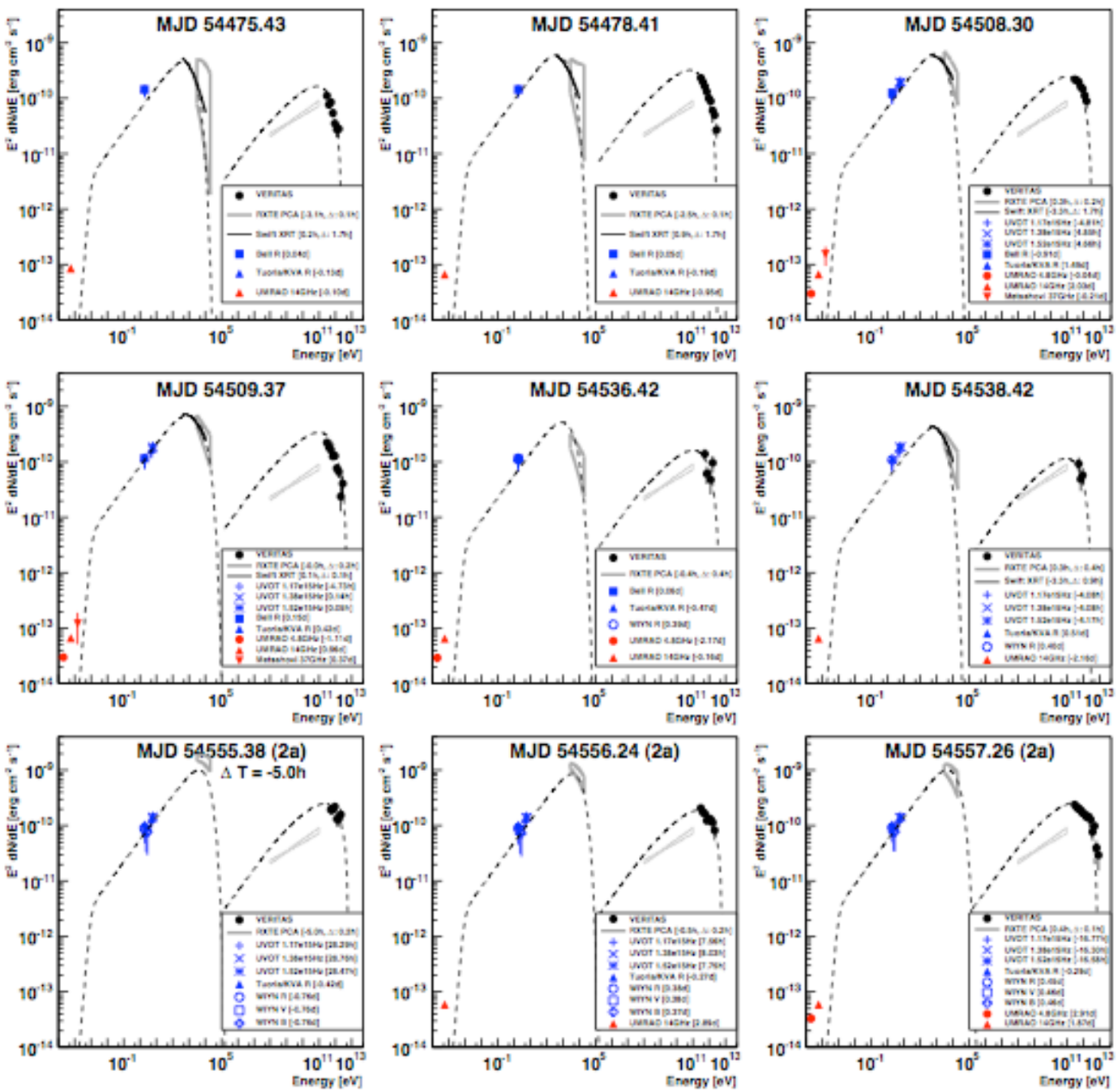

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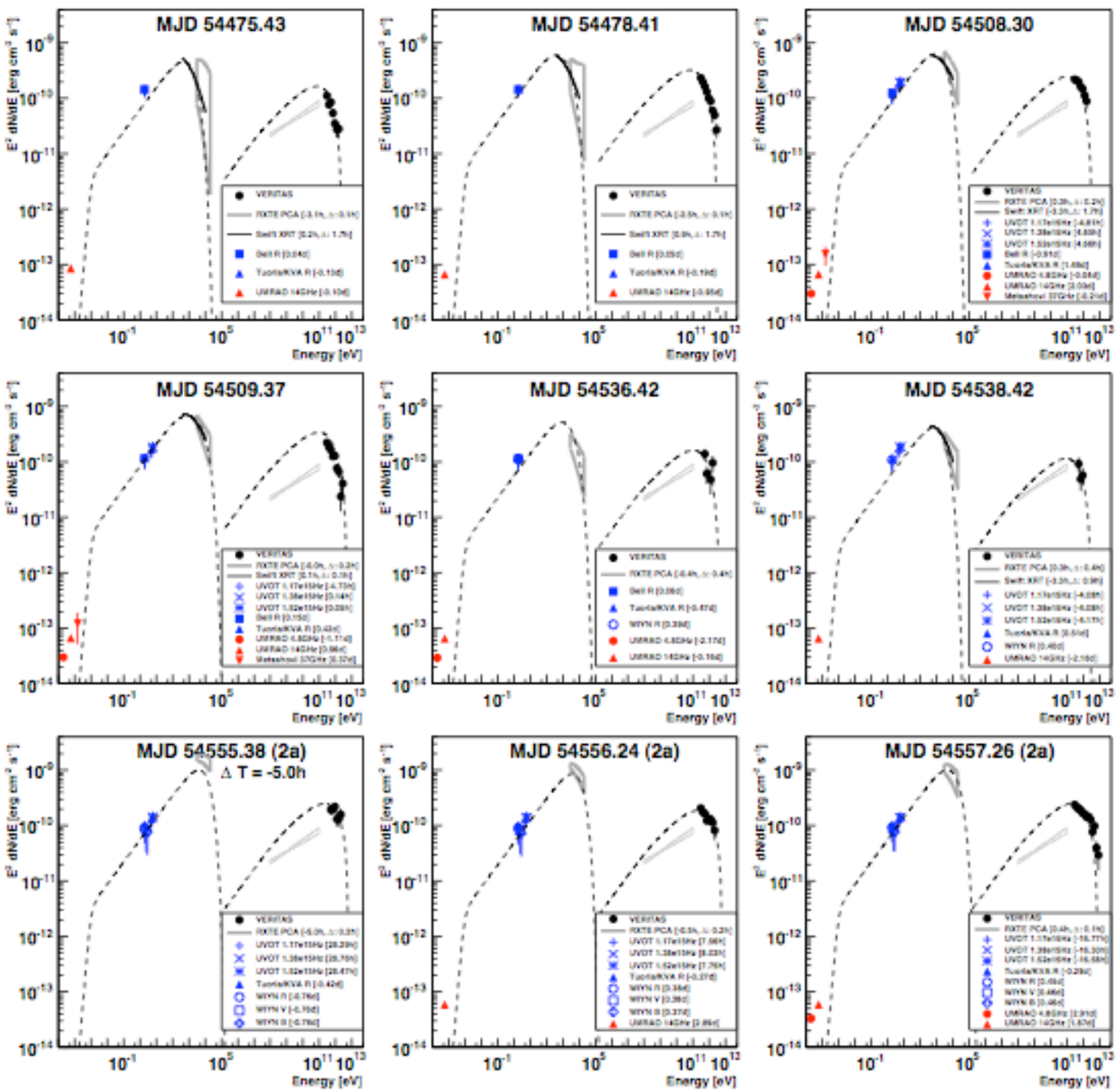

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$(u_e)_{\mathrm{cold}}, u_{\mathrm{P}}$?

Predictions from Models with Shock Acceleration and Synchrotron Cooling

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$$u_s = 0.26\,c$$

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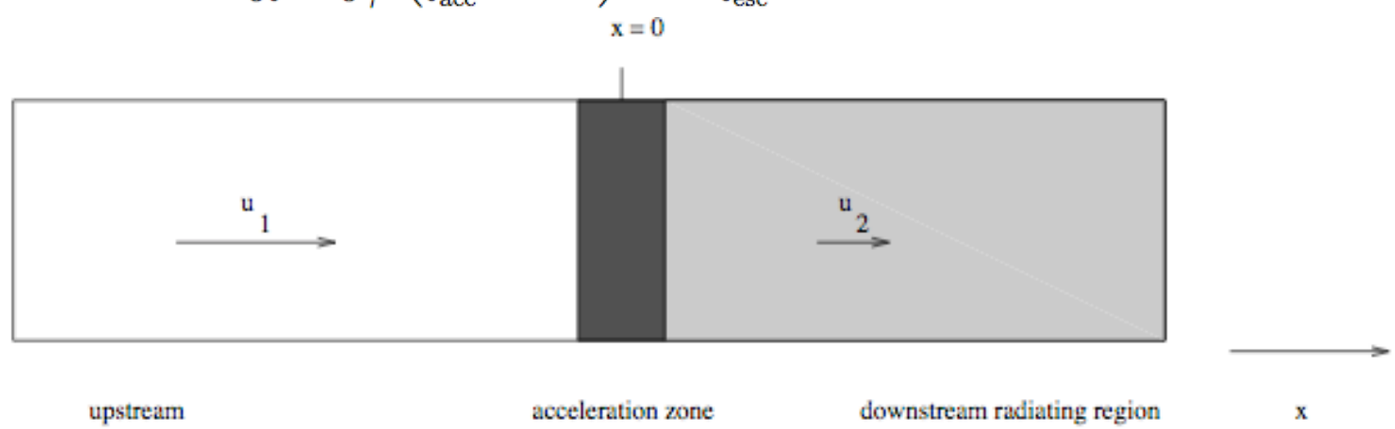

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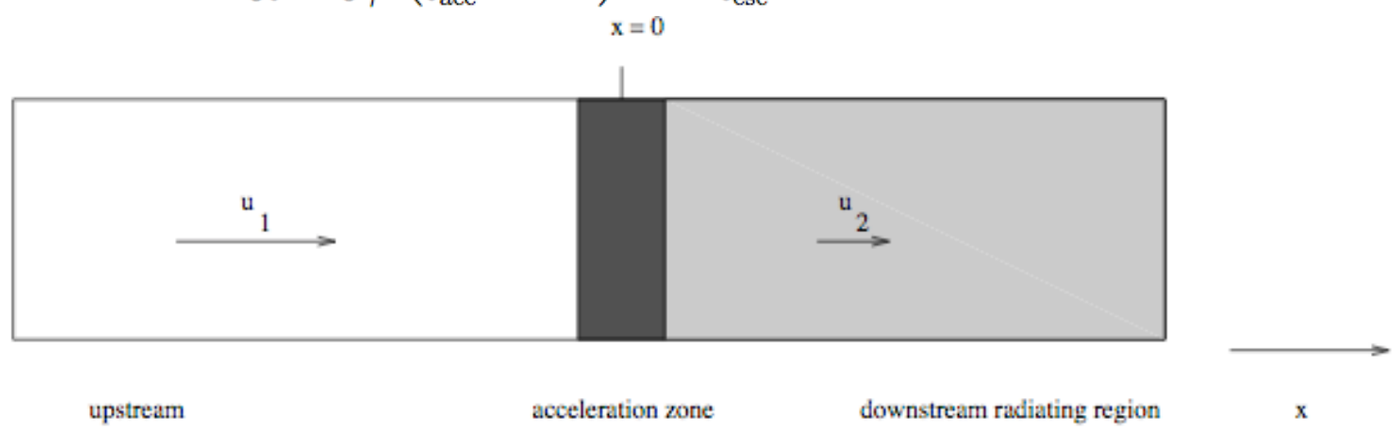

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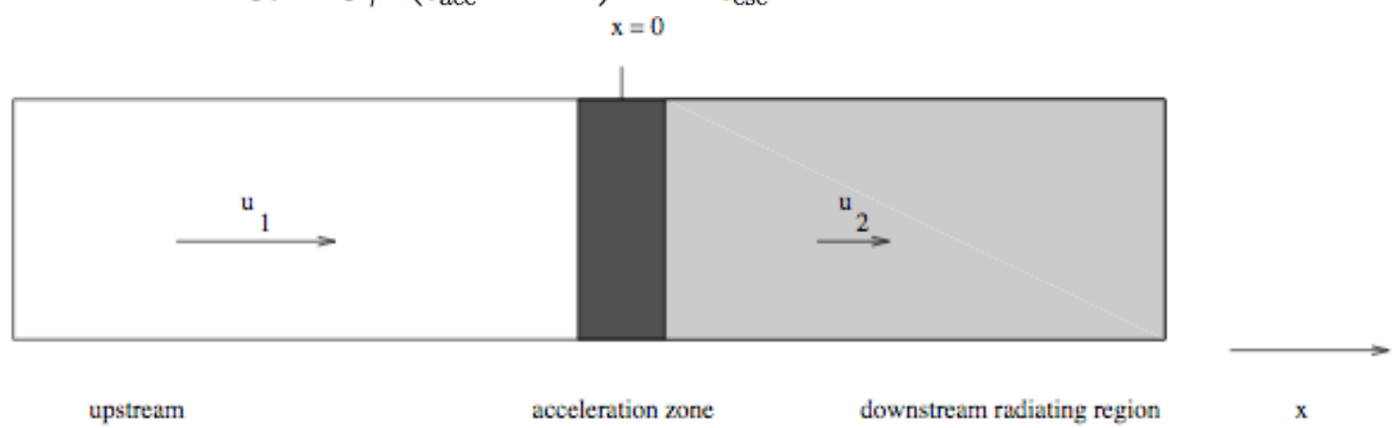

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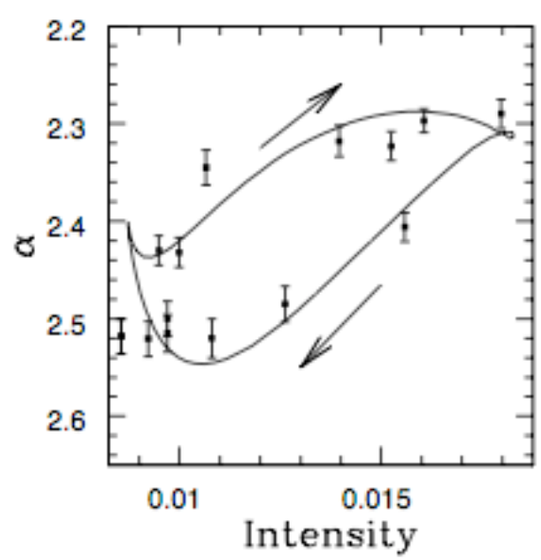

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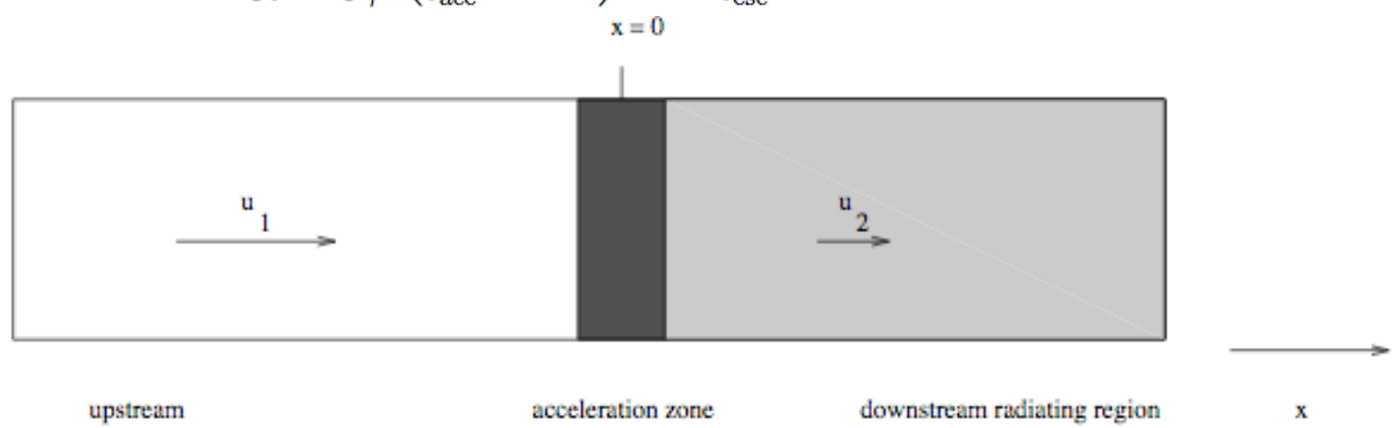

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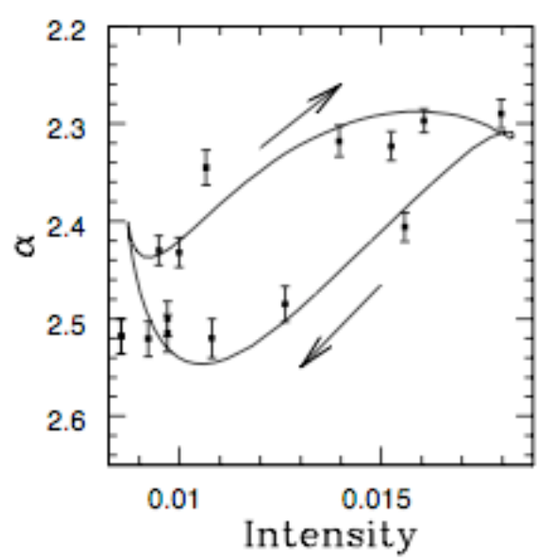
$t_{\rm acc} \ll t_{\rm cool}$



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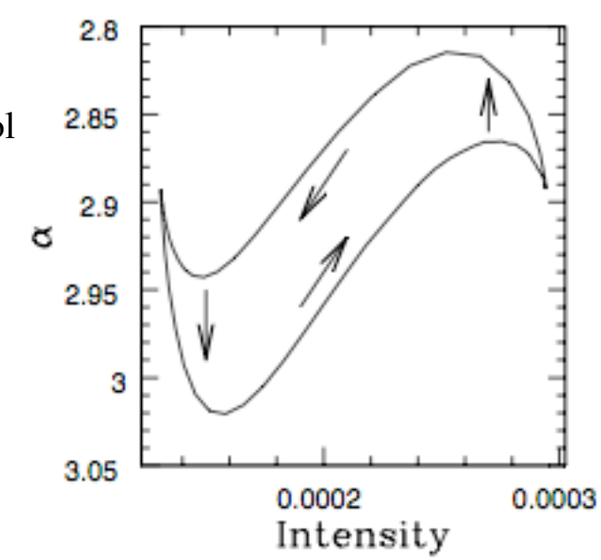
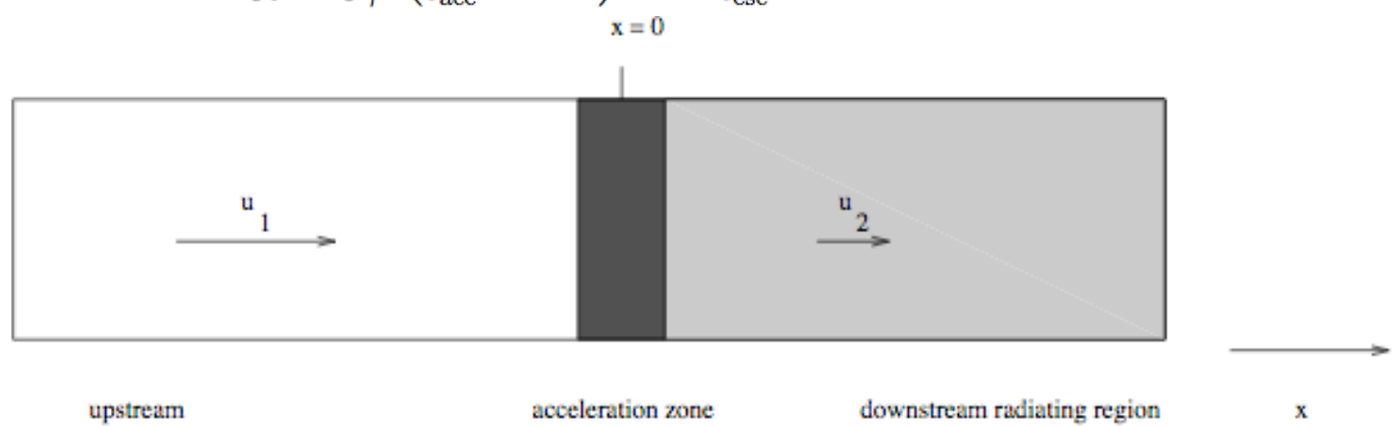


Predictions from Models with Shock Acceleration and Synchrotron Cooling

Rieger, Kirk, Mastichiadis 2000:

$$u_s = 0.26\,c$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \gamma}\left[\left(\frac{\gamma}{t_{\rm acc}} - \beta_s\,\gamma^2\right) N\right] + \frac{N}{t_{\rm esc}} = Q\delta(\gamma - \gamma_0)$$



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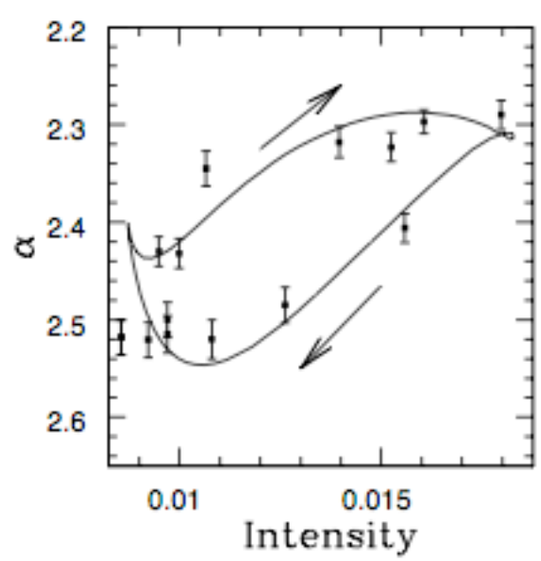

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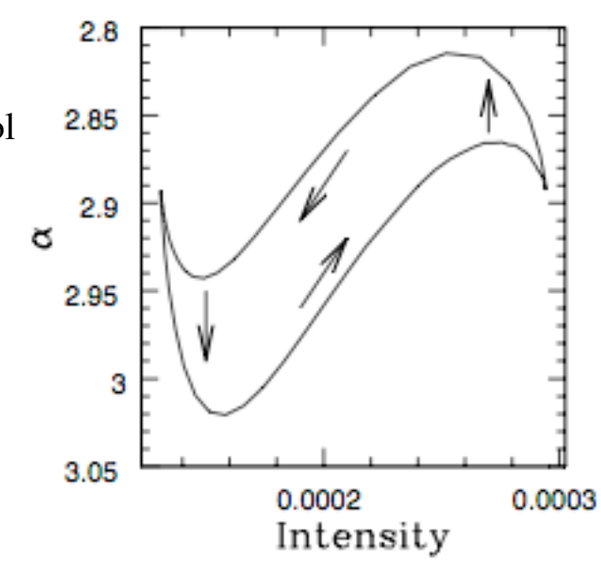
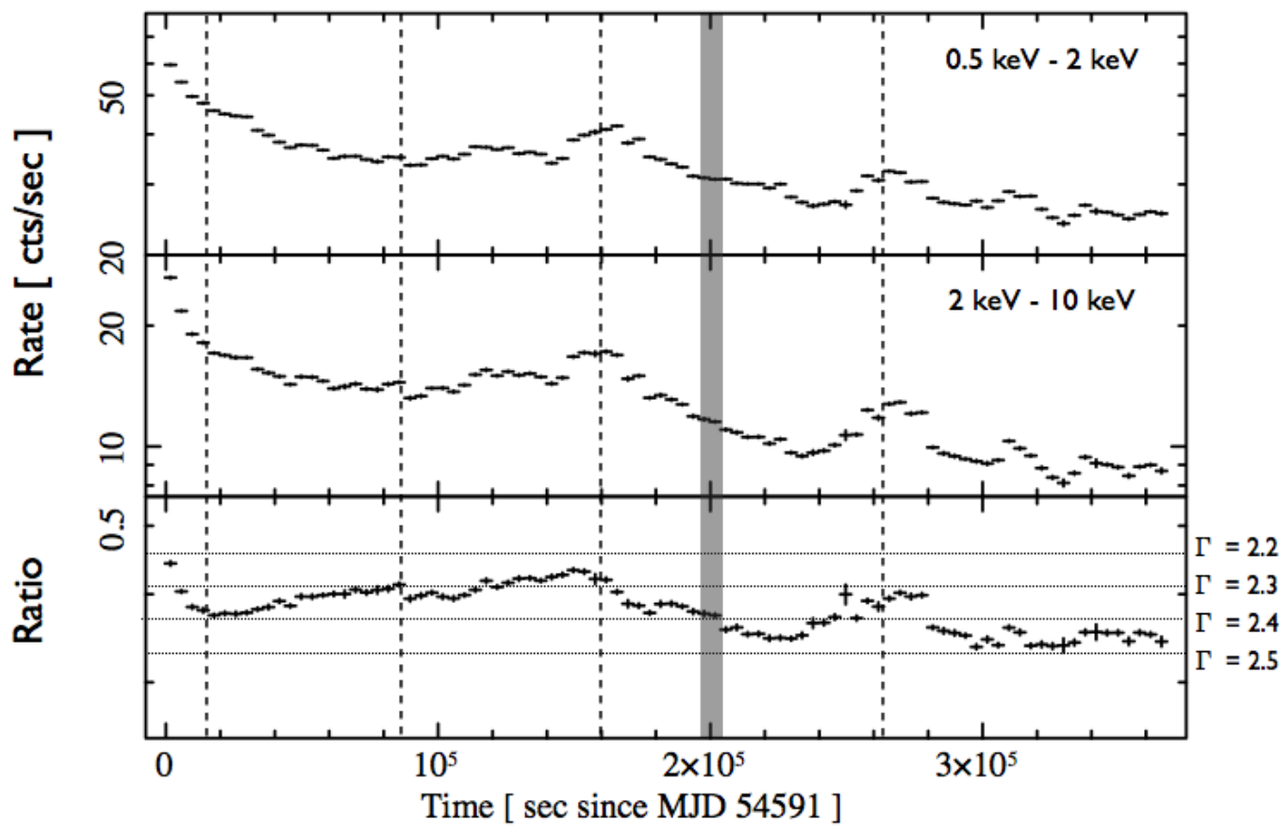


Clockwise or anti-clockwise index-intensity correlations!

High Accuracy X-Ray Observations With Suzaku

Suzaku Observations of Mrk 421 from May 5 - May 9, 2008



Garson, Baring & HK 2010

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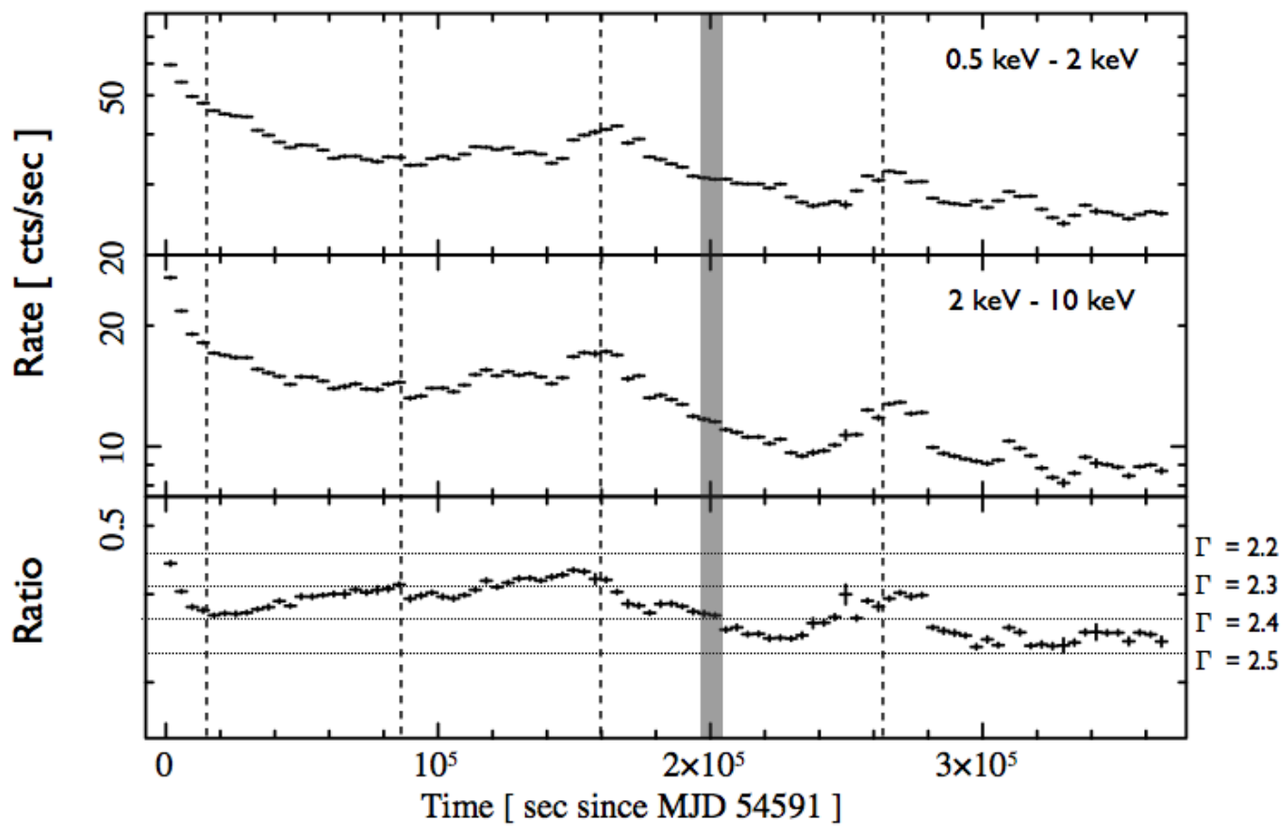

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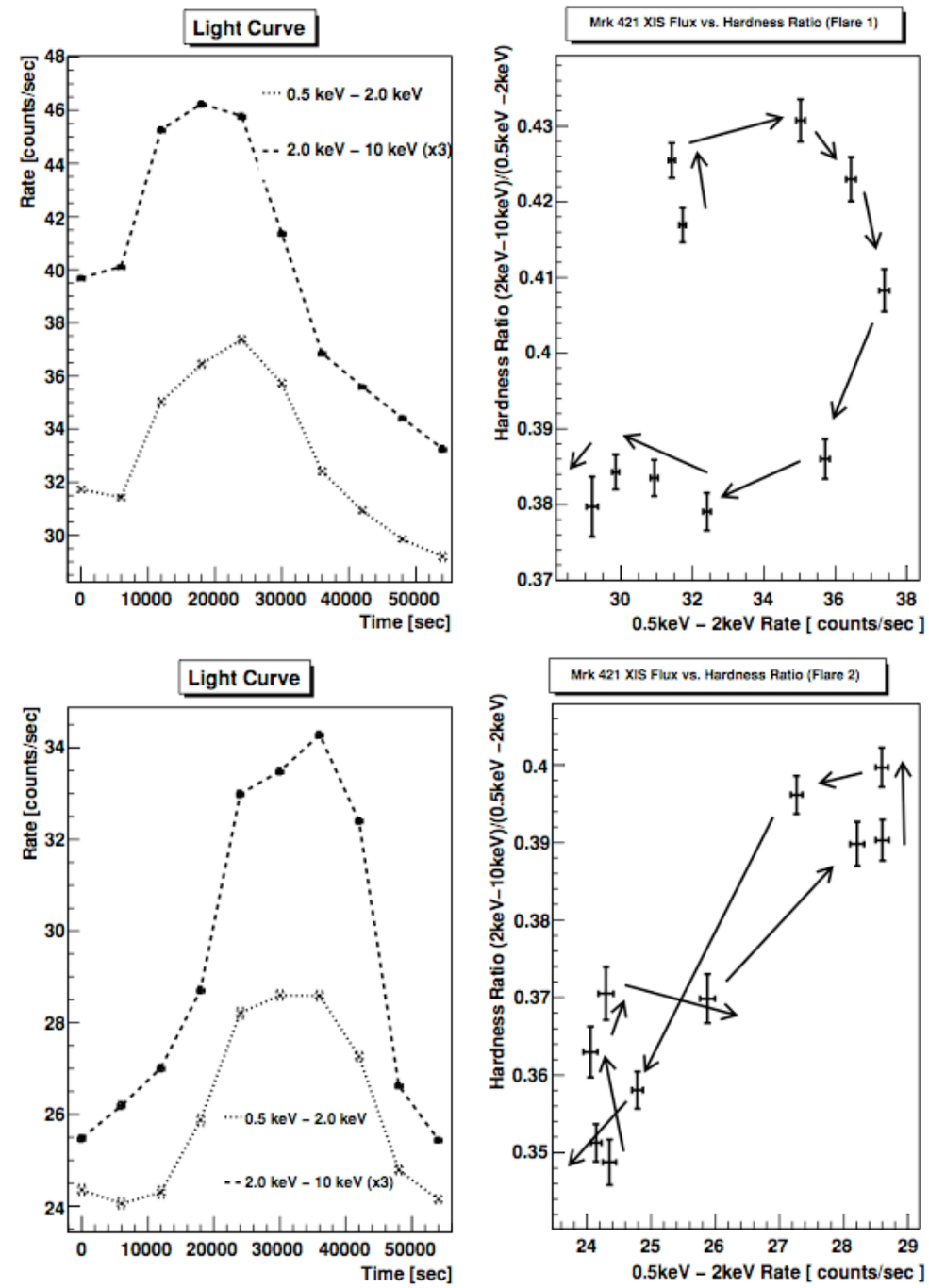

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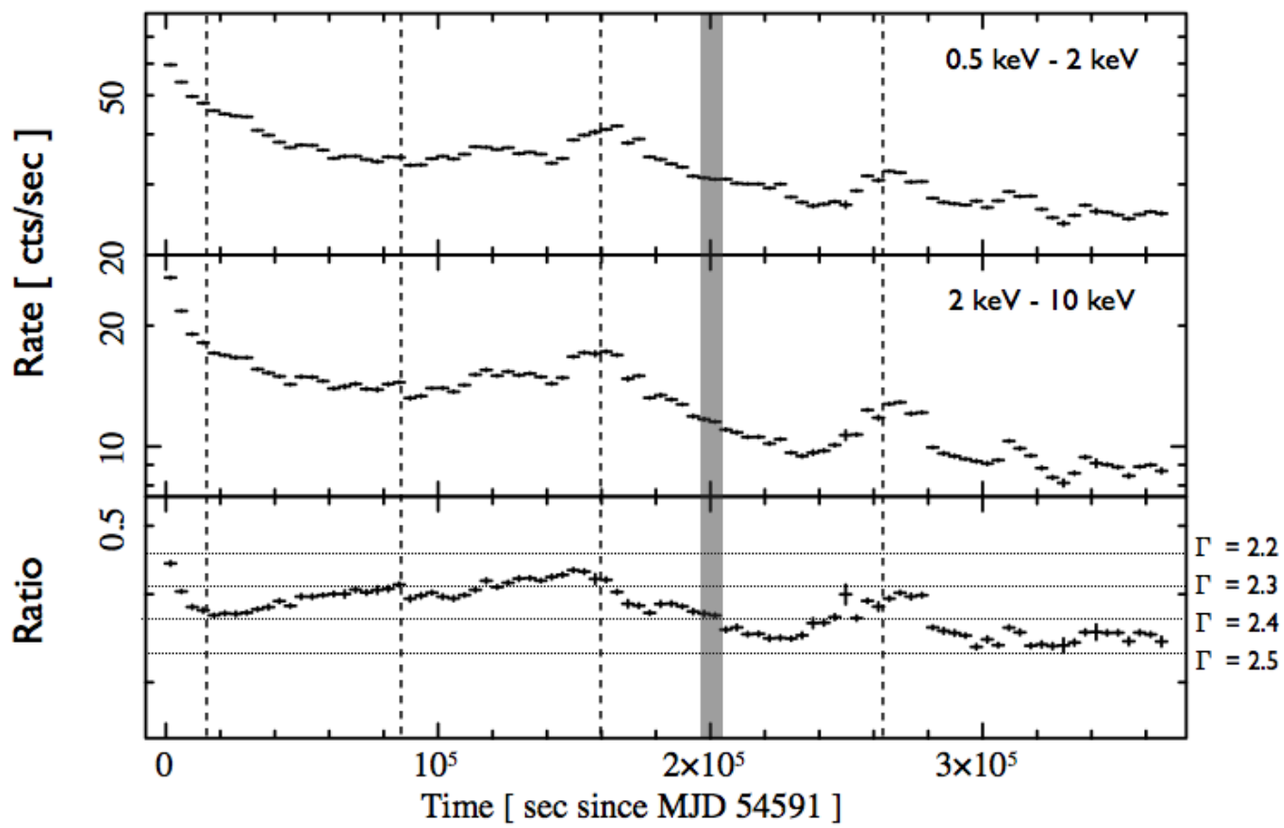

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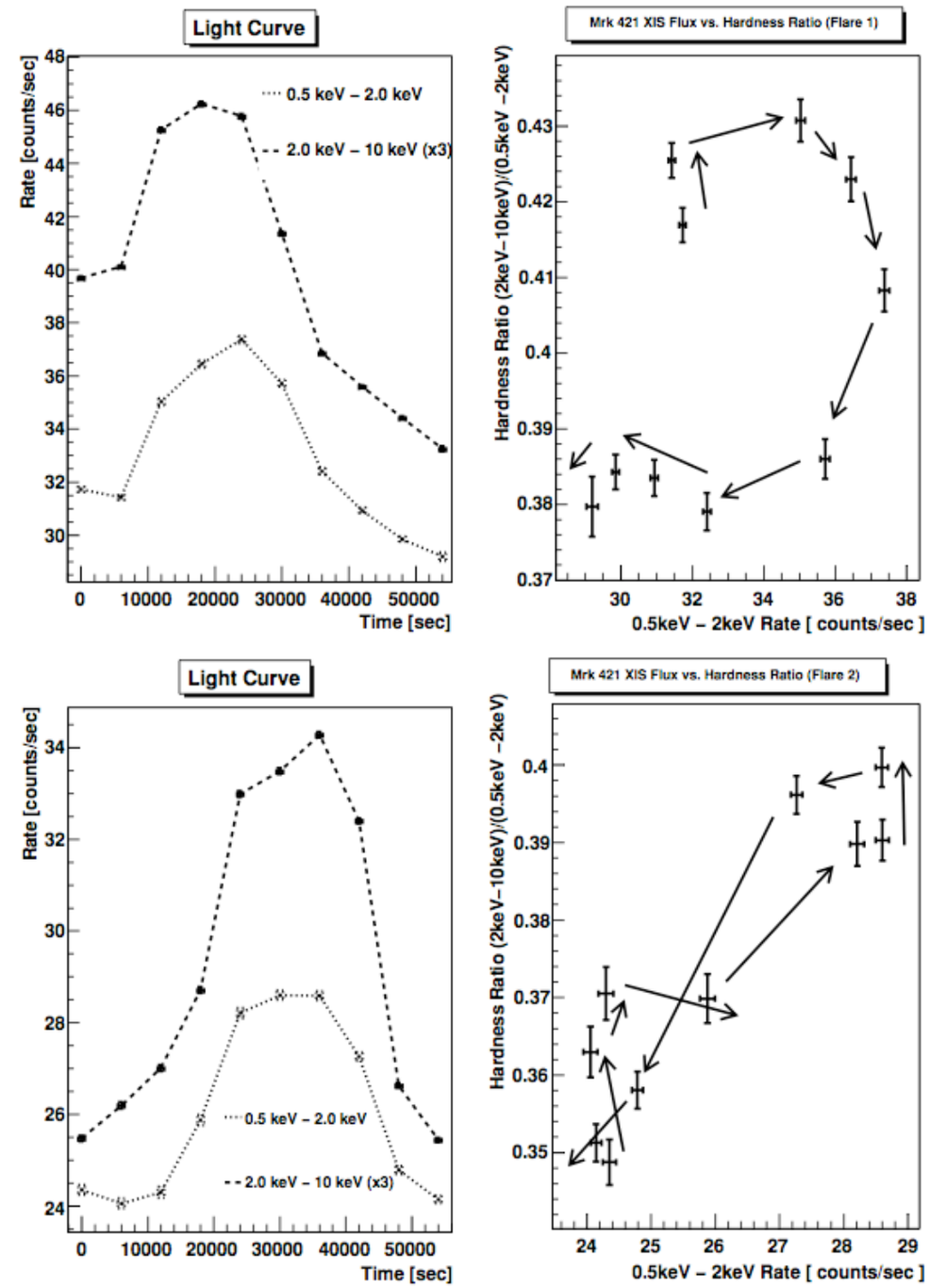
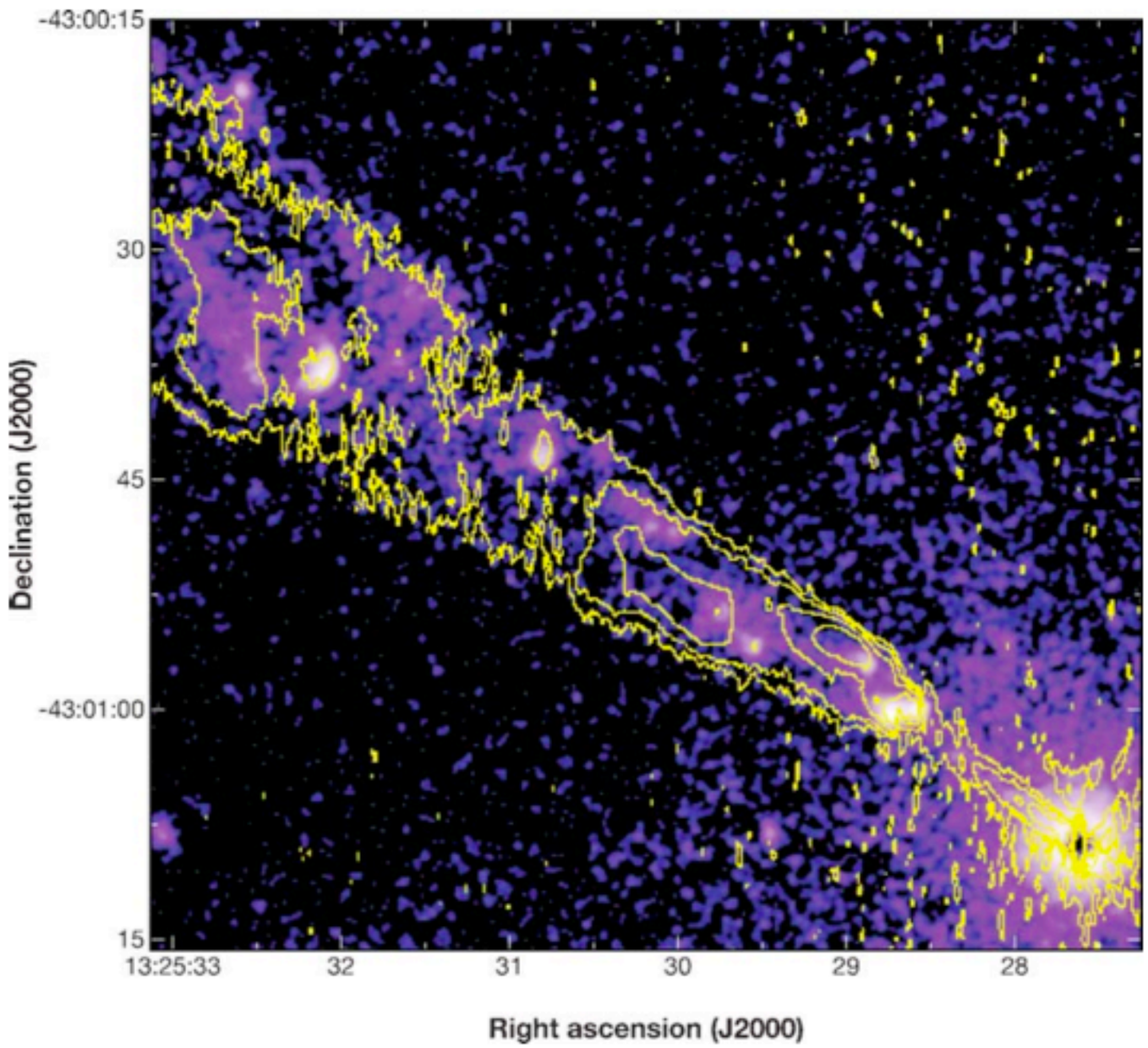


Observations do not validate simple predictions of models with shock acceleration and cooling!

X-Ray Emission from kpc Jets of Low-Power Galaxies

Chandra X-ray (color) and VLA 8 GHz (contours) images of Cen A



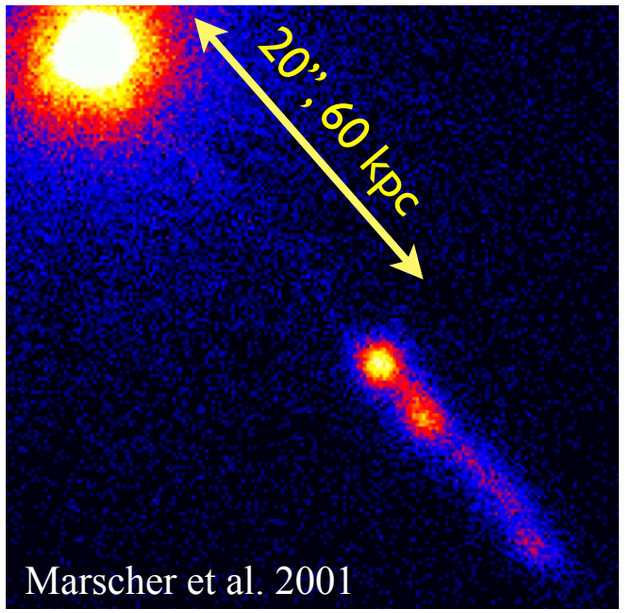
Interpretation:

- Synchrotron em. of $\gamma \sim 10^7$ electrons.
- Radiative cooling time: ~ years → distributed acceleration!

M. Hardcastle (priv. comm), Kataoka et al. 2006

X-Ray Emission from kpc Jets of High-Power Galaxies

3C 273:



Chandra, 0.5-5 keV.

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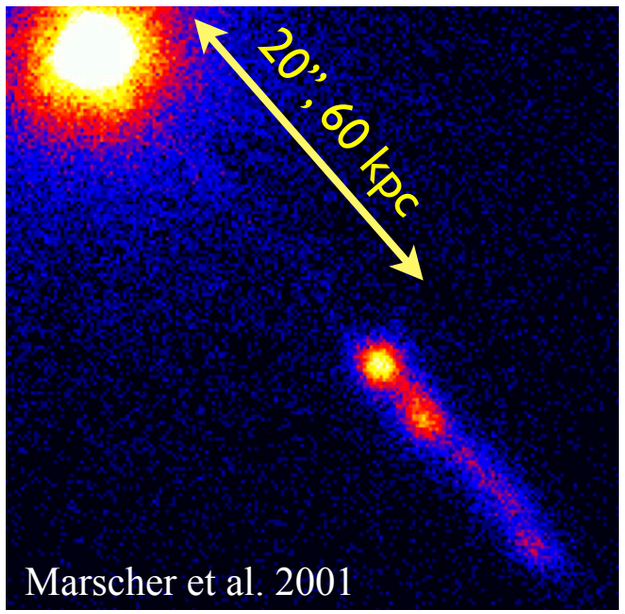

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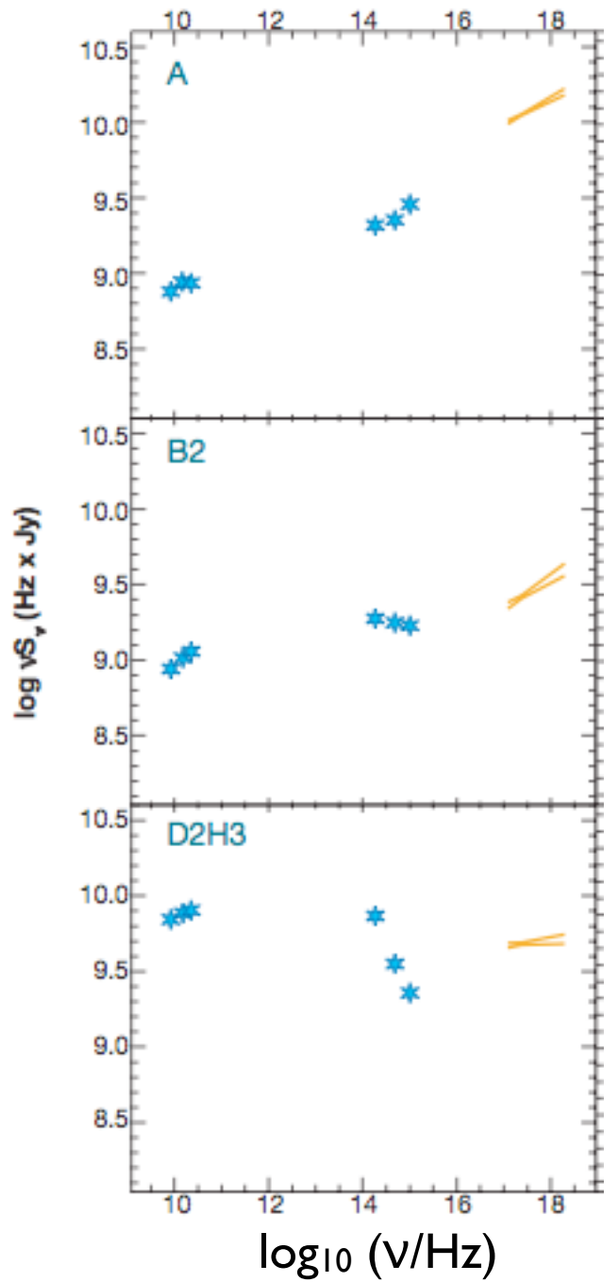

Harris & Krawczynski,
ARA&A, 2006.

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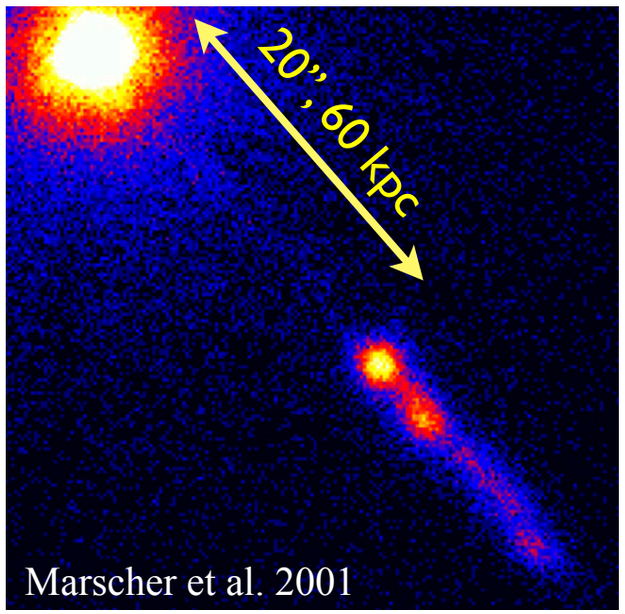

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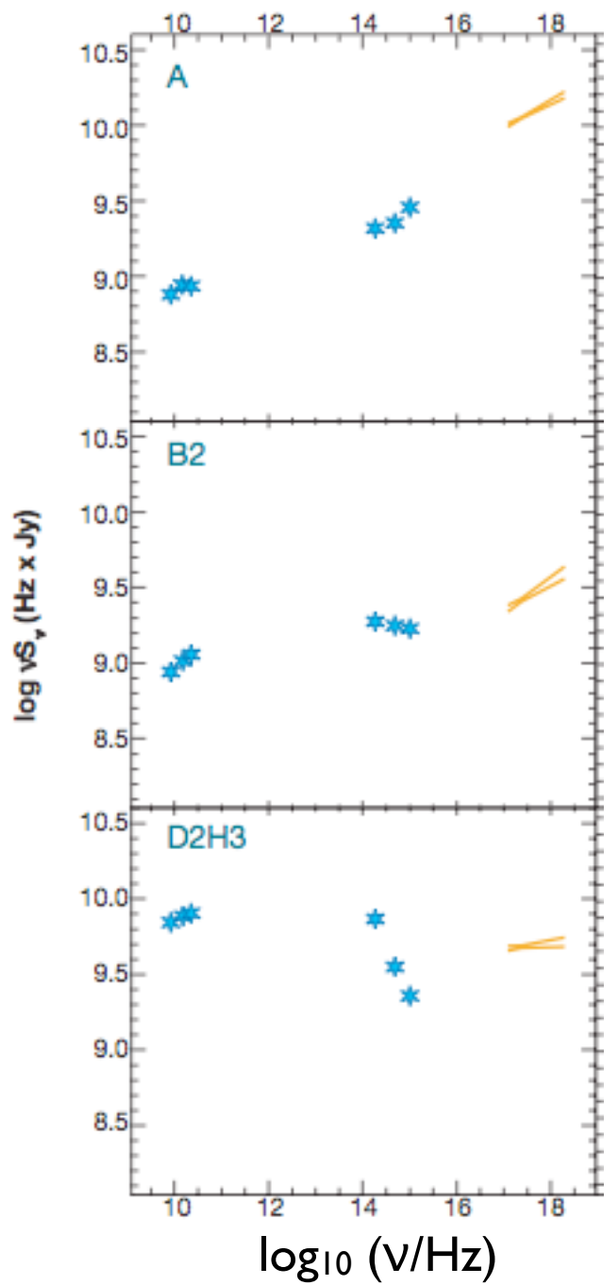

Interpretation:

Relativistic motion at kpc distances from central source:

$$u'(\mathrm{CMB}) = 4 \times 10^{-13}(1+z)^4\Gamma^2 \mathrm{erg\,cm^{-3}}$$

⇒ detectable CMB/IC emission for $\delta \sim \Gamma \sim 10$.

Tavecchio et al. (2000)
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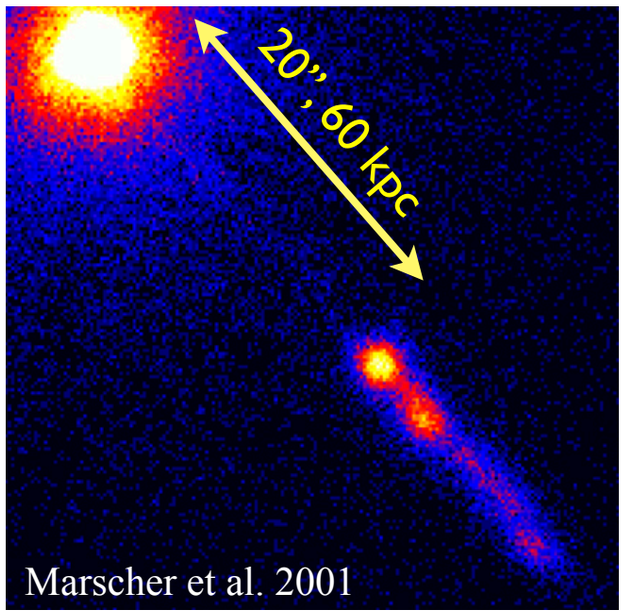

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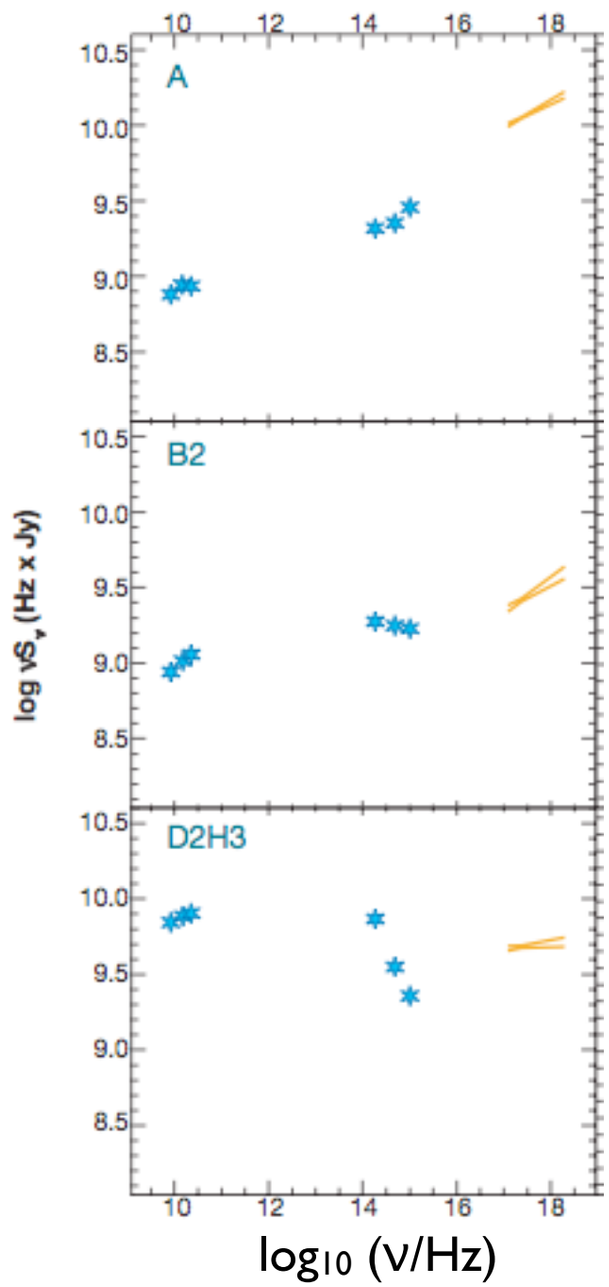

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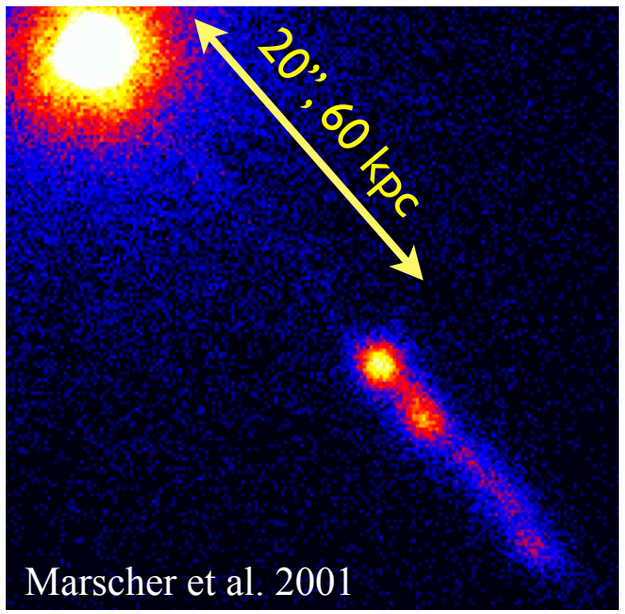

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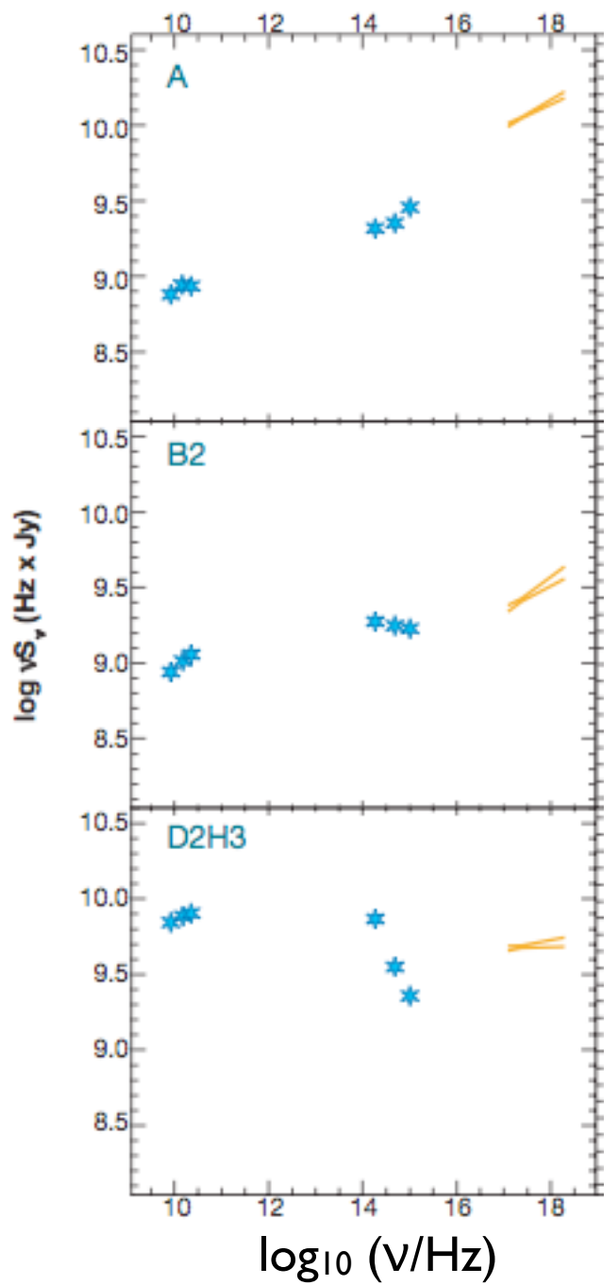

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Problems:
- Explanation of jet knots;
- Length of deprojected X-ray jets (Harris & HK 2001): B2 0738+313 (1.7 Mpc), 0827+243 (1.1 Mpc);
- Energy in low-energy electrons: $\geq 7 \times 10^{46}$ erg s^{-1} (PKS0637-752) (Dermer & Atoyan 2004)

Particle Acceleration at Shocks -- Theory

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Dependence of particle acceleration on:

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(waves, turbulence
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Particles (heating,
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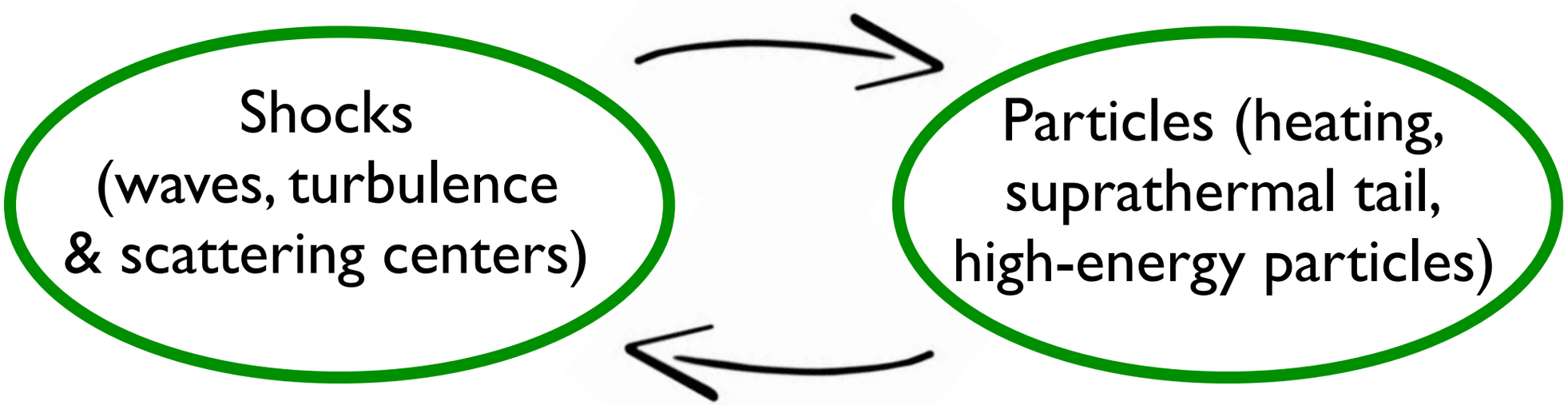

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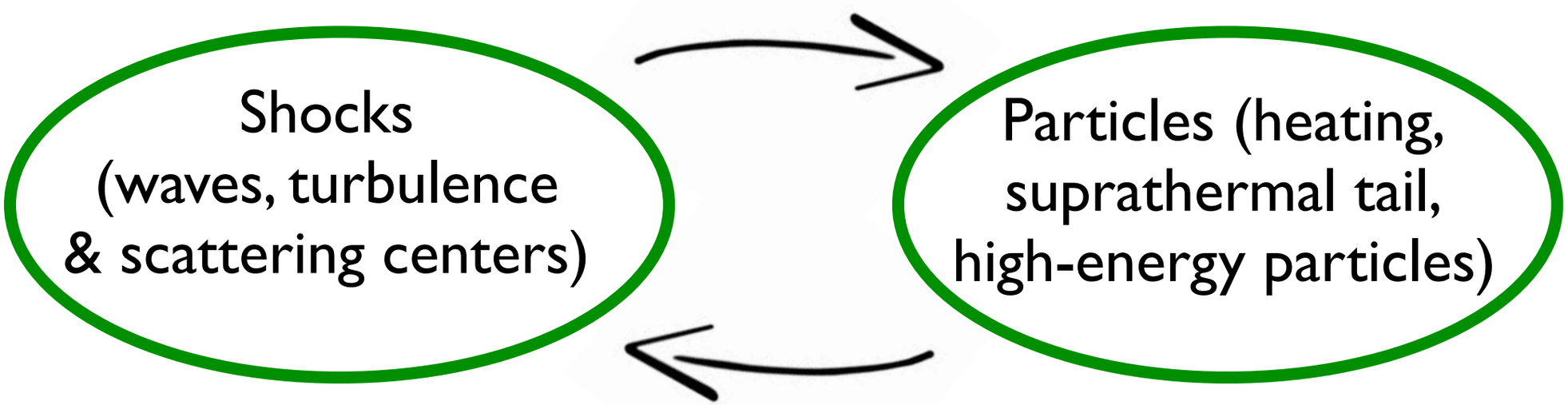
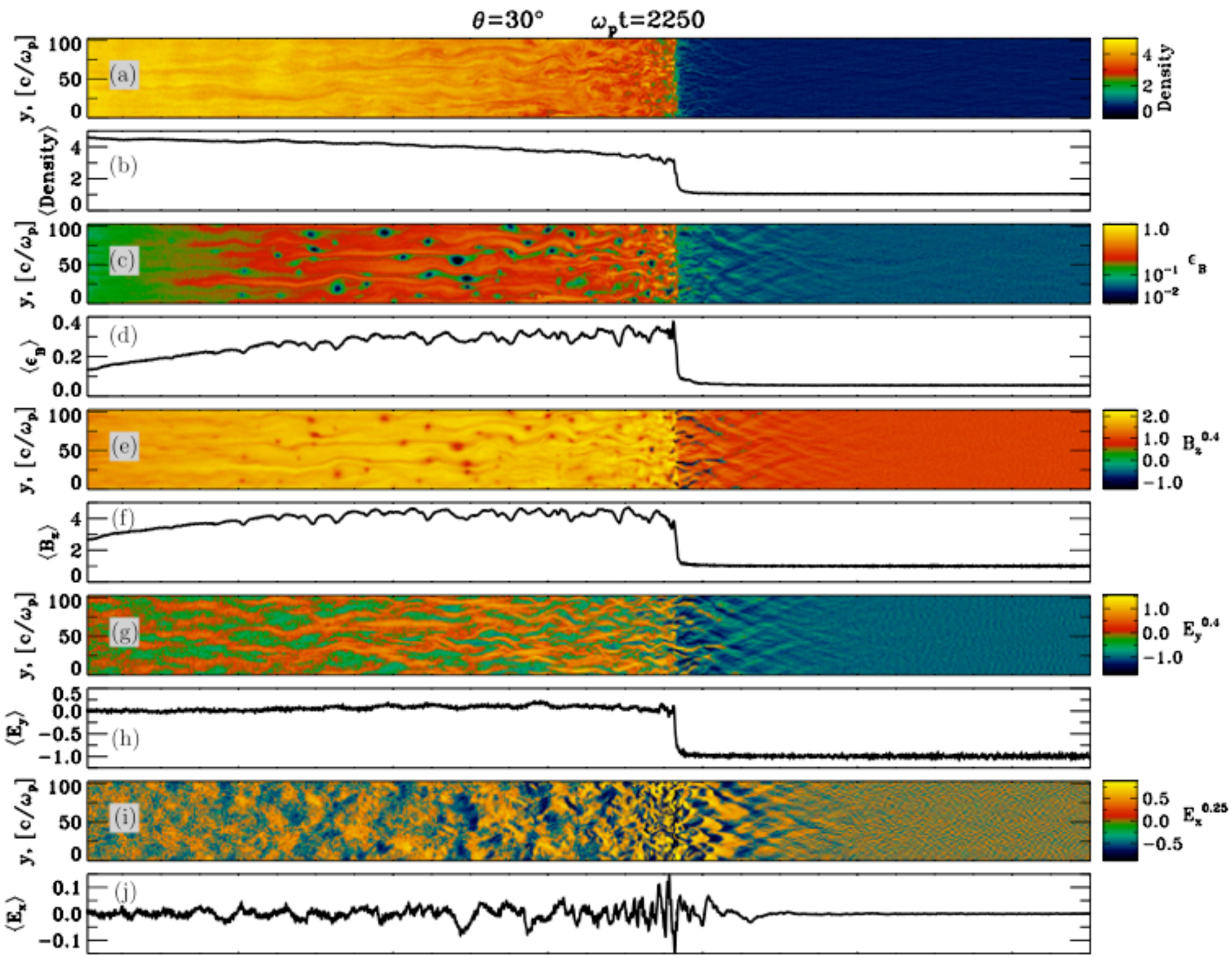


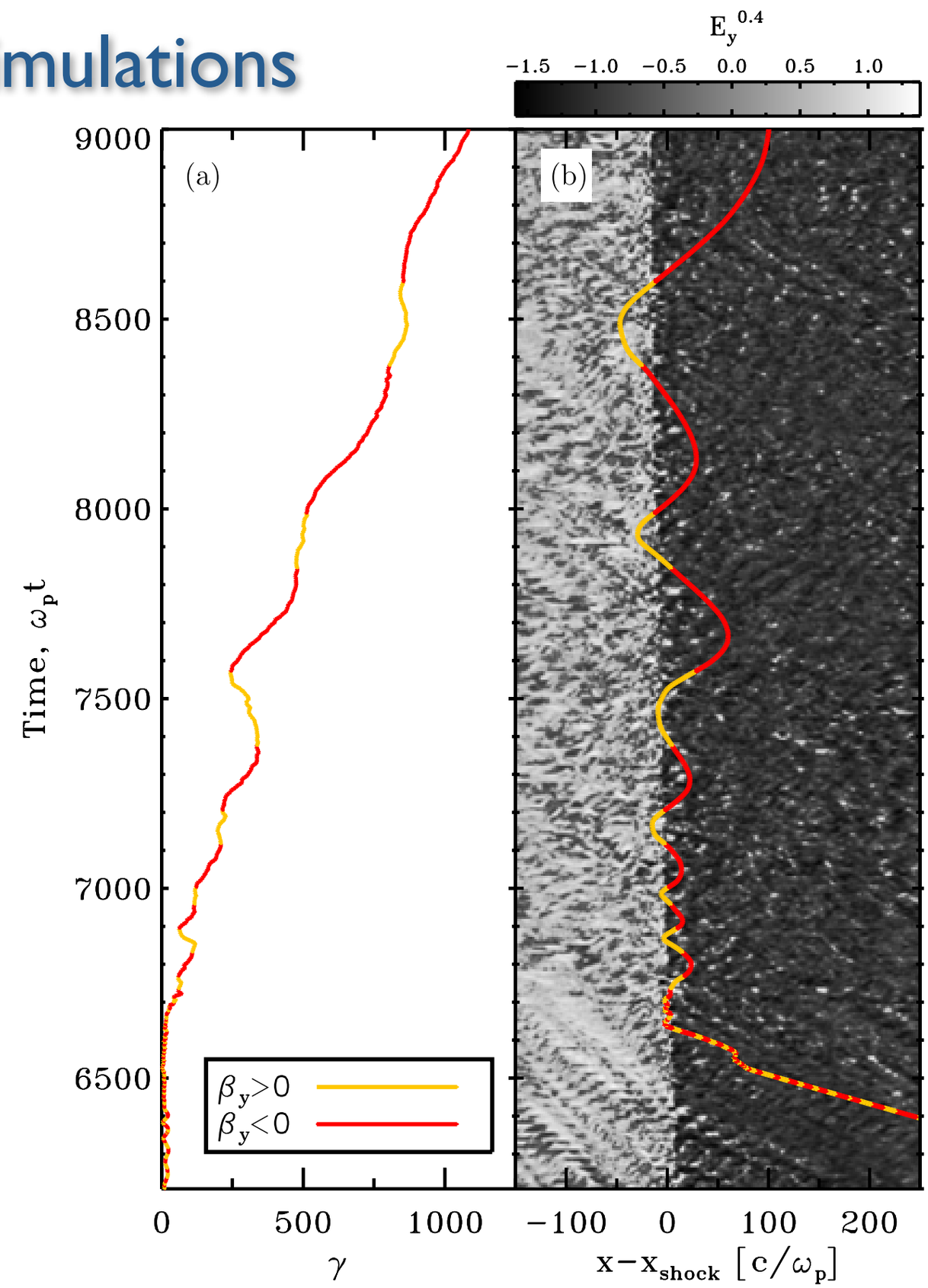
Numerical results: Sironi & Spitkovsky (2009,2011)
Analytical results: Lemoine & Pelletier (2011)

PIC Simulations



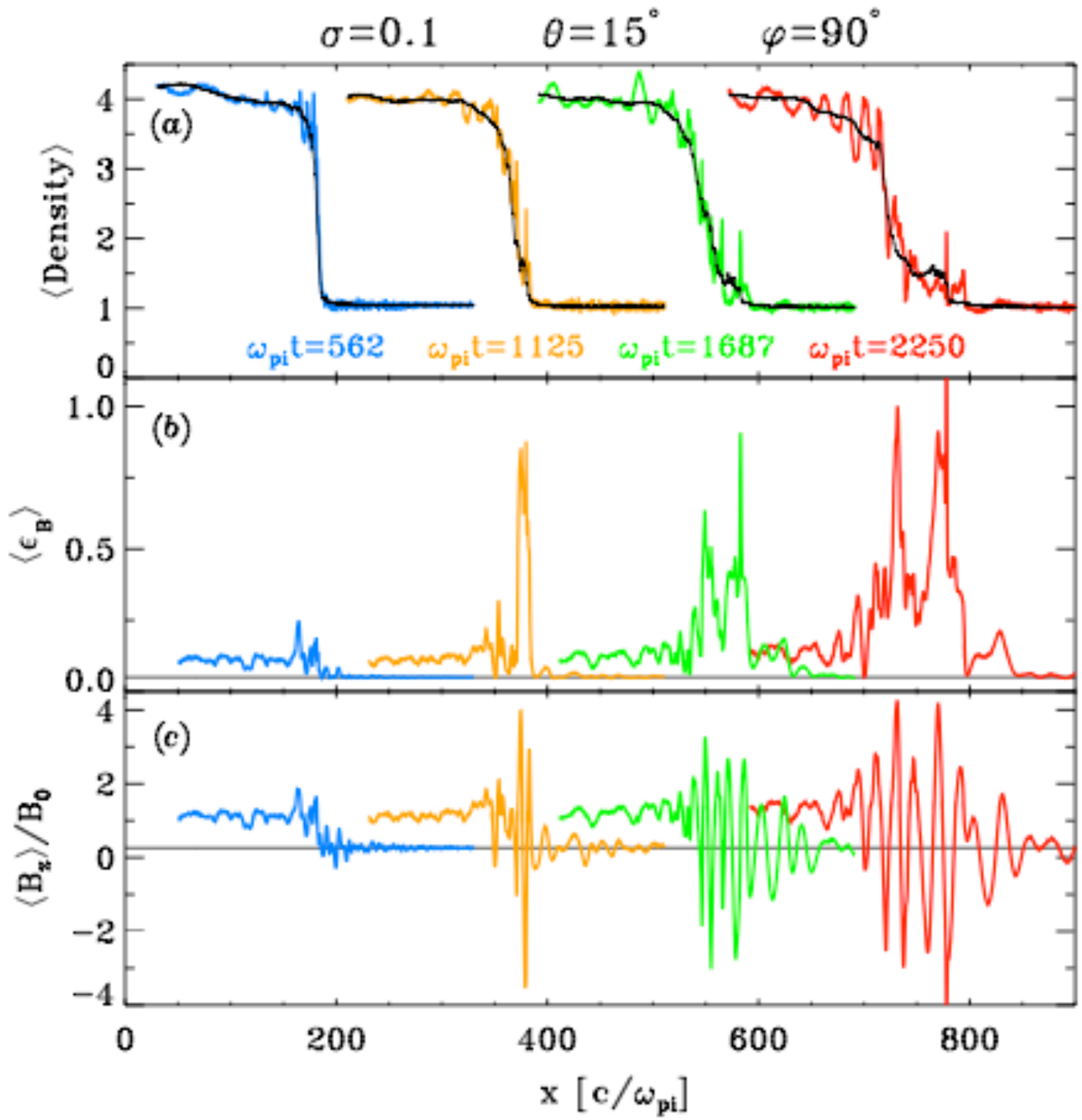
Collisionless Shocks in Pair Plasmas (Sironi & Spitkovsky 2009)

PIC Simulations



Study energy gains (Sironi & Spitkovsky 2009)

PIC Simulations



Collisionless Shocks in Electron-Ion Plasmas (Sironi & Spitkovsky 2011)

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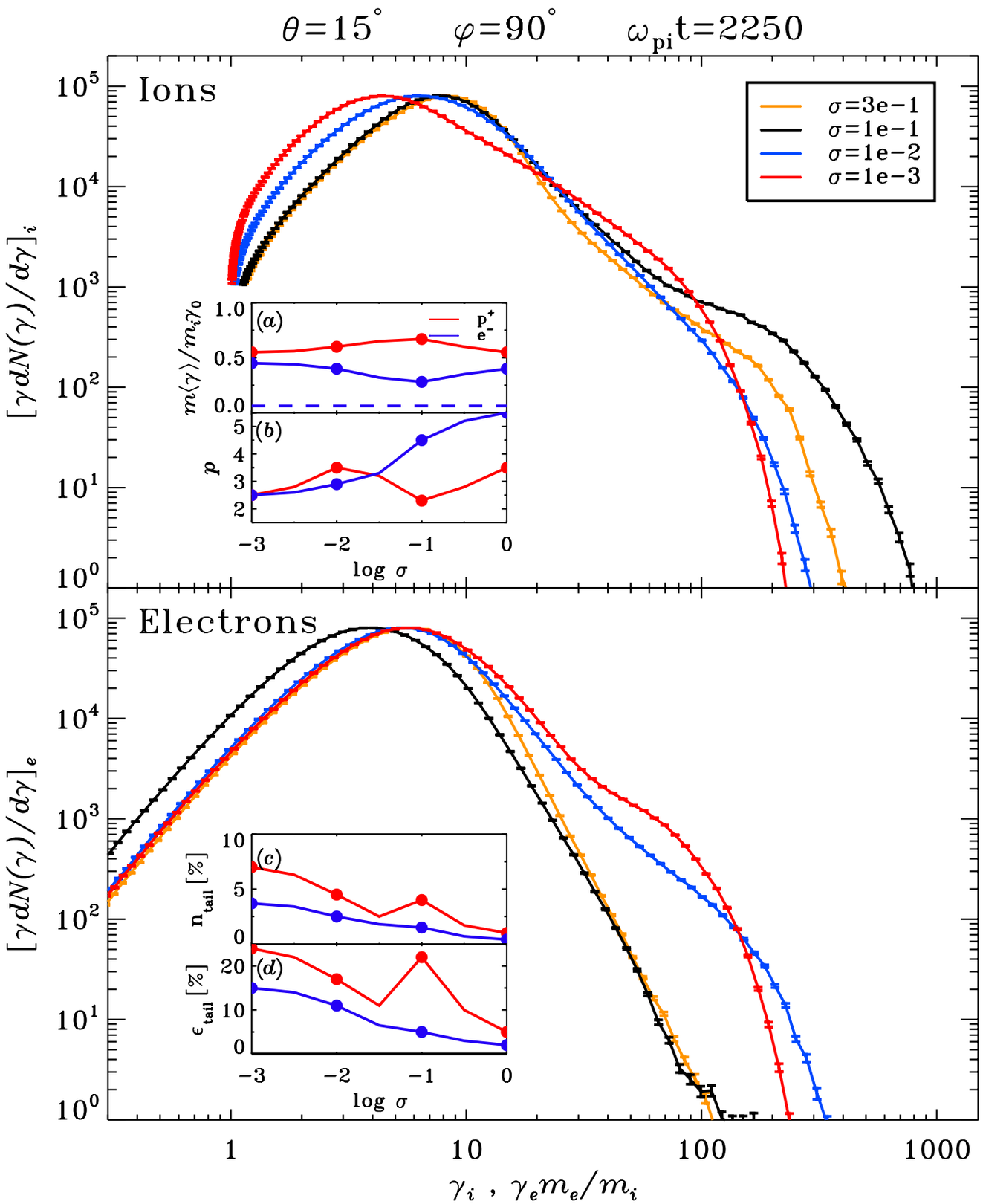
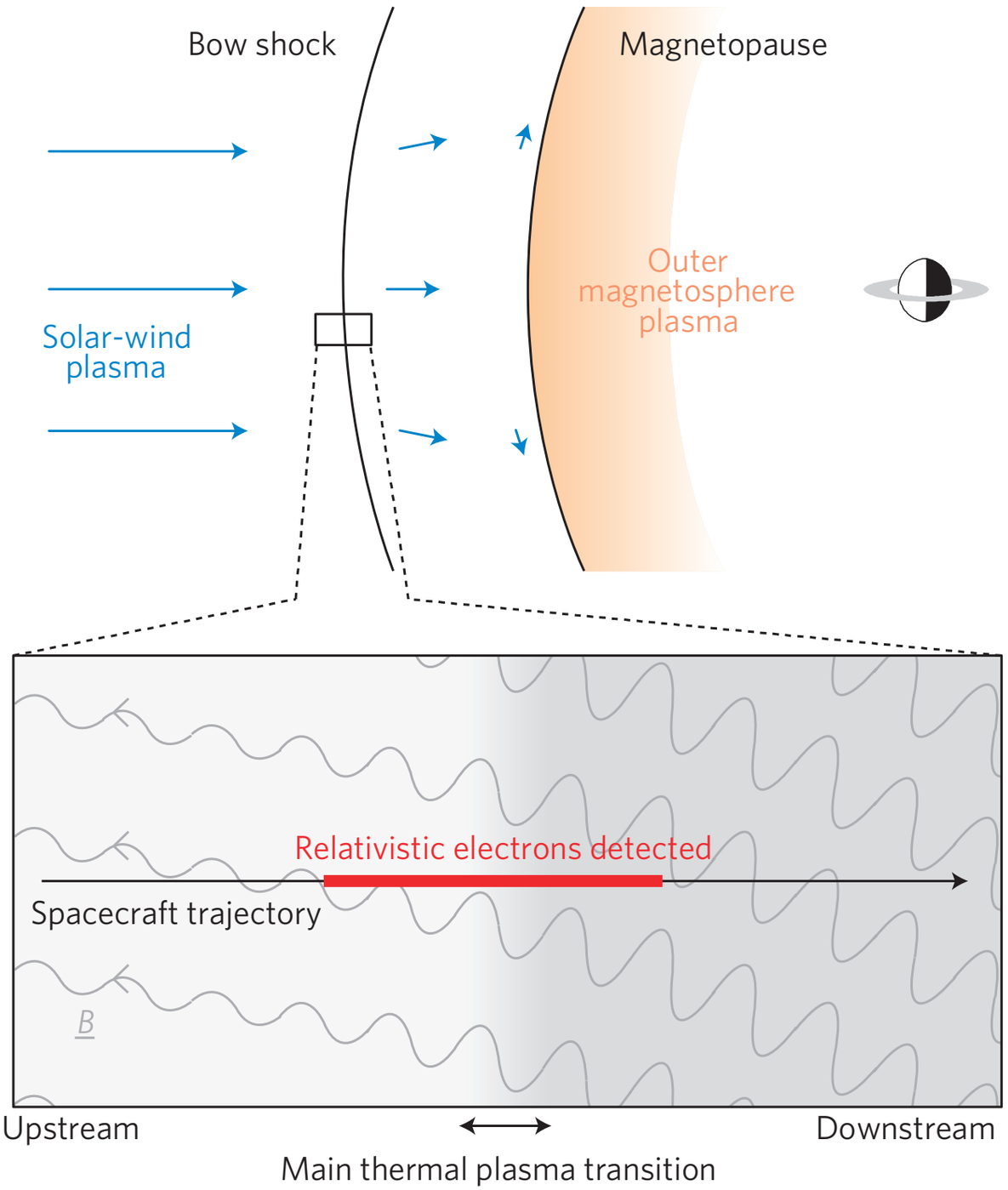
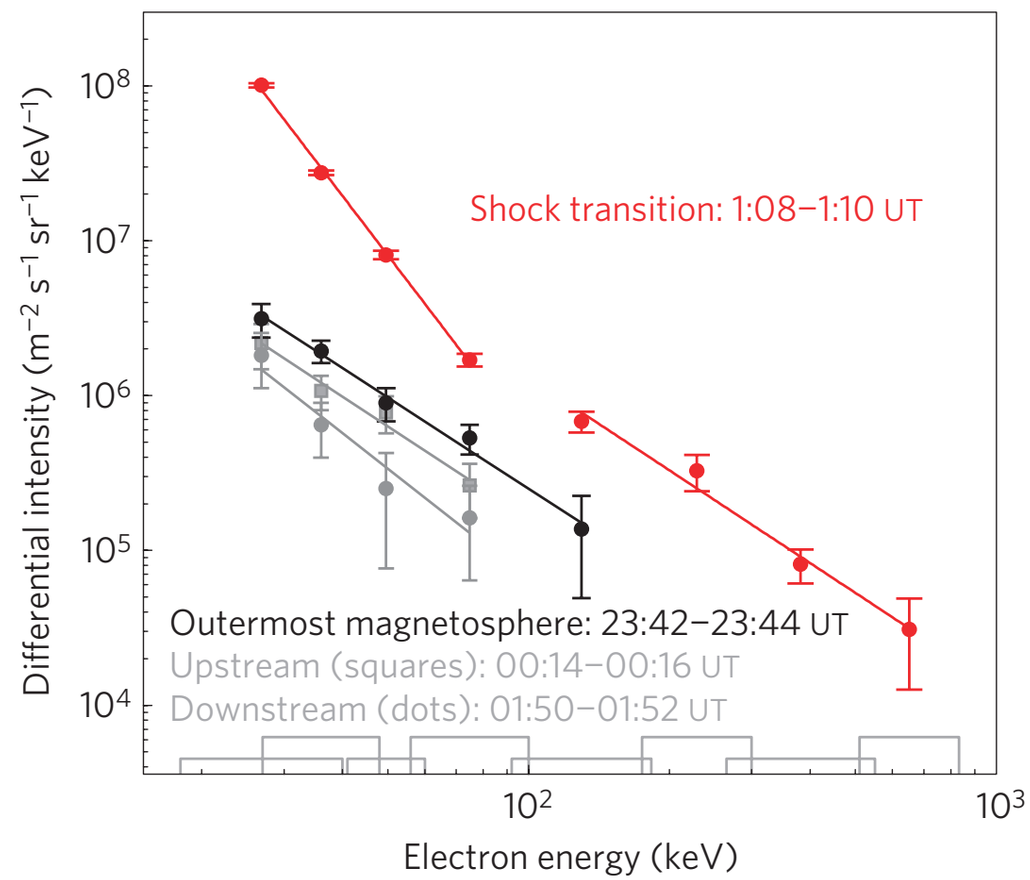


Ion and electron acceleration (Sironi & Spitkovsky 2011)

Electron acceleration limited to low magnetization!

Relativistic Electrons in Quasi-Parallel Shock Wave Observed by the Cassini Spacecraft





Masters et al. 2013

γ-Rays From UHECRs

UHECRs interacting in source with photons or with ISM and/or ICM, initiating electromagnetic cascades.

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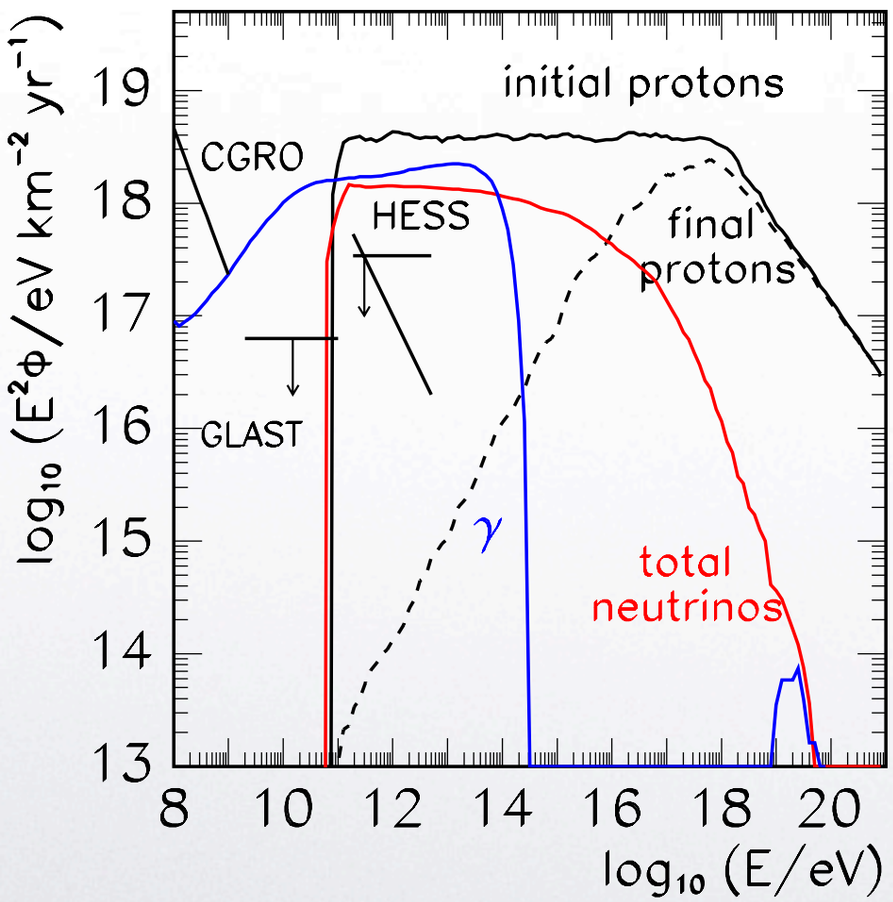

Prediction for Cen-A of Kachelrieß et al. 2008, also Gupta et al. 2008.

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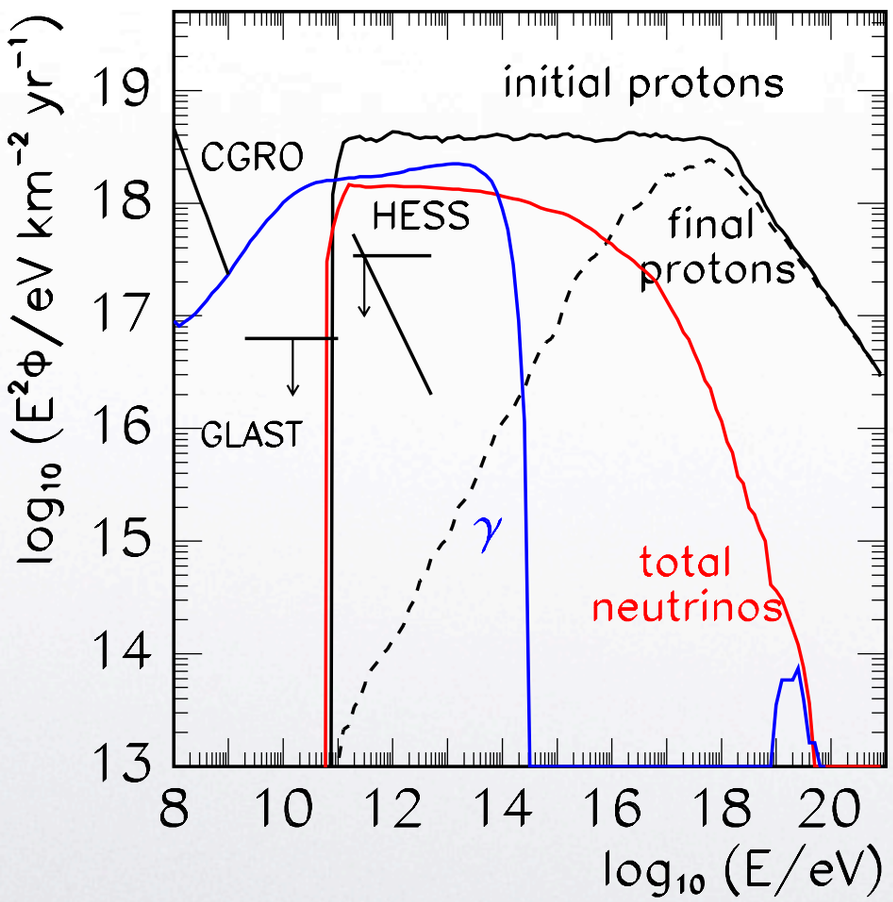

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γ-ray fluxes strongly depend on energy spectrum of UHECRs (normalized $E>6\times10^{19}$ eV).

Avenues for Further Progress

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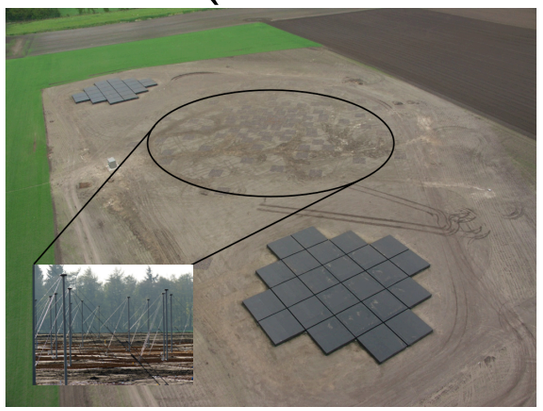
LOFAR (30-240 MHz)



eVLA: 1-50 GHz

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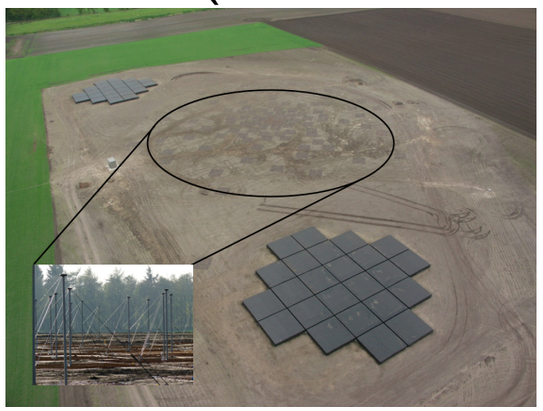

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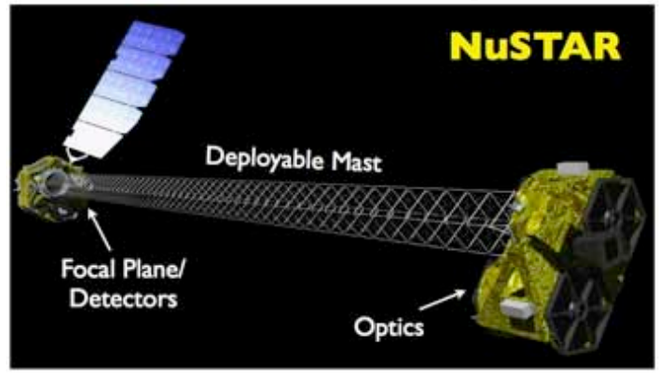
Hard X-ray



+ ASTRO-H

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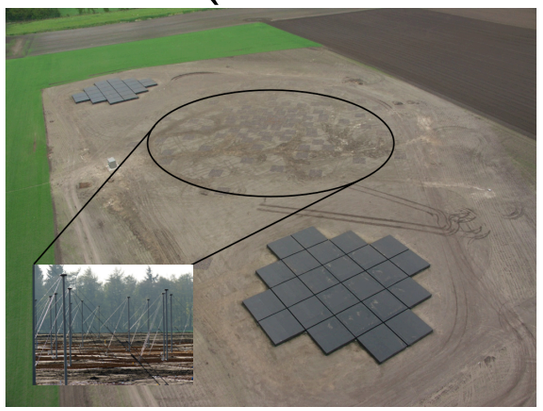

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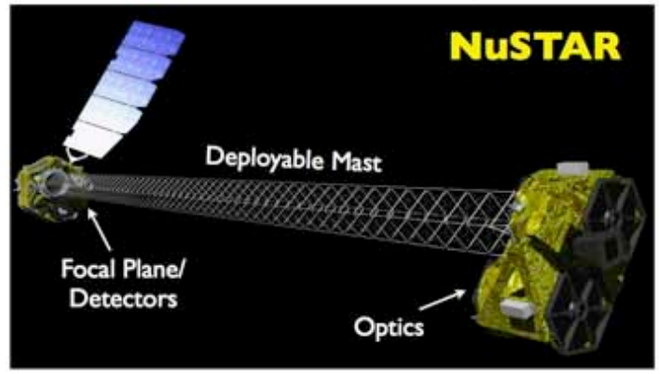

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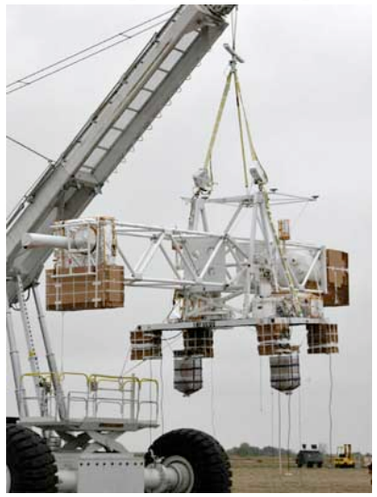
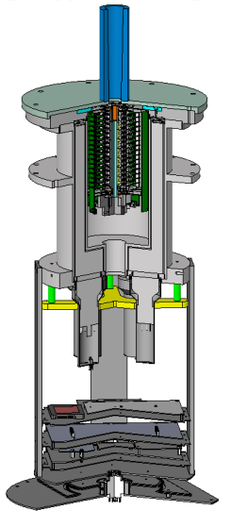
X-ray/γ-Ray Polarimetry





X-Calibur/InFOCuS

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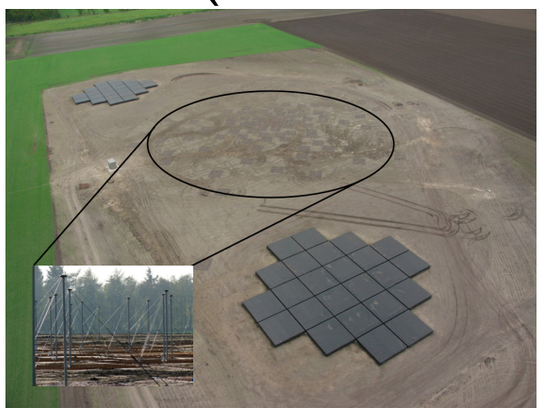

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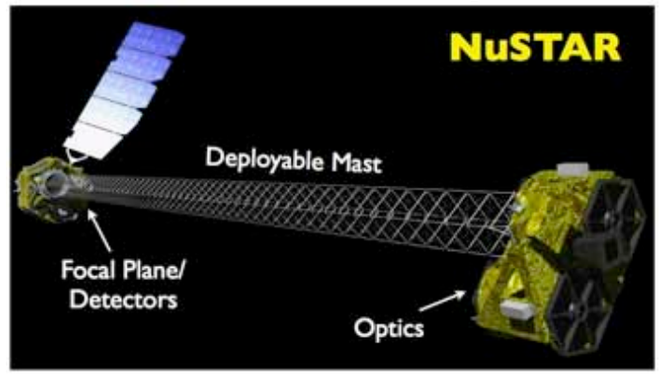

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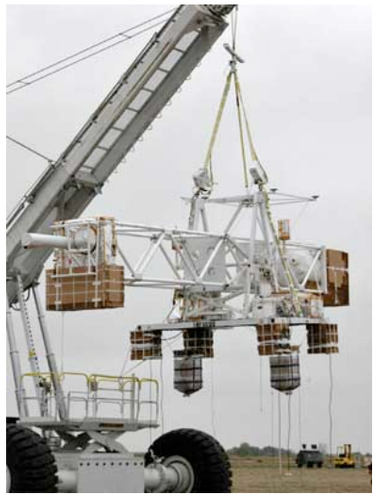
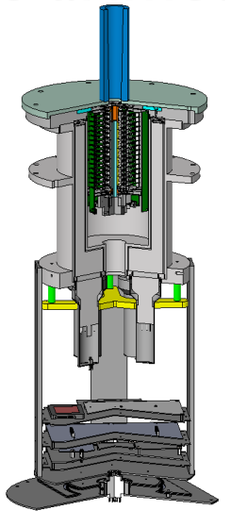
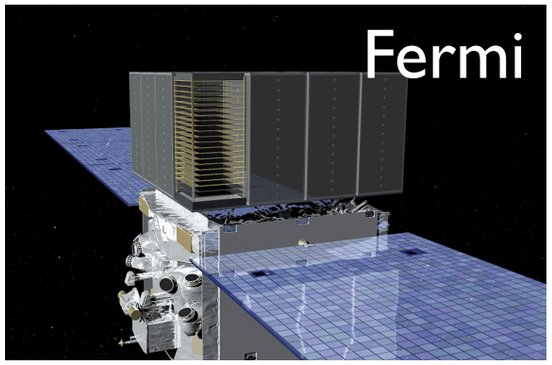




X-Calibur/InFOCuS

γ-Ray Observations



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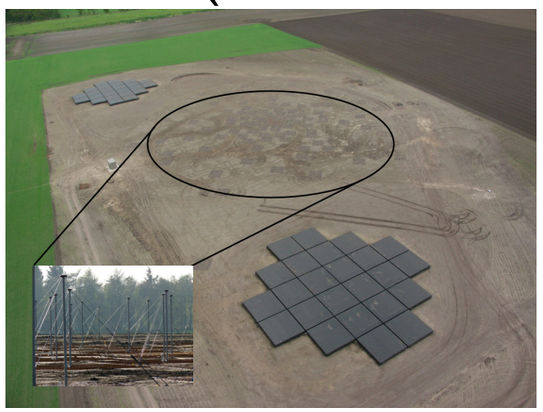
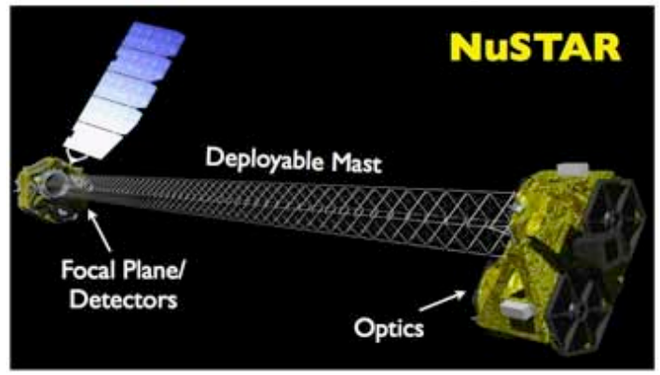


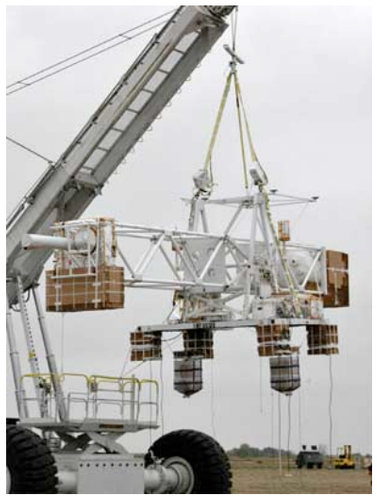
eVLA: 1-50 GHz

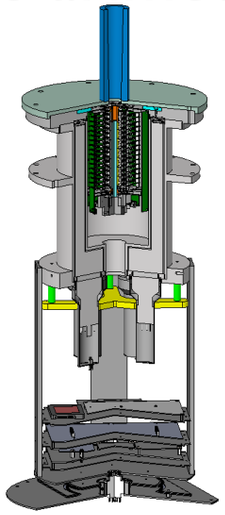
Hard X-ray



+ ASTRO-H

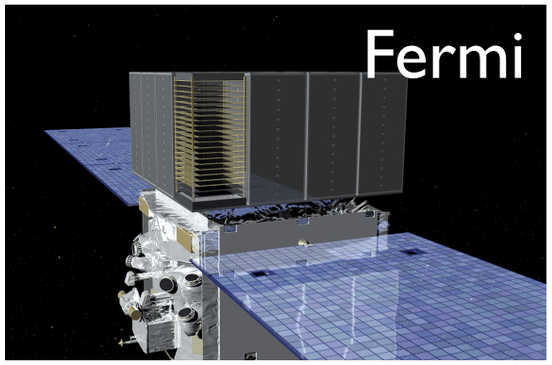
X-ray/γ-Ray Polarimetry





X-Calibur/InFOCuS

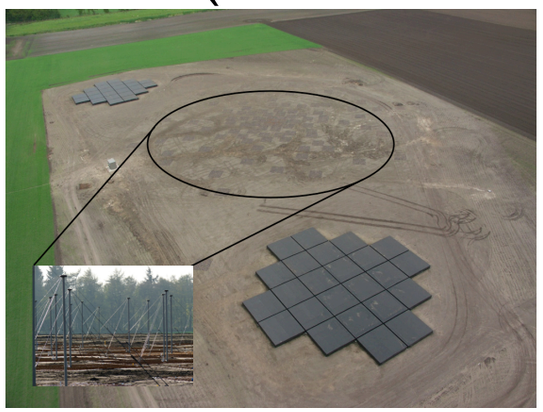
γ-Ray Observations



High-Performance Computing

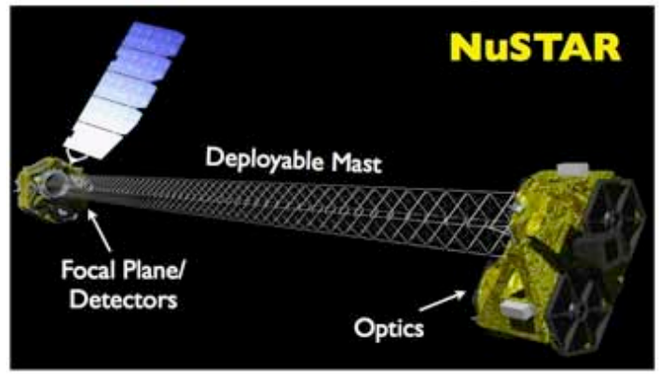
Avenues for Further Progress

LOFAR (30-240 MHz)



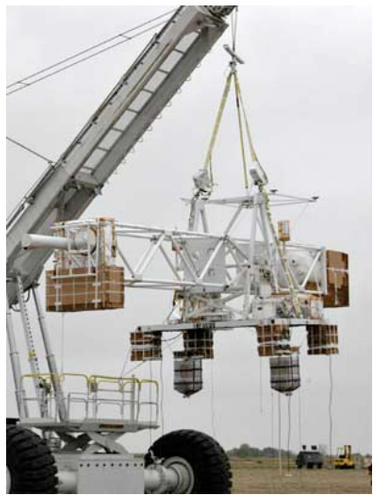
eVLA: 1-50 GHz

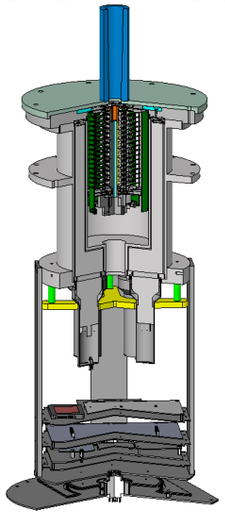
Hard X-ray



+ ASTRO-H

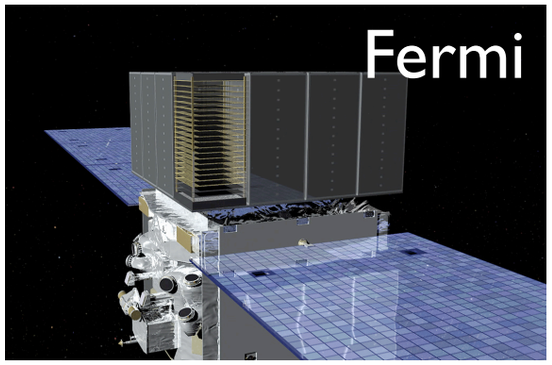
X-ray/γ-Ray Polarimetry





X-Calibur/InFOCuS

γ-Ray Observations



High-Performance Computing

In-Situ Observations