Exploring the properties of astrophysical plasmas: non-linear dynamics, high-energy radiation and beyond

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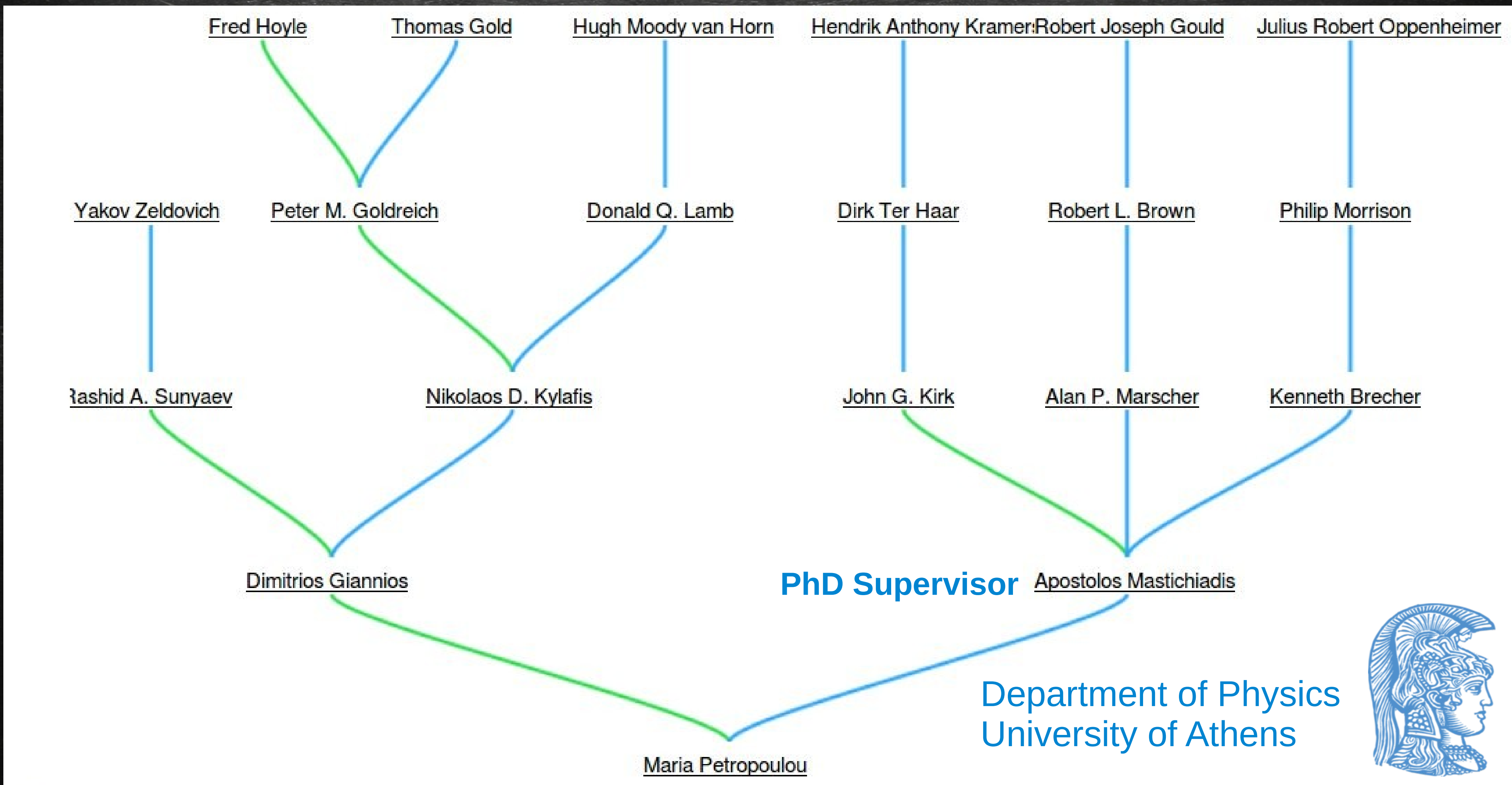
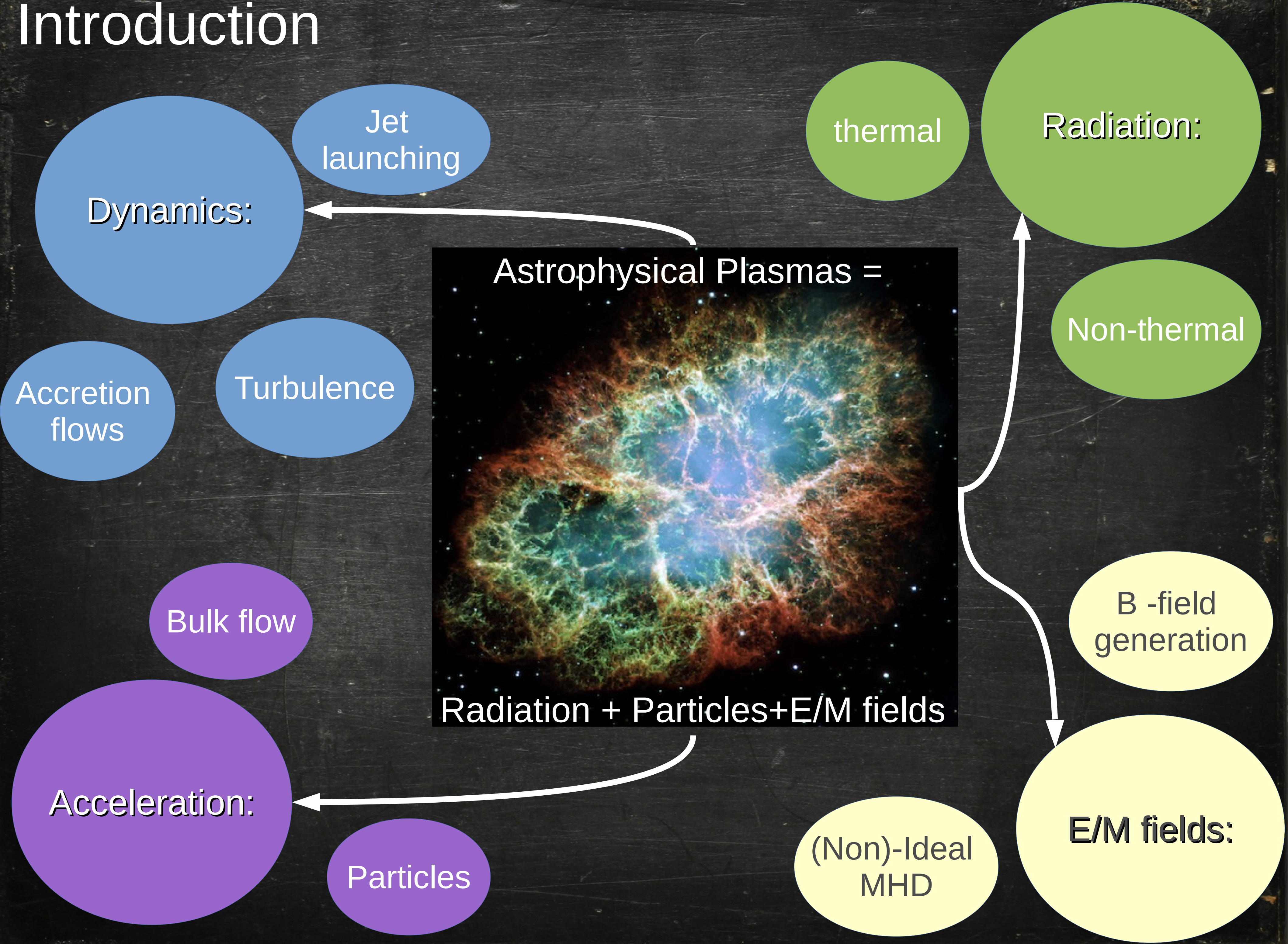
EWASS, 6th July, Athens, Greece

My scientific family tree



http://phdtree.org

Introduction



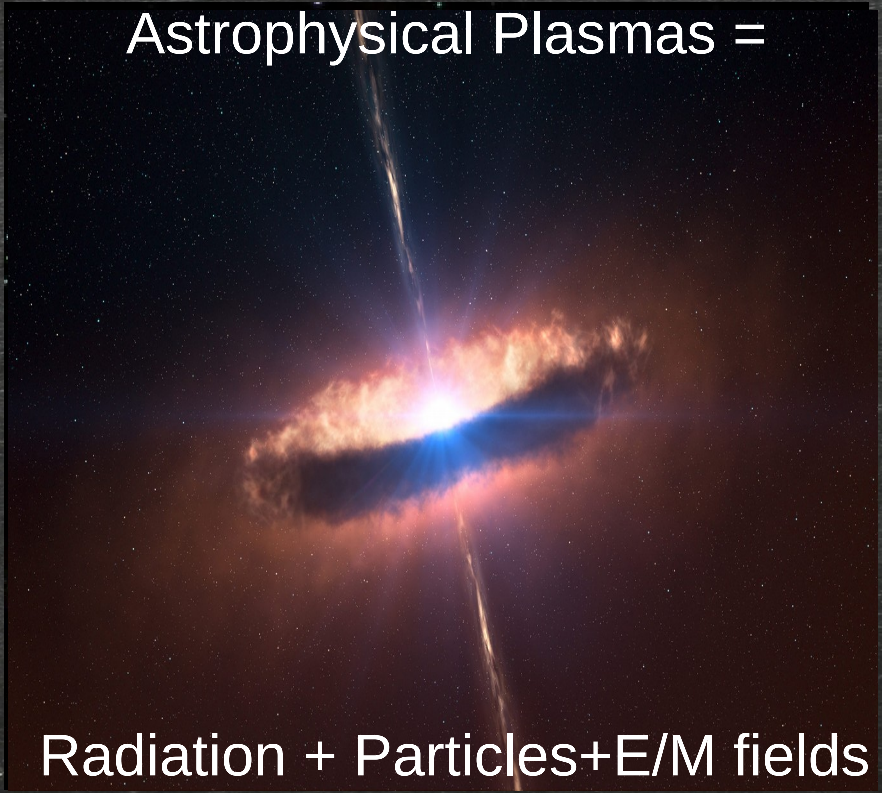
Introduction

The focus of my PhD research

Radiation:

Non-thermal

Astrophysical Plasmas =



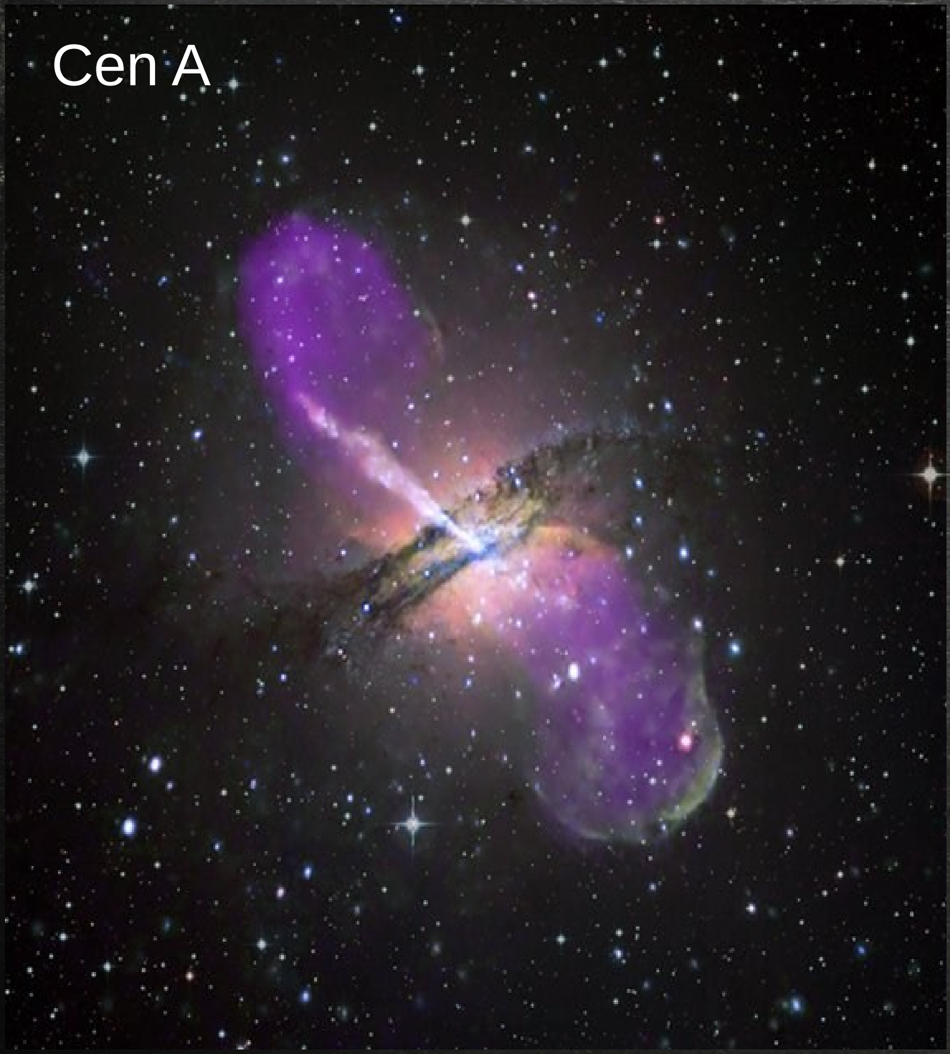
Radiation + Particles+E/M fields

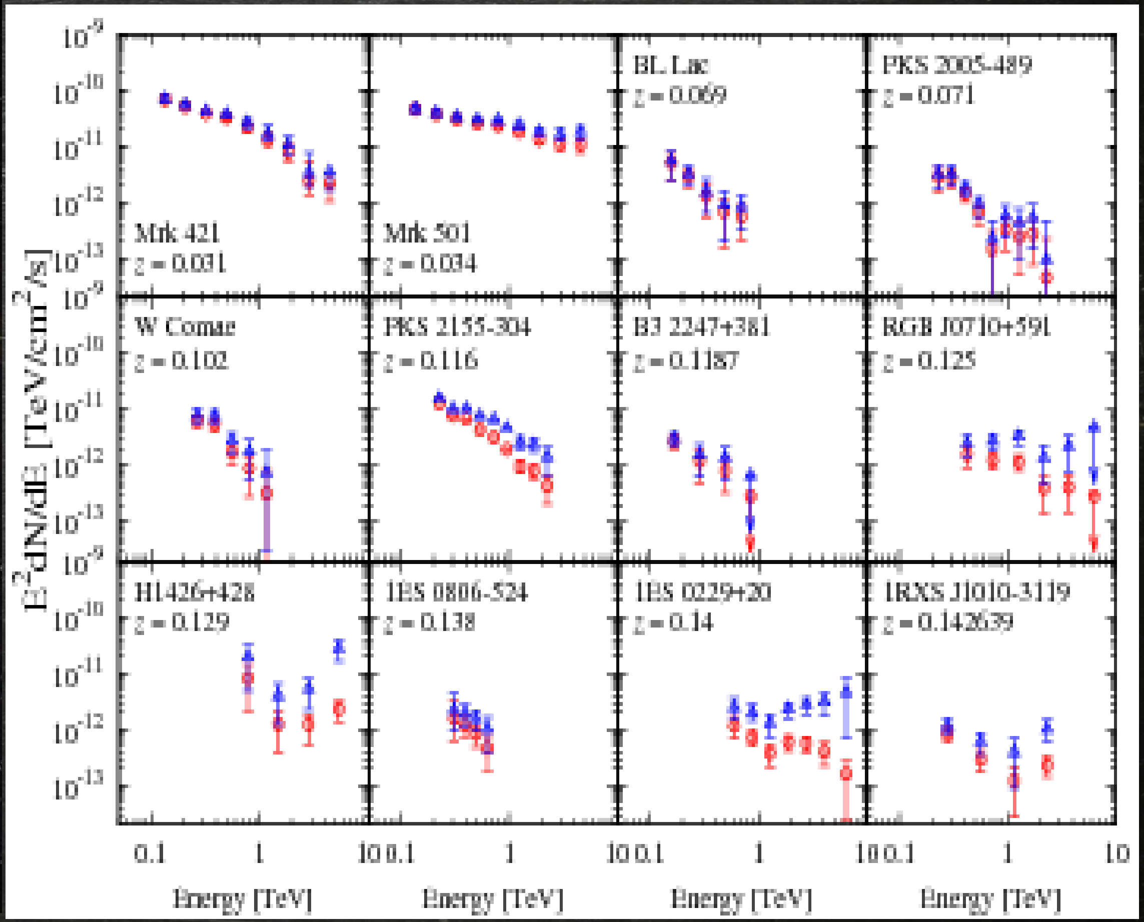
Acceleration:

Particles

Motivation

- Evidence for particle acceleration in relativistic jets

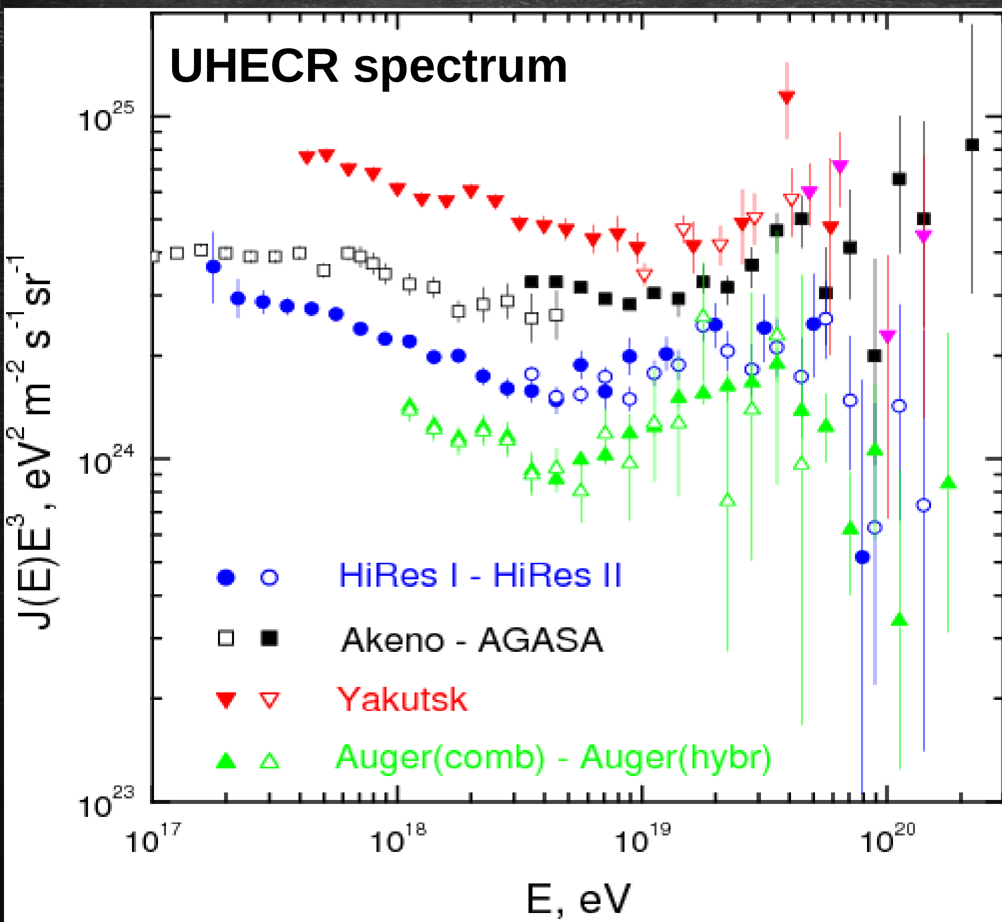


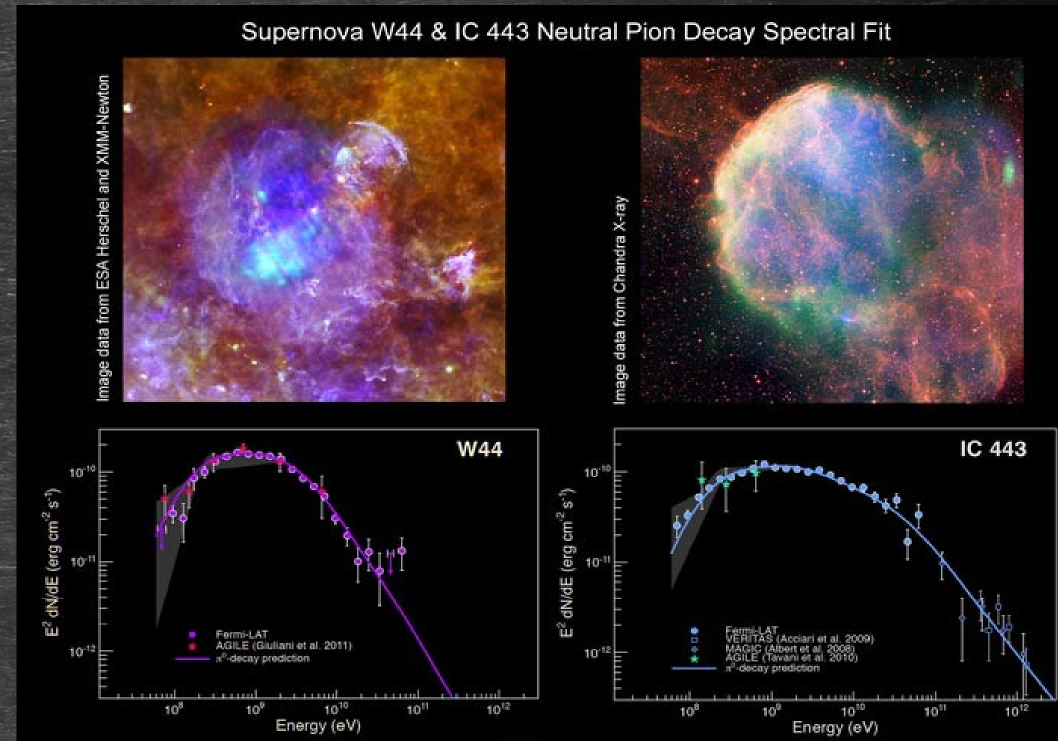


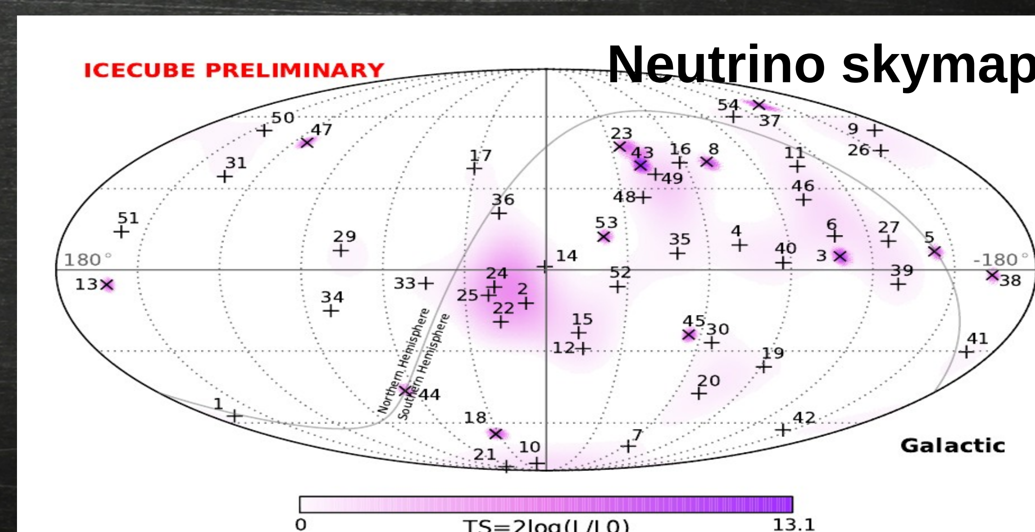
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

Motivation

- Evidence for relativistic hadrons in cosmic accelerators



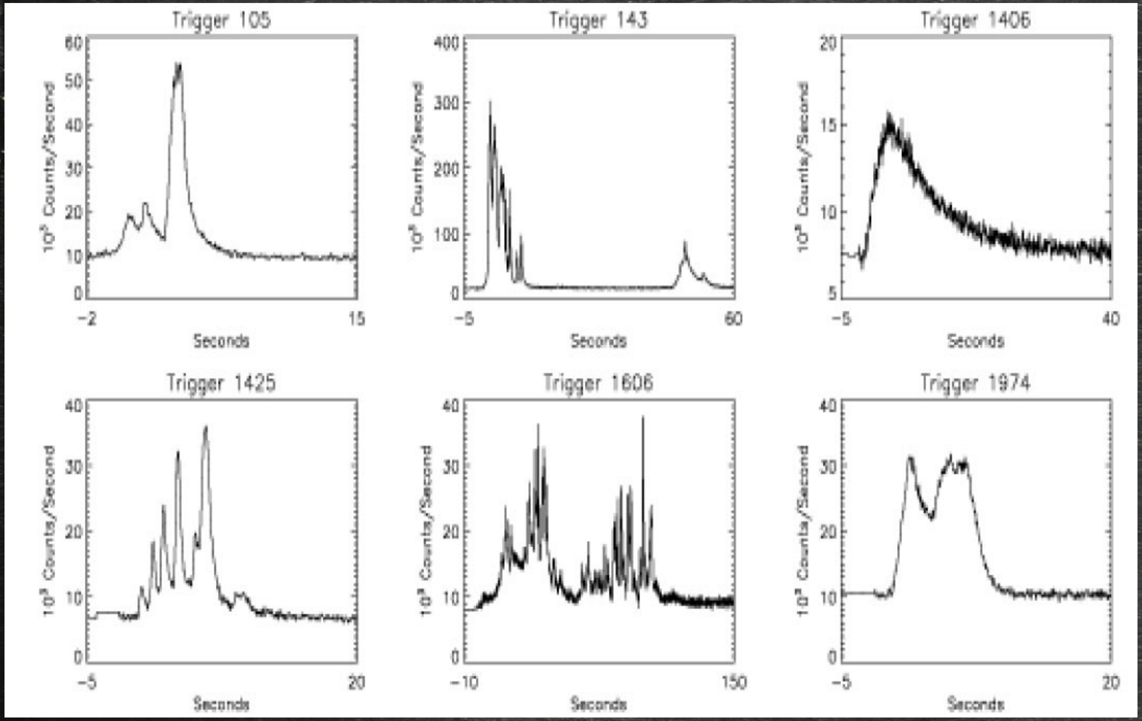




Motivation

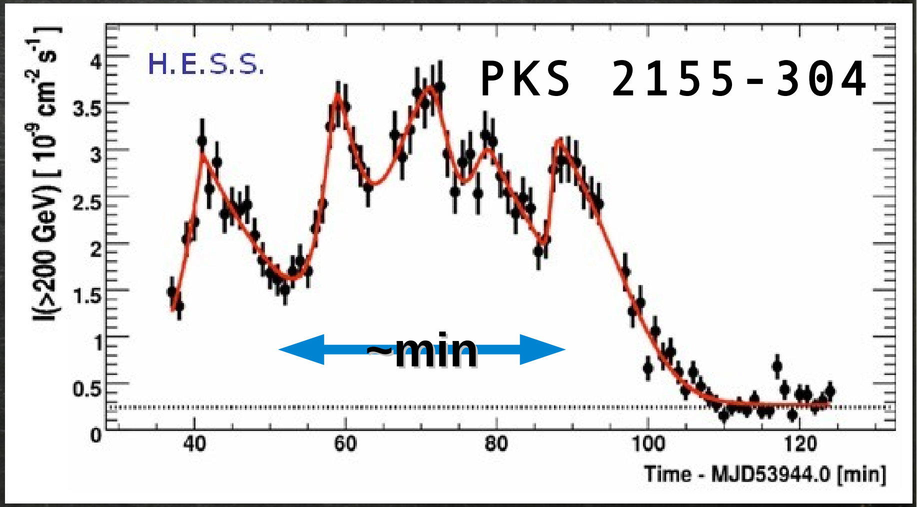
- Flux variability at short timescales !

A variety of GRB light curves

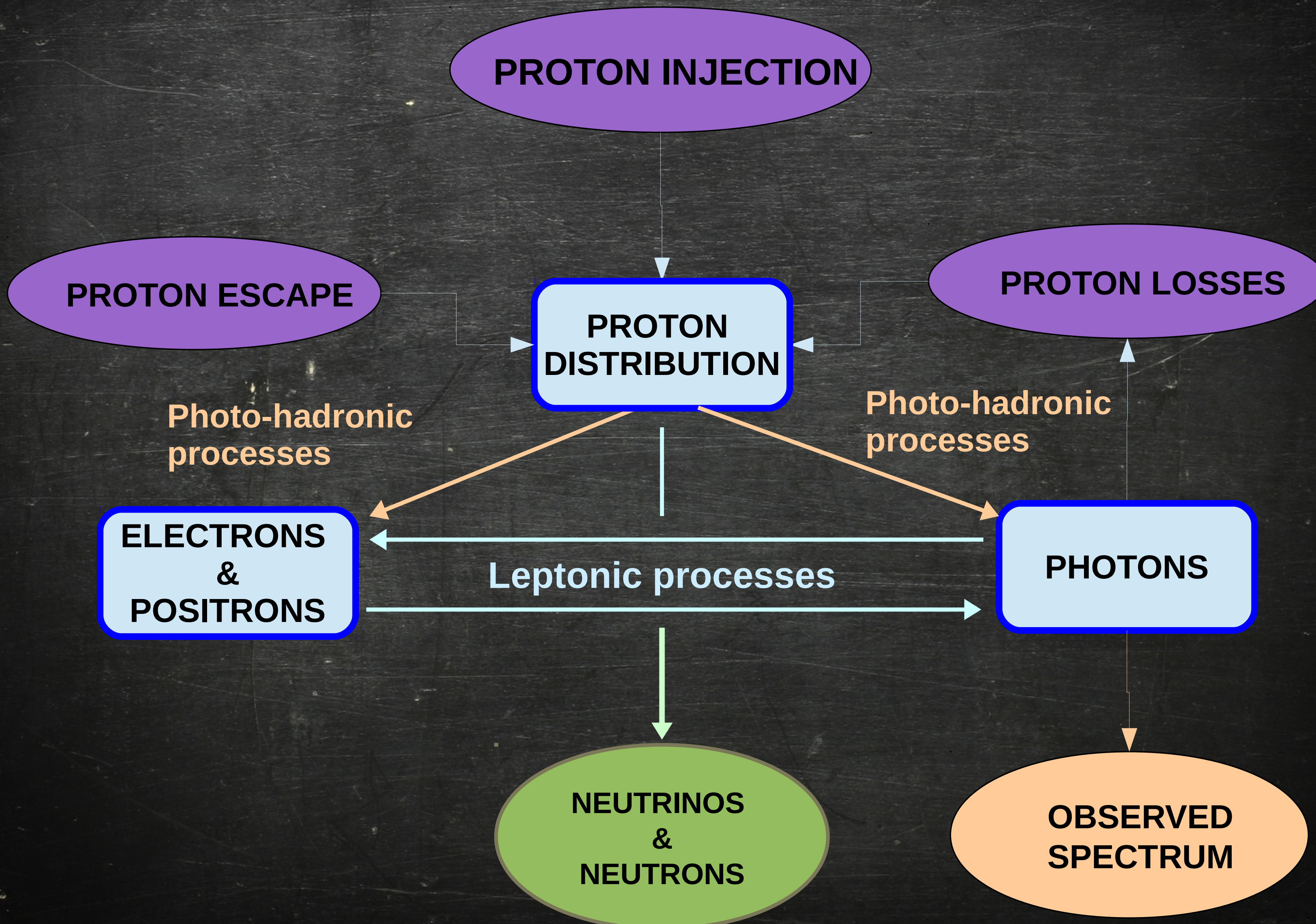


~sec

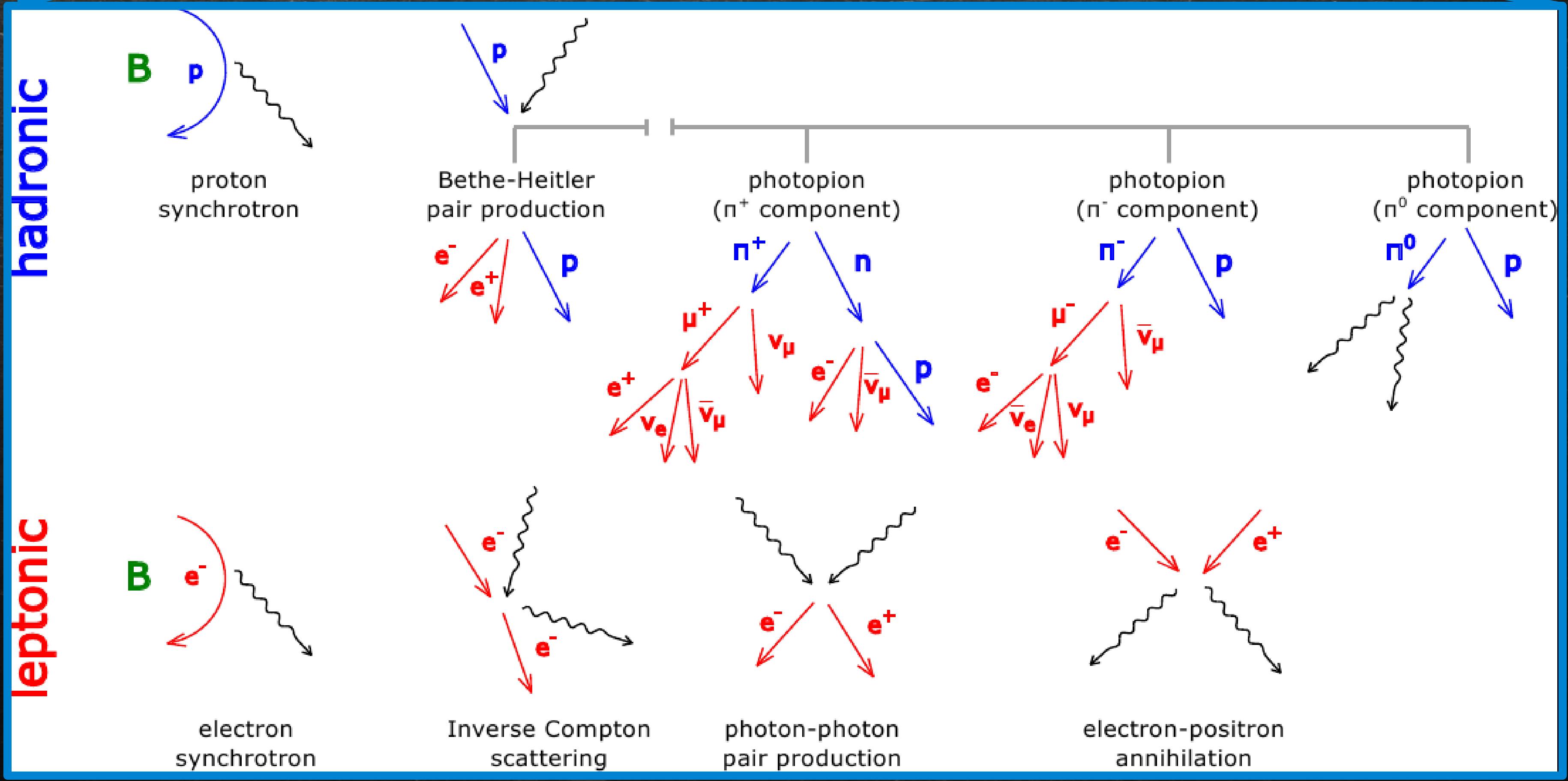
TeV light curve of blazar PKS 2155-304



Leptohadronic plasmas are ubiquitous among non-thermal astrophysical sources!



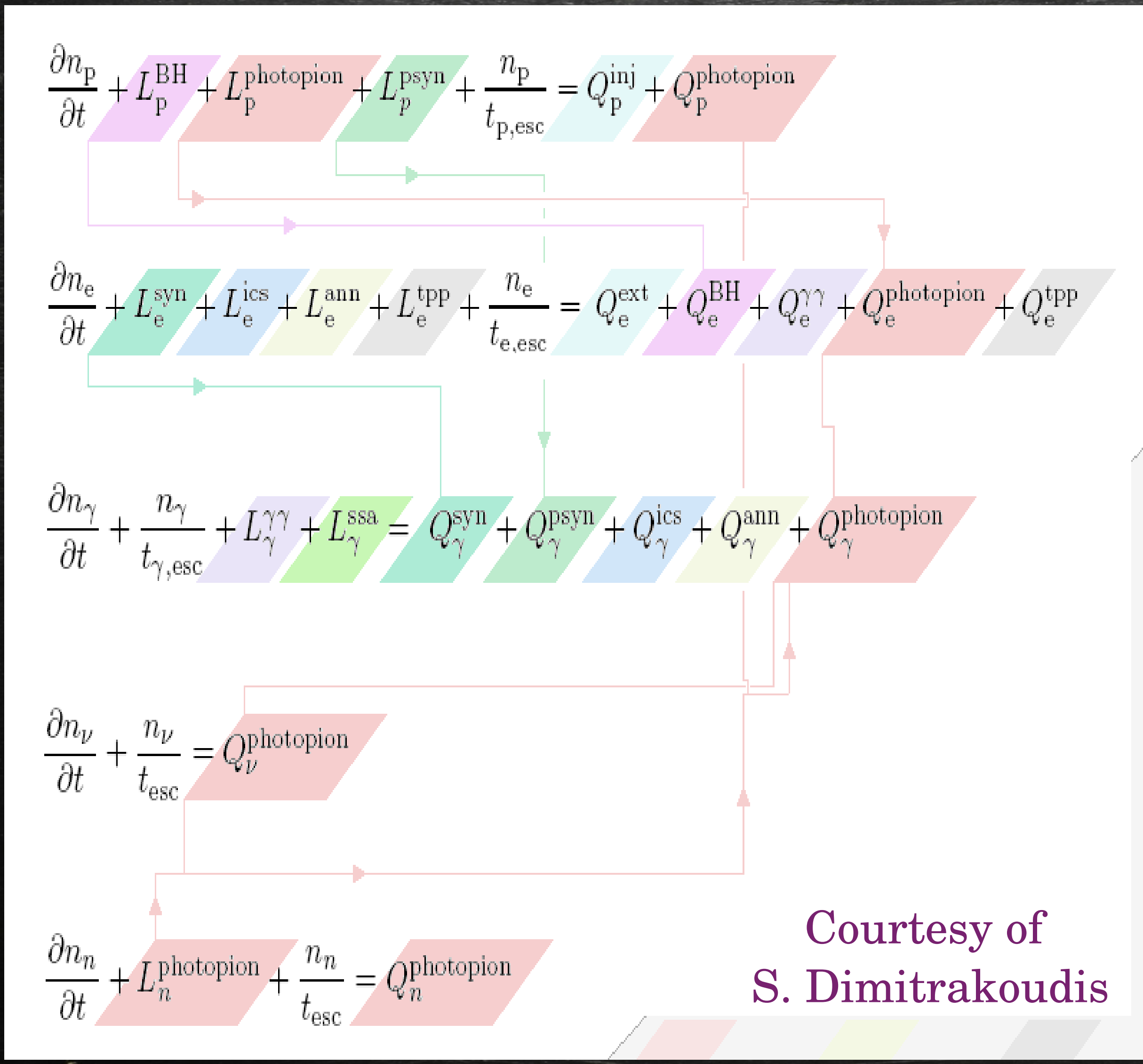
γ-rays from photo-hadronic processes



Credit: S. Dimitrakoudis

Goals

- Study the interplay of the radiative processes



A system of coupled integro-differential equations

↓

Does it simplify to a more familiar problem ? (e.g. Lotka-Volterra system)

Goals

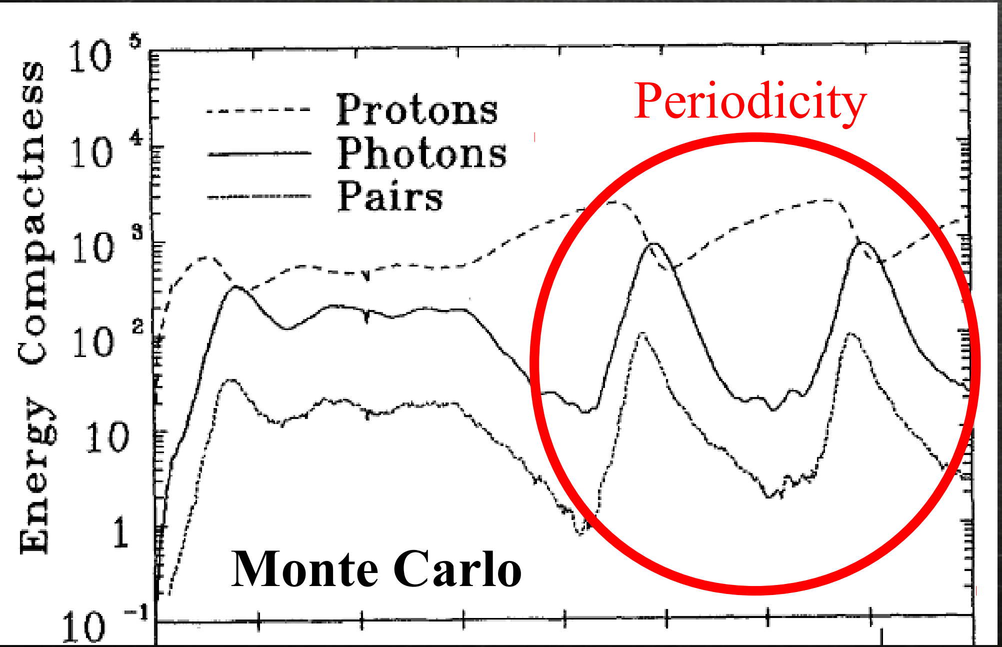
- Understand the temporal properties of the emission

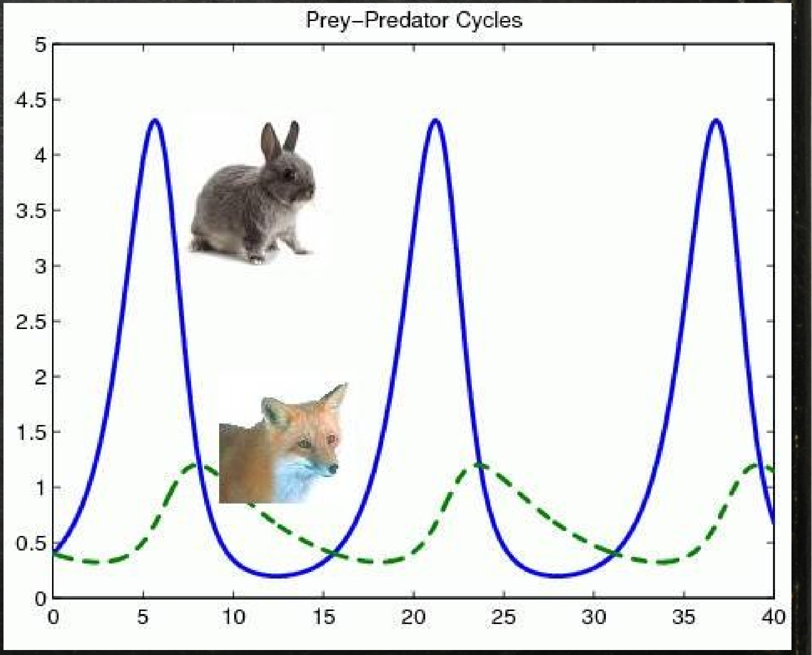
Limit Cycles in Electromagnetic Cascades in Compact Objects (1991)

Boris Stern [1], Roland Svensson [2]

Limit Cycles in
Prey-Predator systems

Which radiative process
is responsible for the limit
cycle behaviour?

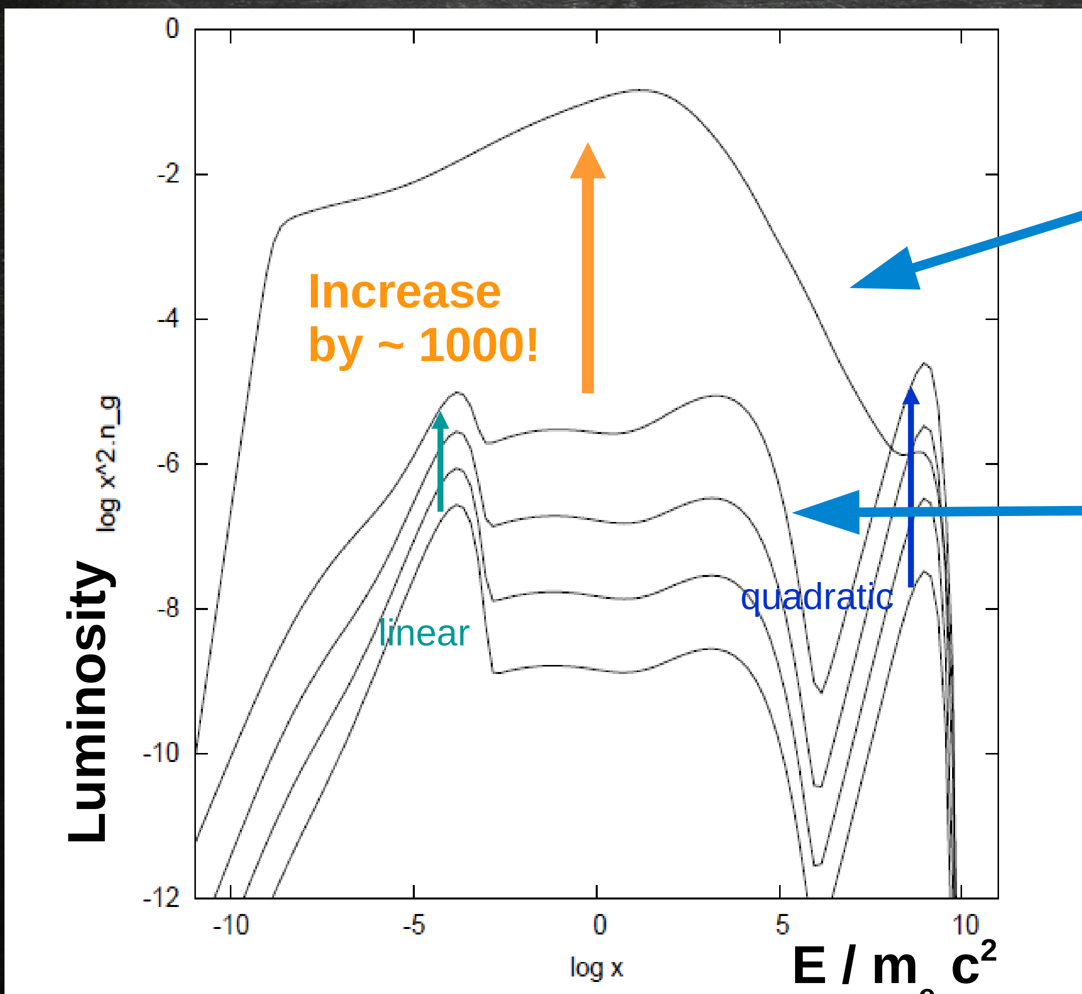




Goals

- Understand the spectral properties of the emission
  – Is the abrupt spectral and flux change a numerical artifact?

  – If not, what are the underlying physics of this transition?



Dimitrakoudis et al. 2012, A&A, 546

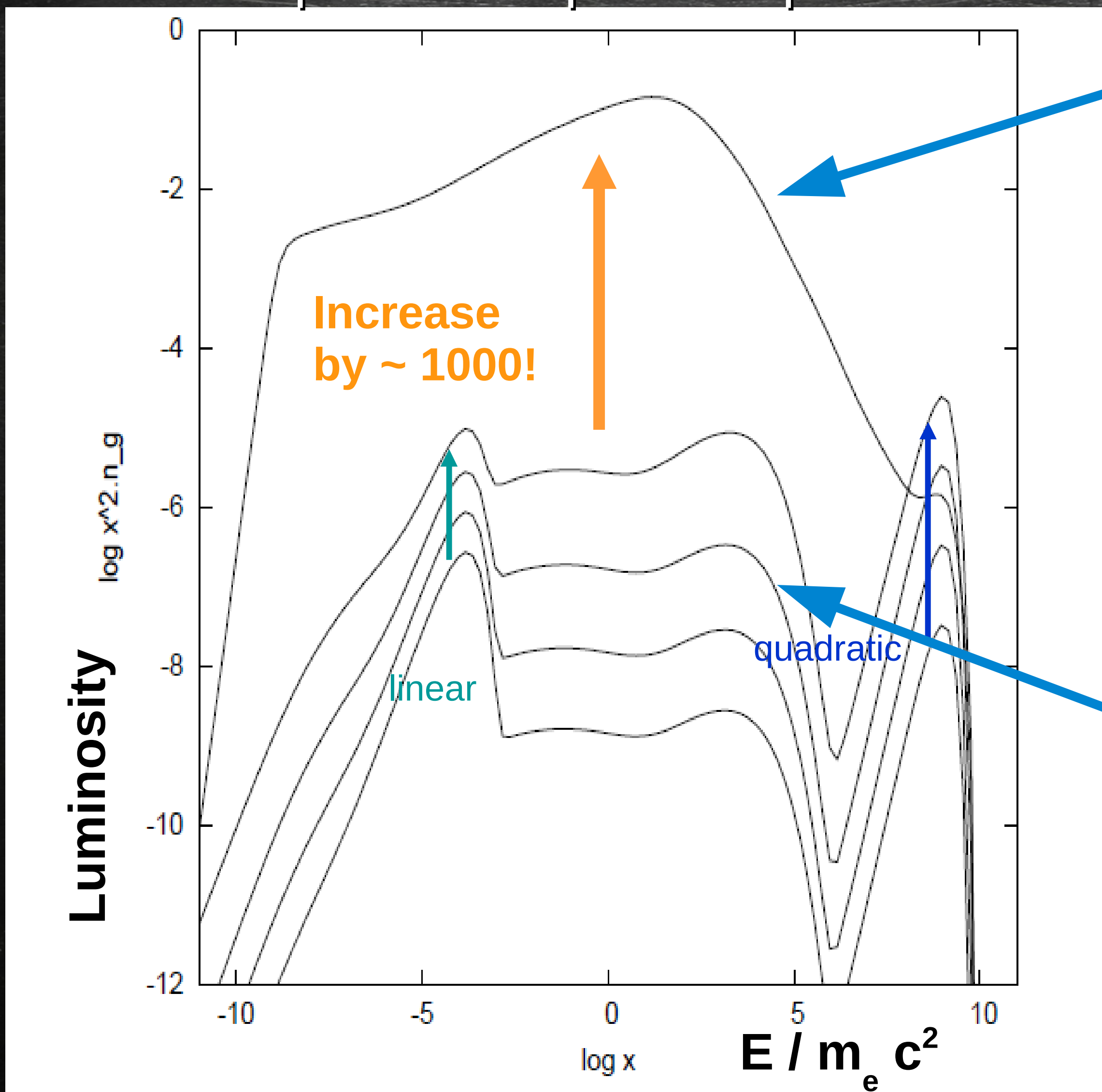
"High luminosity state"
aka
super-critical regime

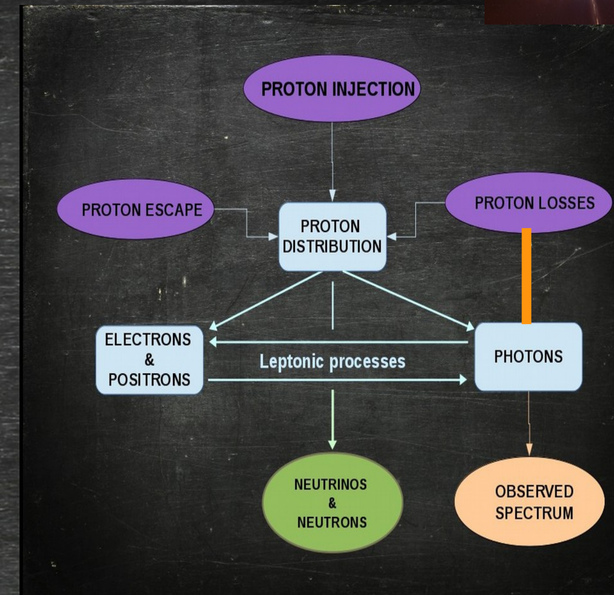
"Low luminosity state"
aka
sub-critical regime

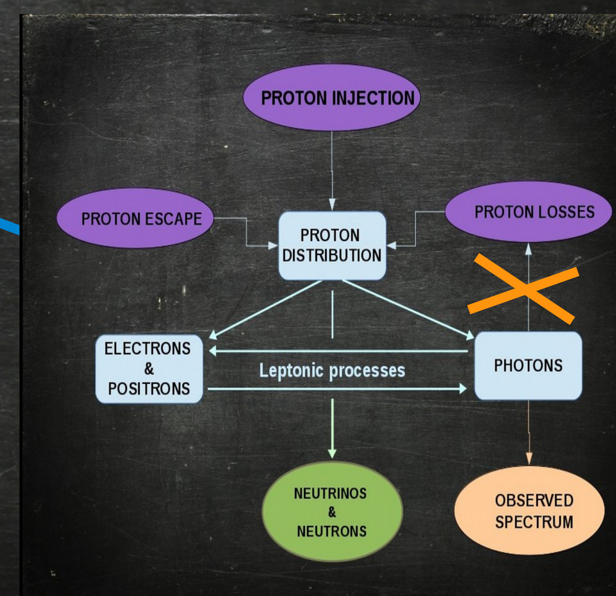
The proton luminosity increases
by a factor of 2 over its previous value!

Feedback loops & luminosity states

Example of MW photon spectrum

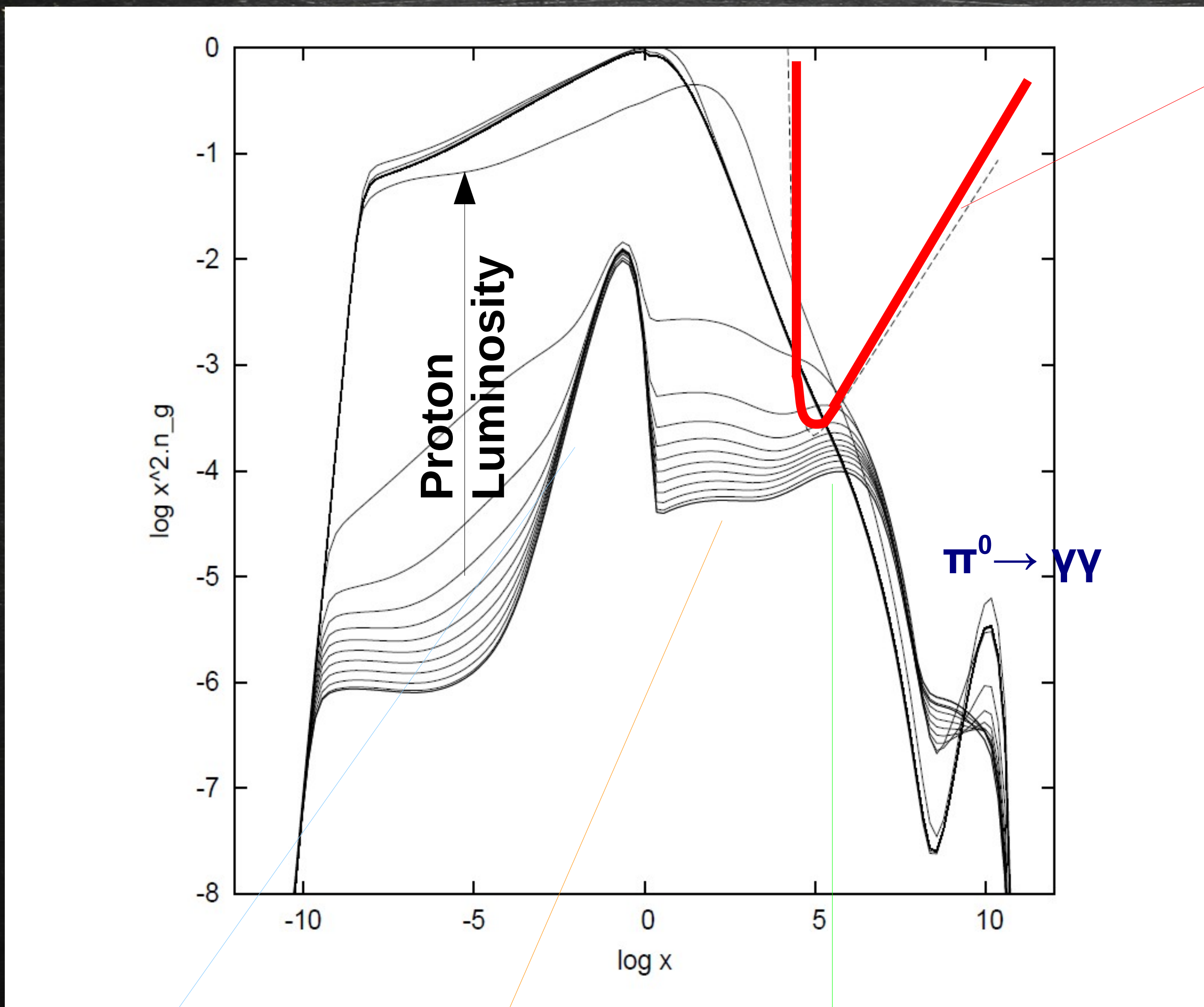






Dimitrakoudis et al. 2012, A&A

Onset of supercriticality



We derived analytically the **Critical γ-ray luminosity**

– Petropoulou & Mastichiadis, 2011, A&A 532

– Petropoulou & Mastichiadis, 2012, MNRAS, 421

– Petropoulou, Arfani & Mastichiadis, 2013, A&A, 557

Take away message

If γ-ray luminosity exceeds the red curve then

1. low-energy photons exponentiate in the source

2. protons lose energy due to these photons

3. more photons are produced

$p+B \rightarrow \gamma$

$p+\gamma \rightarrow e^- e^+ + B \rightarrow \gamma$

$p+\gamma \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+ + B \rightarrow \gamma$

Analytical study of supercriticality

- Keep only "key" processes
- Neglect equation for pairs.
- We replace the pairs by their radiated photon spectrum.

Protons:

$$\dot{n}_{\rm p} = Q_{\rm po} - \frac{n_{\rm p}}{\tau_{\rm p}} - \sigma^0_{\rm p\gamma} n_{\rm p} n_{\rm ex} - \sigma^0_{\rm p\gamma} n_{\rm p} n_{\rm s}$$

γ-ray photons: from photopion processes

$$\dot{n}_{\rm h} = -n_{\rm h} + A n_{\rm p} n_{\rm ex} + A n_{\rm p} n_{\rm s} - C_{\rm h} n_{\rm s} n_{\rm h} - C'_{\rm h} n_{\rm ex} n_{\rm h}$$

Low-energy photons: from synchrotron radiation of $e^- e^+$

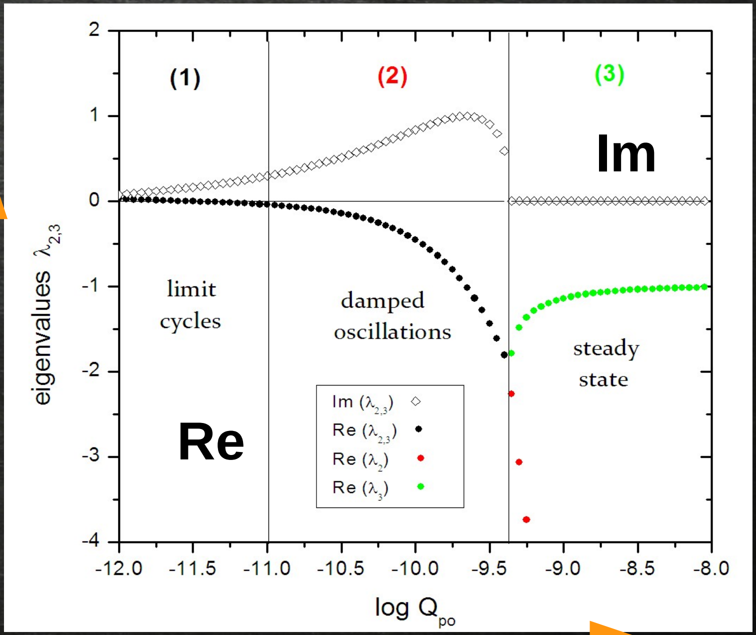
$$\dot{n}_{\rm s} = -n_{\rm s} + C_{\rm s} n_{\rm s} n_{\rm h} + C'_{\rm s} n_{\rm ex} n_{\rm h},$$

– Perform an eigenvalue/eigenvector analysis

– Find the real & complex eigenvalues

– The eigenvalues depend on the proton luminosity

Eigenvalues



Proton Luminosity

Petropoulou & Mastichiadis, 2012, MNRAS, 421

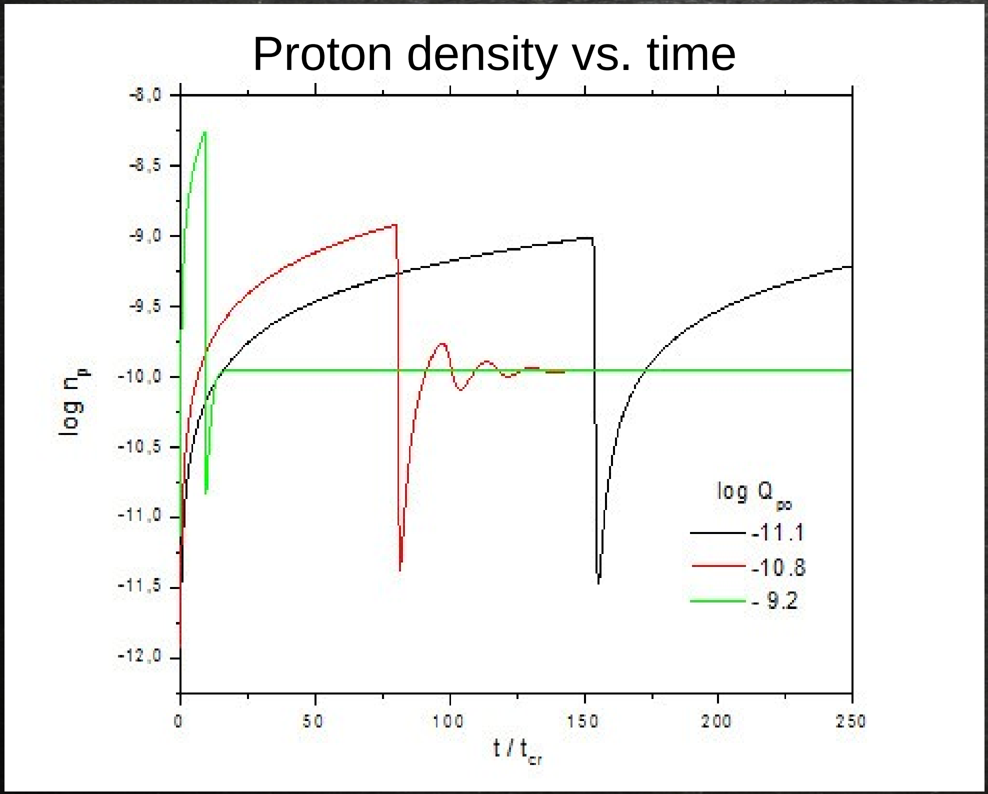
Temporal properties

A variety of temporal behaviours!

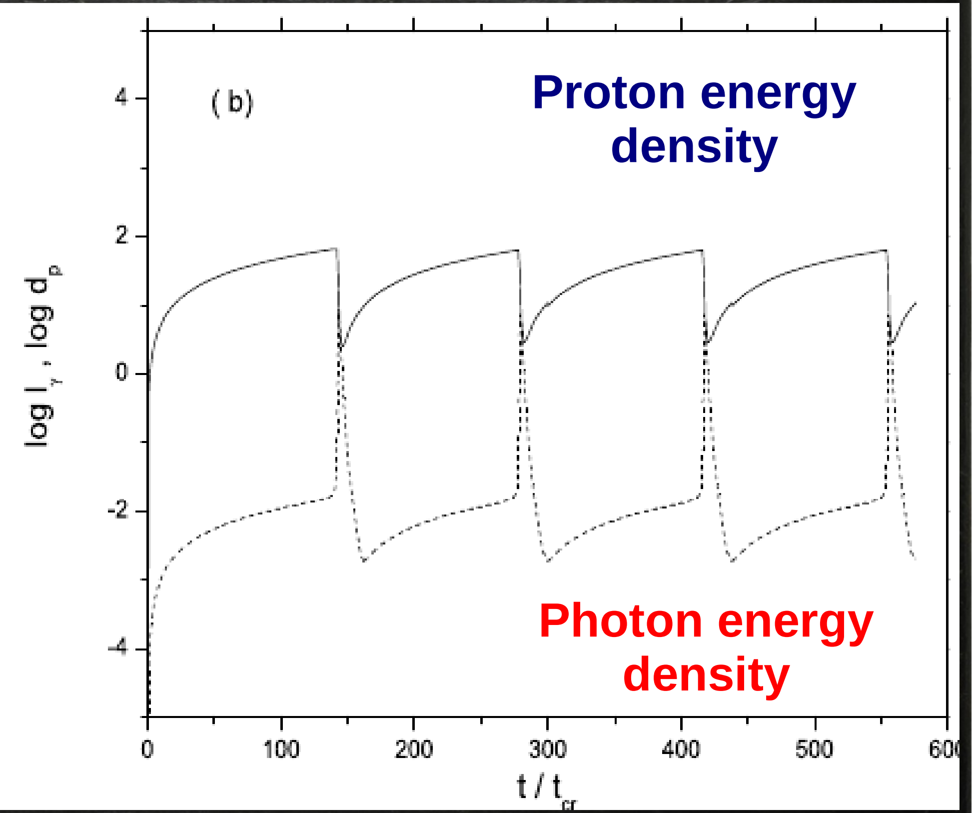
- **limit cycles**
- **damped oscillations**
- **steady state**

- Numerical solution of the full problem leads to the same qualitative results !
- The limit cycle behaviour found by Stern & Svensson (1991) is now understood.

Analytical



Numerical



Petropoulou & Mastichiadis, 2012, MNRAS, 421

Temporal properties

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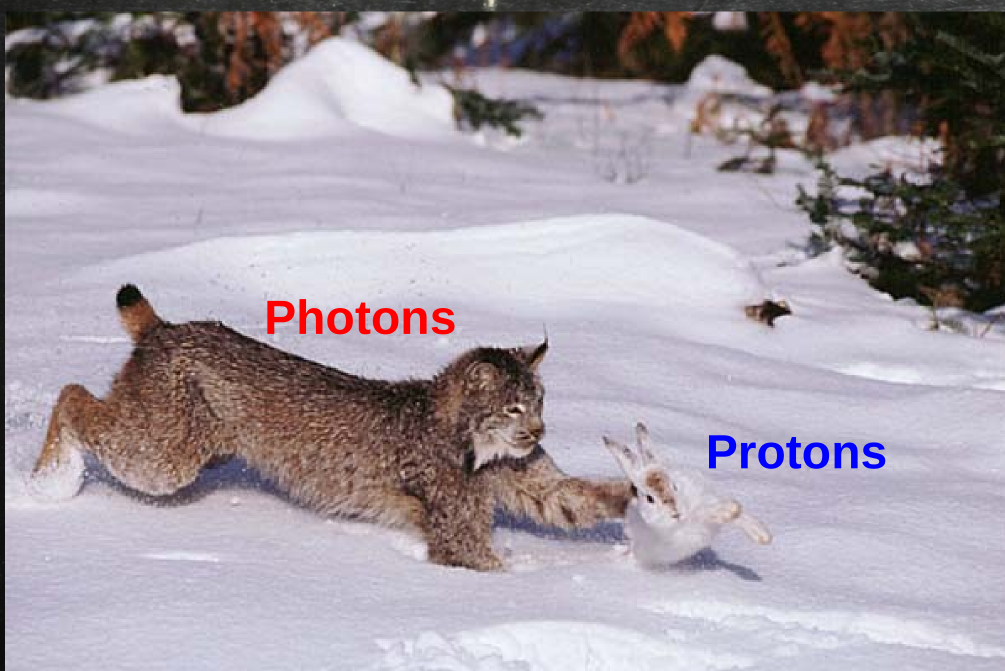
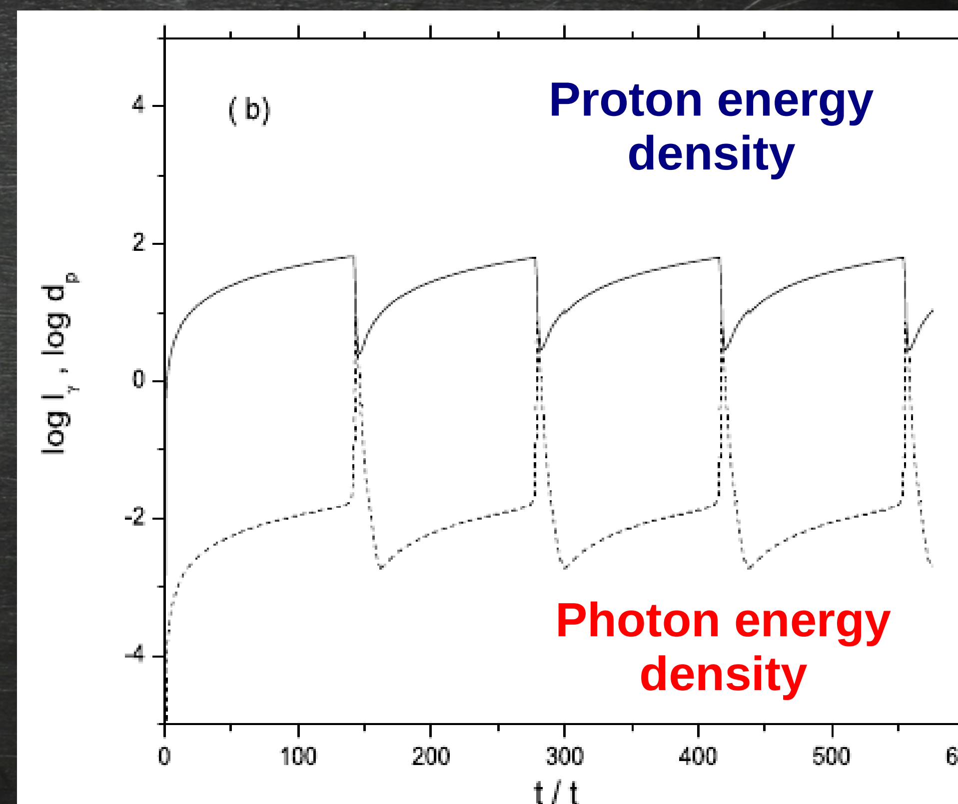
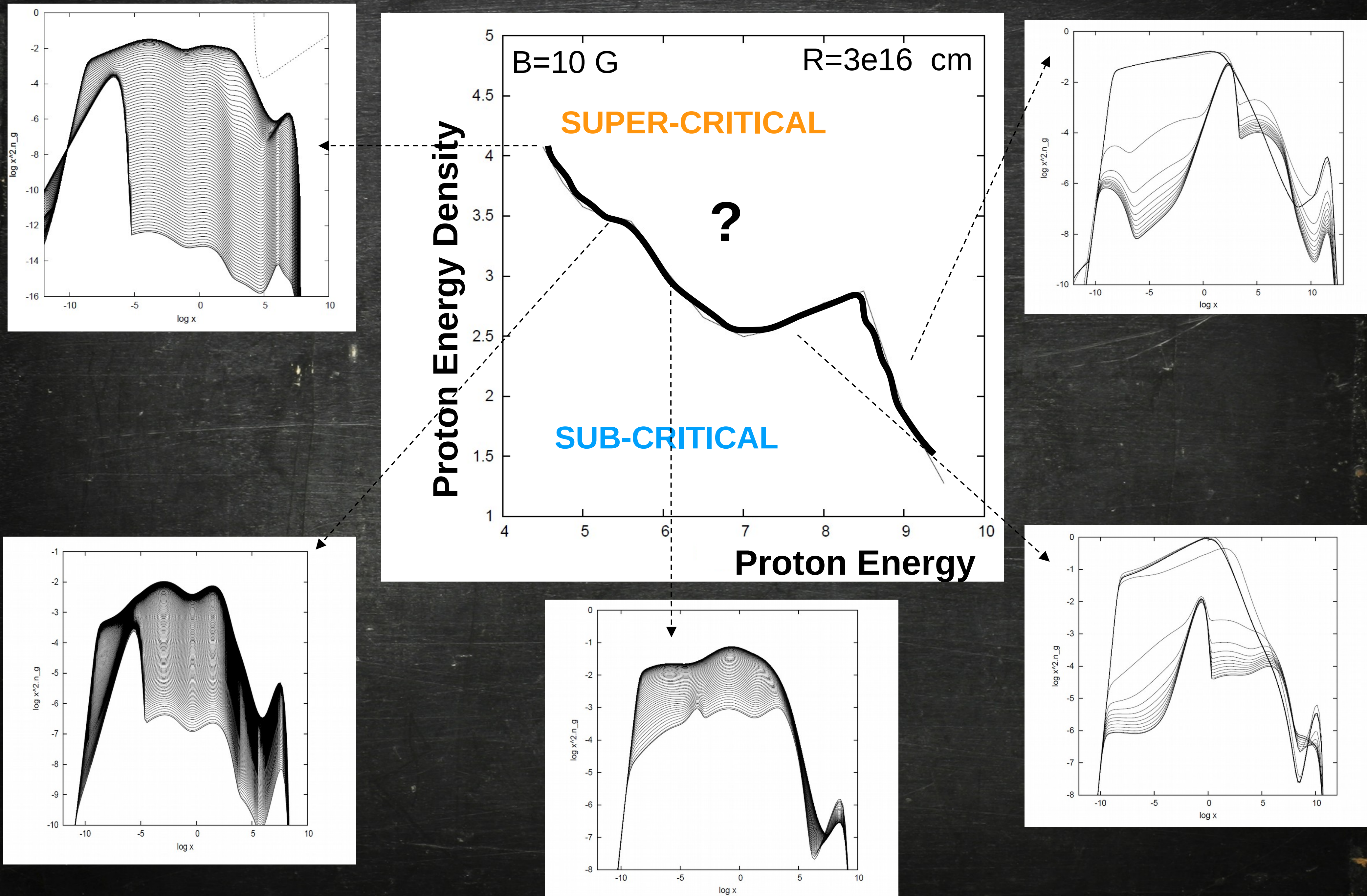
Numerical





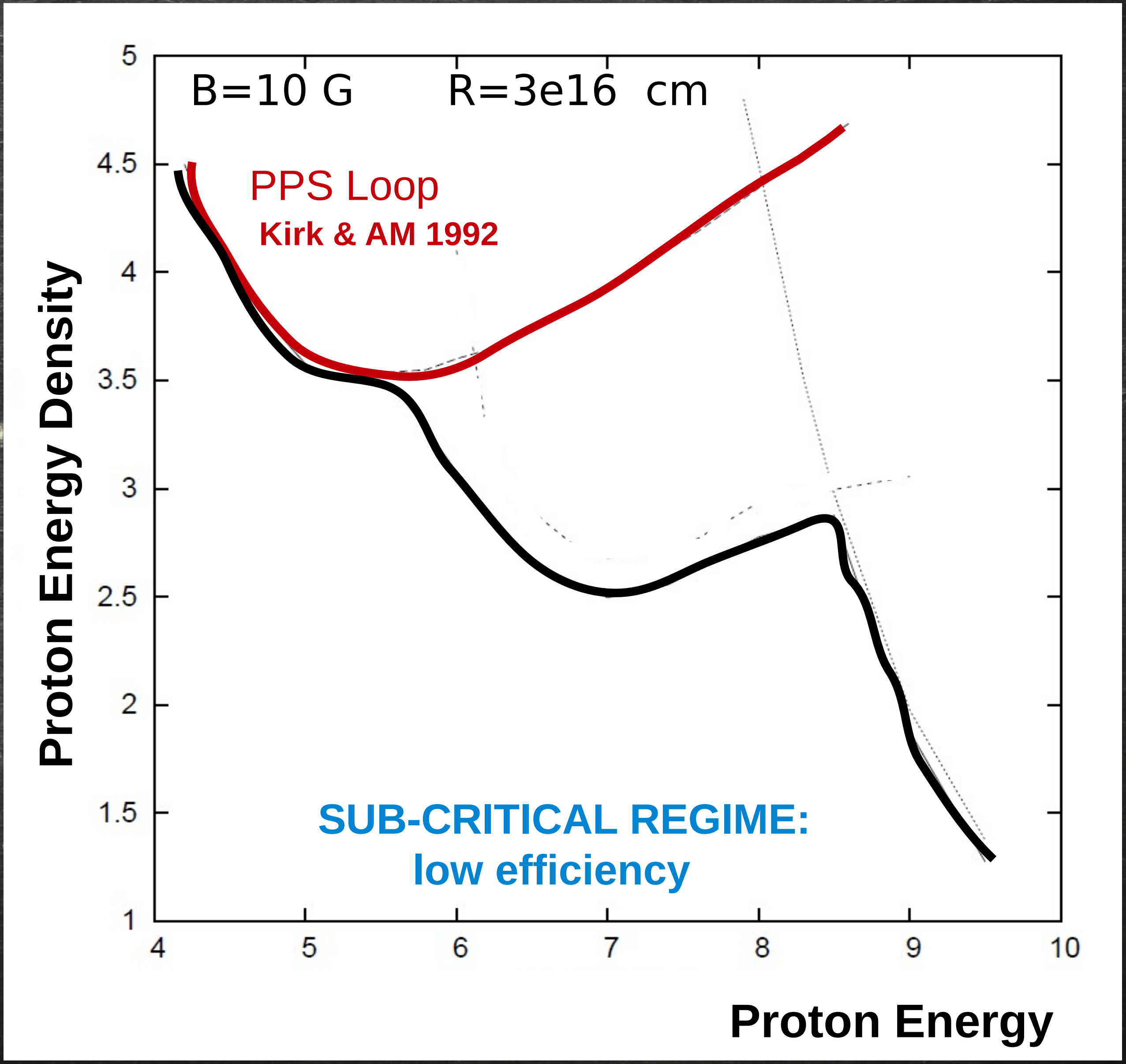
Petropoulou & Mastichiadis, 2012, MNRAS, 421

A “zoo” of transitions



A “zoo” of transitions: our understanding

SUPER-CRITICAL REGIME: high efficiency



Feedback loops are a way of extracting efficiently energy stored in protons

A “zoo” of transitions: our understanding

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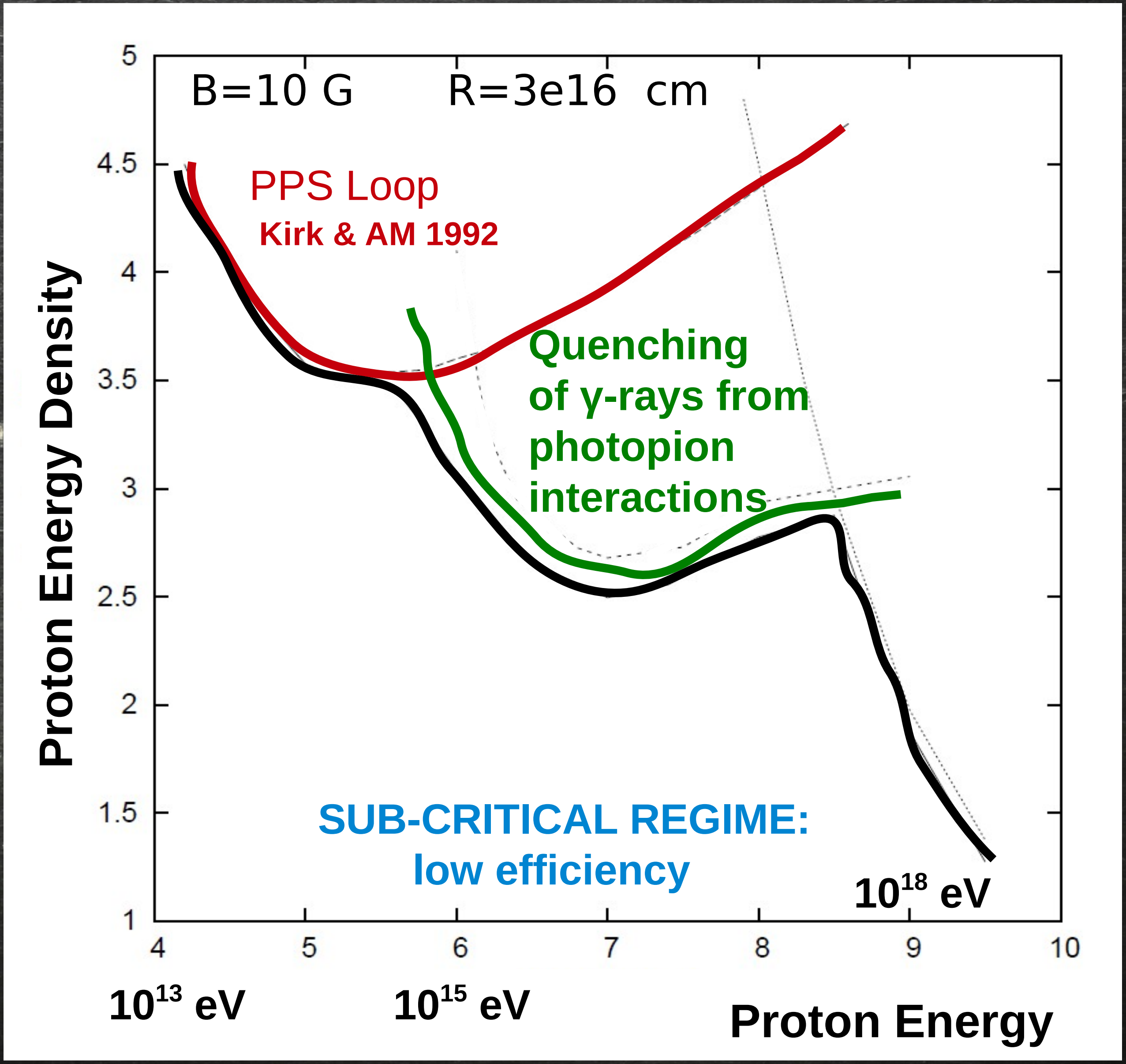

- Stawarz & Kirk, 2007, ApJL, 661
- Petropoulou & Mastichiadis, 2011, A&A, 532
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Feedback loops are a way of extracting efficiently energy stored in protons

A “zoo” of transitions: our understanding

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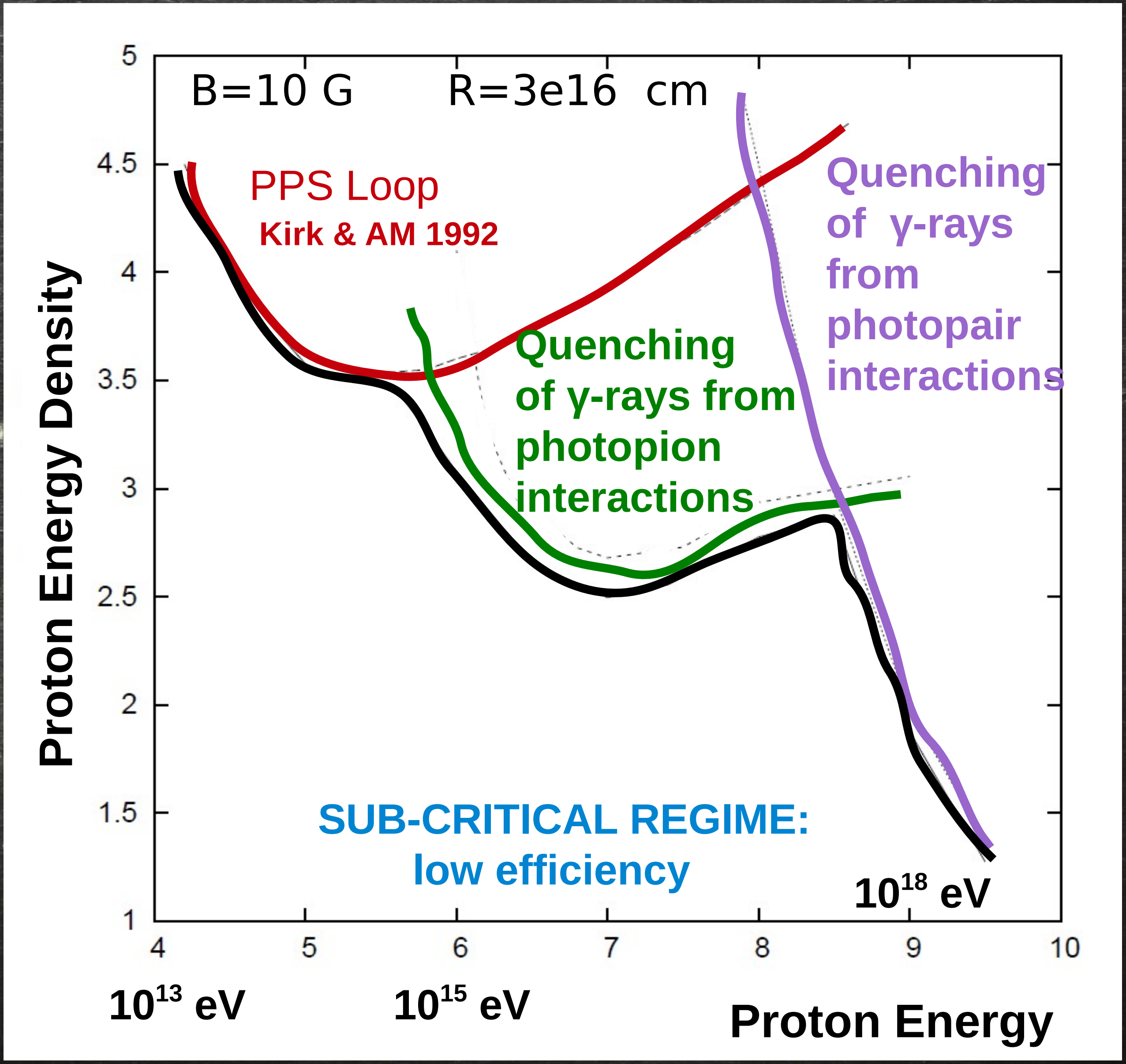

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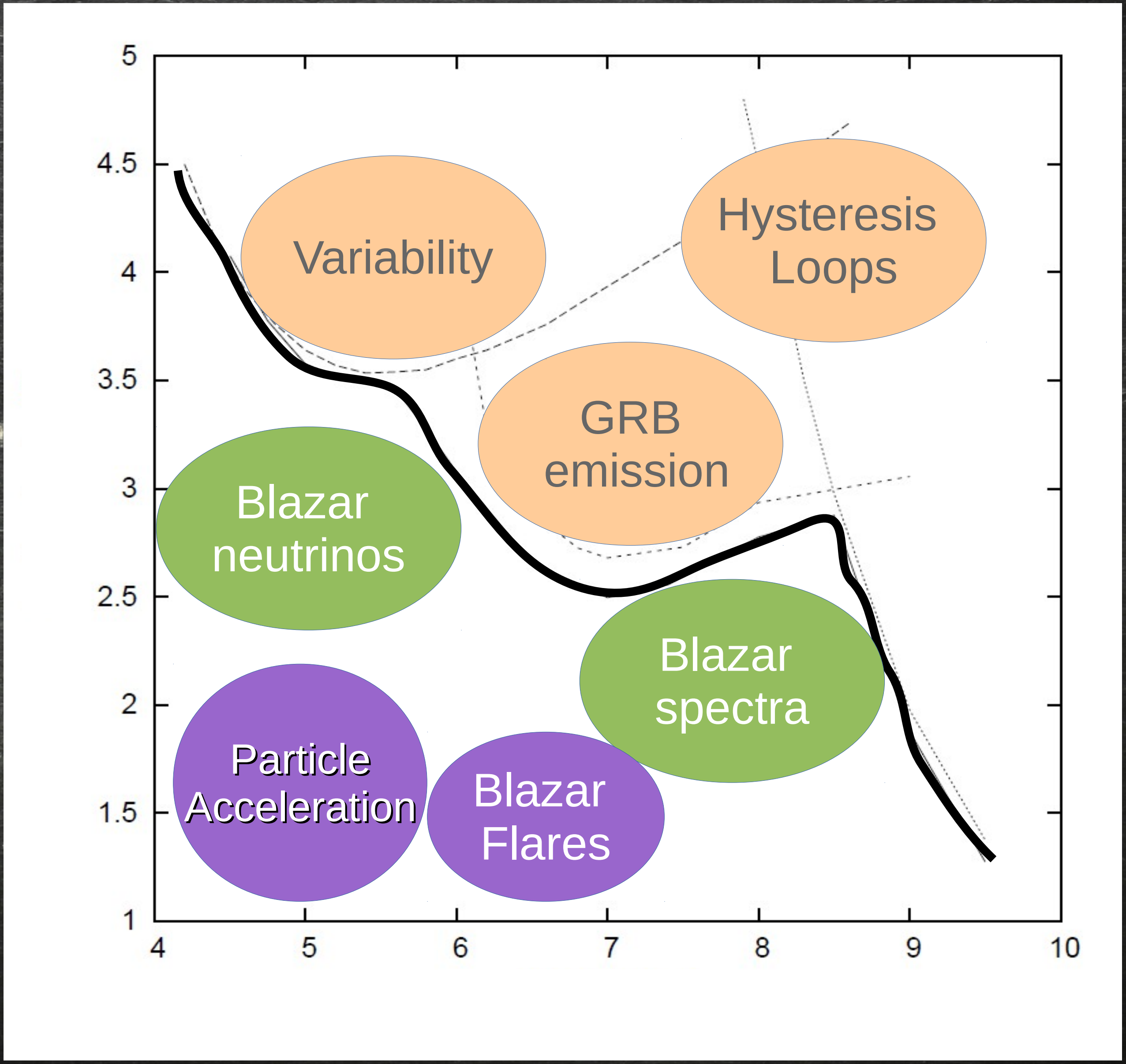
Feedback loops are a way of extracting efficiently energy stored in protons

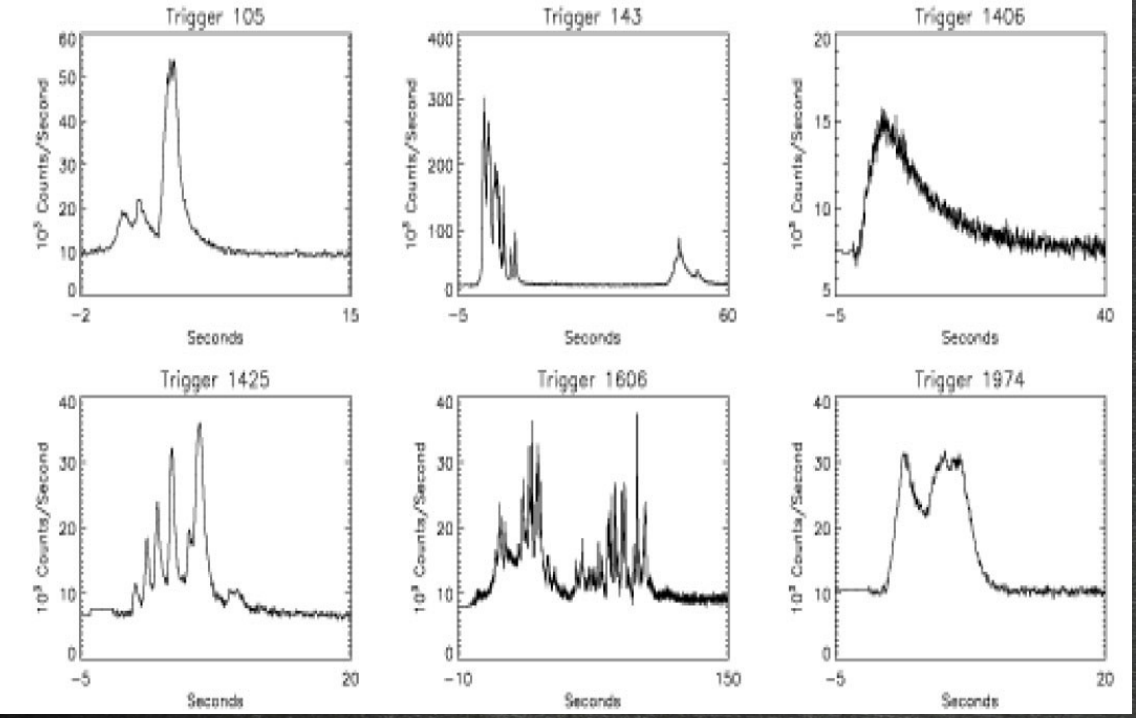
Astrophysical applications



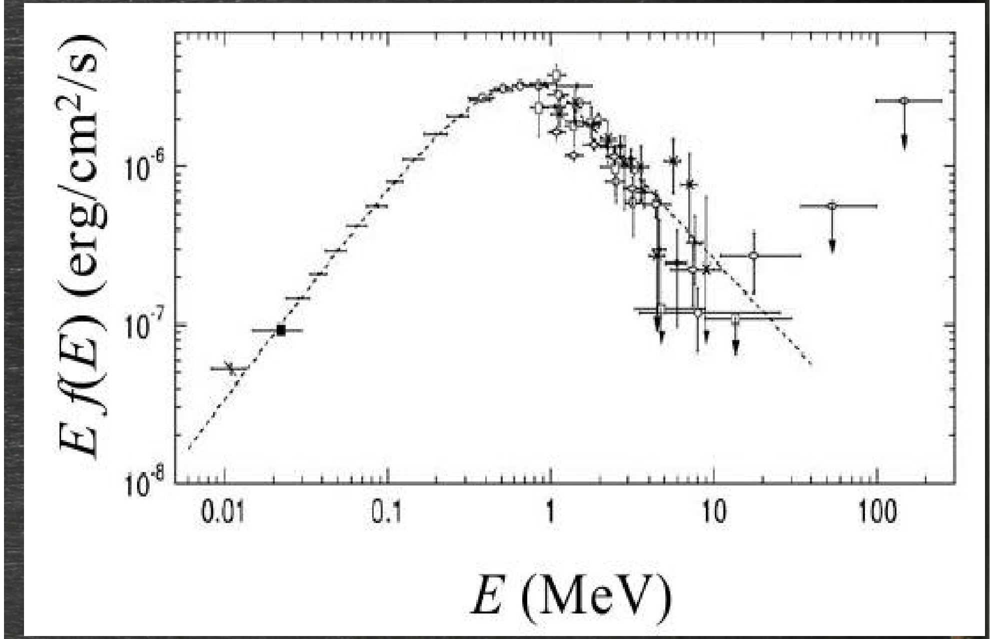
Feedback loops are a way of extracting efficiently energy stored in protons

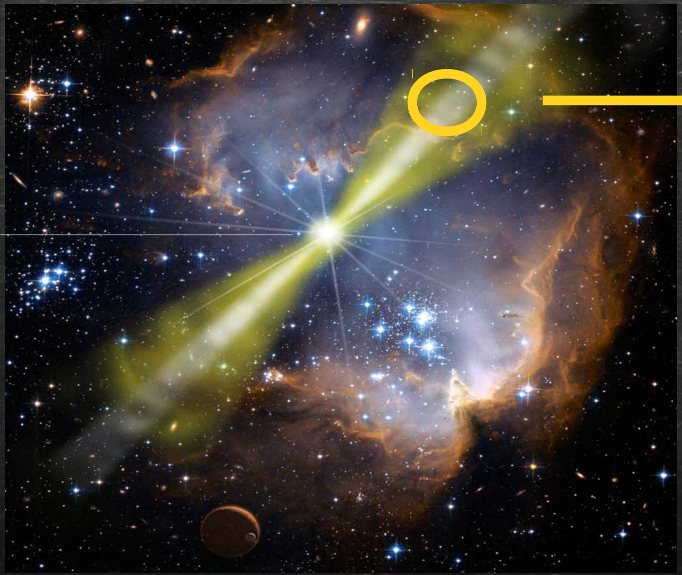
GRB emission

A variety of GRB LC



Typical GRB spectrum



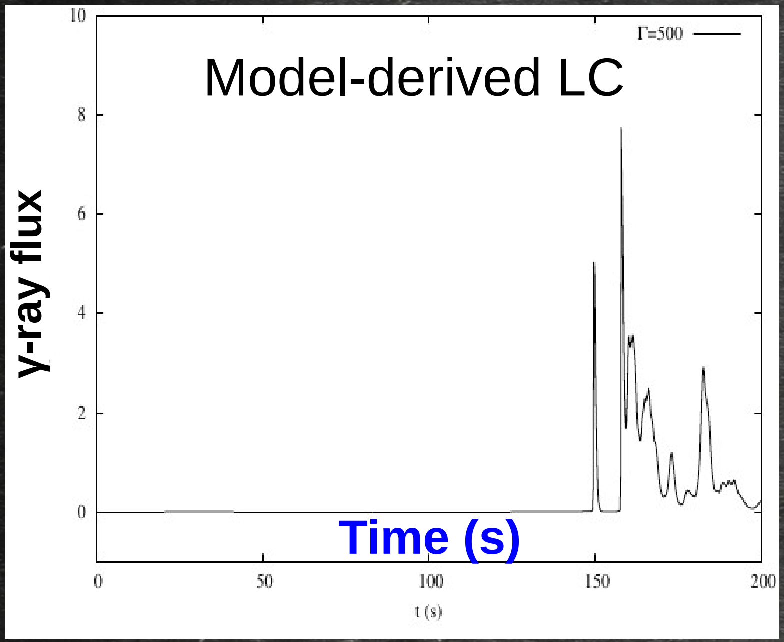


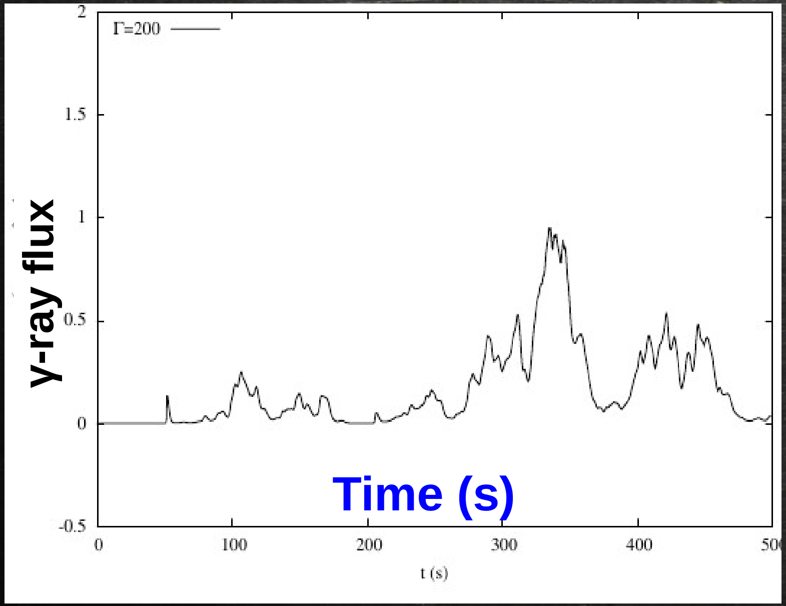
Dissipation region in the GRB jet

Central Engine

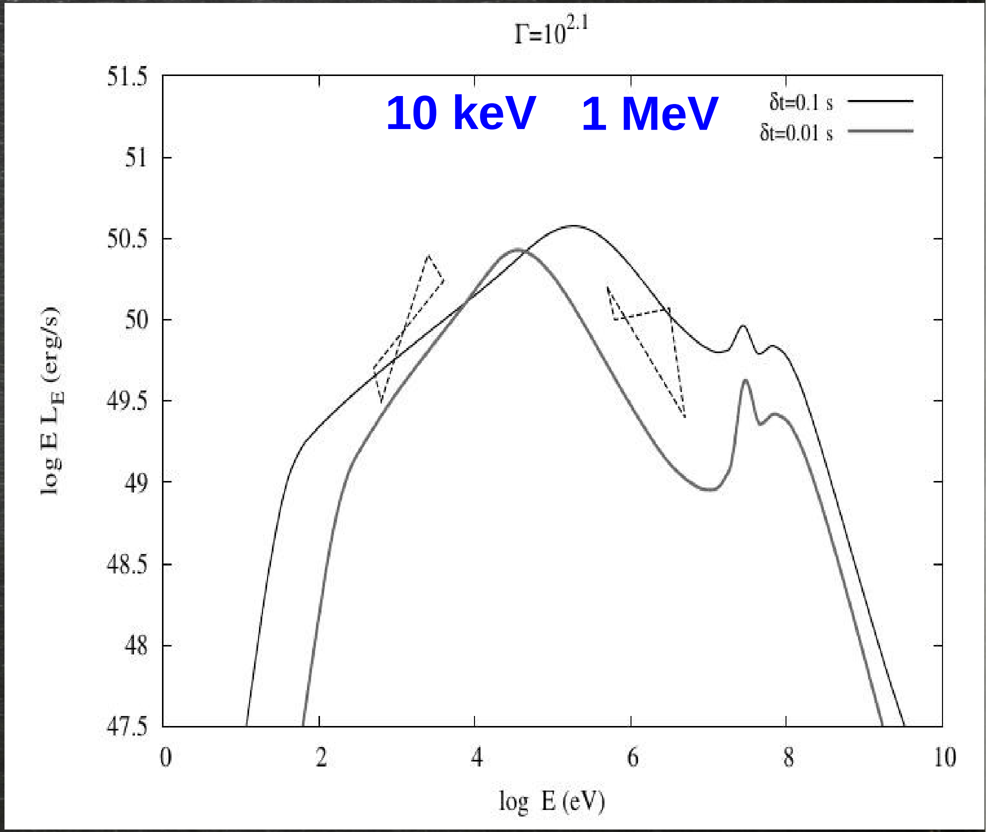
GRB emission

B+p —Super - criticality→ γ ray GRB-like emission !





Model-derived GRB spectrum



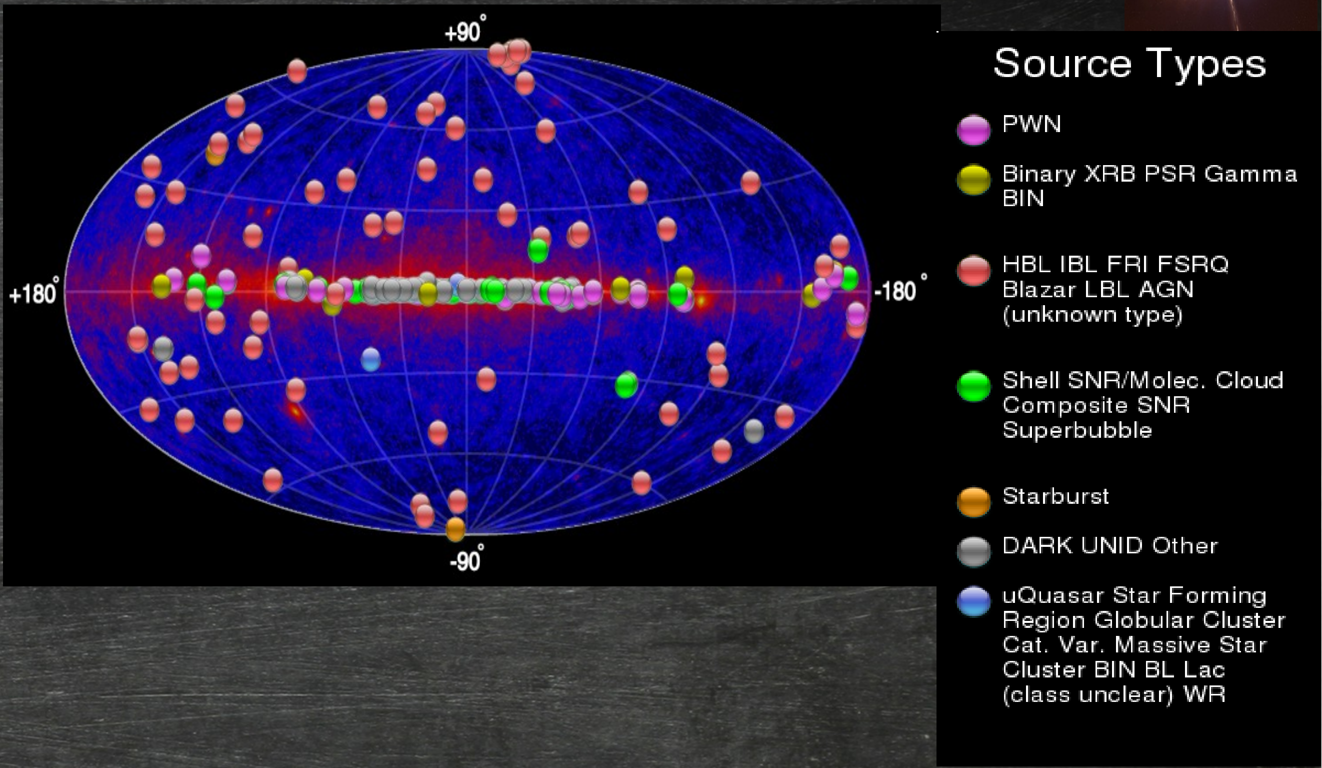
Petropoulou, Vasilopoulos, Mastichiadis, in prep.

Petropoulou et al. 2014, MNRAS, 444

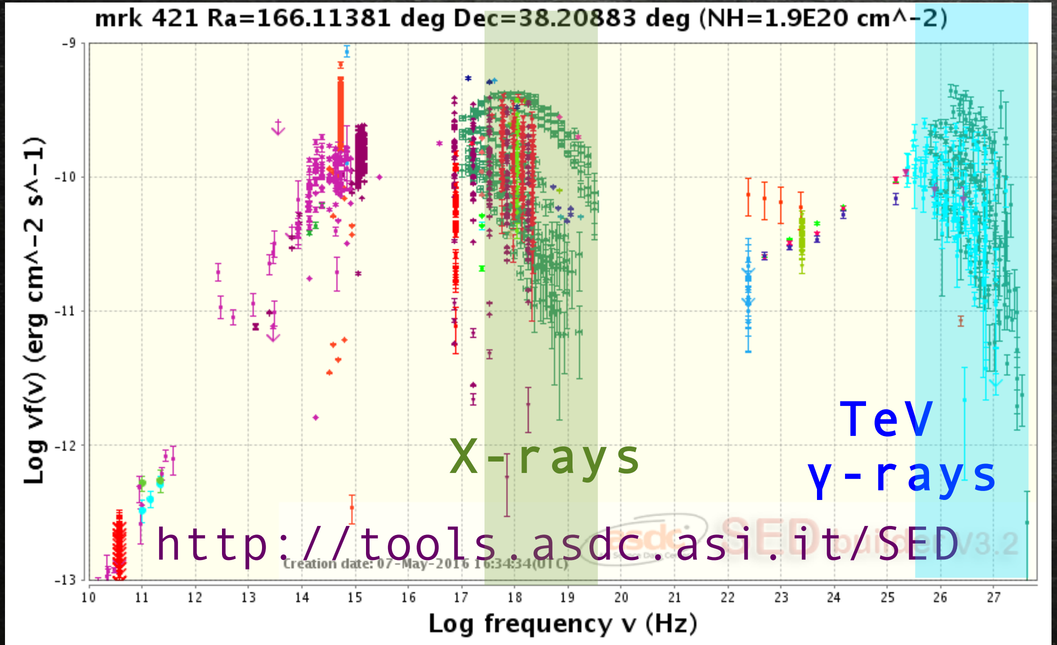
Blazar emission

http://tevcat.uchicago.edu/

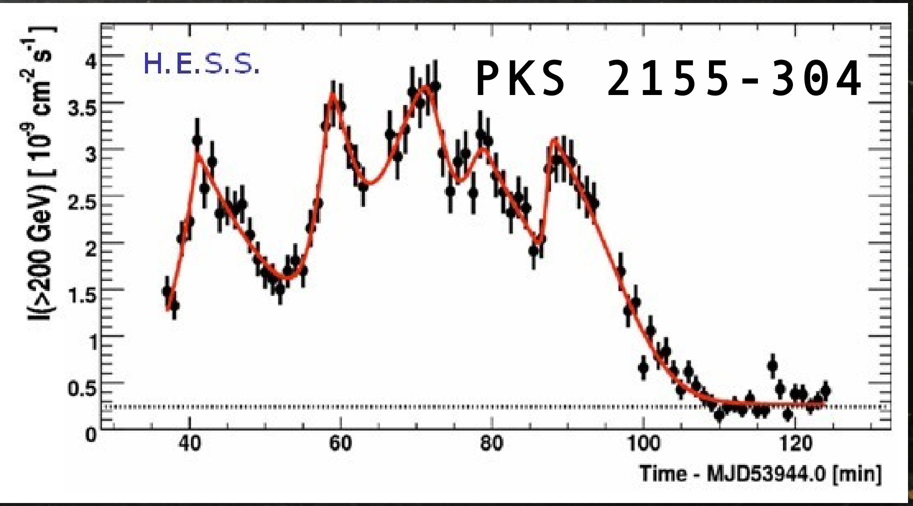
- Radio-loud AGN
  (< 5/% of all AGN)
- Super-luminal motion
- GeV emitters
- TeV emitters



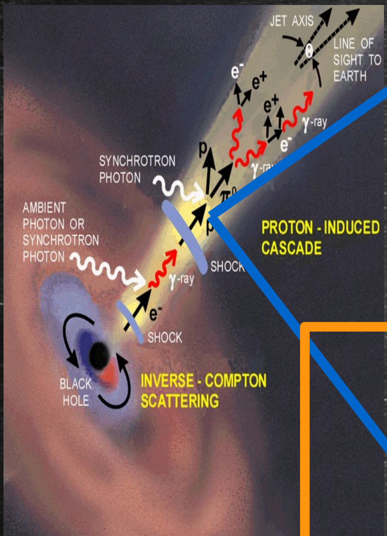
"Double-hump" SED

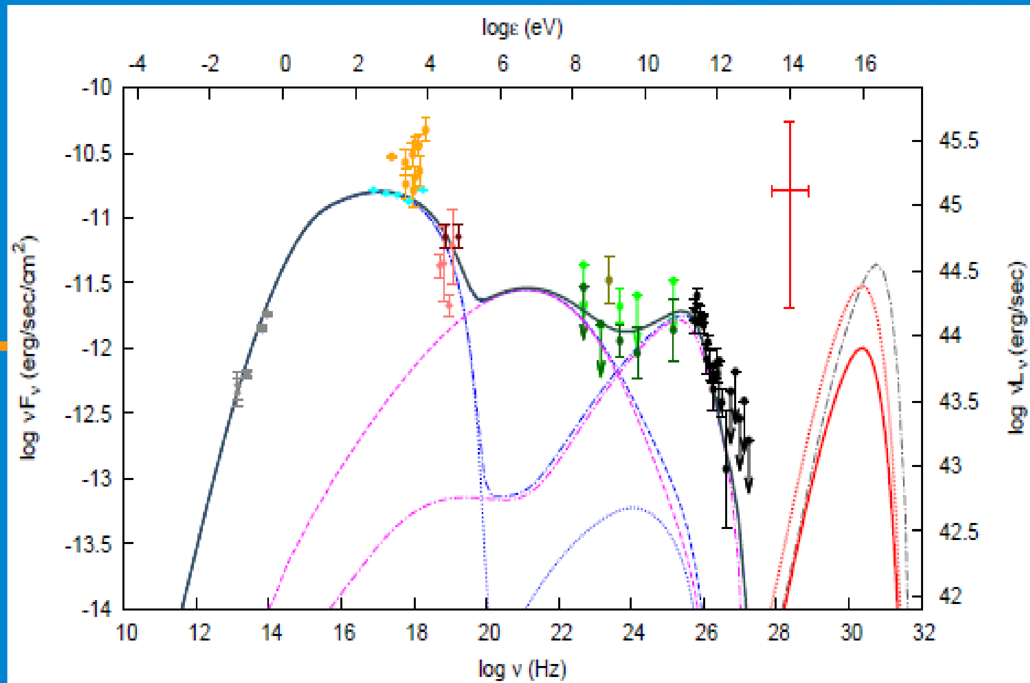


Short variability (min-hr) @ TeV



Blazar emission & neutrinos





Photons

ν

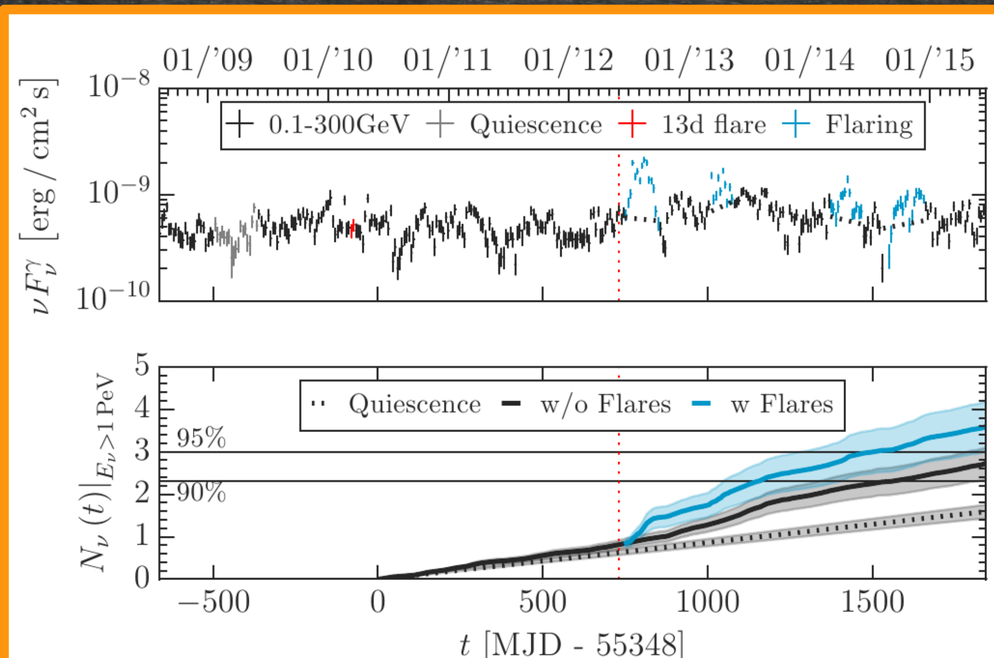
Petropoulou et al. 2015, MNRAS, 448

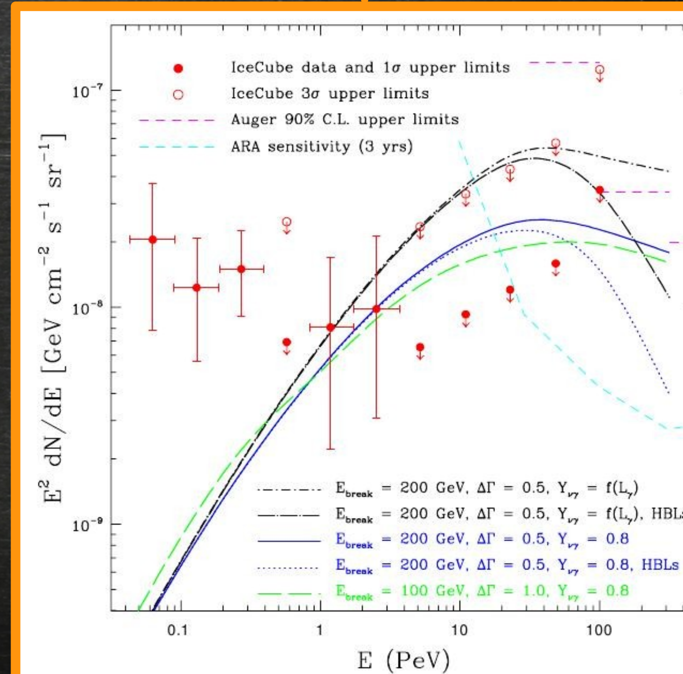
From one blazar

to the whole population

Padovani et al. 2015, MNRAS, 452

γ-ray – ν correlations → # of muon ν

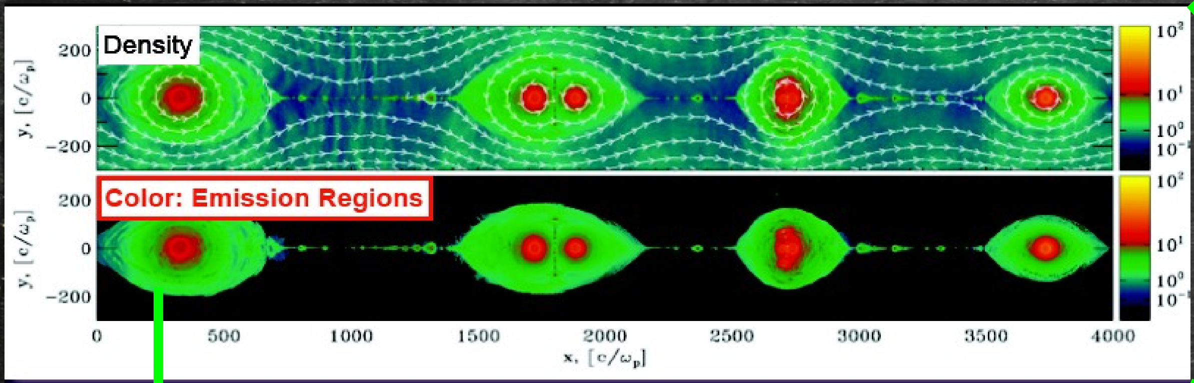




Petropoulou, Coenders, Dimitrakoudis, 2016, APh

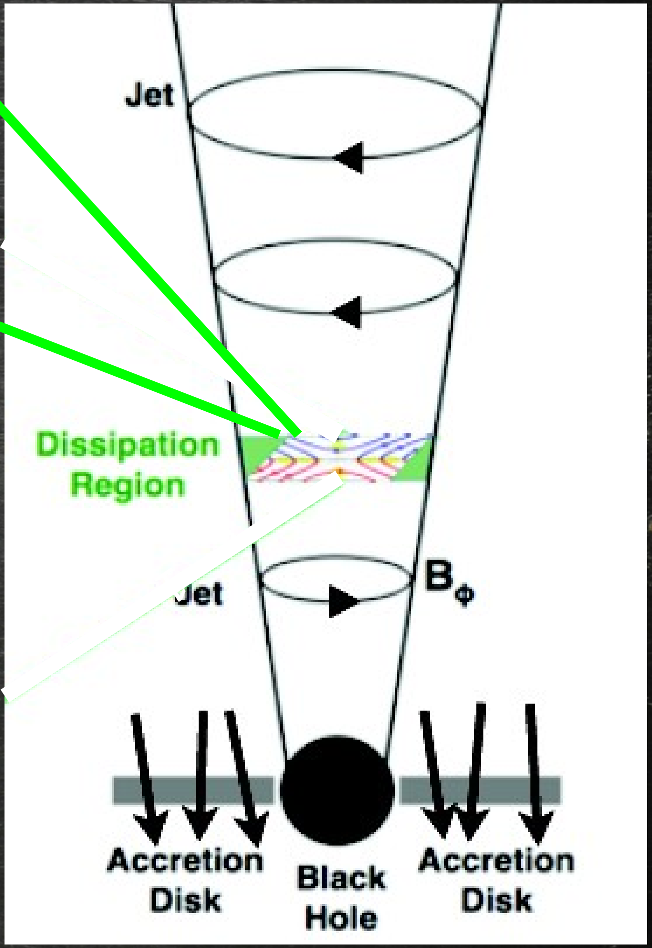
Towards an *ab initio* model for blazars

in collaboration with D. Giannios (Purdue) & L. Sironi (Columbia)



Sironi, Petropoulou & Giannios, 2015, MNRAS

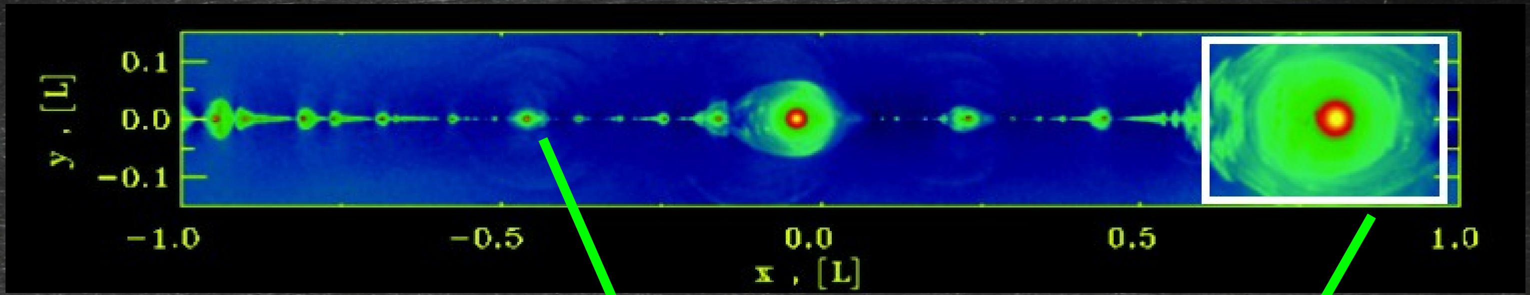
Alternating magnetic field lines → Reconnection



Giannios 2006, Giannios & Spruit 2007, Mc Kinney & Uzdensky 2012, Parfrey, Giannios & Beloborodov 2015

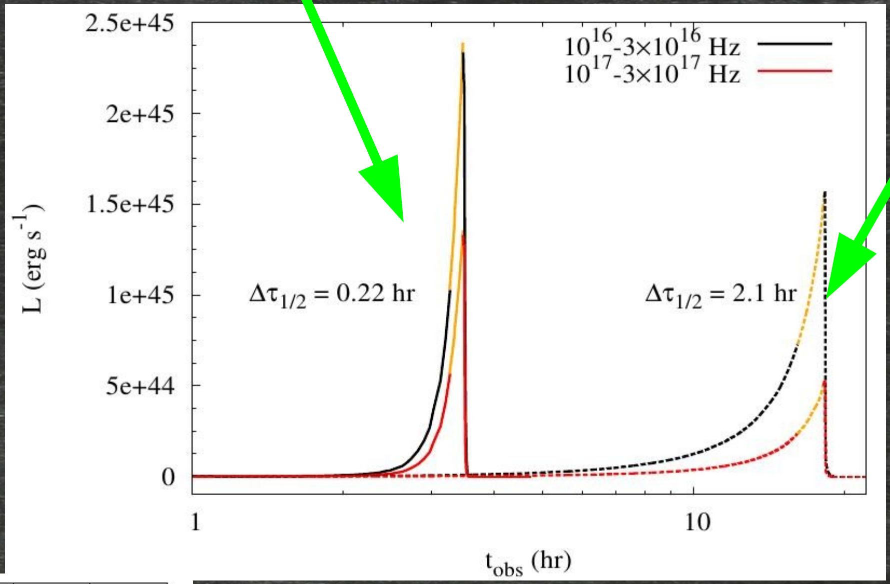
- **Plasmoids** contain B + energetic particles in equipartition
- Proton & Electron power-law distributions
- Plasmoids form, accelerate and grow through mergers in the layer
- *Large* plasmoids exit the layer with *non-relativistic* speeds
- *Small* plasmoids exit the layer with *relativistic* speeds

Light curves & spectra

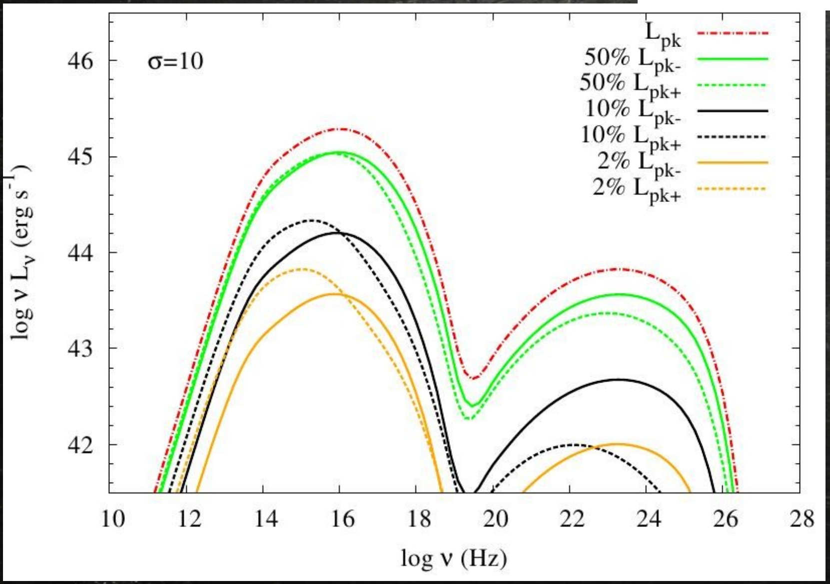


Small & Fast

Large & Slow

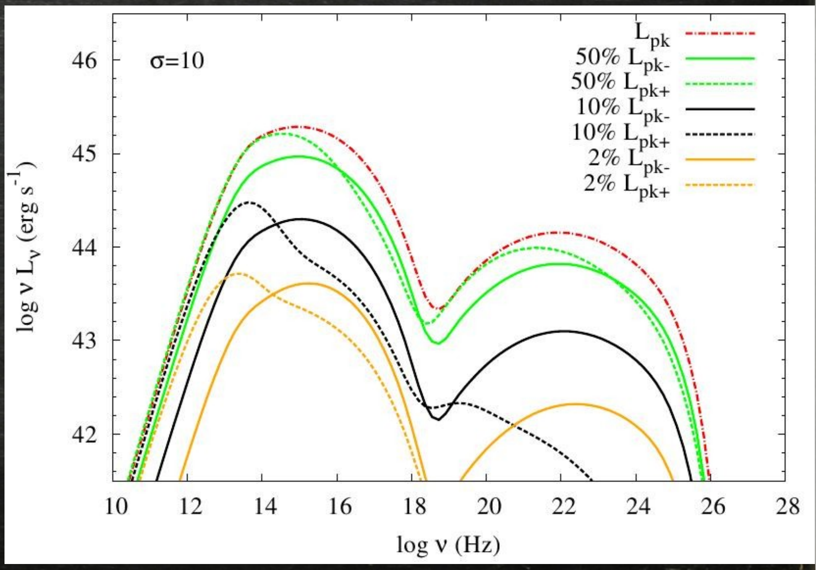


Model Spectrum



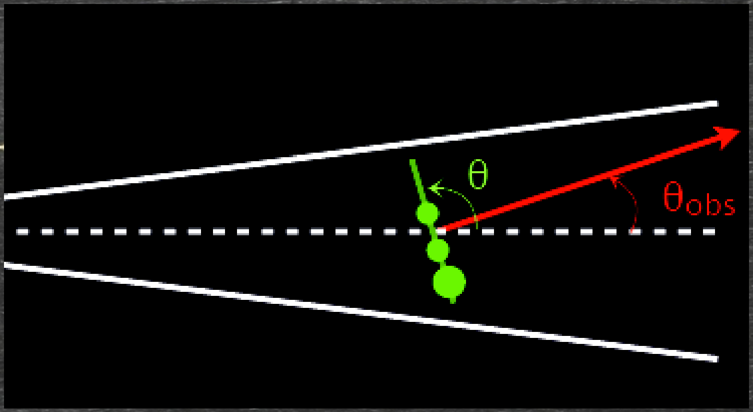
Petropoulou, Giannios & Sironi 2016, submitted to MNRAS

Model Spectrum



Orientation of the layer

Plasmoids move relative to the bulk flow of the jet → Doppler boosting

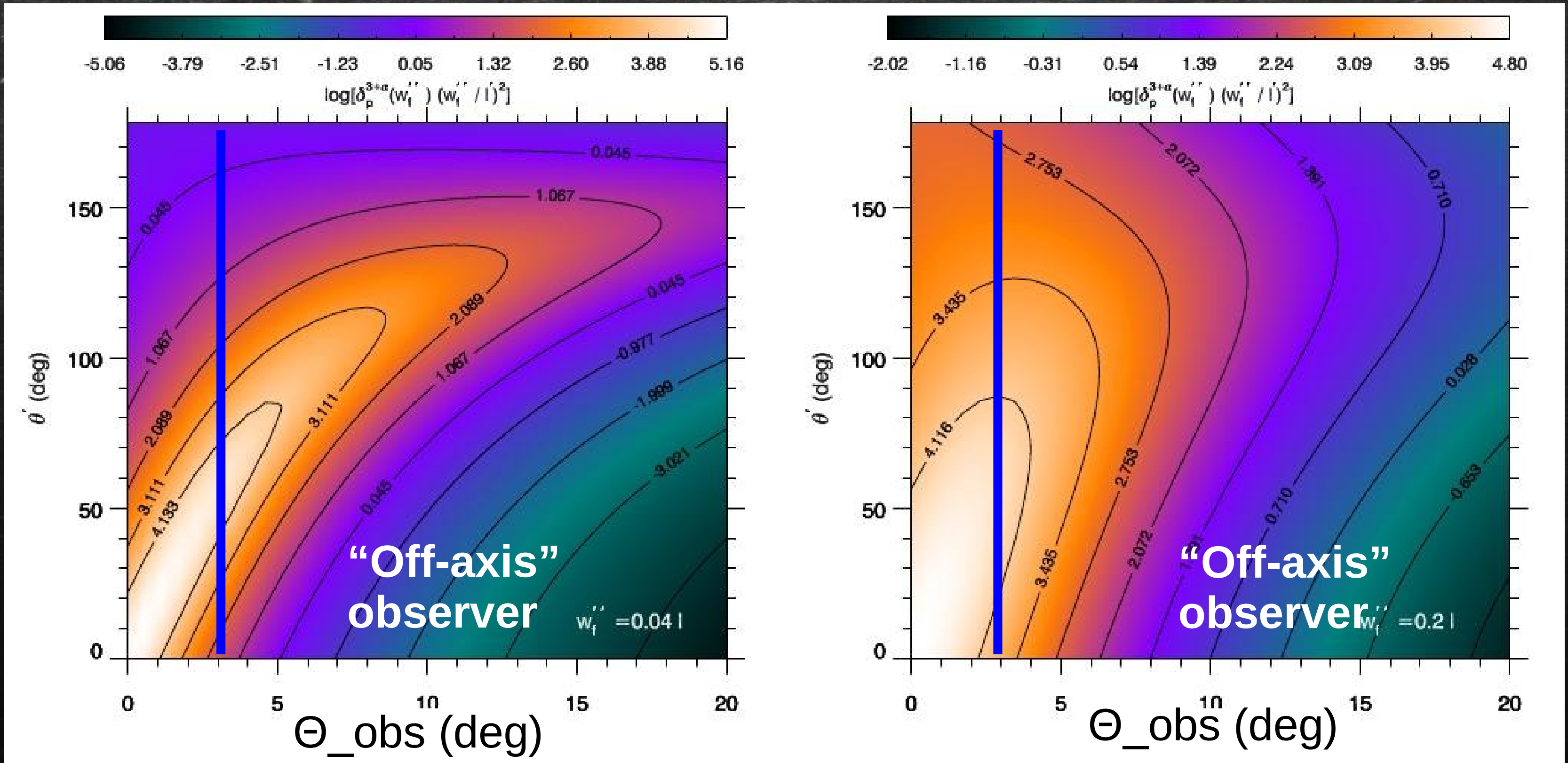


Small & Fast

Peak flare luminosity

Large & Slow

Θ' (deg)



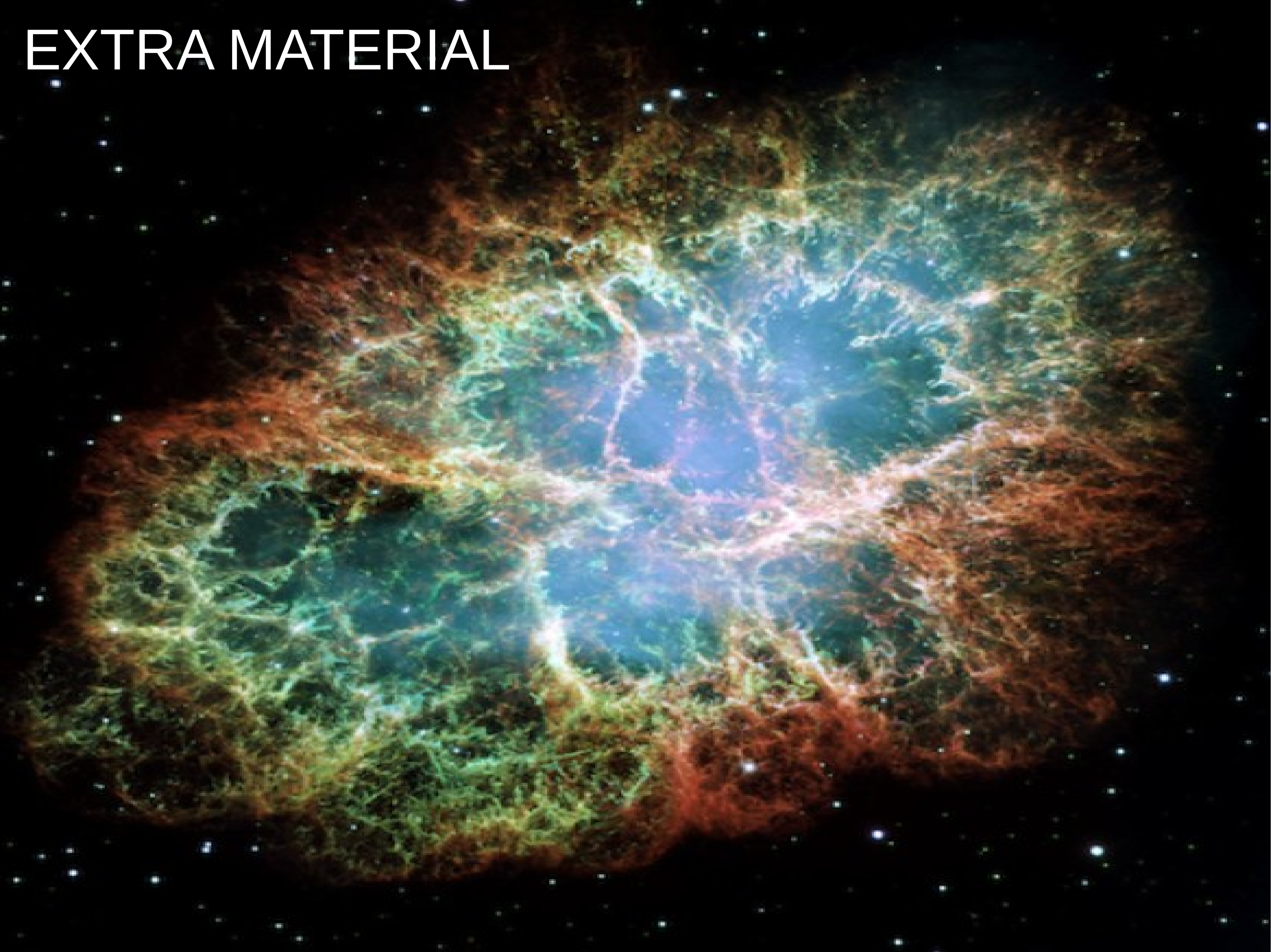
Θ' (deg)

Summary

- Lepto-hadronic plasmas are very common among non-thermal emitting sources.
- The interplay between protons, leptons and photons can be described by a set of non-linear coupled equations.
- It is the first time that a lepto-hadronic system is treated as a dynamical system.
- Understanding the radiative processes in lepto-hadronic plasmas is crucial for modeling of the emission observed from different sources (blazars, GRBs, γ-ray binaries…)
- Many astrophysical applications including photon & neutrino emission, energy dissipation in jets and particle acceleration

Thank you

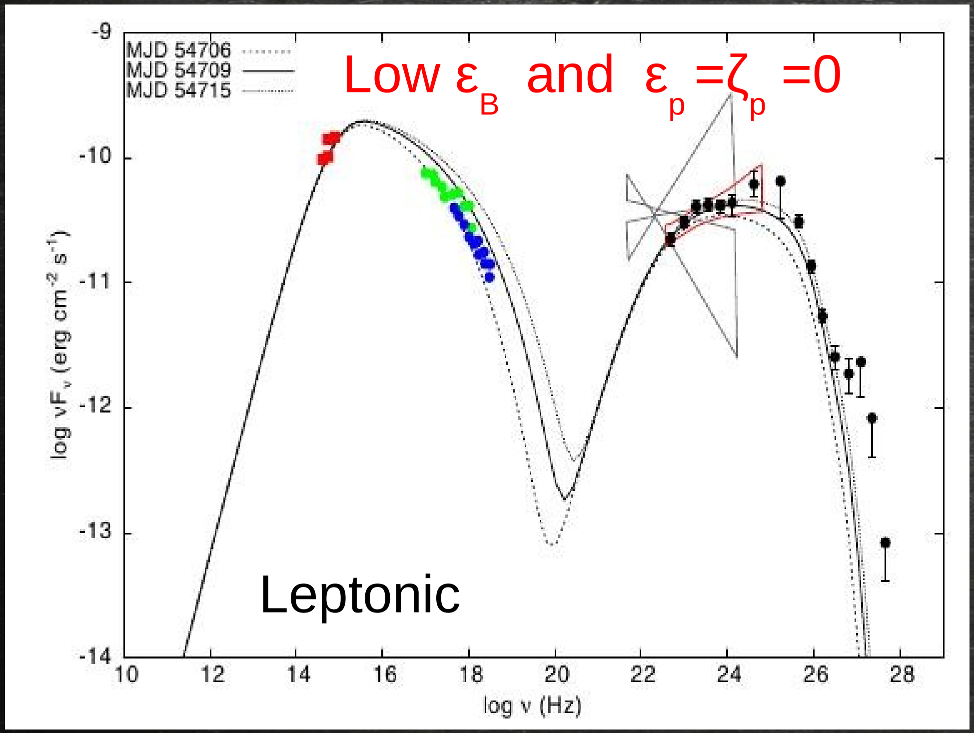
EXTRA MATERIAL

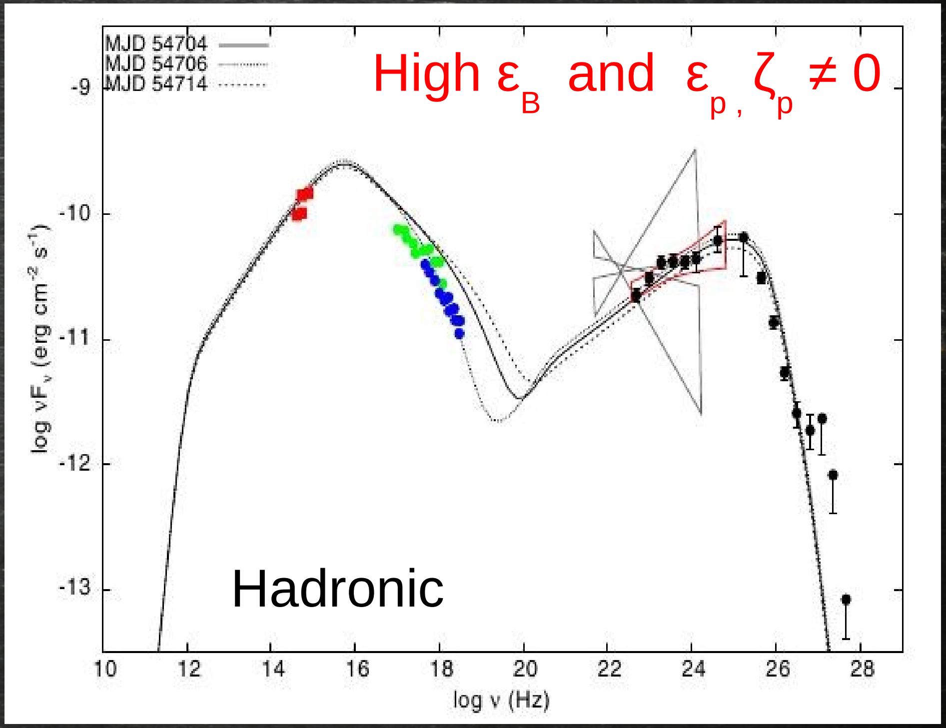


Parameterizing our ignorance

- ζ_e (ζ_p) : fraction of electrons (protons) in the non-thermal tail of the distribution
- ε_e (ε_p) : fraction of jet flow energy in relativistic electrons (protons)
- ε_B : fraction of jet flow energy in magnetic fields

PKS 2155-304

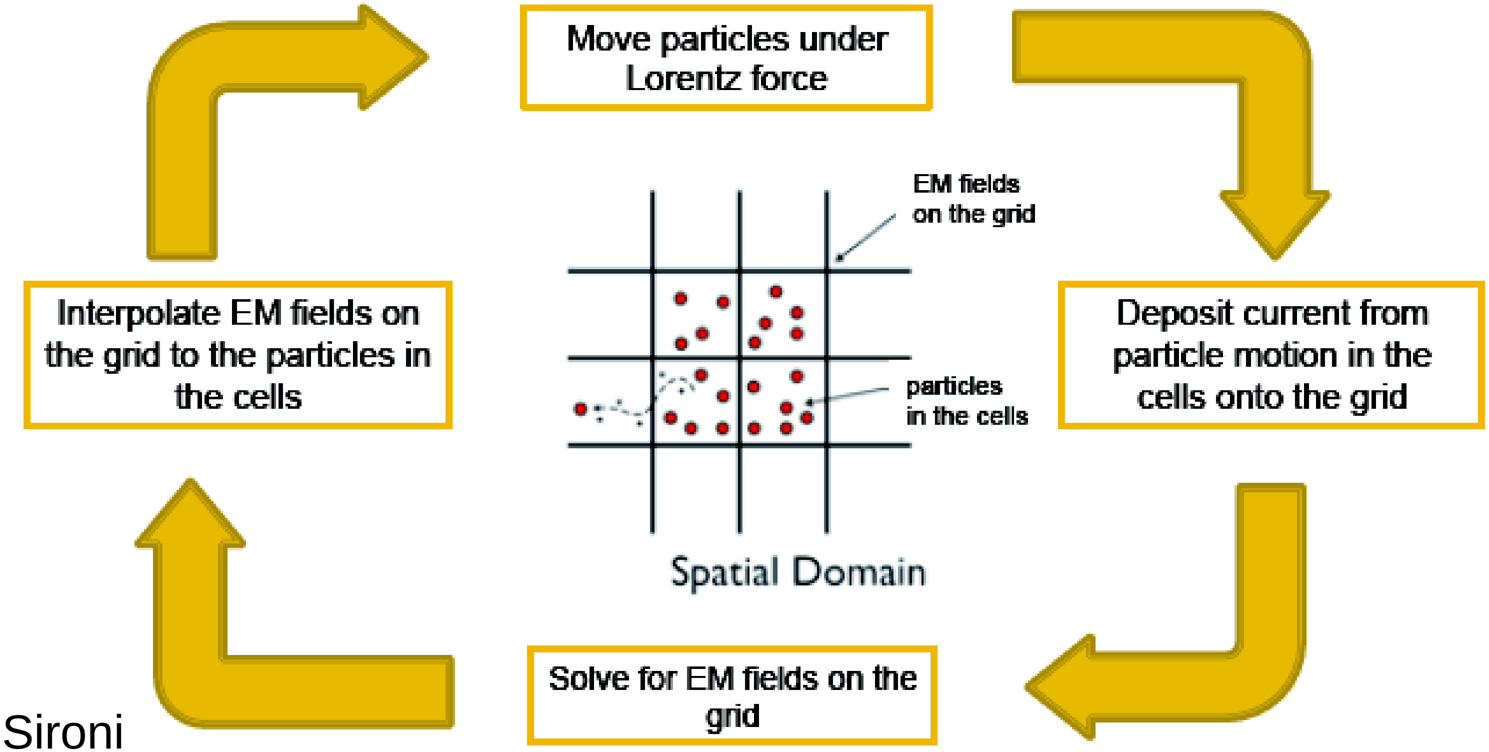




Petropoulou, M. , 2014, A&A

Which model materializes in blazars?

PIC simulations

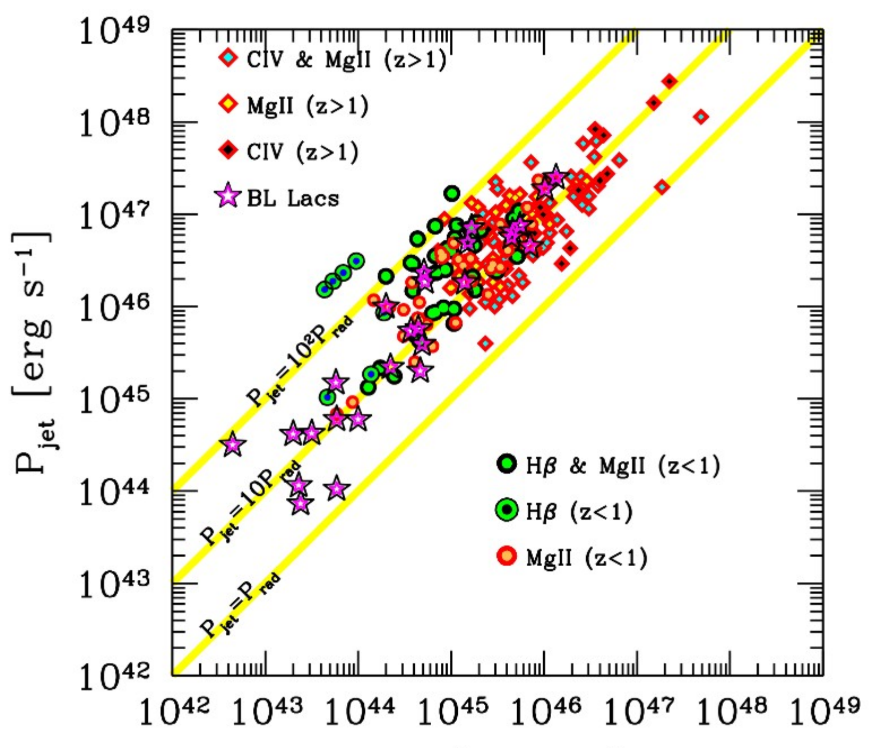


Credit: L. Sironi

- ✓ No approximations – full plasma physics of ions and electrons
- ✗ Tiny length scales need to be resolved → Large & expensive simulations with limited time coverage

Implications for blazar emission

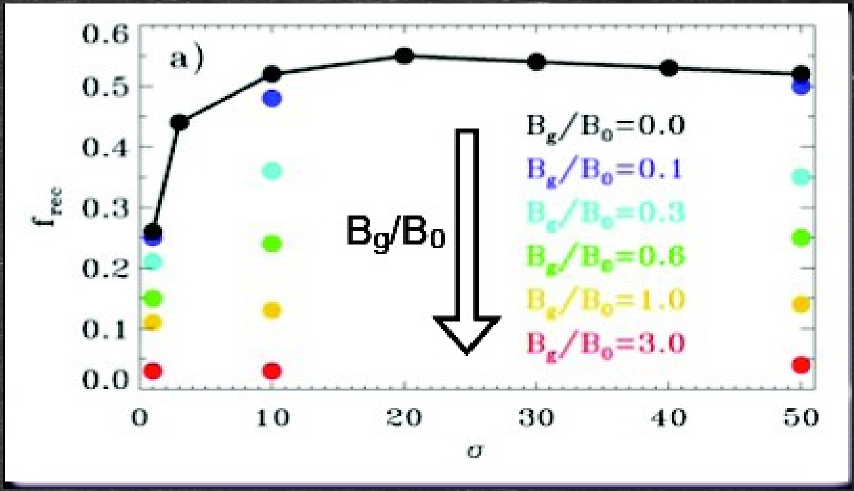
Relativistic reconnection is efficient



Ghisellini et al. 2014

$$f_{rec} \equiv \frac{\sum_i \int_{V_i} U_e dV_i}{\sum_i \int_{V_i} (e + \rho c^2 + U_B)\, dV_i}$$

Efficiency



Blazar phenomenology:

- Blazars are efficient emitters.
- 10% jet power = radiation power

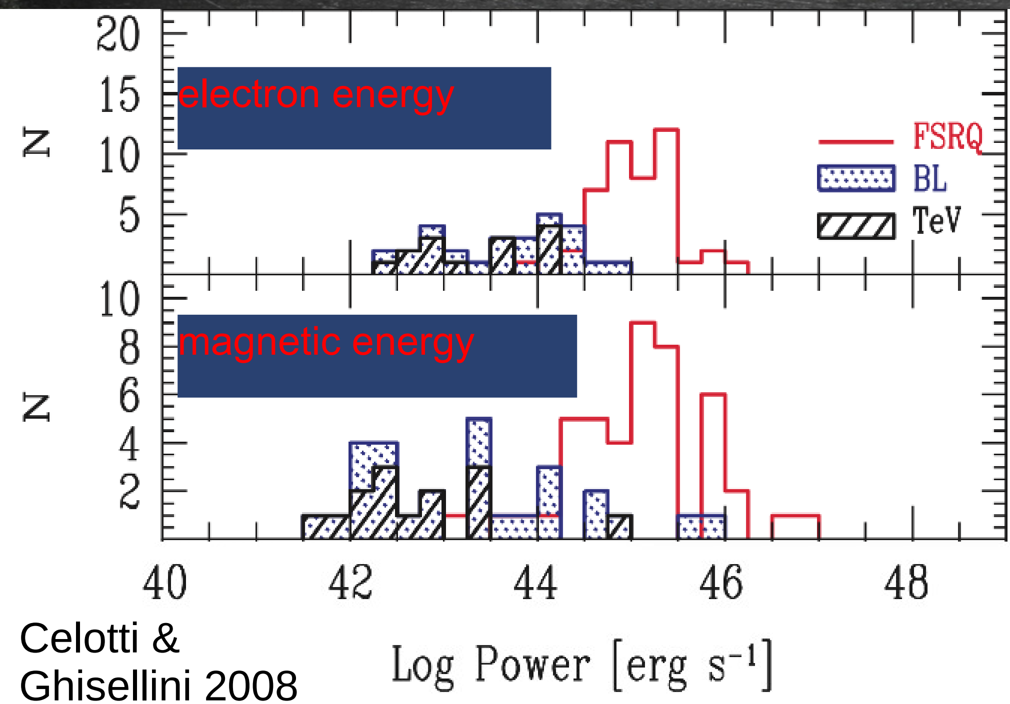
Relativistic reconnection:

- it transfers ~ 50% of the flow energy (electron-positron plasmas) or ~ 25% (electron-proton) to the emitting particles

Sironi, Petropoulou & Giannios, 2015, MNRAS

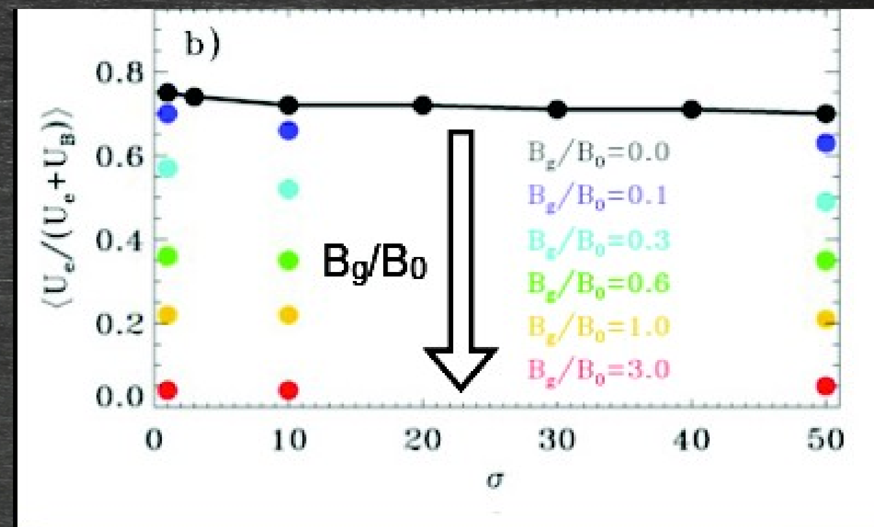
Implications for blazar emission

Equipartition of particles and fields



Celotti & Ghisellini 2008

$$\left\langle \frac{U_e}{U_e + U_B} \right\rangle \equiv \frac{\sum_i \int_{V_i} U_e \frac{U_e}{U_e + U_B} dV_i}{\sum_i \int_{V_i} U_e dV_i}$$



Blazar phenomenology:

- Rough equipartition between radiating particles and magnetic fields

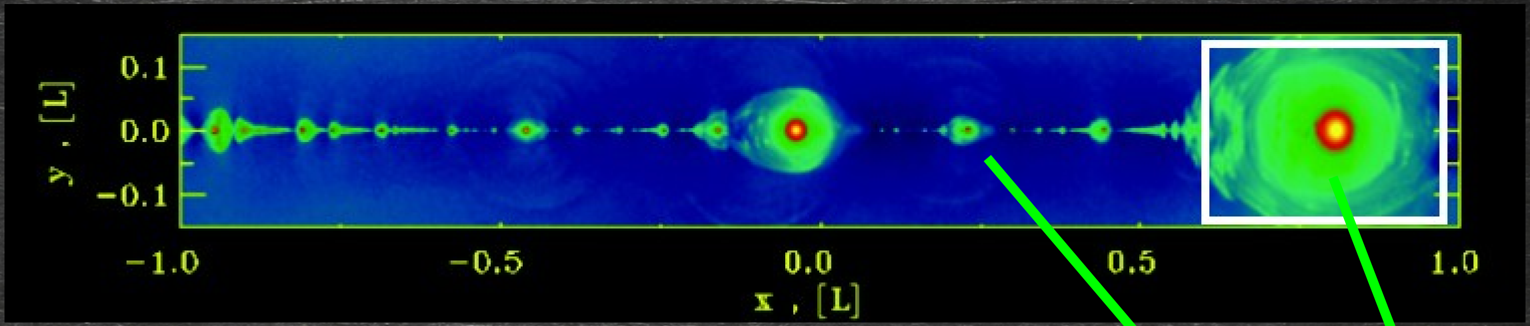
Relativistic reconnection:

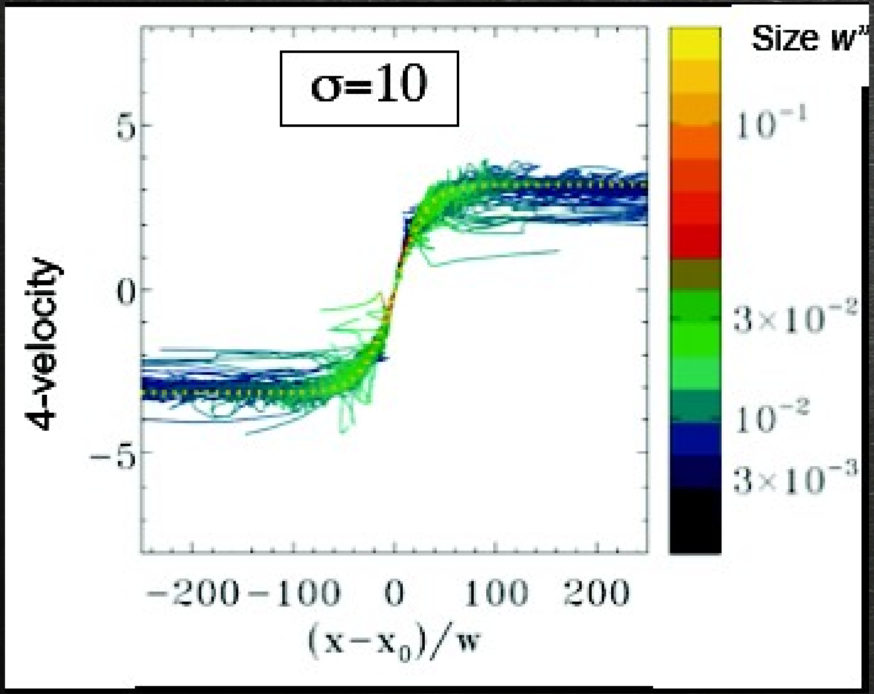
- In the magnetic islands it naturally results in rough energy equipartition between particles and magnetic field
- For strong guide fields then UB >> Ue in the plasmoids

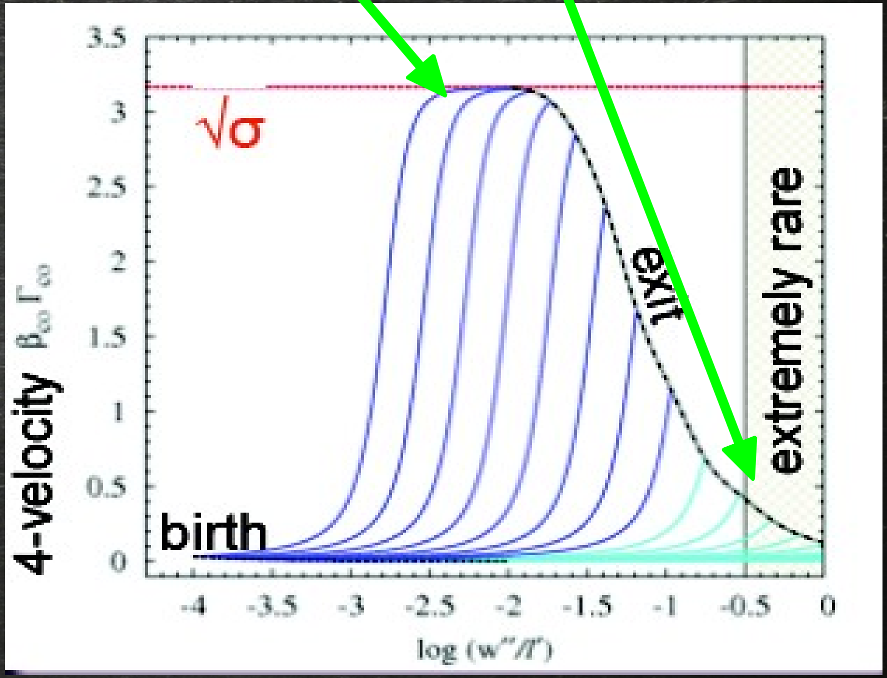
Sironi, Petropoulou & Giannios, 2015, MNRAS

Small & Fast vs. Large and Slow

Credit: L.Sironi





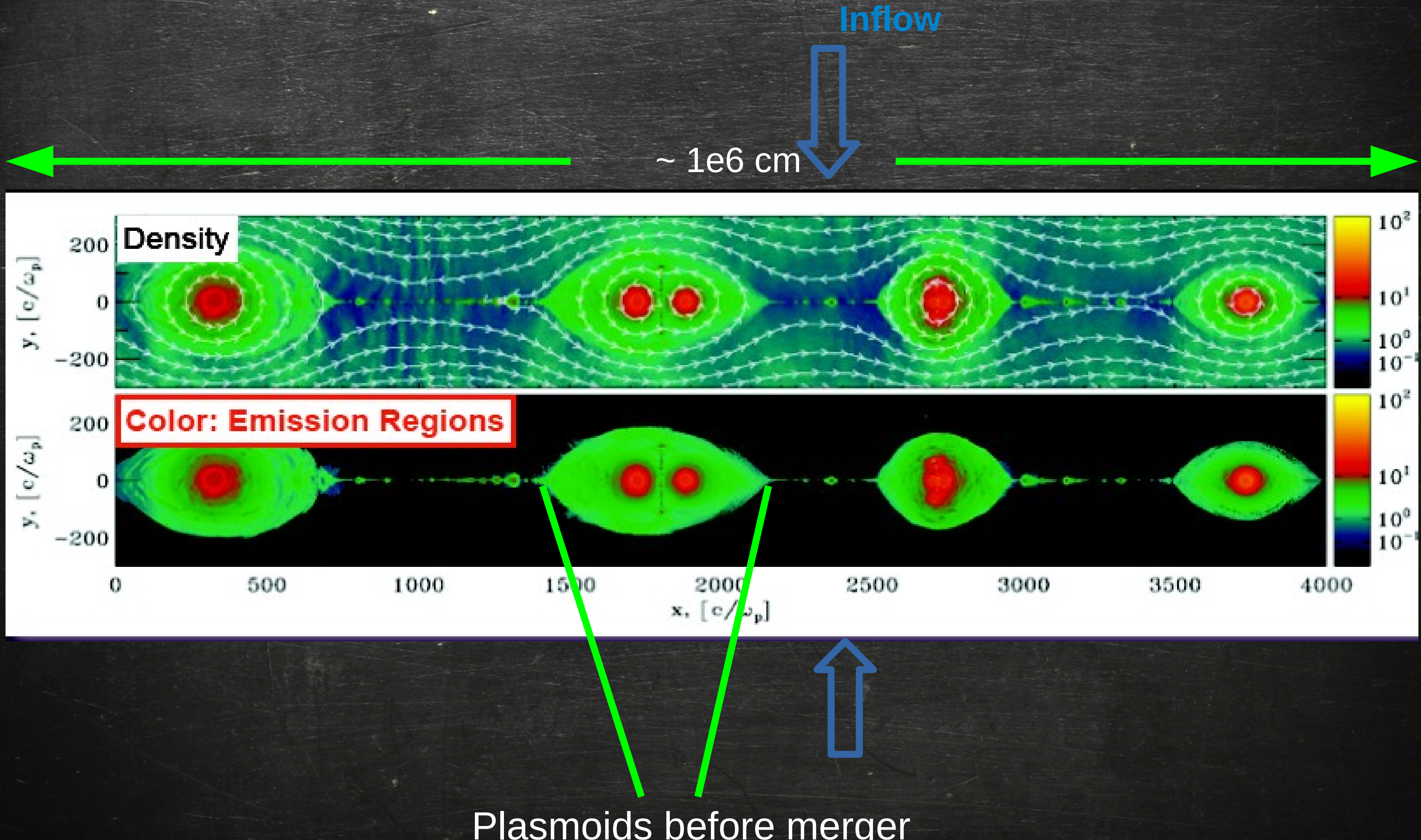


Sironi, Giannios & Petropoulou, 2016, submitted to MNRAS

Petropoulou, Giannios & Sironi 2016, submitted to MNRAS

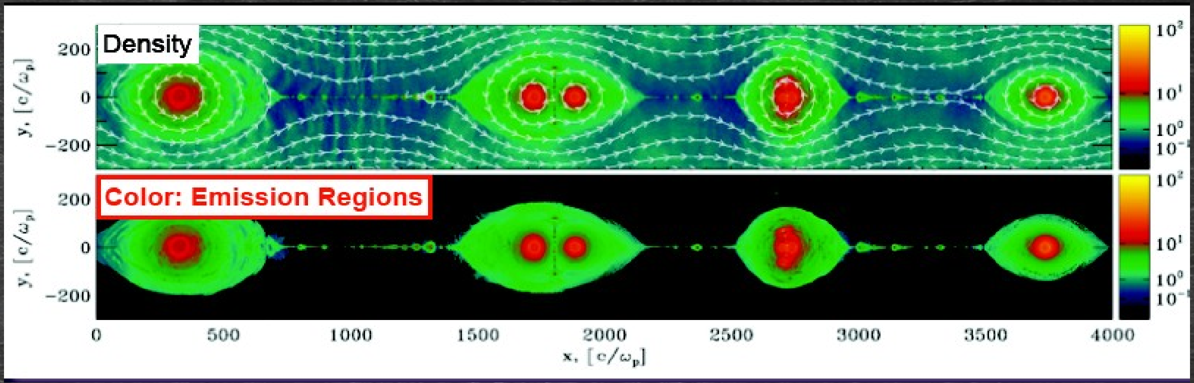
Plasmoid-dominated reconnection

Zenitani & Hoshino 2001, Loureiro+2007, Bhattarjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014; 2015, Sironi & Spitkovsky 2014, Werner+2016



Sironi, Petropoulou & Giannios, 2015, MNRAS

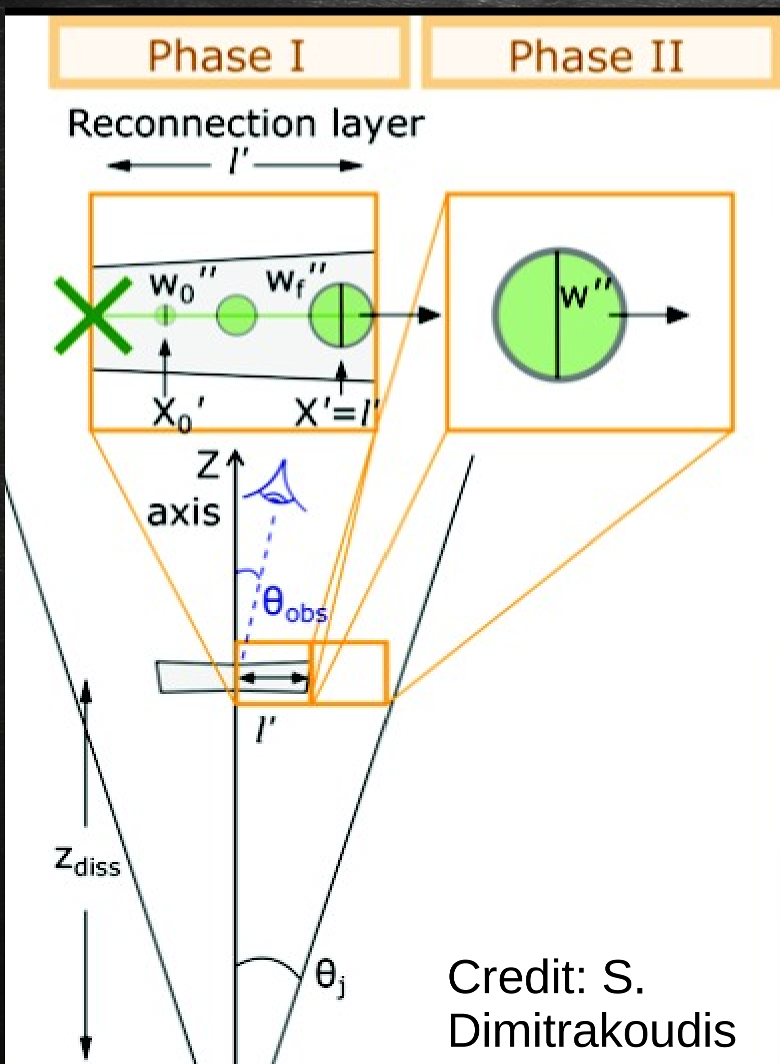
Towards an *ab initio* model for blazars



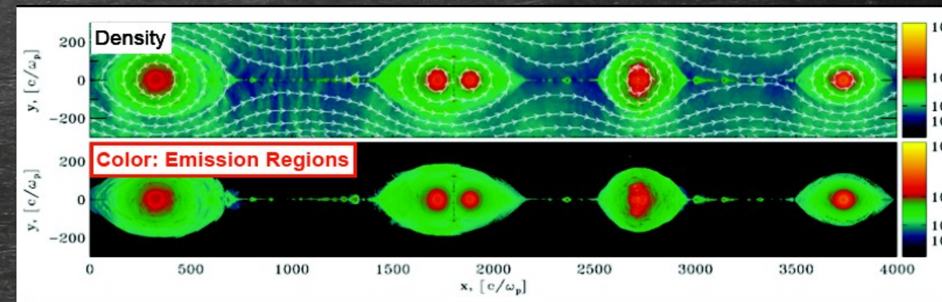
Questions to be addressed:

- Are the plasmoids the emitting regions of blazars?
- What is the spectrum & LC from a plasmoid?
- What is the emission from all plasmoids in the layer?
- What are the flare statistics of the model?
- Are UHECRs accelerated in a layer?
- What is the expected neutrino signal?

The “blobs” of blazar jets



Credit: S. Dimitrakoudis



Phase I (benchmarked with PIC): plasmoids grow and accelerate in the layer, particle & magnetic energy density stay constant, isotropic particle distribution

Phase II: plasmoids leave the layer and expand in the bulk flow of the jet, particle & magnetic energy densities decay

Petropoulou, Giannios & Sironi 2016, submitted to MNRAS

When magnetic reconnection is relativistic?

$$\sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \gg 1$$

$$v_{out} \sim v_A \sim c\sqrt{\frac{\sigma}{1+\sigma}}$$