High-Energy Polarization of Blazars

Current Status and Model Predictions

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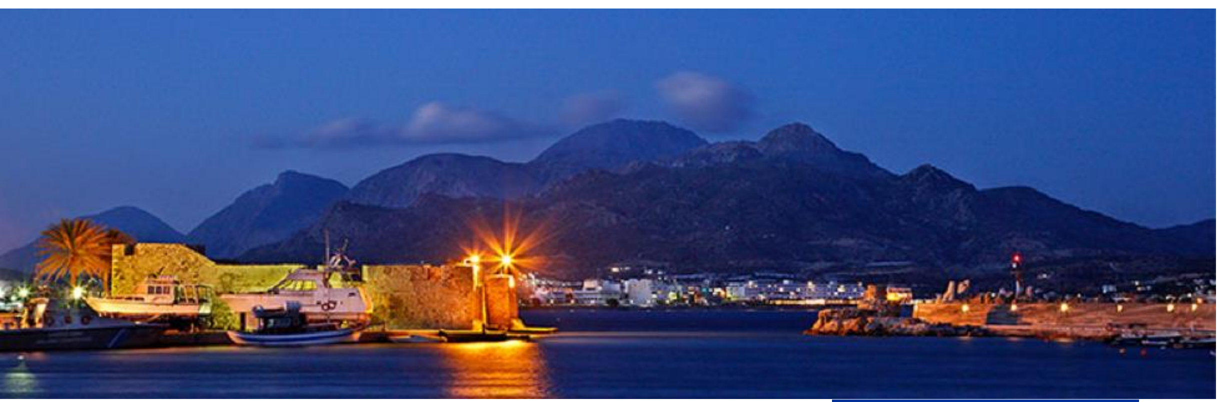

Thanks to Hui Li (LANL), Markus Böttcher (North-West University), Xuhui Chen (DESY), Chris Diltz (Ohio University), Greg Taylor (University of New Mexico), Wei Deng (University of Nevada), Fan Guo (LANL)

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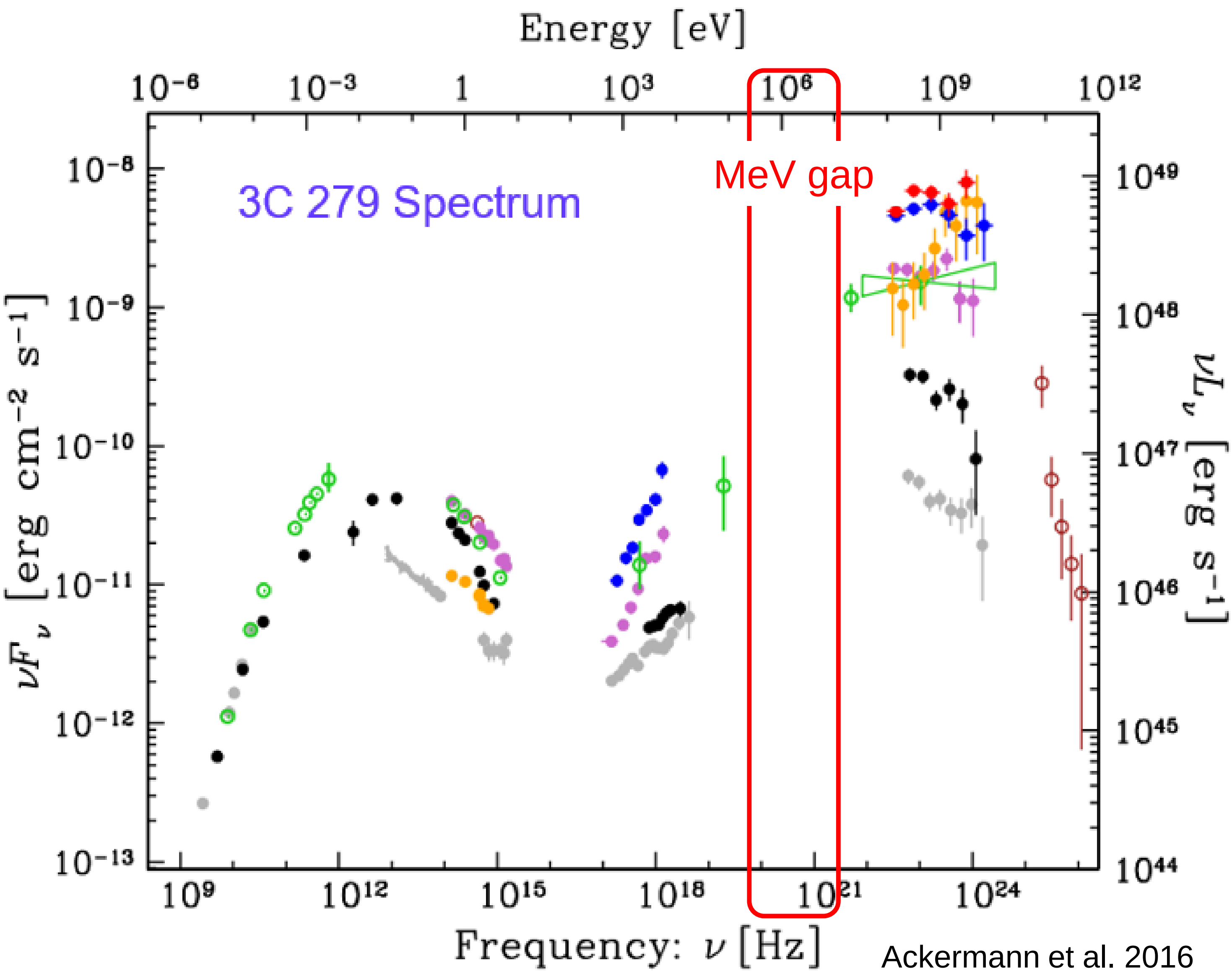
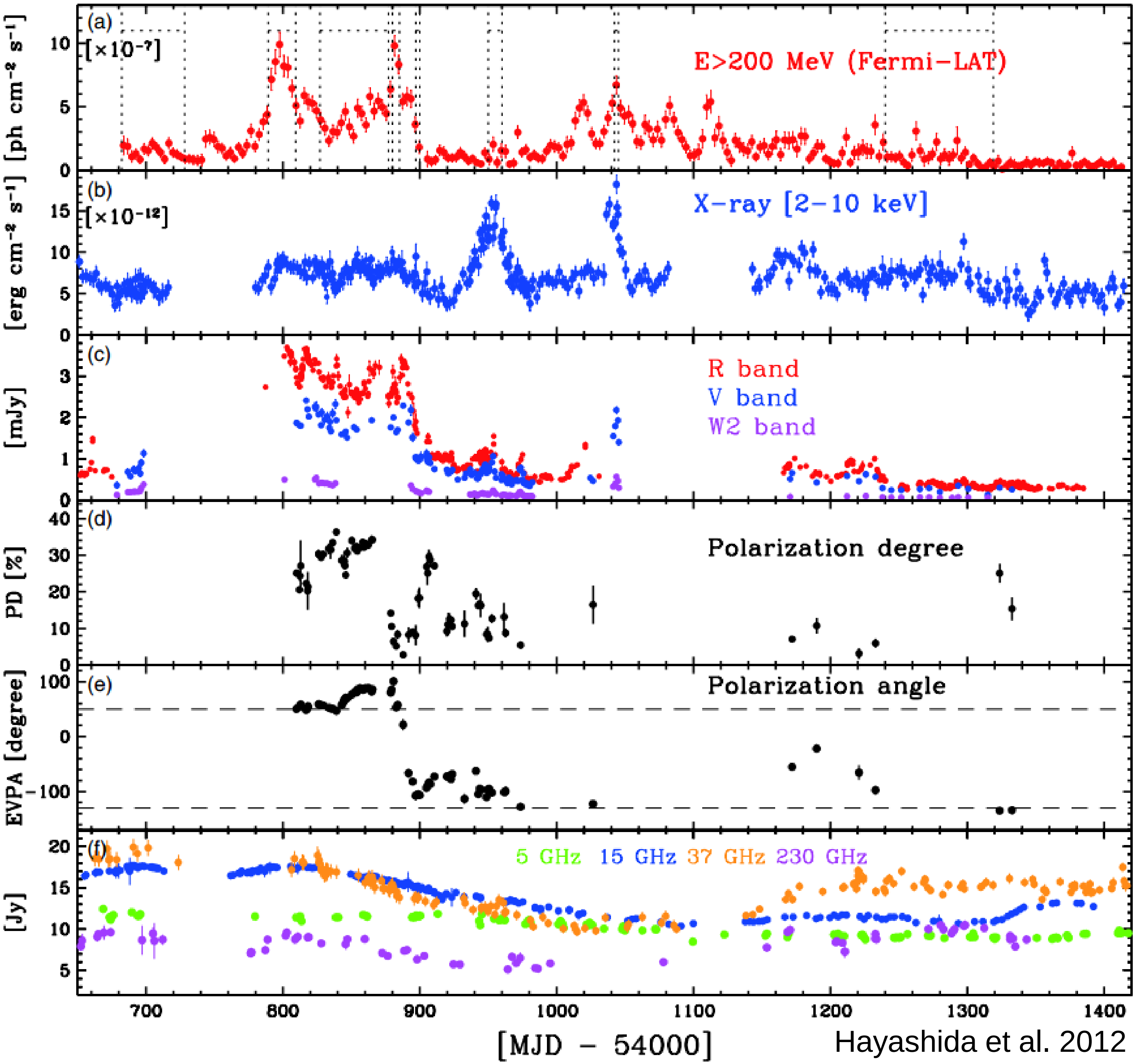
Frequency-Dependence: Blazar Spectrum



Ackermann et al. 2016

Nearly continuous data coverage from radio up to TeV γ-ray

Time-Dependence: Variability & Polarization



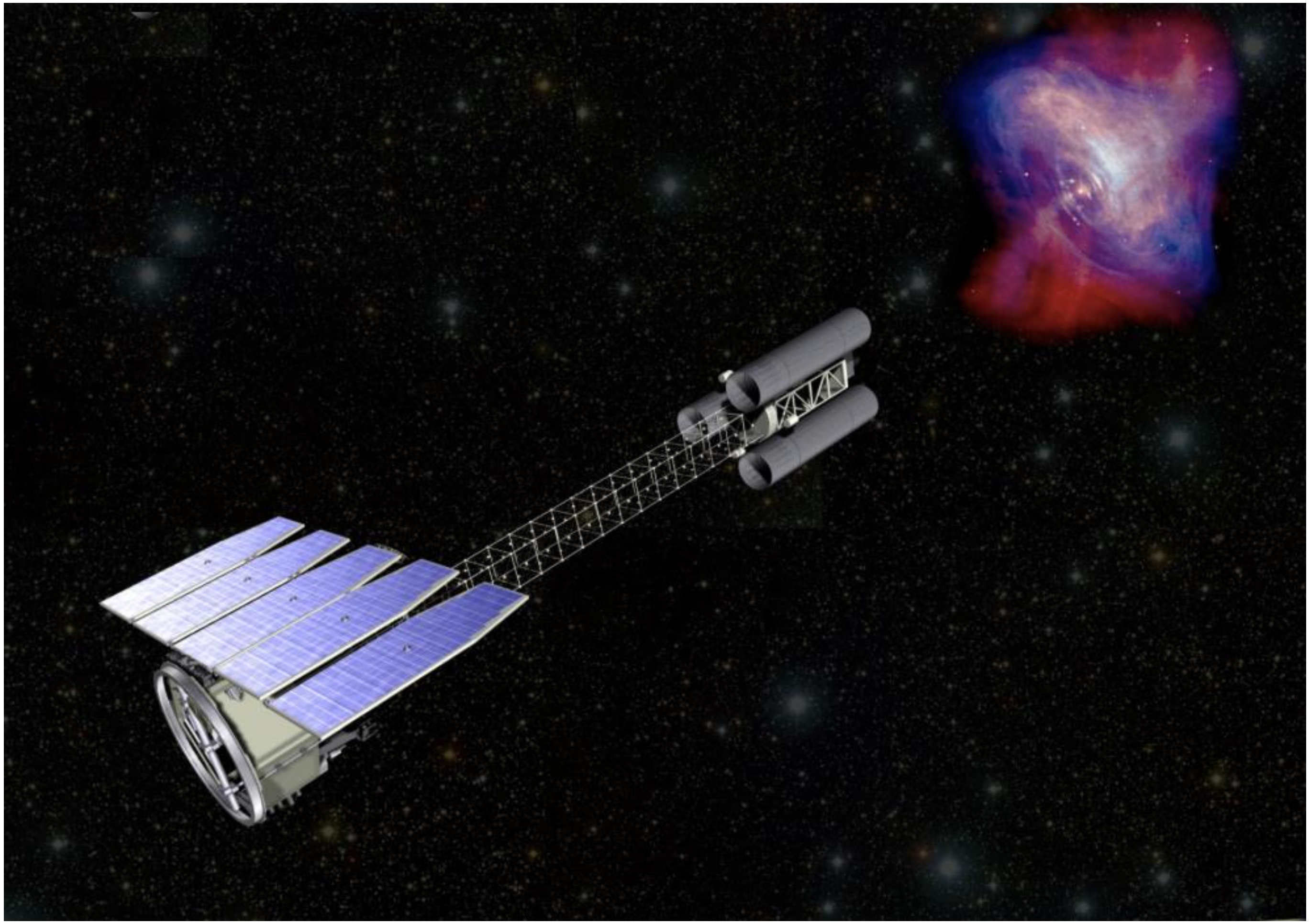
Hayashida et al. 2012

Multiwavelength light curves

Radio to optical polarization signatures

Coming Soon: High-Energy Polarimetry

X-ray: IXPE, XIPE, X-Calibur
γ-ray: AMEGO, e-ASTROGAM, HARPO



Outline

1. Basics of high-energy polarization

- Scientific drivers for high-energy polarimetry
- Synchrotron and Compton scattering polarization
- Toolsets for modeling polarization

2. Expectations from blazar high-energy polarization

- Estimate blazar polarization degree
- Capability of current instruments

3. What can we learn from high-energy polarization?

- Radiation mechanism of high-energy emission
- Particle acceleration mechanism
- How strong the jet is magnetized

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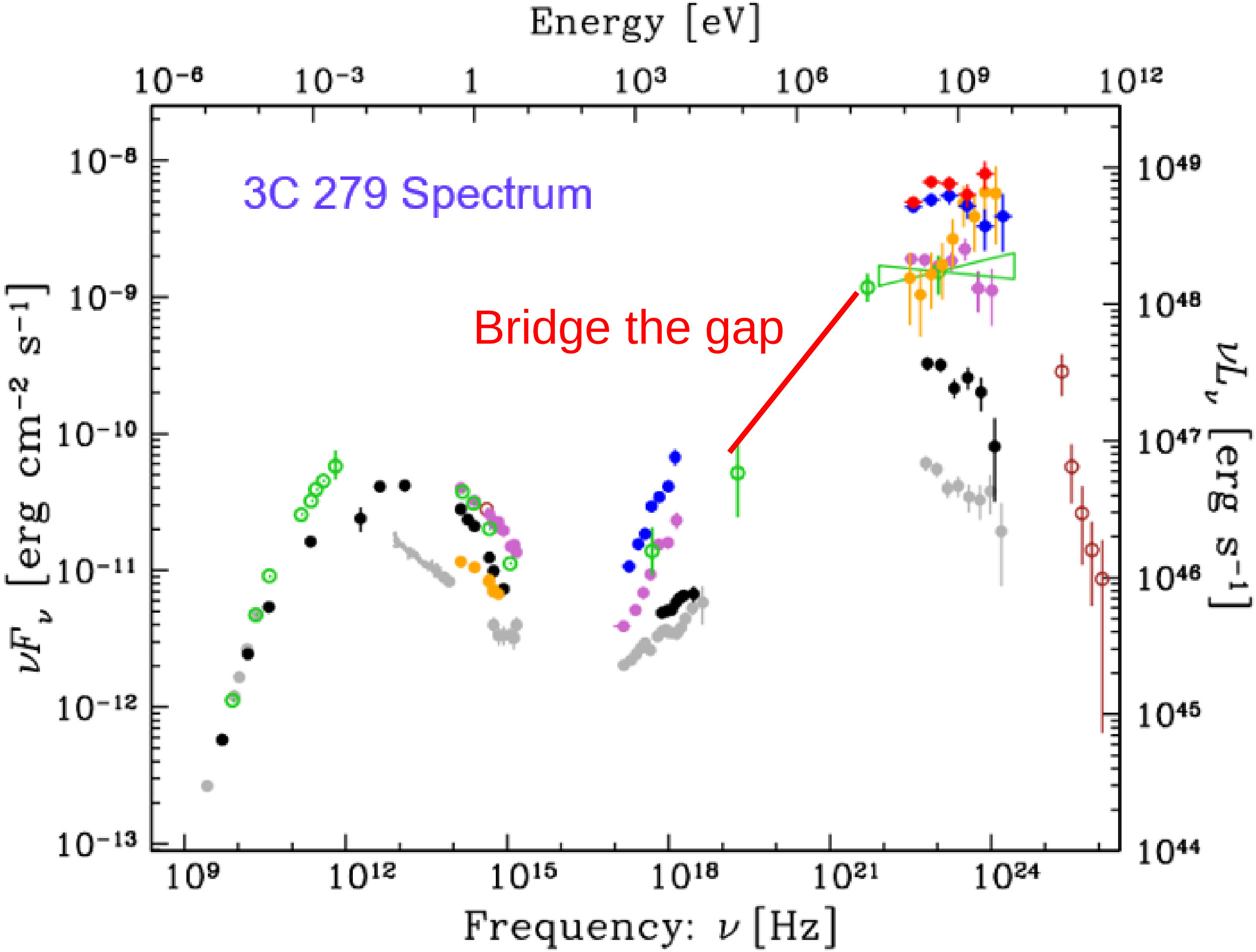
What is Special about High-Energy Polarization?

Reviews: Lei et al. 1997; McConell & Bloster 2006; Krawczynski et al. 2011

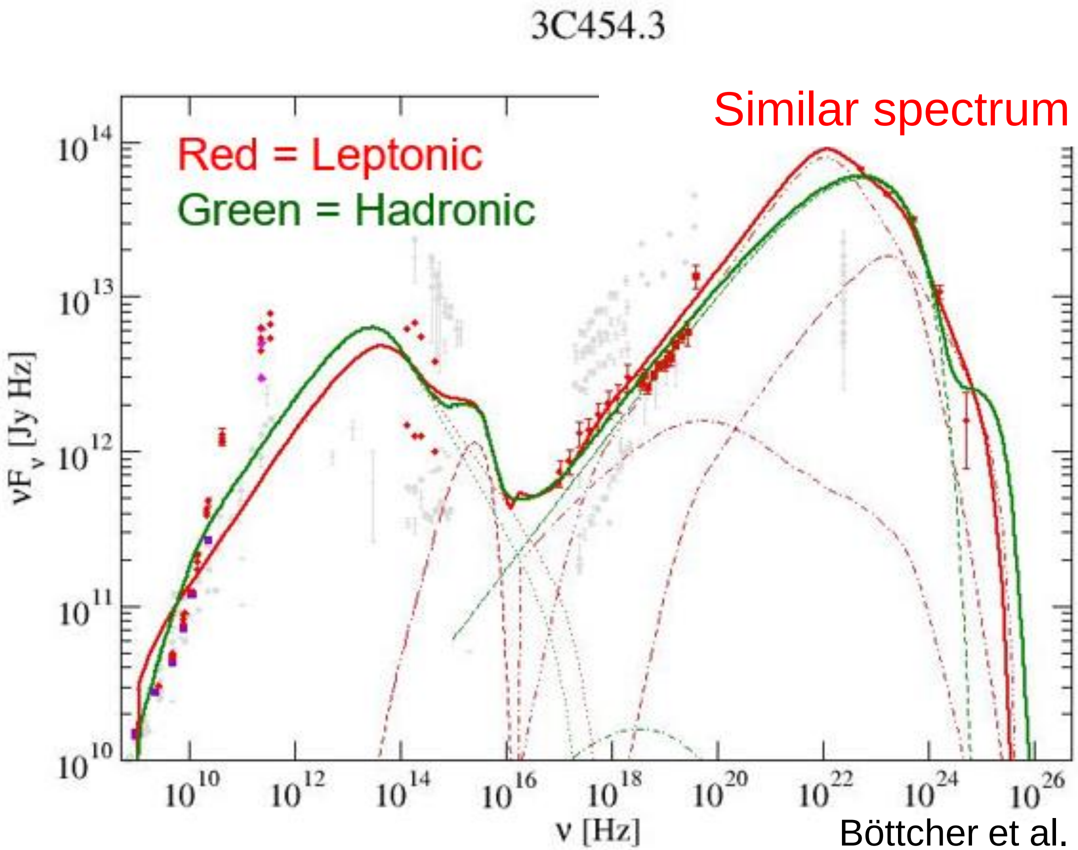
1. Multiwavelength light curves and polarization signatures

- MeV instruments cover the last major gap in blazar spectra
- Both low- and high-energy polarization signatures are available



What is Special about High-Energy Polarization?

1. Multiwavelength light curves and polarization signatures
2. Leptonic or hadronic?
    - Leptonic is dominated by Compton scattering; hadronic is dominated by proton synchrotron and hadronic cascades
    - Compton scattering and synchrotron has different polarization degree

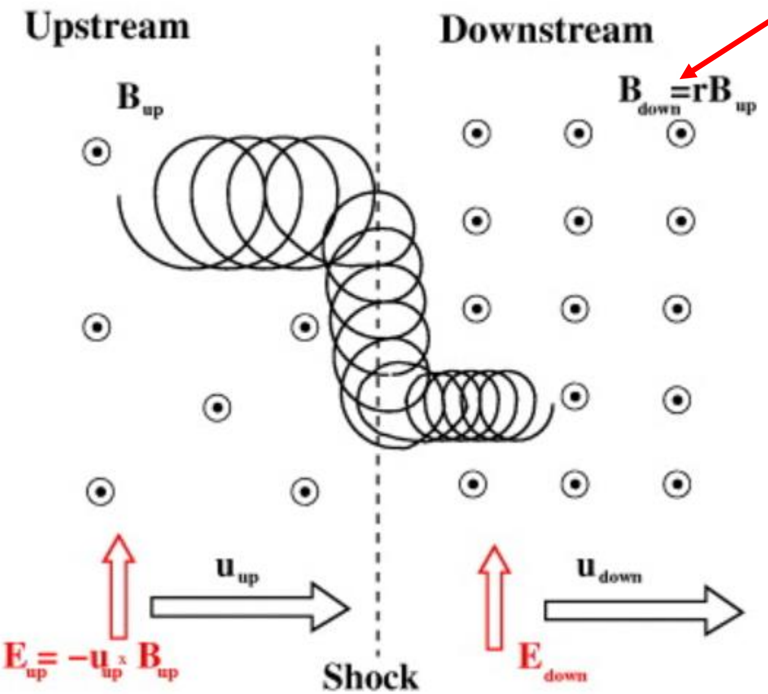


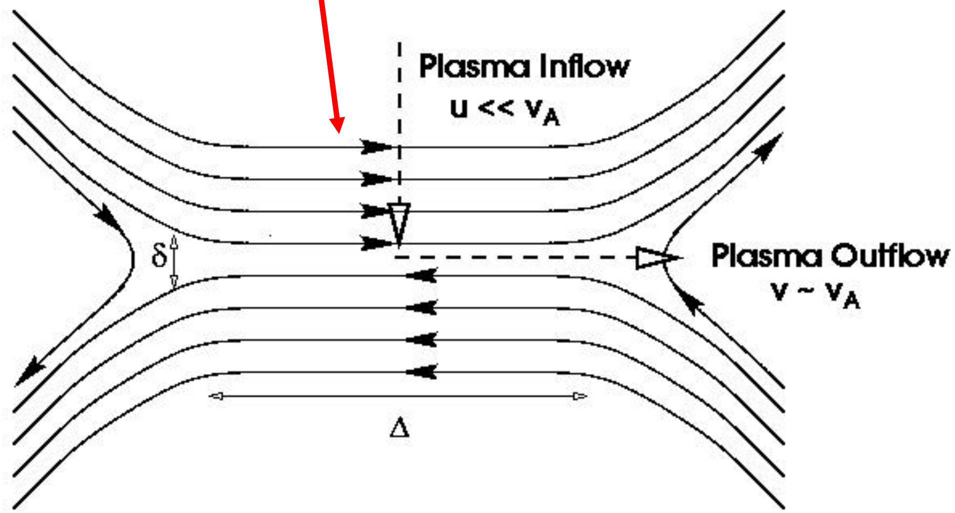
Böttcher et al. 2013

What is Special about High-Energy Polarization?

1. Multiwavelength light curves and polarization signatures
2. Leptonic or hadronic?
3. Shock or magnetic reconnection?
   - Probe the most active region for particle acceleration
   - Magnetic field evolves differently for shock and reconnection

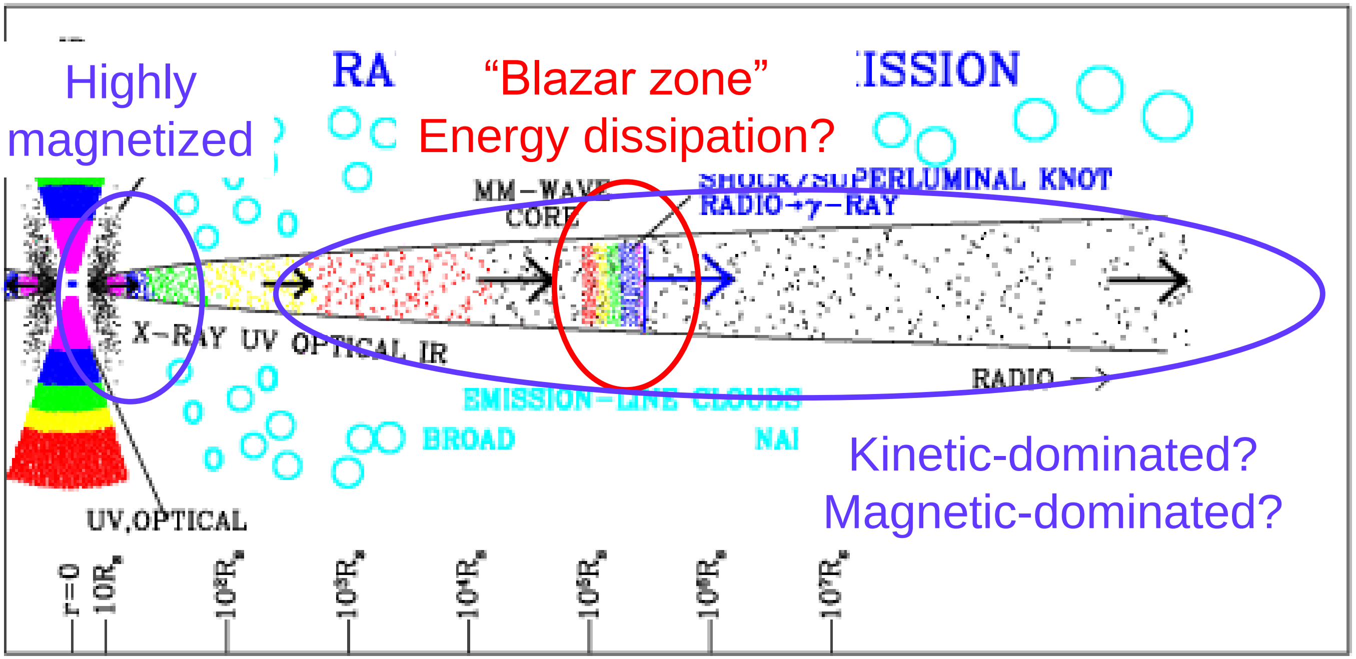
Change of magnetic field





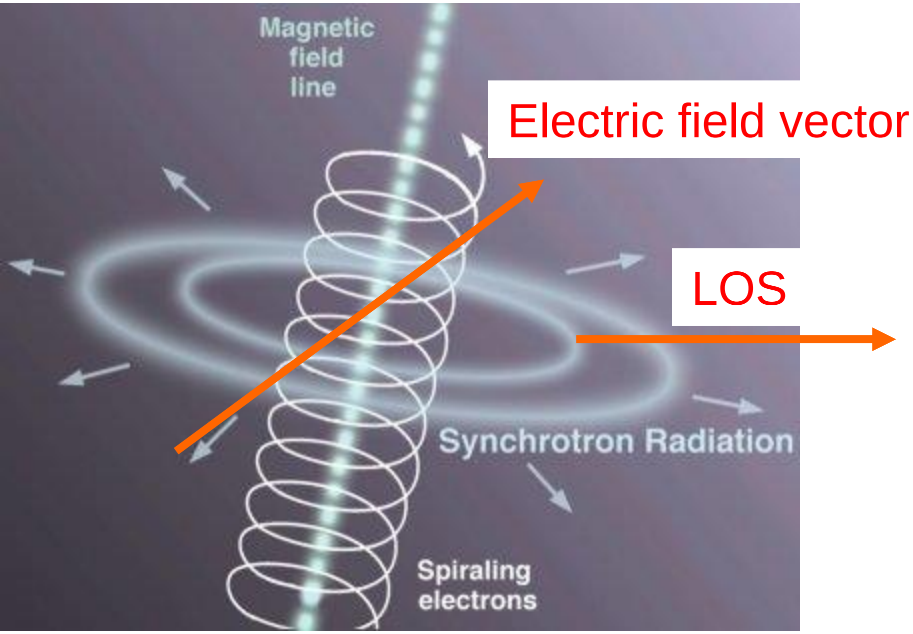
What is Special about High-Energy Polarization?

1. Multiwavelength light curves and polarization signatures
2. Leptonic or hadronic?
3. Shock or magnetic reconnection?
4. Kinetic-dominated or magnetic-dominated?
   - Polarization probe the magnetic field evolution, including energy dissipation

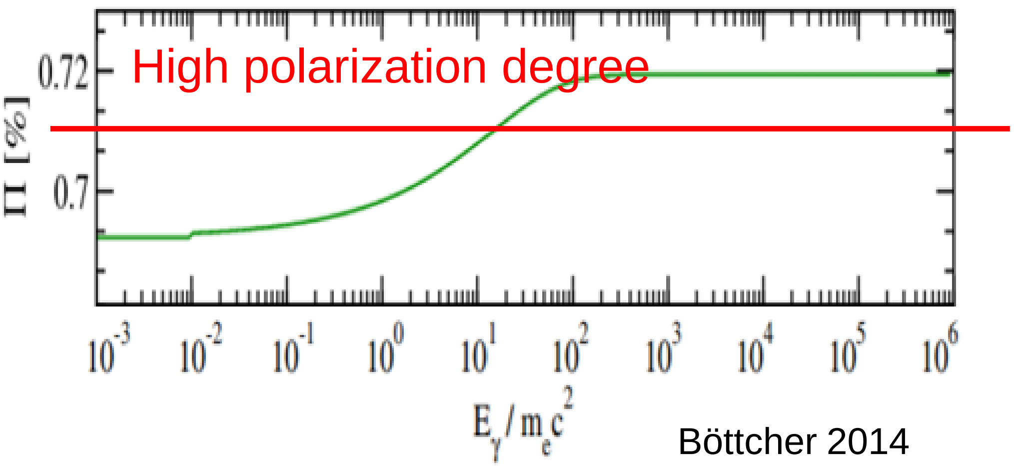


Alan Marscher

Synchrotron Polarization



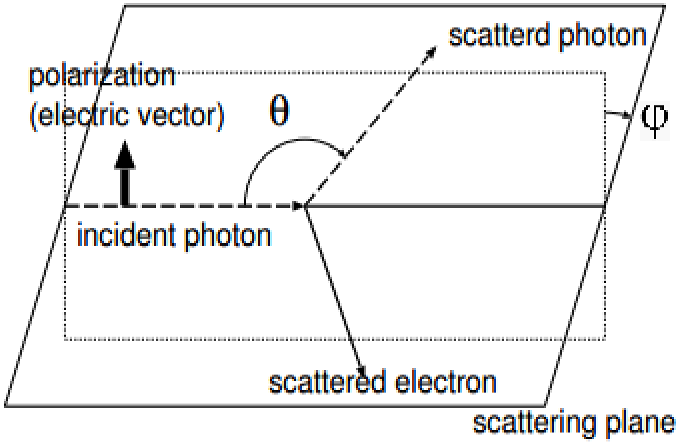
1. Synchrotron is highly polarized
2. Synchrotron polarization degree ~70% in purely ordered magnetic field
3. Polarization degree strongly depends on the orderness of magnetic field and weakly depends on particle spectrum

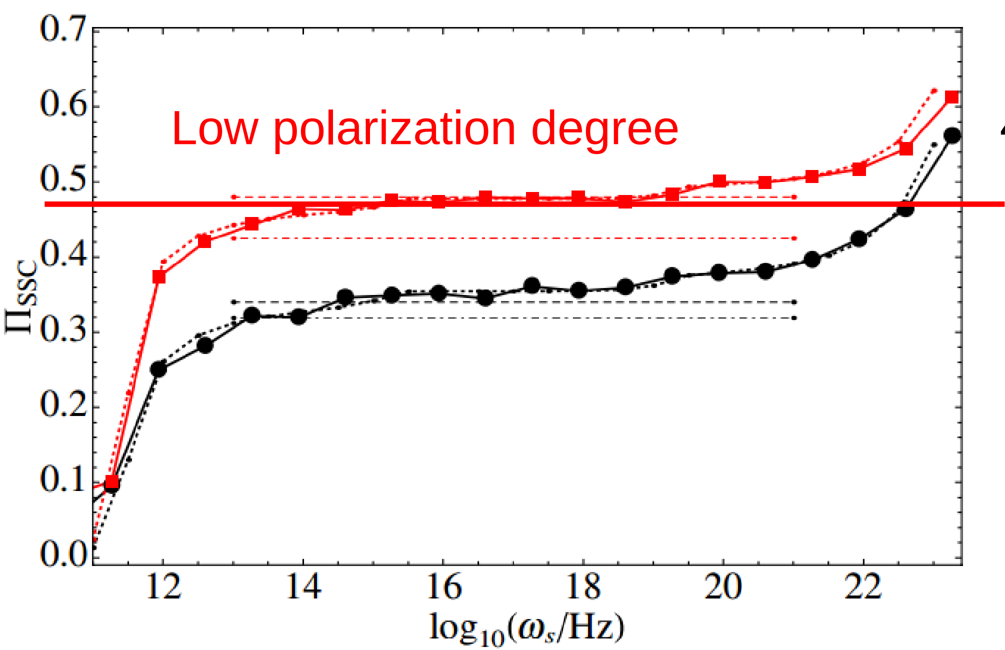


Böttcher 2014

Refer to: Westfold 1959; Rybicki & Lightman, 1979

Compton Scattering Polarization



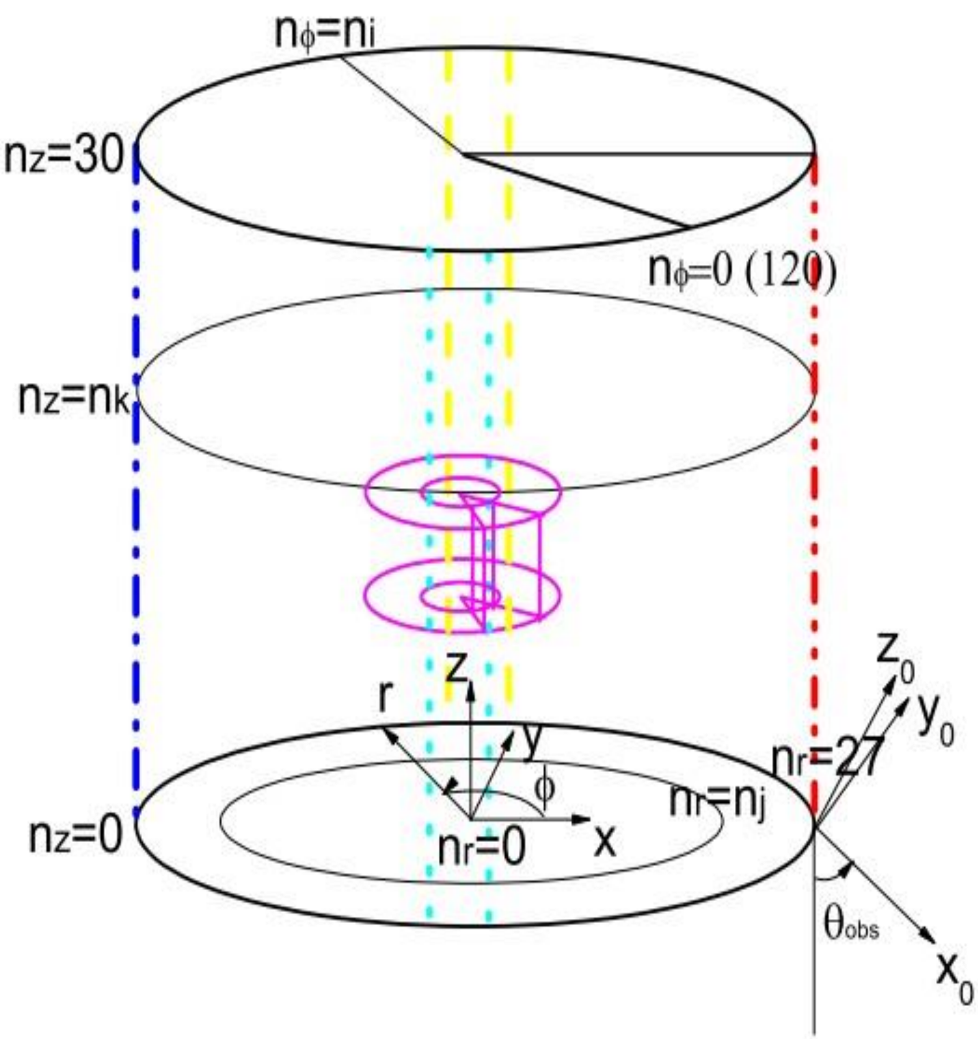


Krawczynski 2012

1. Synchrotron-self Compton (SSC) is moderately polarized
2. SSC polarization degree ~40% in purely ordered magnetic field
3. Polarization degree strongly depends on the orderness of magnetic field and weakly depends on particle spectrum
4. Isotropic external Compton scattering is nearly unpolarized

Refer to: Bonometto et al. 1970; Poutanen 1994; Celloti & Matt 1994; McNamara et al. 2009, Krawczynski 2012, Chang et al. 2014

Polarized Radiation Transfer



Zhang et al. 2014

3DPol features:

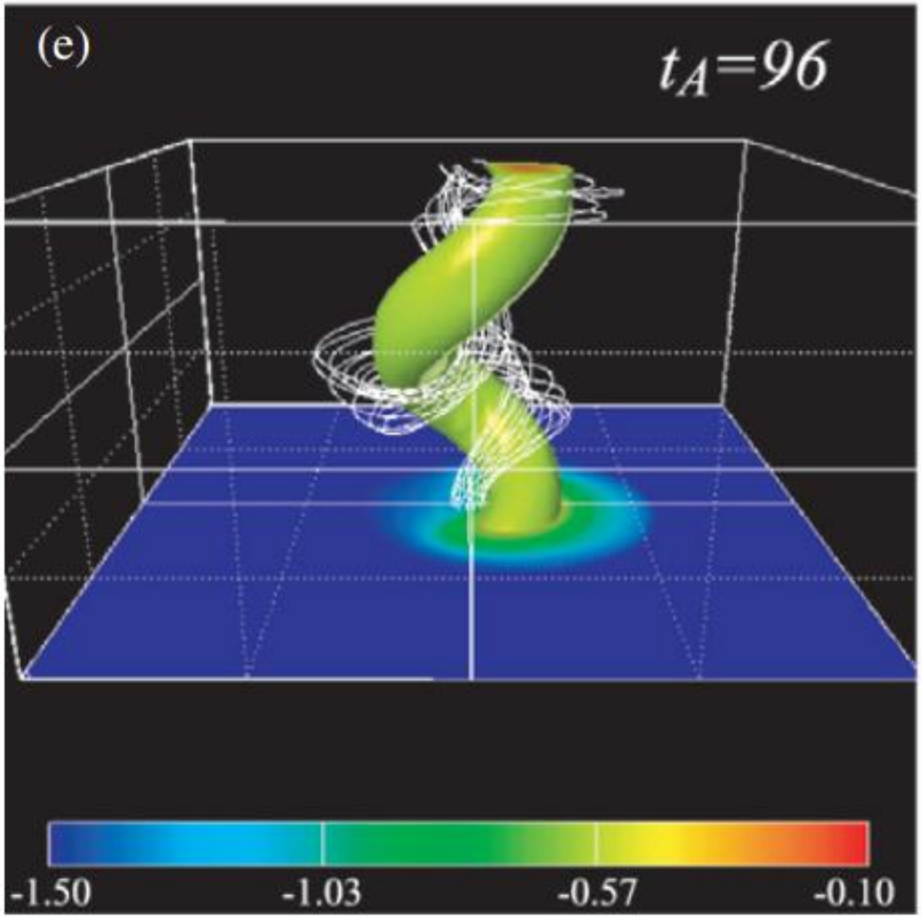
1. No presumed physical or geometrical conditions
2. Easy to connect to MHD and PIC simulations
3. Include polarization-dependent radiation transfer
4. Time-, space-, and frequency-dependencies

Similar tools:

- TEMZ model by Alan Marscher, great for simulating turbulent magnetic field
- A Monte-Carlo SSC code by Beheshtipour et al., track polarized Compton scattering

Refer to: Marscher 2014, Zhang et al. 2014, Beheshtipour et al. 2017

Global Dynamics: Magnetohydrodynamics



Mizuno et al. 2009

MHD can:

Evolve magnetic field based on first principles

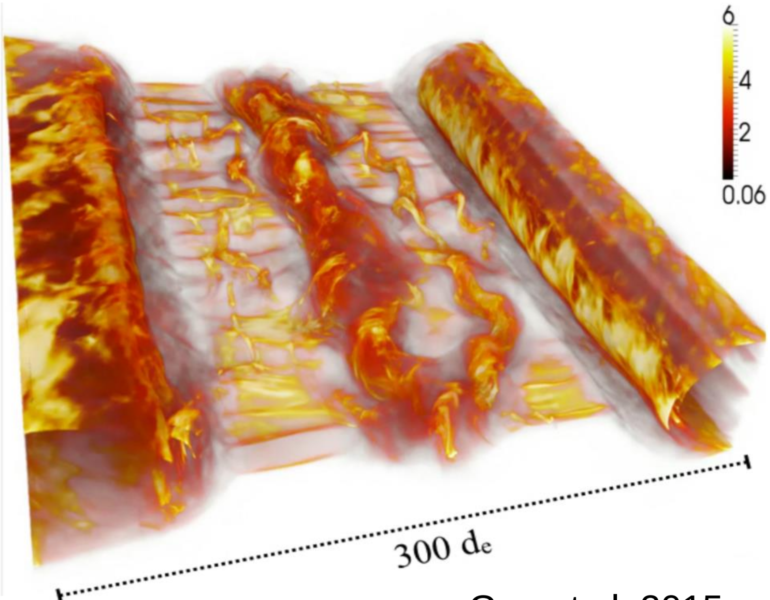
Moderate computational cost

No particle evolution

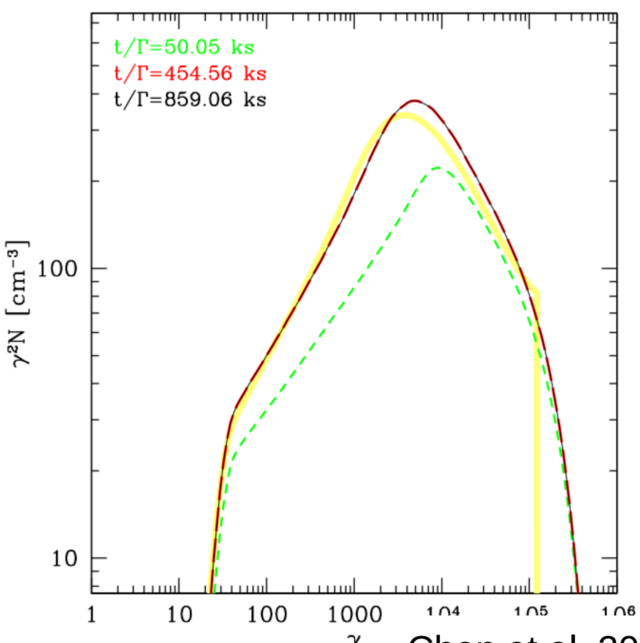
MHD tools:
Athena, Pluto, HARM, LA-COMPASS, etc.

Refer to: Stone et al. 2008, Mignone et al. 2007, Gammie et al. 2003, Li et al. 2006

Local Dynamics: Particle Acceleration



Guo et al. 2015



Chen et al. 2015

PIC features:

- First-principle treat particle acceleration and transport as well as magnetic field evolution
- High computational cost

PIC tools:

VPIC, Tristan-mp, PIConGPU, Zeltron, etc.

Refer to: Bowers et al. 2008, Spitkovsky et al. 2006, Burau et al. 2010, Cerutti et al. 2013

Fokker-Planck equation features:

- Low computational cost
- Approximation of particle acceleration, cooling, and spatial transport

Fokker-Planck tools:

MCFP leptonic code, 3D leptohadronic code

Refer to: Chen et al. 2015, Diltz et al. 2015, Zhang et al. 2016

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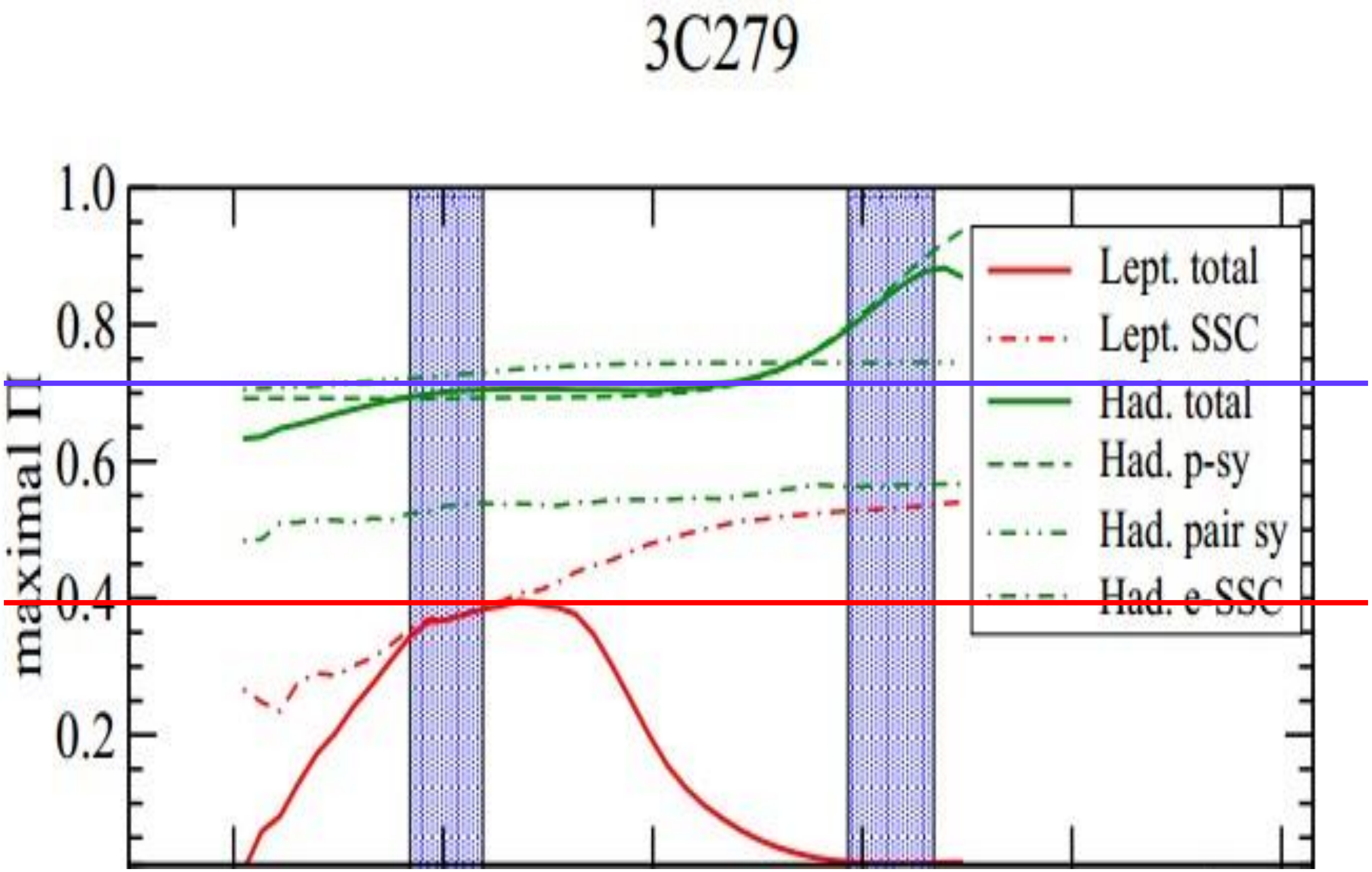
Blazar X-ray and γ-ray Polarization Degree



Hadronic model predicts up to ~75% polarization degree, in more realistic cases ~20%

Leptonic model predicts up to ~40% polarization degree, in more realistic cases ~10%

Zhang & Böttcher 2013

Polarimeter Capability

Observational Prospects for GEMS-like Instruments (2–10 keV): 1 mCrab Source at 2% Polarization is Detectable in 1000 ks

Source	Photon Flux Sensitivity (R_{calib}) ($\times 10^{-5}$ cm^{-2} s^{-1})	MDP (%)	Photon Flux (R_{blazar}) ($\times 10^{-5}$ cm^{-2} s^{-1})	High Energy Polariz. Degree $\Pi_{upscatter}$(%)	Good sensitivity $\frac{T_{obs,blazar}}{T_{obs,calib}}$	3σ (Π, ψ) Measurement Time $\frac{n_\sigma^2}{4}\frac{T_{obs,blazar}}{T_{obs,calib}}$
3C 279	3.8×10^2	2.0	142.0	10.66	9.4×10^{-2}–2.5×10^{-1}	$(2.1–5.7) \times 10^{-1}$
PKS 1510-089			83.0	7.46	0.3–1.5	7.4×10^{-1}–3.4
3C 454.3			2.48×10^2	5.28	2.2×10^{-1}–3.4×10^{-1}	$(5.0–7.6) \times 10^{-1}$

Bright blazars

Chakraborty et al. 2015

High-energy polarimeters can detect bright blazars of 5 to 10% polarization

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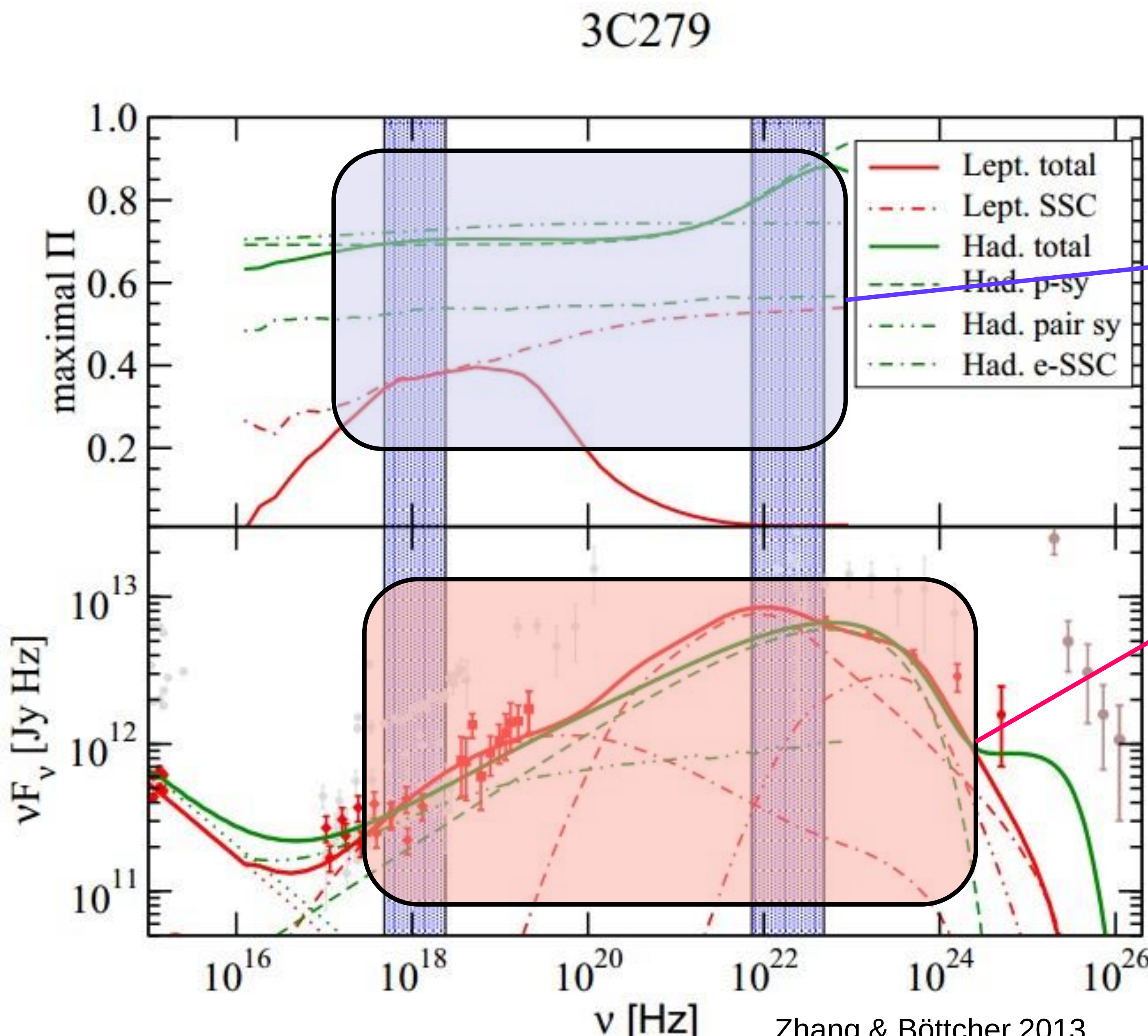
Leptonic vs Hadronic (FSRQ)

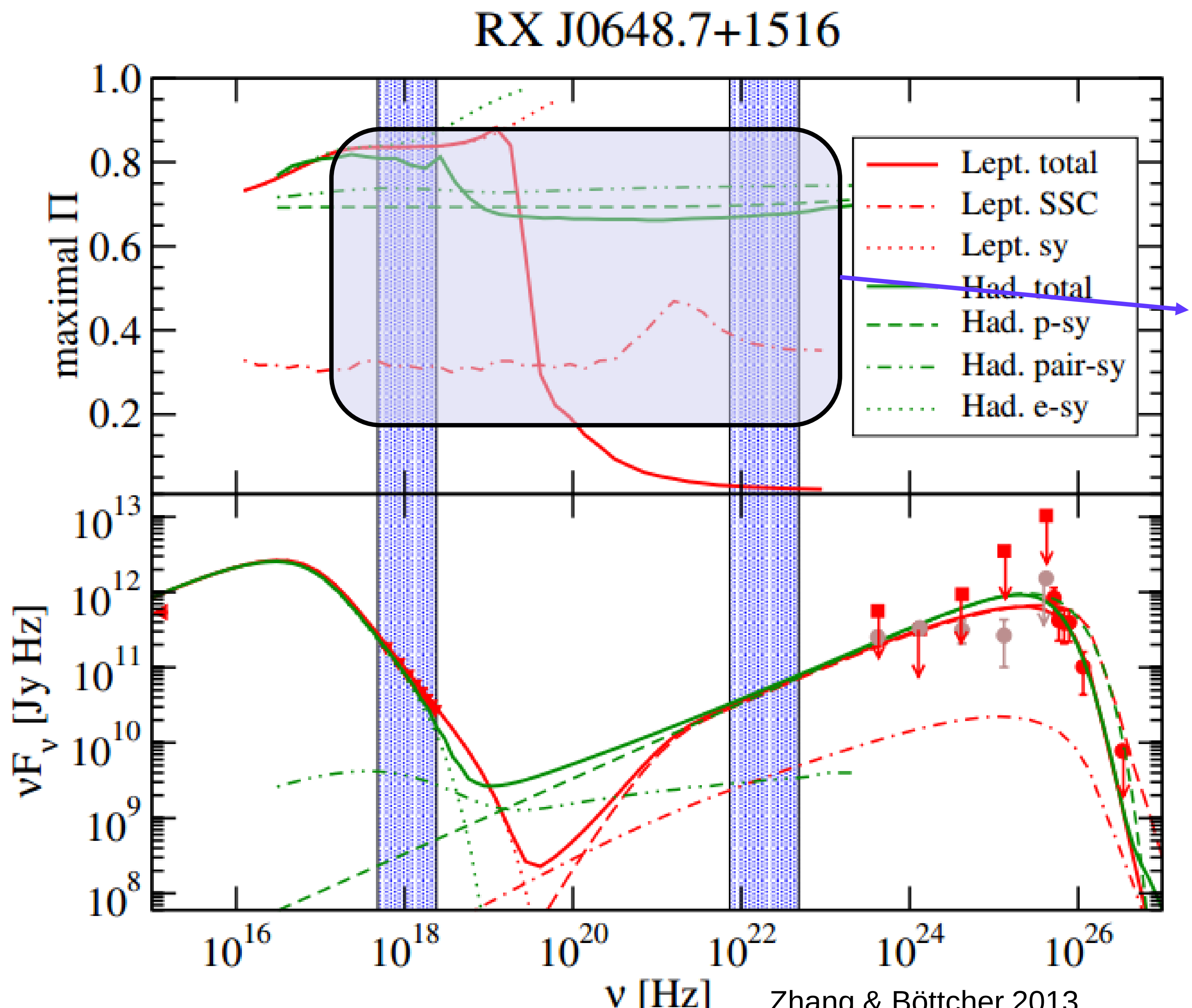


Different keV to MeV polarization degree

Similar spectral fitting

Zhang & Böttcher 2013

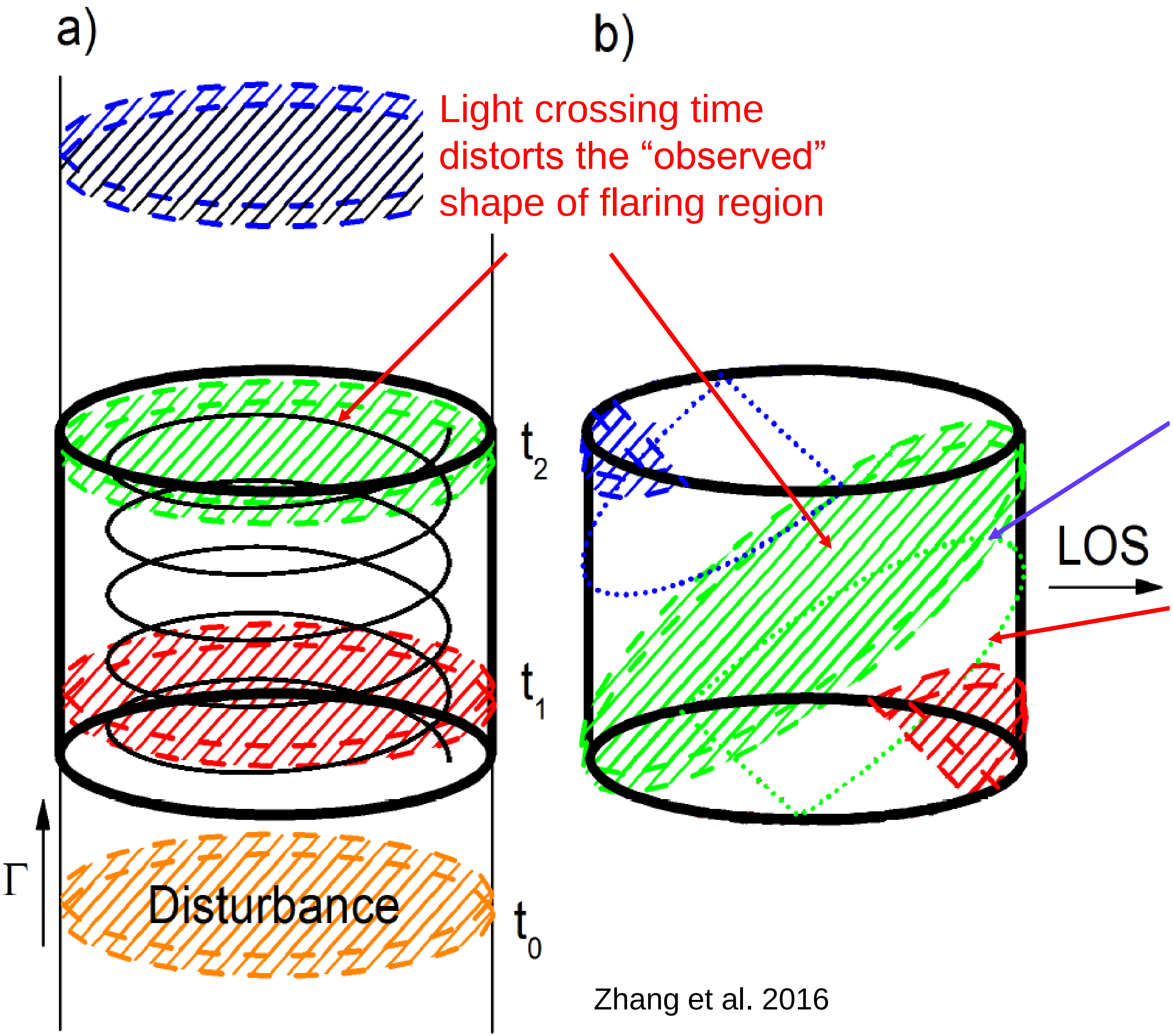
Leptonic vs Hadronic (HBL)



Similar keV polarization degree, but different MeV polarization degree

Zhang & Böttcher 2013

Light Crossing & Particle Cooling

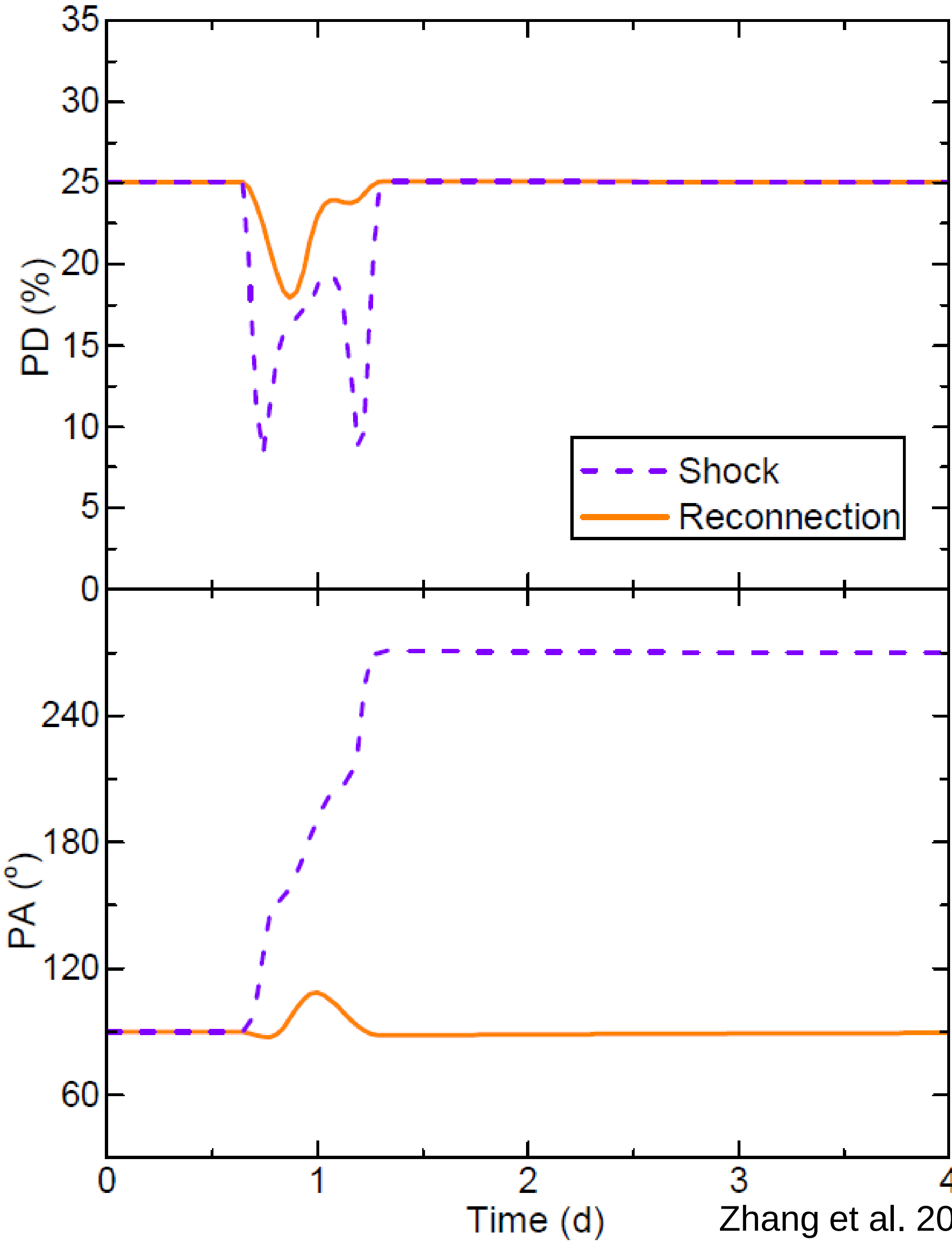


Particle cooling faster than light crossing leads to strong polarization variations

Particle cooling slower than light crossing smooths out the polarization variations

Zhang et al. 2016

Shock vs Reconnection



Zhang et al. 2016

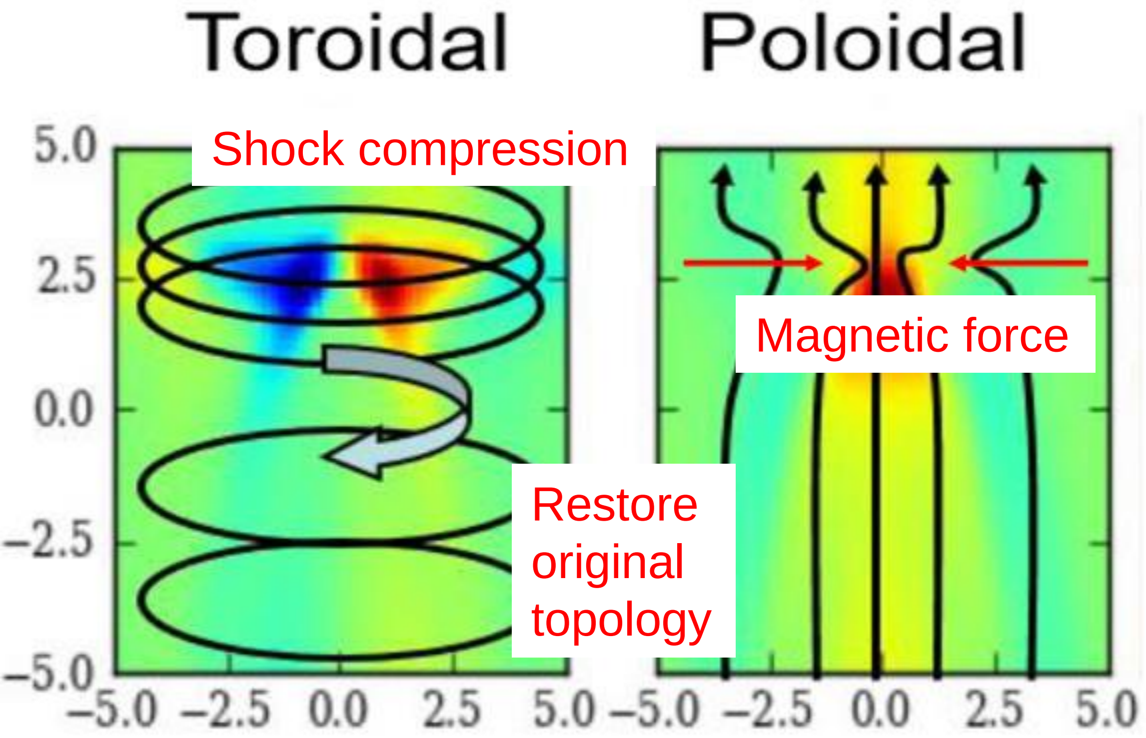
Shock:

1. Compress magnetic field
2. Faster proton cooling than the quiescent state
3. Major polarization variations in high-energy bands

Magnetic reconnection:

1. Dissipate magnetic field
2. Slower proton cooling than the quiescent state
3. Minor polarization variations in high-energy bands

Plasma Evolution under Shock



Zhang et al. 2016

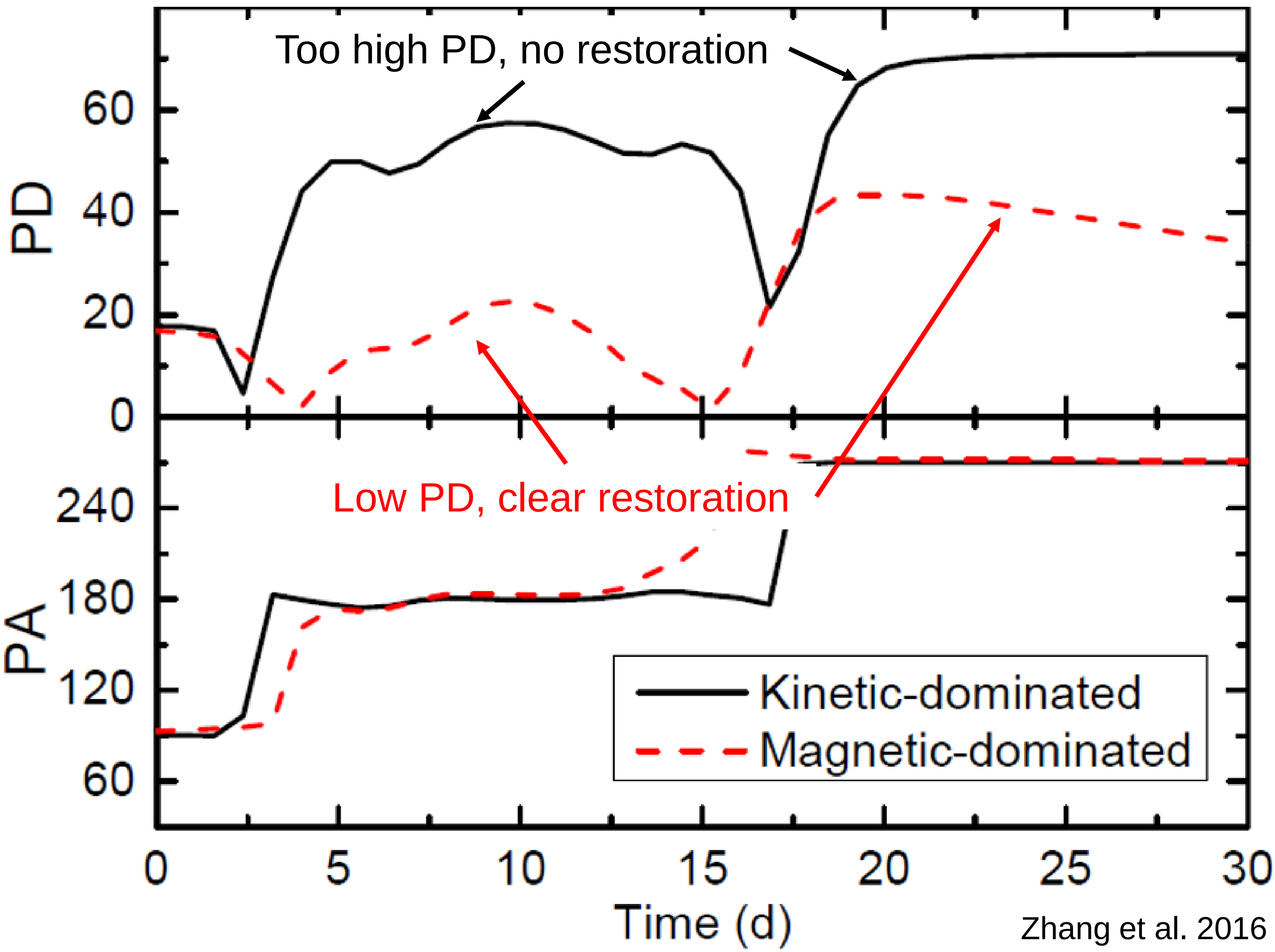
Kinetic-dominated jet:

1. Major change in the magnetic field
2. Slow restoration to the initial magnetic structure

Magnetic-dominated jet:

1. Minor change in the magnetic field
2. Fast restoration to the initial magnetic structure

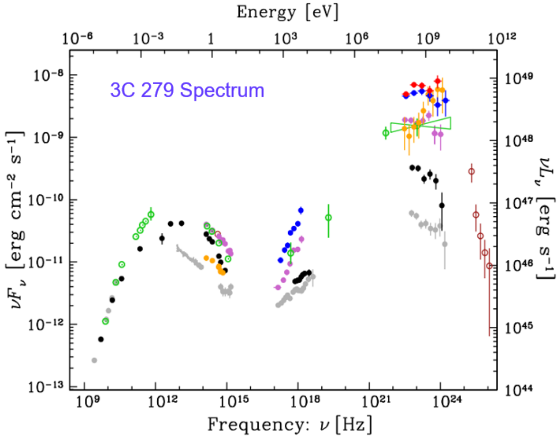
Kinetic-dominated vs Magnetic-dominated



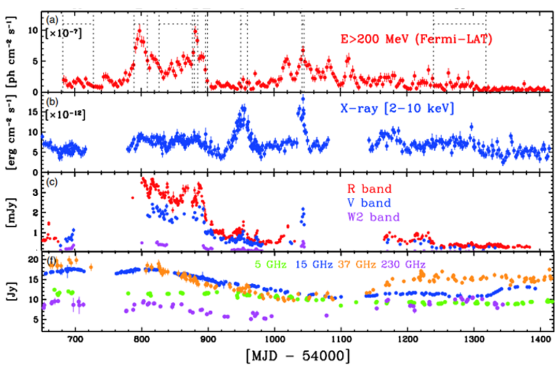
Zhang et al. 2016

Optical polarization prefers a moderate magnetization, but it may be contaminated by a more extended regions. High-energy polarization can put more solid constraints.

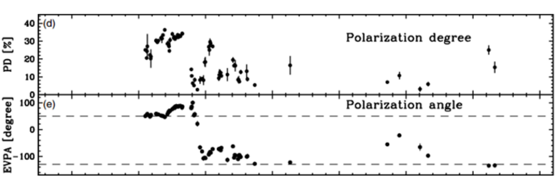
Spectrum



Light curves



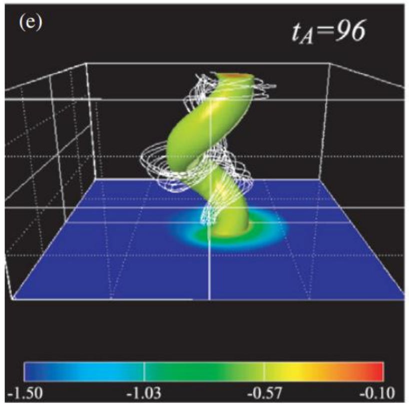
Polarization curves



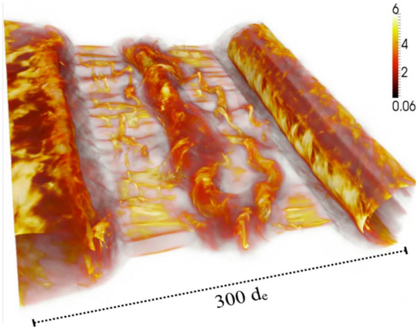
High-energy polarization coming soon

+

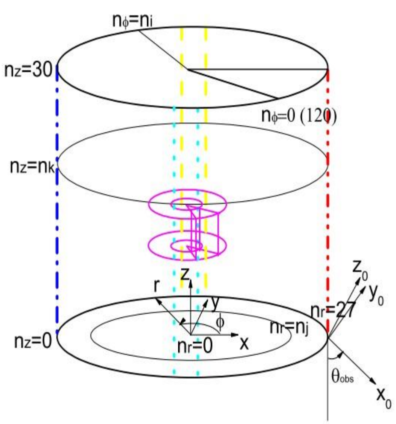
MHD



Particle



Polarization



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- Leptonic vs hadronic
- Shock vs reconnection
- Kinetic-dominated vs magnetic-dominated

Best knowledge of jet physics!