Astrophysical Radiation Mechanisms and Polarization

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Outline

1. Introduction to Radiation Transfer

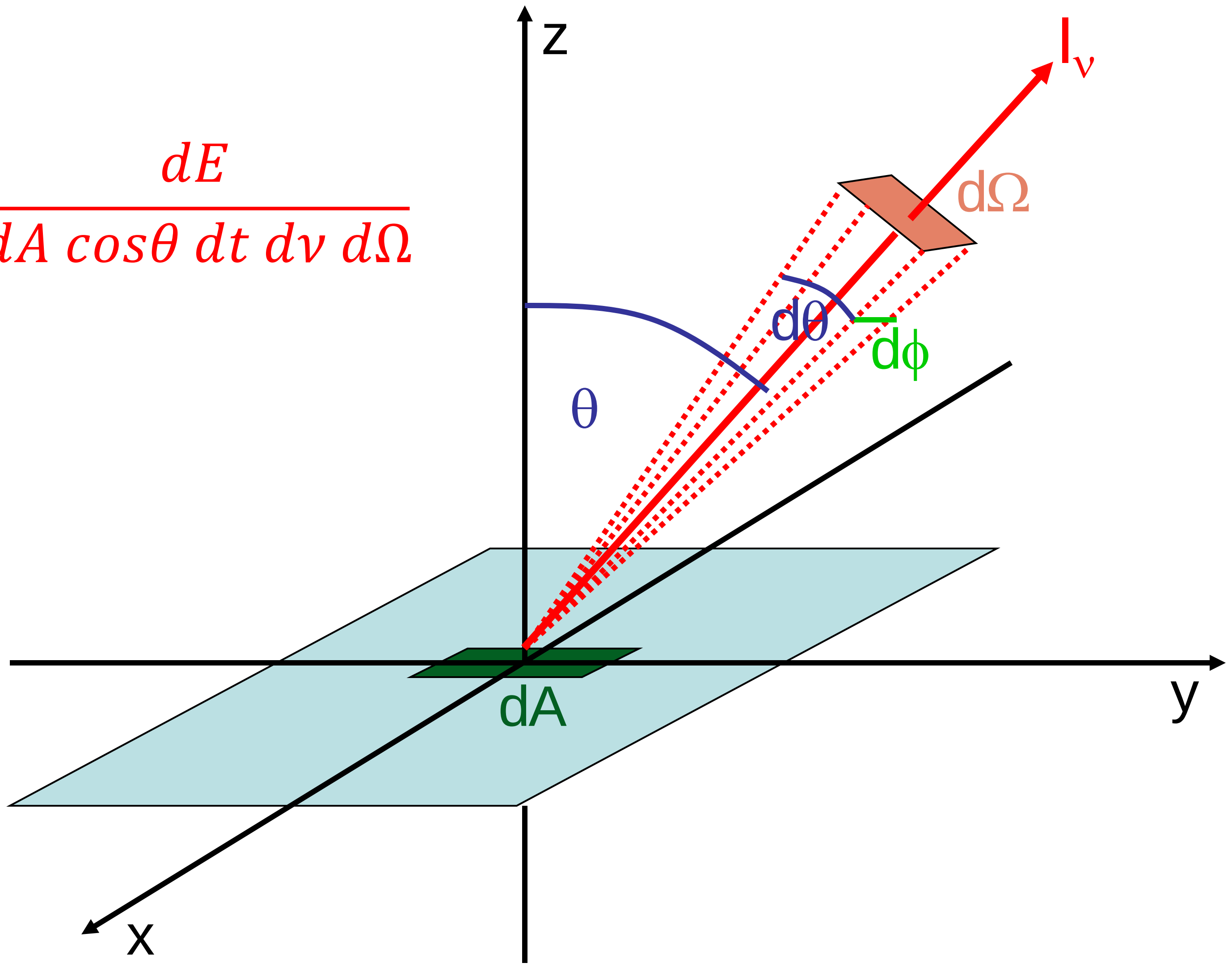
2. Blackbody Spectrum – Brightness Temperature

3. Introduction to Synchrotron Radiation (spectra, energy losses, polarization, Stokes parameters)

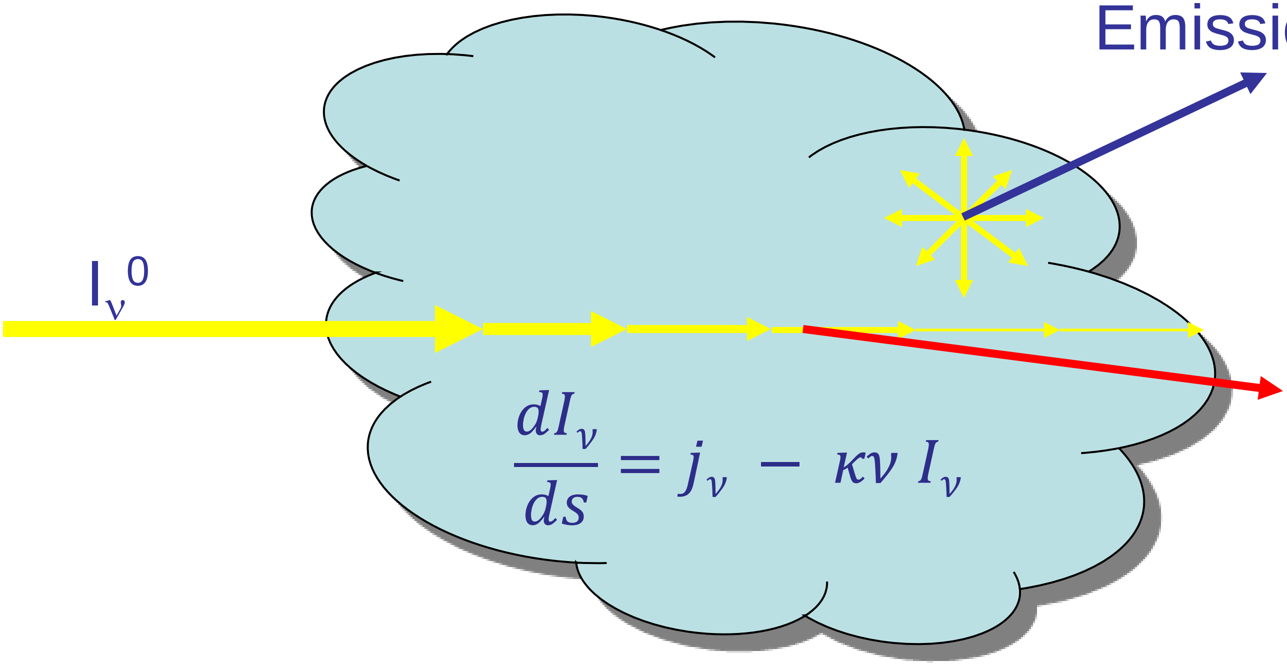
4. Introduction to Compton Scattering (spectra, energy losses, Compton polarization, X-ray/γ-ray polarimetry)

Radiation Transfer

$$I_\nu = \frac{dE}{dA\ cos\theta\ dt\ d\nu\ d\Omega}$$



Radiation Transfer



Emission $\rightarrow j_\nu$

$$\left.\frac{dI_\nu}{ds}\right|_{em} = j_\nu$$

Absorption $\rightarrow \kappa_\nu$

$$\left.\frac{dI_\nu}{ds}\right|_{abs} = -\kappa_\nu I_\nu$$

Optical depth τ_ν: $d\tau_\nu = \kappa_\nu\, ds$ => $\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$

Source Function: $S_\nu = \frac{j_\nu}{\kappa_\nu}$

Radiative Transfer Equation

General solution for homogeneous S_ν:

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + S_\nu\,(1 - e^{-\tau_\nu})$$

Radiation Transfer (II)

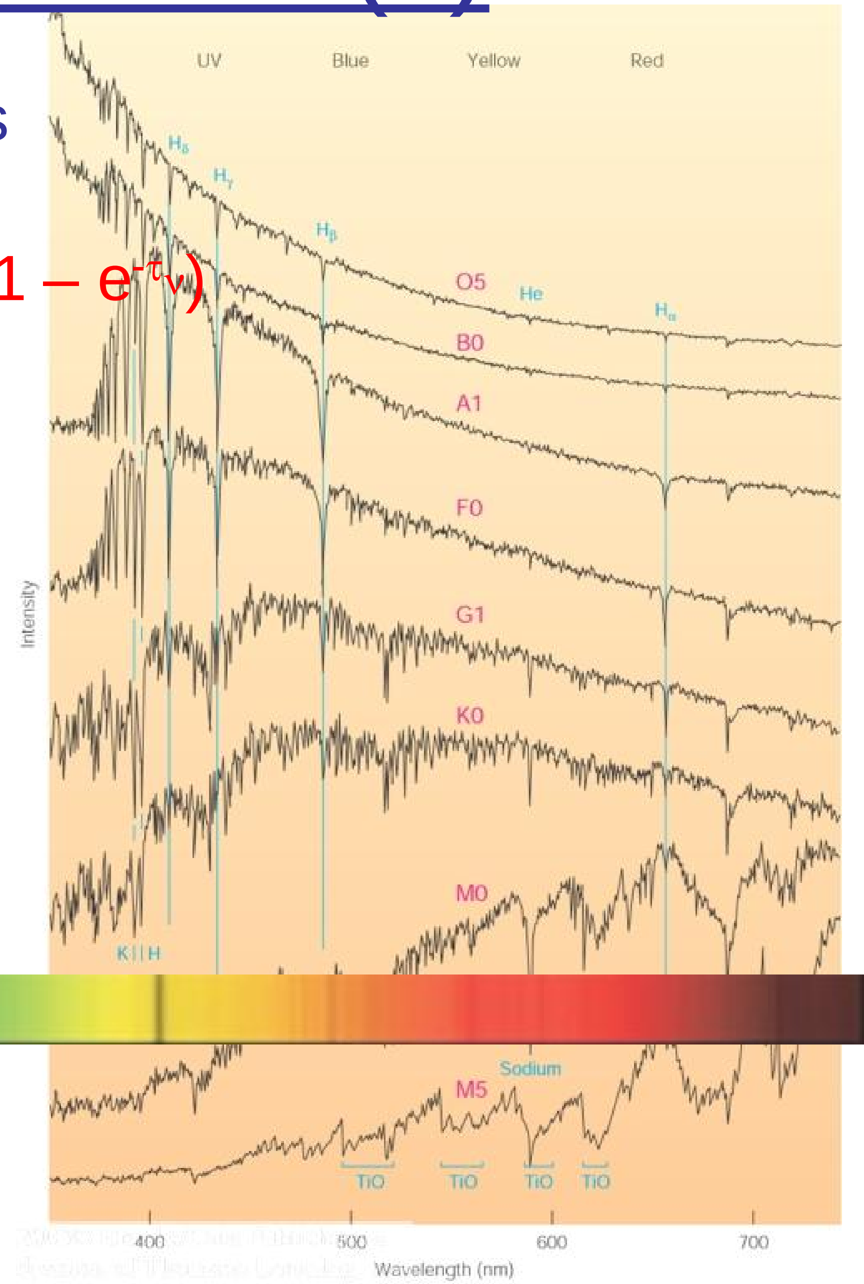
Special Cases

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + S_\nu\,(1 - e^{-\tau_\nu})$$

1) Absorption spectra

Bright background source behind a cold absorber

$(S_\nu \approx 0)$



Radiation Transfer (III)

Special Cases

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + S_\nu\,(1 - e^{-\tau_\nu})$$

2) Emission spectra

No significant background source

$(I_\nu(0) \approx 0)$

I) Optically thick emission:

$(\tau_\nu >> 1)$

Radiation Transfer (IV)

Special Cases

$$I_\nu(\tau_\nu) \approx I_\nu(0)\, e^{-\tau_\nu} + S_\nu\,(1 - e^{-\tau_\nu})$$

$$S_\nu\, \tau_\nu \approx j_\nu\, \Delta s$$

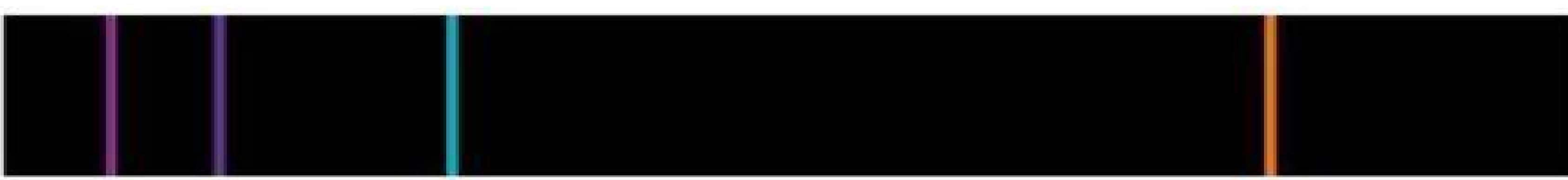
2) Emission spectra

No significant background source

$(I_\lambda(0) \approx 0)$

II) Optically thin emission:

$(\tau_\lambda << 1)$



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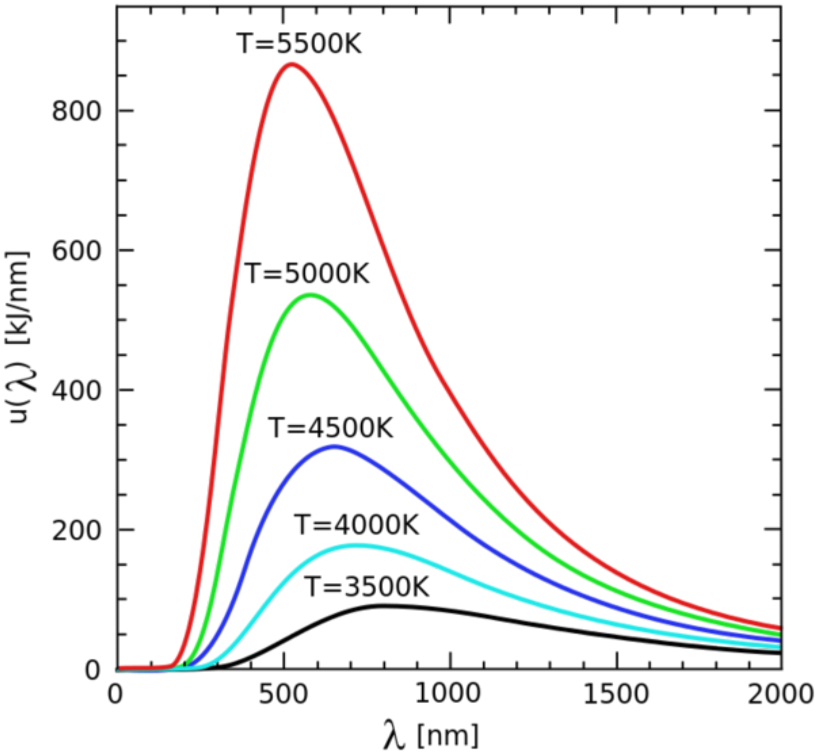
Thermal Blackbody Radiation

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + S_\nu\,(1 - e^{-\tau_\nu})$$

In Thermal Equilibrium (LTE):

$$S_\nu = I_\nu = B_\nu(T) = \frac{2\,h\,\nu^3}{c^2}\frac{1}{(e^{h\nu/k_B T}-1)}$$

= Planck Function

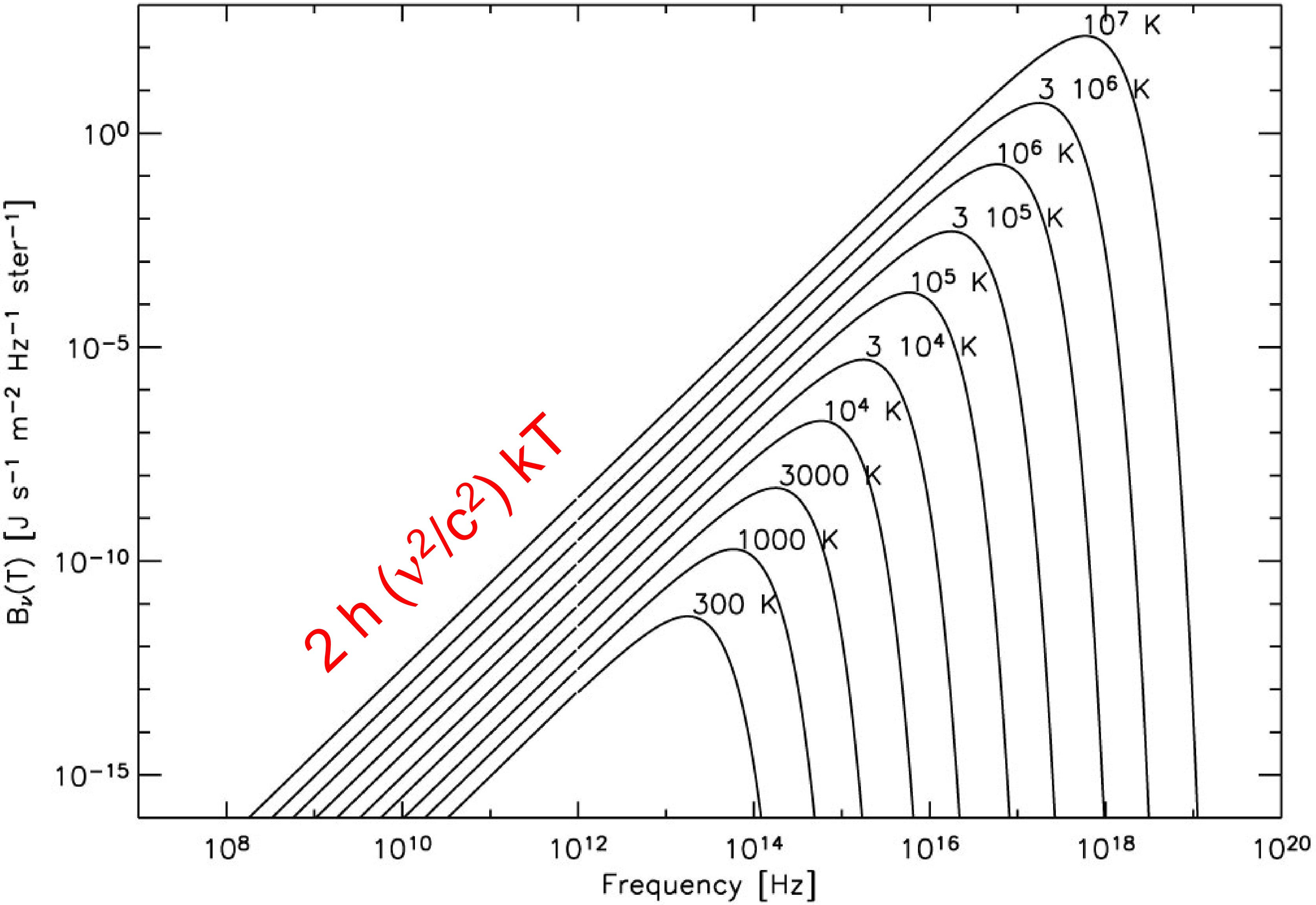


Rayleigh-Jeans Limit:

$$h\nu \ll k_B T$$

$$\Rightarrow \quad B_\nu(T) \approx \frac{2\,\nu^2}{c^2}\, k_B T$$

Thermal Blackbody Spectrum



Brightness Temperature

Define ***Brightness Temperature T_b*** by setting measured intensity I_ν equal to Blackbody in Rayleigh-Jeans Limit:

$$I_\nu = 2\,(\nu^2/c^2)\,k_B T_b$$

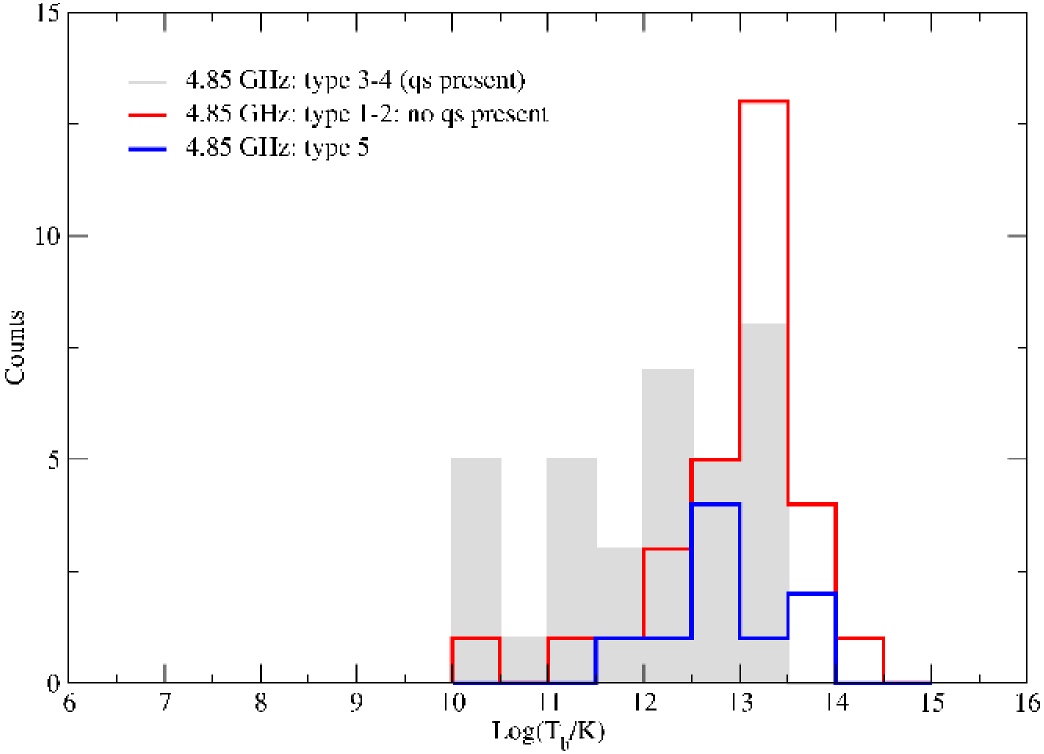
$$\Rightarrow\ T_b = \frac{I_\nu\, c^2}{2\,\nu^2\, k_B}$$

Note: T_b usually has nothing to do with the source's real temperature!

Brightness Temperature

Brightness temperatures $T_b > 10^{12}$ K seem unphysical because of strong Compton scattering (see point 4 below)

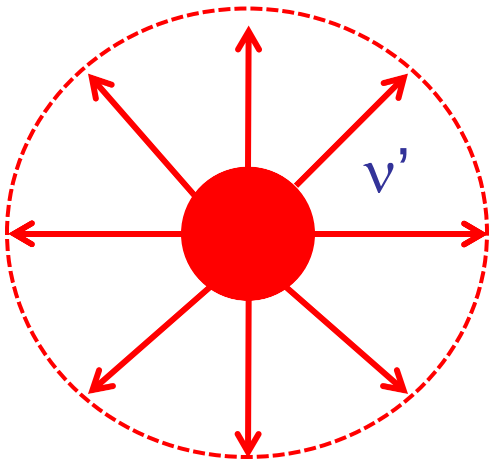
… but many active galactic nuclei show $T_b > 10^{12}$ K …



(Angelakis et al. 2012)

Relativistic Beaming / Boosting

In the co-moving frame of the emission region:



Isotropic emission $I'_{\nu'}$ at frequency ν'

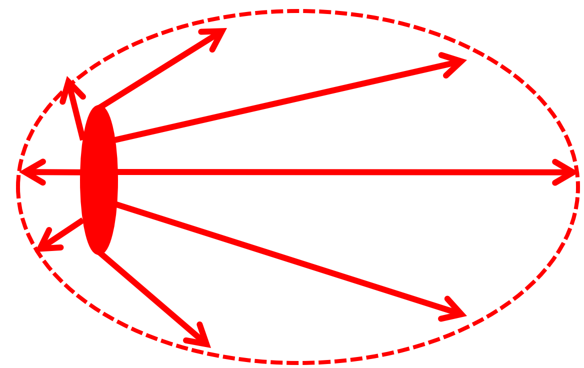
Time interval t'_{var}

$$\Gamma = (1 - \beta_\Gamma^2)^{-1/2}$$

In the stationary (observer's) frame:

$\delta = (\Gamma[1 - \beta_\Gamma \cos\theta])^{-1}$:

Doppler boosting factor



Beamed emission:

$I_\nu = \delta^3 I'_{\nu'}$ $\qquad \nu = \delta\,\nu'$

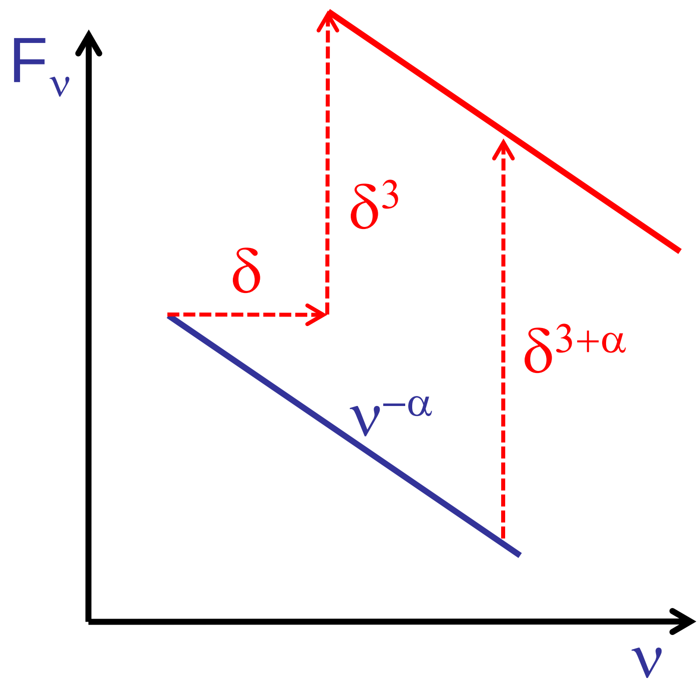
For power-law $F_\nu \sim \nu^{-\alpha}$:

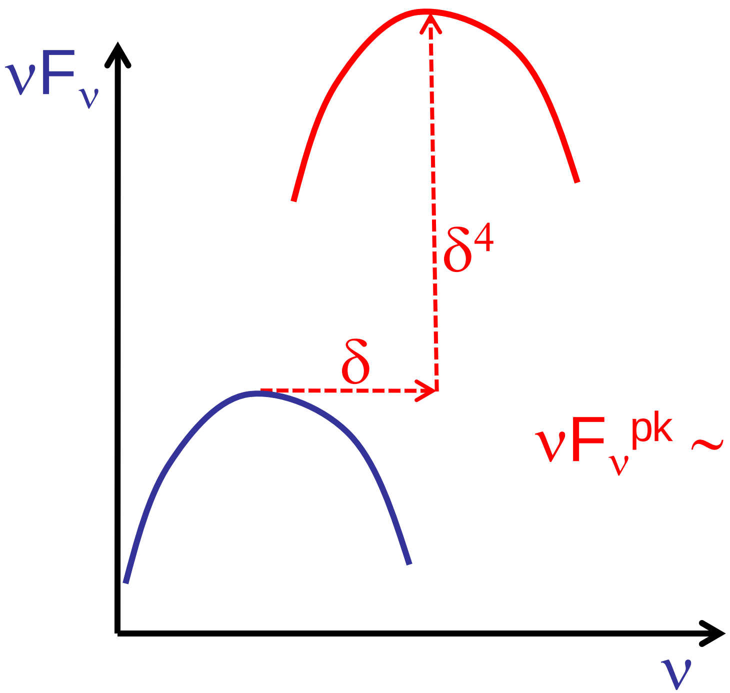
$F_\nu = \delta^{(3+\alpha)} F'_\nu$

Time interval

$t_{var} = t'_{var} / \delta$

Relativistic Beaming / Boosting





$$\nu F_\nu^{pk} \sim \frac{L}{4\pi\, d_L^{\,2}}$$

$$L \sim \delta^4 L'$$

$$T_b \sim \delta^3 T'_b$$

(if the size of the emitter is determined from variability)

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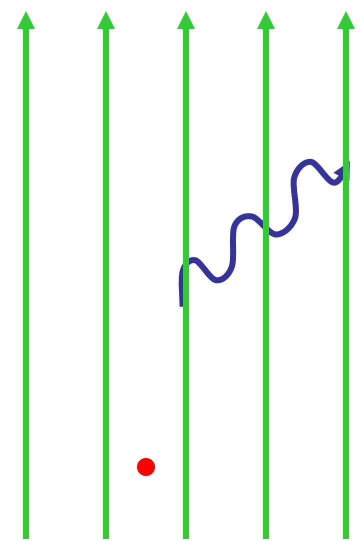
Cyclotron/Synchrotron Radiation

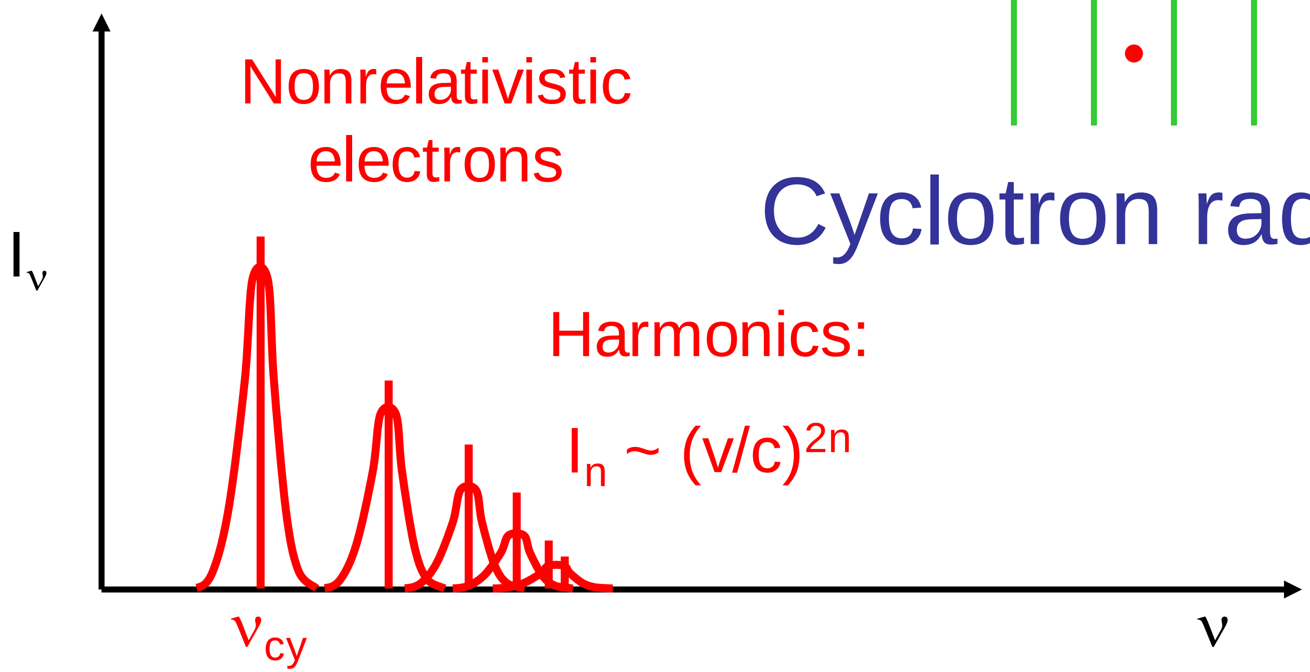
Cyclotron frequency:

$\nu_{cy} = eB/(2\pi m_e c) \sim 2.8*10^6\,(B/G)$ Hz



Cyclotron radiation

Nonrelativistic electrons



Harmonics:

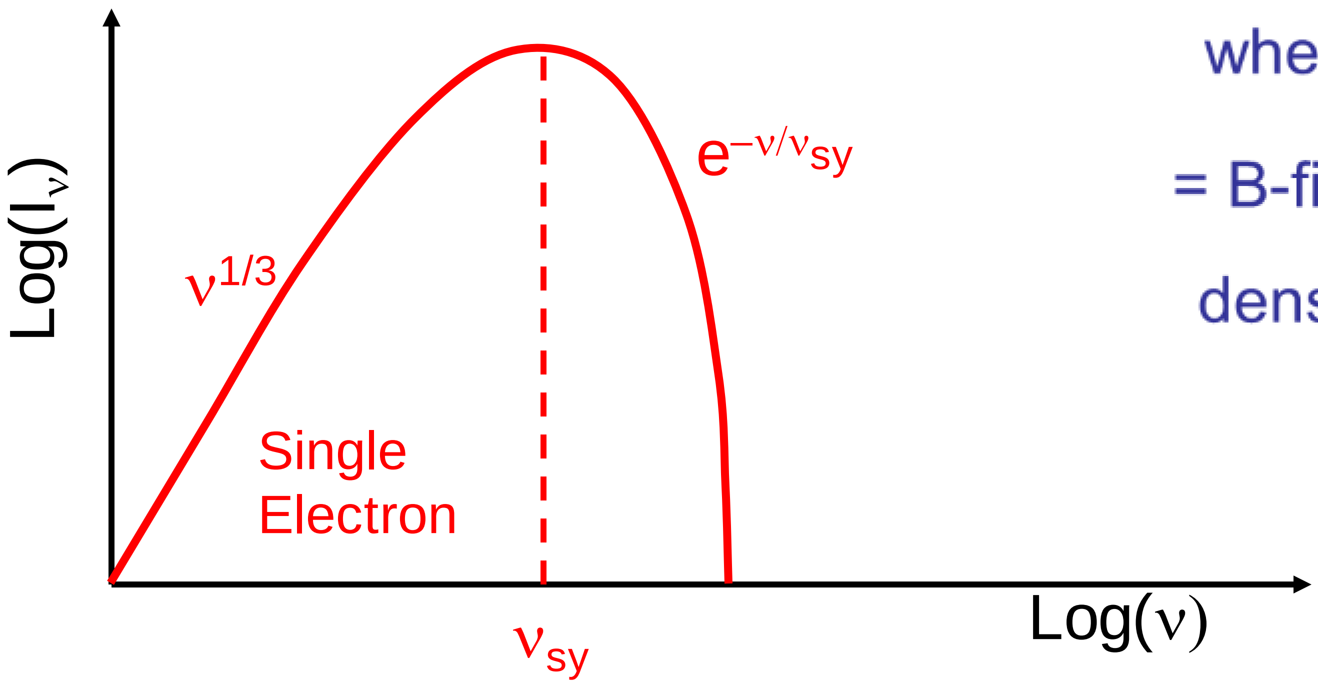
$I_n \sim (v/c)^{2n}$

Synchrotron Radiation

Relativistic electrons:

$\nu_{sy}(\gamma) \sim 4.2{*}10^6\,(B/G)\,\gamma^2$ Hz

Power output into synchrotron radiation (single electron): $\left(\frac{dE}{dt}\right)_{sy}(\gamma) = \frac{4}{3}\, c\, \sigma_T\, u_B\, \gamma^2\beta^2$



where $u_B = \frac{B^2}{8\pi}$

= B-field energy density (c.g.s)

Synchrotron Emissivity

Simple delta-function approximation for single-electron emissivity:

$$P_\nu(\gamma) \approx \left(\frac{dE}{dt}\right)_{sy} \delta(\nu - \nu_{sy}[\gamma])$$

$$\nu_{sy}(\gamma) = \nu_0 \gamma^2$$

$$j_\nu = \int_1^\infty d\gamma \, P_\nu(\gamma) \, N_e(\gamma) \sim N_e(\gamma_c) \, \nu^{1/2}$$

$$\gamma_c = (\nu/\nu_0)^{1/2}$$

Synchrotron Radiation

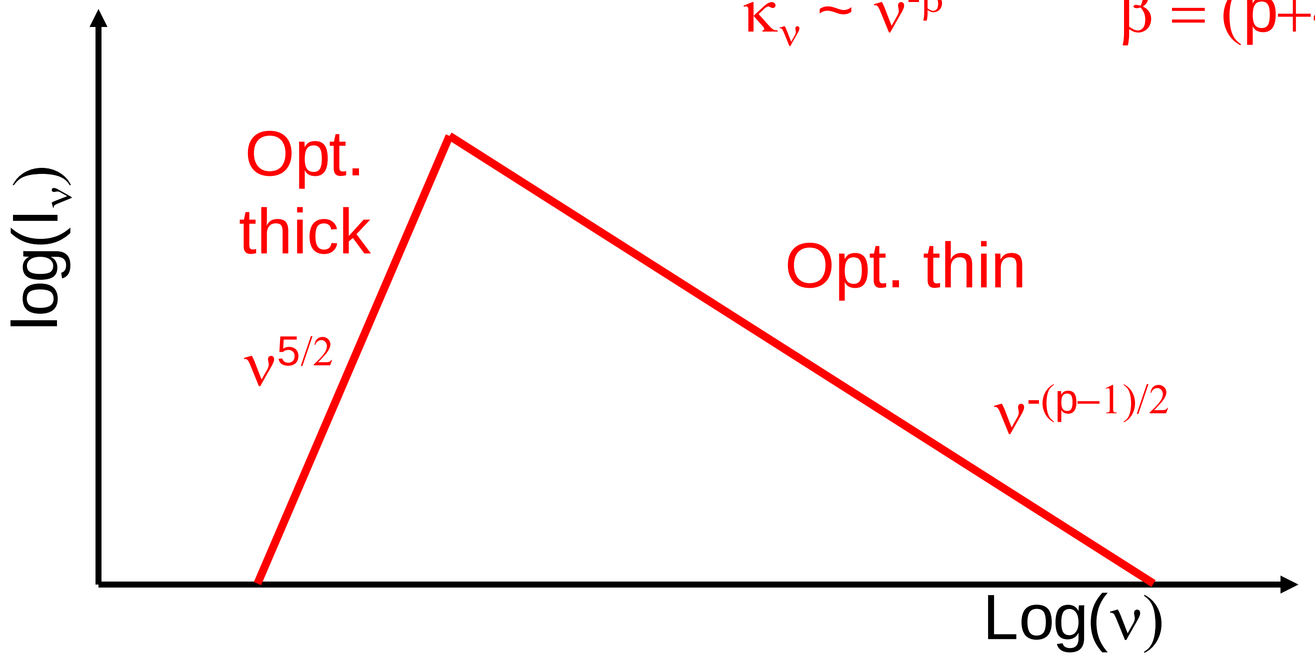
Power-law distribution of relativistic electrons:

$$N_e(\gamma) \sim \gamma^{-p}$$

If there are electrons with $\nu = \nu_{sy}(\gamma)$, then:

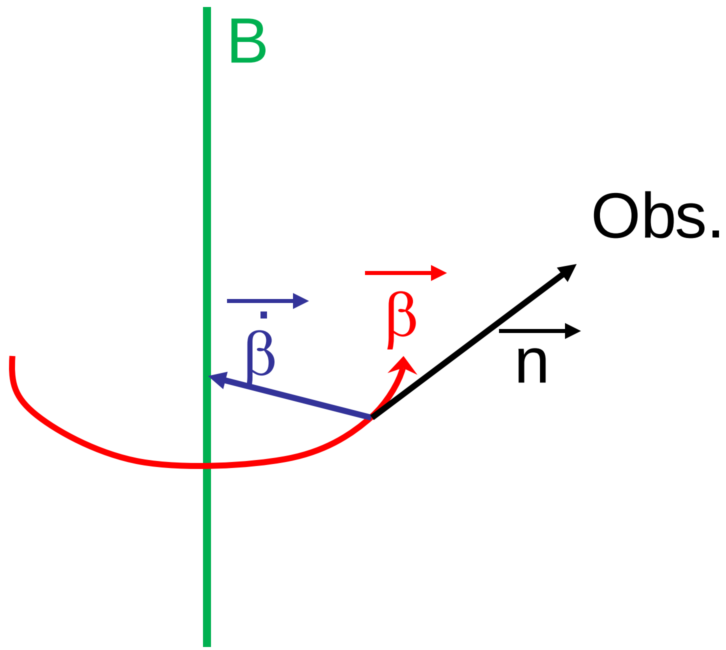
$j_\nu \sim \nu^{-\alpha}$ $\alpha = (p-1)/2$

$\kappa_\nu \sim \nu^{-\beta}$ $\beta = (p+4)/2$



Polarization

Preferred direction of E-field vectors of radiation



$$\vec{E}_{rad} \sim \vec{n} \times [(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}]$$

$\vec{E}_{rad}$ predominantly $\perp$ to projection of $\vec{B}$

Synchrotron Polarization

Calculate polarization-dependent intensities $I_\nu^\perp$ and $I_\nu^\parallel$ perpendicular and parallel to B-field projection

Degree of Polarization:

$$\Pi = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{I_\nu^\perp - I_\nu^\parallel}{I_\nu^\perp + I_\nu^\parallel}$$

In perfectly ordered, homogeneous B-field:

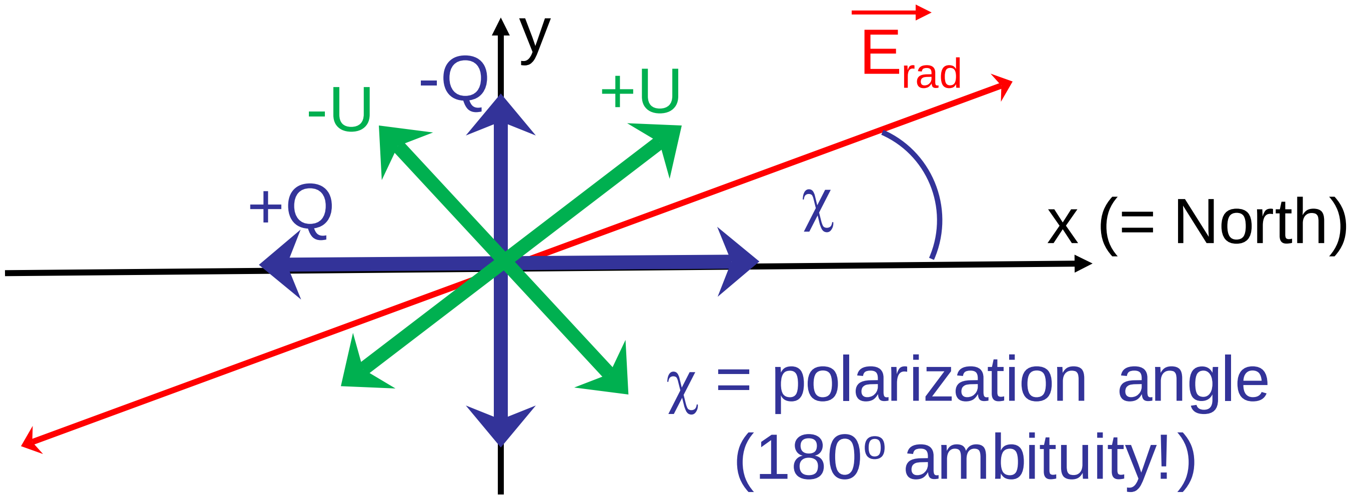
$$\Pi = \frac{p+1}{p+7/3} = \frac{\alpha+1}{\alpha+5/3}$$

$(\alpha = \frac{p-1}{2})$

$p = 2 \rightarrow \Pi = 69\ \%$

$p = 3 \rightarrow \Pi = 75\ \%$

Stokes Parameters



Define Stokes Parameters:

I = Total intensity -> Polarized Intensity $I_{pol} = \Pi\ I$

Q = I_{pol} cos(2β) cos(2χ) (β = phase-shift y vs. x => circ. pol.)

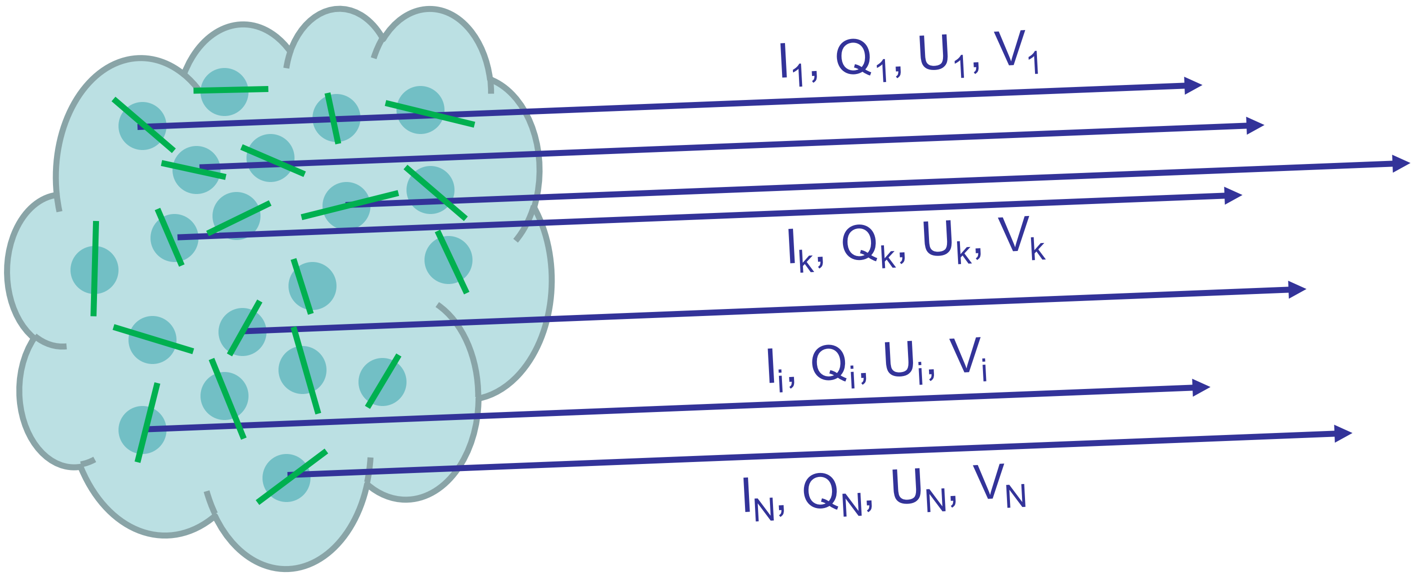
U = I_{pol} cos(2β) sin(2χ)

V = I_{pol} sin(2β) = circularly polarized intensity (typically, β << 1)

$$\Pi = \frac{\sqrt{Q^2+U^2+V^2}}{I}\ ; \qquad \tan(2\chi) = \frac{U}{Q}$$

Stokes Parameters

Stokes parameters are additive:



Simply add up Stokes parameters from different zones:

$$I_{total} = \sum_{k=1}^{N} I_k$$

$$Q_{total} = \sum_{k=1}^{N} Q_k$$

$$U_{total} = \sum_{k=1}^{N} U_k$$

$$V_{total} = \sum_{k=1}^{N} V_k$$

$$\Pi = \frac{\sqrt{Q_{total}^2 + U_{total}^2 + V_{total}^2}}{I_{total}}$$

$$\tan(2\chi) = \frac{U_{total}}{Q_{total}}$$

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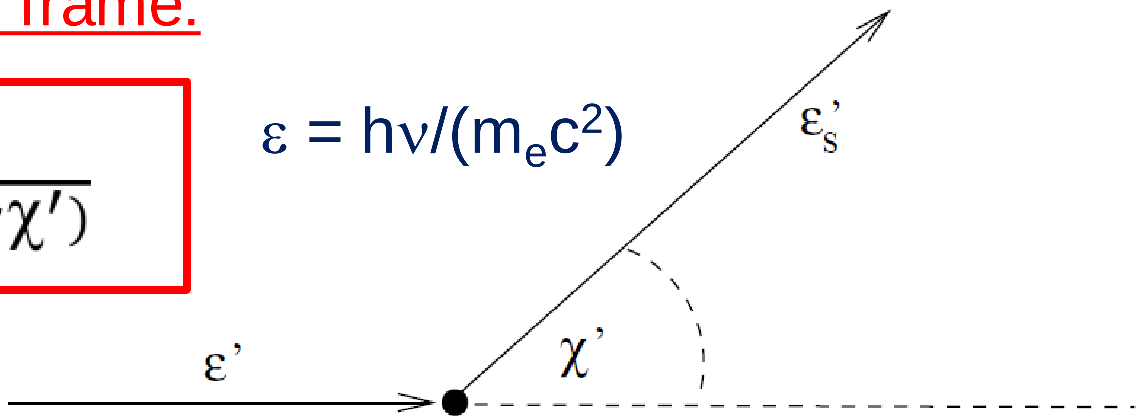
Compton Scattering

In the electron rest frame:

$$\varepsilon'_s = \frac{\varepsilon'}{1+\epsilon'(1-\cos\chi')}$$

$\varepsilon = h\nu/(m_e c^2)$

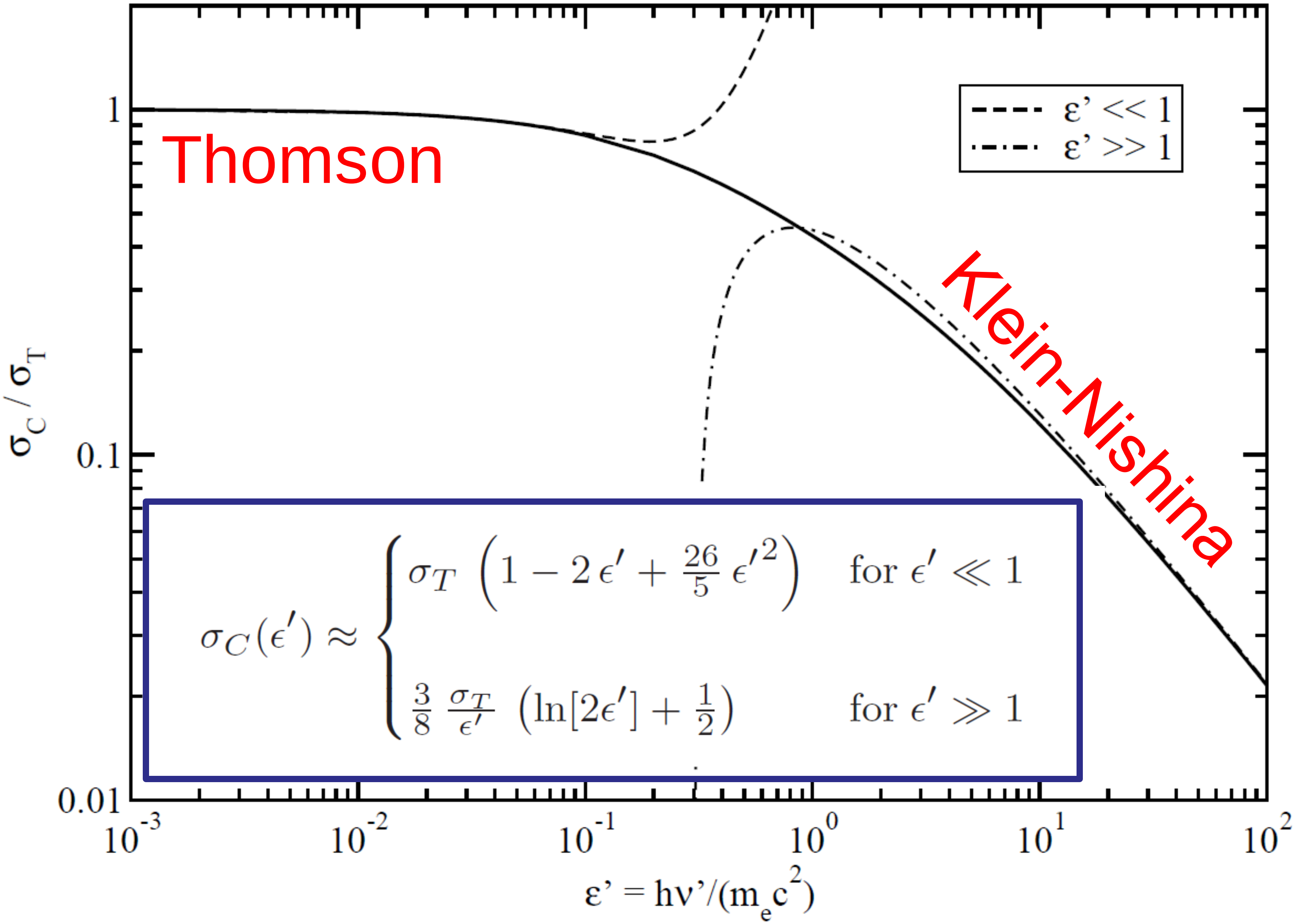


For $\varepsilon' \ll 1 \rightarrow \varepsilon'_s \approx \varepsilon'$ (elastic scattering – Thomson Regime)

For $\varepsilon' \gg 1 \rightarrow \varepsilon'_s \sim 1$ (inelastic scattering – Klein-Nishina [KN] Regime)

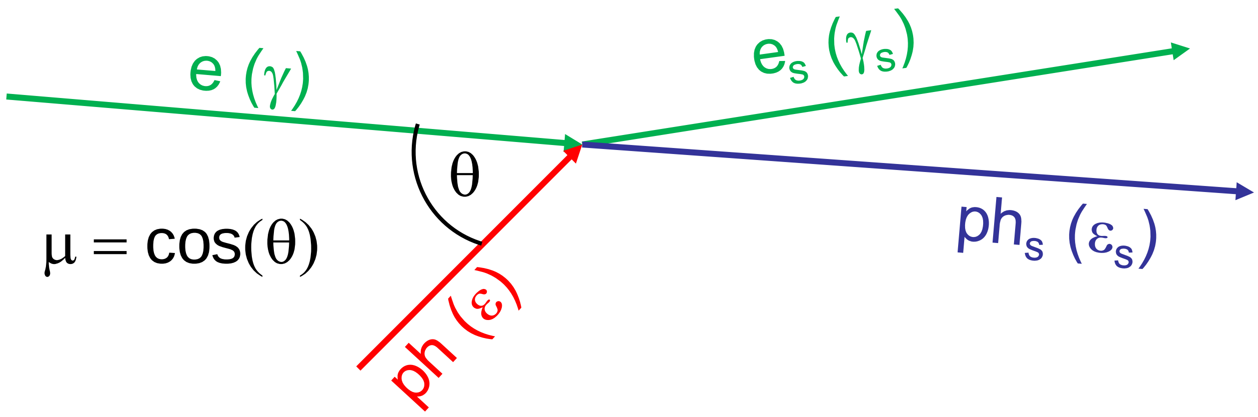
$$\sigma_C(\epsilon') = \frac{\pi r_e^2}{\epsilon'^2}\left(4 + \frac{2\,\epsilon'^2\,(1+\epsilon')}{(1+2\,\epsilon')^2} + \frac{\epsilon'^2 - 2\,\epsilon' - 2}{\epsilon'}\ \ln(1+2\,\epsilon')\right)$$

Compton Scattering



$$\sigma_C(\epsilon') \approx \begin{cases} \sigma_T \left(1 - 2\,\epsilon' + \frac{26}{5}\,\epsilon'^2\right) & \text{for } \epsilon' \ll 1 \\ \frac{3}{8}\,\frac{\sigma_T}{\epsilon'}\,\left(\ln[2\epsilon'] + \frac{1}{2}\right) & \text{for } \epsilon' \gg 1 \end{cases}$$

Compton Scattering by Relativistic Electrons – Thomson Regime



ph in electron rest frame ('): $\varepsilon' = \varepsilon\,\gamma\,(1 - \beta\mu)$

In Thomson Regime ($\varepsilon' \ll 1$): $\varepsilon_s' = \varepsilon'$

Doppler boost into lab frame: $\varepsilon_s = \gamma\,\varepsilon_s' = \varepsilon\,\gamma^2\,(1 - \beta\,\mu)$

Concentrated in forward direction (Ω_e)

Thomson approximation for differential cross section:

$$\frac{d\sigma_C}{d\varepsilon\, d\Omega_s} = \sigma_T\;\delta(\varepsilon_s - \varepsilon\,\gamma^2\,[1 - \beta\mu])\;\delta(\Omega_s - \Omega_e)$$

Compton Losses and Spectra

Power output into Compton radiation (single electron): $(\frac{dE}{dt})_C\,(\gamma) = \frac{4}{3}\ c\ \sigma_T\ u_{rad}\ \gamma^2\beta^2$

Delta-function approximation for single-electron emissivity:

$$P_\nu\,(\gamma) \approx (\frac{dE}{dt})_C\ \delta(\nu - \nu_C[\gamma])$$

$$\nu_C(\gamma) \sim \nu_0\,\gamma^2$$

$$j_\nu = \int_1^\infty d\gamma\ P_\nu(\gamma)\ N_e(\gamma) \sim N_e(\gamma_c)\ \nu^{1/2}$$

$$\gamma_c = (\nu/\nu_0)^{1/2}$$

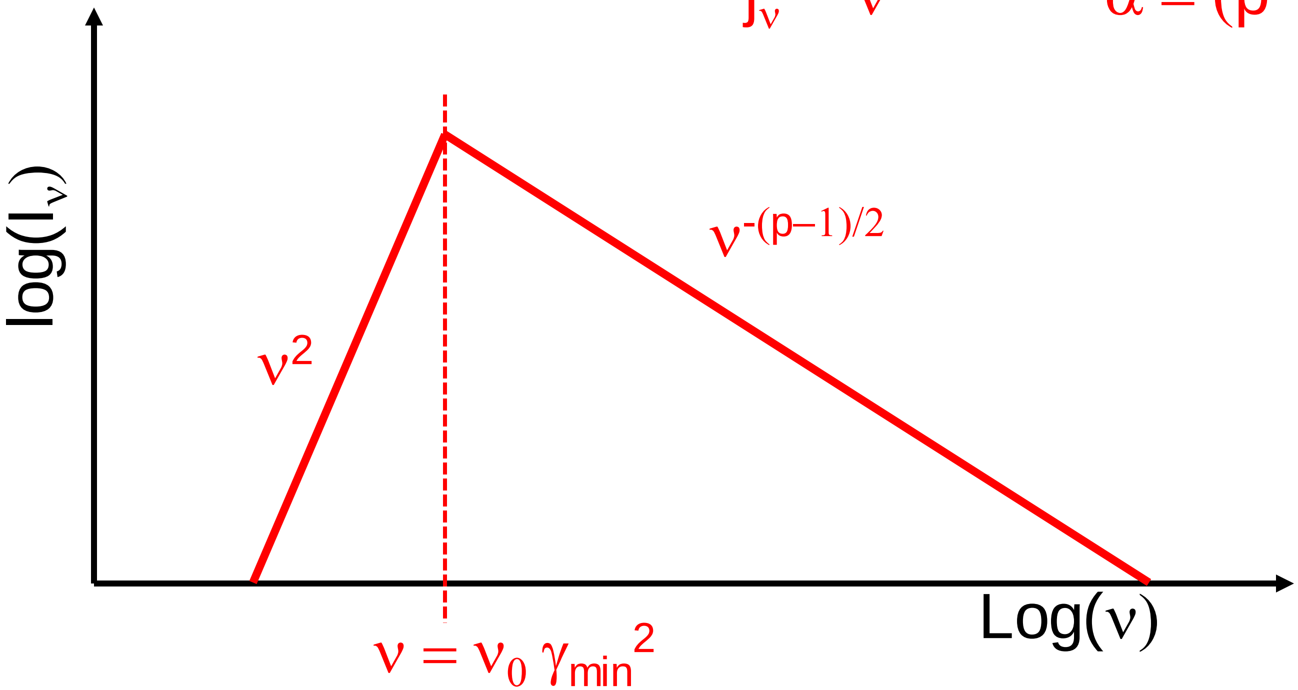
Compton Spectra

Power-law distribution of relativistic electrons:

$$N_e(\gamma) \sim \gamma^{-p}$$

If there are electrons with $\nu = \nu_C\,(\gamma)$, then:

$j_\nu \sim \nu^{-\alpha}$ $\alpha = (p-1)/2$



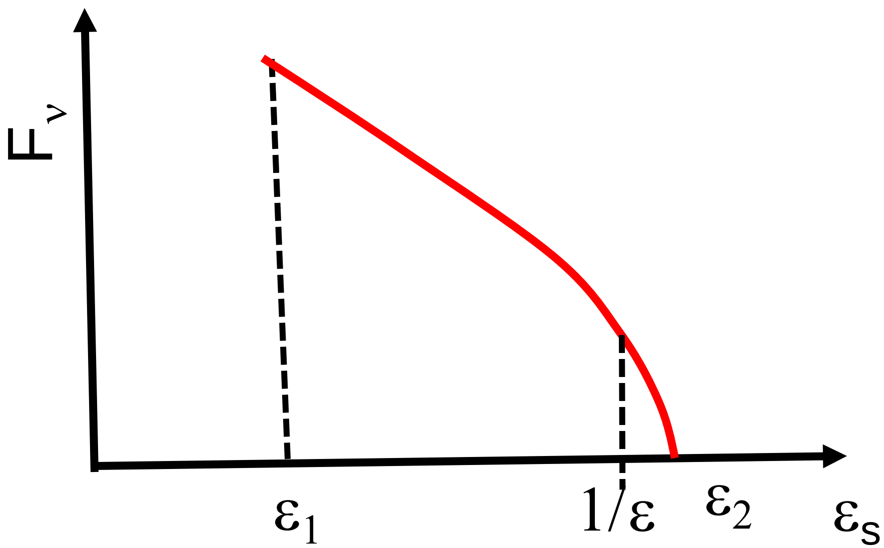
Compton Scattering by Relativistic Electrons – KN Regime

ph in electron rest frame ('): $\varepsilon' = \varepsilon\, \gamma\, (1 - \beta\mu)$

In the KN-Regime ($\varepsilon' >> 1$): $\varepsilon_s' = 1$

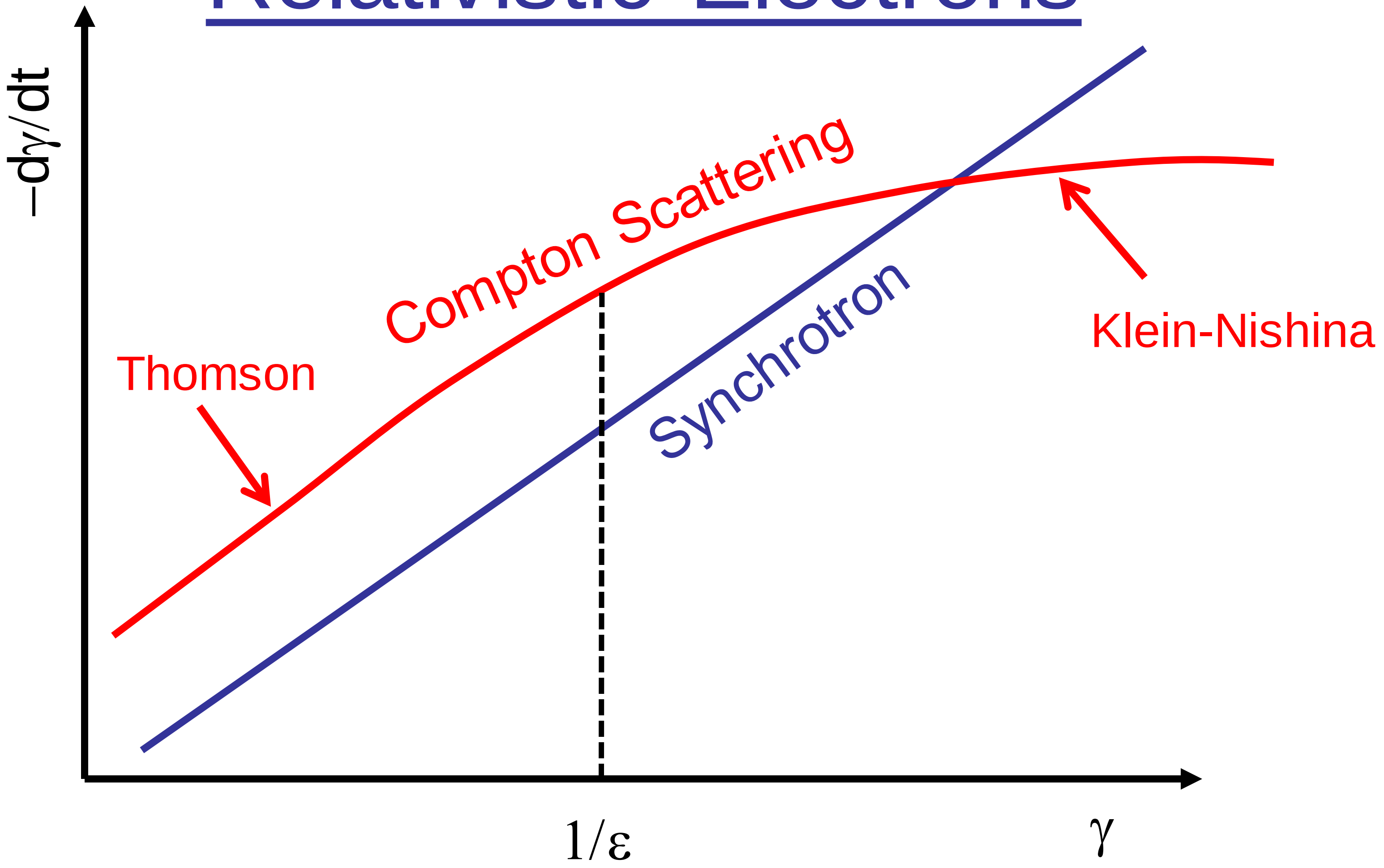
Doppler boost into lab frame: $\varepsilon_s = \gamma\, \varepsilon_s' = \gamma$

$\Rightarrow$ Photon takes all of the electron's energy
($\varepsilon_s \sim \varepsilon\gamma^2 > \gamma$ $\rightarrow$ would violate energy conservation!)



Cut-off in the resulting Compton-scattered spectra around $\varepsilon_s \sim 1/\varepsilon$

Total Energy Loss Rate of Relativistic Electrons



Compton energy loss becomes less efficient at high energies (Klein-Nishina regime).

Compton Polarization

Compton cross section is polarization-dependent:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4}\left(\frac{\epsilon'}{\epsilon}\right)^2\left(\frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4\left[\vec{e}\cdot\vec{e}'\right]^2\right)$$

(e^- rest frame)

$\varepsilon = h\nu/(m_e c^2)$

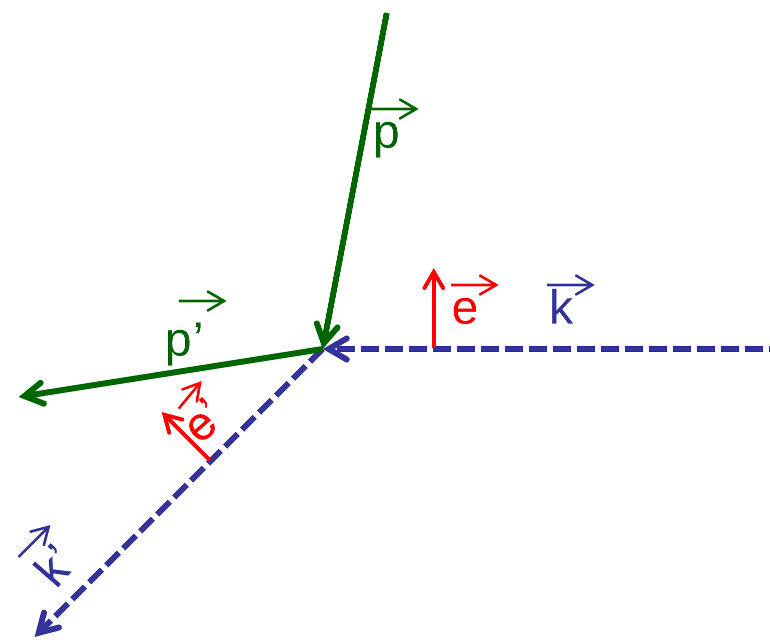
Thomson regime: $\varepsilon \approx \varepsilon'$

$\Rightarrow d\sigma/d\Omega = 0$ if $\vec{e}\cdot\vec{e}' = 0$

$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!

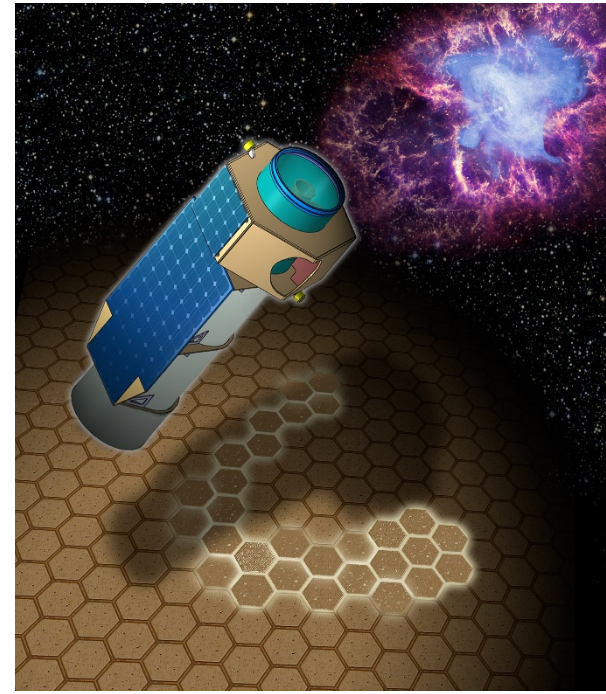
Preferred EVPA is preserved.

Scattering of polarized rad. by relativistic e^- => Π reduced to ~ ½ of target-photon polarization.

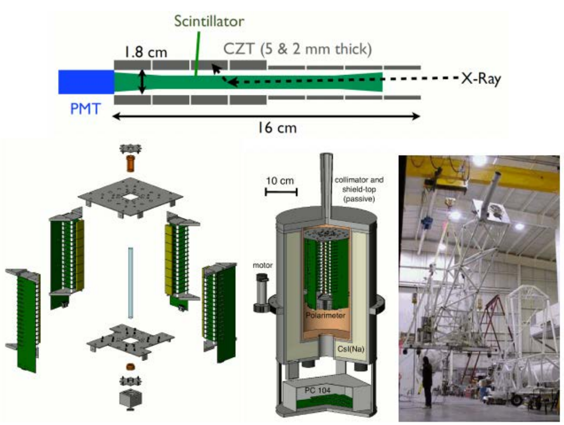


X-ray Polarimeters

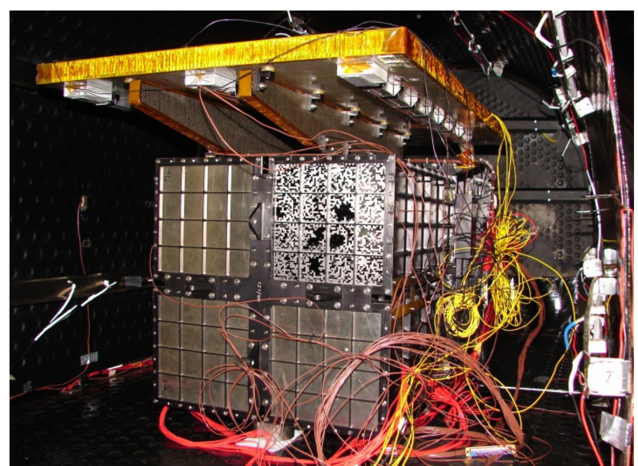
INTEGRAL



XIPE

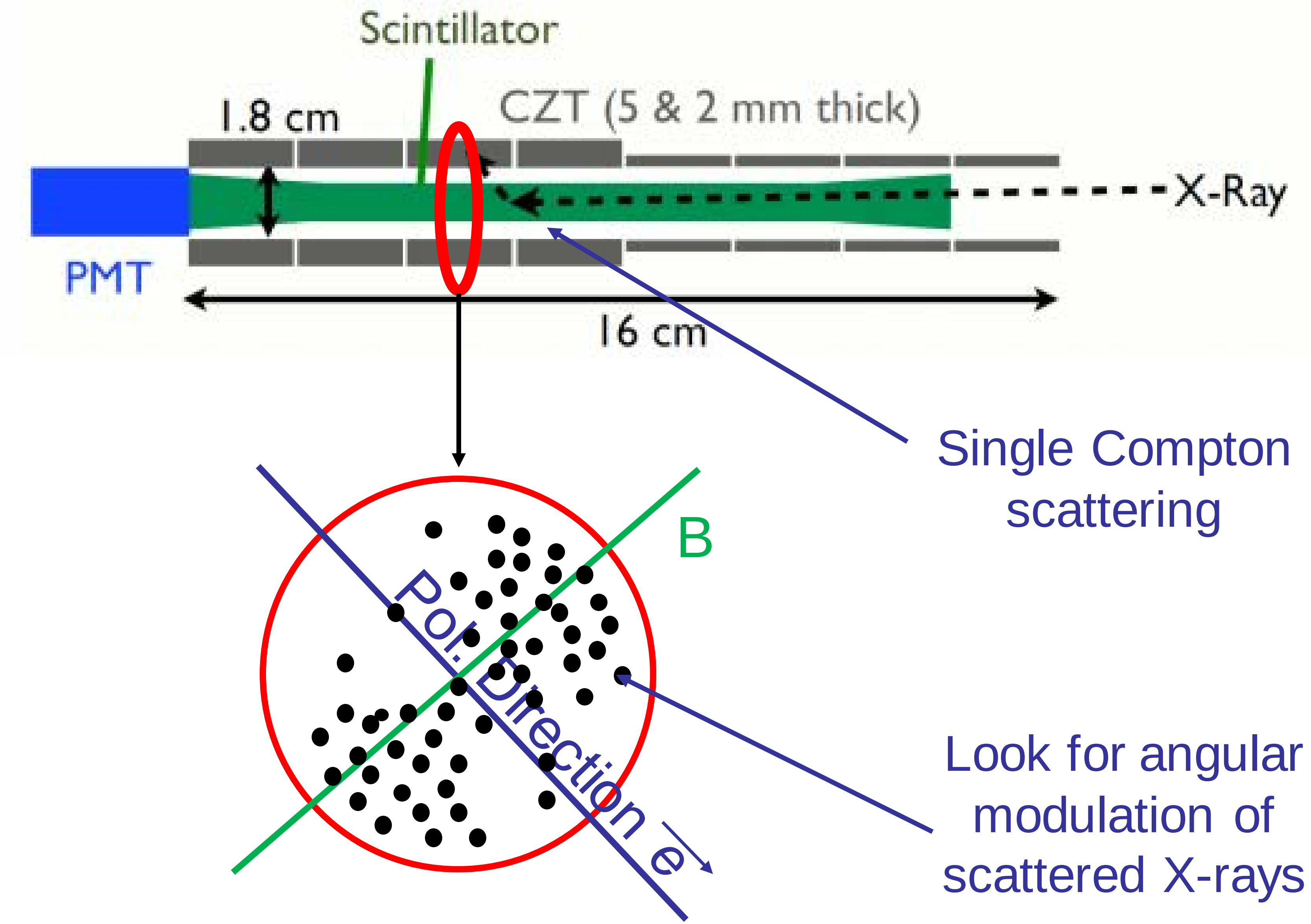


X-Calibur
→ PolSTAR

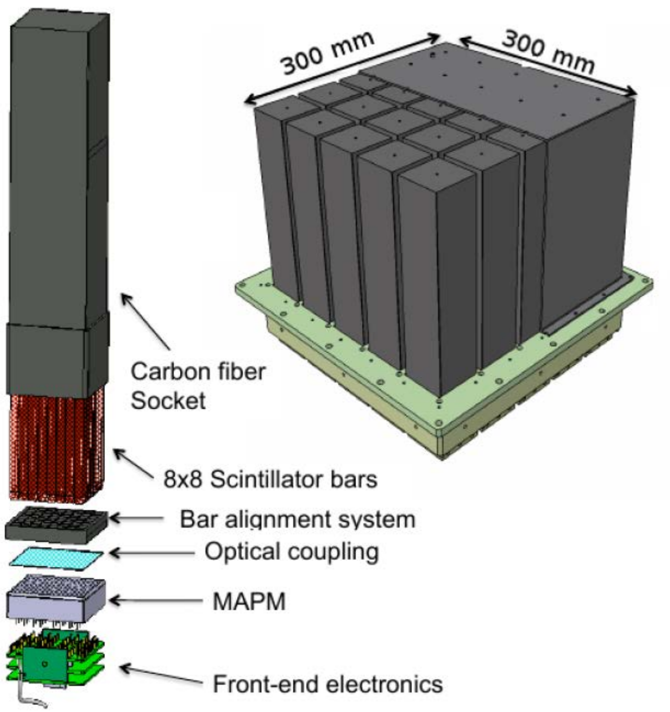


ASTROSAT

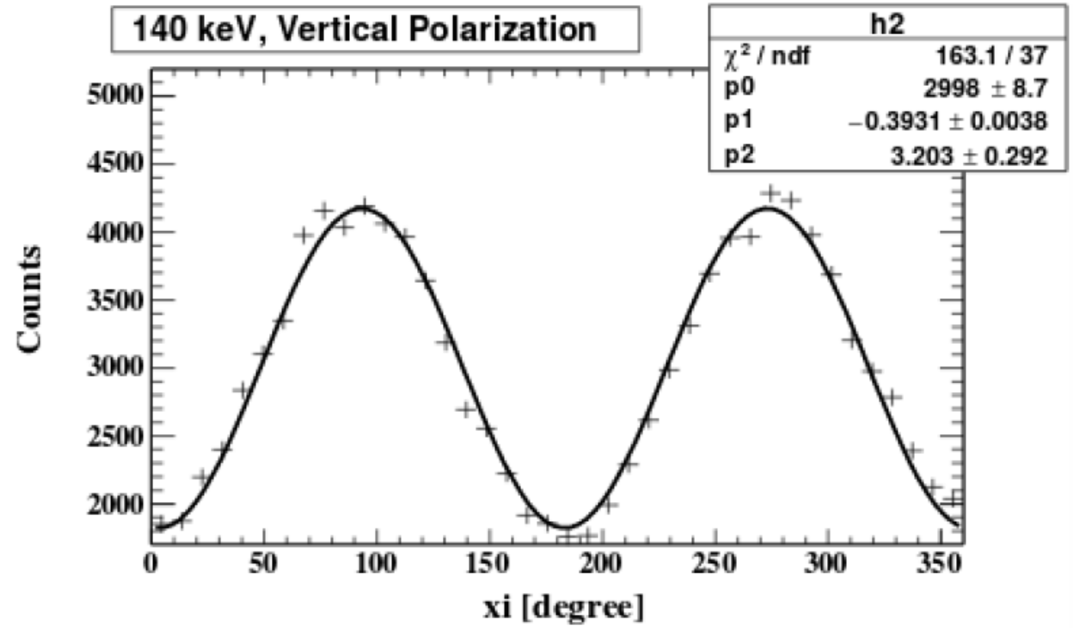
X-Ray Polarimeters

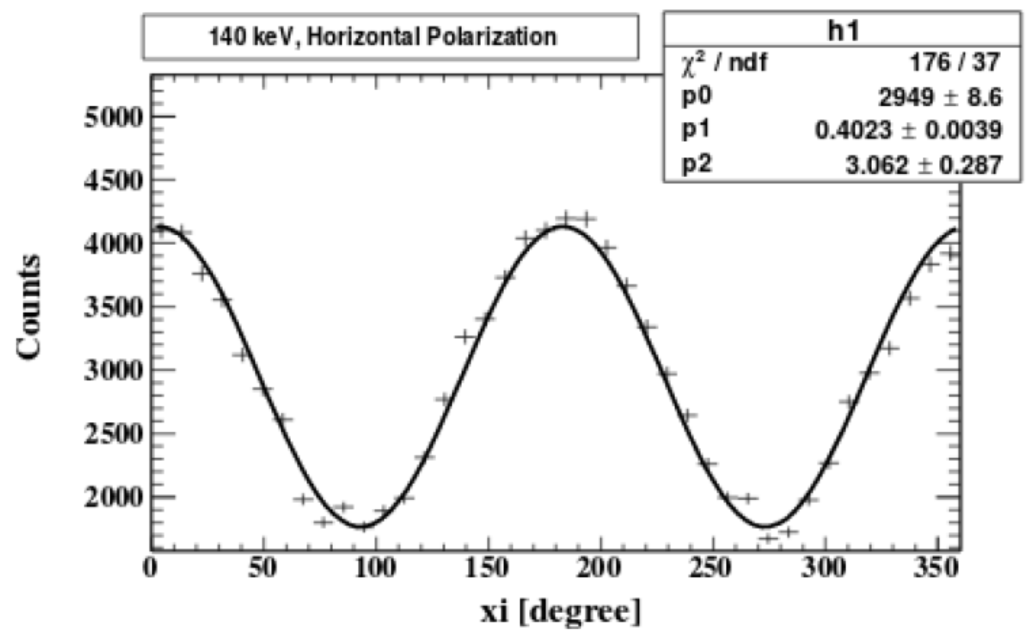


X-Ray Polarimetry

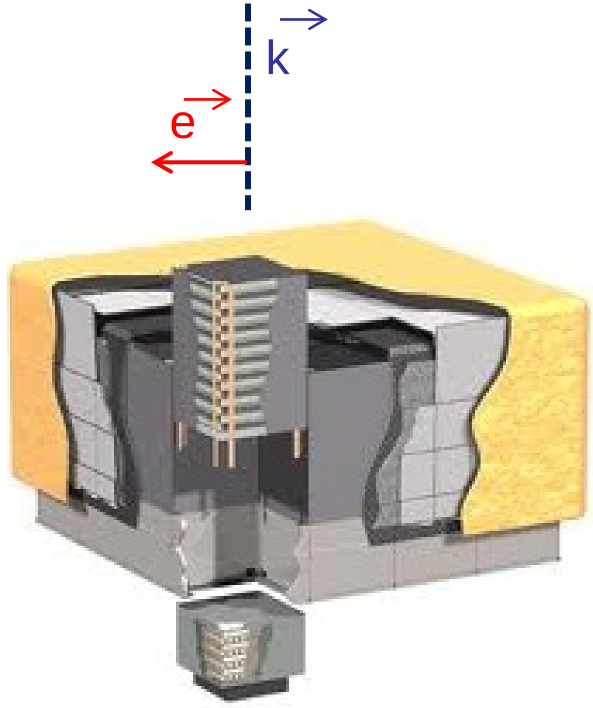


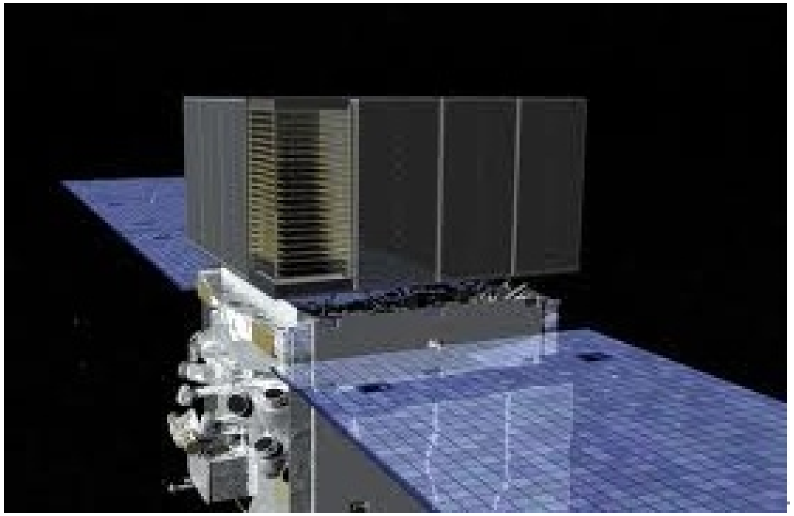
(POLAR: Kole et al. 2016)





Gamma-Ray Polarimetry with Fermi-LAT





e^+e^- pair is preferentially produced in the plane of ($\vec{k}$, $\vec{e}$) of the γ-ray.

Potentially detectable at E < 200 MeV

→ PANGU / eASTROGAM


Thank you!

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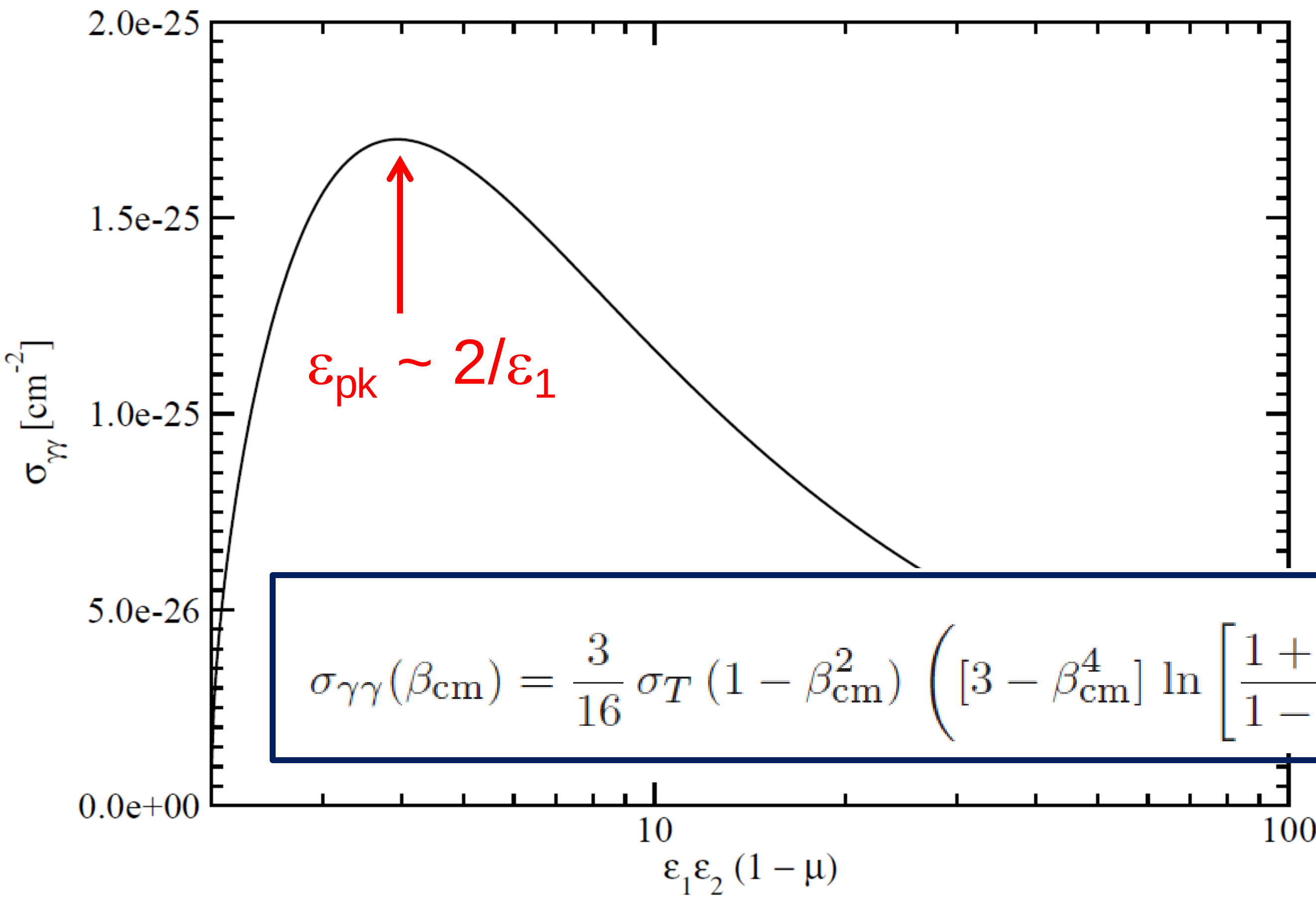
3. Introduction to Compton Scattering (spectra, energy losses, Compton polarization, X-ray/γ-ray polarimetry)

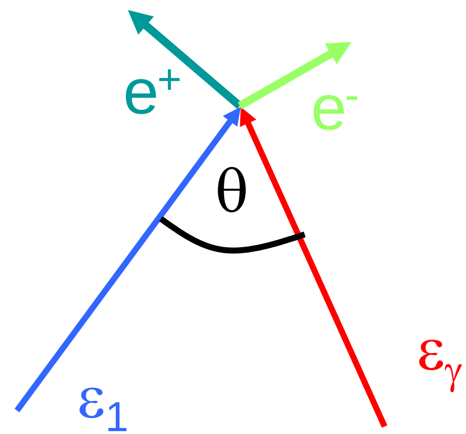
4. Introduction to $\gamma\gamma$ absorption / pair production, Doppler factor estimate from $\gamma\gamma$ opacity

$\gamma\gamma$ Absorption and Pair Production

Threshold energy ε_{thr} of a γ-ray to interact with a background photon with energy ε_1:

$$\varepsilon_{thr} = \frac{2}{\varepsilon_1 \, (1 - \cos\theta)}$$





$$\sigma_{\gamma\gamma}(\beta_{\rm cm}) = \frac{3}{16}\,\sigma_T\,(1-\beta_{\rm cm}^2)\left([3-\beta_{\rm cm}^4]\,\ln\left[\frac{1+\beta_{\rm cm}}{1-\beta_{\rm cm}}\right] - 2\,\beta_{\rm cm}\,[2-\beta_{\rm cm}^2]\right)$$

$\gamma\gamma$ Absorption

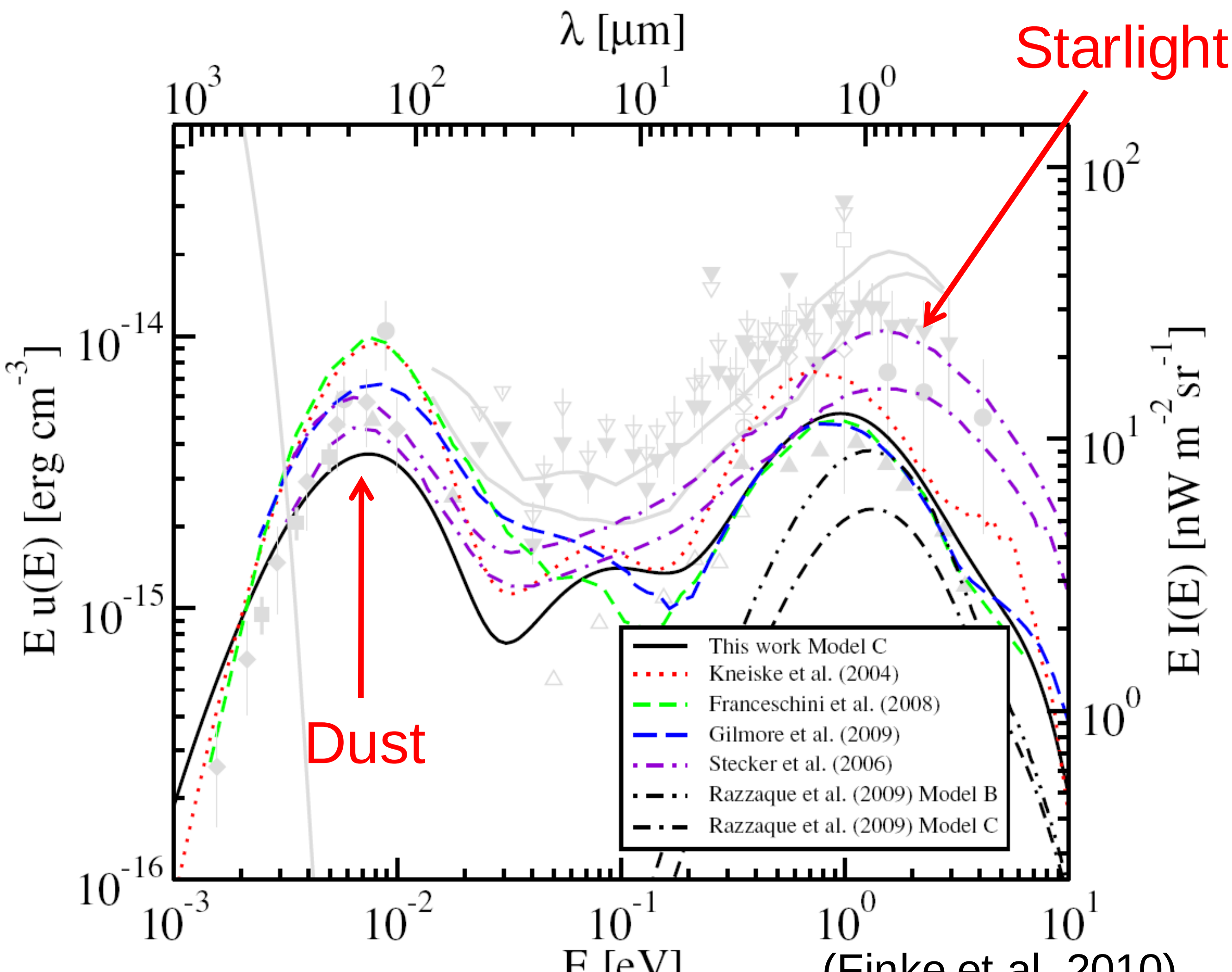
Delta-Function Approximation:

$$\sigma_{\gamma\gamma}^{\delta}(\epsilon_1, \epsilon_2) = \frac{1}{3}\,\sigma_T\,\epsilon_1\,\delta\left(\epsilon_1 - \frac{2}{\epsilon_2}\right)$$

VHE gamma-rays interact preferentially with IR photons:

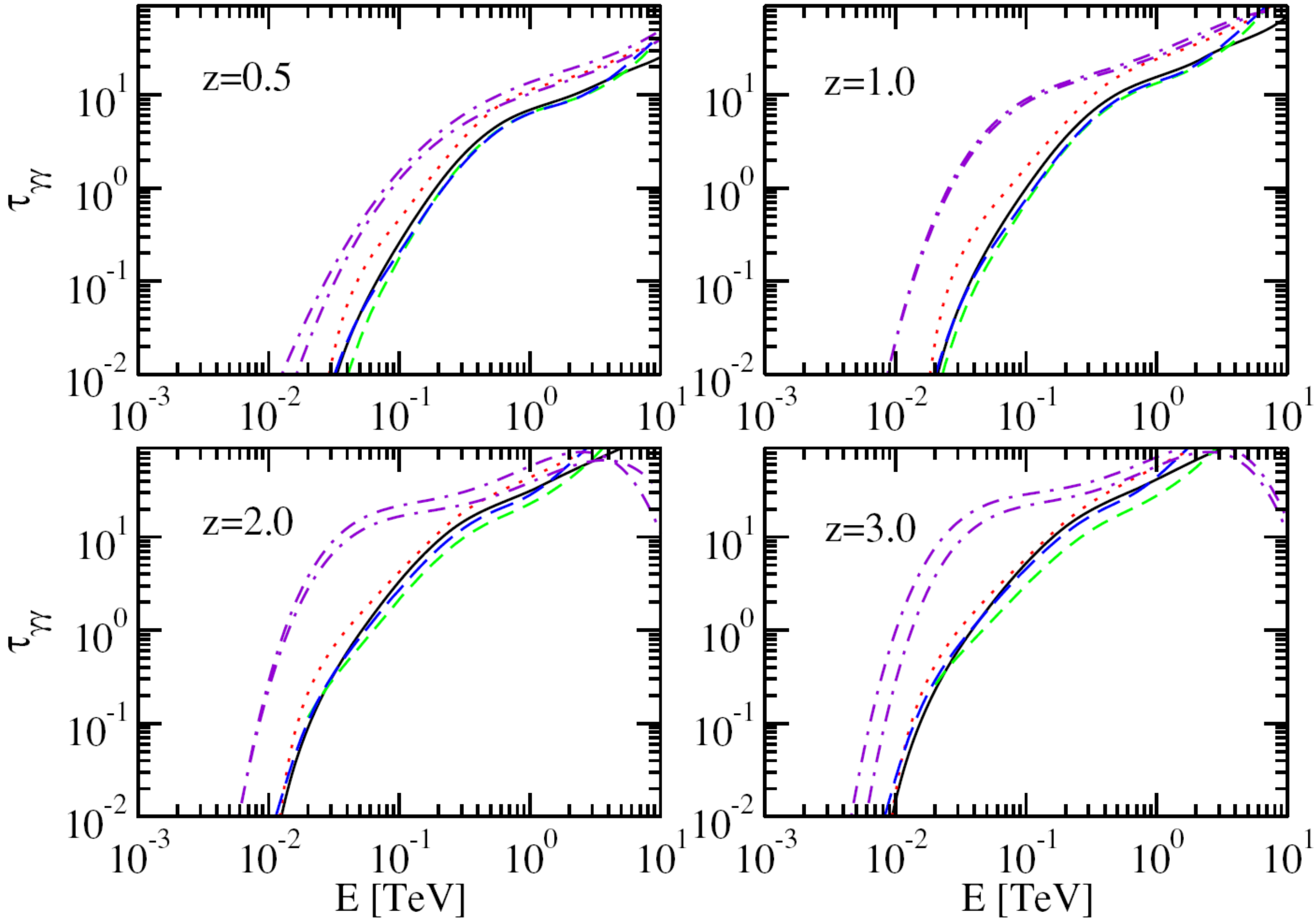
$$\lambda_2 = 2.4\,E_{1,\mathrm{TeV}}\;\mu\mathrm{m}$$

Spectrum of the Extrgalactic Background Light (EBL)



(Finke et al. 2010)

EBL Absorption



(Finke et al. 2010)

$\gamma\gamma$ Absorption Intrinsic to the Source

Optical depth to $\gamma\gamma$-absorption:

$$\tau_{\gamma\gamma}(\epsilon_\gamma) \sim n_{ph} \left(\frac{2}{\varepsilon_\gamma}\right) R \sigma_T$$

$$n_{ph} \sim \frac{L}{4\pi\, R^2\, c\, \varepsilon\, m_e c^2} = \frac{4\pi\, d_L{}^2\, F}{4\pi\, R^2\, c\, \varepsilon\, m_e c^2}$$

Importance of intrinsic $\gamma\gamma$-absorption is estimated by the Compactness Parameter:

$$\ell = \frac{L_\gamma\, \sigma_T}{4\,\pi\, R\, \langle\epsilon\rangle\, m_e c^3}$$

$\gamma\gamma$ Absorption Intrinsic to the Source

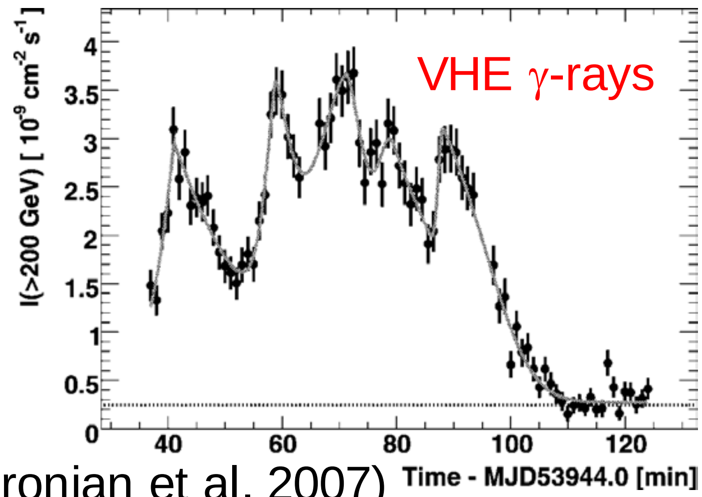
Estimate R from variability time scale:

$$R \sim c\Delta t_{var}$$

Optical depth to $\gamma\gamma$-absorption:

$$\tau_{\gamma\gamma}(\epsilon_\gamma) \sim \frac{d_L{}^2 \, F_\epsilon \left(\frac{2}{\epsilon_\gamma}\right) \sigma_T}{\Delta t_{var} \left(\frac{2}{\varepsilon_\gamma}\right) m_e c^4}$$

PKS 2155-304

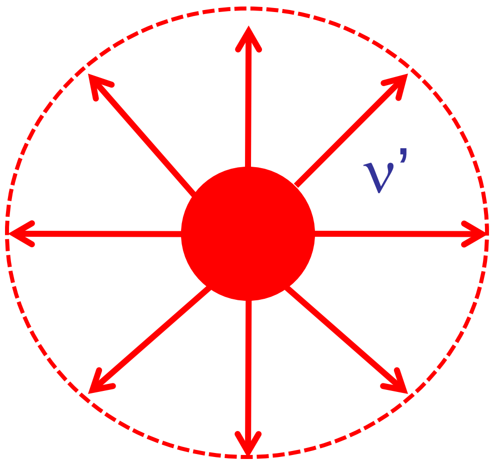


(Aharonian et al. 2007)

With F_x and Δt_{var} from PKS 2155-304: $\tau_{\gamma\gamma}$ (ε_{TeV}) >> 1

Relativistic Beaming / Boosting

In the co-moving frame of the emission region:



Isotropic emission $I'_{\nu'}$ at frequency ν'

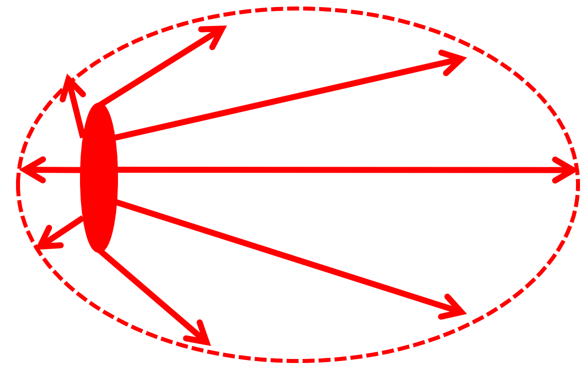
Time interval t'_{var}

$$\Gamma = (1 - \beta_\Gamma{}^2)^{-1/2}$$

In the stationary (observer’s) frame:

$\delta = (\Gamma[1 - \beta_\Gamma \cos\theta])^{-1}$:

Doppler boosting factor



Beamed emission:

$I_\nu = \delta^3 \, I'_{\nu'}$ $\qquad$ $\nu = \delta \, \nu'$

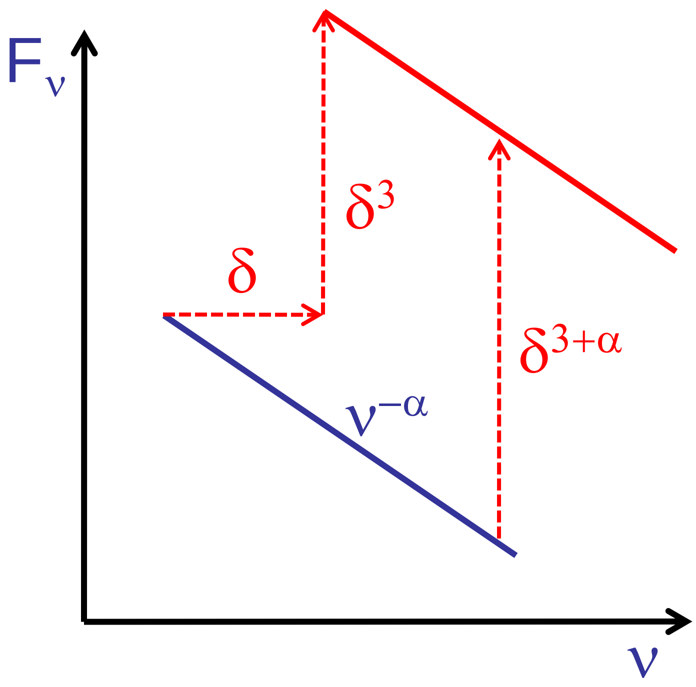
For power-law $F_\nu \sim \nu^{-\alpha}$:

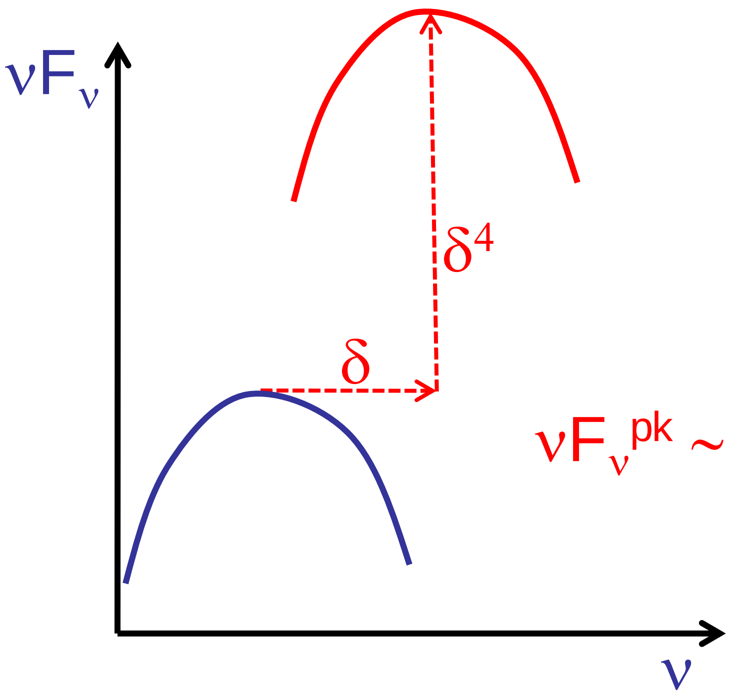
$F_\nu = \delta^{(3+\alpha)} \, F'_\nu$

Time interval

$t_{var} = t'_{var} / \delta$

Relativistic Beaming / Boosting





$$\nu F_\nu^{pk} \sim \frac{L}{4\pi\, d_L^{\,2}}$$

$L \sim \delta^4 L'$

$\gamma\gamma$ Absorption Intrinsic to the Source

Optical depth to $\gamma\gamma$-absorption:

$$\tau_{\gamma\gamma}(\epsilon_\gamma) \sim \frac{{d_L}^2\, F_\epsilon\,(\frac{2}{\epsilon_\gamma})\,\sigma_T}{\Delta t_{var}\,(\frac{2}{\varepsilon_\gamma})\, m_e c^4}$$

$$F_\varepsilon = \delta^{-(3+\alpha)}\, {F_\epsilon}^{obs}$$

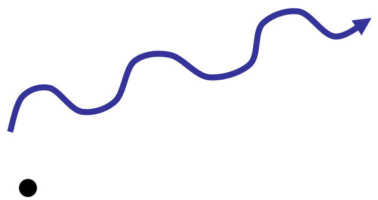
$$\varepsilon_\gamma = {\varepsilon_\gamma}^{obs}/\delta$$

$$\Delta t_{var} = \delta\, \Delta {t_{var}}^{obs}$$

$$\Rightarrow \tau_{\gamma\gamma} \propto \delta^{-(5+\alpha)}$$

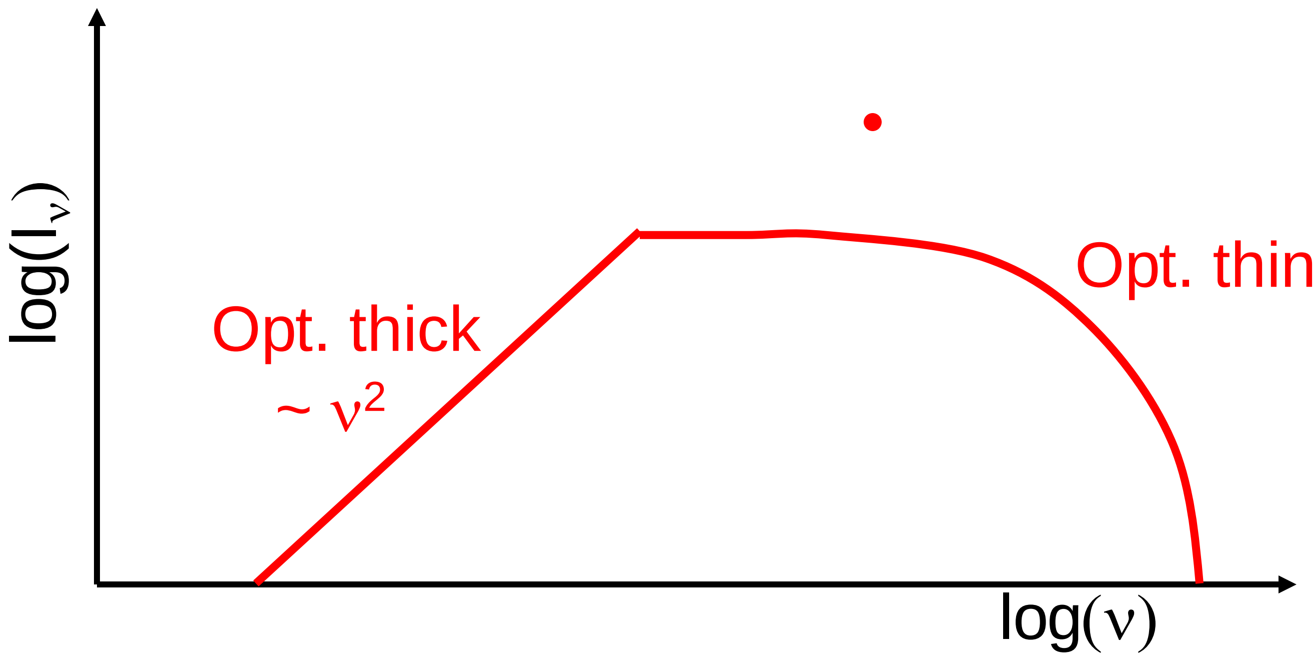
Radiation Mechanisms

Bremsstrahlung

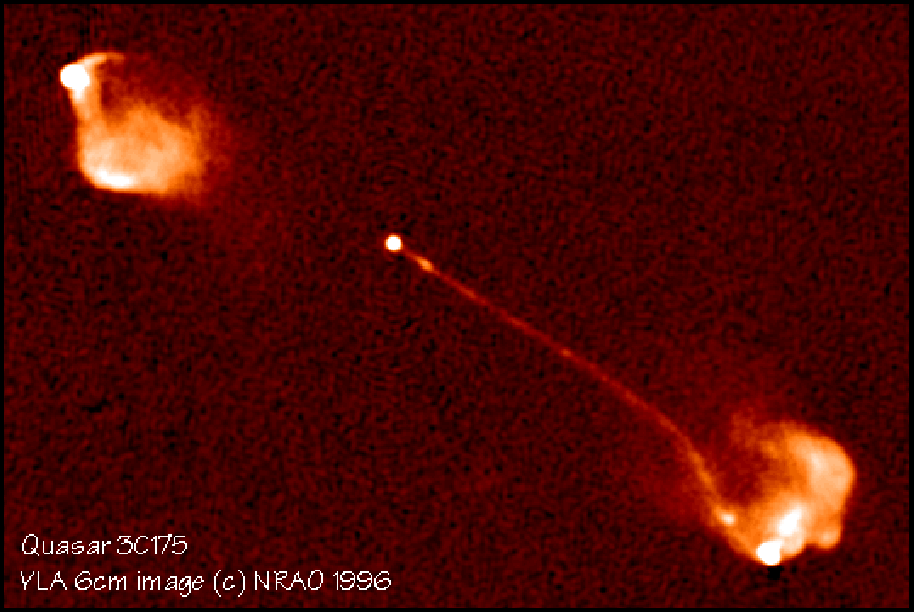


$\varepsilon_\nu \sim e^{-(h\nu/kT)}$

$$\alpha_\nu = \frac{\varepsilon_\nu}{B_\nu(t)} \propto \left(1 - e^{-h\nu/kT}\right)/\nu^3$$

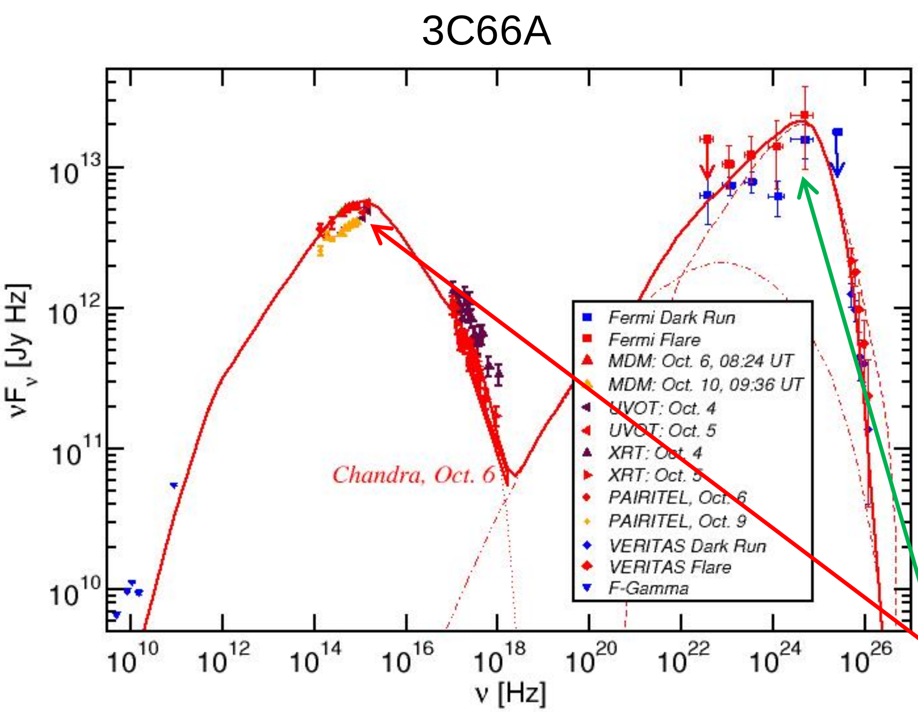


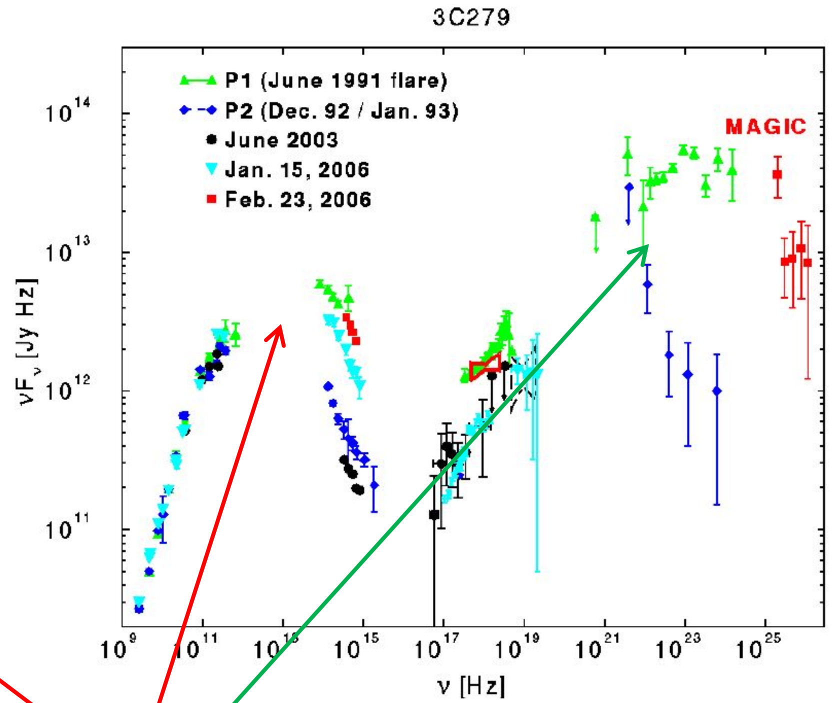
Blazars



- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio jets, often with superluminal motion
- Radio and optical polarization

Blazar Spectral Energy Distributions (SEDs)





Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

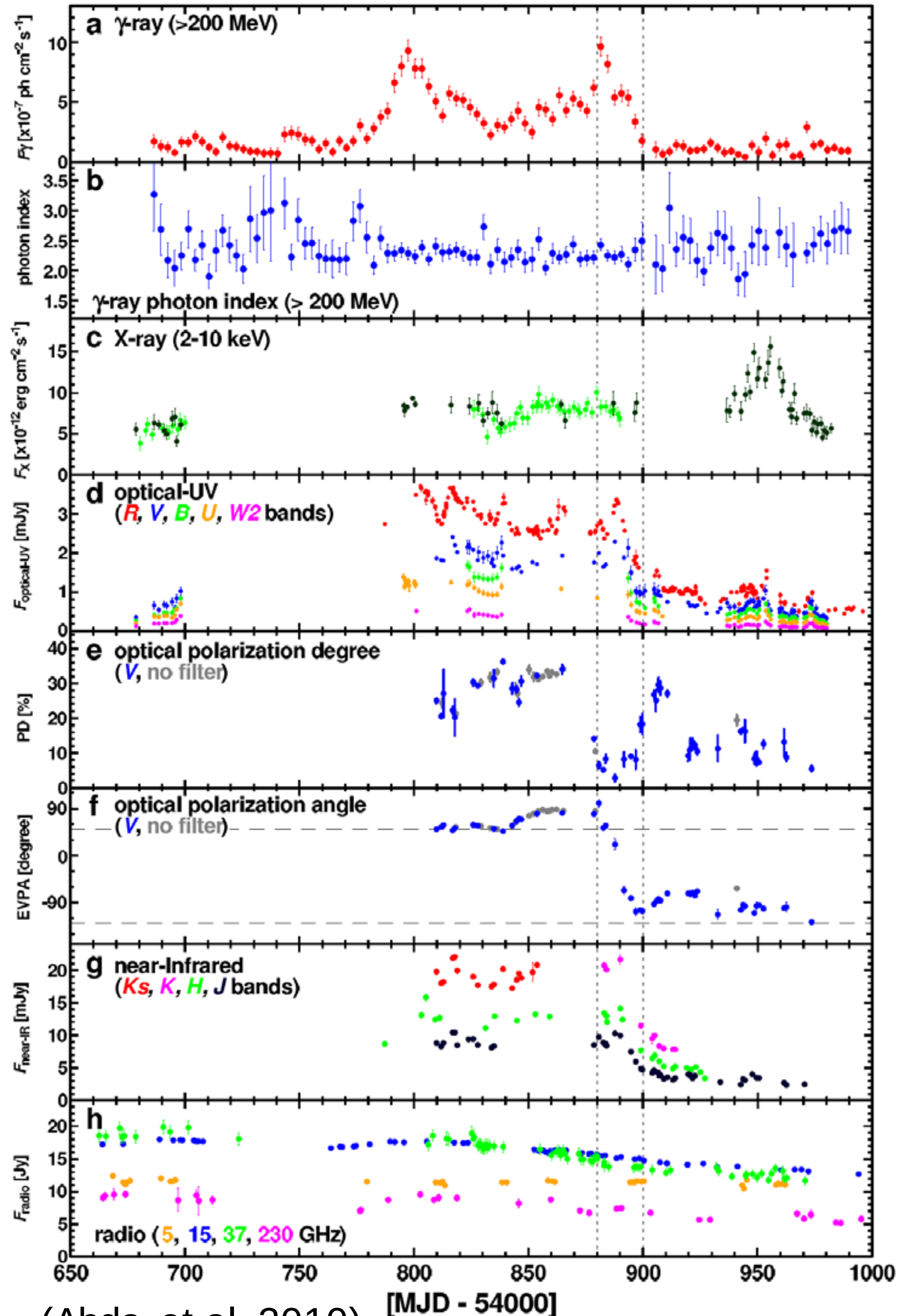
Flux and Polarization Variability

Multi-wavelength variability on various time scales (months – minutes)
Sometimes correlated, sometimes not

Observed polarization fractions
Π_{obs} <~ 10 % << Π_{max}

=> Not perfectly ordered magnetic fields!

Both degree of polarization and polarization angles vary.
Swings in polarization angle sometimes associated with high-energy flares!



(Abdo et al. 2010)

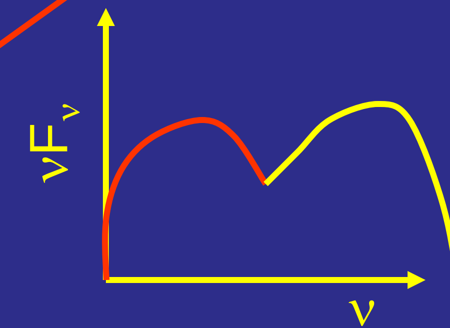
Open Physics Questions

- Source of Jet Power (Blandford-Znajek / Blandford/Payne?)
- Physics of jet launching / collimation / acceleration – role / topology of magnetic fields
- Composition of jets (e^--p or e^+-e^- plasma?) – leptonic or hadronic high-energy emission?
- Mode of particle acceleration (shocks / shear layers / magnetic reconnection?) - role of magnetic fields
- Location of the energy dissipation / gamma-ray emission region

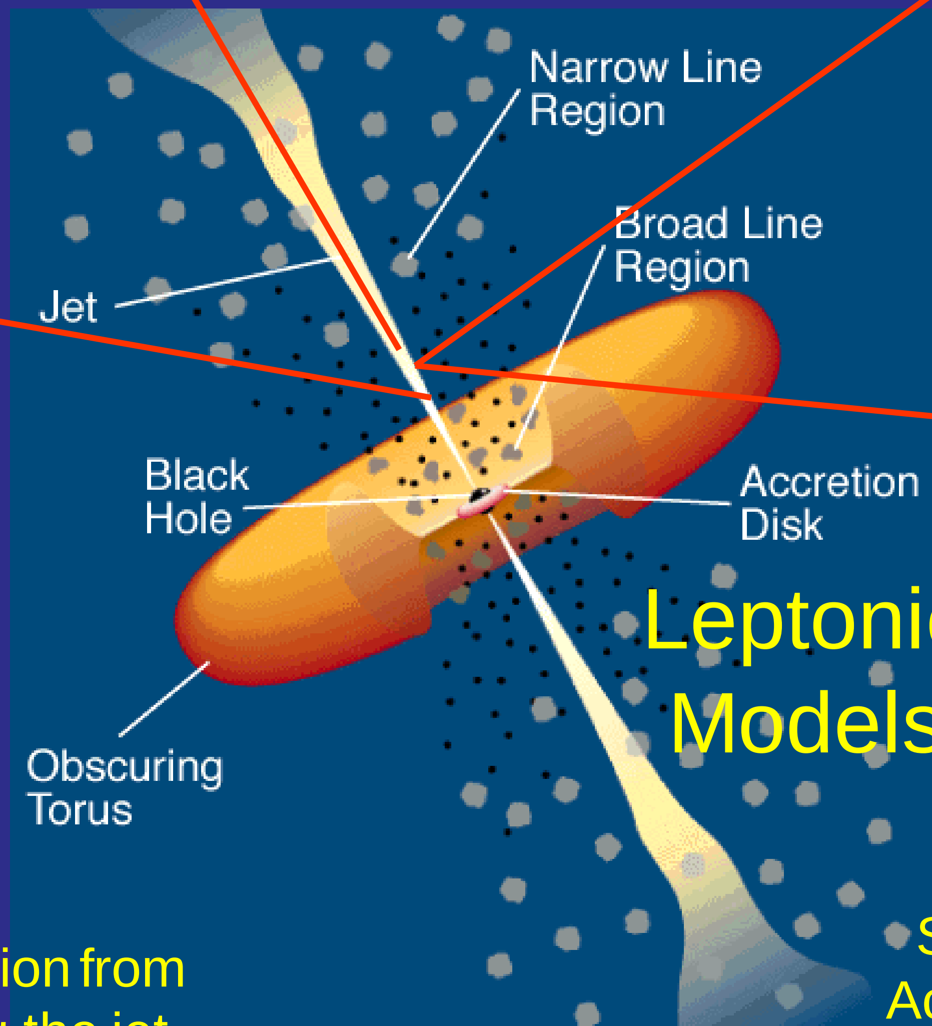
Blazar Models

Relativistic jet outflow with $\Gamma \approx 10$

Synchrotron emission

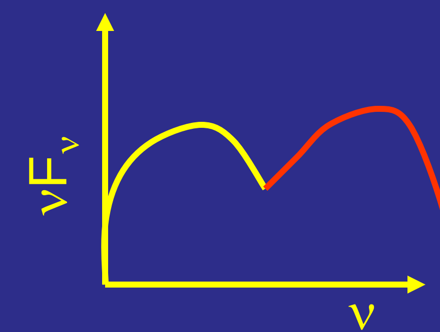


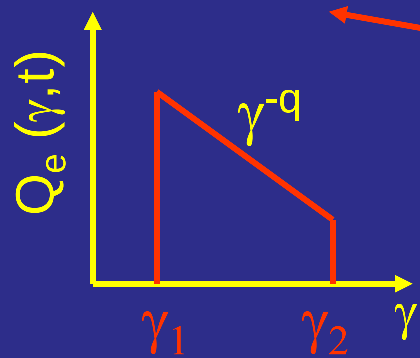
Injection, acceleration of ultrarelativistic electrons



Leptonic Models

Compton emission





Injection over finite length near the base of the jet.

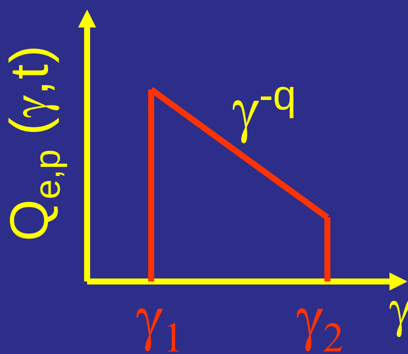
Additional contribution from $\gamma\gamma$ absorption along the jet

Seed photons:

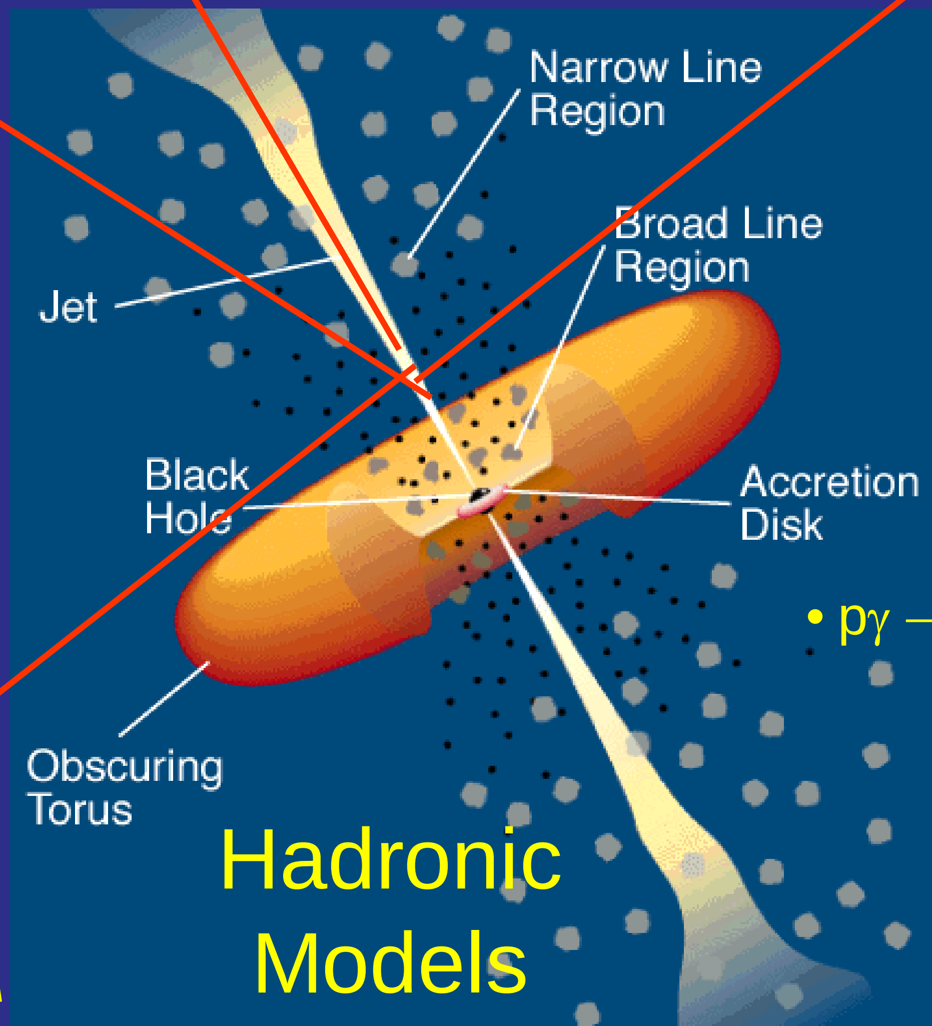
Synchrotron (SSC), Accr. Disk + BLR (EC)

Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

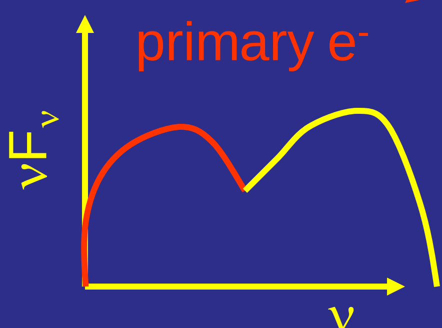


Relativistic jet outflow with $\Gamma \approx 10$

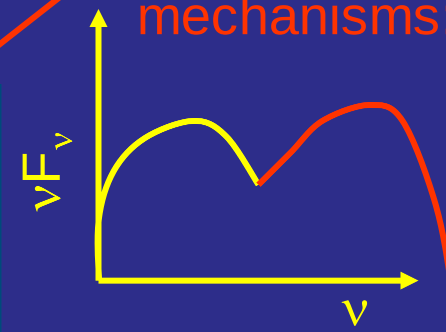


Hadronic Models

Synchrotron emission of primary e-



Proton-induced radiation mechanisms:



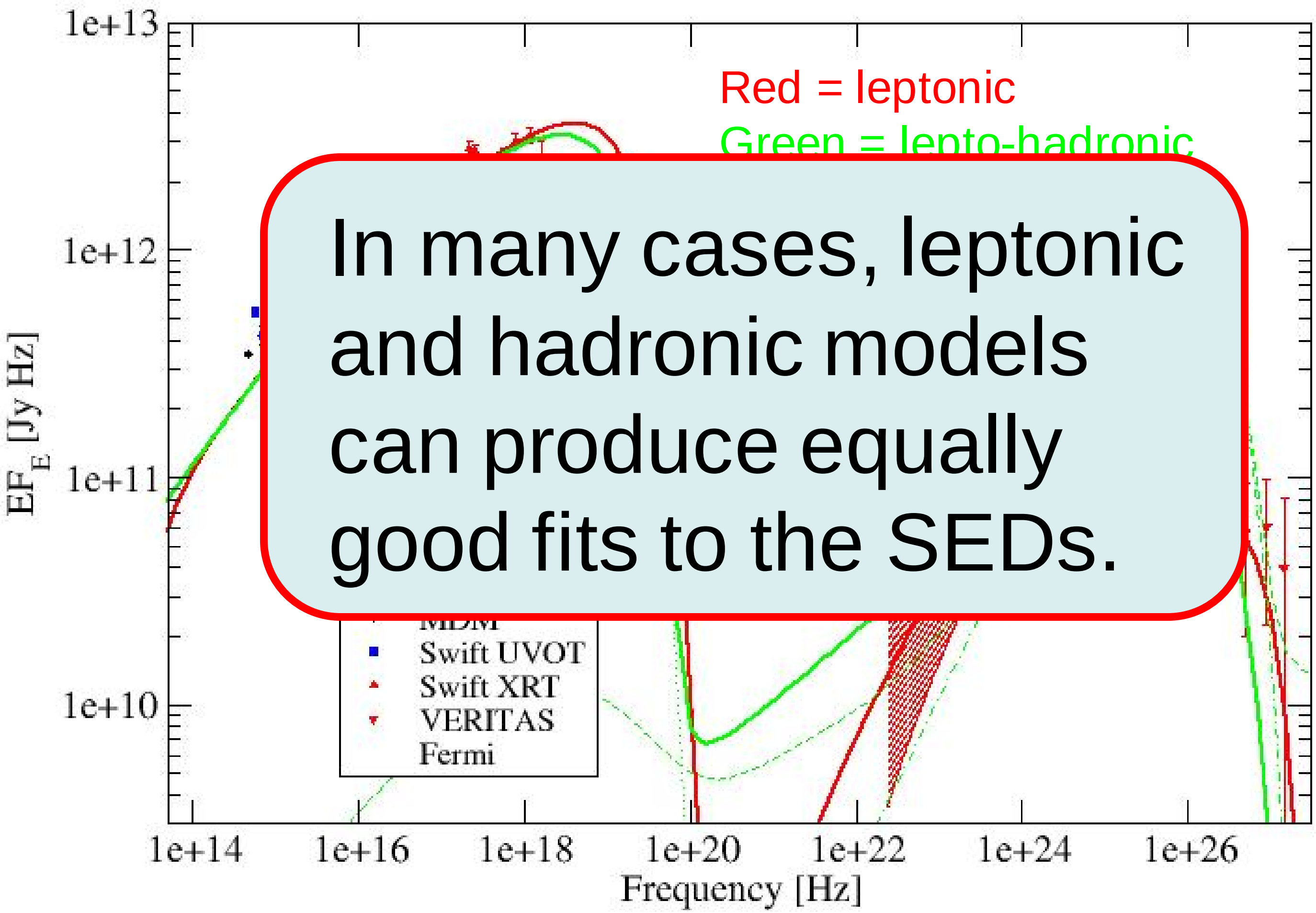
- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Requirements for lepto-hadronic models

- To exceed p-γ pion production threshold on interactions with synchrotron (optical) photons: $E_p > 7\times10^{16}\ E^{-1}_{ph,eV}$ eV
- For proton synchrotron emission at multi-GeV energies: E_p up to ~ 10^{19} eV (=> UHECR)
- Require Larmor radius
  $r_L \sim 3\times10^{16}\ E_{19}/B_G$ cm $\leq$ a few x 10^{15} cm => $B \geq 10$ G
  (Also: to suppress leptonic SSC component below synchrotron) – inconsistent with radio-core-shift measurements if emission region is located at ~ pc scales (e.g., Zdziarski & Böttcher 2015).
- Low radiative efficiency: Requiring jet powers $L_{jet} \sim L_{Edd}$

SED Model Fit Degeneracy

RGB J0710+591 (HBL)

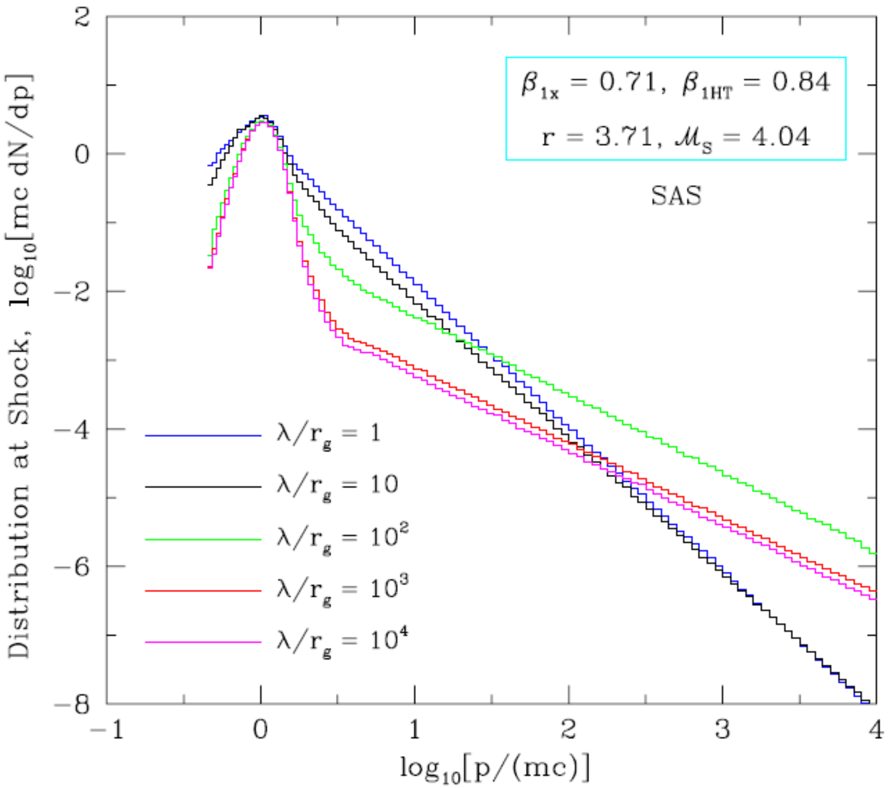


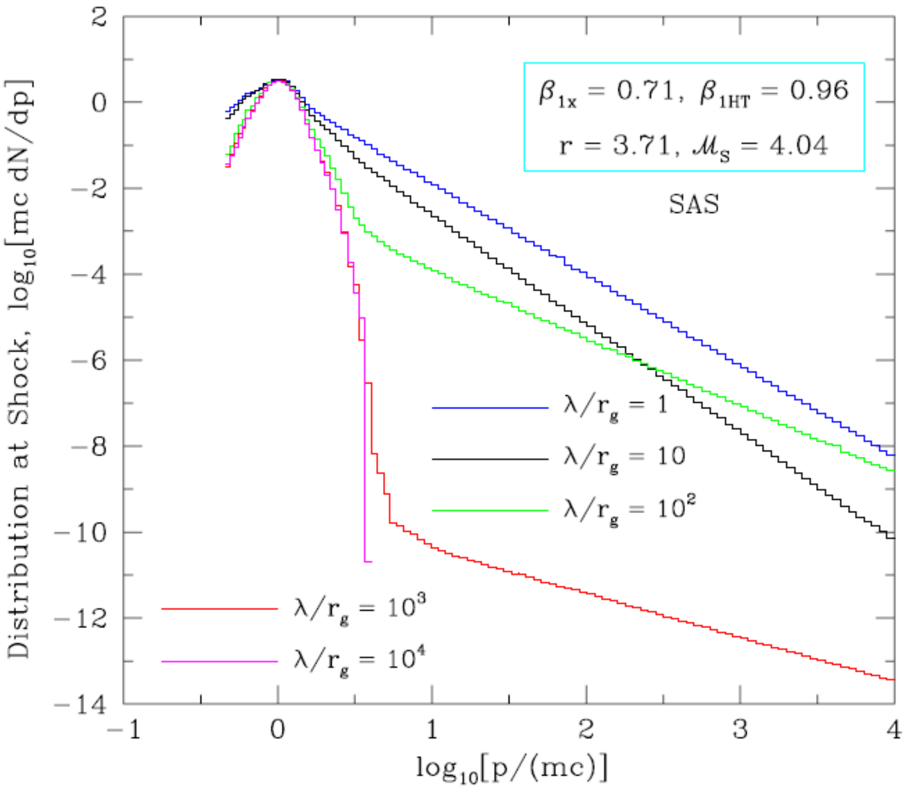
In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

Possible Diagnostics to distinguish:

- Variability
- Neutrinos
- Polarization

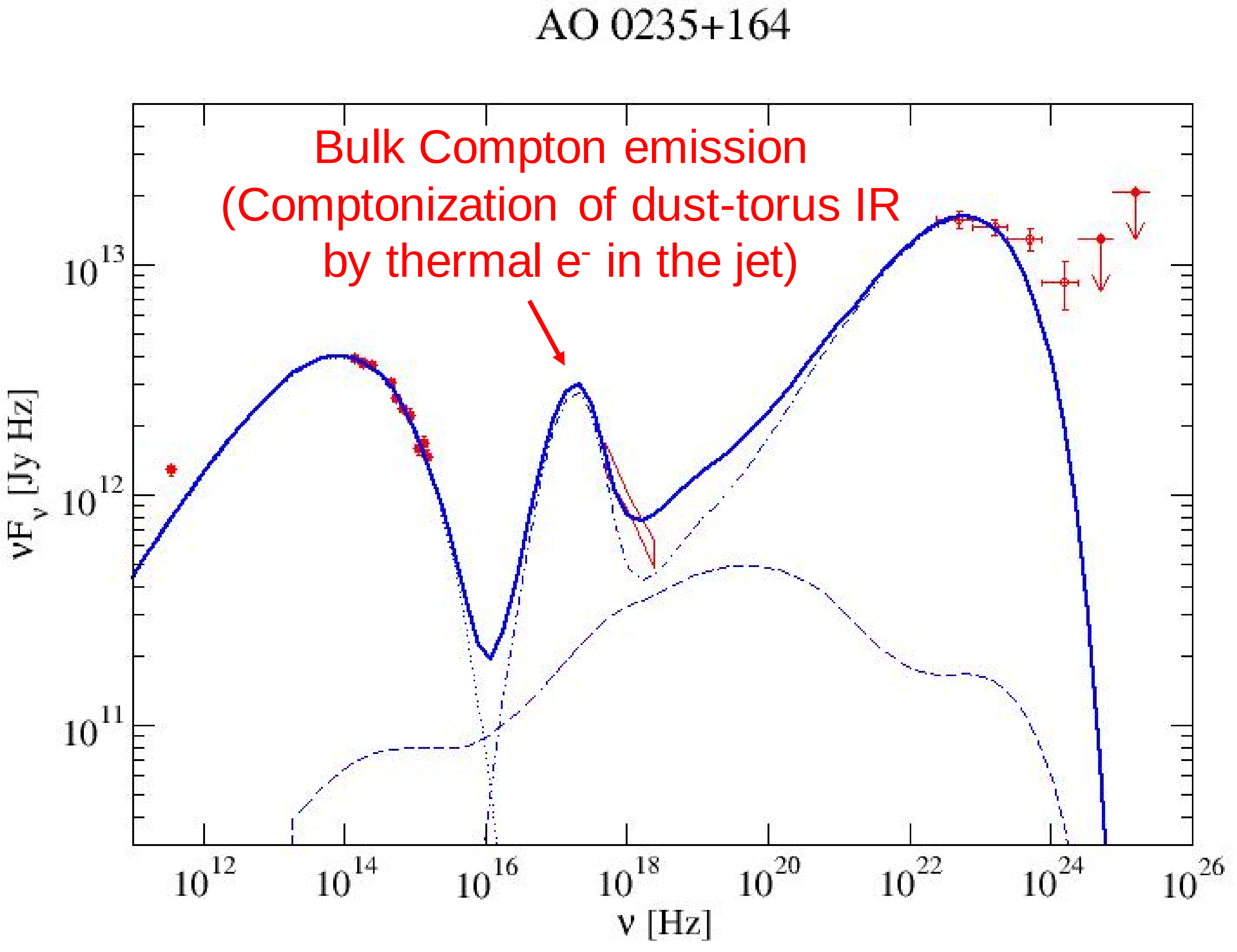
Polarization Induced by Anisotropic Compton Scattering





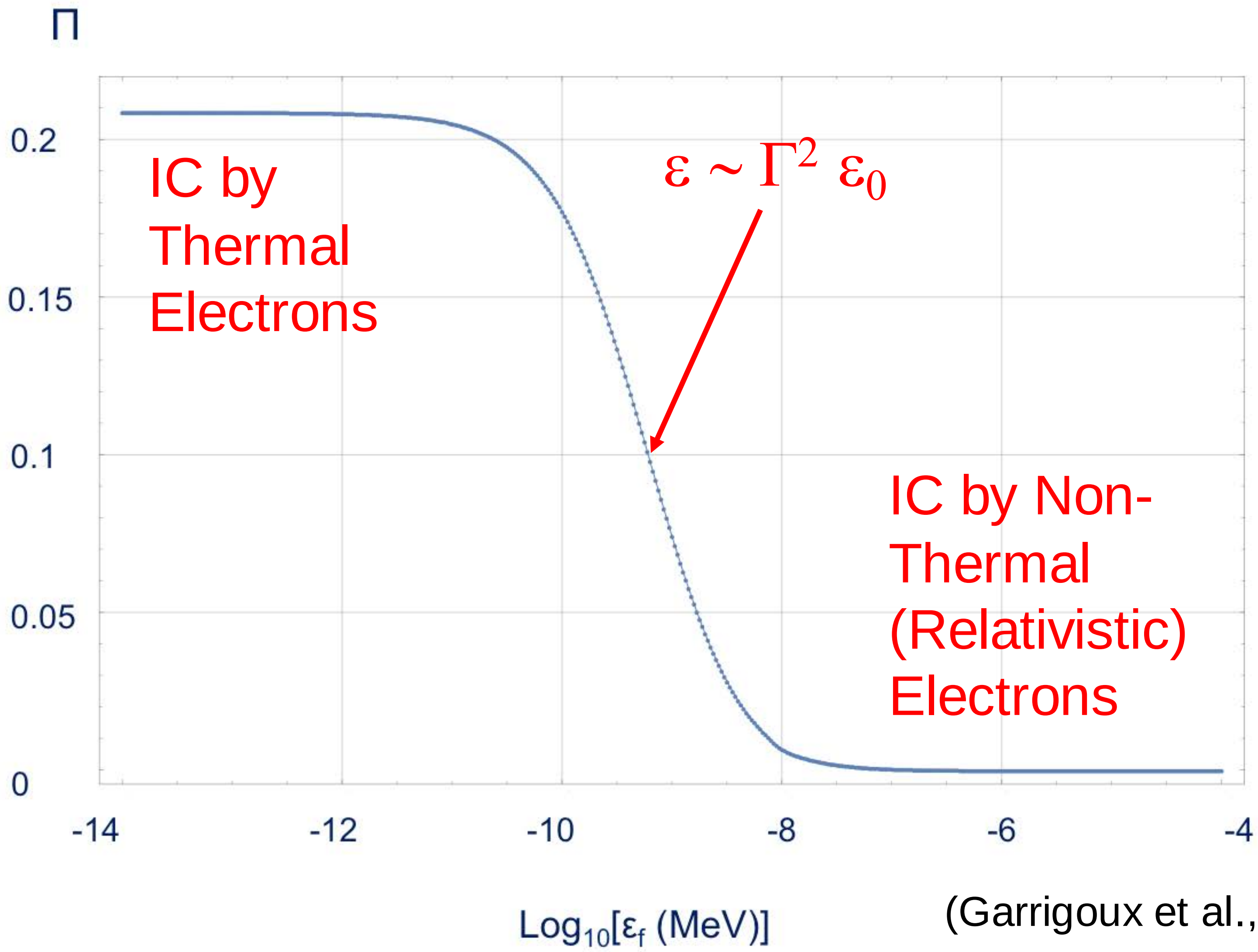
Summerlin & Baring (2012)

- Thermal + Non-Thermal Electron Distributions from Diffusive Shock Acceleration



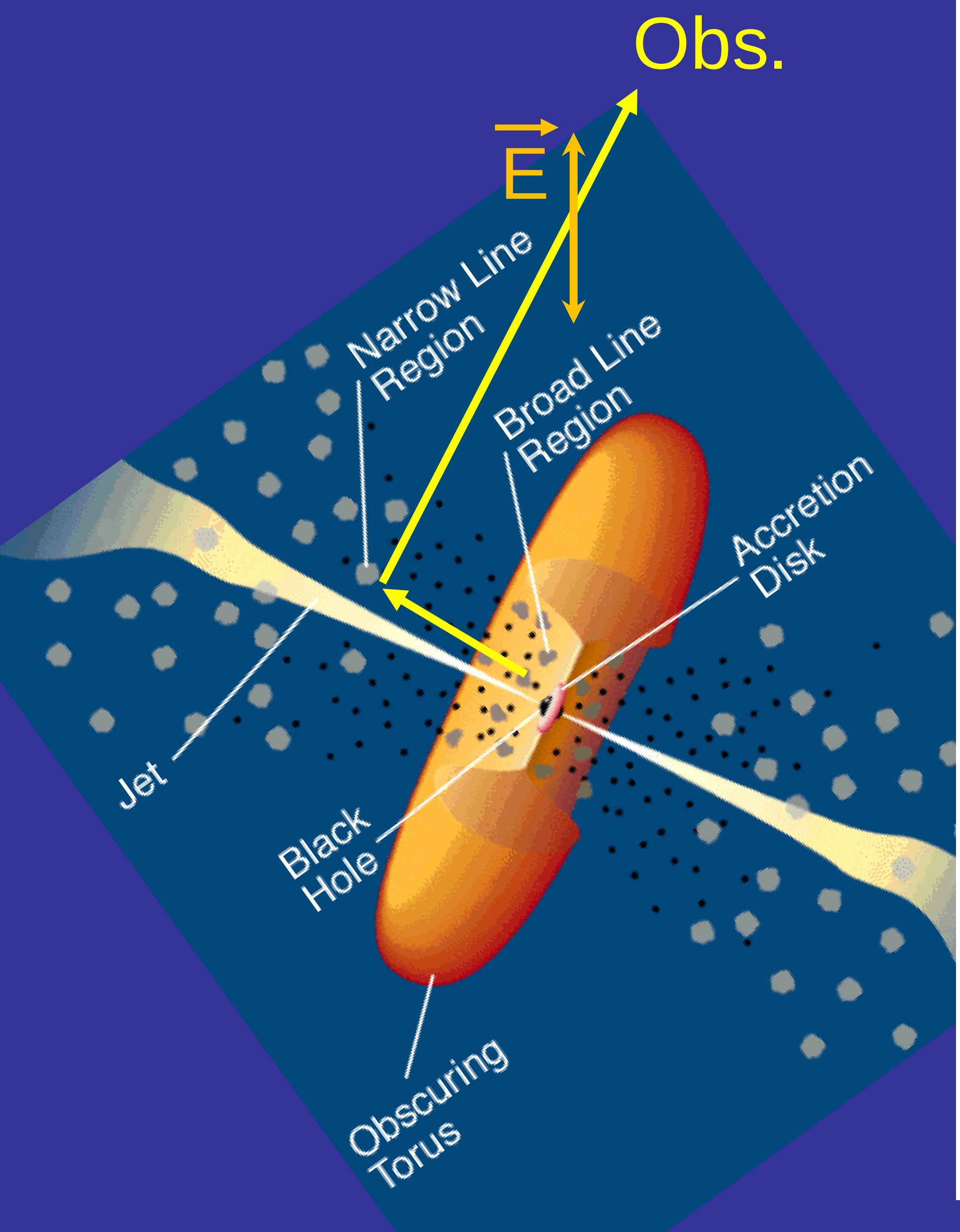
(Baring et al. 2016)

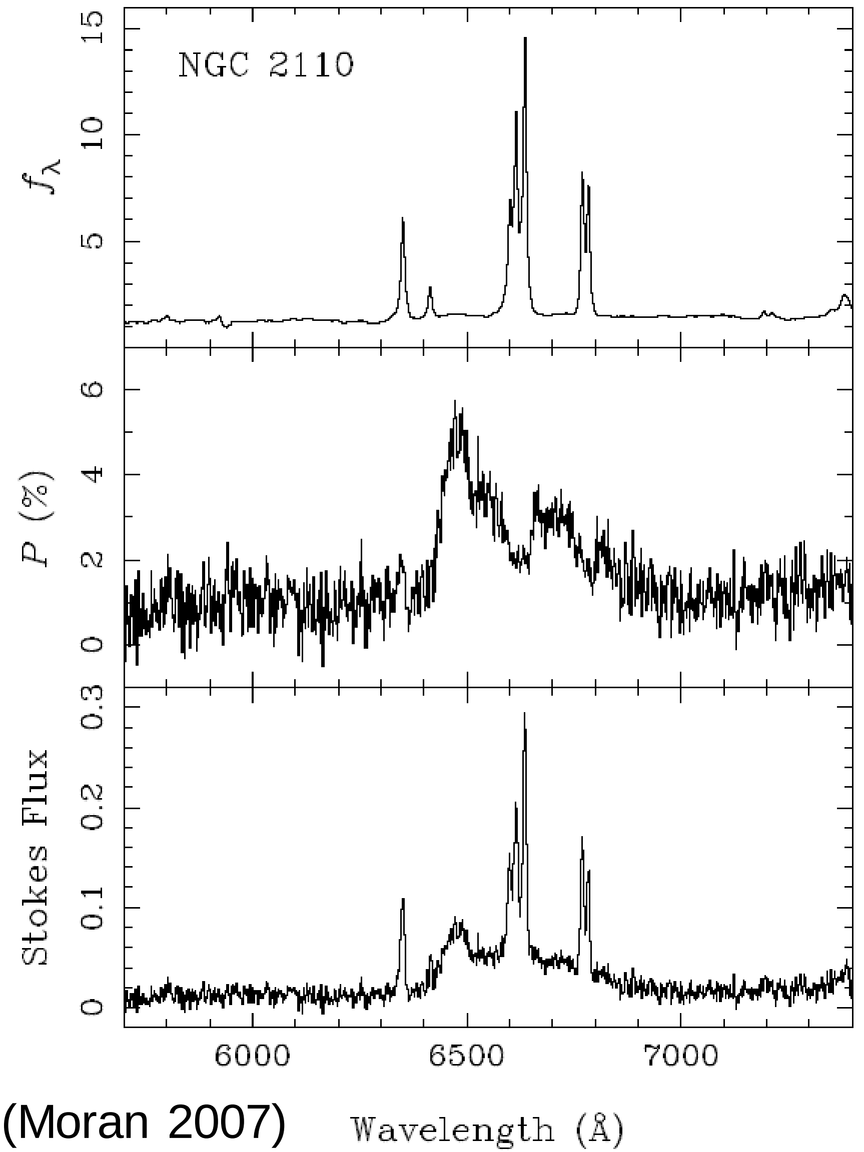
Expected Polarization from Bulk Compton



(Garrigoux et al., in prep.)

Polarization Induced by Anisotropic Scattering





(Moran 2007)

Calculation of X-Ray and Gamma-Ray Polarization in Leptonic and Hadronic Blazar Models

Upper limits on high-energy polarization, assuming perfectly ordered magnetic field perpendicular to the line of sight (Zhang & Böttcher 2013)

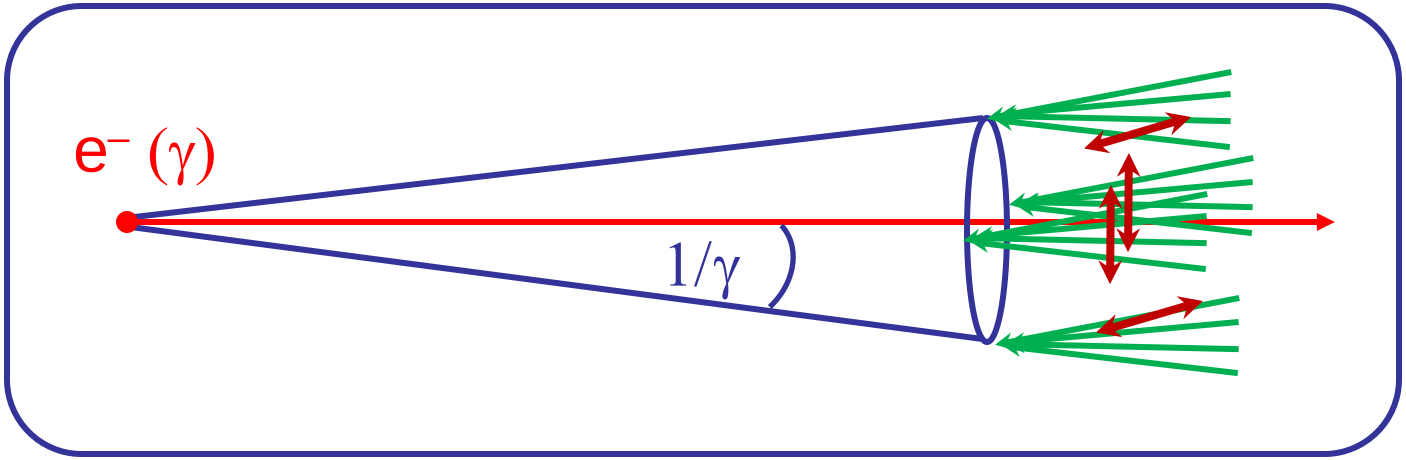
- Synchrotron polarization:

  Standard Rybicki & Lightman description

- SSC Polarization:

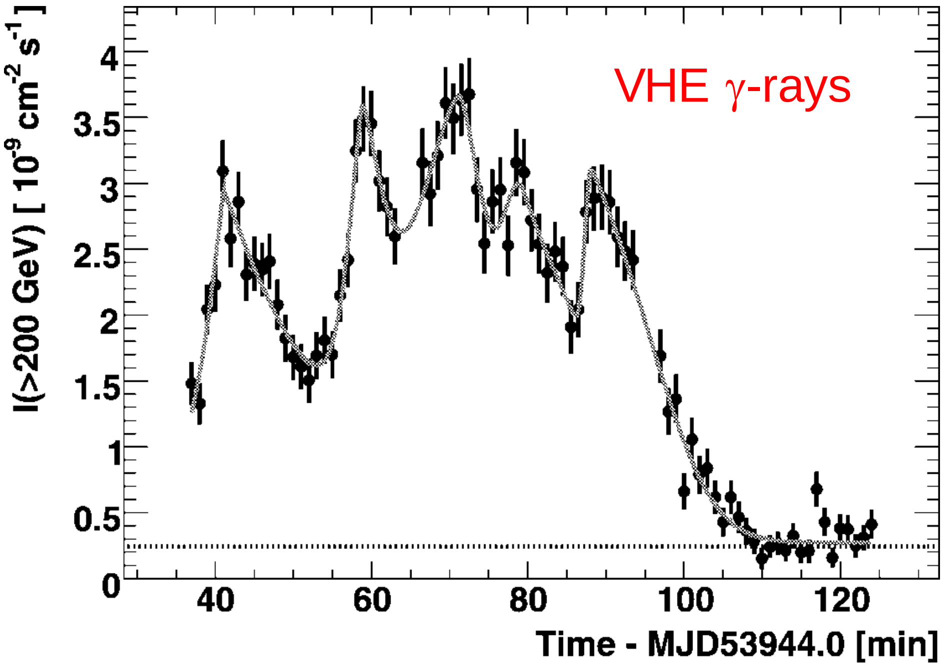
  Bonometto & Saggion (1974) for Compton scattering in Thomson regime

- External-Compton emission (relativistic e^-): **Unpolarized:**



The Doppler Factor Crisis

PKS 2155-304



(Aharonian et al. 2007)

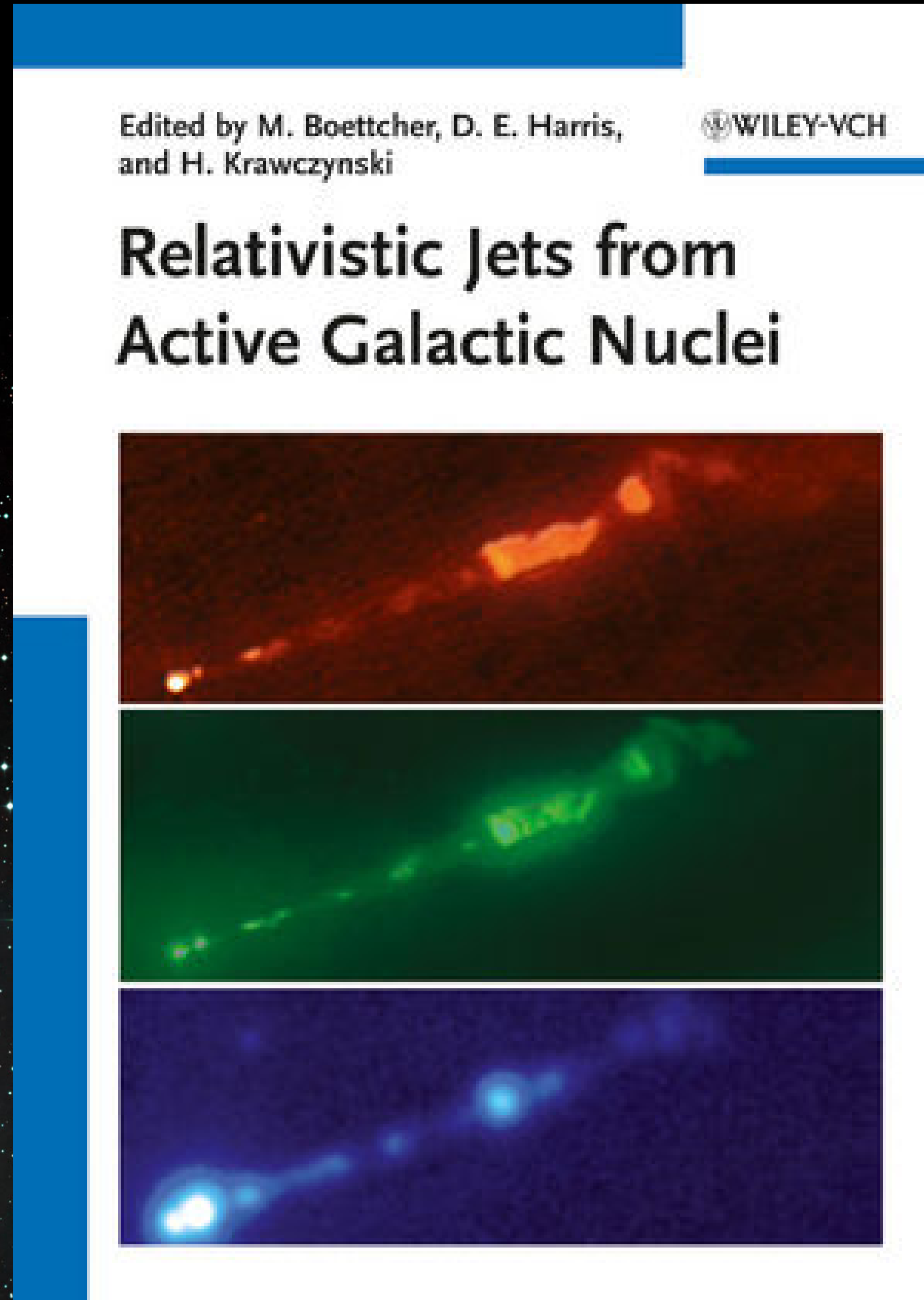
VHE γ-ray variability on time scales as short as a few minutes!

γ–γ opacity constraints, assuming isotropic emission in the co-moving frame of the emission region

=> $\Gamma \sim \delta > 50$

Strong disagreement with observed superluminal motions!

Thank you



Edited by M. Boettcher, D. E. Harris, and H. Krawczynski
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Relativistic Jets from Active Galactic Nuclei