Stochastic Acceleration in the Corona of Accreting Black Holes

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Acceleration in astrophysics

- ✓ Evidence for particle acceleration in astrophysics:
  - ✓ High energy photons (HE, VHE sources)
  - ✓ High energy particles: cosmic rays

- ✓ Microphysics of acceleration/heating:
  - ✓ Strong, steady, electric fields (pulsars)
  - ✓ Eruptive, magnetic reconnection (solar corona, XRBs...)
  - ✓ Steady shocks (SNRs), internal shocks (GRBs, AGN jets, XRB jets)
  - ✓ Turbulent viscosity (MRI in accretion disks, ADAFs)
  - ✓ Stochastic acceleration (Fermi 1949, Melrose 1980):
    - ✓ Solar corona (Miller, Roberts, Li, Steinacker, Schlickeiser, Dung, Petrosian...)
    - ✓ Galactic center (Liu&Petrosian 2006)
    - ✓ Blazars (Katarzinsky&Ghiselini 2006)
    - ✓ Intra-cluster medium (Blasi 2000, Petrosian 2001, Brunetti et al. 2004)
    - ✓ γ-ray bursts (Waxman 1995, Dermer&Humi 2001)
    - ✓ Accreting black holes (Dermer&Miller 1996, Li&Kusunose 1996)

Outline

✓ Acceleration in XRBs

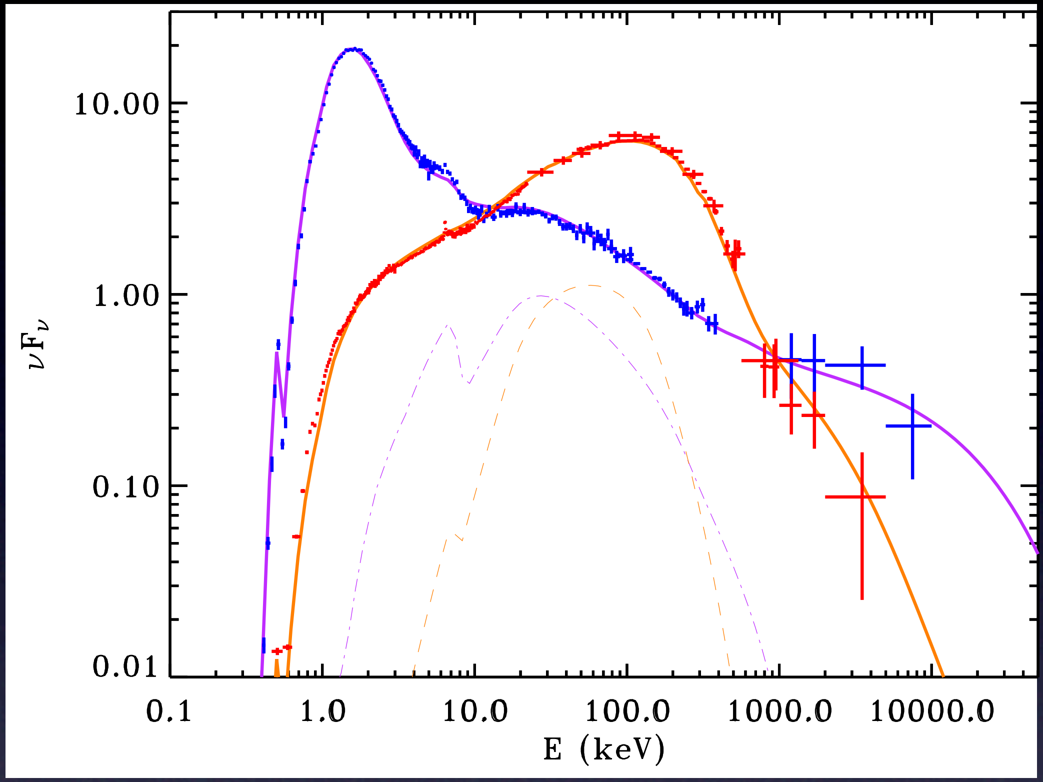
✓ The physics of stochastic acceleration

✓ Numerical model

✓ Qualitative results: acceleration properties in the corona of accreting BH

✓ Preliminary quantitative results: application to Cyg-X1

Acceleration in XRBs

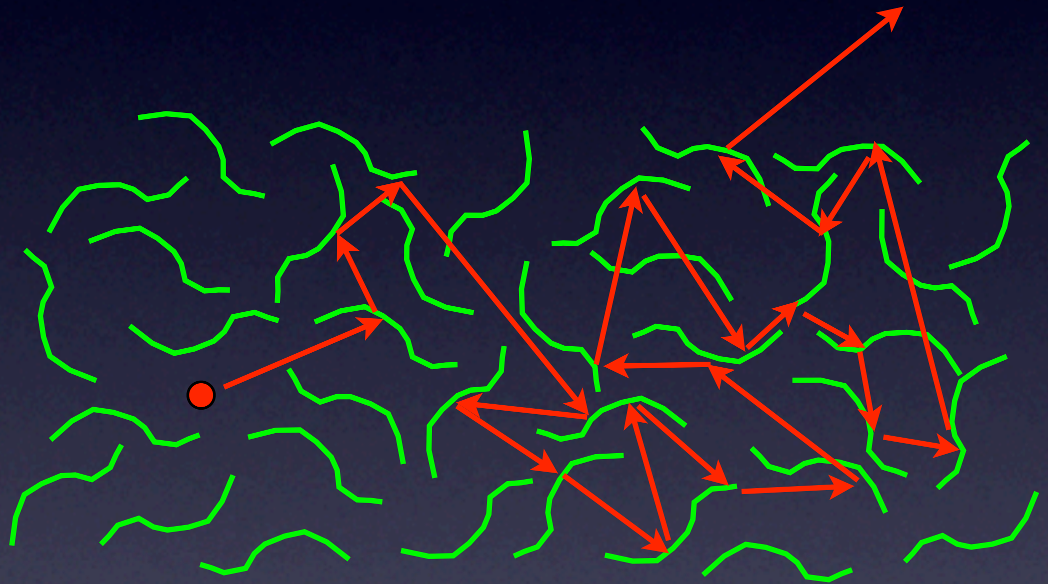


- ✓ Low/hard state
  - ✓ Thermal coronal
  - ✓ Main scenario: heating by hot protons and turbulent viscosity (Ichimaru 1977, Narayan&Li 1995, +++)
- ✓ High/Soft state
  - ✓ Non-thermal corona
  - ✓ Main scenario: acceleration magnetic reconnection (Galeev et al. 1979)
- ✓ Hybrid corona: Thermal + non-thermal
  - ✓ Eqpair and co.: thermal heating + injection of power law electrons
  - ✓ Variability <= accretion rate time evolution
- ✓ No idea what microphysics... Stochastic acceleration ?

Stochastic acceleration

(Fermi 1949, Melrose 1980)

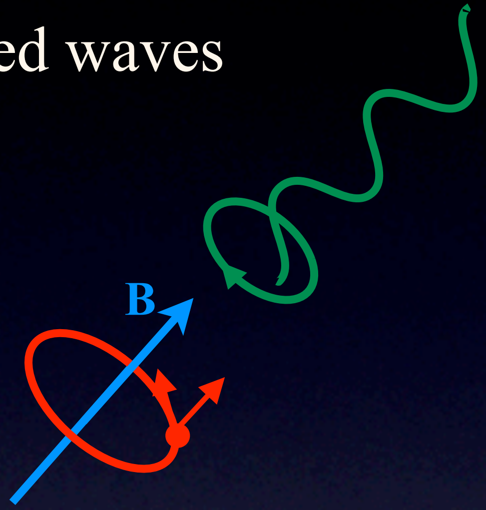
- ✓Turbulent medium
- ✓MHD waves with a full range wavelengths and frequencies



- ✓Particle scattering off MHD waves
- ✓Scattering dominated by resonant wave-particle interactions
- ✓Averaged gain in energy => 2nd order Fermi acceleration process

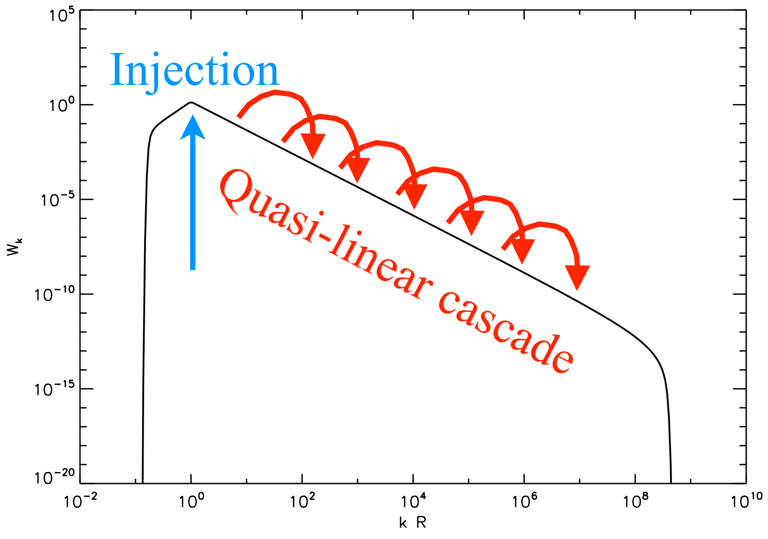
Resonant interactions

- Transverse, parallel-propagating modes: gyro-resonance
  - Acceleration by the perpendicular electric field of circular polarized waves
  - Resonant condition in the particle (GC) rest frame:
    - $\omega(k) = -\Omega_c$
    - A particle is resonant with a wave of specific frequency
    - Electrons (protons) are resonant with R-waves (L-waves)



- Resonant condition in the lab frame: $\omega(k) - k v_{\parallel} = -\dfrac{\Omega_c}{\gamma}$
  - A particle of momentum p is resonant with a wave of specific frequency $k_{res}(p)$
  - For low-frequency waves, high energy particles: $k_{\rm res} r_L \approx 1$ i.e.: $k_{\mathbf{res}} \propto 1/p$
  - Electrons and protons can be resonant with both L&R waves
  - Interaction cross section (e.g. Schlickeiser 1989, Steinacker Miller 1992...): $\sigma(k,p)$

- Consequences
  - Energy transfer from waves to particles
  - Wave spectrum:
    - If only one frequency: no efficient particle acceleration.
    - Need for a full wave spectrum (Kolmogorov, Kraichnan)



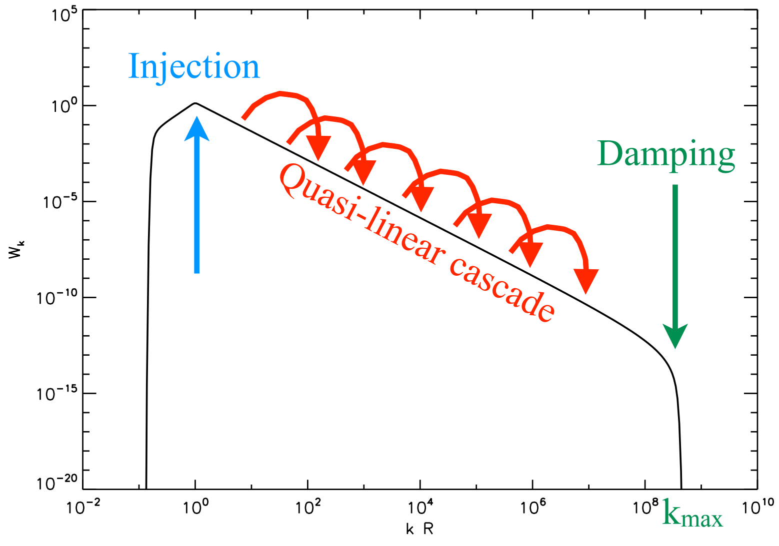
Wave Absorption

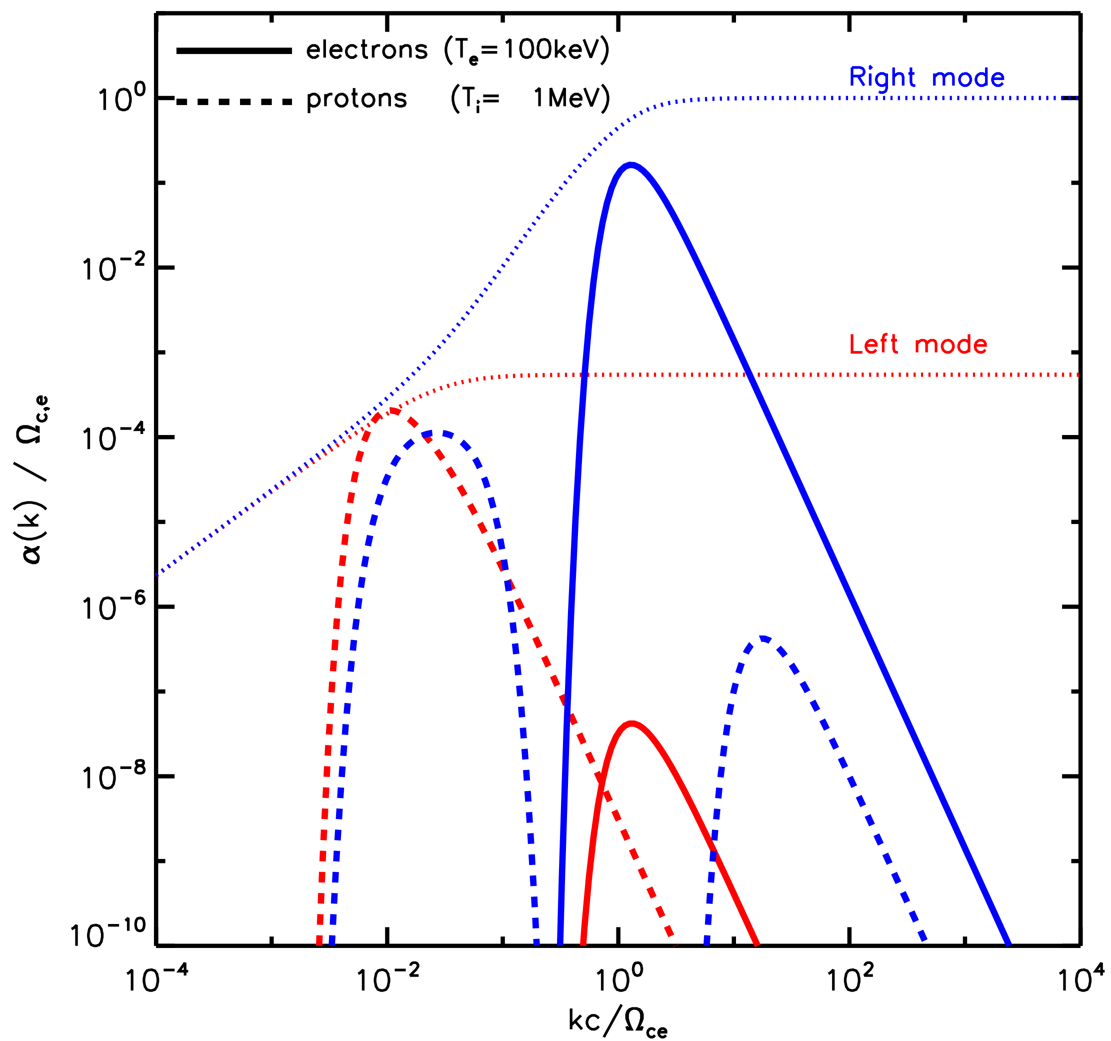
(e.g. Miller&Roberts 1995)

- ✓ Absorption coefficient:

$$\alpha_{\rm damp}(k) \propto 1/\tau_{\rm damp} \propto \int \sigma(k,p) f_{e/i}(p) dp$$

- ✓ Very sharp increase with wave frequency k





  - ✓ Damping of the turbulent spectrum at $k_{\rm max}$
  - ✓ $k_{\rm max}$ decreases with particle energy ($k \propto 1/p$)
- ✓ The spectrum must be computed consistently from cascading and absorption
- ✓ Which species?
  - ✓ Left mode absorbed by protons
  - ✓ Competition of electrons and protons to absorb right modes

Particle Acceleration

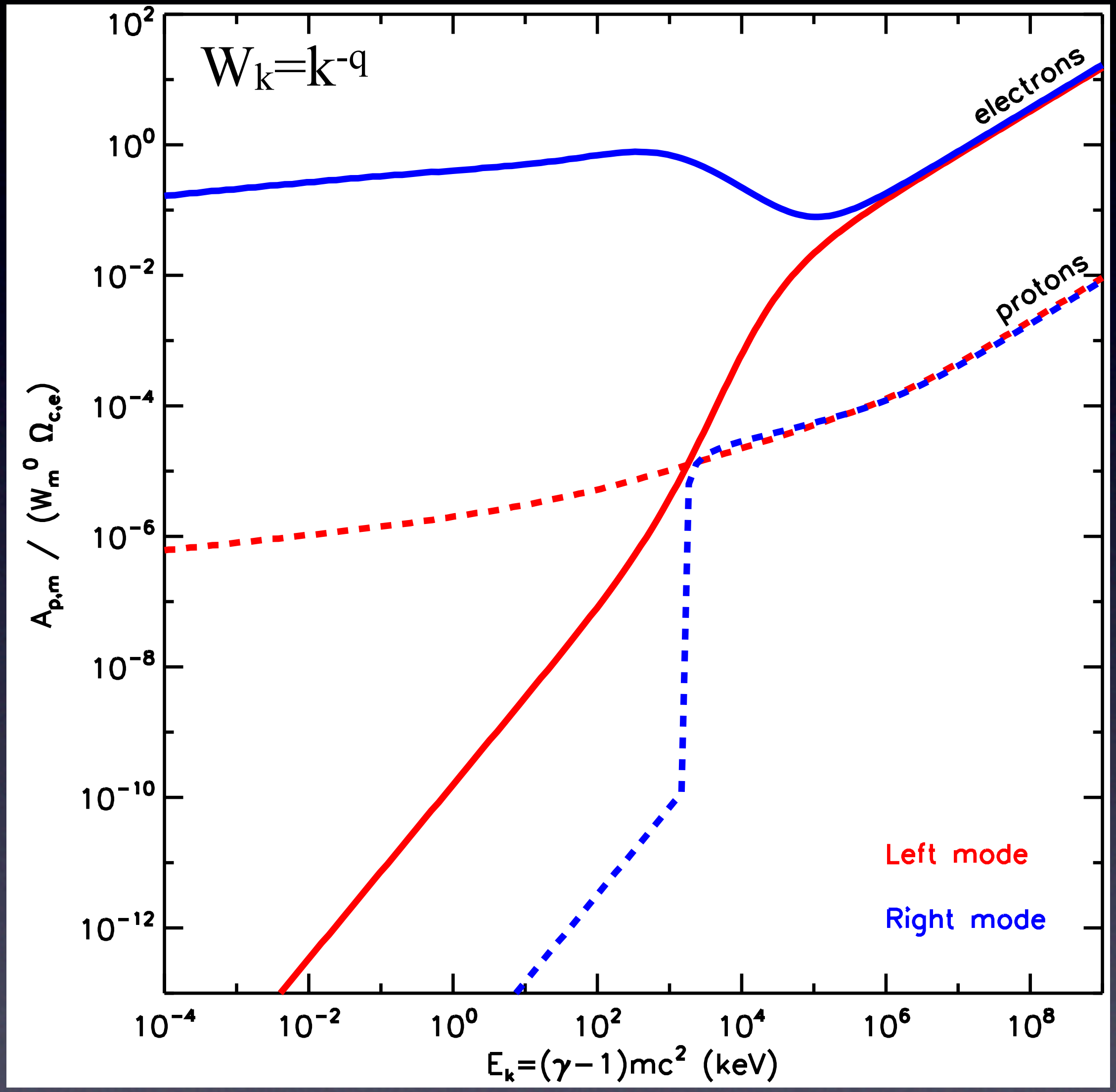
(e.g. Dermer et al. 1997)

✓ Acceleration power:

$$\frac{dE}{dt} \propto \gamma/\tau_{\rm acc} \propto \int \sigma(k,p)W(k)dk$$

✓ Increase with particle energy

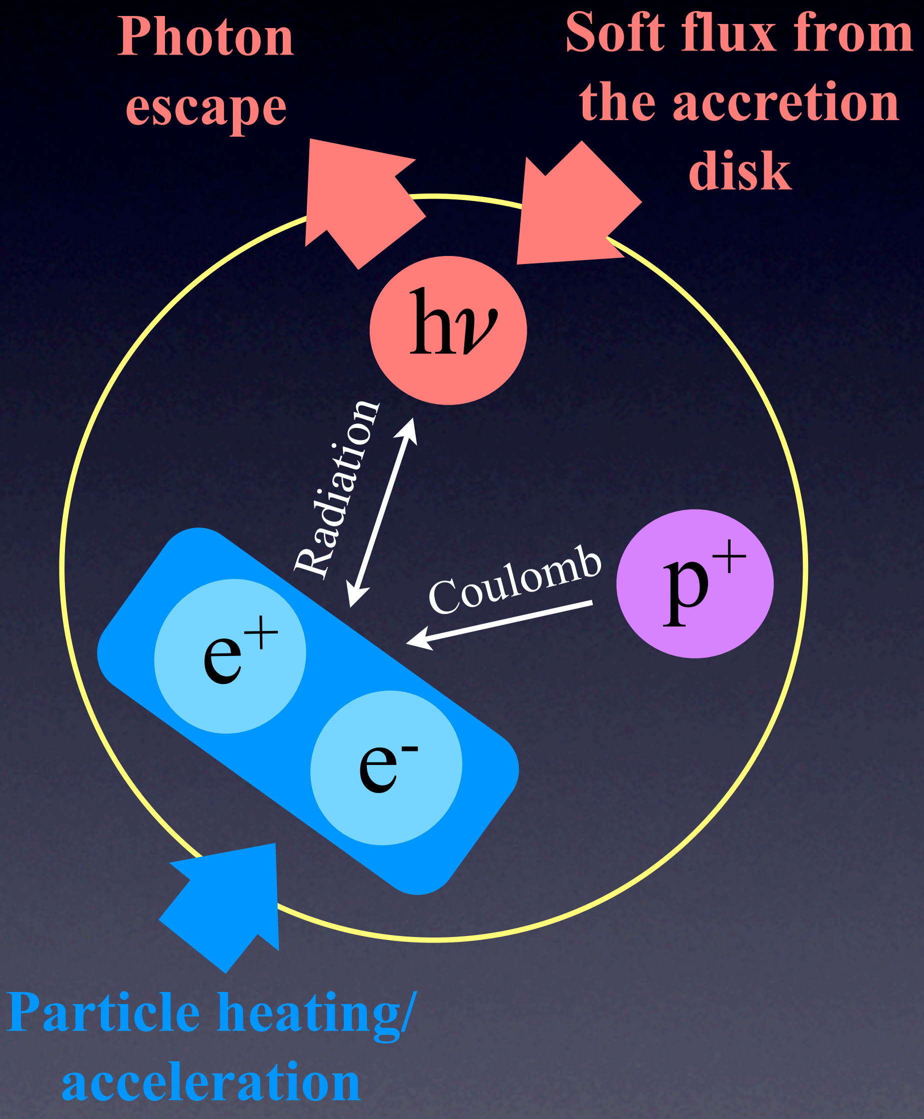
- ✓ At high energy:
  - ✓ Acceleration: $dE/dt \propto p^{q-1} \propto p^{0.5-0.7}$
  - ✓ Electron radiative cooling: $dE/dt \propto p^2$
- ✓ Amplitude and features depend on the Alfvén velocity: $v_A^2/c^2 = B^2/(4\pi n_p m_p c^2)$
  - ✓ Magnetic field intensity
  - ✓ Proton density



✓ Maximal wave frequency $k_{\rm max}$ => energy threshold for particle acceleration: $p_{\rm min} \propto 1/k_{\rm max}$

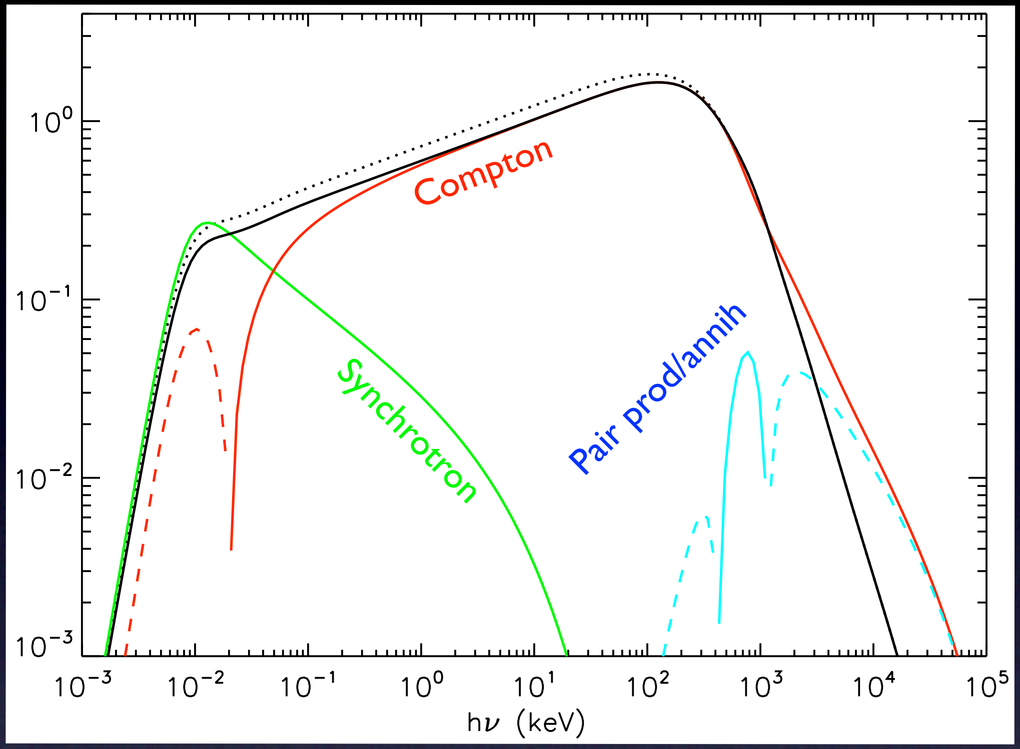
Original Model

- ✓ A kinetic code to model high energy plasmas (Belmont et al. 2008)
  - ✓ Similar to Eqpair
- ✓ Homogeneous, isotropic medium (one-zone model)
- ✓ 3.5 interacting species: electrons, positrons, photons (+protons)
- ✓ Microphysics:
  - ✓ Photon-particle and particle-particle interactions
    - ✓ Compton scattering, self-absorbed bremsstrahlung and synchrotron radiation, pair prod./annih., Coulomb collisions
  - ✓ Injection of soft photons from the accretion disk
  - ✓ Particle thermal heating/non-thermal acceleration

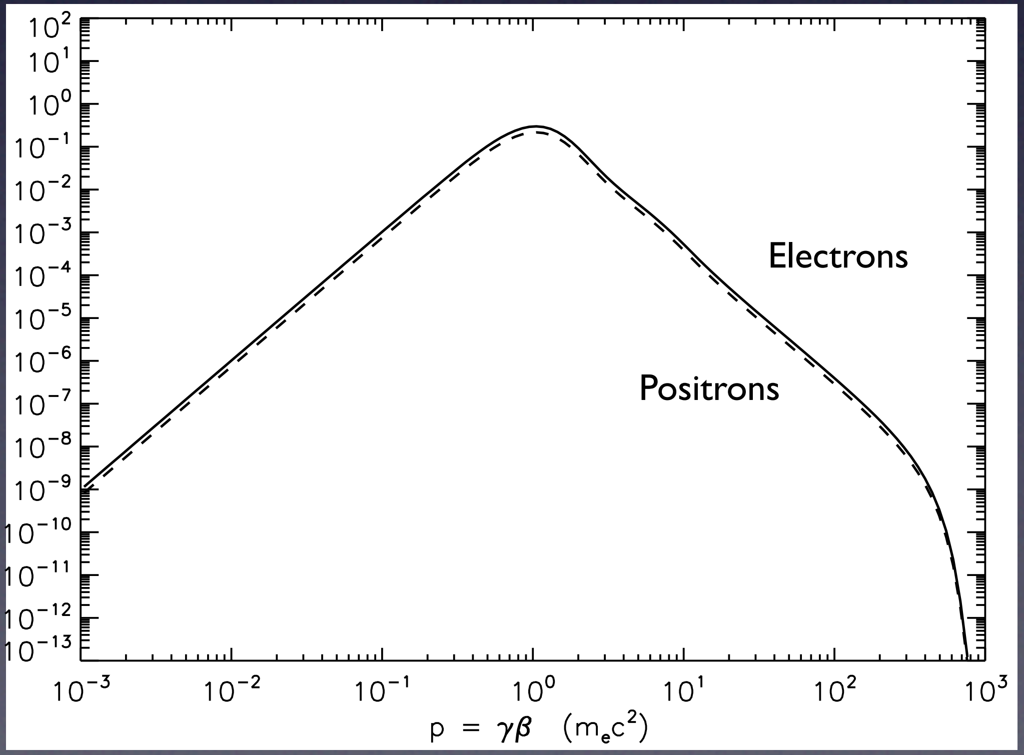


Original Model

- ✓ Inputs:
  - ✓ Optical depth: τ
  - ✓ Magnetic field: $l_b = \frac{\sigma_T}{8\pi m_e c^2} R B^2$
  - ✓ Disk soft photons: kT_{in} and $l_s = \frac{\sigma_T}{m_e c^3} \frac{L_s}{R}$
  - ✓ Proton temperature: T_p
  - ✓ Acceleration properties: l_{acc} (+++)

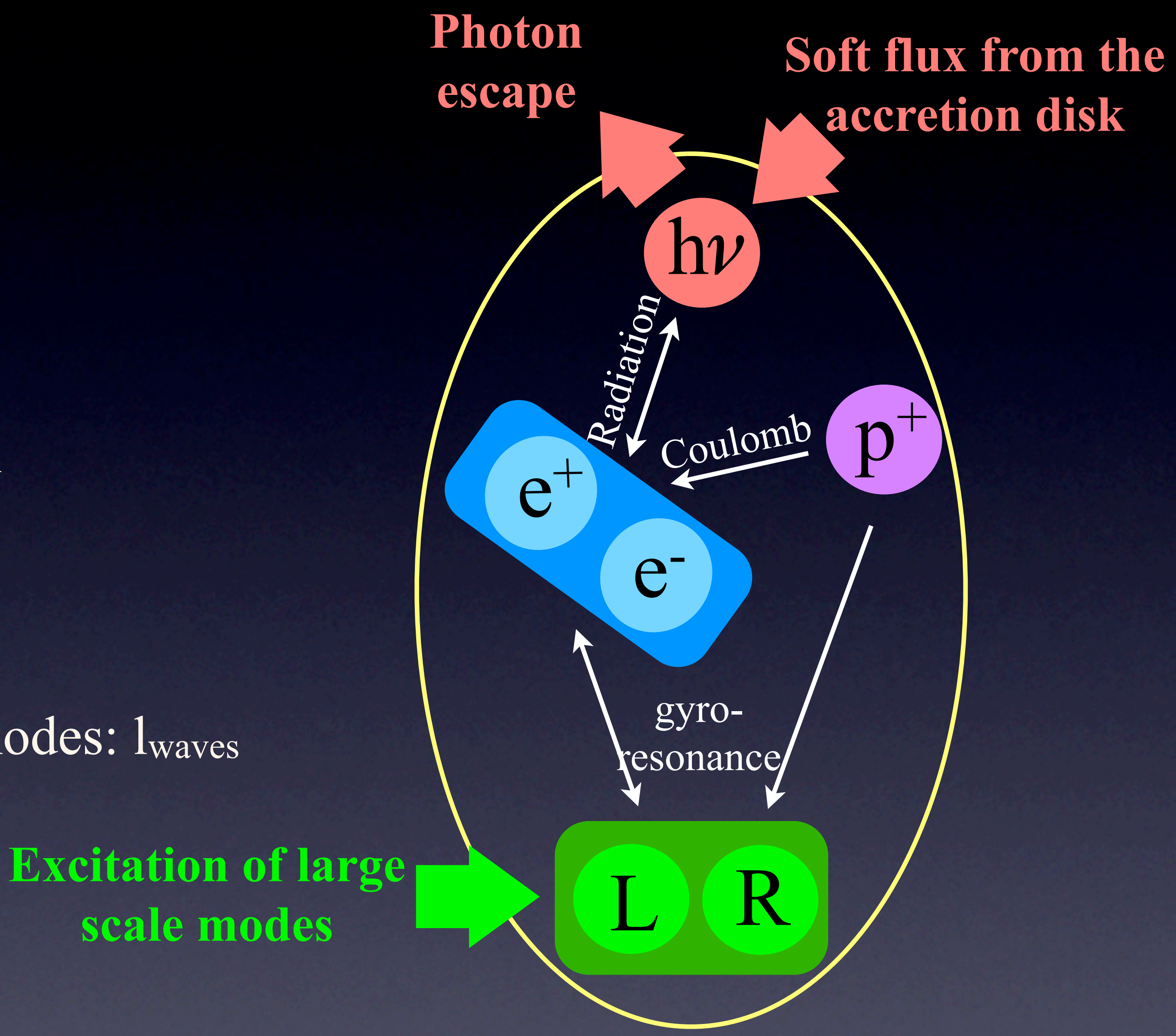


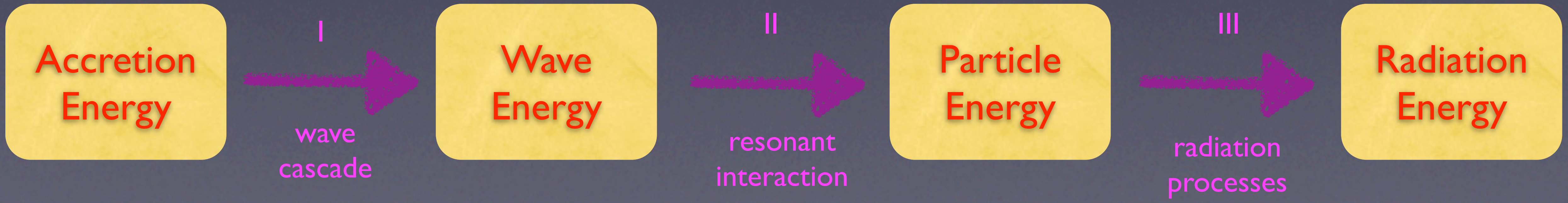
- ✓ Outputs
  - ✓ Lepton distribution
  - ✓ Photon spectra
  - ✓ Tables of spectra
    - ✓ Tables usable in the X-ray fitting library *Xspec*
    - ✓ Constraints on Cyg X-1 (Malzac et Belmont 2009)
    - ✓ Constraints on GX 339-4 (Droulans et al. 2010)



Model with stochastic acceleration

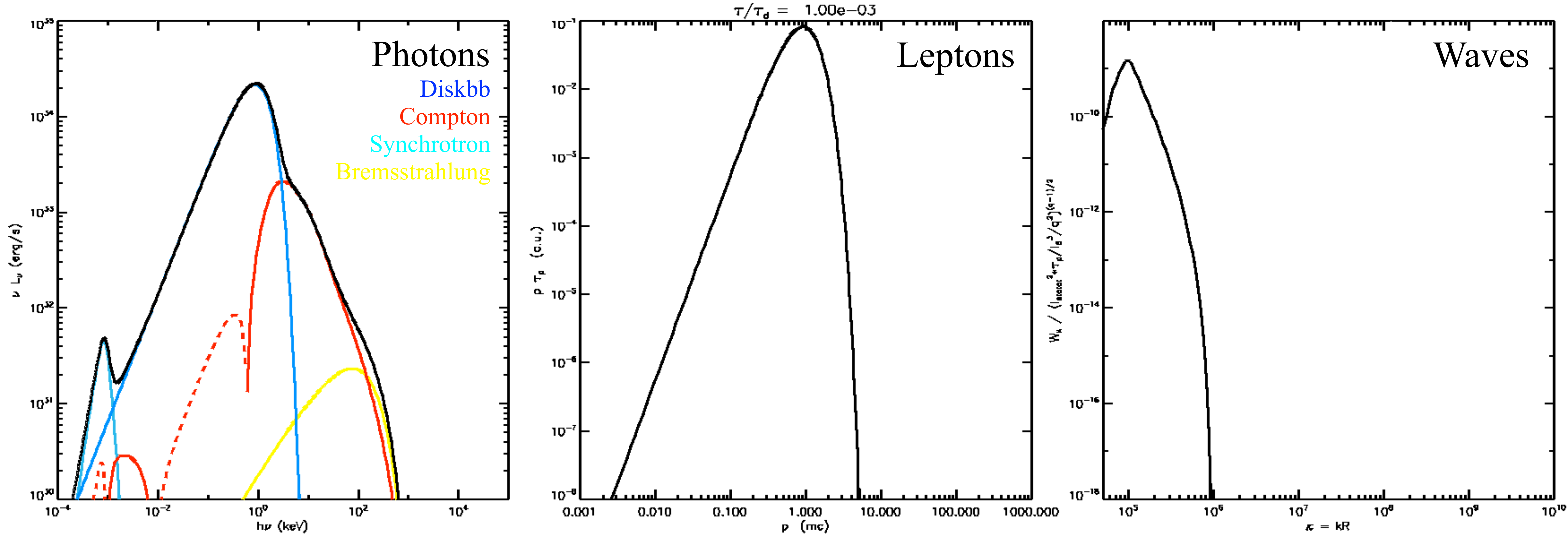
- ✓ Two more species and equations:
  - ✓ R-waves
  - ✓ L-waves
- ✓ One more term in the particle equation
- ✓ Additional parameters
  - ✓ Power injected at large scale in each modes: $l_{\rm waves}$
  - ✓ Turbulent index q




Accretion Energy → I wave cascade → Wave Energy → II resonant interaction → Particle Energy → III radiation processes → Radiation Energy

An example

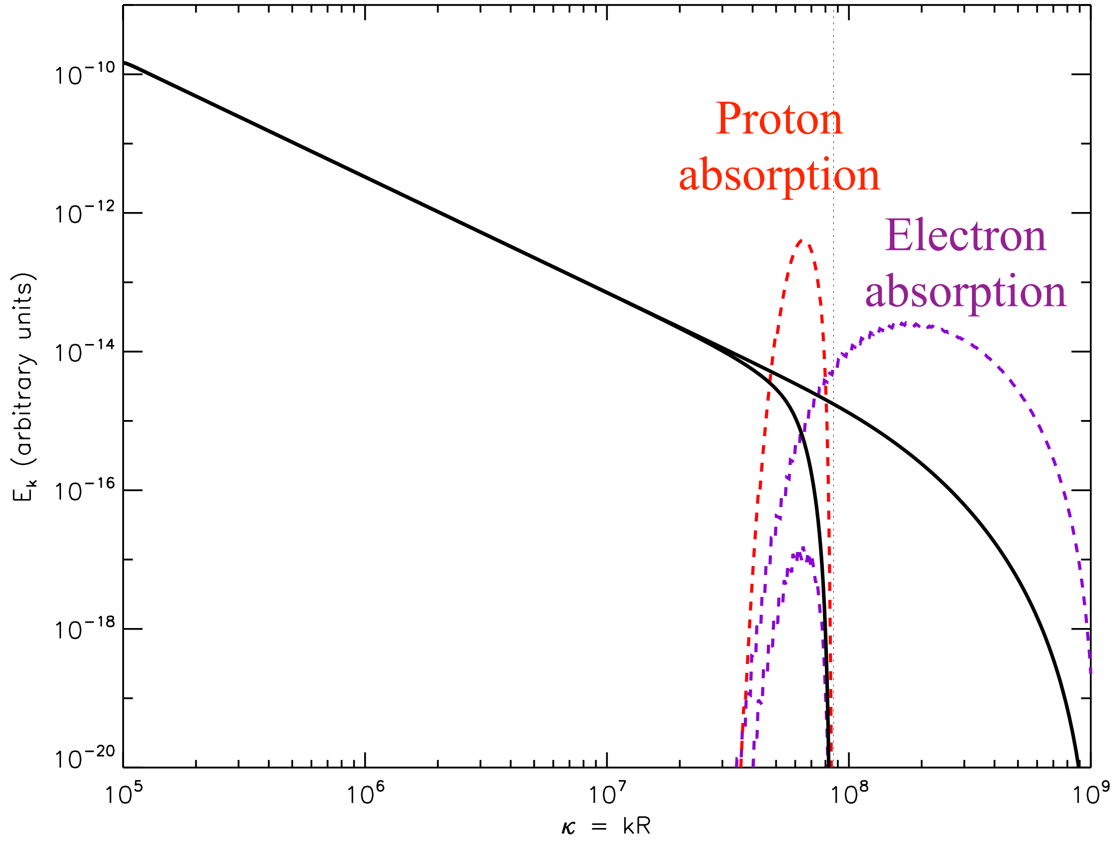
- ✓ Starting equilibrium with no acceleration
  - ✓ τ=0.1, l_s=0.1, l_b=1, T_p=1 MeV (β=0.2)
  - ✓ Thermal lepton distribution (heated by hot protons)
  - ✓ Thermal Comptonization spectrum (typical of low/hard states)
- ✓ Time evolution
  - ✓ From t=0: energy injection (l_{waves}=1) into large scale MHD waves
  - ✓ Cascade time scale = $1/k^{q-1}$



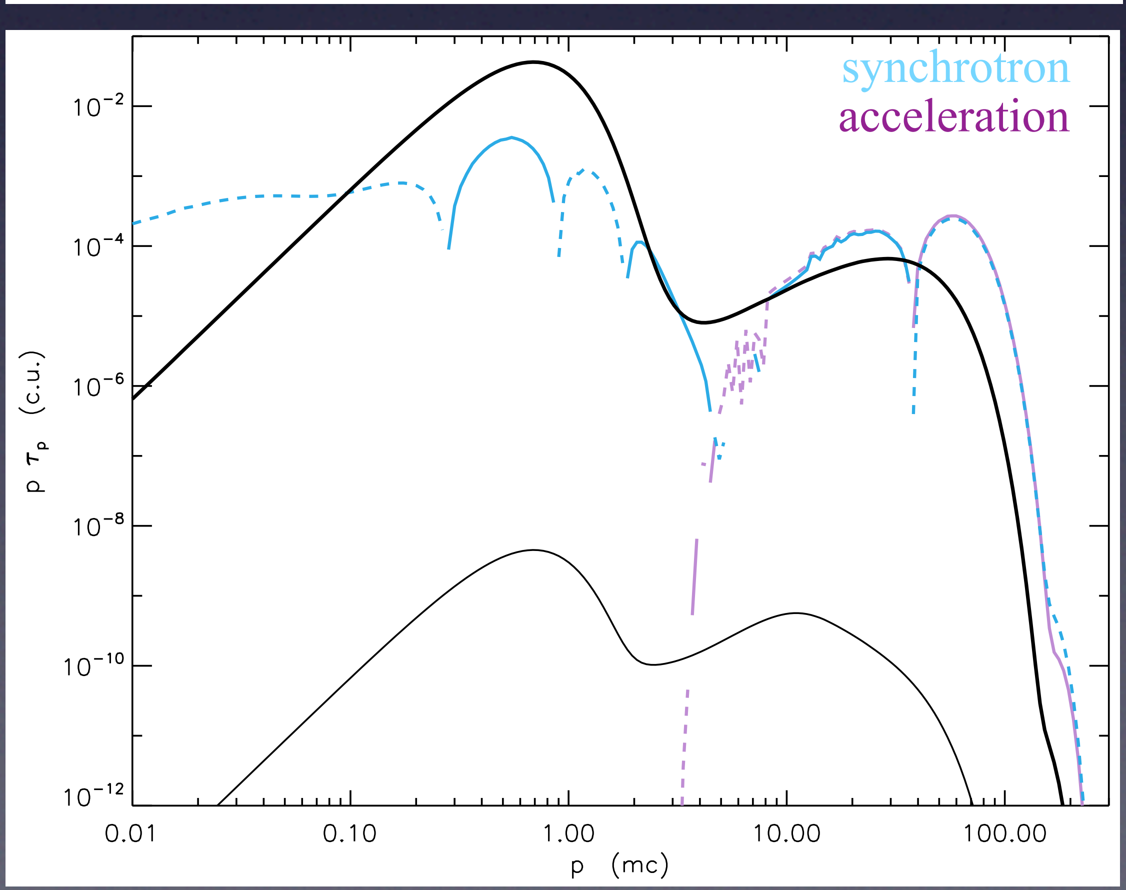
Typical Distributions

- ✓ A 2-population lepton distribution
  - ✓ Thermal, non-accelerated electrons
  - ✓ Accelerated electrons
- ✓ Comptonization by accelerated electrons

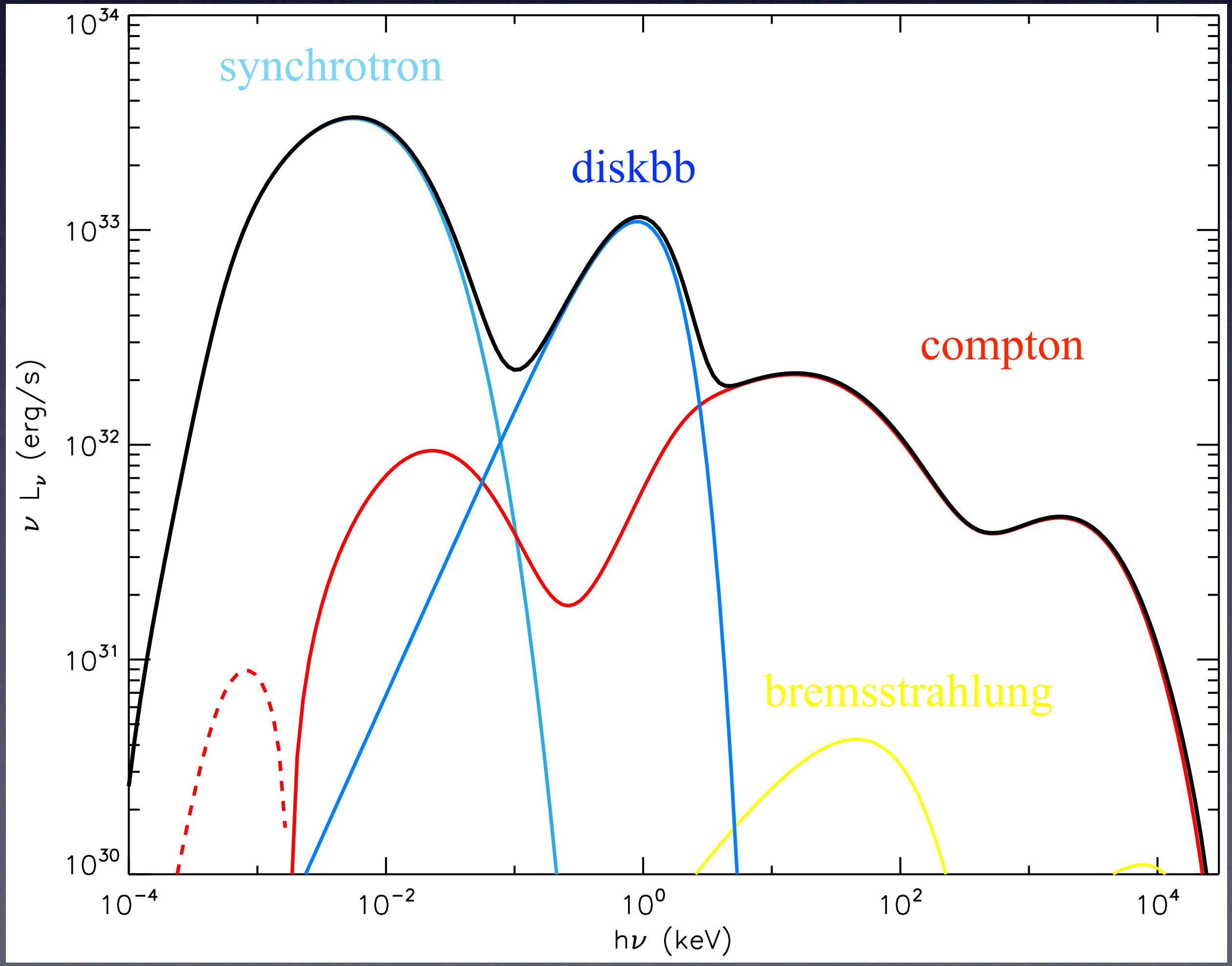
Waves



Leptons



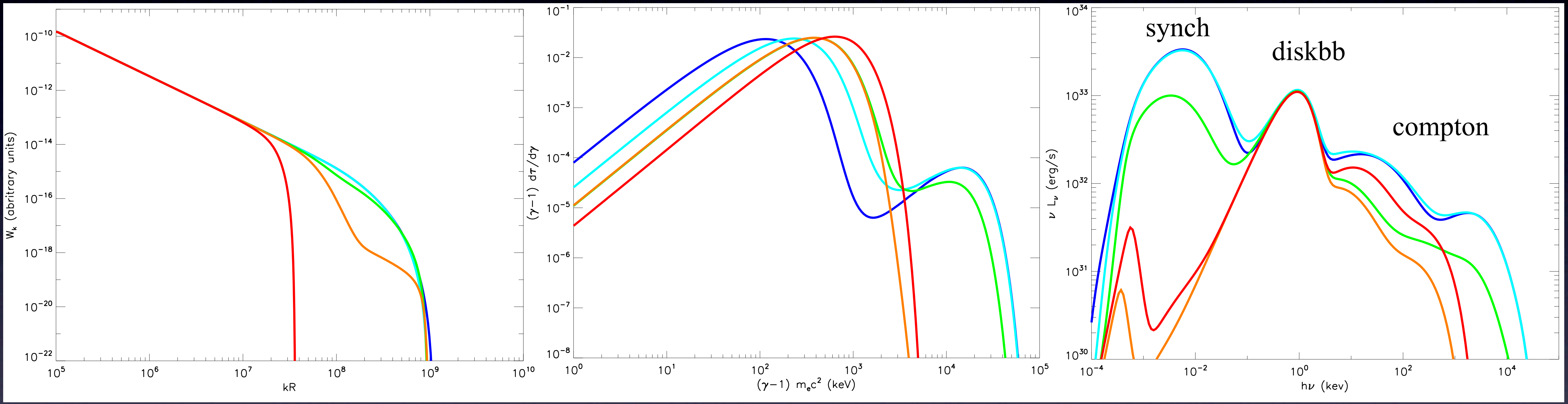
Photons



The Proton Switch

- Plasma β parameter for protons: β = 0.1, 0.6, 1.0, 1.3, 4

$$\beta = \frac{n k_B T_p}{B^2/8\pi} = \frac{U_{th}}{U_B}$$

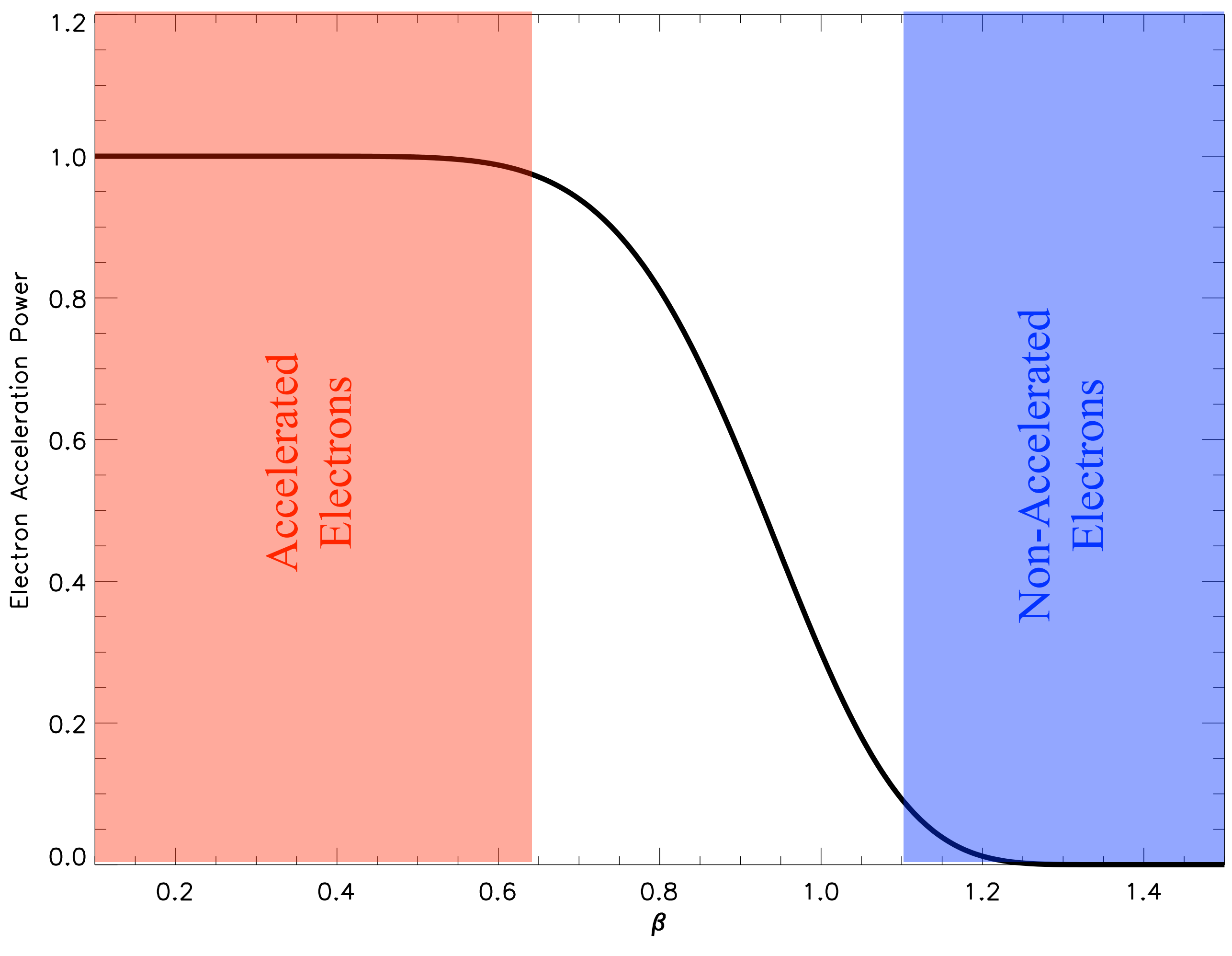


- For cold protons (β < 1):
  - Right modes are absorbed by electrons
  - Electrons are accelerated by waves
  - Two electron populations

- For hot protons (β > 1):
  - Right modes are absorbed by protons
  - Electrons are not accelerated
  - Electrons are heated by hot protons
  - One thermal electron distribution

The Proton Switch

- ✓ Very sharp transition:

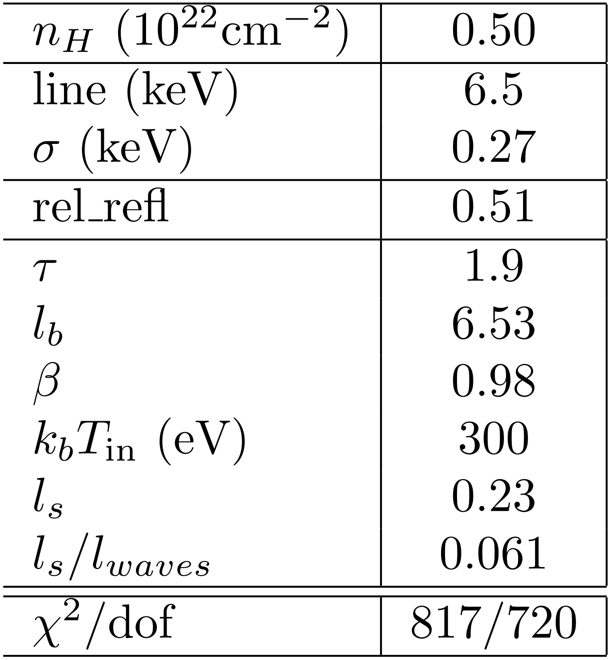


- ✓ Critical temperature: $T_* \approx 1\ \tau^{-1} \left(\frac{B}{10^6\mathrm{G}}\right)^2 \left(\frac{R}{10^8\mathrm{cm}}\right)$ MeV

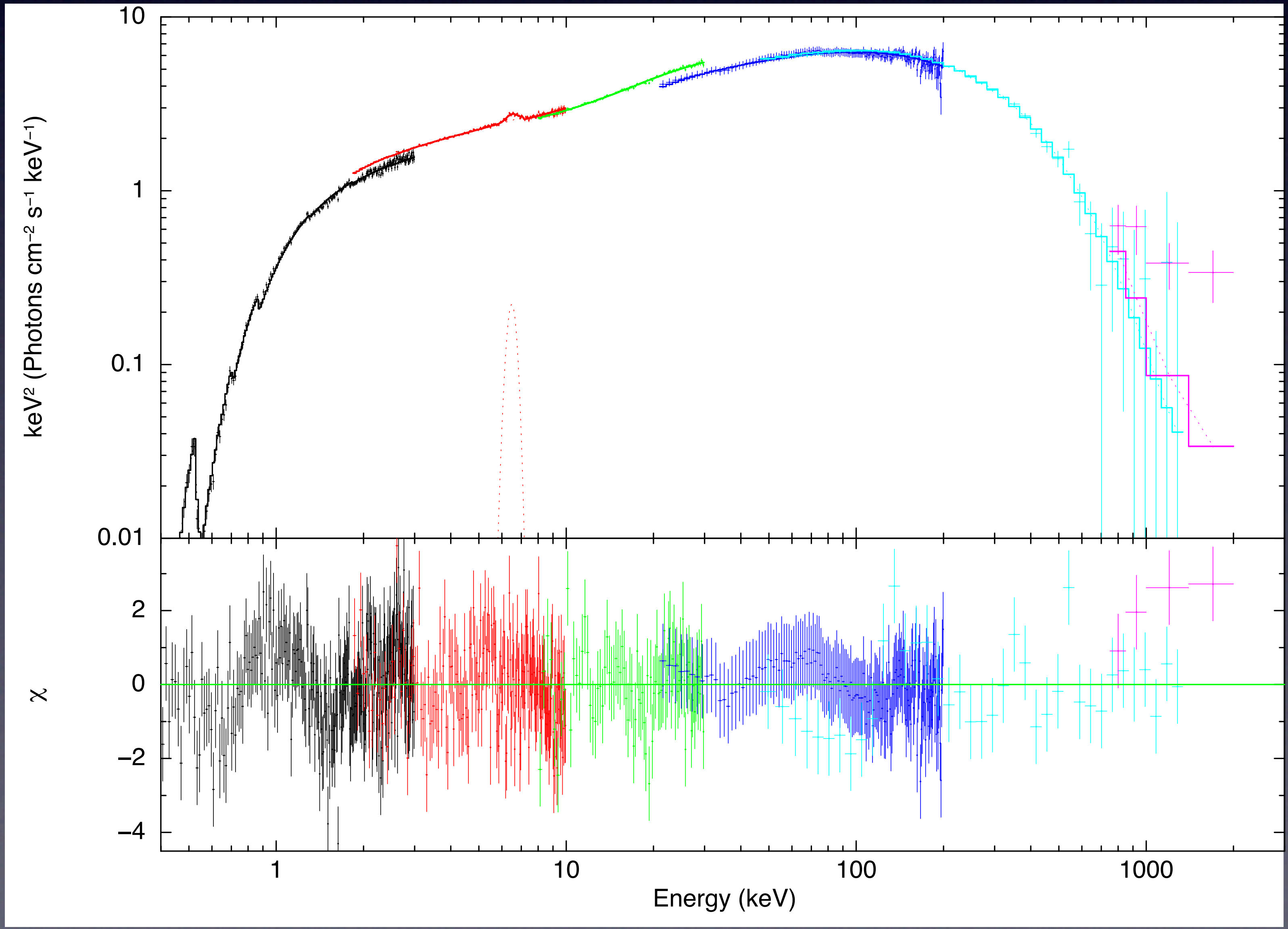
Cyg-X1

Cléaud A.

- ✓ Computation of a large table of spectra
  - ✓ 6 varying parameters (kT_{in}, l_s, β, τ, l_{waves}, l_b) => 500 000 spectra
  - ✓ Used in Xspec as a table model
- ✓ Data: Beppo-Sax + CGRO (McConnell et al. 2002, courtesy: A. Zdziarsky)
- ✓ Low/hard state:



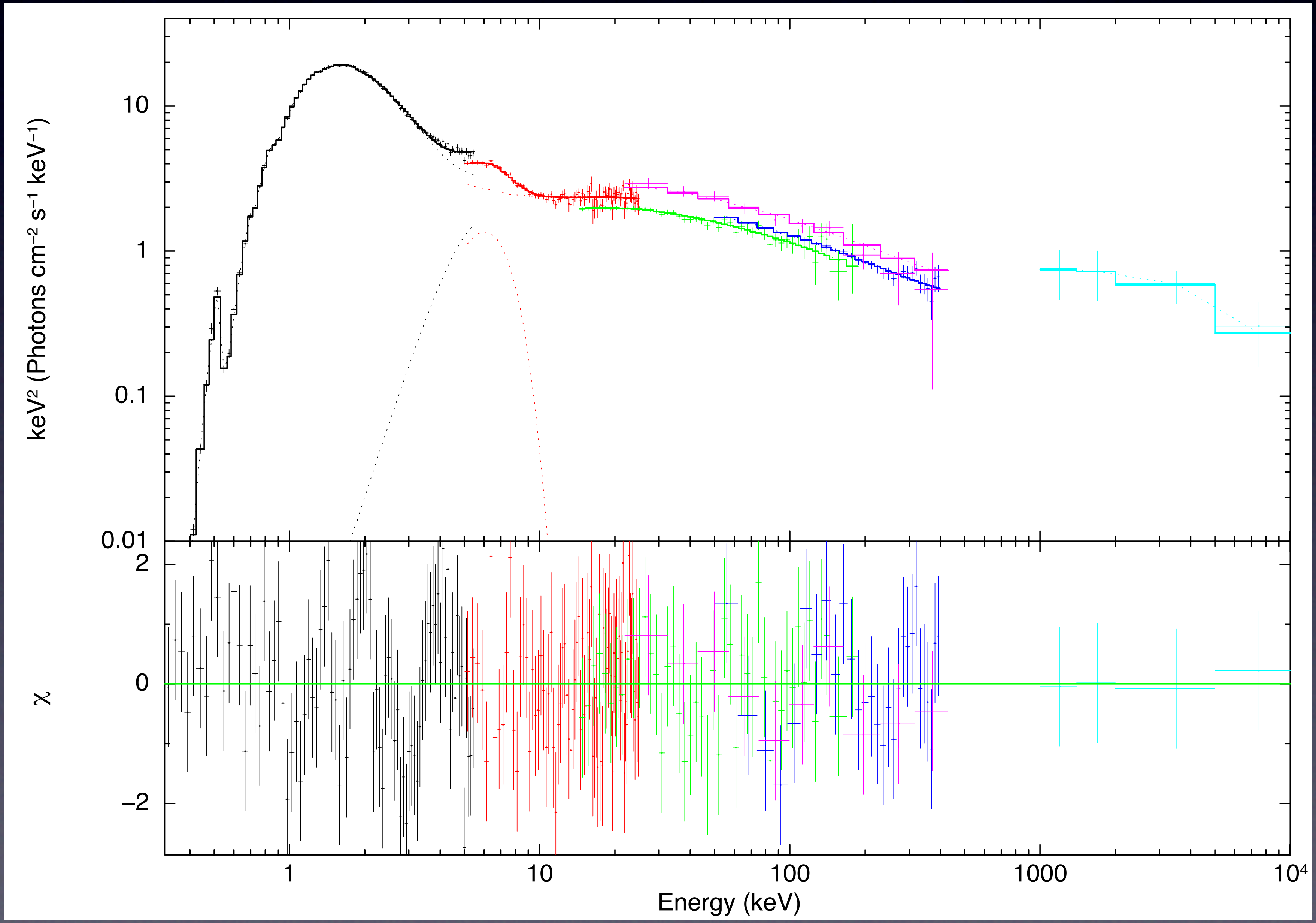
n_H $(10^{22}\mathrm{cm}^{-2})$	0.50
line (keV)	6.5
σ (keV)	0.27
rel_refl	0.51
τ	1.9
l_b	6.53
β	0.98
k_bT_{in} (eV)	300
l_s	0.23
l_s/l_{waves}	0.061
χ^2/dof	817/720



Cyg-X1

Cléaud A.

✓High/soft state



n_H $(10^{22}\mathrm{cm}^{-2})$	0.63
line (keV)	5.2
σ (keV)	1.6
rel_refl	0.89
τ	0.046
l_b	0.19
β	0.33
$k_b T_{\mathrm{in}}$ (eV)	380
l_s	0.011
l_s/l_{waves}	0.20
χ^2/dof	231/236

Conclusion

- ✓ A general model for stochastic acceleration in astrophysical plasmas

- ✓ Consistent computation of the lepton distribution, wave spectrum and photon spectrum

- ✓ Application to the corona of accreting black holes:
  - ✓ Leptons can be accelerated to high energy
  - ✓ Protons can switch on/off lepton acceleration depending in their temperature (β=1)
  - ✓ The soft state of Cyg-X1 can be reproduced using such a model

- ✓ Next steps:
  - ✓ Error computation and constraints (e.g. magnetic field)
  - ✓ Look at other sources (blazars...)
  - ✓ Self consistent computation of the proton distribution