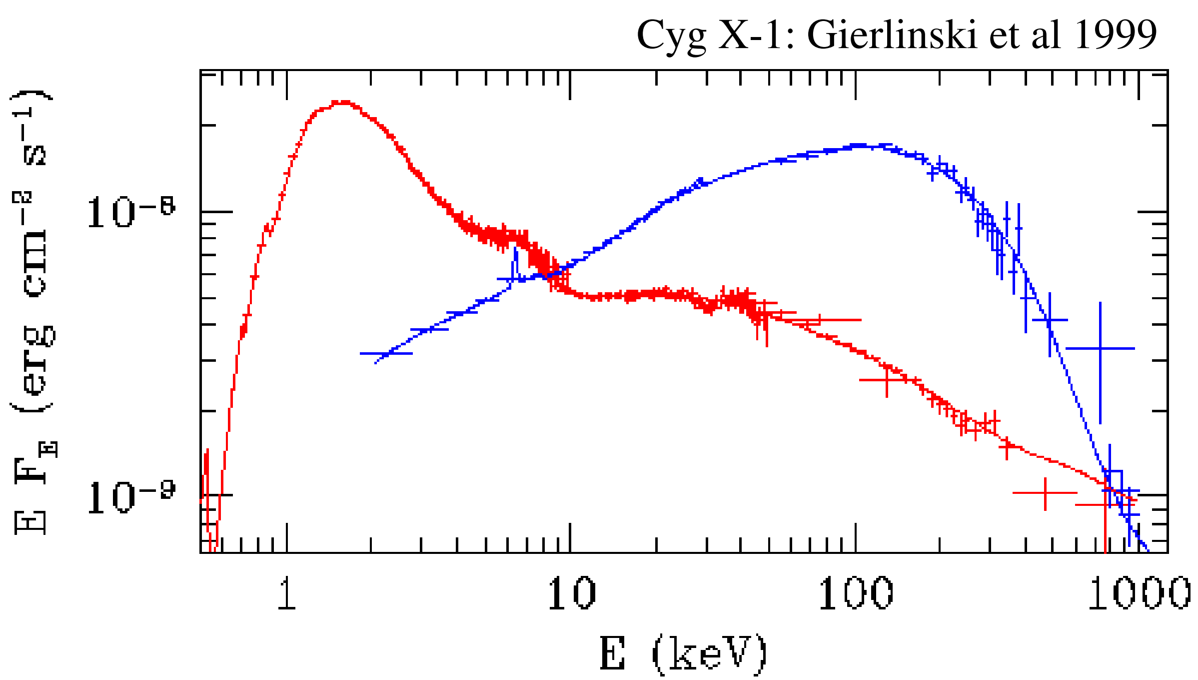
How to make high energy spectra!

Chris Done
University of Durham

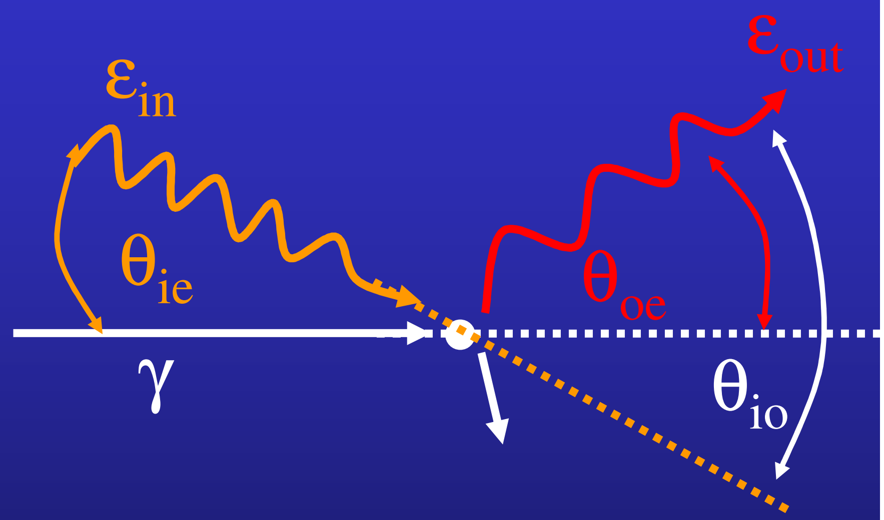
Observations



- Low state spectra peak at 100 keV. Well modelled by thermal electron distribution
- High state spectra need predominantly non-thermal electron distribution

Compton scattering theory

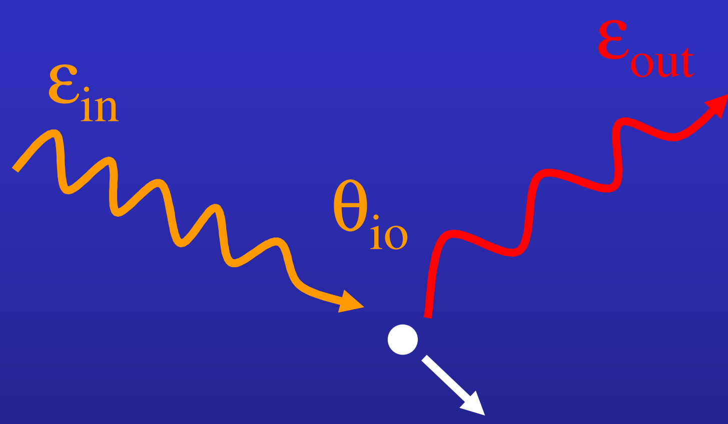
- Collision – redistribute energy
- If photon has more energy than electron then it loses energy – downscattering
- If photon has less energy than electron then it gains energy – upscattering
- Easiest to talk about if scale energies to mc^2 so electron energy γmc^2 just denoted γ while photon energy becomes $\varepsilon = h\nu/mc^2 = E/511$ for E (keV)



$$\varepsilon_{out} = \frac{\varepsilon_{in}(1 - \beta\cos\theta_{ei})}{1 - \beta\cos\theta_{eo} + (\varepsilon_{in}/\gamma)(1 - \cos\theta_{io})}$$

Downscattering: electron at rest

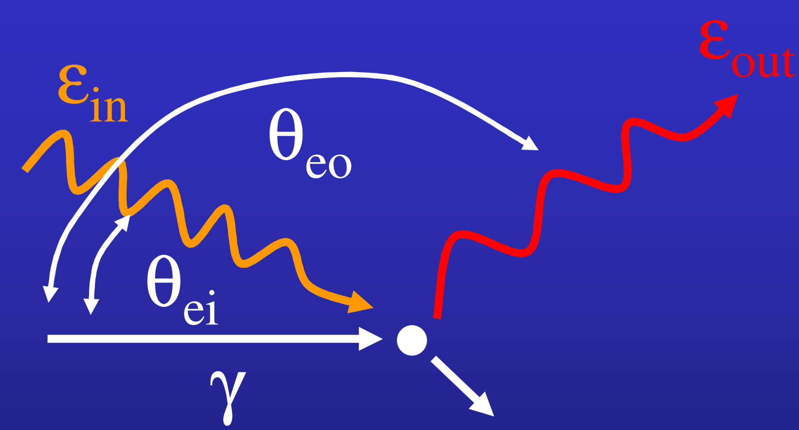
- Always downscatter in electron rest frame as electron must recoil from collision
- Rest frame so $\beta=0$, $\gamma=1$,
- Lose very little energy for $\varepsilon_{in} << 1$ $\varepsilon_{out} \approx \varepsilon_{in}(1-\varepsilon_{in})$
- Lose almost all energy for $\varepsilon_{in} >> 1$ $\varepsilon_{out} \sim 1$



$$\varepsilon_{out} \sim \frac{\varepsilon_{in}}{1 + \varepsilon_{in}\,(1 - \cos\theta_{io})}$$

Thermal compton upscattering:

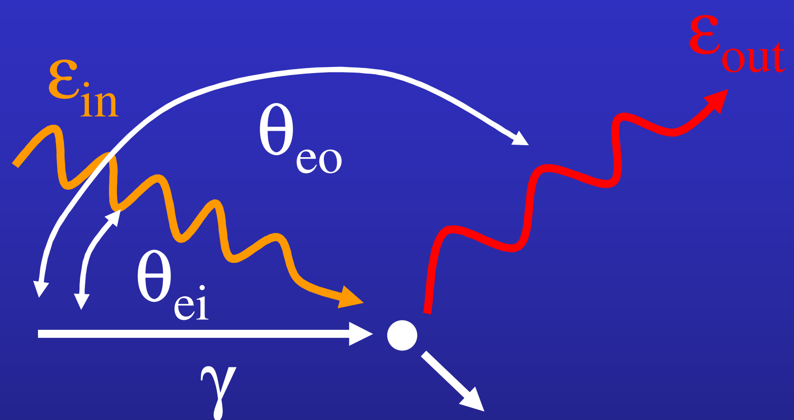
- If $\varepsilon_{in} << \Theta$ then electron has most energy so loses it to photon
- Average over angle for isotropic electron and photon distribution.
- Integrate over Maxwellian distribution of γ to get : $\varepsilon_{out} = (1+4\Theta+16\Theta^2)\, \varepsilon_{in}$ where $\Theta = kT_e/mc^2$



$$\varepsilon_{out} \sim \frac{\varepsilon_{in}(1 - \beta\cos\theta_{ei})}{1 - \beta\cos\theta_{eo}}$$

Limits

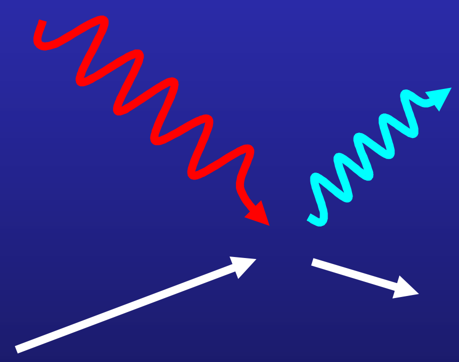
- Can't get more energy out than put in: $\varepsilon_{out} < \varepsilon_{in} + \gamma$
- If upscattering then just reach electron energy limit so for thermal $\varepsilon_{out} \sim 3\Theta$



$\varepsilon_{out} \sim 3\Theta$

How much scattering ?

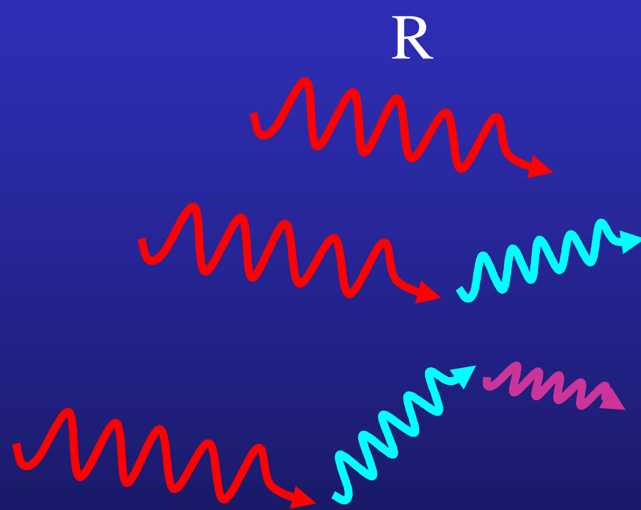
- Compton scattering seed photons from accretion disk. Photon energy boosted by factor $\Delta\varepsilon/\varepsilon \sim 4\Theta+16\Theta^2$ if thermal in each scattering.



How much scattering ?

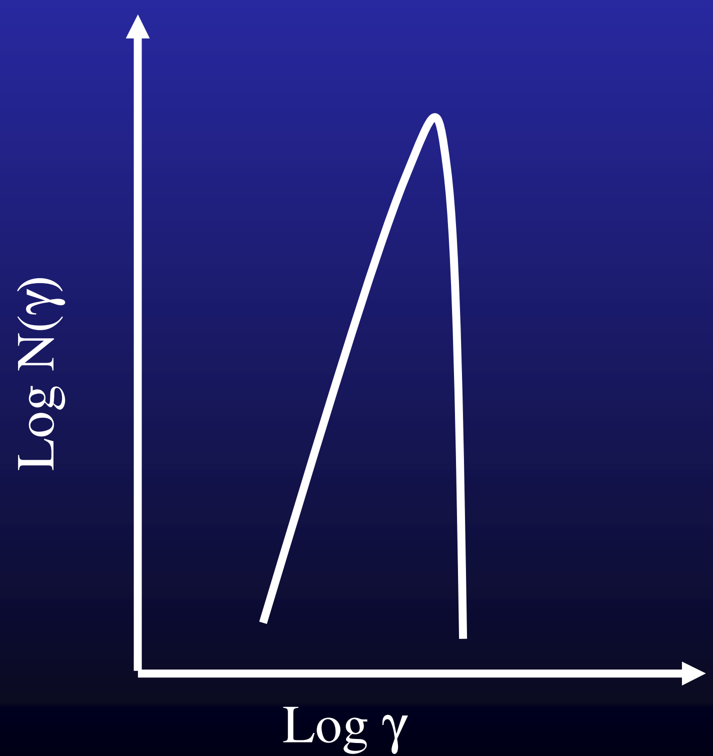
- Number of times scattered given by optical depth, $\tau = \sigma n R$
- Scattering probability $\exp(-\tau)$
- Optically thin $\tau << 1$ prob $\sim \tau$ average number $\sim \tau$
- Optically thick $\tau >> 1$ prob~ 1 and average number $\sim \tau^2$
- Total fractional energy gain = frac.gain in 1 scatt x no.scatt
- Compton $y = (4\Theta + 16\Theta^2)(\tau + \tau^2)$

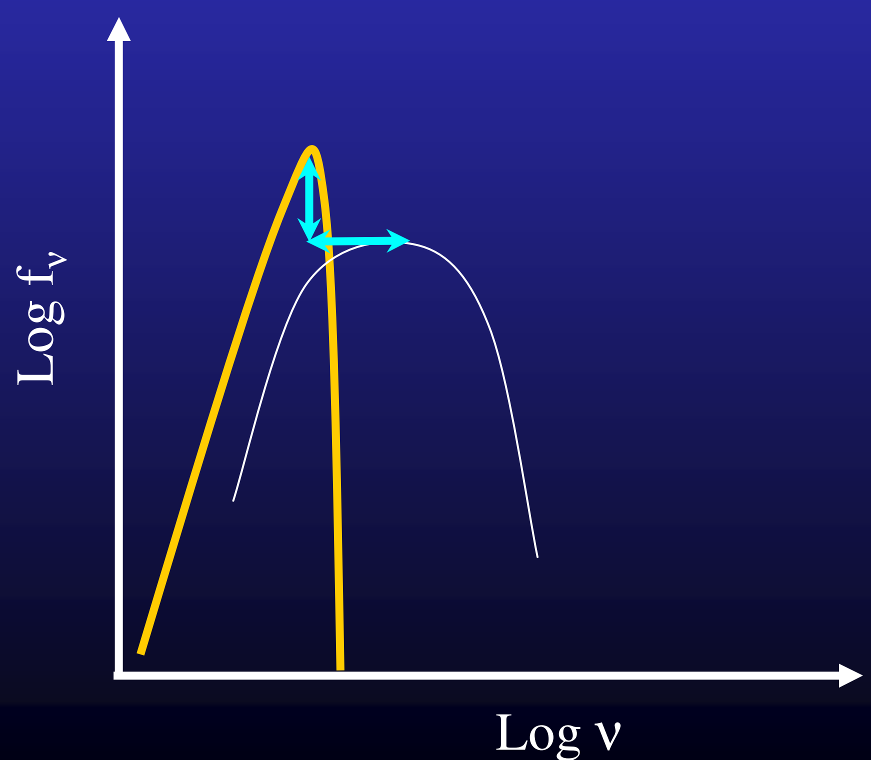
  $\sim 4\Theta\tau^2$ for $\Theta < 1$ $\tau > 1$



Optically thin thermal compton

- power law by multiple scattering of thermal electrons
- Number of photons dN/dE dE = E dN/dE dLog E = f (ε) dlog $\varepsilon \propto \varepsilon^{-\alpha}$
- For $\tau<1$ scatter τ photons each time to energy $\varepsilon_{out}=(1+4\Theta+16\Theta^2)\varepsilon_{in}$
- index α=log(prob)/log(energy boost) ~ -log τ/log $(1+4\Theta+16\Theta^2)$





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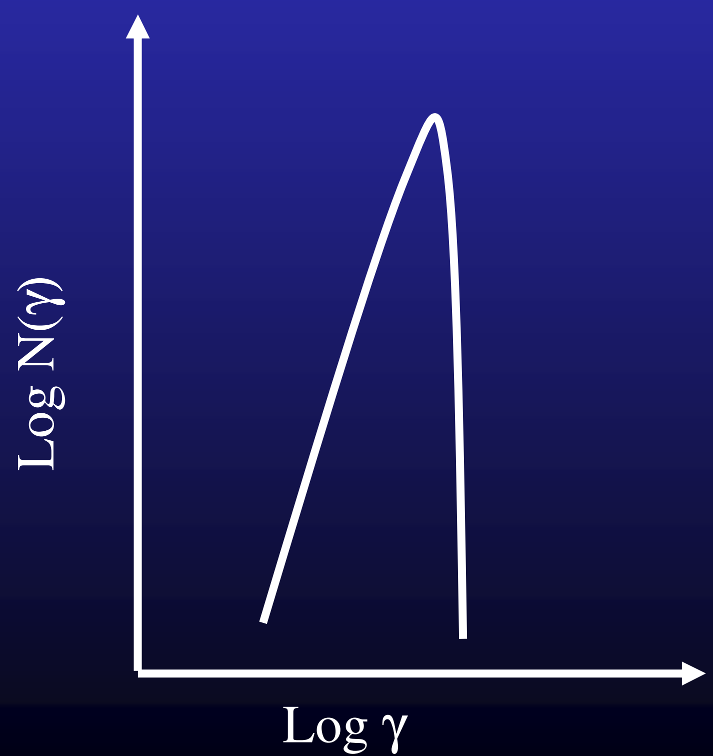

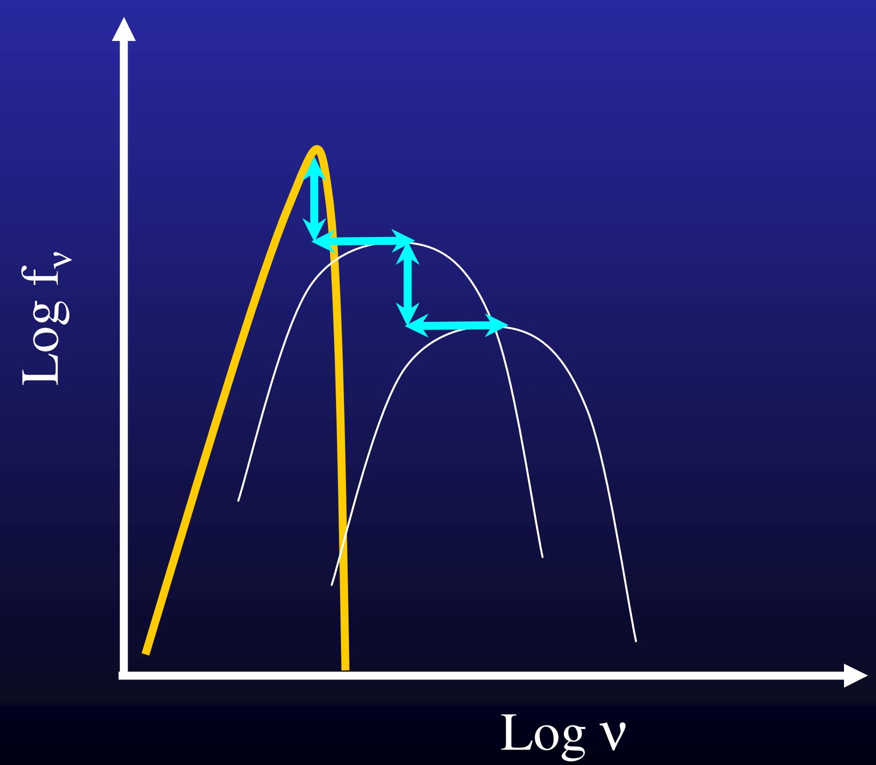

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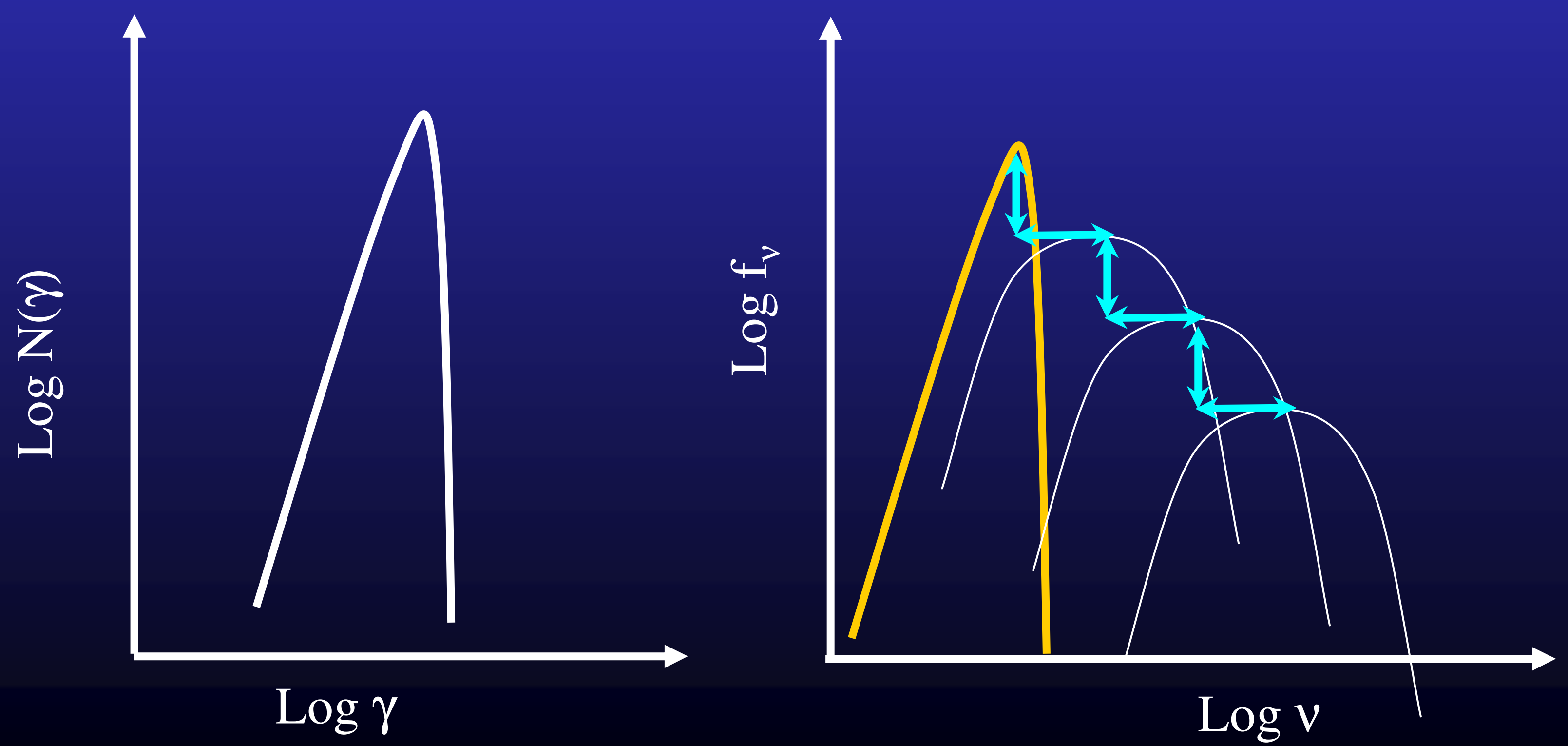

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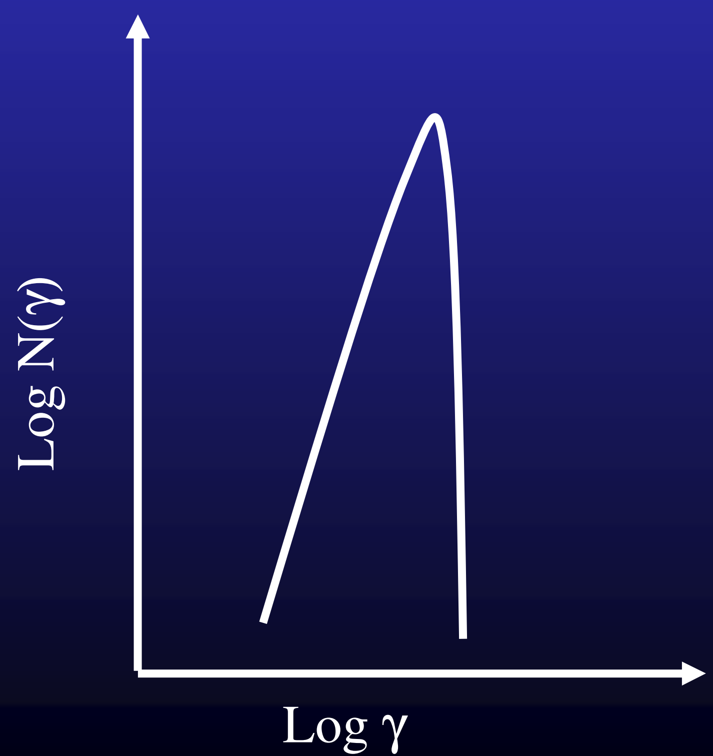
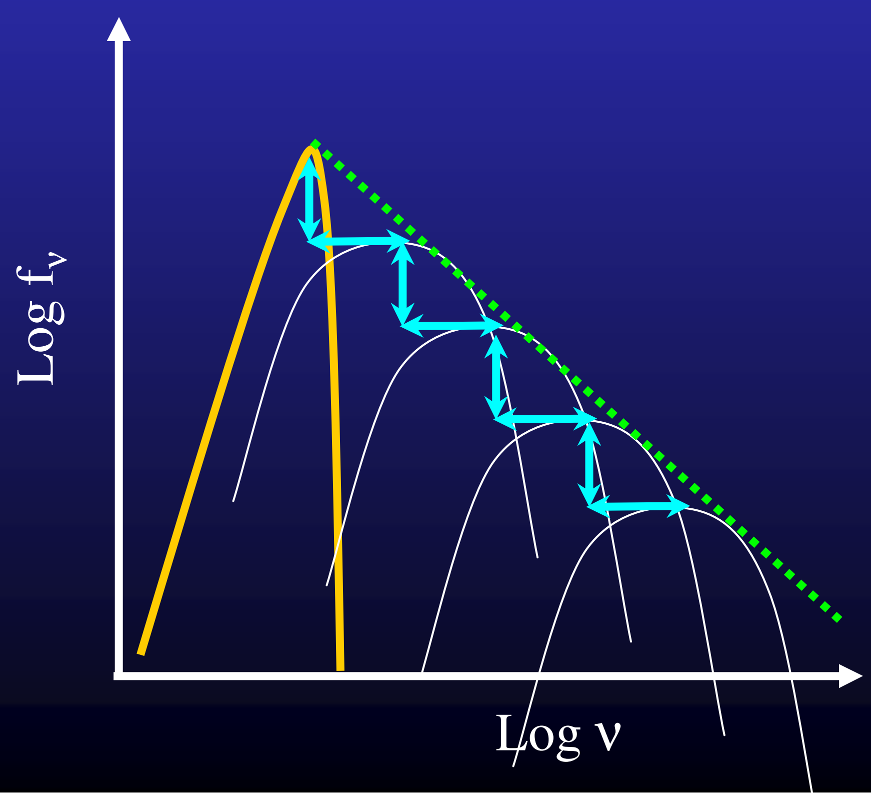
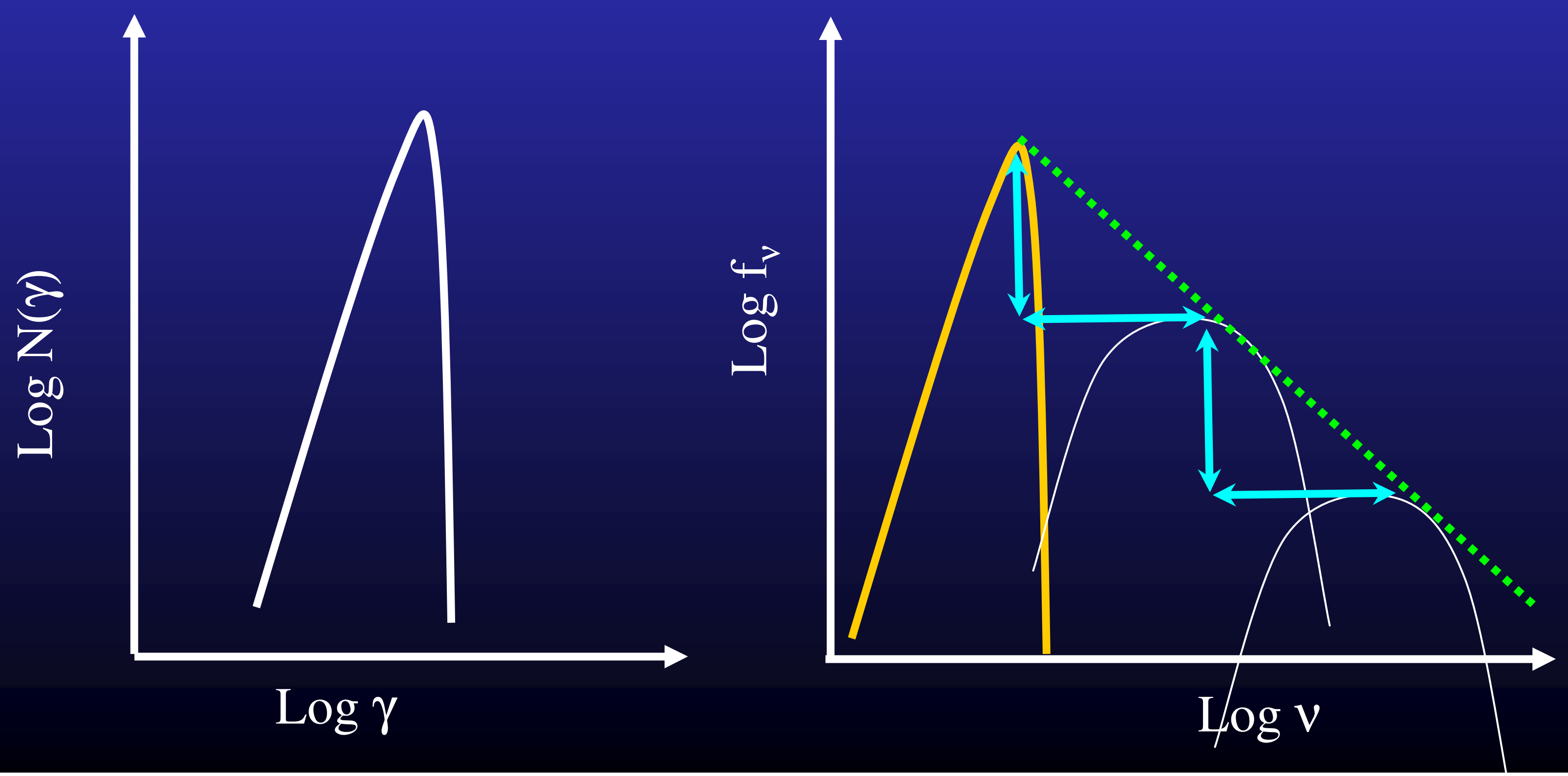




Optically thin thermal compton

- index α=log(prob)/log(energy boost) ~ -log τ/log $(1+4\Theta+16\Theta^2)$
- Same index for lower τ higher Θ
- BUT BUMPY spectrum if τ <<1



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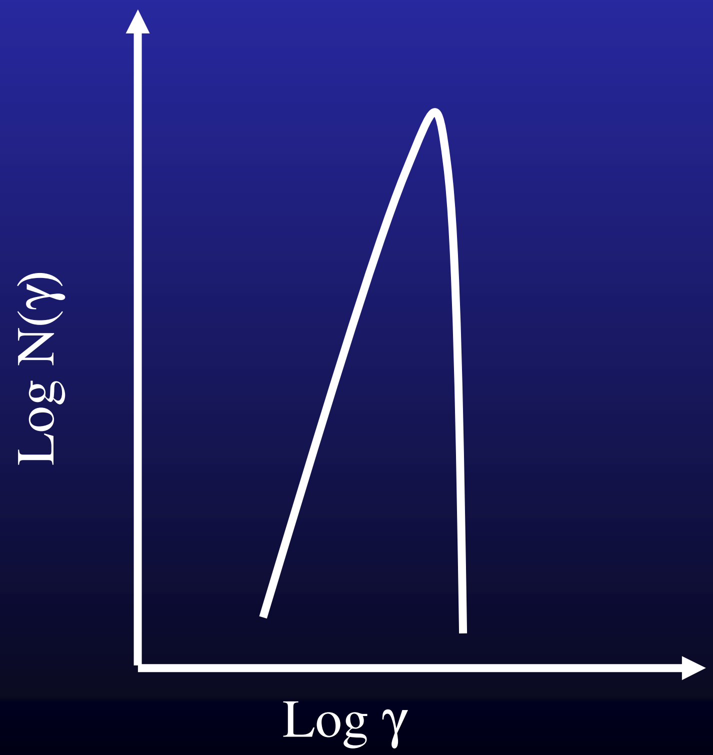
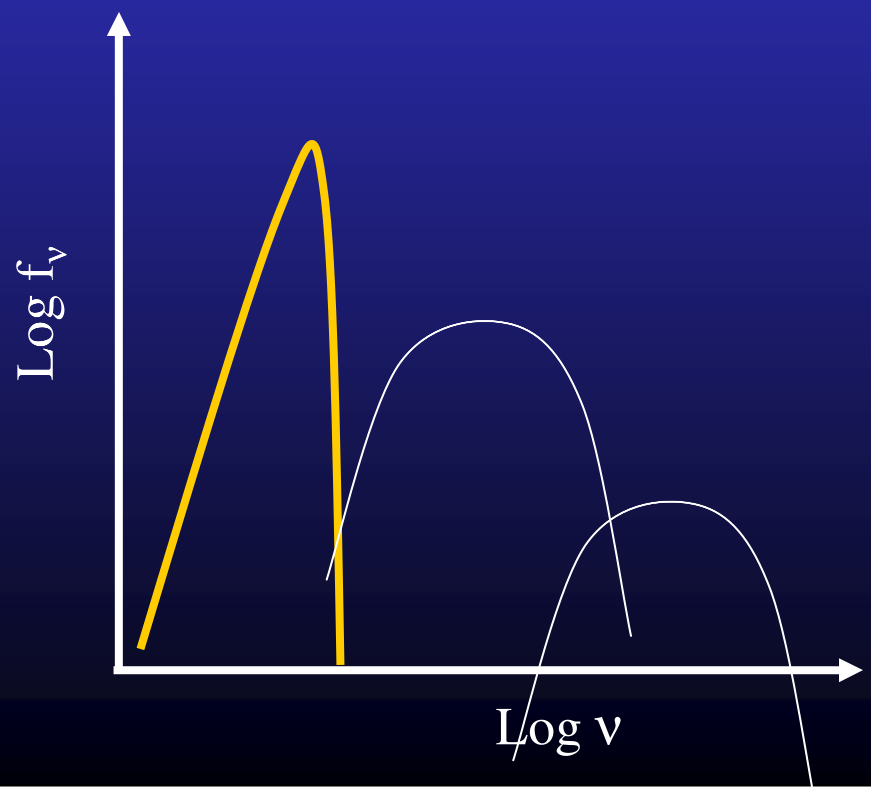
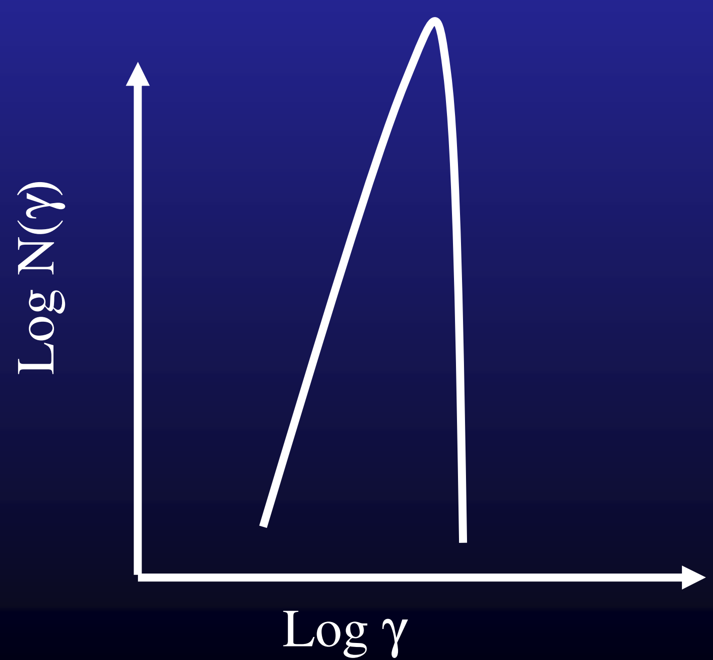
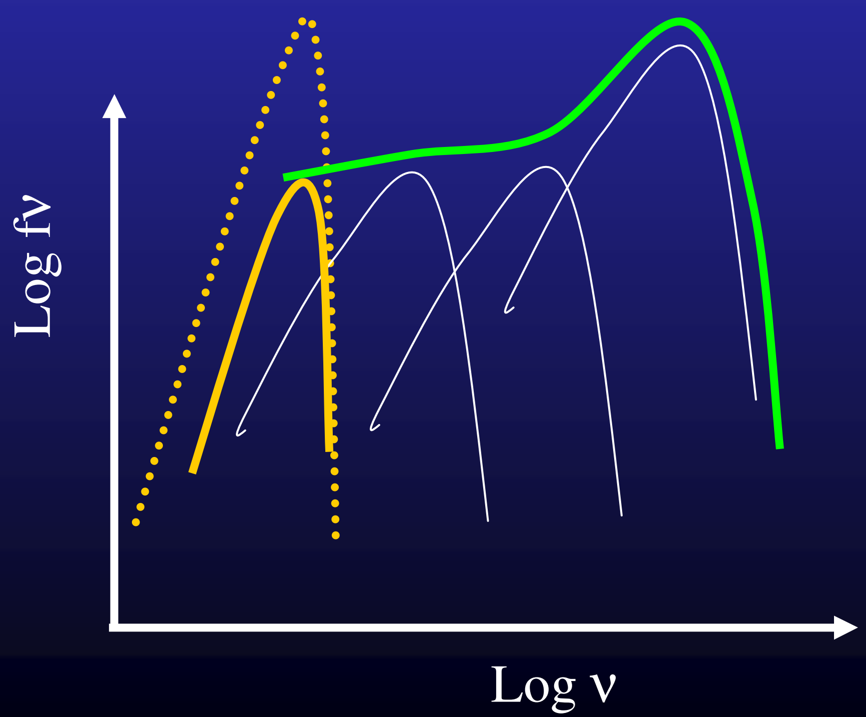




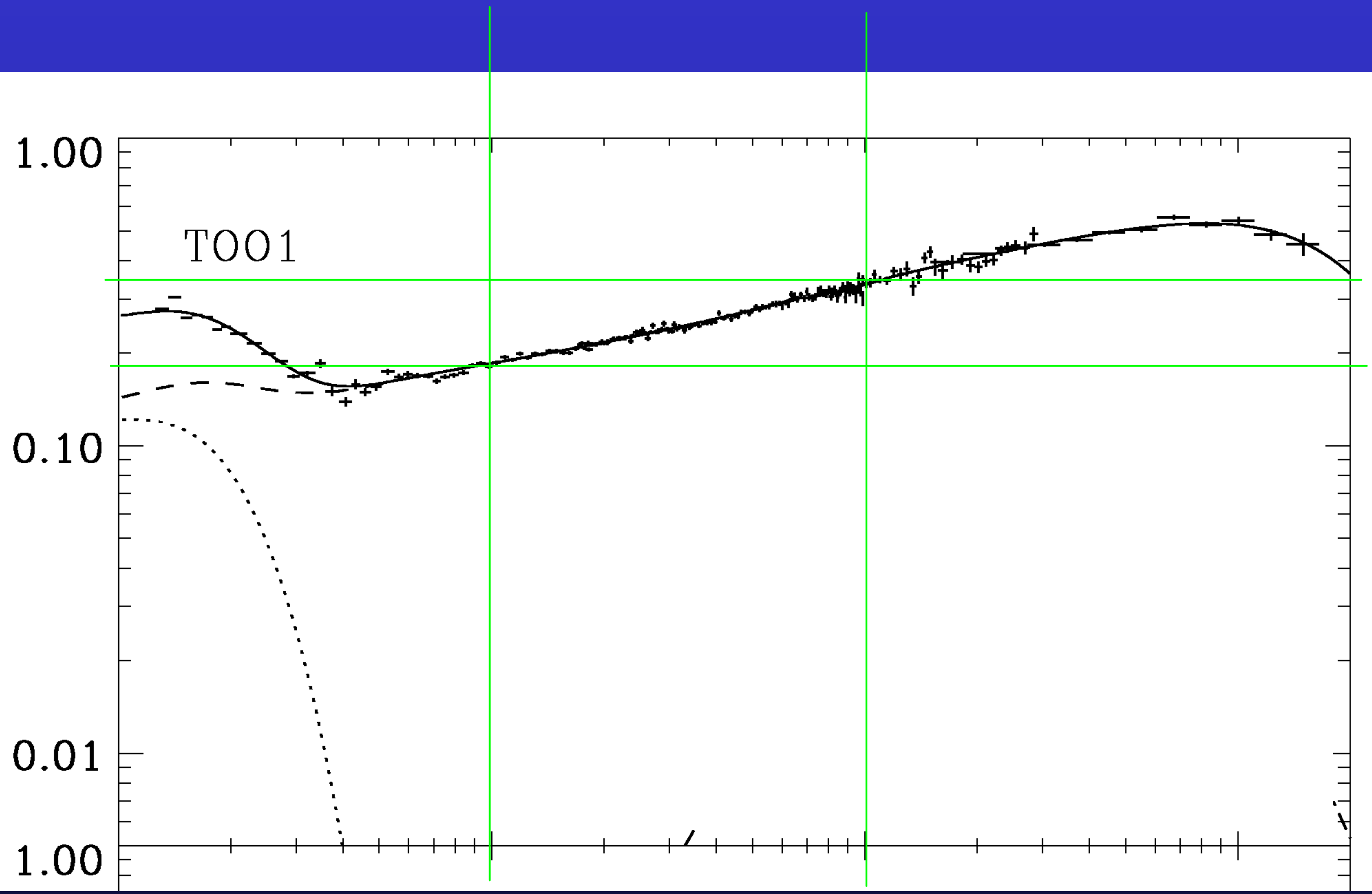
Optically thick thermal

- Optical depth $\tau > 1$, multiple scattering – average $N \sim \tau^2$
- Not much left of original seed photon spectrum $\exp(-\tau)$
- if $(1+4\Theta)^N \varepsilon_{in} > 3\Theta$ ($y \gg 1$) then majority of photons reach 3Θ
- Can't go any higher so they pile up – try to thermalise but little true absorption so still comptonised. Wien peak.



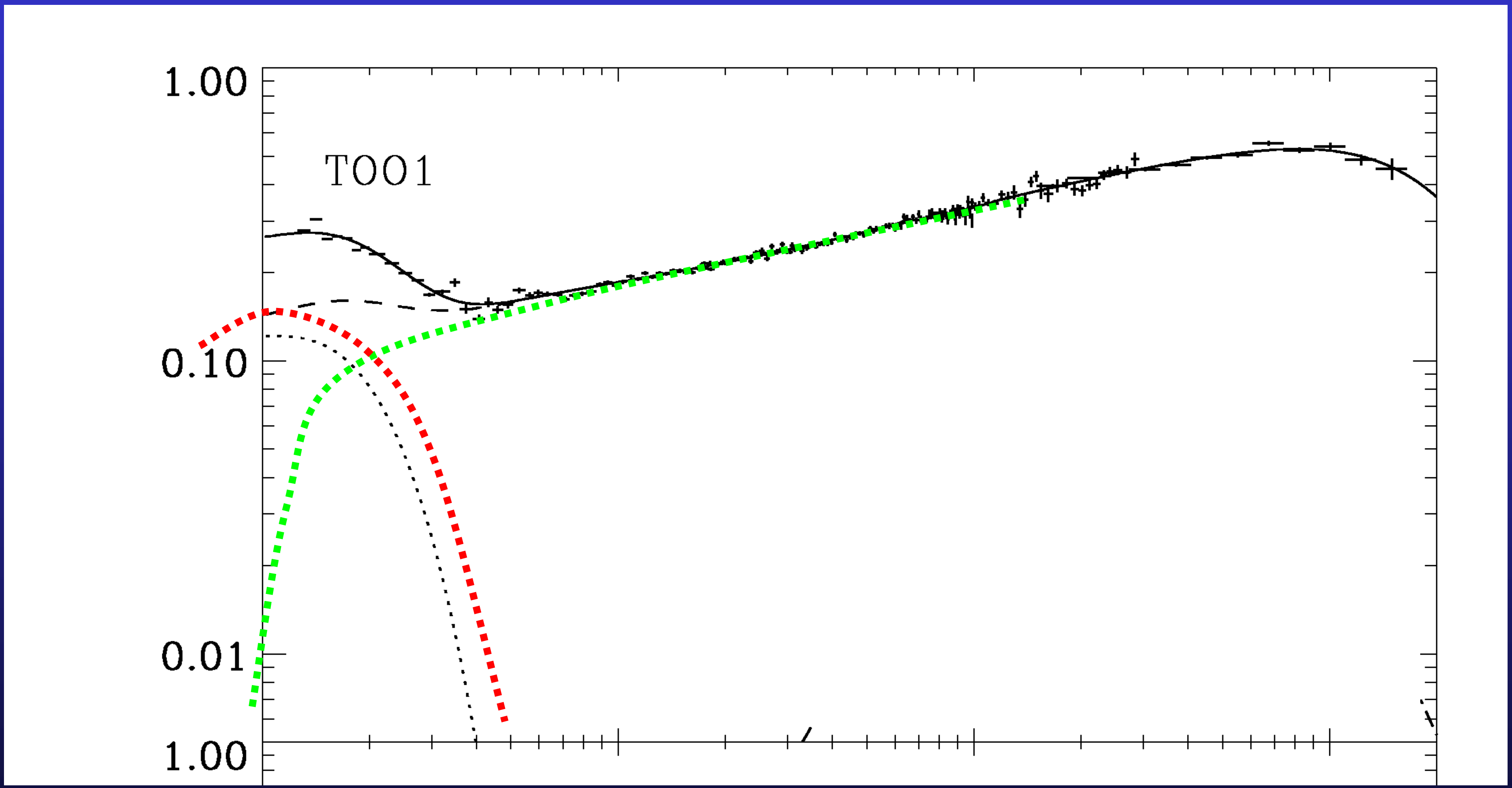


Practice!! Mystery object



- Estimate Θ and τ

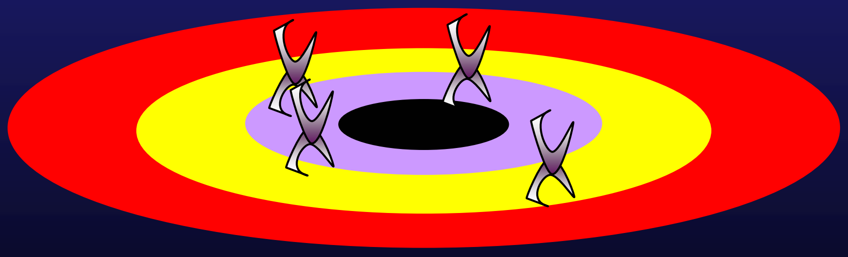
Seed photons

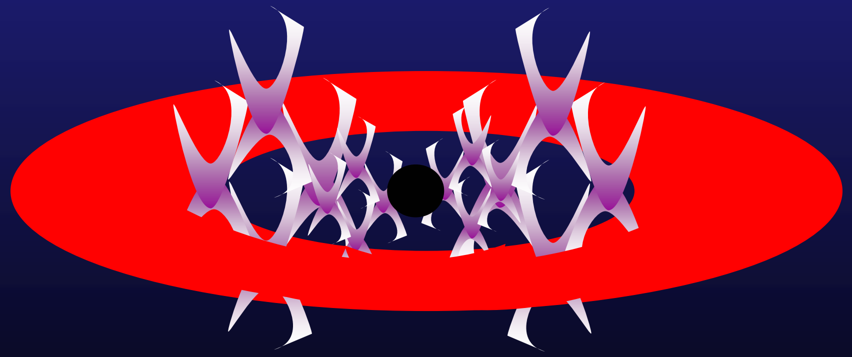


- Need more soft emission than exp(- τ)
- Not all disc comptonised! Patchy corona or truncated disc

Energetics!

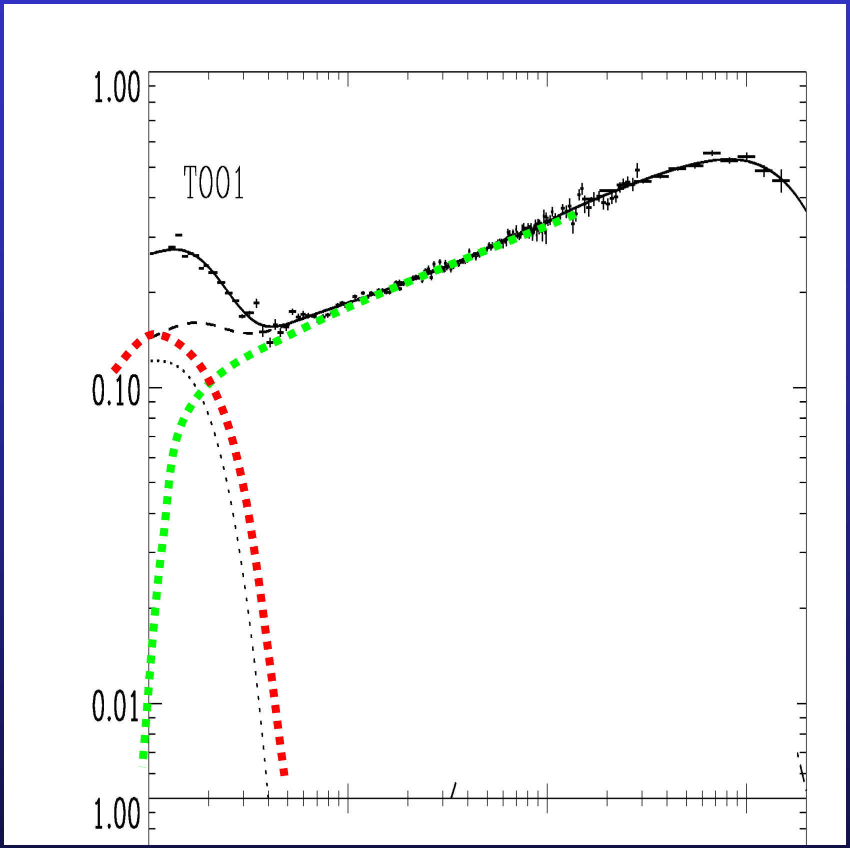
- Seed photon power illuminating flow Ls
- Heating of electrons gives comptonisation power Lh
- Lh >> Ls to get hard spectrum
- Easy to see how in truncated disc. Less easy in corona (see L5)





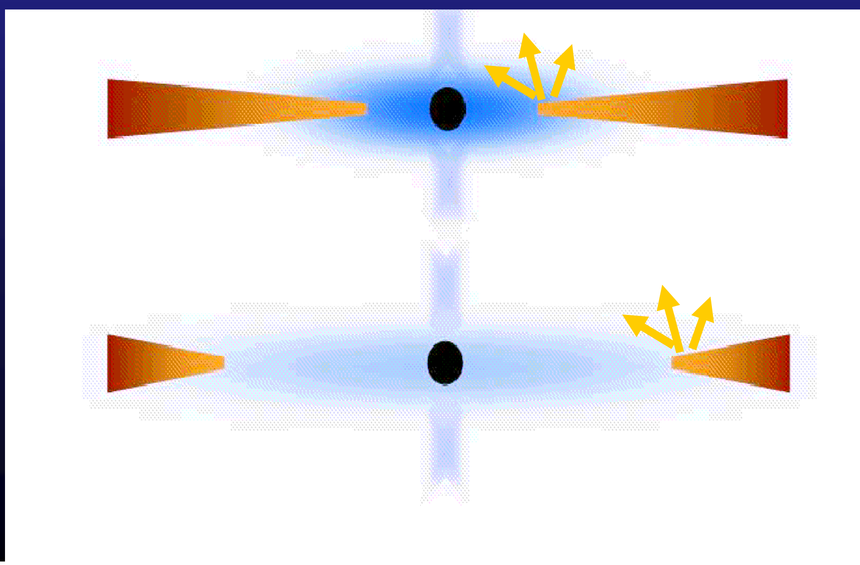
Energetics!

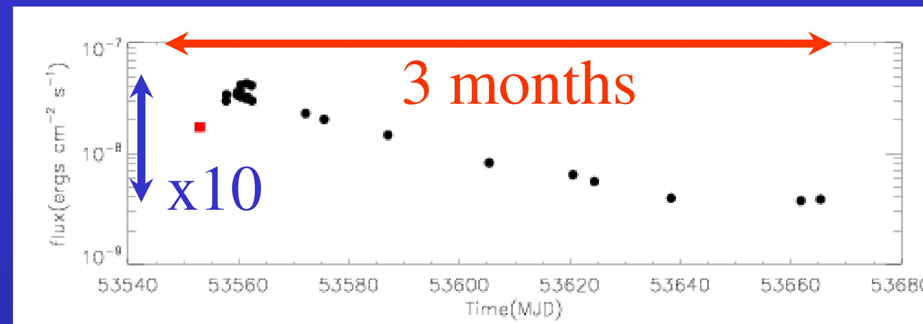
- Seed photon power illuminating flow Ls
- Heating of electrons gives comptonisation power Lh
- y axis τ Ls to Lh, x axis from ε_{in} to 3Θ
- Get self consistent Θ from energetics

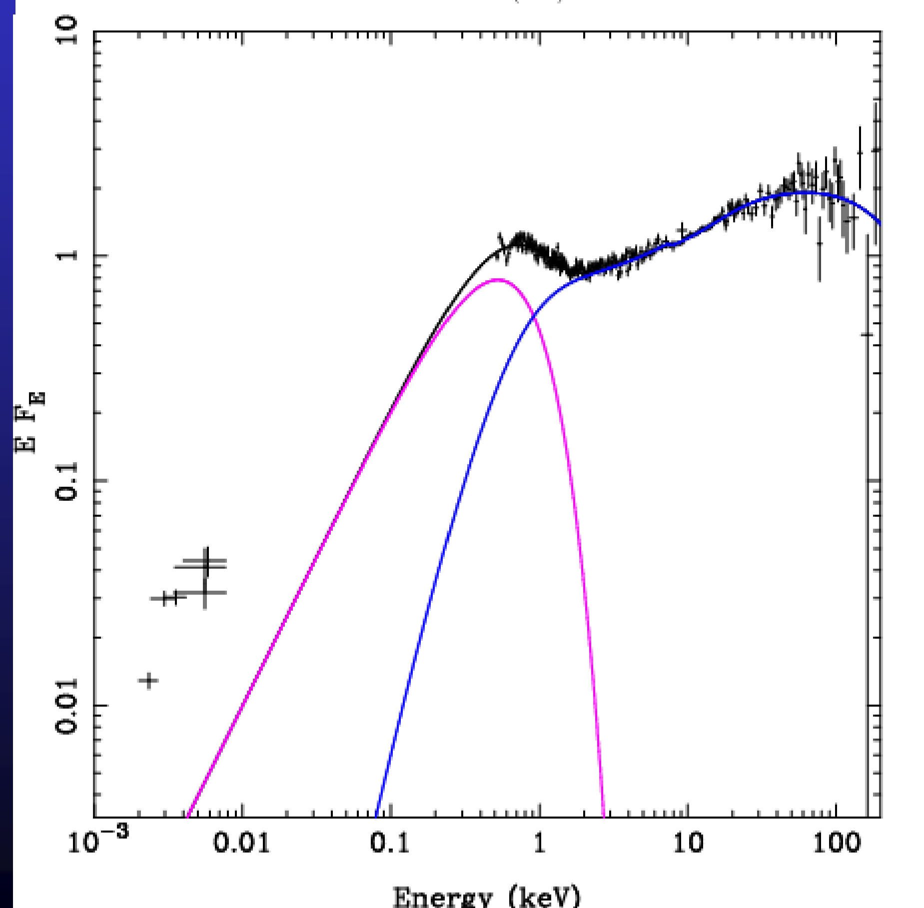


Seed photons in low/hard state

- Low/hard state outburst
- Swift optical/UV/X-ray plus RXTE 3-200 keV
- Low Nh ($2x10^{21}$ cm^{-2})
- Factor 10 ↓ in 3 months
- Seed photons disc at peak
- Probably cyclo-sync later



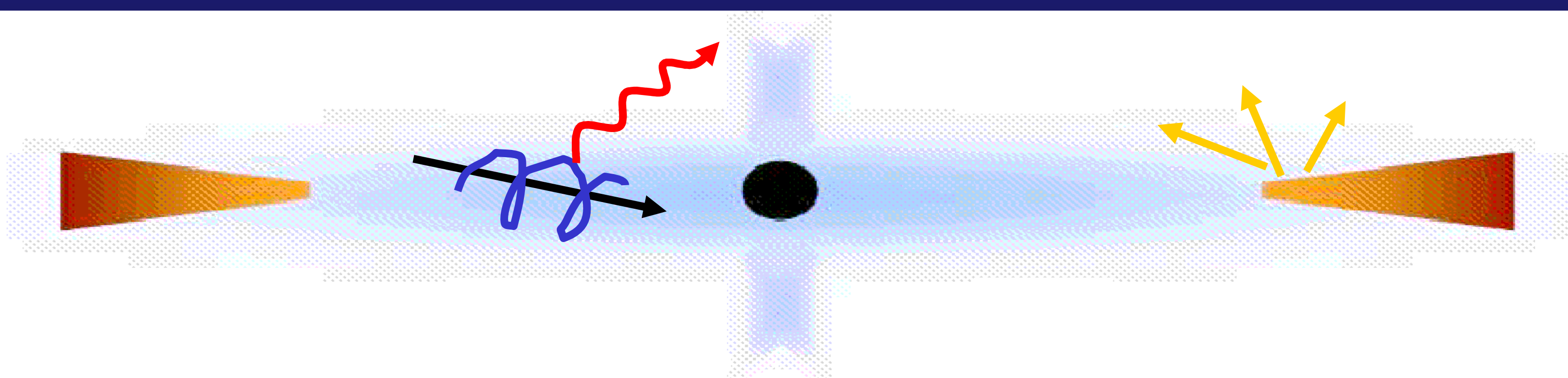




Chiang & Done 2009

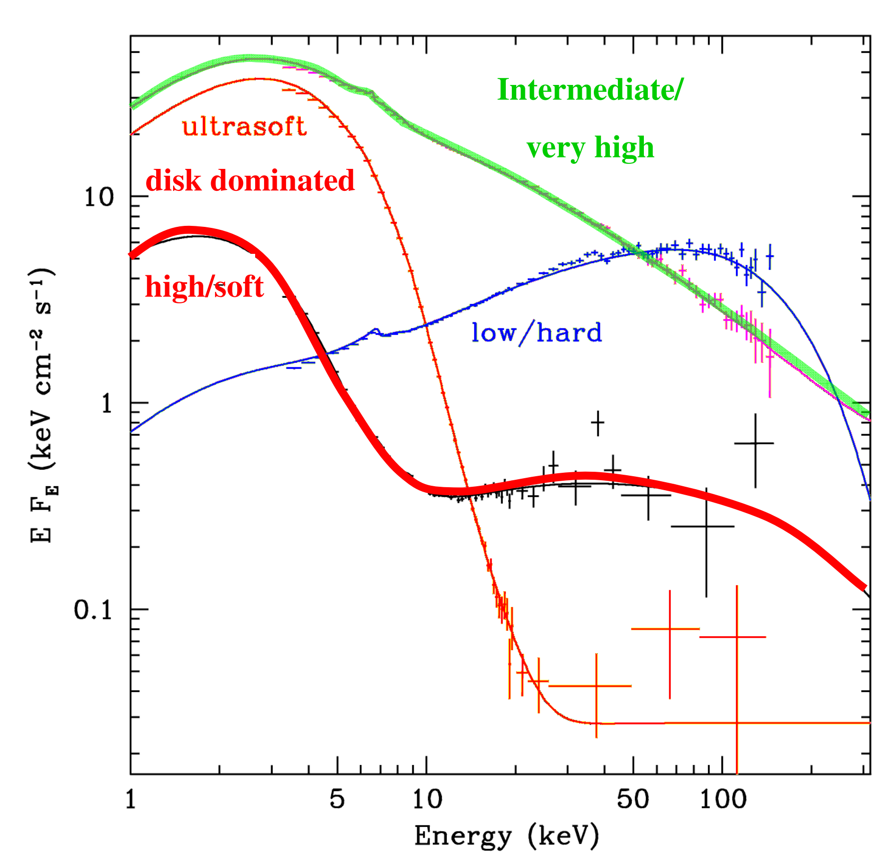
Seed photons in low/hard state

- Most photons from disc don't intercept hot flow
- So Ls << Lh and predict very HARD spectra
- Never see this!
- So need another source of seed photons
- Got B field and hot electrons – the thermal electrons can spiral around the B field lines and give cyclo-synchrotron in the flow itself so it makes it own seed photons!



Spectral states

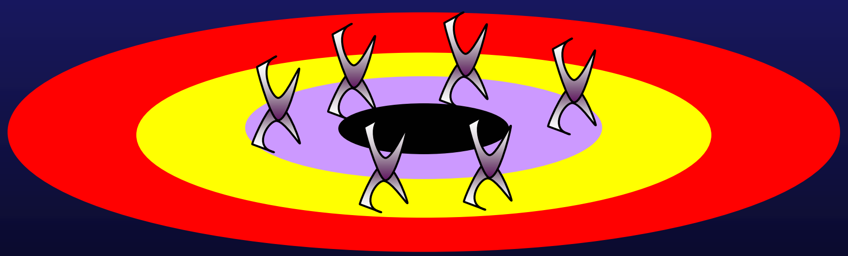
- Dramatic changes in continuum – single object, different days
- Underlying pattern in all systems
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail
- Lower L/L_{Edd}: hard spectrum, peaks at high energies, not like a disc (McClintock & Remillard 2006)

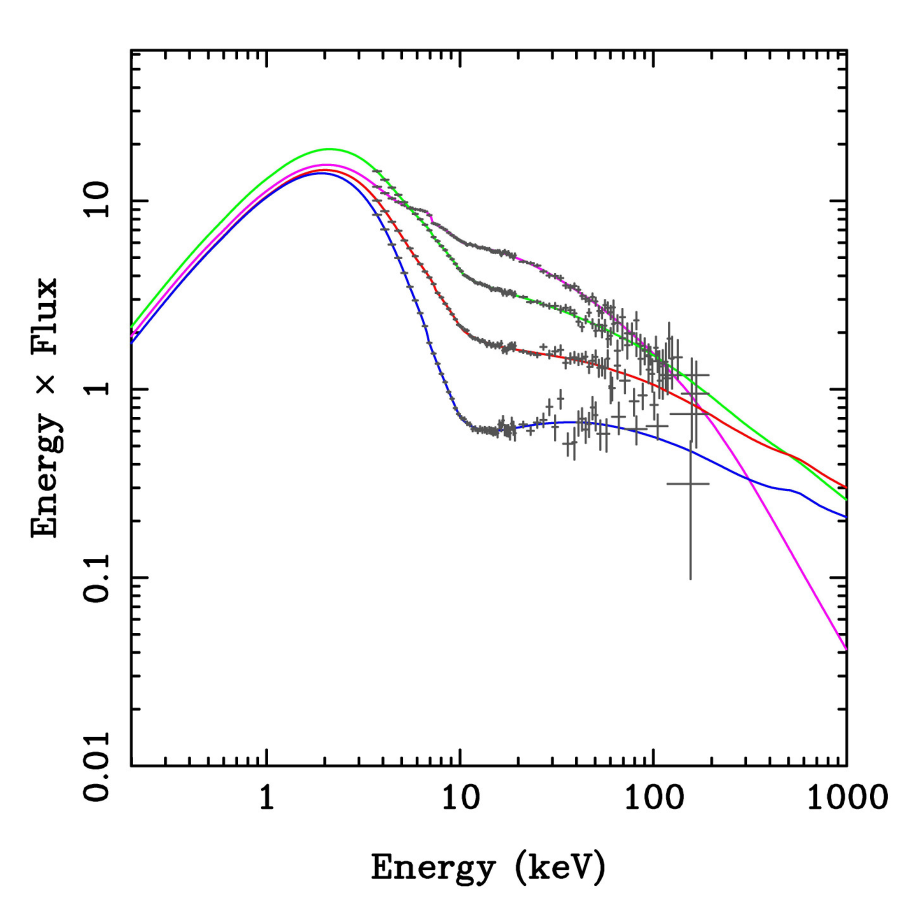


Gierlinski & Done 2003

X-ray spectra at high L/L_{Edd} are not always disc dominated

- Disc dominated spectra tail – either small t or small covering fraction
- Merge smoothly onto VHS
- Most extreme show no clear disc rise – high optical depth AND high covering fraction





DGK07

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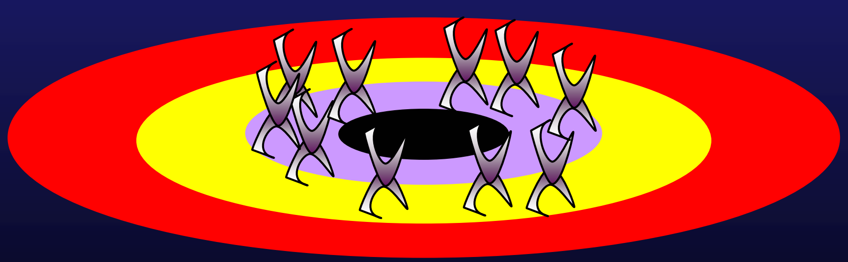

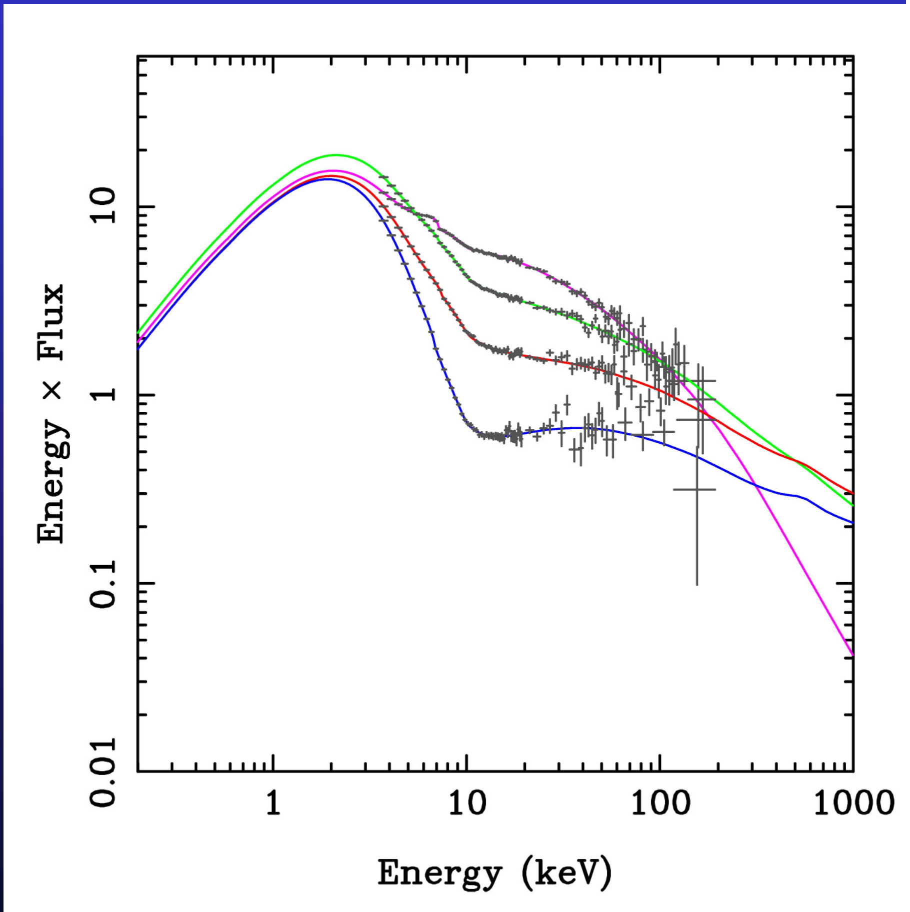

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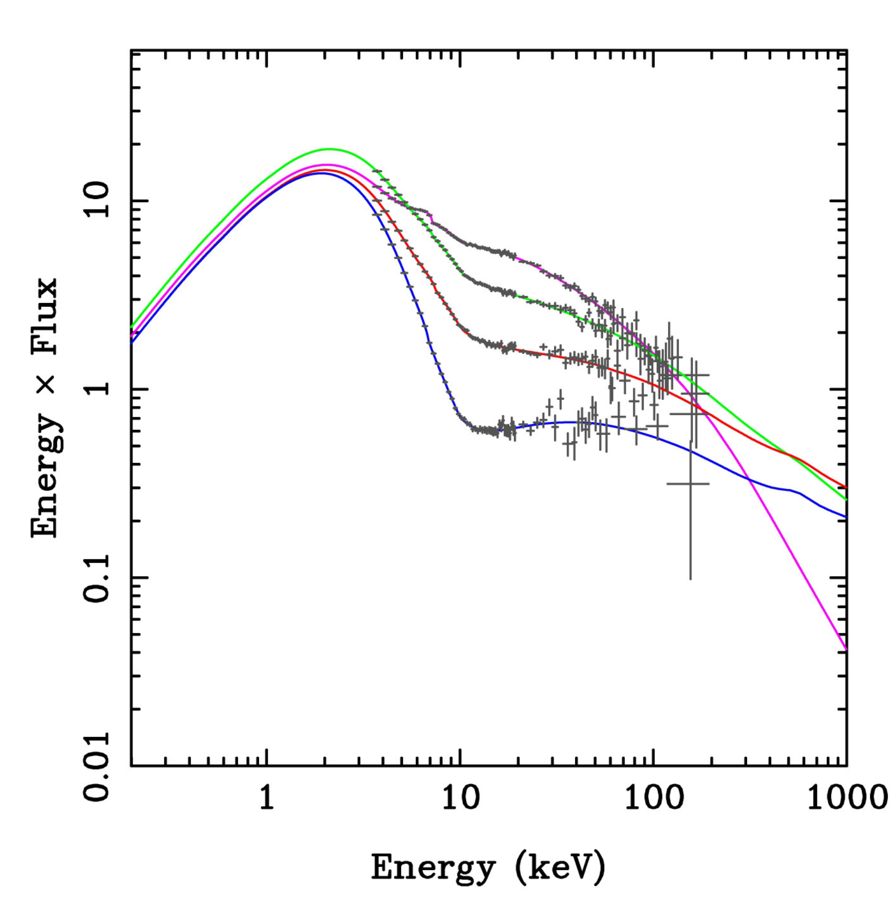
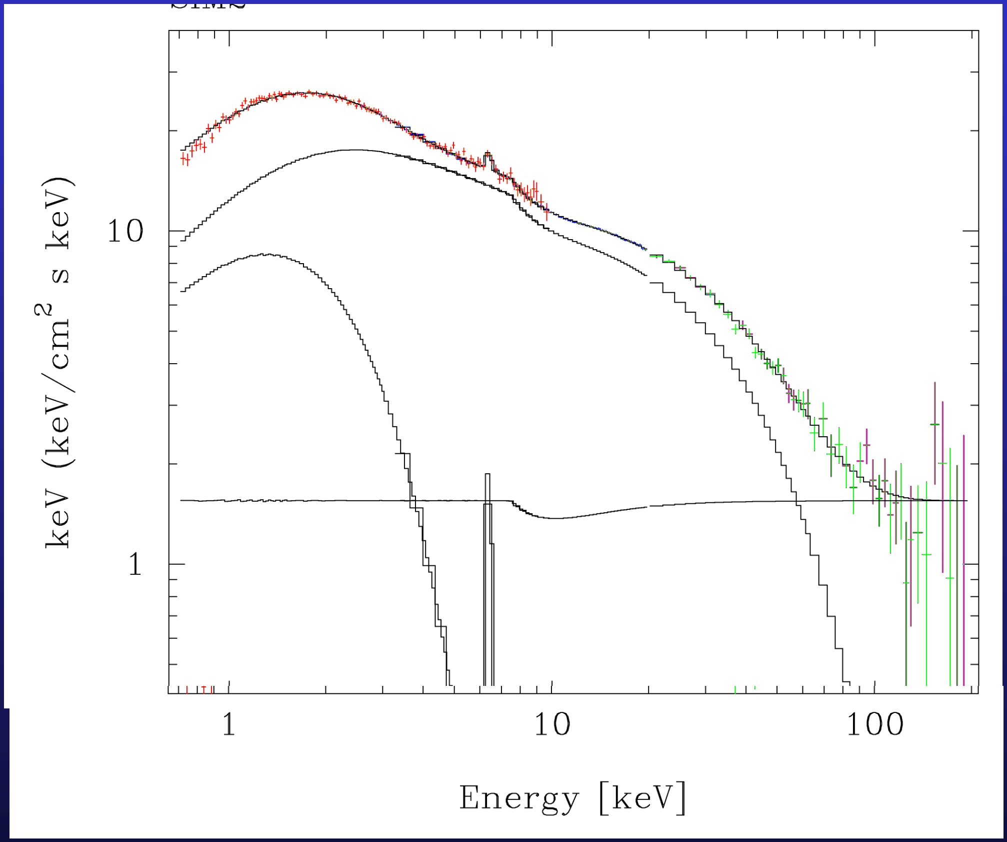


DGK07

Very high state

- Disk does not dominate!
- Sometimes hard to see as separate component from continuum – optically thick comptonisation completely covering inner disc
- kT_e ~10-20 keV, τ~2 optically thick Kubota et al 2001; Kubota & Done 2004

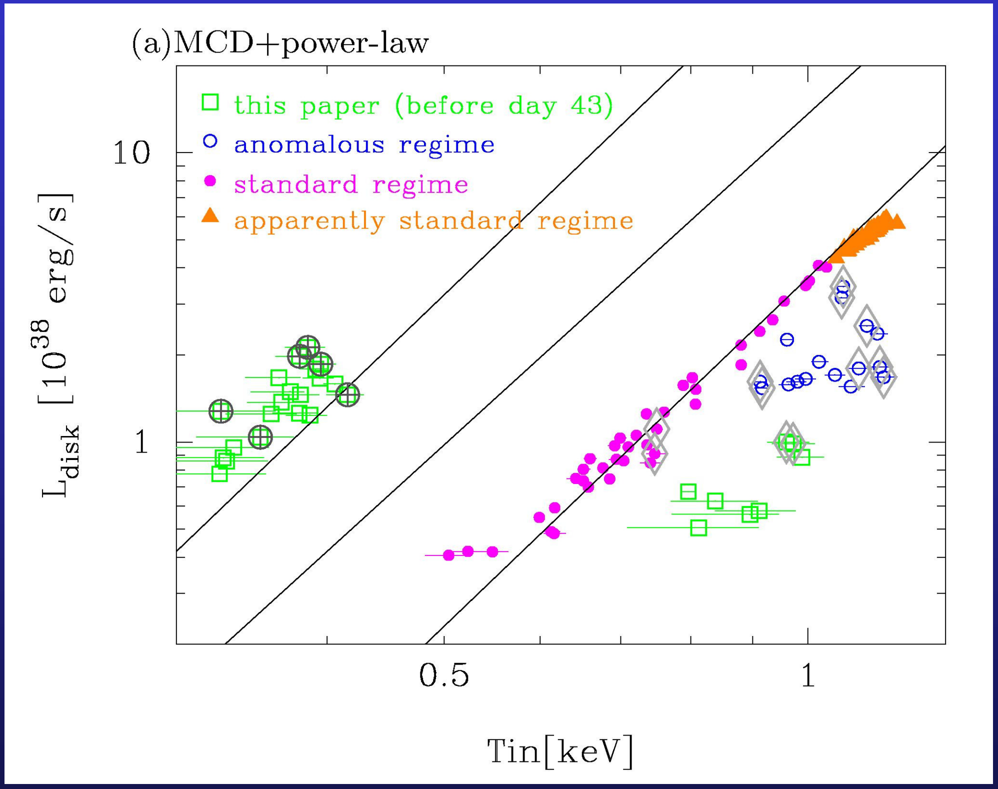


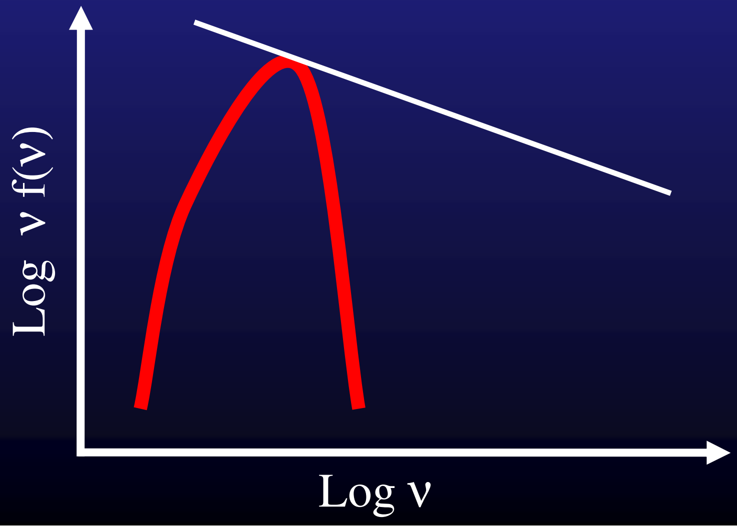
Done & Kubota 2006

Very High State: Spectrum

Kubota & Done 2004

- Disc AND tail have roughly equal power. BE CAREFUL!!!
- Now depends on models - Comptonized spectrum is NOT a power law close to seed photons!





- Disc dominated (low L / high L)
- Very high state (comp < disc)
- Very high state (comp > disc)

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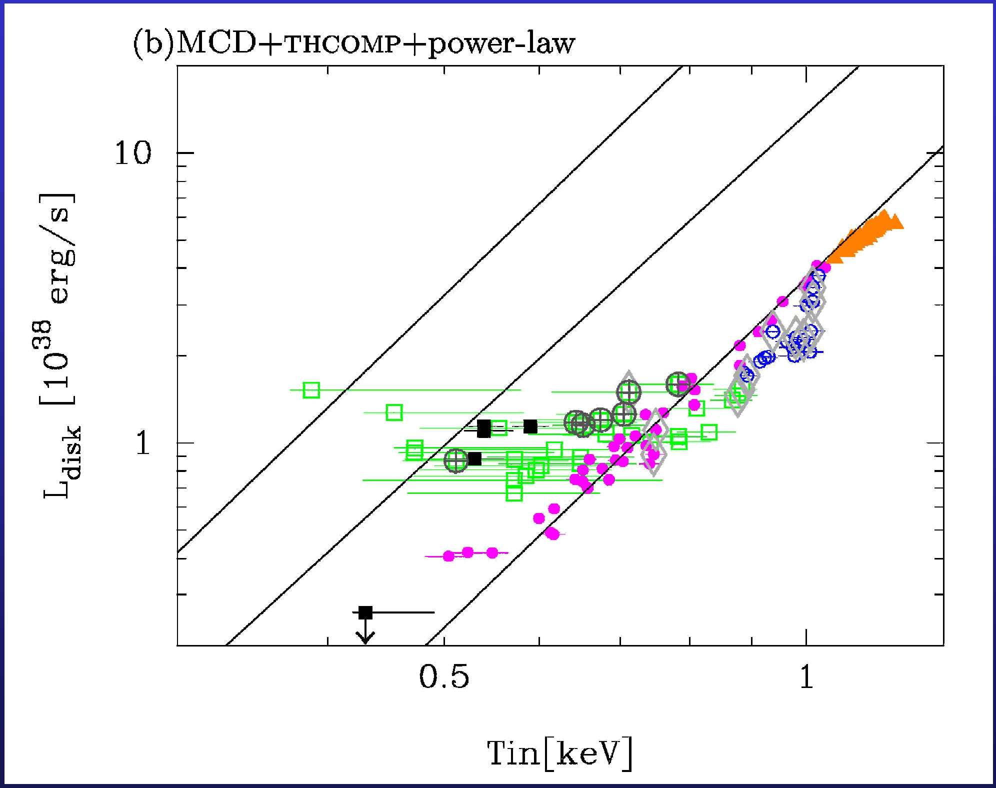

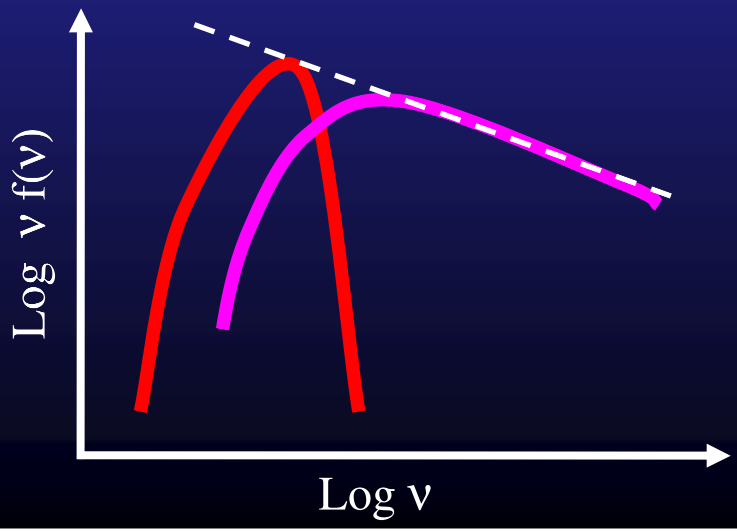

- Disc dominated (low L / high L)
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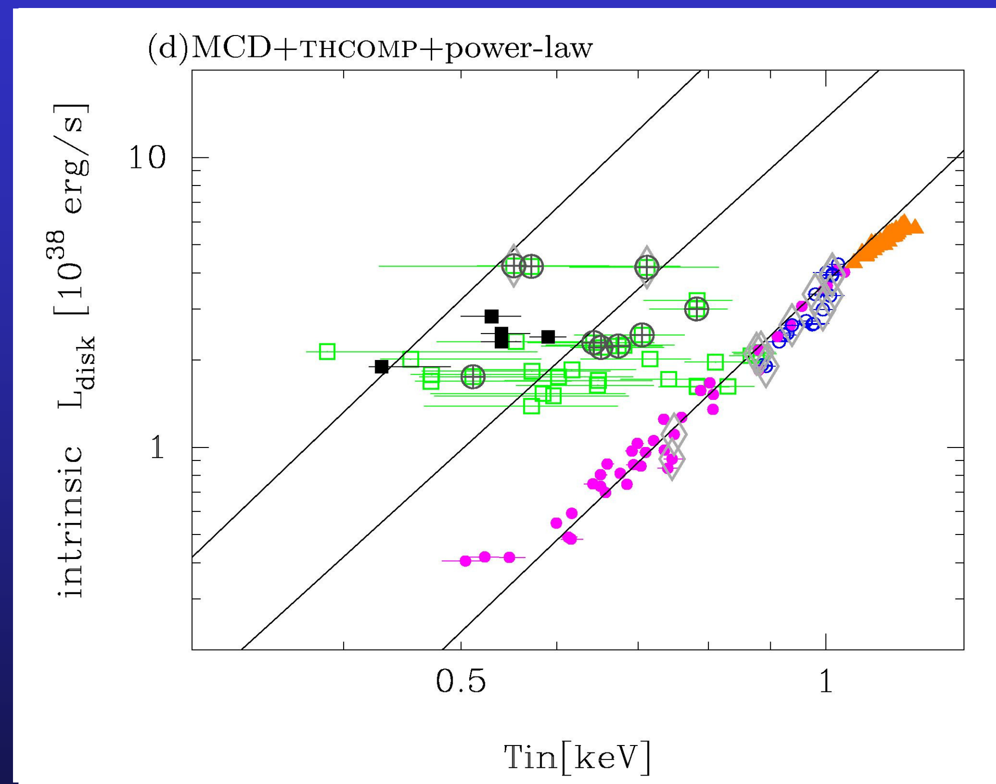
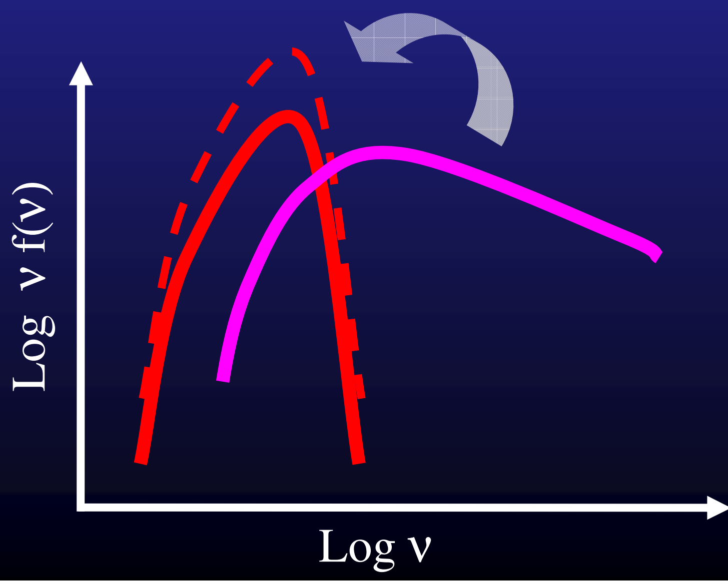
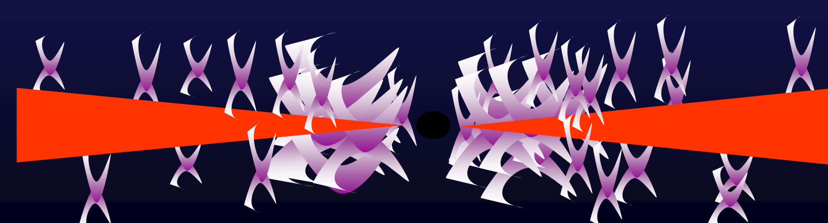
Very High State: photons

Kubota & Done 2004

- But Comptonised photons come from the disc – optically thick so suppresses apparent disc emission
- Correct for this







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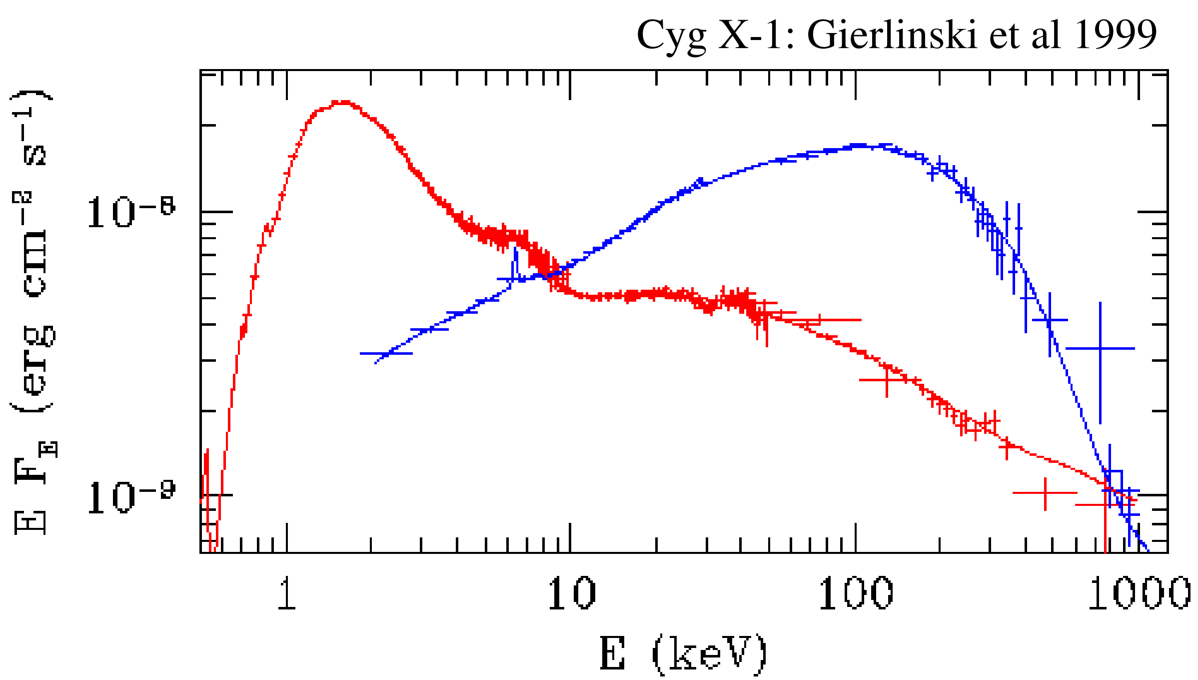
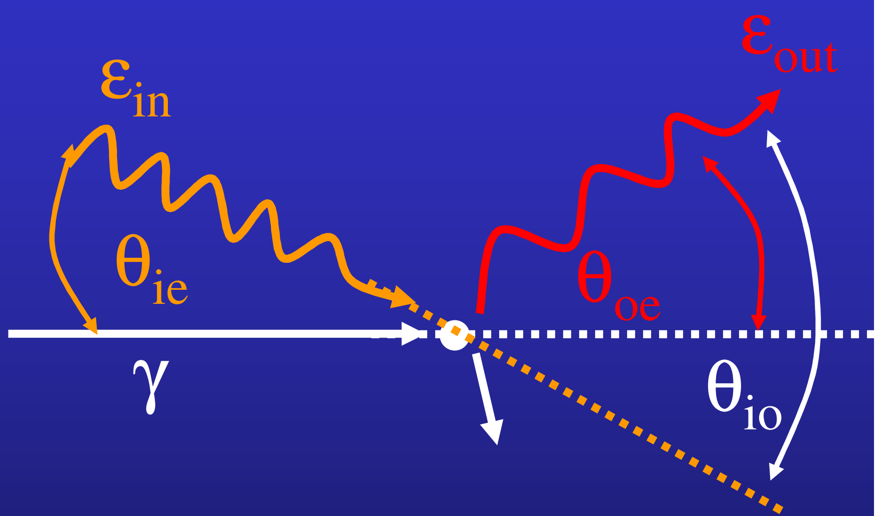


- Low state spectra peak at 100 keV. Well modelled by thermal electrons $\Theta \sim 0.1\text{–}0.2$ $\tau \sim 1$
- High state spectra need predominantly non-thermal electron distribution

Non-thermal compton upscattering:

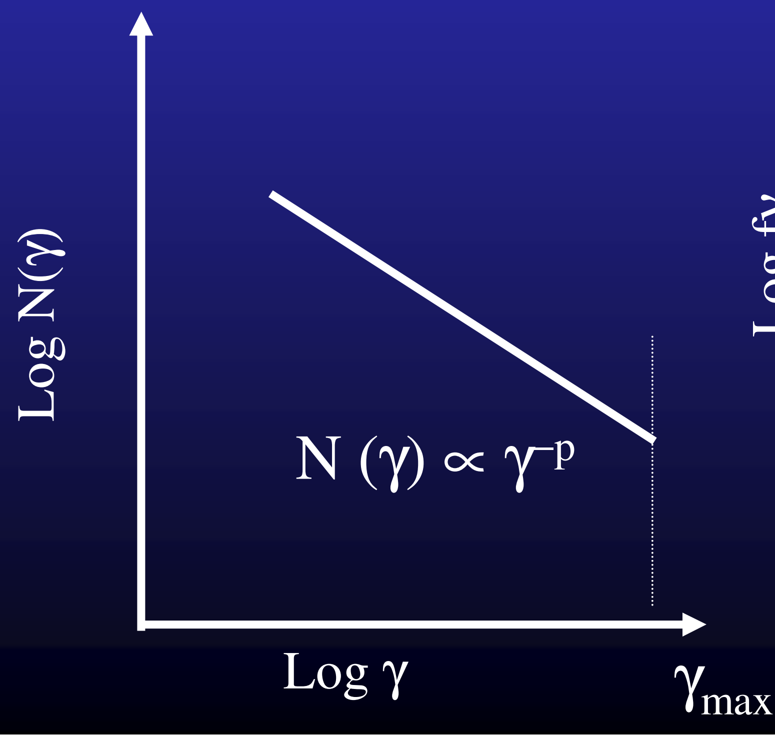
- If $\varepsilon_{in} << \gamma$ then electron has most energy so loses it to photon
- Average over angle for isotropic electron and photon distribution.
- Output photons beamed into angle $1/\gamma$ from electrons
- Nonthermal $\varepsilon_{out} \sim \gamma^2 \varepsilon_{in}$
- Limit is $\varepsilon_{out} < \gamma$

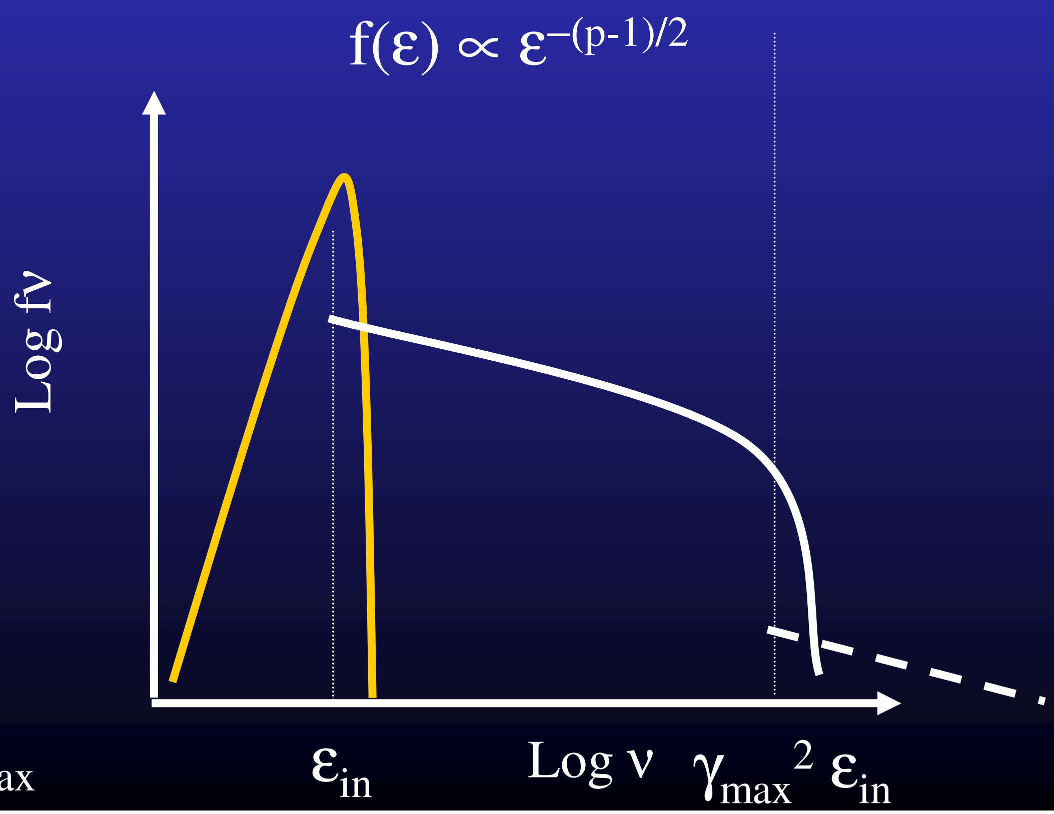


$$\varepsilon_{out} \sim \frac{\varepsilon_{in}(1 - \beta\cos\theta_{ei})}{1 - \beta\cos\theta_{eo}}$$

Optically thin nonthermal compton

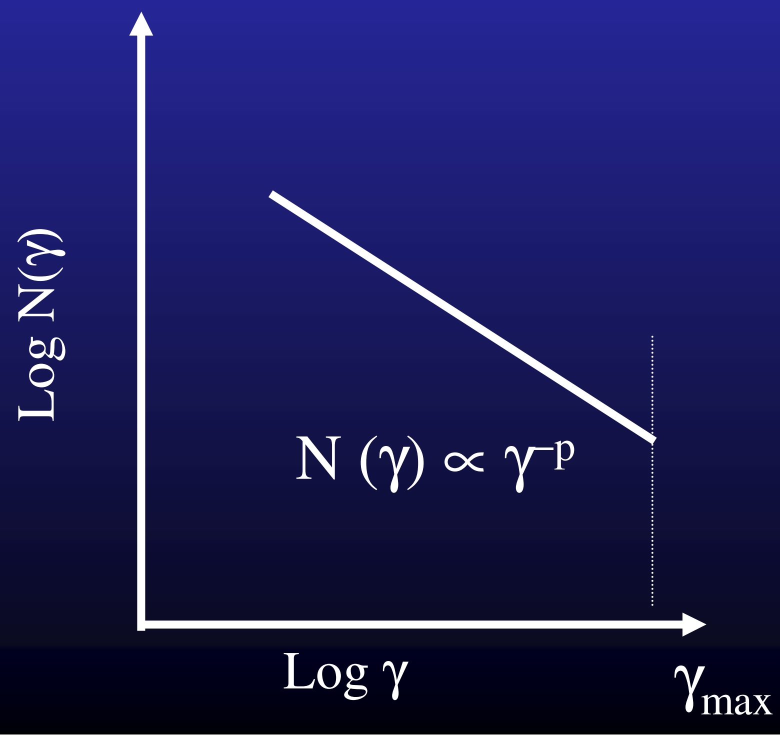
- power law by single scattering of nonthermal electrons $N(\gamma) \propto \gamma^{-p}$
- index $\alpha = (p-1)/2$ (p >2 so $\alpha > 0.5$ – monoenergetic injection)
- Starts a factor τ down from seed photons, extends to $\gamma_{max}^2\ \varepsilon_{in}$

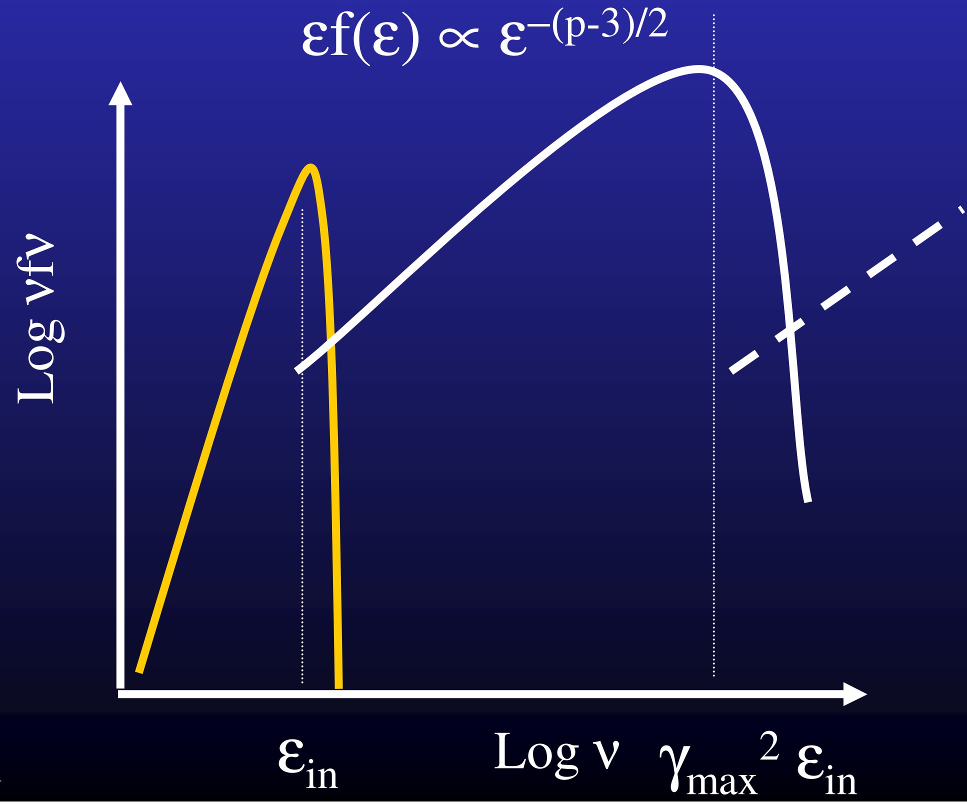




Optically thin nonthermal compton

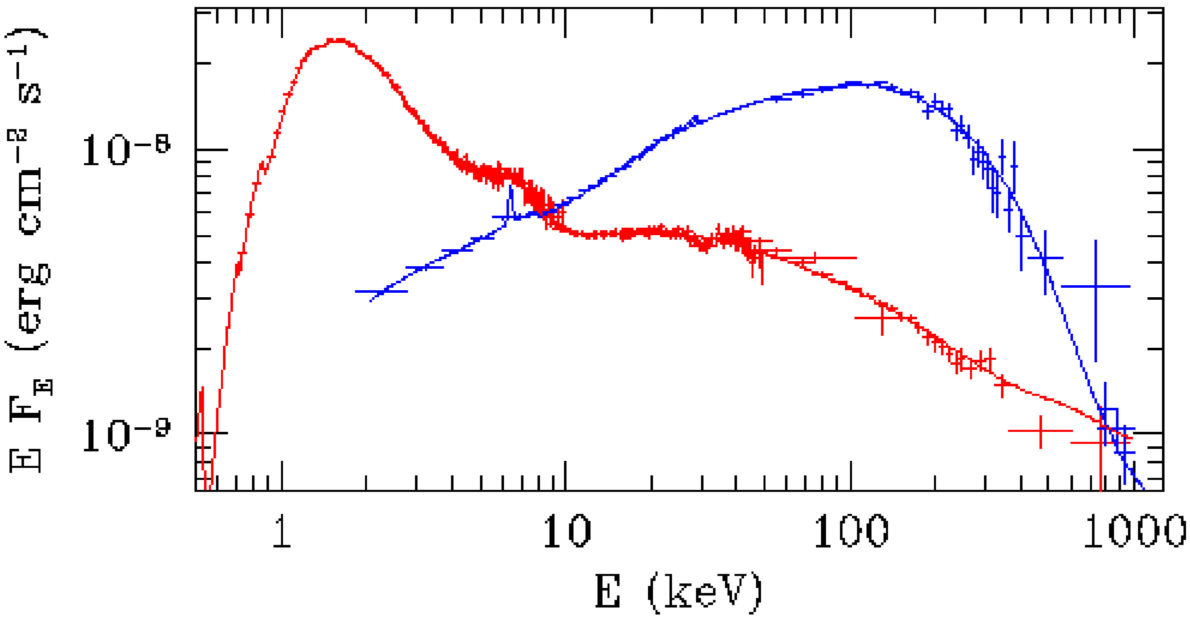
- Again, can do by energy
- Lh in electron power, Ls in seed photons
- Y axis τ Ls to Lh, x axis from ε_{in} to $\gamma_{max}^2\ \varepsilon_{in}$





Observations

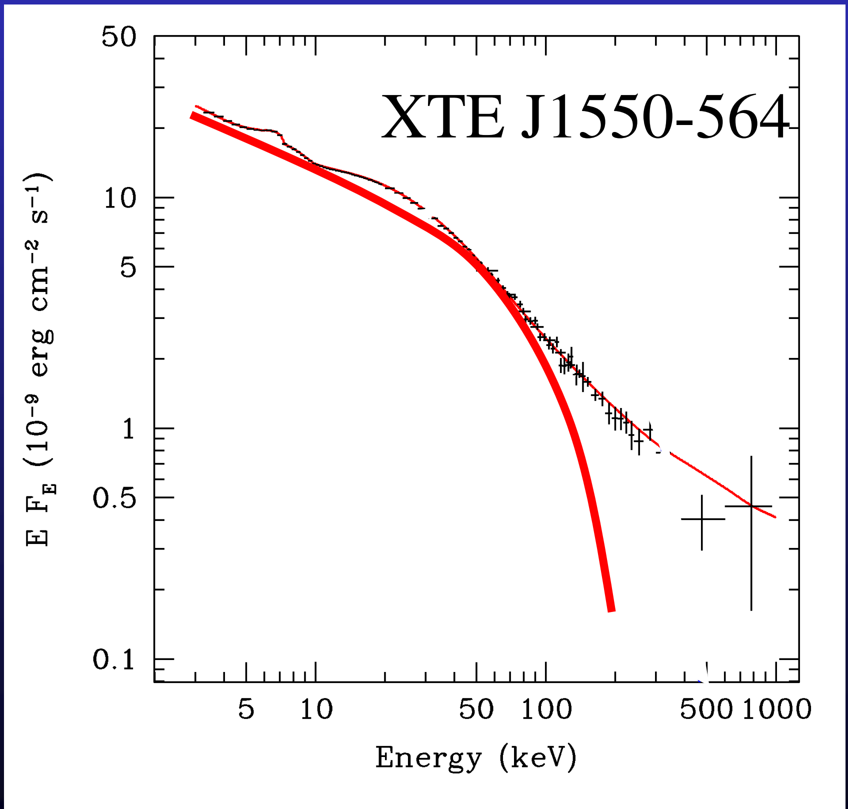
Cyg X-1: Gierlinski et al 1999

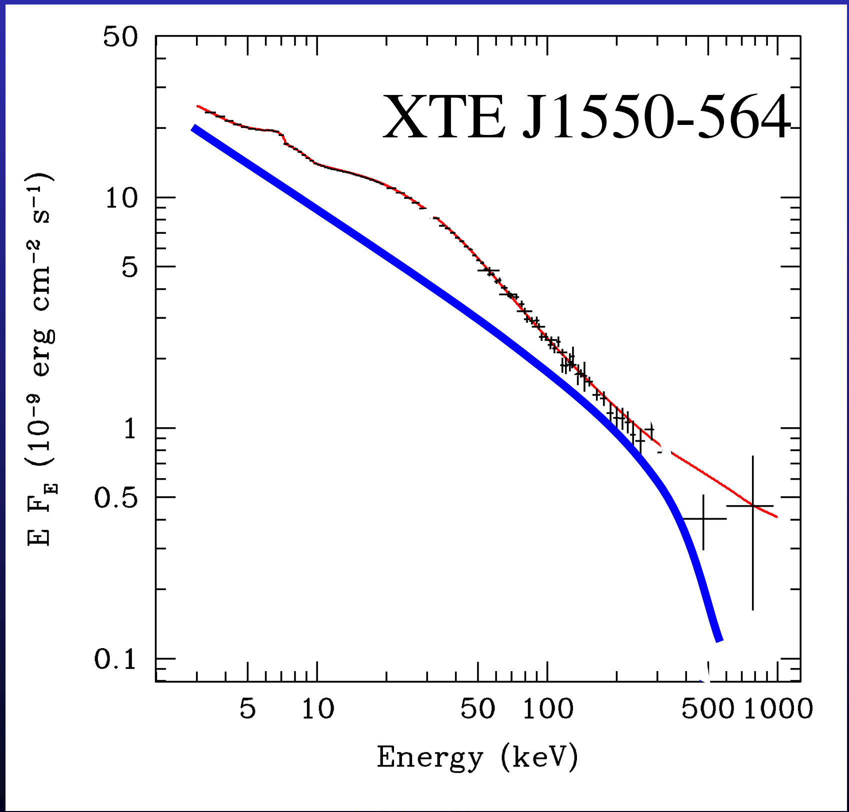


- Low state spectra peak at 100 keV. Well modelled by thermal electrons Θ~0.1–0.2 τ~1
- High state spectra need predominantly non-thermal electron distribution

Hybrid plasma

- Very high states in GBH look like this
- NOT POWER LAW CONTINUUM Kubota & Makashima 2004
- thermal doesn't fit , nonthermal doesn't fit either as steep

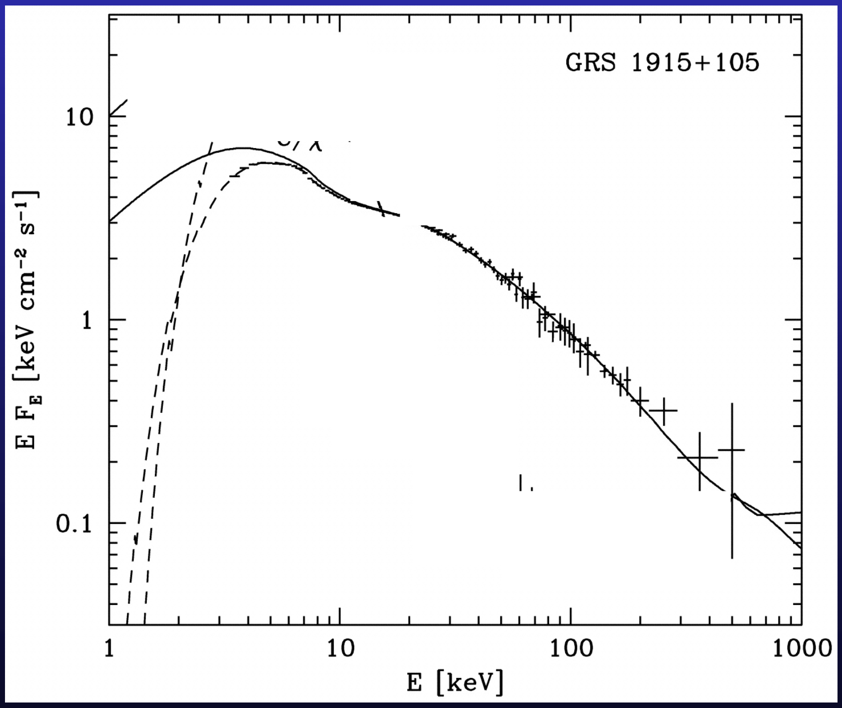




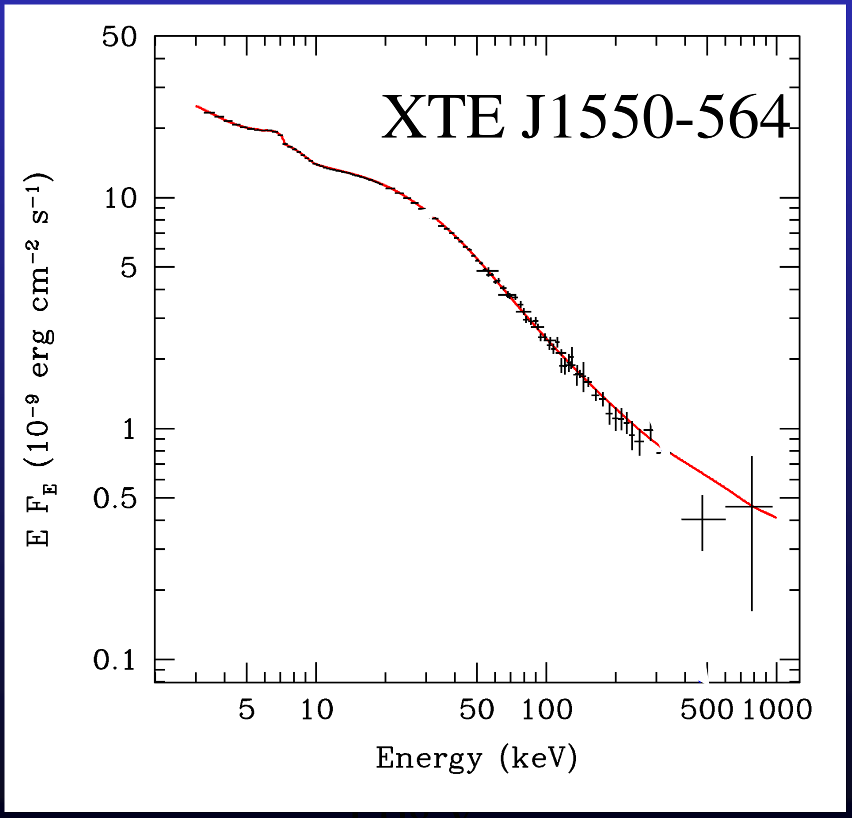
Gierlinski & Done 2002

Hybrid plasma

- Very high states in GBH look like this
- NOT POWER LAW CONTINUUM Kubota & Makashima 2004
- thermal doesn't fit , nonthermal doesn't fit either as steep



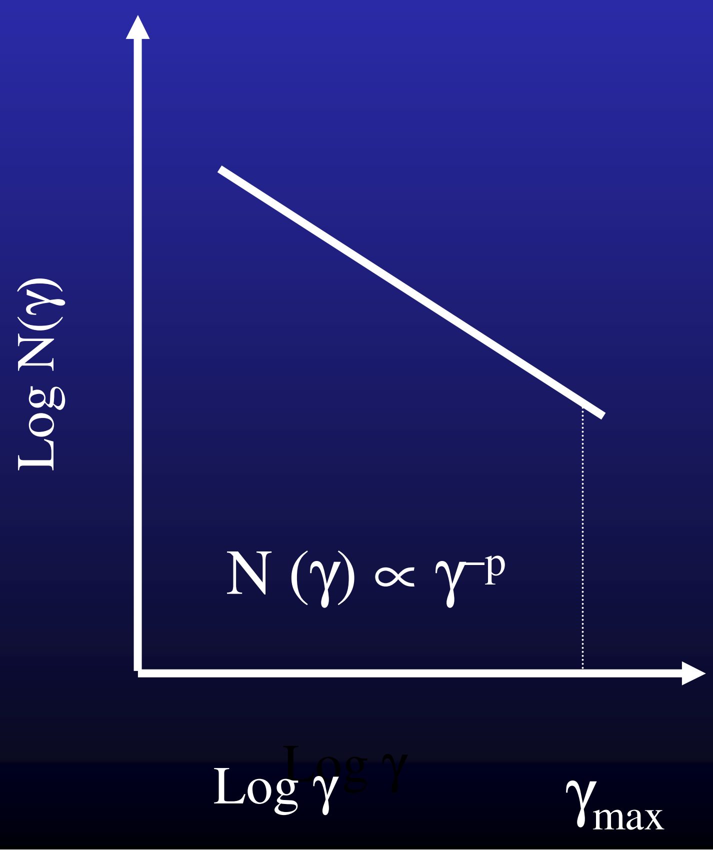
Zdziarski et al 2001

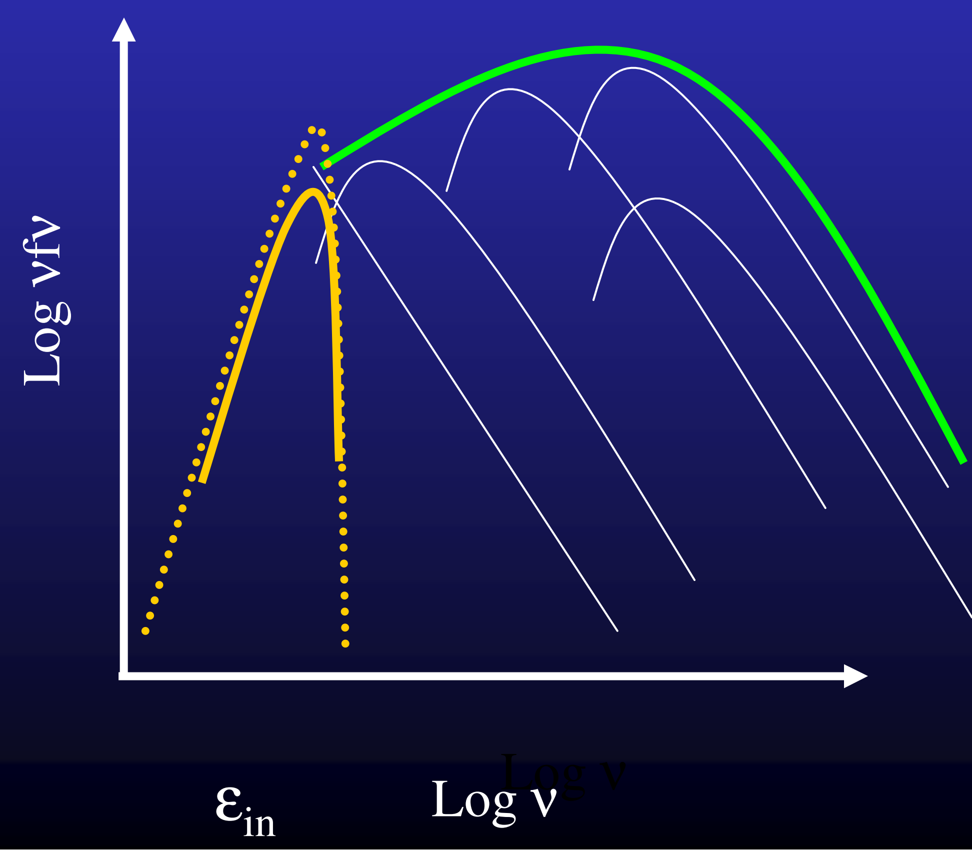


Gierlinski & Done 2002

Optically thick nonthermal

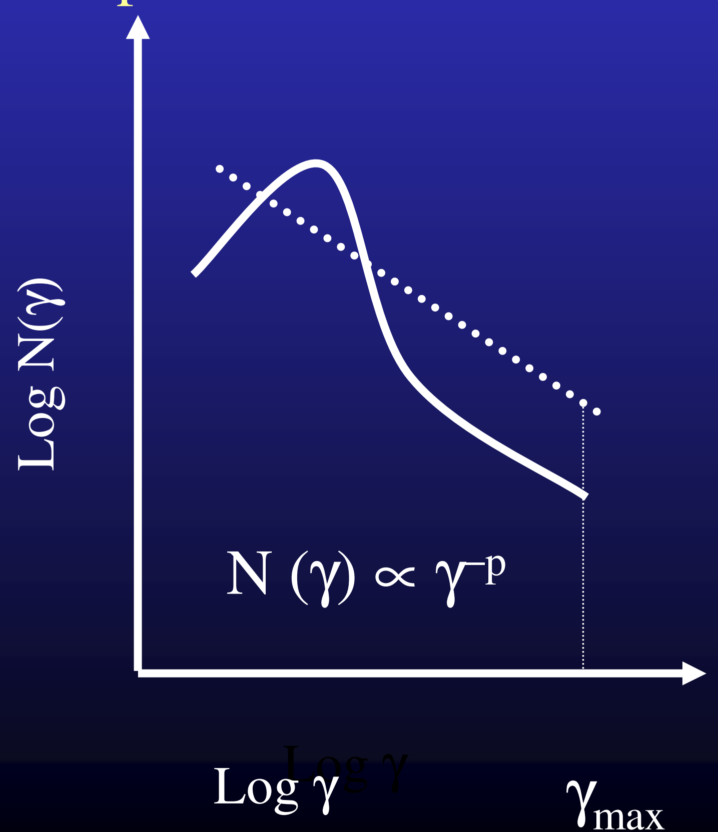
- Multiple scattering $\tau>1$ Ghisellini 1989
- If steep power law non-thermal electrons then $<\gamma>$ ~ 1 so get small energy boost each time – similar to thermal.
- But max energy is $<\gamma>$ ~ 1 ie mc^2, 511 keV

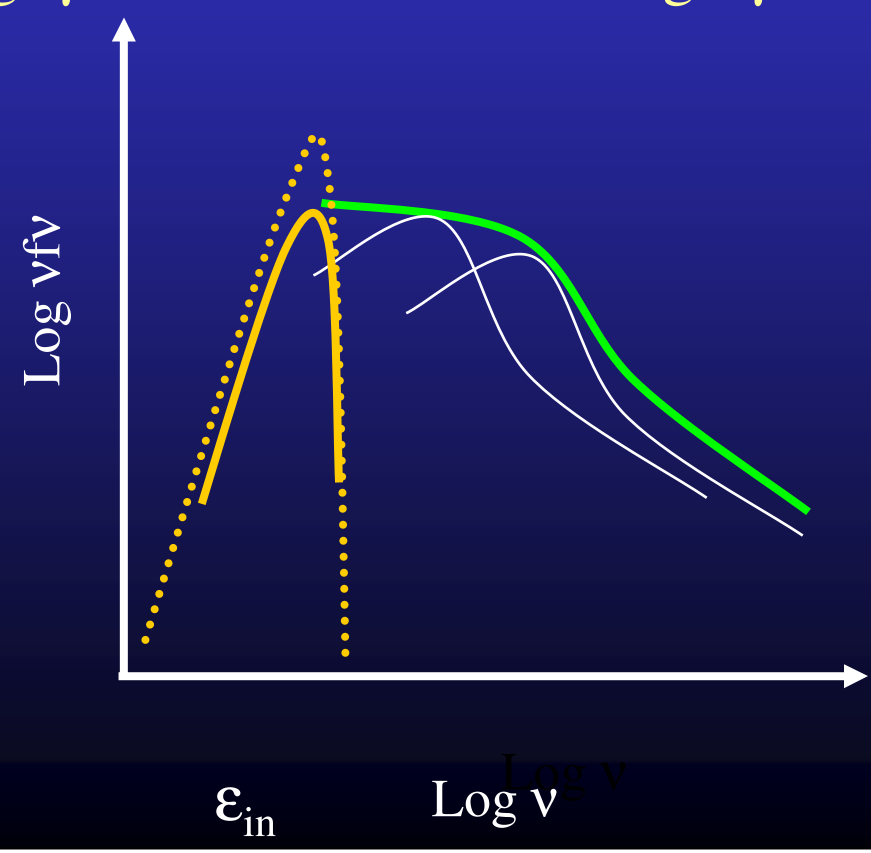




Hybrid plasma

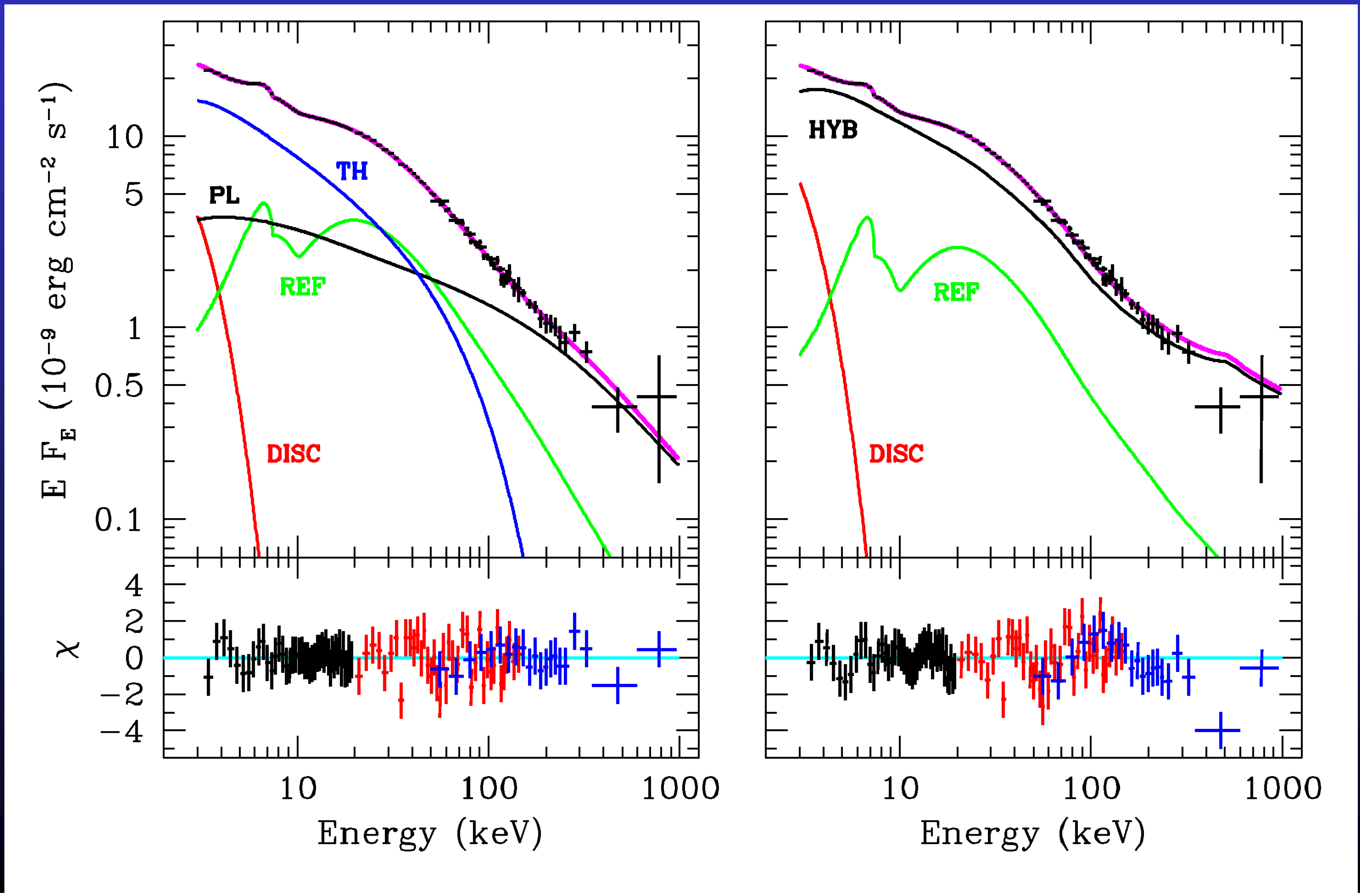
- Optically thick nonthermal ? Contradiction?
- Multiple scattering $\tau>1$ implies electron thermalise
- Coulomb collisions –between electrons. Most efficient at low γ
- Compton collisions – cooling γ^2 so most efficient at high γ





Very high state

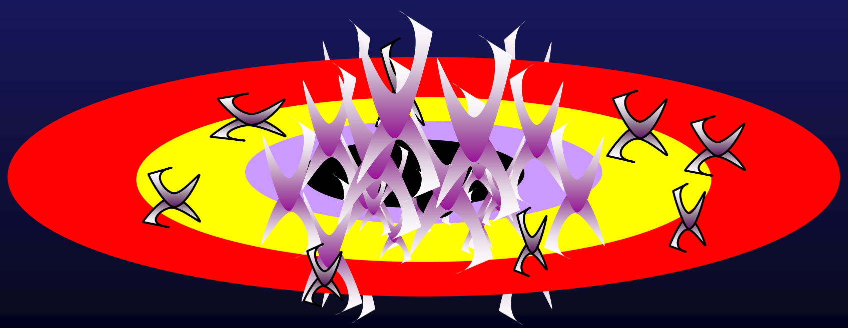
Complex curvature – 2 electron dist, one thermal, one nonthermal ?
Or hybrid - single electron dist, low E thermal, high E nonthermal



Gierlinski & Done 2003

Self consistent spectra: nonthermal

- nonthermal need shape of injected electrons as well as Lh and τ
- $Q(\gamma) \propto \gamma^{-s}$ between γ_{min} and γ_{max}
- Illuminate region with seed photons Ls
- Heating (inject) = cooling (coulomb, comp) $\Rightarrow$ self consistent $N(\gamma)$ rate leaving γ = rate injected
- Where compton dominates $d\gamma/dt \propto \gamma^2$ integrate $N(\gamma) \propto \gamma^{-2} \int Q(\gamma)\, d\gamma$
- $= \gamma^{-2} [\ \gamma^{-(s-1)} - \gamma max^{-(s-1)}\ ] / (s-1)$ so can't be flatter than γ^{-2} hence spectrum can't be flatter than α=0.5



- But could have separate thermal component plus hybrid!!

Conclusions

- Compton scattering – just photon and electrons!
- Incredible variety and subtle interplay
- Only approximately a power law
- low energy break (seed photons – disc or cyclo-sync)
- high energy break (mean electron energy)
- Need not be single thermal component – thermal plus nonthermal or hybrid

Log v