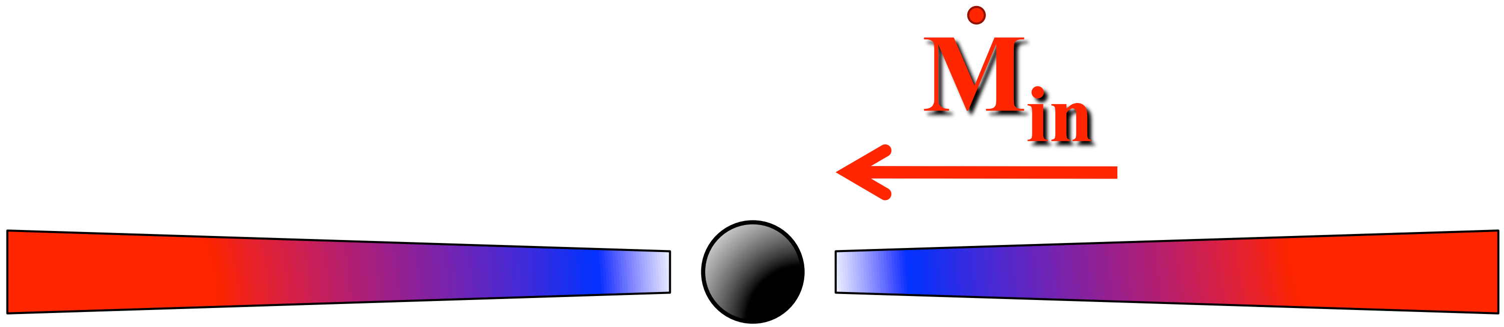
Accretion and jets

Gabriele Ghisellini

INAF - Osservatorio di Brera

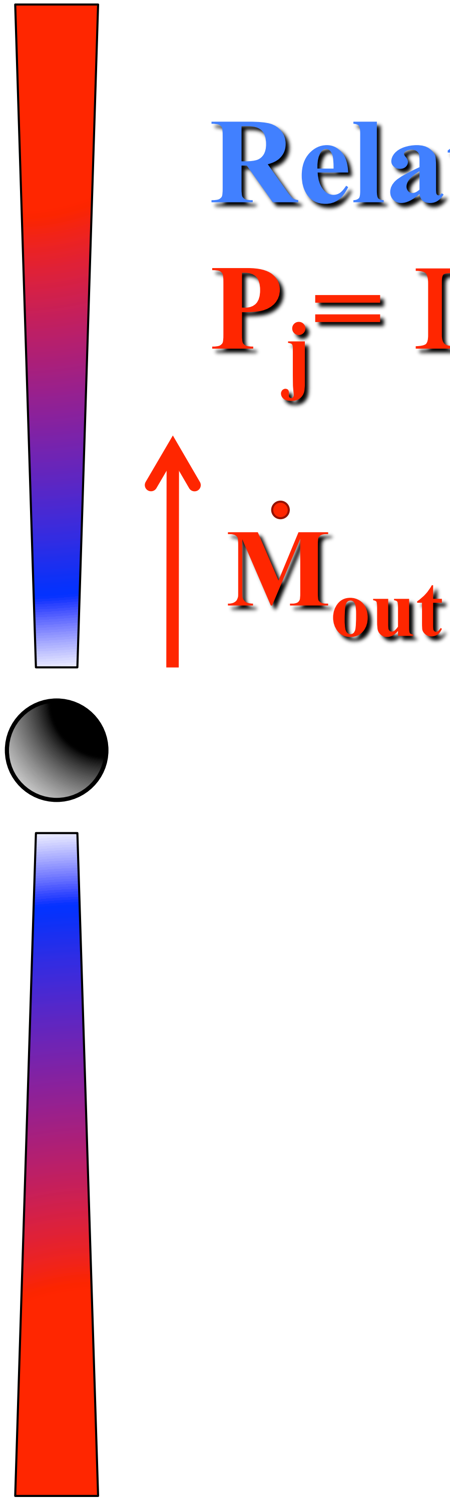
Accretion disk

$$L_d = \eta \dot{M}_{in} c^2$$



Relativistic jets

$$P_j = \Gamma \dot{M}_{out} c^2$$

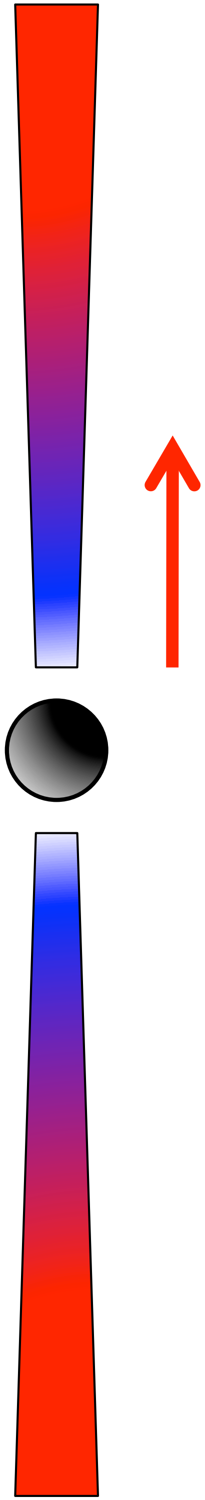


Accretion disk

$$L_d = \eta \dot{M}_{in} c^2$$

Relativistic jets

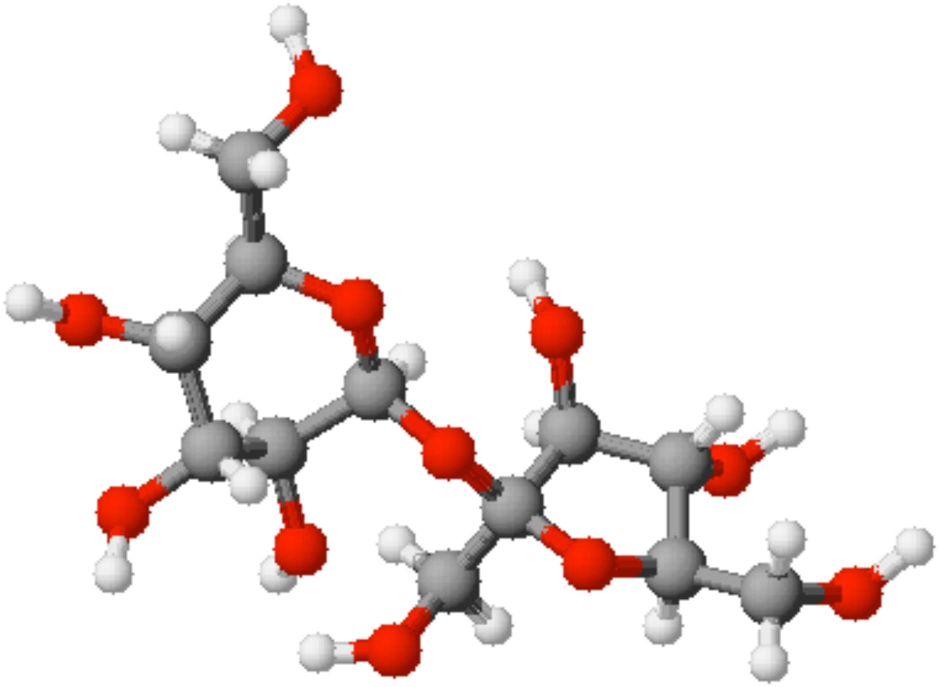
$$P_j = \Gamma \dot{M}_{out} c^2$$

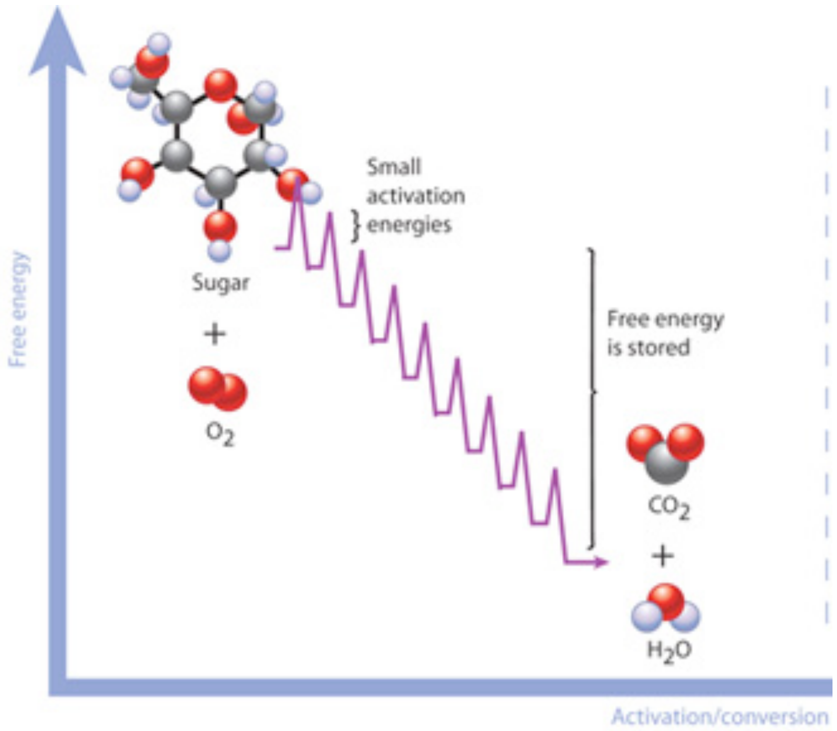


$$\frac{\dot{M}_{out}}{\dot{M}_{in}} = \frac{\eta \, P_j}{\Gamma \, L_d}$$

Efficiency in astrophysics

$$\eta = \frac{\Delta E}{\Delta m c^2}$$

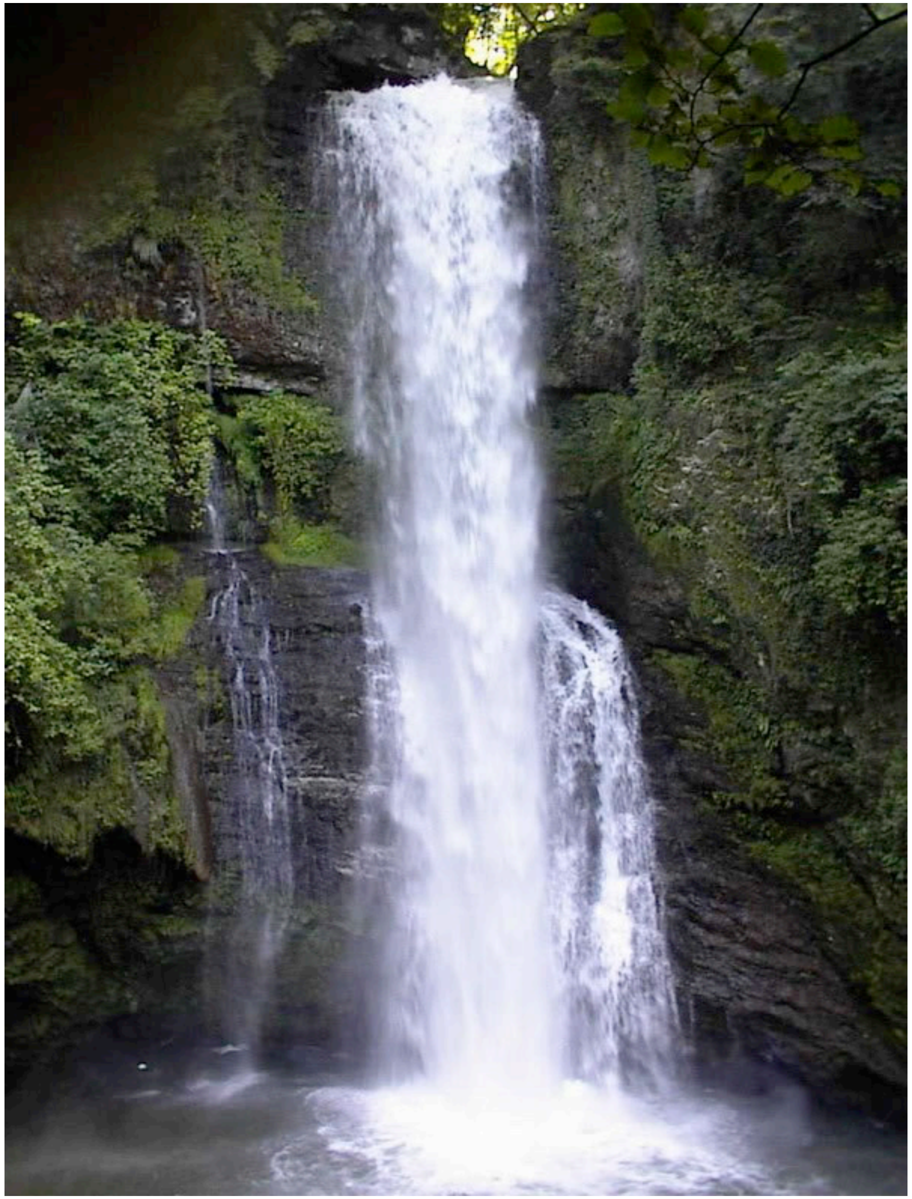




Sugar saccharose $C_{12}H_{22}O_{11}$

1g → 4 kcal= 16.7 kJ = 10^{23} eV ~ 1.6×10^{11} erg
~ 1 eV per bound

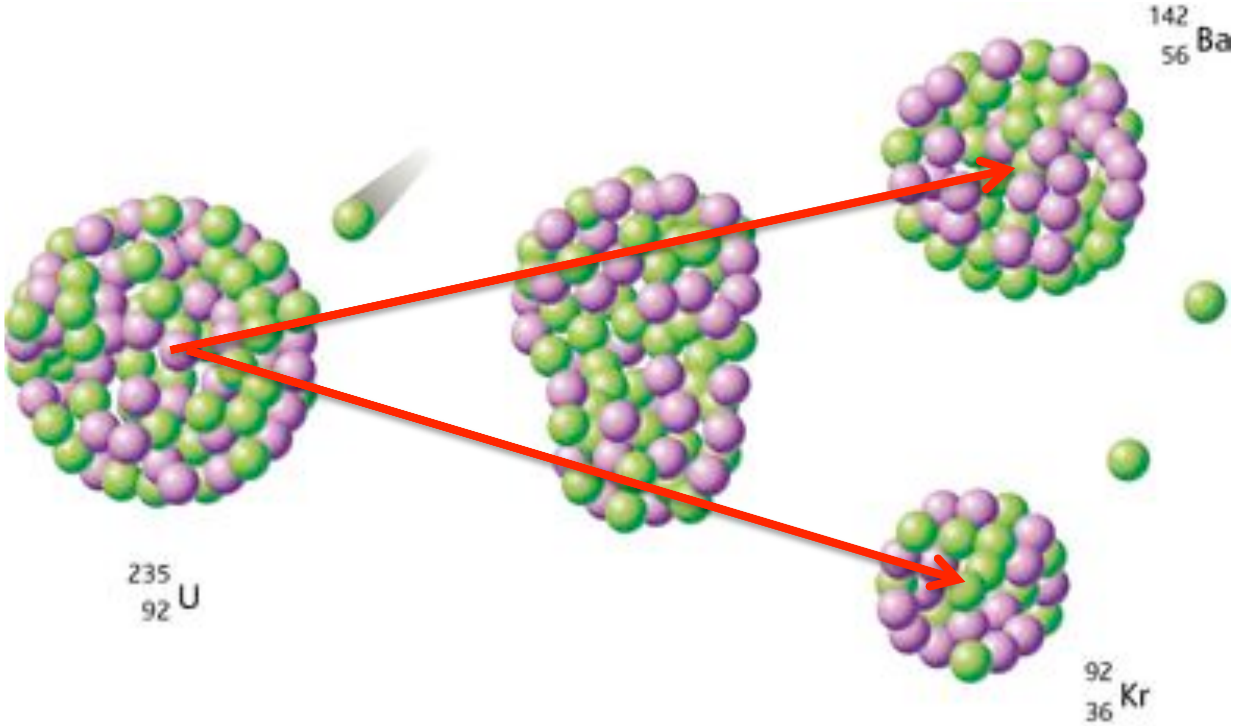
$$\eta = \frac{E}{mc^2} = \frac{1.6\times10^{11}\,\text{erg}}{9\times10^{20}\,\text{erg}} = 1.8\times10^{-10}$$



$$\eta = \frac{mgh}{mc^2} = \frac{980 \times 10^4 \, (h/100 \text{ m})}{9 \times 10^{20} \text{ erg}} \sim 10^{-14}$$

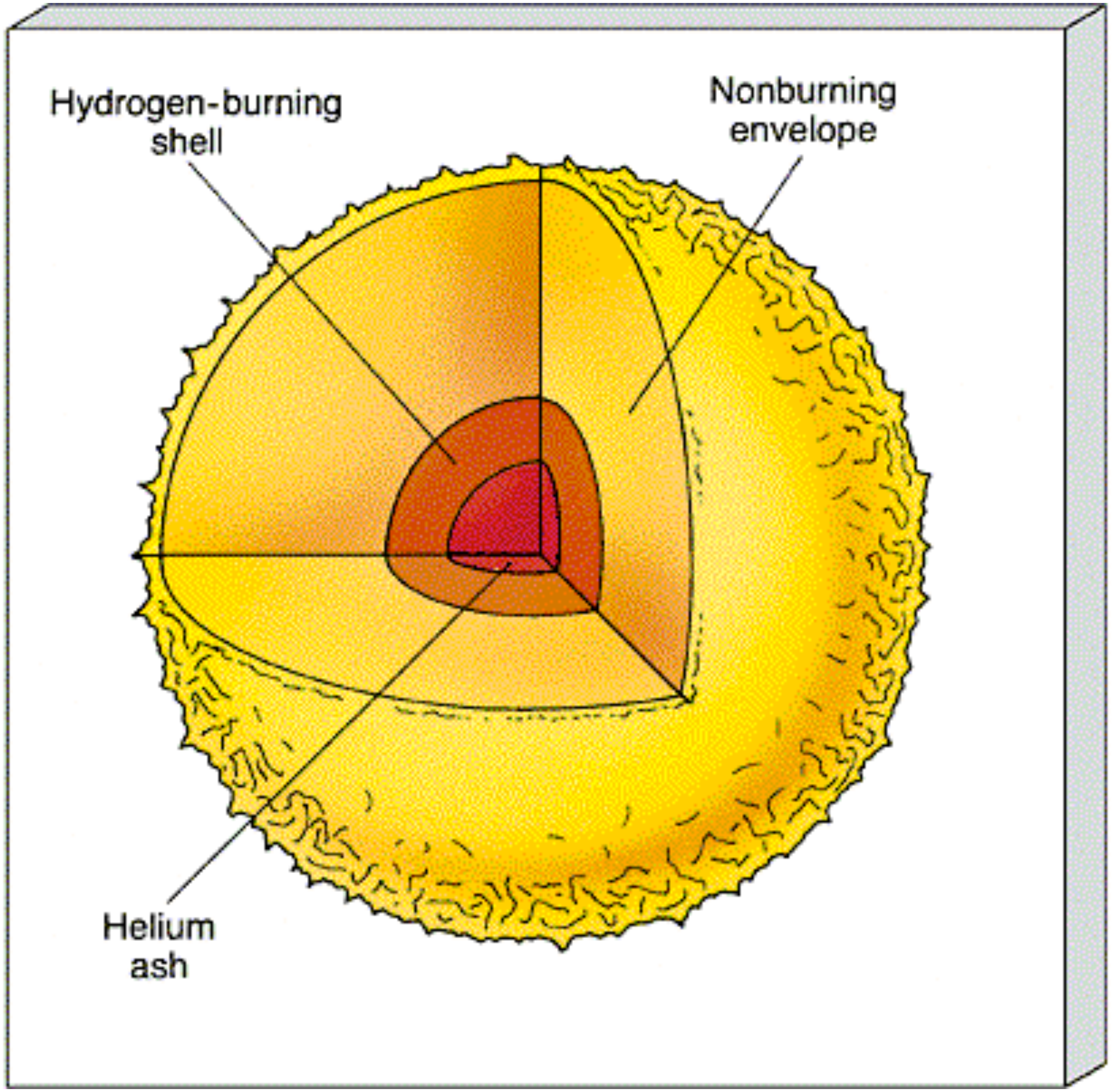
$$\eta = \frac{mv^2}{2\ mc^2} = \frac{(v/c)^2}{2} = 4\times10^{-15}\,(v/100\ km/h)^2$$

Nuclear fission

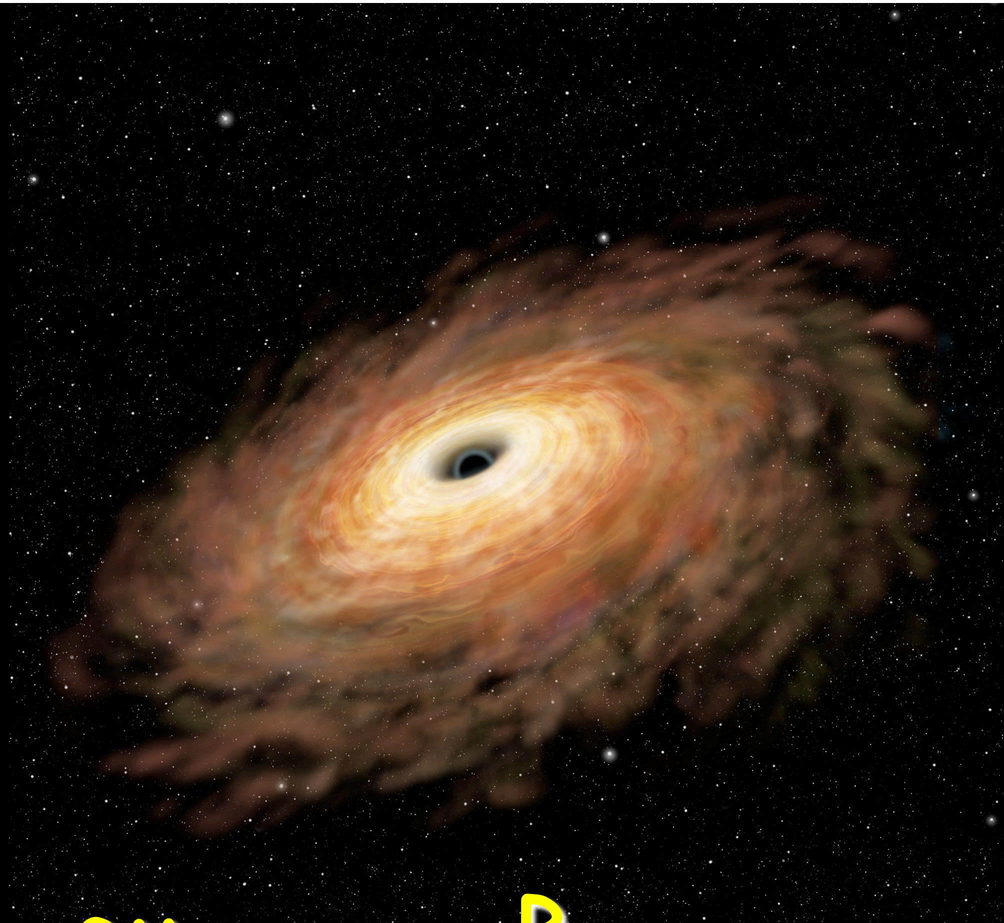


$$\eta = \frac{E}{mc^2} = \frac{0.2\times10^{9}\,\mathrm{eV}}{235\times9.4\times10^{8}\,\mathrm{eV}} \sim 9\times10^{-4}$$

Fusion



$$\eta = 0.008 \times 0.1 \sim 8\times10^{-4}$$



$$\eta = \frac{1}{2}\,\frac{GM\,m}{R\,mc^2} = \frac{R_g}{2R}$$

(Newton)

$R_{min}=R_g$ for max spin

η = 0.1 up to 0.3 for accreting Kerr
(Thorne 1974)

1974, ApJ, 191, 507

DISK-ACCRETION ONTO A BLACK HOLE. II. EVOLUTION OF THE HOLE*†

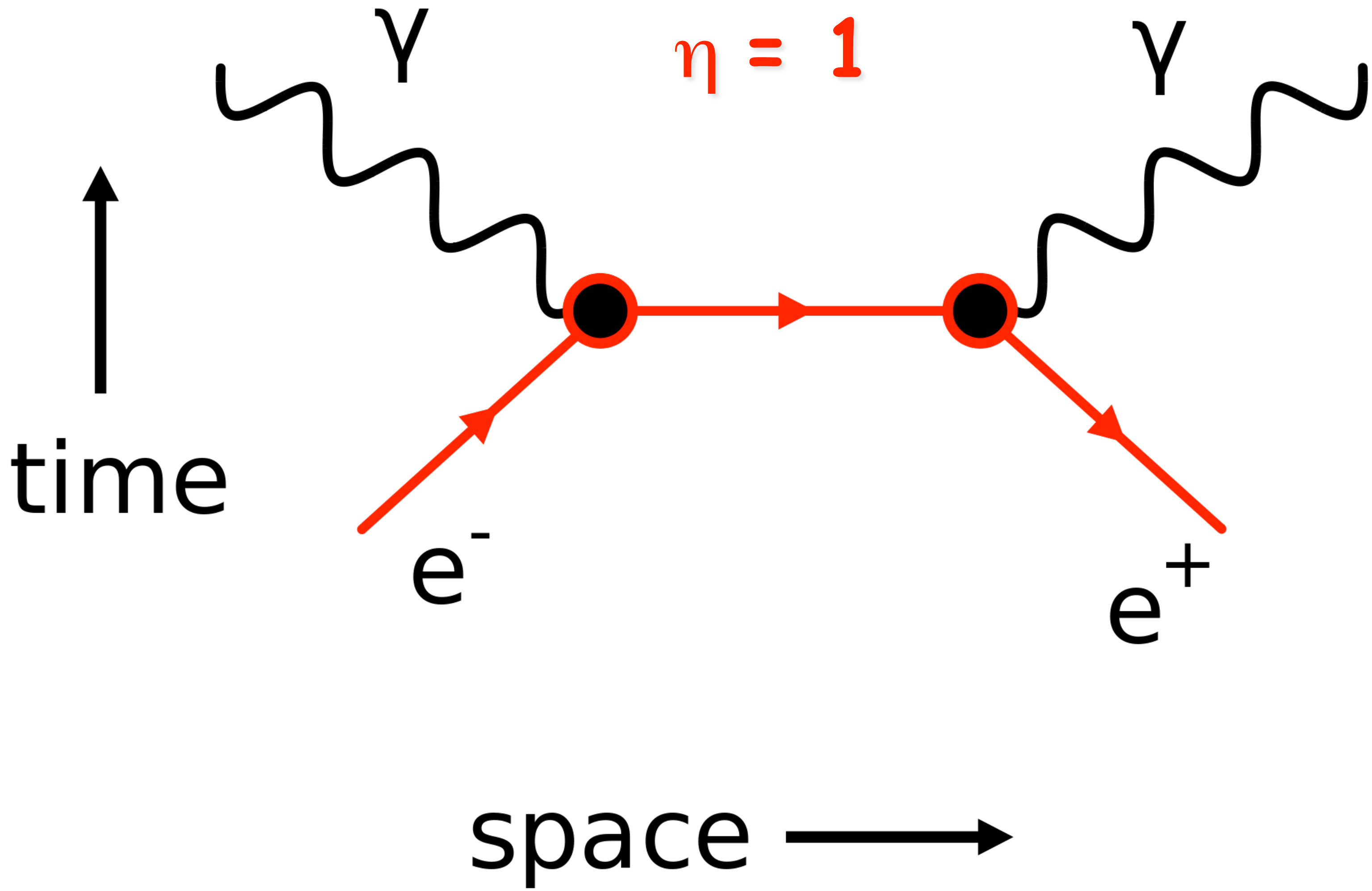
KIP S. THORNE
California Institute of Technology, Pasadena, California
Received 1974 December 26

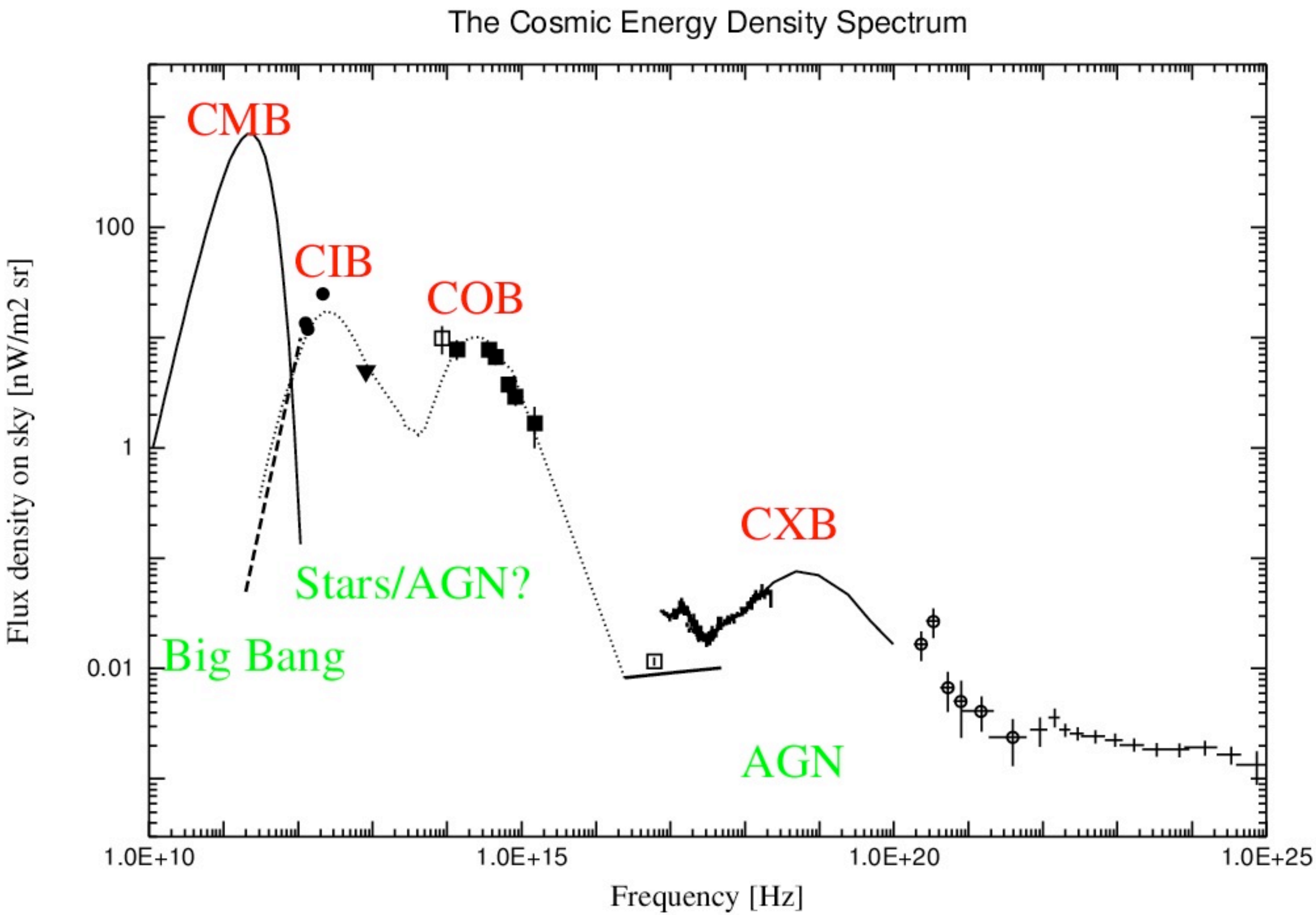
ABSTRACT

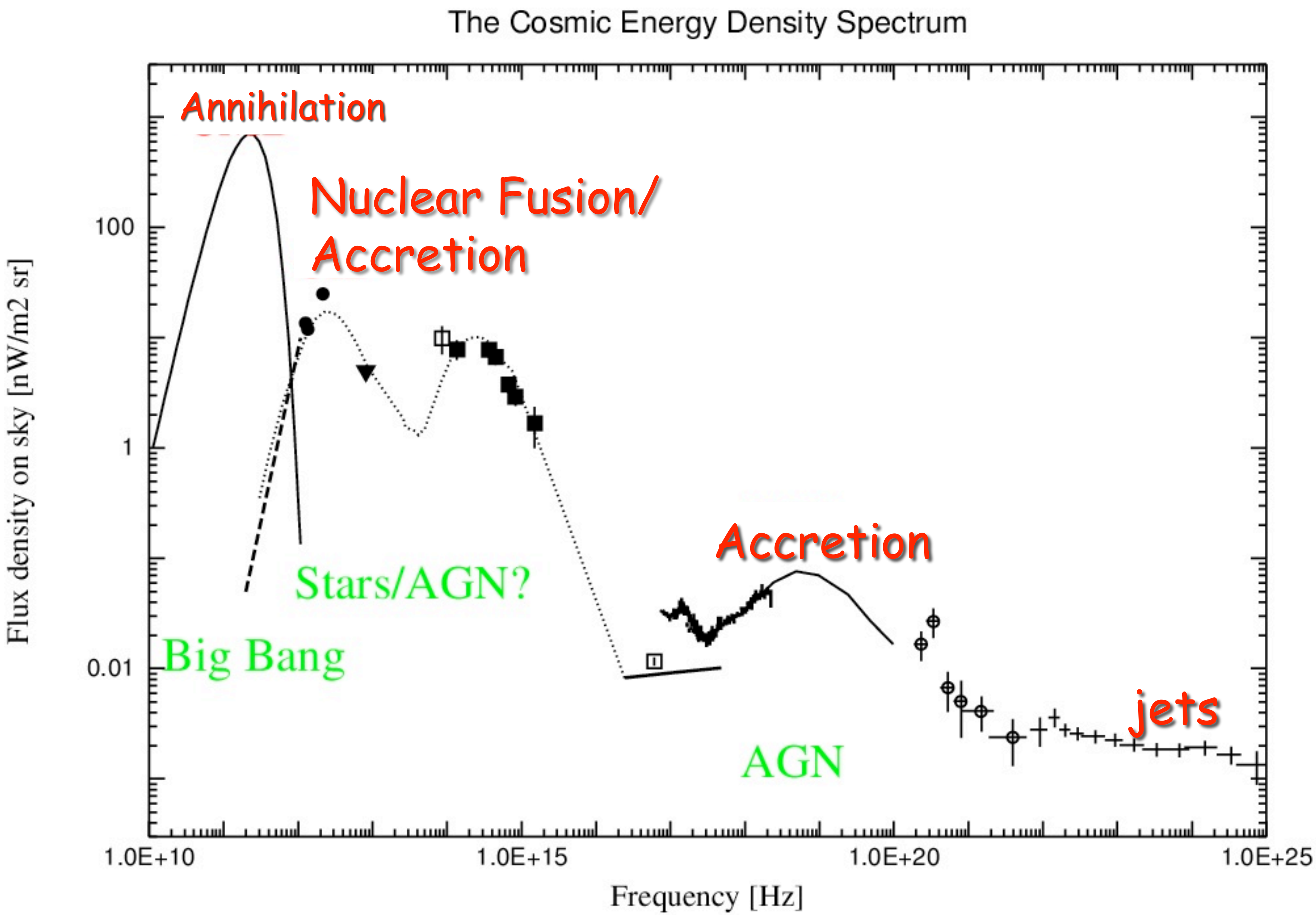
When a black hole swallows matter and radiation from an accretion disk, its mass M and angular momentum $J \equiv Ma$ change—i.e., the hole evolves. The details of that evolution are calculated. The accreting matter, by itself, would spin the hole up to $a = M$ ("extreme-Kerr hole") after a modest amount of accretion ($\Delta M/M_i \sim 1.5$). However, the radiation emitted by the disk and swallowed by the hole produces a counteracting torque, which prevents spin-up beyond a limiting state of $(a/M)_{\rm lim} \simeq 0.998$. This limiting state corresponds to a maximum efficiency of 30 percent for the hole's conversion of accreting mass into outgoing photon energy. In § IV it is argued that realistic phenomena ignored in this calculation (magnetic fields dragged down the hole by accreting matter; heating of outer parts of disk by X-rays from inner parts; . . .) might not change significantly the values $(a/M)_{\rm lim} \simeq 0.998$ and (maximum efficiency) $\simeq 0.30$.

Subject headings: black holes — rotation

Annihilation




The Cosmic Energy Density Spectrum
CMB
CIB
COB
CXB
Stars/AGN?
Big Bang
AGN
100
1
0.01
Flux density on sky [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]



The Cosmic Energy Density Spectrum
Annihilation
Nuclear Fusion/
Accretion
Accretion
jets
Stars/AGN?
Big Bang
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100
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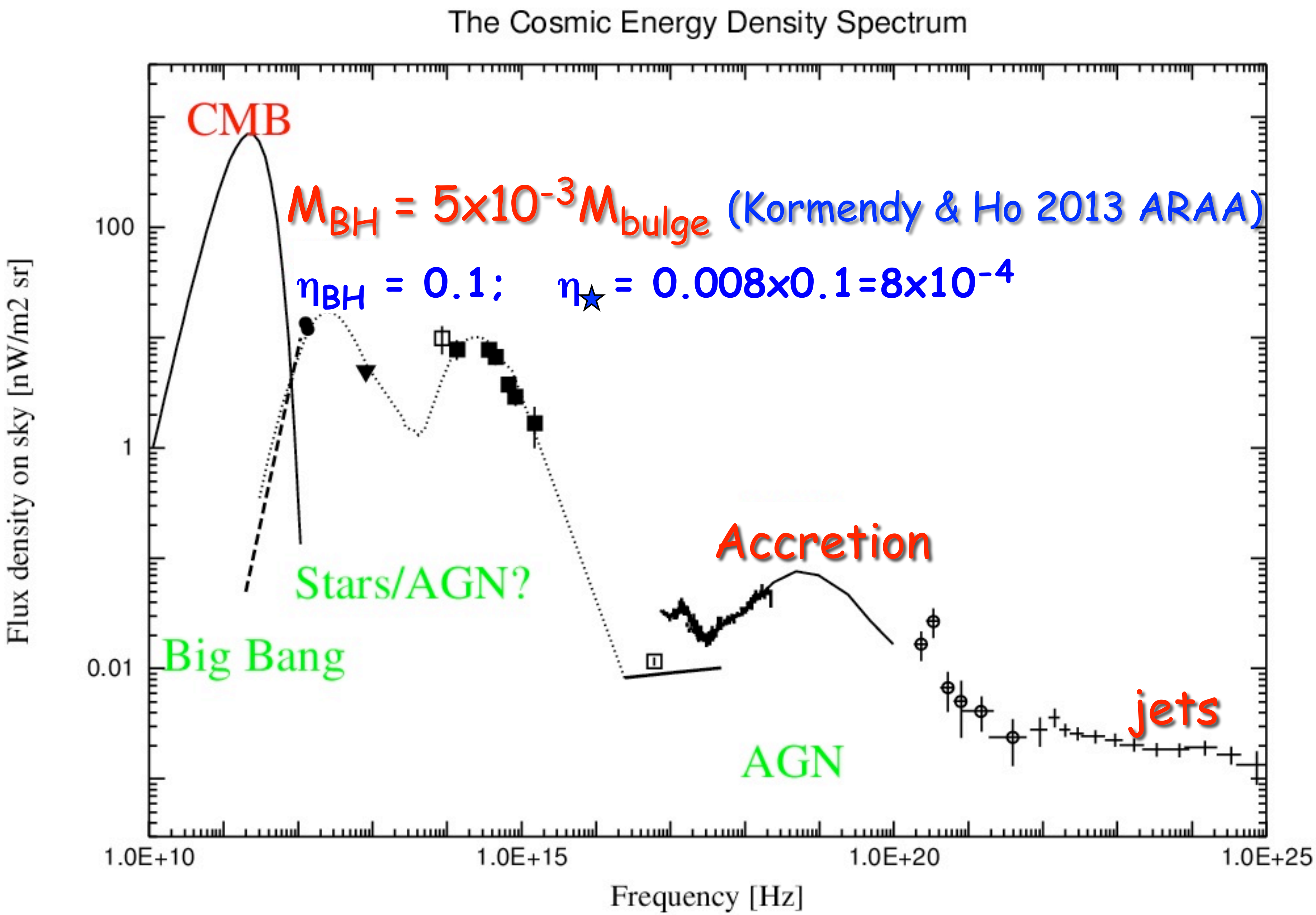
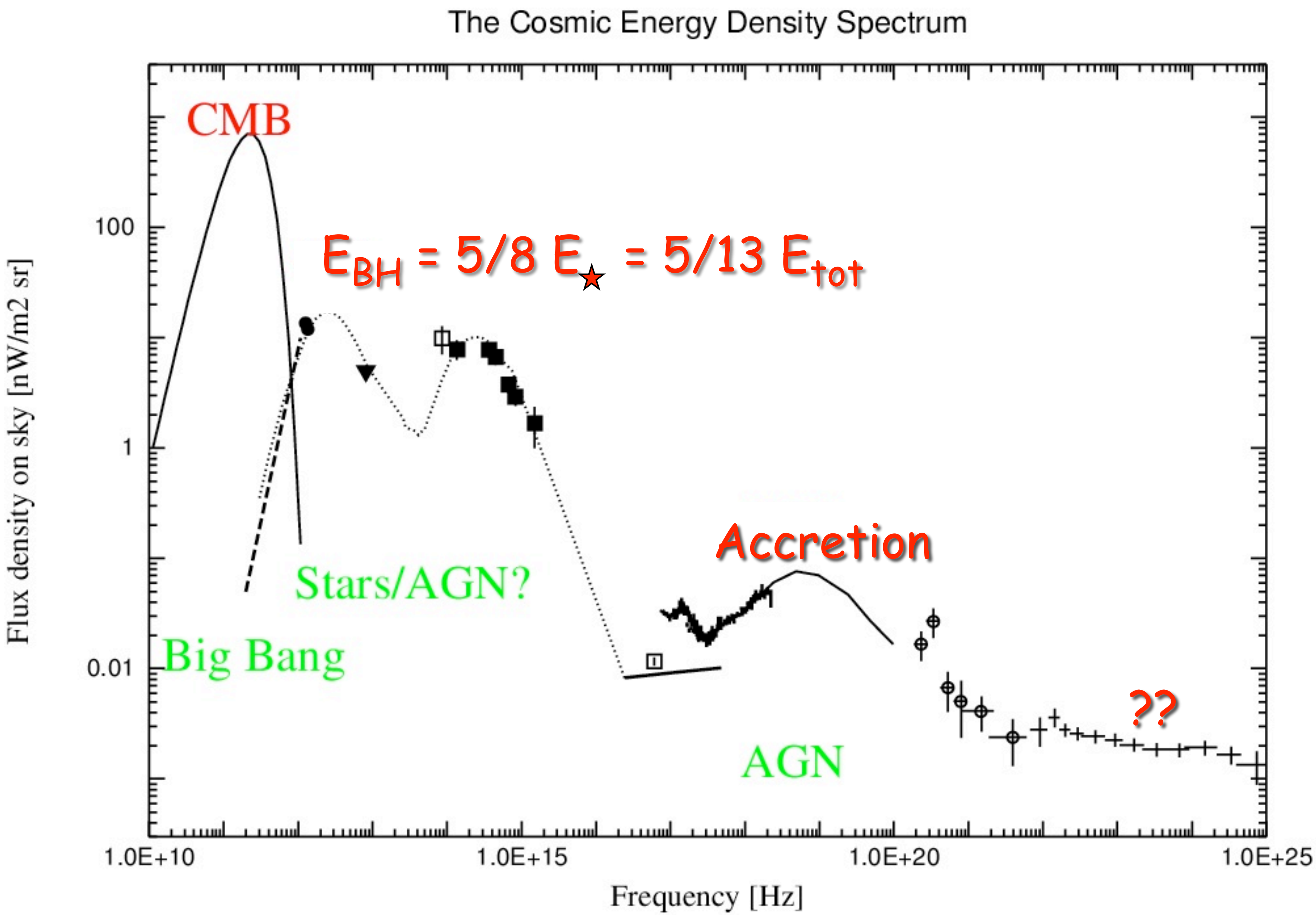

The Cosmic Energy Density Spectrum
CMB
M_BH = 5x10^-3 M_bulge (Kormendy & Ho 2013 ARAA)
η_BH = 0.1; η★ = 0.008x0.1=8x10^-4
Accretion
Stars/AGN?
Big Bang
AGN
jets
100
1
0.01
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Flux density on sky [nW/m2 sr]
Frequency [Hz]

$E_{opt,\ BH}$ from BH: 10% of their mass

The mass of BH is $5x10^{-3}$ of the mass of the stars in the central part of the galaxies → $E_{opt,BH} = 5x10^{-4}\ M_{\star}$

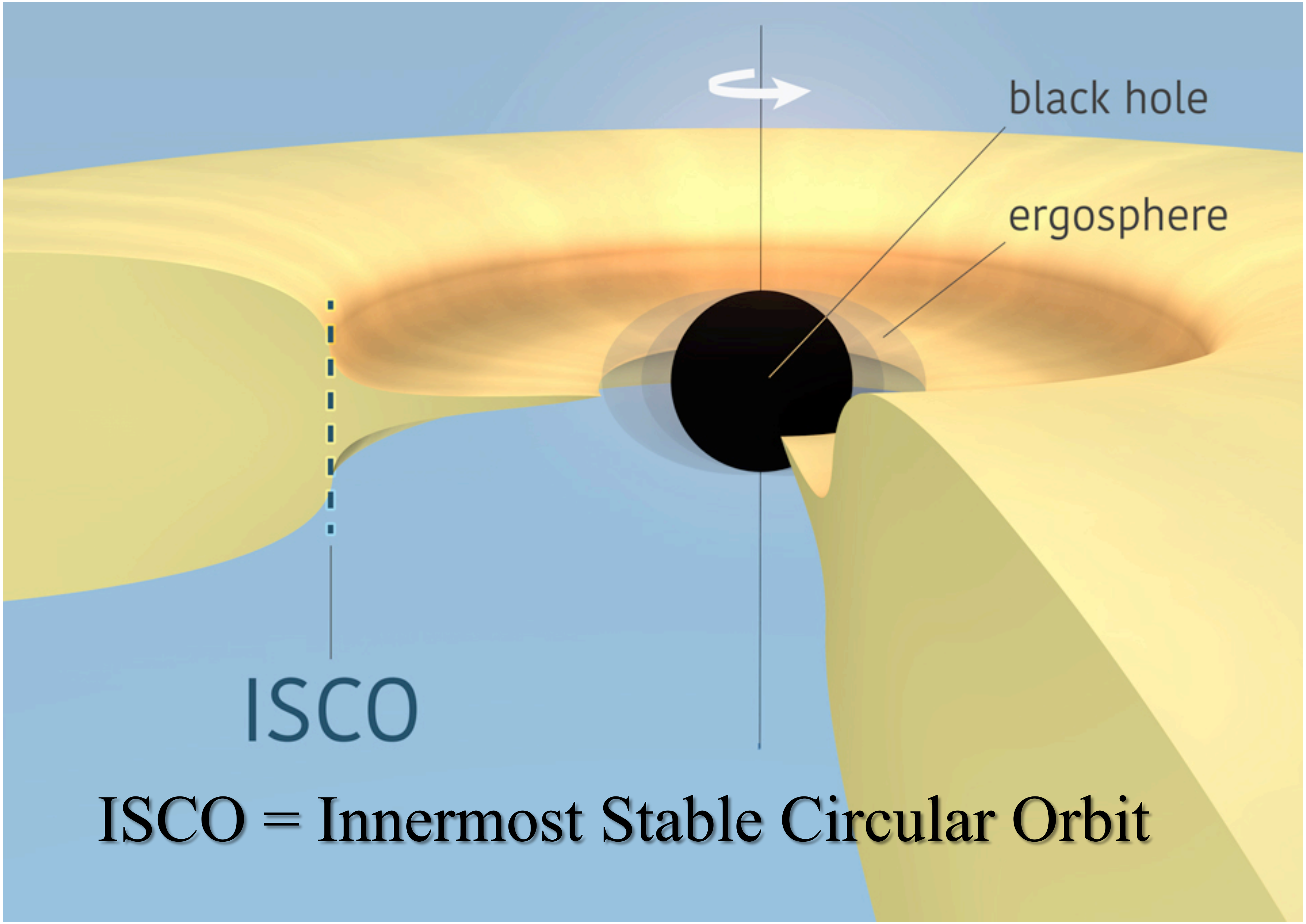
E_{opt} from stars: 0.008 of their nuclear mass. The nucleous is 10% of their mass $M_{\star}$ → $E_{opt,\star} = 8x10^{-4}\ M_{\star}$

$$E_{opt,\ BH} \sim 5/8\ E_{opt,\ \star}$$



The Cosmic Energy Density Spectrum
CMB
$E_{BH} = 5/8\ E_{\star} = 5/13\ E_{tot}$
Accretion
Stars/AGN?
Big Bang
AGN
??
100
1
0.01
Flux density on sky [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]

Accretion disks

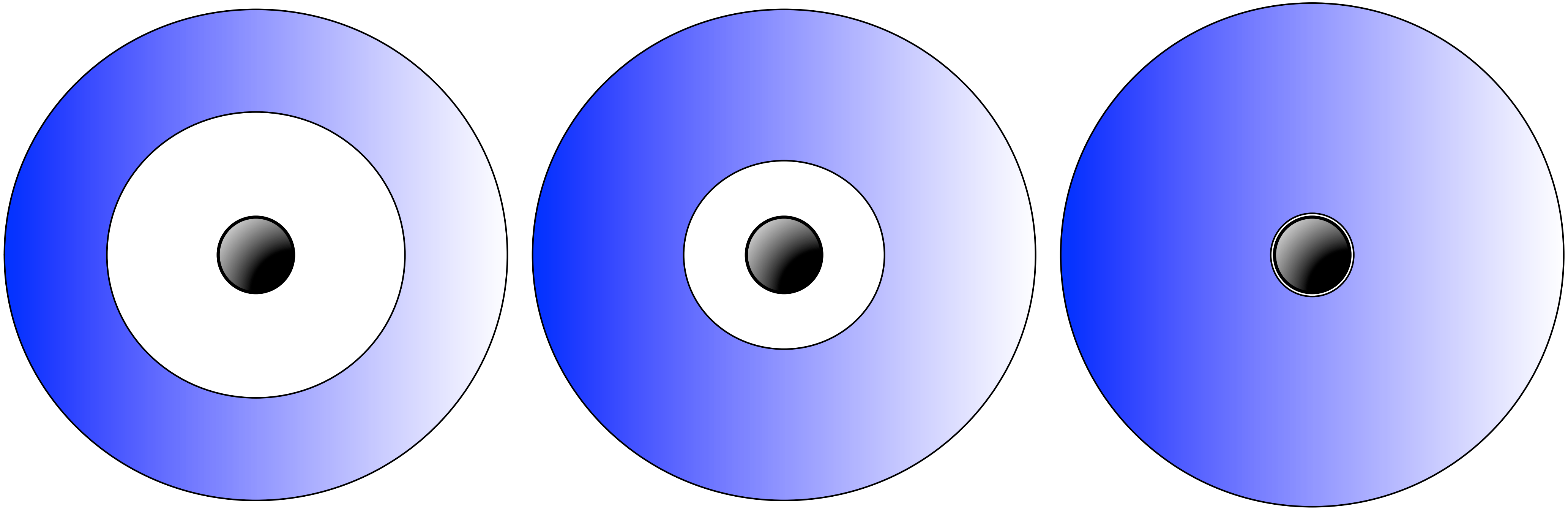


ISCO = Innermost Stable Circular Orbit

counter-rotating
max BH spin

non-rotating
BH spin=0

co-rotating
Max BH spin



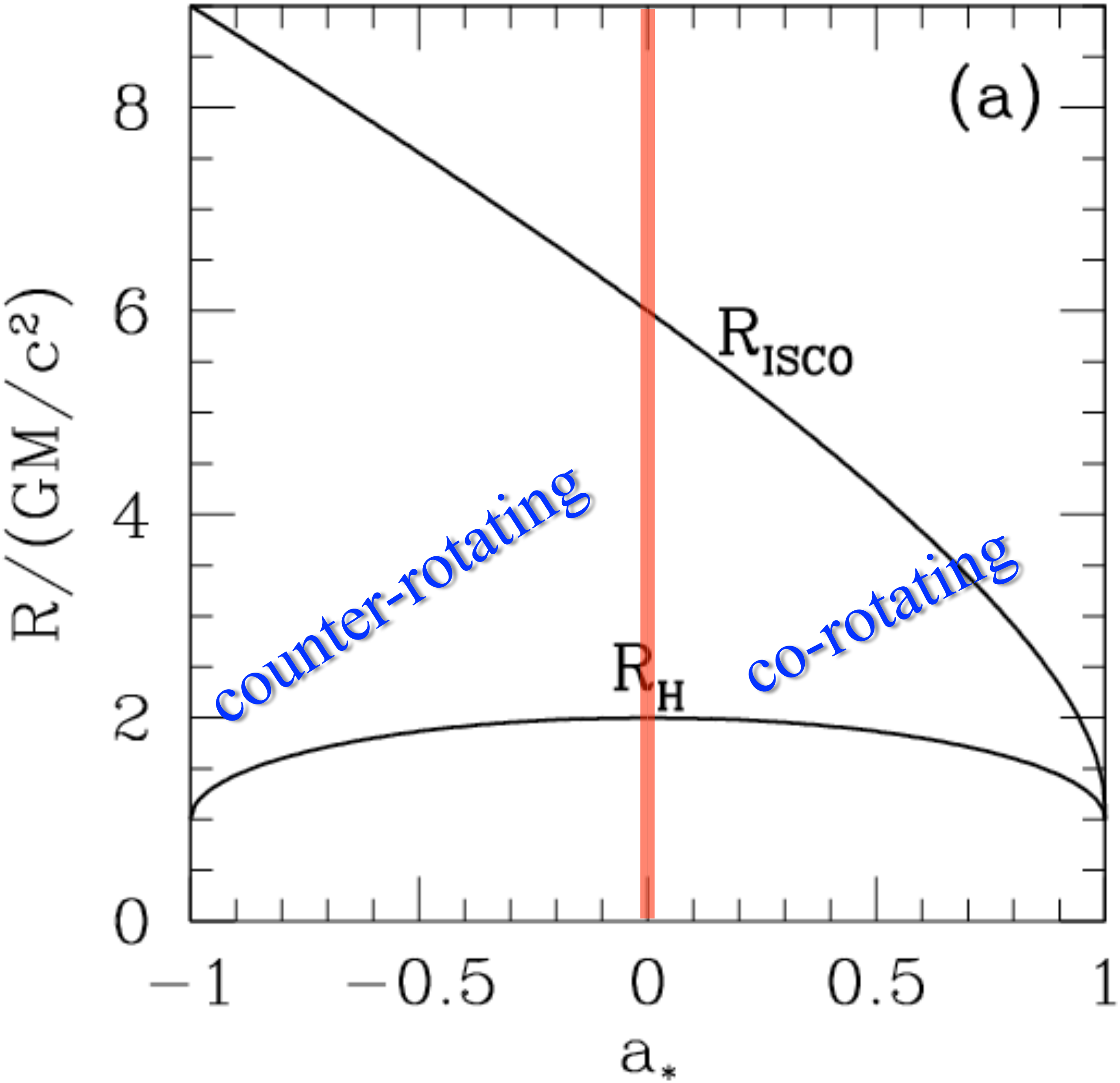
$R_{ISCO} = 9R_g$

$R_{ISCO} = 3R_g$

$R_{ISCO} = R_g$

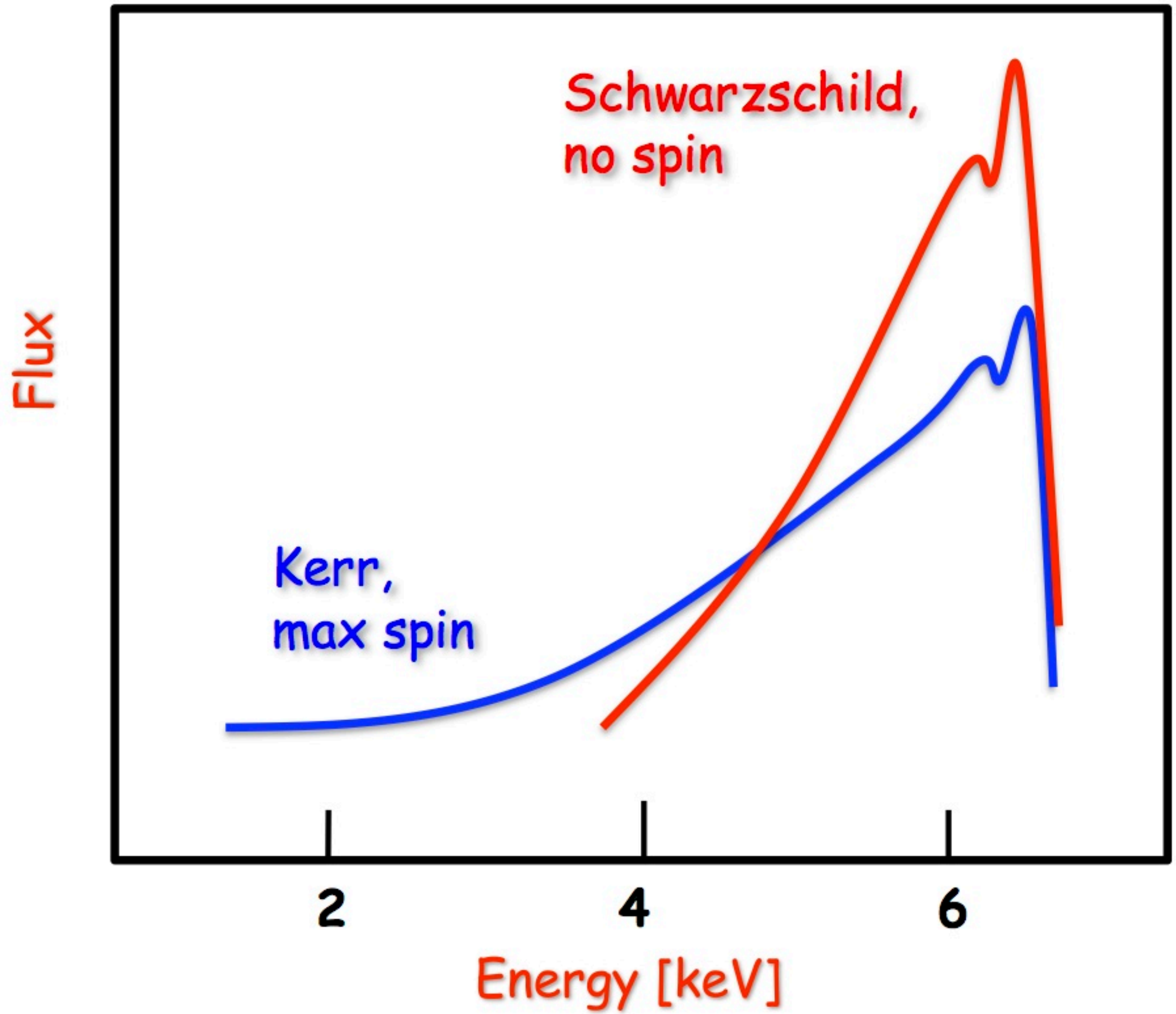
Great gravity
Big efficiency
Large velocities
Large Doppler

R_{ISCO}



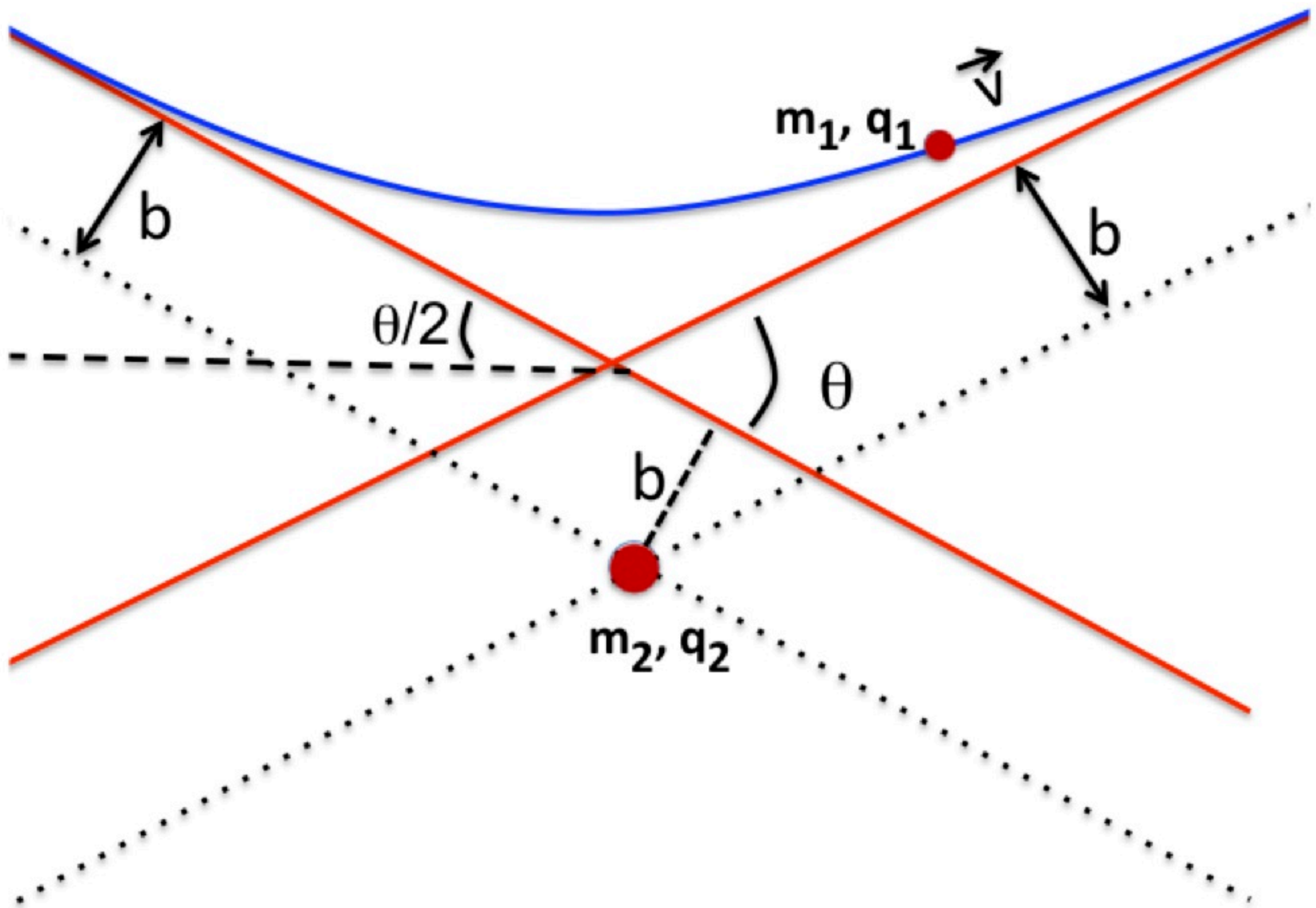
McClintock, Narayan, & Steine 2014

Kα Iron line (6.4 keV) tells the spin (→ATHENA)



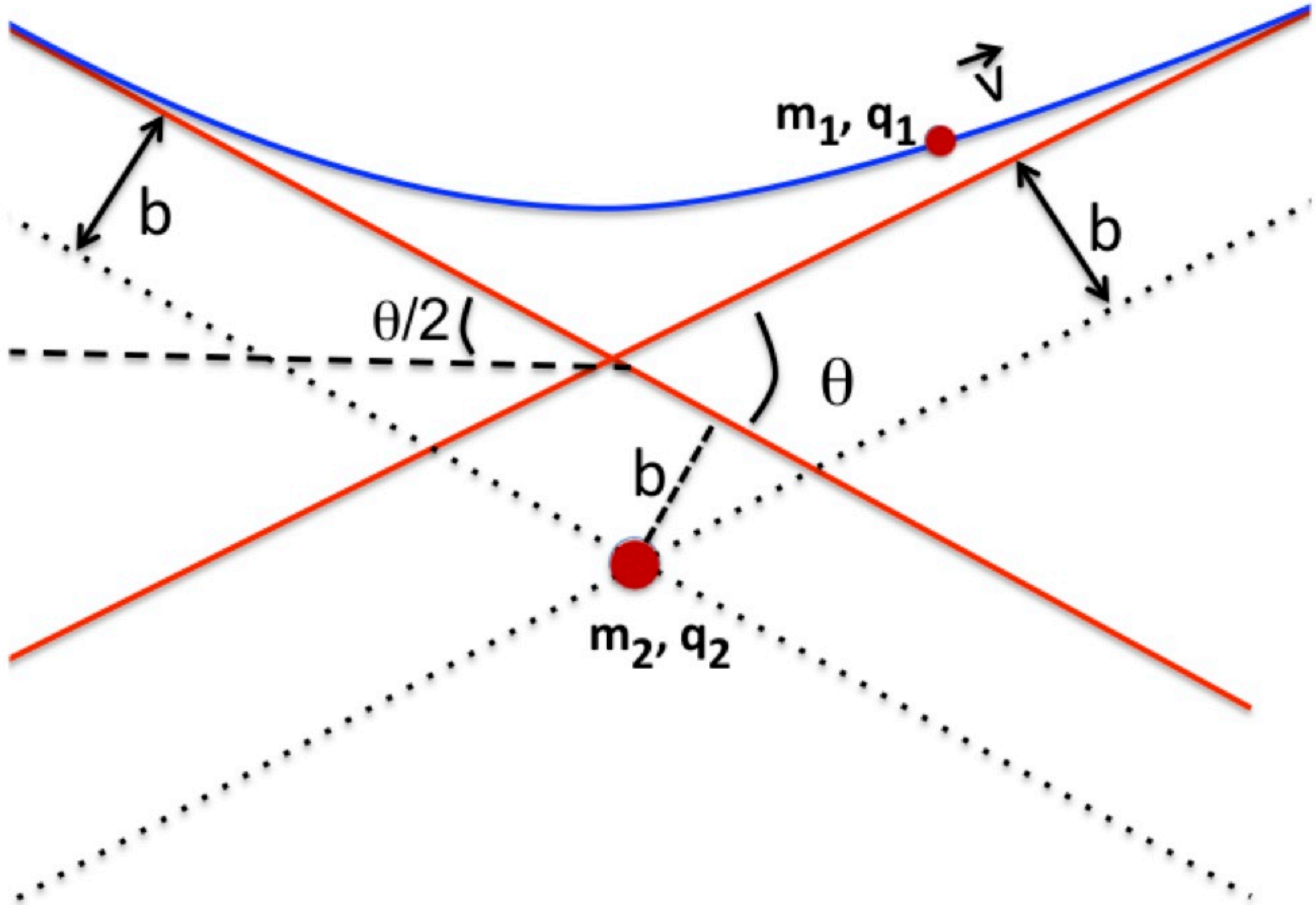
Accreting protons have the energy
Electrons emit
There must be exchange of energy between p and e-

Accreting protons have the energy
Electrons emit
Proton-electron energy exchange : Coulomb collisions



Coulomb collisions cross section

$$\sigma_{cc} = \frac{3\sigma_T}{32\pi\, \beta^4 \sin(\theta/2)^4}$$



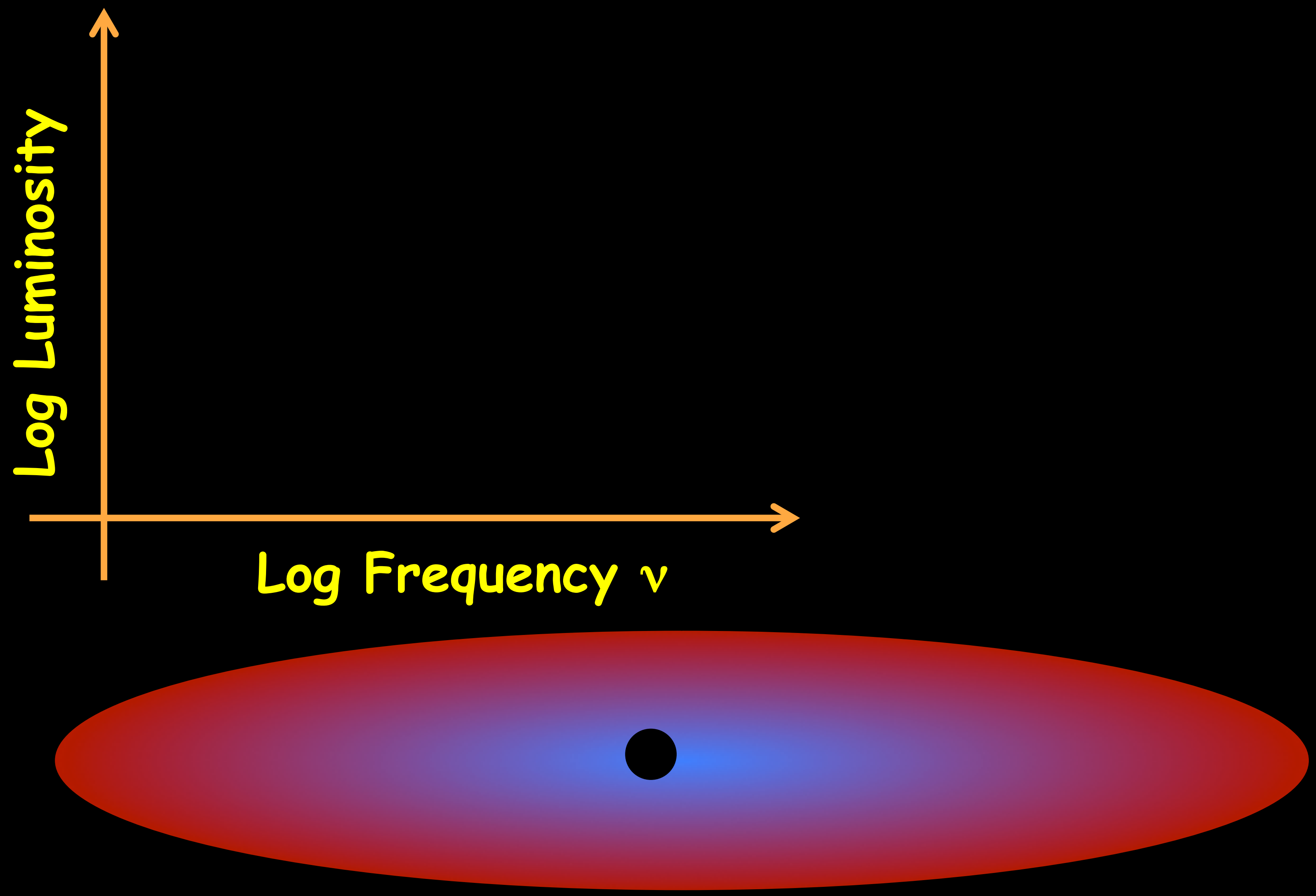
Three regimes of accretion

Low accretion rates: small density, Coulomb collisions are not sufficient to pass energy from protons to electrons

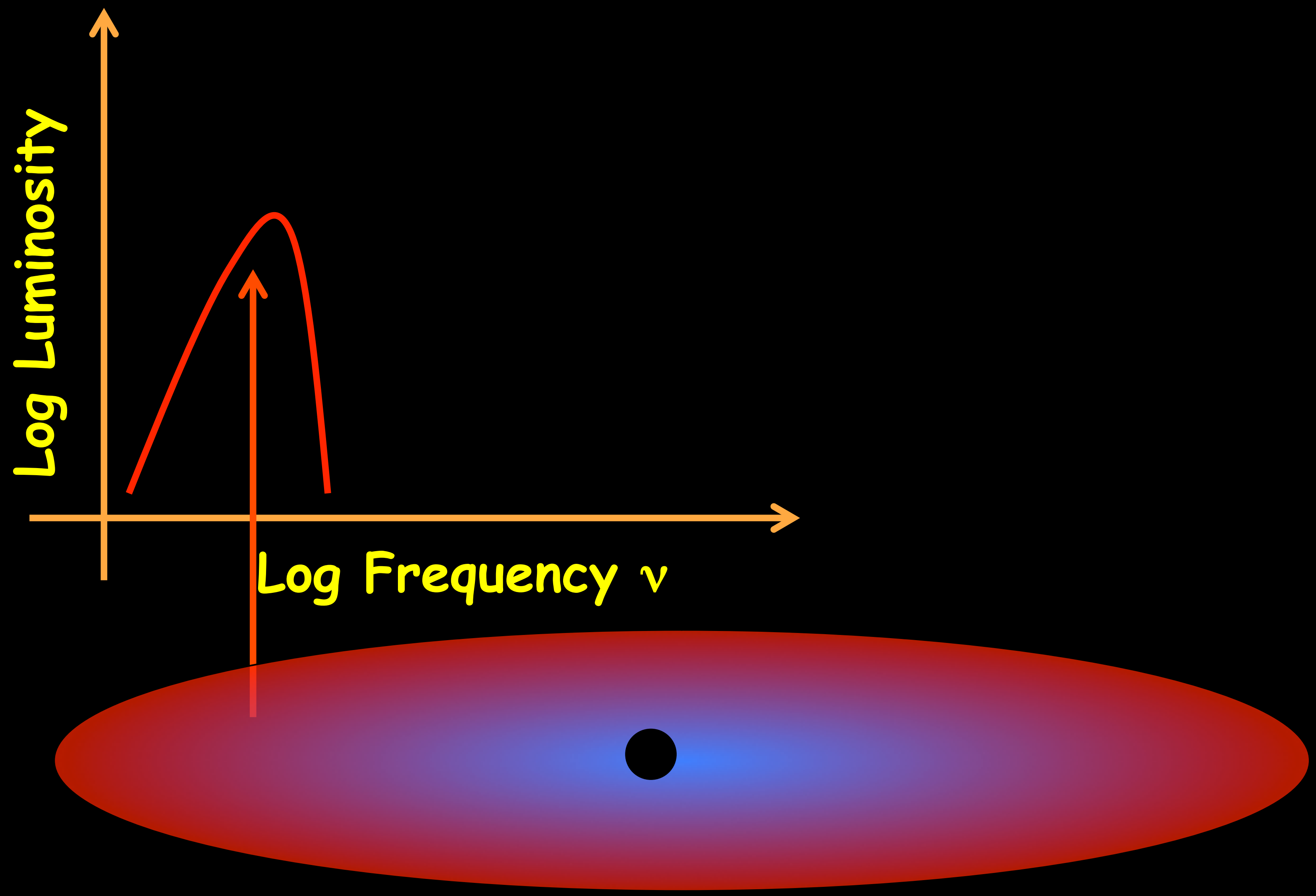
Intermediate accretion rates: Shakura Sunjaev disk: optically thick, geometrically thin

High accretion rates: large density, large optical depth: the produced photons cannot escape, they are advected into the black hole

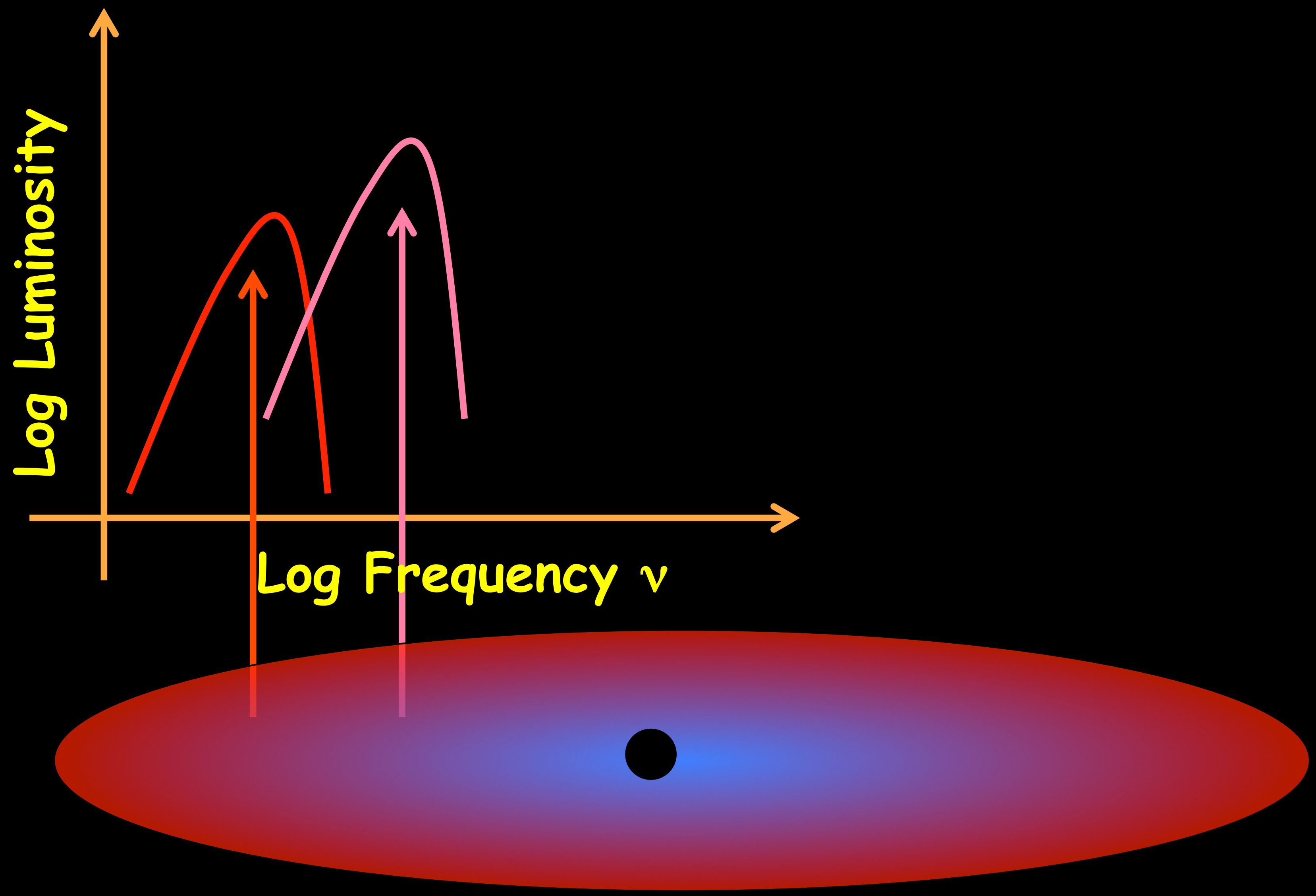
Shakura Sunjaev disk



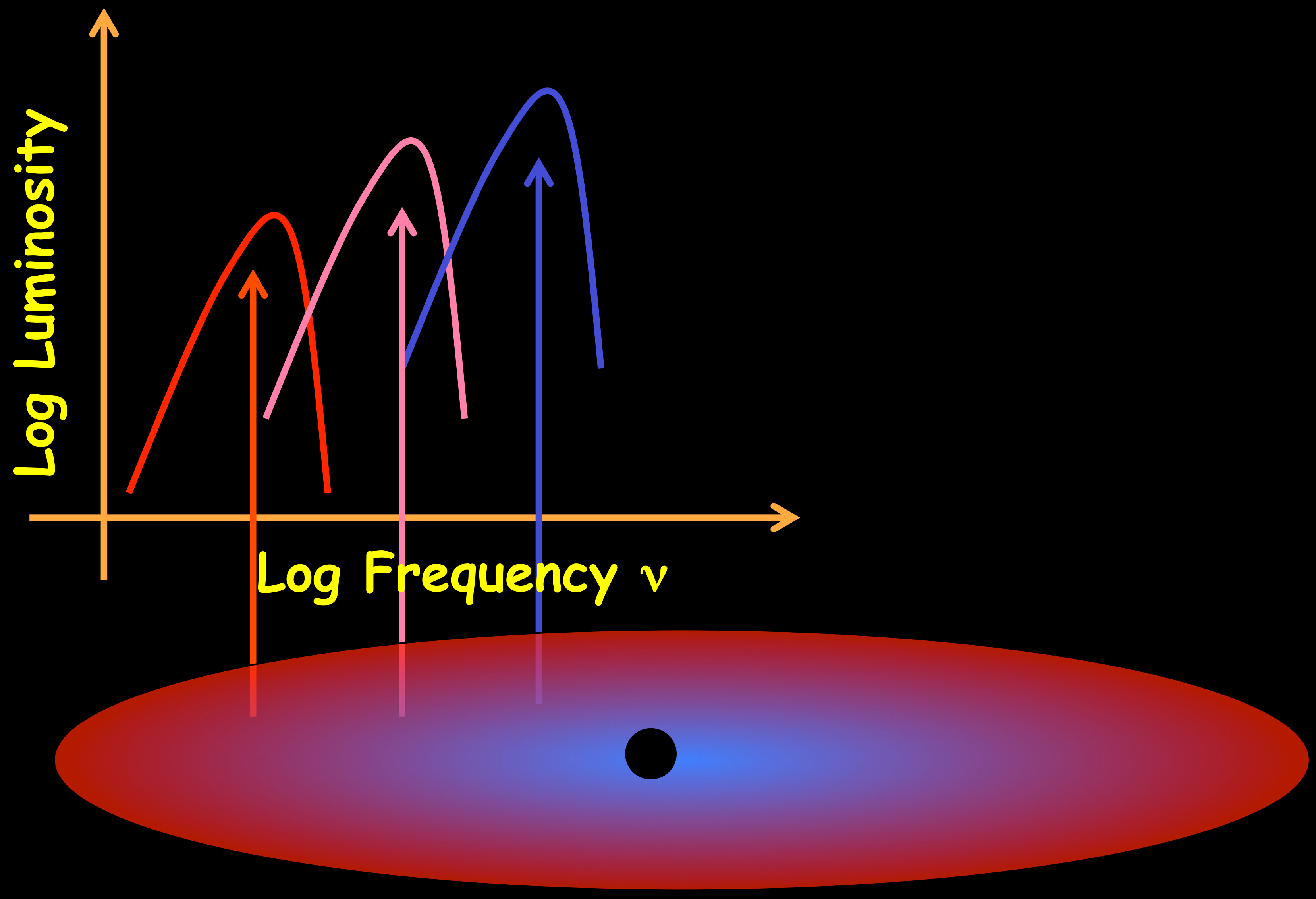
Shakura Sunjaev disk



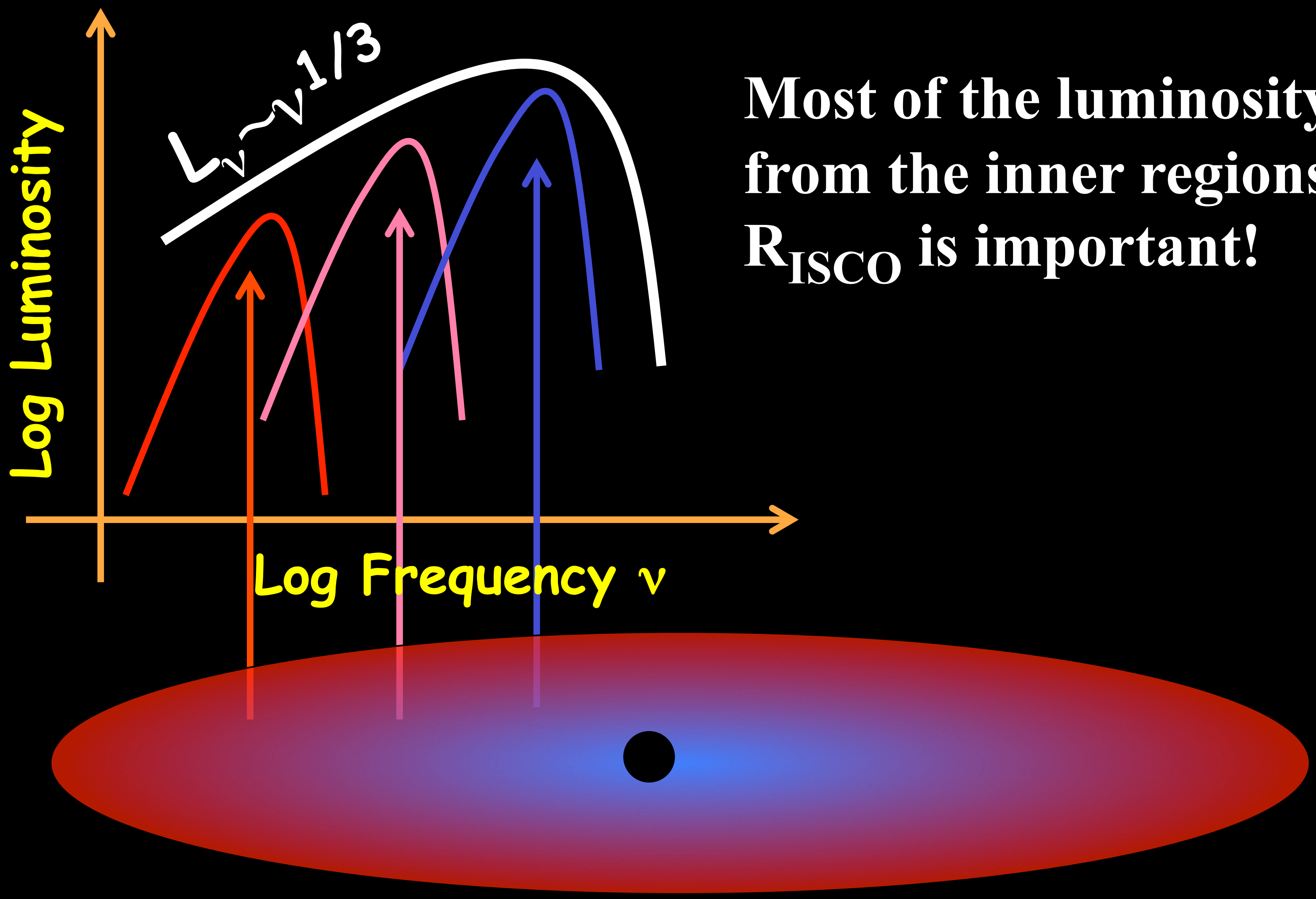
Shakura Sunjaev disk



Shakura Sunjaev disk

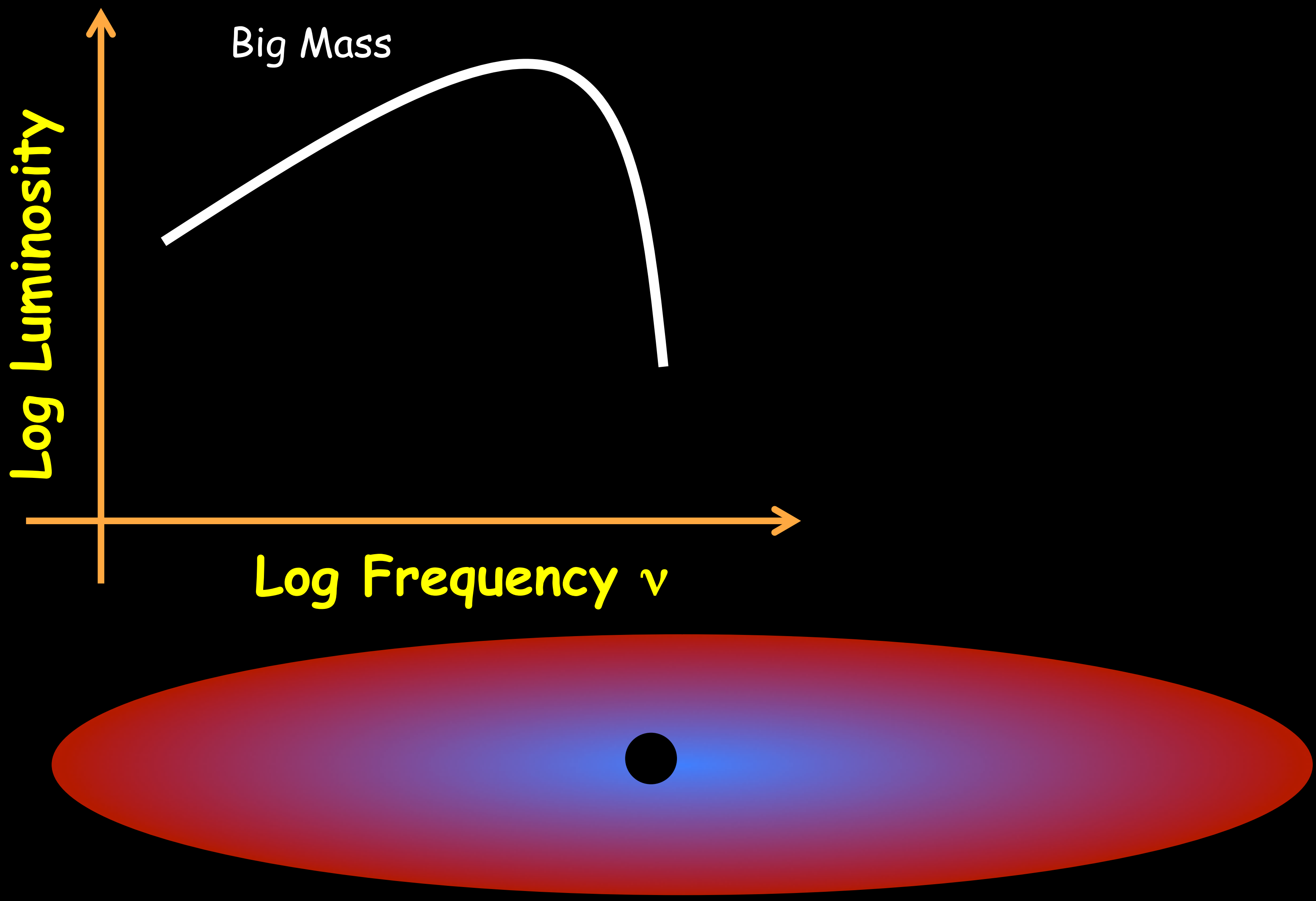


Shakura Sunjaev disk

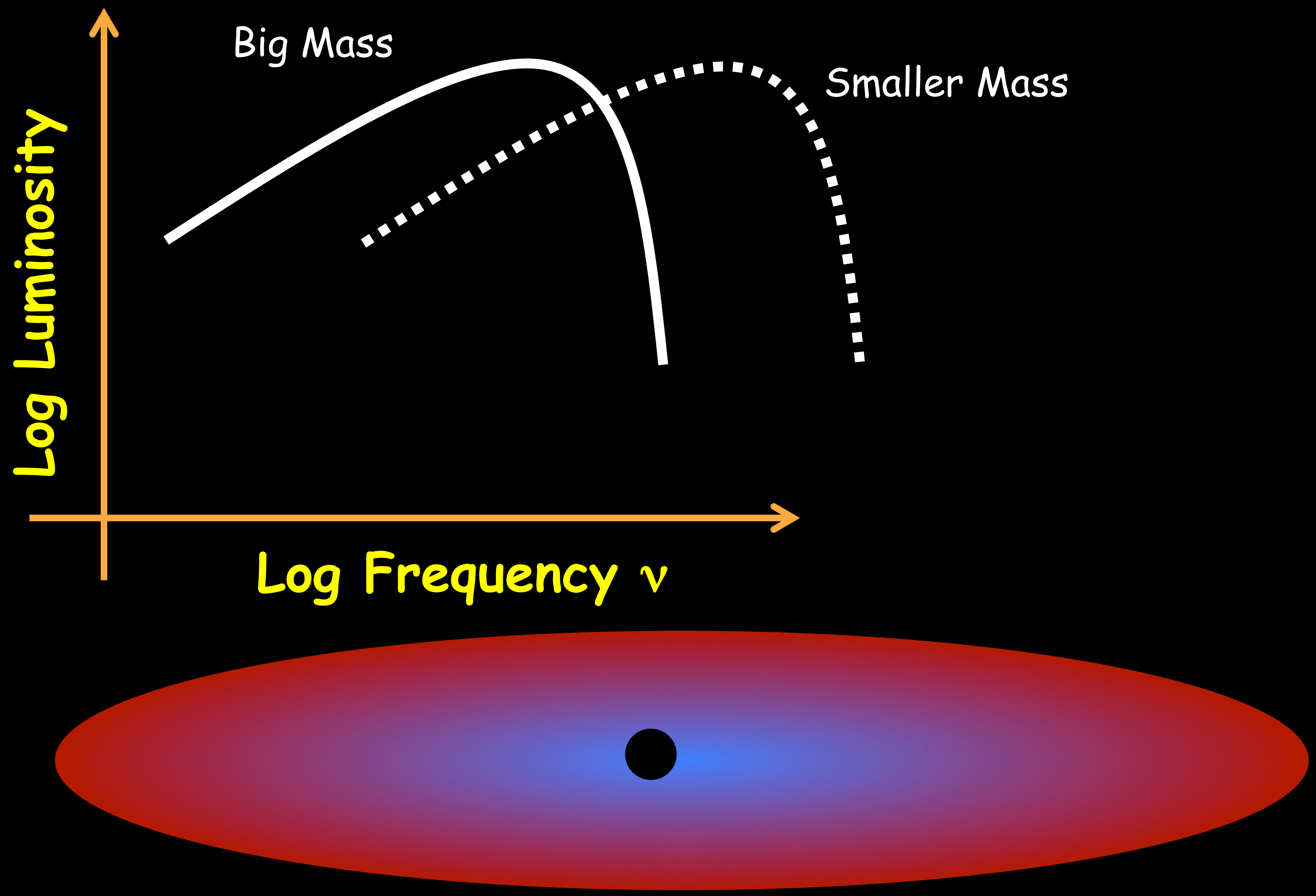


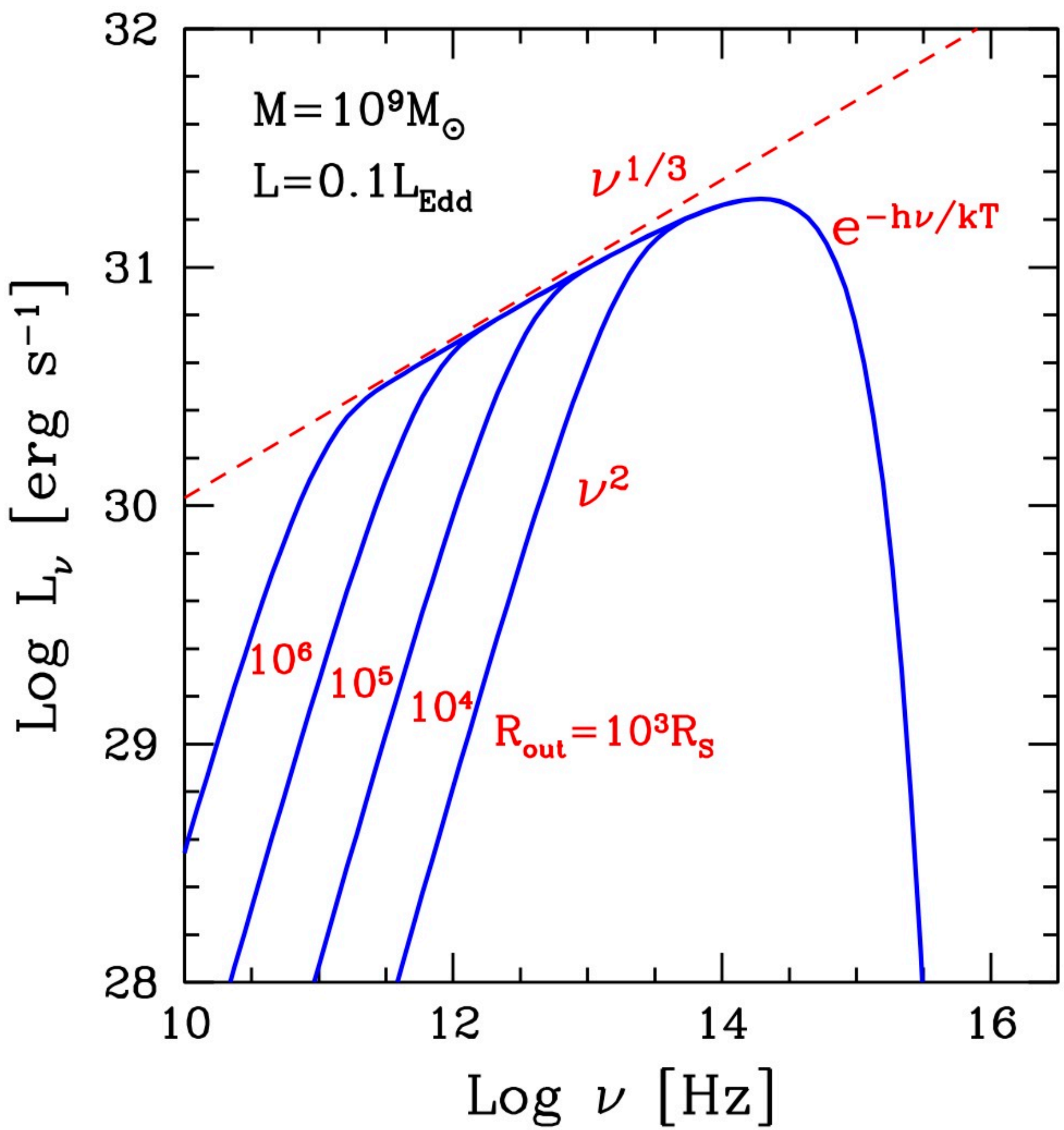
Most of the luminosity from the inner regions, R_{ISCO} is important!

Shakura Sunjaev disk



Shakura Sunjaev disk

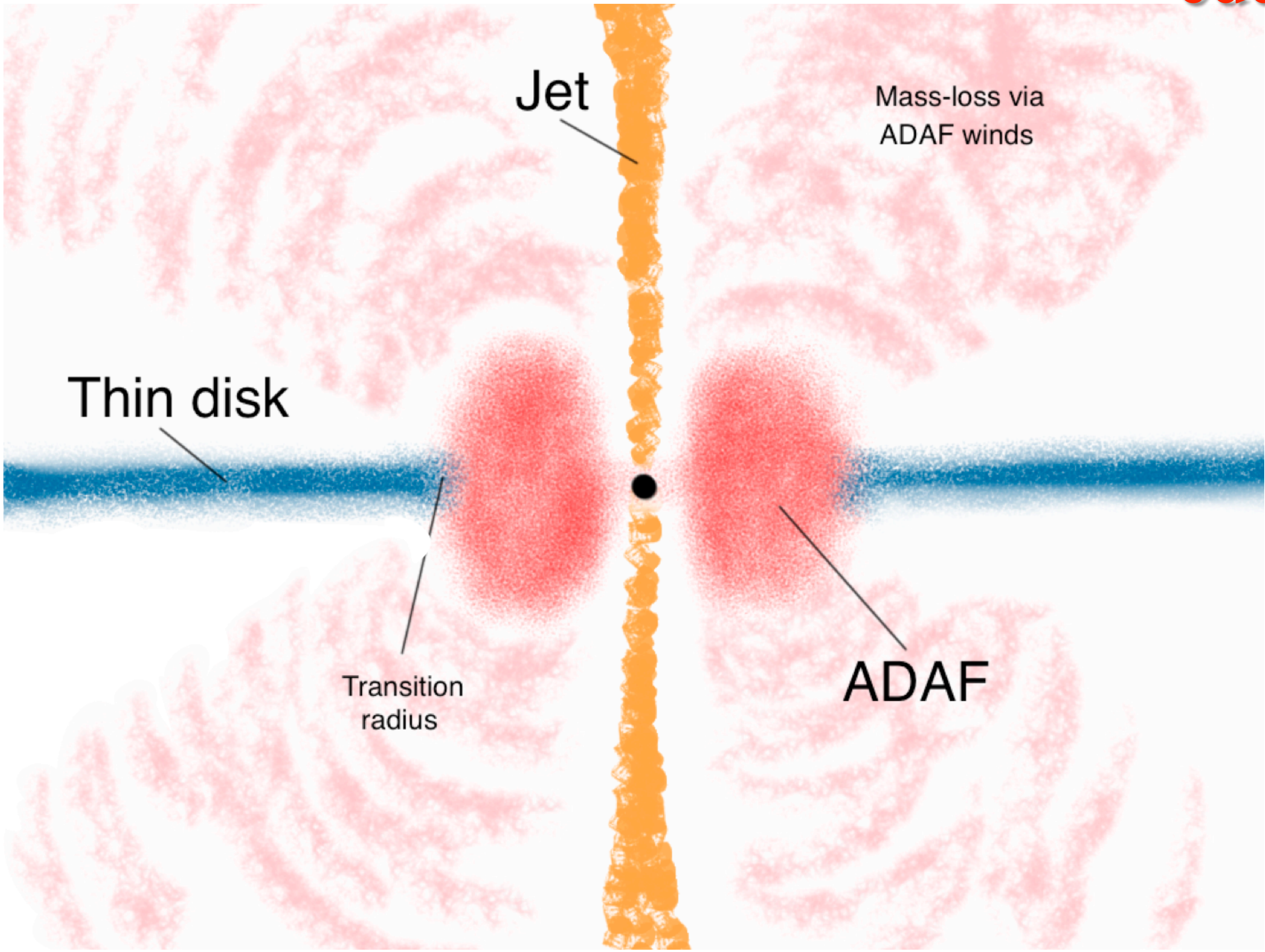




$\nu^{1/3}$ visible if $R_{out} >> R_{ISCO}$

Small ν : $L_\nu \sim \nu^2$

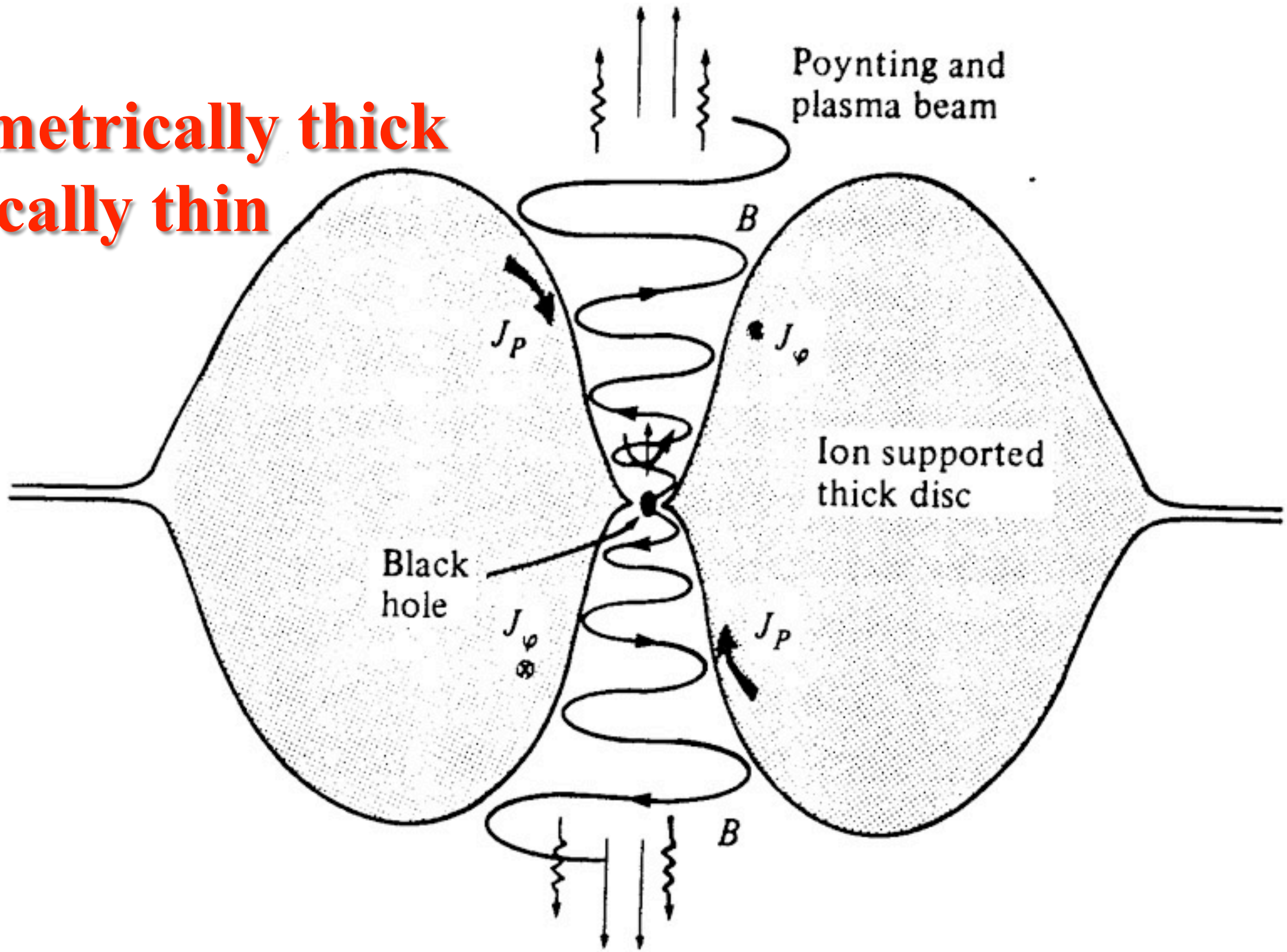
Low accretion rate: $L < 10^{-2} L_{edd}$



Ion Supported Tori

Rees, Begelman, Blandford & Phinney, 1982, Nature, 295, 17.

geometrically thick
optically thin



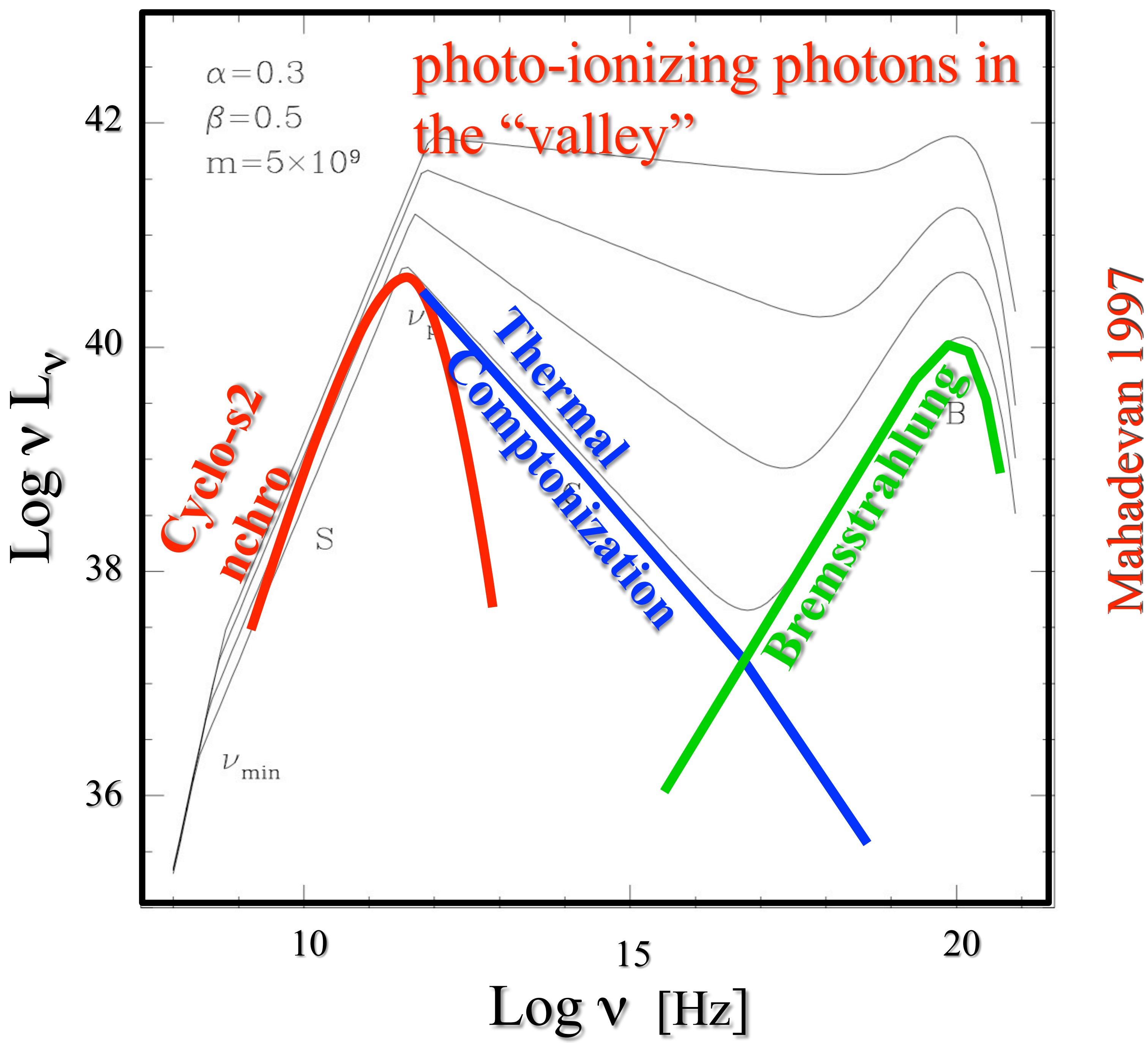
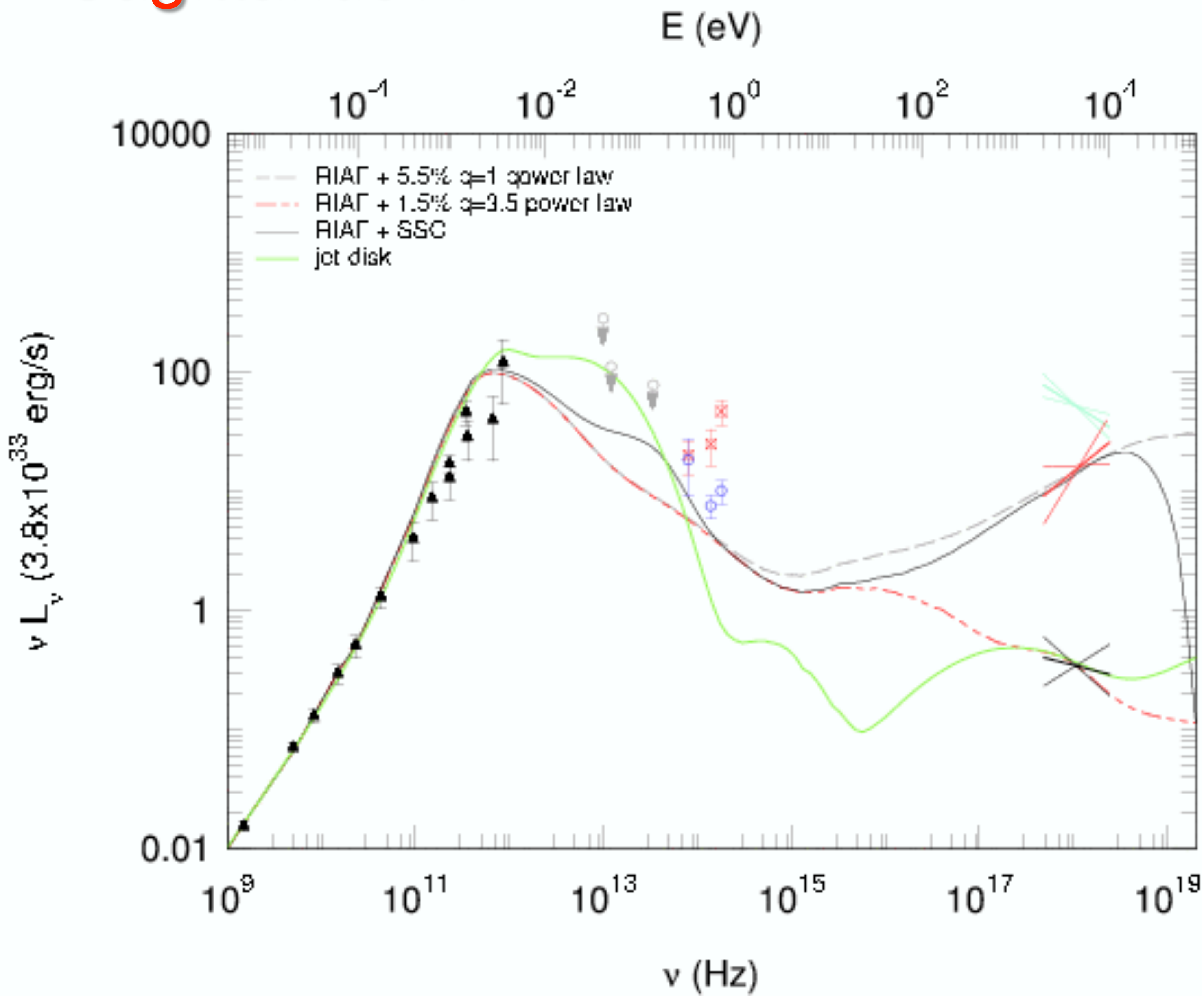


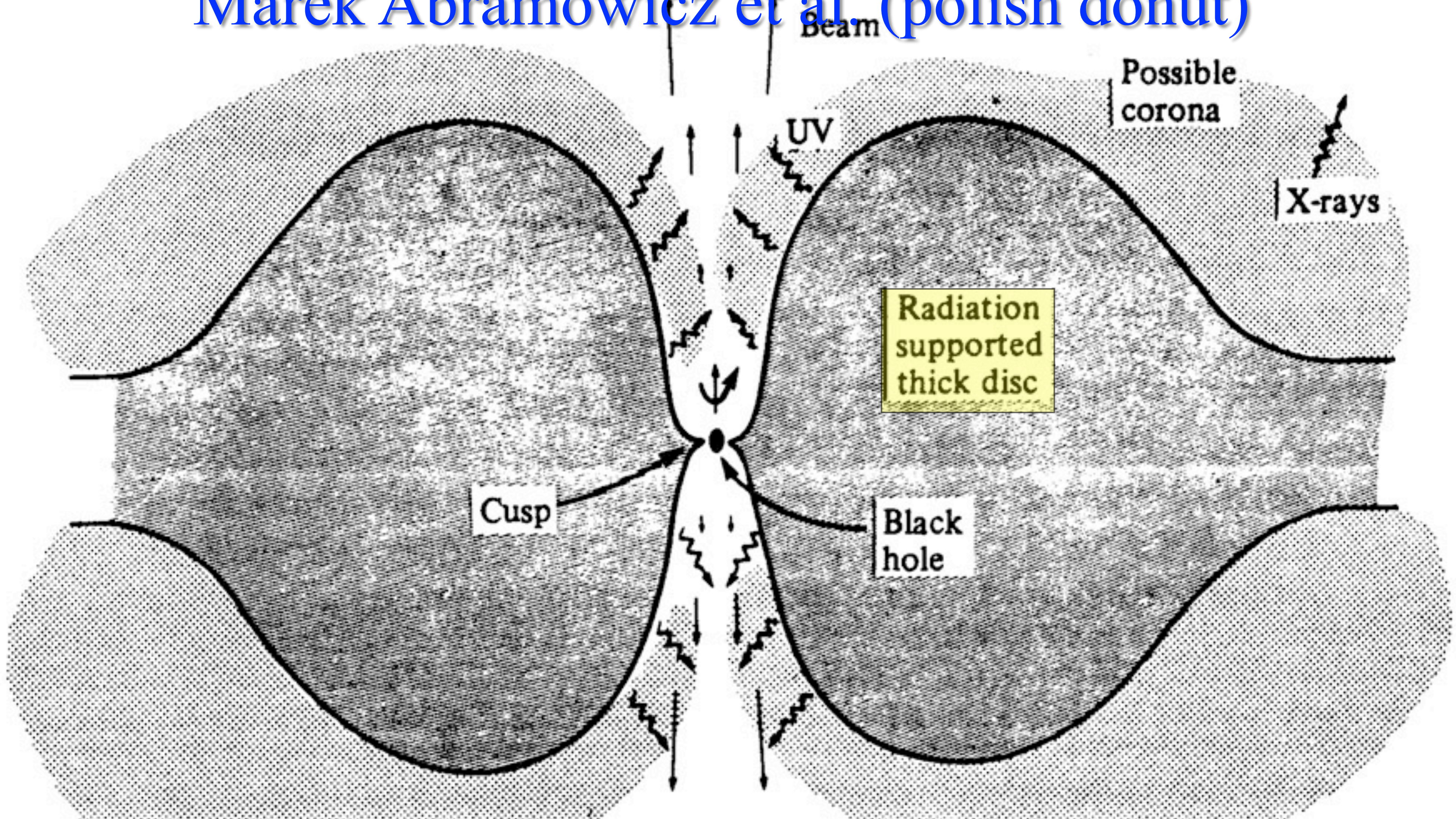
photo-ionizing photons in the “valley”
α=0.3
β=0.5
m=5×10⁹
Cyclo-s2 nchro
Thermal Comptonization
Bremsstrahlung
Mahadevan 1997
Log ν L_ν
Log ν [Hz]
42
40
38
36
10
15
20
S
B
ν_min

Sagittarius A*



High accretion rate: $L \sim L_{edd}$

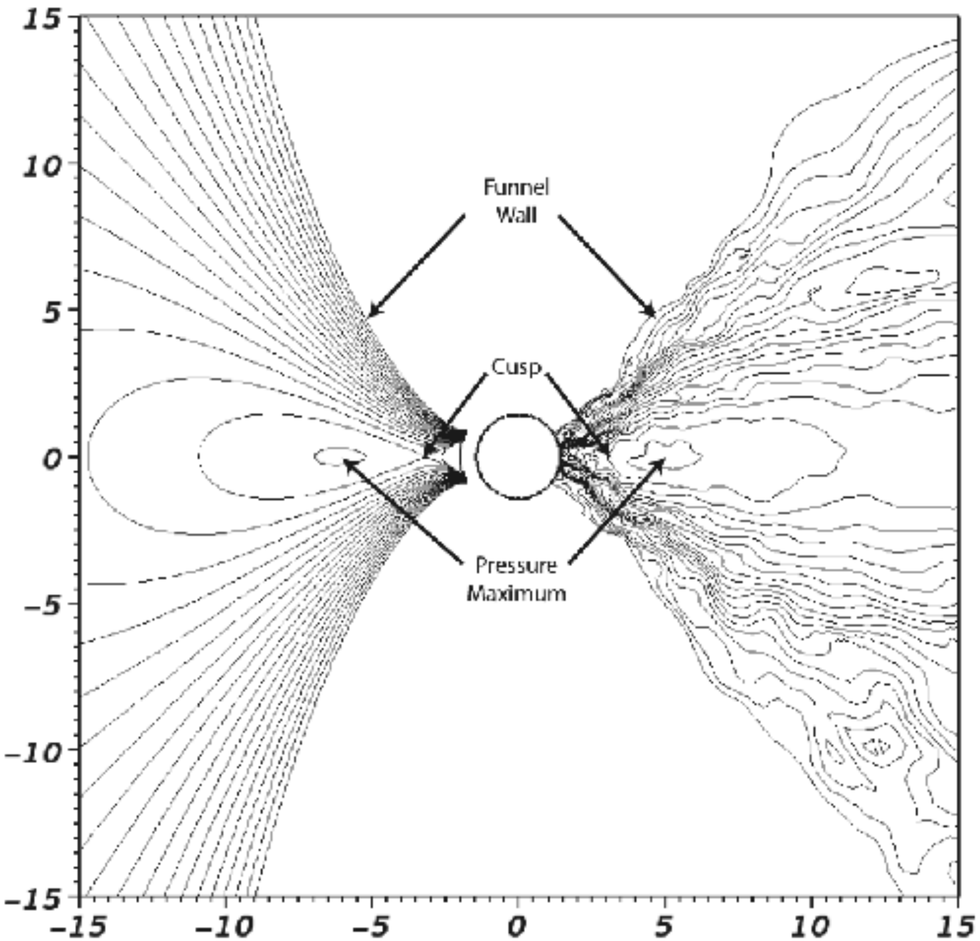
Marek Abramowicz et al. (polish donut)

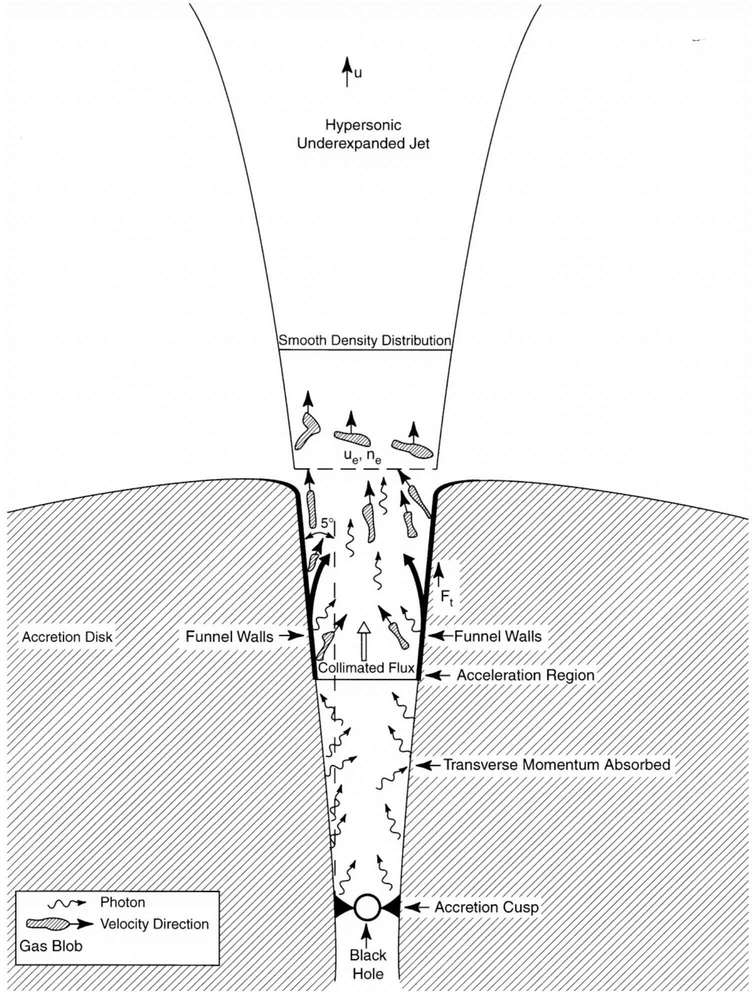


geometrically thick
optically thick

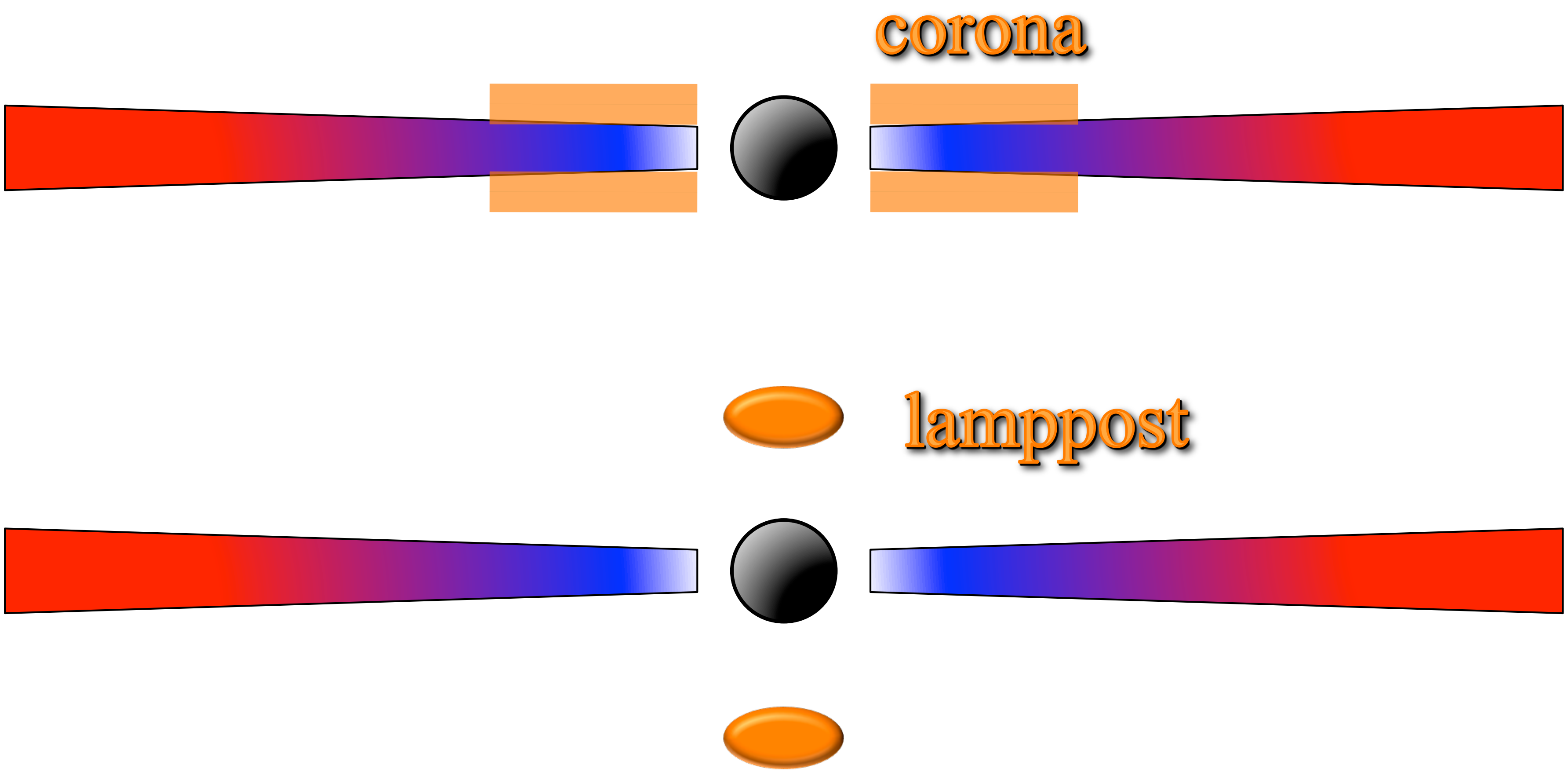
Radiation supported

Funnel collimates: apparent $L \gg L_{Edd}$ if $\theta_{view} < \theta_{funnel}$

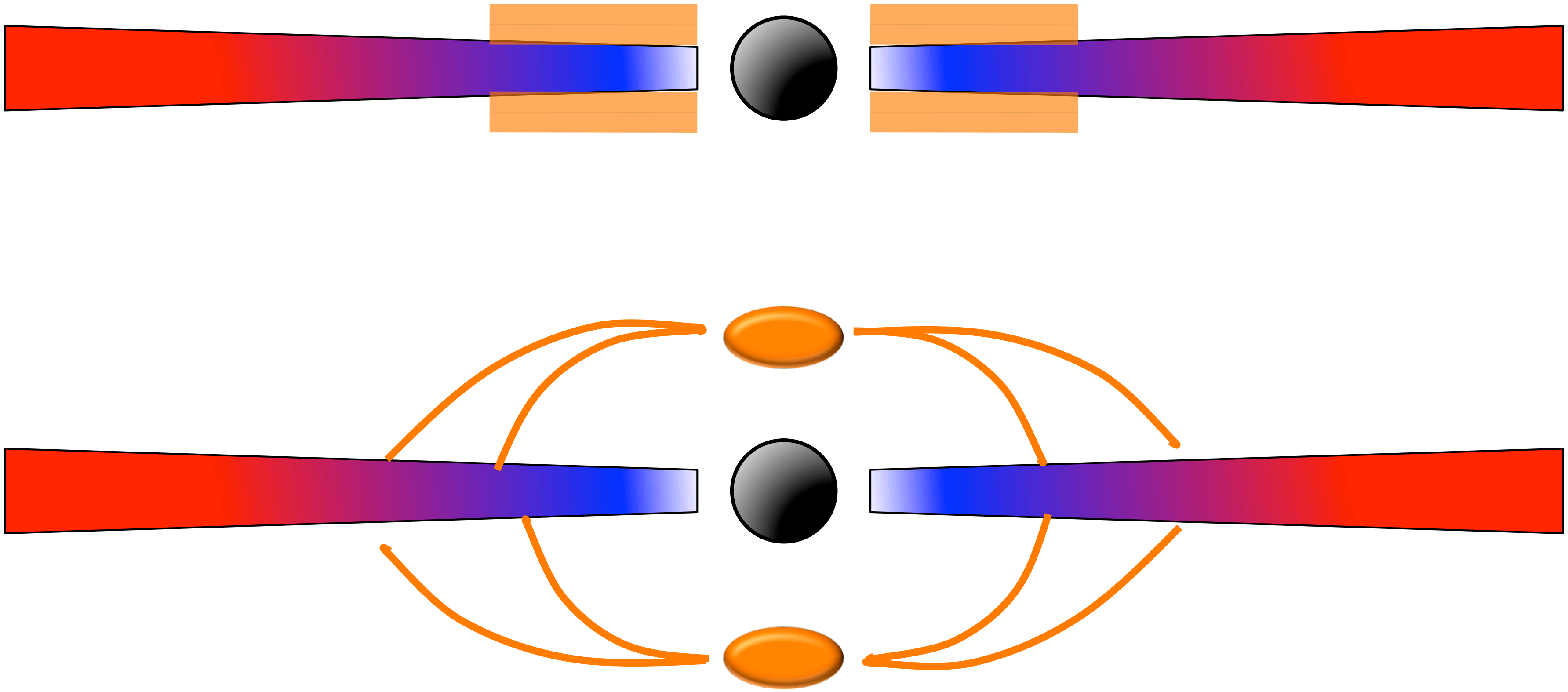




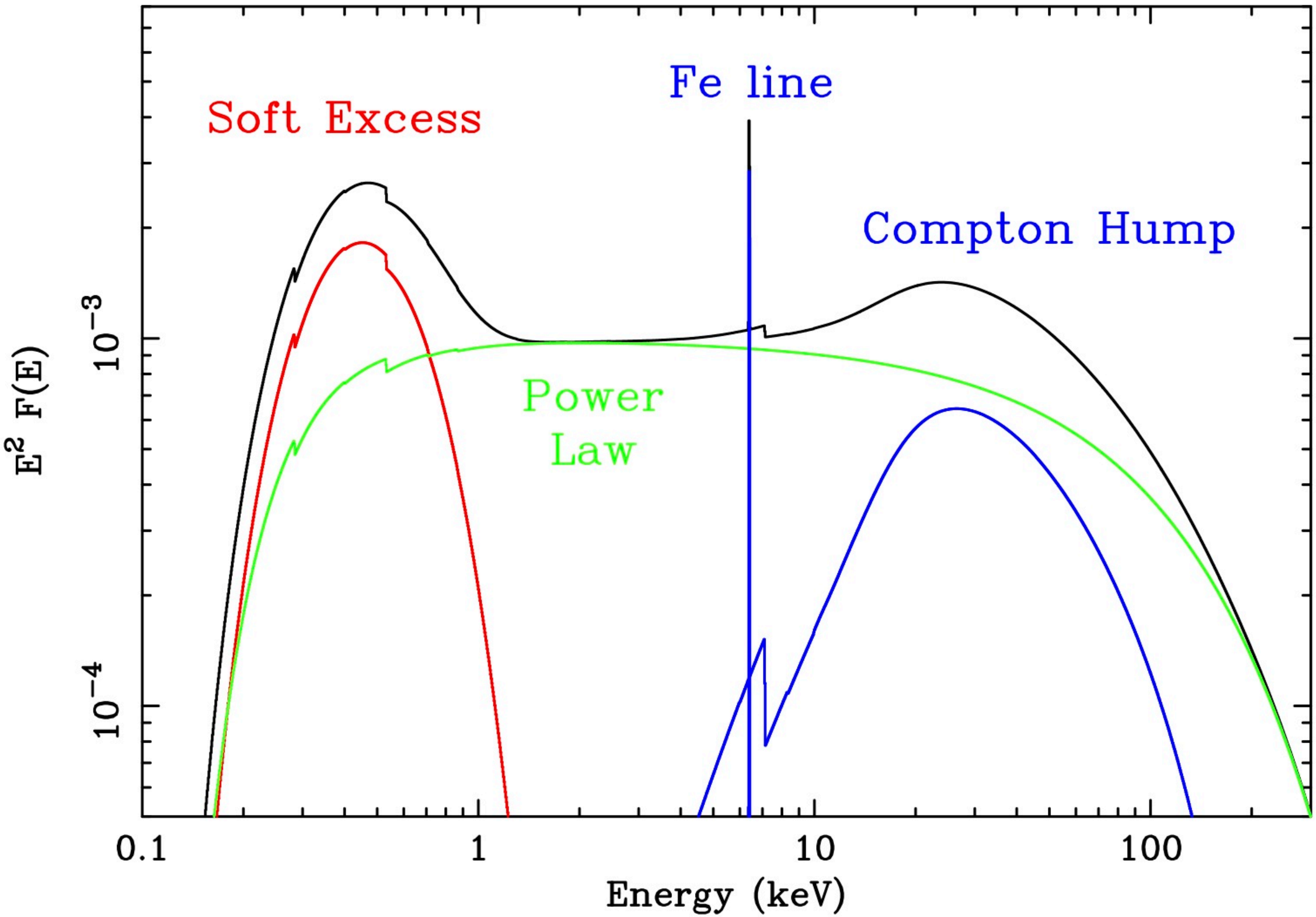
Accretion disk + X-ray corona



Accretion disk + X-ray corona



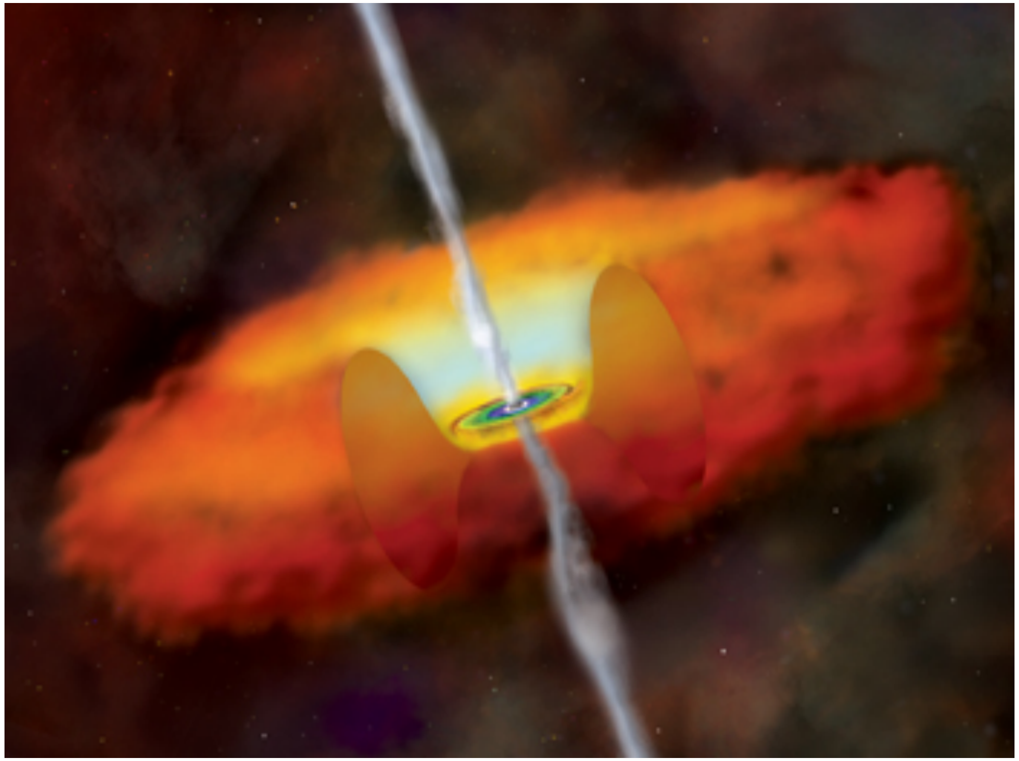
Light bending (the closer the stronger)


Fe line
Soft Excess
Compton Hump
Power
Law
10^{-3}
10^{-4}
E^2 F(E)
0.1
1
10
100
Energy (keV)

- Efficiency
- background radiation
- Importance of R_{ISCO}
- Accretion modes
  - Shakura-Sunyaev
  - ADAF
- X-ray corona

Special relativity at work
Beaming

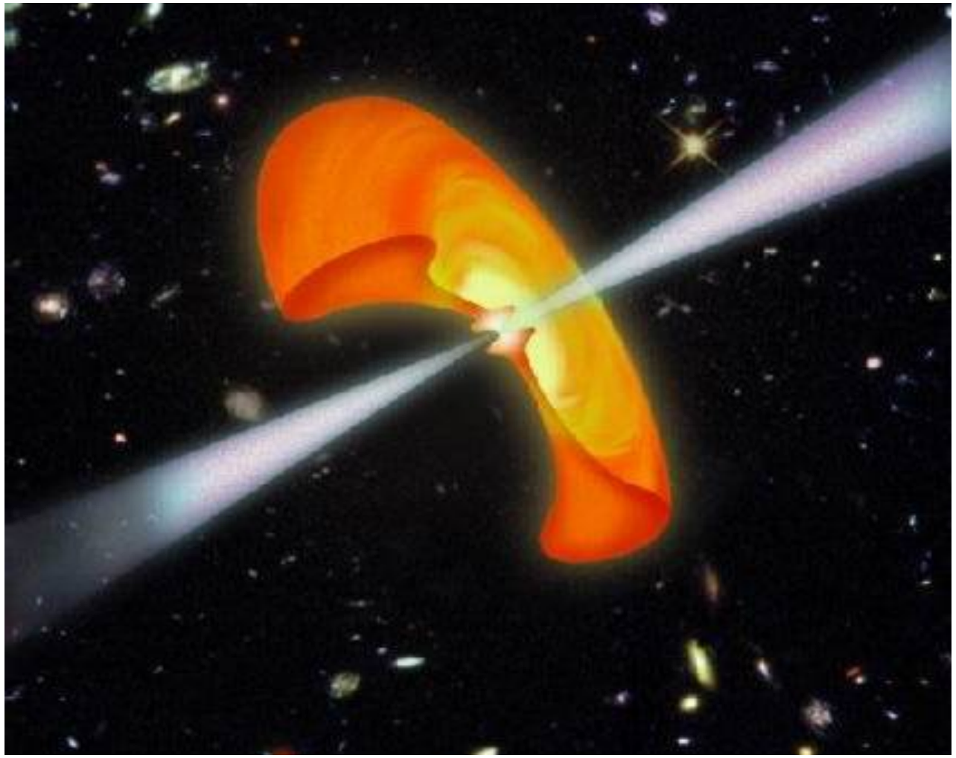
Radio-loud AGNs



$\sim 0.1\ M_o\ yr^{-1}$

$\Gamma \sim 20$

Gamma Ray Bursts

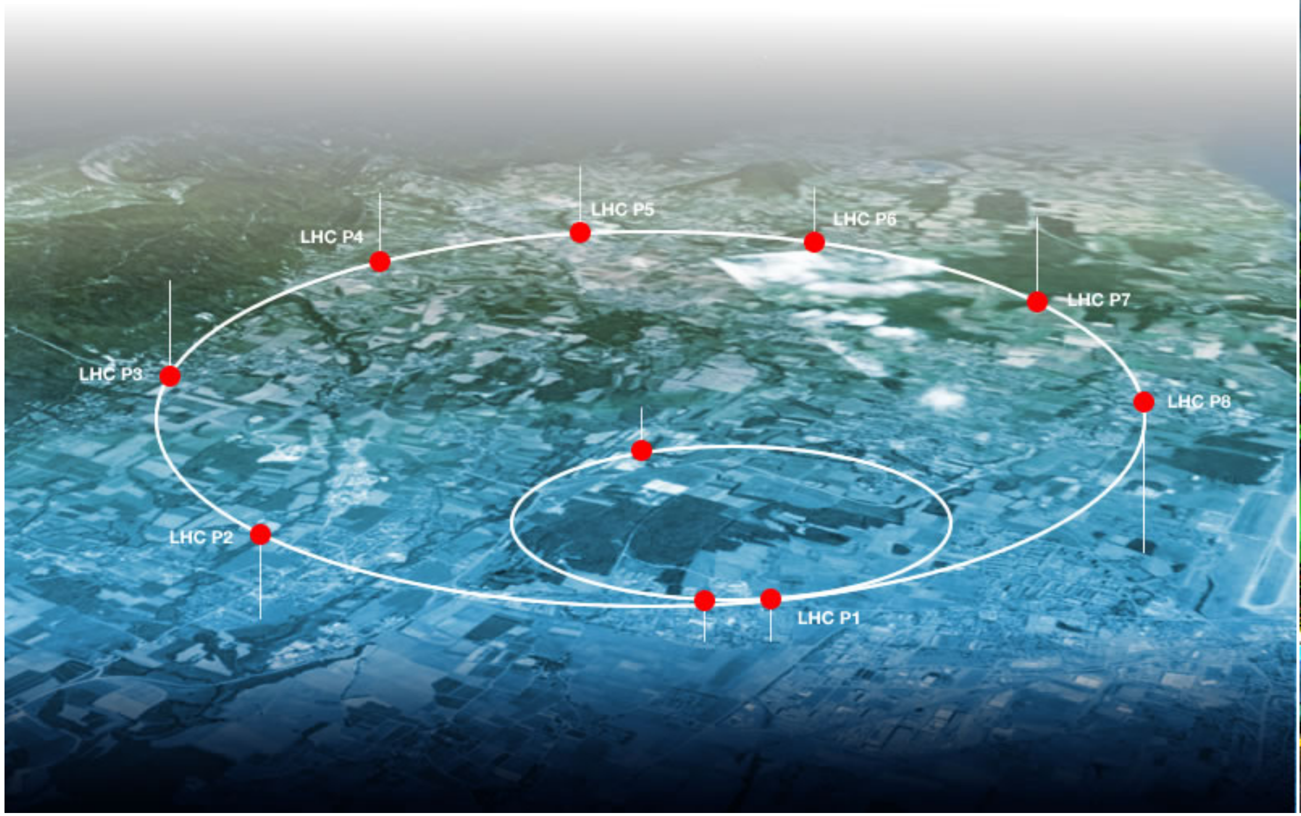


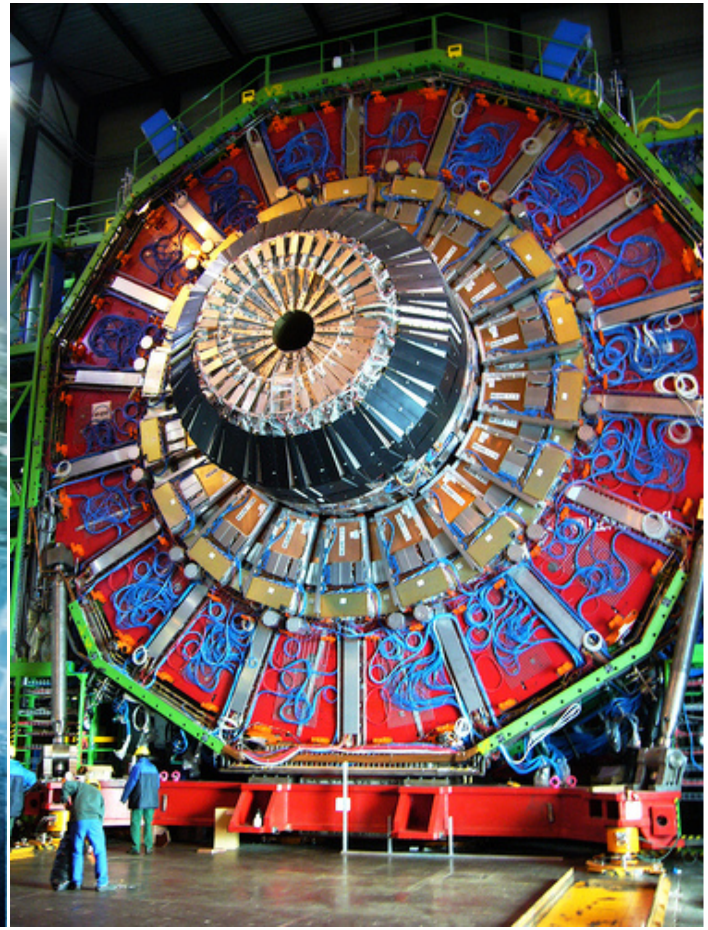
$\sim 10^{-5}\ M_o$

in a few sec

$\Gamma \sim 300$

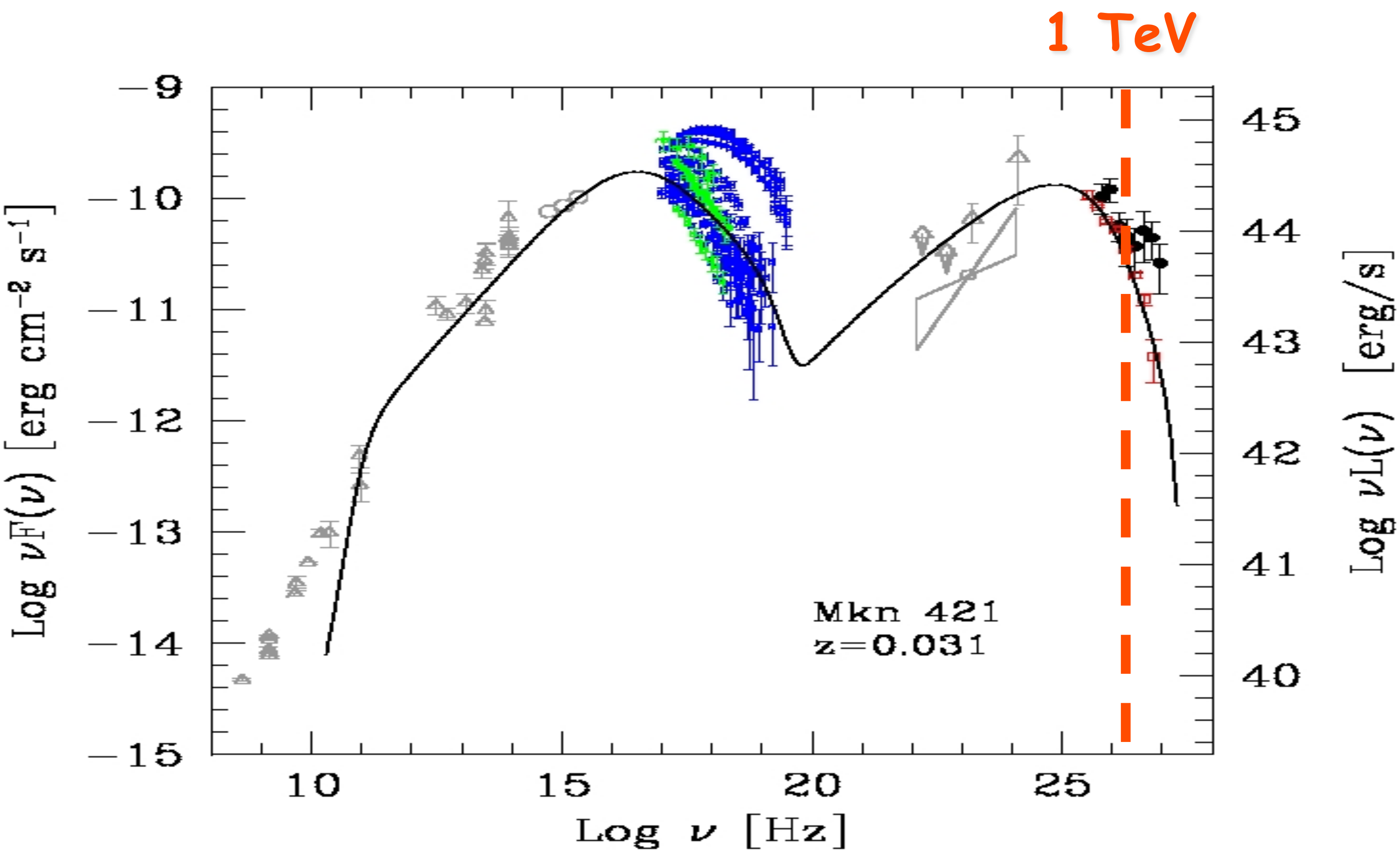
CERN



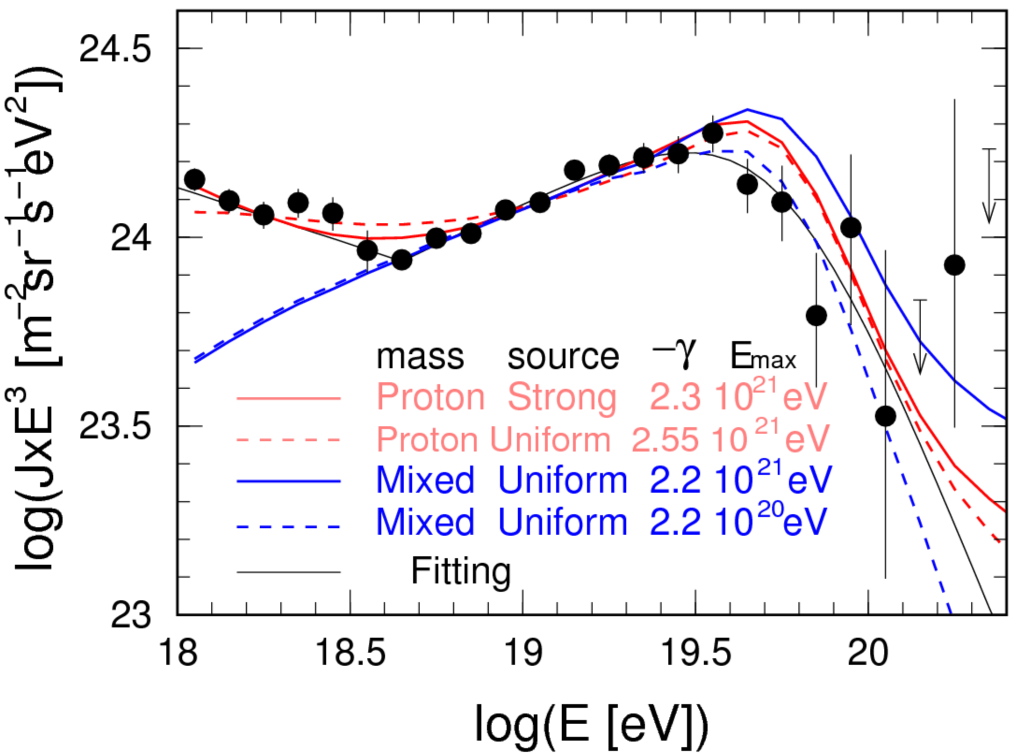


LHC → ~7 TeV protons → γ = 7000

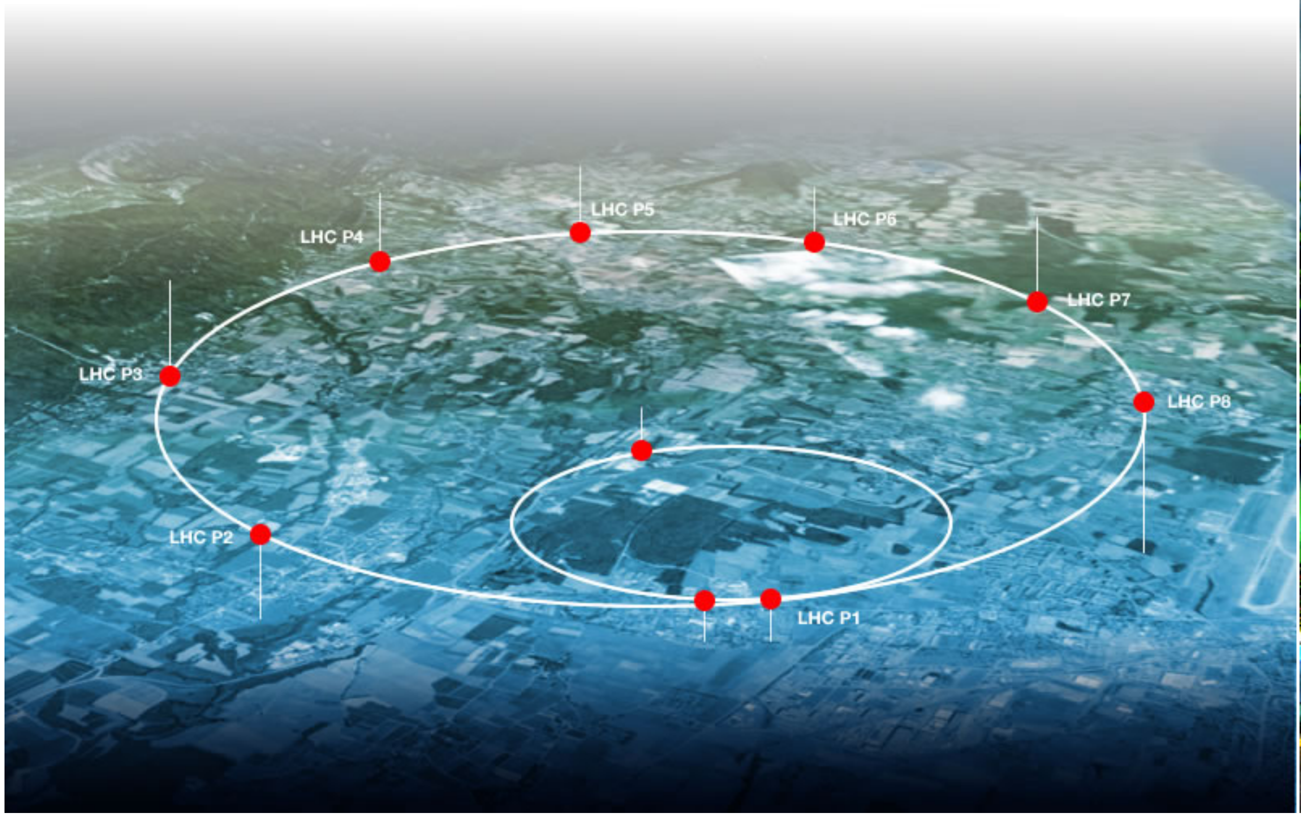
TeV blazars

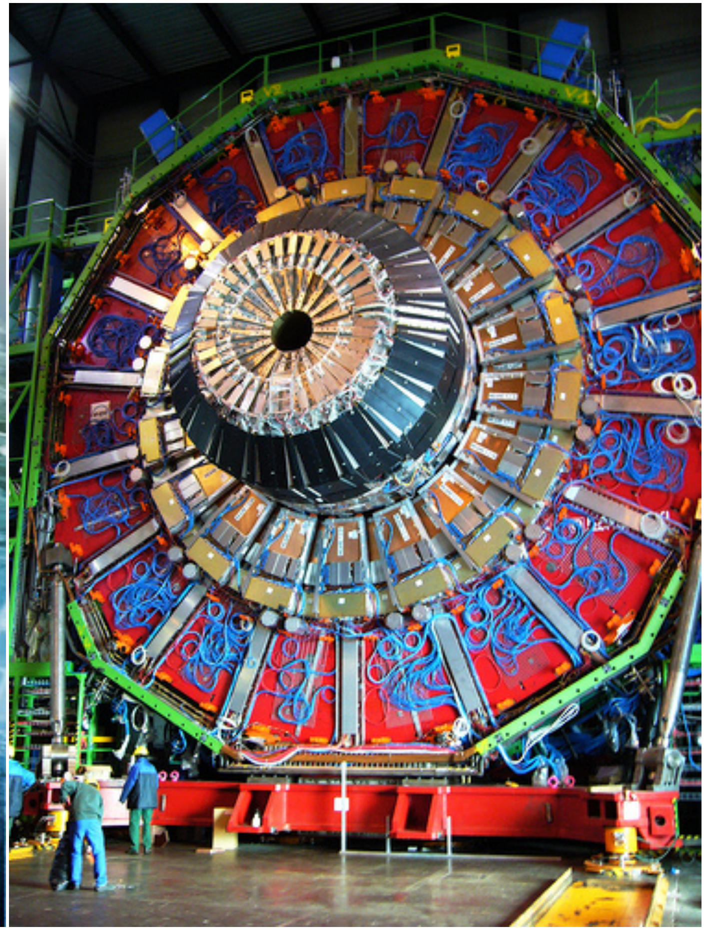

1 TeV
Log νF(ν) [erg cm⁻² s⁻¹]
Log νL(ν) [erg/s]
Log ν [Hz]
Mkn 421
z=0.031
−9
−10
−11
−12
−13
−14
−15
10
15
20
25
45
44
43
42
41
40

Cosmic rays



10^{20} eV = 10^{8} TeV = 10^{11} $m_p c^2$ =
tennis ball at 100 km/h





A few milligrams per decade?

Text book special relativity

Lorentz transformations: $\vec{v}$ along x

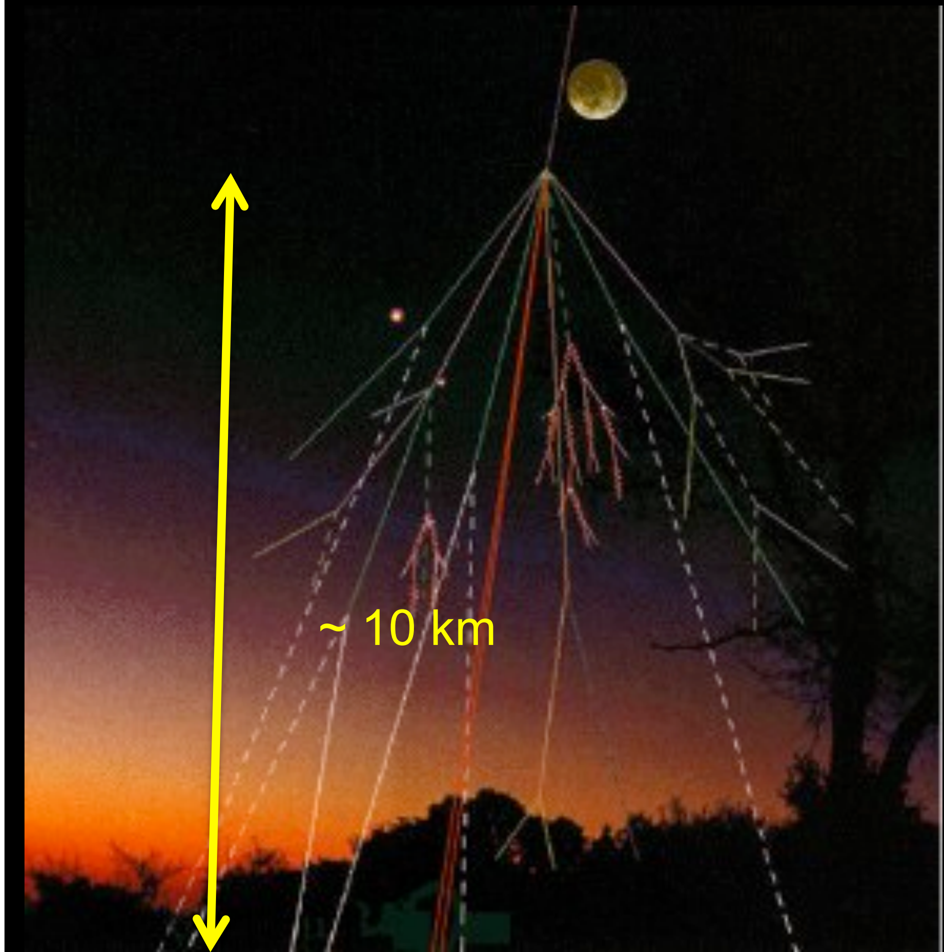
$x' = \Gamma\,(x - vt)$	$x = \Gamma\,(x' + vt')$
$y' = y$	$y = y'$
$z' = z$	$z = z'$
$t' = \Gamma\,(t - v\,x/c^2)$	$t = \Gamma\,(t' + v\,x'/c^2)$

for $\Delta t = 0 \rightarrow \Delta x = \Delta x'/\Gamma$ **Contraction**

for $\Delta x' = 0 \rightarrow \Delta t = \Gamma\,\Delta t'$ **time dilation**

To remember: mesons created at a height of ~10 km can reach the earth, even if their lifetime is a few microsec → ct'_{life}=hundreds of meters.

Long-lived mesons …



Meson lifetime:
2.2 microseconds

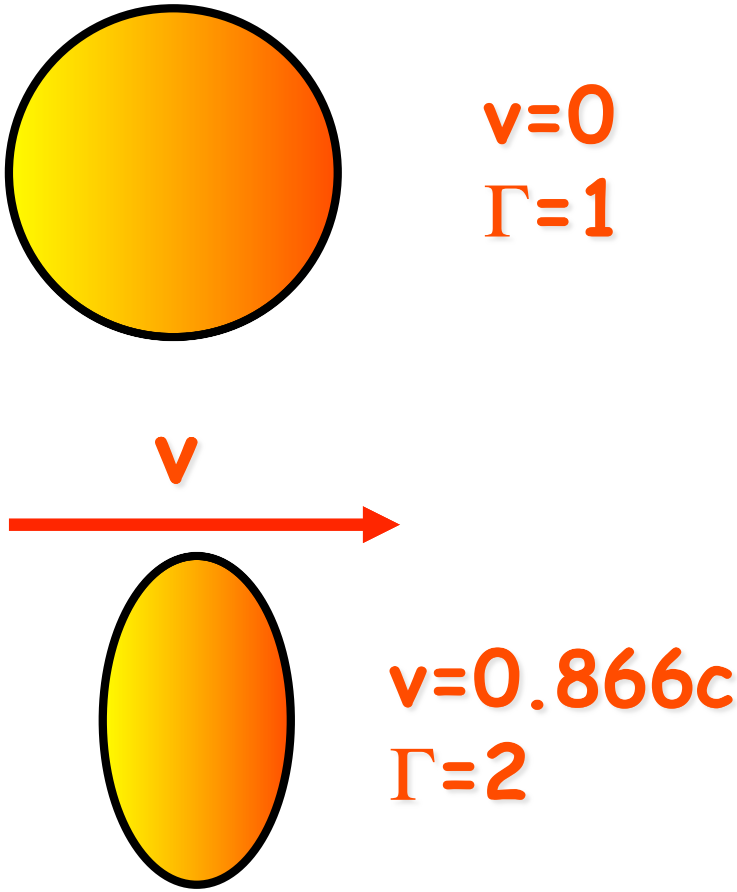
c x 2.2 μs = 660 meters

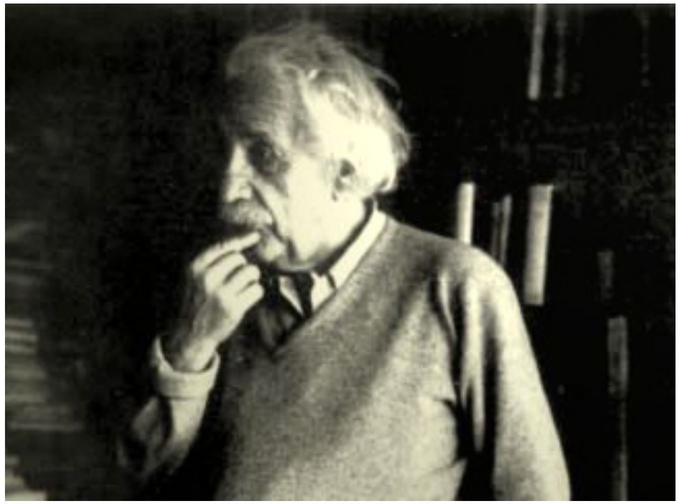
How can it run for 10 km?

10 km / 0.66 km = 15

$t_{obs} > 15\ t'_{decay}$

Can we see contracted spheres?



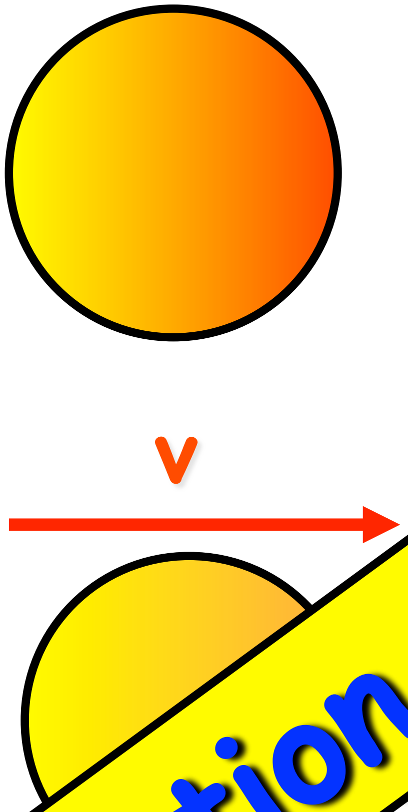


Einstein: Yes!

PHYSICAL REVIEW VOLUME 116, NUMBER 4 … 15, 1959

Invisibility of the Lorentz Contra…

JAMES TERRELL
Los Alamos Scientific Laboratory, University of C…
(Received Jun…



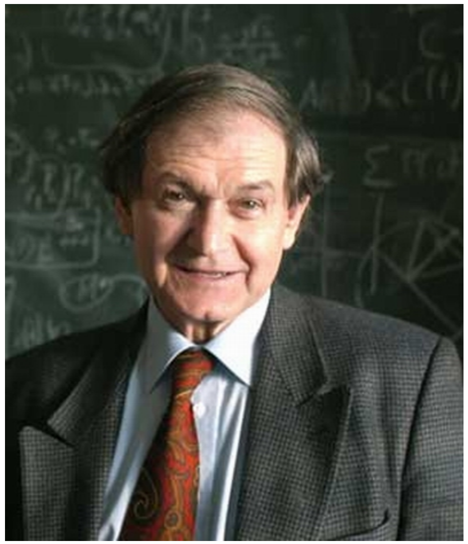
v=0
Γ=1

.866c
=2

J… 1959

NO!

Roger Penrose 1959



Rotation, not contraction!

Relativity with photons

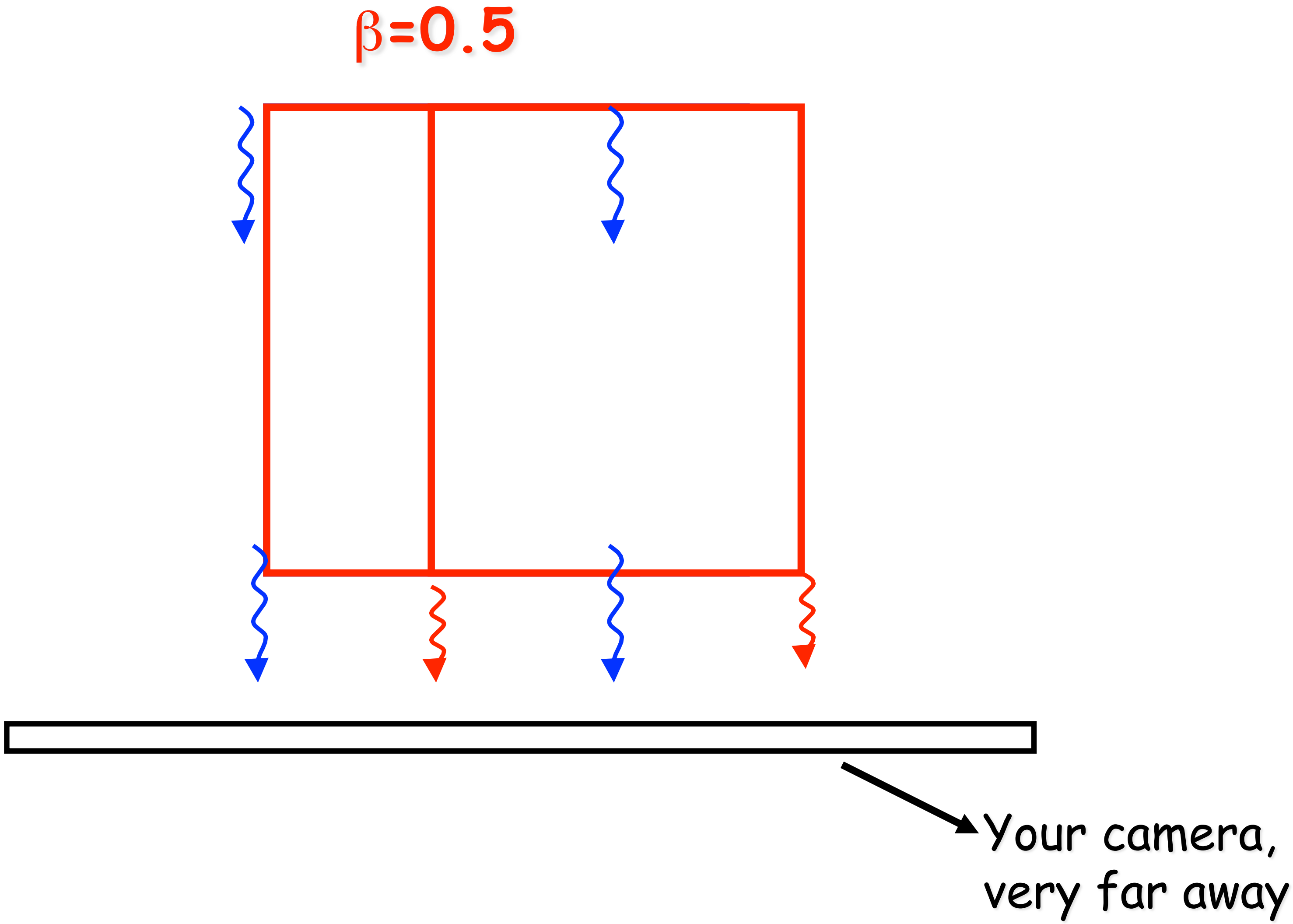
From rulers and clocks

to photographs and frequencies

Or:

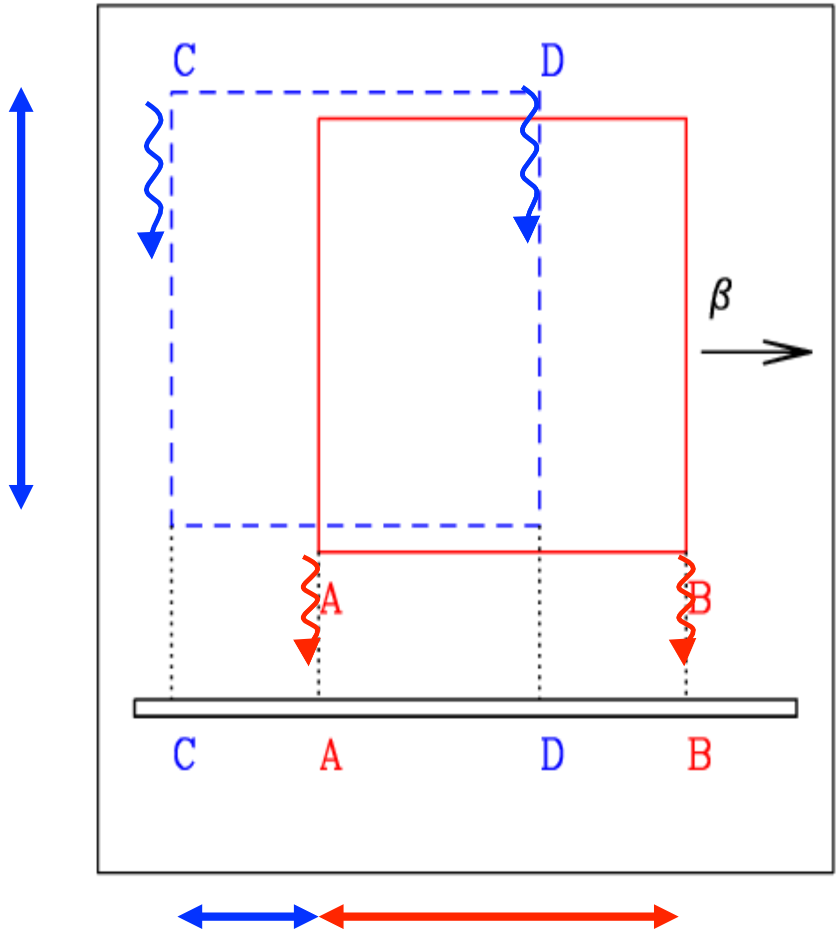
from elementary particles to extended objects

The moving square



The moving square

$t = l'/c$



$vt = \beta l'$

l'/Γ

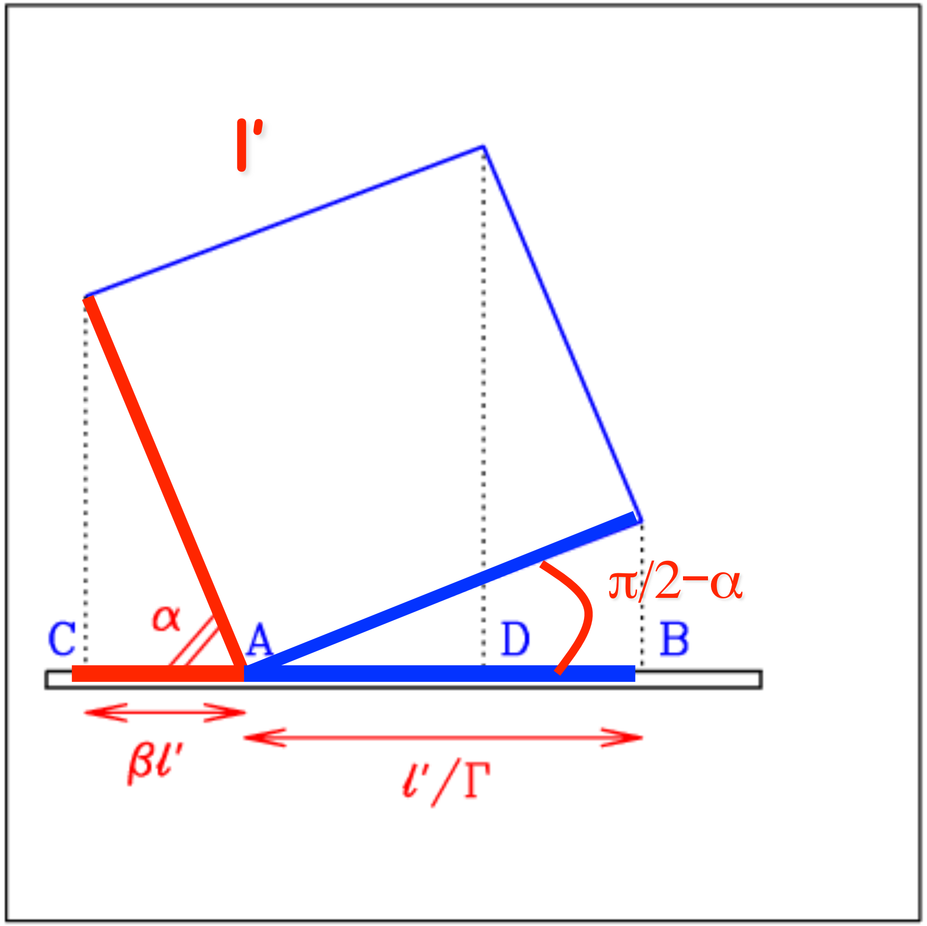
$l_{tot} = l'\,(\beta + 1/\Gamma)$

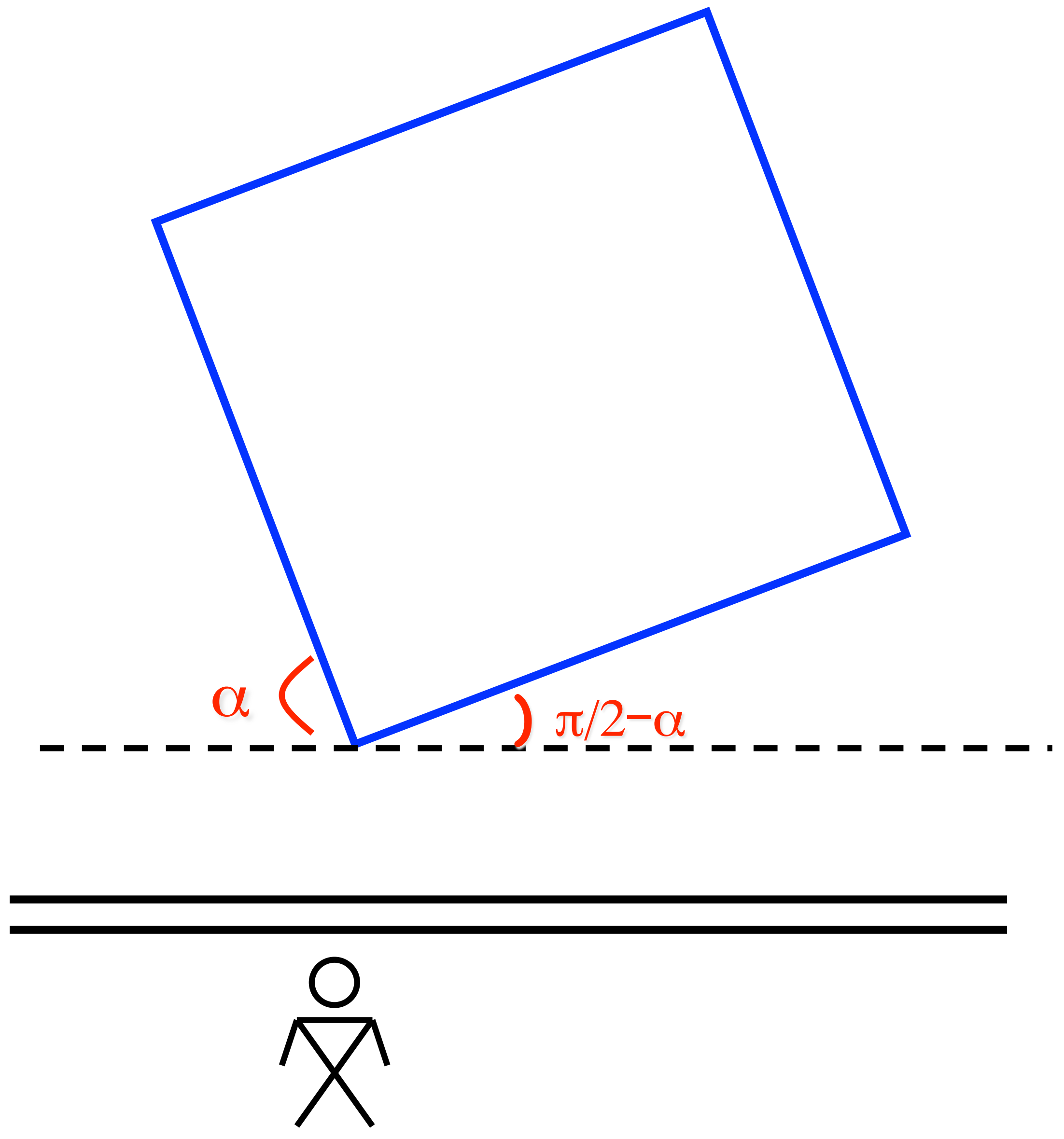
max: $2^{1/2} l'$ (diag)

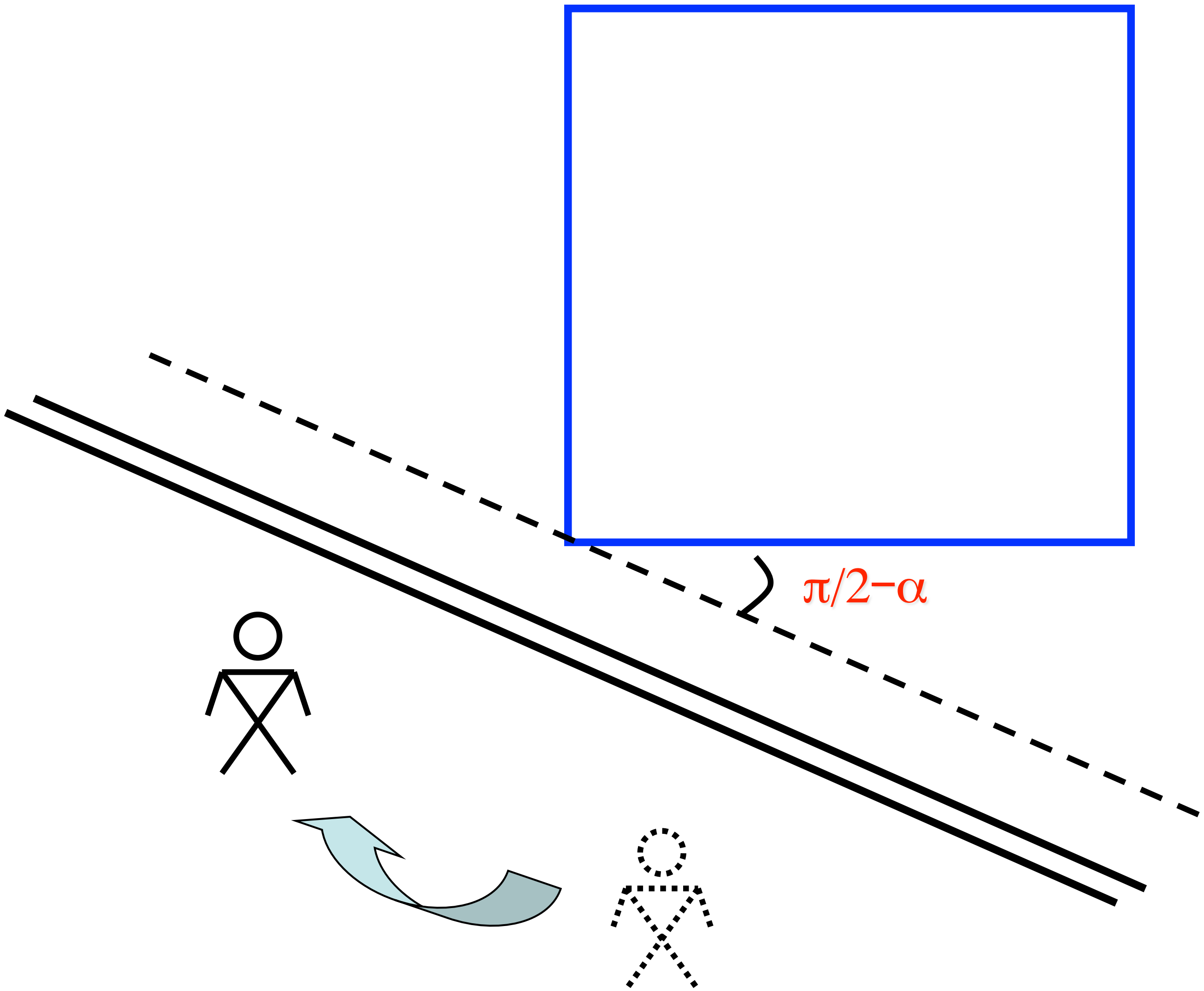
min: l' (for $\beta = 0$)

$$l'\cos\alpha = \beta l' \rightarrow \cos\alpha = \beta$$

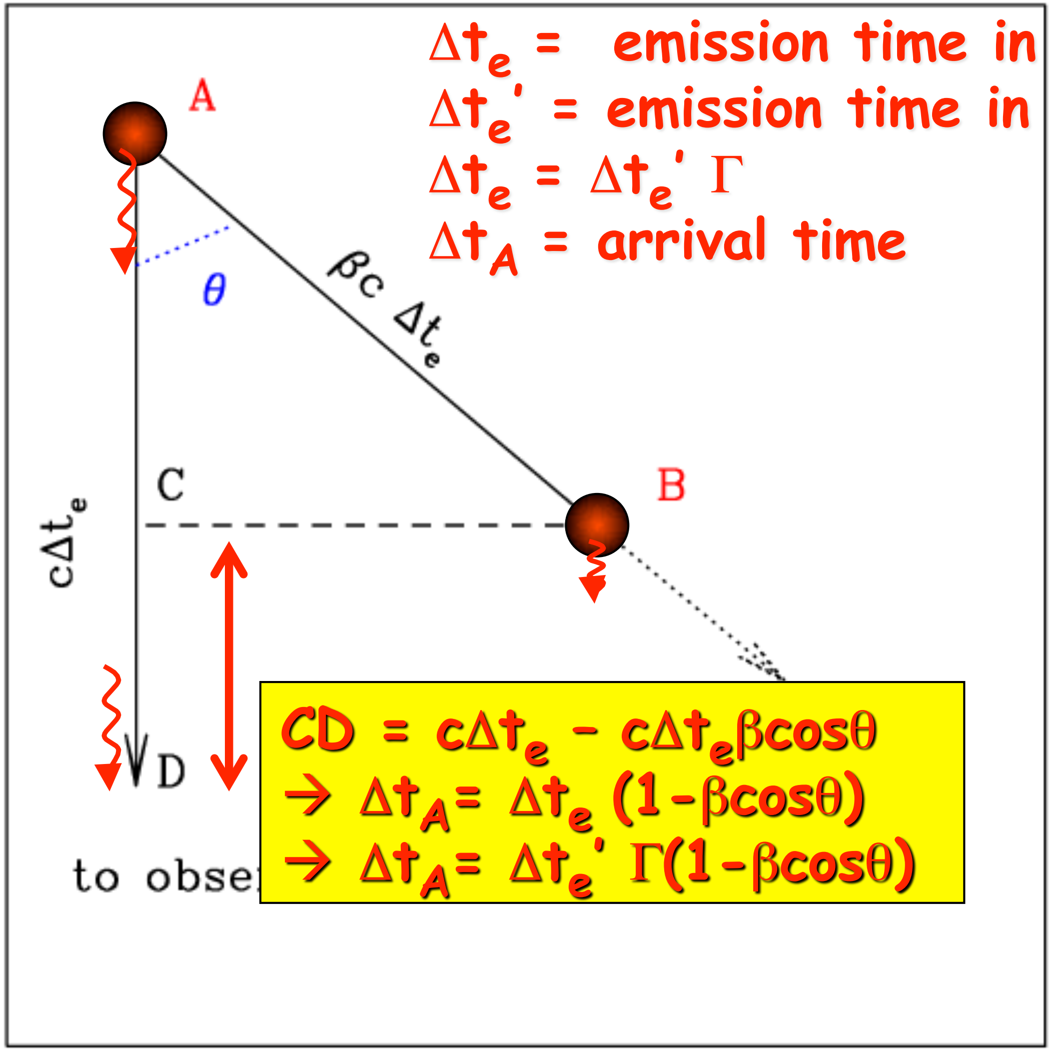
$$\cos(\pi - \pi/2 - \alpha) = \sin\alpha = 1/\Gamma$$




α
π/2−α


π/2−α

Time



Δt_e = emission time in lab frame

$\Delta t_e'$ = emission time in comov. frame

$\Delta t_e = \Delta t_e' \, \Gamma$

Δt_A = arrival time

$CD = c\Delta t_e - c\Delta t_e \beta\cos\theta$

$\rightarrow \Delta t_A = \Delta t_e \, (1-\beta\cos\theta)$

$\rightarrow \Delta t_A = \Delta t_e' \, \Gamma(1-\beta\cos\theta)$

Relativistic Doppler factor δ

$$\Delta t_A = \Delta t_e' \, \Gamma(1-\beta\cos\theta)$$

$$\nu = \nu' / \Gamma(1-\beta\cos\theta)$$

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

You change frame

Standard relativity

Doppler effect

You remain in lab frame

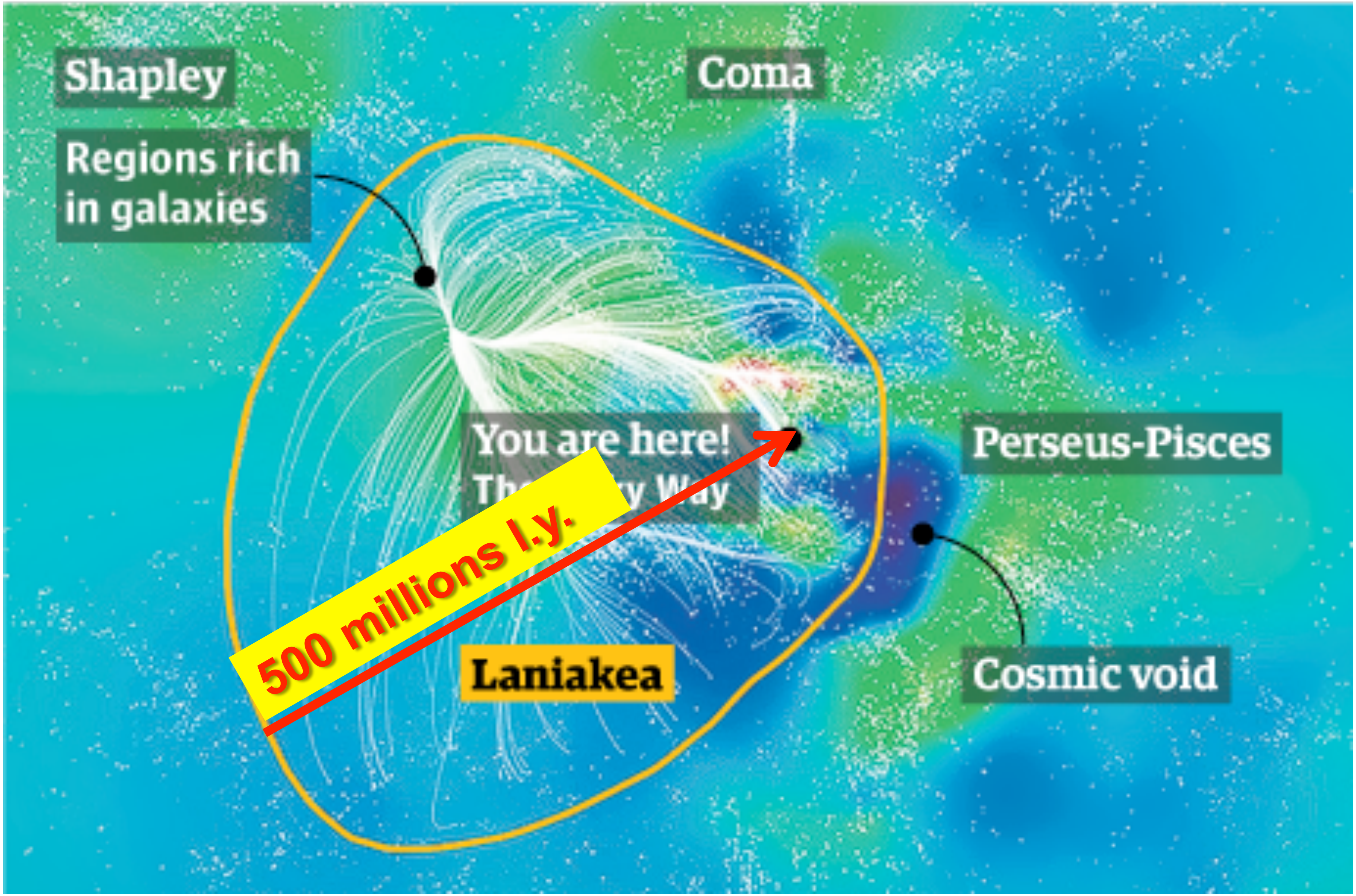
Relativistic Doppler factor δ

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)} = \begin{cases} 2\Gamma & \text{for } \theta=0^o \\ \Gamma & \text{for } \theta=1/\Gamma \\ 1/\Gamma & \text{for } \theta=90^o \end{cases}$$

At small angles, Doppler wins over Spec. Relat.

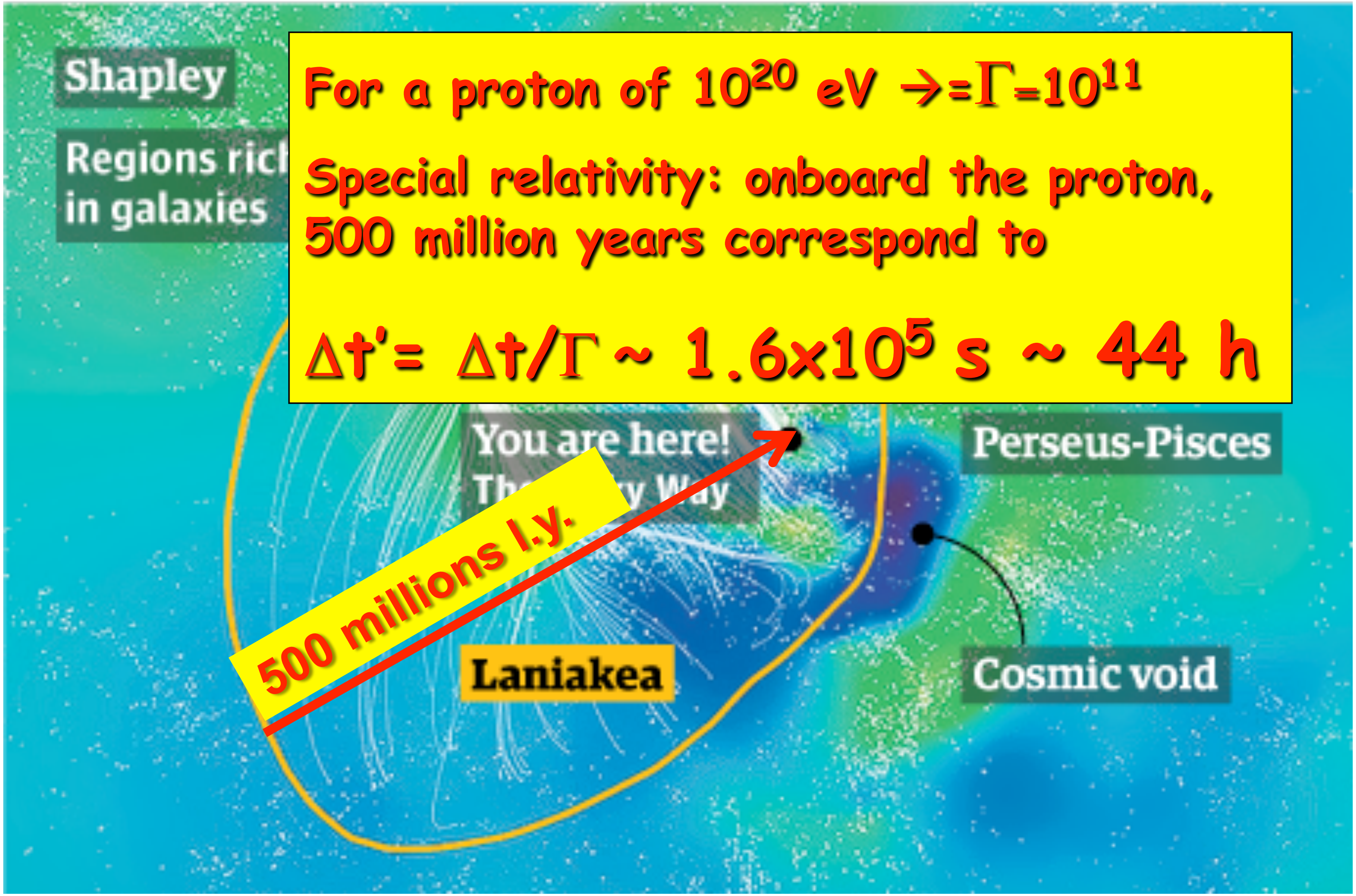
Our cosmic address

Earth, the Solar System, the Milky Way, Laniakea, the Universe



Our cosmic address

Earth, the Solar System, the Milky Way, Laniakea, the Universe

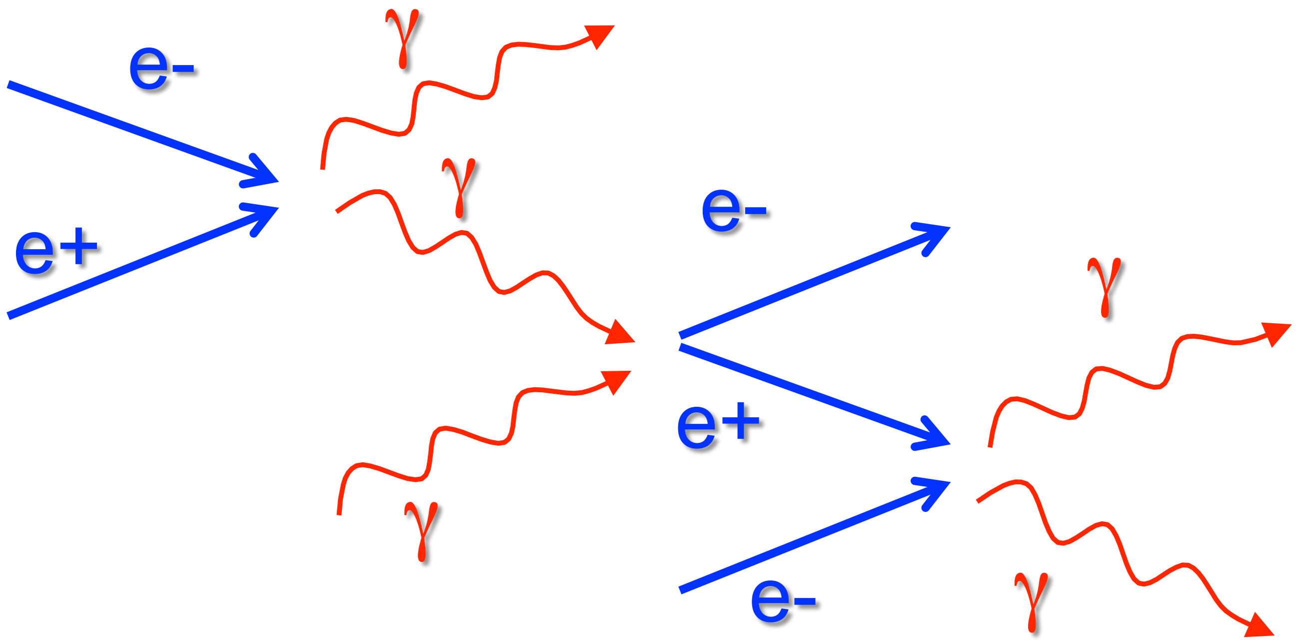


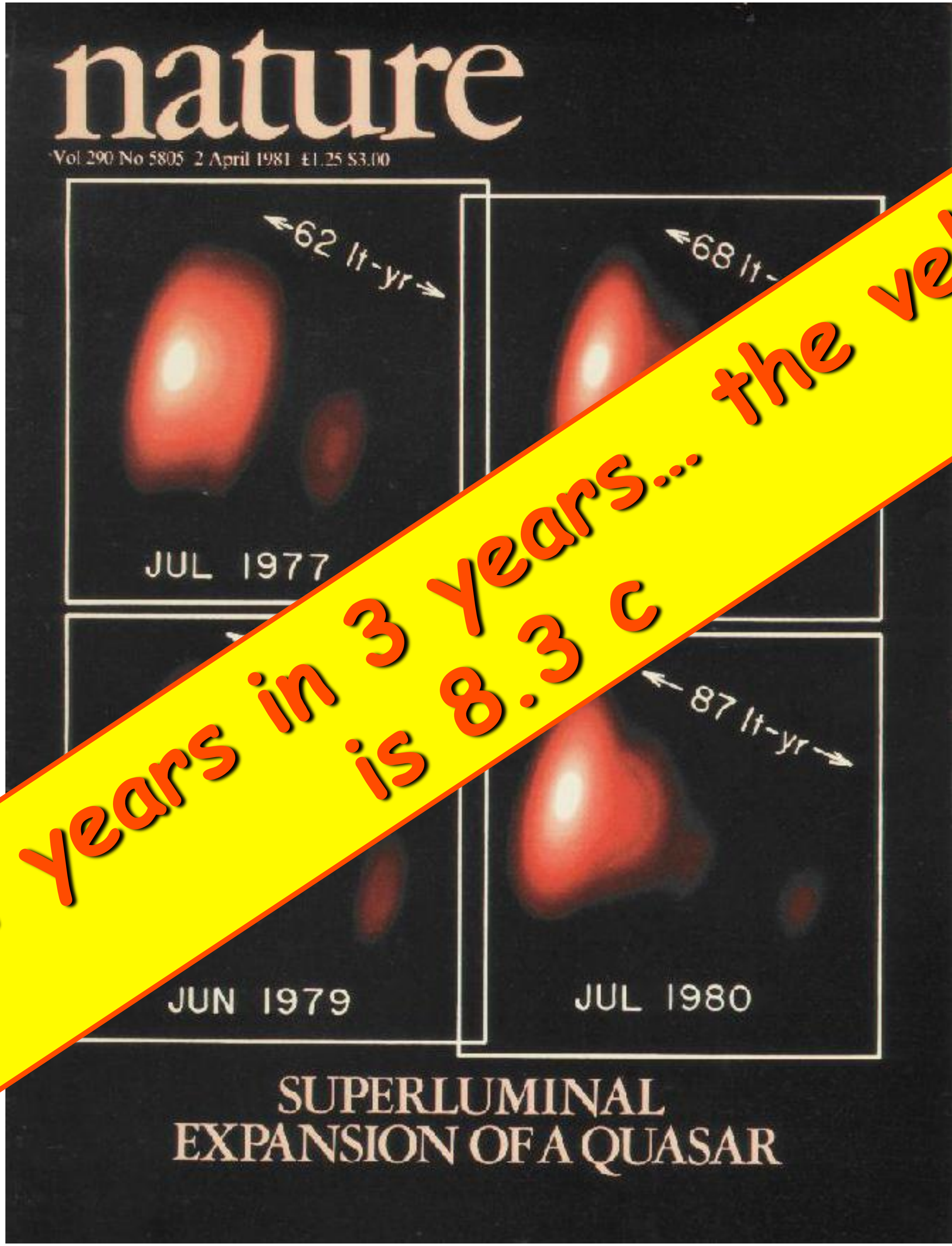
For a proton of 10^{20} eV $\rightarrow = \Gamma = 10^{11}$

Special relativity: onboard the proton, 500 million years correspond to

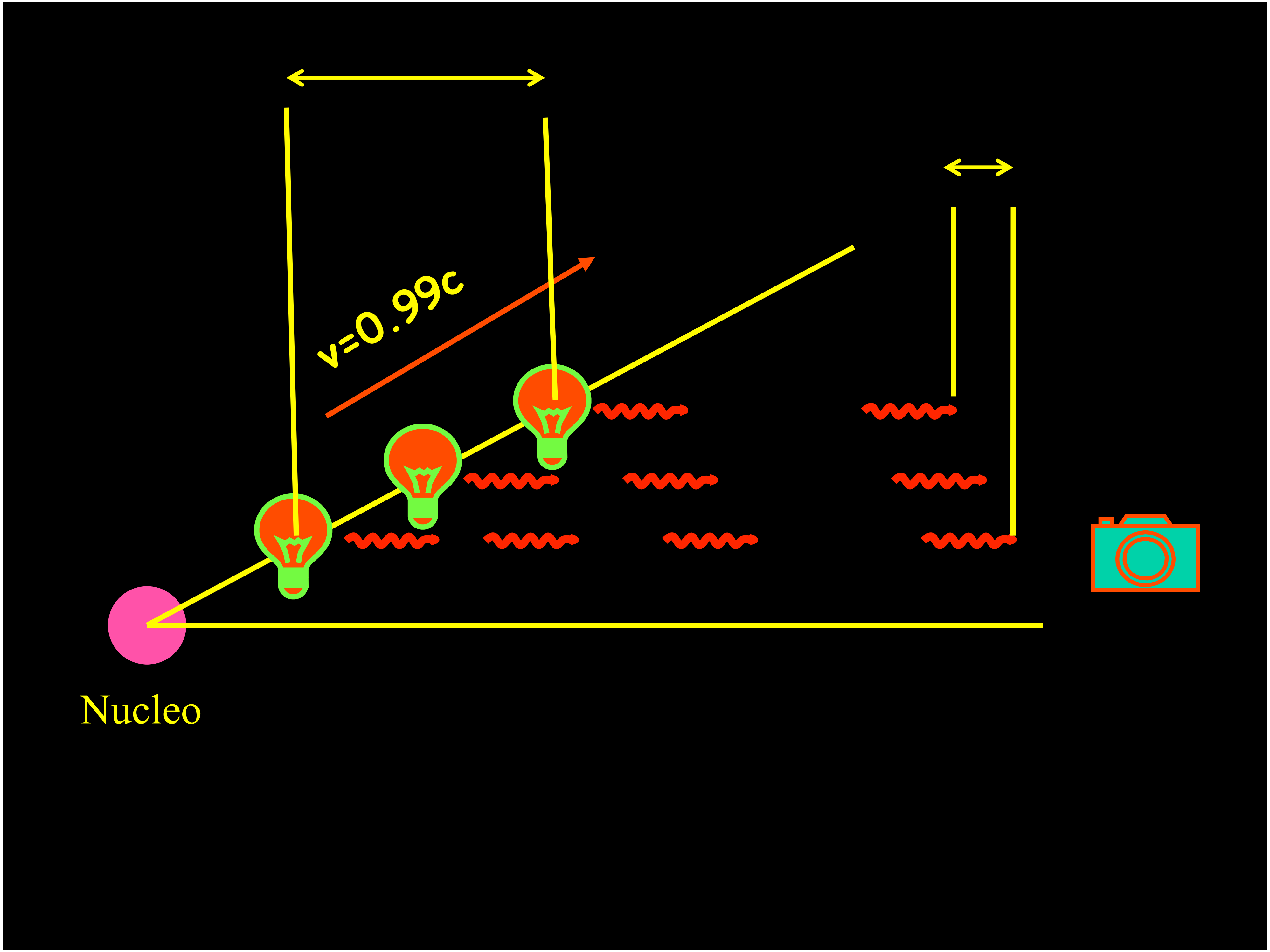
$$\Delta t' = \Delta t/\Gamma \sim 1.6 \times 10^{5}\ \text{s} \sim 44\ \text{h}$$

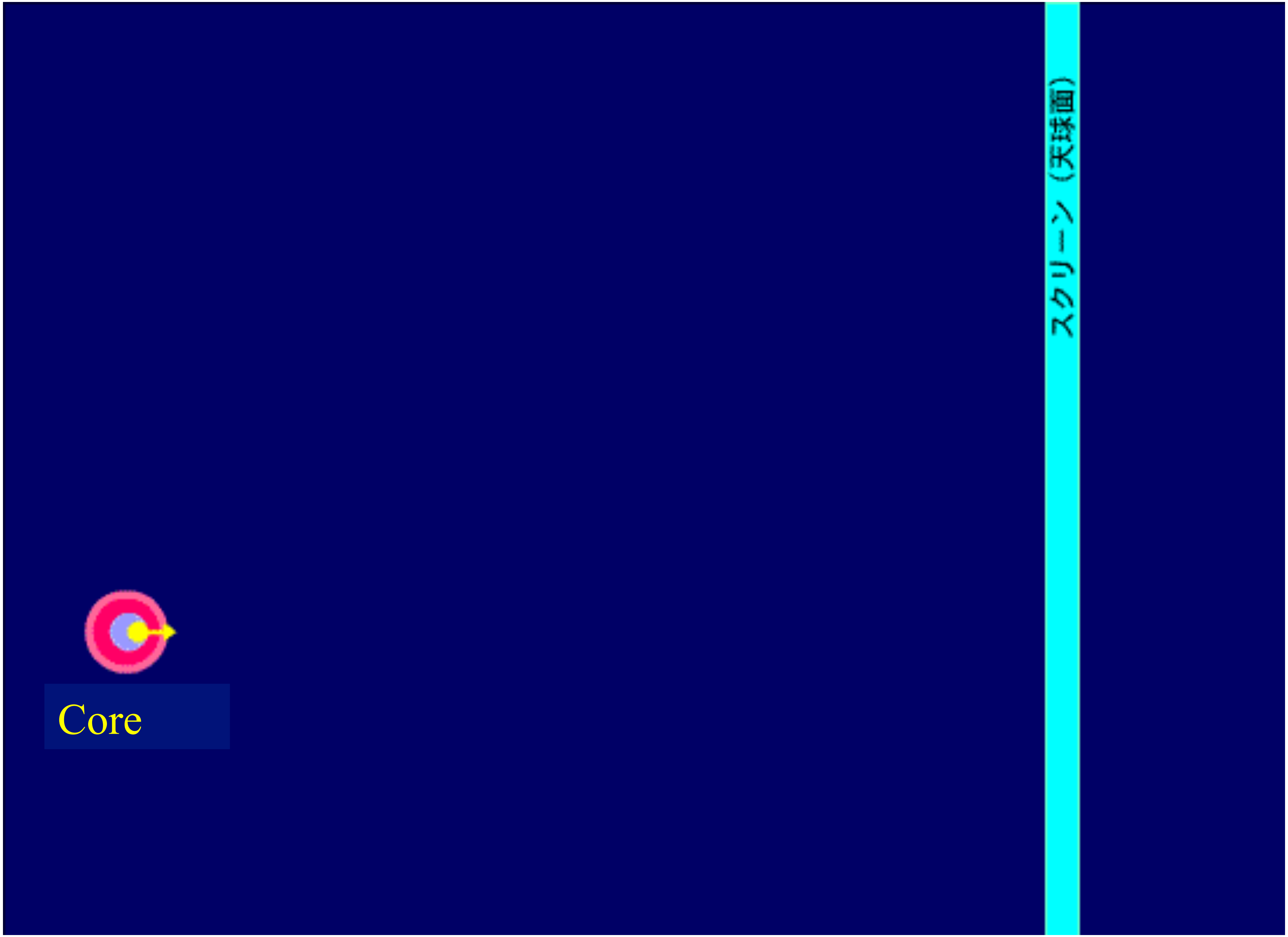
Time….





25 light years in 3 years… the velocity
is 8.3 c

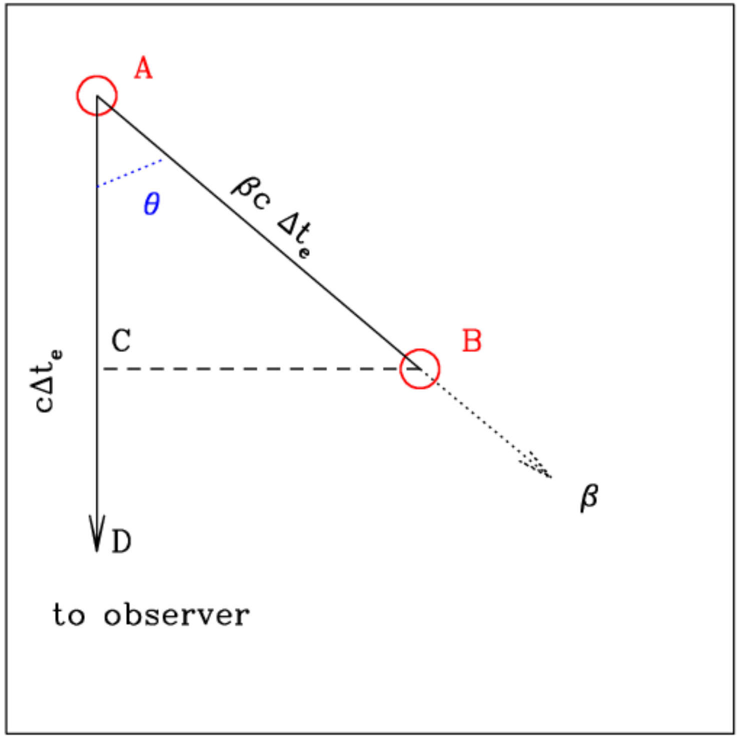

v=0.99c
Nucleo


スクリーン（天球面）
Core

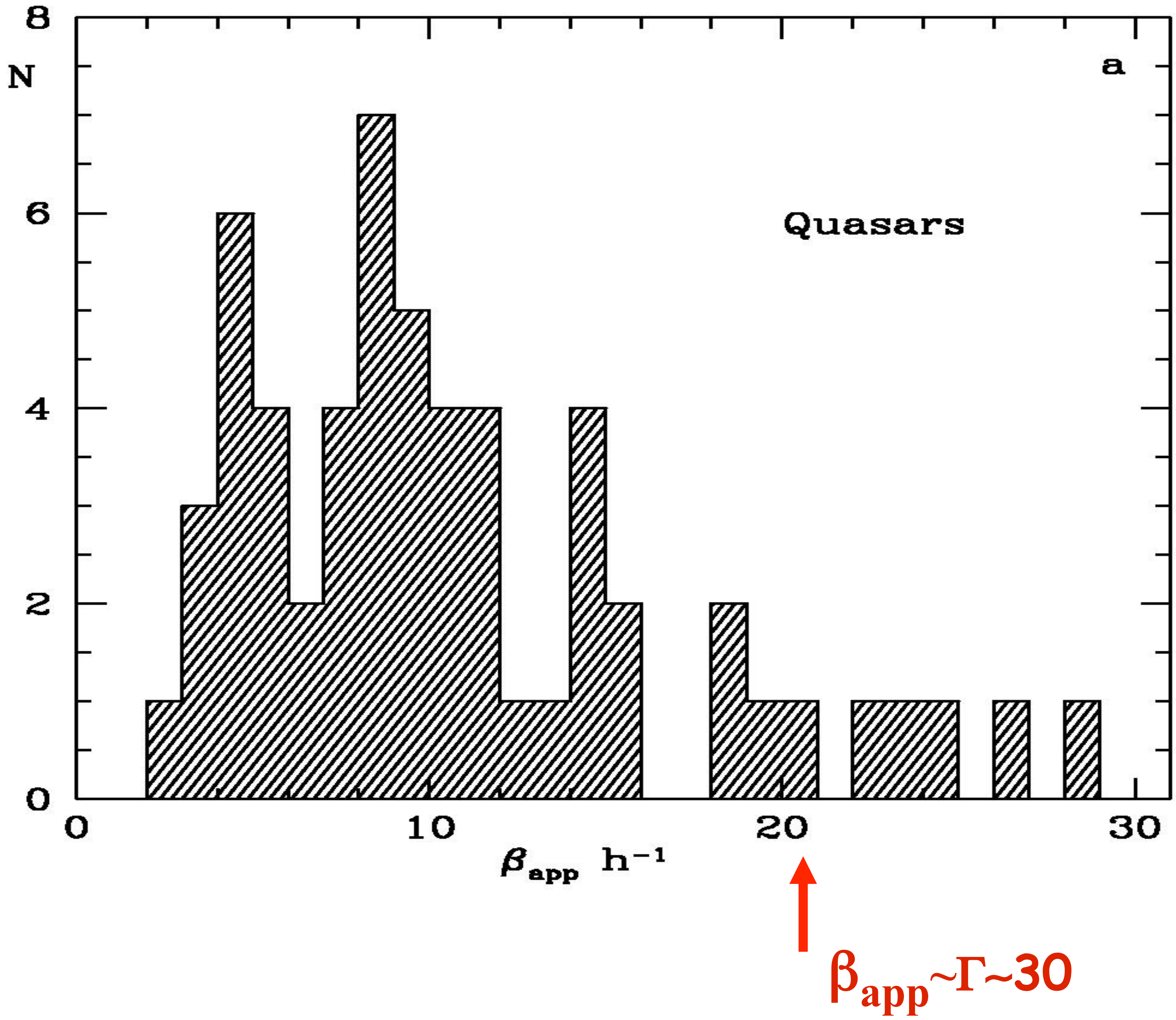
$$\frac{\Delta s_{app}}{\Delta t_A} = v_{app} = \frac{v\,\Delta t_e \sin\theta}{\Delta t_e\,(1-\beta\cos\theta)}$$

There is no Γ. Correct?

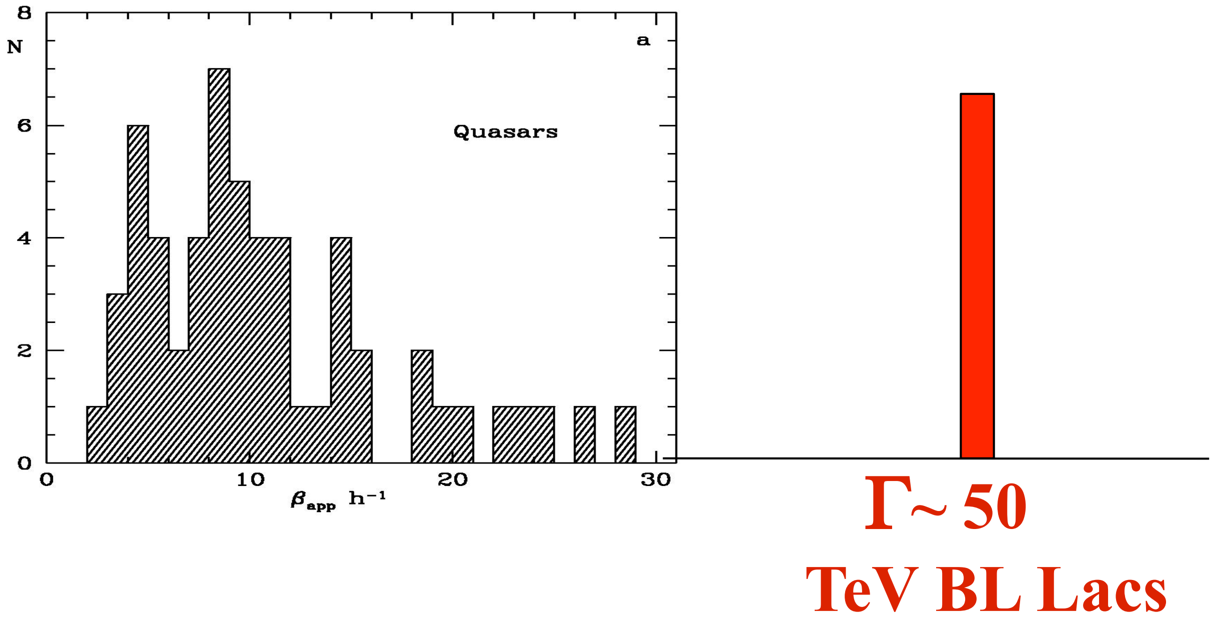
$$\beta_{app} = \frac{\beta \sin\theta}{1-\beta\cos\theta}$$

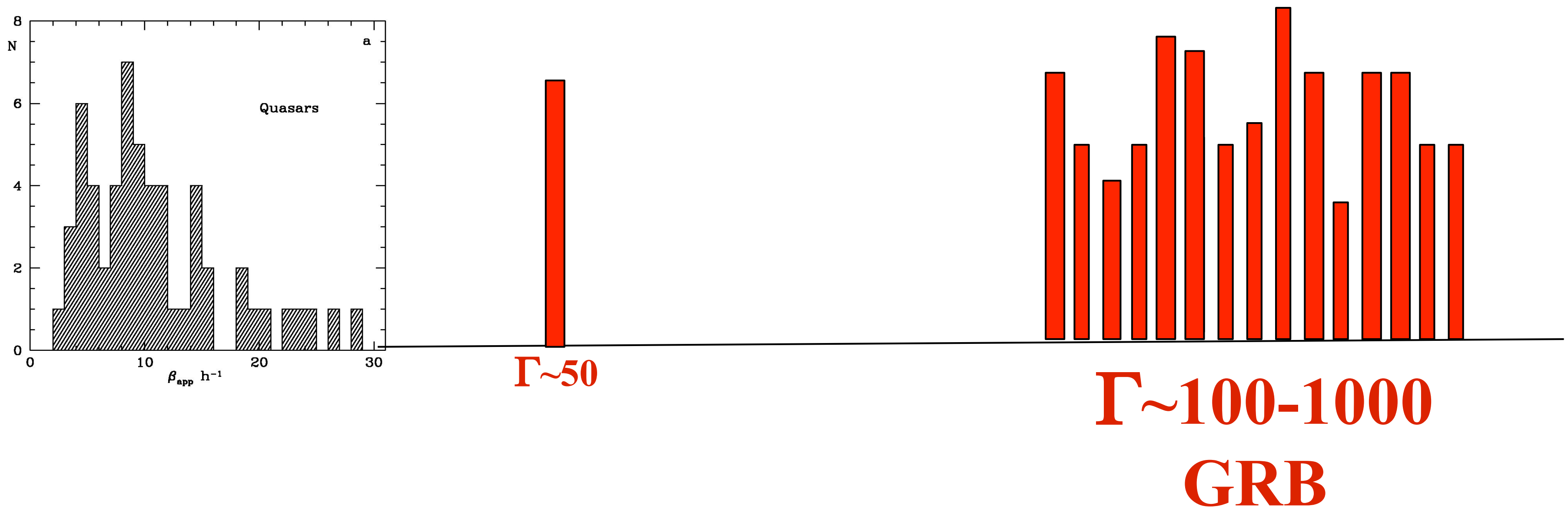


Γ



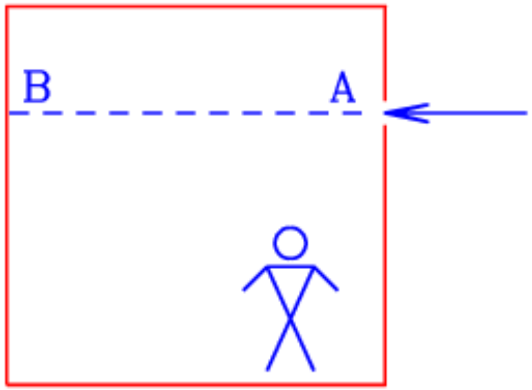
N
a
Quasars
8
6
4
2
0
0
10
20
30
β_{app} h^{-1}
β_{app}~Γ~30

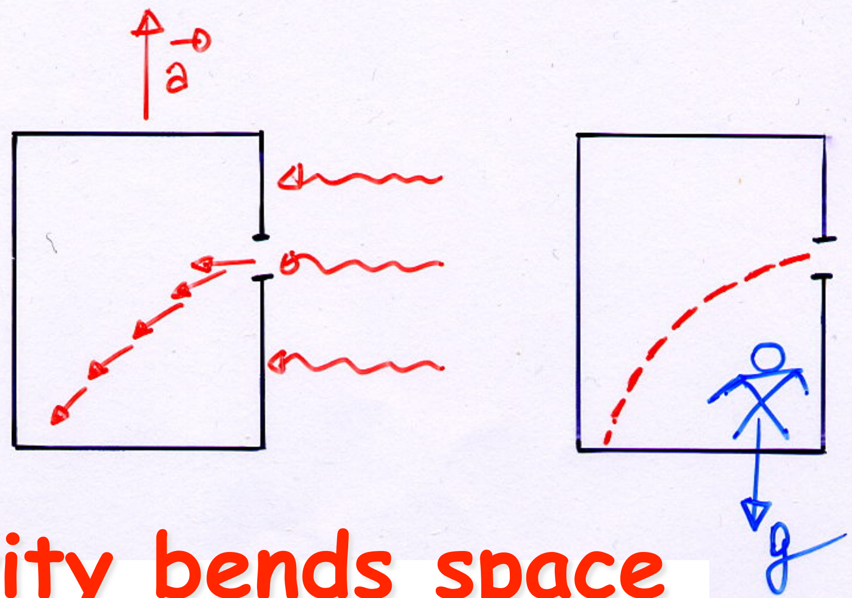

8
N
a
6
Quasars
4
2
0
0
10
20
30
β_{app} h^{-1}
Γ~ 50
TeV BL Lacs



8
N
6
4
2
0
a
Quasars
0
10
20
30
β_{app} h^{-1}
Γ~50
Γ~100-1000
GRB

Aberration of light



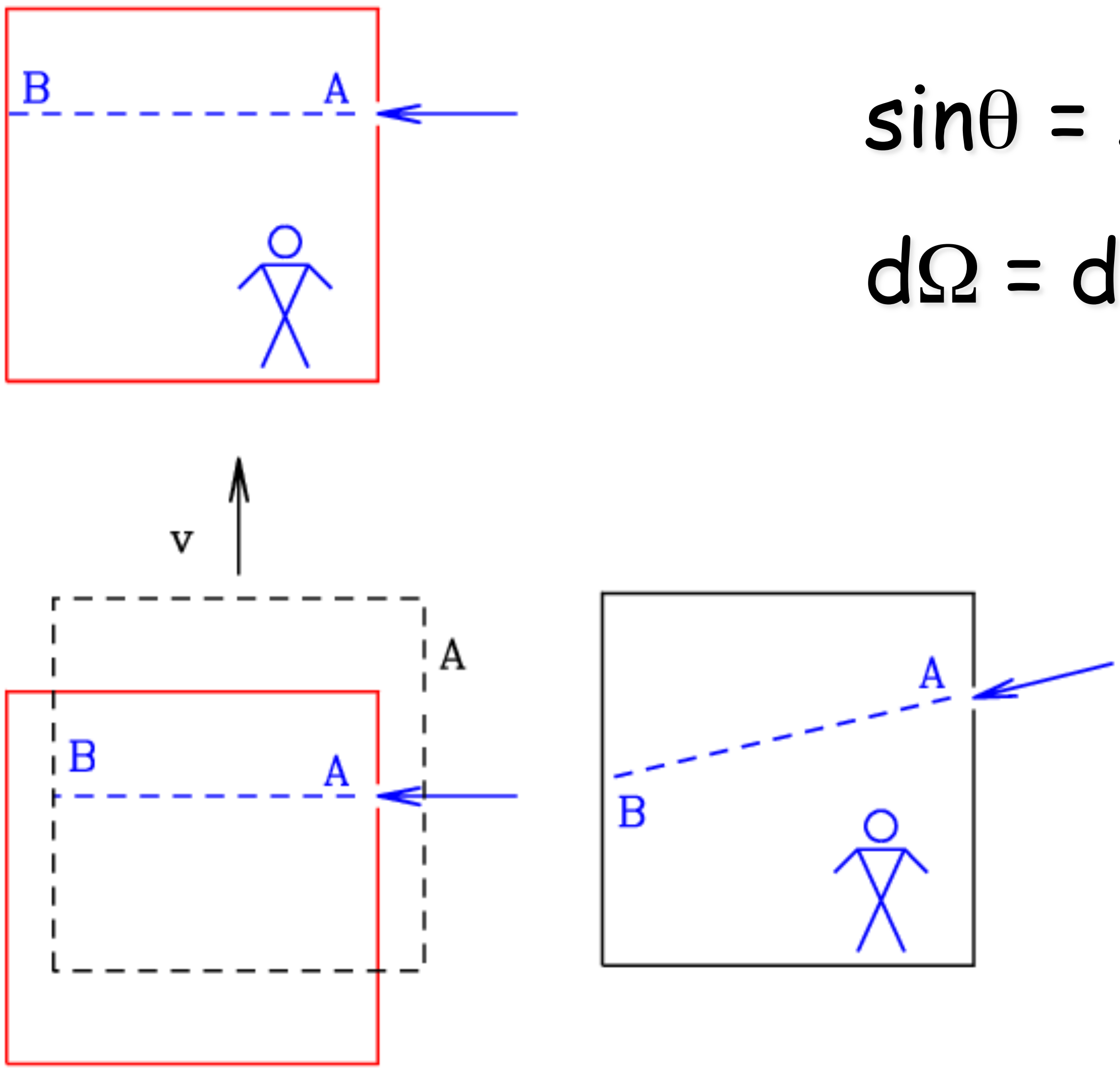


Gravity bends space

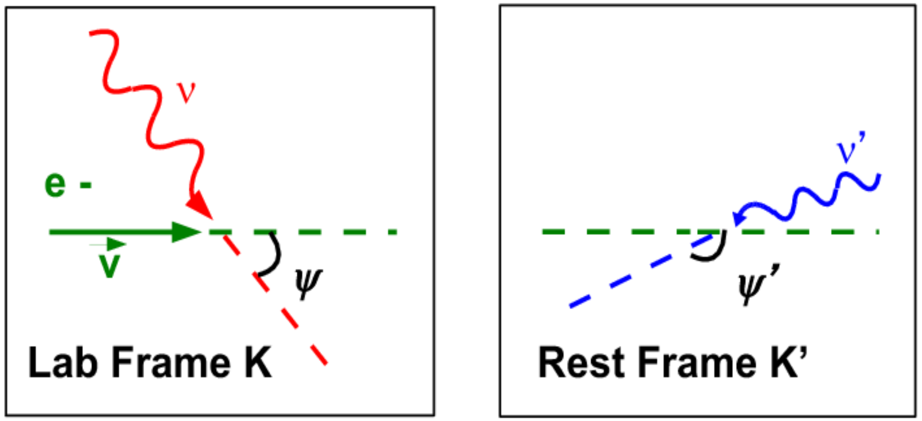
Aberration of light

$$\sin\theta = \sin\theta'/\delta$$

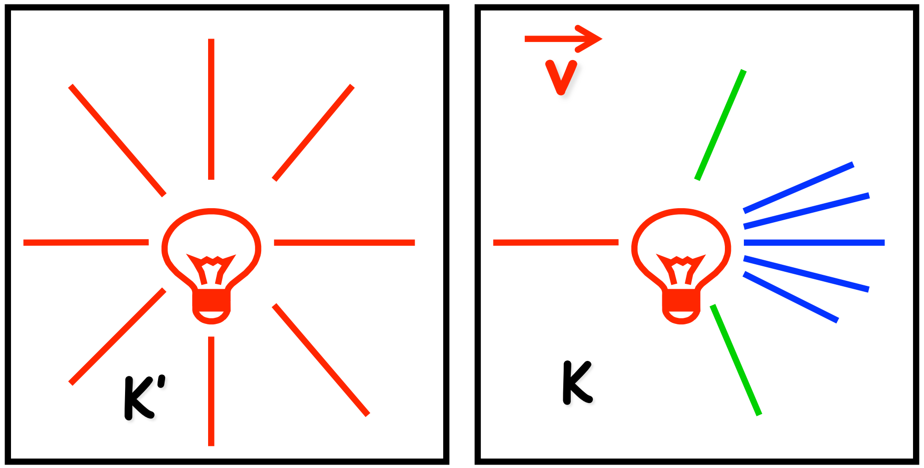
$$d\Omega = d\Omega'/\delta^2$$



Aberration of light



$$\sin\theta = \sin\theta'/\delta$$



$$d\Omega = d\Omega'/\delta^2$$

1

Observed vs intrinsic Intensity

$$\frac{I(\nu)}{\nu^3} = \frac{I'(\nu')}{\nu'^3} = \text{invariant} \Rightarrow I(\nu) = \delta^3 I'(\nu')$$

$$I(\nu) = \frac{\text{erg}}{\text{cm}^2\ \text{s Hz sterad}} = \frac{E}{dA\ dt\ d\nu\ d\Omega}$$

Observed vs intrinsic Intensity

$$\frac{I(\nu)}{\nu^3} = \frac{I'(\nu')}{\nu'^3} = \text{invariant} \Rightarrow I(\nu) = \delta^3 I'(\nu')$$

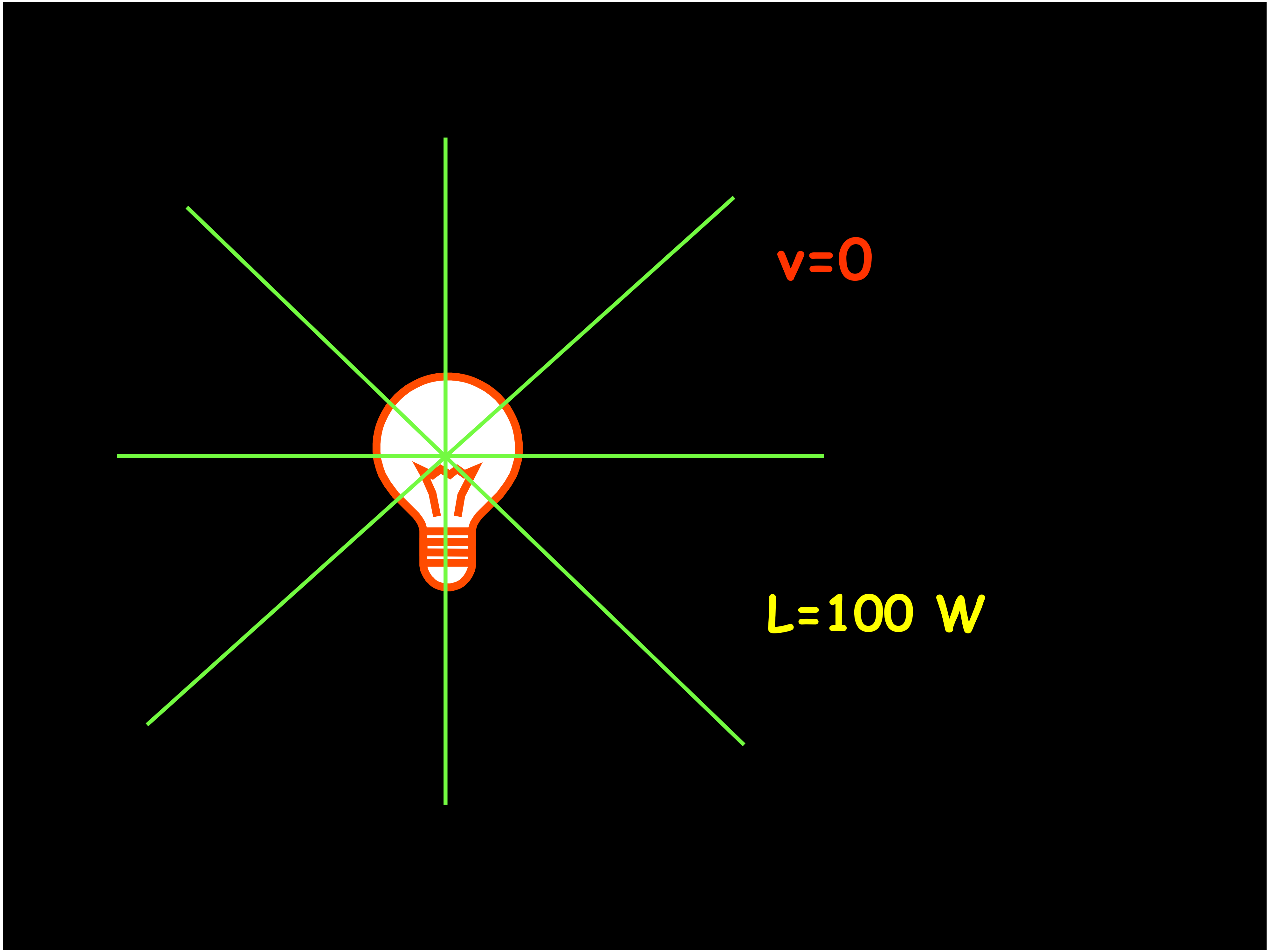
$$I(\nu) = \frac{\text{erg}}{\text{cm}^2 \text{ s Hz sterad}} = \frac{E}{dA\, dt\, d\nu\, d\Omega}$$

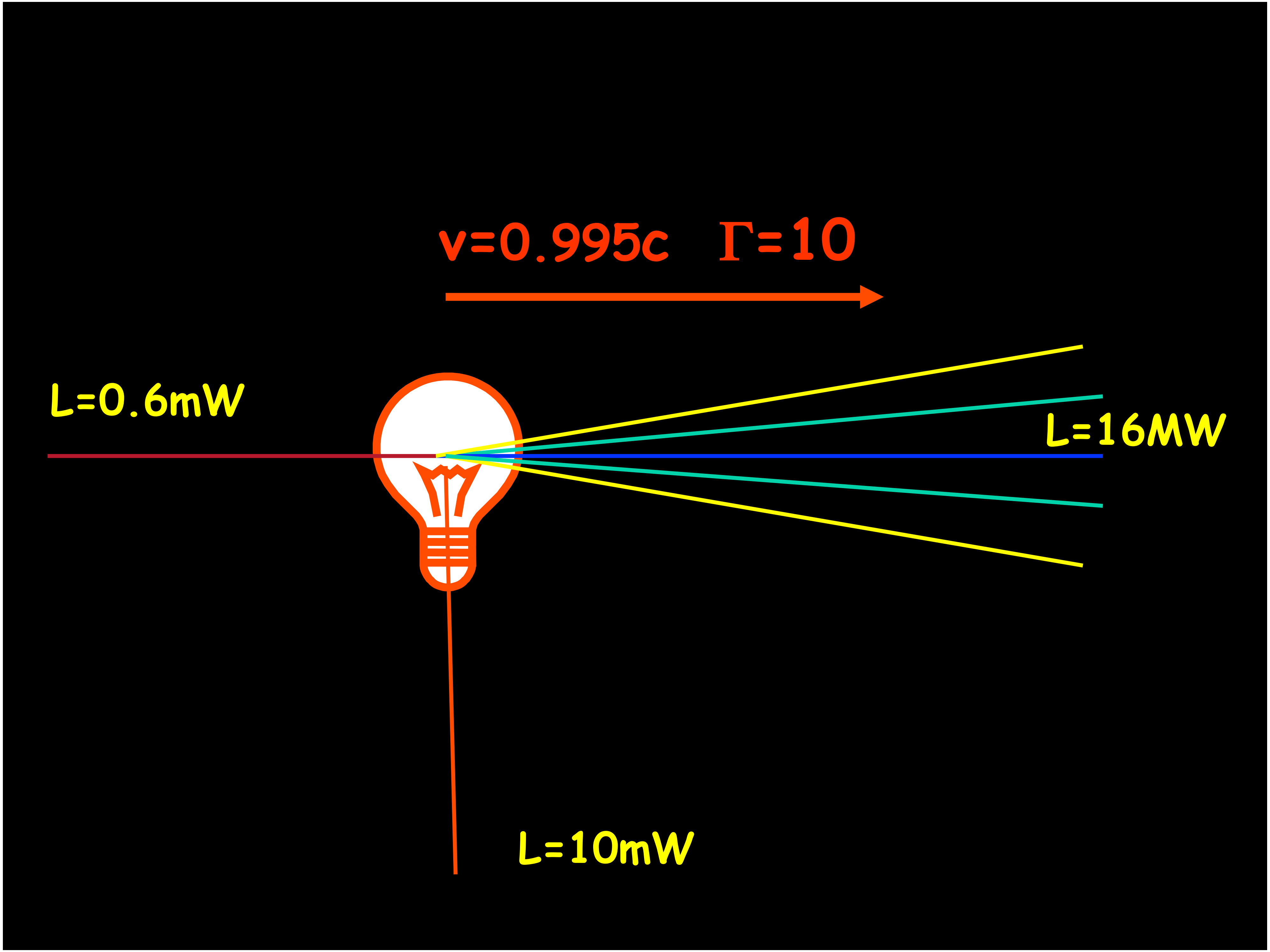
Observed vs intrinsic Intensity

$$\frac{I(\nu)}{\nu^3} = \frac{I'(\nu')}{\nu'^3} = \text{invariant} \rightarrow I(\nu) = \delta^3 I'(\nu')$$

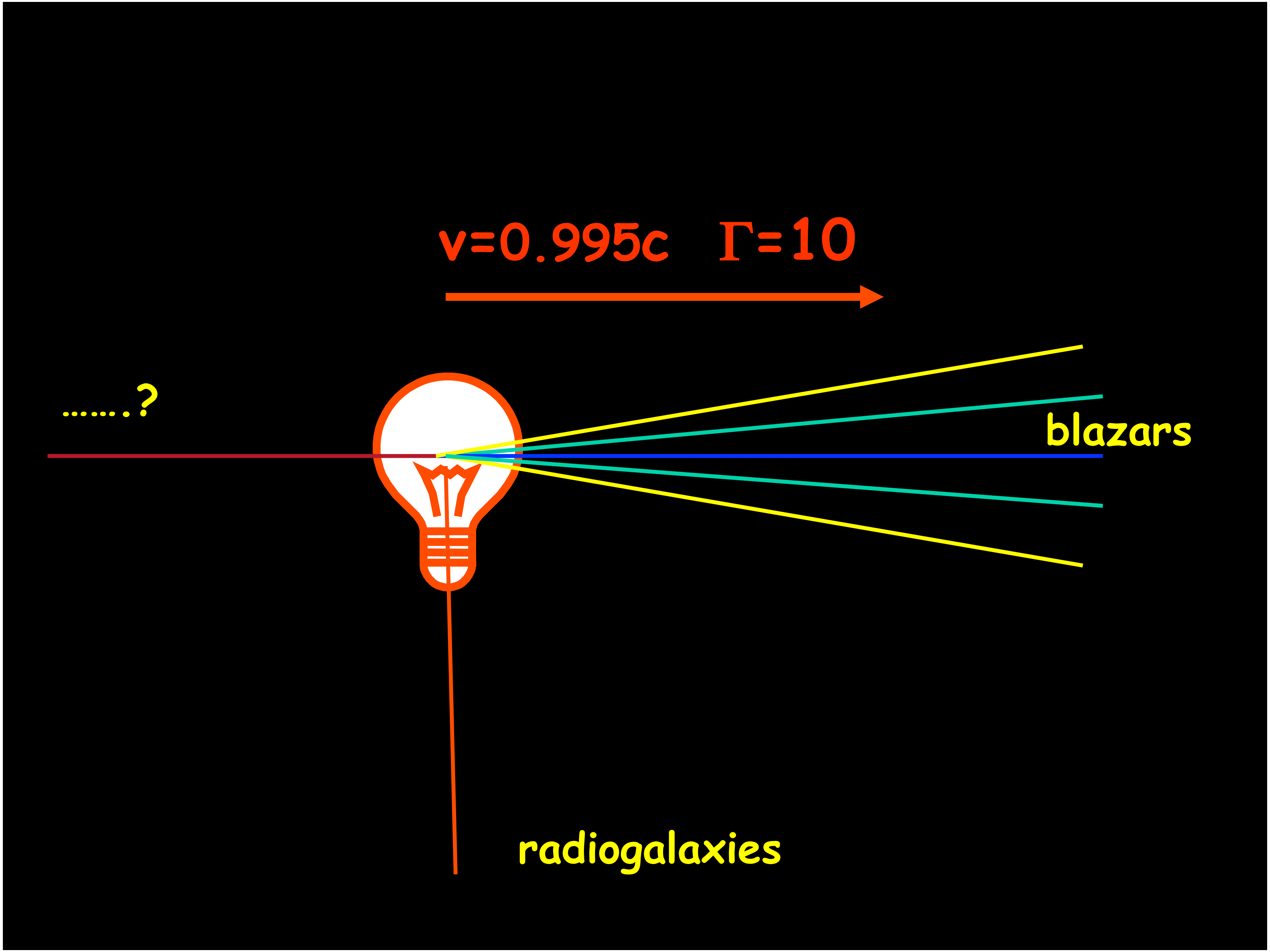
$$I(\nu) = \frac{\text{erg}}{\text{cm}^2\ \text{s Hz sterad}} = \frac{E'\delta}{dA'\ d\Omega'/\delta^2} = \delta^3 I'(\nu')$$

$$\rightarrow \boxed{I = \delta^4 I'} \rightarrow \boxed{F = \delta^4 F'}$$

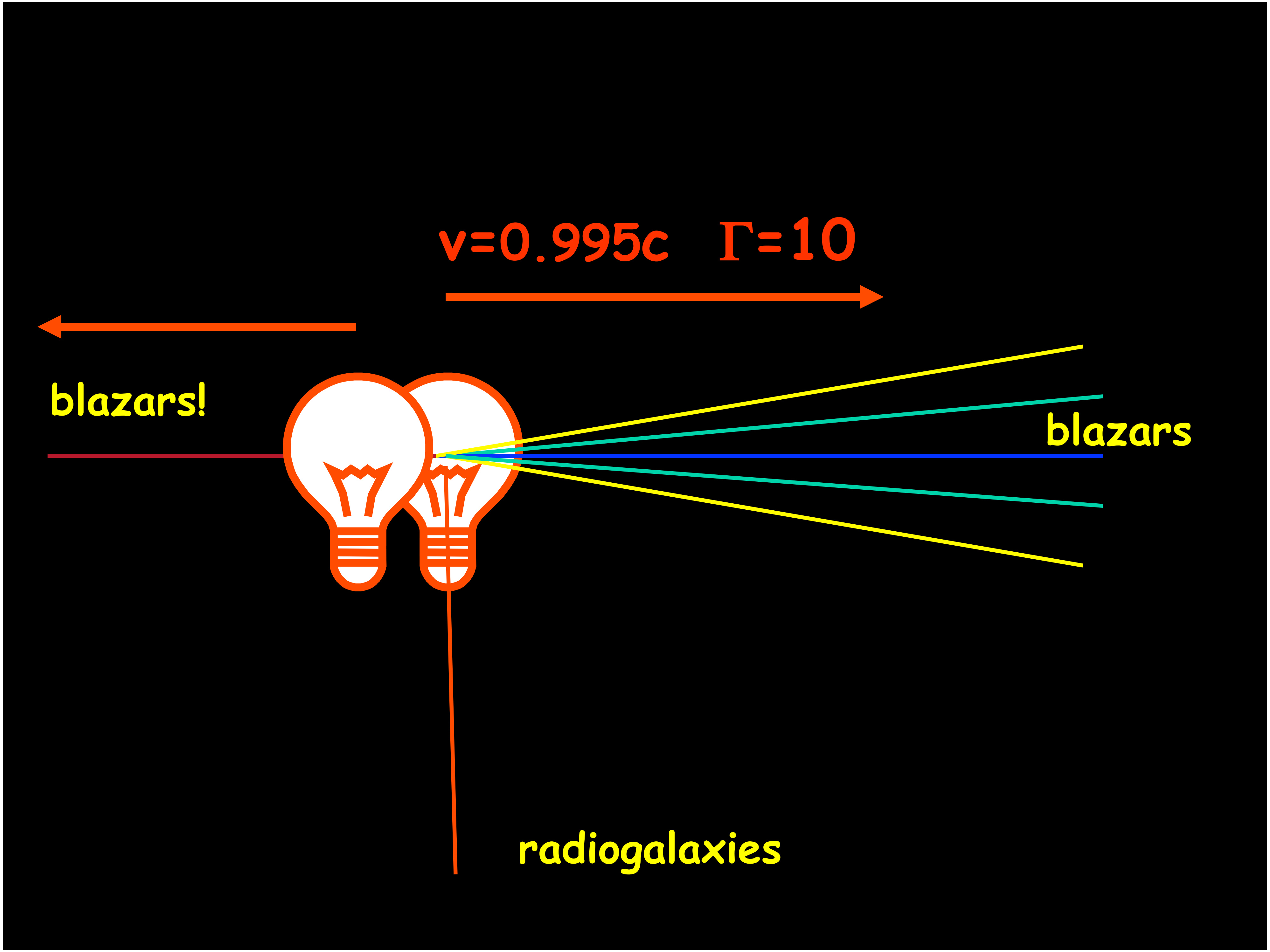

v=0
L=100 W

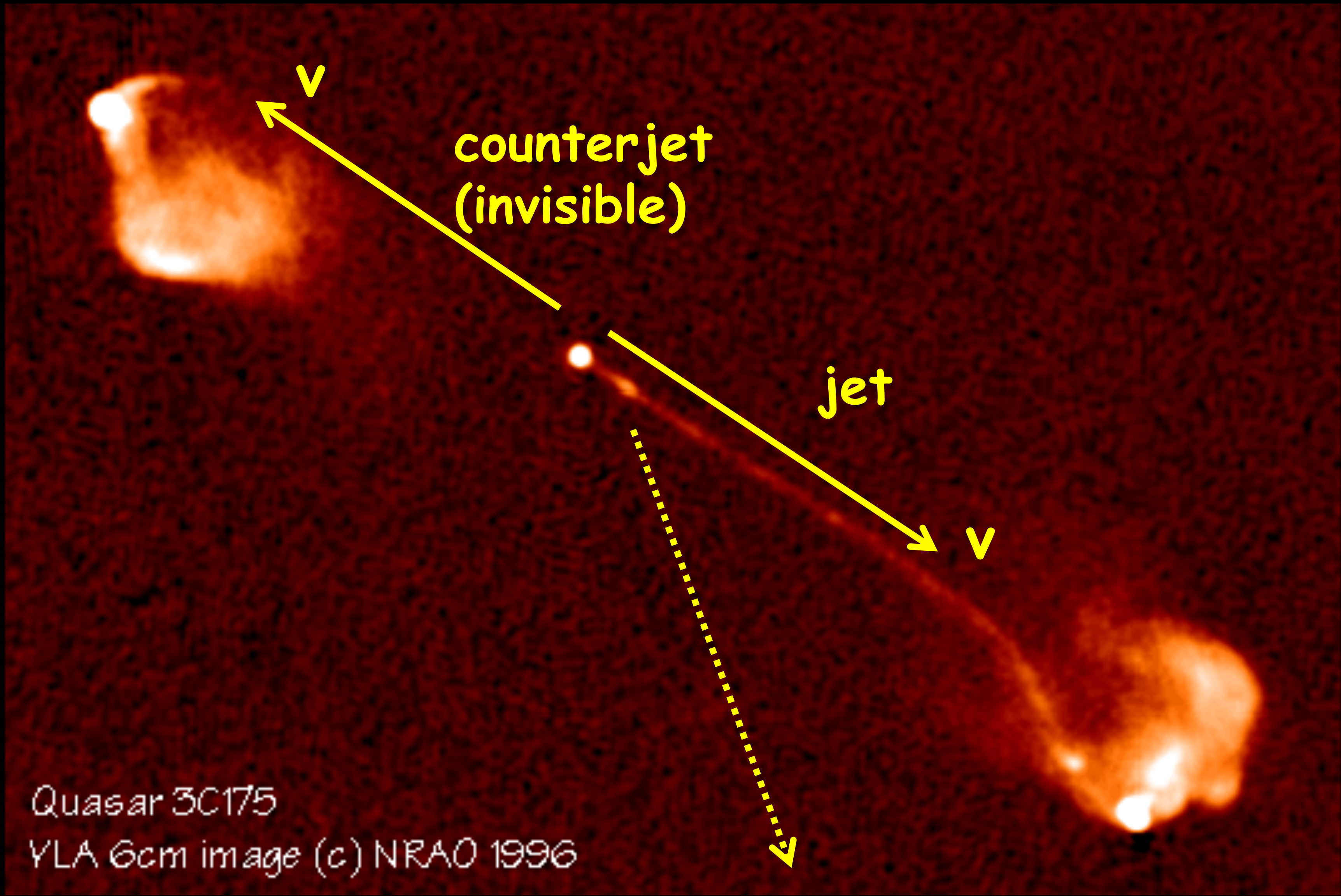


v=0.995c Γ=10
L=0.6mW
L=16MW
L=10mW

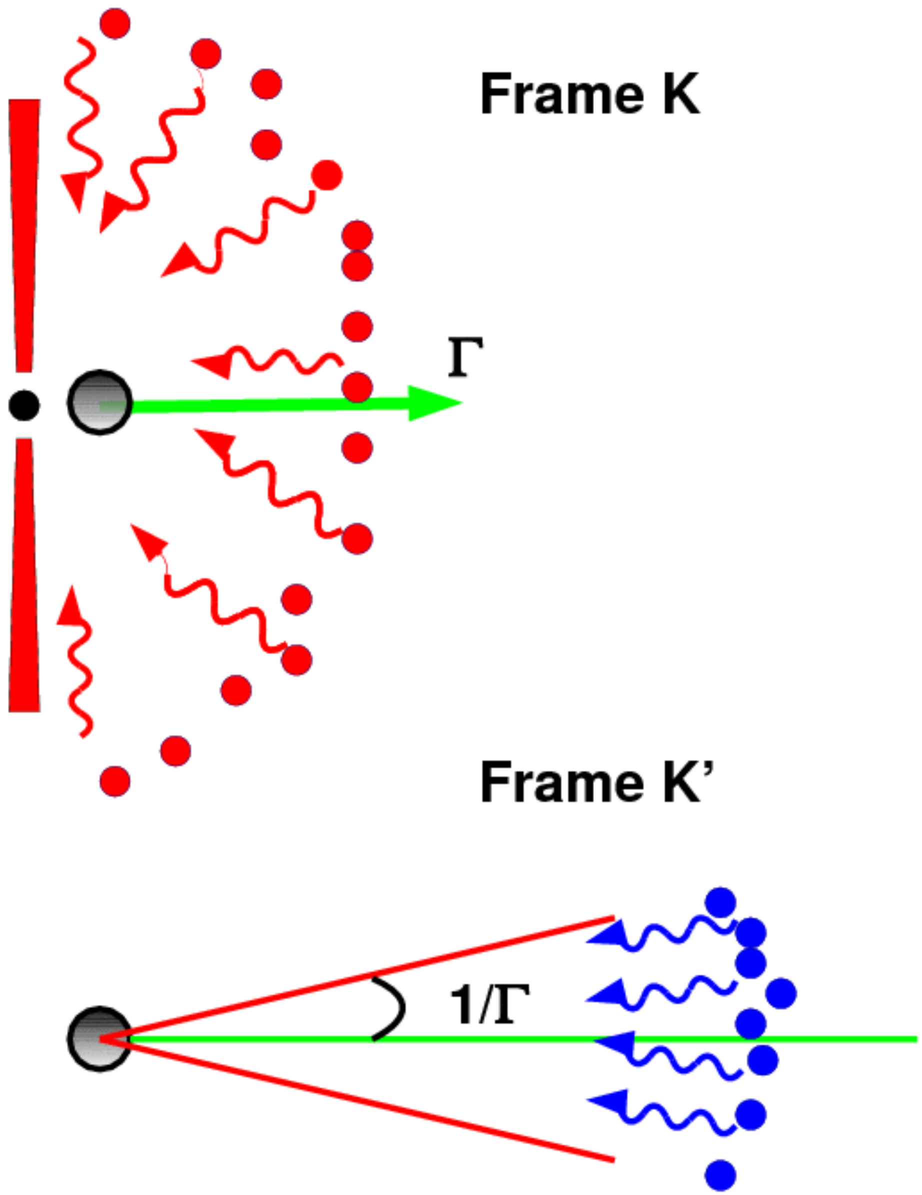


v=0.995c Γ=10
……?
blazars
radiogalaxies


v=0.995c Γ=10
blazars!
blazars
radiogalaxies


v
counterjet
(invisible)
jet
v
Quasar 3C175
YLA 6cm image (c) NRAO 1996

Moving (fast) in a radiation field



$$U_{rad}$$

$$U'_{rad} \sim \Gamma^2 \, U_{rad}$$

- Special relativity with rulers
- Special relativity with photons
- Rotation, not contraction
- Beaming factor
- Superluminal motion

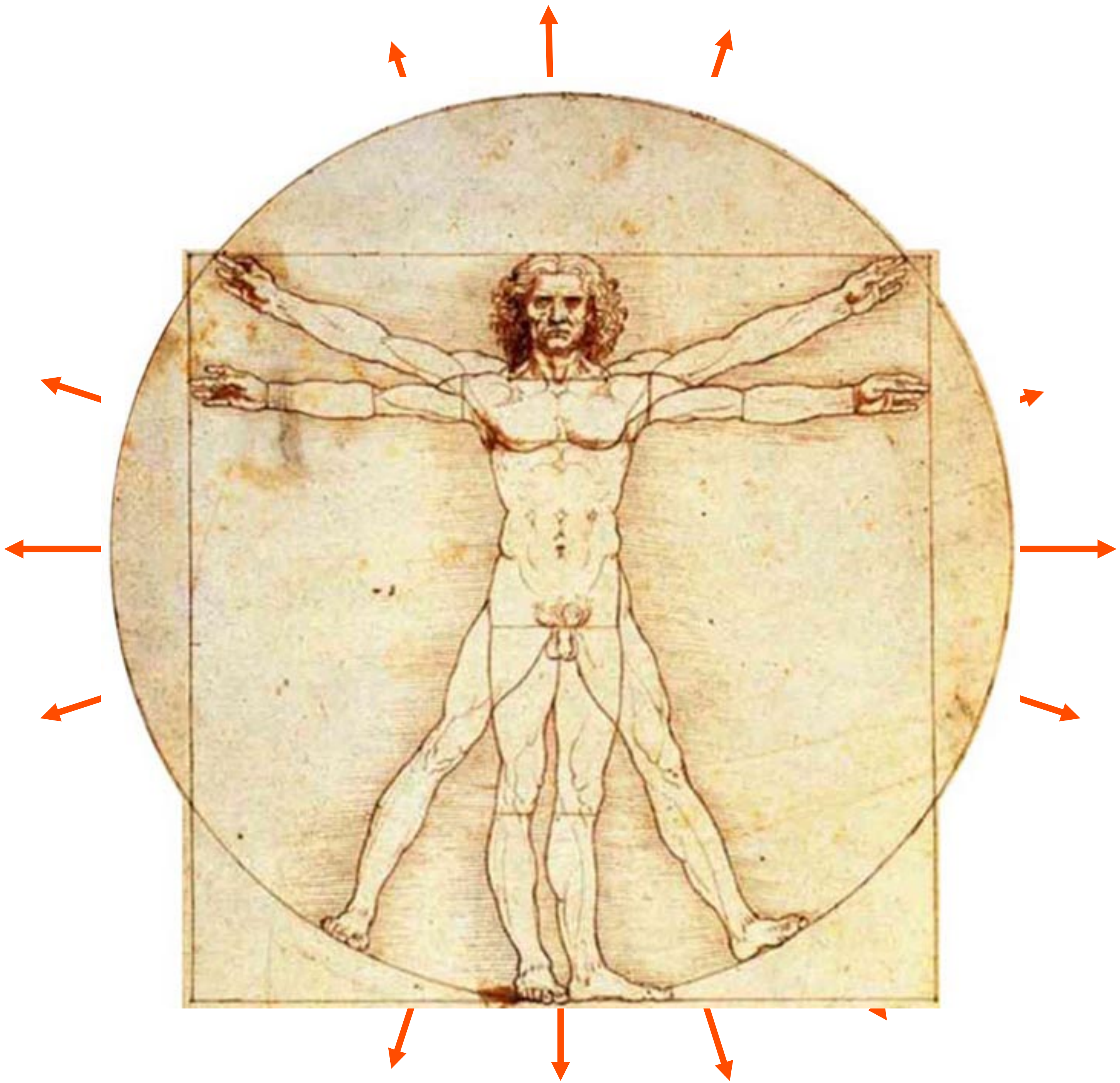
Radiation processes

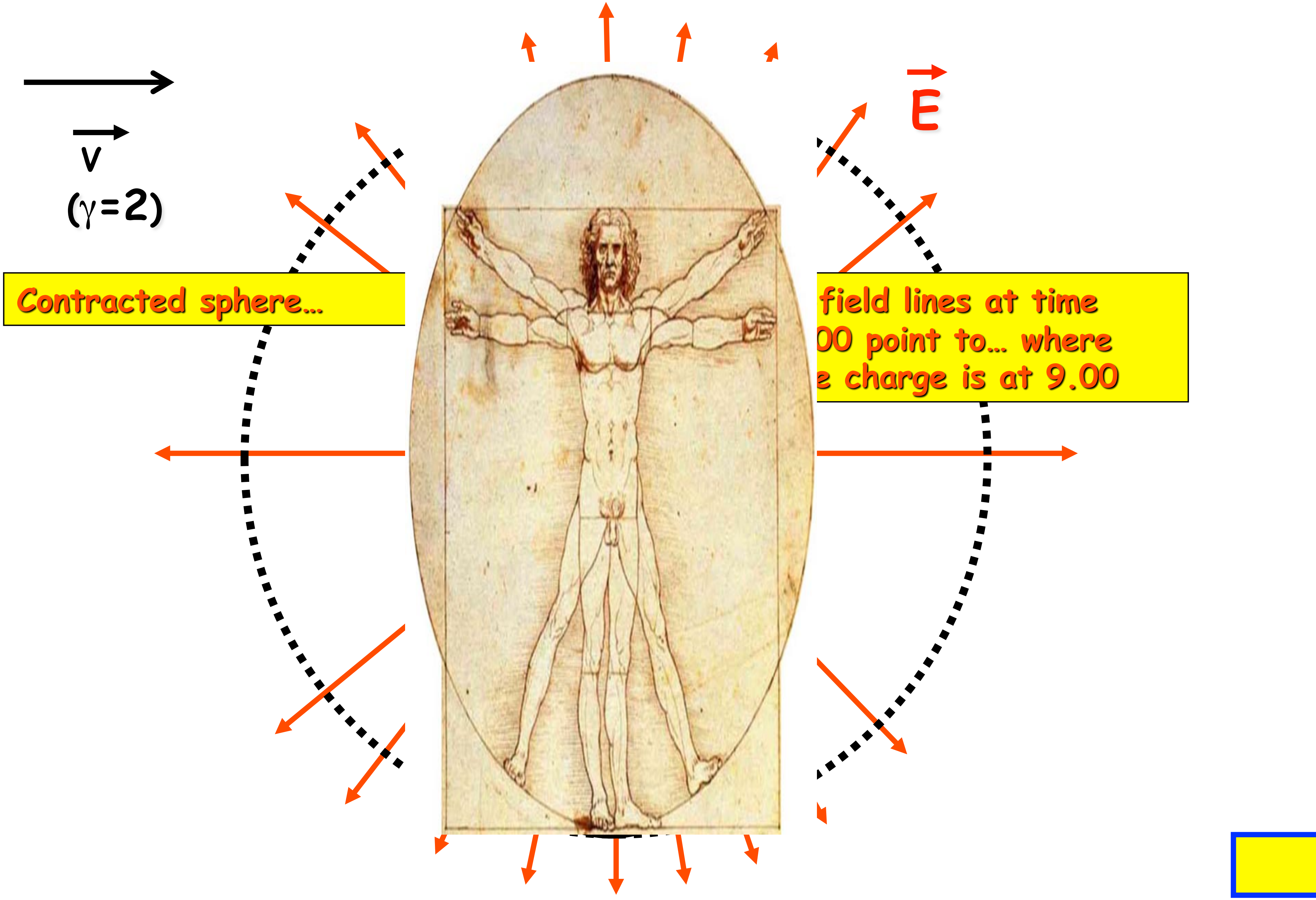
Radiation processes

Radiation processes

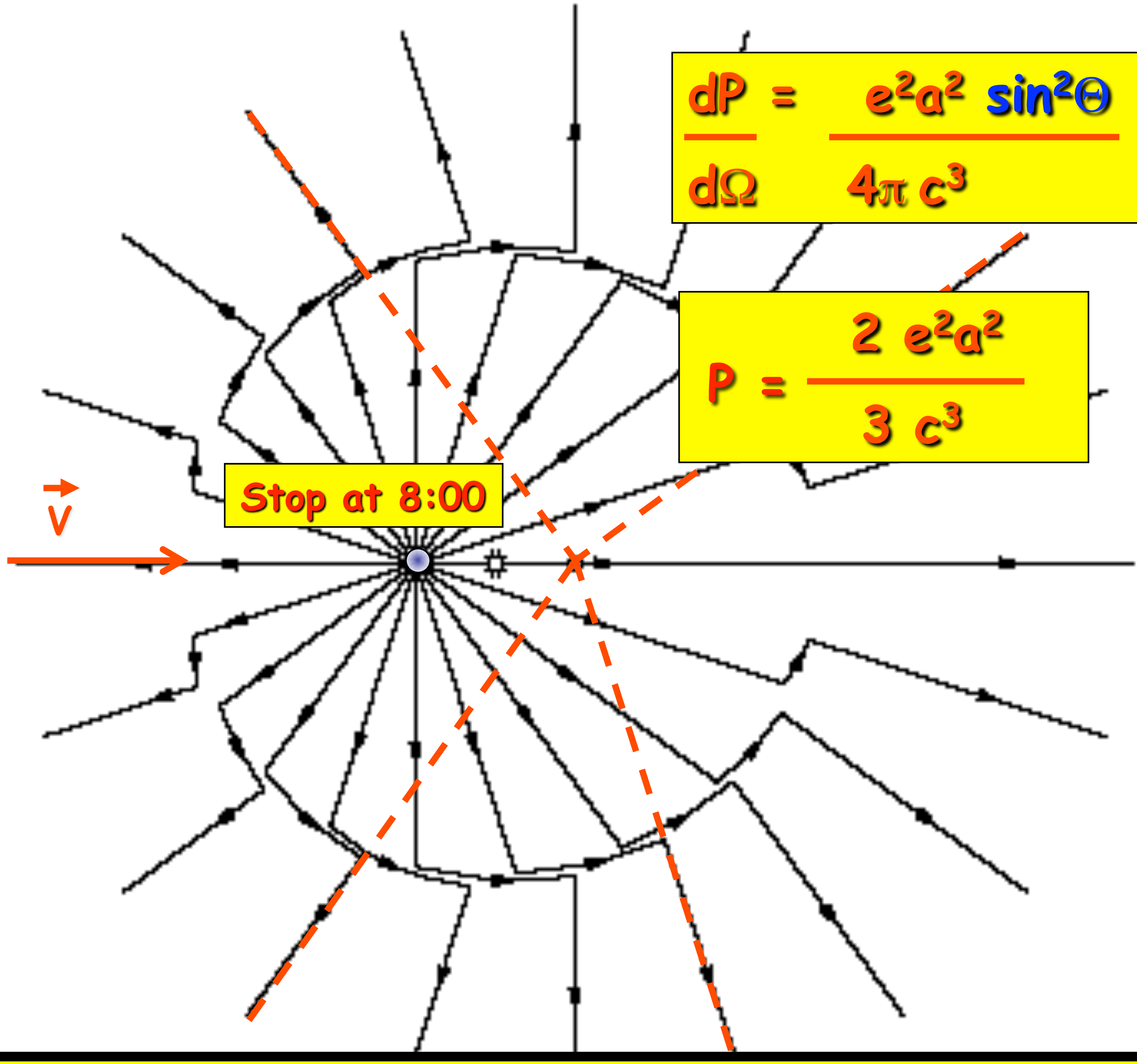
- Line emission and radiative transitions in atoms and molecules
- Breemstrahlung/Blackbody
- Curvature radiation
- Cherenkov
- Annihilation
- Unruh radiation
- Hawking radiation
- Synchrotron
- Inverse Compton

$\vec{V}=0$





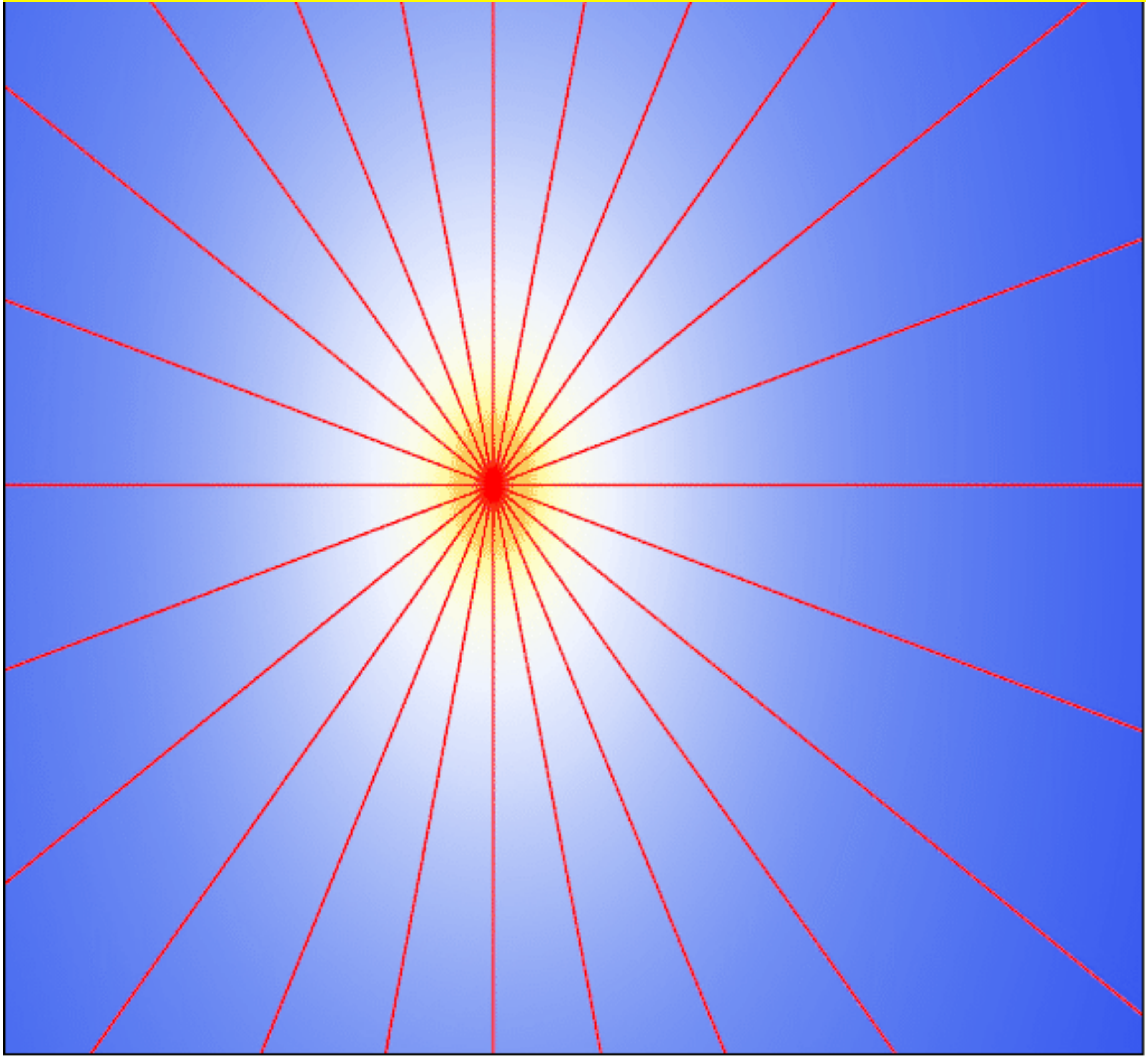
v
(γ=2)
E
Contracted sphere…
field lines at time
00 point to… where
e charge is at 9.00



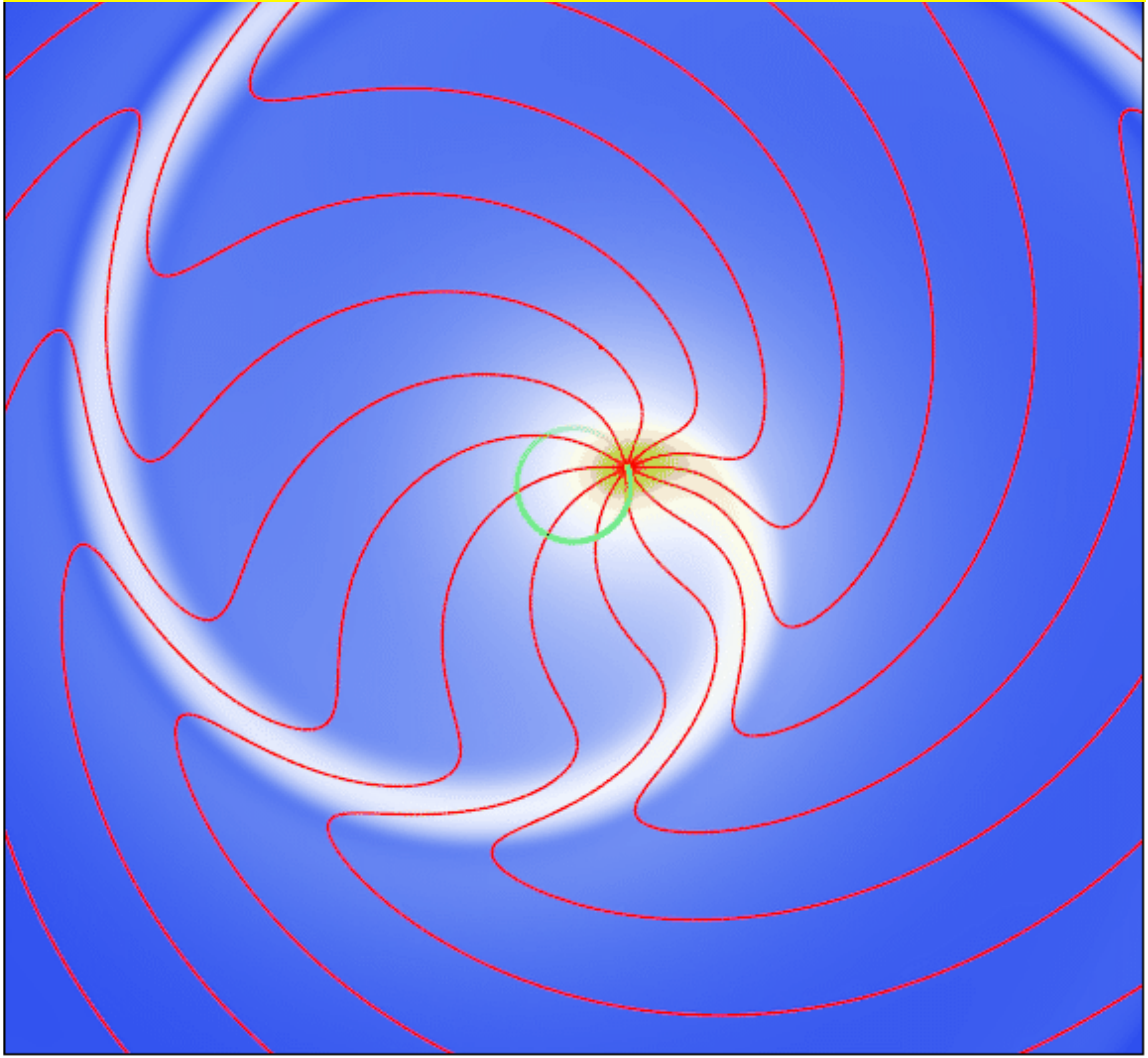
$$\frac{dP}{d\Omega} = \frac{e^2 a^2 \sin^2\Theta}{4\pi c^3}$$

$$P = \frac{2\, e^2 a^2}{3\, c^3}$$

http://www.cco.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html www.joerg-enderlein.de/relativistic-charge



www.joerg-enderlein.de/relativistic-charge

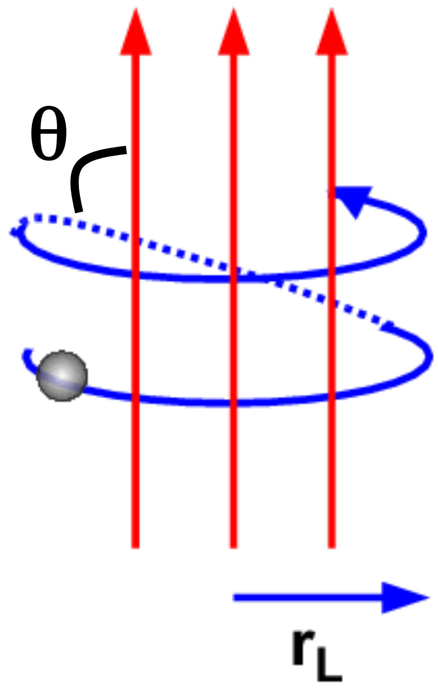


Synchrotron

Synchrotron

- Ingredients: Magnetic field and relativistic charges
- Responsible: Lorentz force
- Curiously, the Lorentz force doesn't work.

$$\vec{F}_L = \frac{d}{dt}(\gamma m \vec{v}) = \frac{e}{c}\,\vec{v} \times \vec{B}$$



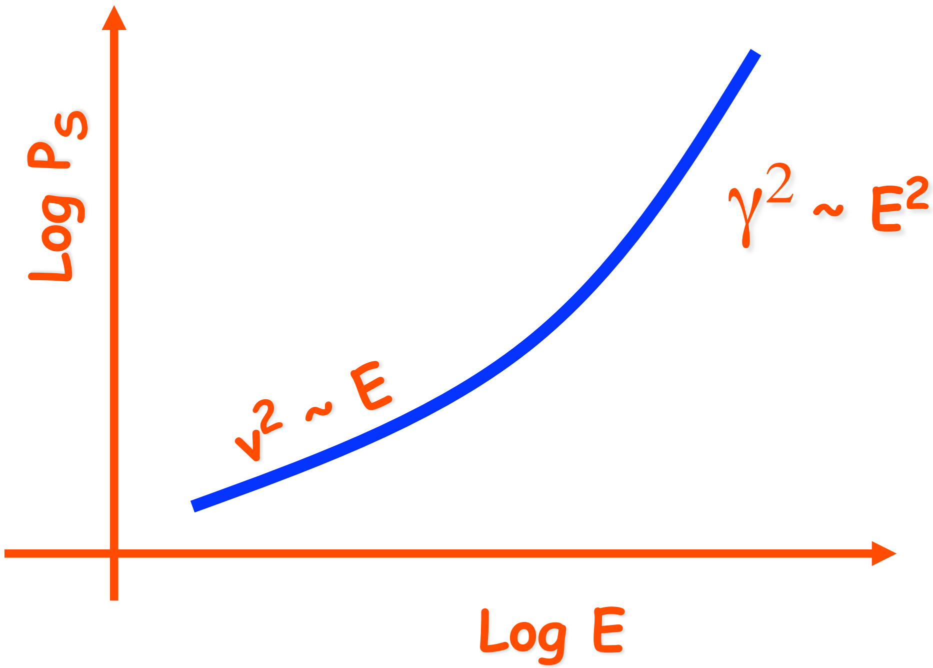
Total losses

$$P_S(\theta) = 2\sigma_T c U_B \gamma^2 \beta^2 \sin^2\theta$$

$$\sigma_T = 8\pi r_0^2/3$$

$$\langle P_S \rangle = \frac{4}{3} \sigma_T c U_B \gamma^2 \beta^2$$

If pitch angles are isotropic



Synchrotron Spectrum

Characteristic frequency

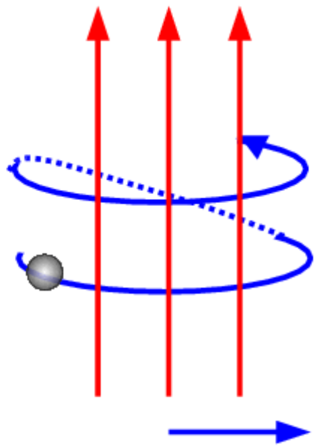
$$r_L = \frac{v_\perp^2}{a_\perp} = \frac{\gamma\, mc^2\, \beta\, \sin\theta}{eB}$$

$$\nu_B = \frac{a_\perp}{2\pi\, v_\perp} = \frac{e\,B}{2\pi\, \gamma mc}$$

$$a_\perp = \frac{e\, v\, B\, \sin\theta}{\gamma\, mc}$$

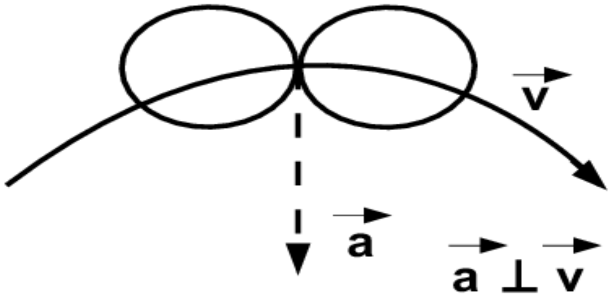
$$\nu = 1/T$$

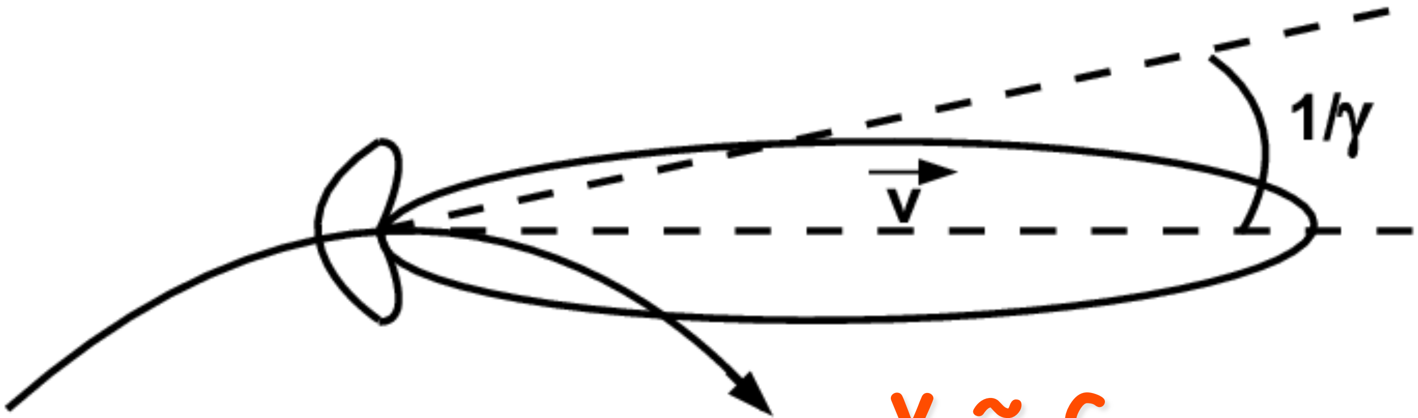
$$T = 2\pi\, r_L / v_\perp$$



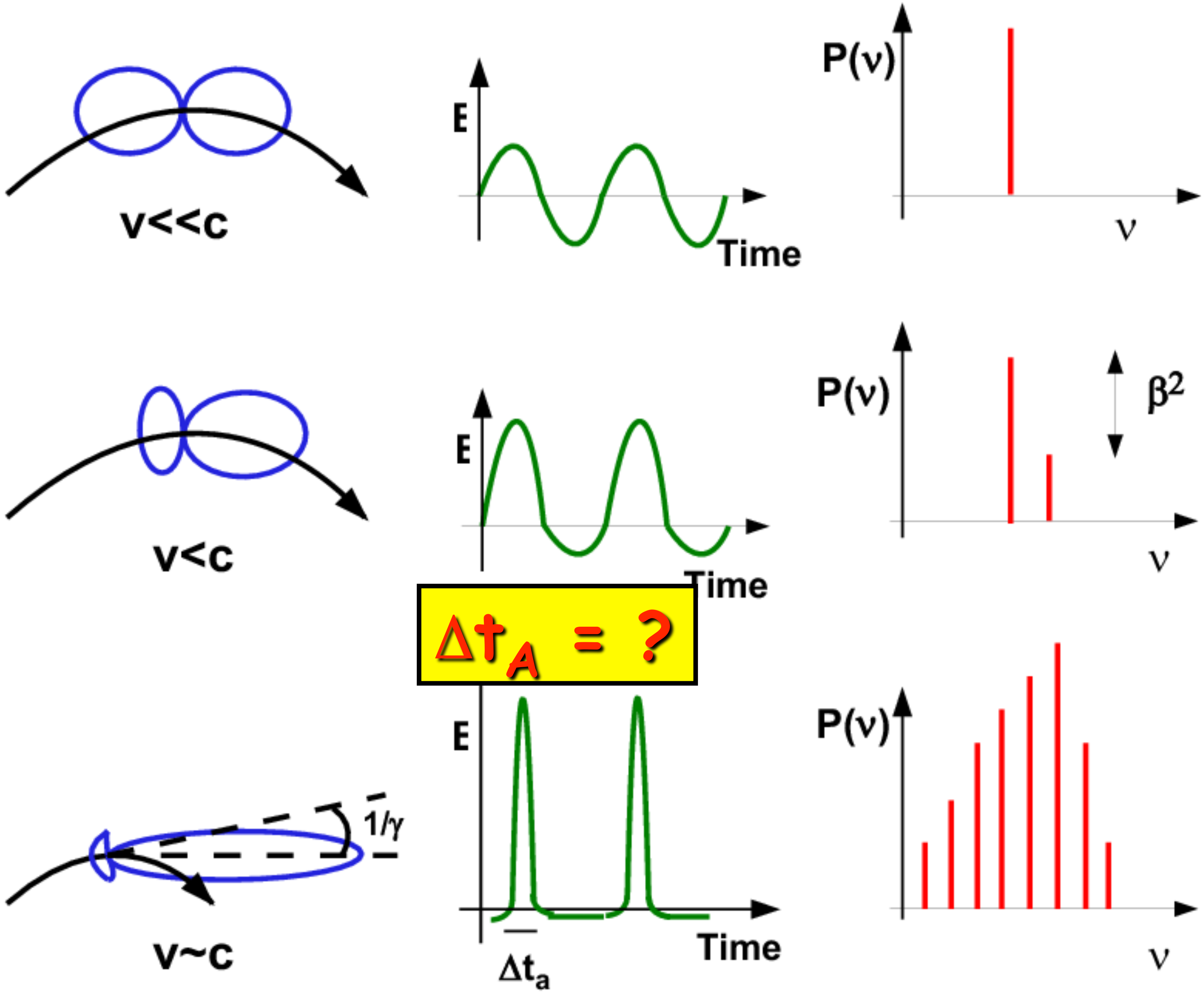
This *is not* the characteristic frequency

v<<c



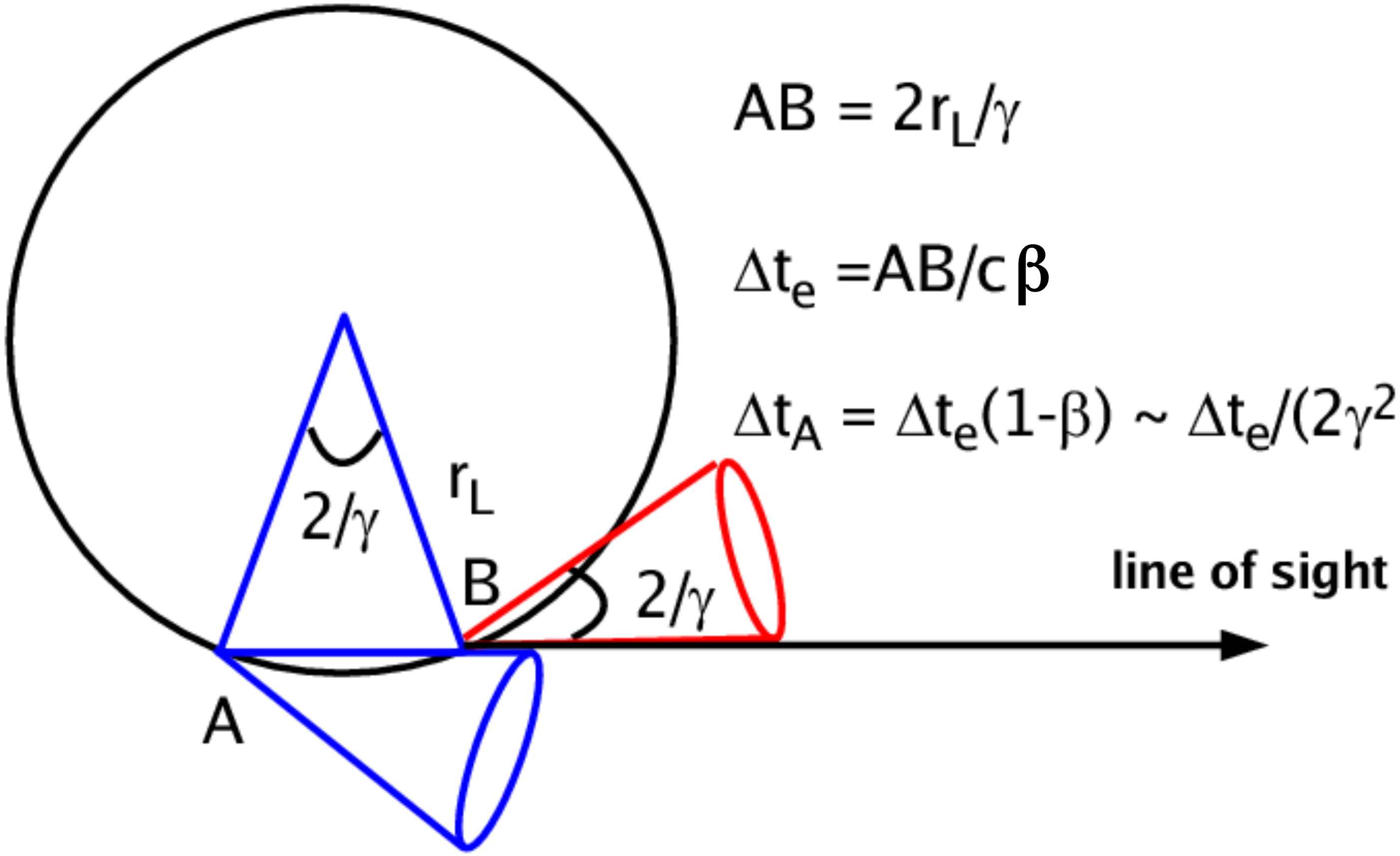


v ~ c



v<<c
E
Time
P(ν)
ν
v<c
E
Time
P(ν)
β2
ν
Δt_A = ?
v~c
1/γ
E
Δt_a
Time
P(ν)
ν

$$\nu_S = \frac{1}{\Delta t_A} = \gamma^3 \frac{eB}{2\pi\gamma\, mc} = \gamma^2 \frac{eB}{2\pi mc}$$

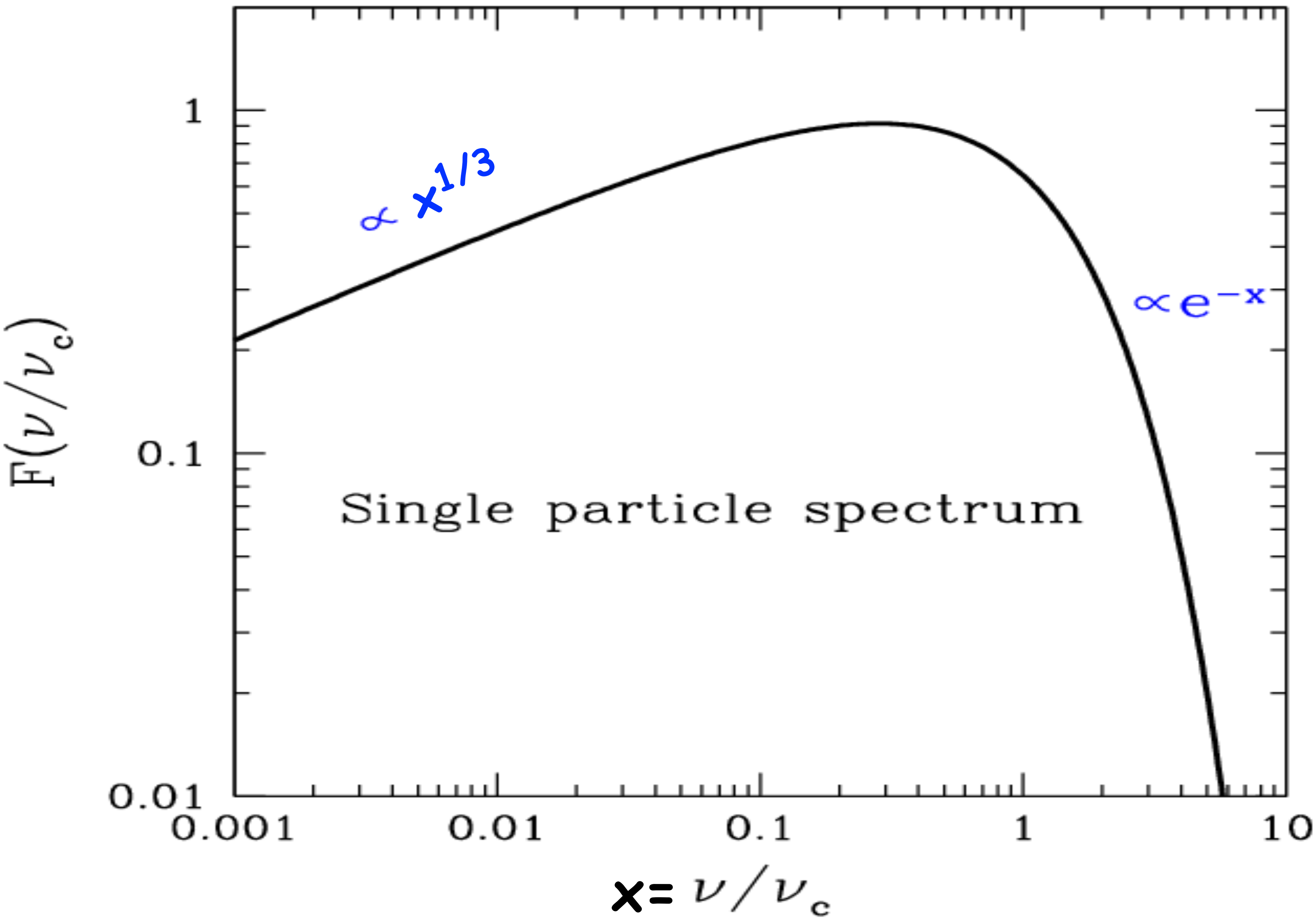


$AB = 2r_L/\gamma$

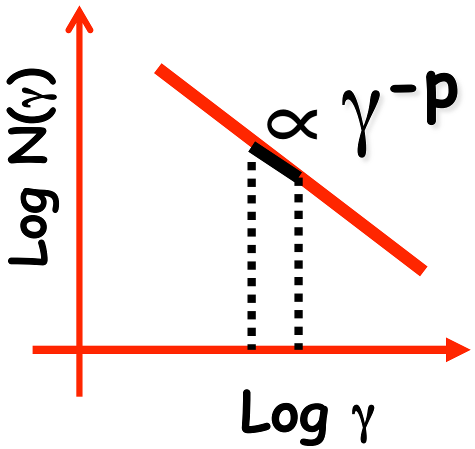
$\Delta t_e = AB/c\beta$

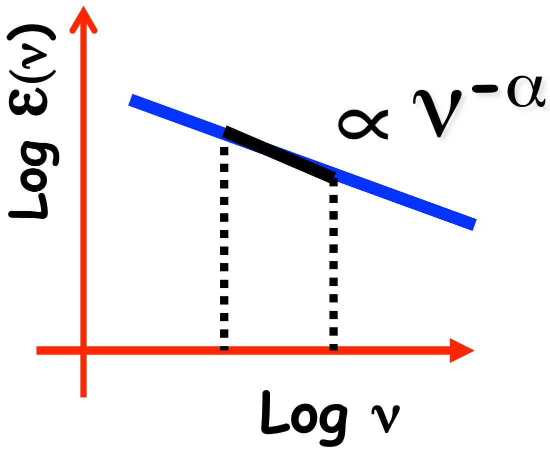
$\Delta t_A = \Delta t_e(1-\beta) \sim \Delta t_e/(2\gamma^2)$

The real stuff



Emission from many particles





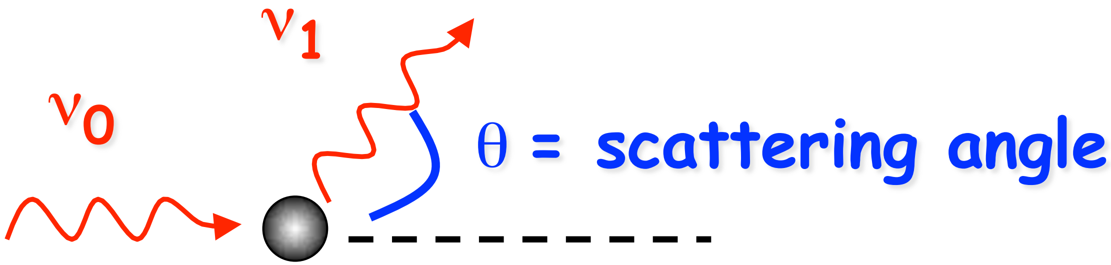
$$\alpha = \frac{p-1}{2}$$

Inverse Compton

Inverse Compton

- **Scattering is one the basic interactions between matter and radiation.**
- **At low photon frequencies it is a classical process (i.e. *e.m. waves*)**
- **At low frequencies the cross section is called the Thomson cross section, and it is a peanut.**
- **At high energies the electron recoils, and the cross section is the Klein-Nishina one.**

Thomson scattering



- $h\nu_0 << m_e c^2$
- tennis ball against a wall
- The wall doesn't move
- The ball bounces back with the same speed (if it is elastic)

$$\nu_1 = \nu_0$$

Thomson cross section

$$\frac{d\sigma_T}{d\Omega} = \frac{r_0^2}{2}(1+\cos^2\theta)$$ → a peanut

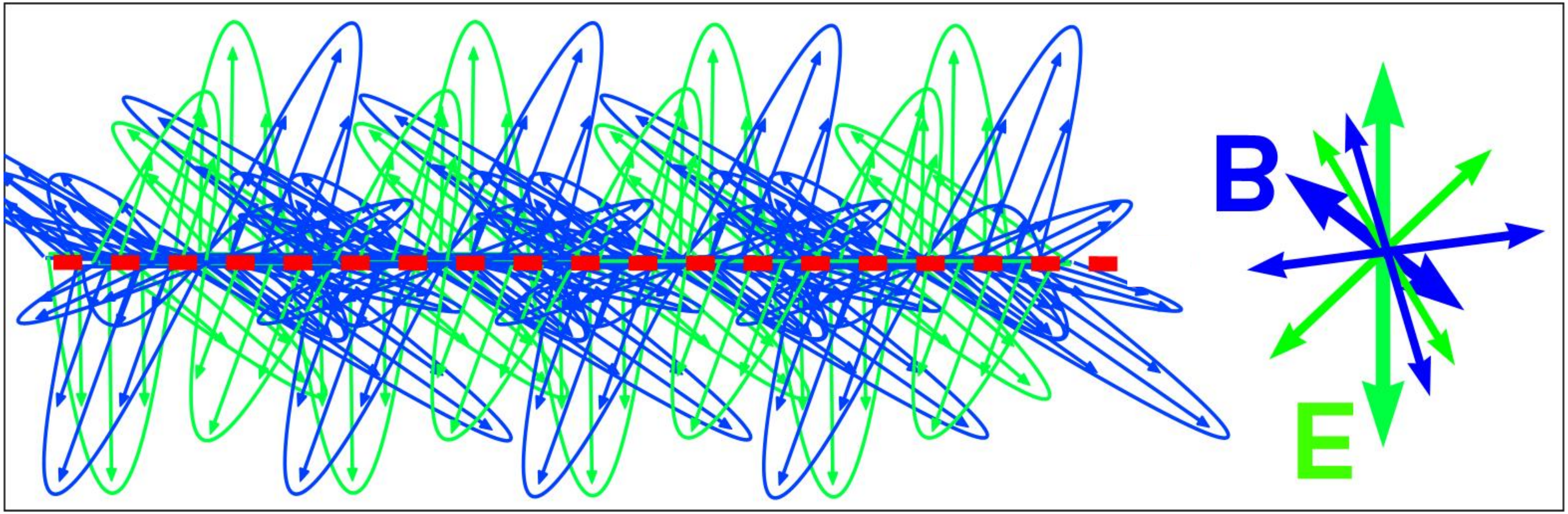
$$\sigma_T = \frac{8\pi}{3} r_0^2$$

$$r_0 = \frac{e^2}{m_e c^2}$$

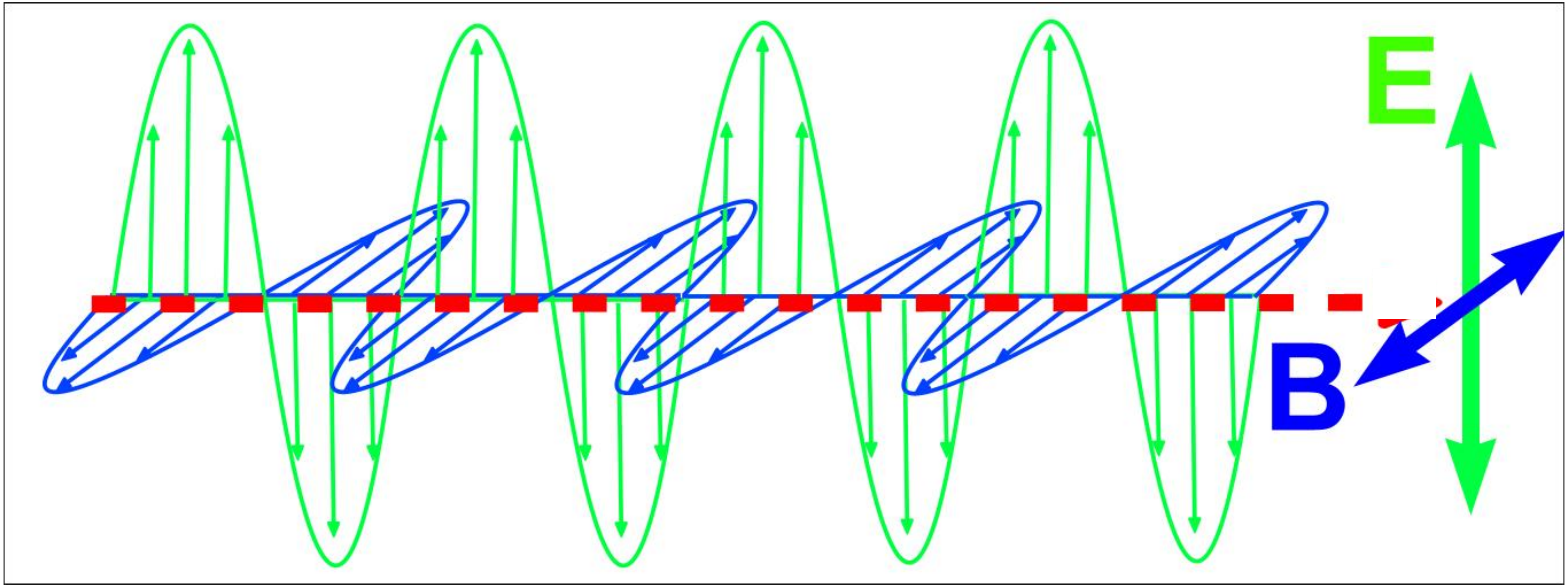
$$m_e c^2 = \int_{a_o}^{\infty} \frac{E^2}{8\pi} 4\pi r^2 dr = \int_{a_o}^{\infty} \frac{e^2}{2r^2} dr \rightarrow a_0 = \frac{1}{2}\frac{e^2}{m_e c^2}$$

Electromagnetic mass of the electron:
See Vol. 2, chapter 28.3 of *The Feynman Lectures on Physics*

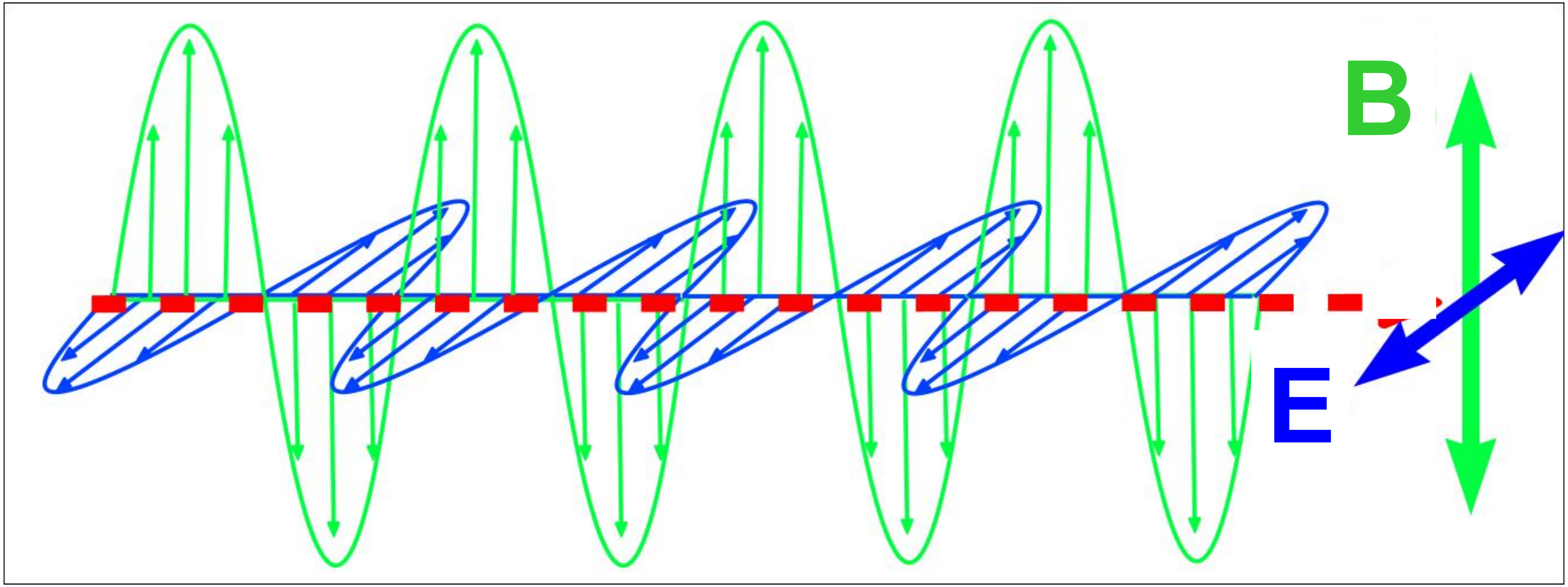
Why a peanut?



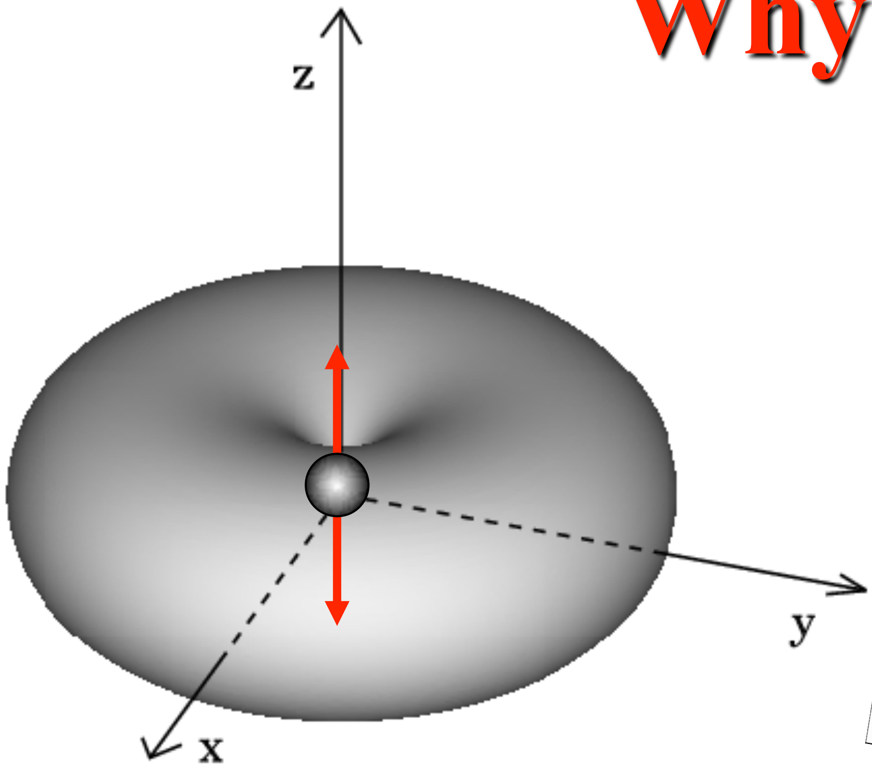
Why a peanut?

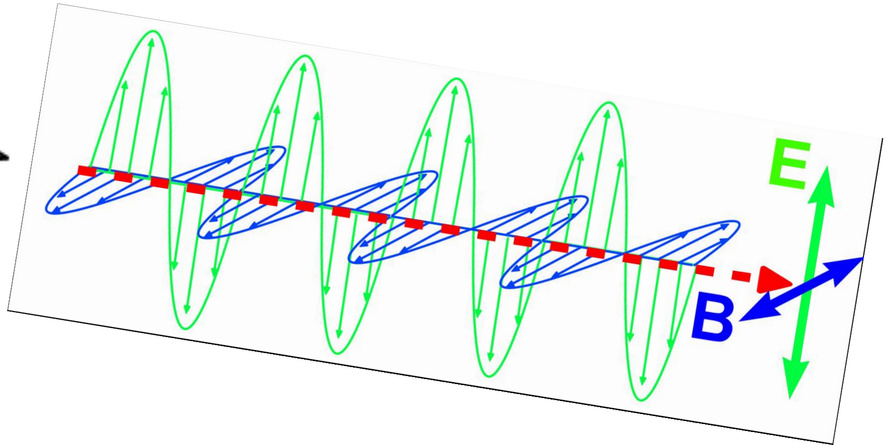


Why a peanut?



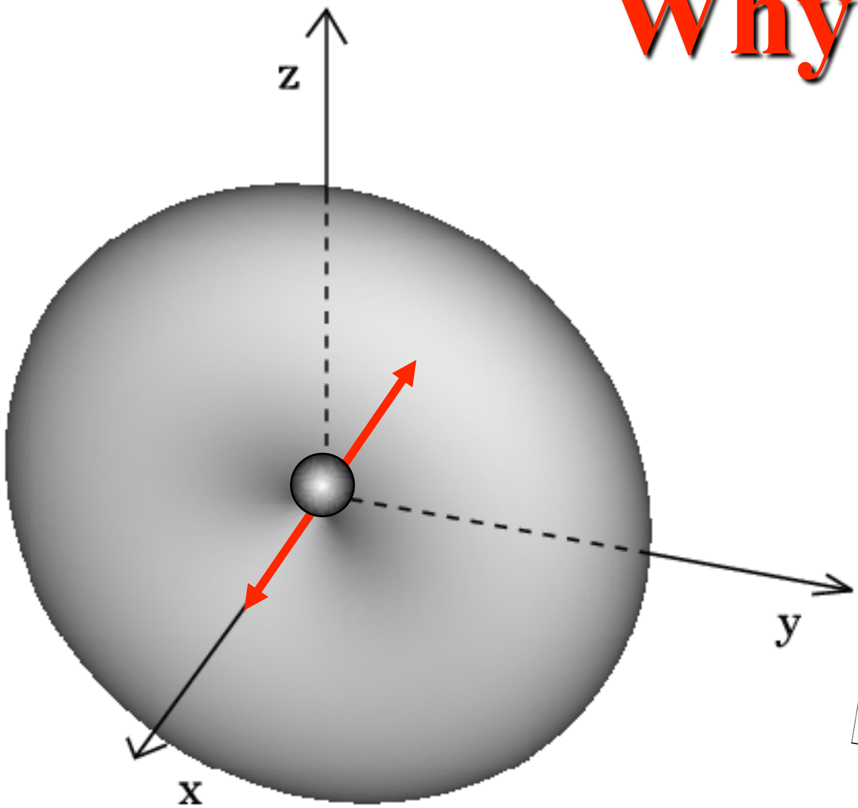
Why a peanut?

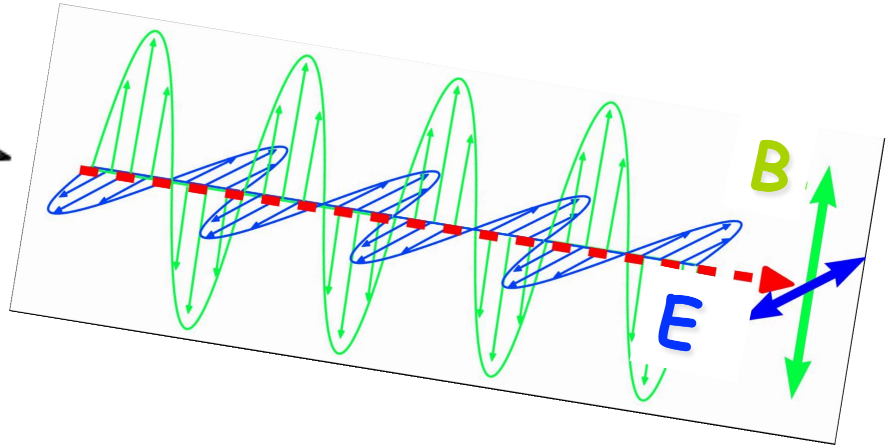


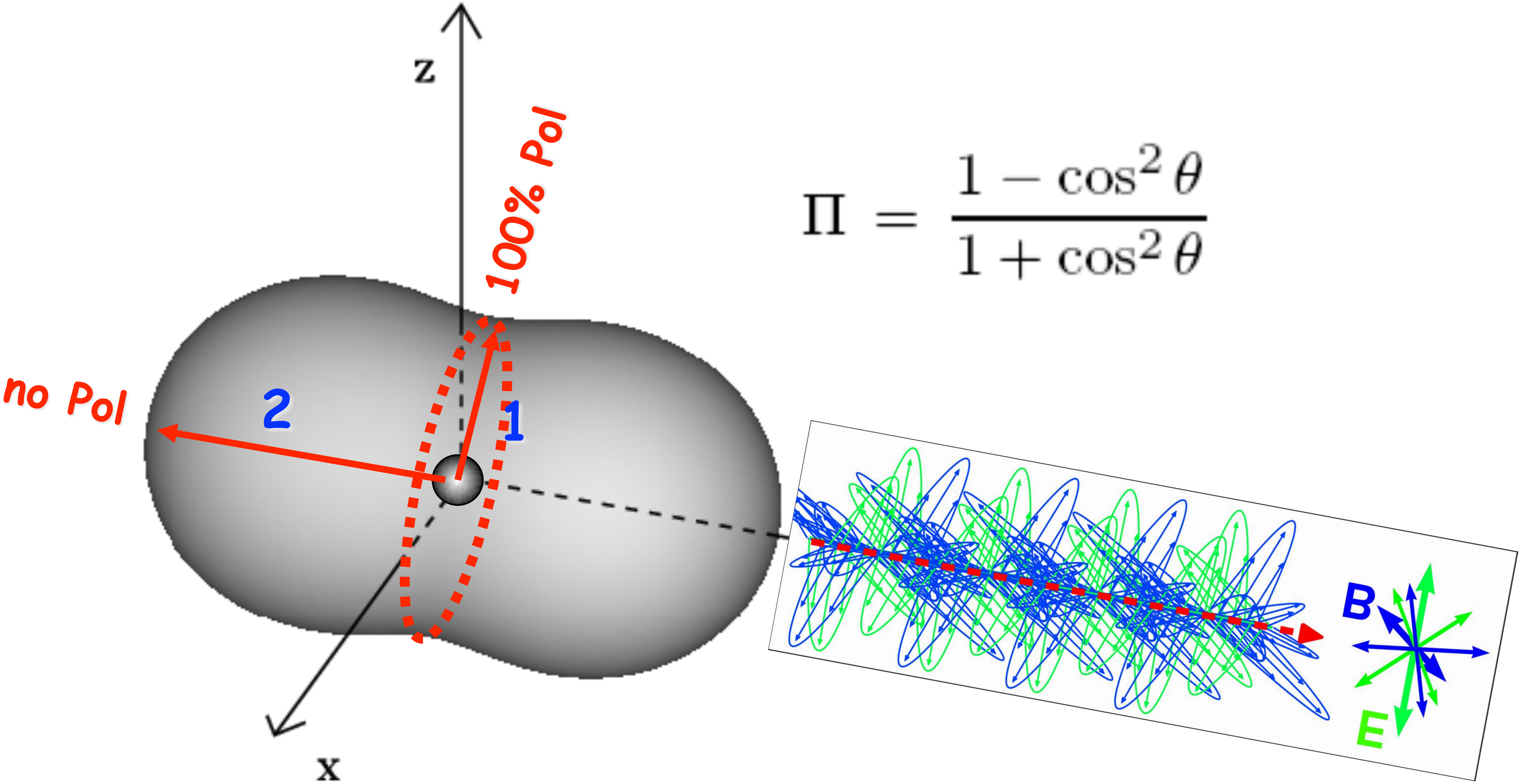


Remember: $\frac{dP}{d\Omega} = \frac{e^2 a^2}{4\pi c^3} \sin^2\Theta$

Why a peanut?



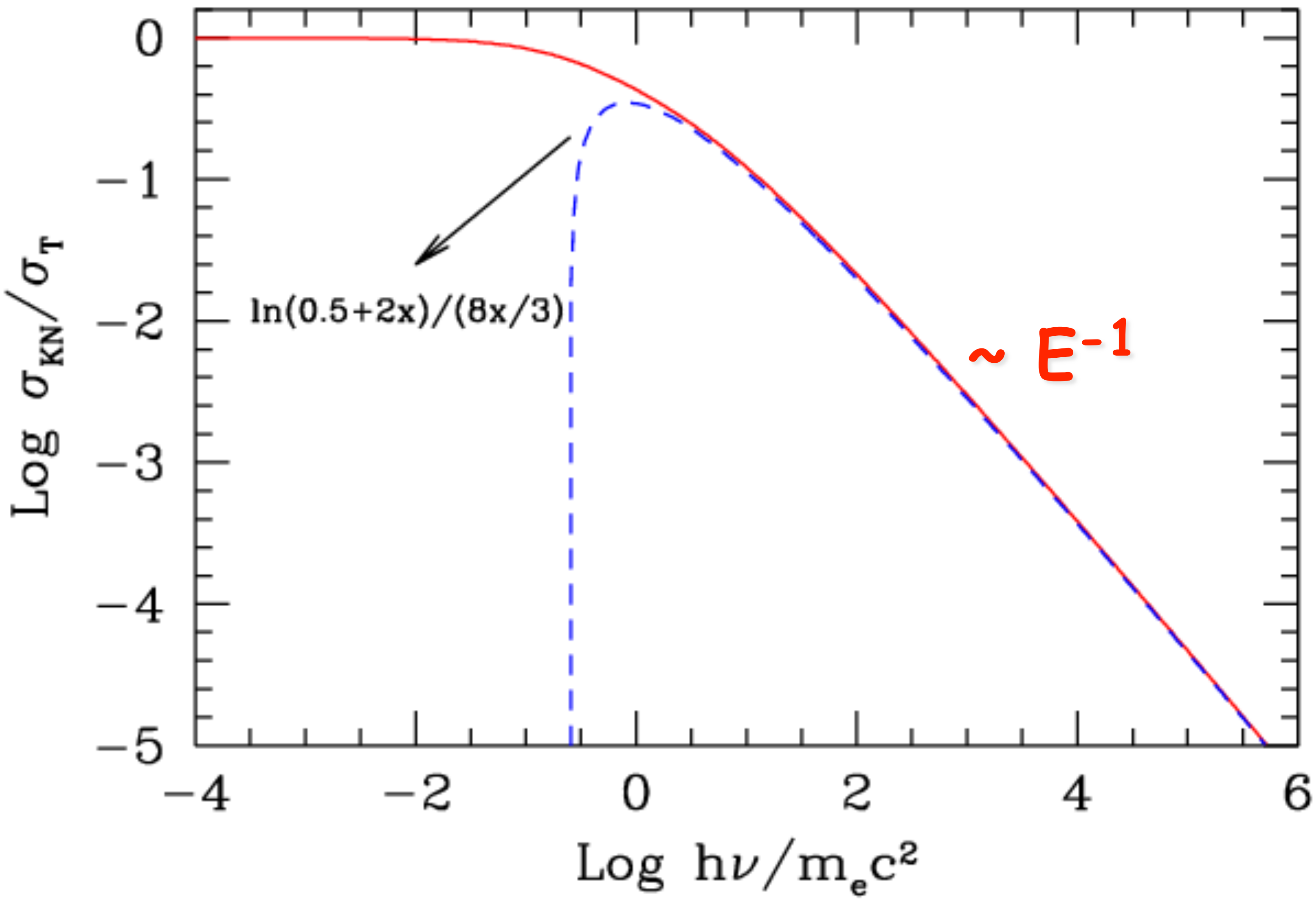




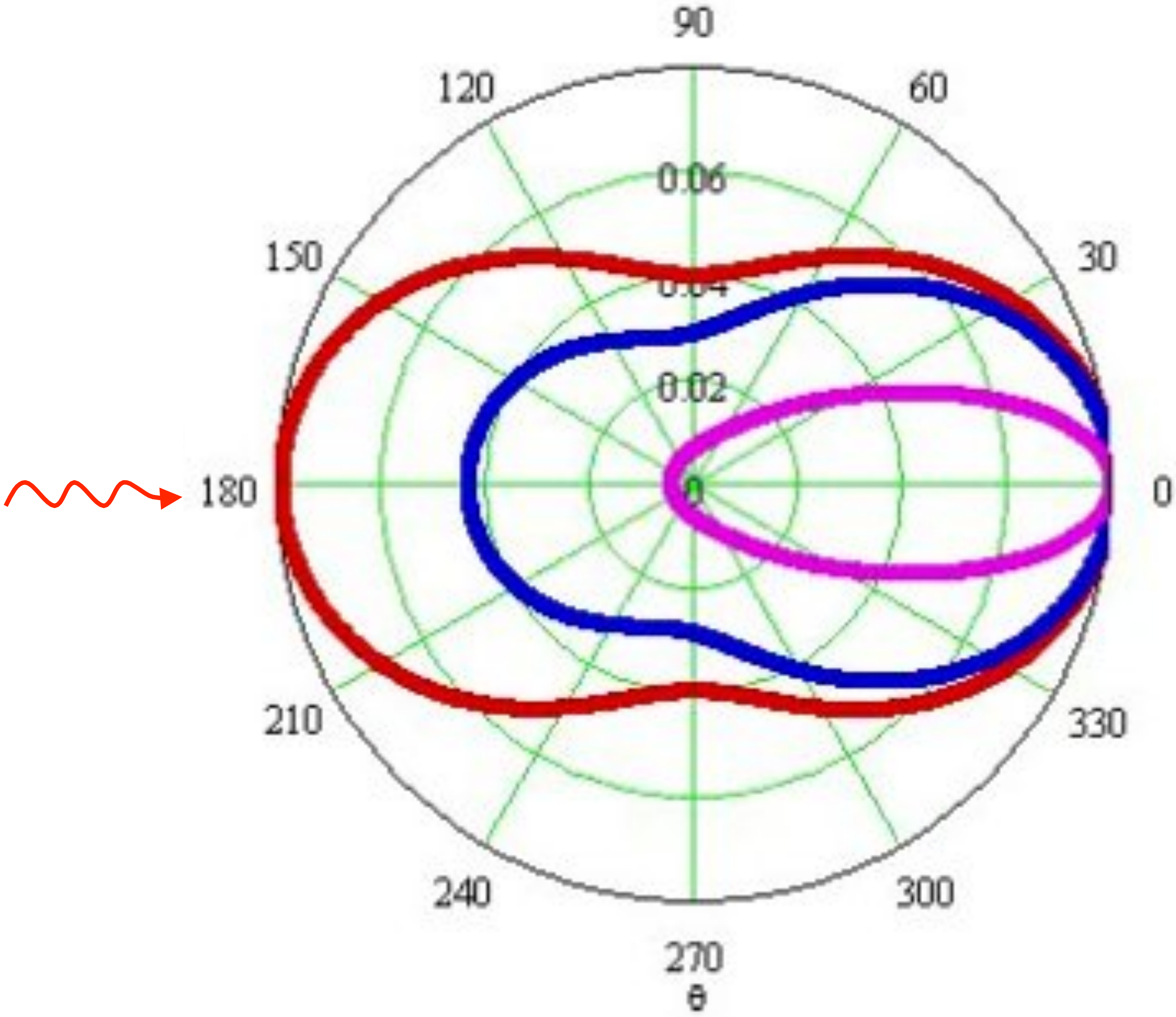
$$\Pi = \frac{1-\cos^2\theta}{1+\cos^2\theta}$$

$$\frac{d\sigma_T}{d\Omega} = \frac{r_0^2}{2}(1+\cos^2\theta)$$

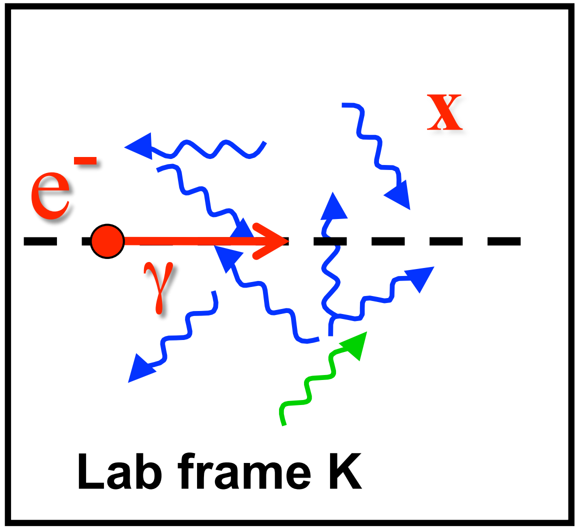
Klein-Nishina cross section



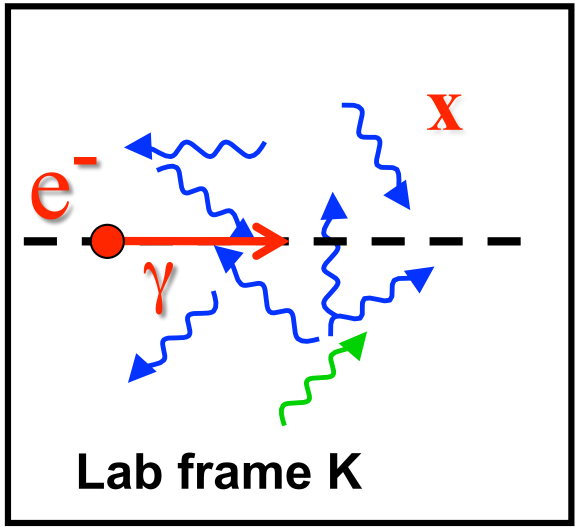
Klein-Nishina cross section

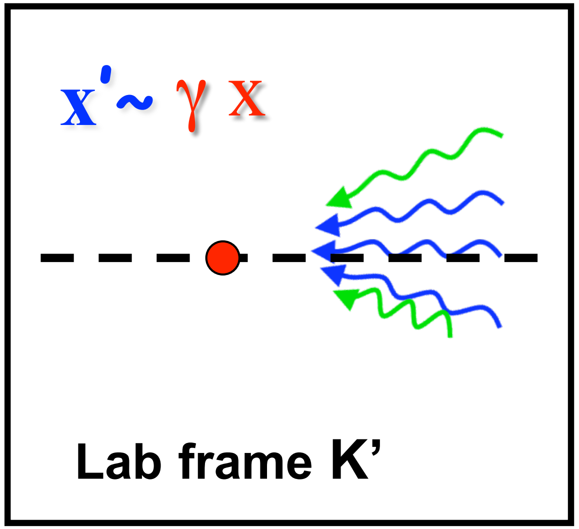


Typical frequencies in Thomson regime

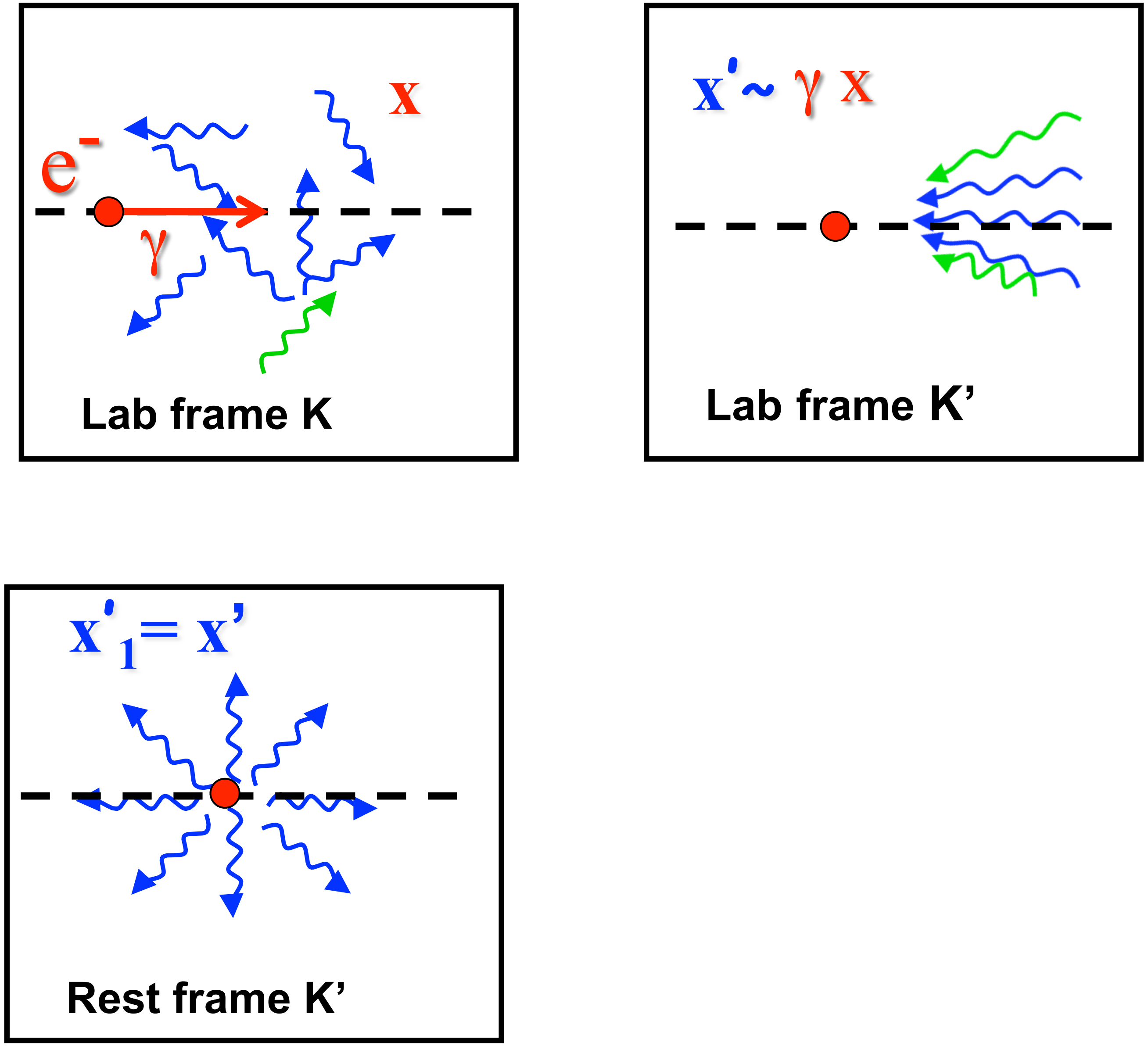


Typical frequencies in Thomson regime

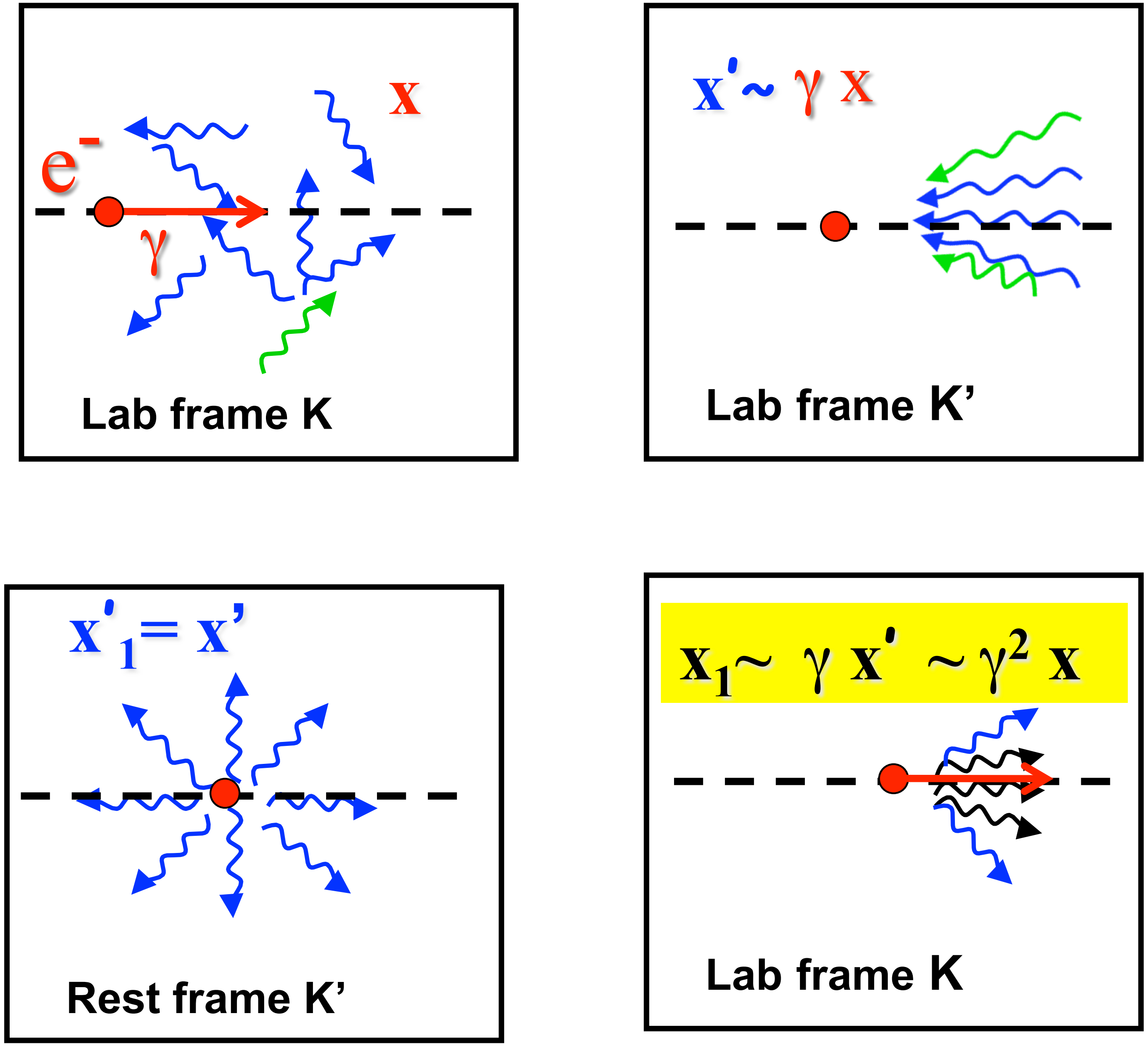




Typical frequencies in Thomson regime



Typical frequencies in Thomson regime



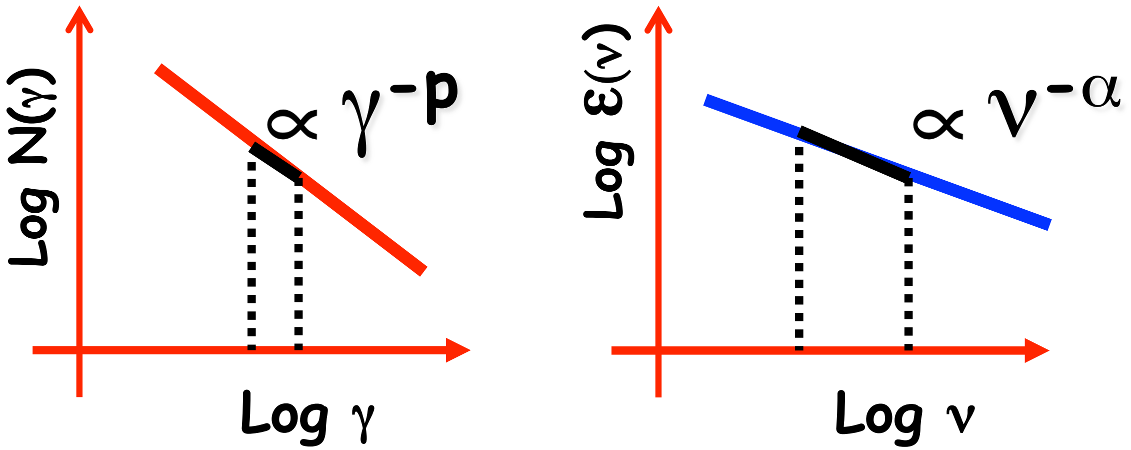
Total loss rate

$$\langle P_c \rangle = \frac{4}{3} \sigma_T c U_{rad} \gamma^2 \beta^2$$

Compare with synchrotron losses:

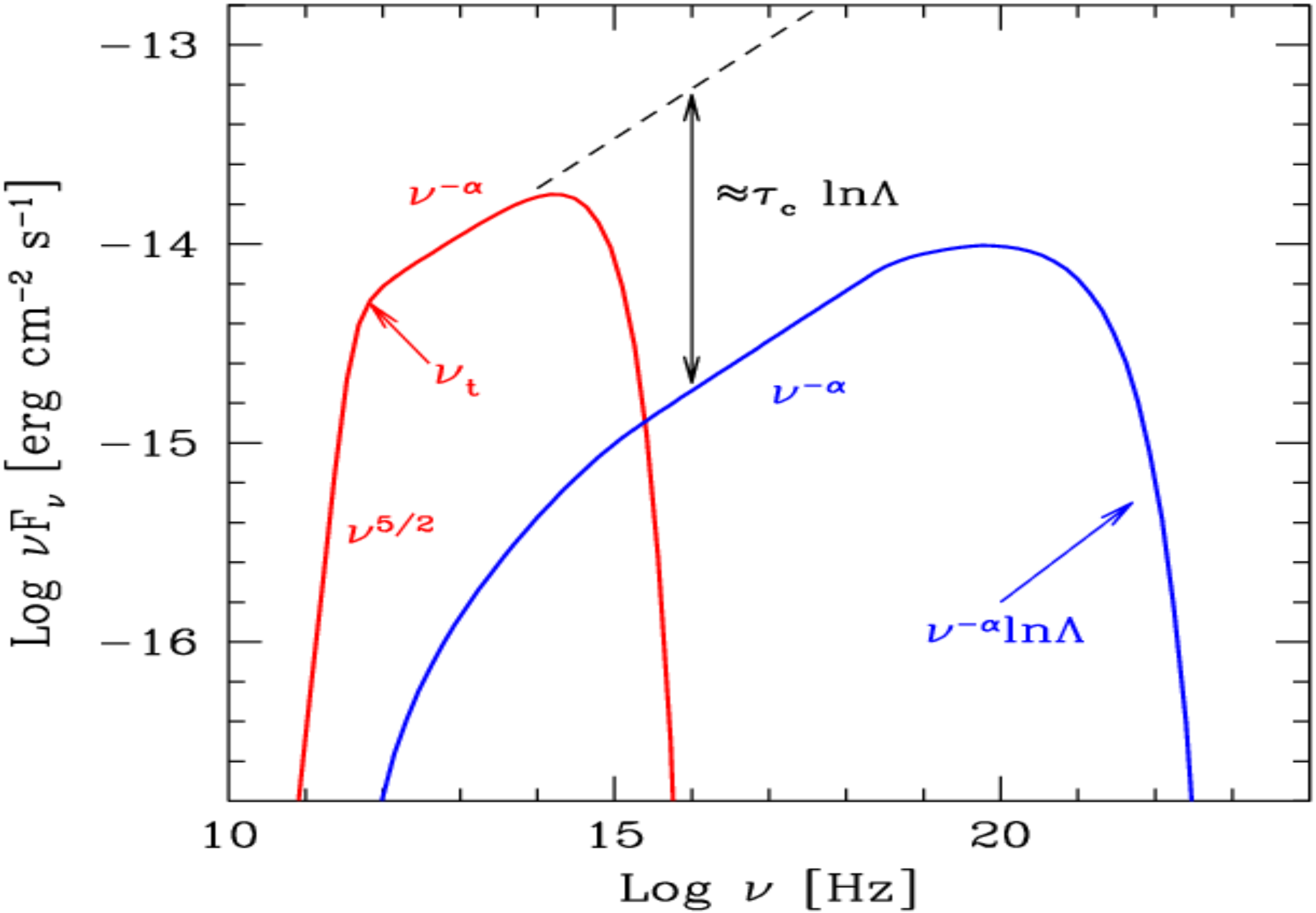
$$\langle P_S \rangle = \frac{4}{3} \sigma_T c U_B \gamma^2 \beta^2$$

Inverse Compton spectrum



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

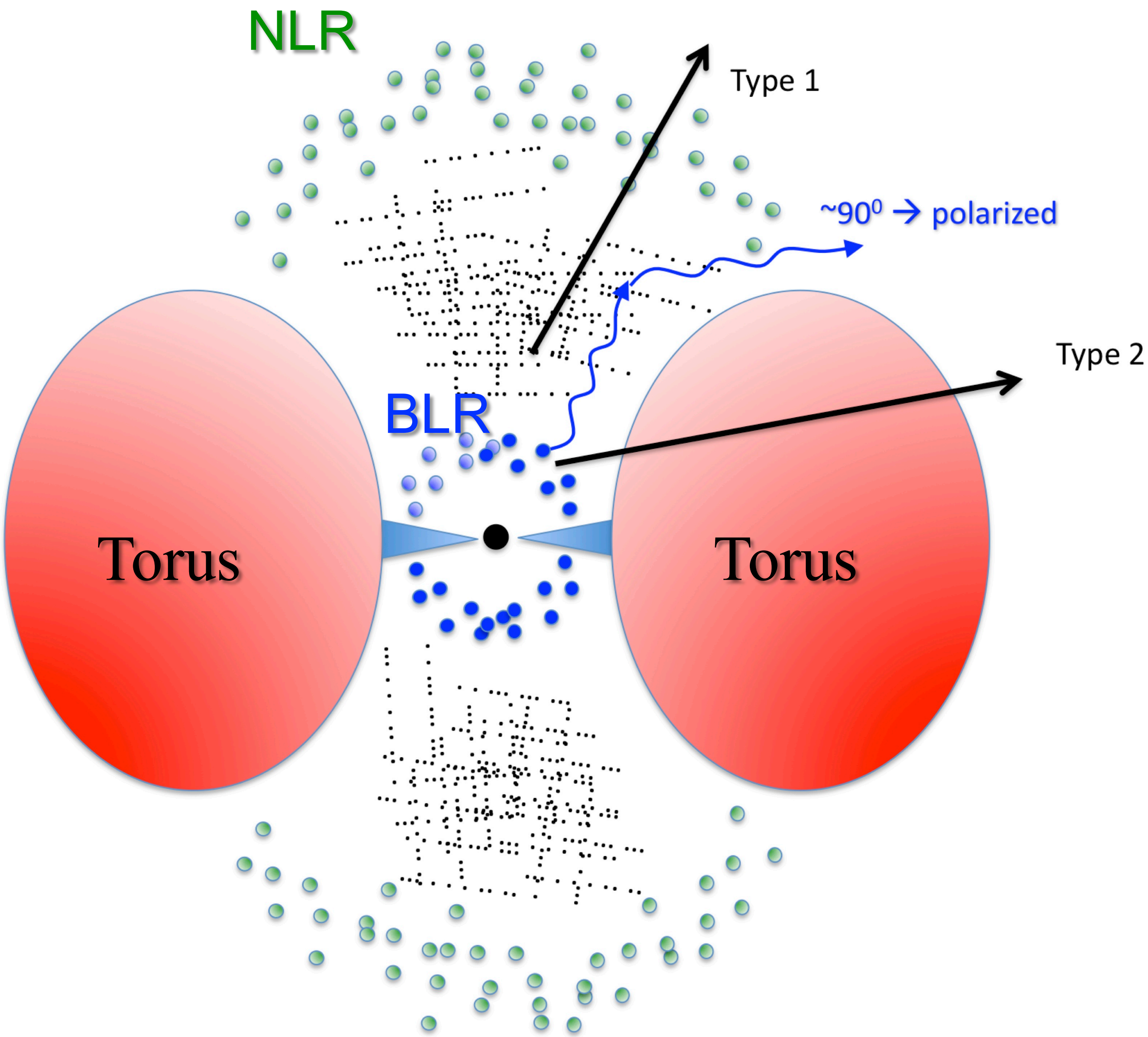
Synchrotron Self Compton: SSC



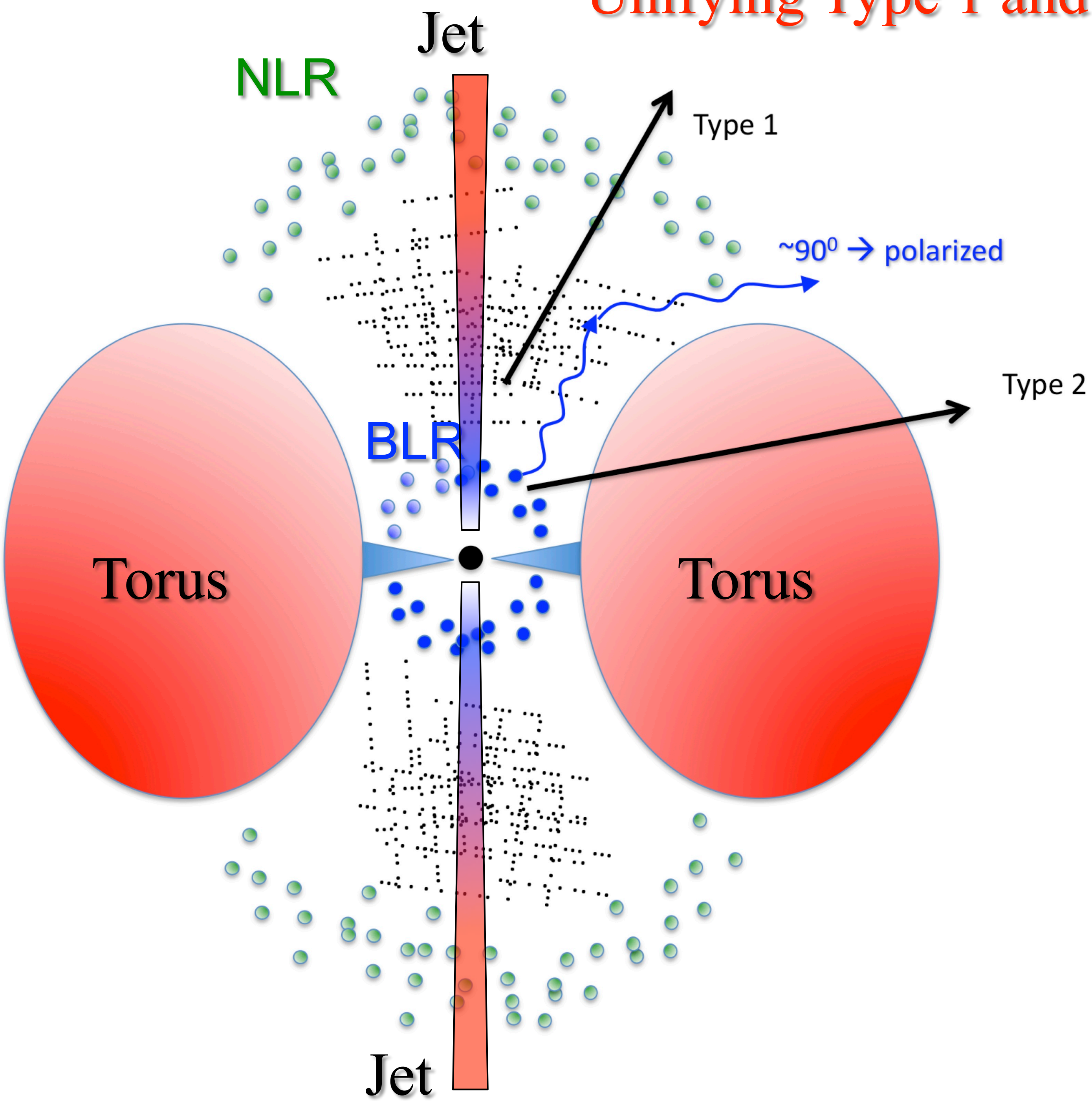
- Many kind of radiation
- Radiation from accelerated charges
- Synchro: why γ^2
- Inverse Compton:
    - why the peanut
    - why γ^2

Relativistic jets

Unifying Type 1 and Type 2

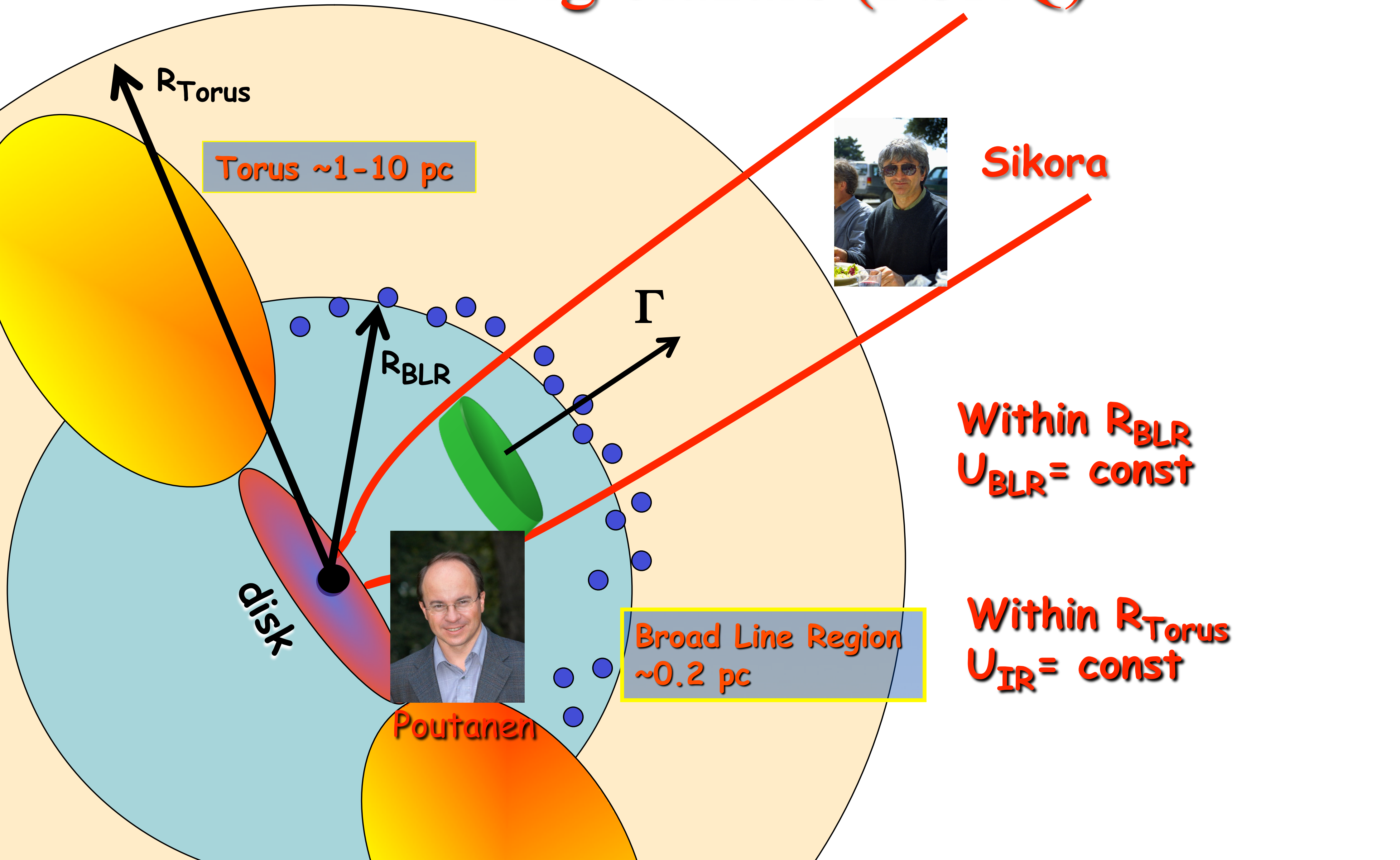


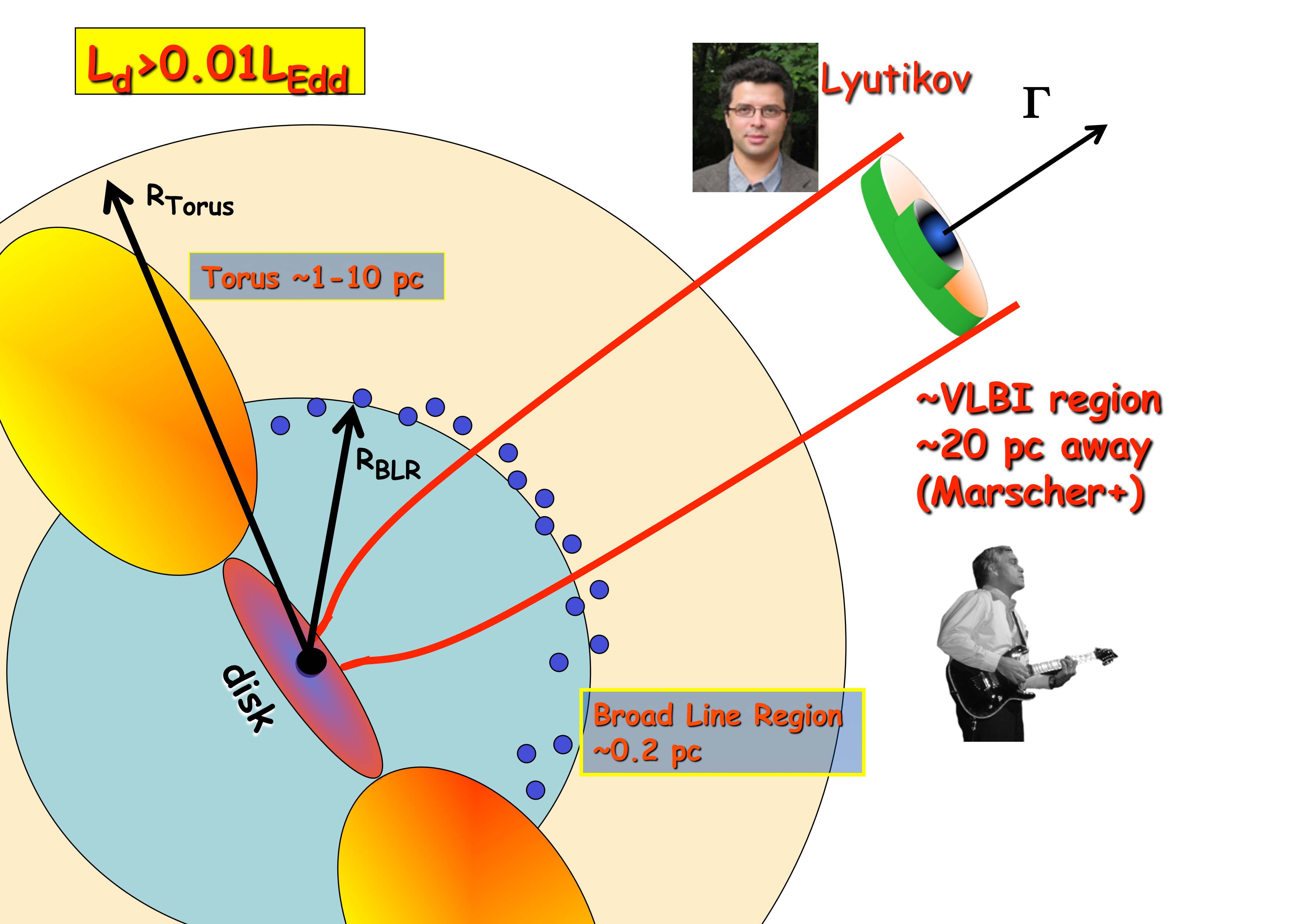
Unifying Type 1 and Type 2



$L_d > 0.01 L_{Edd}$

Big blazars (FSRQ)

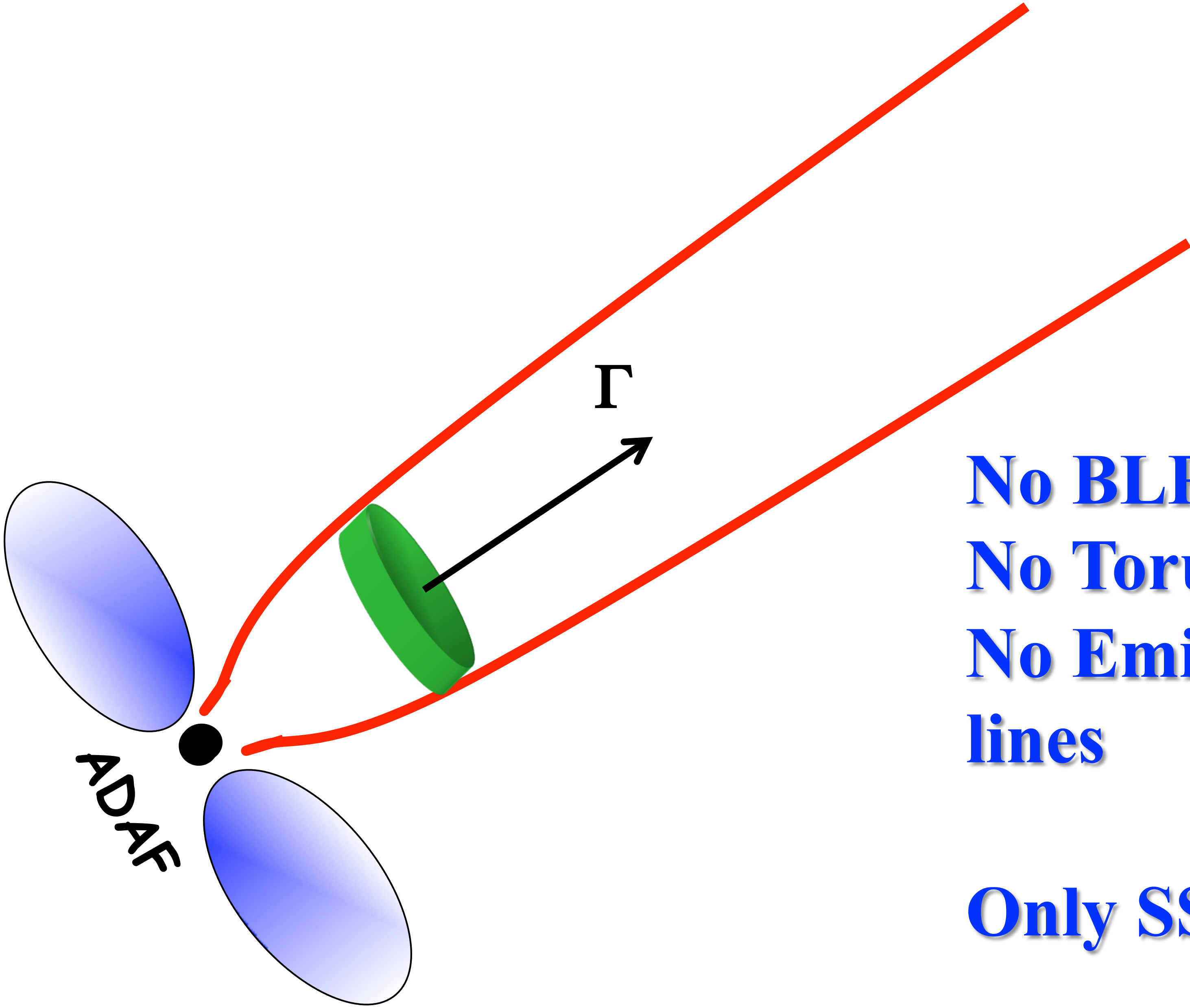




$L_d > 0.01 L_{Edd}$
Lyutikov
Γ
R_{Torus}
Torus ~1-10 pc
R_{BLR}
~VLBI region
~20 pc away
(Marscher+)
disk
Broad Line Region
~0.2 pc

L_d<0.01L_{Edd}

Weak blazars (BL Lacs)



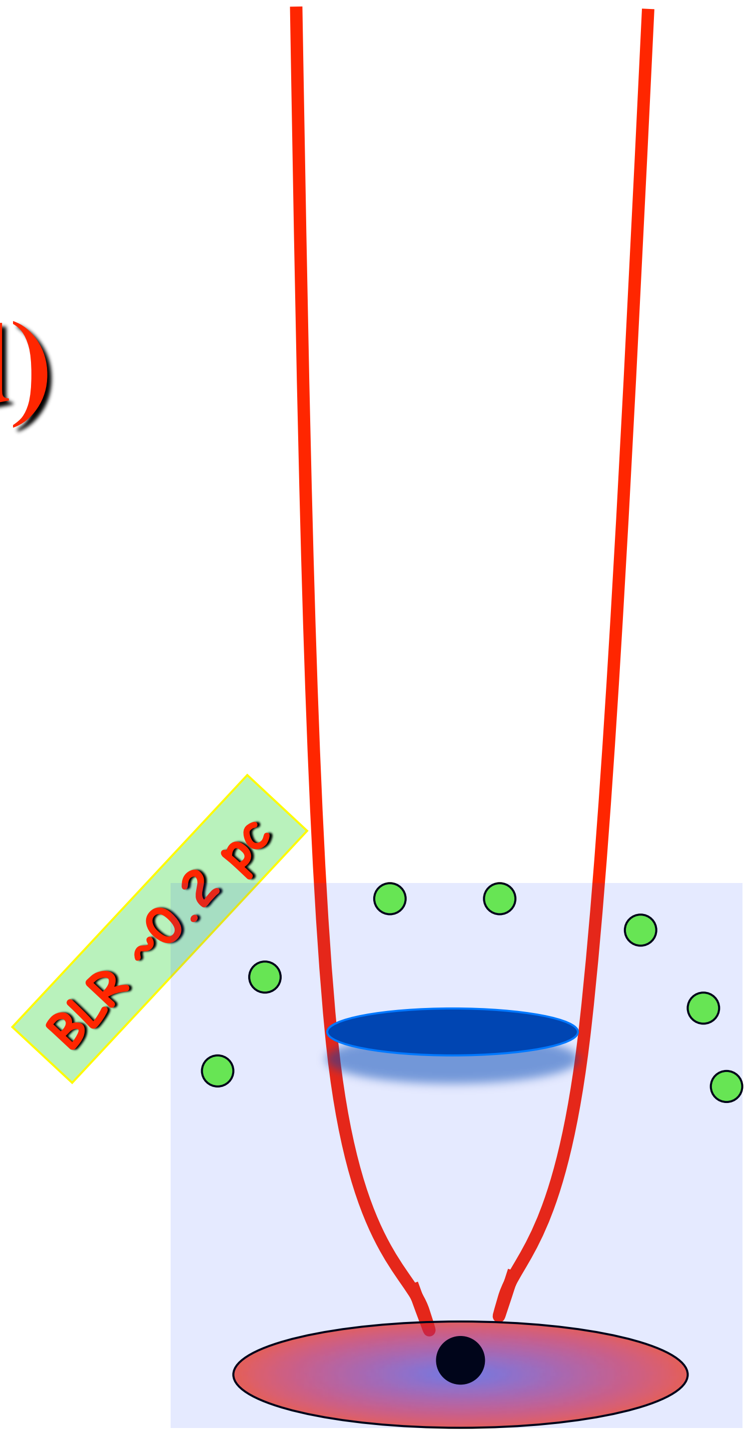
No BLR
No Torus
No Emission lines

Only SSC

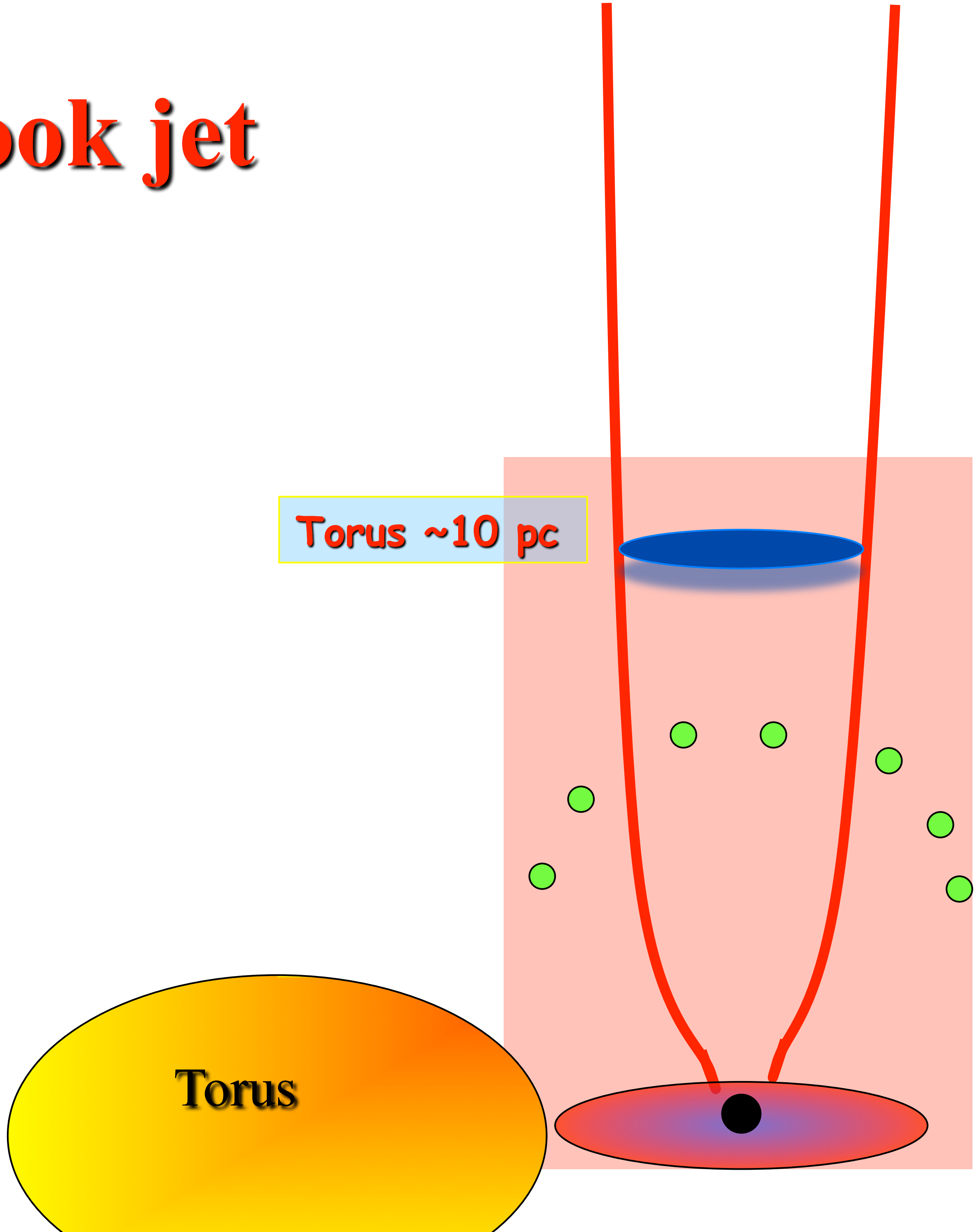
A text-book jet

(of the powerful kind)

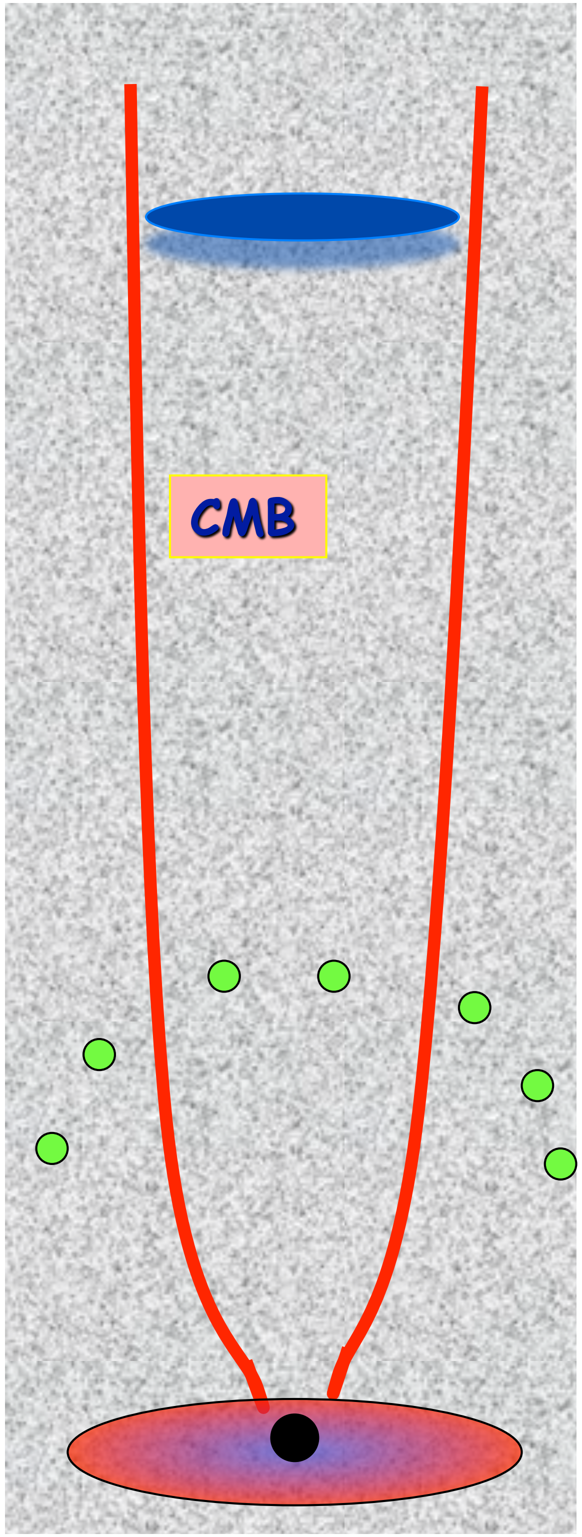
- B propto 1/R
- n propto $1/R^2$
- N(γ) from continuity equation (injection and cooling)

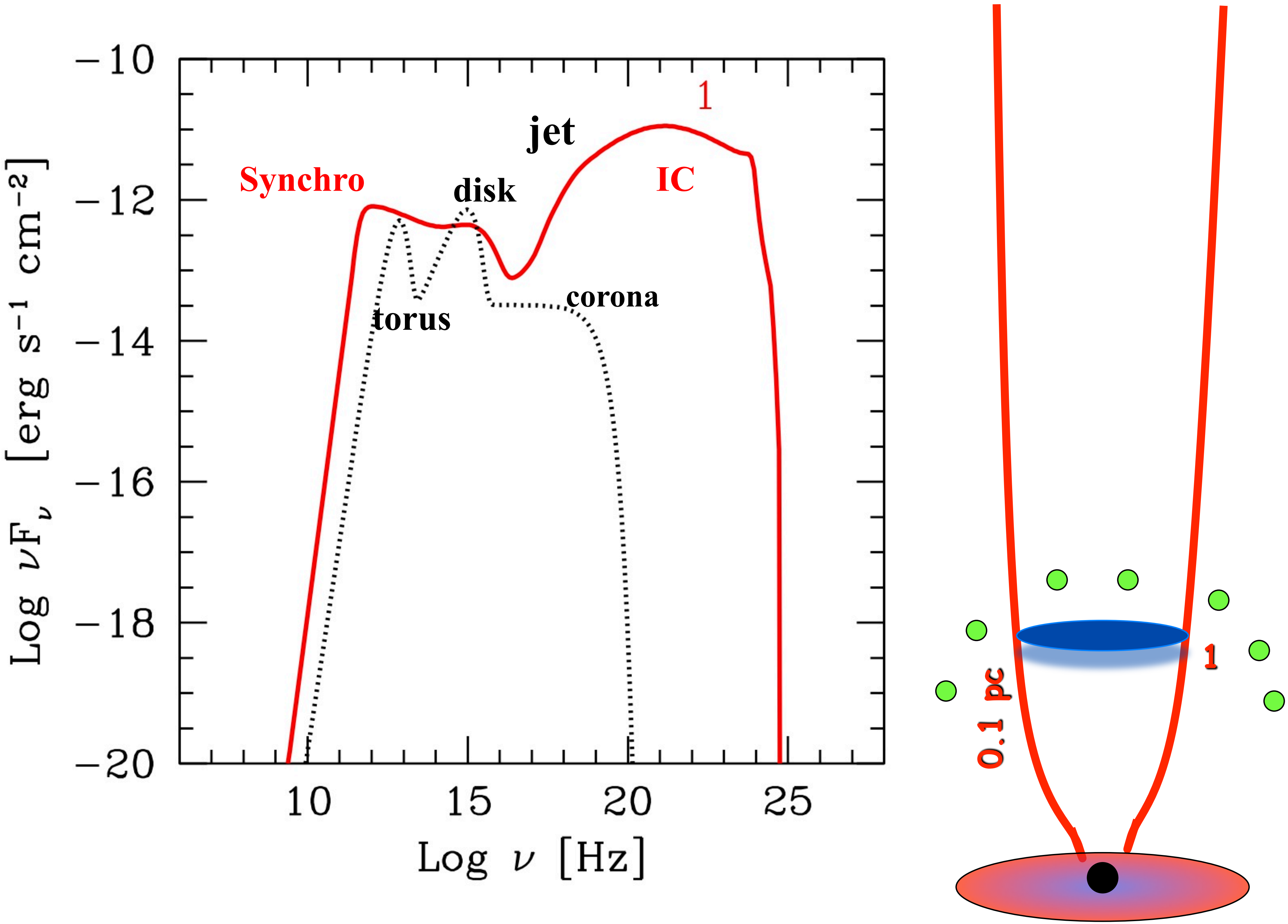


A text-book jet

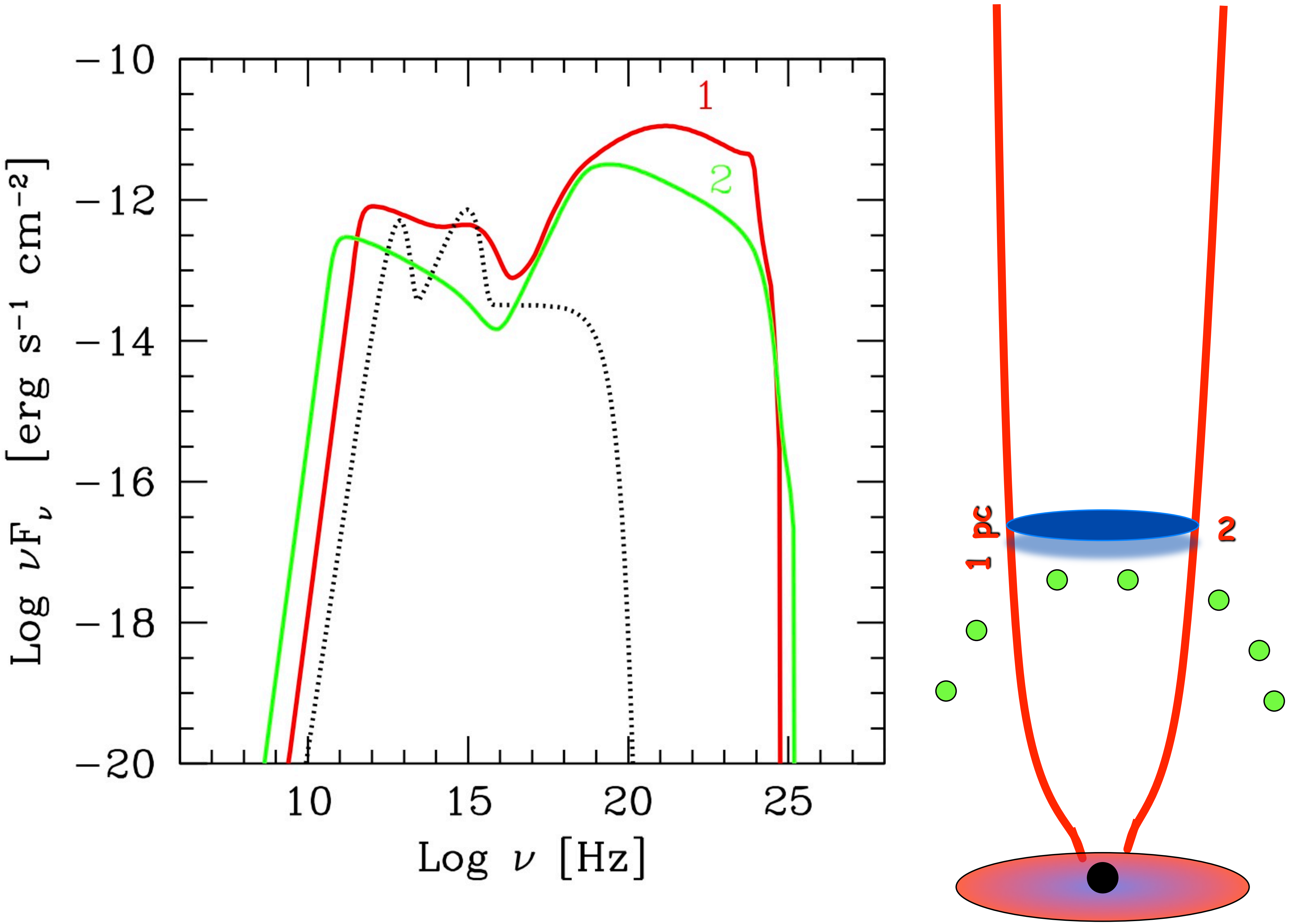


A text-book jet

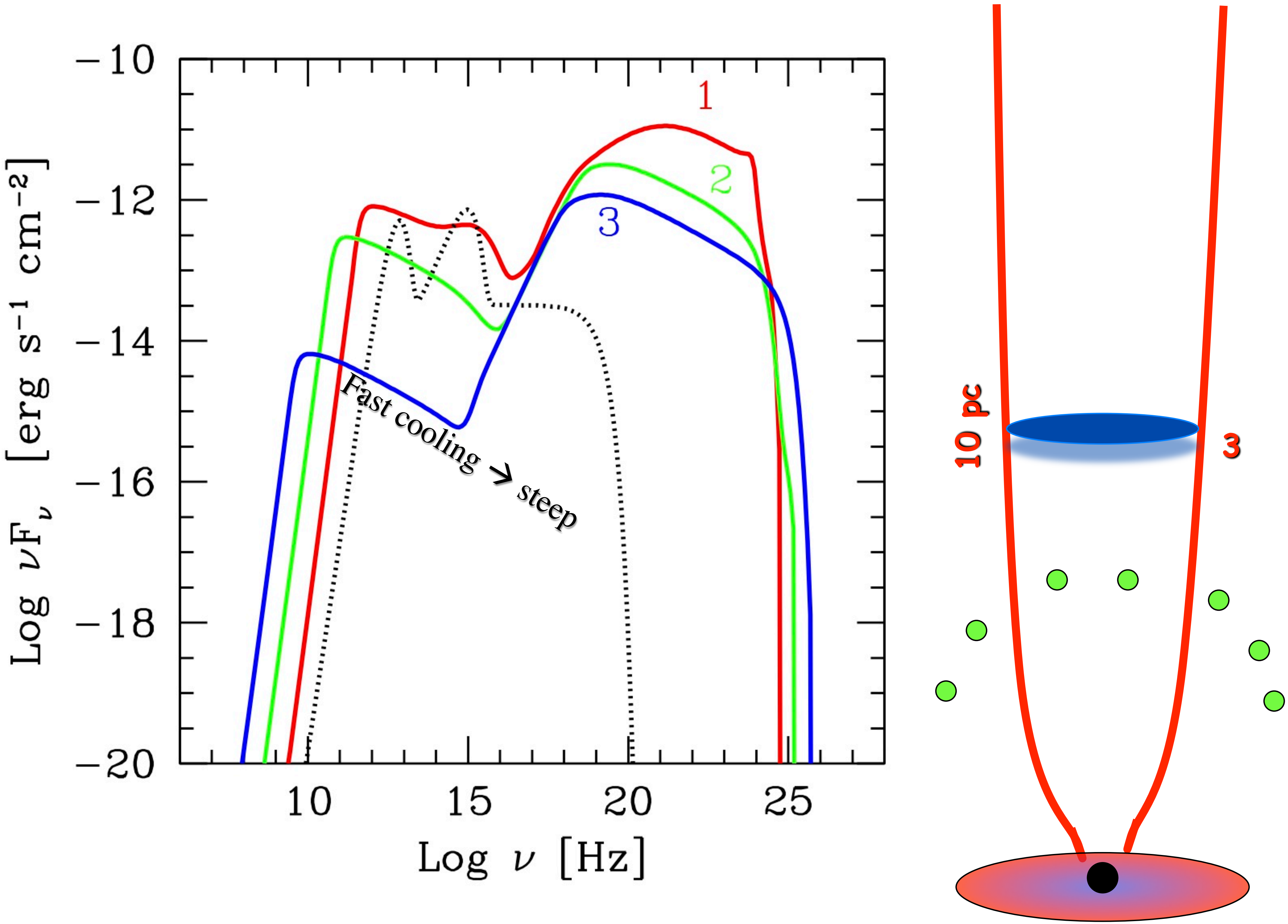




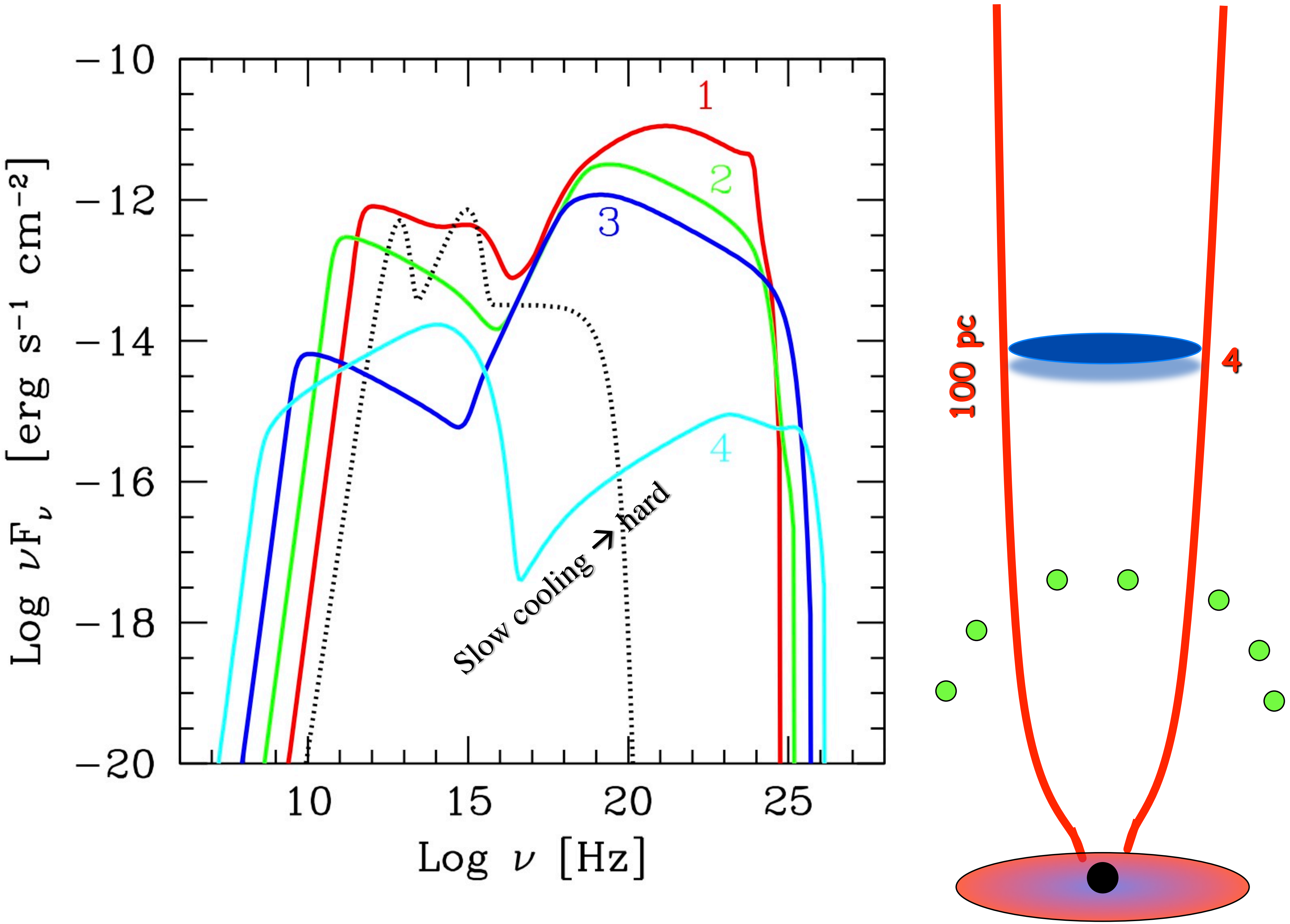
Log νFν [erg s⁻¹ cm⁻²]
−10
−12
−14
−16
−18
−20
10
15
20
25
Log ν [Hz]
Synchro
disk
jet
1
IC
torus
corona
0.1 pc
1



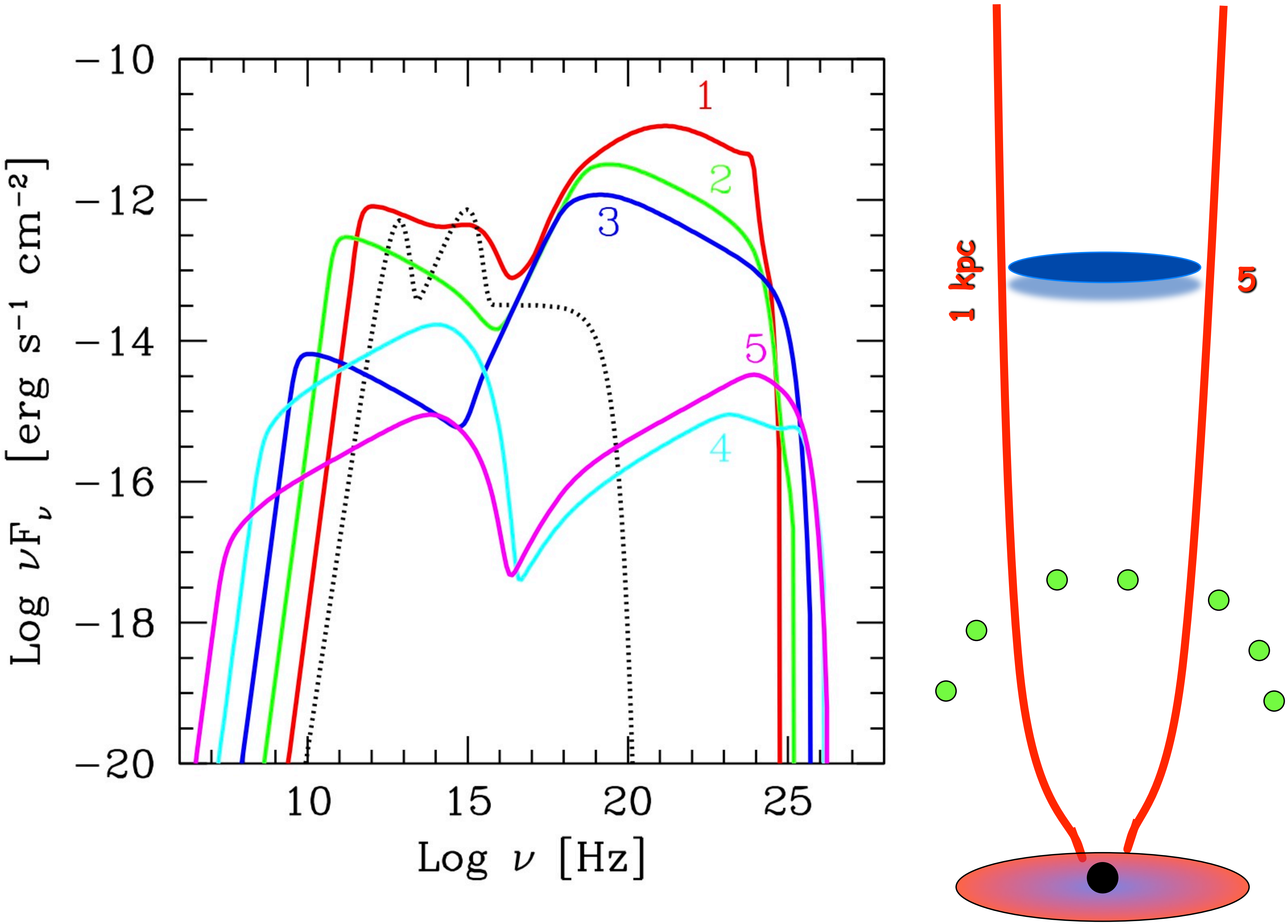
−10
−12
−14
−16
−18
−20
1
2
10
15
20
25
Log ν [Hz]
Log νF_ν [erg s^−1 cm^−2]
1 pc
2



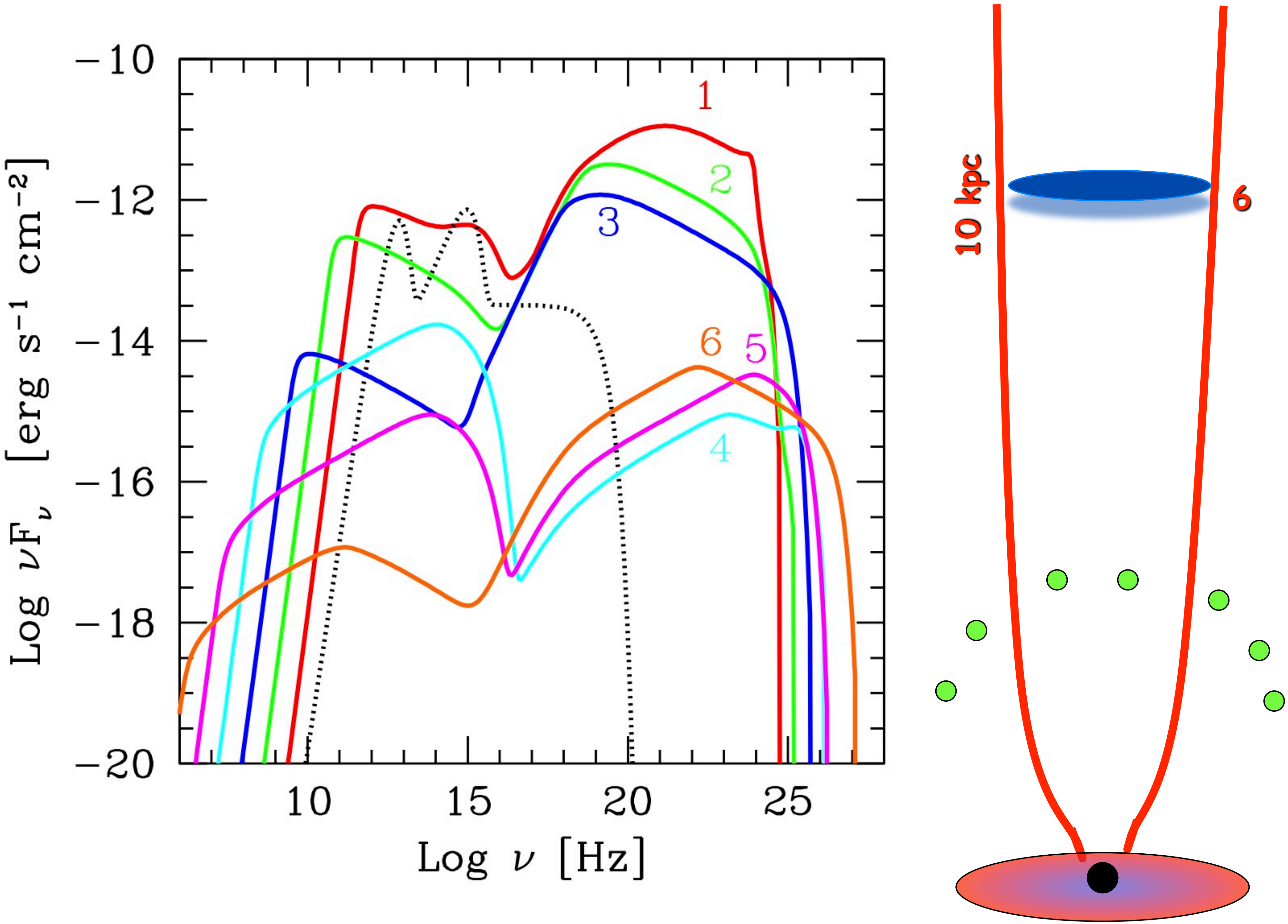
Log νF_ν [erg s⁻¹ cm⁻²]
Log ν [Hz]
1
2
3
Fast cooling → steep
10 pc
3



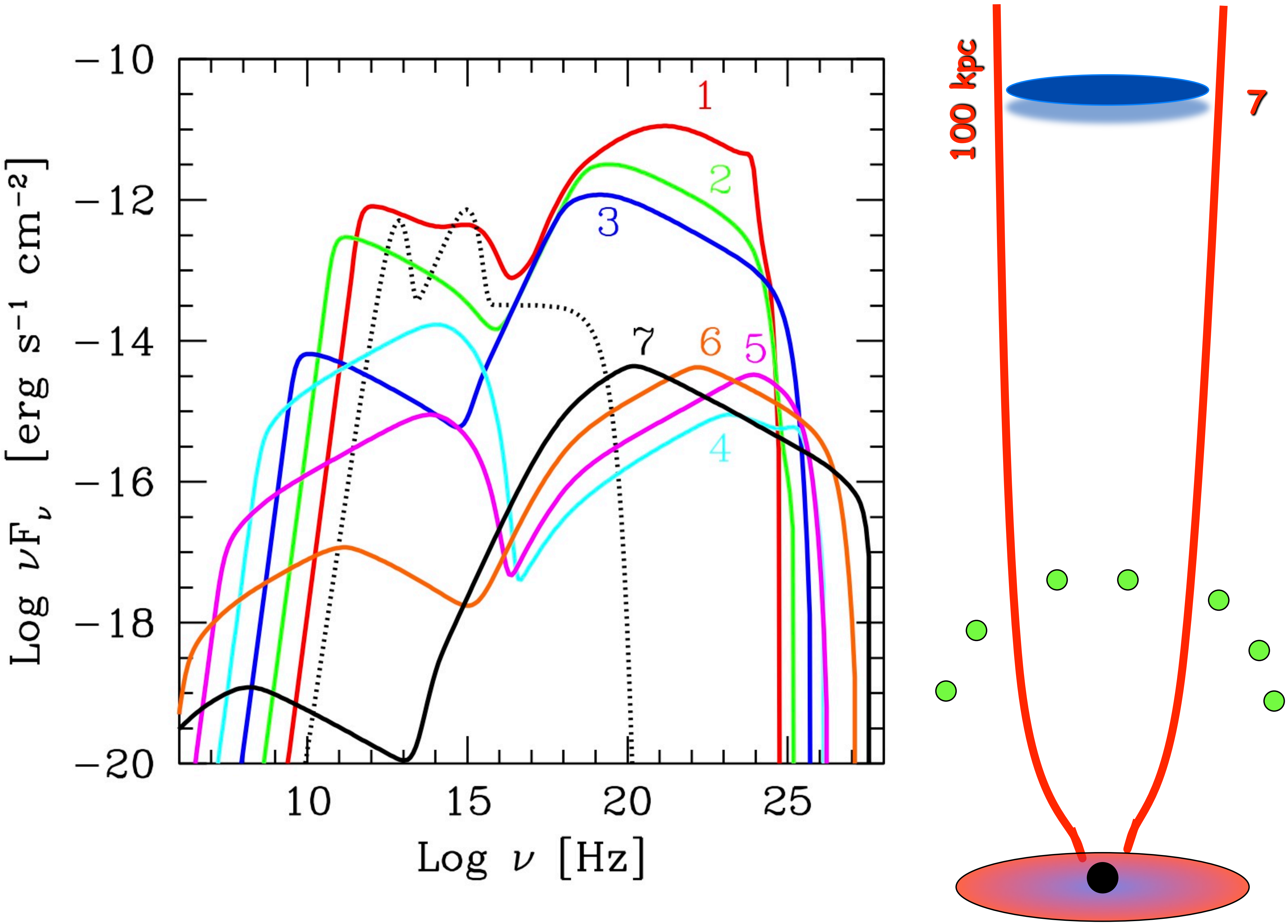
−10
−12
−14
−16
−18
−20
Log νF_ν [erg s^−1 cm^−2]
10
15
20
25
Log ν [Hz]
1
2
3
4
Slow cooling → hard
100 pc
4

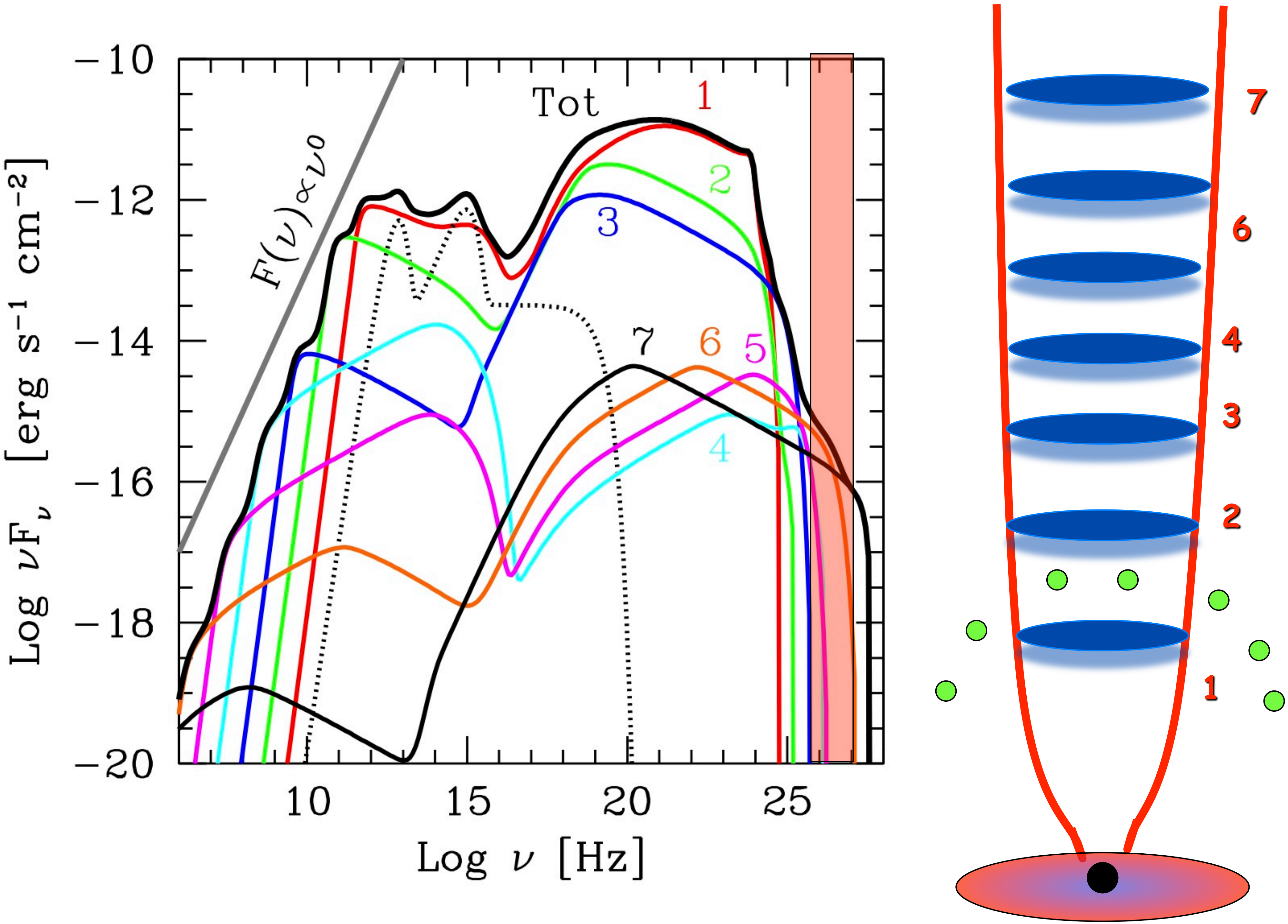


Log νF_ν [erg s⁻¹ cm⁻²]
−10
−12
−14
−16
−18
−20
10
15
20
25
Log ν [Hz]
1
2
3
4
5
1 kpc
5



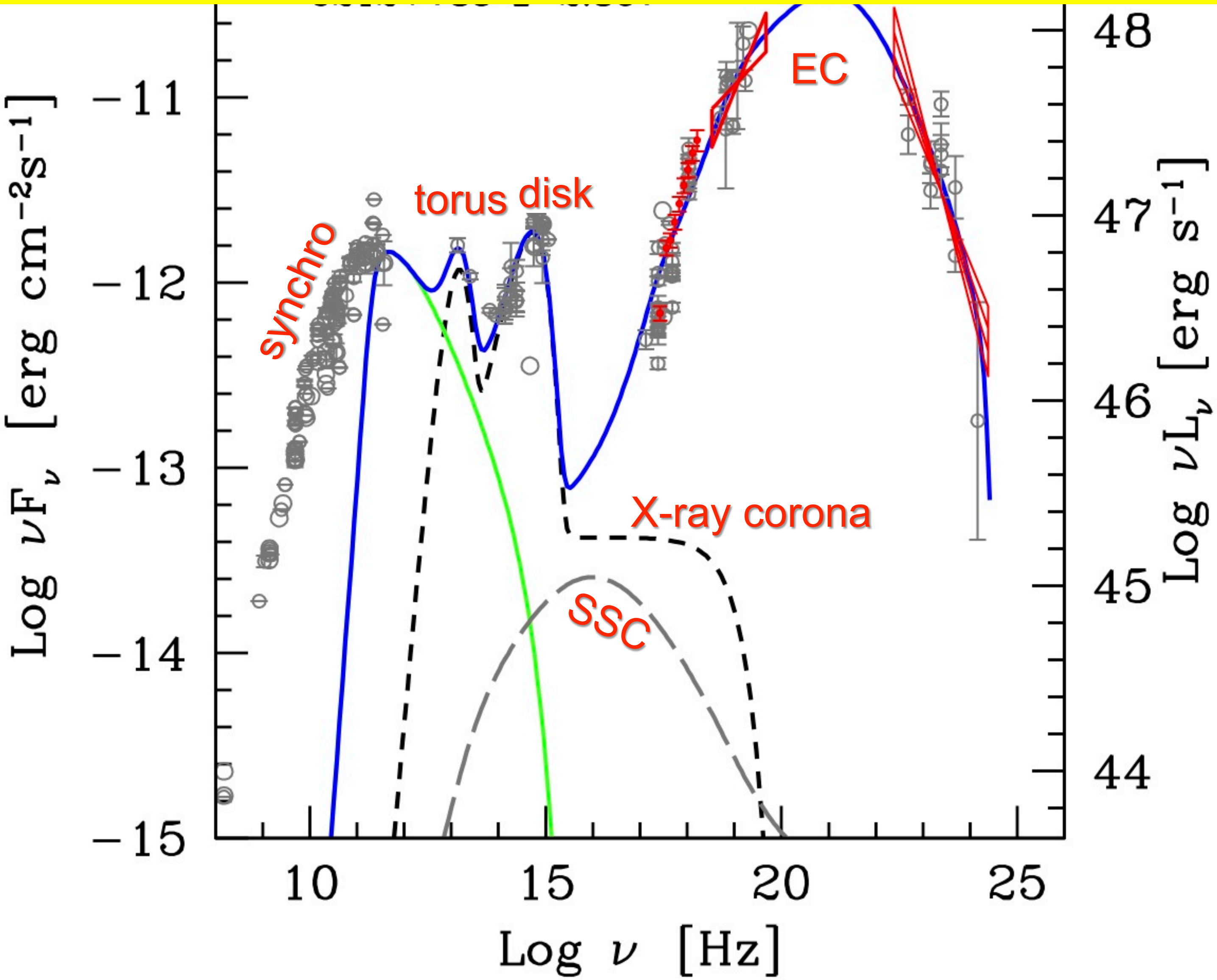
−10
−12
−14
−16
−18
−20
10
15
20
25
Log νF$_ν$ [erg s^{-1} cm^{-2}]
Log ν [Hz]
1
2
3
4
5
6
10 kpc
6


Log νF_ν [erg s⁻¹ cm⁻²]
Log ν [Hz]
−10
−12
−14
−16
−18
−20
10
15
20
25
1
2
3
4
5
6
7
100 kpc
7

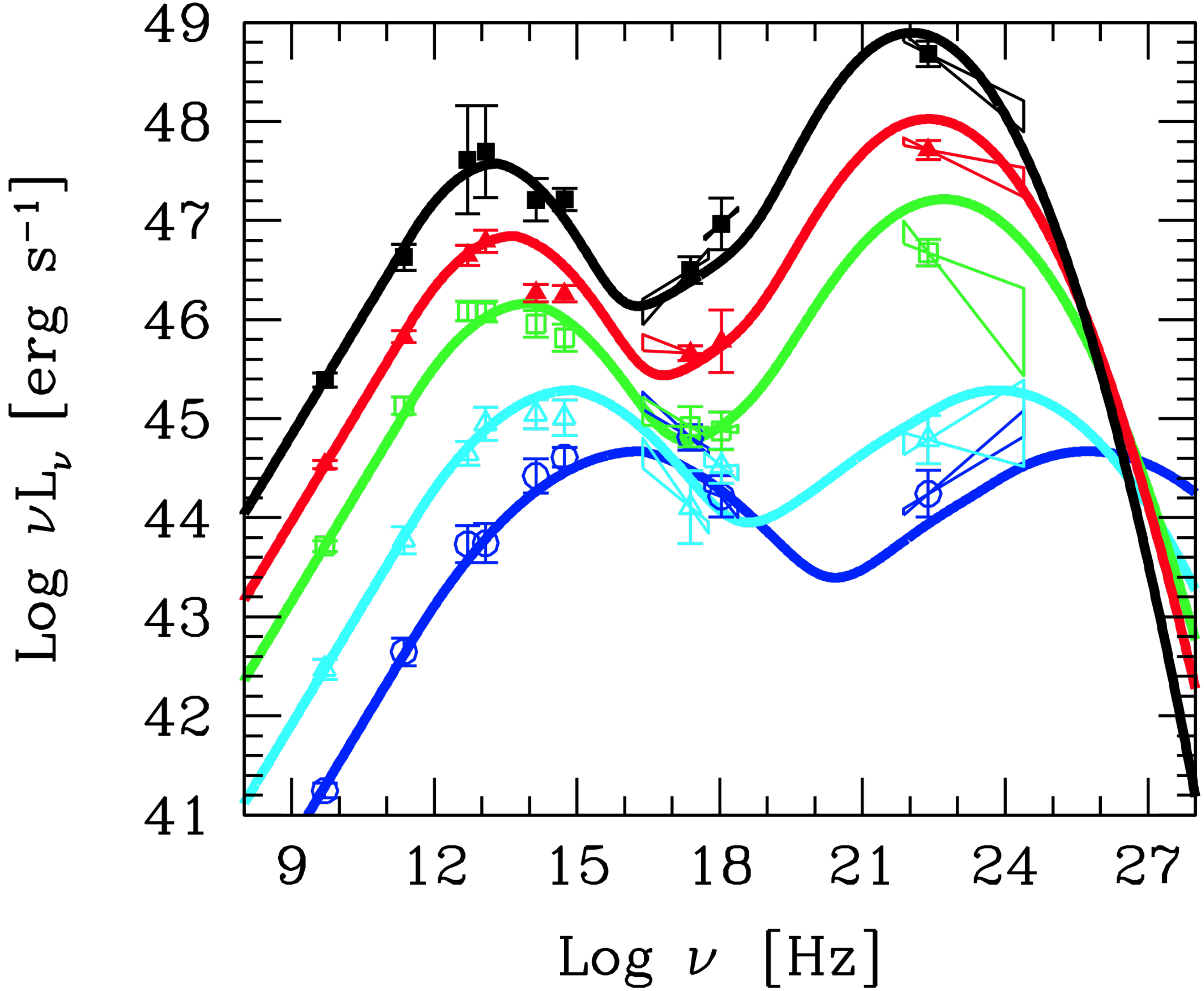


Log νF_ν [erg s⁻¹ cm⁻²]
Log ν [Hz]
F(ν) ∝ ν0
Tot
1
2
3
4
5
6
7
−10
−12
−14
−16
−18
−20
10
15
20
25
7
6
4
3
2
1

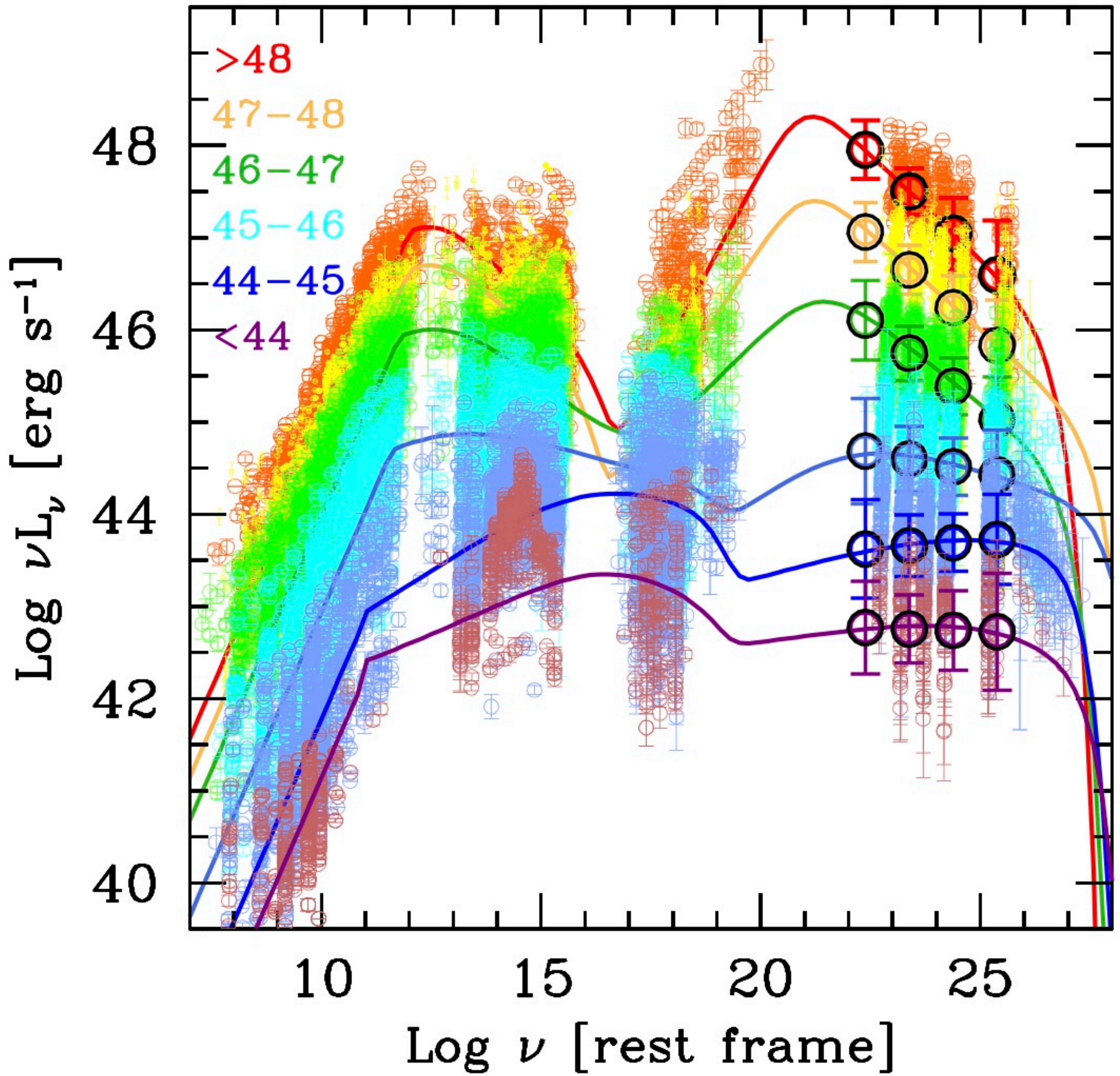
In powerful blazars at z>2 the accretion disk is well visible. Also the torus is visible.



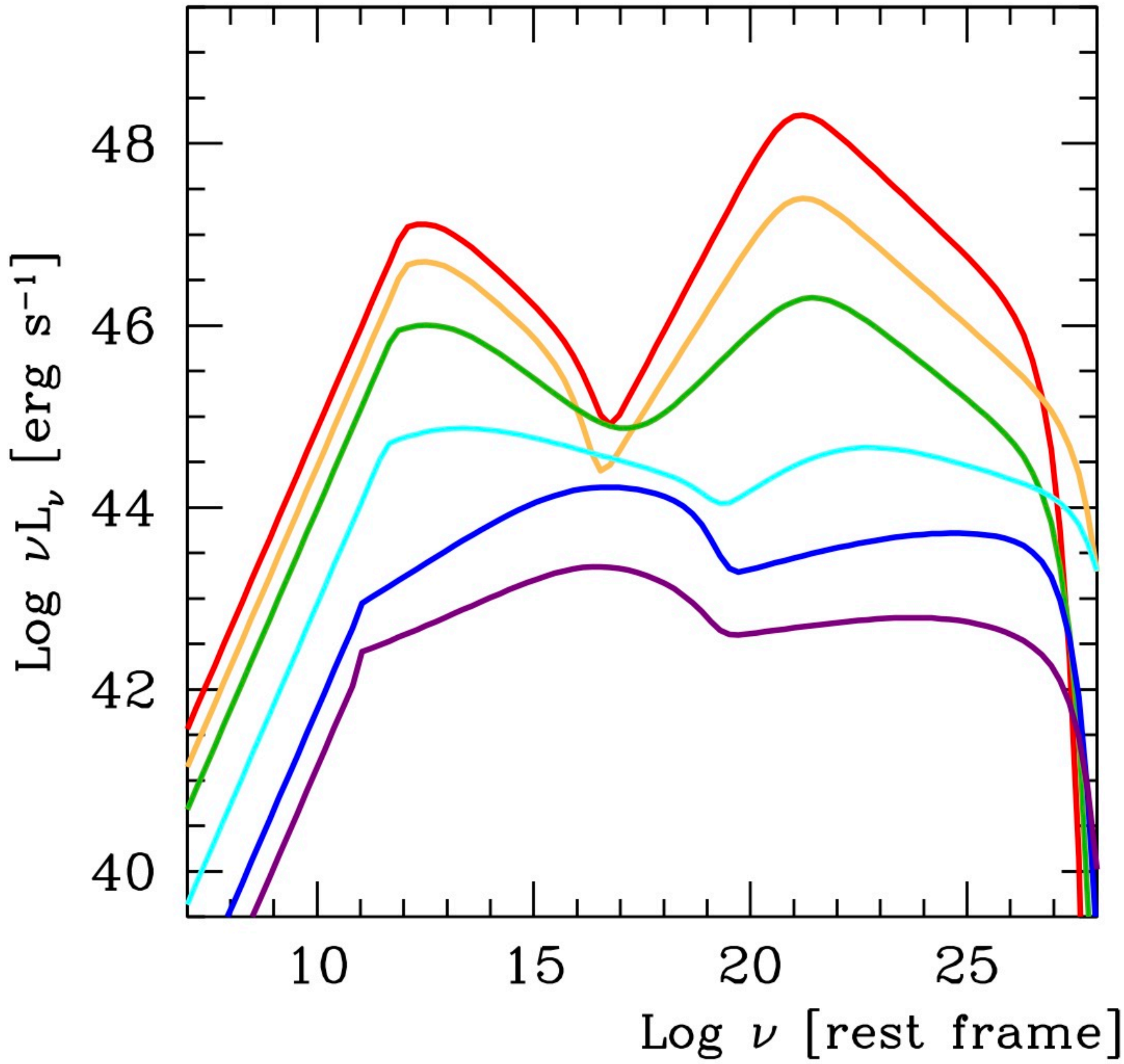
1992+: EGRET - Most of power of blazars emitted in γ-rays



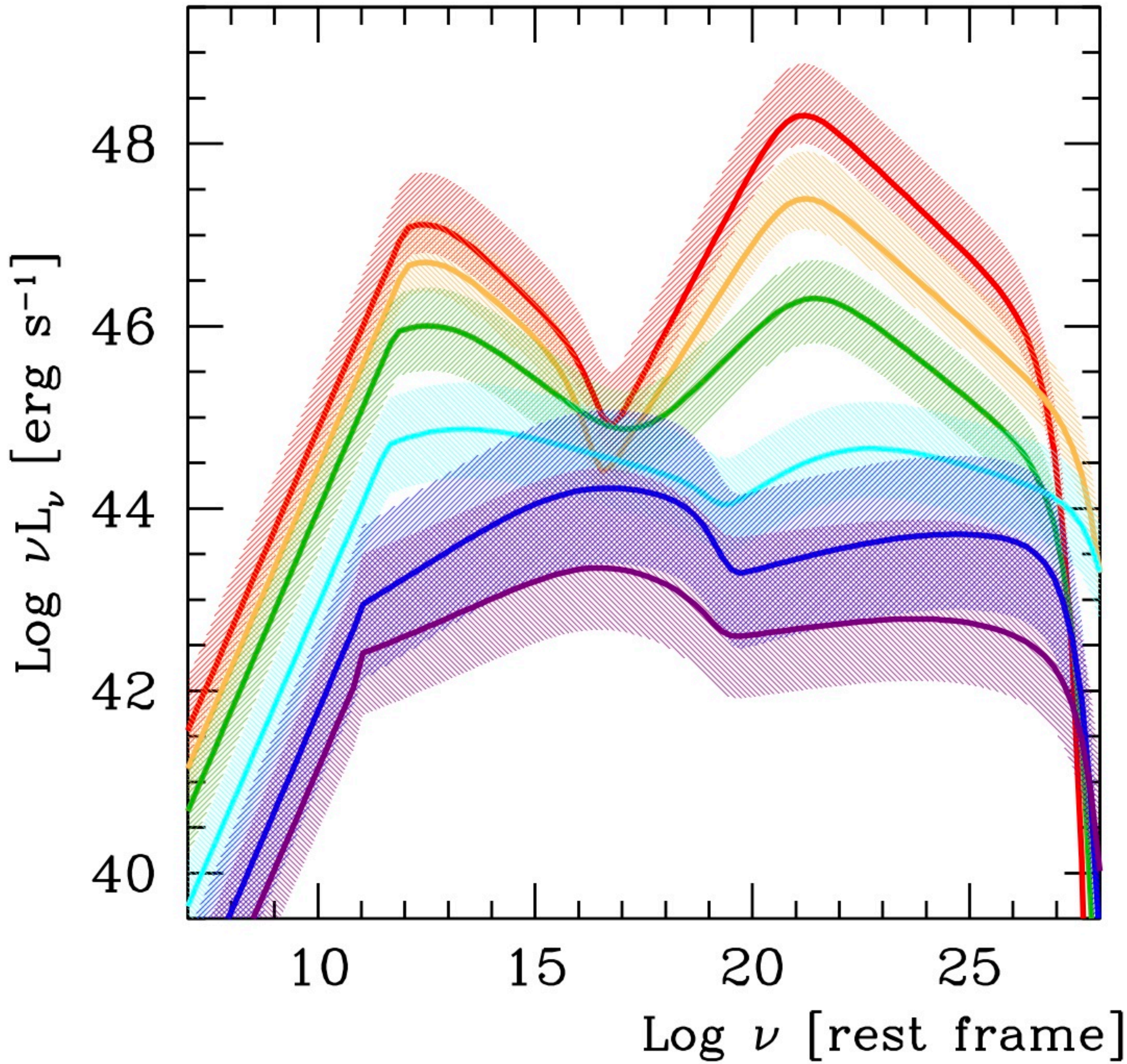
Fossati et al. 1998; Donato et al. 2001



GG, Righi+, 2017



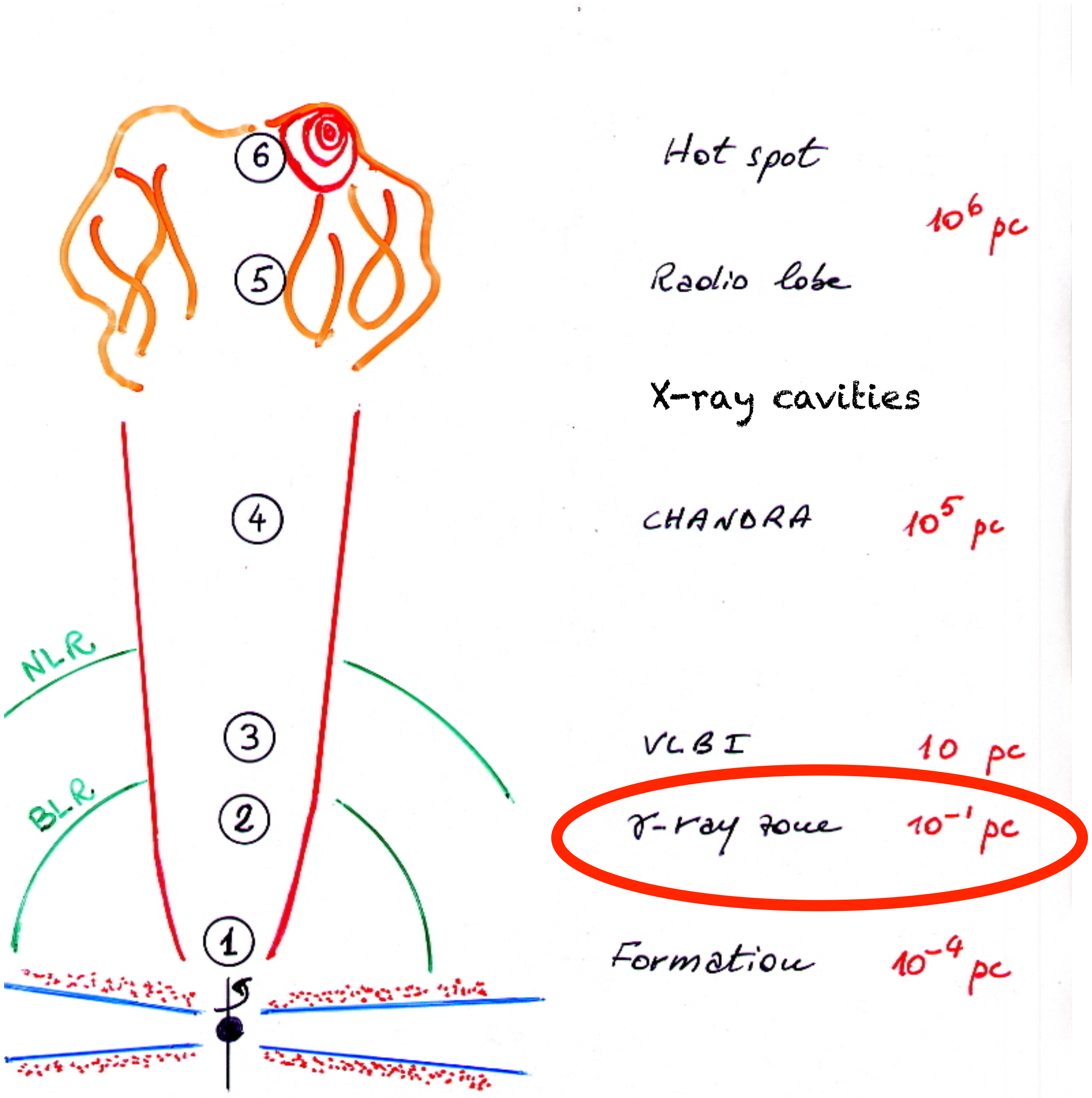
48
46
44
42
40
Log νL_ν [erg s^{-1}]
10
15
20
25
Log ν [rest frame]



GG, Righi+, 2017

The power of jets

Power of jets



jet power and accretion luminosity

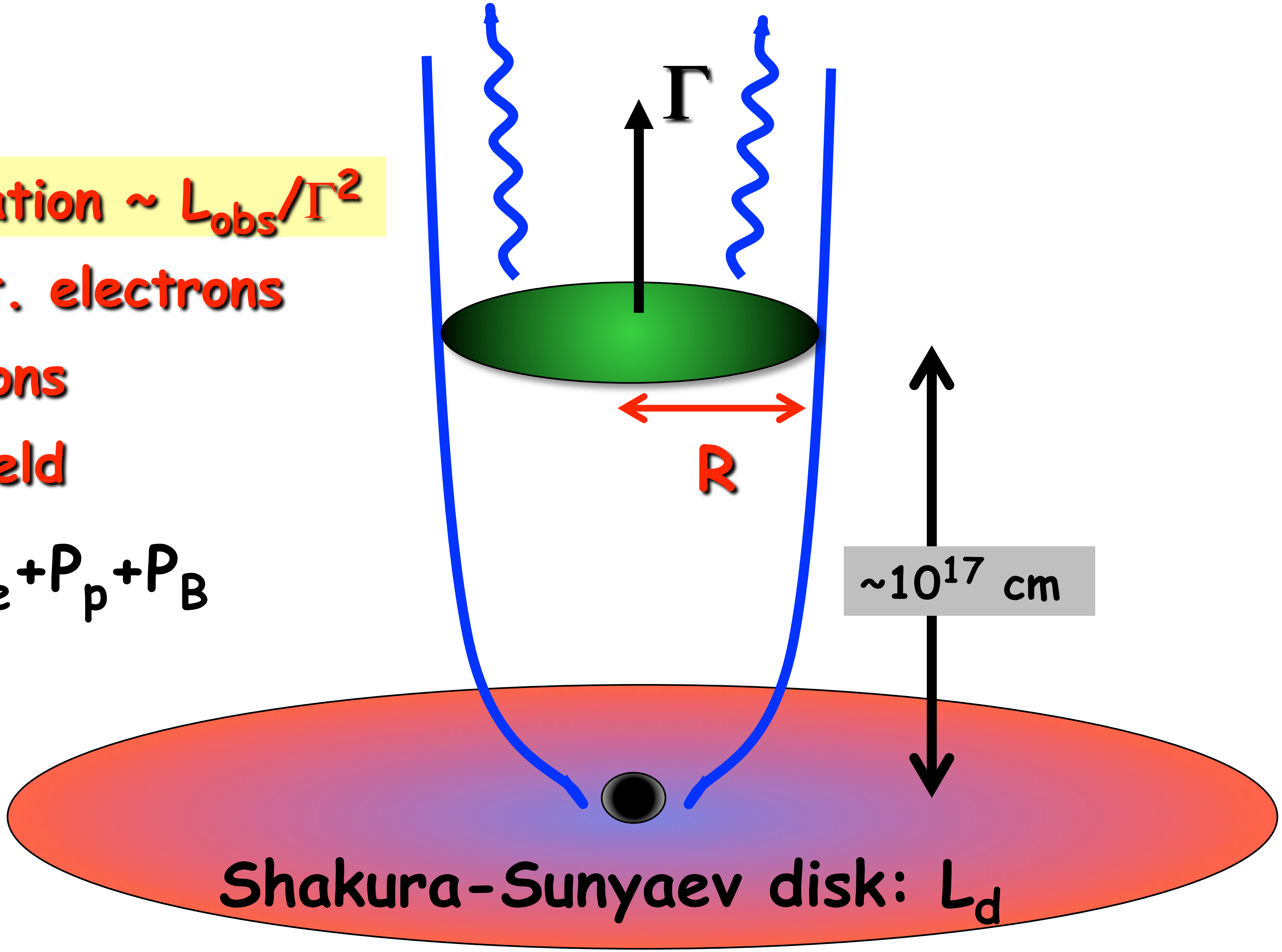
P_r = radiation ~ L_{obs}/Γ^2

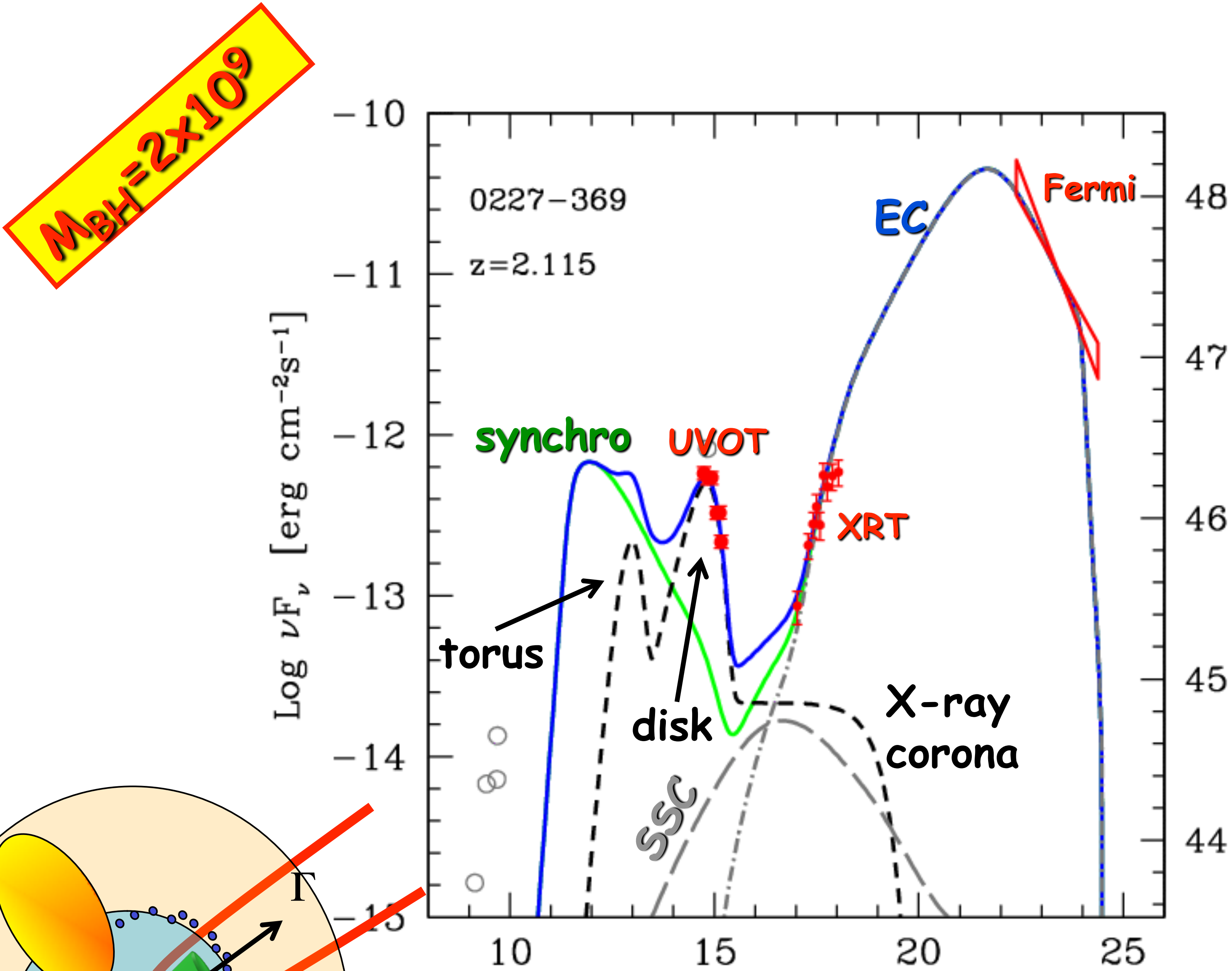
P_e = relat. electrons

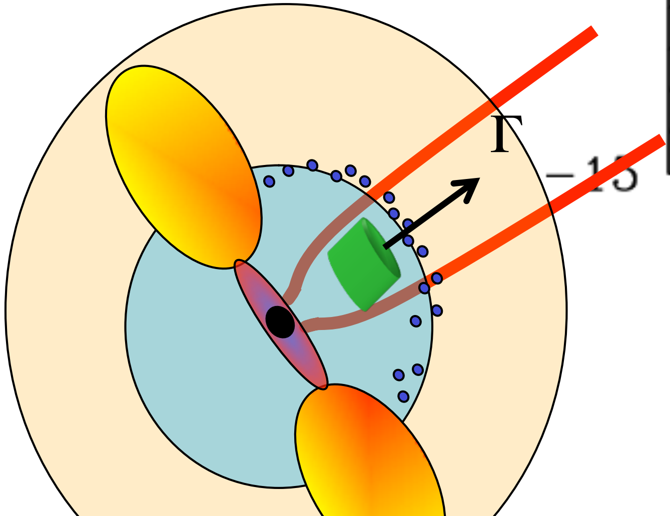
P_p = protons

P_B = B-field

$$P_{jet} = P_e + P_p + P_B$$

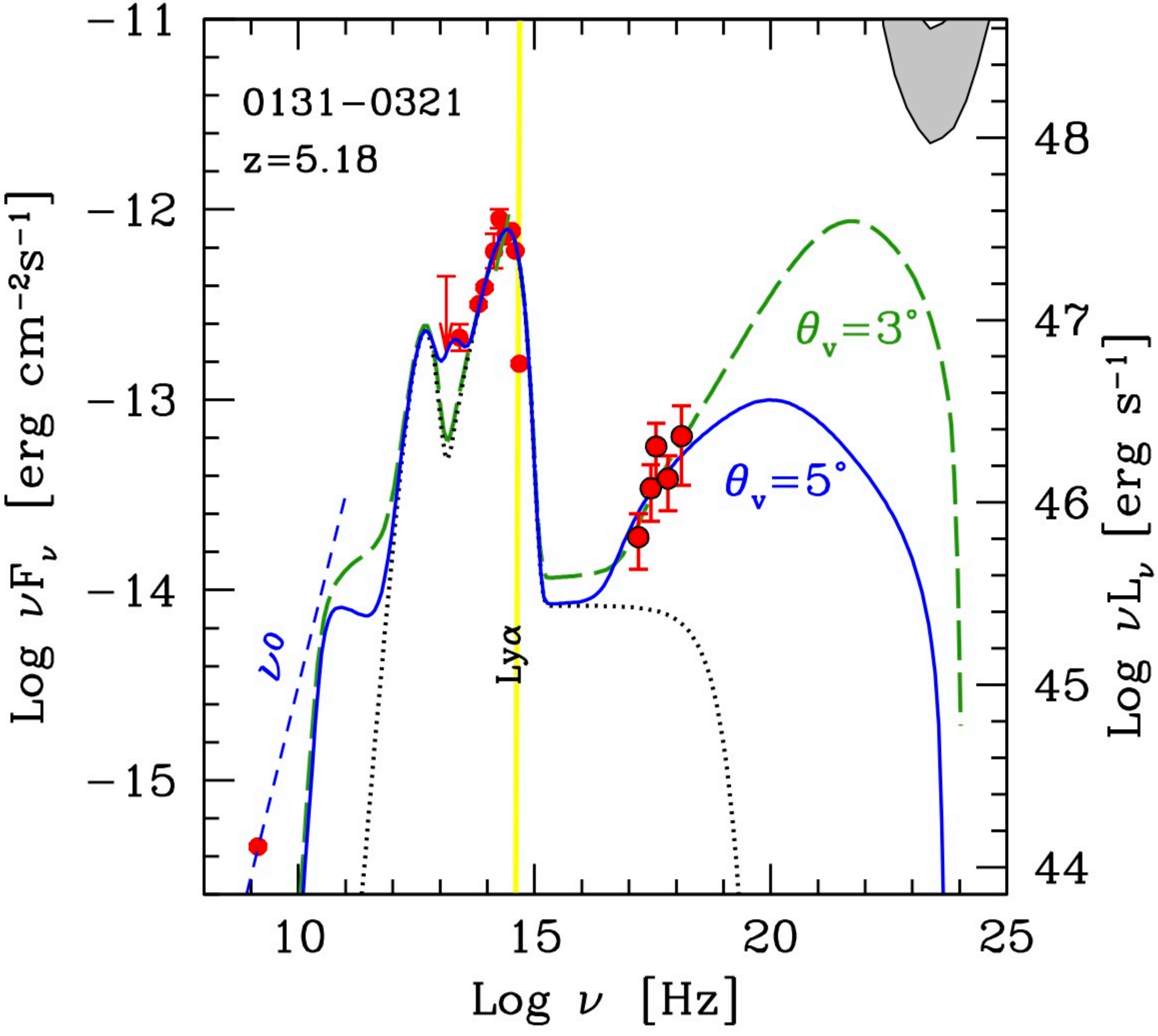




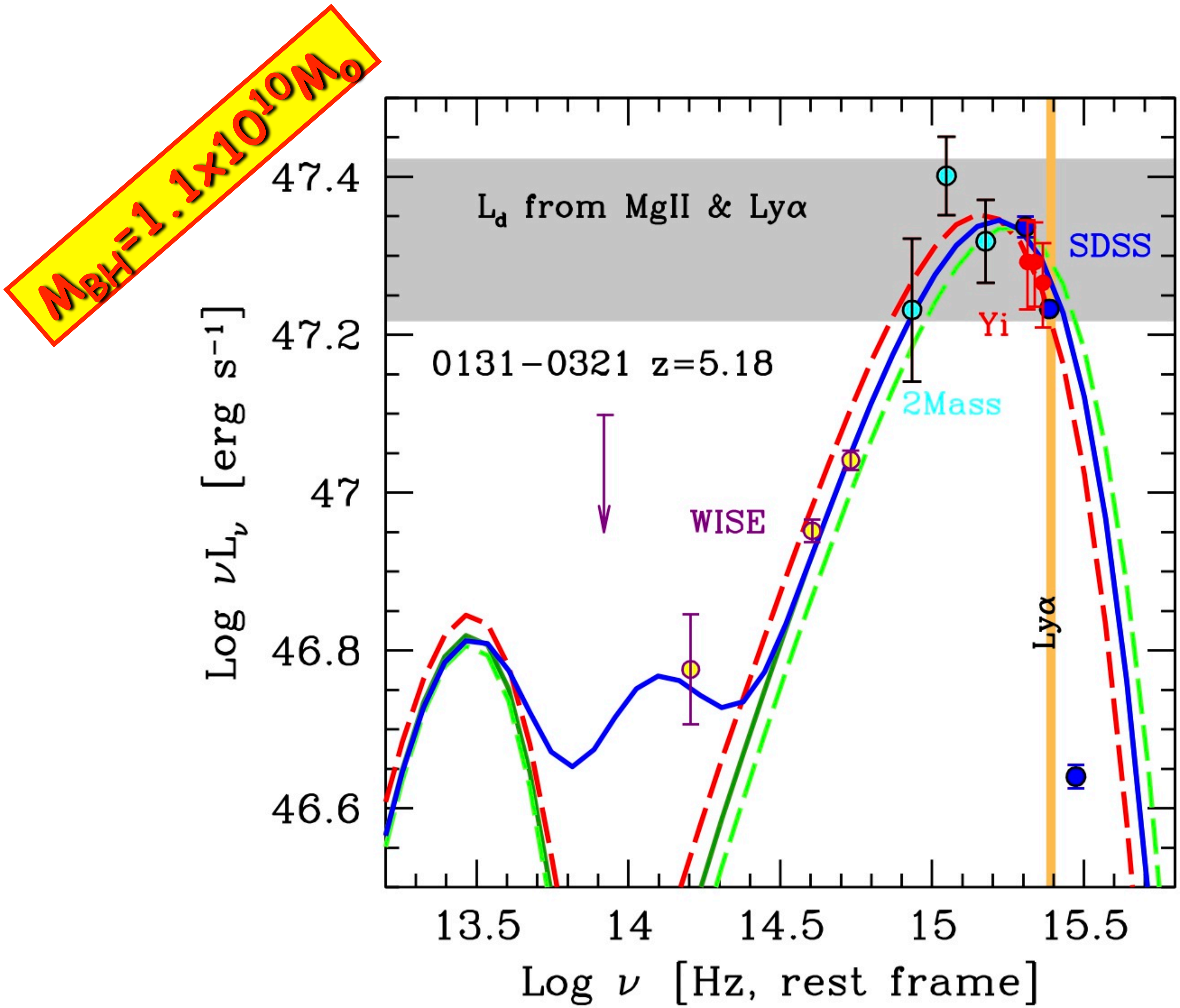


Low energy synchro peak:
leave the disk naked!

GG, Tavecchio & Ghirlanda 2009



0131−0321
z=5.18
Lyα
ν0
θv=3°
θv=5°
Log νFν [erg cm−2s−1]
Log νLν [erg s−1]
Log ν [Hz]
−11
−12
−13
−14
−15
48
47
46
45
44
10
15
20
25



M_BH=1.1x10^10 M_o
L_d from MgII & Lyα
0131−0321 z=5.18
WISE
2Mass
SDSS
Yi
Lyα
47.4
47.2
47
46.8
46.6
13.5
14
14.5
15
15.5
Log νL_ν [erg s^-1]
Log ν [Hz, rest frame]

If you want to compare disk luminosity and jet power, the best sample is:

Blazars detected
by Fermi → $L_{obs, jet}$
with broad emission lines → L_{disk}

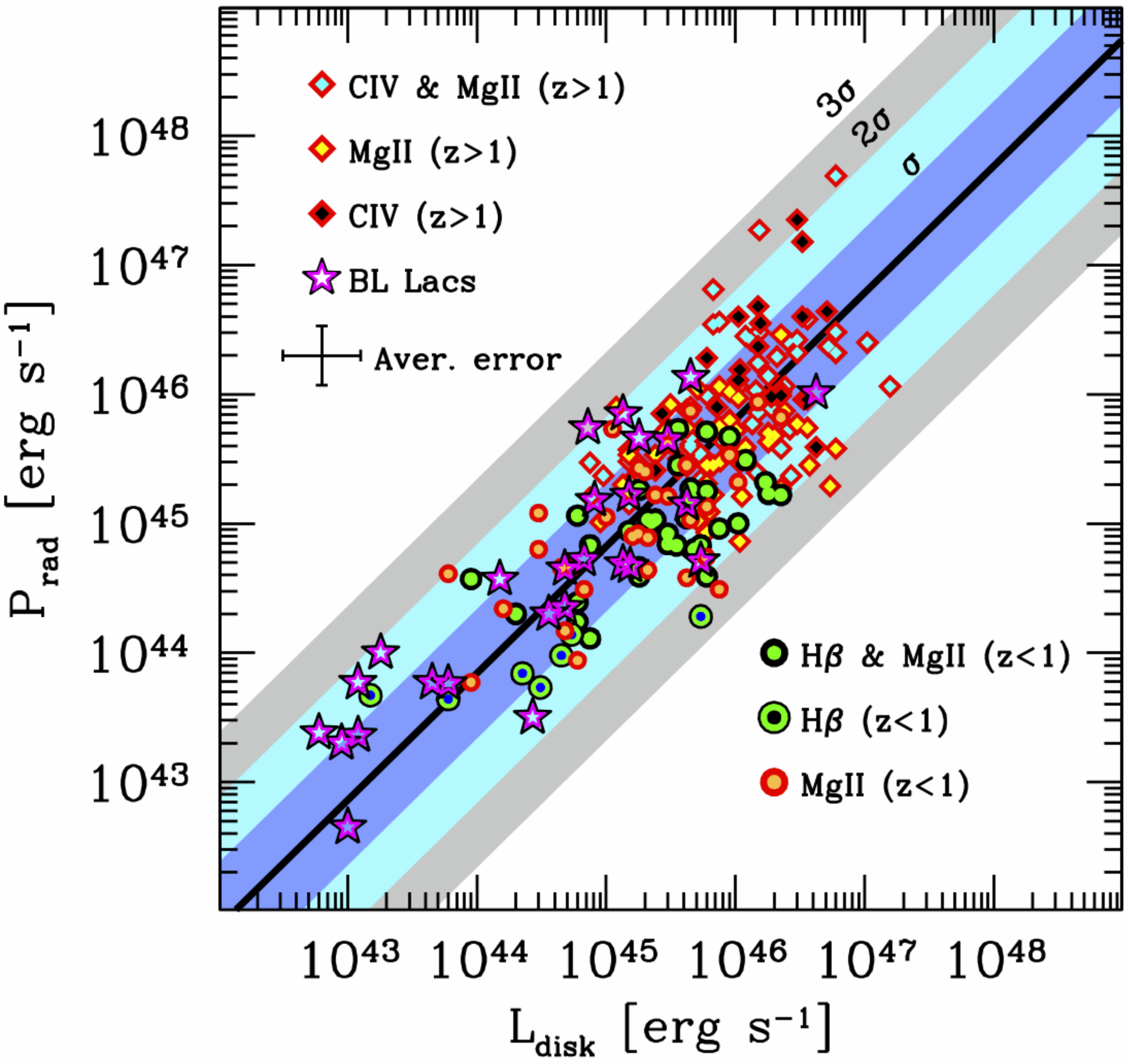
Shaw+ 2012: FSRQs (~220 sources)
Shaw+ 2013: BL Lacs (26 with BLR)

The jet cannot have less power than what required to produce the observed luminosity:

$$P_{jet} > P_{rad} = \frac{L_{obs}}{\Gamma^2}$$

If P_{jet} is twice as much, Γ halves.
We can take P_{rad} as the minimum P_{jet}.

This limit is model-independent.



GG+ Nature, 2014

From P_{rad} to P_{jet}

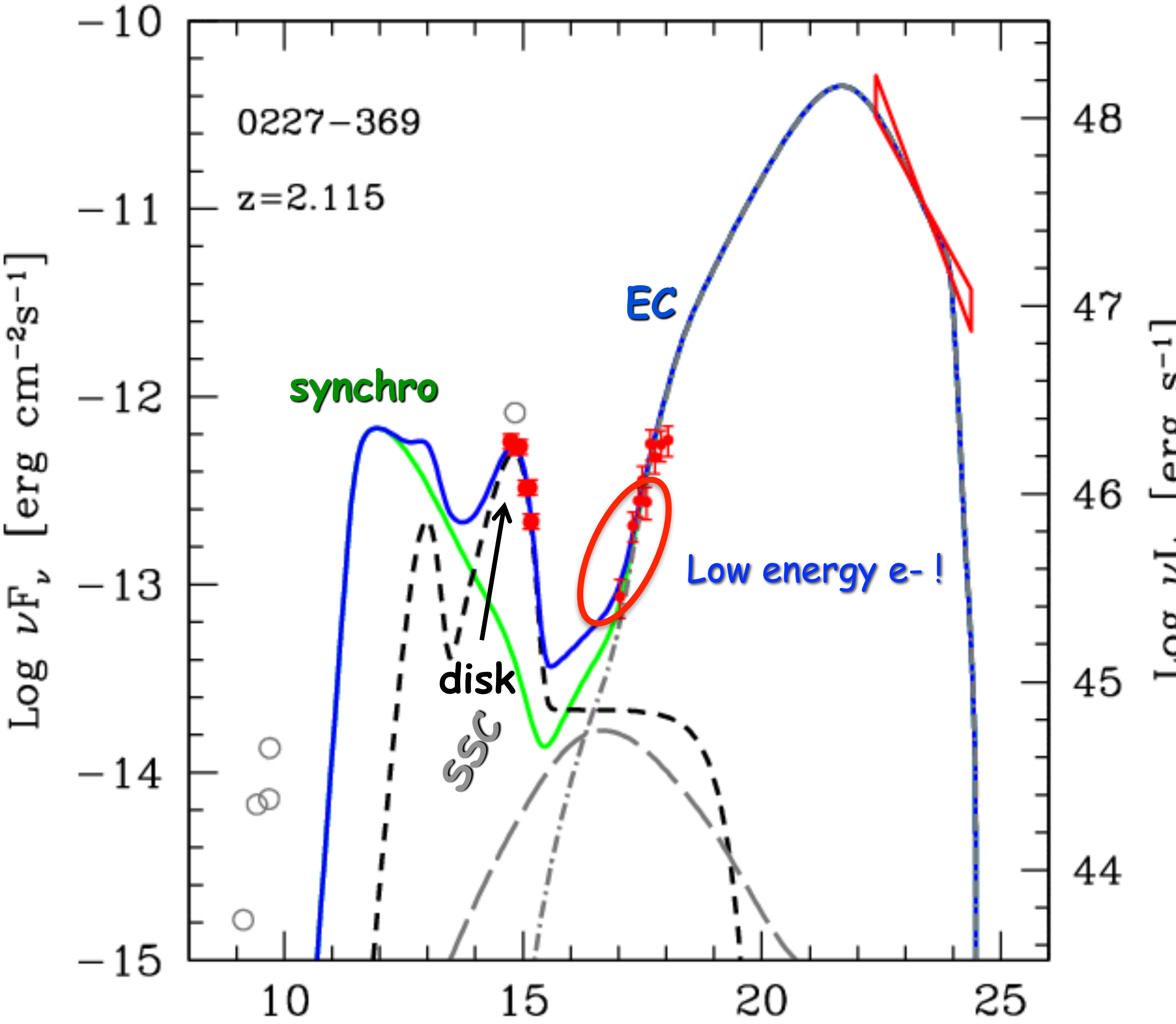
- γ_{min} → total number of e- (and of protons, if no pairs…)
- Presence of electron positron pairs
- Radiative model: SSC vs EC vs baryons

From P_{rad} to P_{jet}

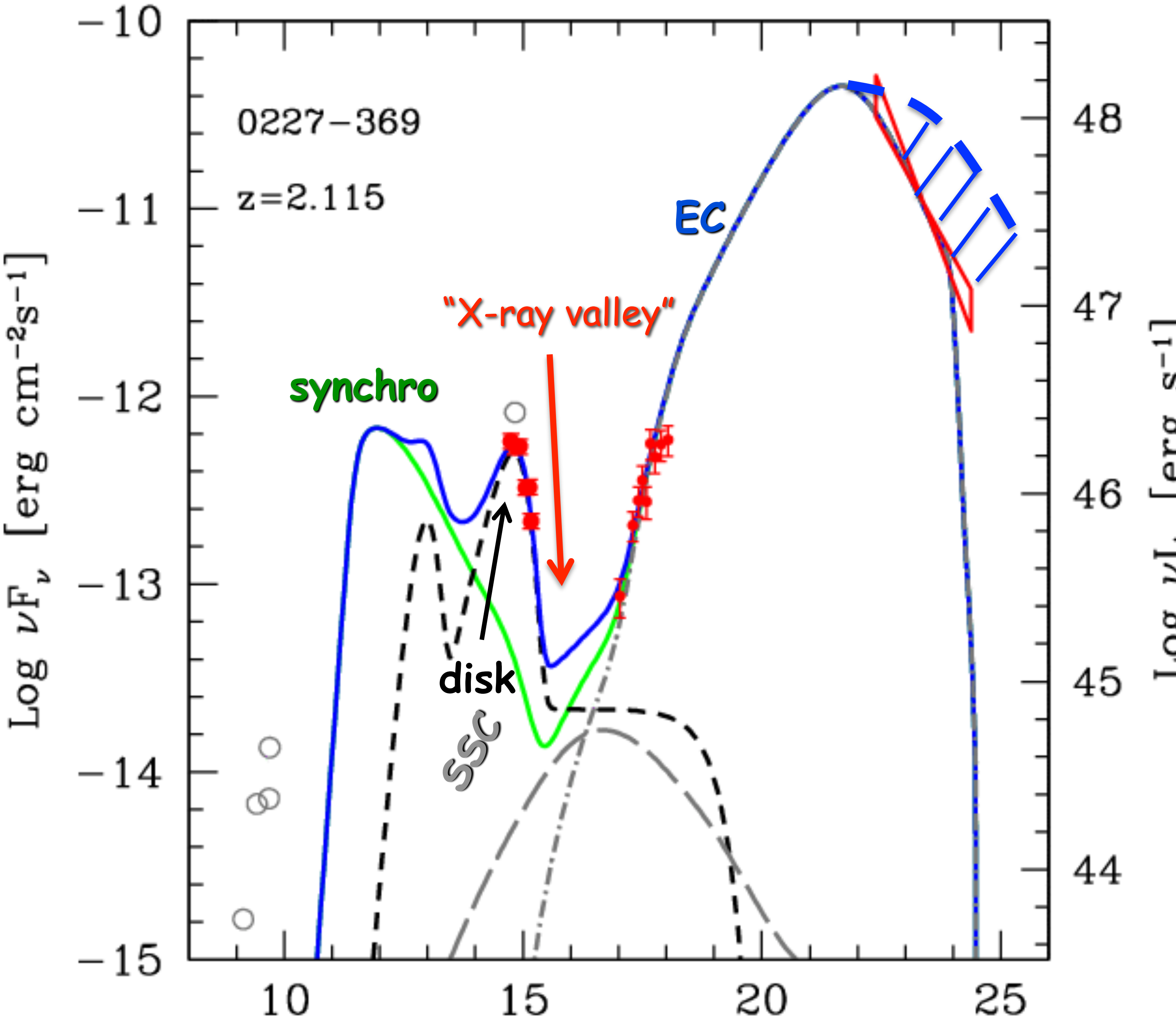
- γ_{min} → total number of e- (and of protons, if no pairs…)
- Presence of electron positron pairs
- Radiative model: ~~SSC~~ vs EC vs ~~baryons~~

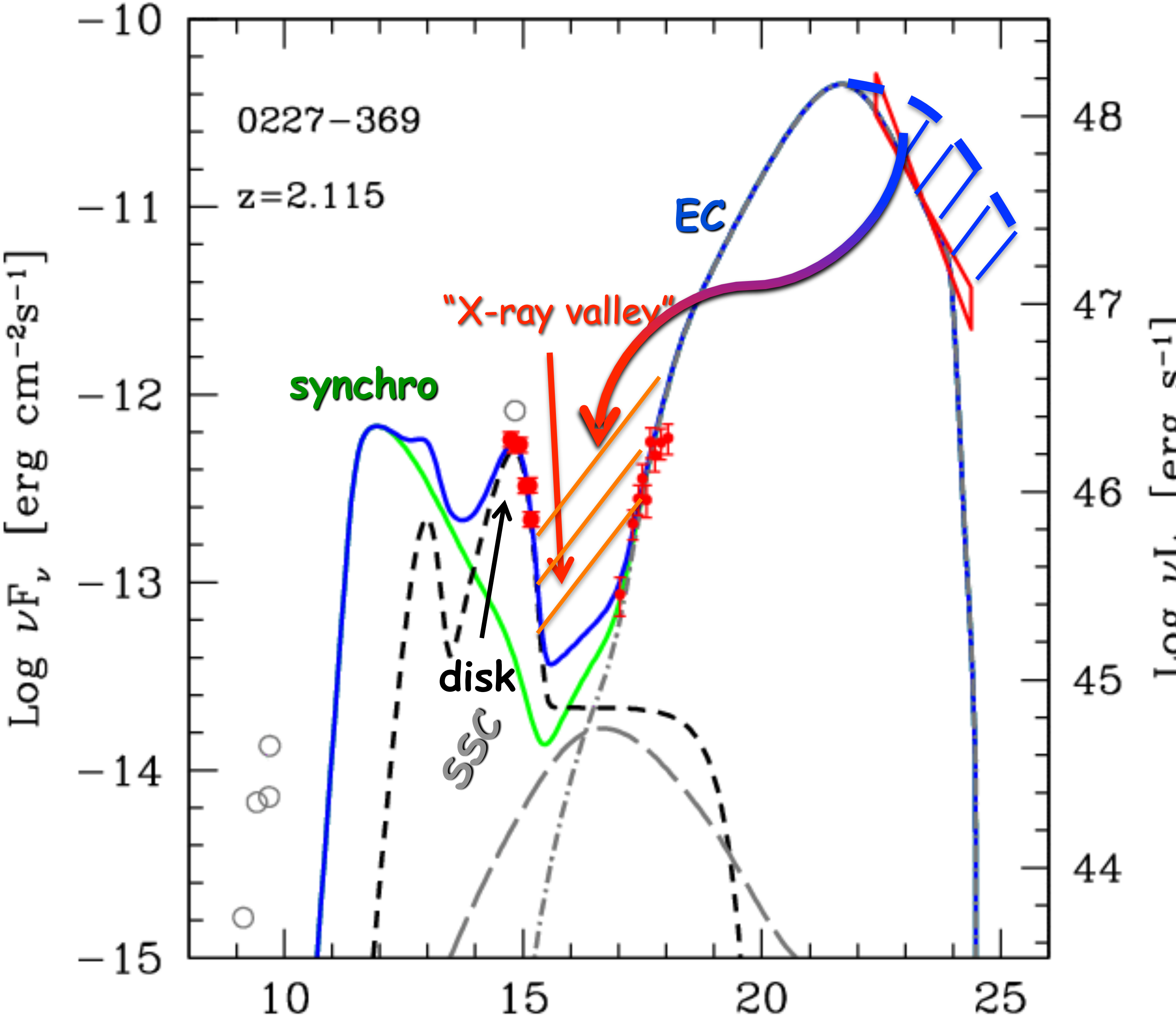
doesn't fit

even more power

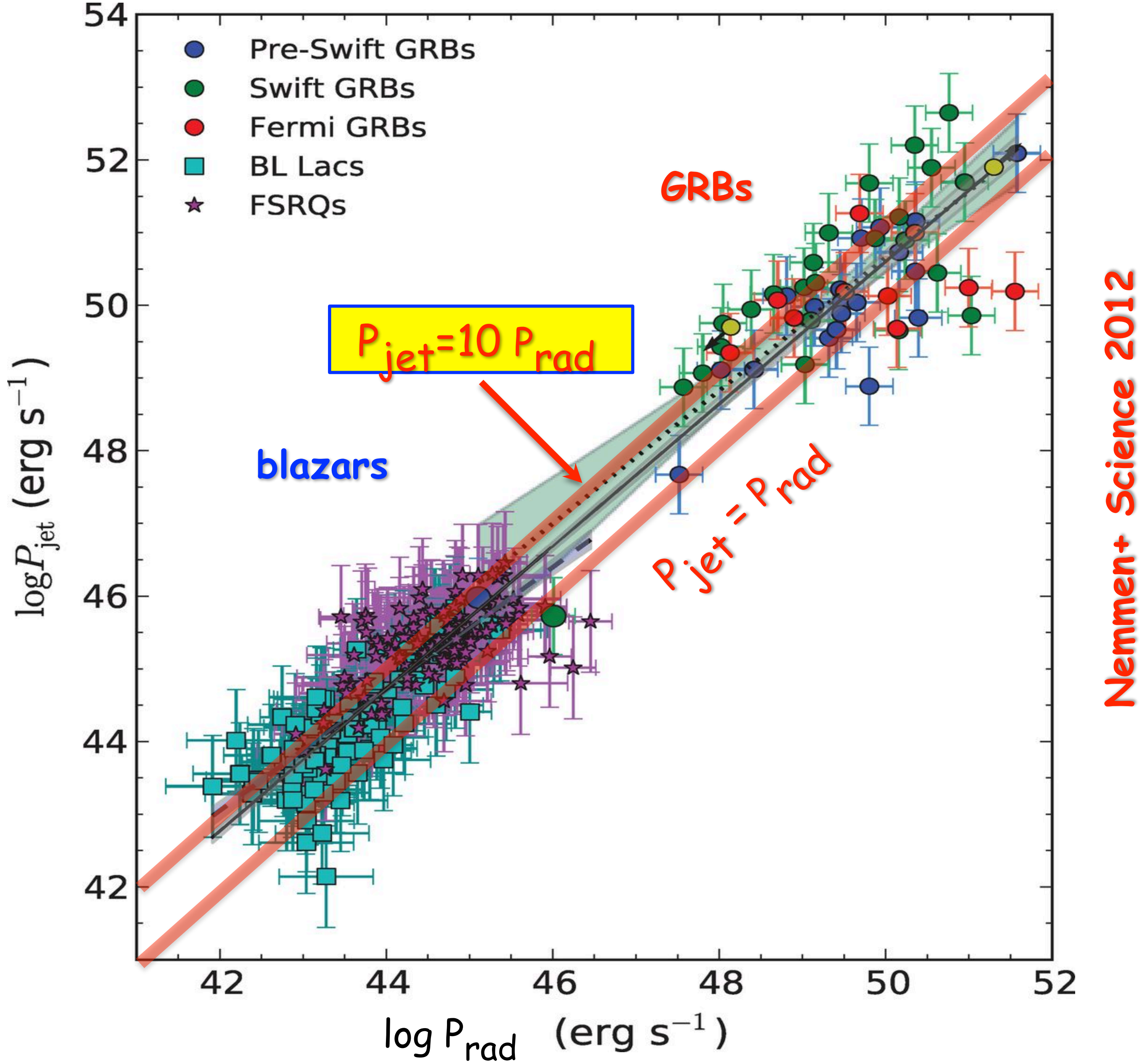


0227−369
z=2.115
synchro
EC
disk
SSC
Low energy e- !
Log νF_ν [erg cm⁻²s⁻¹]
Log νL_ν [erg s⁻¹]
−10
−11
−12
−13
−14
−15
48
47
46
45
44
10
15
20
25

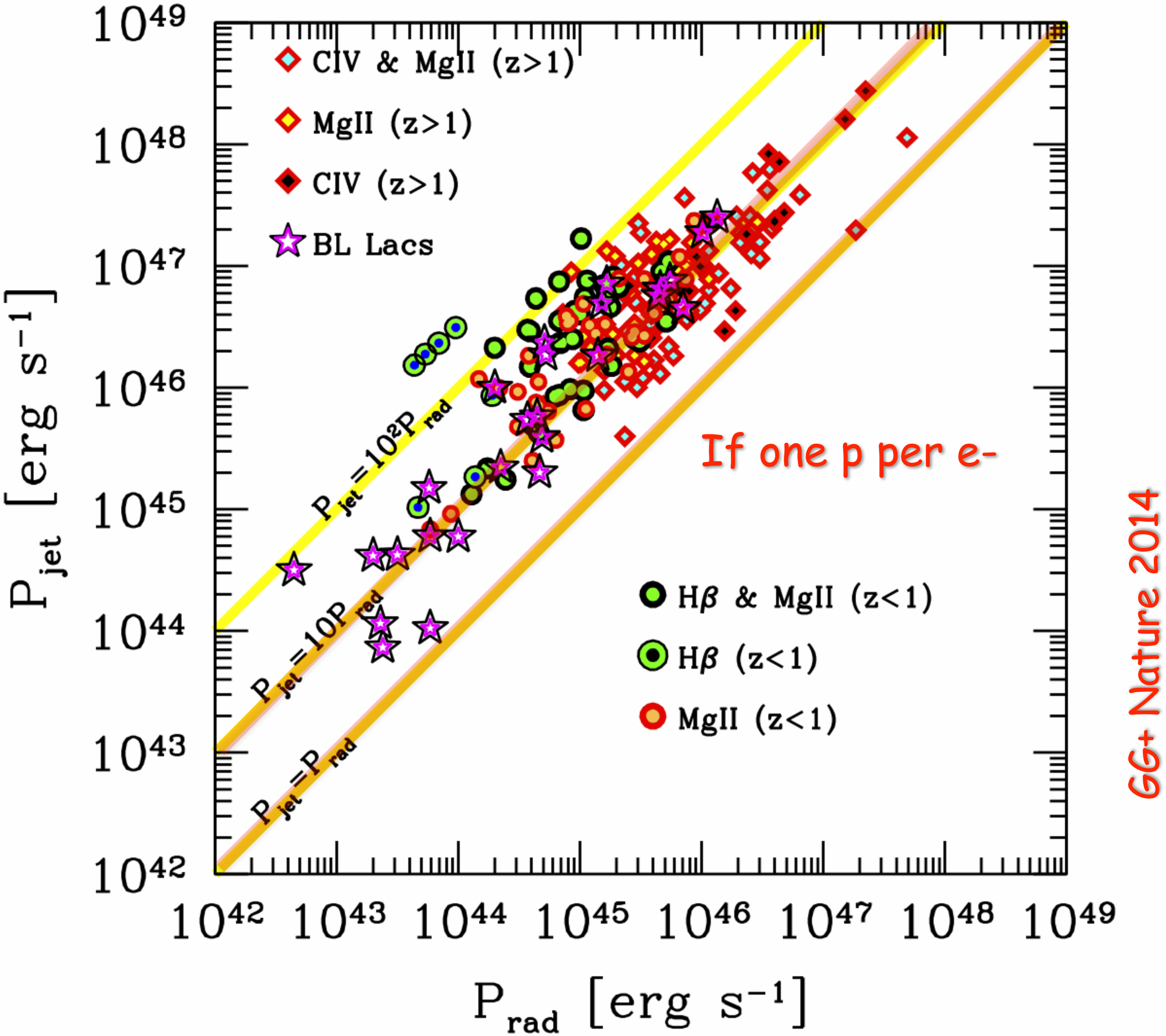

0227−369
z=2.115
EC
"X-ray valley"
synchro
disk
SSC
Log νF_ν [erg cm⁻²s⁻¹]
Log νL_ν [erg s⁻¹]
−10
−11
−12
−13
−14
−15
48
47
46
45
44
10
15
20
25



0227−369
z=2.115
EC
"X-ray valley"
synchro
disk
SSC
Log νFν [erg cm⁻²s⁻¹]
Log νLν [erg s⁻¹]
−10
−11
−12
−13
−14
−15
48
47
46
45
44
10
15
20
25

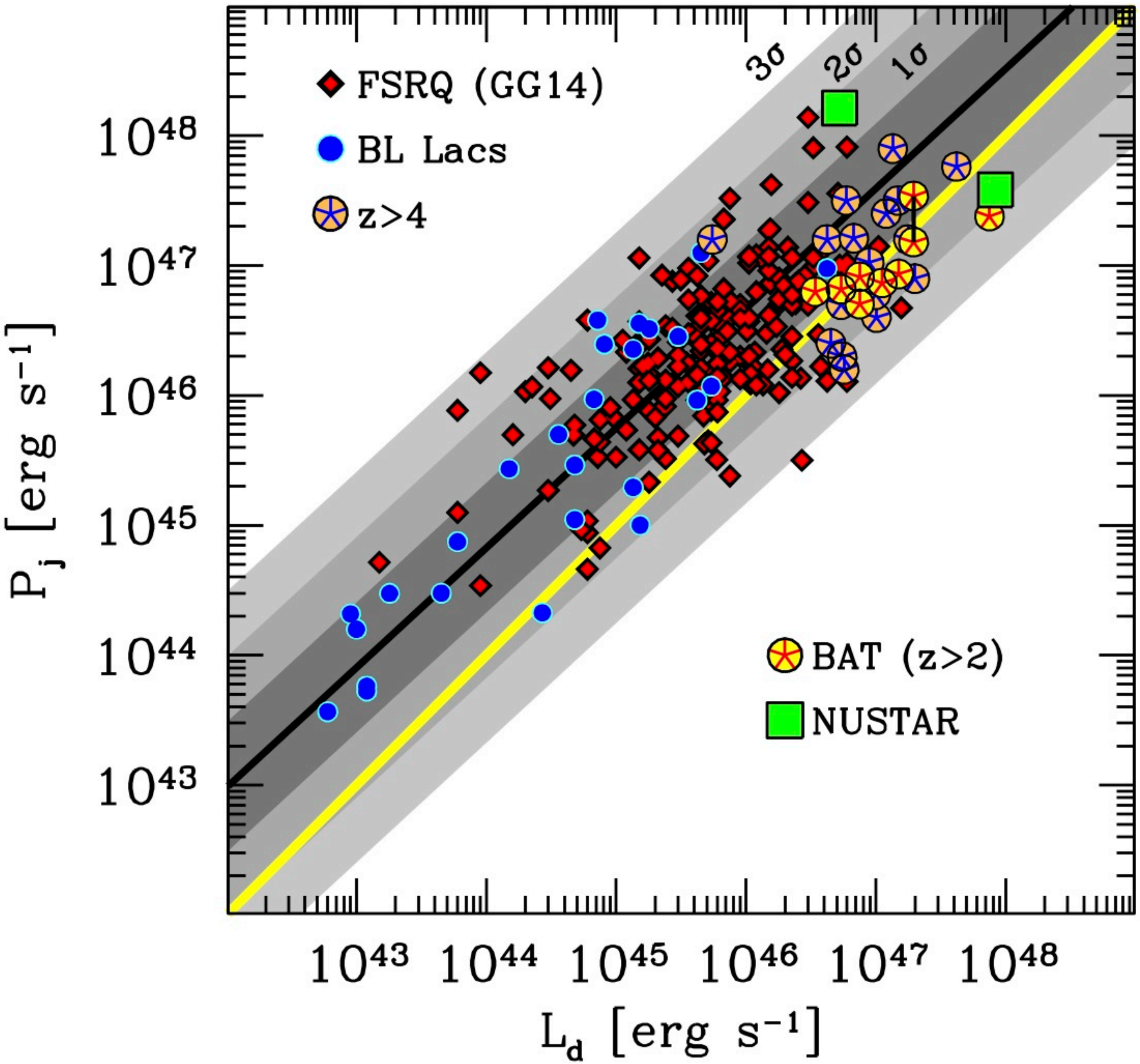


Pre-Swift GRBs
Swift GRBs
Fermi GRBs
BL Lacs
FSRQs
GRBs
P jet=10 P rad
blazars
P jet = P rad
Nemmen+ Science 2012
log P jet (erg s^-1)
log P rad (erg s^-1)
54
52
50
48
46
44
42
42
44
46
48
50
52



CIV & MgII (z>1)
MgII (z>1)
CIV (z>1)
BL Lacs
Hβ & MgII (z<1)
Hβ (z<1)
MgII (z<1)
$P_{jet}=10^2 P_{rad}$
$P_{jet}=10 P_{rad}$
$P_{jet}=P_{rad}$
If one p per e-
P_{jet} [erg s^{-1}]
P_{rad} [erg s^{-1}]
10^{42} 10^{43} 10^{44} 10^{45} 10^{46} 10^{47} 10^{48} 10^{49}
GG+ Nature 2014

1 proton per electron → no pairs



Sbarrato+, 2016

Apparent paradox:

Jet power proportional to accretion

And yet it is greater....

Blandford Znajek

$$P_{BZ} \sim a^2 B^2 M^2$$

Blandford Znajek

$$P_{BZ} \sim a^2B^2M^2$$

$$\downarrow$$

$$P_{BZ} \sim a^2B^2R_g{}^2c$$ Poynting Flux

Blandford Znajek

$$P_{BZ} \sim a^2 B^2 M^2$$

$\downarrow$

$$P_{BZ} \sim a^2 B^2 R_g^2 c$$

Poynting Flux

$\downarrow$

$$P_{BZ} \sim a^2 \rho c^2 R_g^2 c$$

$\rho c^2 \sim B^2/8\pi$

$$P_{BZ} \sim a^2 \dot{M} c^2$$

Rotation > Accretion

B-field amplified by accretion can tap the spin energy of the hole

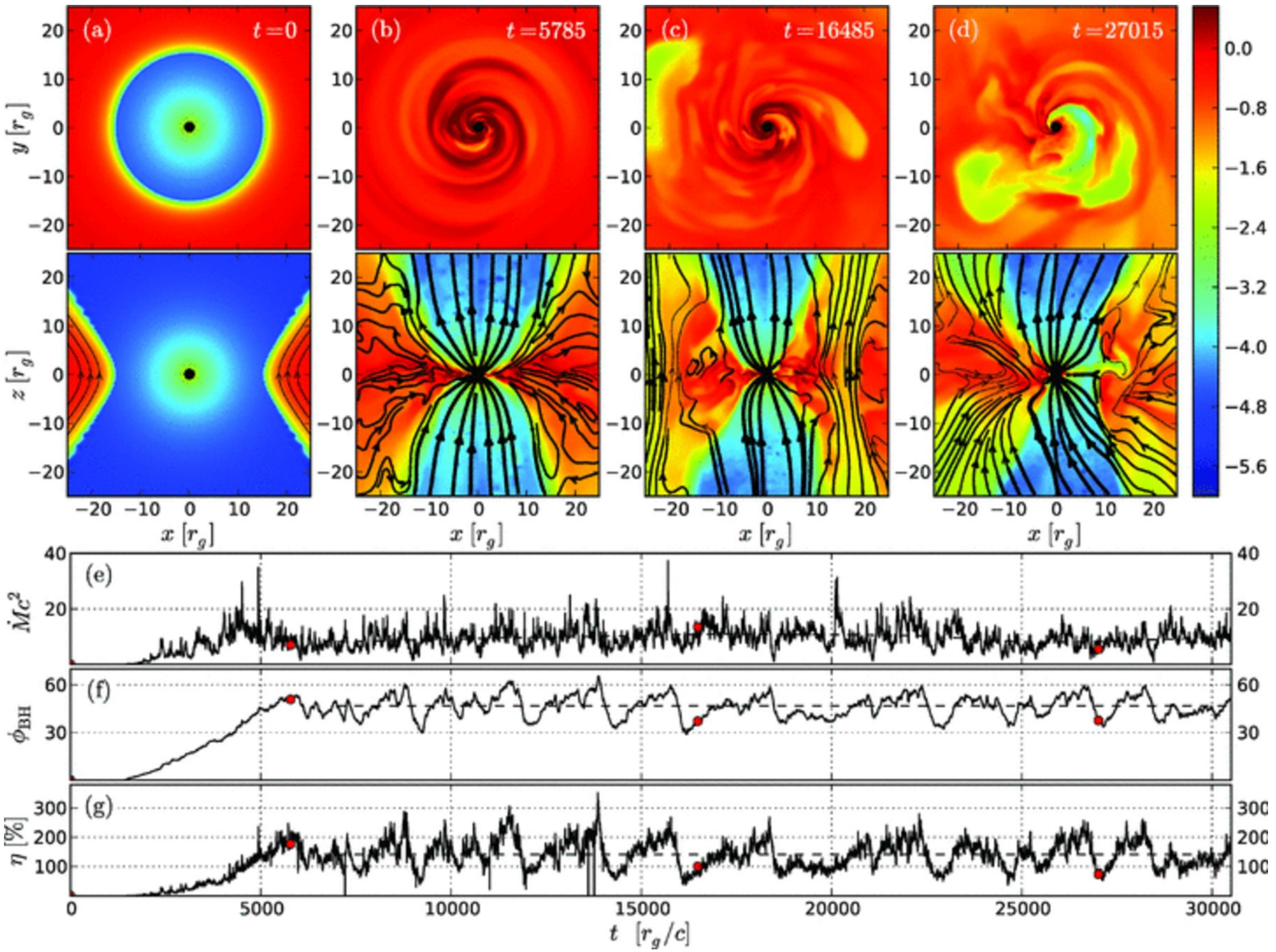
This process is very efficient

The B-field "does not work", the jet power comes from the BH spin

Yet it is the catalyst for the process. No B no jet.

But B is linked to accretion, that's why P_{jet} is propto L_d

Shows results from the fiducial GRMHD simulation A0.99fc for a BH with spin parameter a = 0.99; see Supporting Information for the movie.



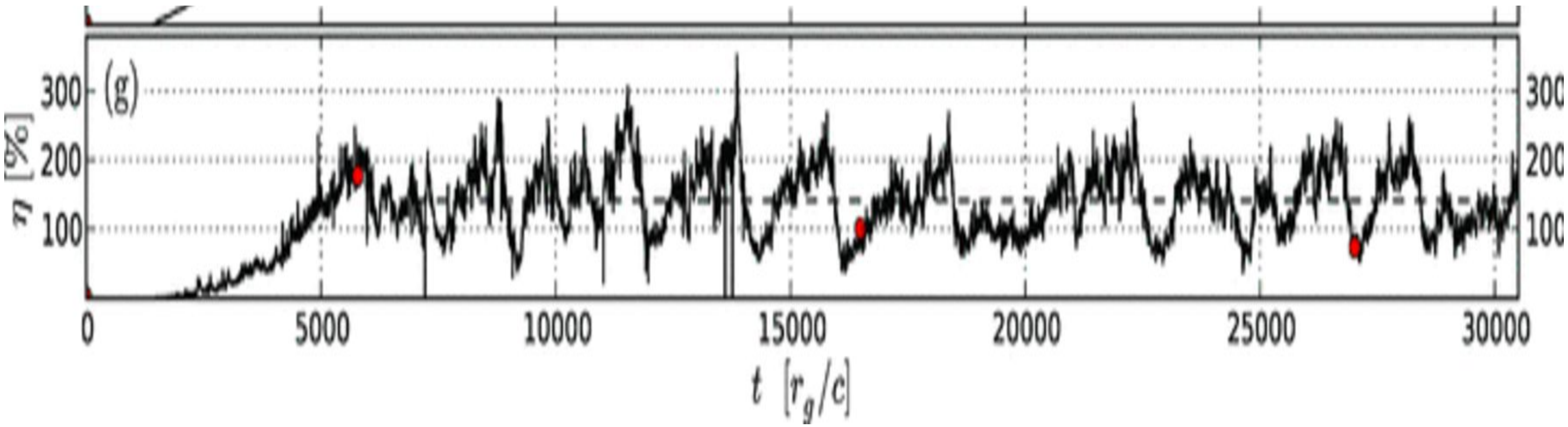
$$\frac{P_{jet}}{\dot{M}c^2}$$

Tchekhovskoy A et al. MNRAS 2011;418:L79-L83

MONTHLY NOTICES of the Royal Astronomical Society LETTERS

Shows results from the fiducial GRMHD simulation A0.99fc for a BH with spin parameter a = 0.99; see Supporting Information for the movie.

$$\frac{P_{jet}}{\dot{M}c^2}$$



On average: 1 g in → 1.5 c^2 erg out

Tchekhovskoy A et al. MNRAS 2011;418:L79-L83

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LETTERS

- Location is important
- A textbook powerful jet
- The blazar sequence
- The jet power
- Rotation > Accretion

End