The most powerful persistent engine of Nature

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With:

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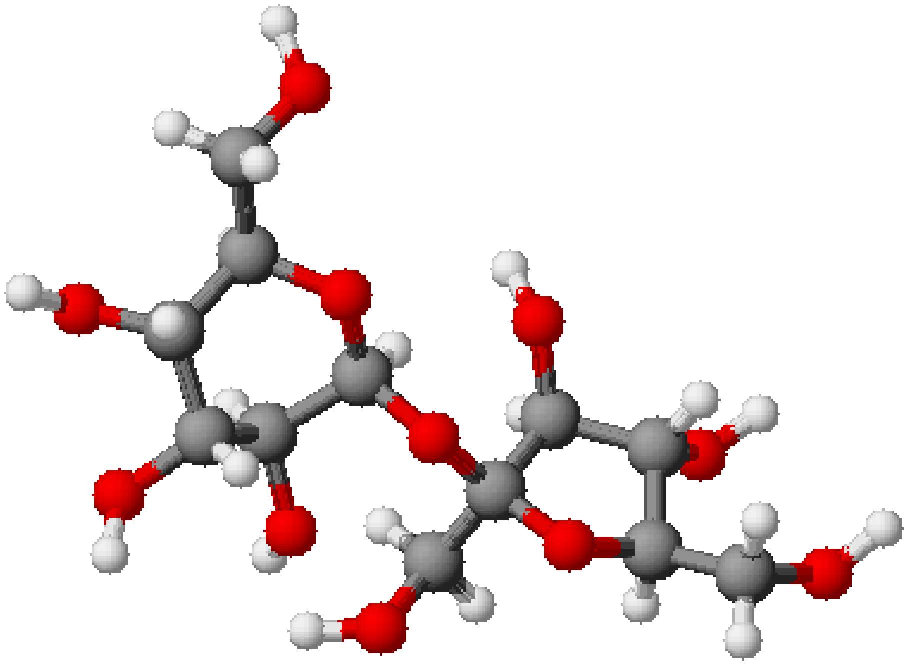
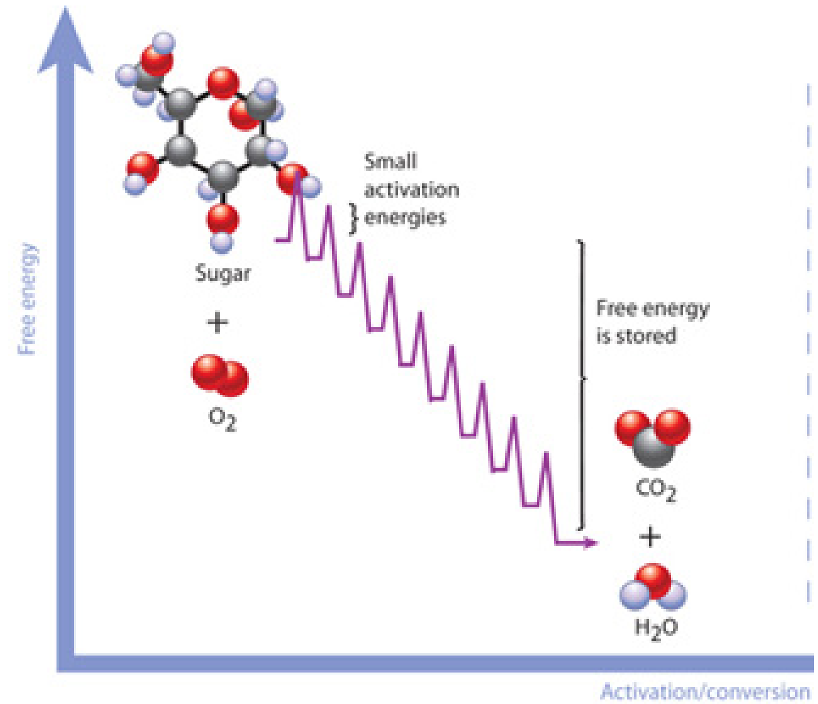
Efficiency

$$\eta = \frac{E}{mc^2}$$



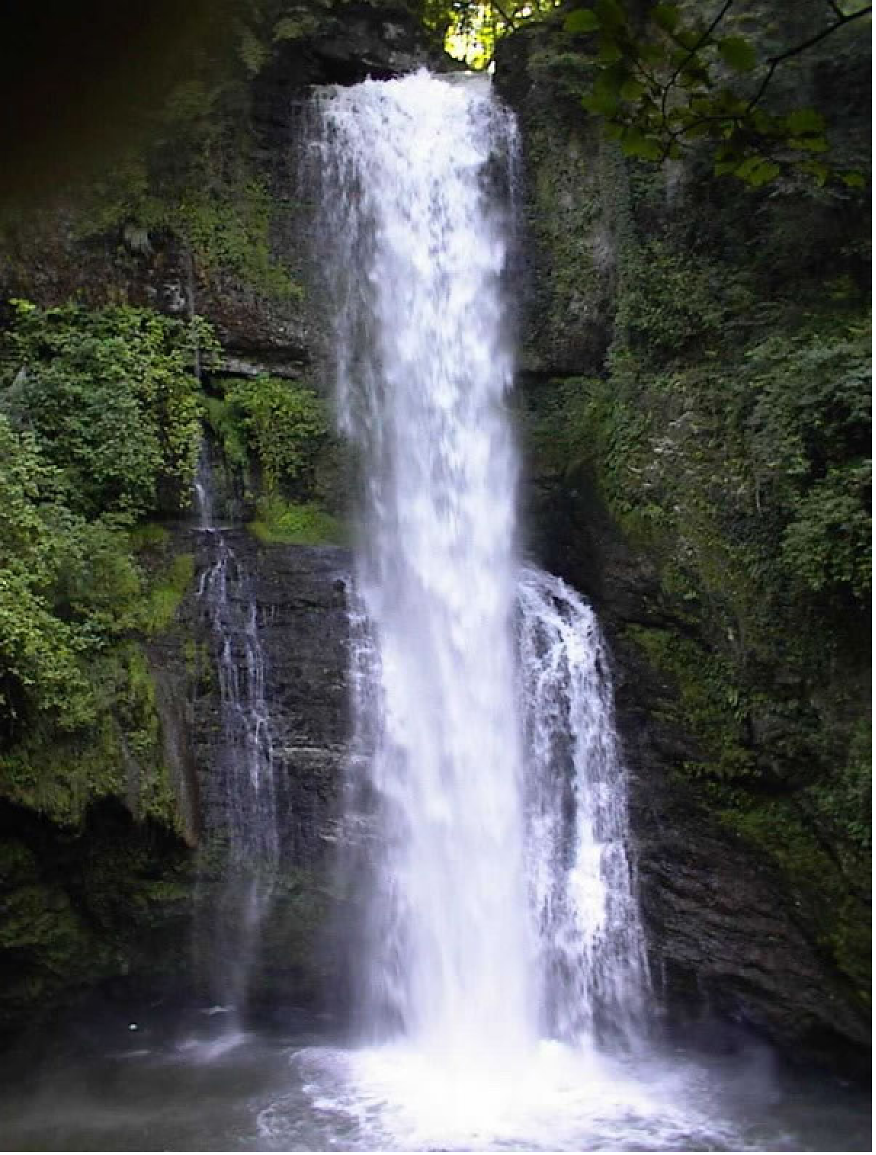


Sugar saccharose

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

1g □ 4 kcal= 16.2 kJ = 1e23 eV = 4.7 eV per molecule

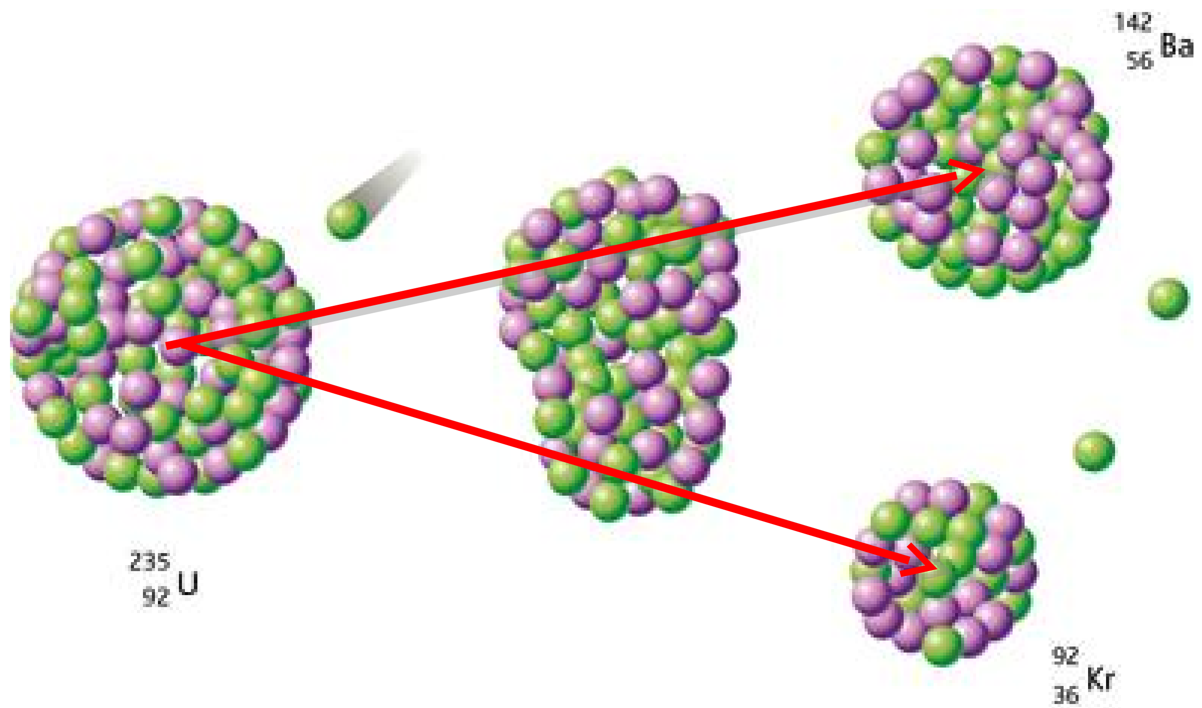
$$\eta = \frac{E}{mc^2} = \frac{1.6\text{x}10^{11}\,\text{erg}}{9\text{x}10^{20}\,\text{erg}} = 1.8\text{x}10^{-10}$$



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

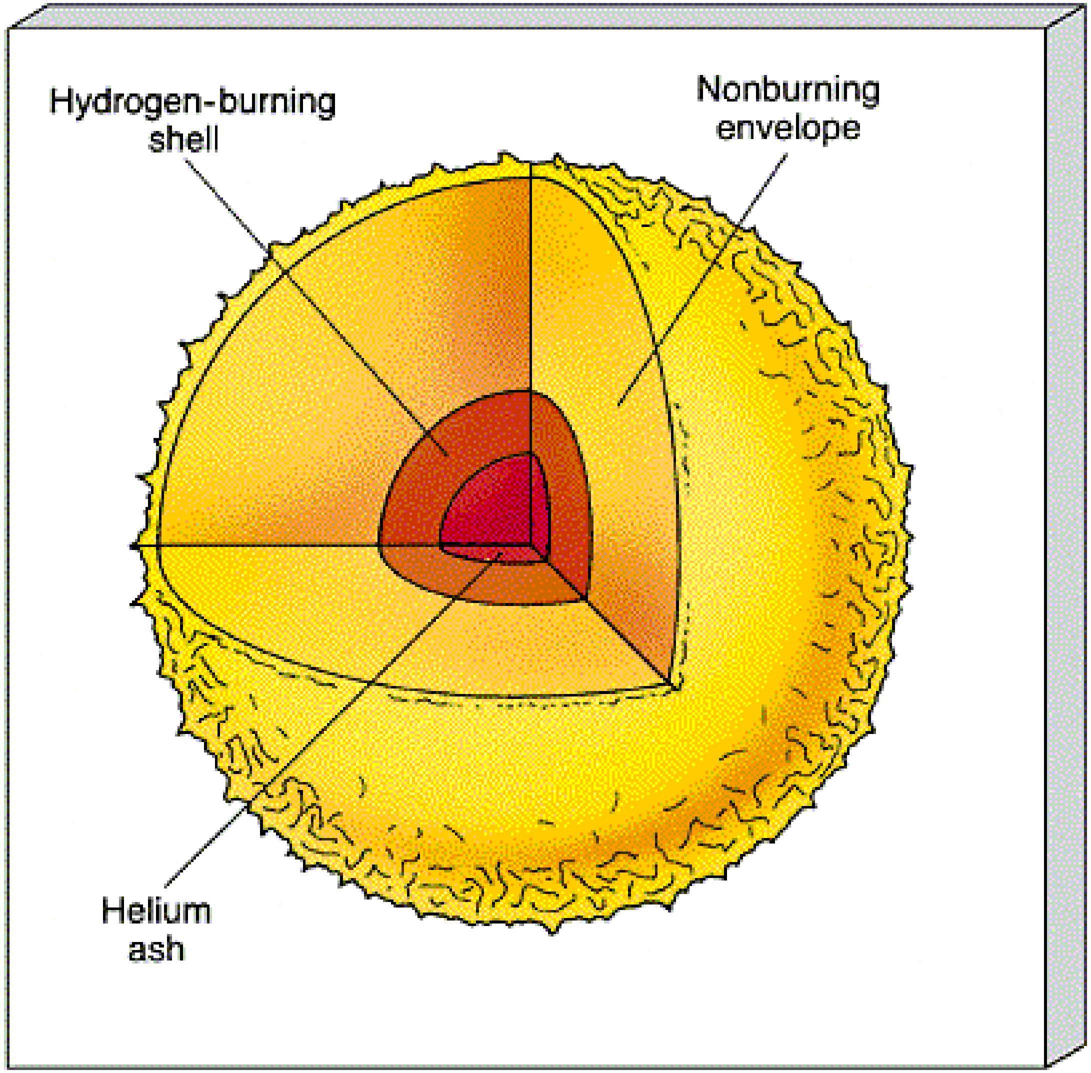
$$\eta = \frac{mv^2}{2} \Big/ mc^2 = \frac{(v/c)^2}{2} = 4x10^{-15}\,(v/100\ \text{km/h})^2$$

Nuclear fission



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

Fusio
n



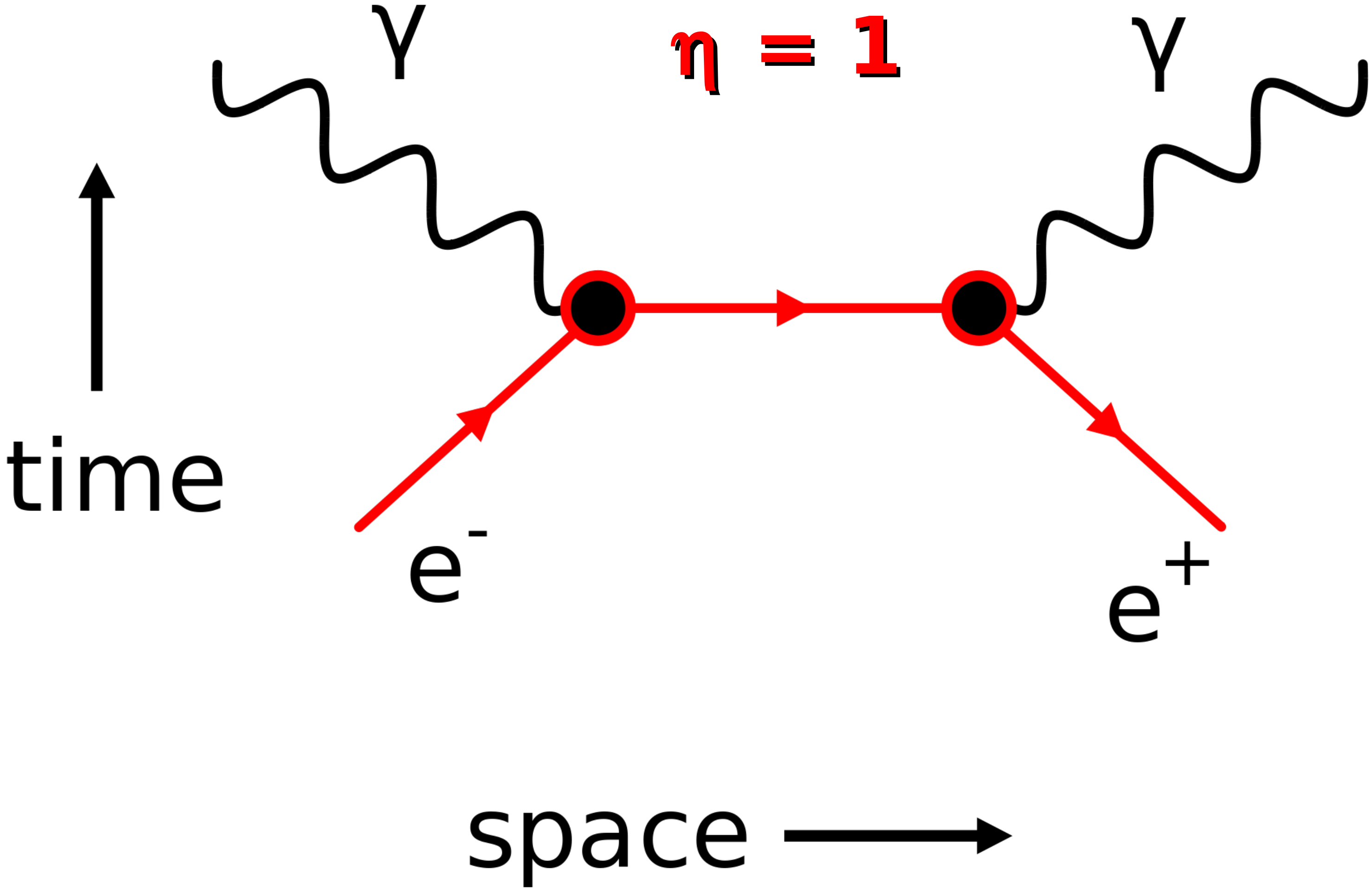
$$\eta = 0.008 \times 0.1 \sim 8\times10^{-4}$$

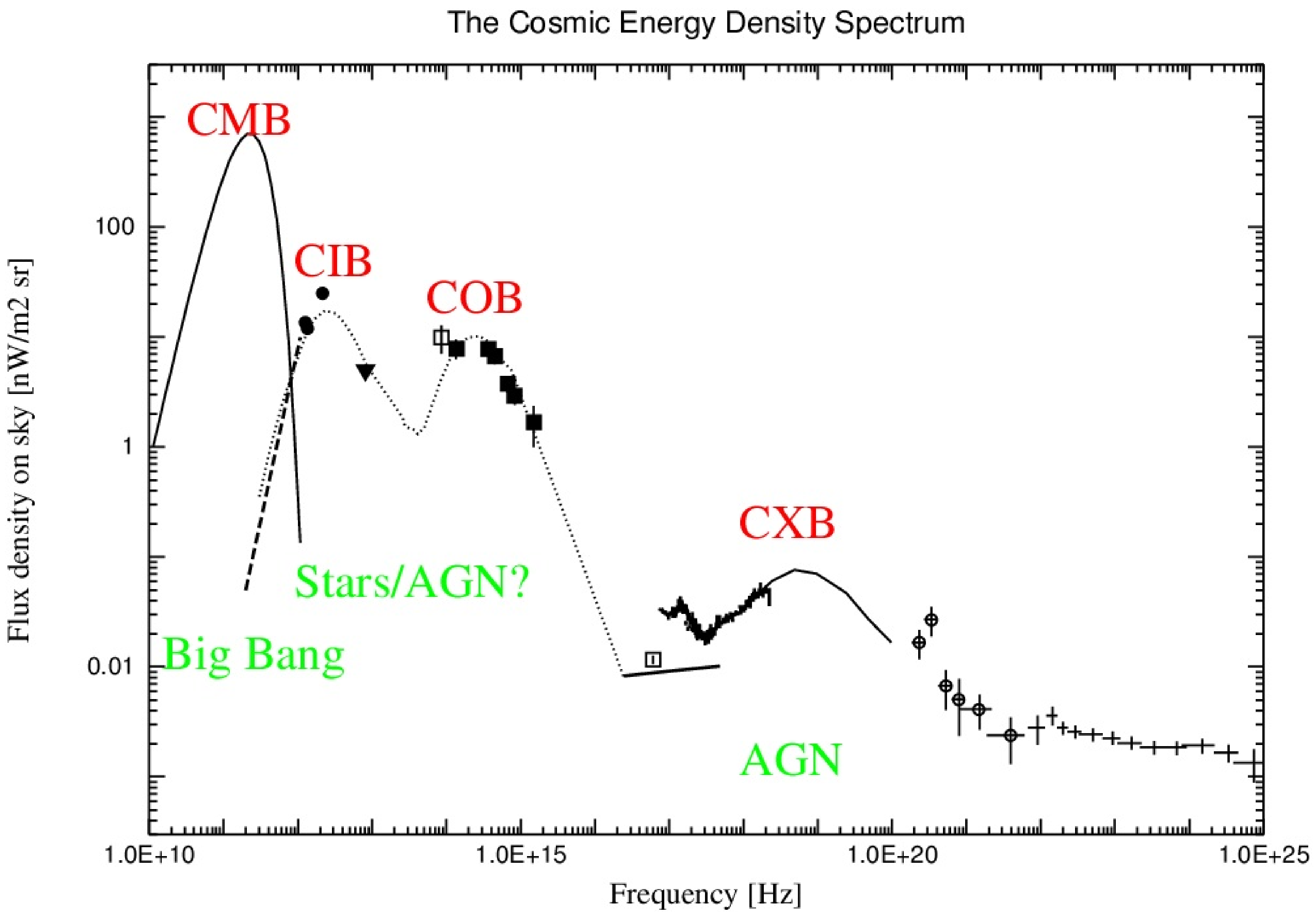
$$\eta = \frac{1}{2}\,\frac{GM\,m}{R\,mc^2} = \frac{R_g}{2R}$$

(Newton)
$R_{min} = R_g$ for max spin

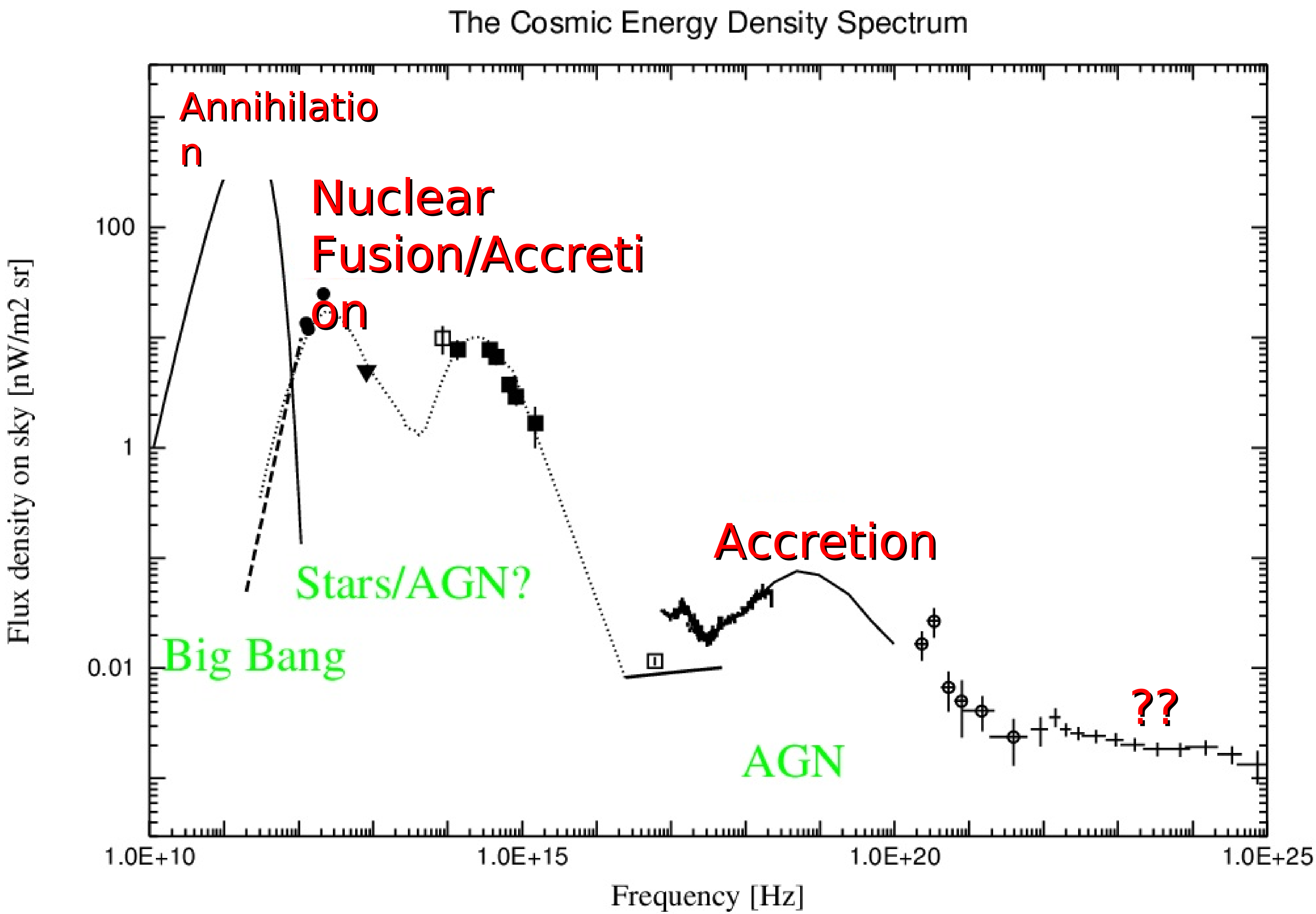
η = **0.1 up to 0.3 for accreting Kerr** (Thorne 1974)

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
??
Stars/AGN?
Big Bang
AGN
100
1
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Flux density on sky [nW/m2 sr]
1.0E+10
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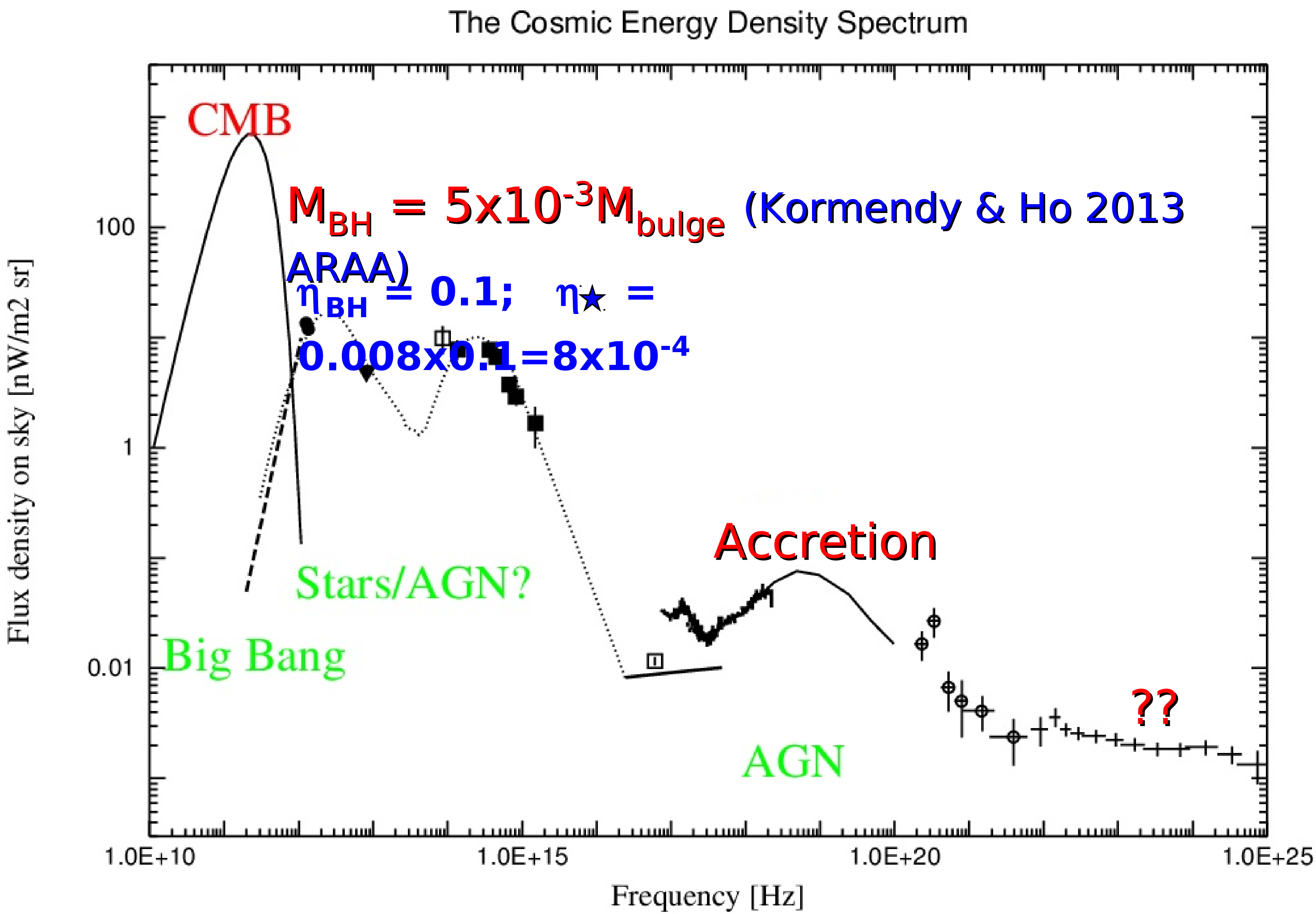
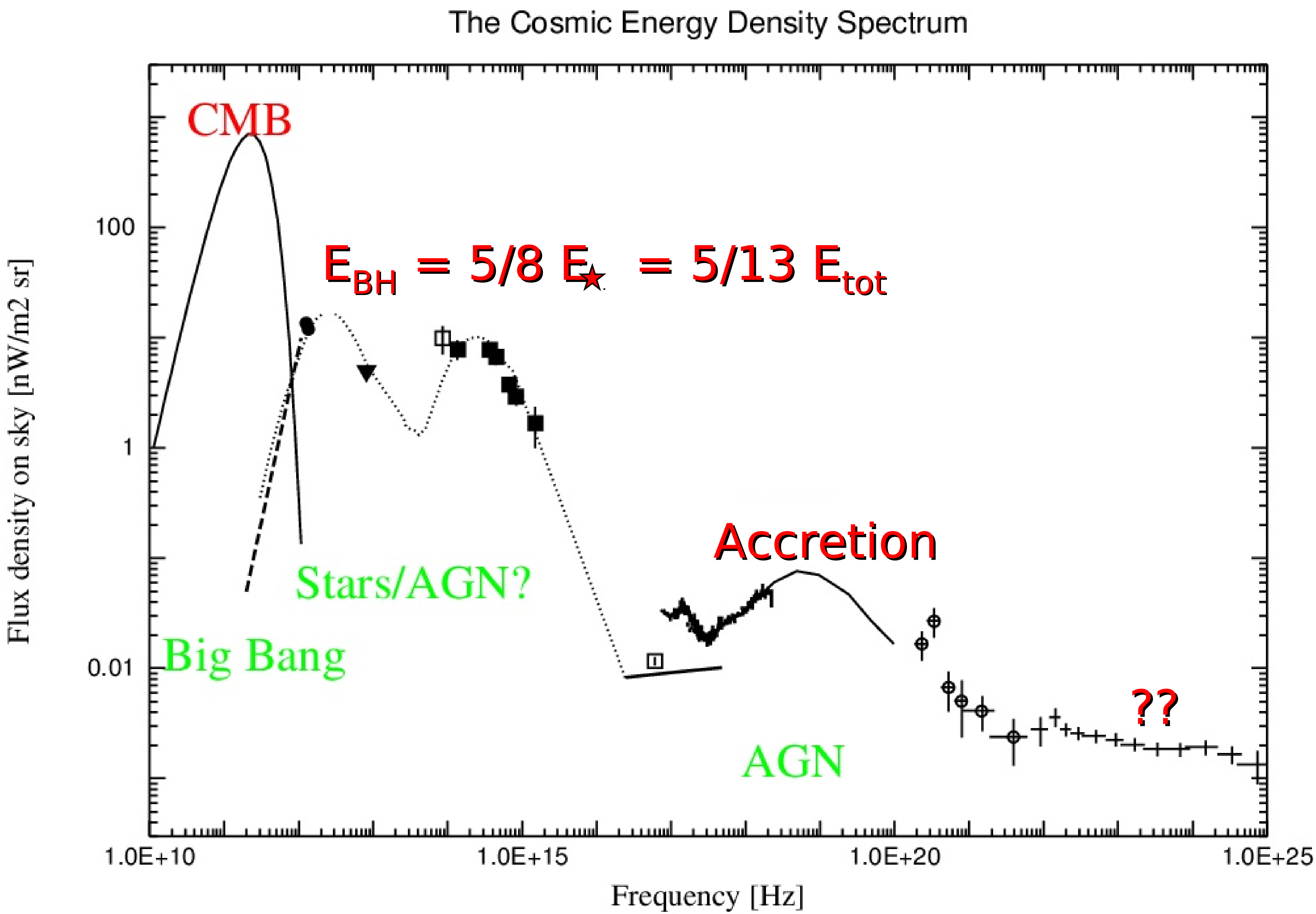


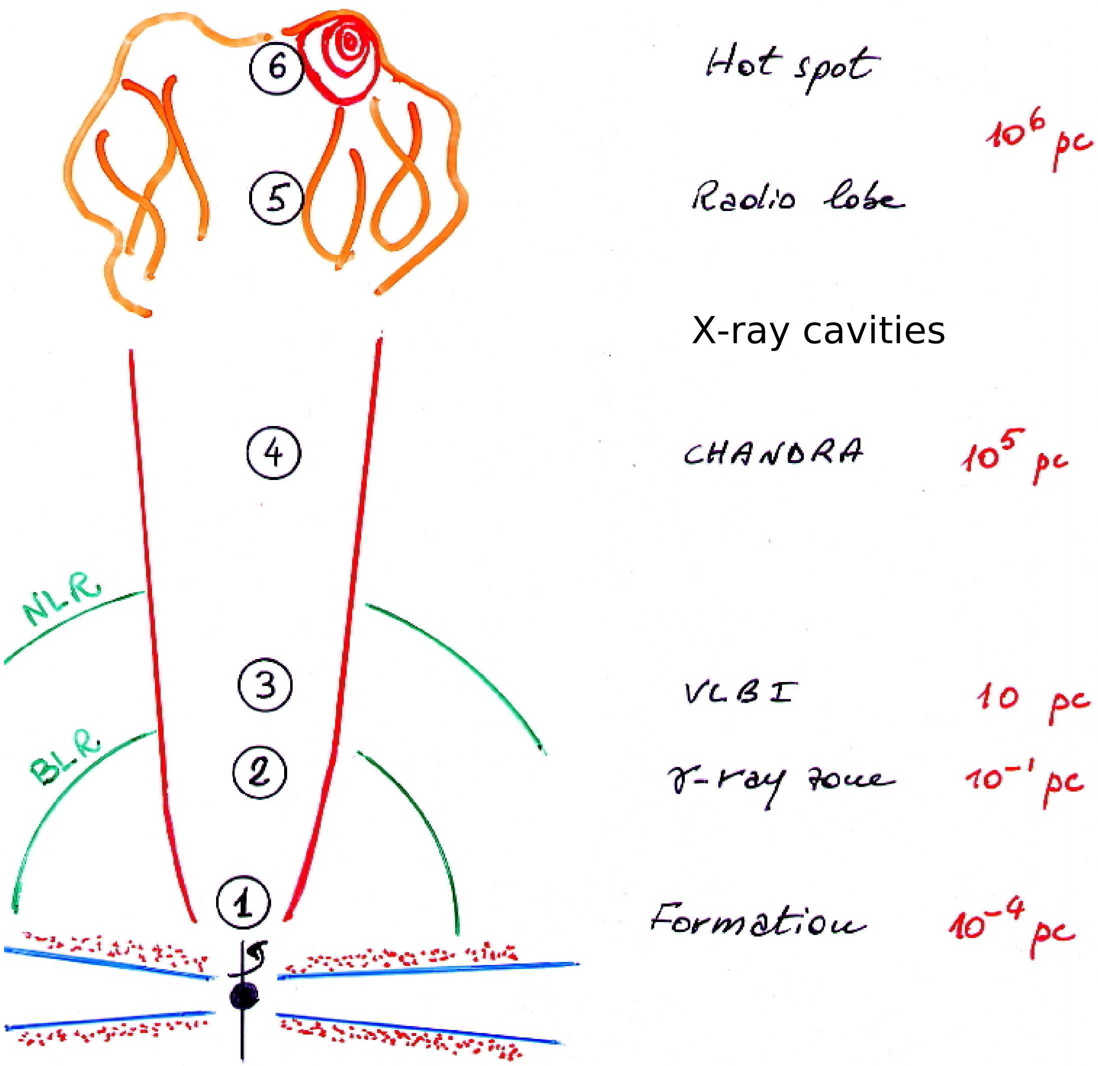
The Cosmic Energy Density Spectrum
CMB
$M_{BH} = 5x10^{-3}M_{bulge}$ (Kormendy & Ho 2013 ARAA)
η_{BH} = 0.1; $\eta_{\star}$ = 0.008x0.1=$8x10^{-4}$
Stars/AGN?
Big Bang
Accretion
AGN
??
100
1
0.01
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]
Flux density on sky [nW/m2 sr]



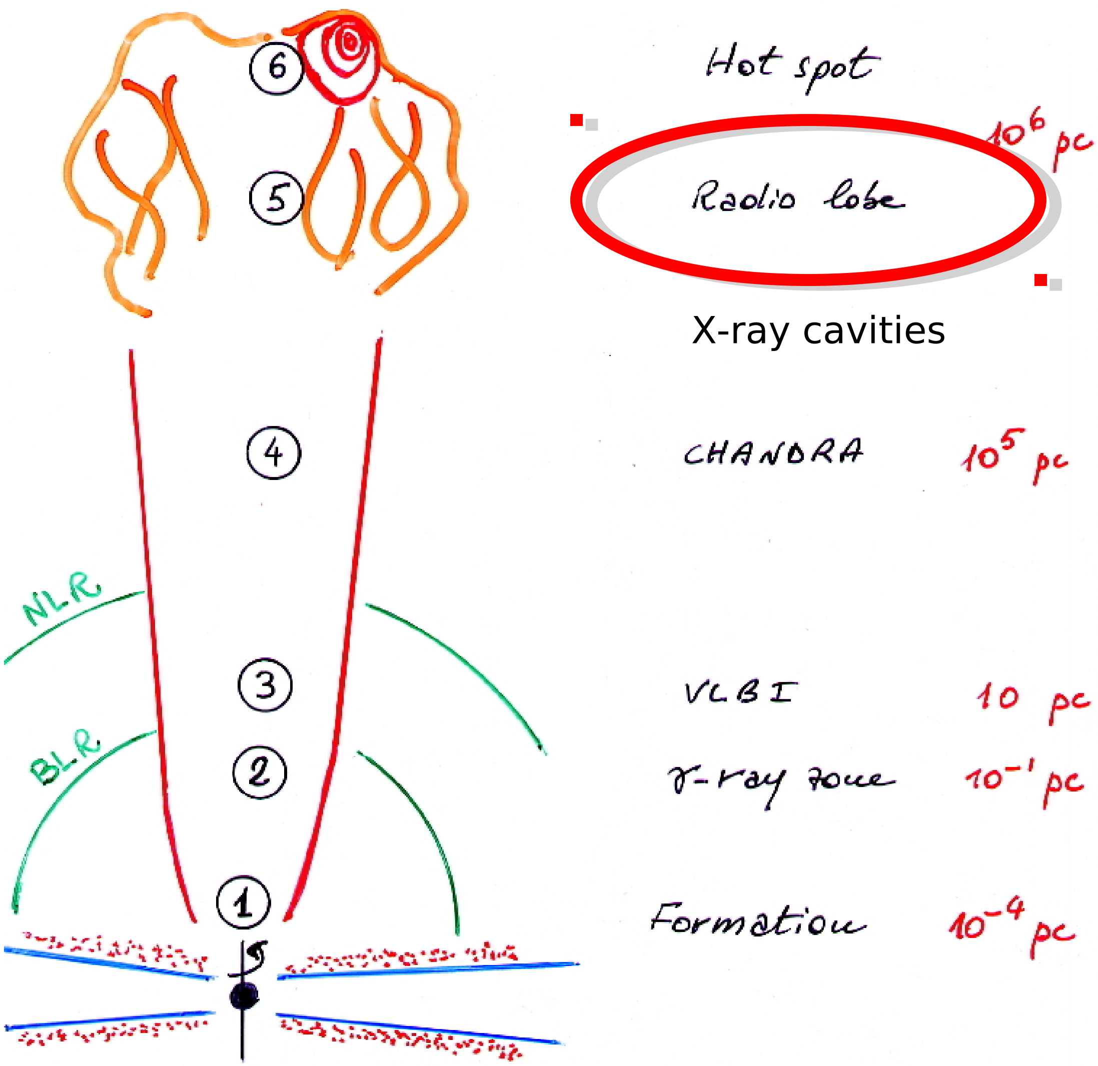
The Cosmic Energy Density Spectrum
CMB
$E_{BH} = 5/8\ E_{\star} = 5/13\ E_{tot}$
Stars/AGN?
Big Bang
Accretion
AGN
??
Flux density on sky [nW/m2 sr]
100
1
0.01
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]

Jets?

Power of jets in blazars

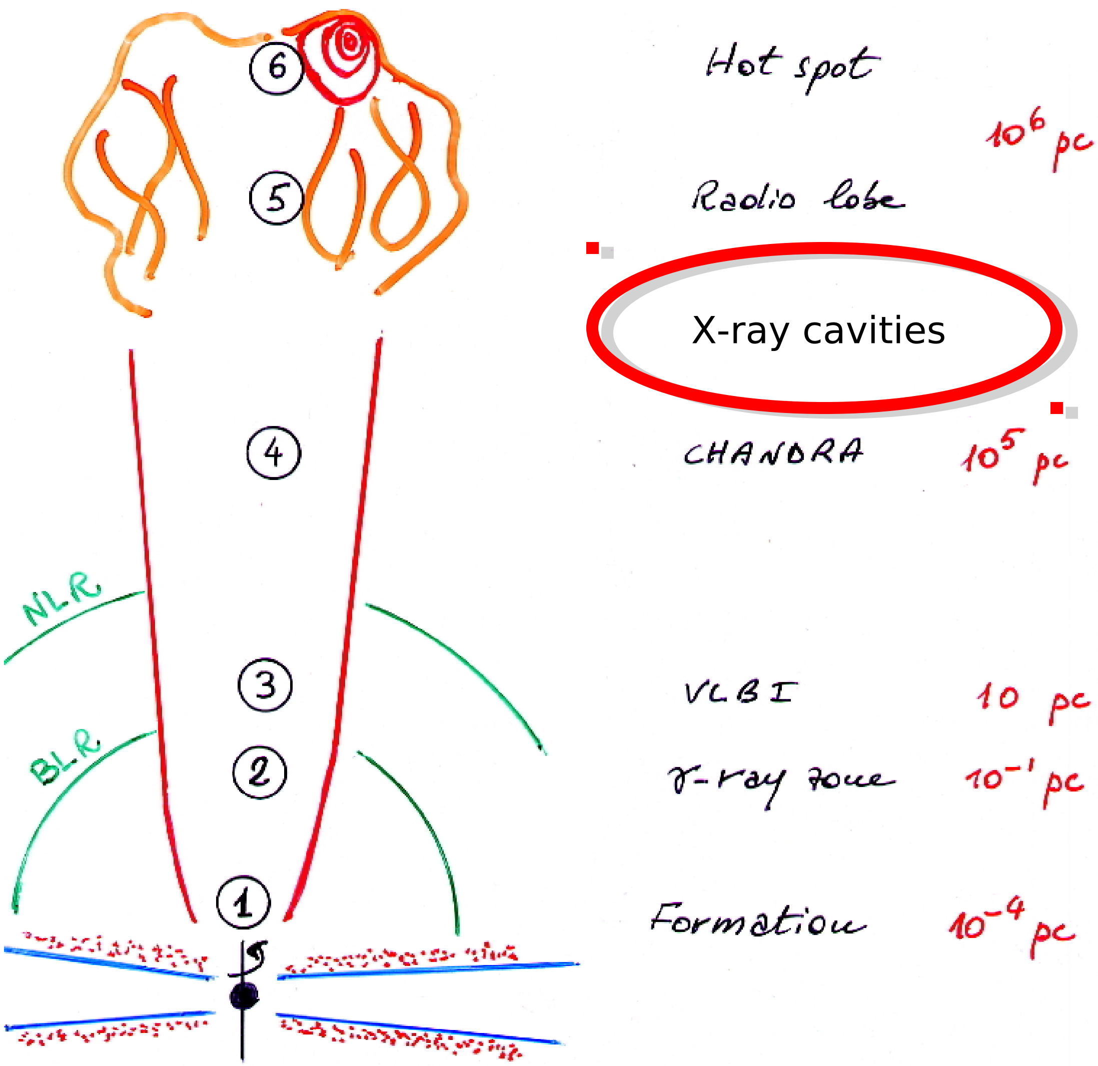


Power of jets in blazars



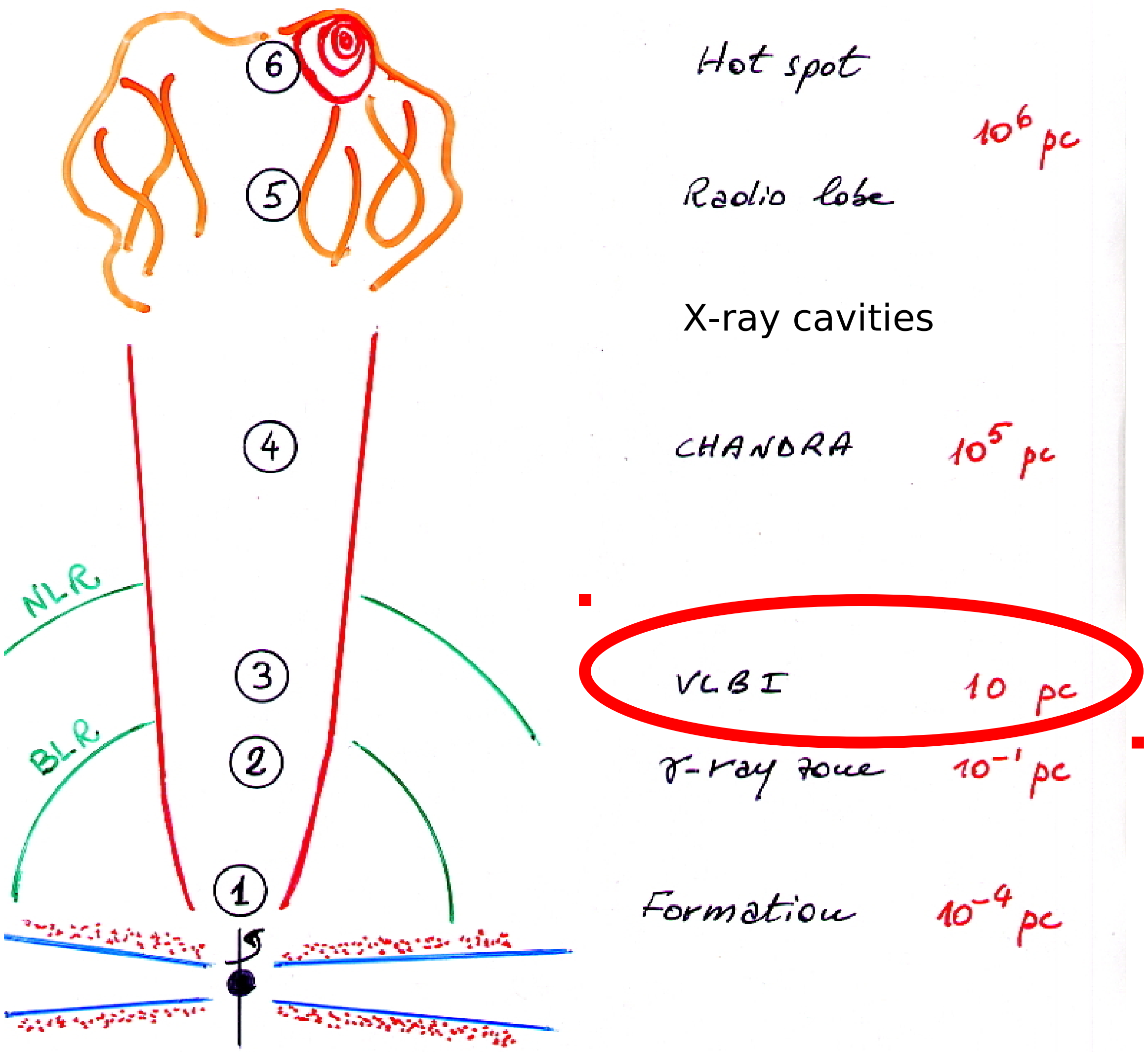
$$\frac{\text{Minimum energy}}{t_{lobe}}$$

Power of jets in blazars



PV work / t_{sound}

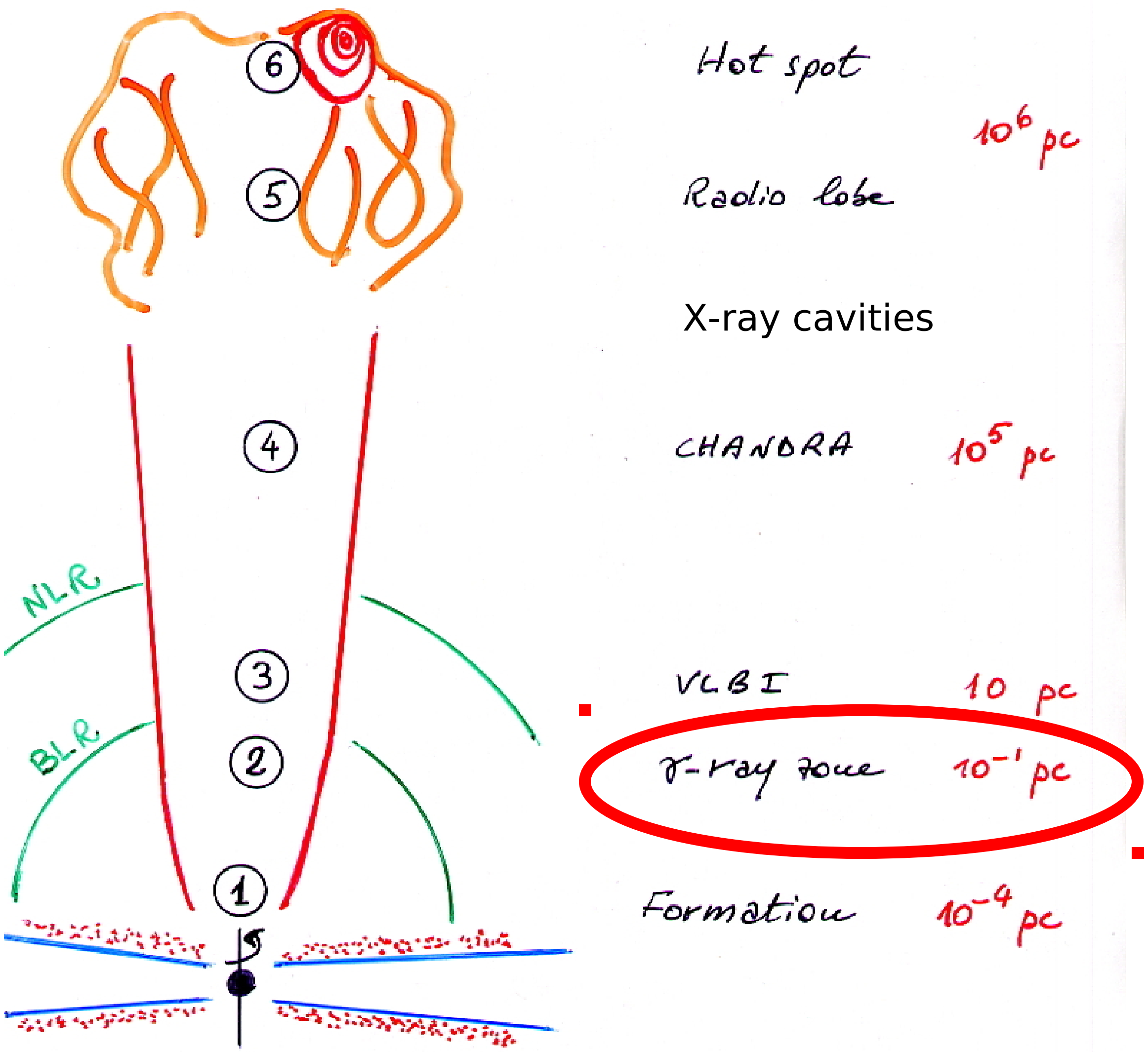
Power of jets in blazars



- Measure the size, apply SSC model, find δ and # of e-

1992: launch of EGRET on the Compton Gamma-ray Observatory

Power of jets in blazars



jet power and accretion luminosity

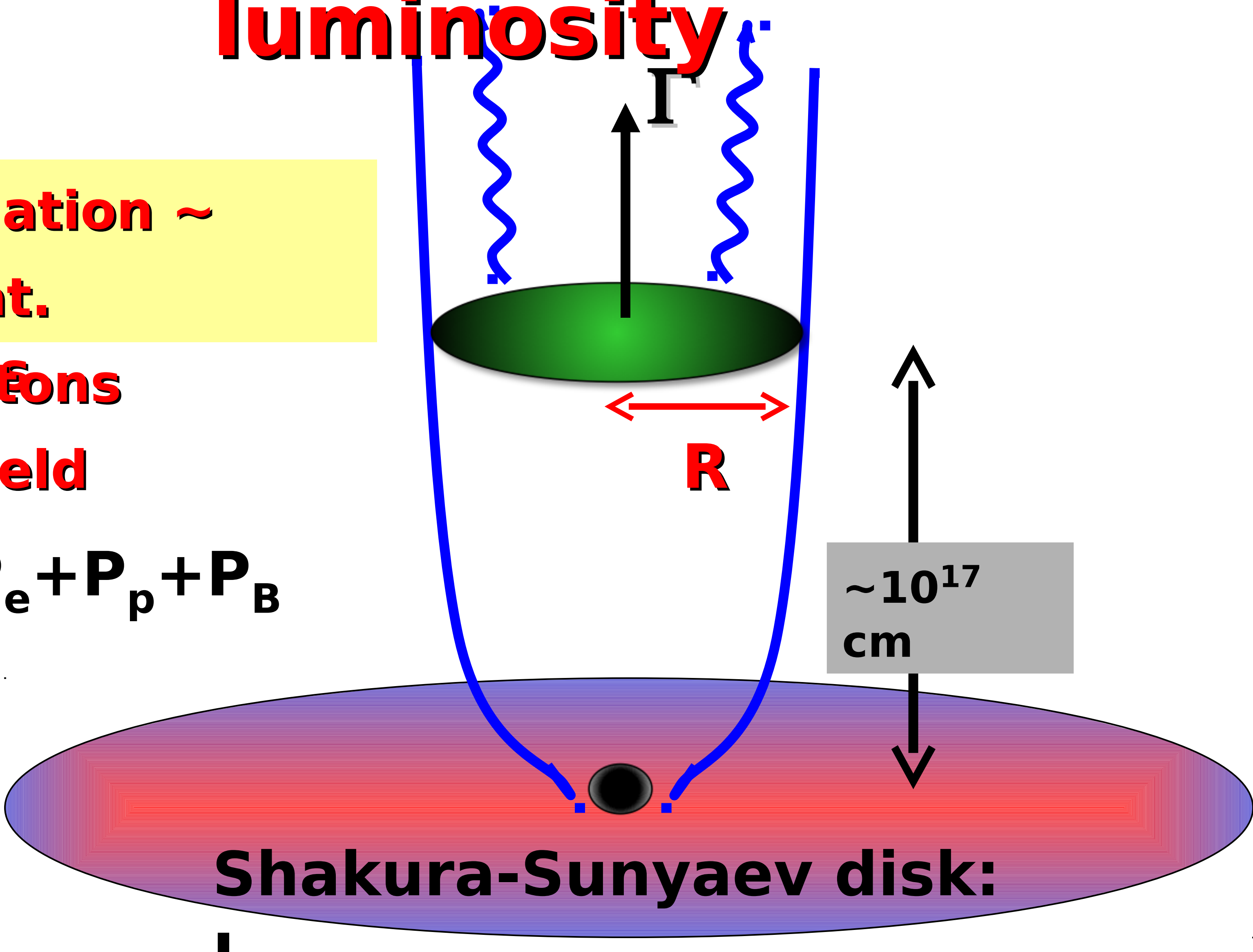
P_r = radiation ~ P_{obs}/Γ^2

P_e = relat. electrons

P_p = protons

P_B = B-field

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



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:

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

If P_{jet} is twice as much, Γ halves.

We can take P_{rad} as the minimum P_{jet}.

This limit is model-independent.

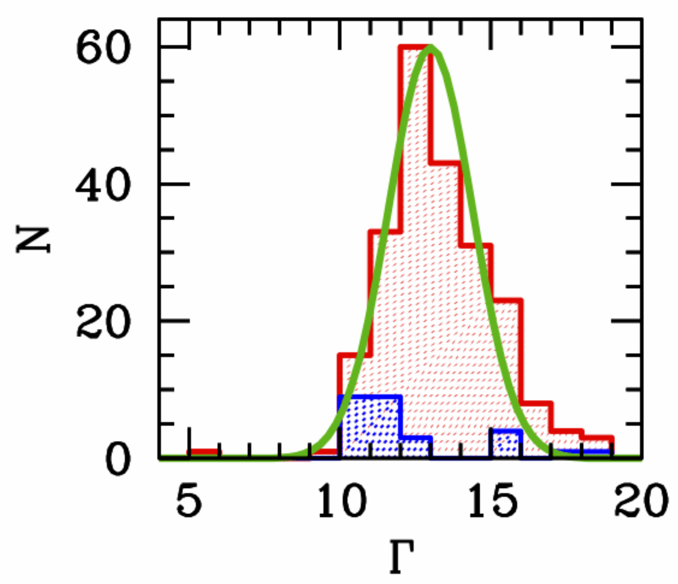
The jet cannot have less power than what required to produce the observed luminosity:

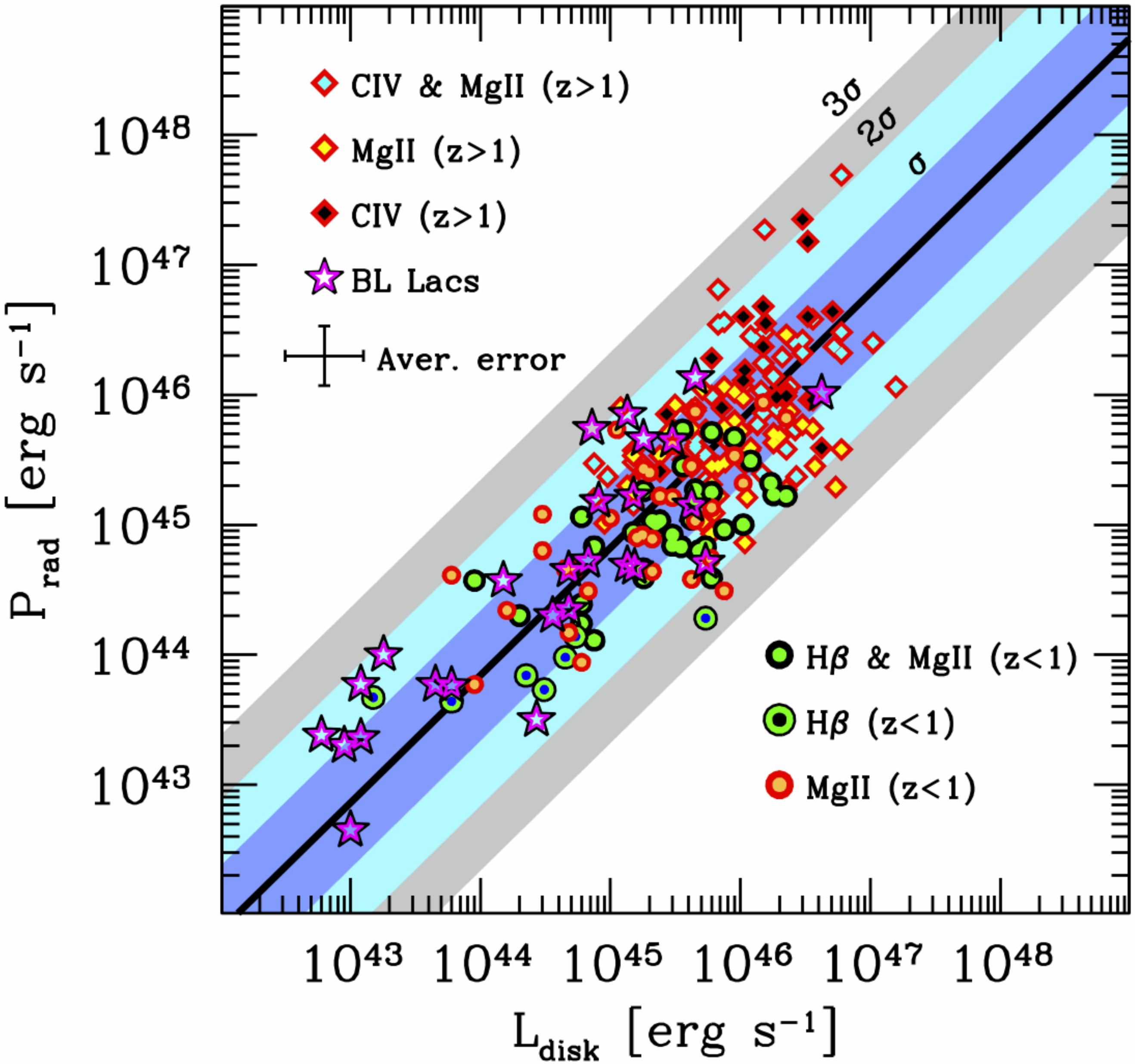
$$P_{jet} > \frac{L_{obs}}{\Gamma^2}$$

If P_{jet} is twice as much, Γ h

We can take P_{rad} as the m

This limit is model-indepe





GG+ Nature, 2014

From P_{rad} to P_{jet}

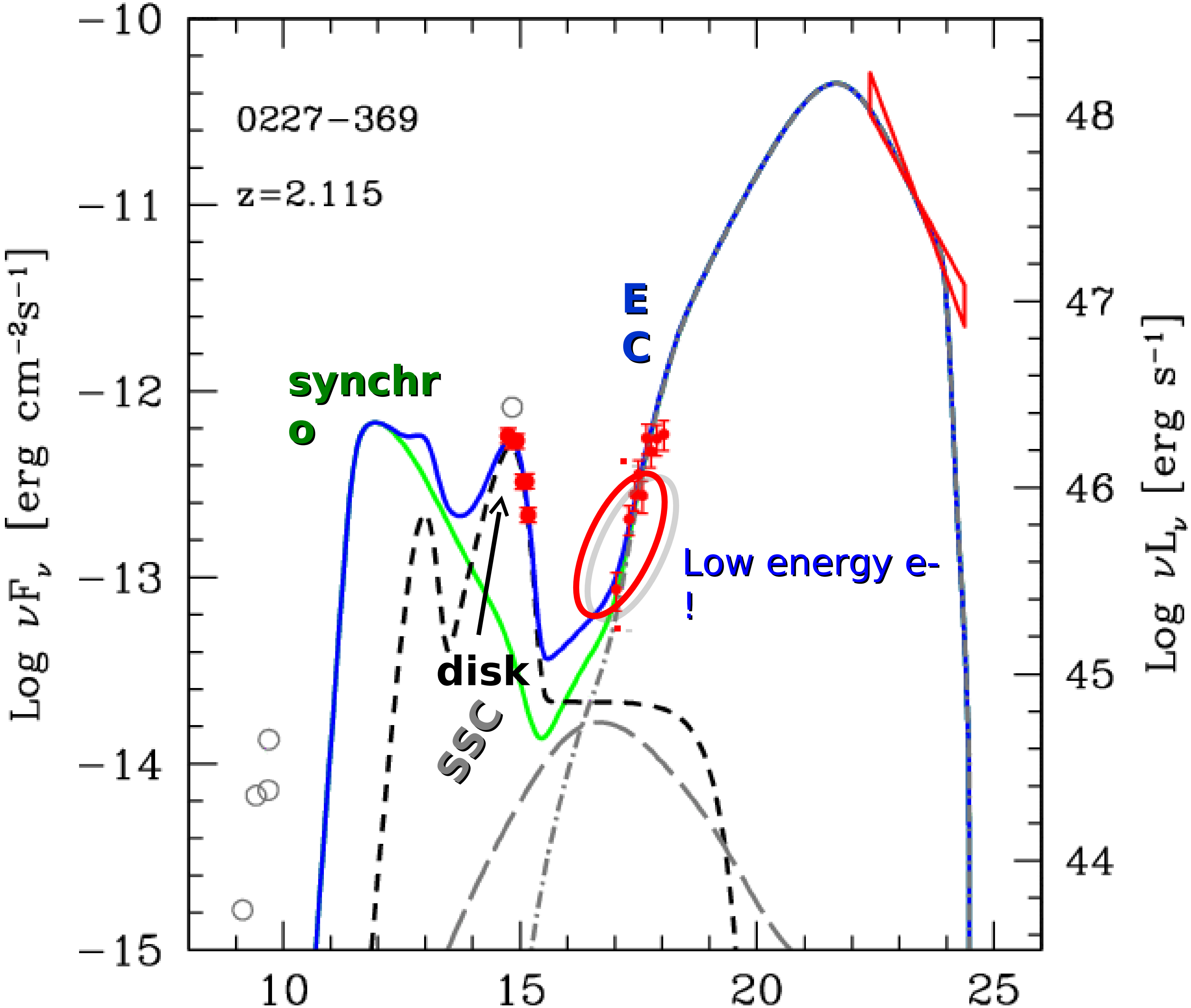
- γ_{min} total number of e- (and of protons, if no pairs...)
- Presence of electron positron pairs
- Radiative model: SSC vs EC vs baryons

From P_{rad} to P_{jet}

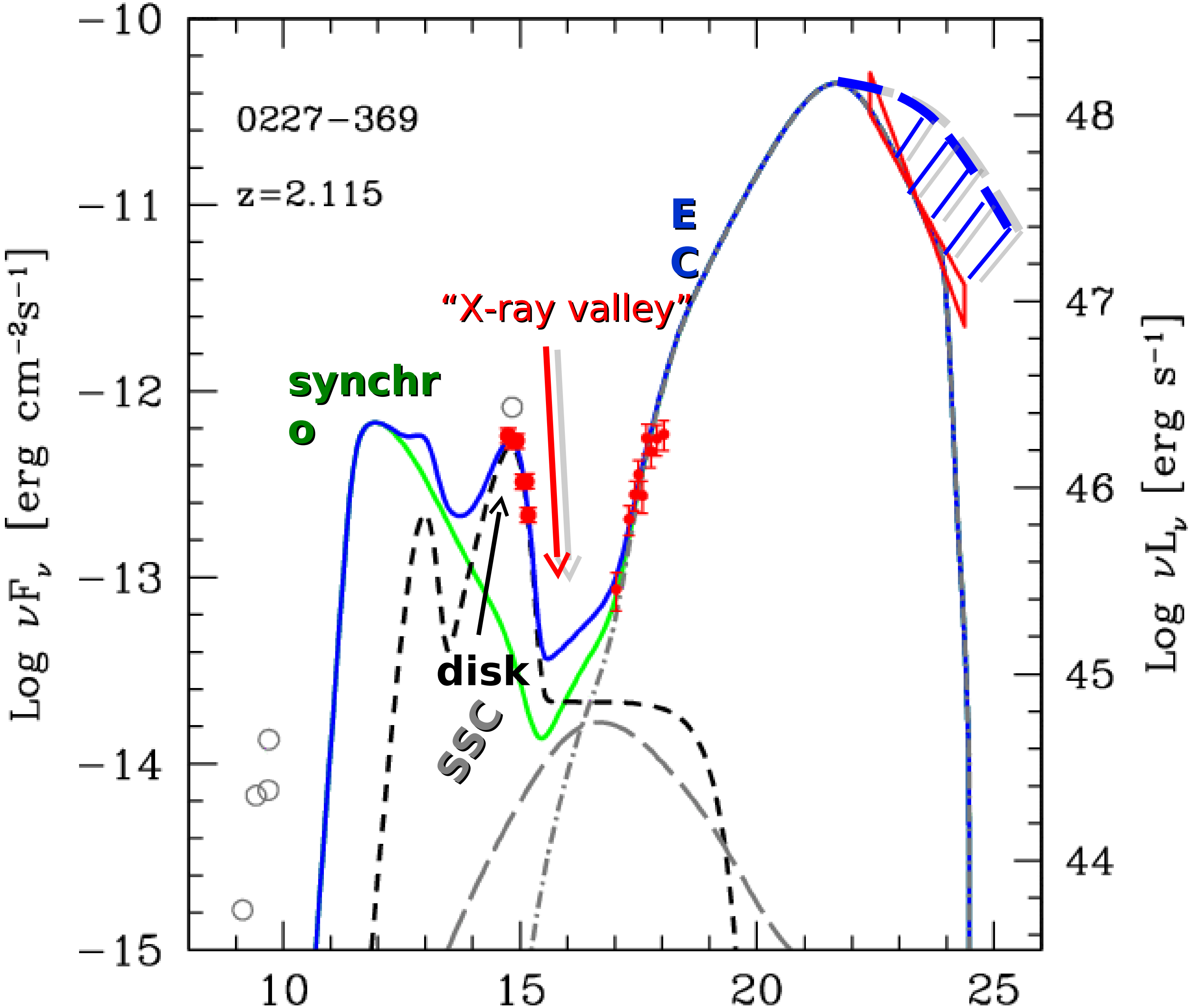
- γ_{min} □ total number of e- (and of protons, if no pairs…)
- Presence of electron positron pairs
- Radiative model: SSC vs EC vs baryons

doesn’t fit

even more power



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



0227−369
z=2.115
synchro
disk
SSC
"X-ray valley"
EC
Log νF_ν [erg cm^-2 s^-1]
Log νL_ν [erg s^-1]
−10
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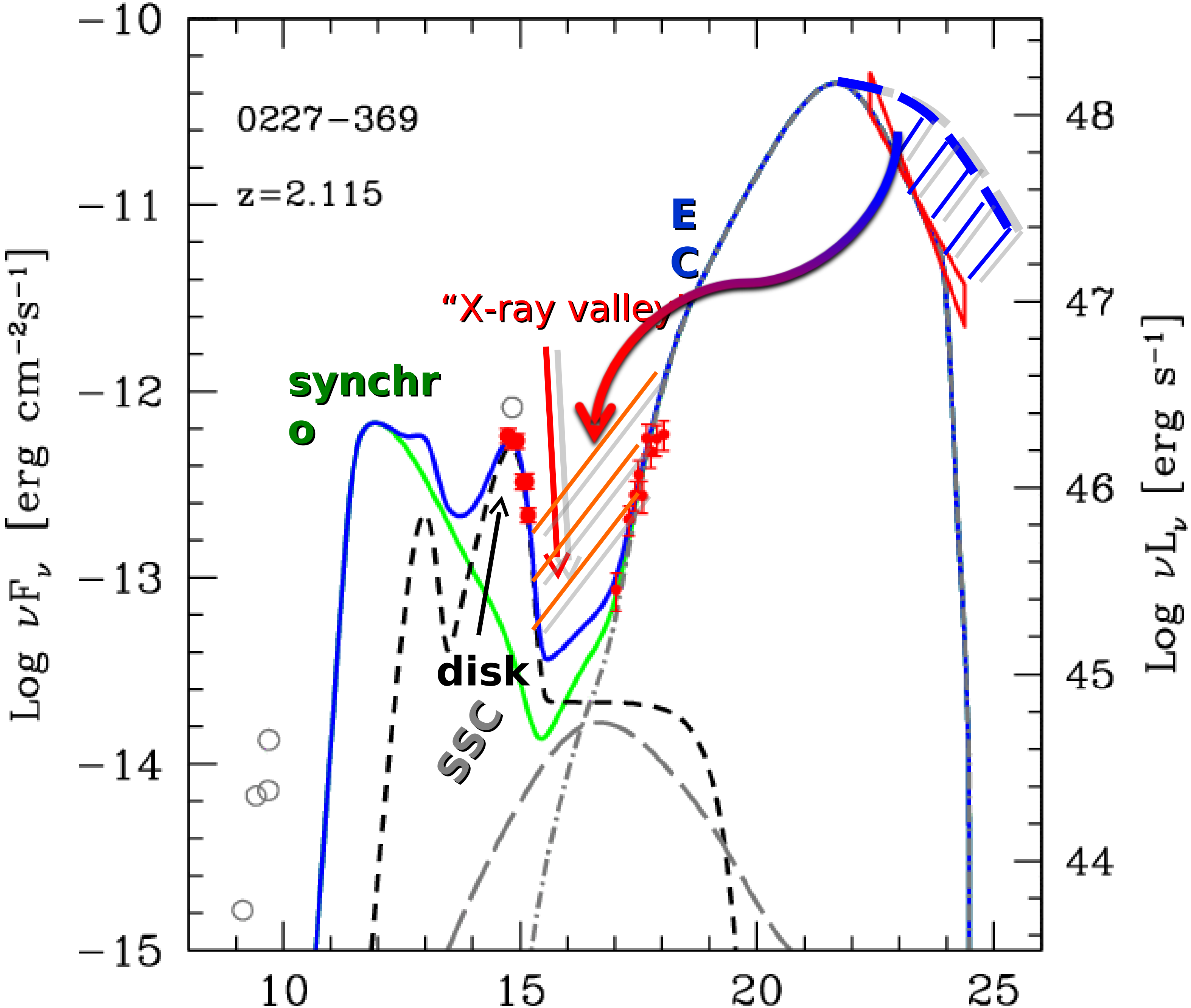

0227−369
z=2.115
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Log νF_ν [erg cm⁻² s⁻¹]
Log νL_ν [erg s⁻¹]
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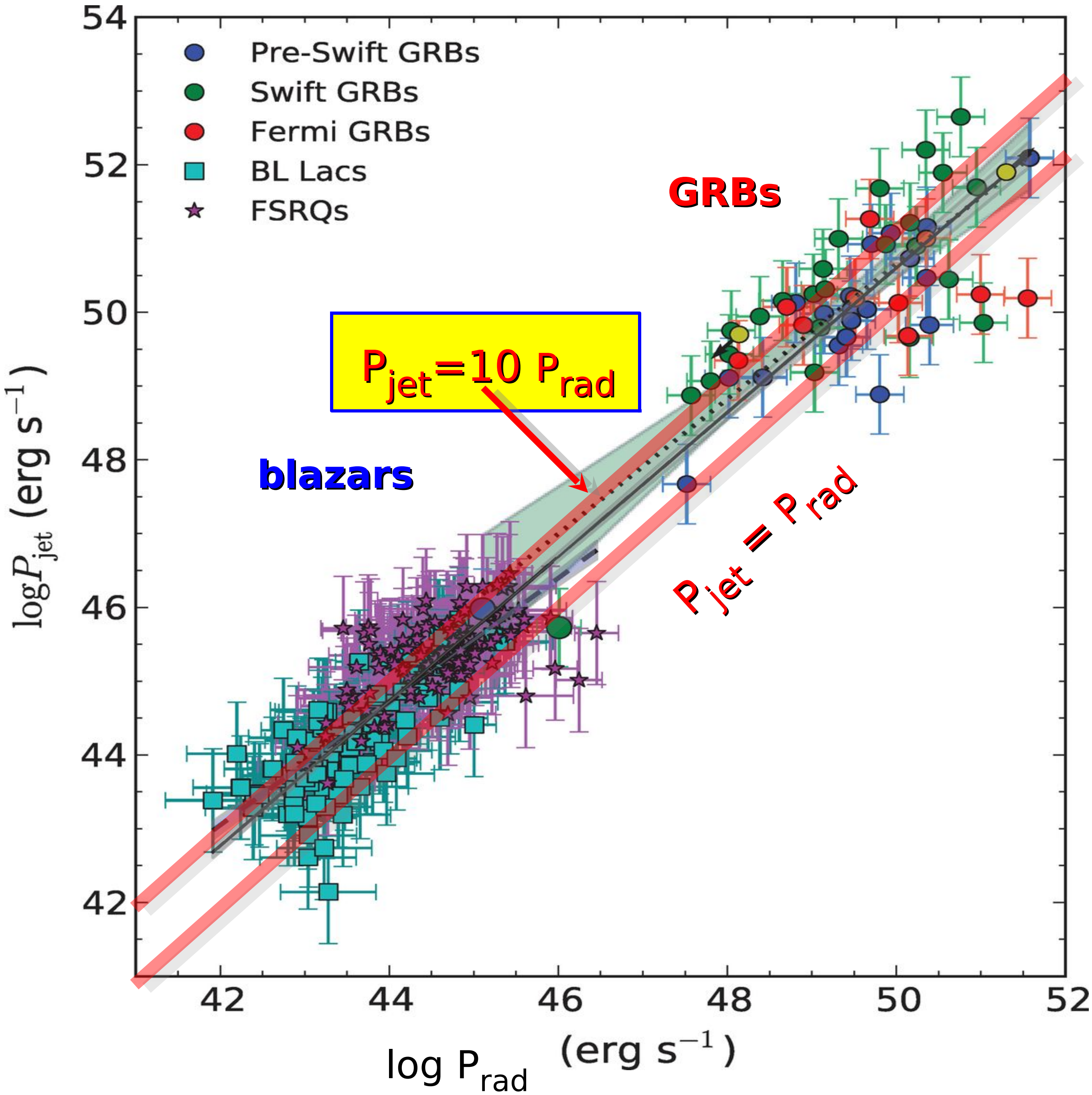
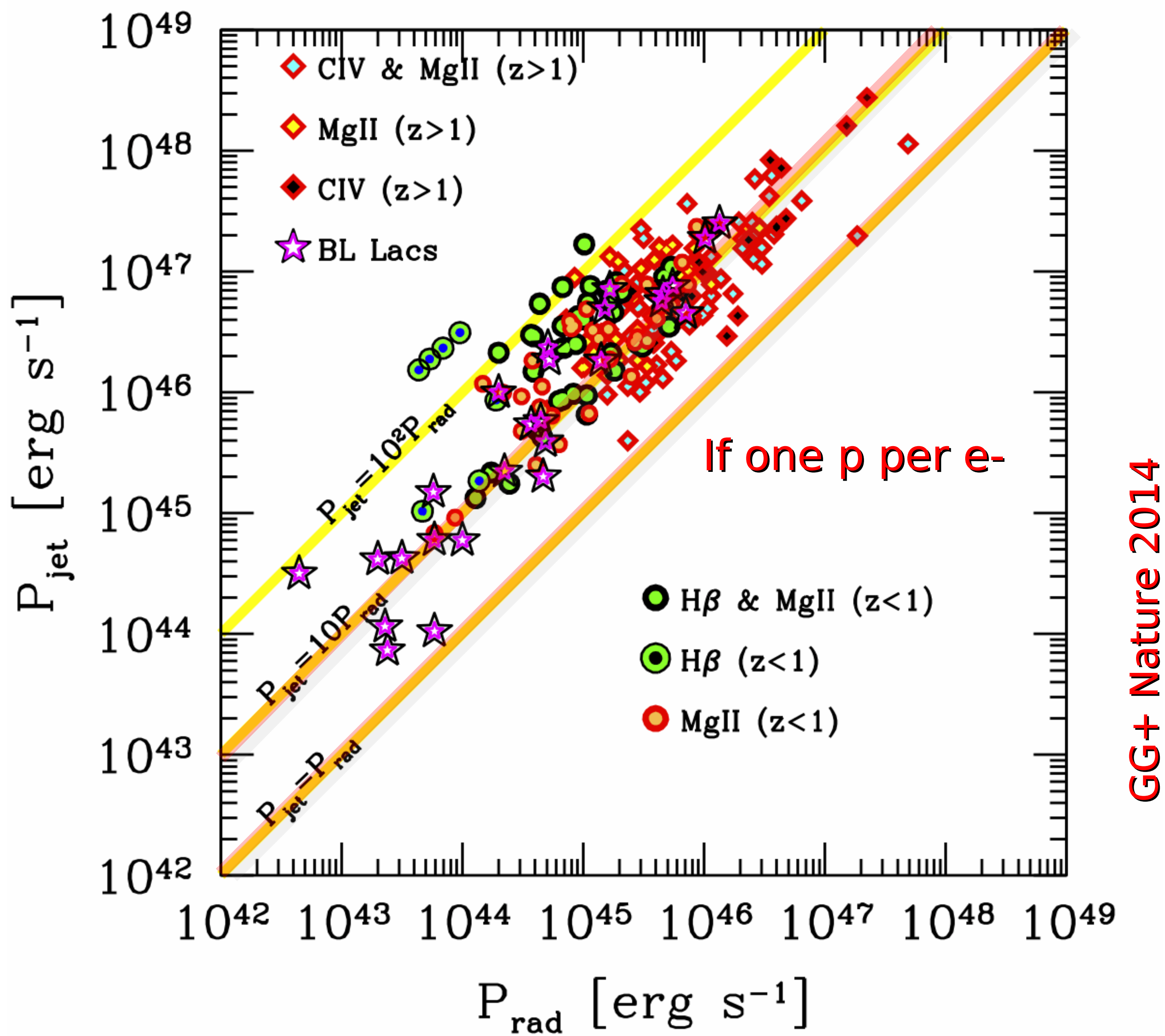
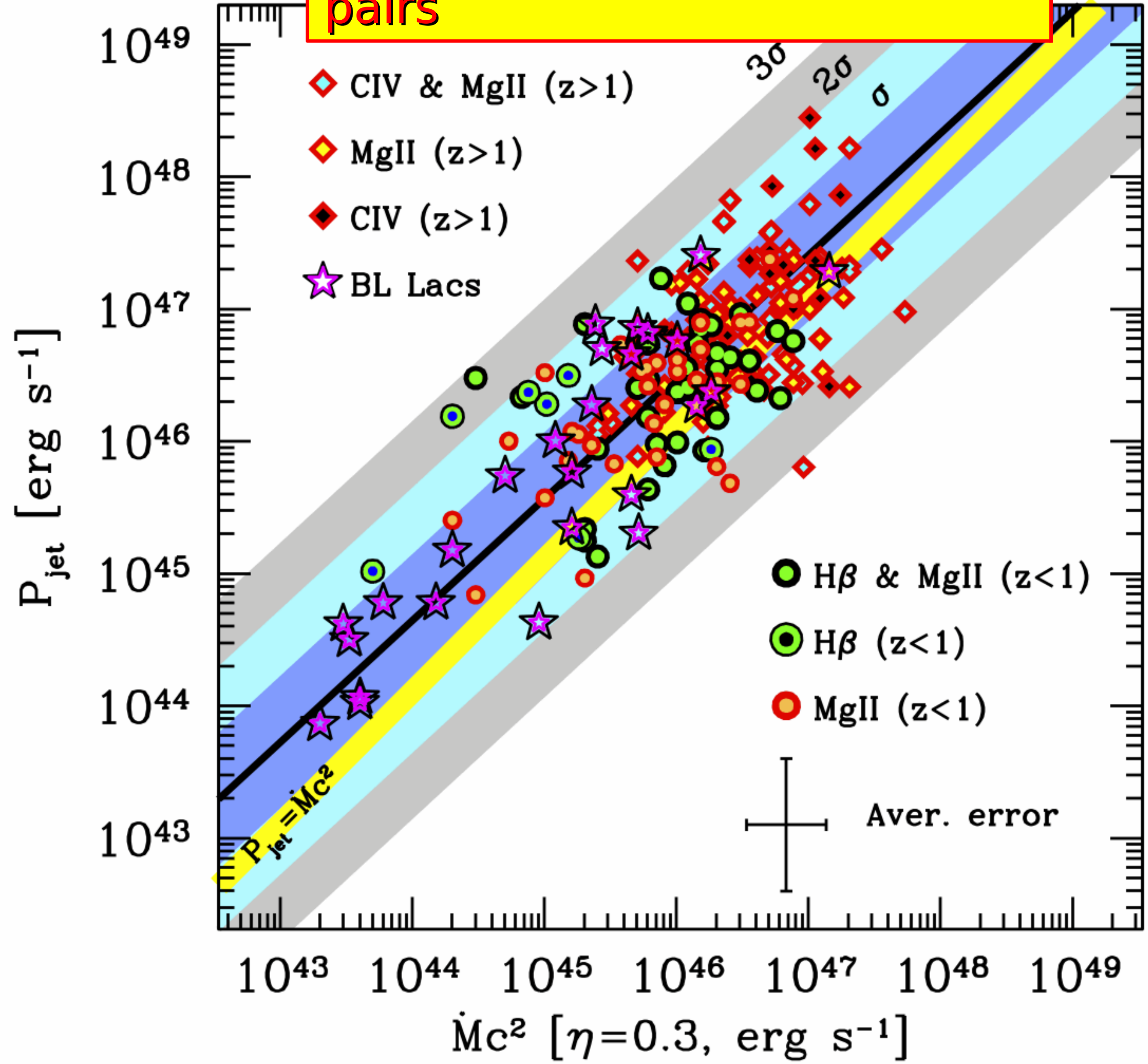


Nemmen+ Science 2012



CIV & MgII (z>1)
MgII (z>1)
CIV (z>1)
BL Lacs
Hβ & MgII (z<1)
Hβ (z<1)
MgII (z<1)
$P_{jet}=10^2P_{rad}$
$P_{jet}=10P_{rad}$
$P_{jet}=P_{rad}$
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



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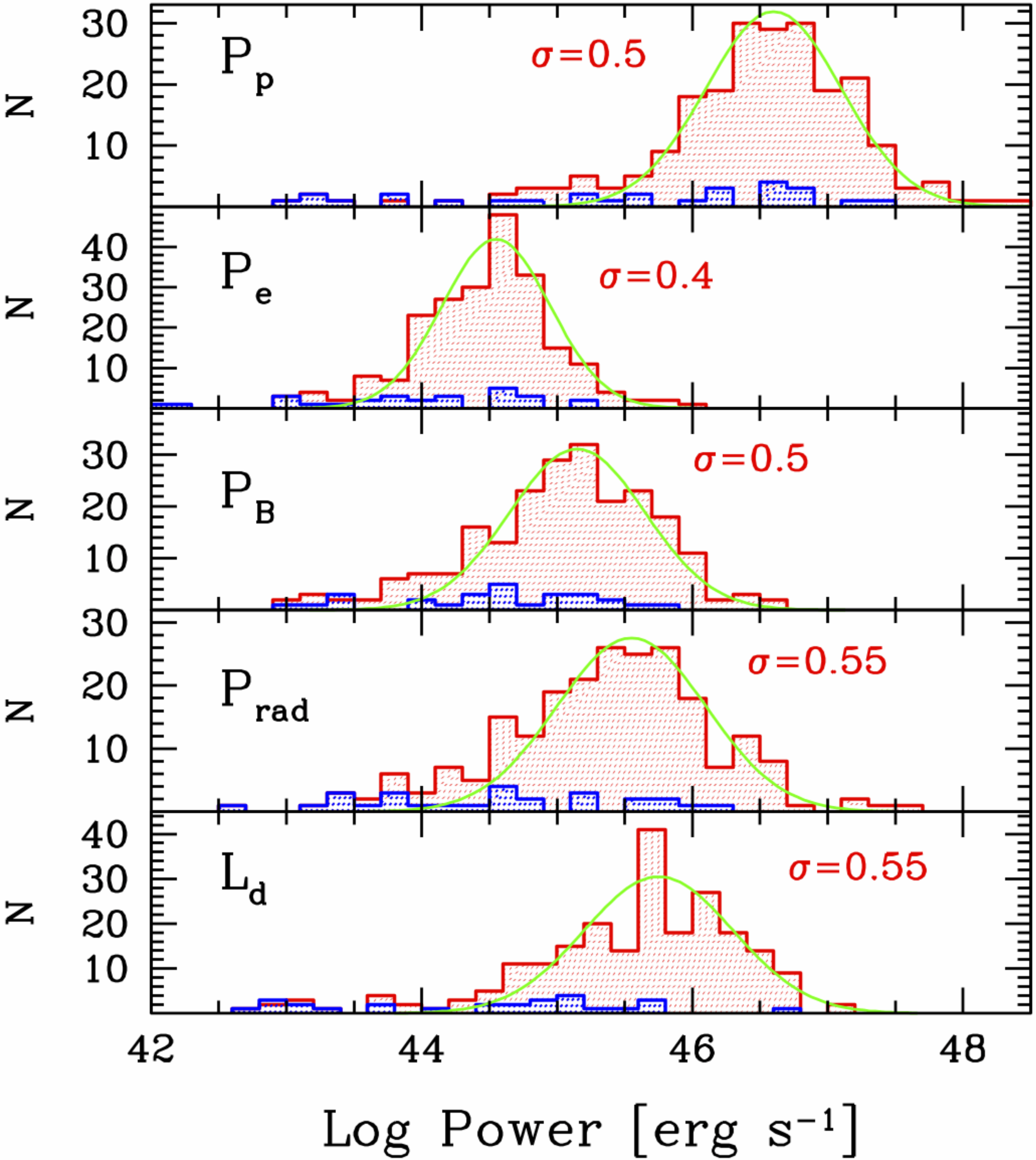


If one p per e-

Relat. electrons

Magnetic Field

Radiation

Disk

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

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

⇓

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

Poynting

Flux

Blandford Znajek

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

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

Flux

$\mathbf{P_{BZ} \sim a^2 \rho c^2 R_g^{\ 2} c}$ **$\rho c^2 \sim B^2/8\pi$**

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

Rotation > Accretion

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

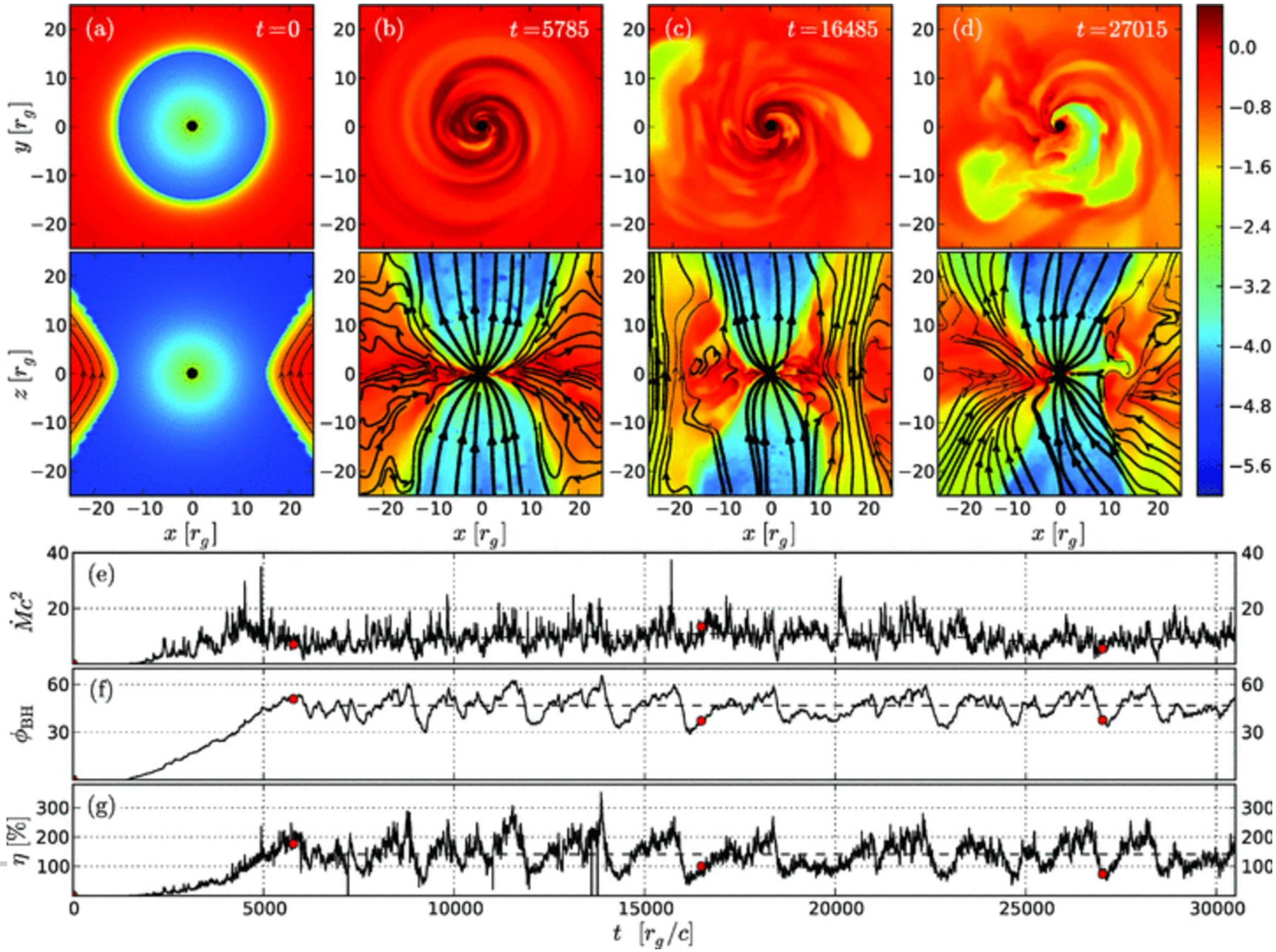
This process is very efficient

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.



P_{jet}

Mc^2

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

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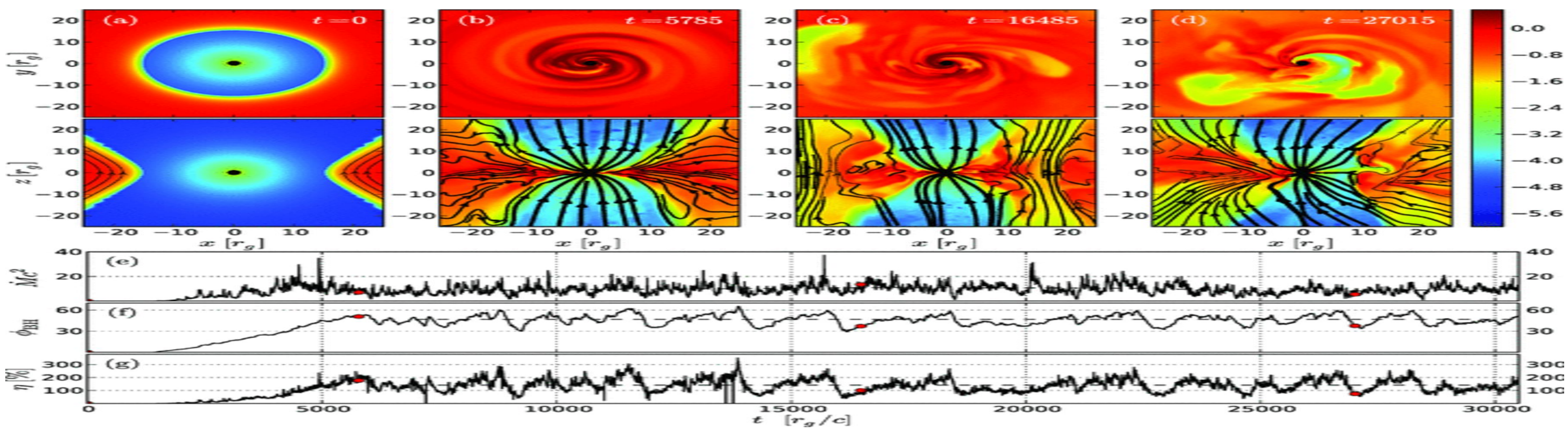
Shows results from the fiducial GRMHD simulation A0.99fc for a BH with spin parameter a = 0.99; see Supporting Information for the movie.

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



On average: 1 g in → 1.5 c^2 erg out

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

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Conclusion

- $P_{jet} \sim \dot{M}c^2$, larger than L_d

The jet uses to energy stored in the rotation of the hole, that was provided by accretion. But it takes it out faster than when it was put in.