The nature of relativistic jets produced when a star falls into a BH♪

Pawan Kumar

Outline†

- Observations of relativistic jets & radiation
- TDEs: a brief summary of observations
- Radiation process for TDE jets and jet composition

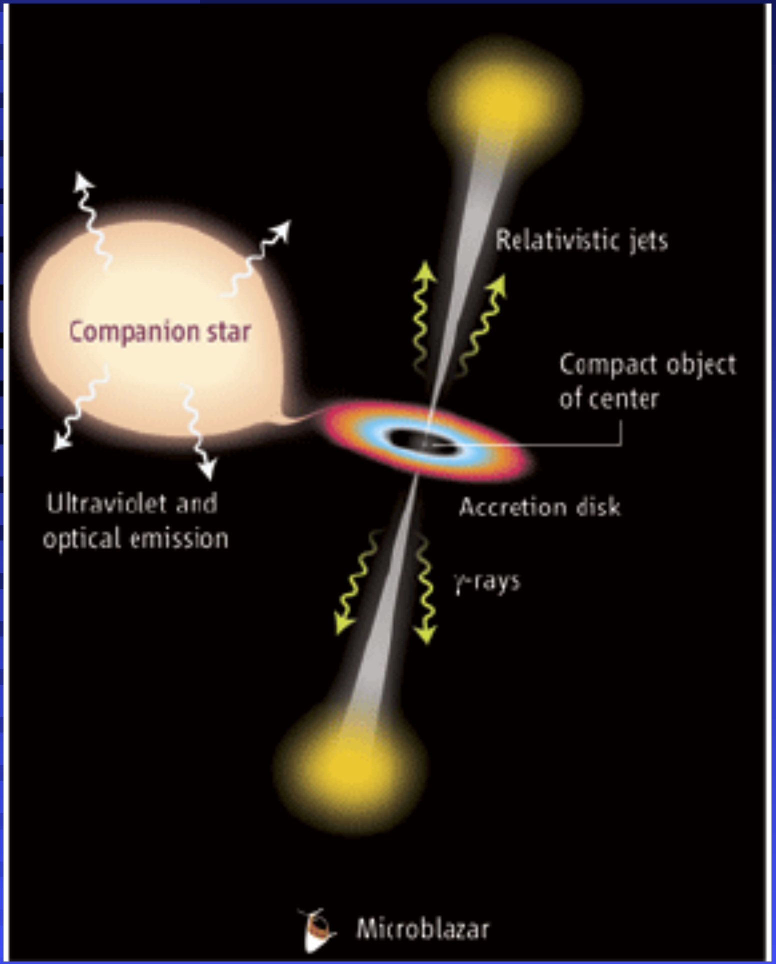
♪Rodolfo Barniol Duran, Patrick Crumley, Wenbin Lu



TIFR, June 29, 2017

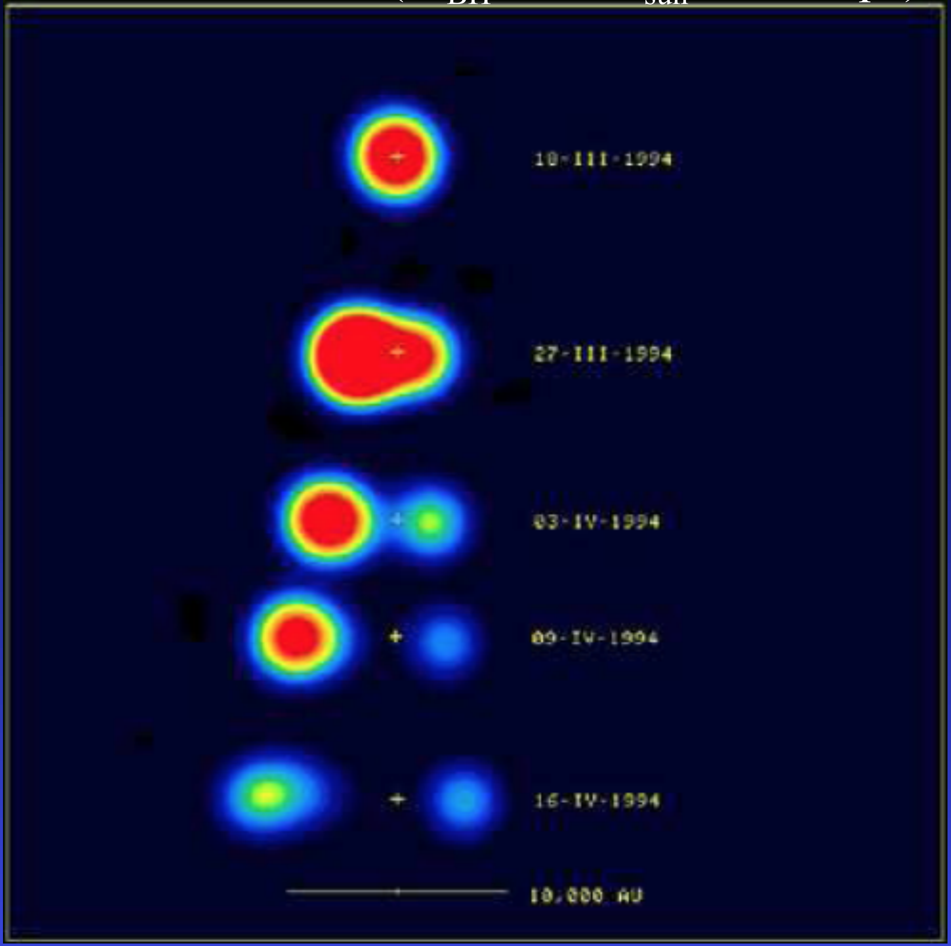
Systems with Relativistic Jets/outflows

X-ray Binaries (aka micro-quasars)



Artist rendition – Mirabel (2012)

GRS 1915+105 ($M_{BH} \sim 12\ M_{sun}$, d = 8 kpc)



The sequence of 3.6 cm radio maps shows the temporal evolution of a pair of plasma clouds ejected from close vicinity of a black hole at a velocity of 0.98 C (Lorentz factor = 5): Mirabel & Rodriguez, Nature (1994)

Systems with Relativistic Jets/outflows

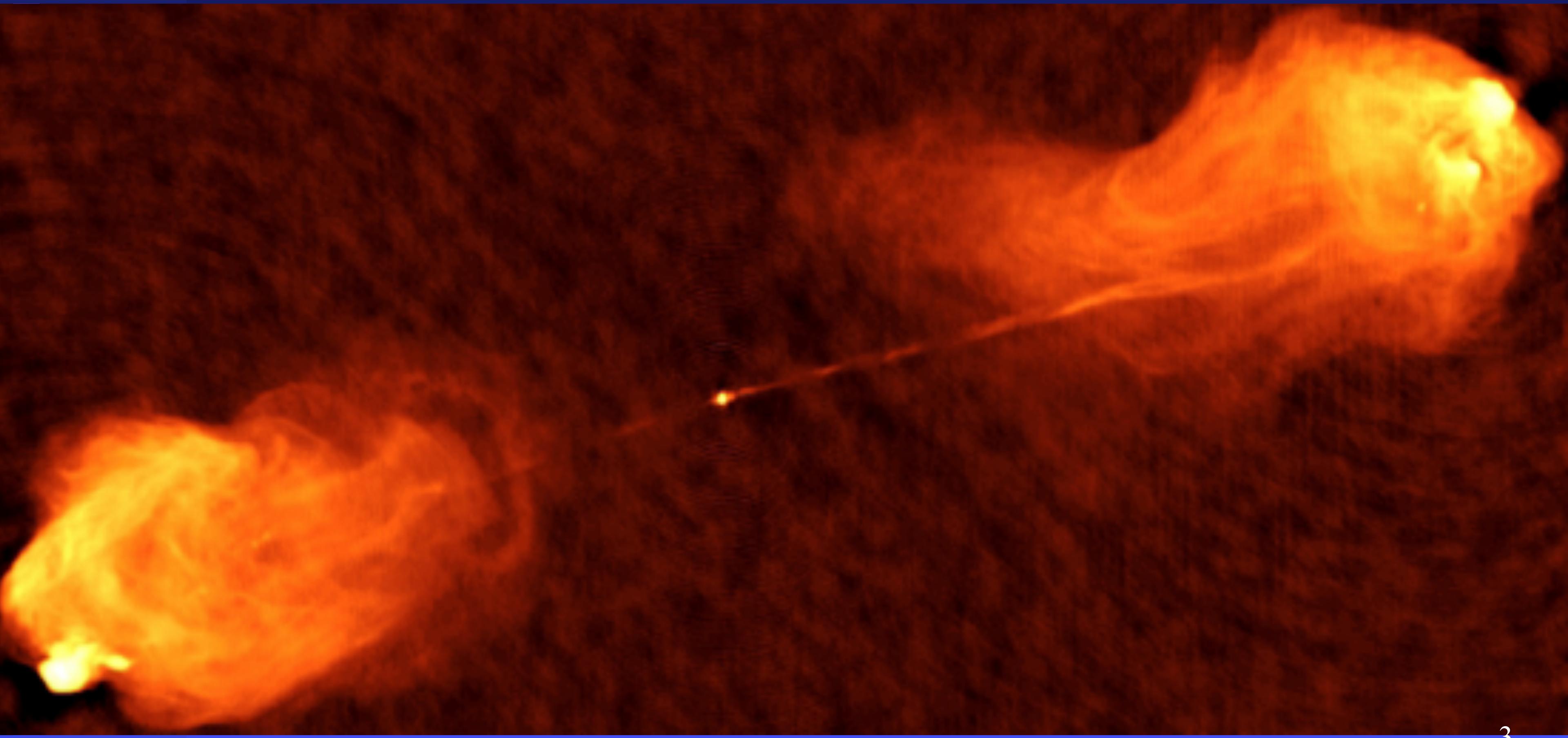
Quasars

~10% of all quasars have jets

Jet Lorentz factor ~ 10

Z=0.056, d_L = 250 Mpc

$M_{BH} = 2.5 \times 10^9\ M_{sun}$

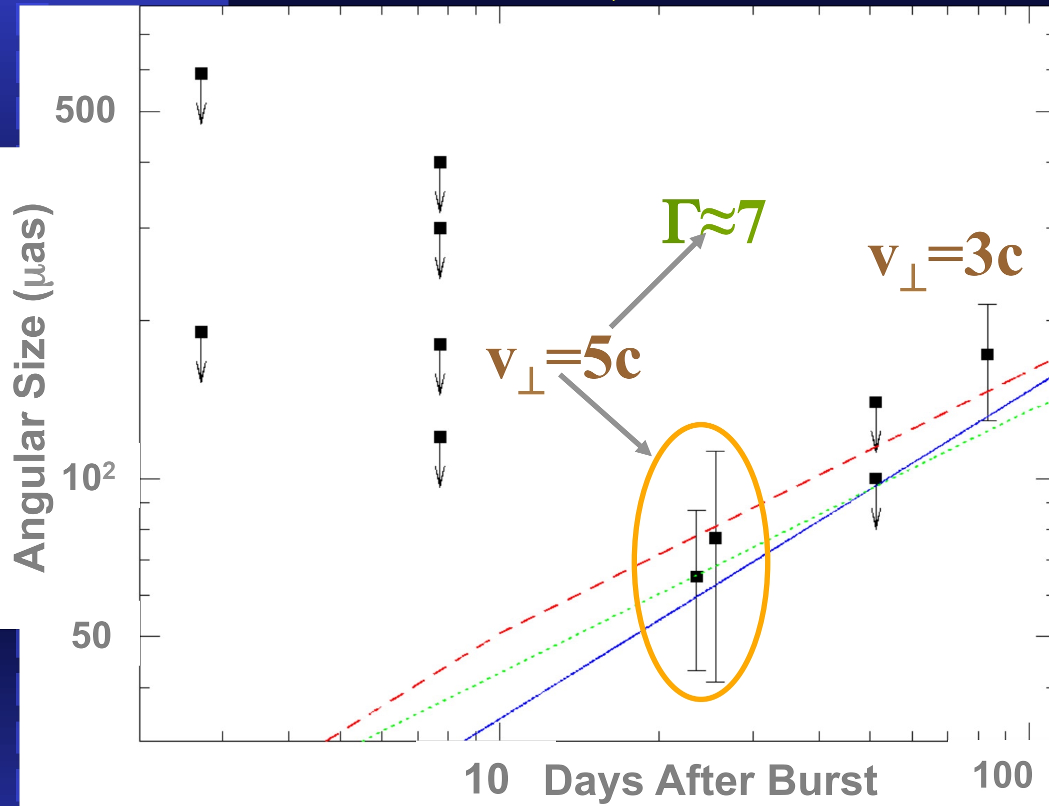


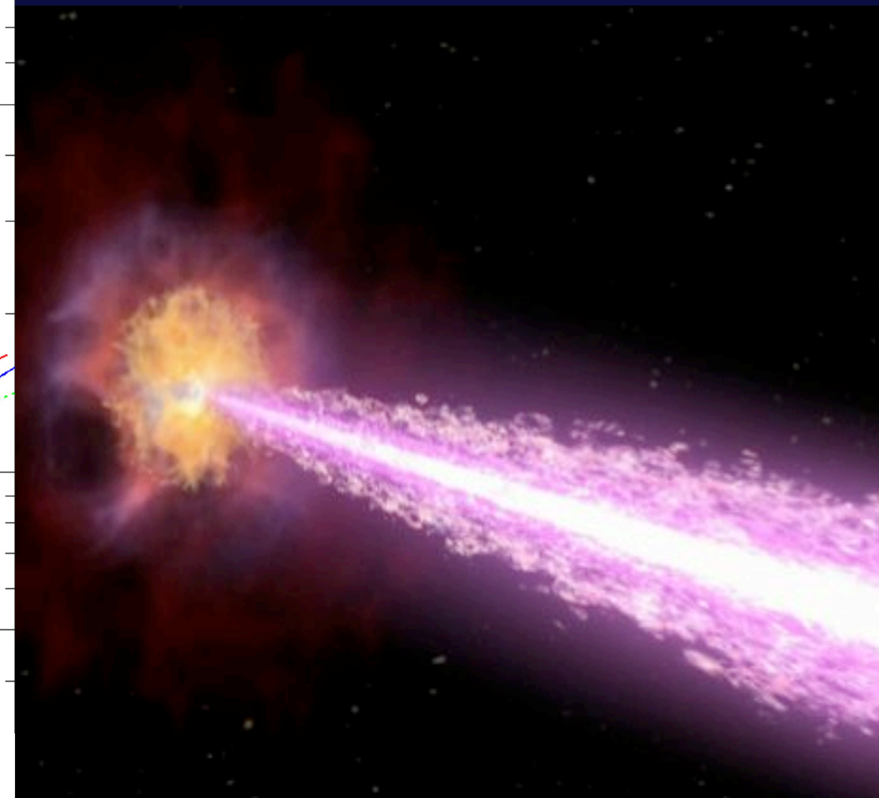
Cygnus A – radio map (820 MLy away); Carilli and Perley, NRAO

Systems with Relativistic Jets/outflows

Gamma-ray Bursts

GRB 030329, z = 0.17





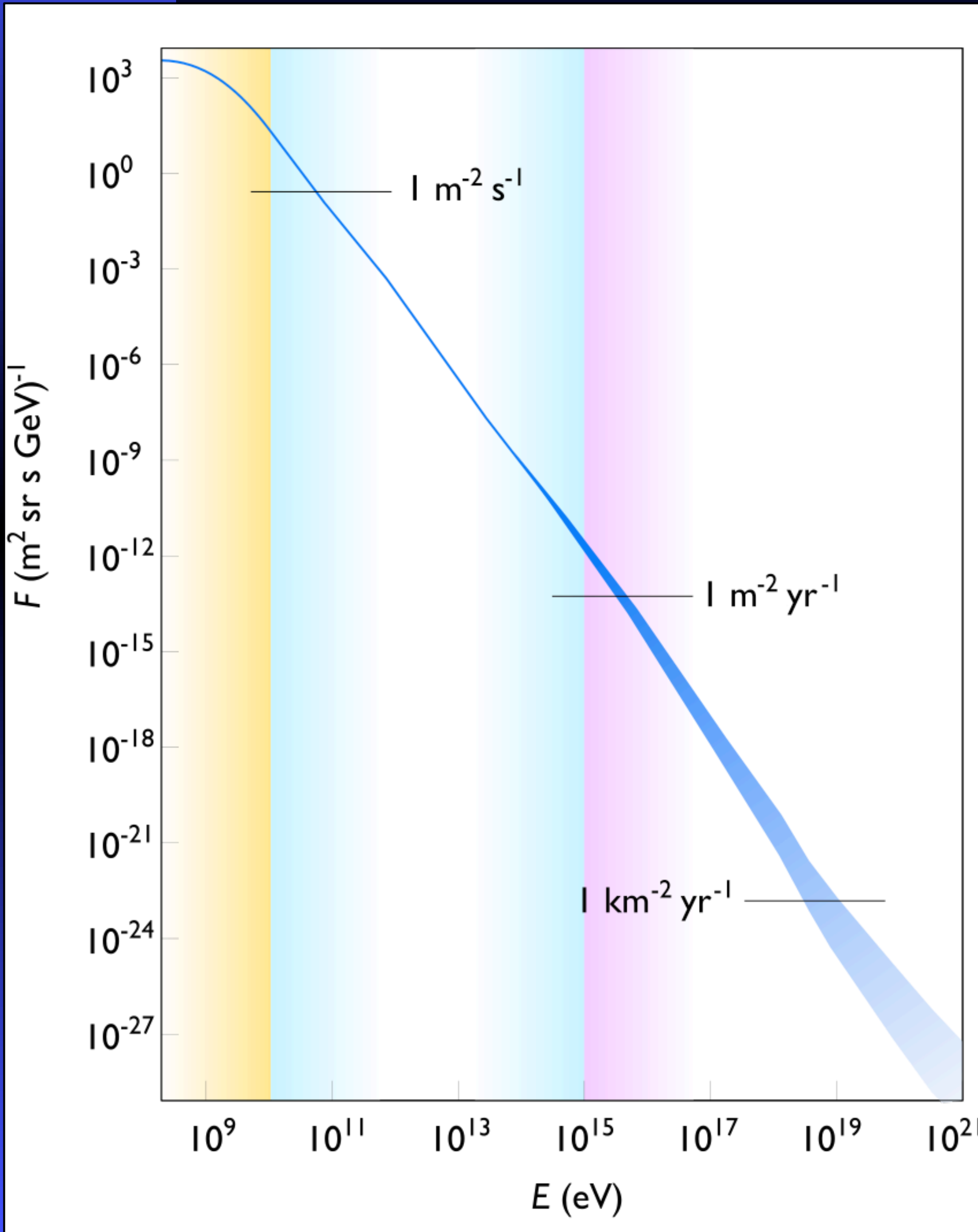
Artist Rendition of GRB jet

8-22 GHz VLBI data; Taylor et al. (2004)

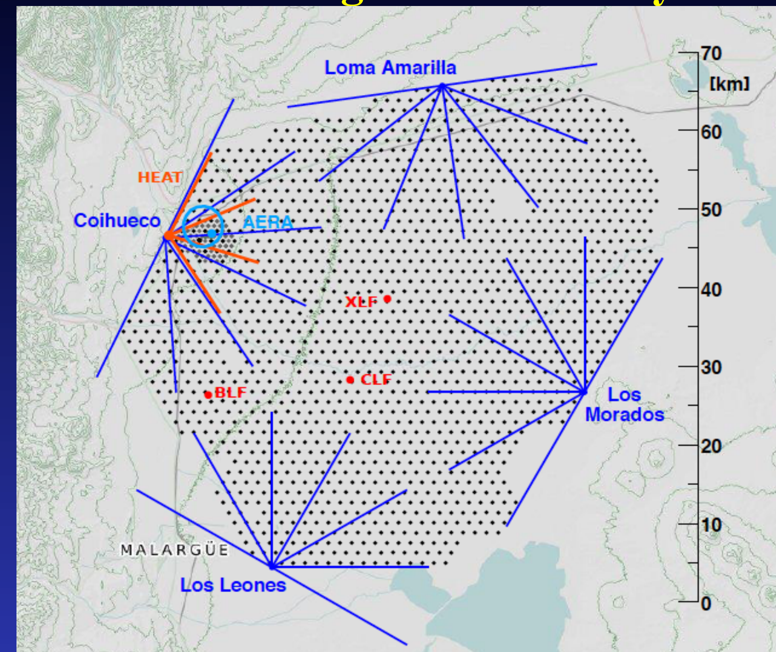
Jet Lorentz factor ≈ 7 (t=25 days)

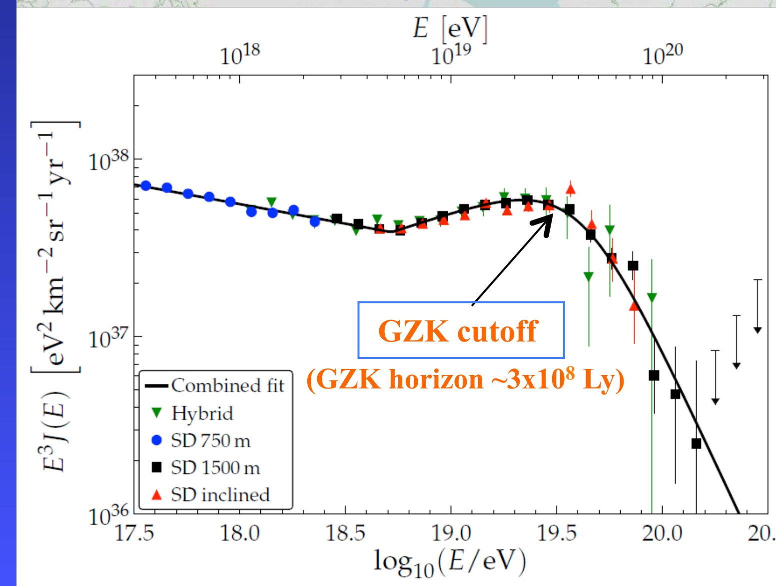
Initial jet Lorentz factor ~ 10^2

It is believed that ultra-high energy Cosmic-rays (>10^6 TeV) are accelerated in black hole jets….



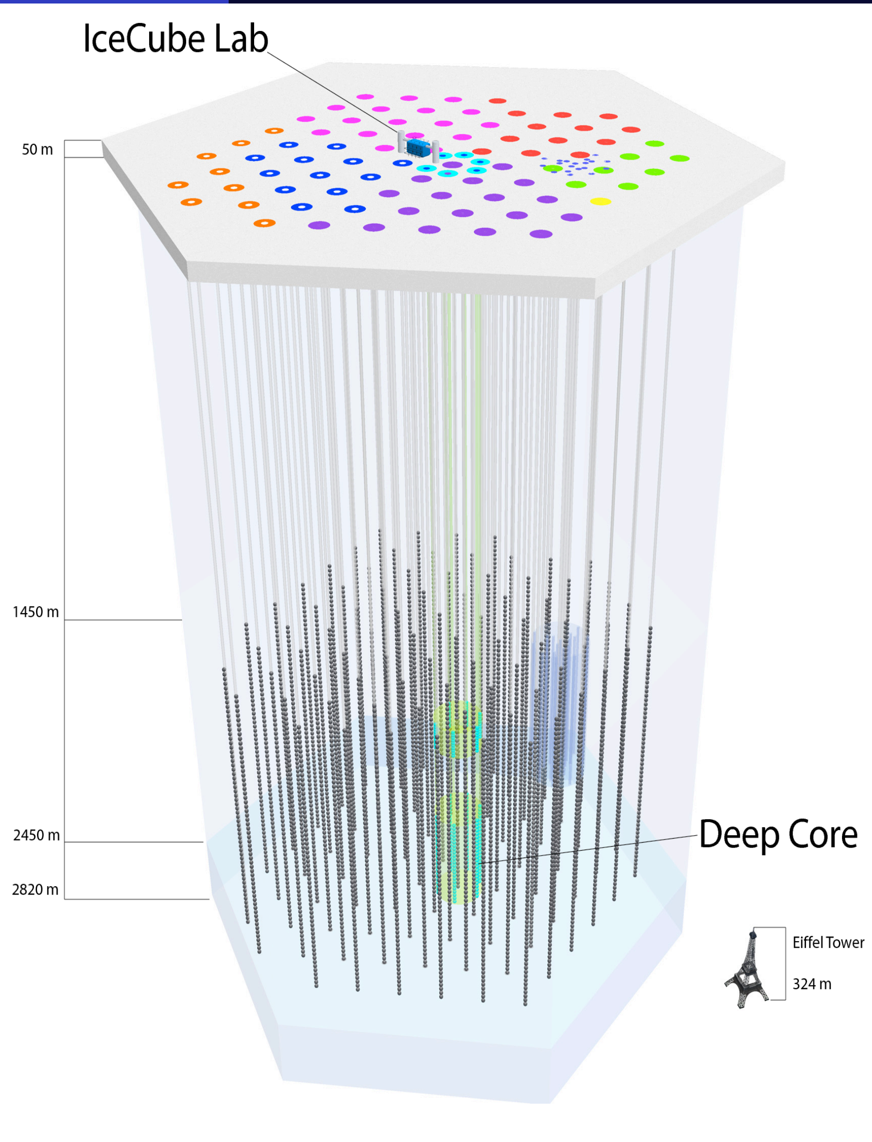
Pierre Auger Observatory

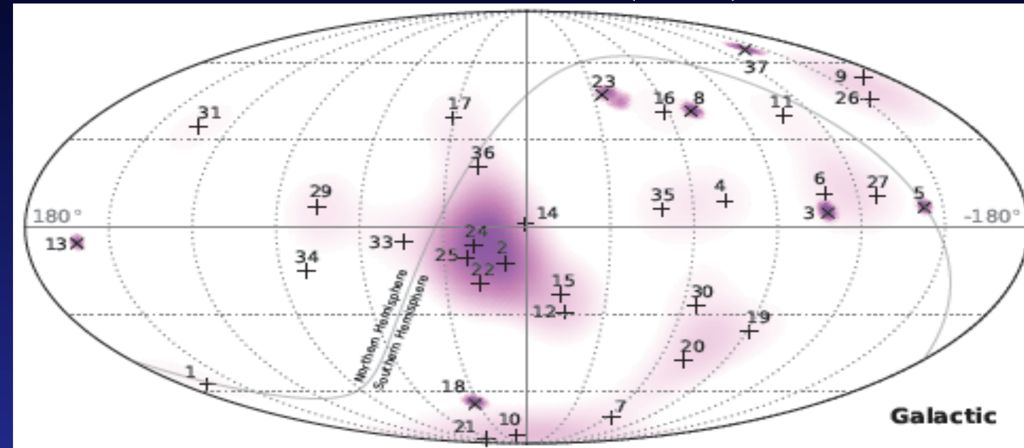


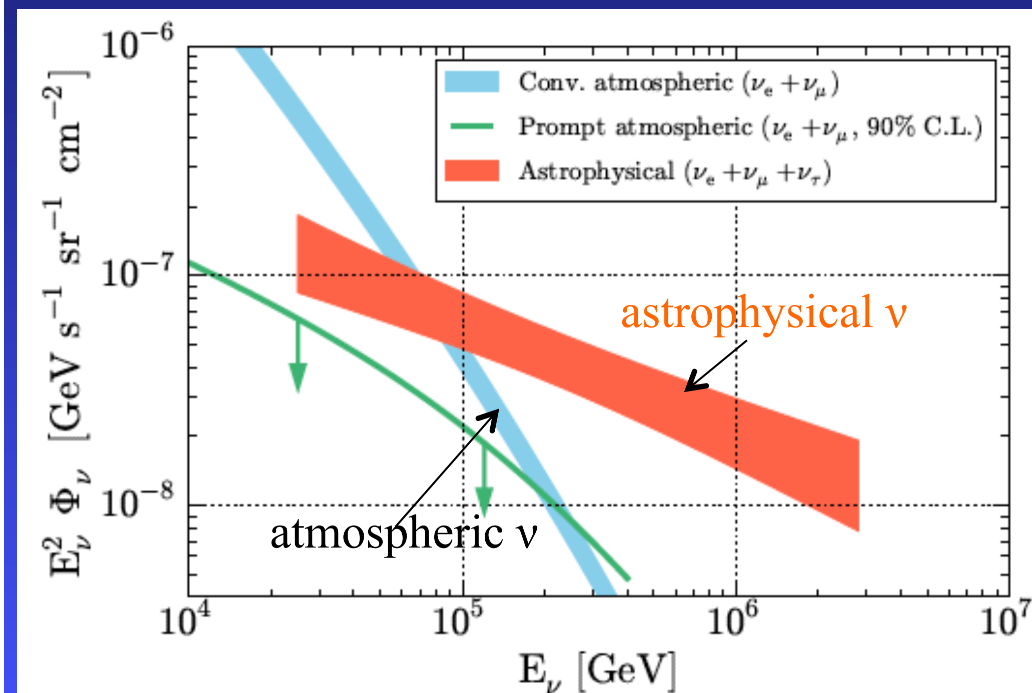


And also high energy neutrinos (>30 TeV)

Aartsen et al. (2014)







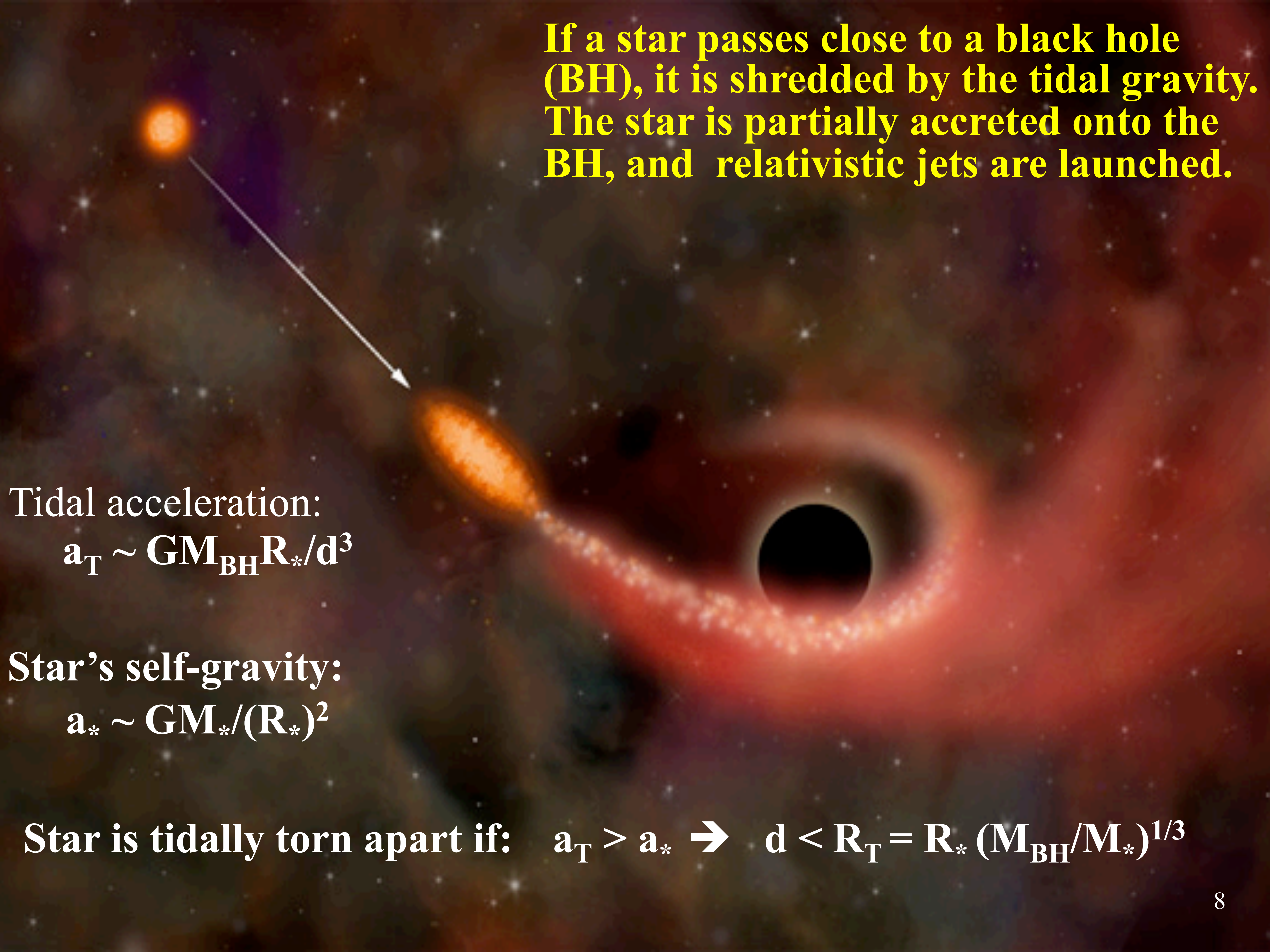
5160 optical modules on 86 strings

Aartsen et al. (2015)

Questions about BH jets that have been around for ~ 40 years

- ✧ **How are high-energy photons produced (synchrotron, SSC or something else?) and particles accelerated?**
- ✧ **What are jets made of?**
- ✧ **How are jets launched, powered and collimated?**

I will, next, describe another phenomenon associated with black holes …



If a star passes close to a black hole (BH), it is shredded by the tidal gravity. The star is partially accreted onto the BH, and relativistic jets are launched.

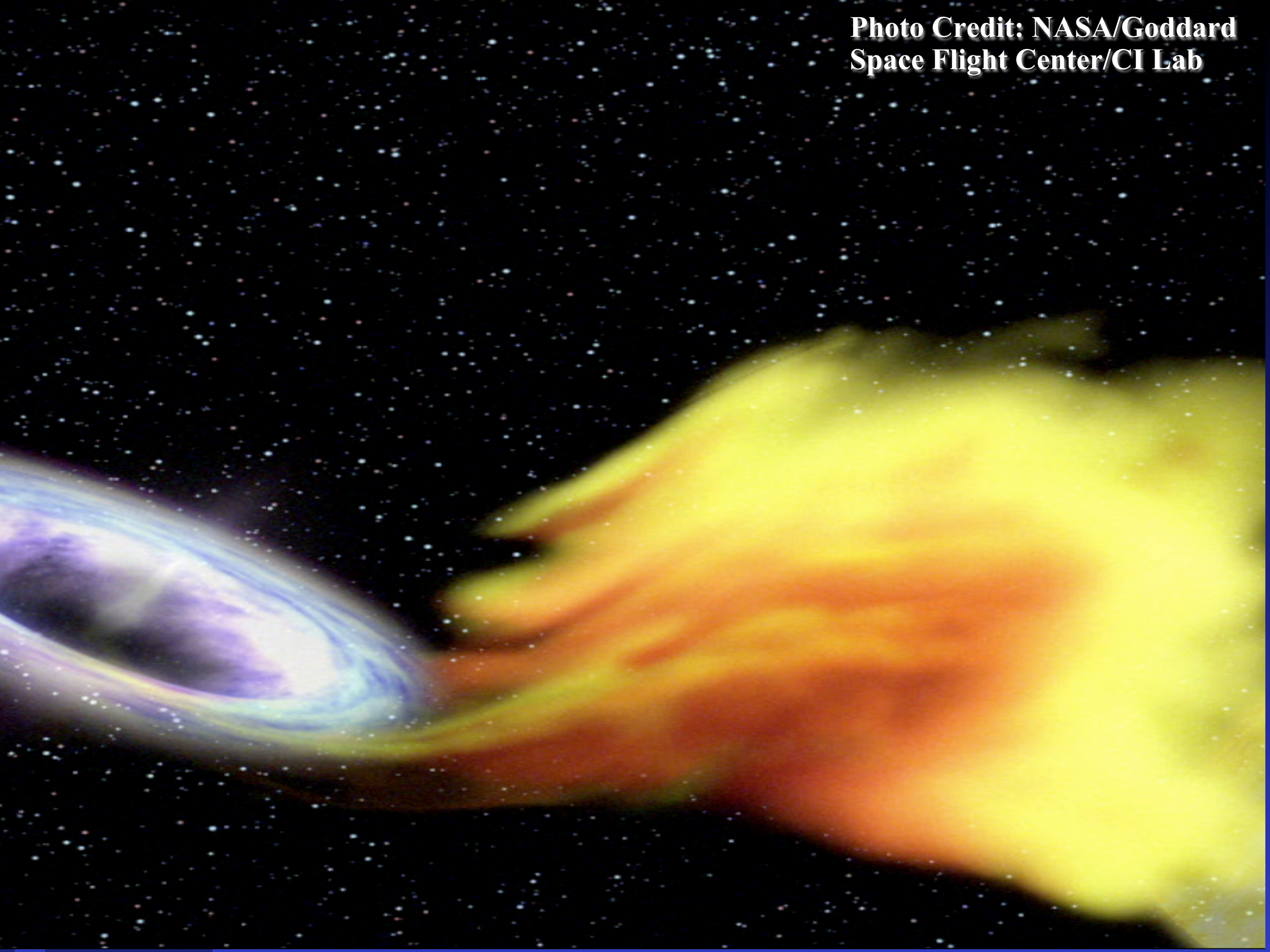
Tidal acceleration:

$$a_T \sim GM_{BH}R_*/d^3$$

Star's self-gravity:

$$a_* \sim GM_*/(R_*)^2$$

Star is tidally torn apart if: $a_T > a_* \rightarrow d < R_T = R_* (M_{BH}/M_*)^{1/3}$



A stellar mass main sequence star is tidally shredded outside the event horizon provided that the BH mass is smaller than ~ $3x10^7 M_{sun}$

$R_T \approx 10^2 R_g$

(For $M_{bh} \sim 10^6 M_{sun}$)

The star is tidally disrupted, an accretion disk forms and roughly half the mass of the star falls into the black hole.

$M_{fb} \sim$ a few $M_\odot \, yr^{-1} \sim 10^2 \; L_{Edd}/c^2$

Tidal Disruption Events or TDE

- **The observed event rate is ~ 10^{-5} yr^{-1} galaxy^{-1}**
- **4 TDEs discovered by ROSAT in 90s (all sky survey) as soft X-ray (~0.1 keV) bright flares (L_x~10^{43} erg/s) in quiescent galaxies.**
- **A number of them observed by Chandra (2), XMM-Newton (5), Swift (3).**
- **Many candidates discovered in optical/UV surveys – SDSS (2), GALEX (3), PTF (3), Pan-STARRS (2), ASAS-SN (3); spectral peak at ~ 10^4 K, and L_{iso} ~ 10^{42} erg/s.**
- **3 of these TDEs had relativistic jets pointing toward us (Swift J1644+57, J2058+0516 and J1112-8238; all detected within 3 months! z=0.35, 1.2 and 0.89 respectively.)**

(X-ray LCs of all 3 are similar and have similar luminosity)

Optical depth of relativistic jets

- For a baryonic jet of isotropic luminosity L_{iso} the optical depth at radius R is:

$$\tau = \frac{\sigma_T L_{iso}}{4\pi R\, m_p\, c^3\, \Gamma^3}$$

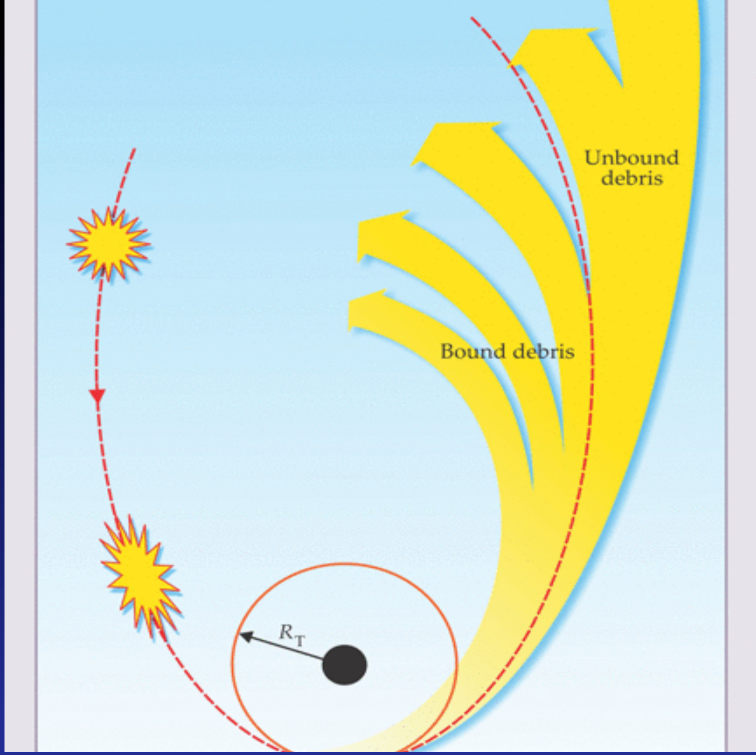
- Expressing L_{iso} & R in terms of the Eddington luminosity (L_E) & Schwarzschild radius (R_s) we find

$$\tau = \frac{L_{iso}}{L_E} \frac{R_s}{R} \frac{1}{\Gamma^3}$$

For narrow jets $L_{iso}/L_E >>1$, and so the jet can be optically thick at the launching radius unless $\Gamma>>1$.

(Wind from the accretion disk can also keep the jet hidden up to a large radius unless the jet is pointing directly at us.)

Jets produced when a star is shredded by a black hole are excellent for answering some long standing questions, because:



- ***they are extremely bright, so we can collect high quality, multi-wavelength, data & variability time can be accurately measured to constrain the size of system.***

- ***we know how much mass falls into the black hole┘, and hence we know the total energy budget for the event.***

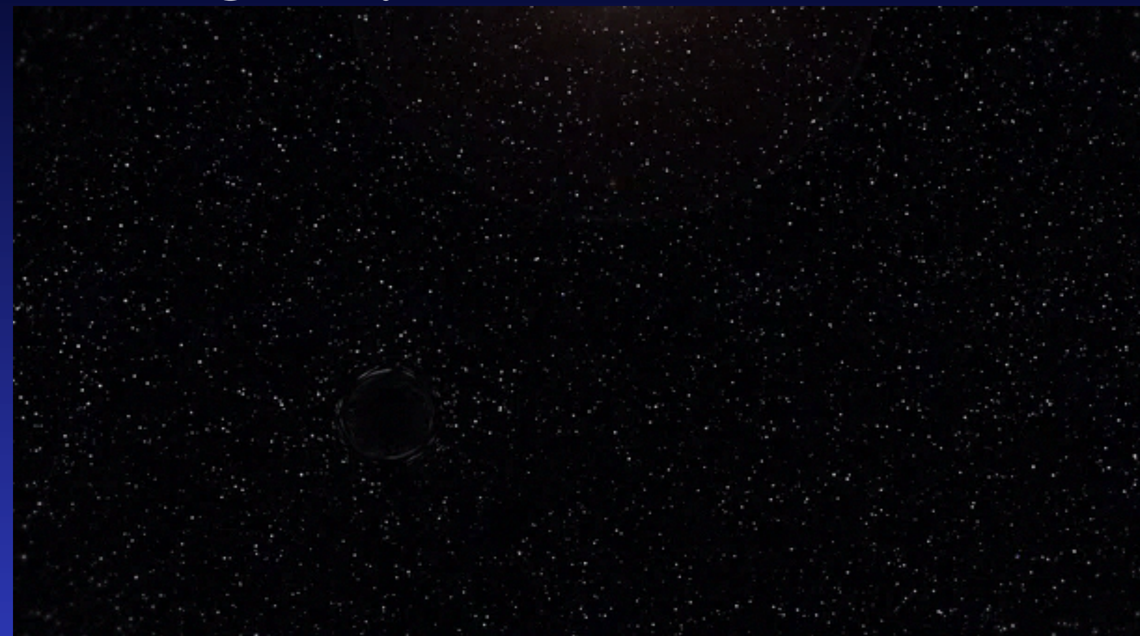
- ***the jet is transparent at the launching site (because of the large Schwarzschild radius of massive BHs) so we can see the entire jet.***

┘ One of the TDE candidates with jet is at the center of an elliptical galaxy where stars have mass ~ 1 $M_\odot$

The BH at the center of Milkyway swallows a star once every ~10^5 years.

- A star wandered too close to a massive black hole on March 25, 2011, in a galaxy ~ 3.8 billion light years away, and the star was shredded by the tidal gravity of the black hole.

- A relativistic jet was produced as a part of stellar debris fell into the black hole, and powerful radiation from X-ray to mm bands was observed.



- This event – Swift J1644+57 – is an excellent system to address some long standing questions regarding relativistic jets:

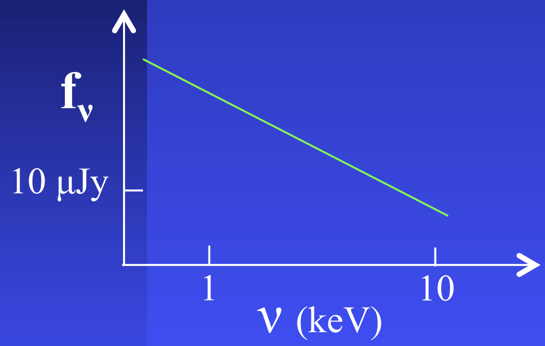
  ✧ How are X-ray photons produced?

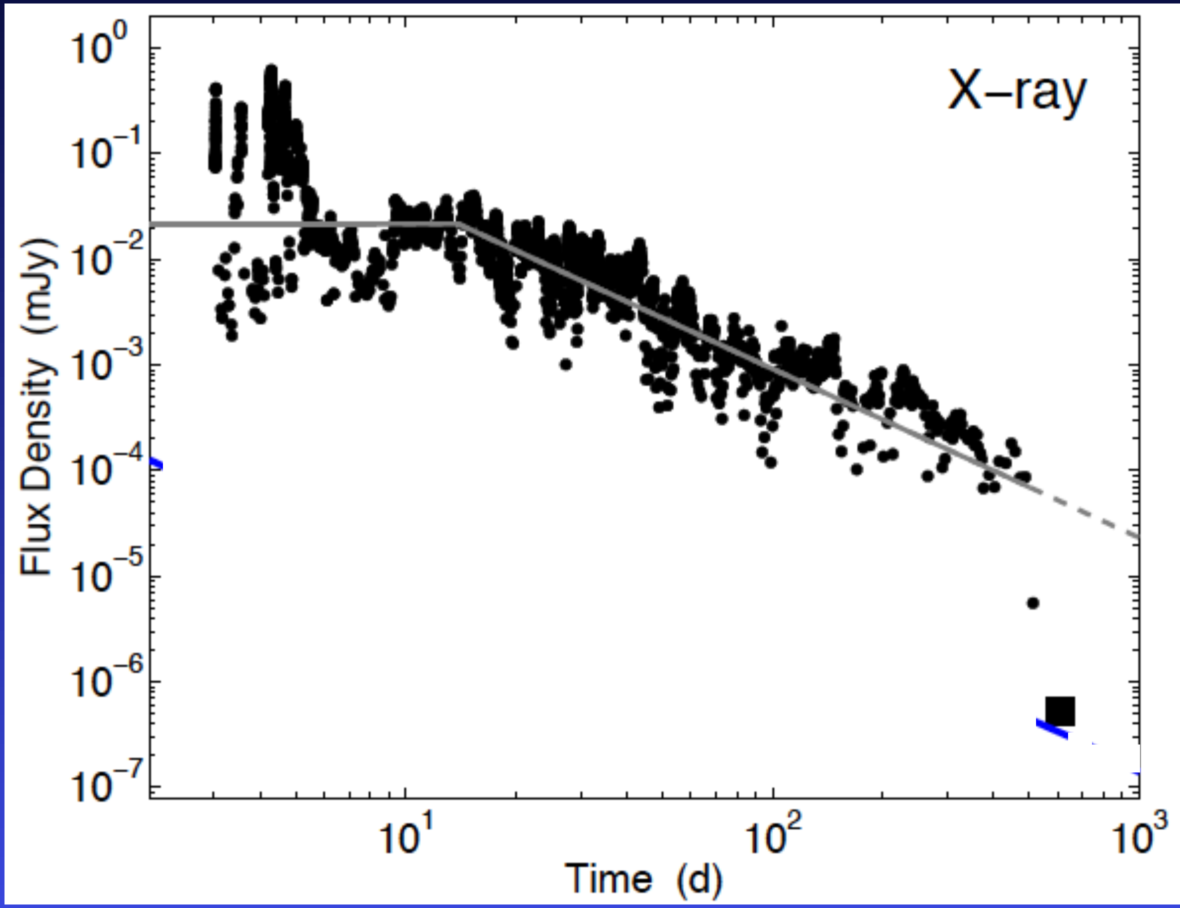
  ✧ What are jets made of?

Swift J1644+57: X-ray data

- X-ray data show a period of intense flaring lasting for ~10 days. The variability time is ~10^2s.
- Spectrum is a simple power-law function from 0.3 – 10 keV:

$$f_\nu \propto \nu^{-0.8}$$





Swift/XRT data
Burrows et al. (2011)

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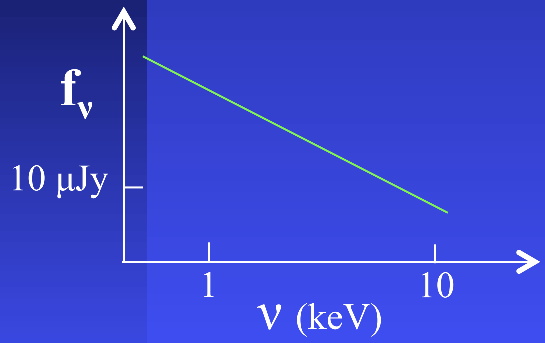

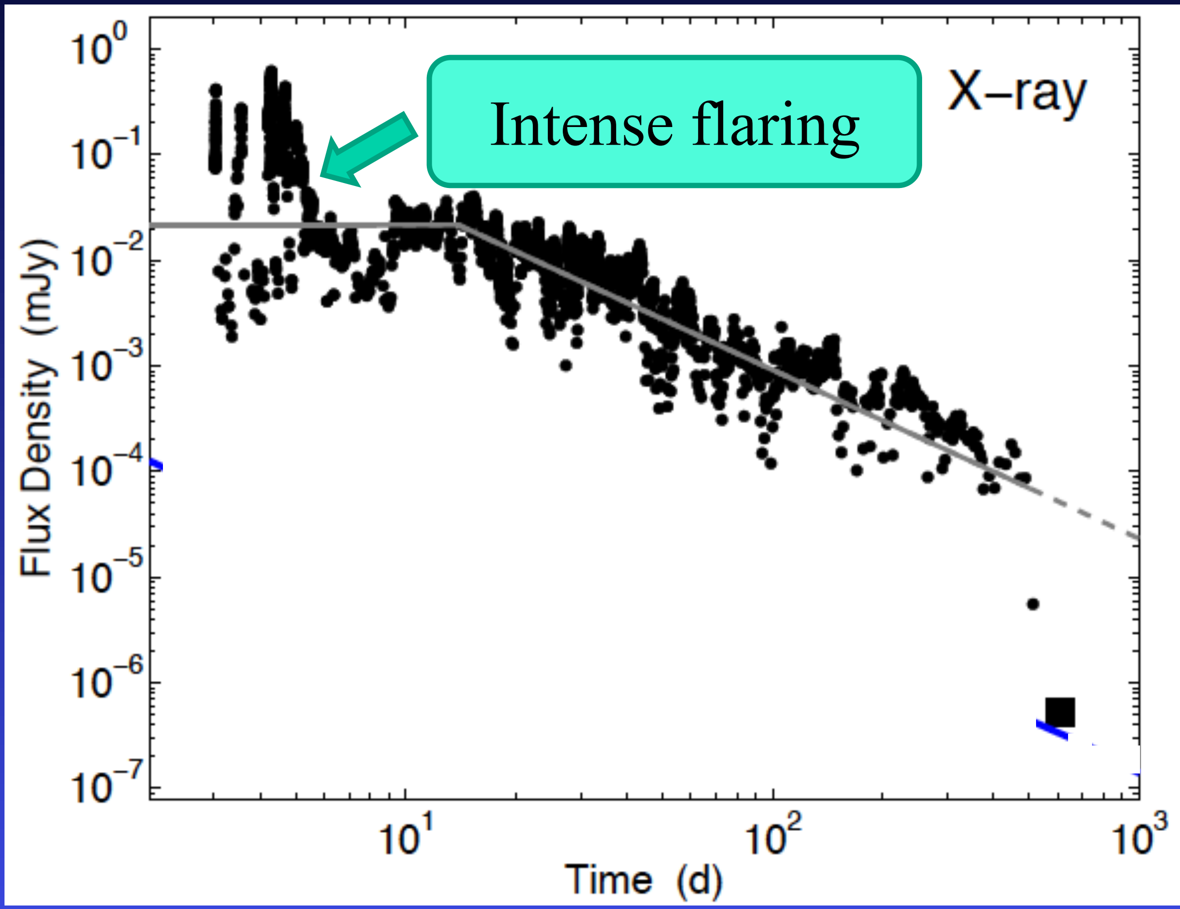

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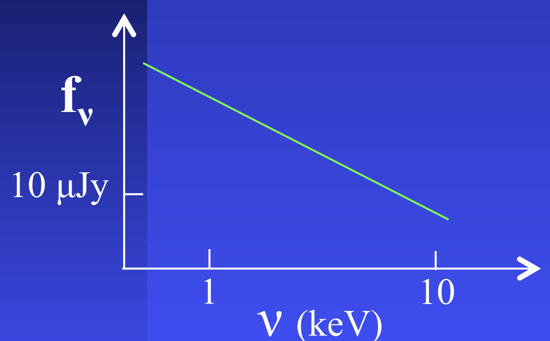

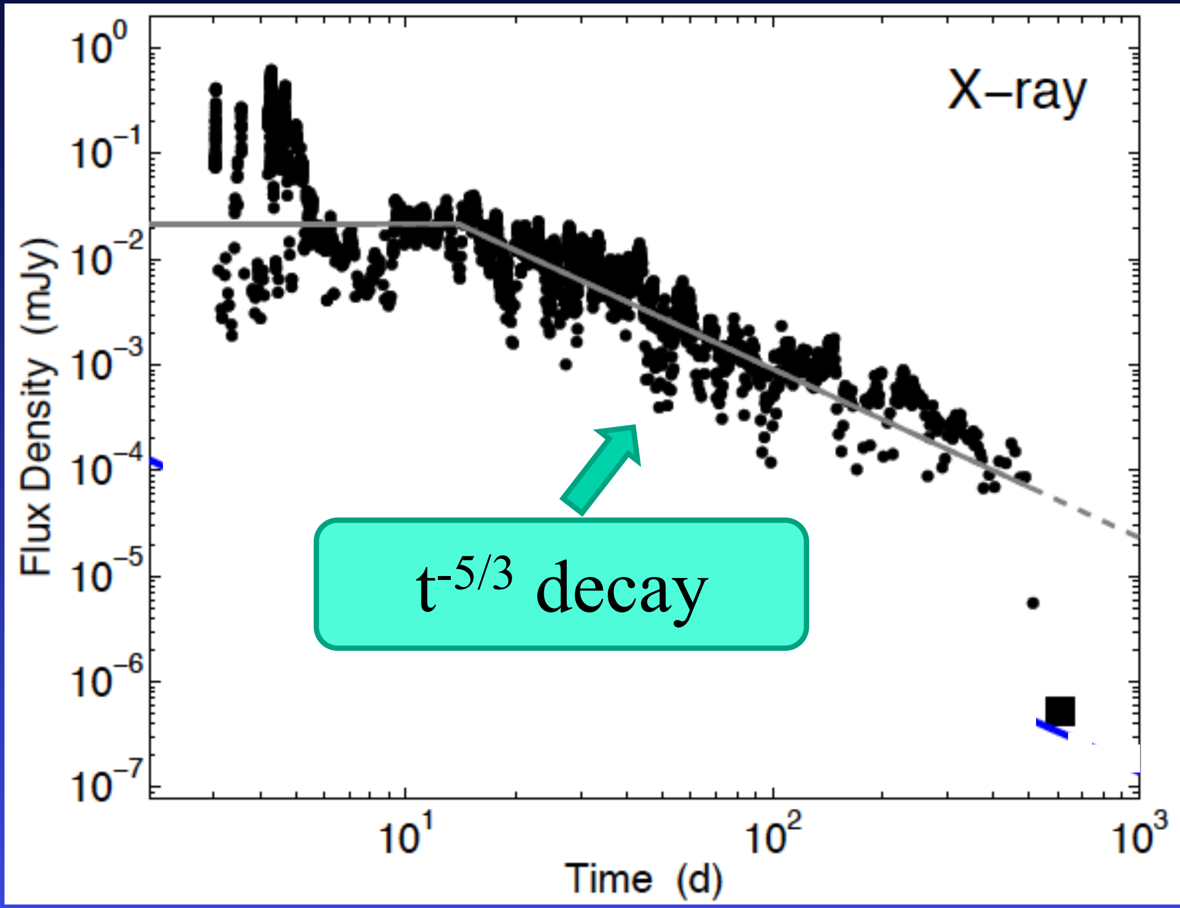

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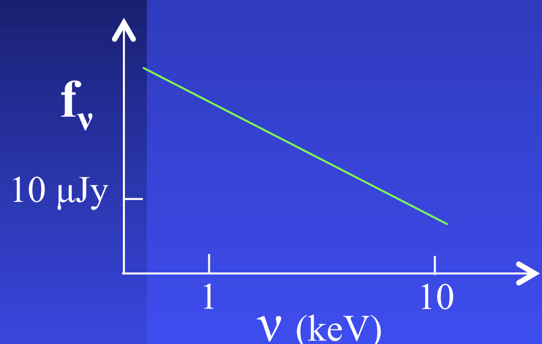
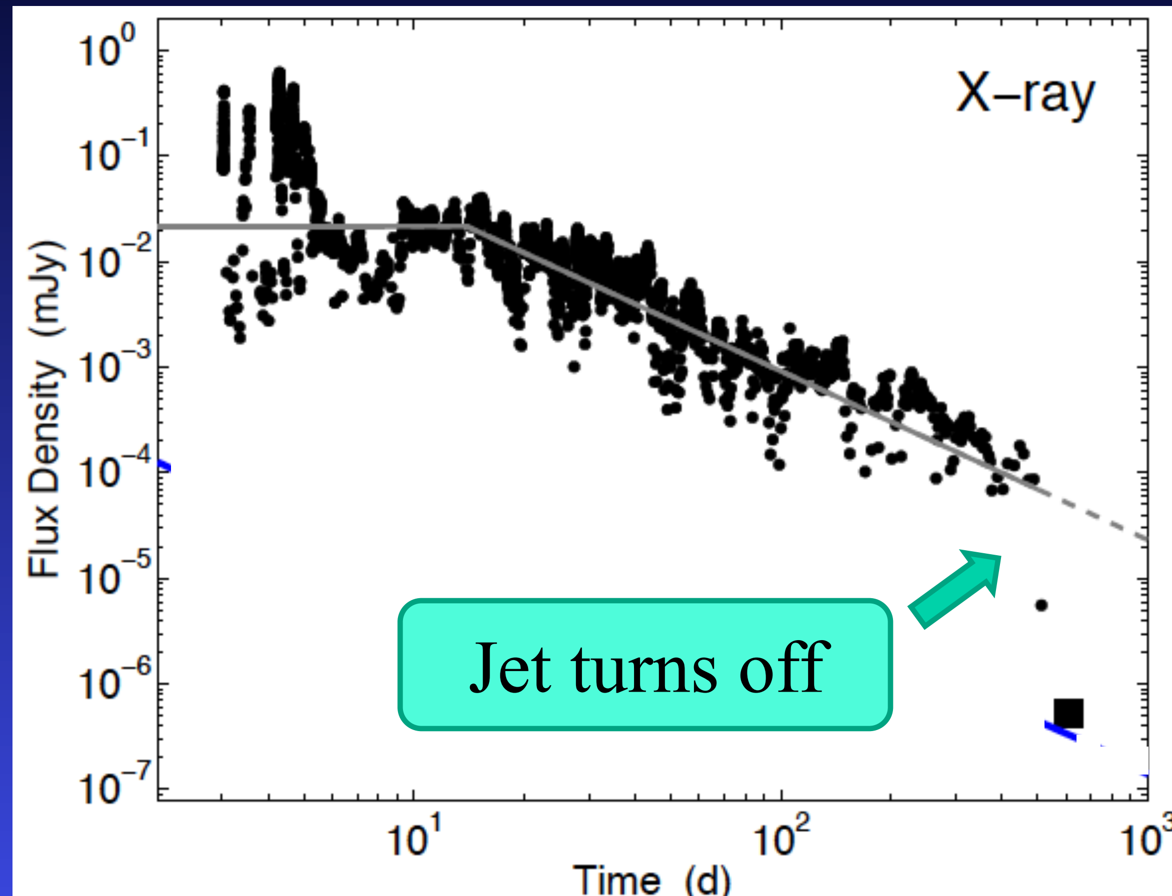
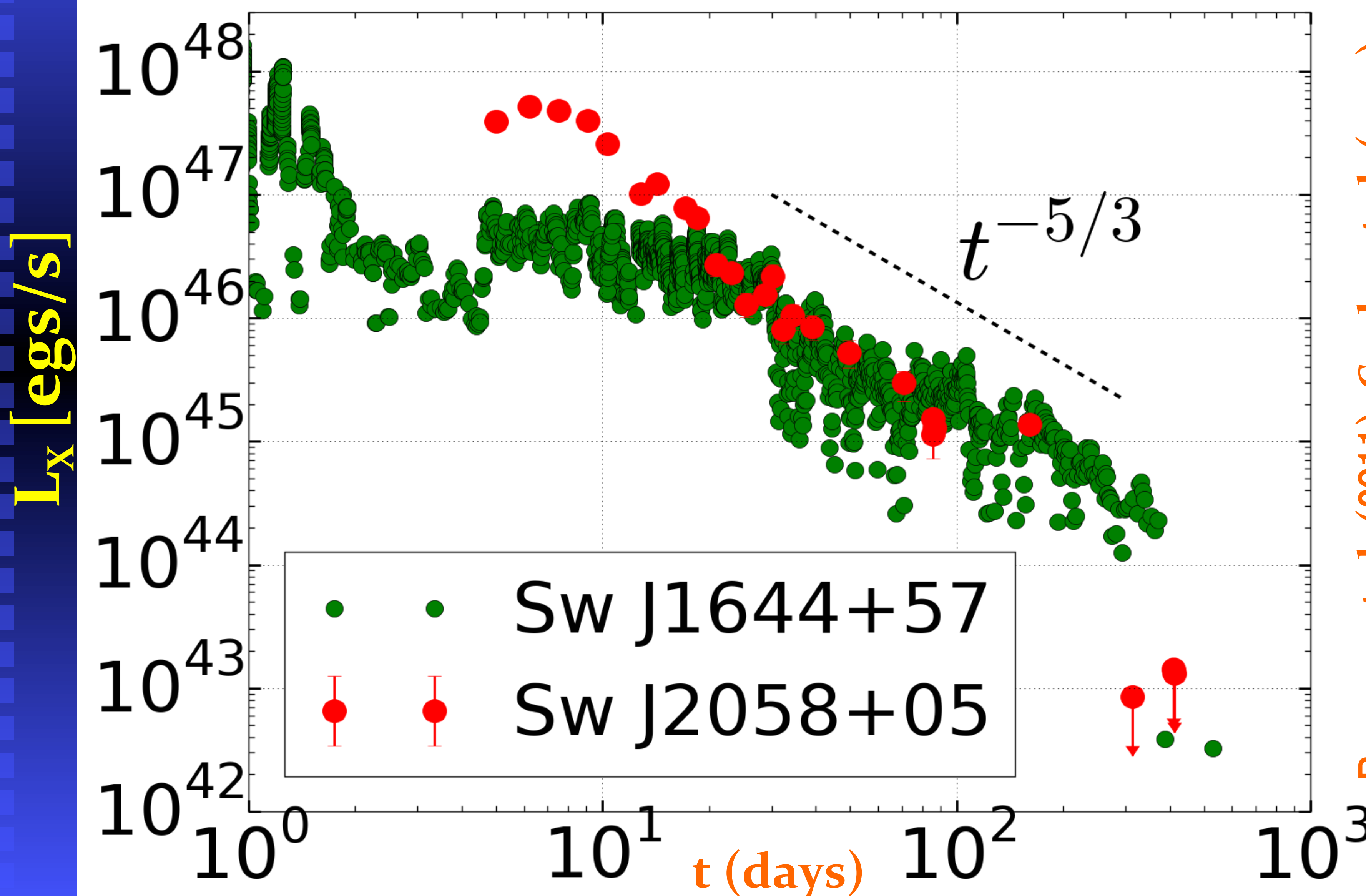




Swift/XRT data
Burrows et al. (2011)

X-ray light-curves of TDEs with jets

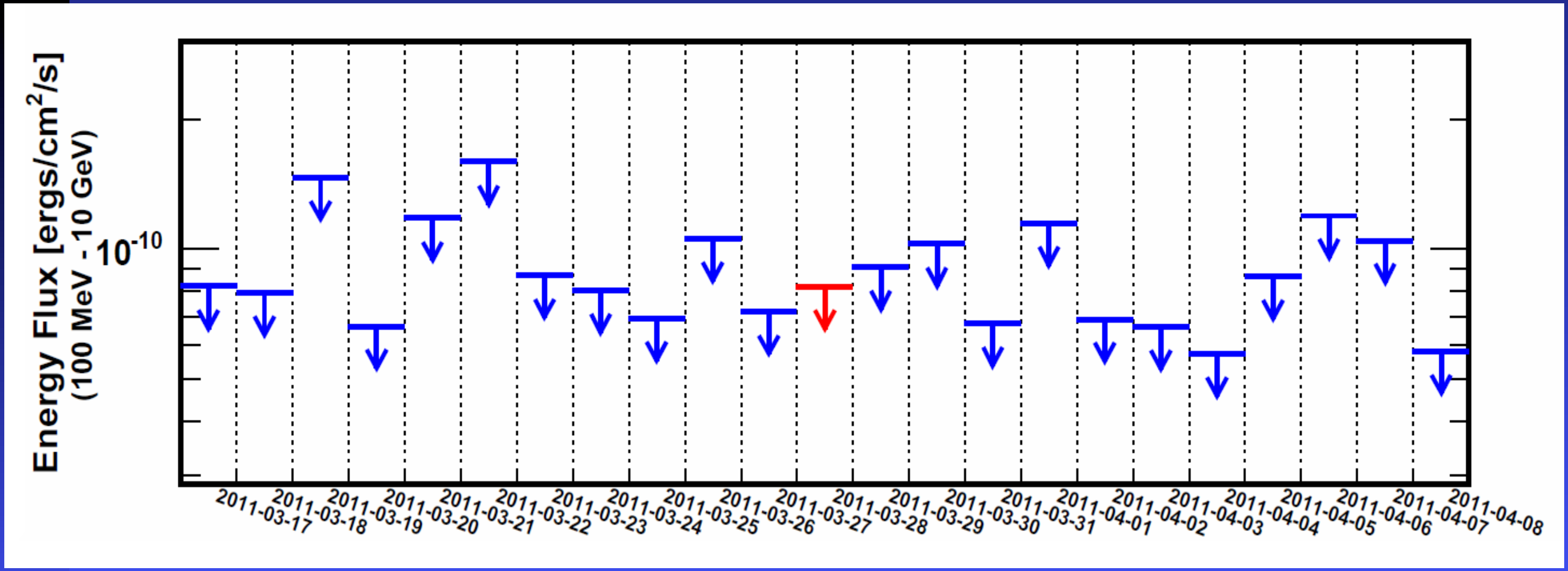
$10^3\ L_{edd}$; $c\delta t \sim 10\ R_g$



Burrows et al. (2011); Cenko et al. (2012)

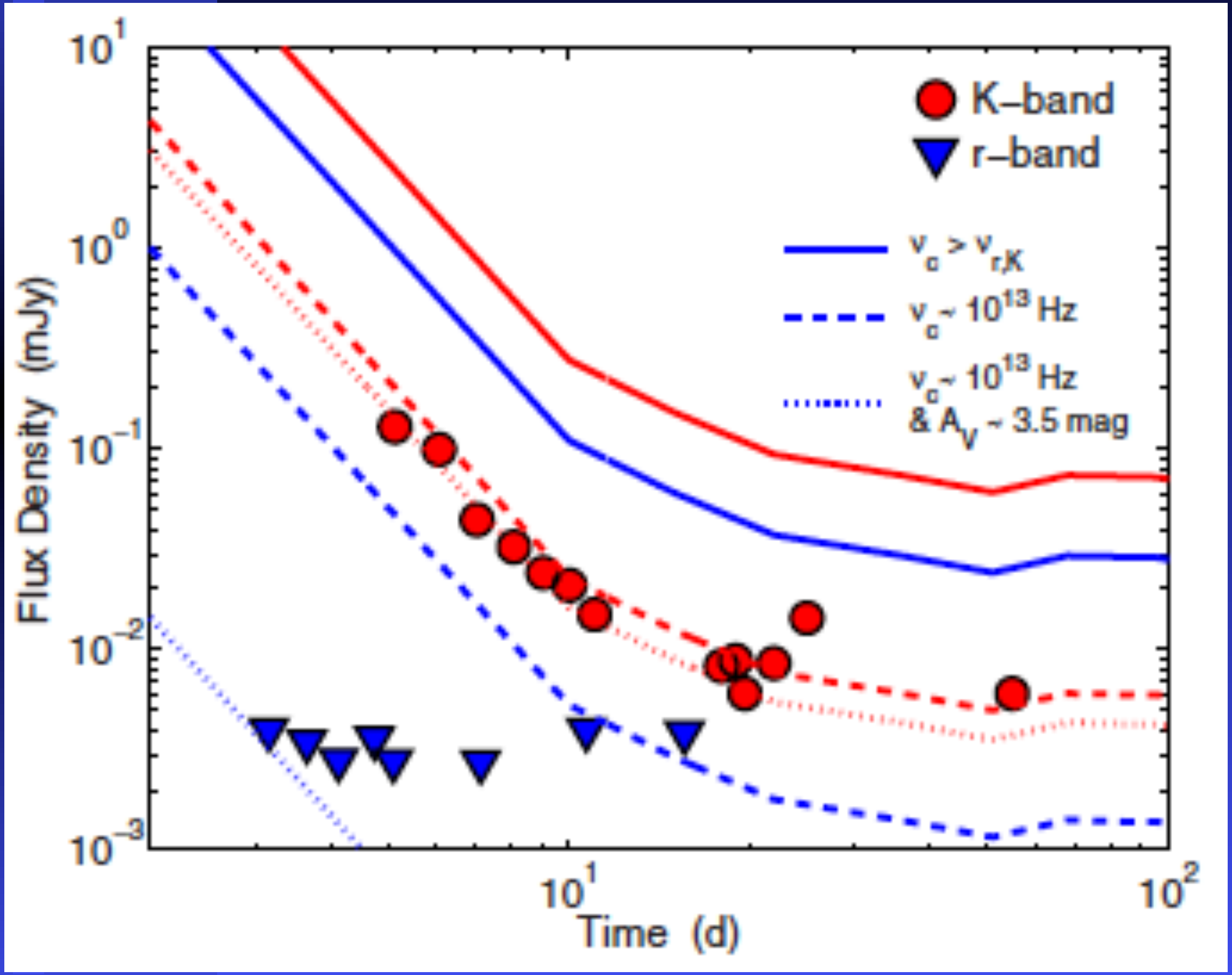
Swift J1644+57: γ-ray data

- Fermi/LAT upper limits on the 100 MeV- 10 GeV integrated flux of 3×10^{-11} erg/cm^2/s ($L_{LAT} < 10^{46}$ erg/s)
- Veritas upper limits at 500 GeV ~ 10^{-10} erg/cm^2/s ($L_{ver} < 10^{45}$ erg/s)



Burrows et al. (2011)

Swift J1644+57: optical/IR data

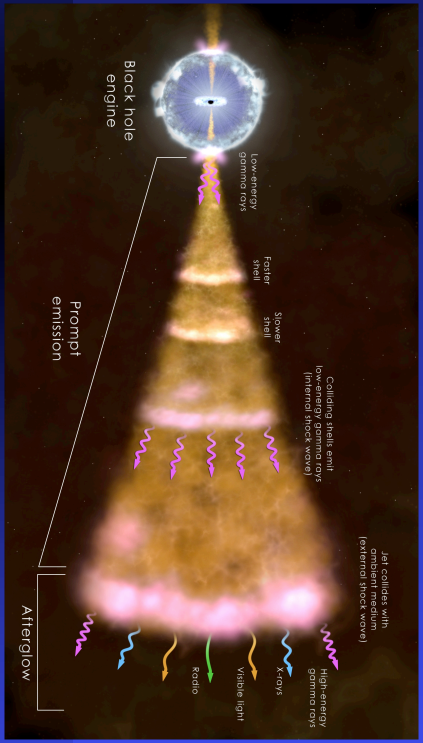


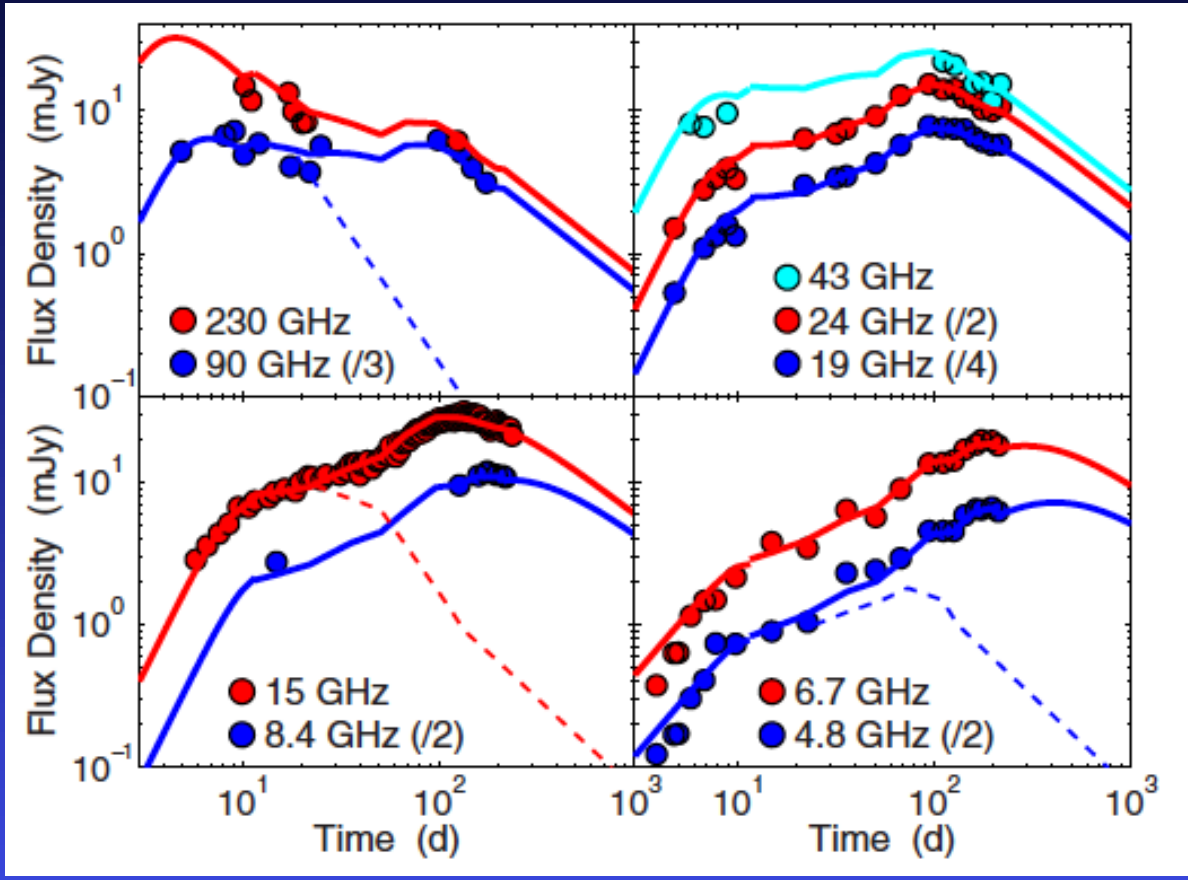
Infra-red K-band data are extremely constraining of jet properties.

Levan et al. 2011

Swift J1644+57: radio/mm data

Consistent with being the afterglow of a mildly relativistic jet.





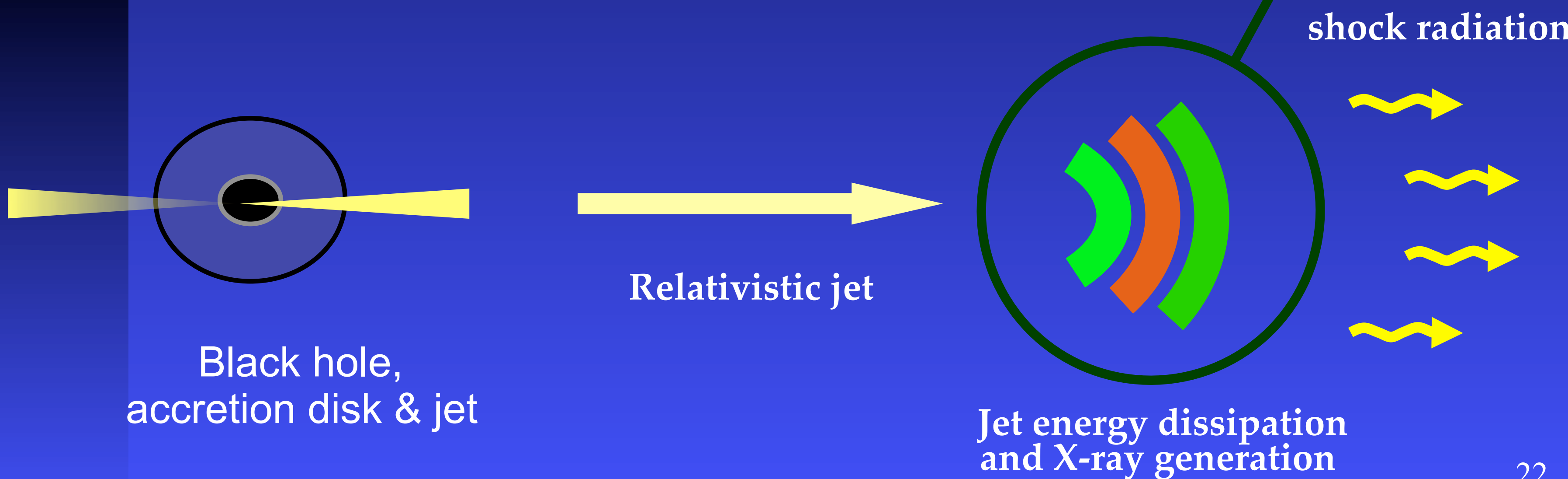
Berger et al. 2012

March 25, 2011 event (Swift J1644+57)

- **X-ray photon generation mechanism**
- **And Jet composition & particle acceleration**

The basic strategy is to assume that the jet is

Either *baryon* or *Poynting flux* dominated & calculate radiation from it, and confront that with data



Baryonic jets

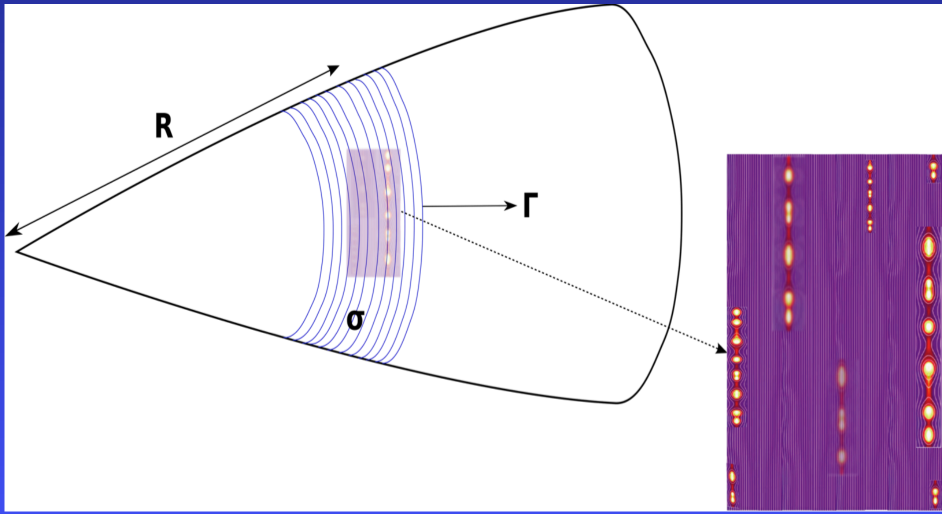
Jet KE is converted to particle energy via shocks and the Fermi acceleration mechanism is at work.

Electrons are accelerated near the shock front, and once they leave the acceleration region they cool down due to radiative loss.

Poynting jet

Jet magnetic energy converted to particle energy in current sheets (magnetic reconnections).

Electrons continually accelerated over an extended period



Kumar & Crumley, 2015

There are many different radiative processes we need to consider for generating X-ray photons:

- **Synchrotron (non-thermal spectrum)**
- **Synchrotron + inverse-Compton (SSC)**
- **Thermal photons (Planck spectrum) produced in the jet and inverse-Compton scattered to higher energies.**
- **Photons from the accretion disk/wind inverse Compton scattered by electrons in the jet**

And confront these with IR to γ-ray data to figure out jet composition & particle acceleration.

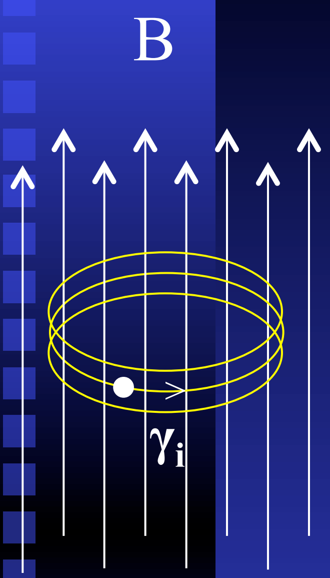
The bottom line is that the only way we can explain the data is if the jet energy is carried by magnetic fields & particles accelerated in current sheets.

Consistent with Burrows et al. (2011) conclusion

Constraints on radiation mechanism

- **Variability time <10^2s.**
- **Source must be at R > R_s (~2×10^{11} $M_{BH,6}$ cm).**
- **The jet Γ ~ 10 (from mm/radio data & total energy constraint).**
- **X-ray luminosity ~3×10^{47} erg/s for a duration of ~10 days requires an efficiency >1% to avoid an unphysically large amount of energy.**
- **Energy flux below the X-ray band should decrease as ~ $\nu^{1/3}$ (or faster) otherwise the IR flux would be larger than the observed value.**

Synchrotron Radiation Process



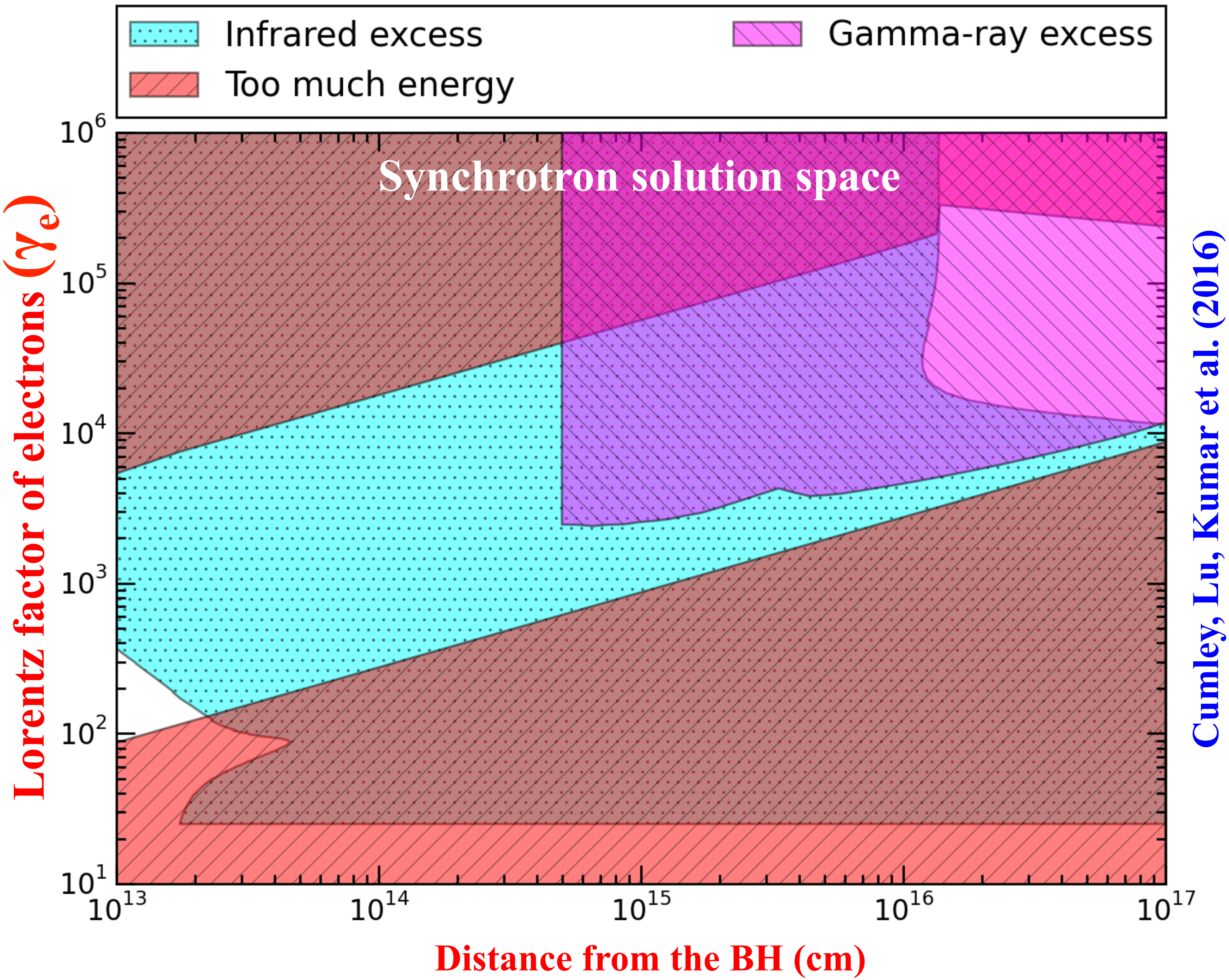
- An electron with a Lorentz factor γ_i traveling through a magnetic field of strength B' in a jet moving at bulk Lorentz factor Γ radiates at a frequency ν_i:

$$\nu_i = \frac{qB'\gamma_i^2\Gamma}{2\pi m_e c(1+z)} \approx (1.2\times 10^{-8}\ \mathrm{eV})B'\gamma_i^2\Gamma(1+z)^{-1}$$

- We add up the contributions of N_e electrons to produce the total observed flux at ν_i

$$\begin{aligned} f_i &= \frac{\sqrt{3}q^3 B' N_e \Gamma(1+z)}{4\pi d_L^2 m_e c^2} \\ &\approx (1.8\times 10^2\ \mathrm{mJy}) N_{e,55} B' \Gamma (1+z)/d_{L,28}^2 \end{aligned}$$

In other words, we can find the total number of electrons in the jet from the observed flux (and known distance).

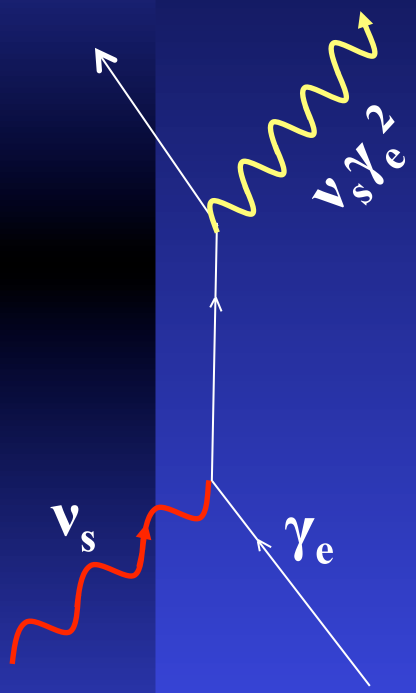


Infrared excess
Gamma-ray excess
Too much energy
Synchrotron solution space
10^6
10^5
10^4
10^3
10^2
10^1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
Lorentz factor of electrons (γ_e)
Distance from the BH (cm)
Cumley, Lu, Kumar et al. (2016)

Synchrotron + inverse Compton

- The Thomson scattering optical depth of the jet is:

$$\tau_T = N_e\, \sigma_T/(4\pi R^2)$$



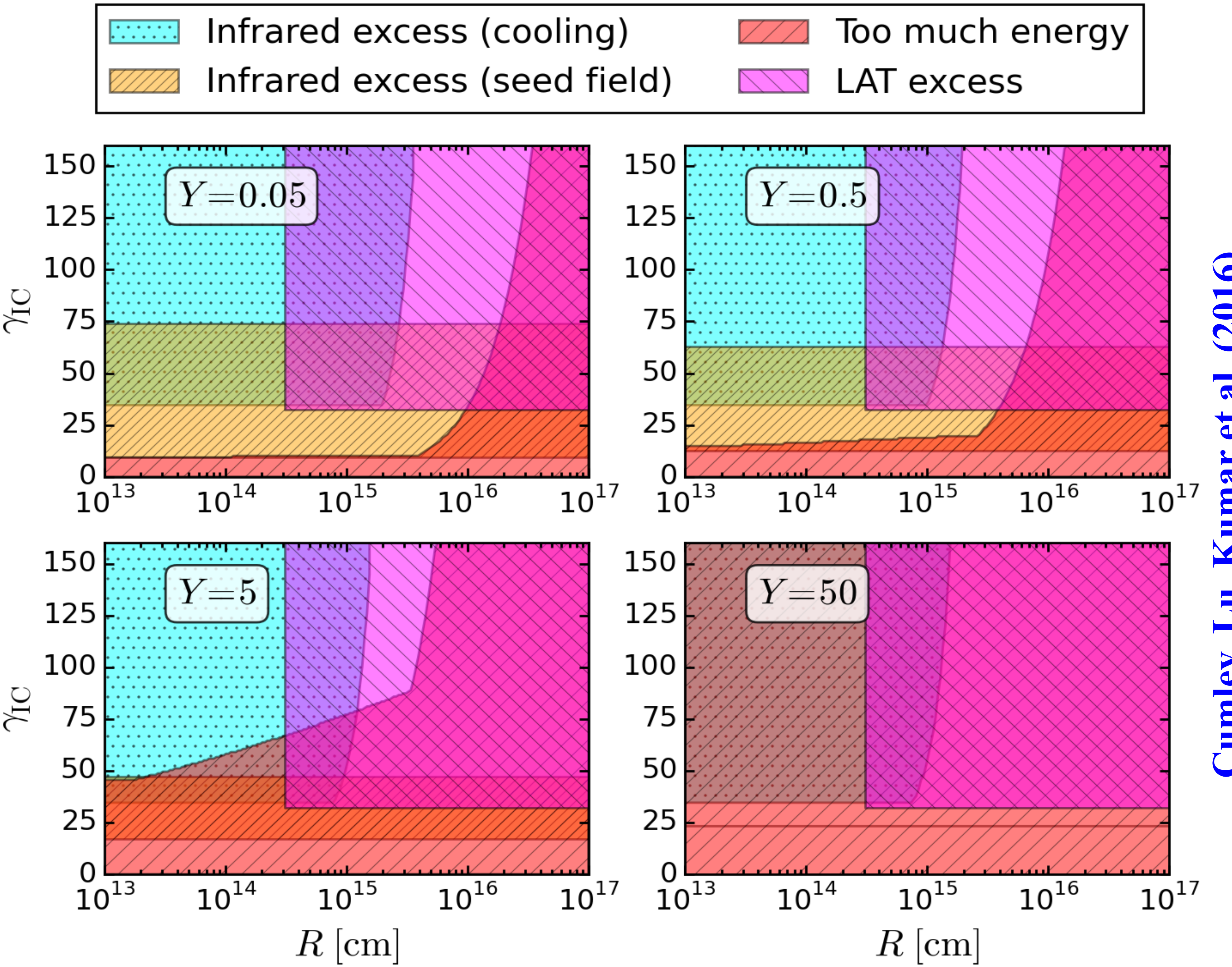
For electrons with Lorentz factor γ_e the inverse-Compton scattered photon frequency and flux can be related to the synchrotron photon frequency and flux as

$$\nu_{IC} \approx \gamma_e^2\ \nu_s\,, \qquad f_{\nu,ic} \approx \tau_T\, f_{\nu s}$$

The electrons will cool due to this process –

$$t'_c \sim 120\ \mathrm{s}\ \frac{R_{14}^2\, \Gamma_1^2}{\gamma_e\, L_{x,47}}$$

This time should not be less than the dynamical time, otherwise excessive IR emission will be produced.



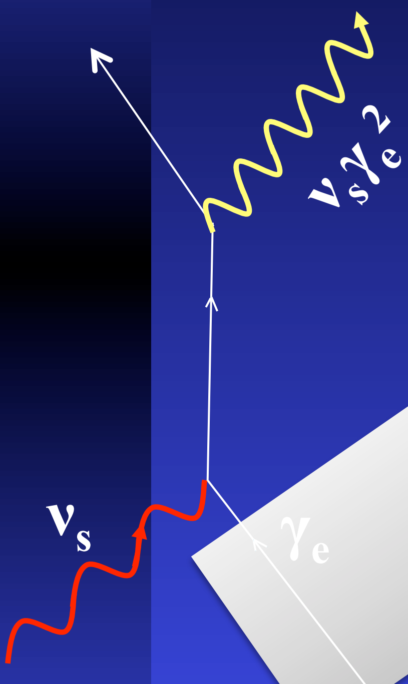
Cumley, Lu, Kumar et al. (2016)

Internal inverse-Compton solution space

Synchrotron + inverse Compton

- **Let us consider electrons with Lorentz factor γ_e and Thomson scattering optical depth of the jet is:**

$$\tau_T = N_e\, \sigma_T/(4\pi R^2)$$



Ruled Out

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Thermal Emission + inverse-Compton

- **Small optical depth even at the base of makes it very difficult to reprocess**

$$\tau_S = 3.97 L_{j,}$$

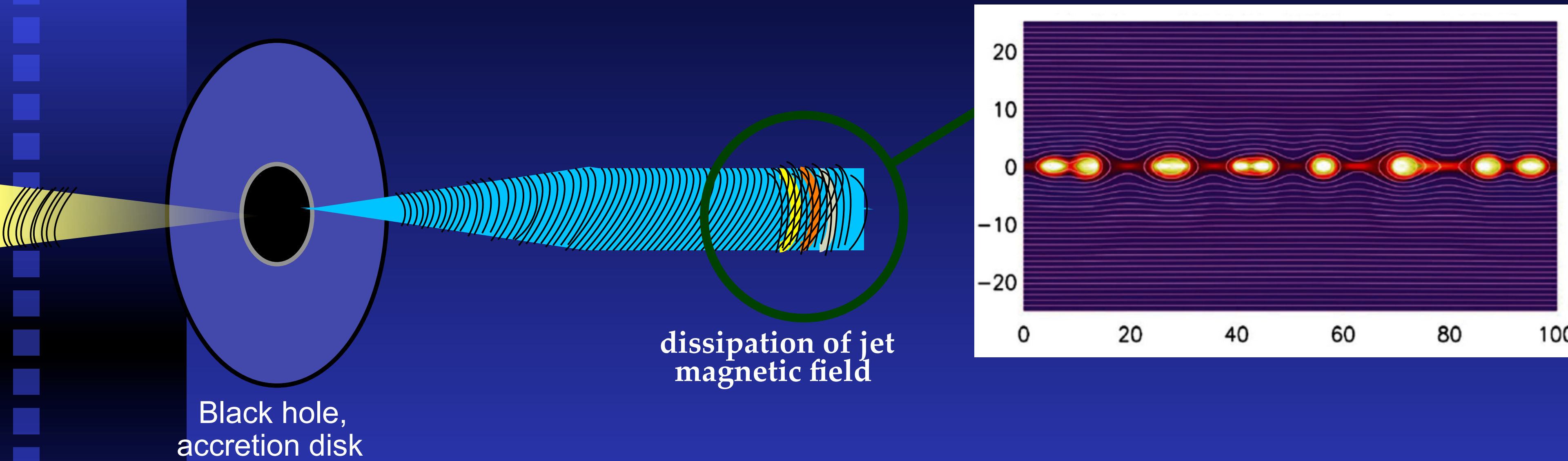
Ruled Out

- **At late times w is decreasing ∝ $t^{-5/3}$, the spectru opposite of the expected behavi heric radiation.**

So m iple IC scatterings below photospheric is unlikely to be responsible for the observed X-rays.

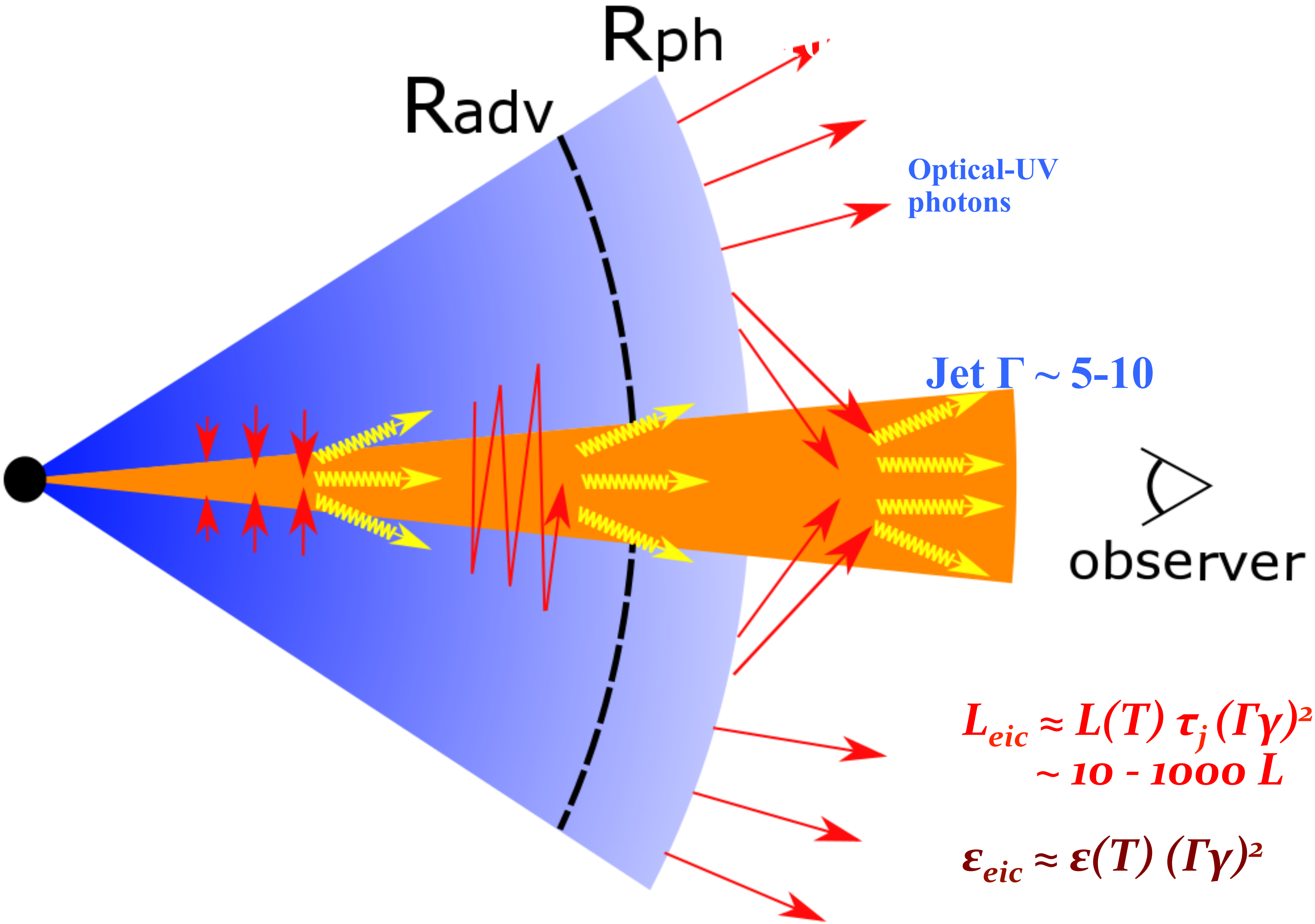
Synchrotron Radiation from Poynting Jet

Works, because electrons are continuously accelerated in current sheets



- ✓ **Able to avoid infrared excess because electrons are not able to cool to energies where they would produce IR.**
- ✓ **Energy requirement is much more reasonable since we need fewer protons/electrons as all electrons in reconnection zones radiate in the X-ray band.**

External IC radiation mechanism: basic picture

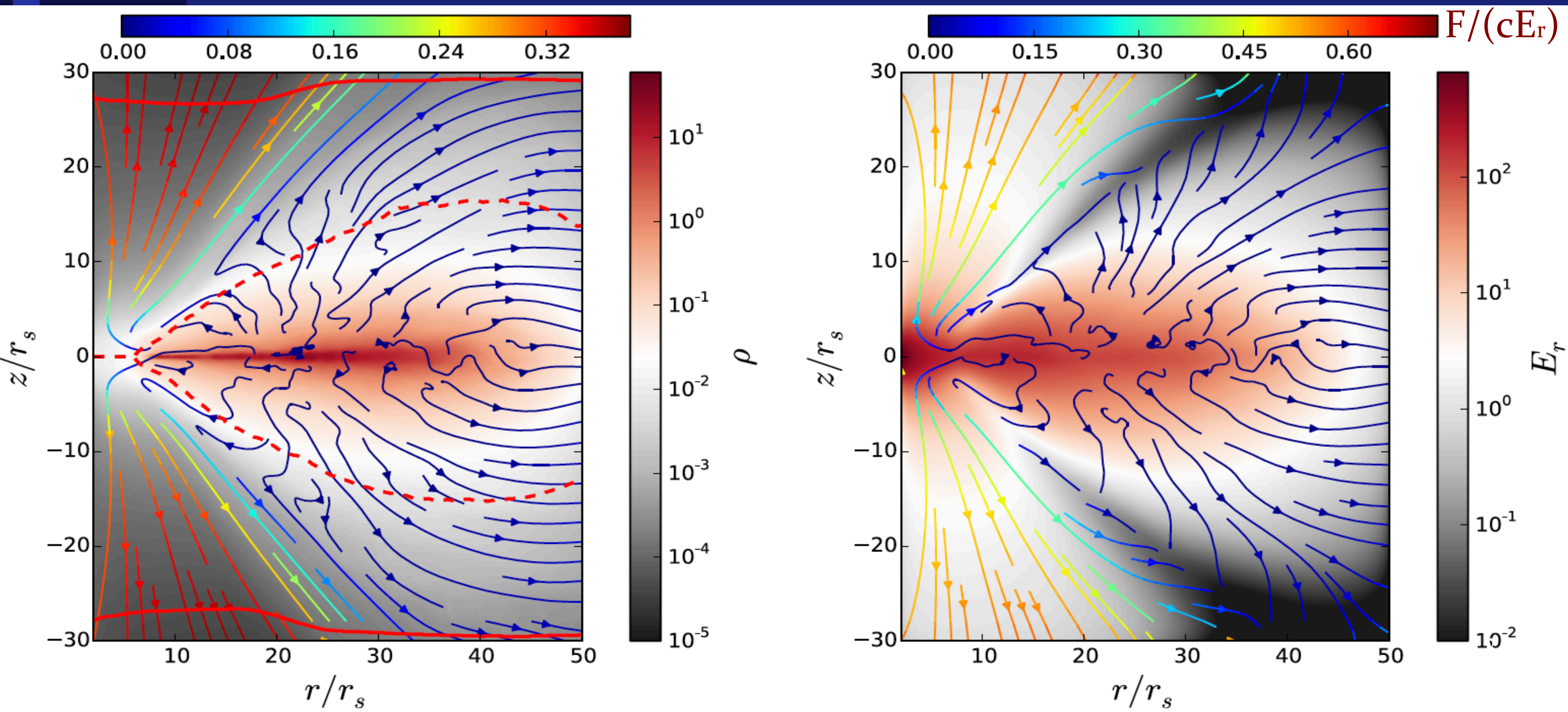


External Radiation Field?

- **Disk (thick, rad-dominated)**
- **Wind (opt-thick)**
- **Shocks (rad-domt)**
- **Cooling stellar debris**

Jiang, Stone & Davis (2014)

- $\dot{M}_{acc} \sim 200\ L_{Edd}/c^2$
- $L_{rad} \sim 10\ L_{Edd}$ (5% efficiency)
- $\dot{M}_{wind} \sim 10^2\ L_{edd}/c^2$

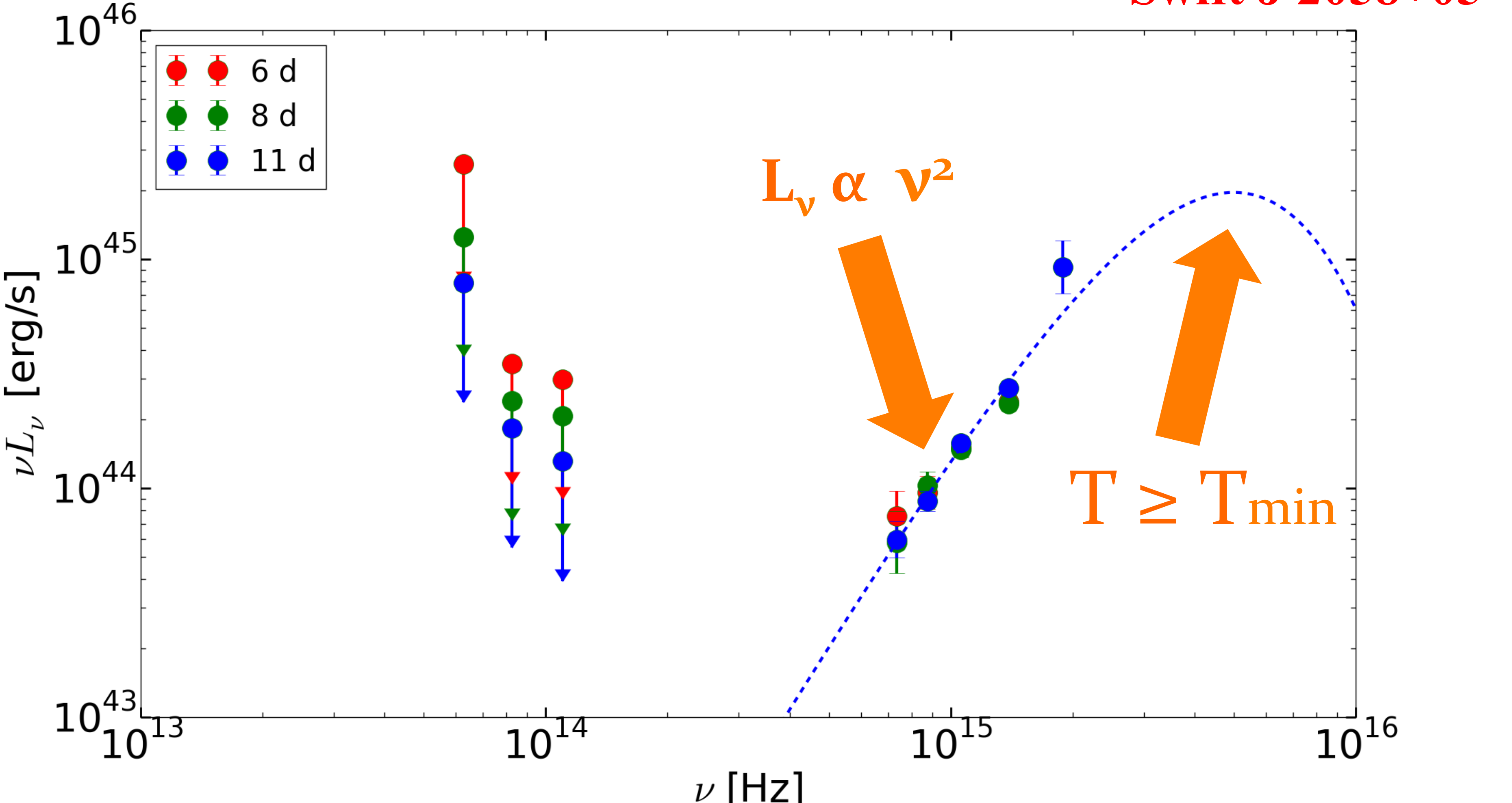


External photon field (opt-UV)

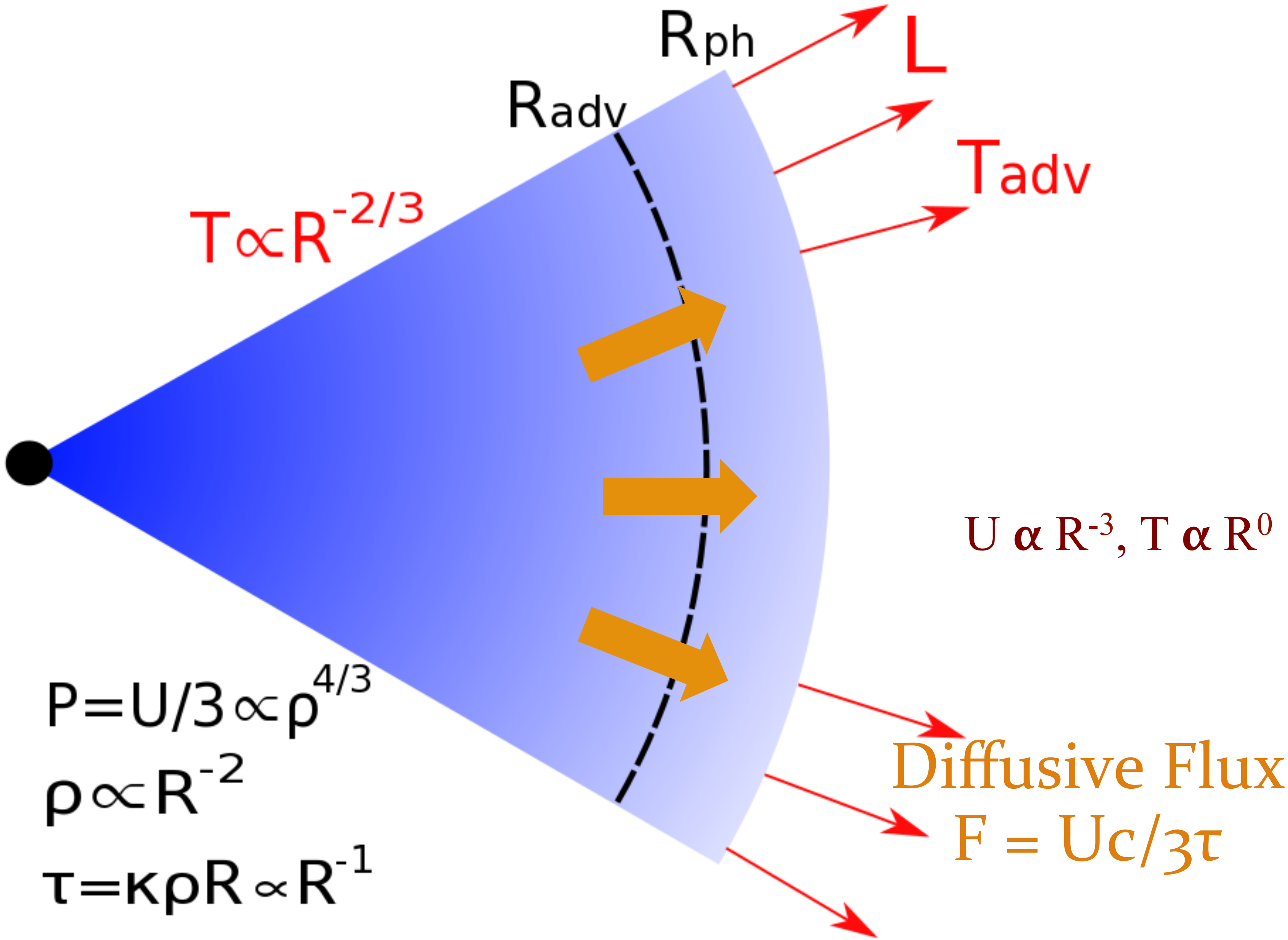
$R_{ph} \approx 10^{15}$ cm $L_{45}^{1/2}/T_5^2 \sim 10^3 R_g$

→ Wind with $\dot{M} \sim$ a few $M_\odot$/yr $\sim 10^2 L_{Edd}/c^2$

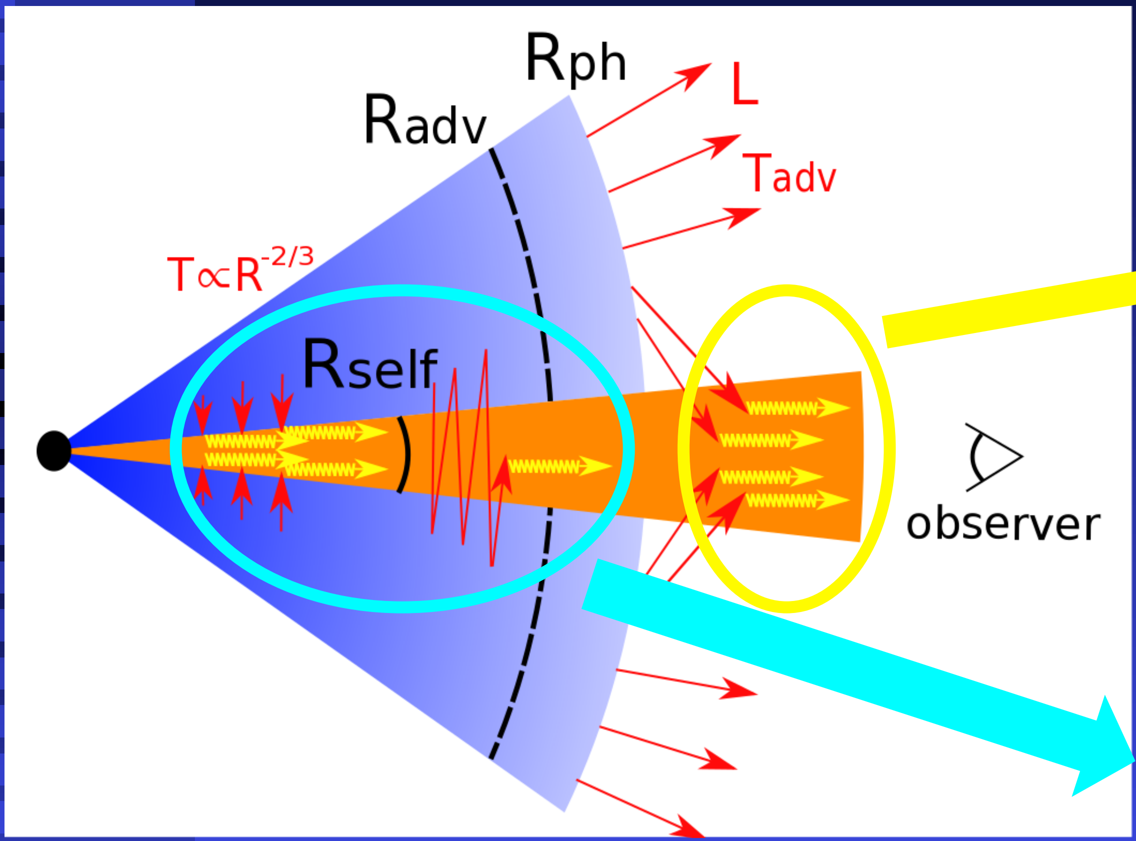
Swift J 2058+05



Radiation field above & below the Photosphere



IC above and below the photosphere



Above photosphere:

$L_{eic} \approx L(T)\, \tau_j (\Gamma\gamma)^2$

$\varepsilon_{eic} \approx \varepsilon(T)\, (\Gamma\gamma)^2$

Below photosphere:

$L_{eic} \approx L(T_{adv})\, 2\theta_j^{-1} (\Gamma\gamma)^2$

$\varepsilon_{eic} \approx \varepsilon(T_{adv})\, (\Gamma\gamma)^2$

Exceeds the observed L_x!

Mildly relativistic wind can solve this problem

Relative Lorentz Factor: $\Gamma_r = \Gamma_j \Gamma_w (1 - \beta_j \beta_w)$

- Above the photosphere

$$L_{eic} \approx L(T)\, \tau_j\, (\Gamma_r \gamma)^2 / \Gamma_w^2$$
$$\varepsilon_{eic} \approx \varepsilon(T)\, (\Gamma_r \gamma)^2$$

- Below the photosphere

$$L_{eic} \approx L(T_{adv})\, 2\theta_j^{-1} (\Gamma_r \gamma)^2 / f(\Gamma_w)$$
$$\varepsilon_{eic} \approx \varepsilon(T_{adv})\, (\Gamma_r \gamma)^2$$

$$f(\Gamma_w) = (1 - \beta_w/3)(1 + \beta_w)^3\, \Gamma_w^2$$

$\Gamma_w \sim 1.5$ ($L_w \sim 10^{46}$ erg s^{-1}) can prevent L_{eic} from getting too large below the photosphere

- Power-law electron Spectrum needs to be maintained to produce $F_\nu \sim \nu^{-\alpha}$ ($\alpha \approx 0.7$) between 0.3 and 10 keV: $n_\gamma \sim \gamma^{-p}$ with $p \sim 2.4$

- Because of the short IC cooling time, electrons need to be continuously accelerated, and that again suggests a Poynting jet.

Magnetic field strength in the jet

- **For a Poynting jet, the jet's power can be used to find B**

$$L = B_0'^2 \Gamma^2 R^2 c \quad \Longrightarrow \quad B_0' = \frac{(L/c)^{1/2}}{\Gamma R} = (58\ \mathrm{G}) \frac{L_{48}^{1/2}}{\Gamma_2 R_{15}}$$

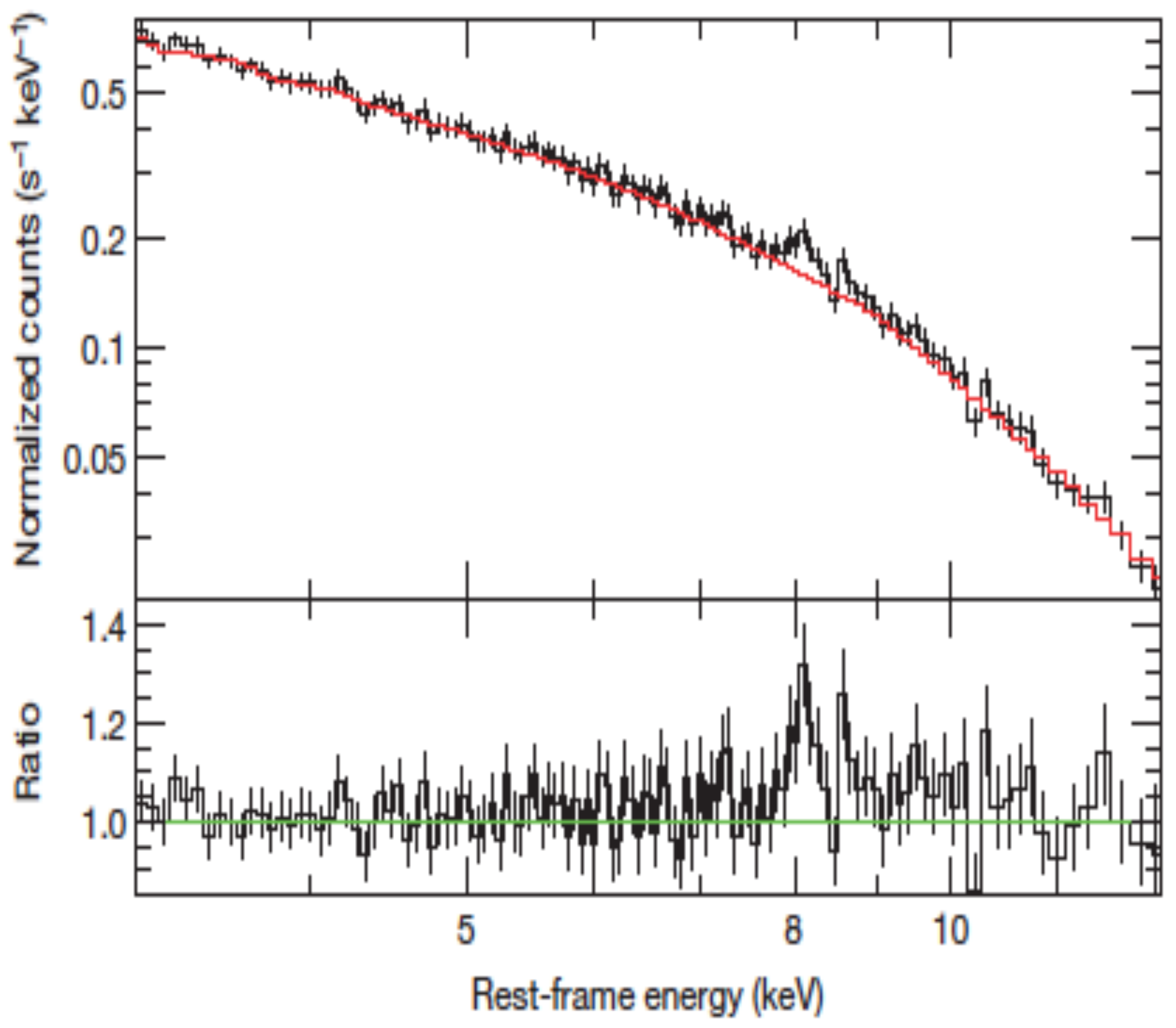
- **The electron LF can be found by using synchrotron frequency formula:**

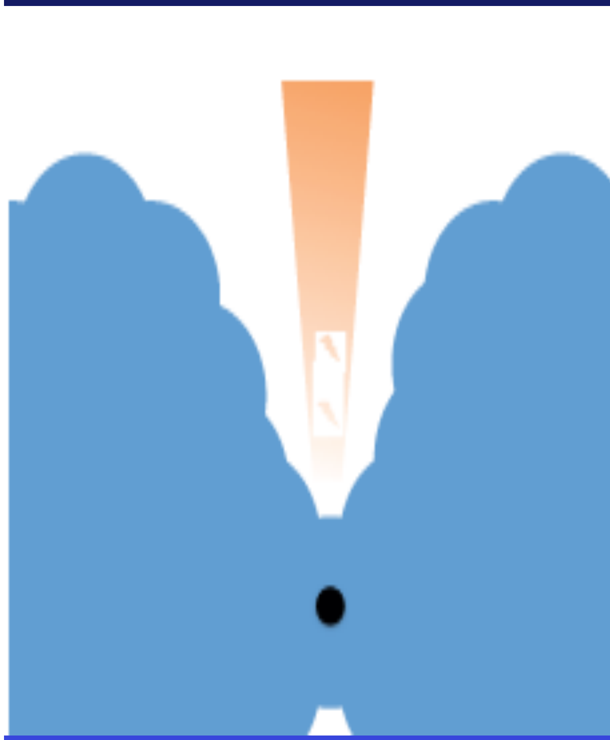
$$\nu_i = \frac{q B' \gamma_i^2 \Gamma}{2\pi m_e c (1+z)} \approx (1.2 \times 10^{-8}\ \mathrm{eV}) B' \gamma_i^2 \Gamma (1+z)^{-1}$$

Lorentz factor of e^- in lab frame ($\gamma_i \Gamma$) ≈ 10^5 (for 10 keV X-rays)

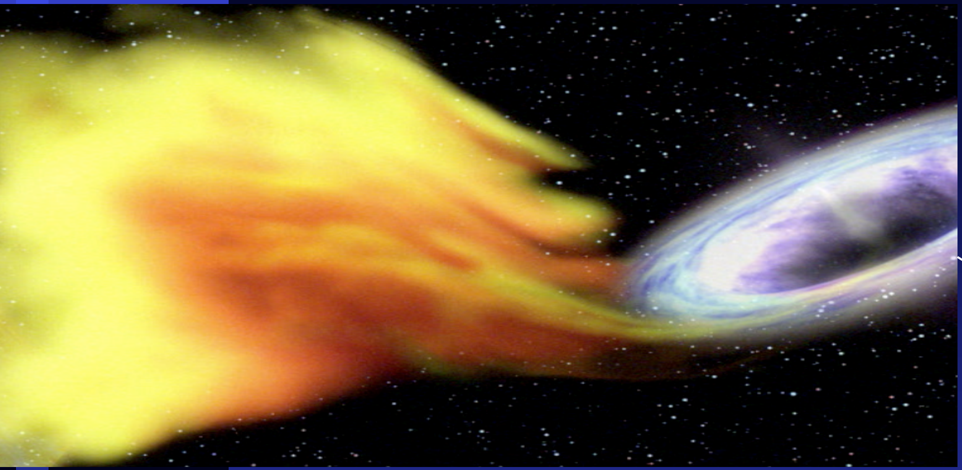
Protons are accelerated to larger energy (because of lower loss rate) by a factor $(m_p/m_e)^2 \approx 10^{18}$ eV

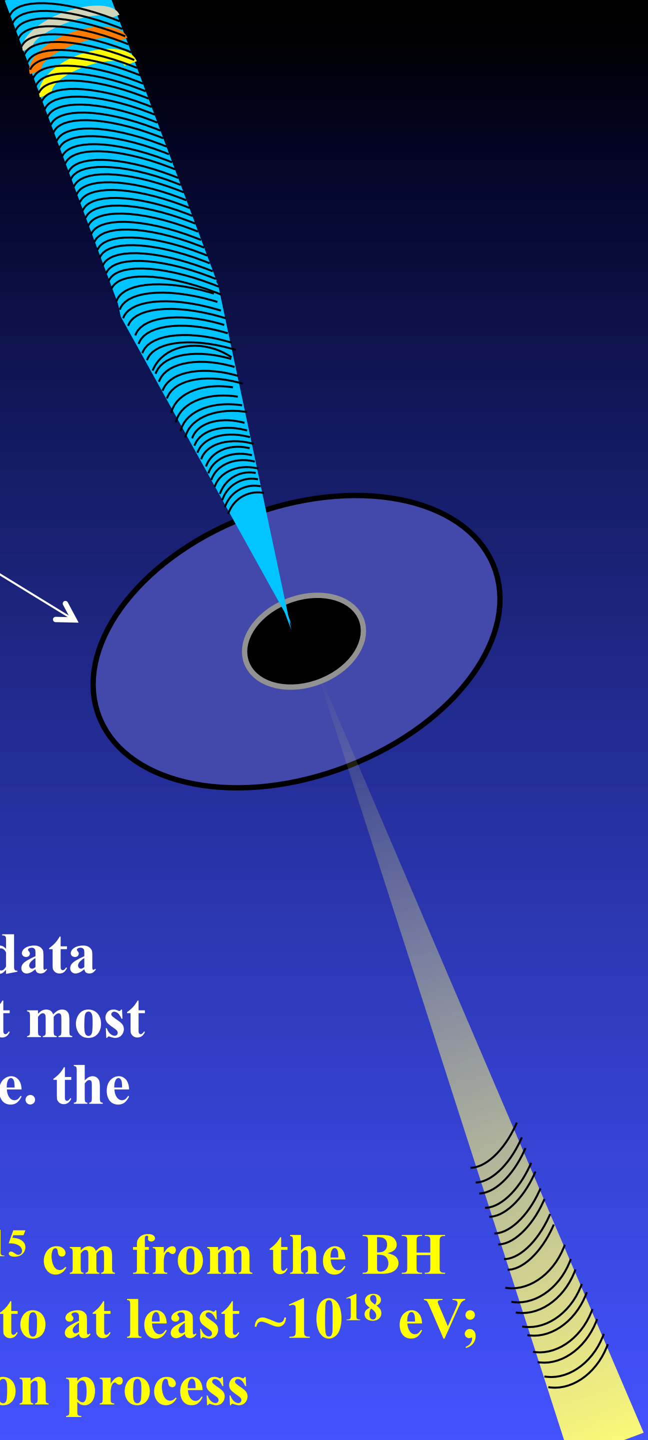
J1644+57 Fe K_α line (Kara et al. 2016, Nature); v~0.15c (blueshift)





Here is a summary of our recent results:





A good fraction of star's mass is converted to energy ($E \sim m_* c^2/20$) – in the form of a relativistic jet

Piecing together the multi-wavelength data (mm to γ-rays) we are able to show that most of the jet energy is in magnetic fields, i.e. the BH produced a Poynting jet.

Magnetic field is dissipated at $\sim 10^{15}$ cm from the BH and e^- accelerated to ~TeV, and p^+ to at least $\sim 10^{18}$ eV; X-rays produced by the synchrotron process

Reprocessed infrared radiation from TDEs

$$E_{rad} \sim 10^{51} - 10^{52}\ \mathrm{erg}\ \ \&\ \ \Delta t \sim 10^{6} - 10^{7}\ \mathrm{s}$$

- Ionize Hydrogen (and photo-dissociate H_2)

  If no dust extinction,

  $$M_{ion} \sim m_p E_{rad}/25\ \mathrm{eV} \sim 10^4\ M_\odot\ E_{rad,51.5}$$

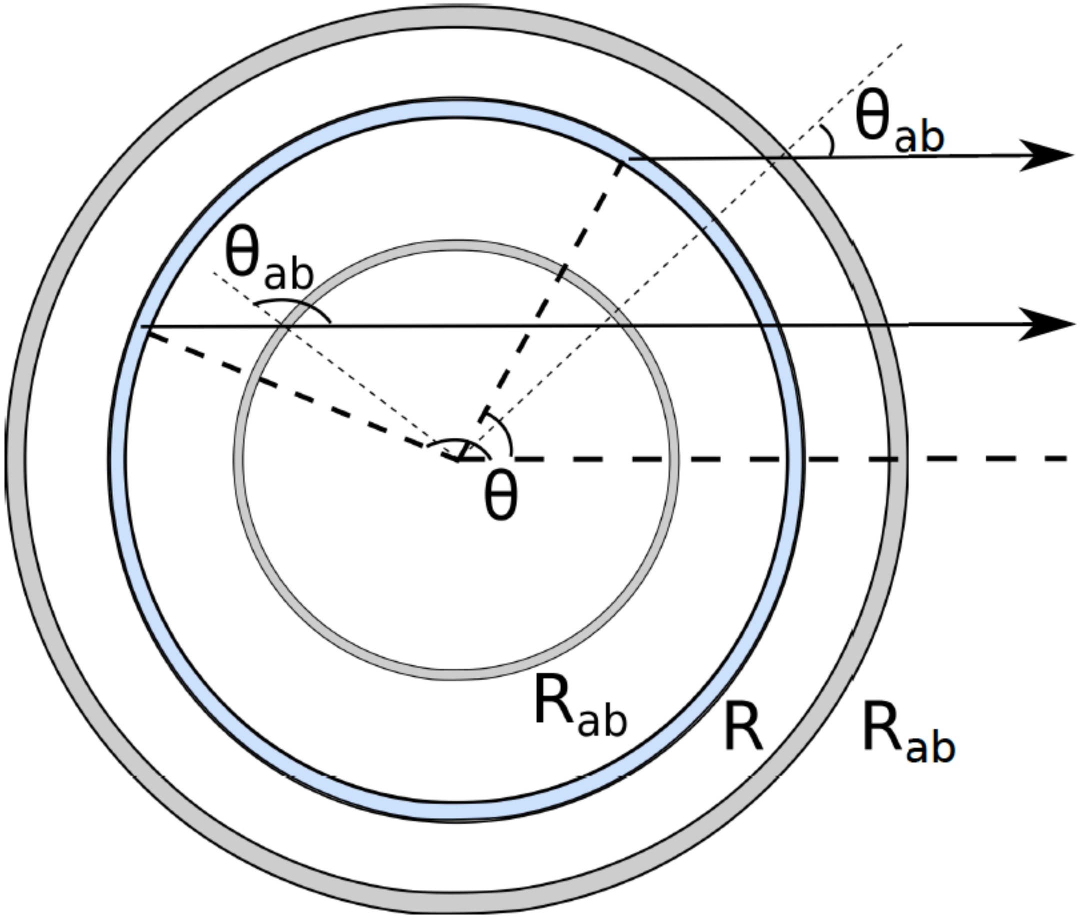
  $$R_{ion} \sim 2.6\mathrm{x}10^{19}\ \mathrm{cm}\ (E_{rad,51.5}/n_3)^{1/3} \qquad (t_{rec} \sim 10^3/n_3\ \mathrm{yr})$$

- Heat up dust

  $$N_H = nR_{ion} = 2.6\mathrm{x}10^{22}\ n_3^{2/3}\ E_{rad,51.5}^{1/3}\ \mathrm{cm}^{-2}$$

  $$A_V \sim 14\ n_3^{2/3}\ E_{rad,51.5}^{1/3}\ \mathrm{mag}$$

Geometry of IR radiation from UV/optical heated dust. IR photons travelling from radius R are partially absorbed by dust shells (radius R_{ab}) lying inside R or outside R depending on angle θ.



Equation for dust sublimation and temperature:

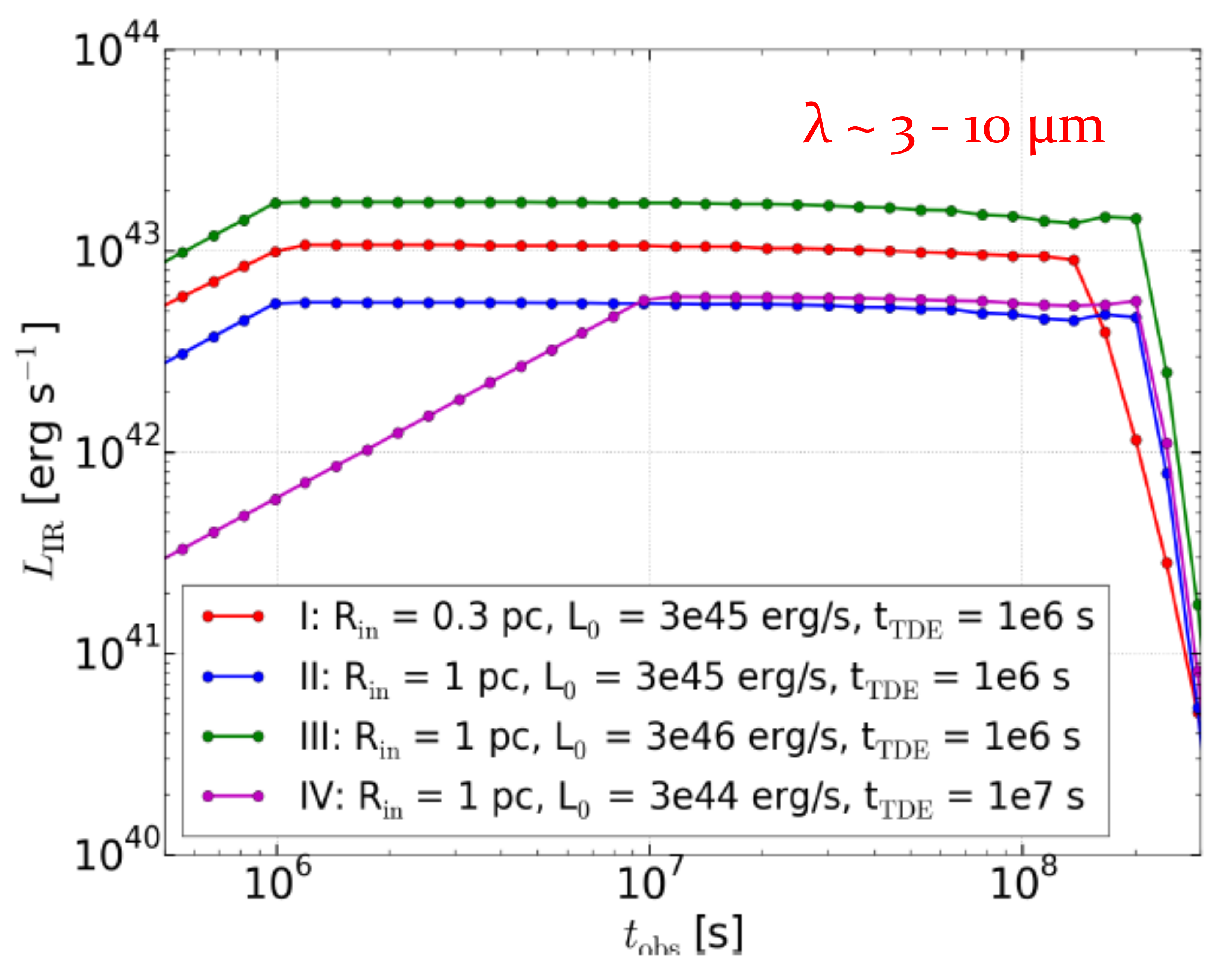
$$e^{-\tau}\frac{L(t_r)}{4\pi R^2}\pi a^2 Q_{\rm UV} = \langle Q_{\rm abs}\rangle_P\, 4\pi a^2 \sigma T^4 - 4\pi a^2 \frac{{\rm d}a}{{\rm d}t}\frac{\rho}{\mu}B$$

$$\frac{{\rm d}a}{{\rm d}t} = -\nu_0 \left(\frac{\mu}{\rho}\right)^{1/3} e^{-B/kT}$$

$L_{IR} \sim f_\Omega E_{rad}/(2R_{sub}/c)$

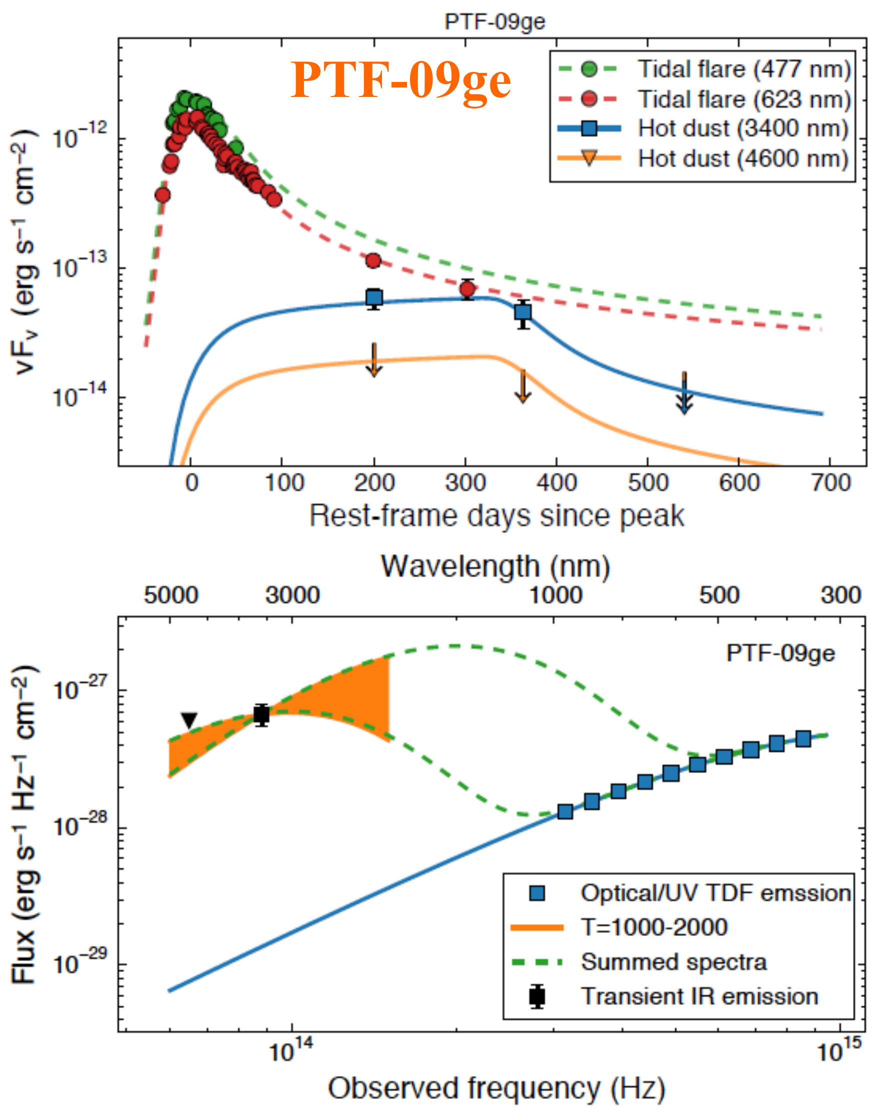
$\sim$ (1.5x10^{42} erg/s) $f_{\Omega,-1}\, E_{rad,51.5}\, /R_{sub,pc}$

IR Emission from Dust



Observations

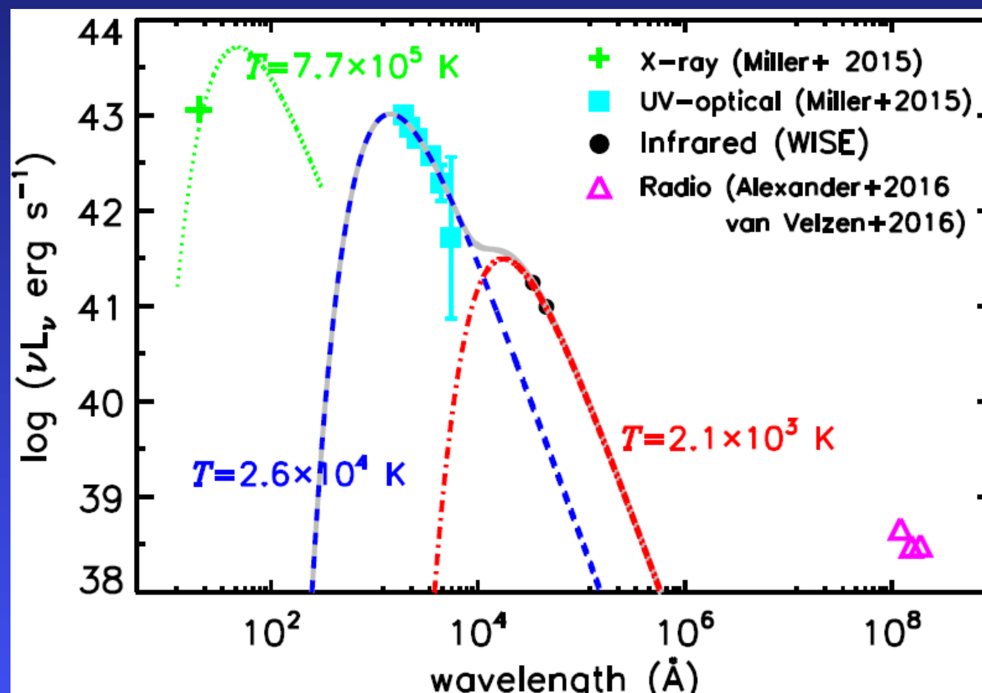
Wide-field Infrared Survey Explore (WISE); van Velzen et al. (2016)



drawn. At last, we show that the two nearby TDE candidates ASSASN-14ae and -14li are good candidates to search for the dust IR emission. If the pc-scale dusty clouds have

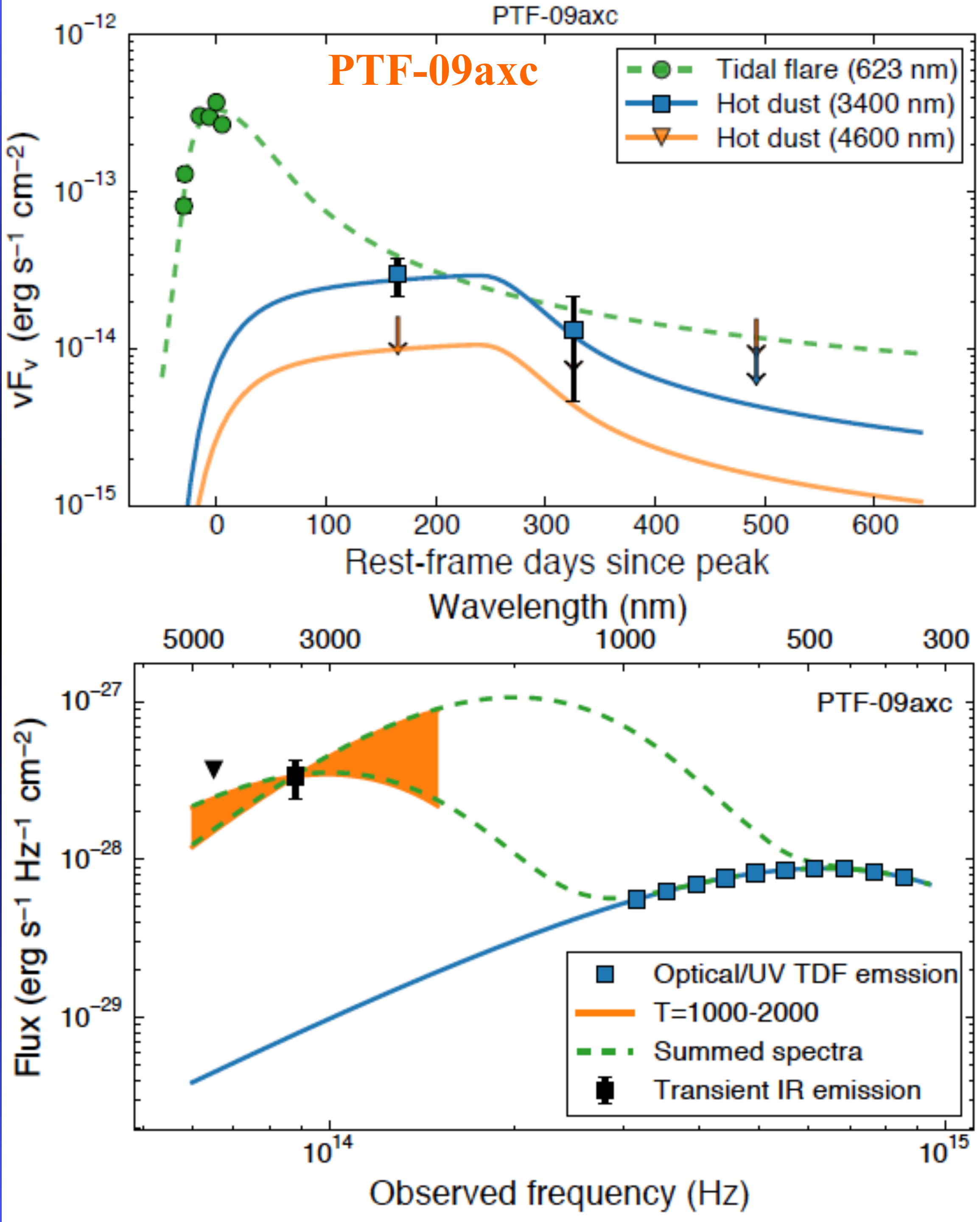
– Lu & Kumar (2016)

ASASSN-14li – 36 d after trigger, Jiang+16



$L_{IR} \sim (1.5\text{x}10^{42}$ erg/s$)\ f_{\Omega,-1}\ E_{rad,51.5}\ /R_{sub,pc}$

$R_{sub} \sim 0.1$ pc; $E_{rad} \sim 10^{52}$ erg; $f_\Omega \sim 1\%$



Observation of IR emission by dust which was predicted by Lu and Kumar (2016)

Wide-field Infrared Survey Explore (WISE);
van Velzen et al. (2016)

Summary

- ☆ Powerful jets, moving close to the speed of light, have been observed associated with black holes for about 40 years. But only recently, we have begun to understand the jet physics.
- ☆ Our analysis of the IR to γ-ray data for one such jet – produced when a star fell into a black hole – shows that most of the jet energy was likely in magnetic fields (but particle KE dominated jet is also possible).
- ☆ Circum-nuclear dust heated by TDEs produces bright IR radiation, $10^{41} - 10^{43}$ erg/s, that lasts for 1 – 10 yrs; it is useful for investigating dust within ~1 pc of galactic nuclei.

Open questions

- **TDEs – event rate**
- **Hydrodynamics following a tidal disruption event and circularization of bound debris orbit**
- **Why so few TDEs have jets?**

UHECR and TDEs

Longstanding questions about BHs and relativistic jets that TDEs might be able to answer:

- Properties of super-Eddington accretion.
- How are jets launched, powered and collimated?
- What are relativistic jets made of? (Baryonic, $e^{\pm}$, magnetic)
- How are high-energy photons produced (synchrotron, IC or something else?)
- Particle acceleration mechanism. UHECR?
- What is the low end of the SMBH mass function?
- Quiescent SMBH spin distribution.