O Lado Violento do Universo

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Jun. 17th 2013
Café com Física / USP São Carlos

The Extreme Side of the Universe

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Fermi LAT Collaboration

Gamma-ray Space Telescope

>300 people around the world

Violence in the Cosmos

Black holes: outstanding prediction of general relativity - Schwarzschild solution (1916)

Ricci curvature:

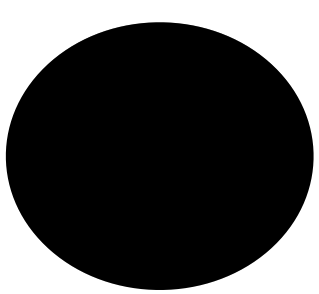
$$R_{\alpha\beta} = \frac{\partial \Gamma^{\gamma}_{\alpha\beta}}{\partial x^{\gamma}} - \frac{\partial \Gamma^{\gamma}_{\alpha\gamma}}{\partial x^{\beta}} + \Gamma^{\gamma}_{\alpha\beta}\Gamma^{\delta}_{\gamma\delta} - \Gamma^{\gamma}_{\alpha\delta}\Gamma^{\delta}_{\beta\gamma}$$

Einstein's field equation in vacuum:

$$R_{\alpha\beta} = 0$$

Schwarzschild metric:

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right)(c\,dt)^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

M 

Spacetime around slowly rotating objects (Earth, Sun etc)

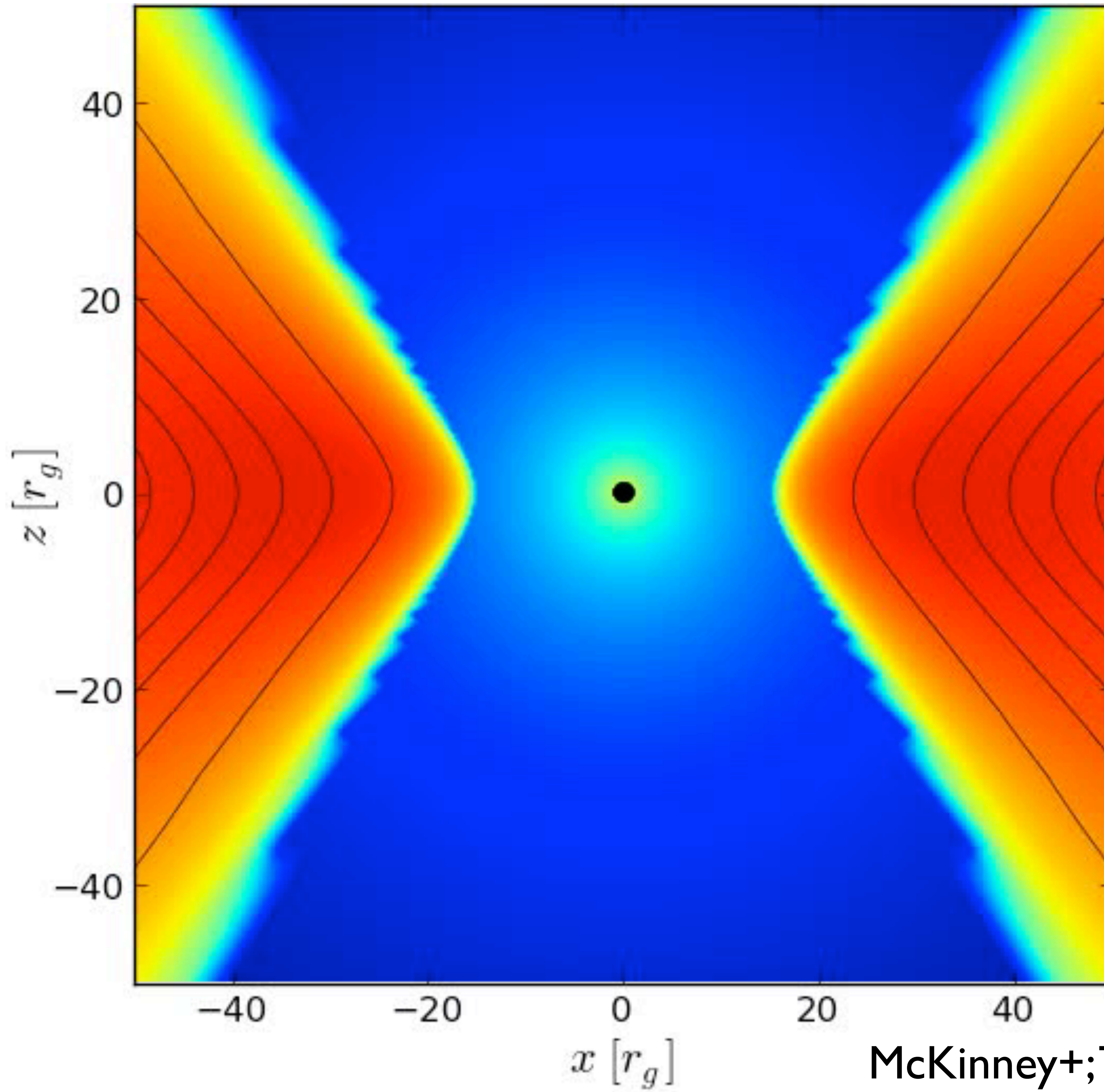
Properties of a black hole

Surface escape velocity = Speed of light

$$R = \frac{2GM}{c^2}$$

Completely described by **mass & spin**

Black holes are also the ultimate particle accelerators: Accretion produces *relativistic jets*



McKinney+; Tchekhovskhoy+

Field equations

$$(\rho u^{\mu})_{;\mu} = 0$$

$$T^{\mu}{}_{\nu;\mu} = 0$$

$$F_{\mu\nu,\lambda} + F_{\lambda\mu,\nu} + F_{\nu\lambda,\mu} = 0$$

$$J^{\mu} = F^{\mu\nu}{}_{;\nu}$$

$$u_{\mu}F^{\mu\nu} = 0 \quad \text{(MHD)}$$

$$ds^2 = -\left(1 - \frac{2r}{\rho^2}\right)dt^2 + \left(\frac{4r}{\rho^2}\right)dr\,dt$$
$$+ \left(1 + \frac{2r}{\rho^2}\right)dr^2 + \rho^2\,d\theta^2$$
$$+ \sin^2\theta\left[\rho^2 + a^2\left(1 + \frac{2r}{\rho^2}\right)\sin^2\theta\right]d\phi^2$$

Mass/energy/momentum

$$T^{\mu\nu}_{\text{fluid}} = (\rho + u + p)u^{\mu}u^{\nu} + pg^{\mu\nu}$$

E e B fields

$$b^{\mu} \equiv \tfrac{1}{2}\epsilon^{\mu\nu\kappa\lambda}u_{\nu}F_{\lambda\kappa}$$

$$F^{\mu\nu} = \epsilon^{\mu\nu\kappa\lambda}u_{\kappa}b_{\lambda}$$

$$T^{\mu\nu}_{\text{EM}} = F^{\mu\alpha}F^{\nu}_{\alpha} - \tfrac{1}{4}g^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}$$

Gammie+03

Field equations

$$(\rho u^\mu)_{;\mu} = 0$$

$$\left(T^\mu_\nu + R^\mu_\nu\right)_{;\mu} = 0$$

$$F_{\mu\nu,\lambda} + F_{\lambda\mu,\nu} + F_{\nu\lambda,\mu} = 0$$

$$J^\mu = F^{\mu\nu}{}_{;\nu}$$

$$u_\mu F^{\mu\nu} = 0$$ (MHD)

Radiation

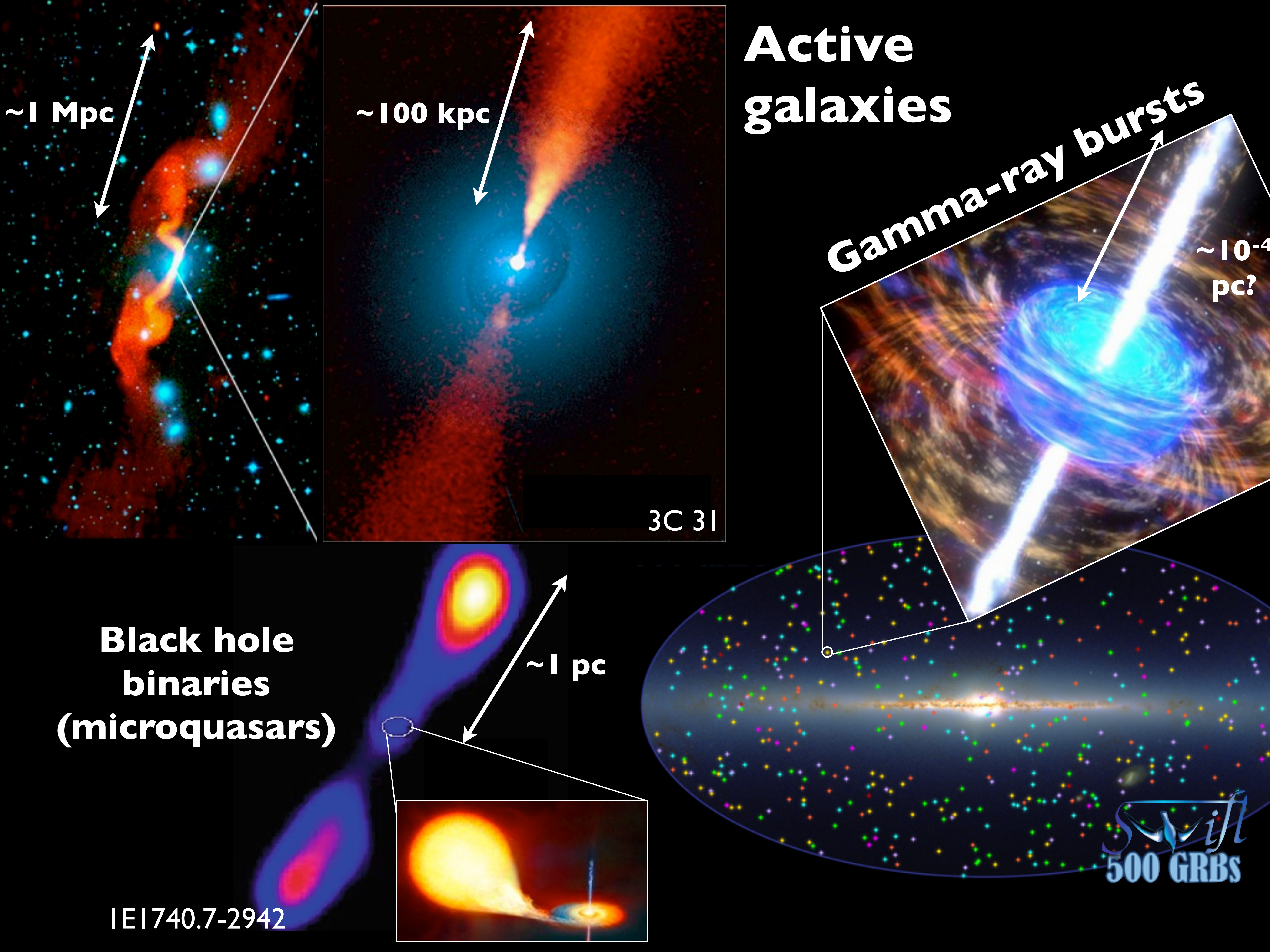
$$\widehat{R} = \begin{bmatrix} \widehat{E} & \widehat{F}^i \\ \widehat{F}^j & \widehat{P}^{ij} \end{bmatrix}$$

$$\widehat{E} = \int \widehat{I}_\nu \,\mathrm{d}\nu \,\mathrm{d}\Omega$$

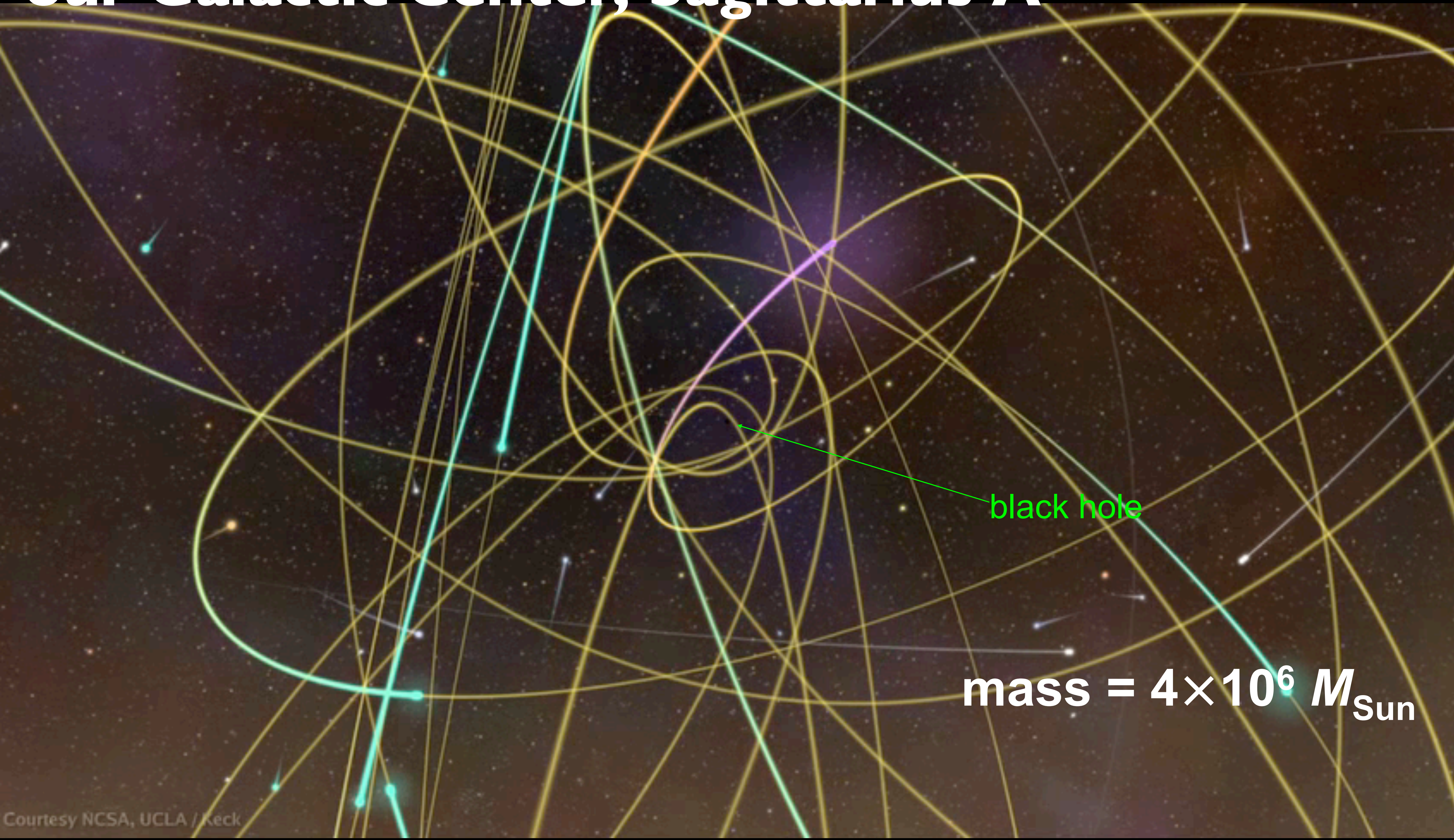
$$\widehat{F}^i = \int \widehat{I}_\nu \,\mathrm{d}\nu \,\mathrm{d}\Omega \, N^i$$

$$\widehat{P}^{ij} = \int \widehat{I}_\nu \,\mathrm{d}\nu \,\mathrm{d}\Omega \, N^i N^j$$

Sadowski+13


Active galaxies
~1 Mpc
~100 kpc
3C 31
Gamma-ray bursts
~10-4 pc?
Black hole binaries (microquasars)
~1 pc
1E1740.7-2942
Swift
500 GRBs

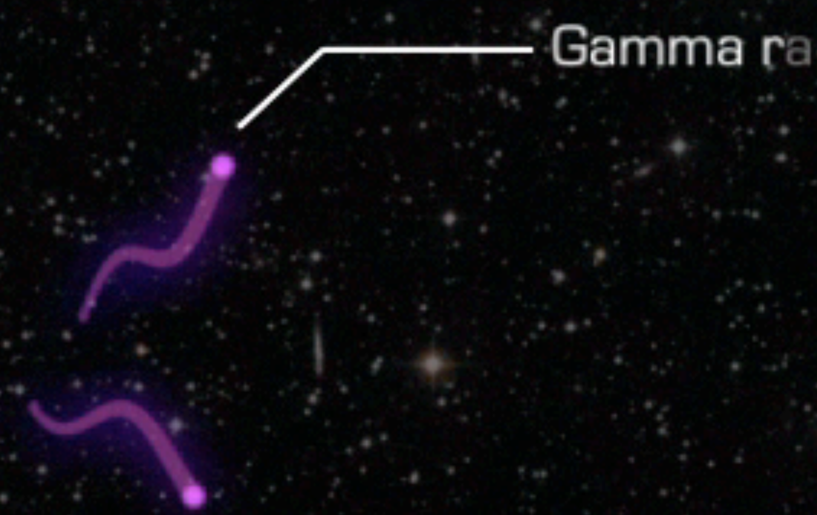
The best case for the existence of black holes: our Galactic Center, Sagittarius A*



10 light-days

Ghez, Schödel, Genzel et al.

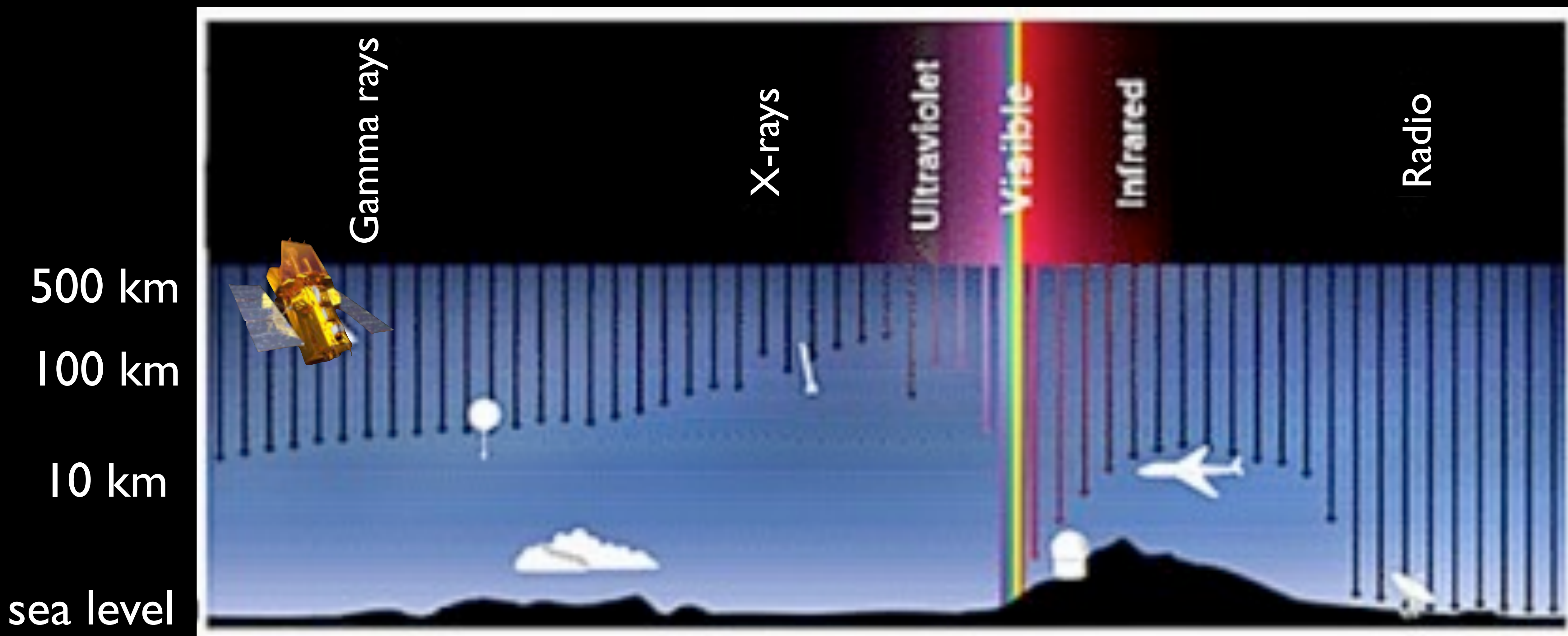
How to Detect a Gamma-ray?



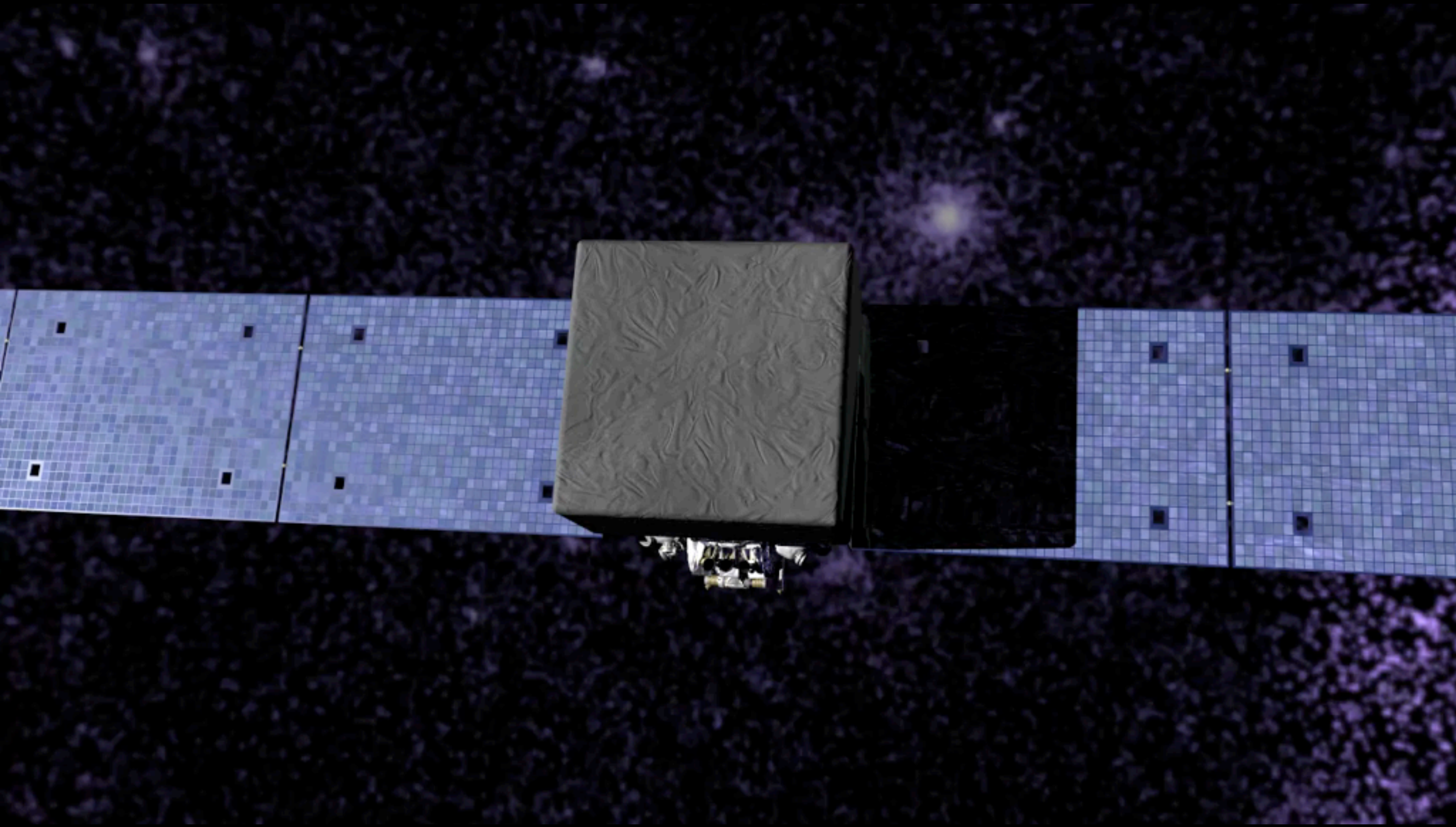
Optical photon

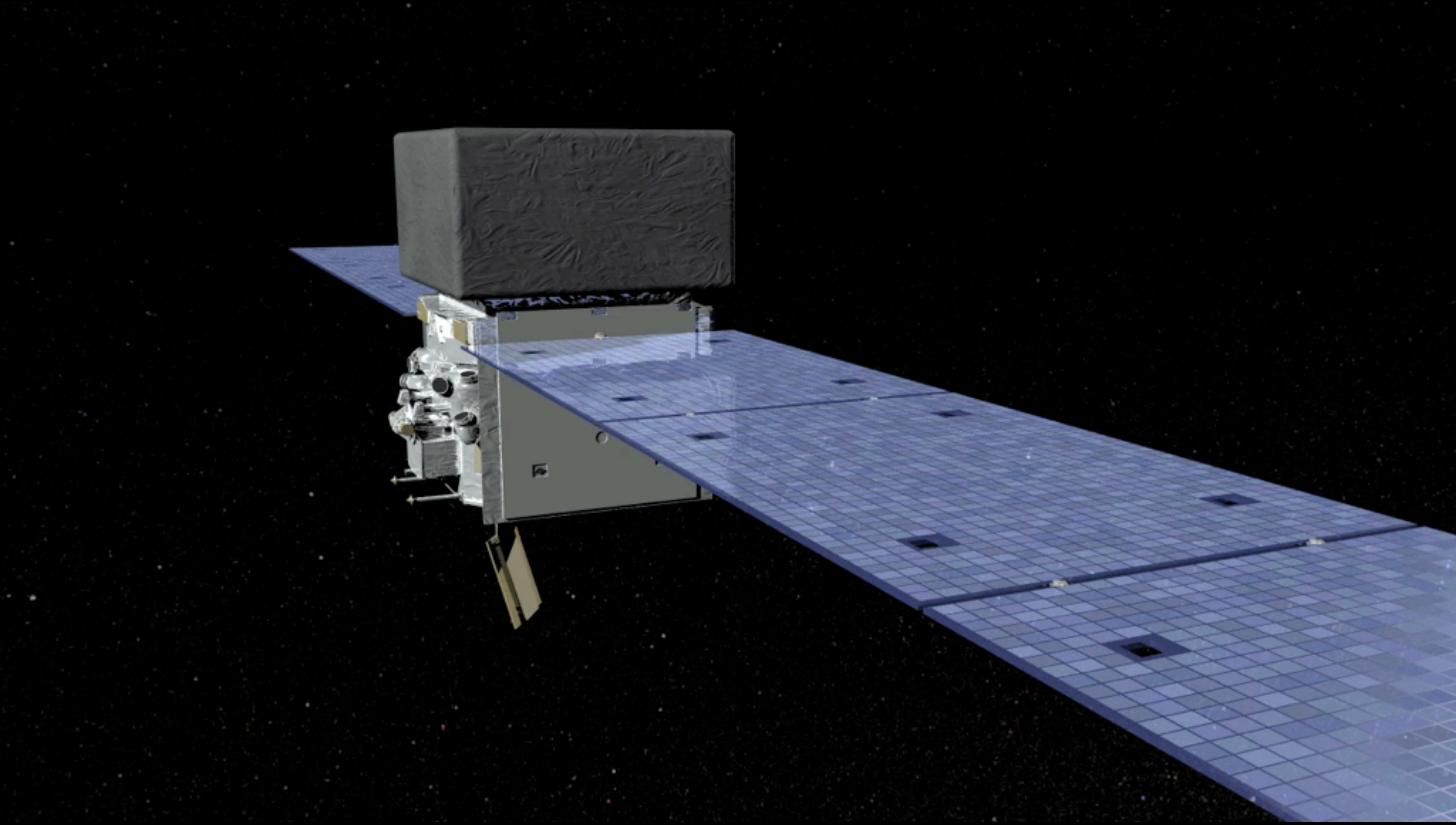
We detect ~100 gamma-rays / hr

Optical telescopes detect zillions of optical photons / min


500 km
100 km
10 km
sea level
Gamma rays
X-rays
Ultraviolet
Visible
Infrared
Radio

Fermi Large Area Telescope

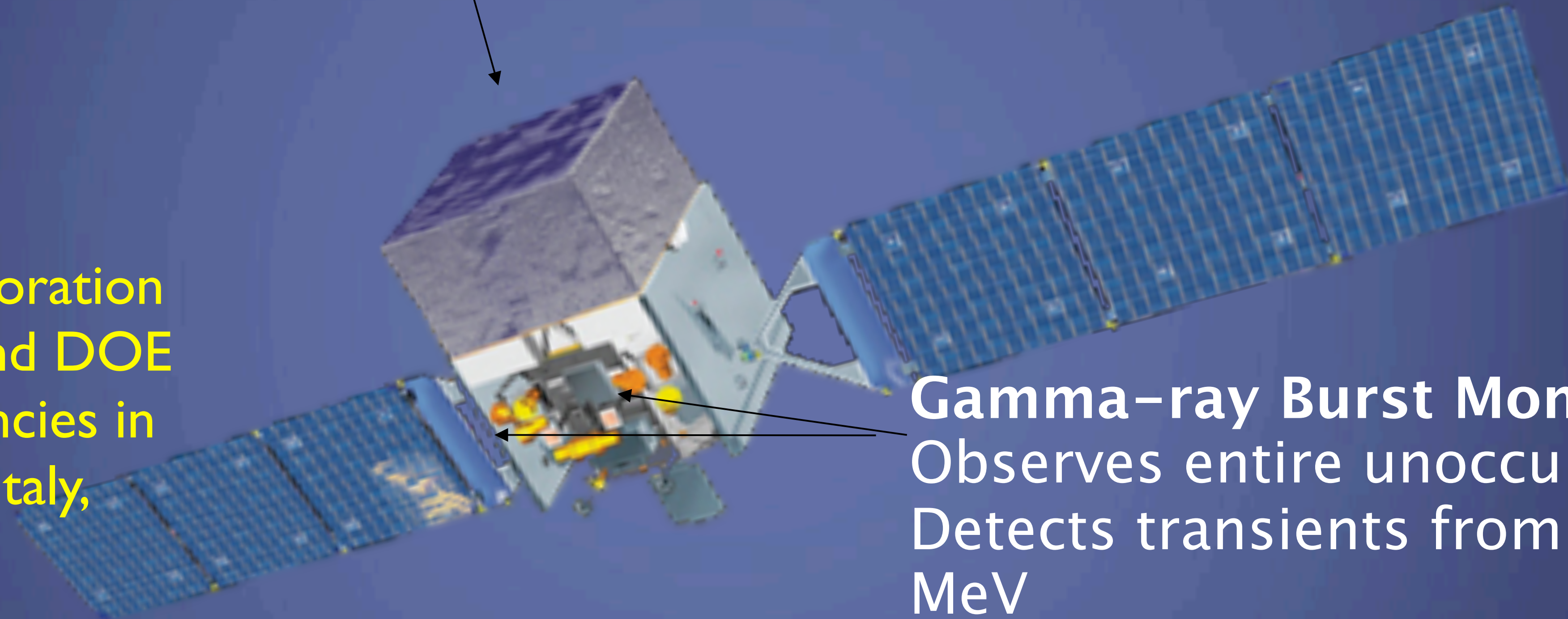




The Fermi Observatory

Slide: Julie McEnery

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV



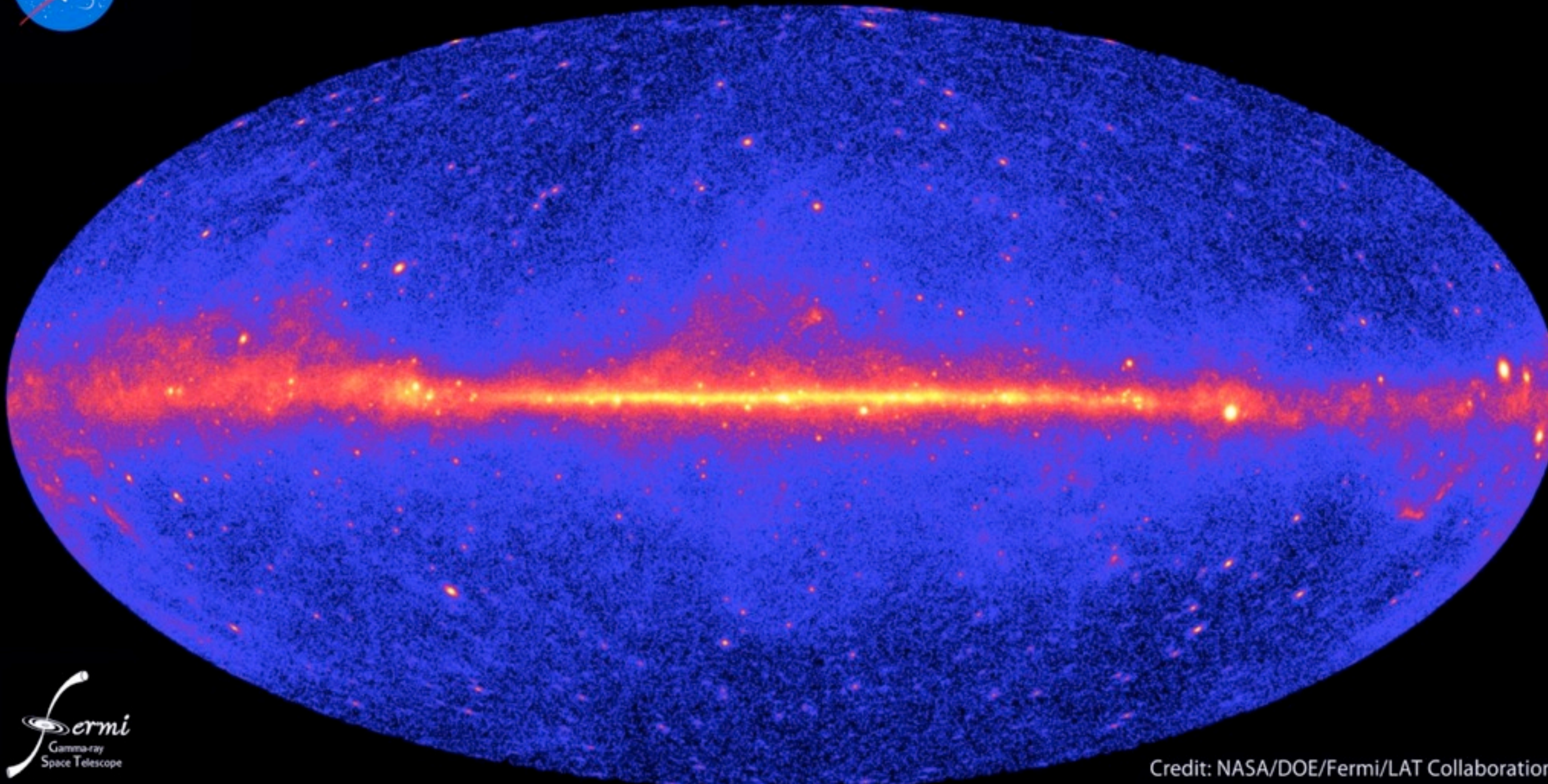
International and interagency collaboration between NASA and DOE in the US and agencies in France, Germany, Italy, Japan and Sweden

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV – 40 MeV

- **Unique Capabilities for GeV astrophysics**
  - **Large effective area**
  - **Good angular resolution**
  - **Huge energy range**
  - **Wide field of view**

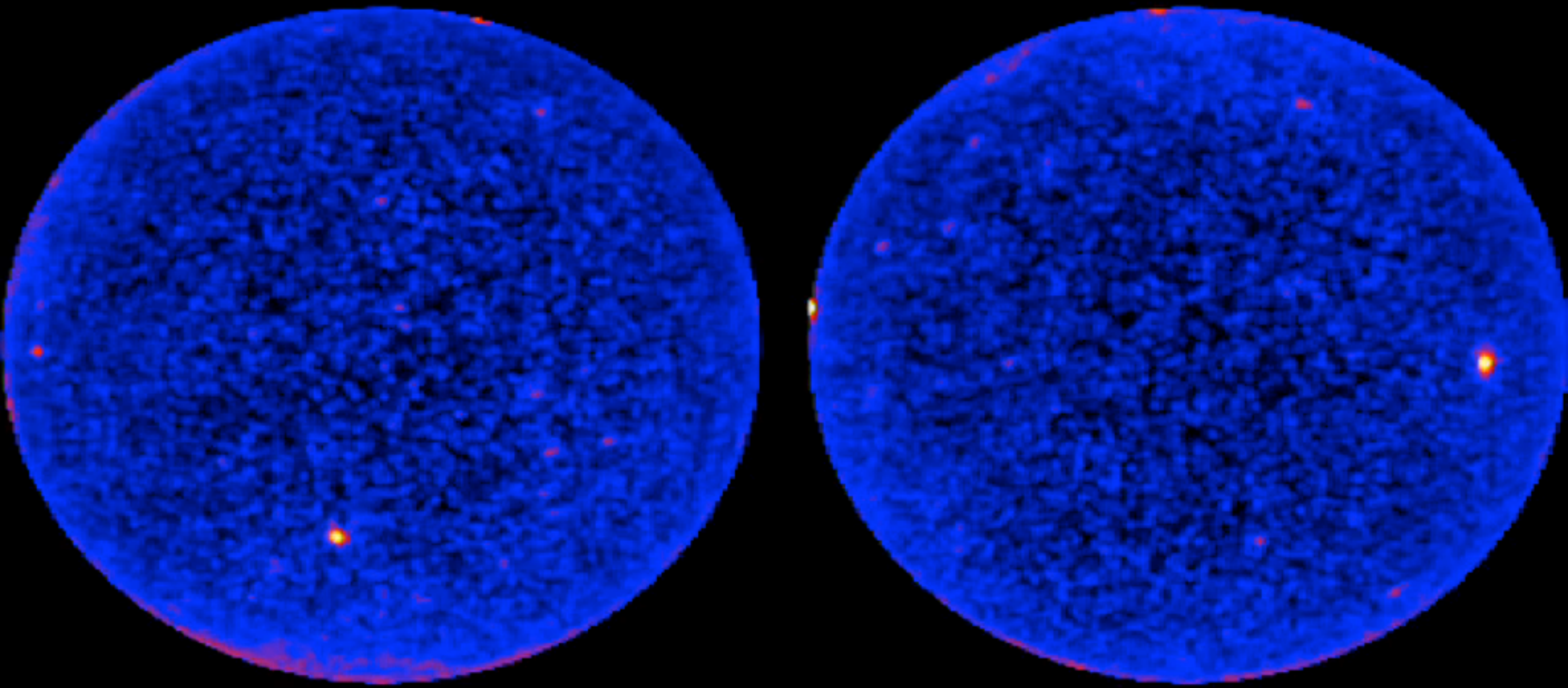
Mission Lifetime: 5 year requirement, 10 year goal

Fermi two-year all-sky map

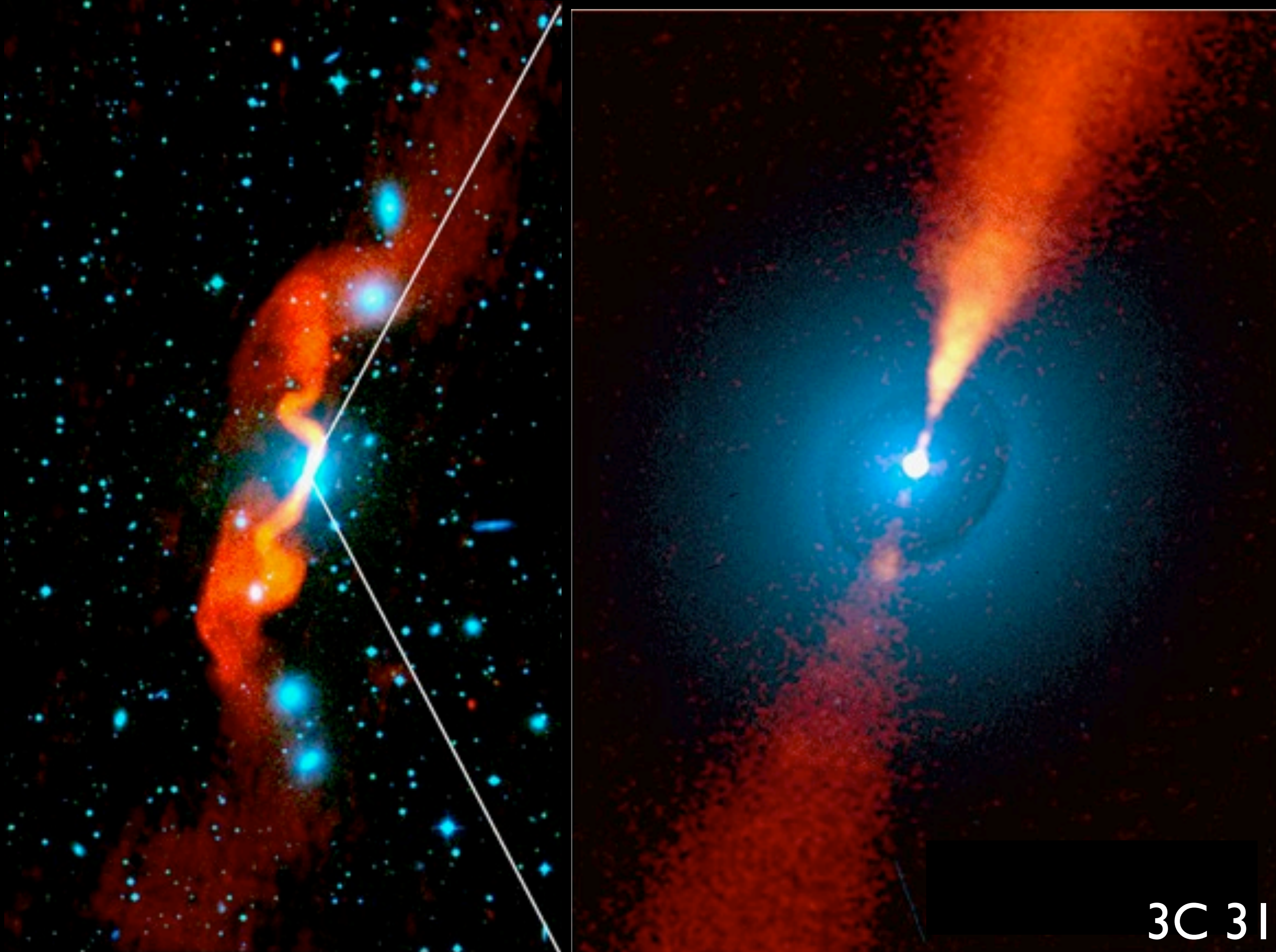


Credit: NASA/DOE/Fermi/LAT Collaboration

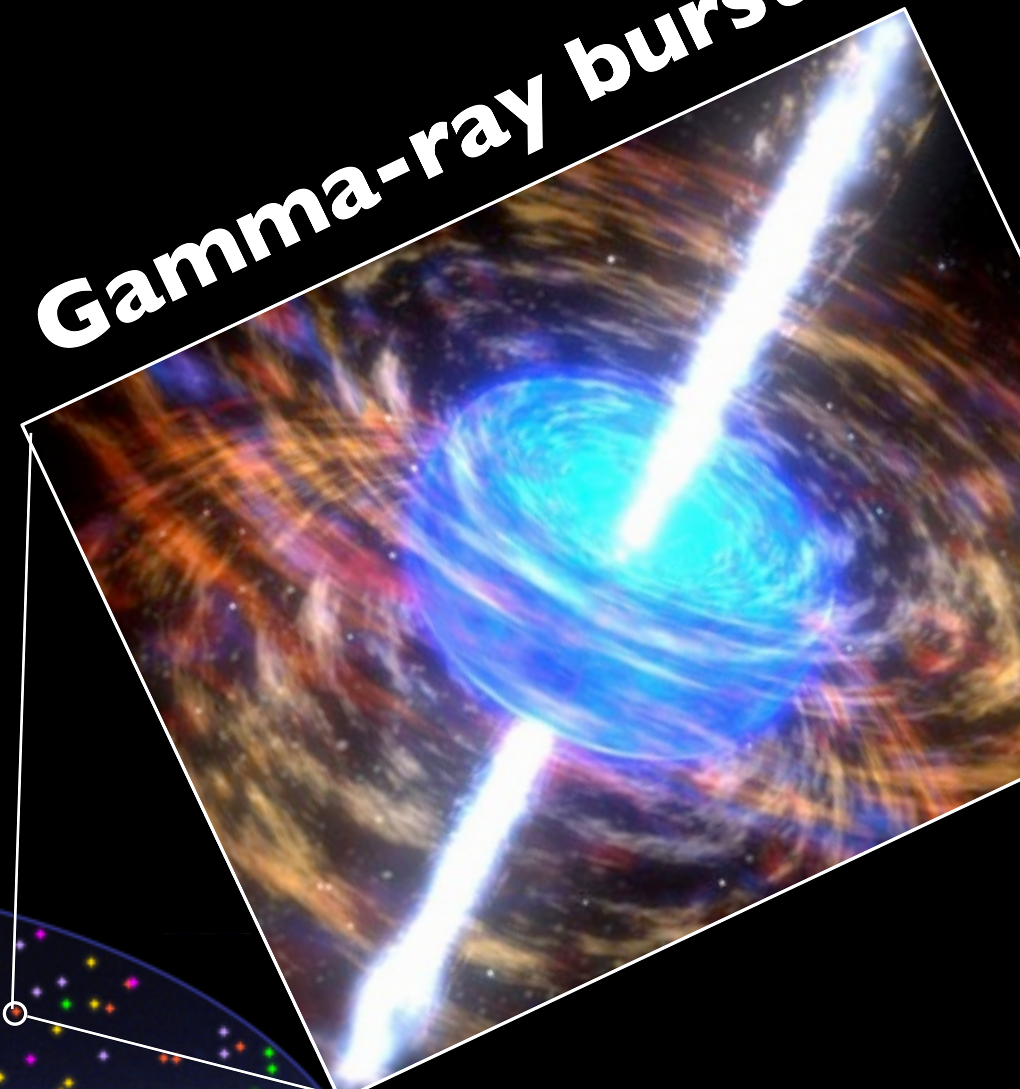
The variable gamma-ray sky



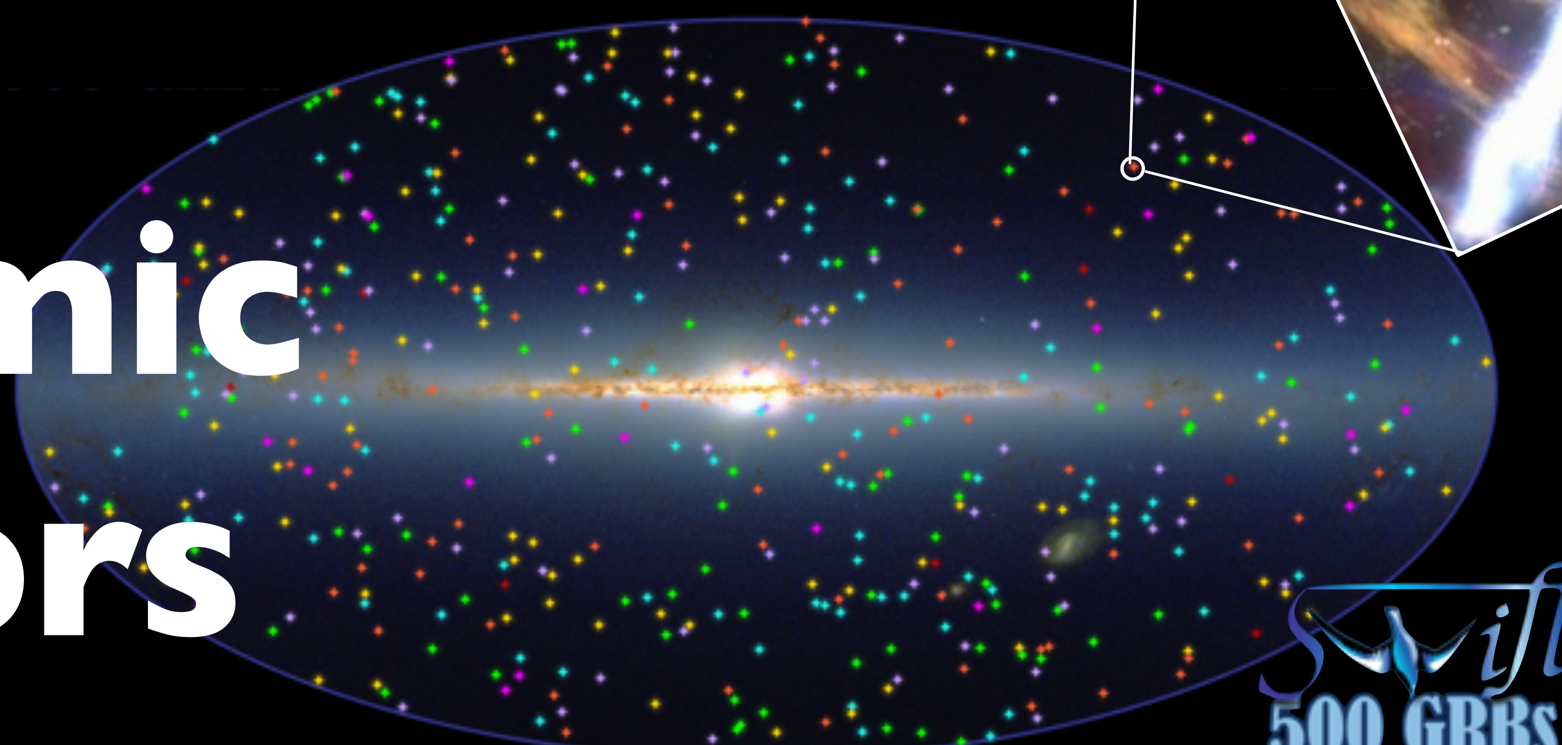
Active galaxies



Gamma-ray bursts

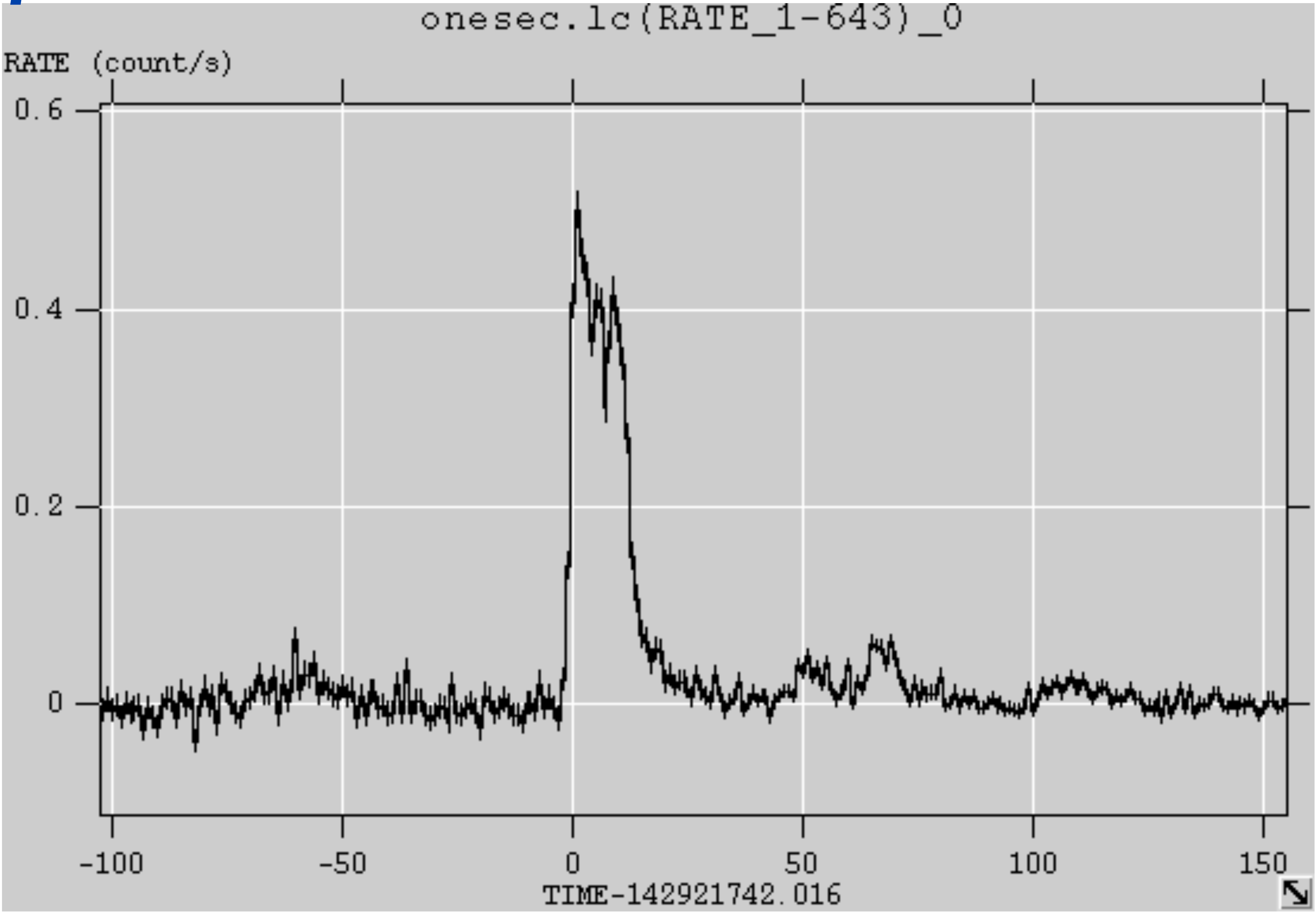


The Cosmic Actors



Gamma-ray bursts: the most violent explosions in the Cosmos

One day in the life of a GRB observed with *Swift*: GRB 050713A



Gamma-ray bursts: the most violent explosions in the Cosmos

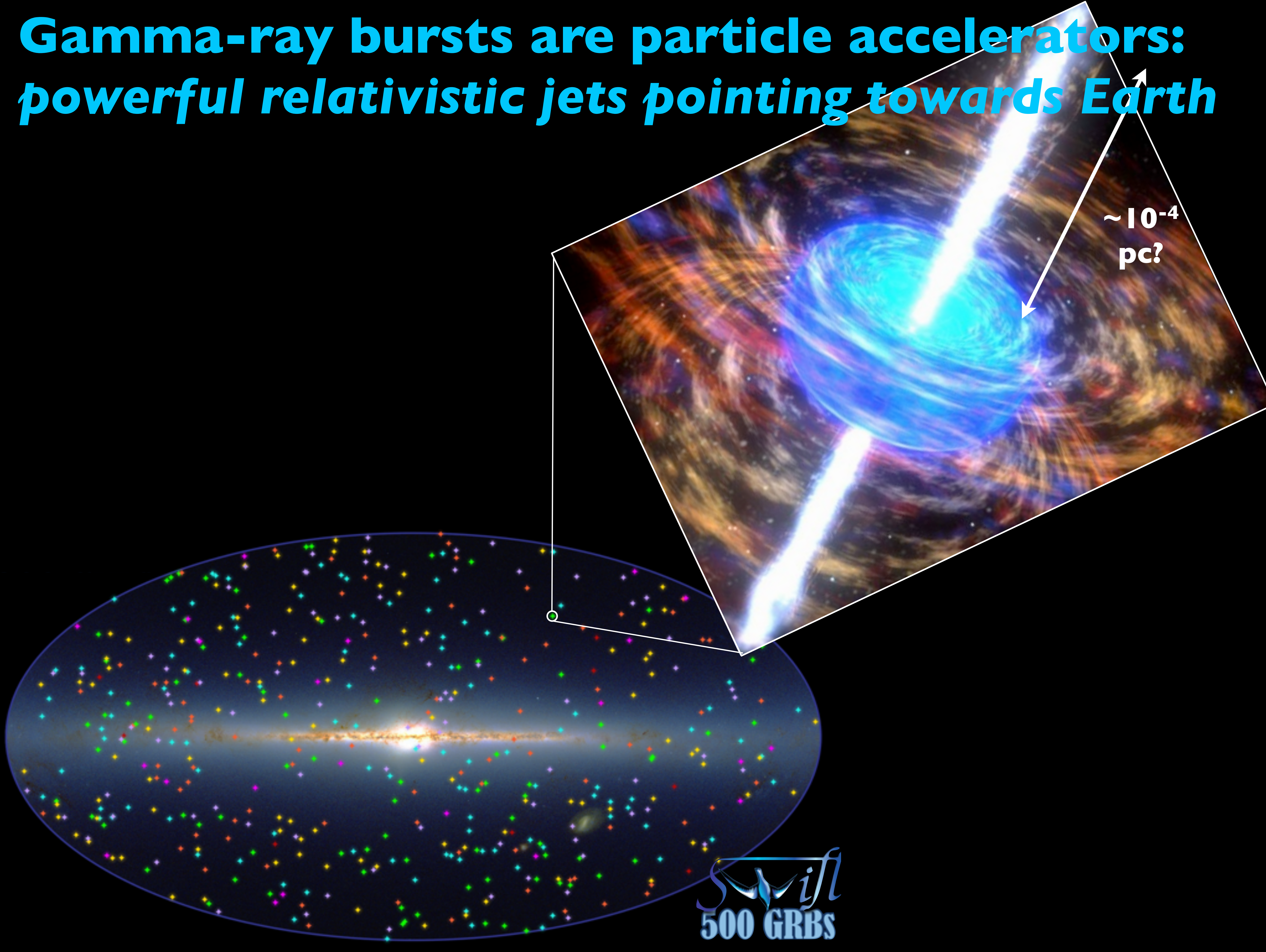
Happen in all directions of sky

~a few per day

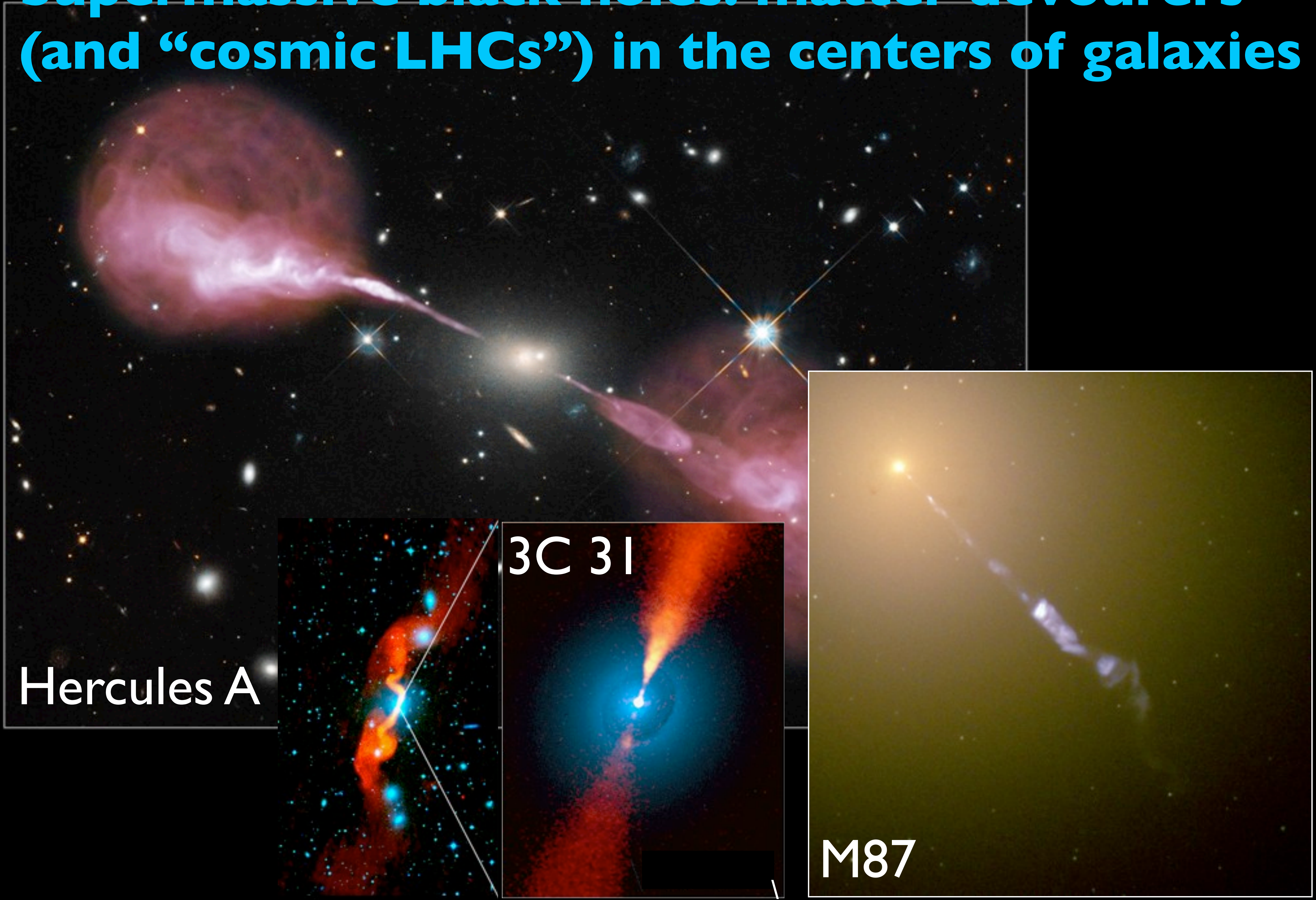
Extragalactic

Energy released $\lesssim 10^{54}$ erg $\sim 1\ M_\odot c^2$
in ~a few seconds - minutes

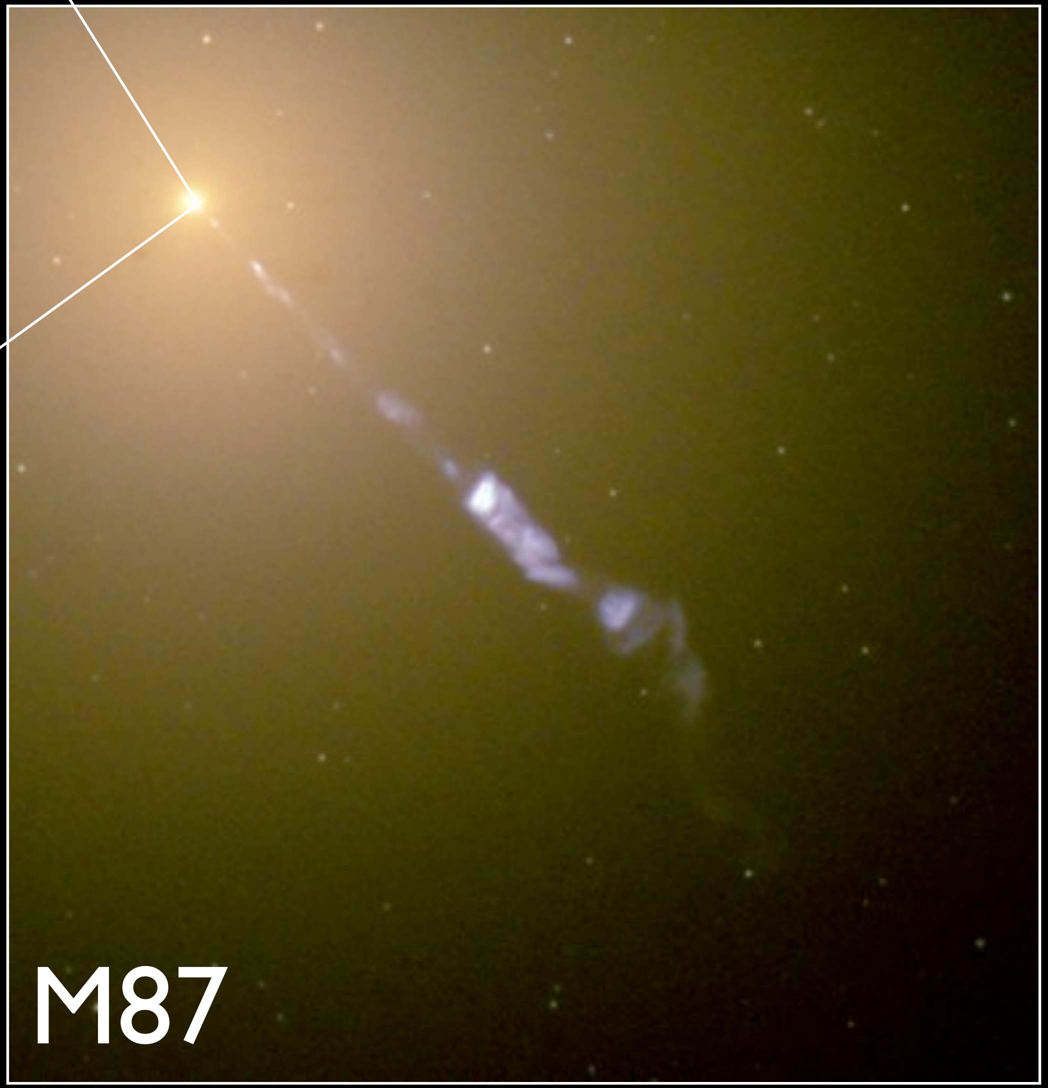
Gamma-ray bursts are particle accelerators: *powerful relativistic jets pointing towards Earth*



Supermassive black holes: matter devourers (and "cosmic LHCs") in the centers of galaxies



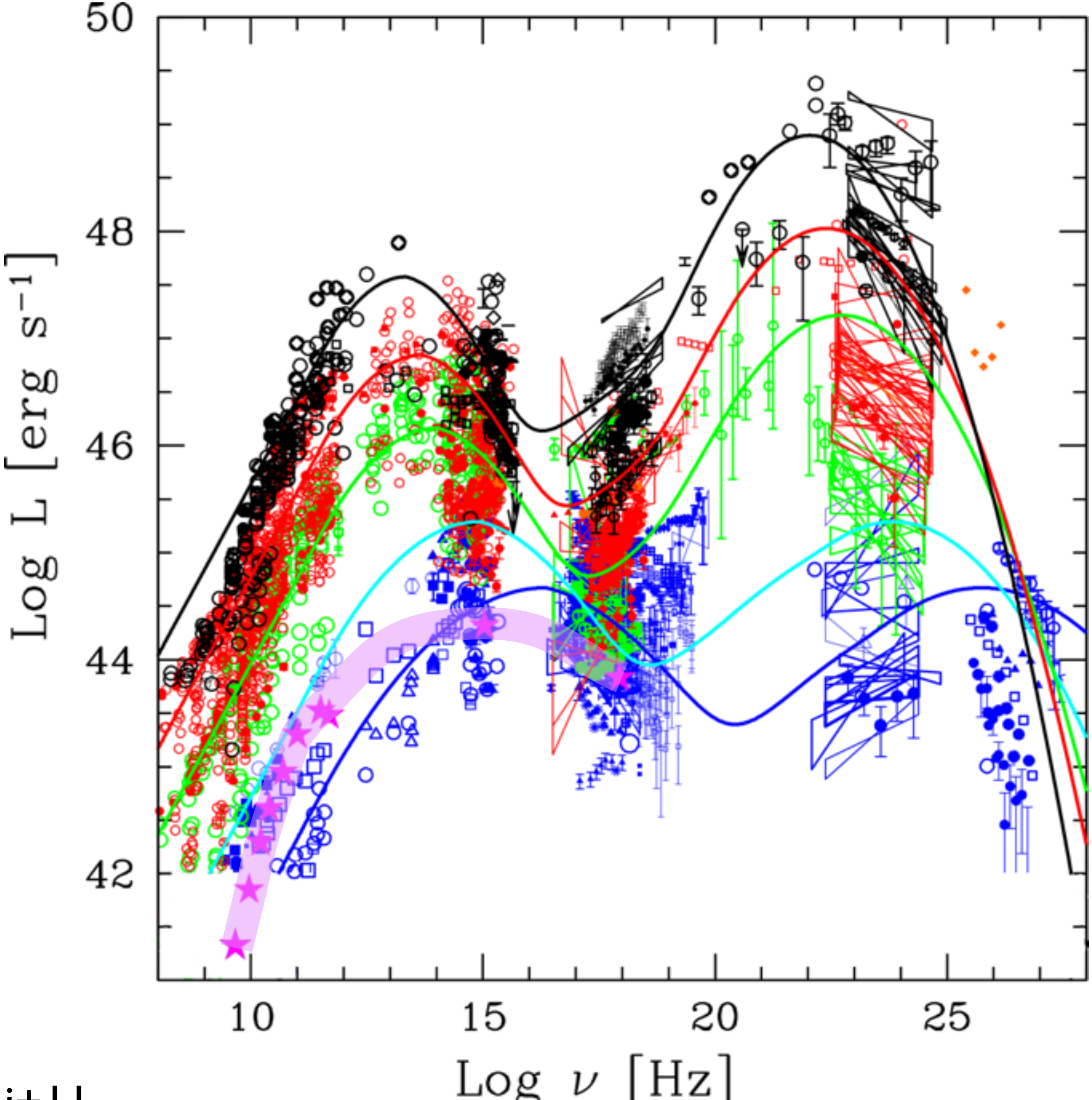
Supermassive black holes: matter devourers (and "cosmic LHCs") in the centers of galaxies



“Radio galaxy”

“Blazars”

Spectra of blazars



Ghisellini+11

Gamma-ray sky dominated by blazars

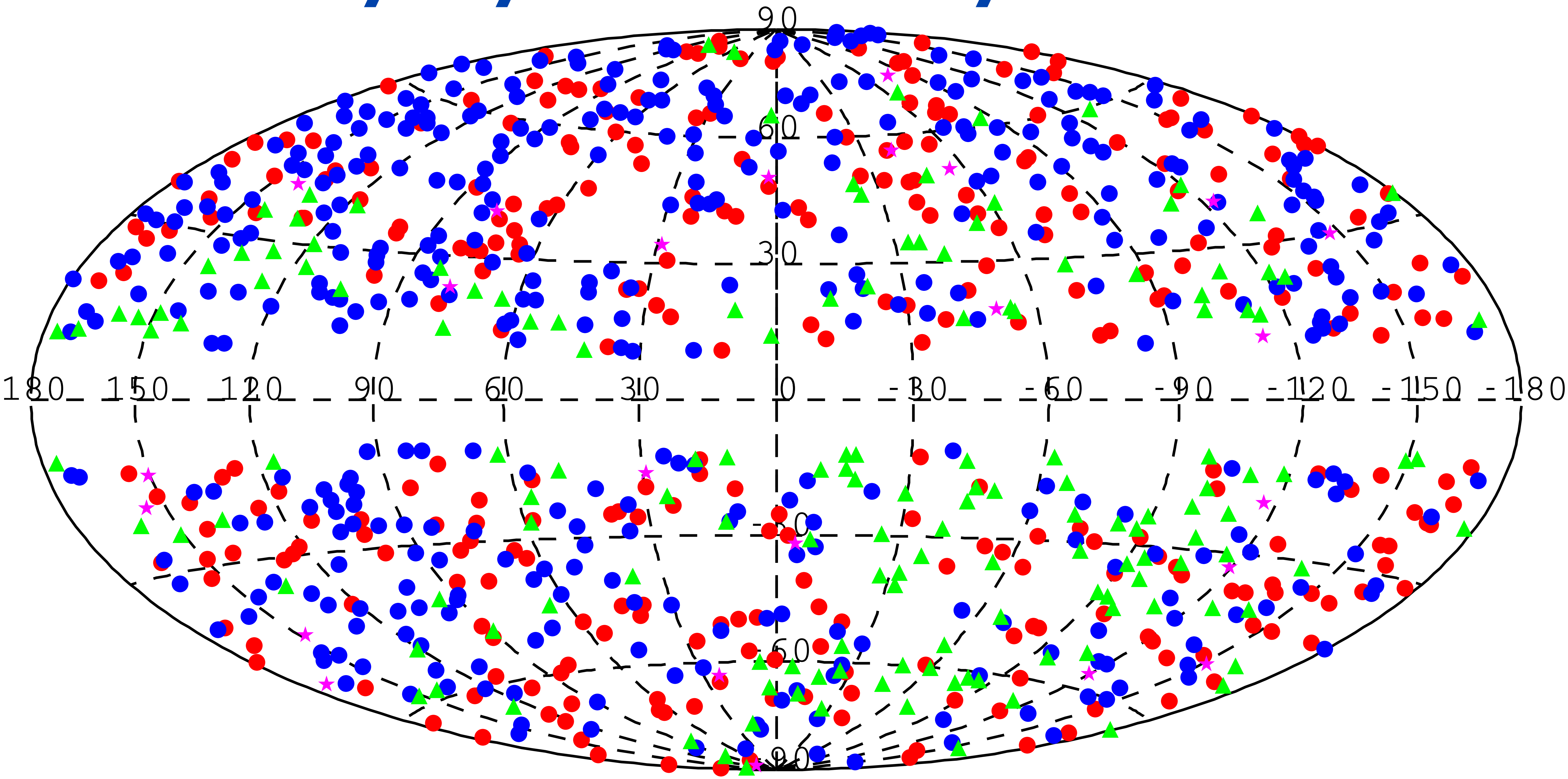
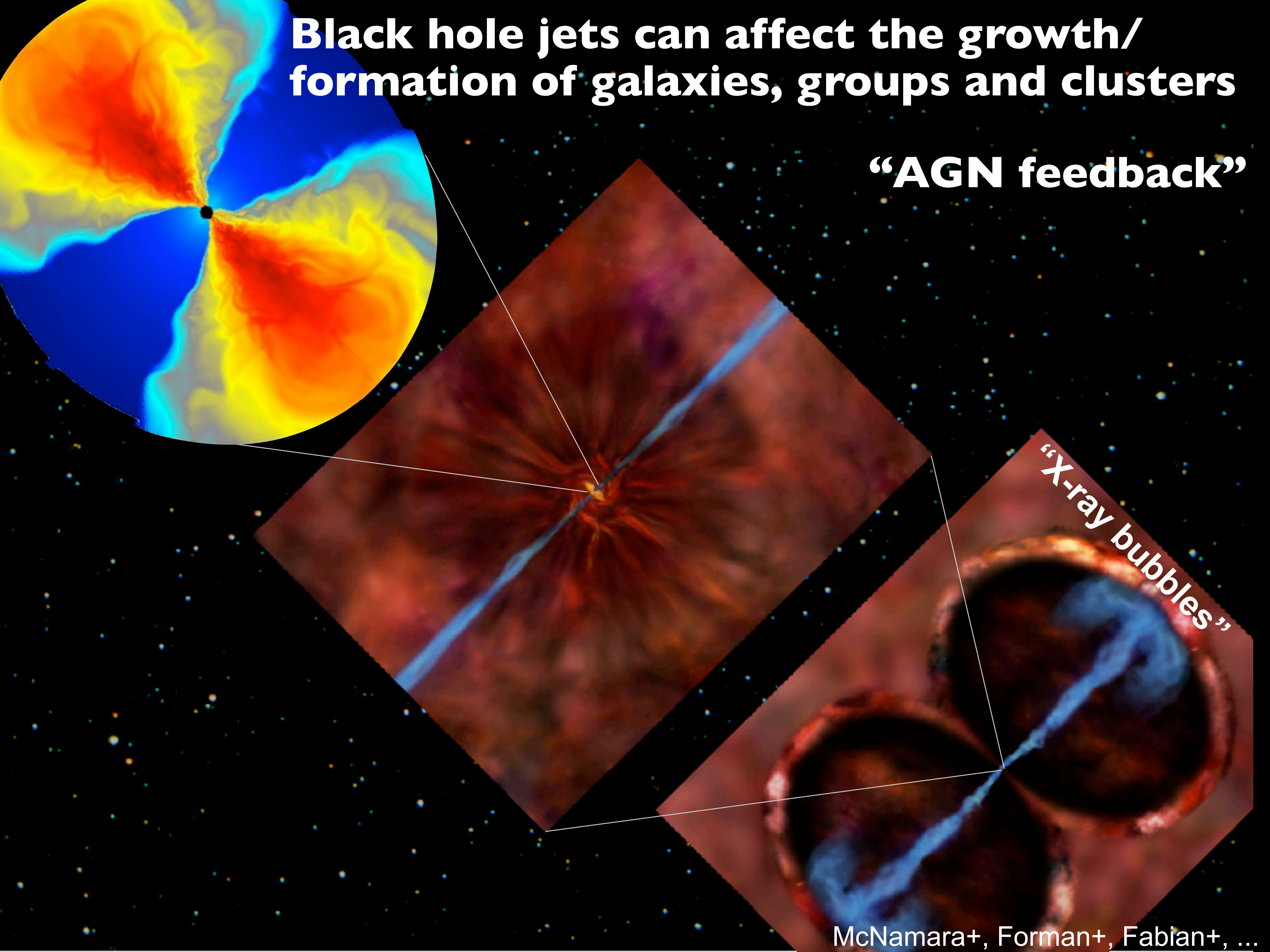
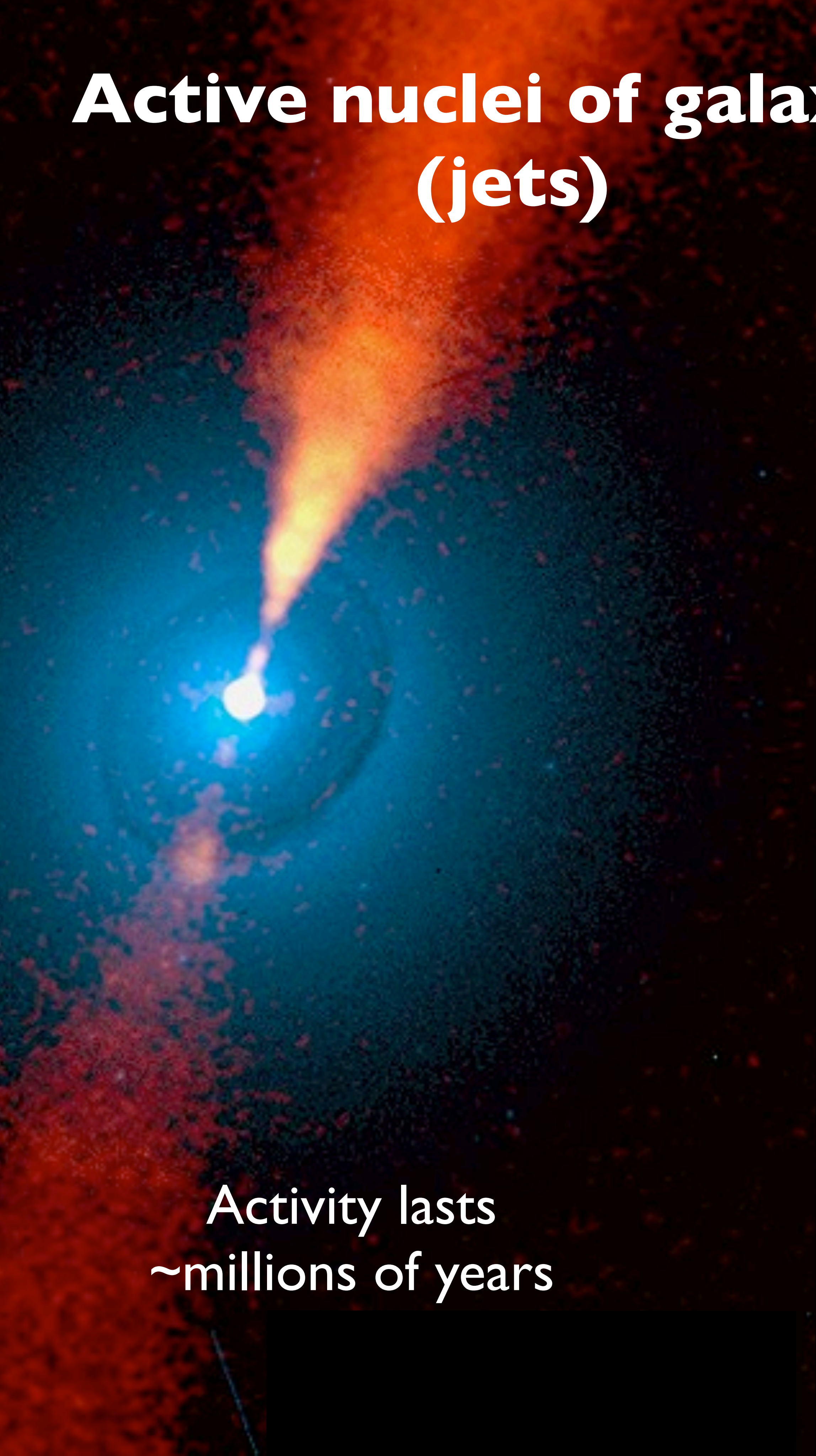


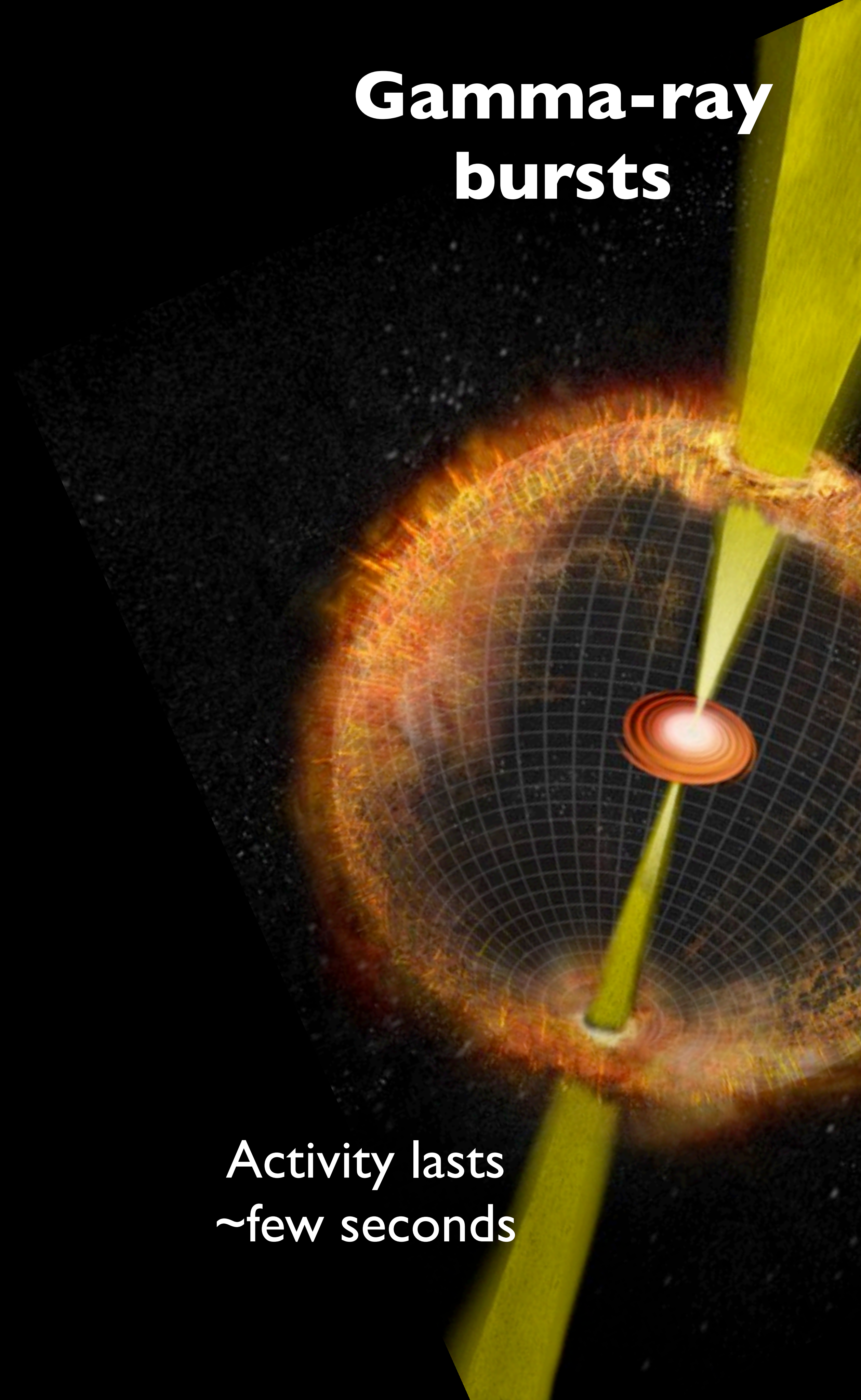
Figure 9. Locations of the sources in the Clean Sample. Red: FSRQs, blue: BL Lac objects, magenta: non-blazar AGNs, and green: AGNs of unknown type.
(A color version of this figure is available in the online journal.)

Ackermann+11

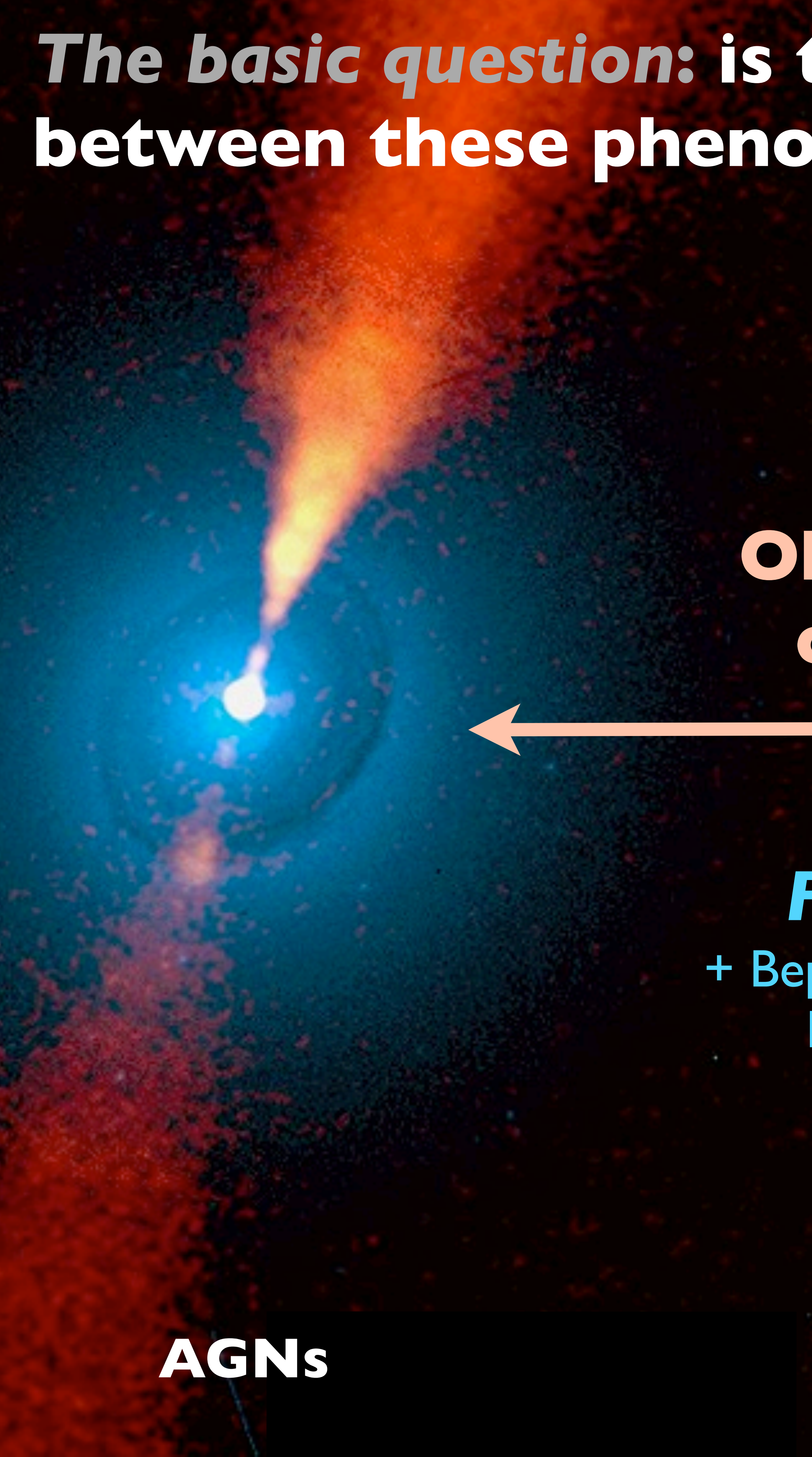

Black hole jets can affect the growth/ formation of galaxies, groups and clusters
"AGN feedback"
"X-ray bubbles"
McNamara+, Forman+, Fabian+, ...

The Discovery


Active nuclei of galaxies
(jets)
Activity lasts
~millions of years


Gamma-ray
bursts
Activity lasts
~few seconds

The basic question: **is there a physical connection between these phenomena? Can we unify them?**

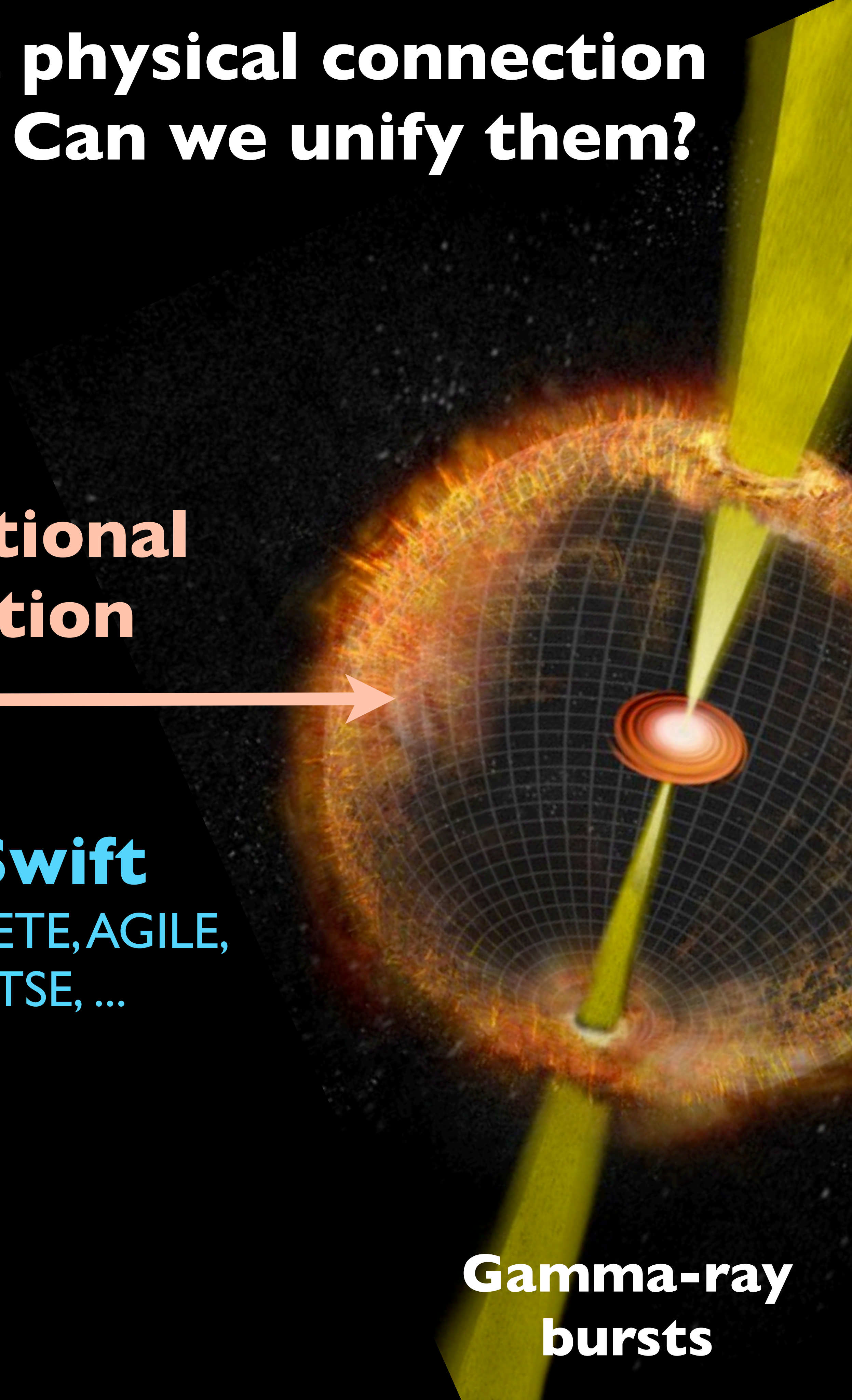


AGNs

Observational connection

***Fermi*, Swift**

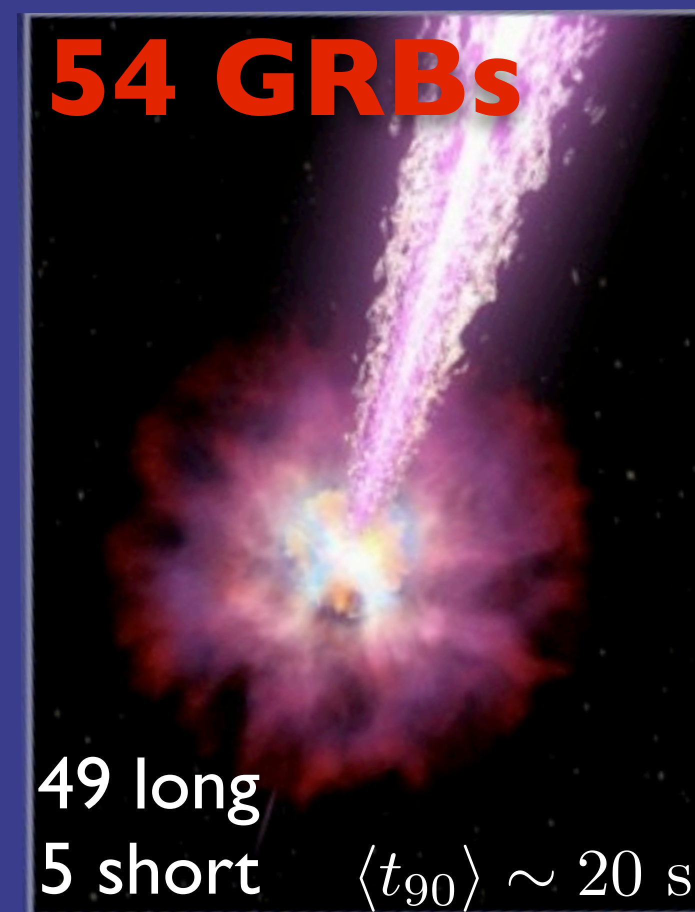
+ BeppoSAX, HETE, AGILE, Integral, BATSE, ...



Gamma-ray bursts

Jet energetics: data from *Fermi*, *Swift* and others

Fermi
and
VLA



***Fermi*, *Swift*,**
BeppoSAX,
HETE,
BATSE,
Integral

Selected because of available

- ***γ-ray emission*** (proxy of jet $L_{\rm bol}$)
- ***jet kinetic power***

Estimating the γ-ray luminosity and jet power

Blazars

L_γ^{iso}: *Fermi* 2FGL

Jet power P_{jet} from "cavity power": using extended radio emission and L_{radio}-P_{cav} correlation (Cavagnolo+ 10)

$$P_{\rm cav} \approx 6 \times 10^{43} \left(\frac{P_{\rm radio}}{10^{40}\ {\rm erg\ s^{-1}}} \right)^{0.7} {\rm erg\ s^{-1}}$$

GRBs

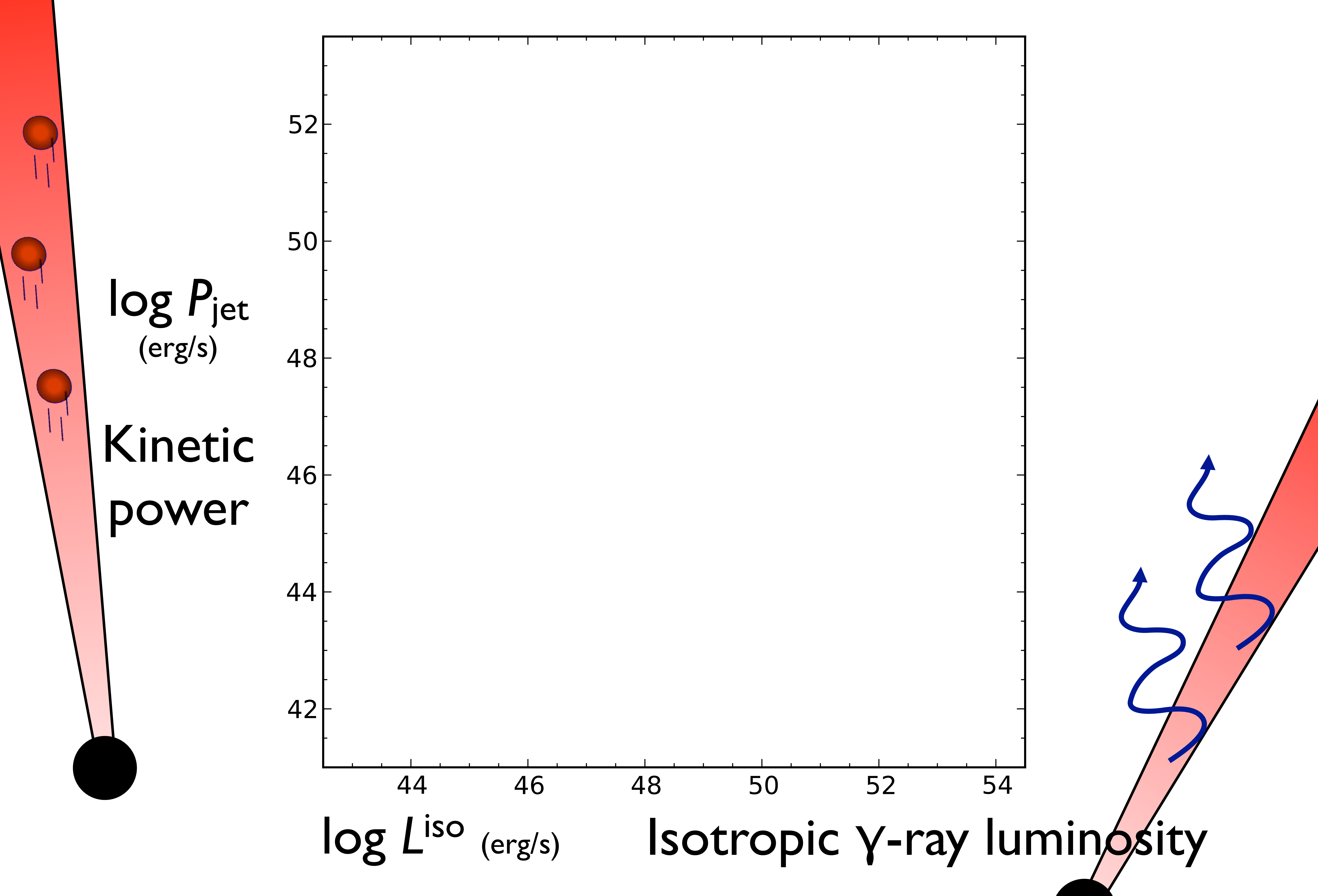
E_γ: prompt emission

pre-*Swift*, *Swift* and *Fermi* GRBs

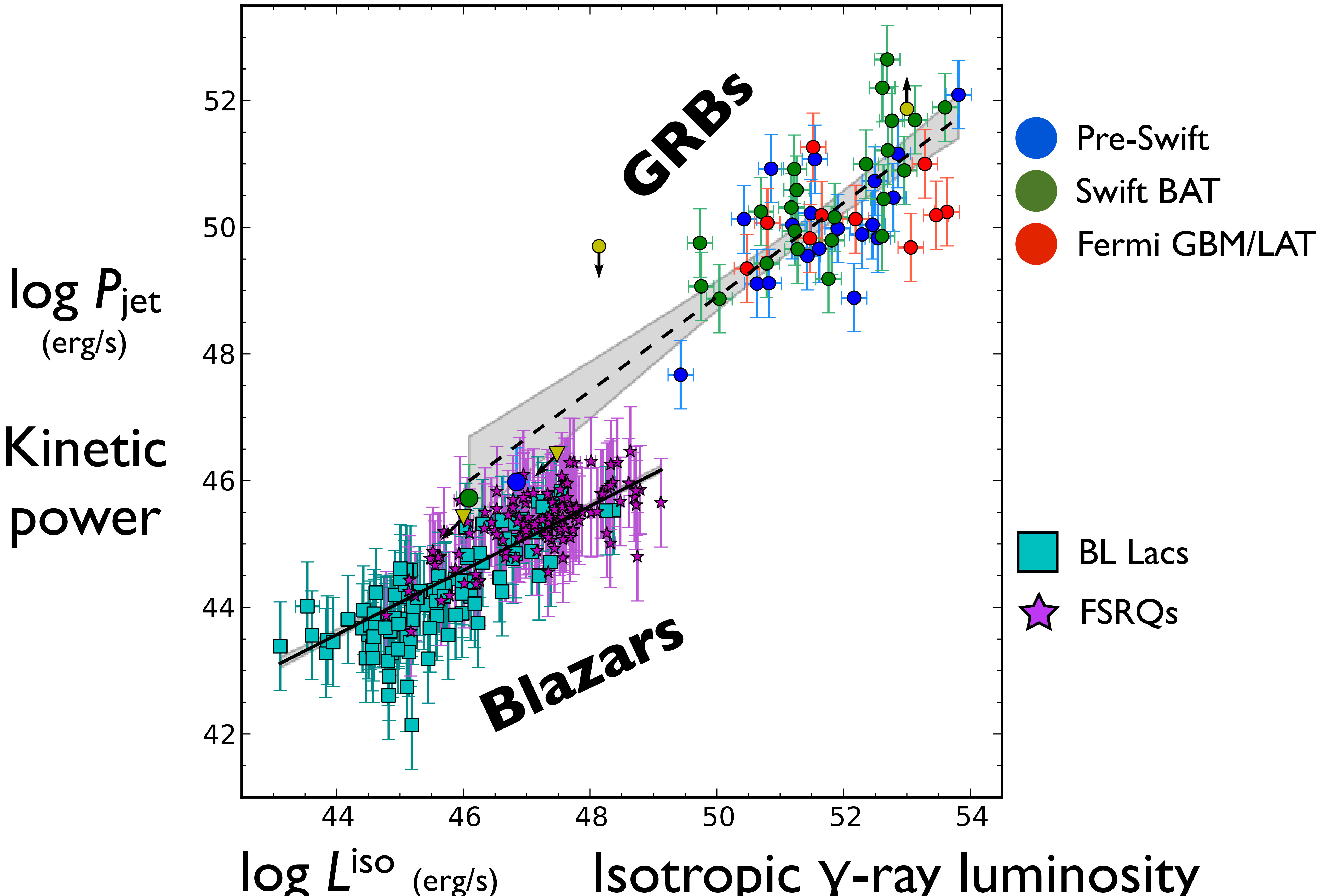
Jet kinetic energy E_K: afterglow modeling with fireball

$$L_\gamma^{iso} = E_\gamma^{iso}\,(1+z)/\,t_{90}$$
$$P_{jet} = E_K\,(1+z)/\,t_{90}$$

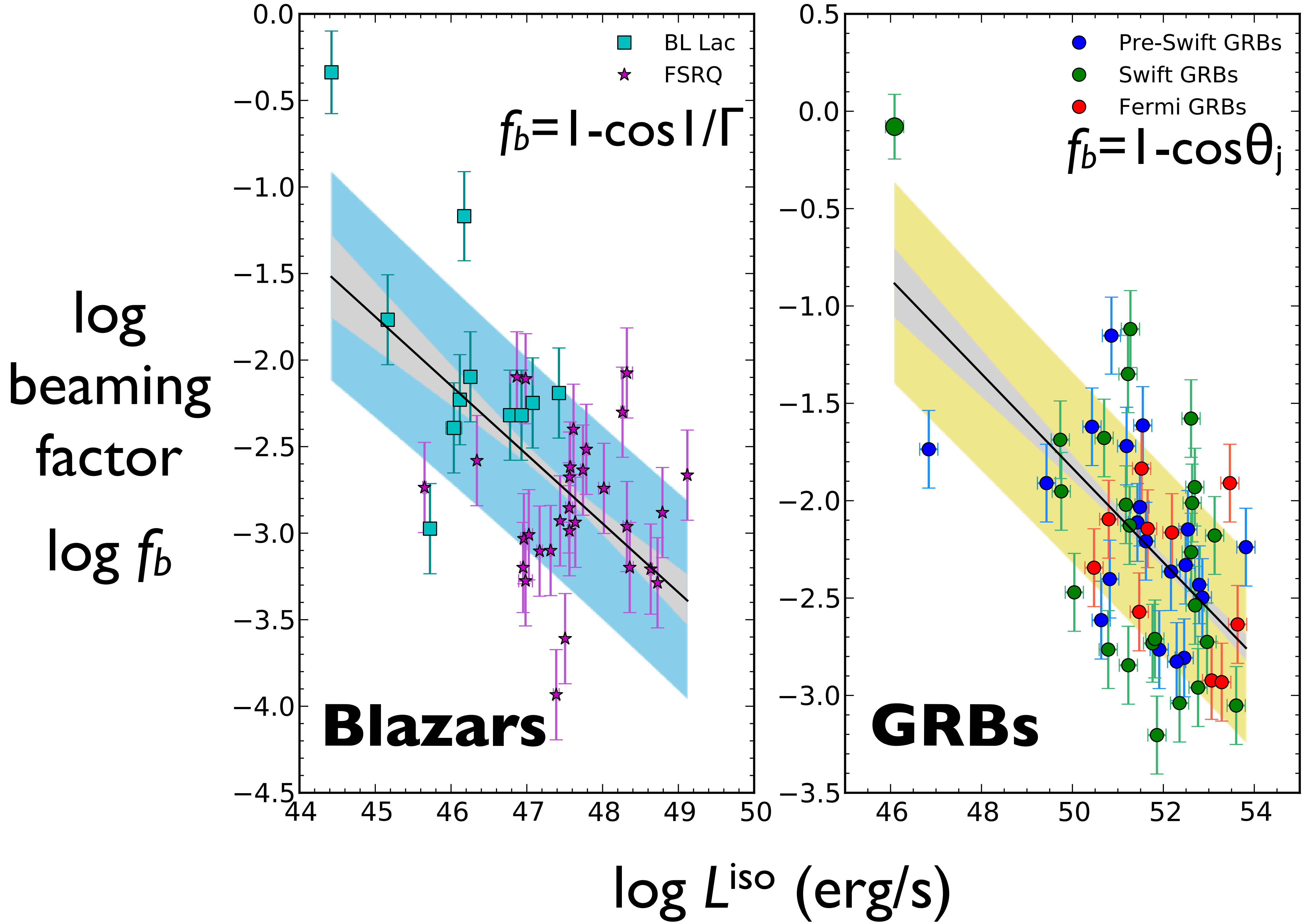
Energetics of GRBs and blazars



Energetics of GRBs and blazars

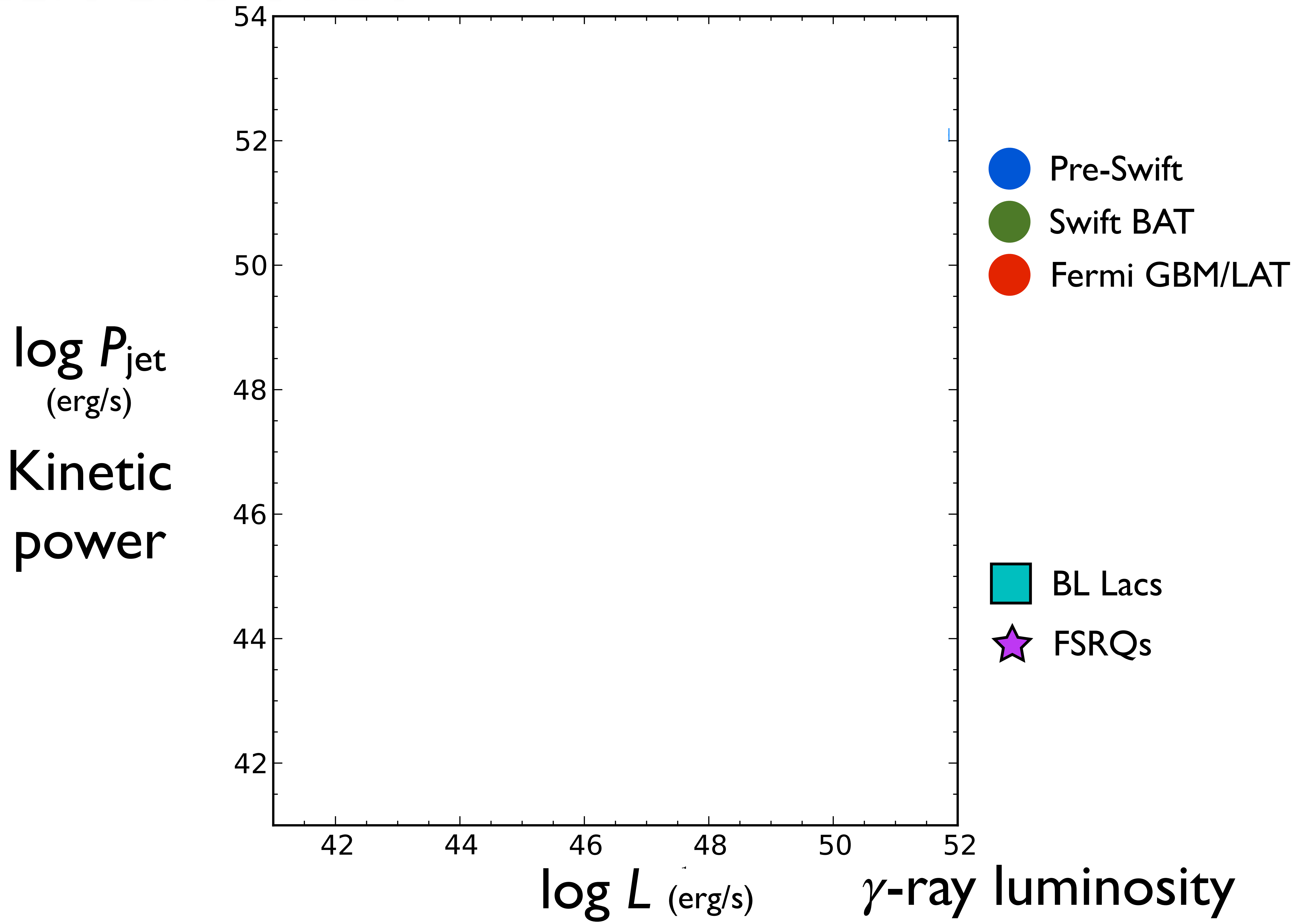


"Collimation-corrected" energetics: $L = (\textit{beaming factor}) \times L_{iso}$



Nemmen+12

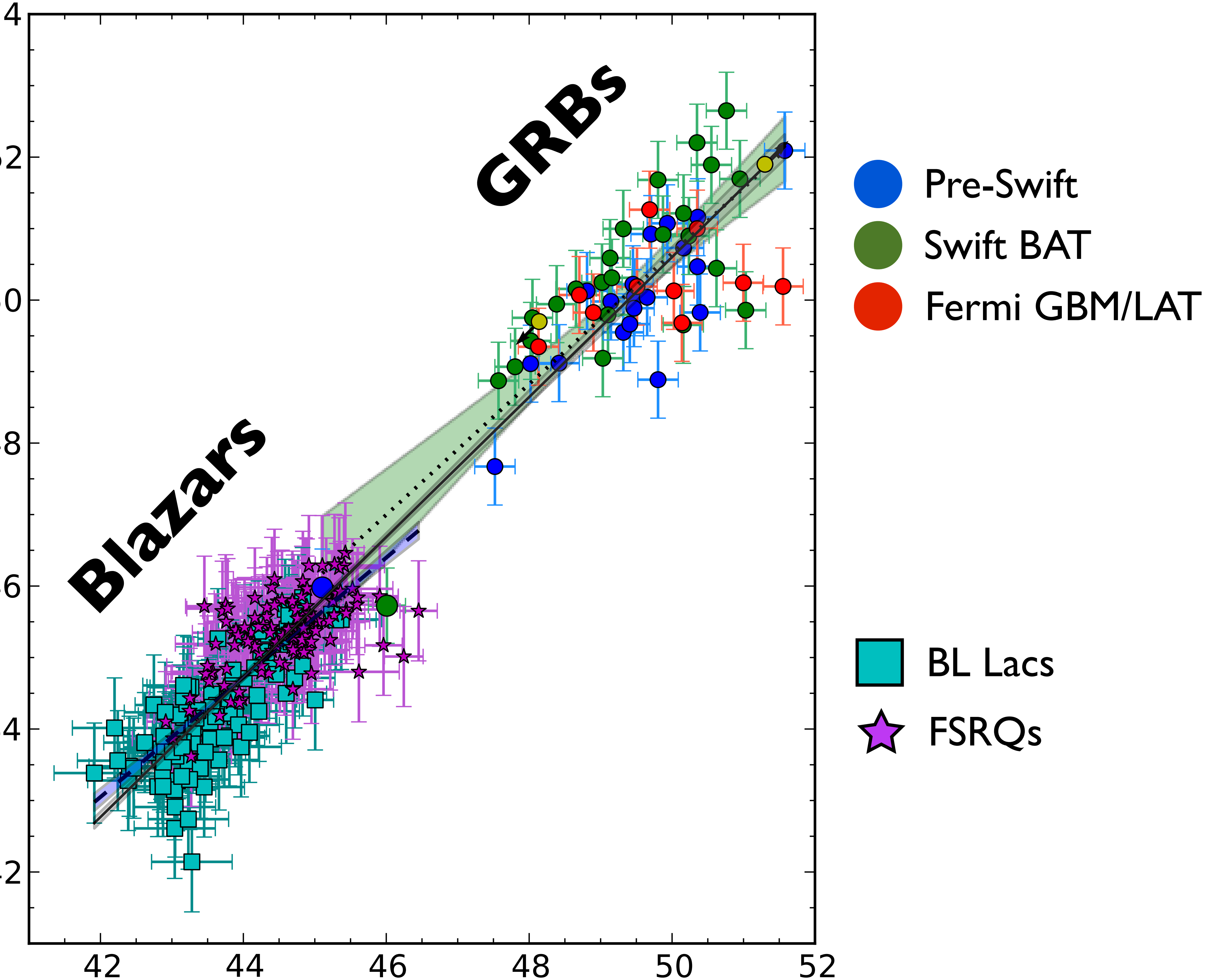
Collimation-corrected energetics of blazars and GRBs



Collimation-corrected energetics of blazars and GRBs

log P_{jet} (erg/s)

Kinetic power



log L (erg/s) γ-ray luminosity

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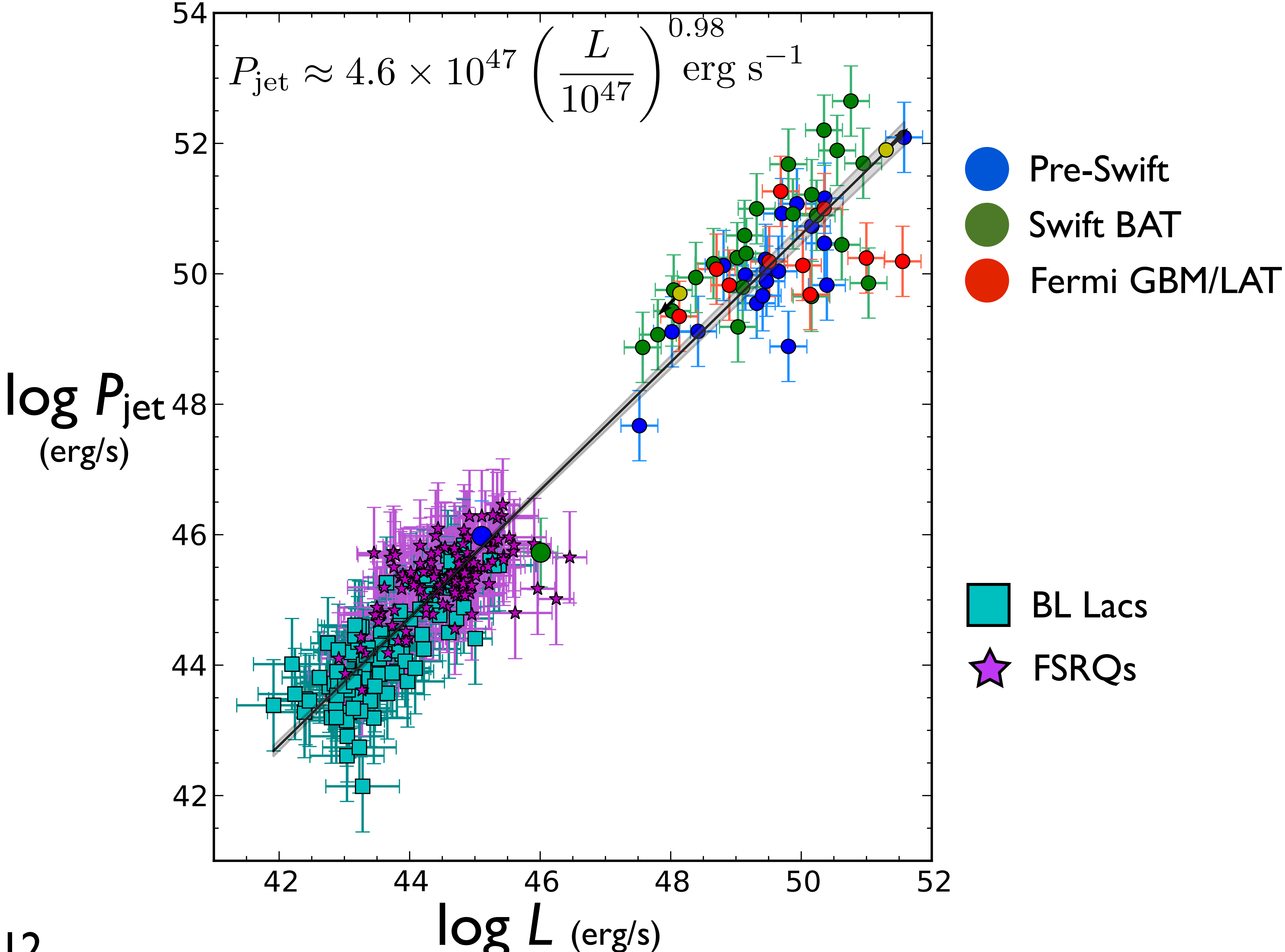
A universal scaling for the energetics of relativistic jets



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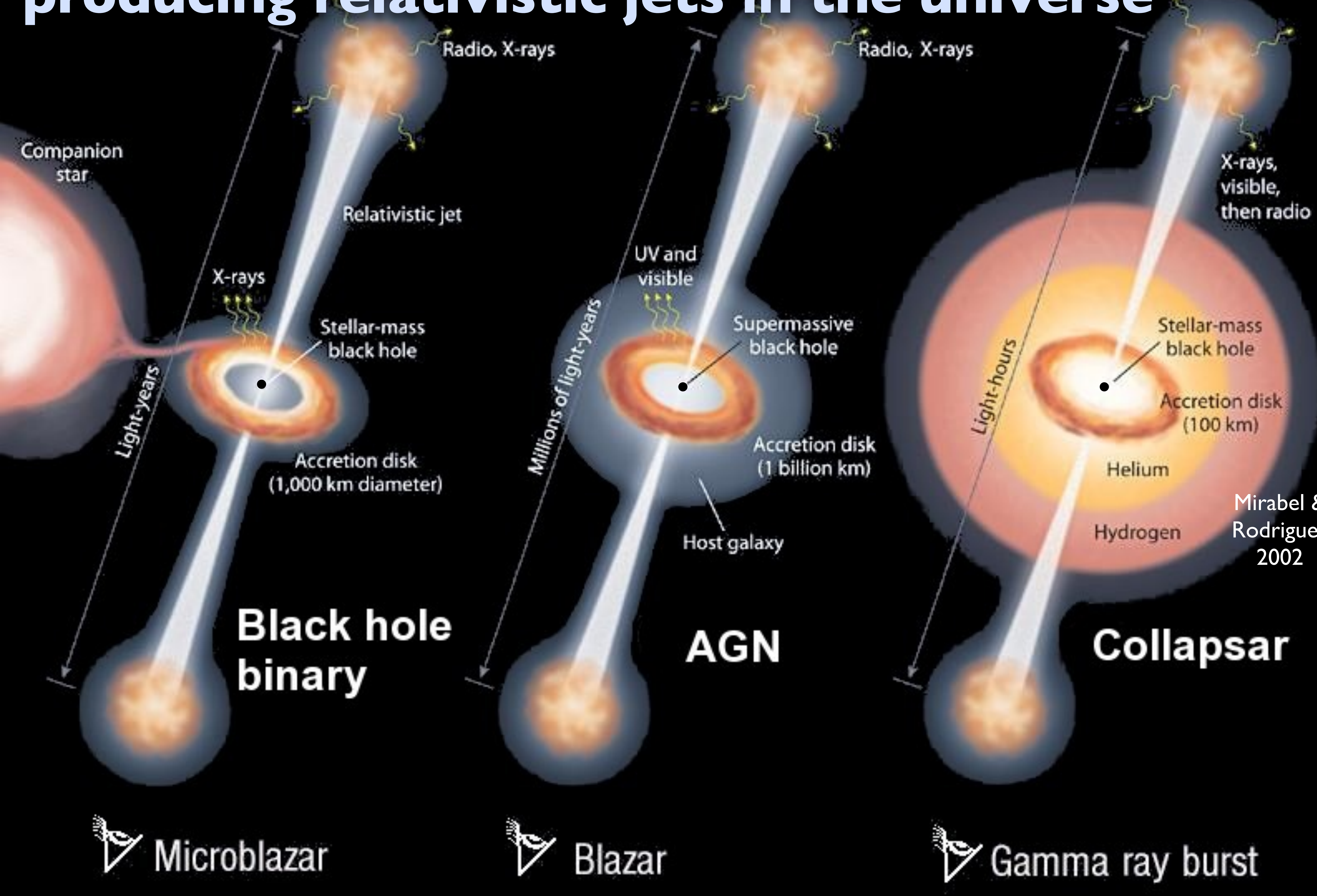
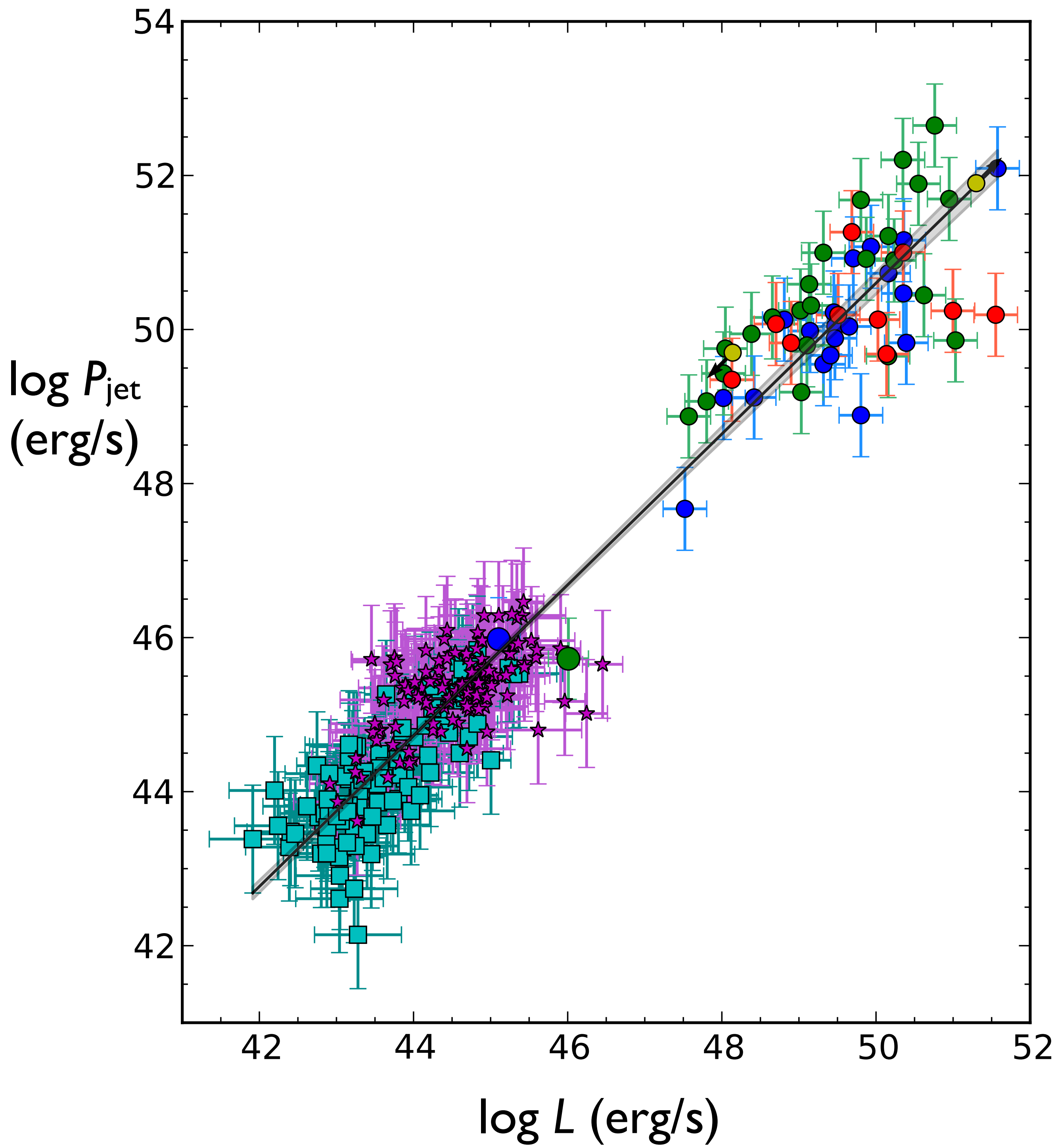
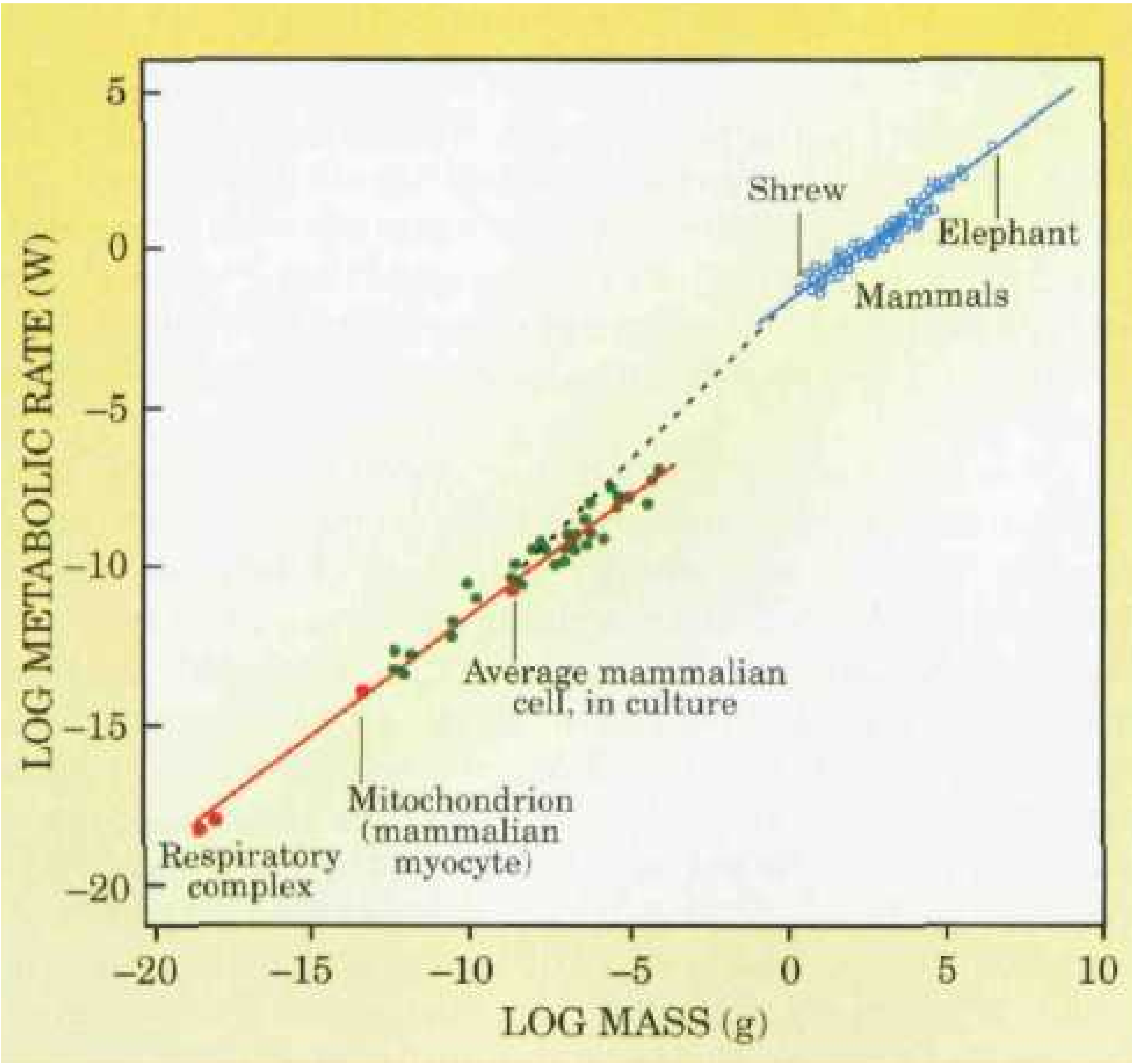
Evidence for universal mechanism for producing relativistic jets in the universe



Mirabel & Rodriguez 2002

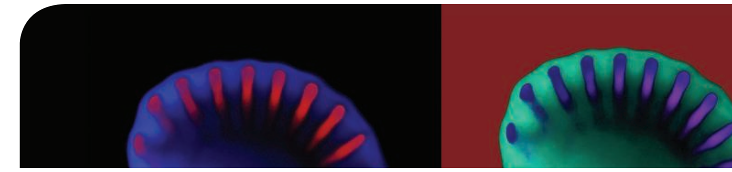




West & Brown 04, Physics Today

THIS WEEK IN Science
EDITED BY STELLA HURTLEY

inside a diamond anvil cell. An increase in pressure extended dislocation activity to smaller grain sizes, indicating that pressure compensates for the



A Universal Scaling for the Energetics of Relativistic Jets from Black Hole Systems

R. S. Nemmen,[1]* M. Georganopoulos,[1,2] S. Guiriec,[1] E. T. Meyer,[3,5] N. Gehrels,[1] R. M. Sambruna[4]

Black holes generate collimated, relativistic jets, which have been observed in gamma-ray bursts (GRBs), microquasars, and at the center of some galaxies [active galactic nuclei (AGN)]. How jet physics scales from stellar black holes in GRBs to the supermassive ones in AGN is still unknown. Here, we show that jets produced by AGN and GRBs exhibit the same correlation between the kinetic power carried by accelerated particles and the gamma-ray luminosity, with AGN and GRBs lying at the low- and high-luminosity ends, respectively, of the correlation. This result implies that the efficiency of energy dissipation in jets produced in black hole systems is similar over 10 orders of magnitude in jet power, establishing a physical analogy between AGN and GRBs.

Relativistic jets are ubiquitous in the cosmos and have been observed in a diverse range of black hole systems spanning from stellar mass (~$10M_\odot$; $M_\odot$, solar mass) to supermassive scales (~10^5 to $10^{10}M_\odot$), particularly in the bright flashes of gamma-rays [known as gamma-ray bursts (GRBs)] (*1*, *2*), the miniature versions of quasars lurking in our Galaxy erable theoretical efforts, many aspects of black hole jets still remain mysterious, such as the mechanism(s) responsible for their formation and the nature of their energetics, as well as their high-energy radiation (*6*, *7*). Jets and outflows from supermassive black holes have important feedback effects on scales ranging from their host galaxies to groups and clusters of galaxies (*8*).

tures in the universe and the coevolution of black holes and galaxies (*9*).

One outstanding question is how the jet physics scale with mass from stellar to supermassive black holes. Interestingly, there is evidence to suggest that jets behave in similar ways in microquasars and radio-loud AGN (*10*–*12*). However, a clear connection between AGN and GRBs has not yet been established, though recent work provides encouraging results (*13*, *14*).

As a first step in understanding how the properties of jets vary across the mass scale, we focus on the energetics of jets produced in AGN and GRBs. Therefore, we searched the literature for published and archival observations that allow us to estimate the jet radiative output and the kinetic power for a sample of black hole systems in which the jet is closely aligned with our line of sight and characterized by a broad range of masses. For this reason, our sample consists of blazars—AGNs with their jets oriented

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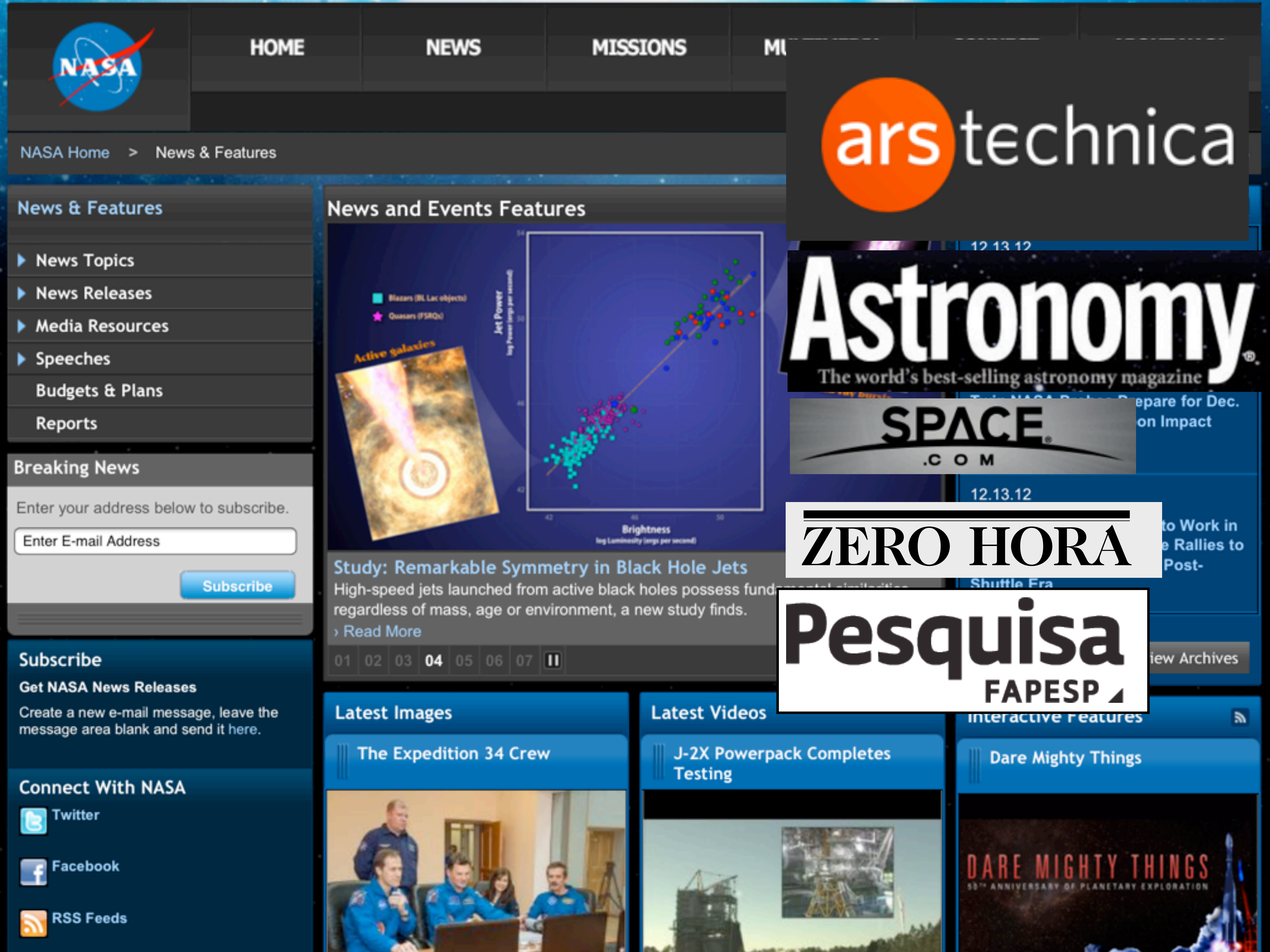
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Create a new e-mail message, leave the message area blank and send it here.
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Jet Power
Brightness
Study: Remarkable Symmetry in Black Hole Jets
High-speed jets launched from active black holes possess fund
regardless of mass, age or environment, a new study finds.
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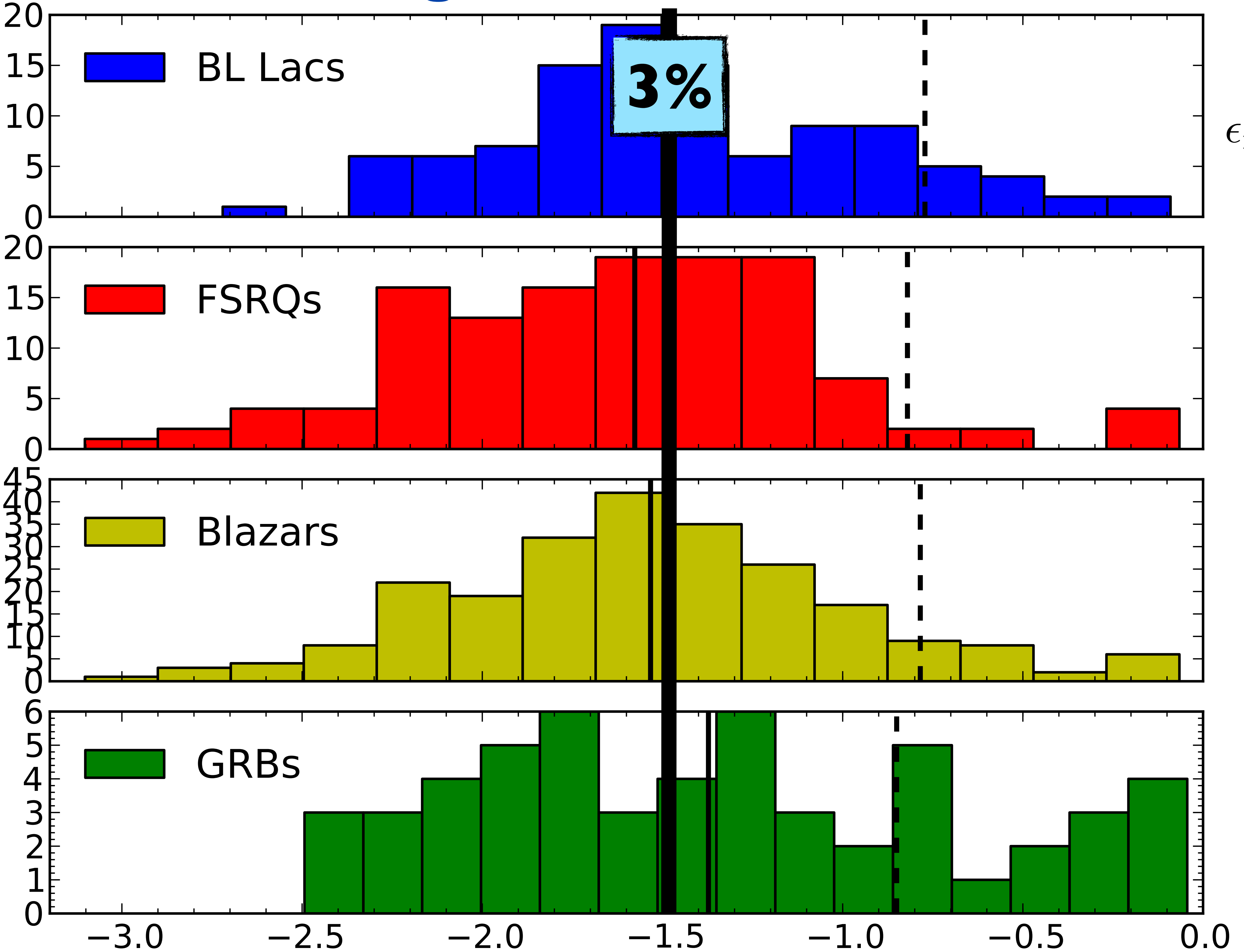
Jets are efficient channels for energy dissipation in "black hole engines": ε_{rad} >3% for most sources



$$\epsilon_{\rm rad} \equiv \frac{L}{L + P_{\rm jet}}$$

log ε_{rad} [1σ lower limits]

Nemmen+12

Low-luminosity AGNs and *Fermi* LAT

Plot from work in progress
Not for online distribution

Conclusions I

We live in a violent universe

Active galactic nuclei, gamma-ray bursts, neutron stars

Gamma-ray observations are required to decode the extreme side of the Cosmos

Fermi Telescope: amazing advances

Synergies with other missions: CTA

Conclusions II

A new symmetry: Jets from galactic centers and gamma-ray bursts follow the universal scaling $P_{\rm jet} \approx 4.6 \times 10^{47} \left(\frac{L}{10^{47}} \right)^{0.98} {\rm erg\ s^{-1}}$

Independent of *black hole nutrition diet* and *its environment*

Valid over *10 orders of magnitude of luminosity/jet power*

Evidence for same physics operating in relativistic jets across the mass scale

Radiative dissipation in jets can be quite efficient: $\varepsilon_{\rm rad} > 3\%$

Whole new territory for exploration: AGN-GRB connections!

Other Science Highlights with *Fermi*