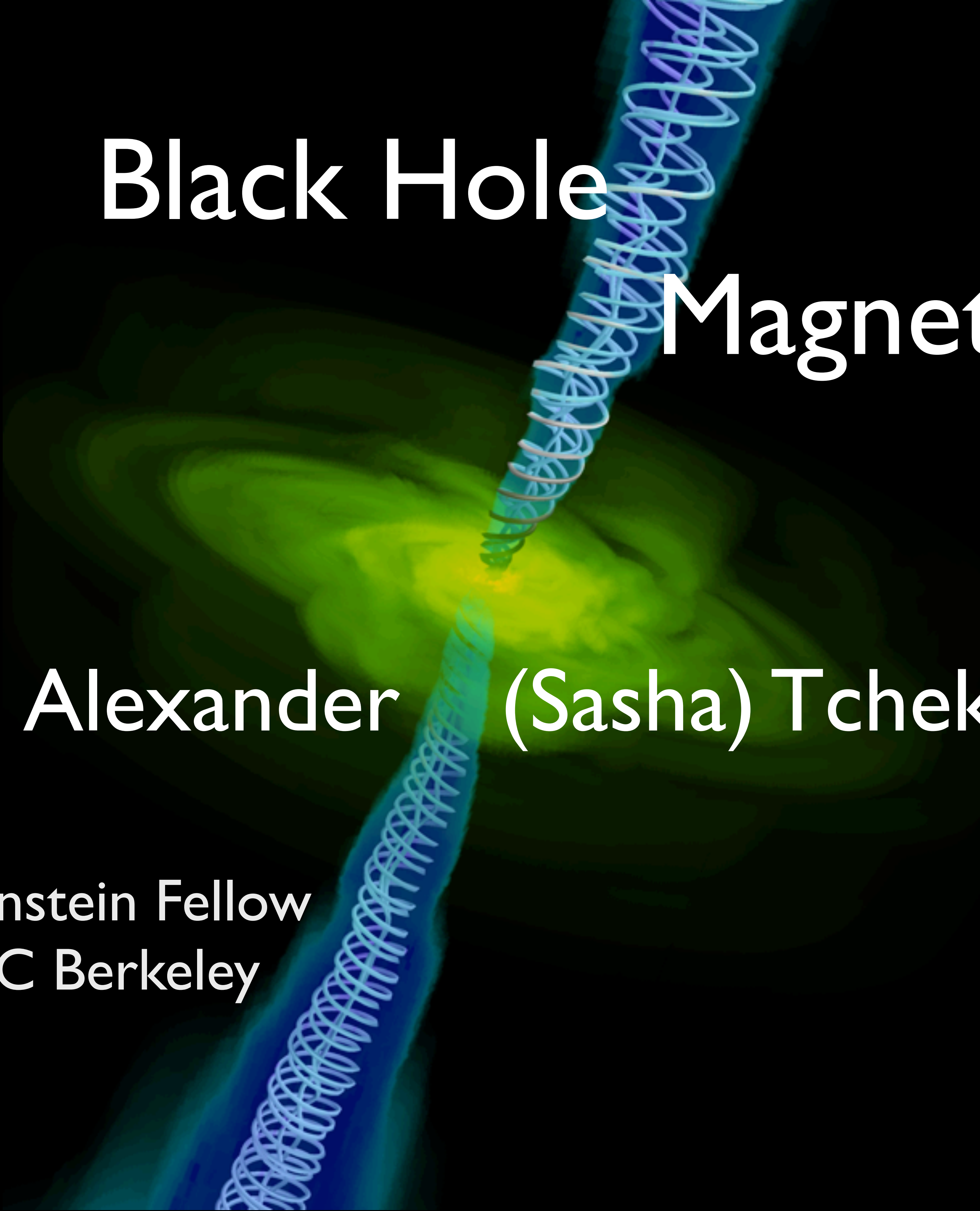
Black Hole Magnetospheres

Alexander (Sasha) Tchekhovskoy

Einstein Fellow
UC Berkeley



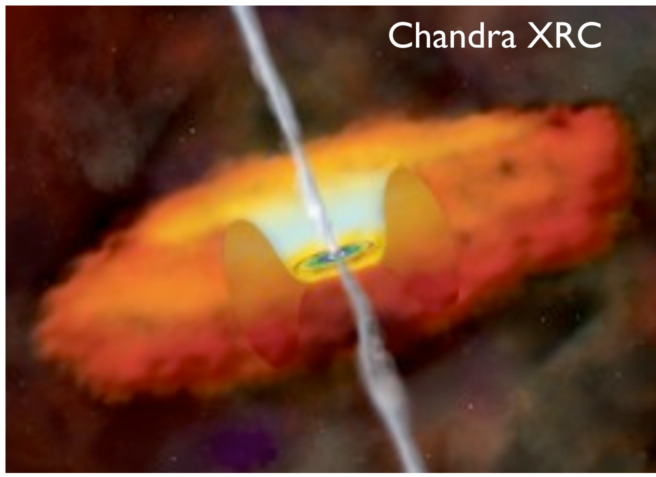
Black Holes Power in the Universe

Supermassive $M \sim 10^{6-10} M_{\odot}$

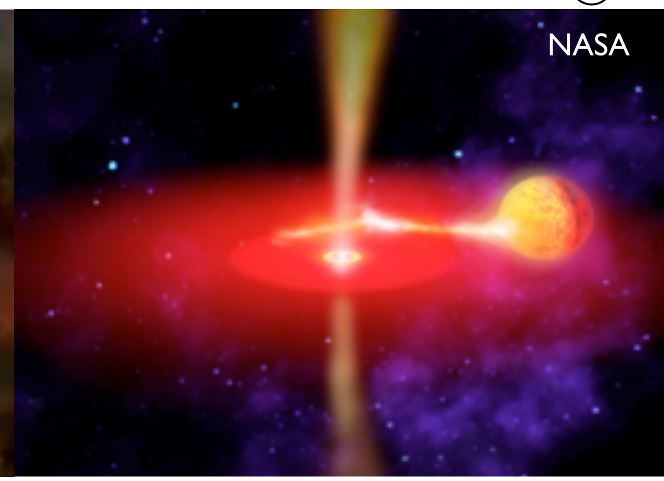
Intermediate $M \sim 10^{2-5} M_{\odot}$

—— Stellar-mass —— $M \sim \text{few} - 10 M_{\odot}$

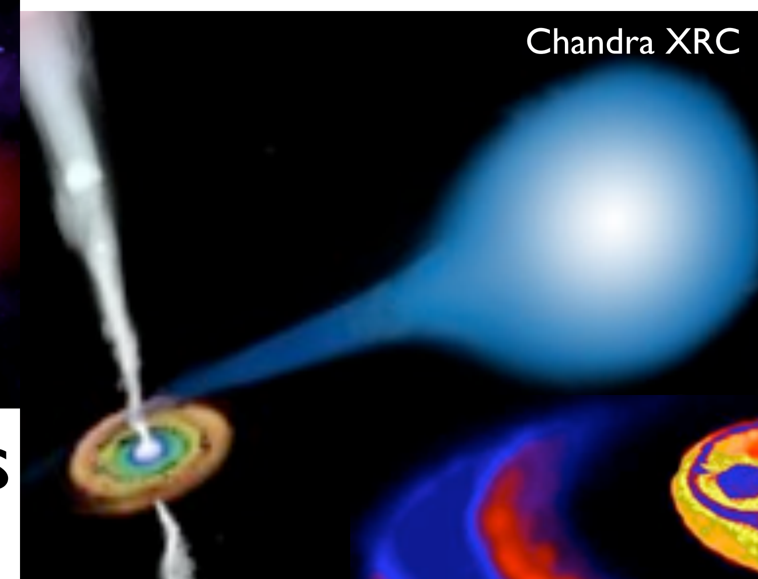
(AT 2015)



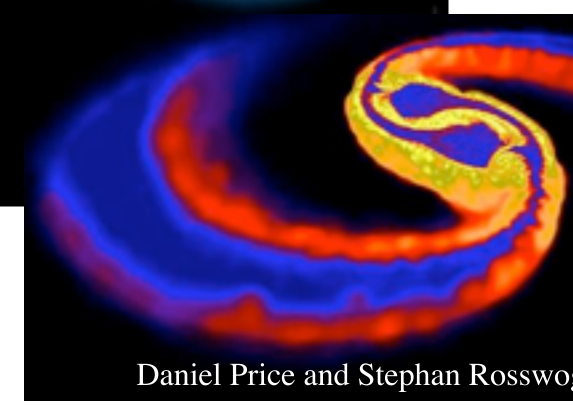
Quasars/AGN



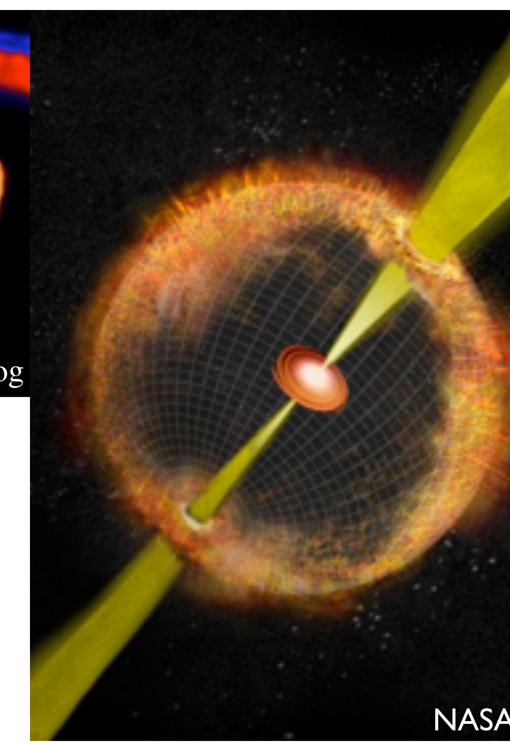
Intermediate-mass black holes/ultra-luminous X-ray sources?



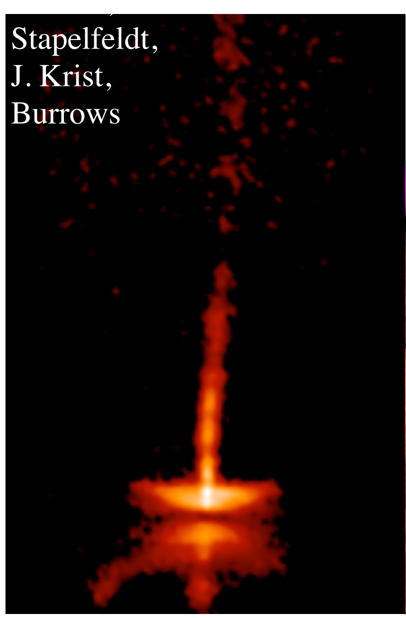
Black Hole Binaries



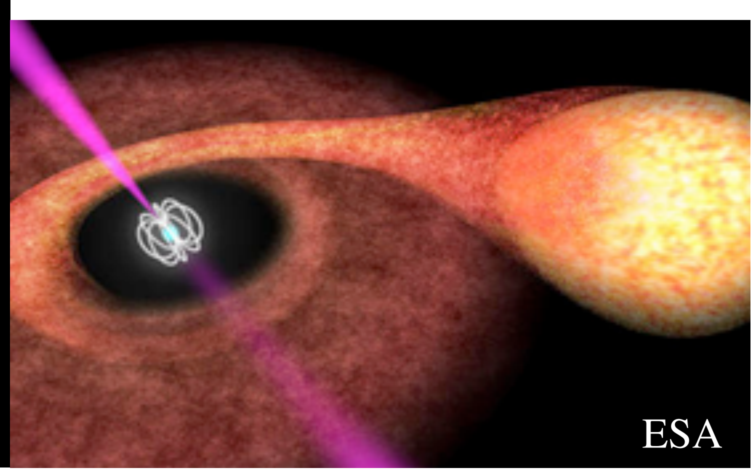
Gamma-ray bursts



Black hole or Neutron star



Stars



Neutron Stars, White Dwarfs; $M \sim M_{\odot}$

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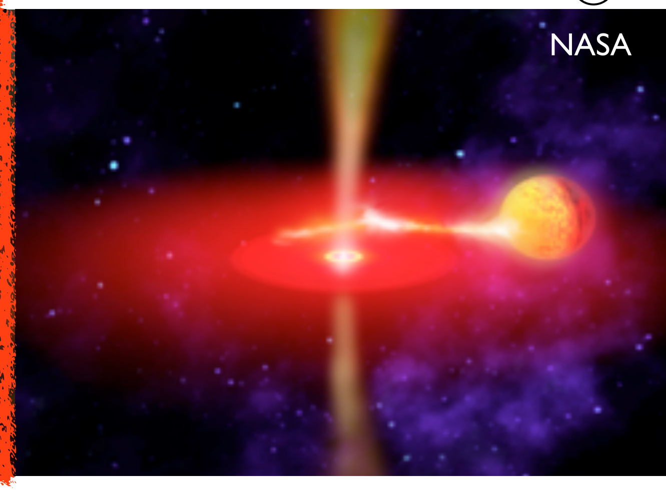

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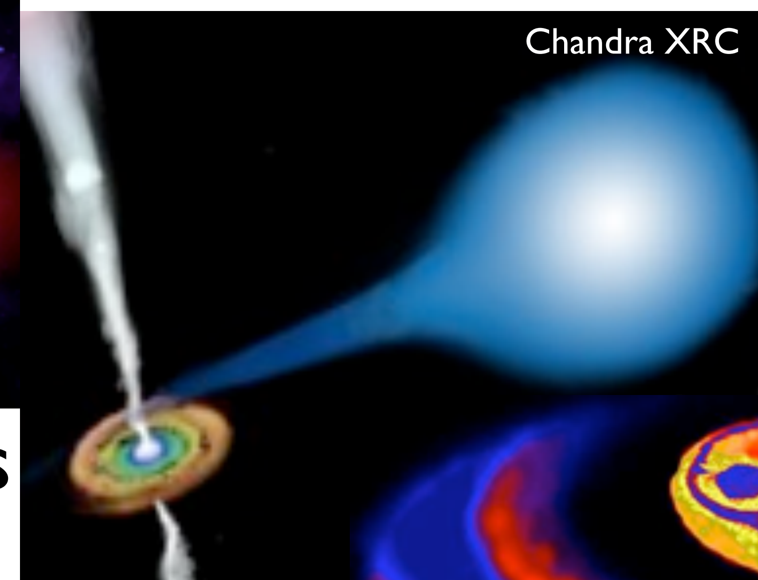

(AT 2015)

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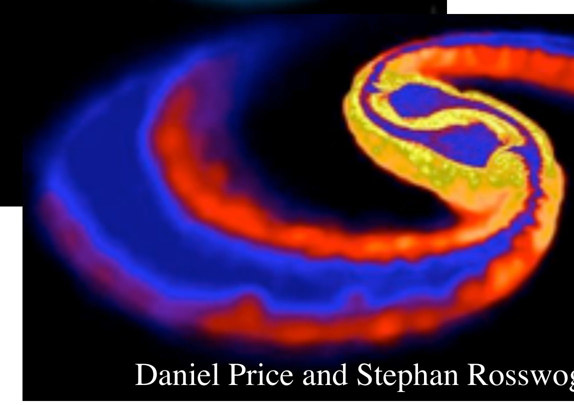

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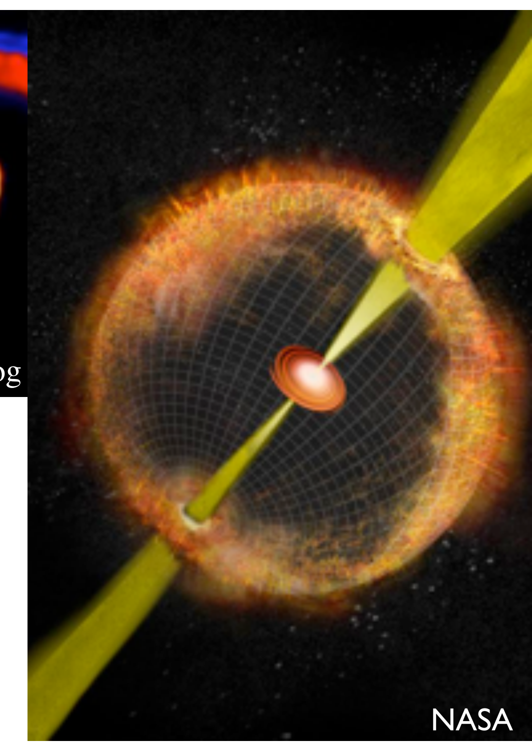

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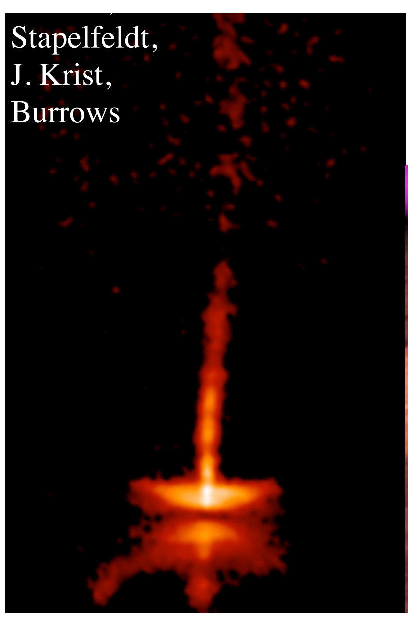

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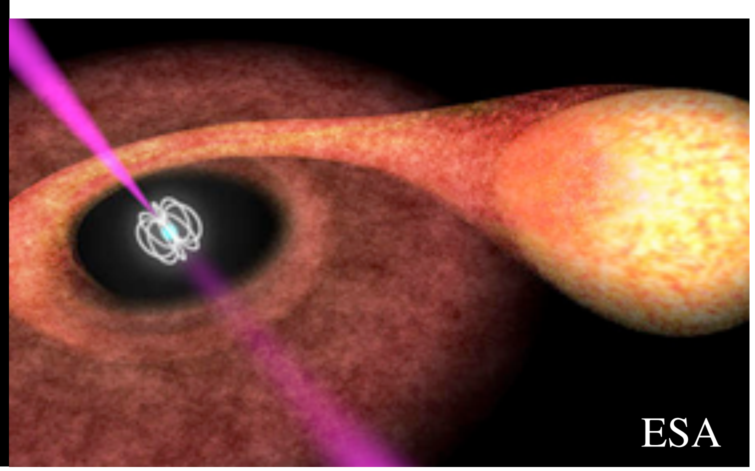

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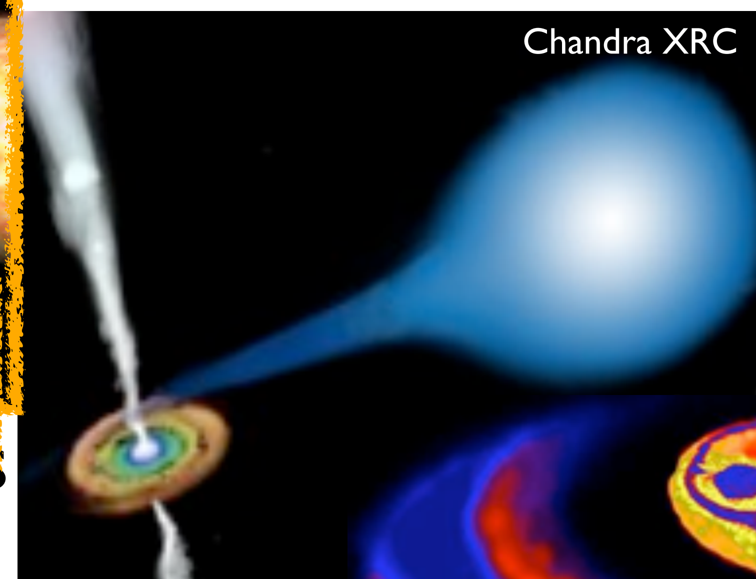

Black Hole Binaries

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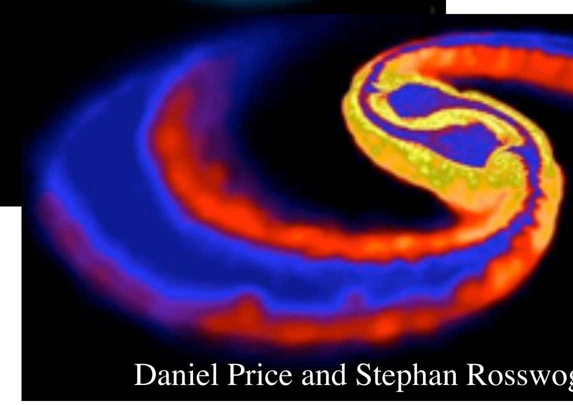

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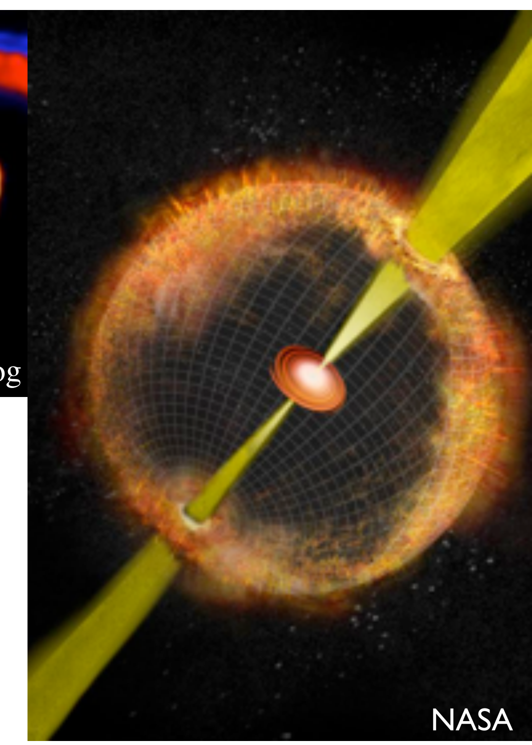

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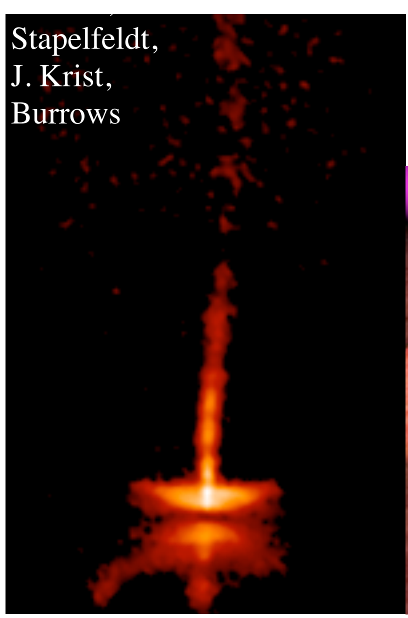

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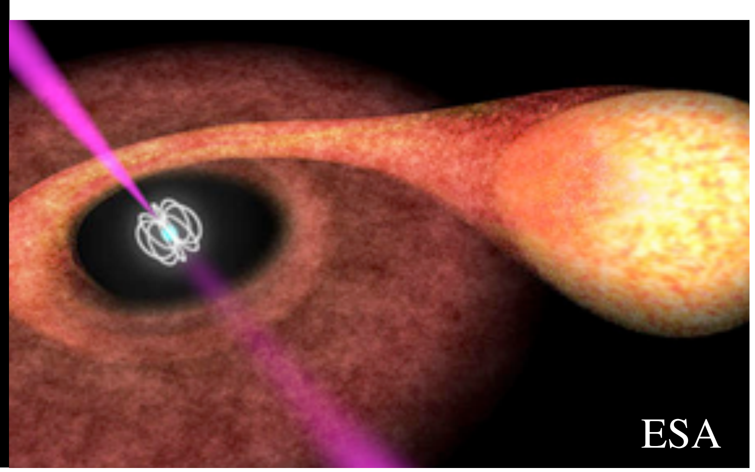

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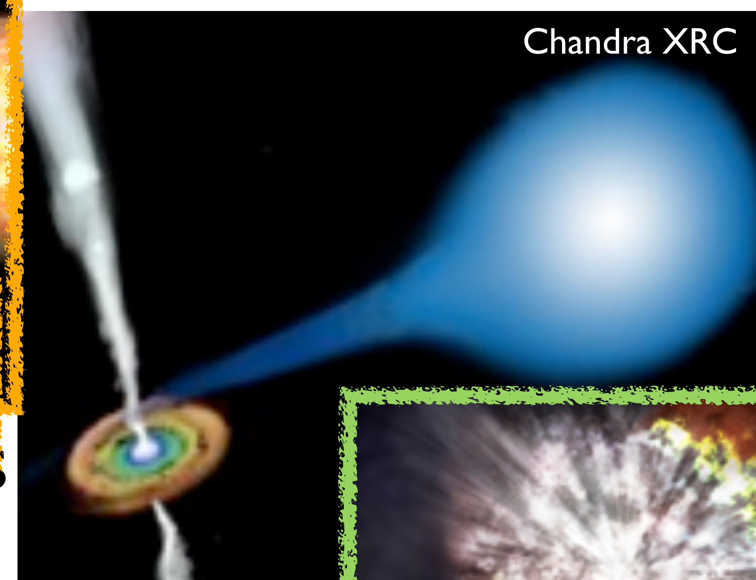
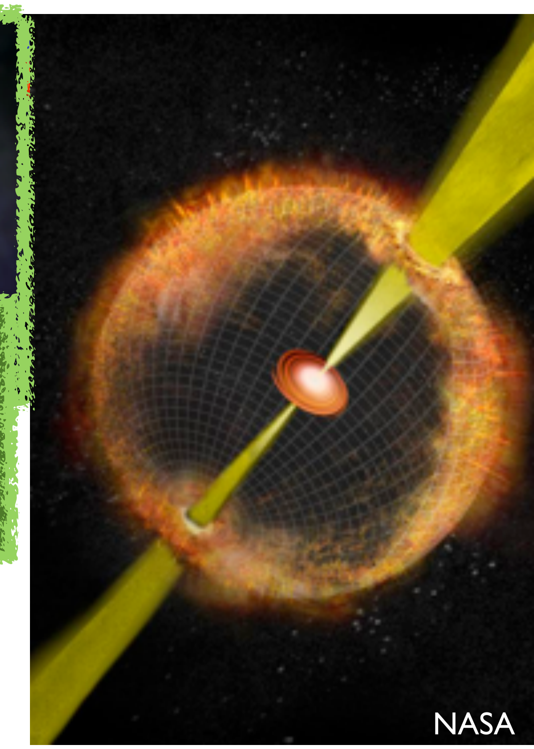


(AT 2015)

Black Hole Binaries

bursts



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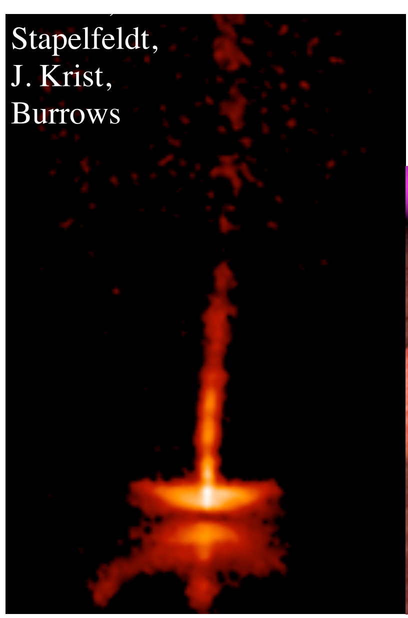
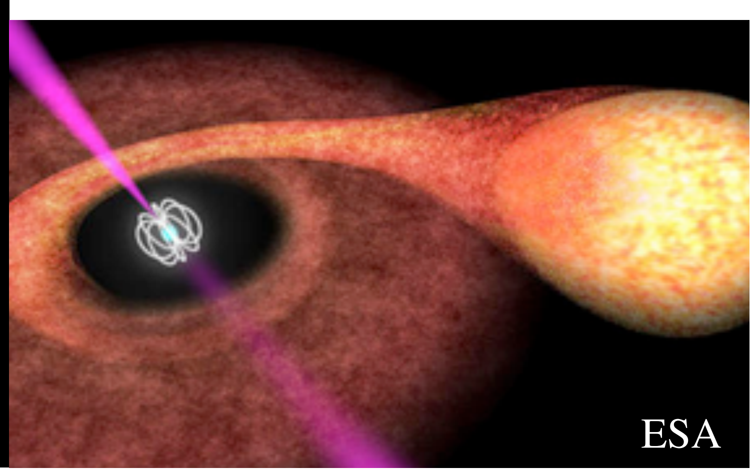


Stars



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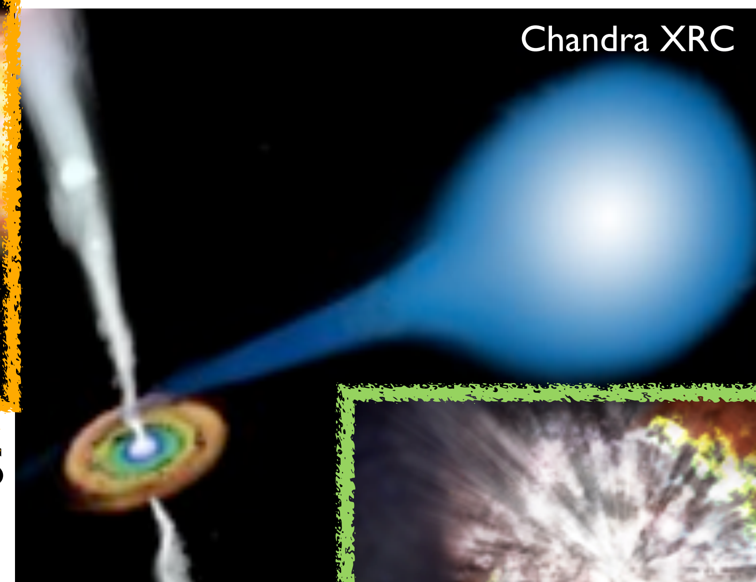


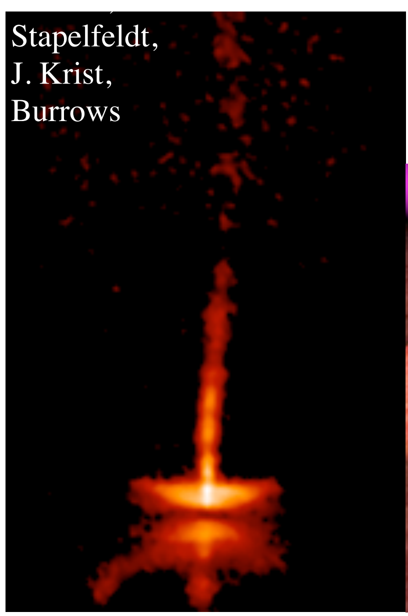
Black Hole Binaries

(AT 2015)

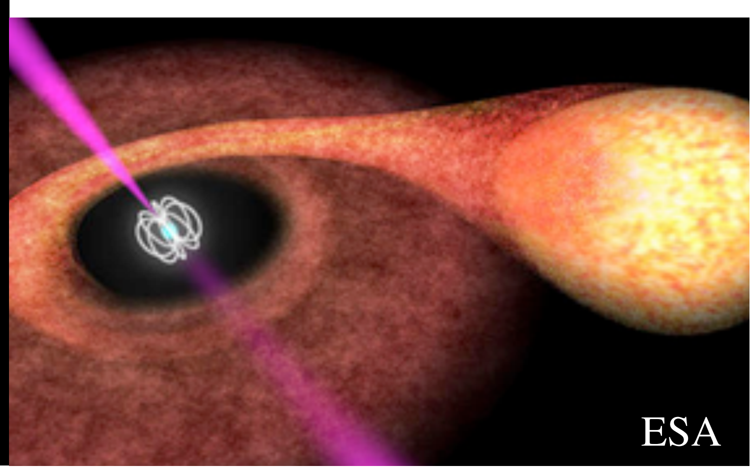
bursts

E

Neutron star



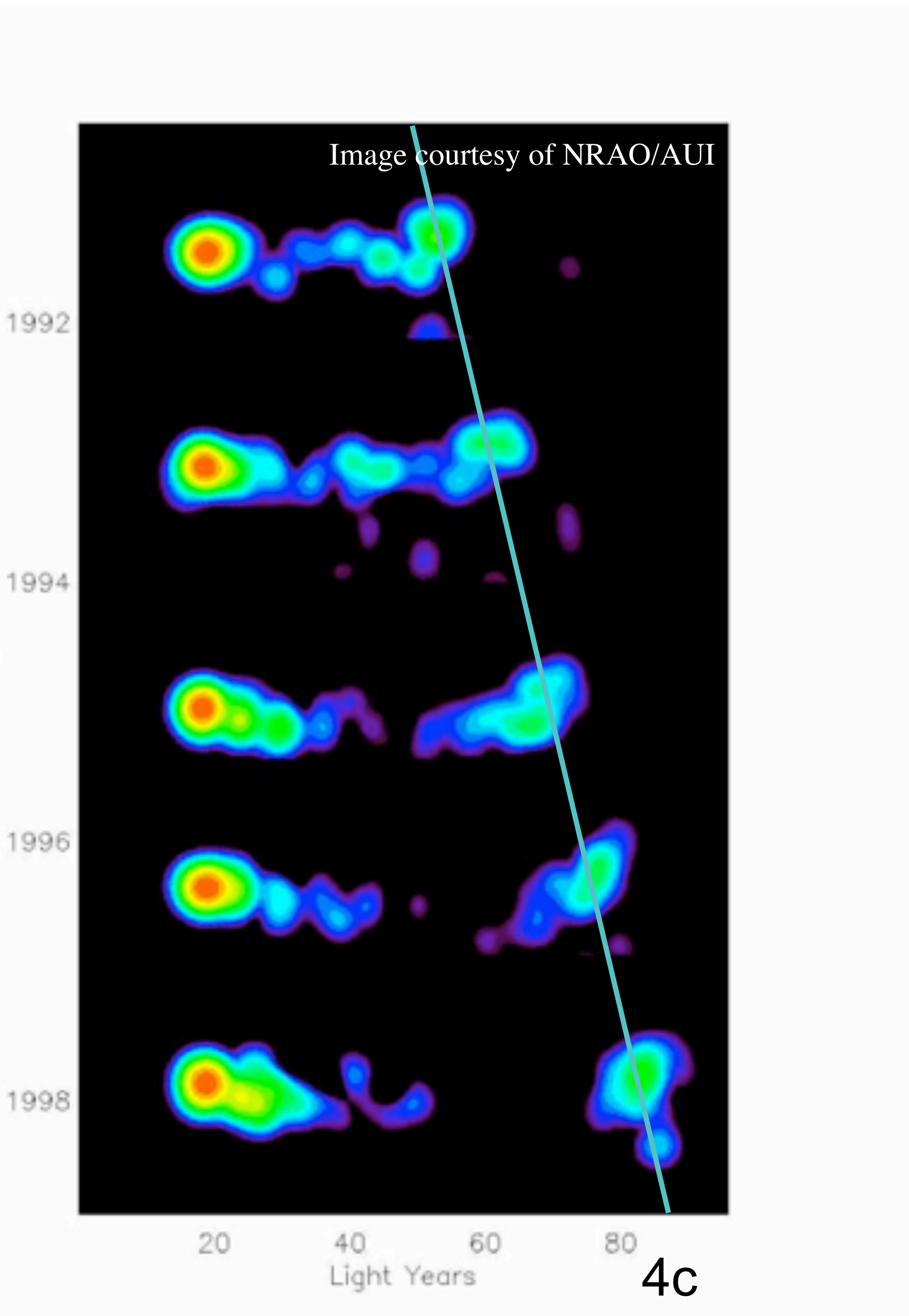
Stars



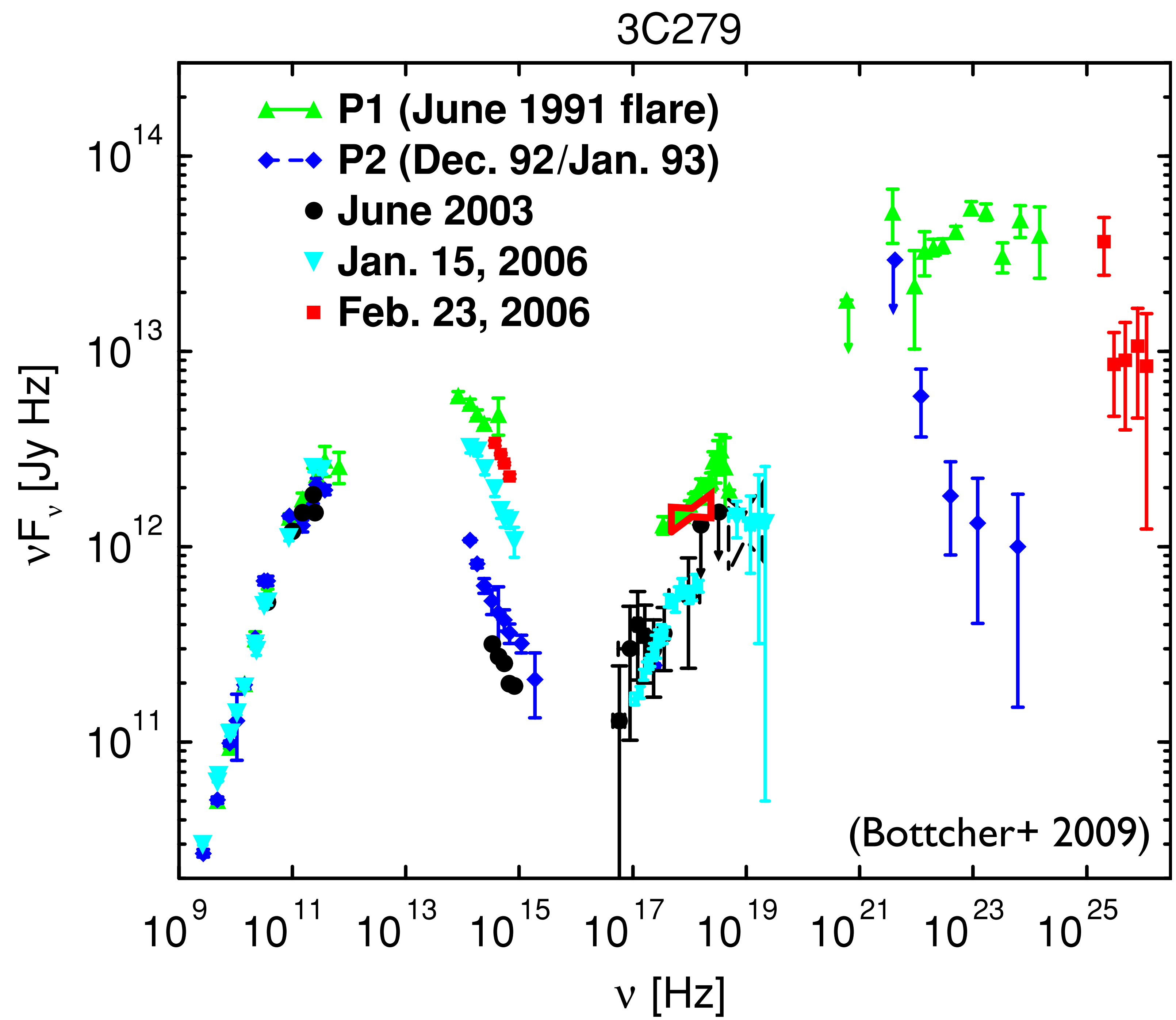
Neutron Stars, White Dwarfs; $M \sim M_\odot$

Jet Beaming Allows Observing Dim Sources

Active Galaxy with Jet Pointing at us: 3C279



$v \approx 0.997\, c$



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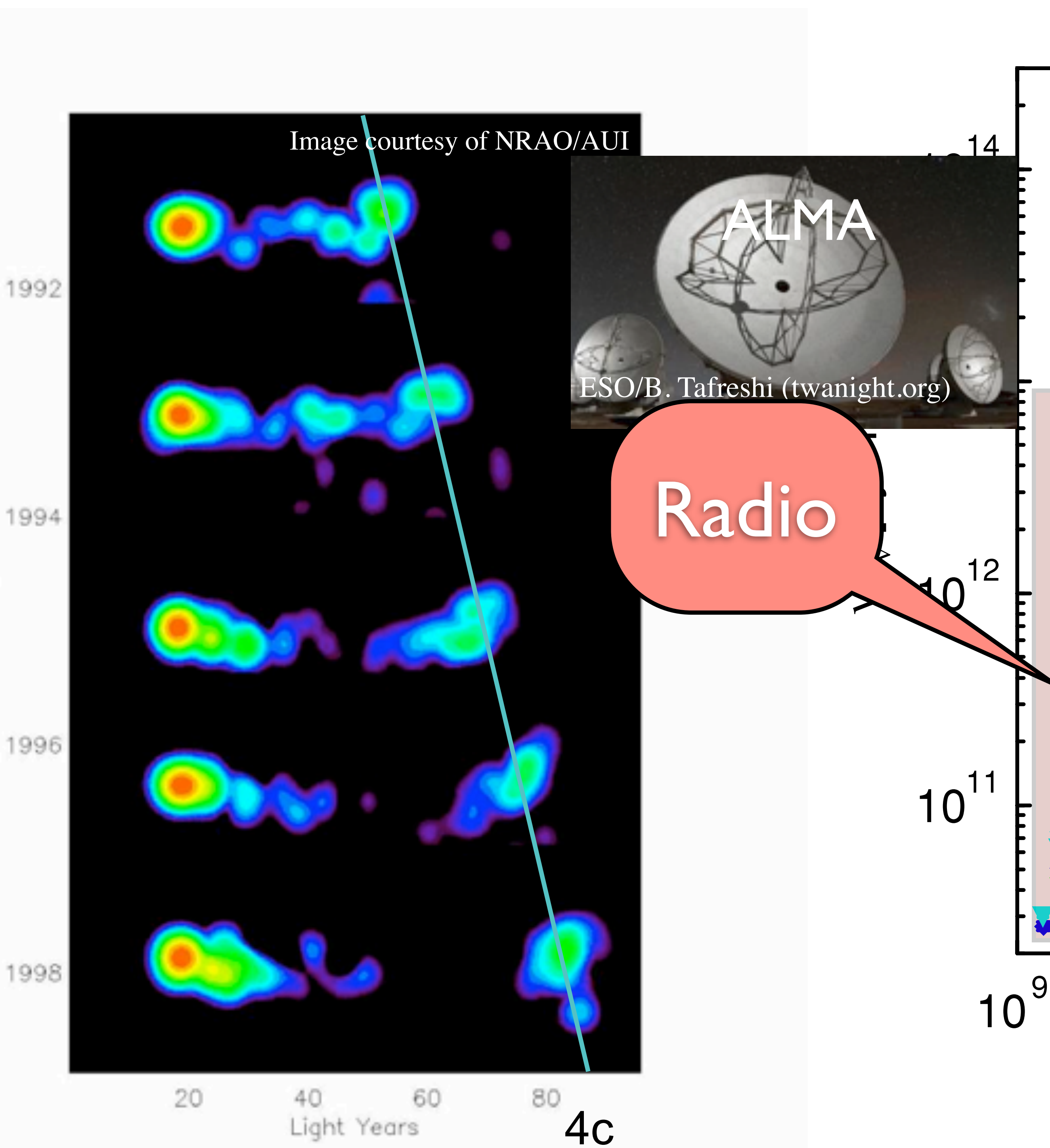

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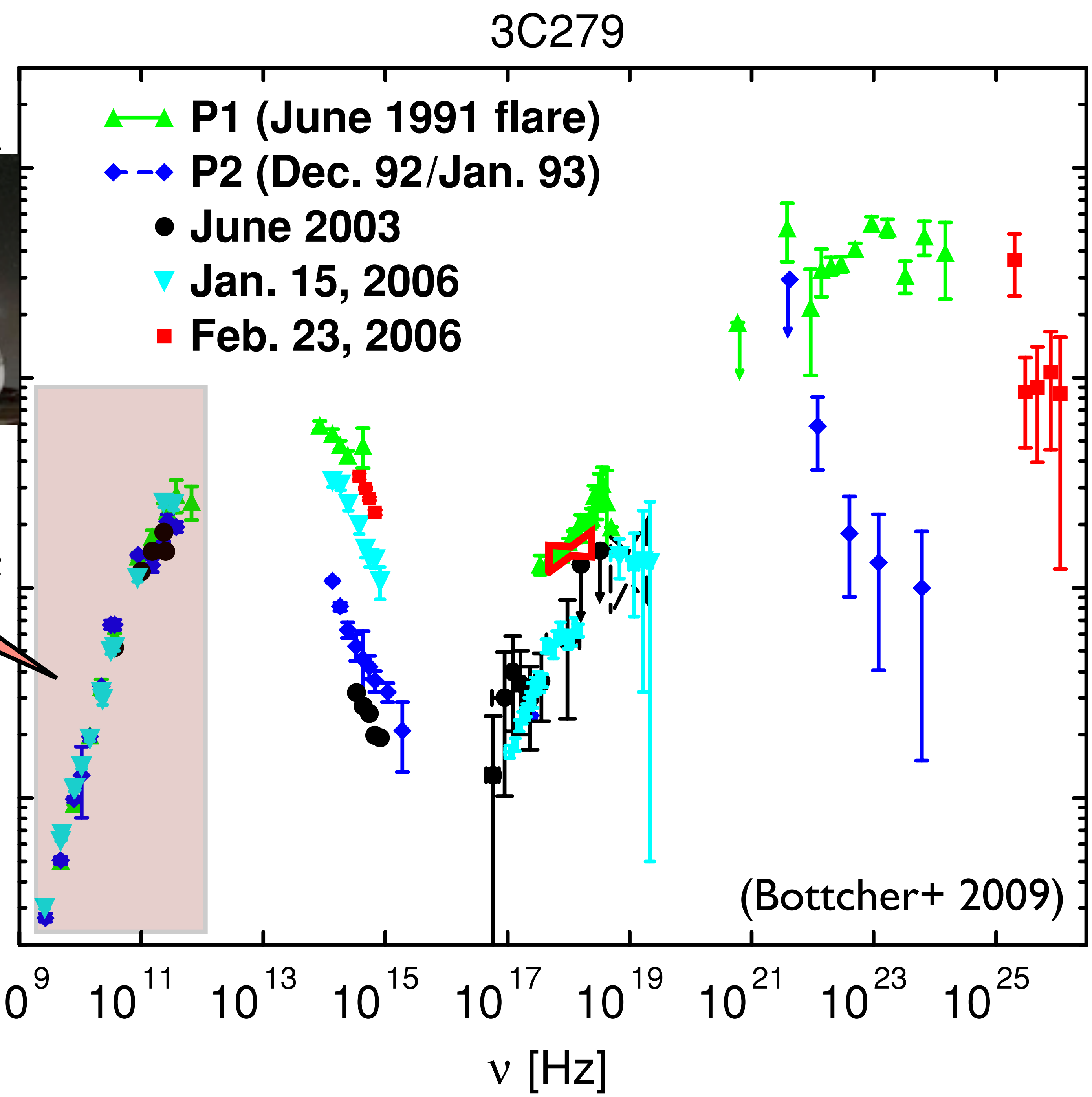

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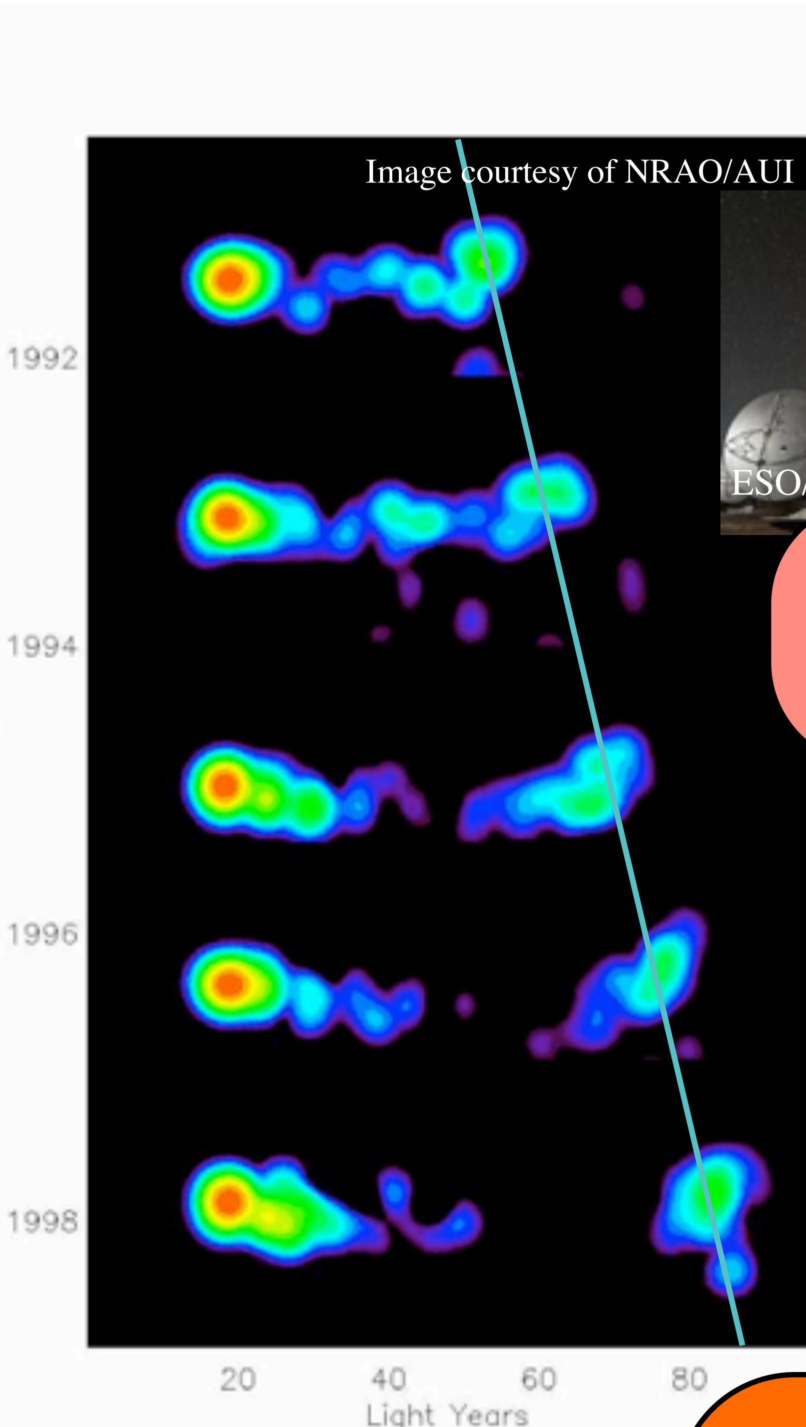

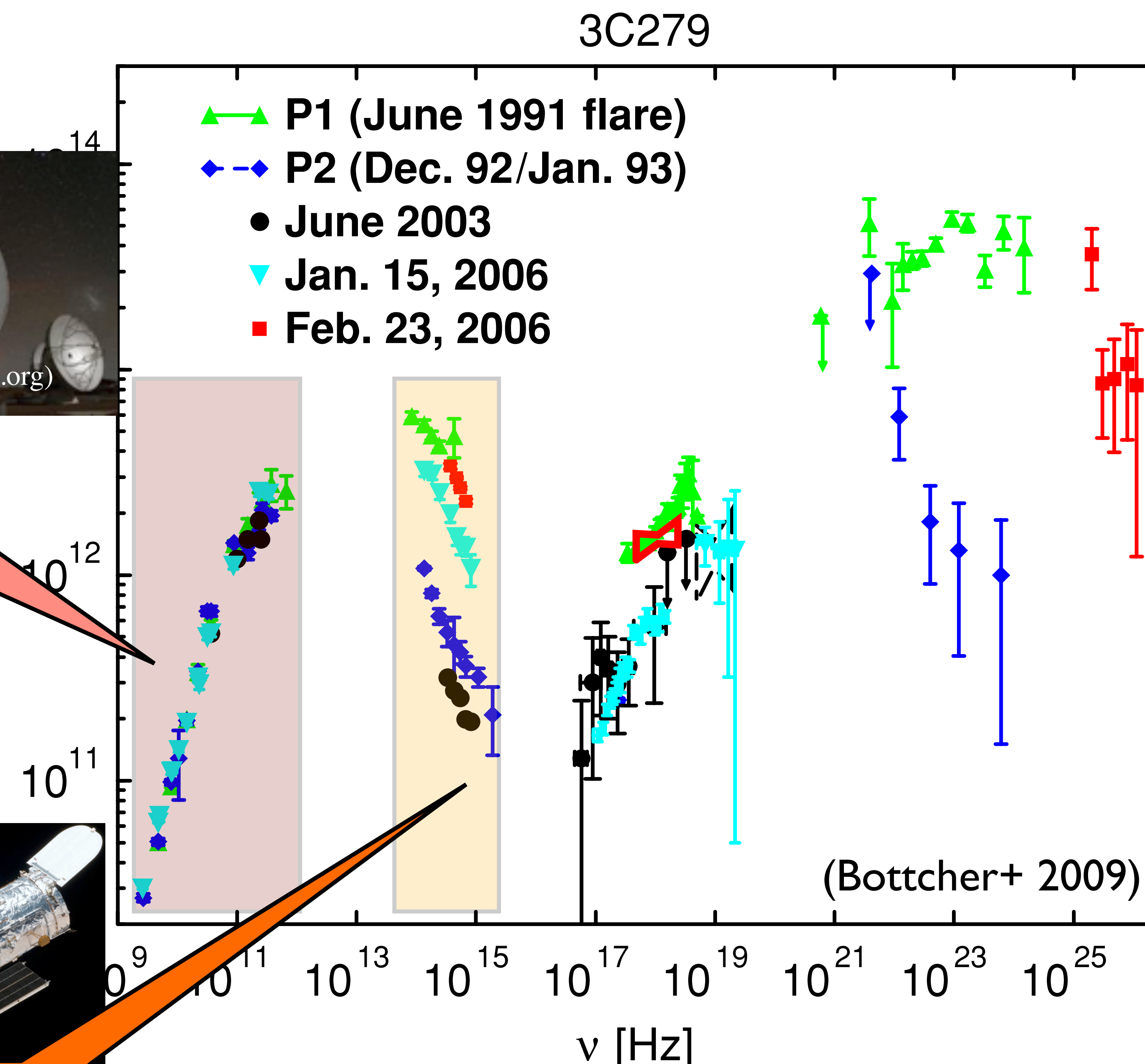

Radio

IR/Optical/UV

$v \approx 0.997\ c$

Jet Beaming Allows Observing Dim Sources

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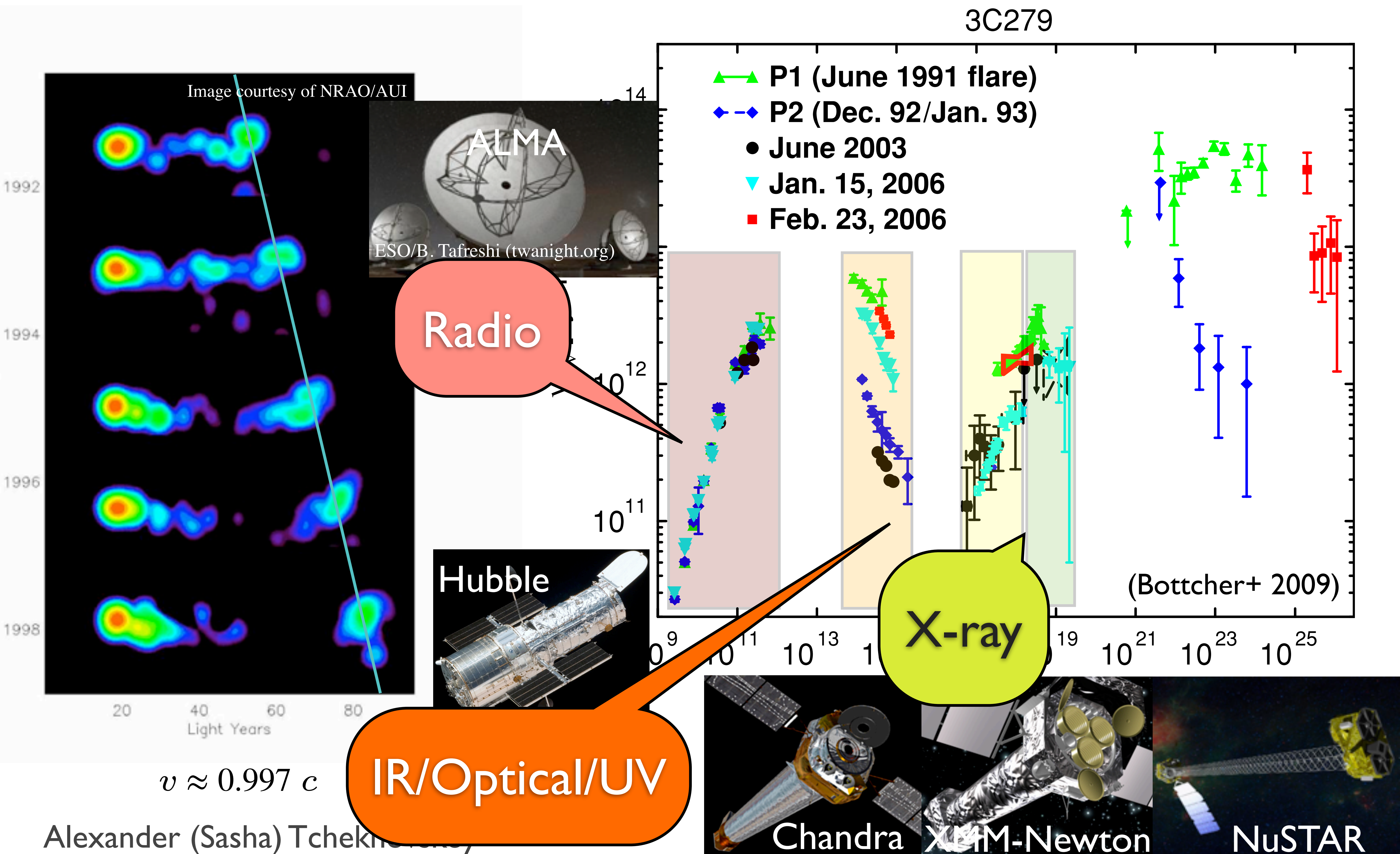
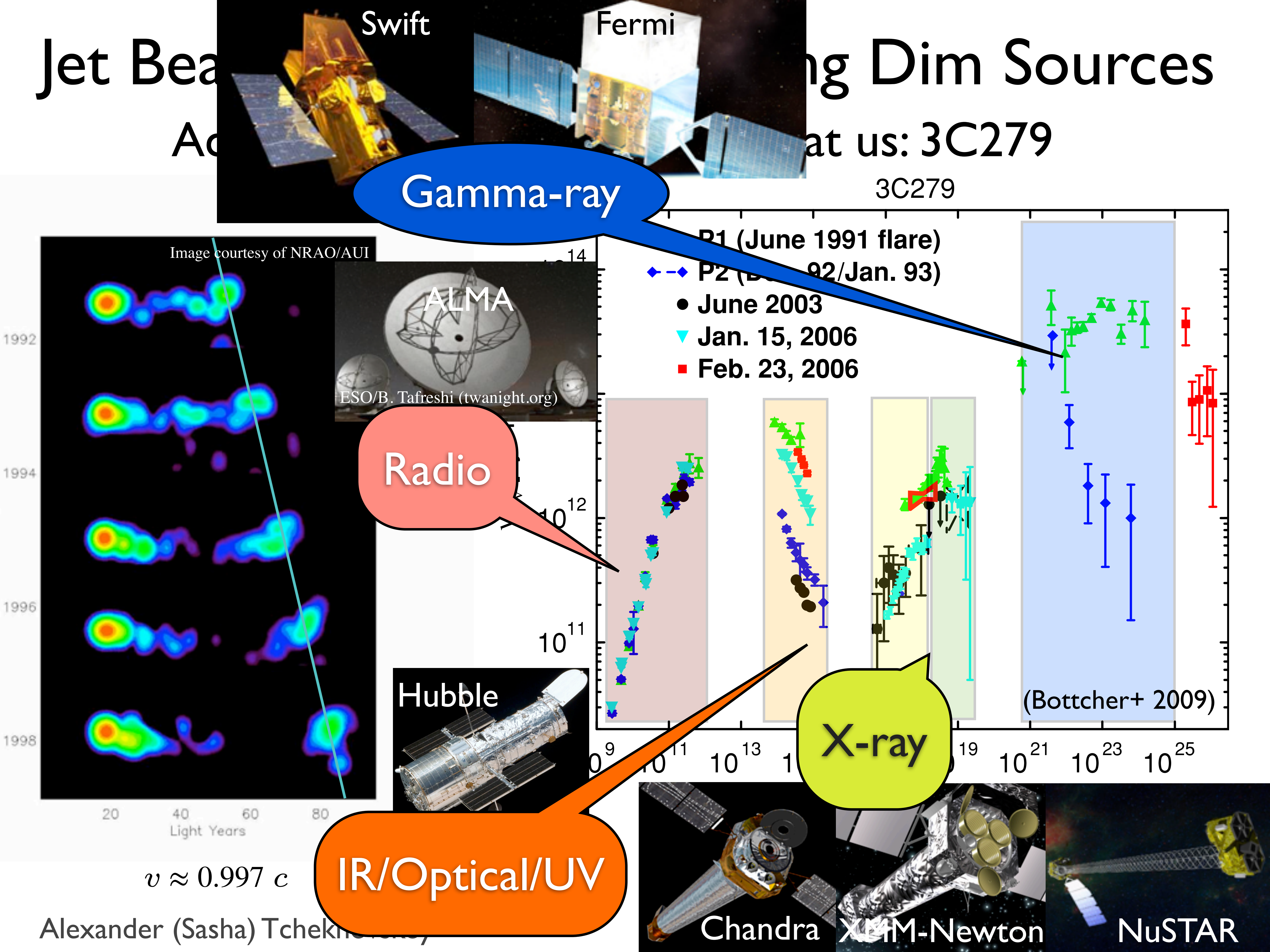
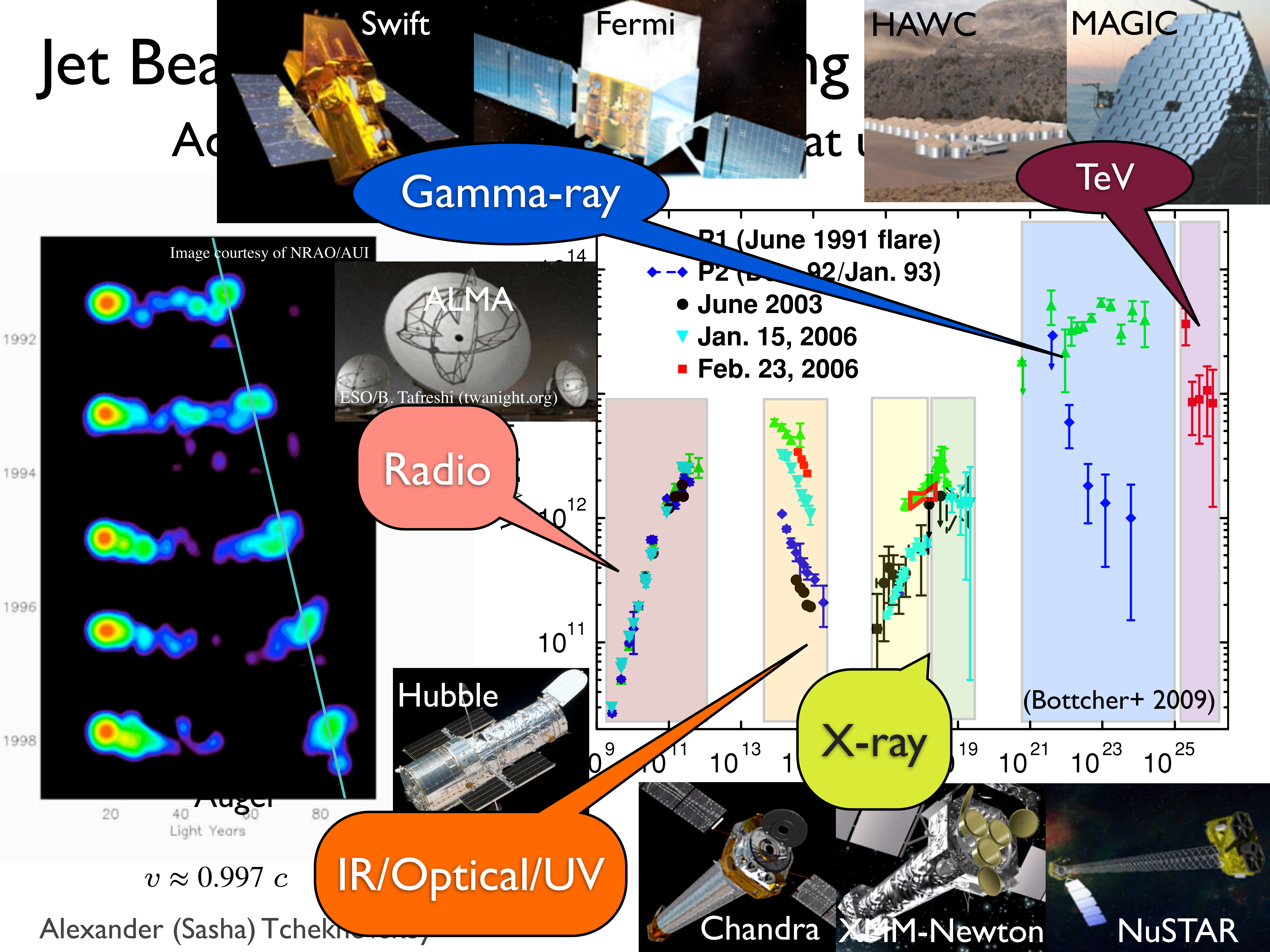


Alexander (Sasha) Tchekhovskoy

Jet Bea ng Dim Sources

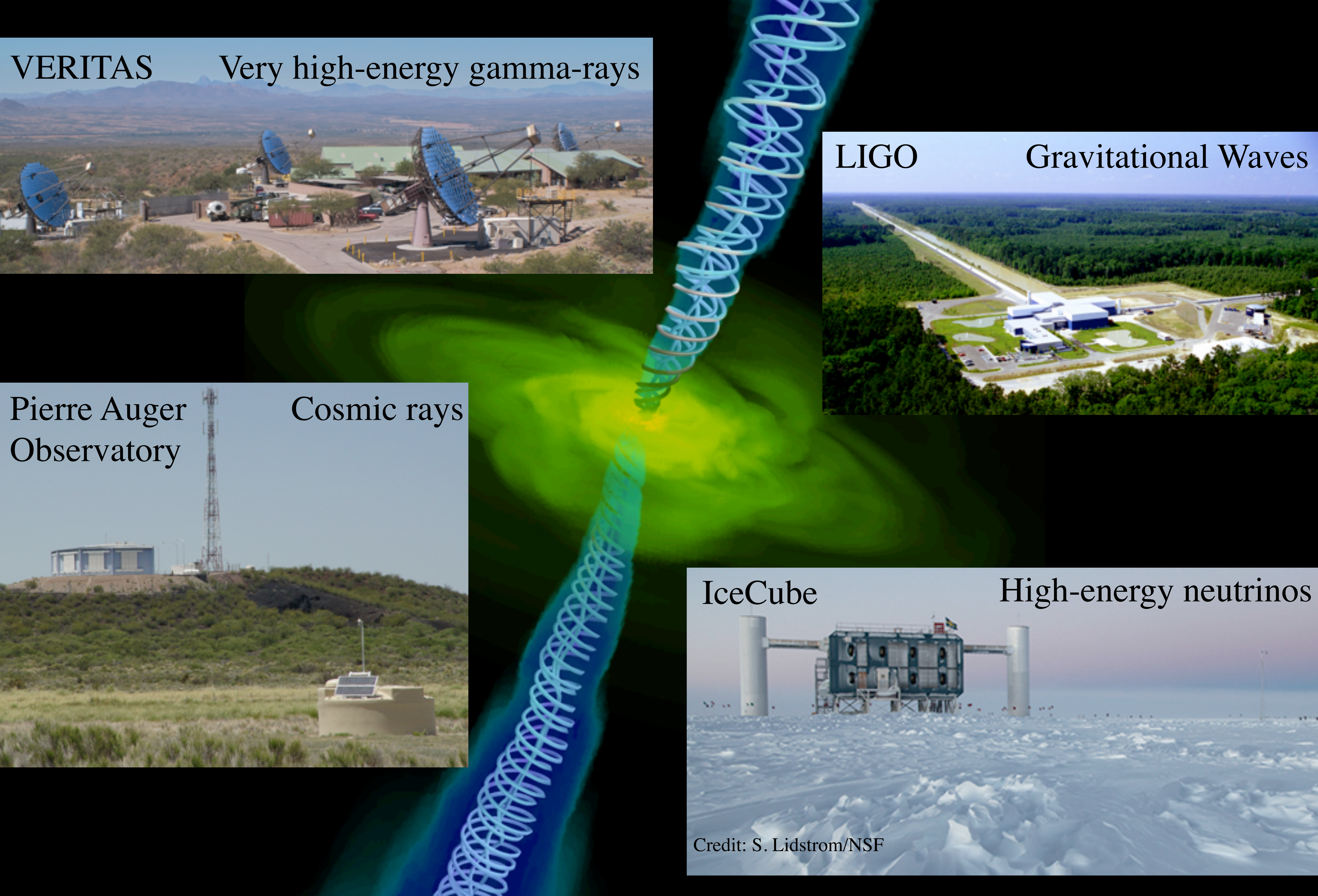
Ac at us: 3C279



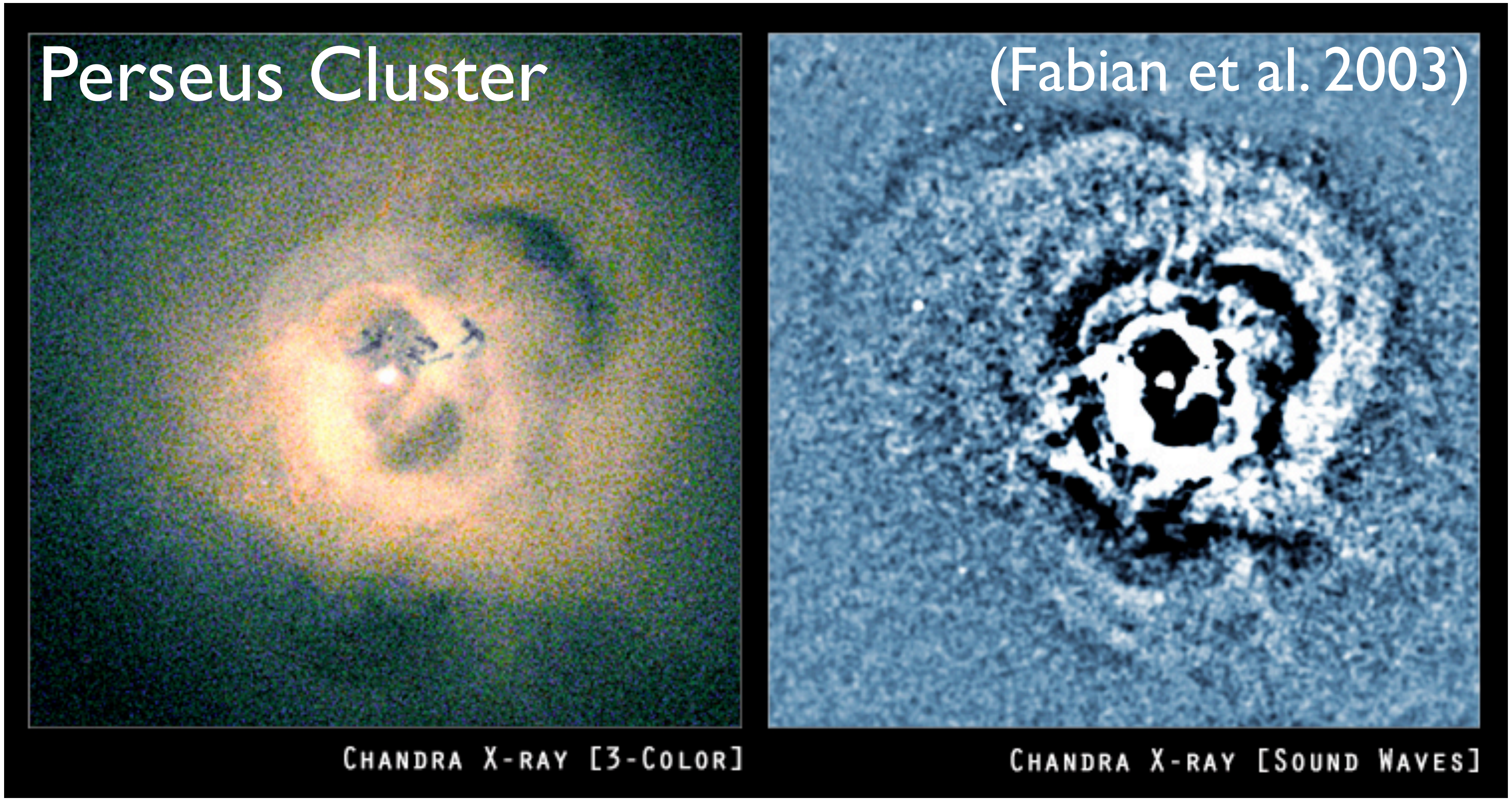


Jet Bea
ng
Ac
at u
Swift
Fermi
HAWC
MAGIC
Gamma-ray
TeV
Image courtesy of NRAO/AUI
ALMA
ESO/B. Tafreshi (twanight.org)
Radio
1992
1994
1996
1998
20
40
80
Light Years
Hubble
$v \approx 0.997\ c$
IR/Optical/UV
X-ray
P1 (June 1991 flare)
P2
92/Jan. 93)
June 2003
Jan. 15, 2006
Feb. 23, 2006
10^{14}
10^{12}
10^{11}
10^{11}
10^{13}
10^{19}
10^{21}
10^{23}
10^{25}
(Bottcher+ 2009)
Chandra
XMM-Newton
NuSTAR
Alexander (Sasha) Tchek

Jets Enable Multimessenger Astronomy with Black Holes



Jets Affect Galaxies/Clusters



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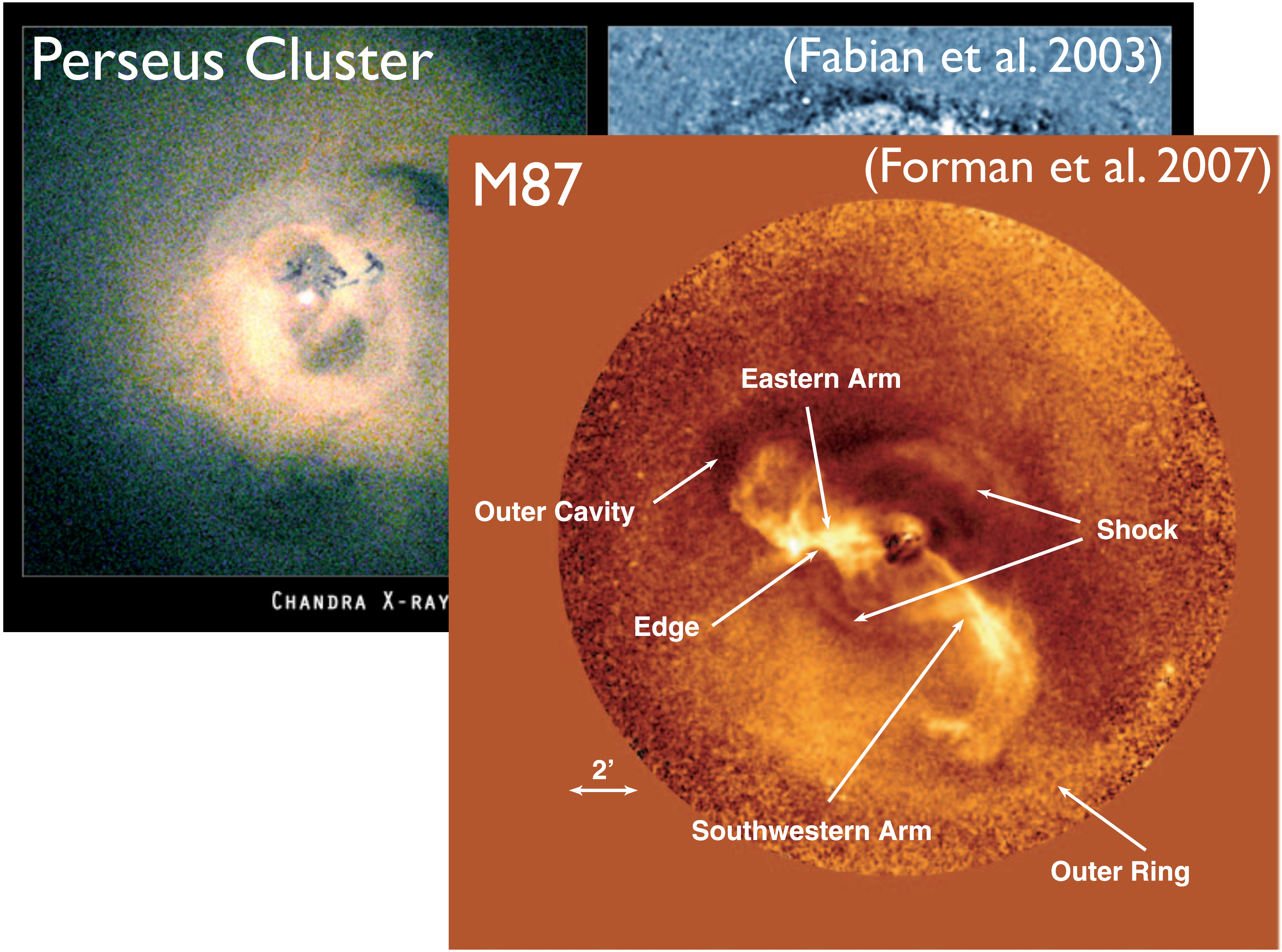

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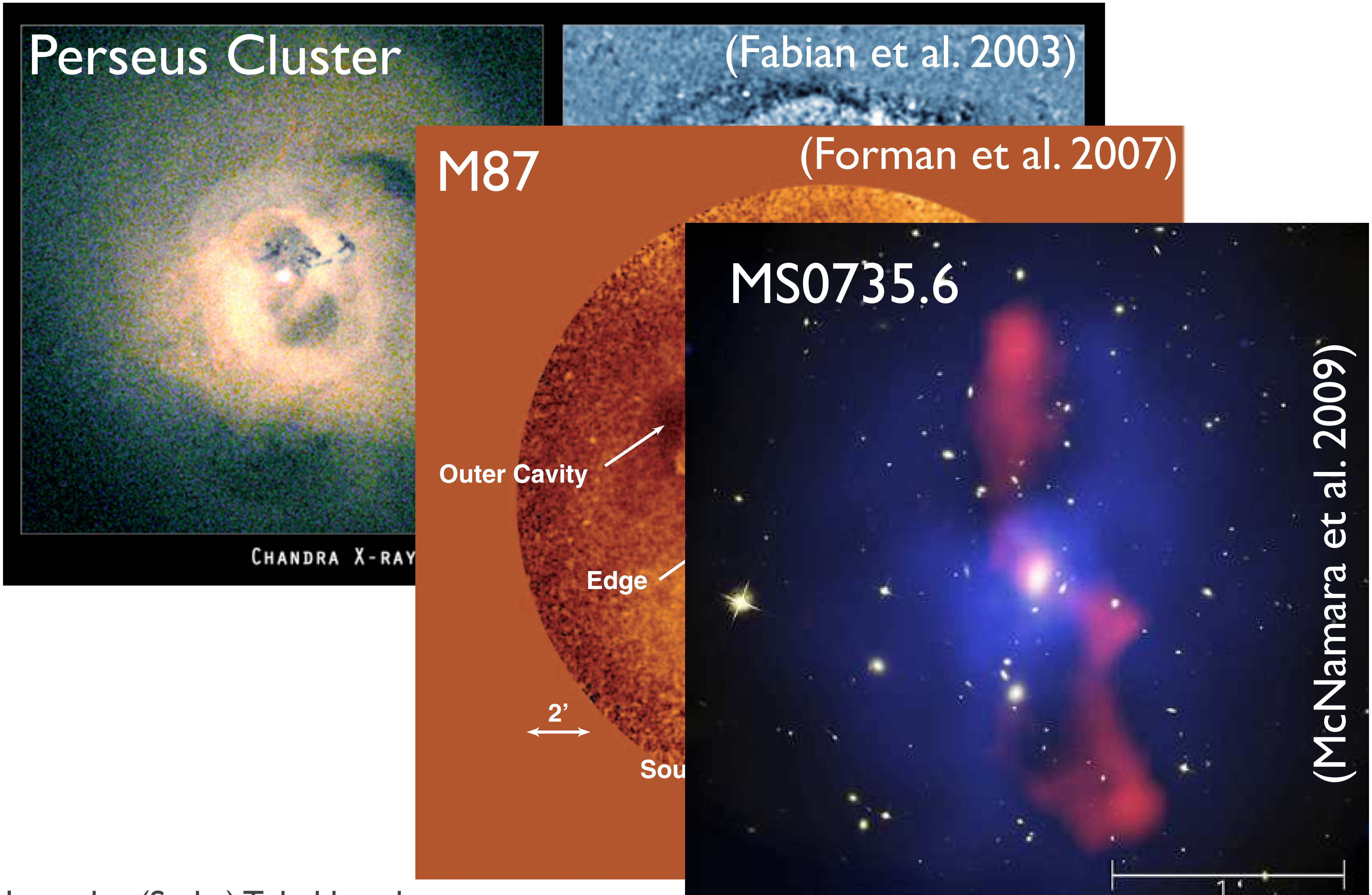
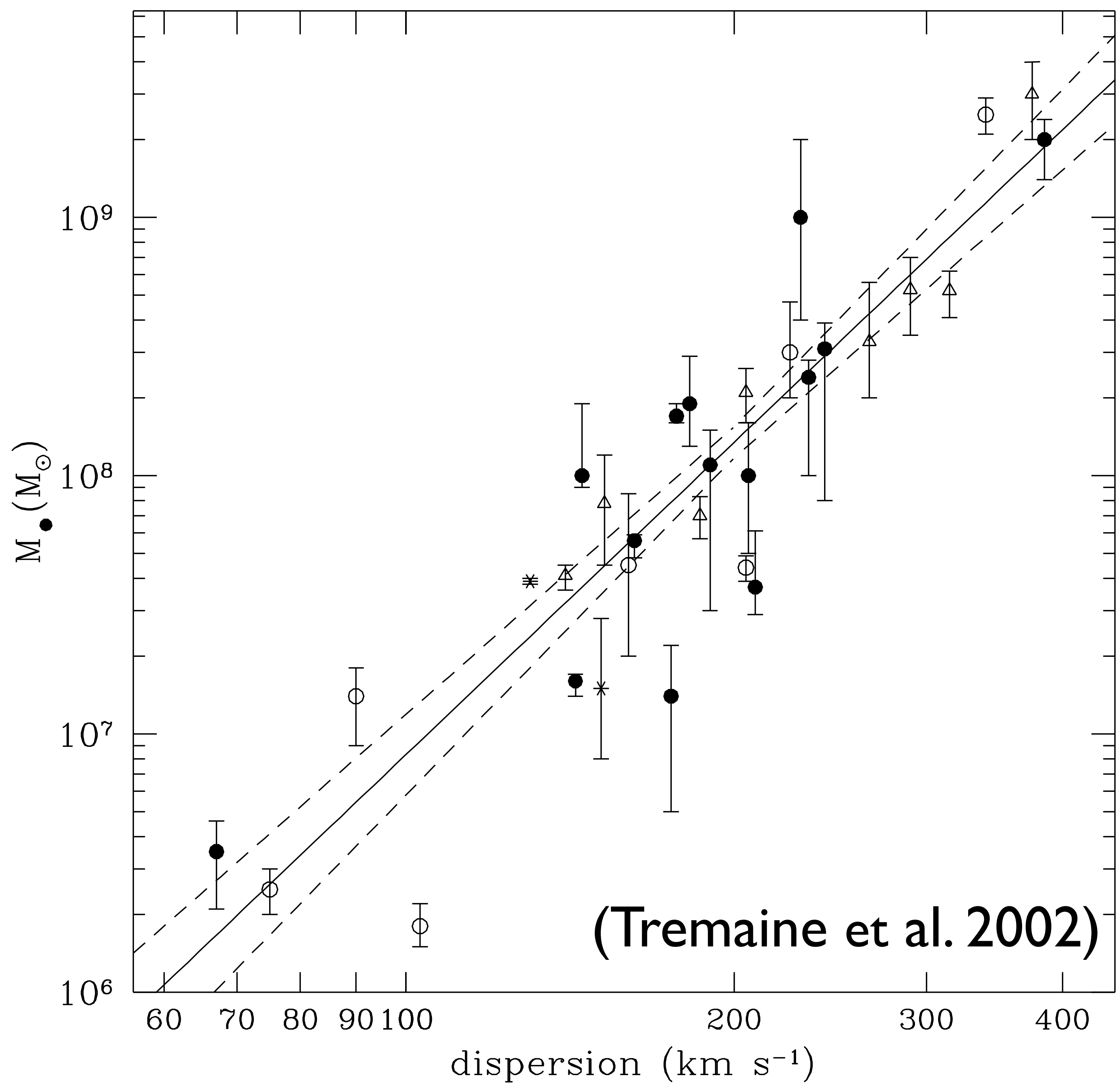


Jets Affect Galaxies/Clusters

"M-sigma" relation: BH mass and stellar velocity dispersion are correlated

- Growth of the central BHs and their host galaxies are inter-connected
- Jet feedback?
- Radiative feedback?

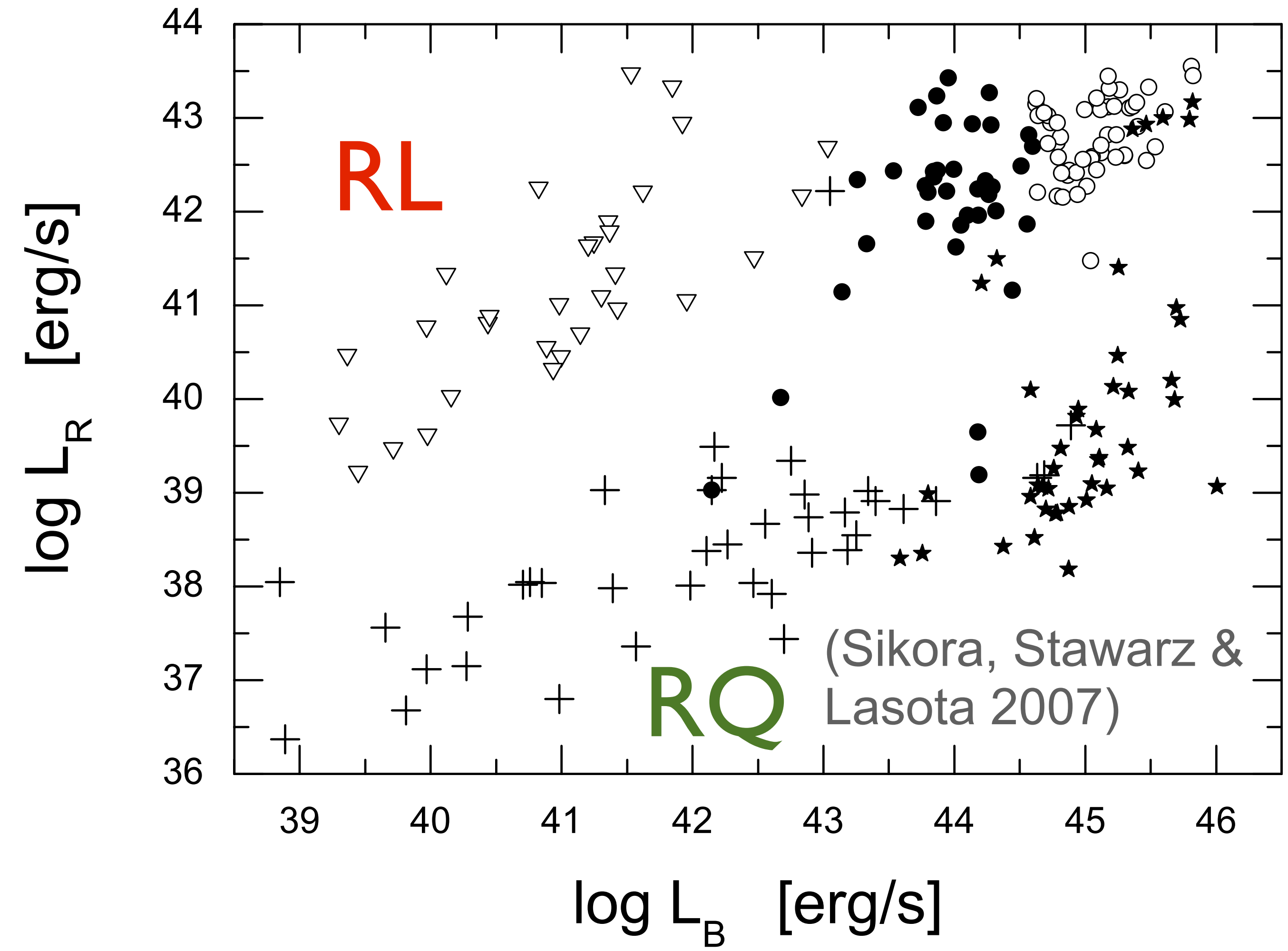


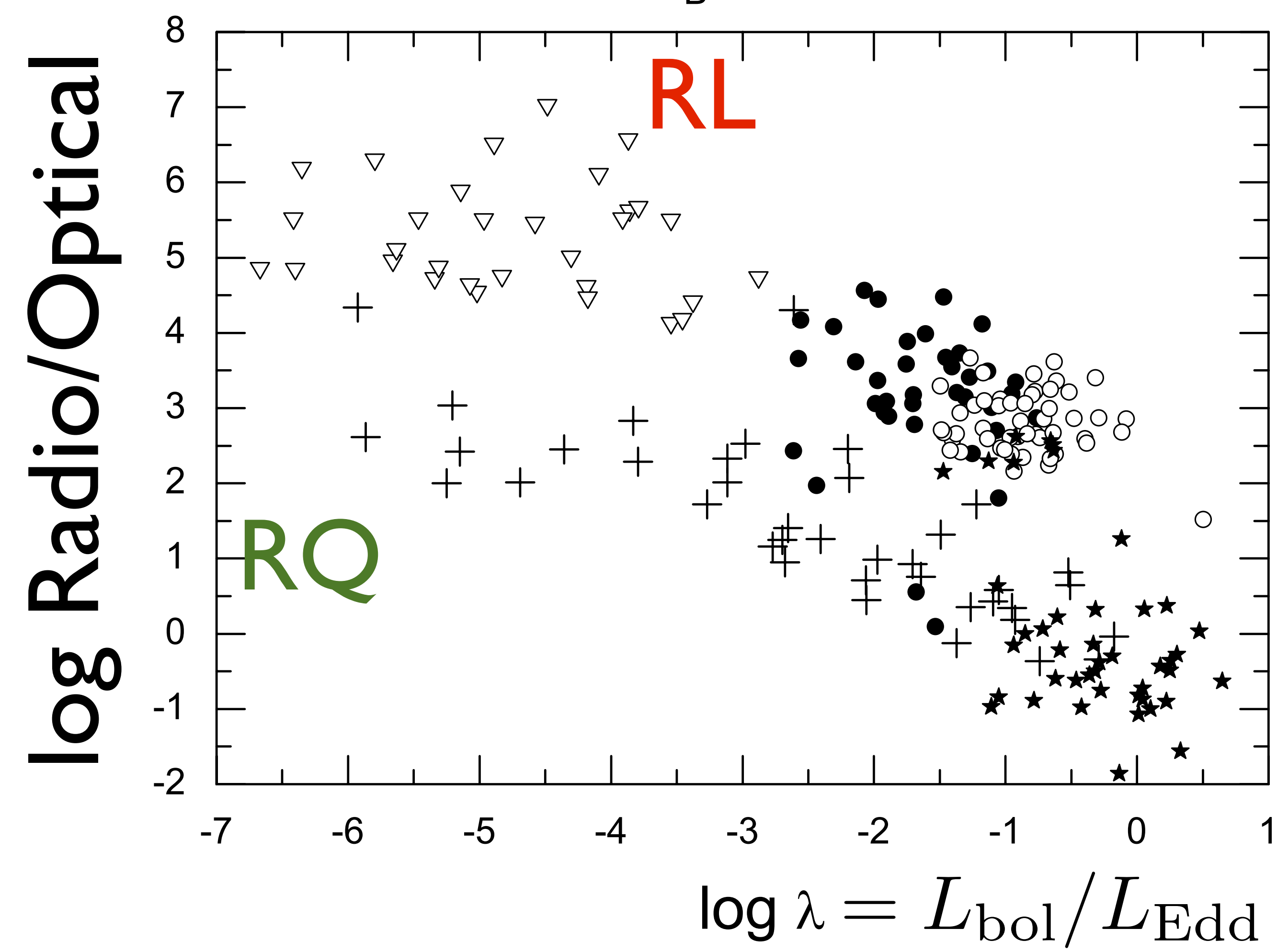
AGN Radio Loud/Quiet Dichotomy

- Factor of 1000 difference in radio luminosity.
- There must be at least one other parameter in addition to M and $\dot{M}$:

$$P_{\rm jet}(M, \dot{M}; ??)$$

- Magnetic flux?
  Ambient medium? (Broderick & Fender 2012)
  BH spin? (Blandford 1990, Tchekhovskoy et al. 2010)

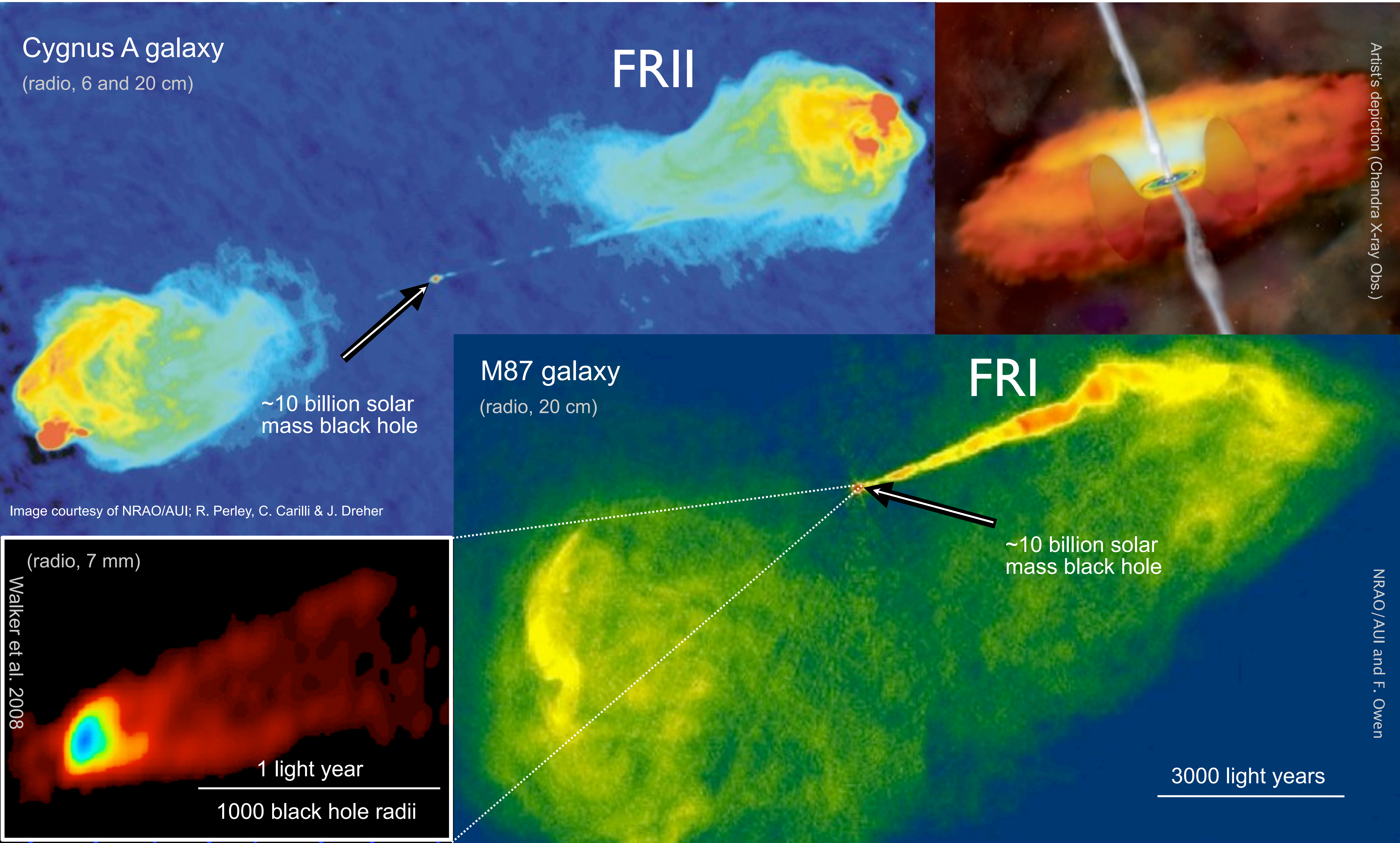




Alexander (Sasha) Tchekhovskoy

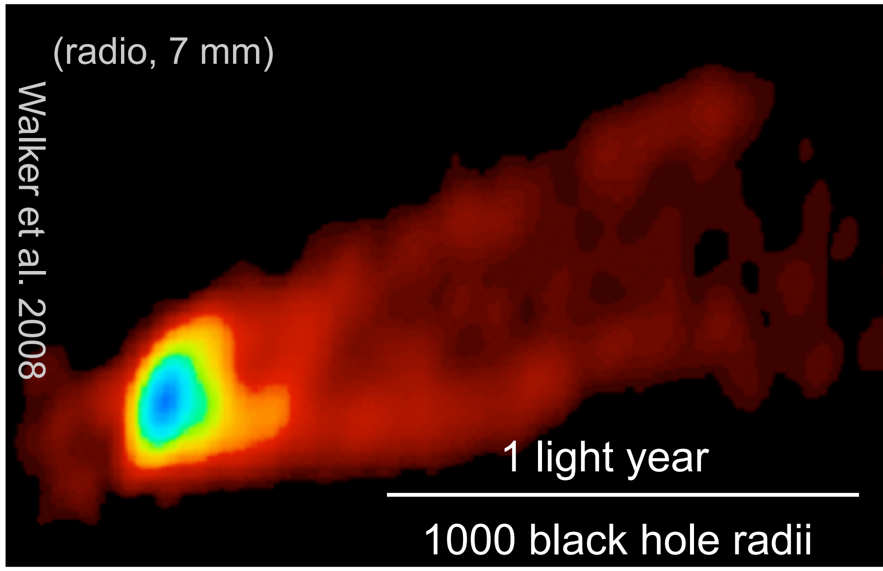
Jets: Beautiful and Challenging

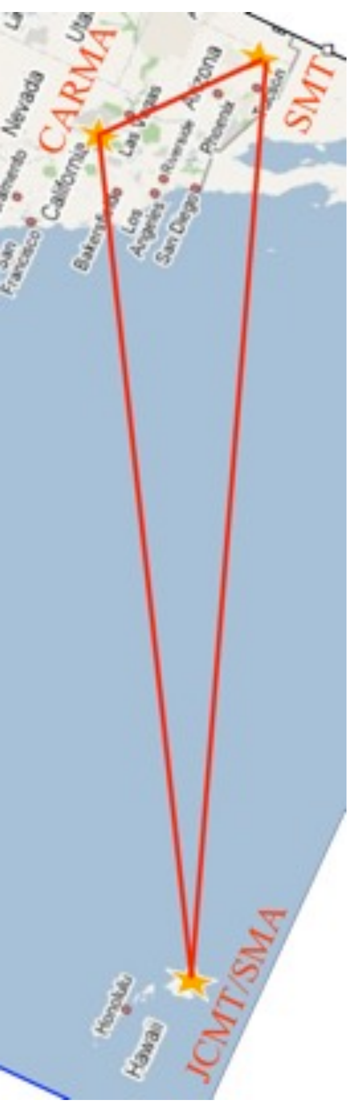
FRI/FRII dichotomy (Fanaroff & Riley, 1974)

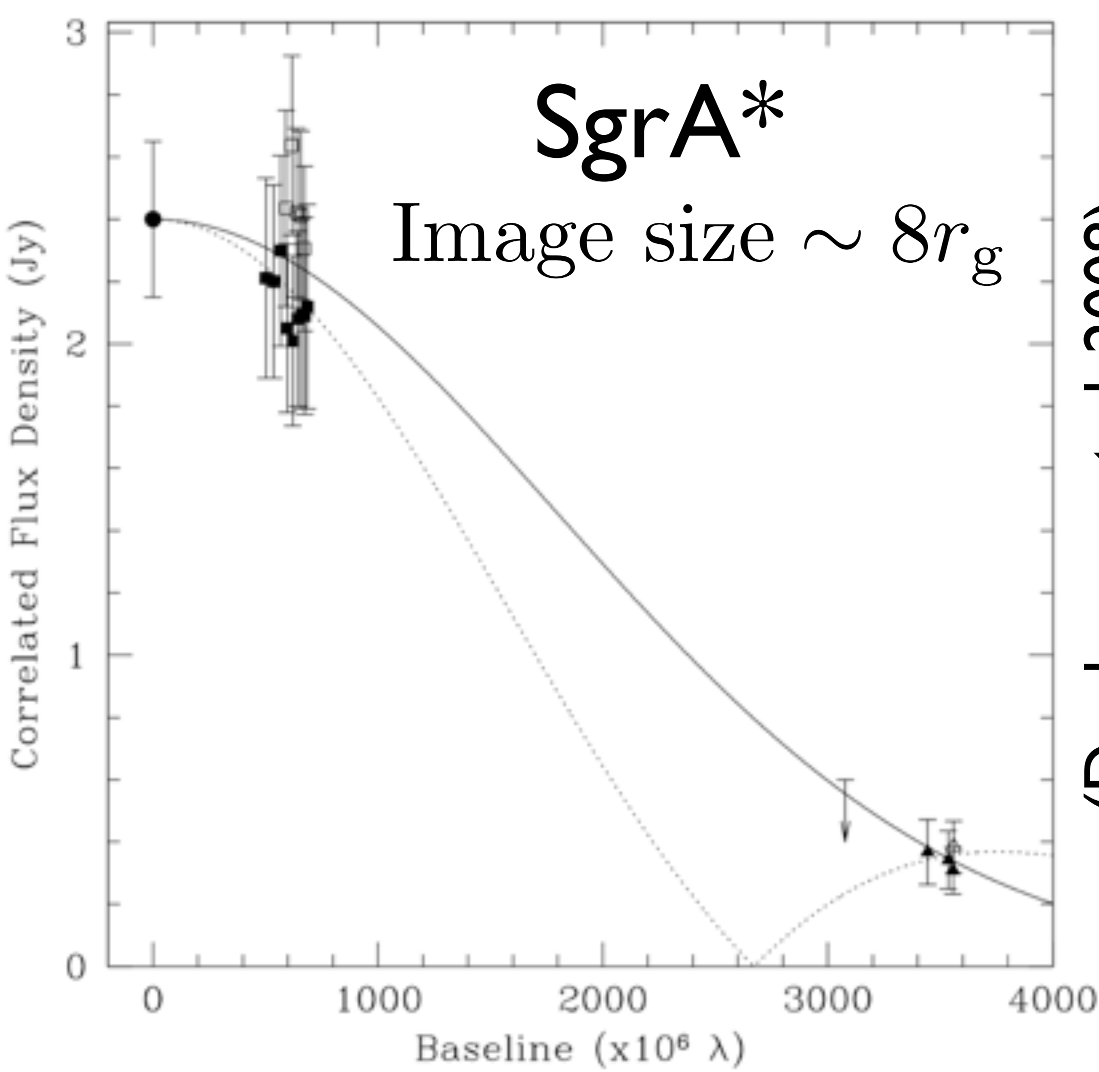


Event Horizon Telescope (*EHT*): VLBI images of Black Holes

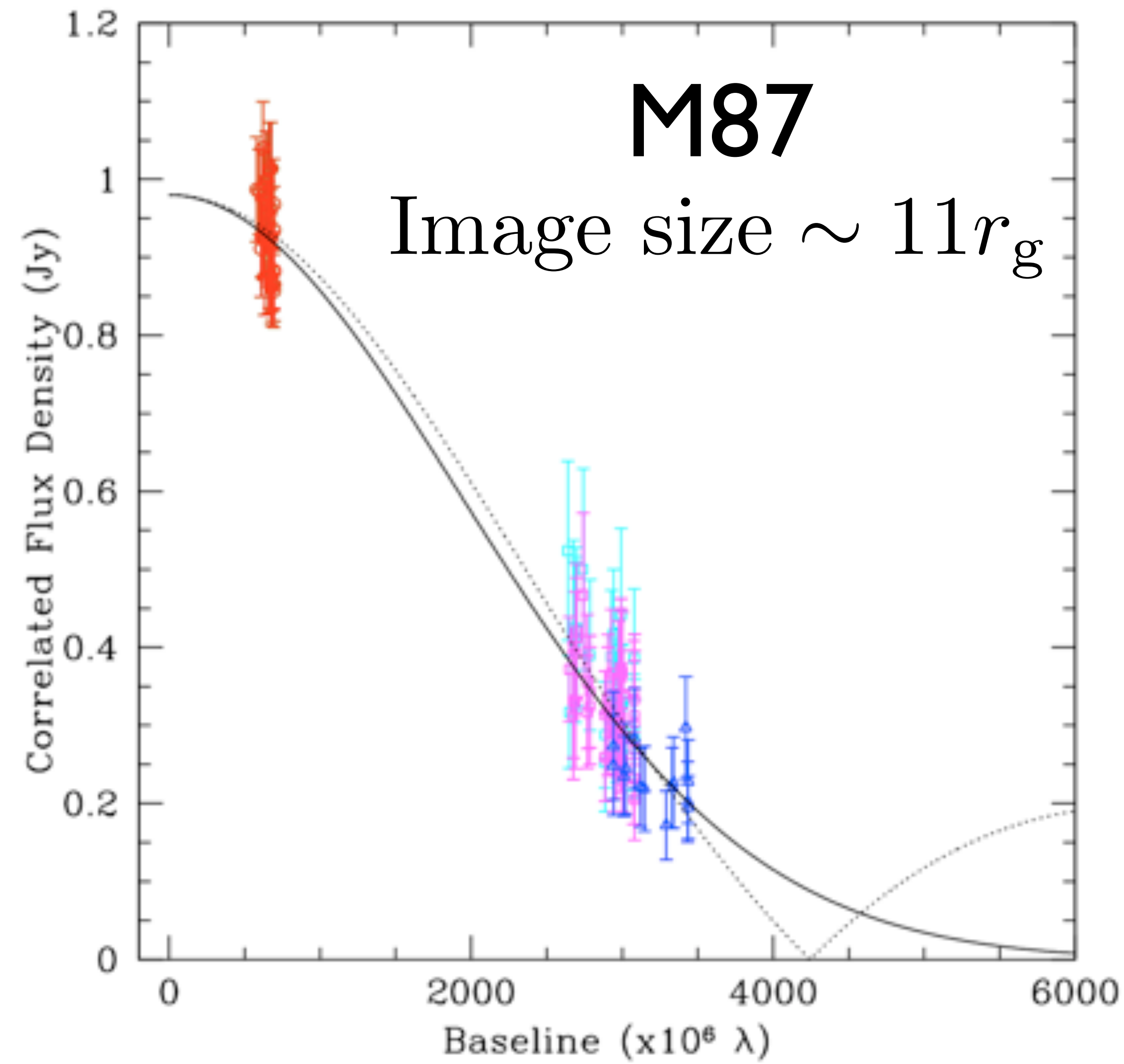
- Two largest black holes on the sky
- Data is interpretation limited!







(Doeleman et al. 2008)



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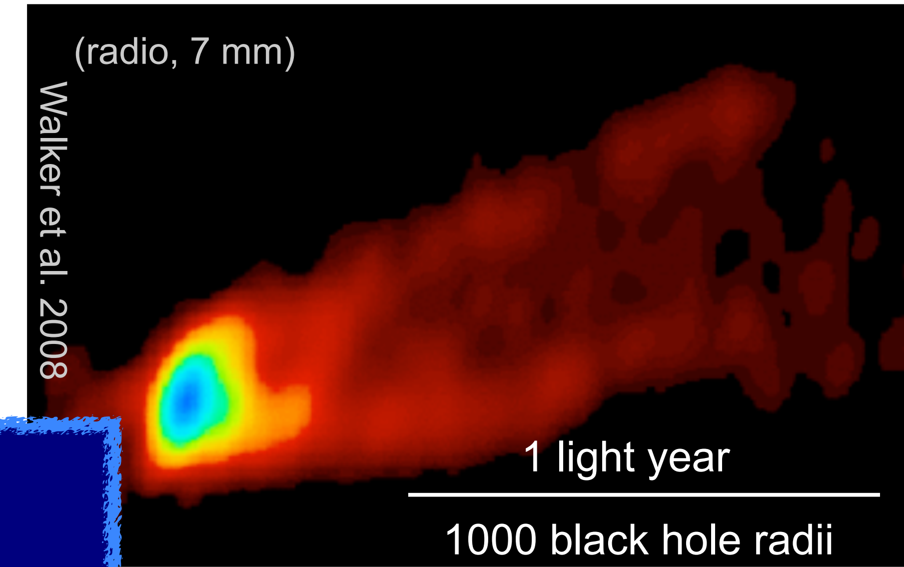

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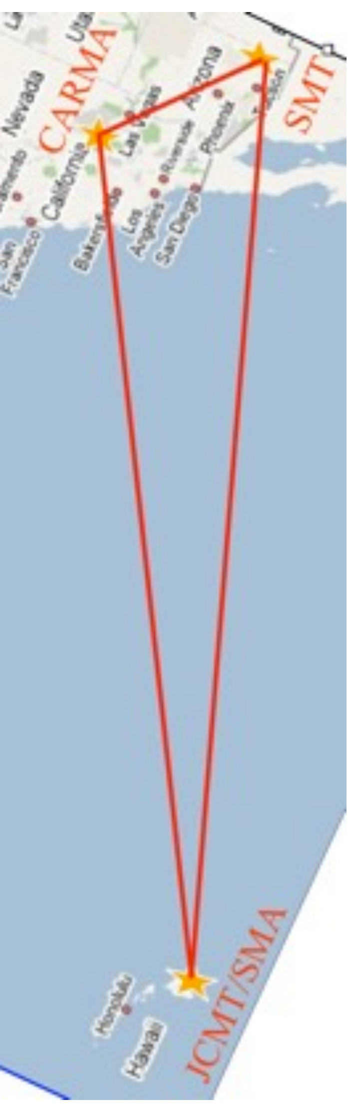
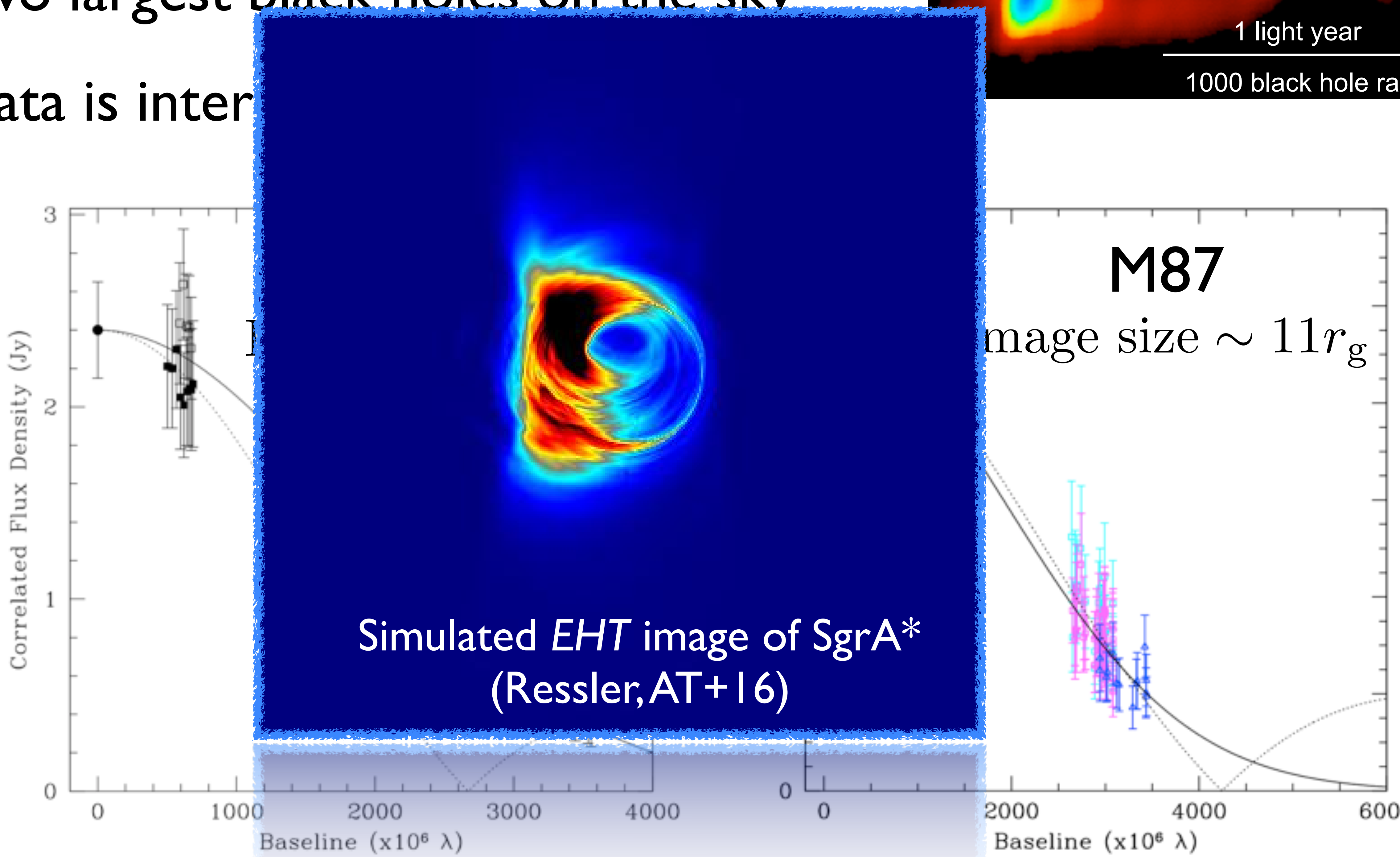
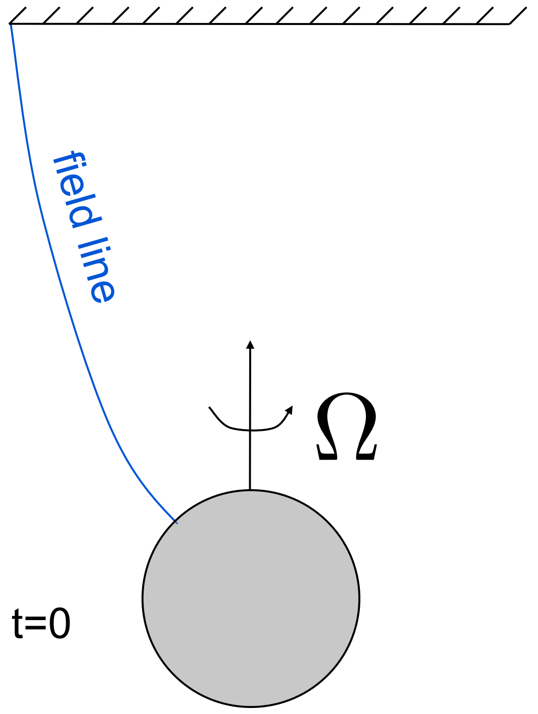


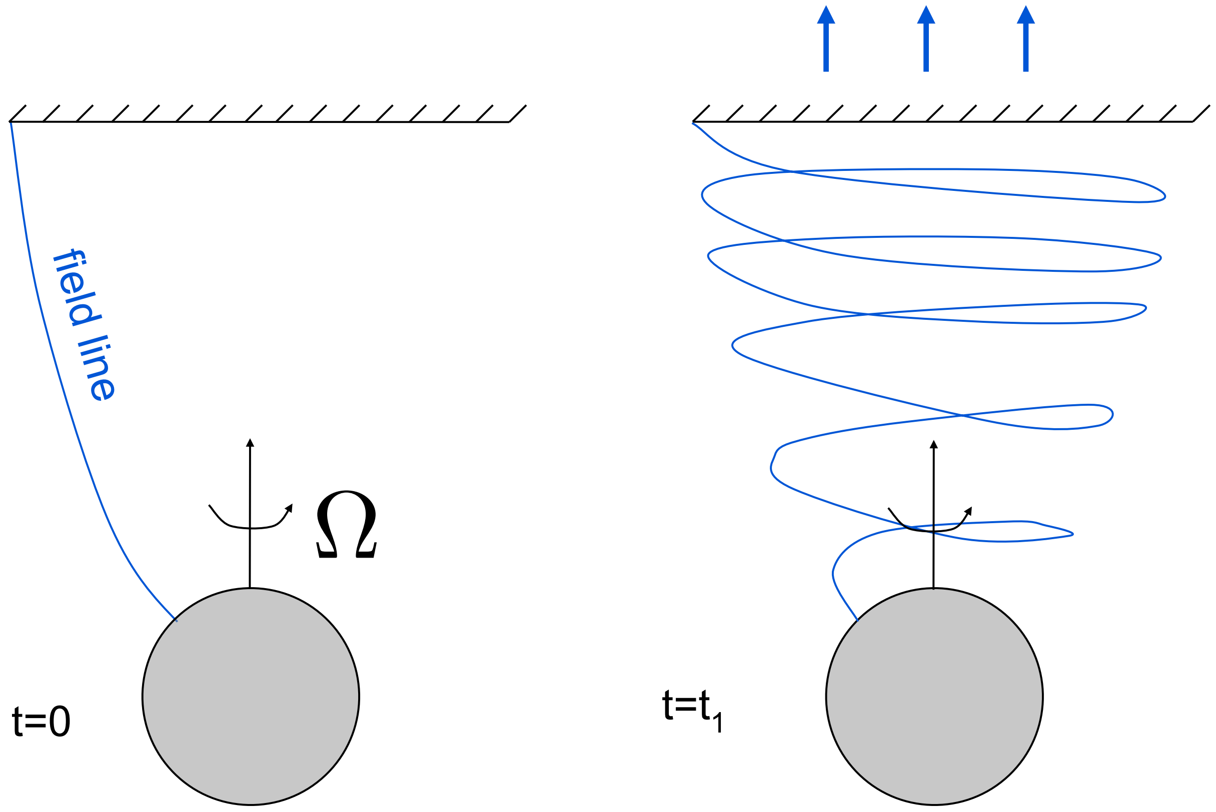


Jets 101



Jets 101

$$P = \frac{B_\varphi^2}{8\pi}$$



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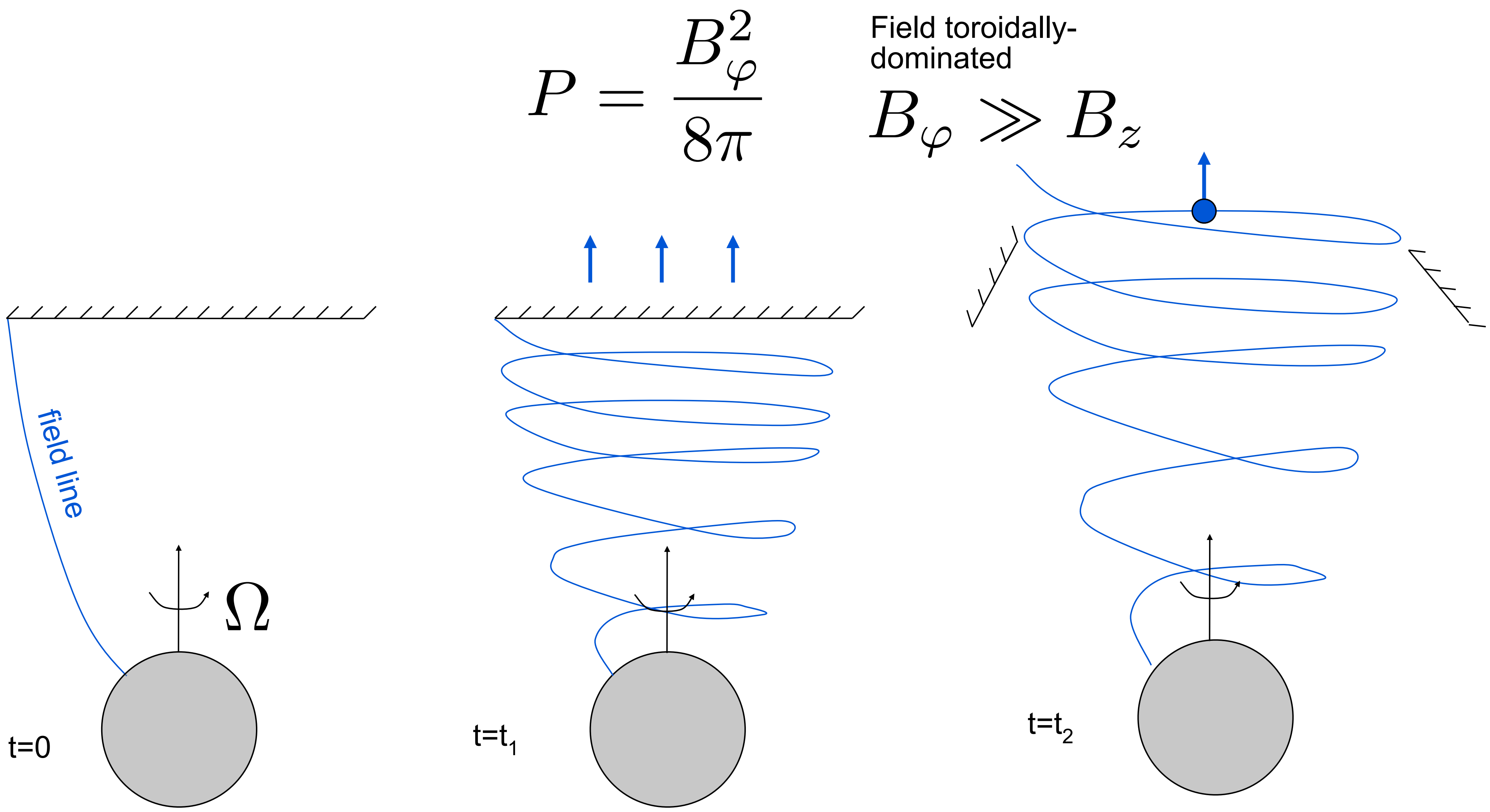


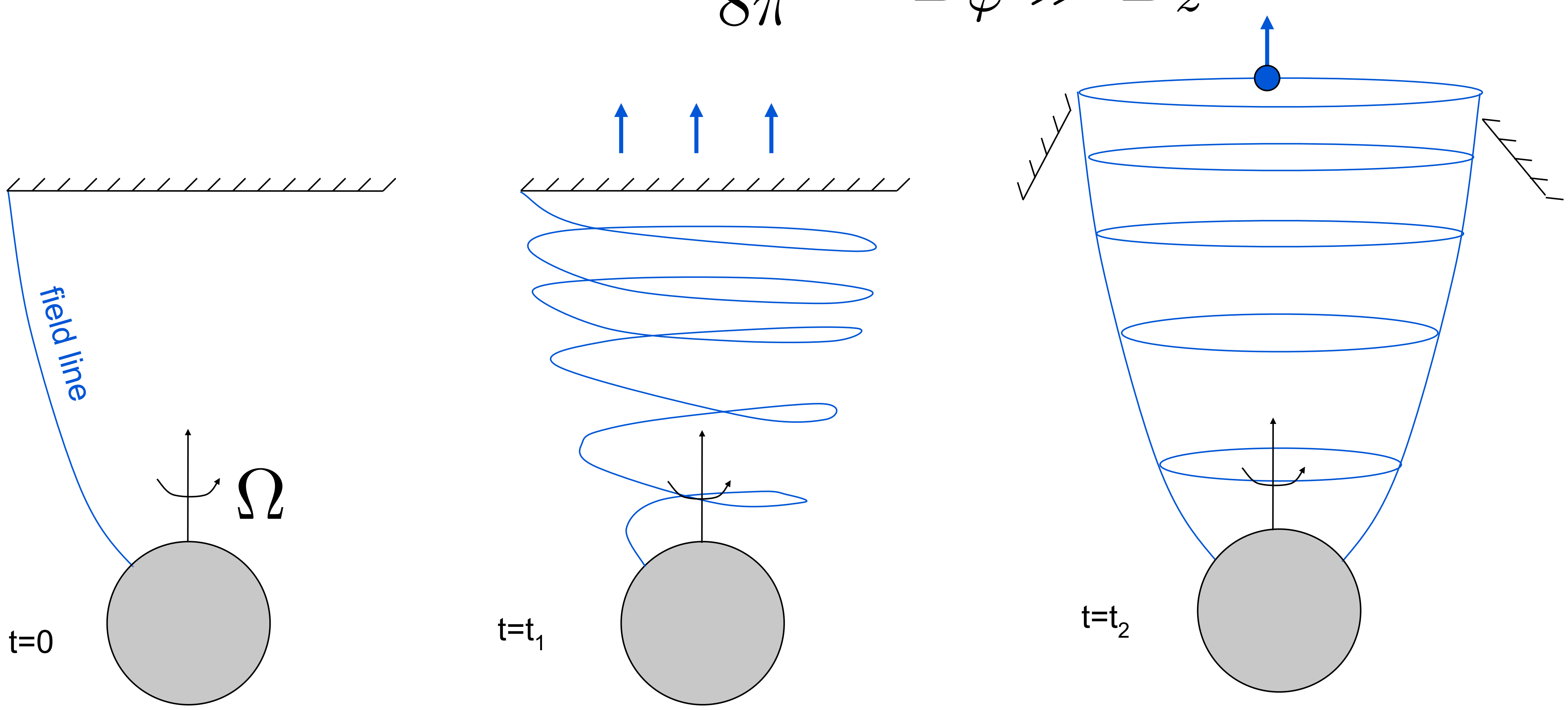
(Beskin & Nokhrina 06, Komissarov 07-10, AT+08,09,10,12, Lyubarsky 10, AT 15)

Jets 101

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



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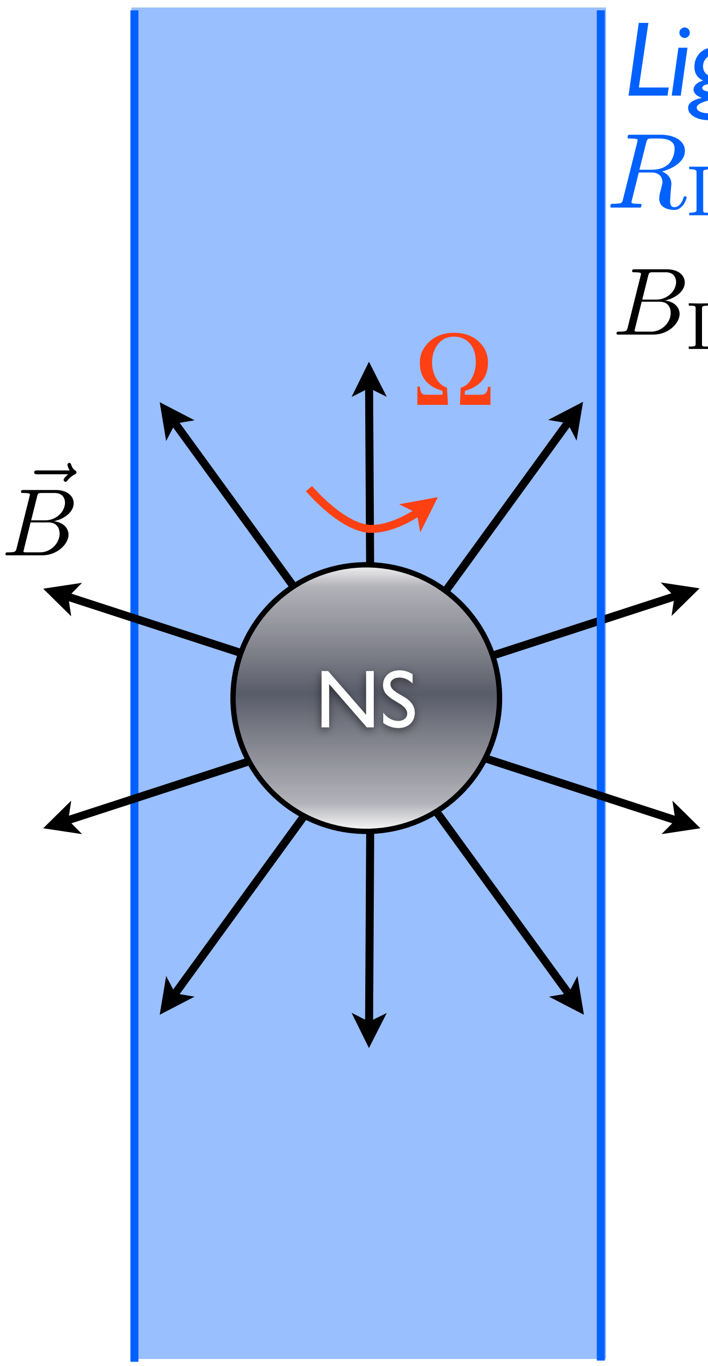
What Powers Outflow?



Light cylinder (LC):

$$R_{\rm L} = c/\Omega$$

$$B_{\rm L} = \Phi/2\pi R_{\rm L}$$

- Flow separates from NS at LC
- Spindown power

$$P \sim \frac{c}{4\pi}(\vec{E}\times\vec{B}) \times 4\pi R_{\rm L}^2 = cB_{\rm L}^2 R_{\rm L}^2$$

$$P \sim \frac{1}{6\cancel{4}\pi^2 c}\Phi^2\Omega^2$$

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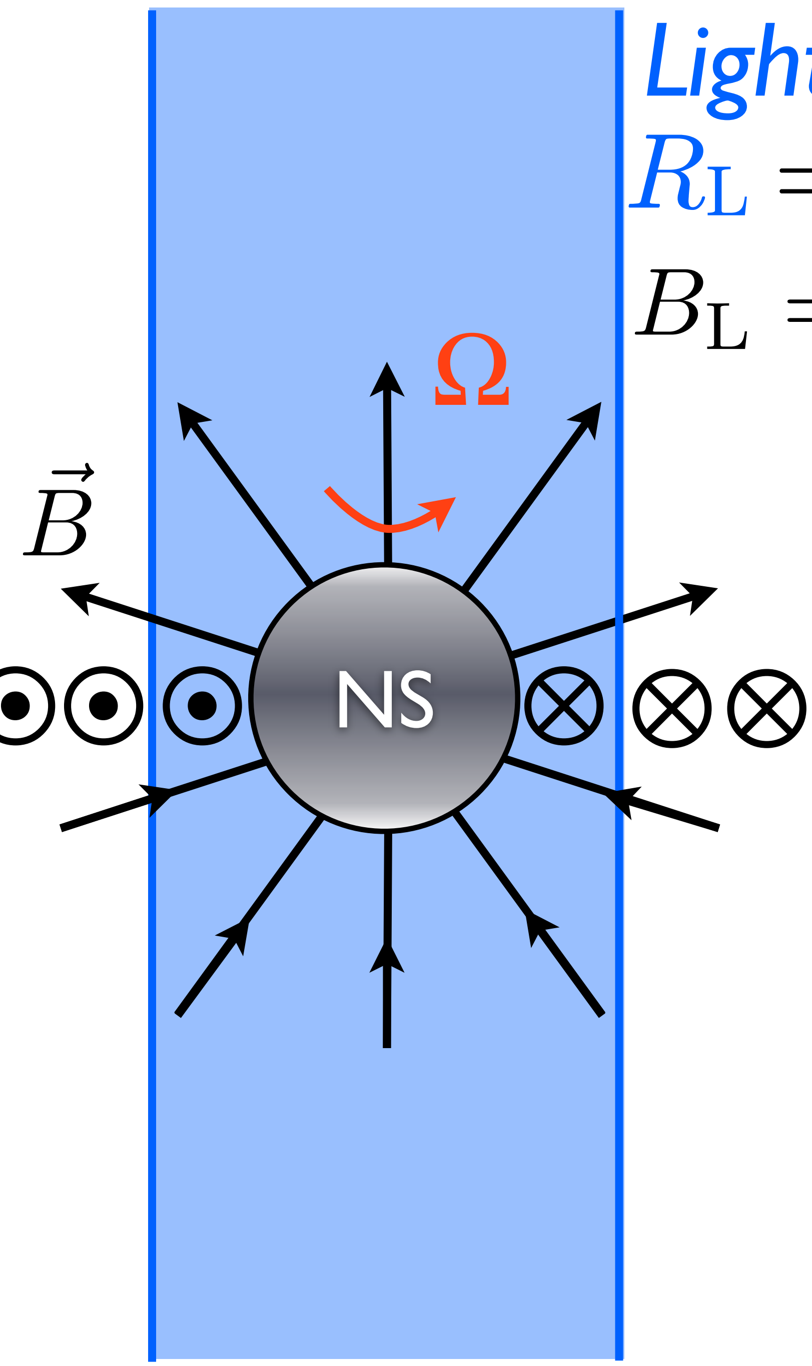

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- Split-monopole

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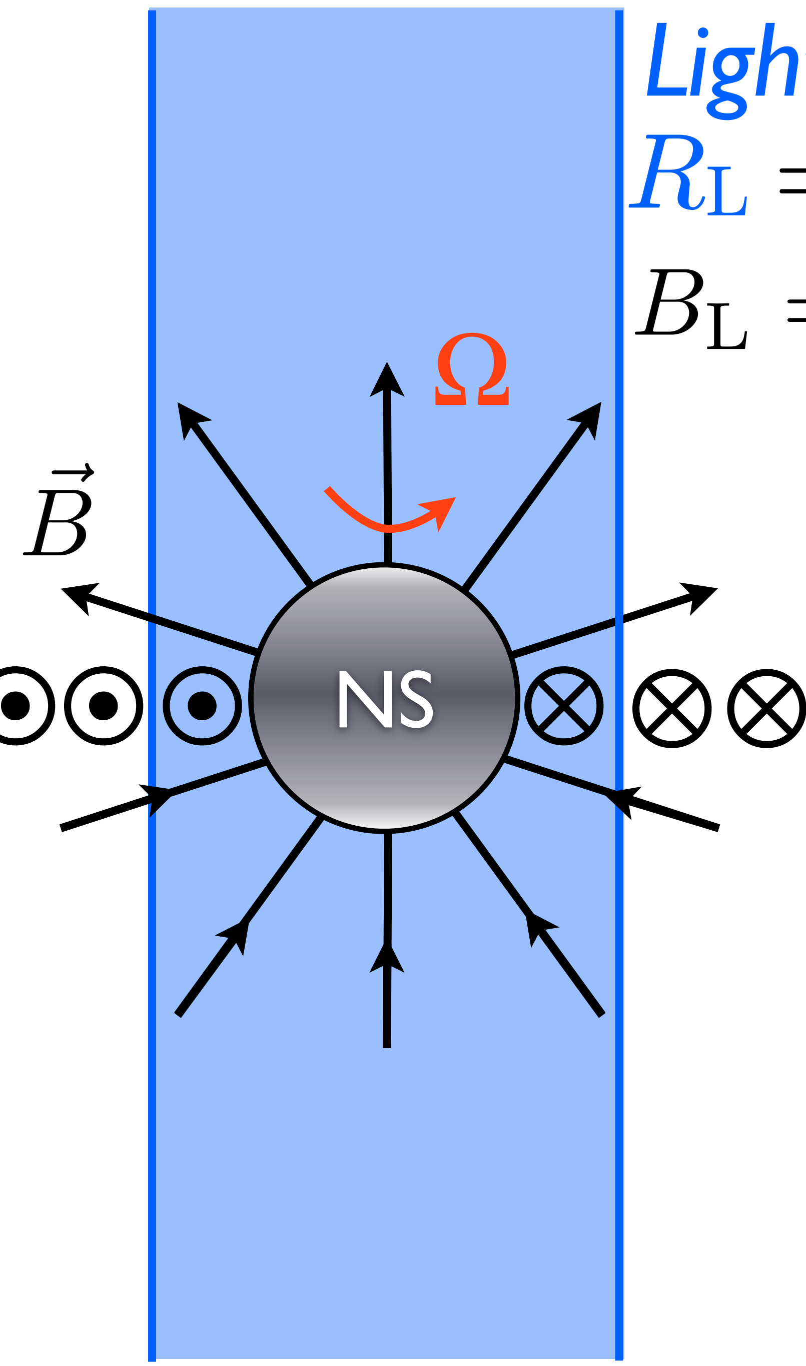

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- Split-monopole
- What about black holes?

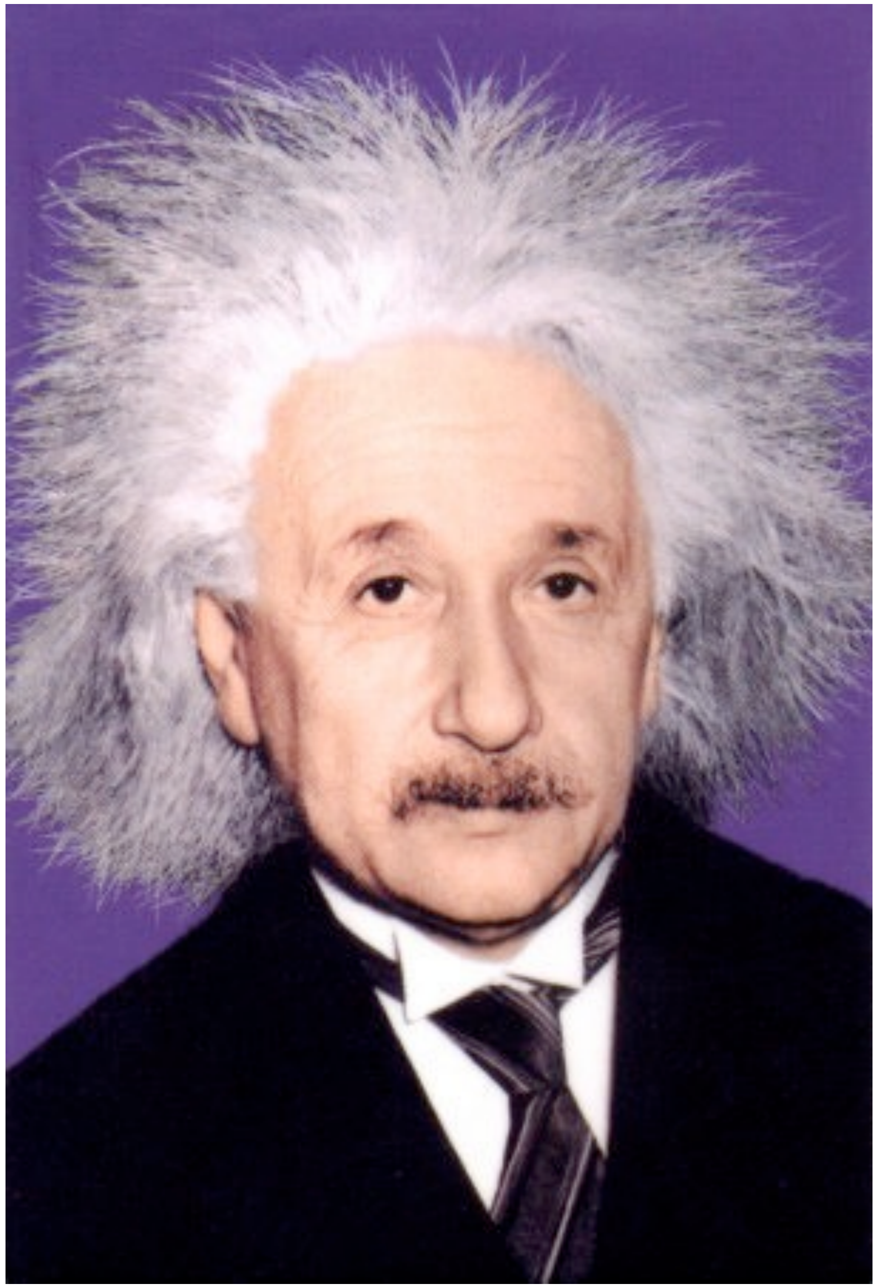
Slide: R. Narayan

A Black Hole is VERY Simple

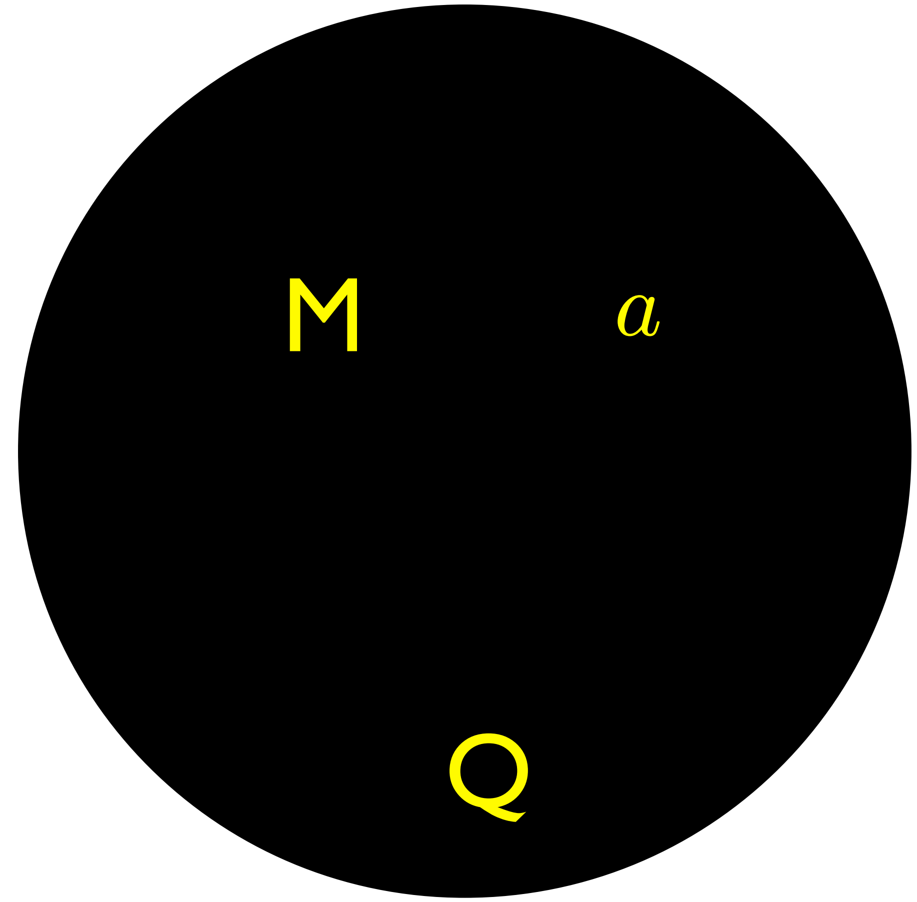
- Mass: **M**
- Spin: a **(J=a GM²/c)**
- ~~Charge: Q~~

A Black Hole has no Hair! (No Hair Theorem)
To be precise, a BH has 2 (at most 3) hairs

Slide: R. Narayan

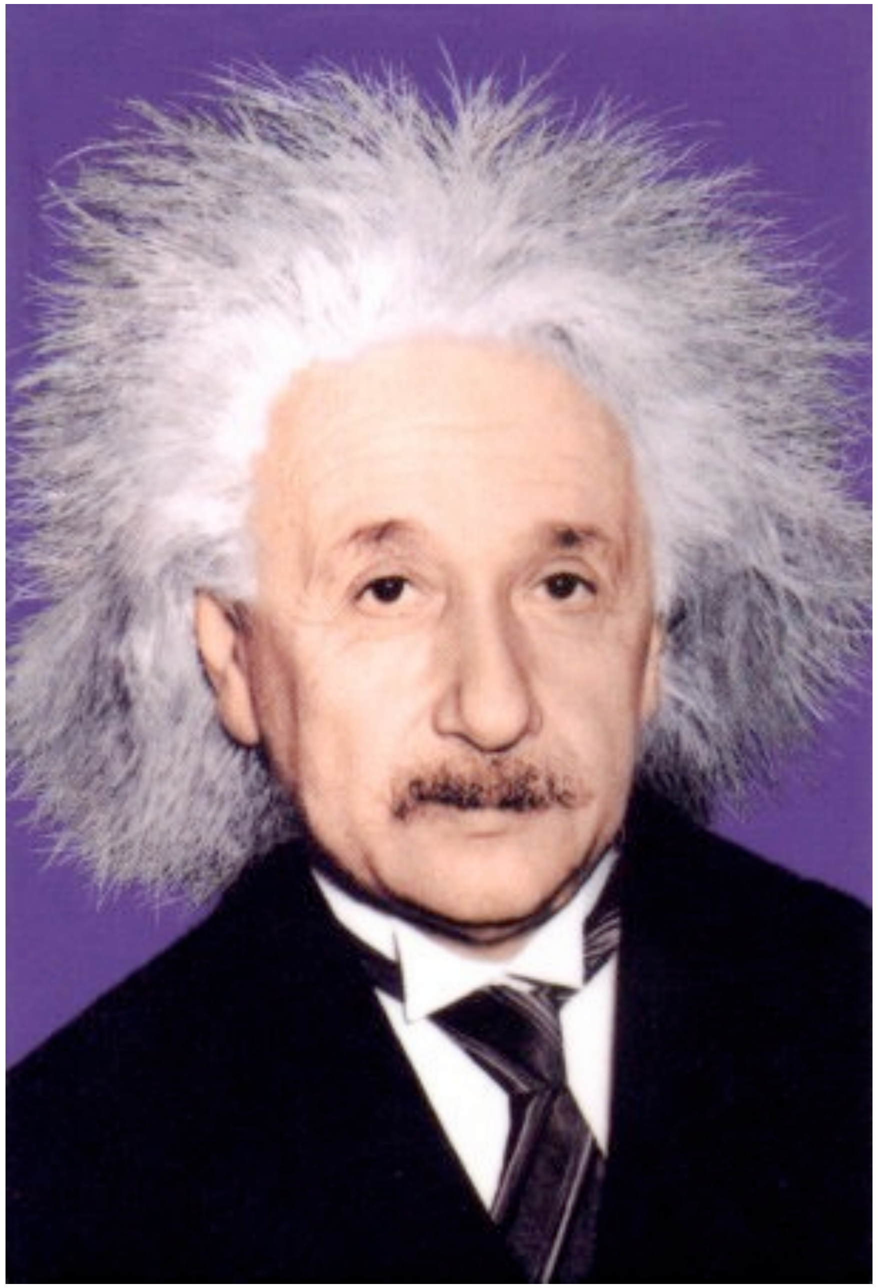


Einstein had a lot of hair!



Black Hole has **3** hairs!

Slide: R. Narayan



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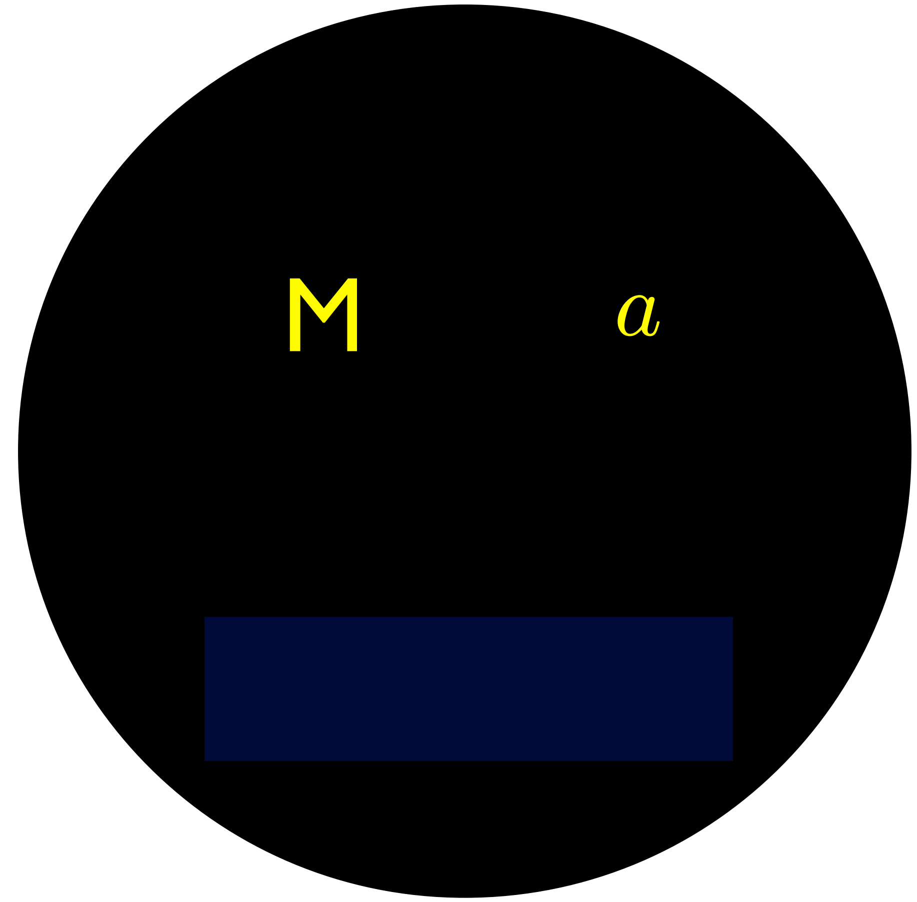
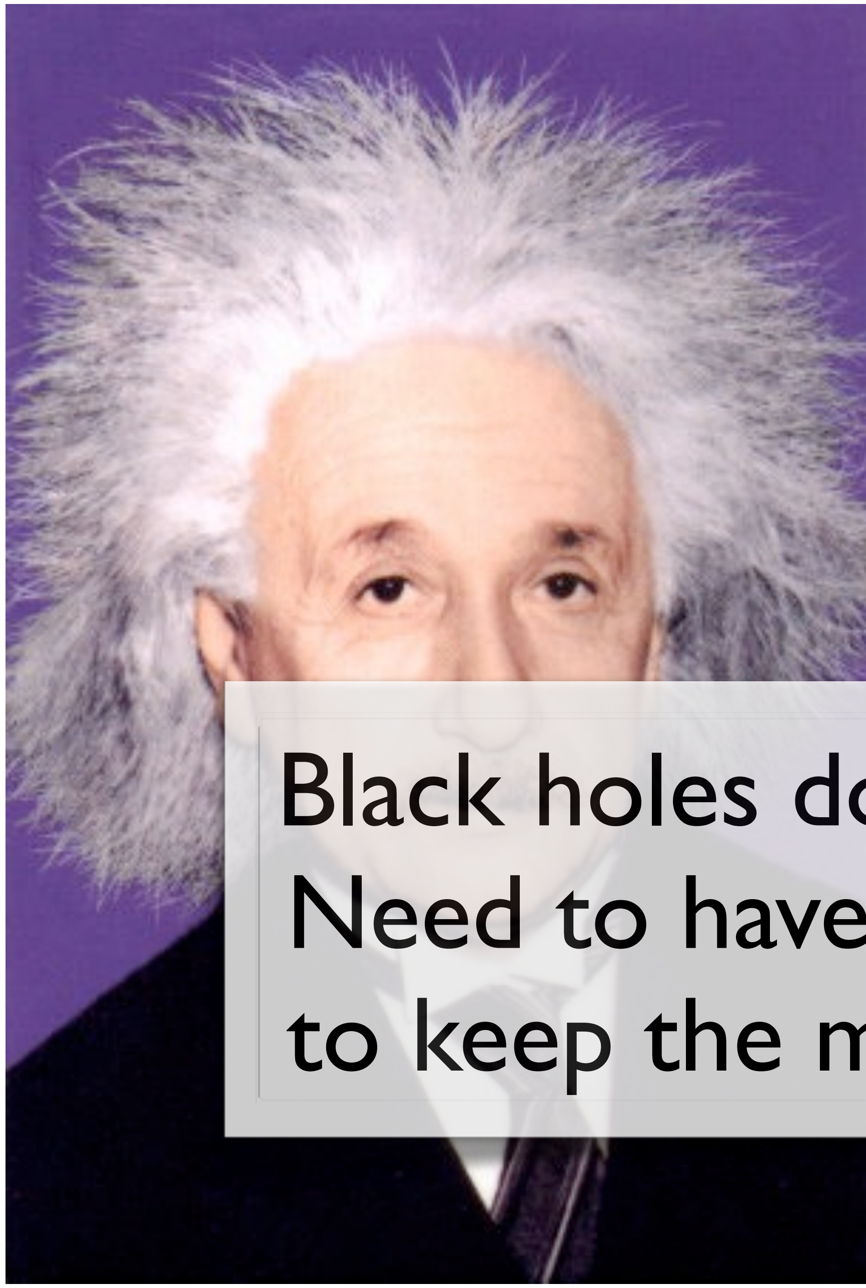


A **Black Hole** has only **2** hairs

Slide: R. Narayan

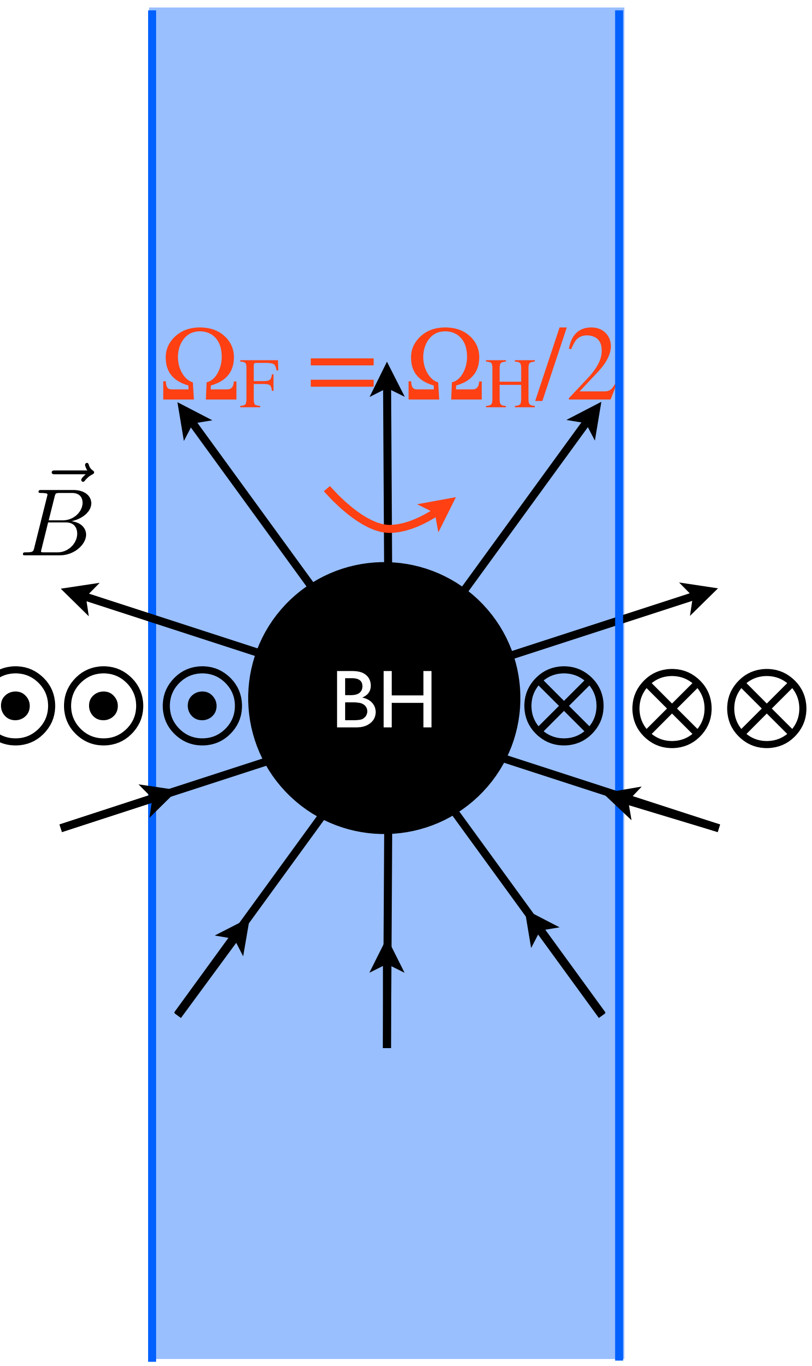


Black holes do not have magnetic hair. Need to have currents *outside* the BH to keep the magnetic field on the BH.

Einstein had a lot of hair!

A **Black Hole** has only **2** hairs

What about Black Holes?



- Black hole drags space-time at

$$\omega \simeq \Omega_{\rm H}(r/r_{\rm H})^{-3}, \quad \Omega_{\rm H} = ac/2r_{\rm H}$$

- At the event horizon $\omega = \Omega_{\rm H}$
- At infinity $\omega = 0$
- Field line tries to please both:

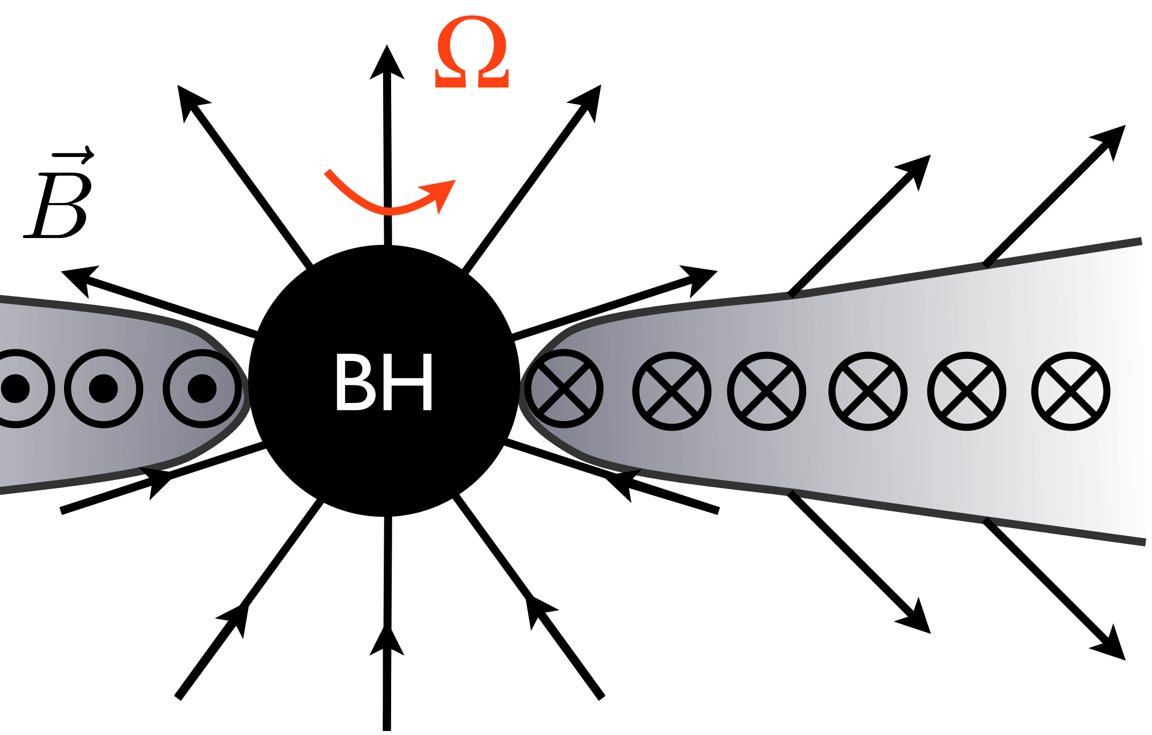
$$\Omega_{\rm F} = \Omega_{\rm H}/2$$

- Otherwise, behaves almost like a NS!

$$P \sim \frac{1}{6\cancel{4}\pi^2 c}\Phi^2\Omega_{\rm F}^2 \sim \frac{1}{24\cancel{16}\pi^2 c}\Phi^2\Omega_{\rm H}^2$$

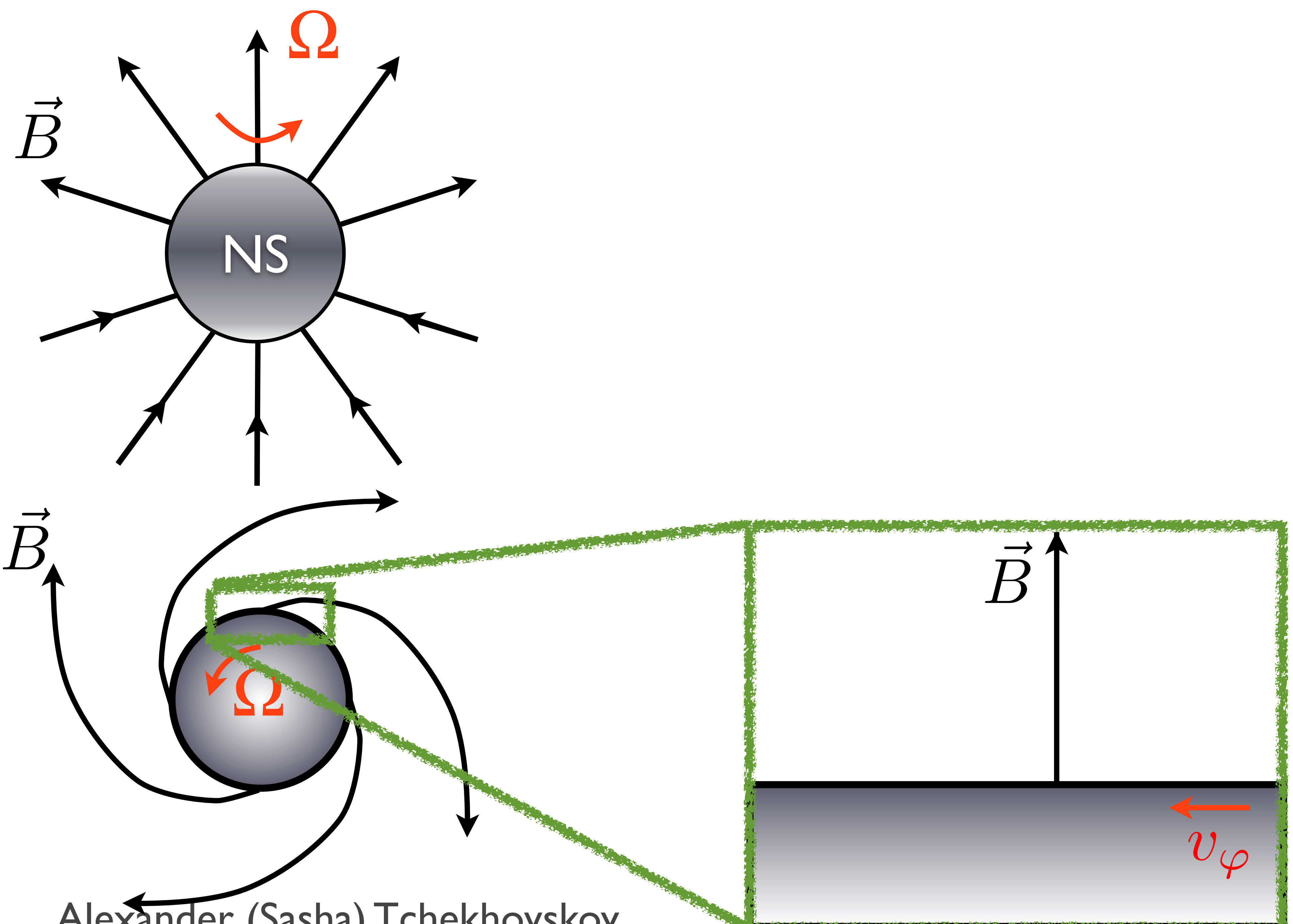
(~10% corrections for other field geometries, AT+10, AT15)

Where Does Φ Come from?



- Accretion disk:
  - either drags B from large scales
  - or generates B in situ
  - presently unsolved problem
- *Black hole must be accreting in order to form magnetosphere and produce jets*

How do Jets Accelerate?



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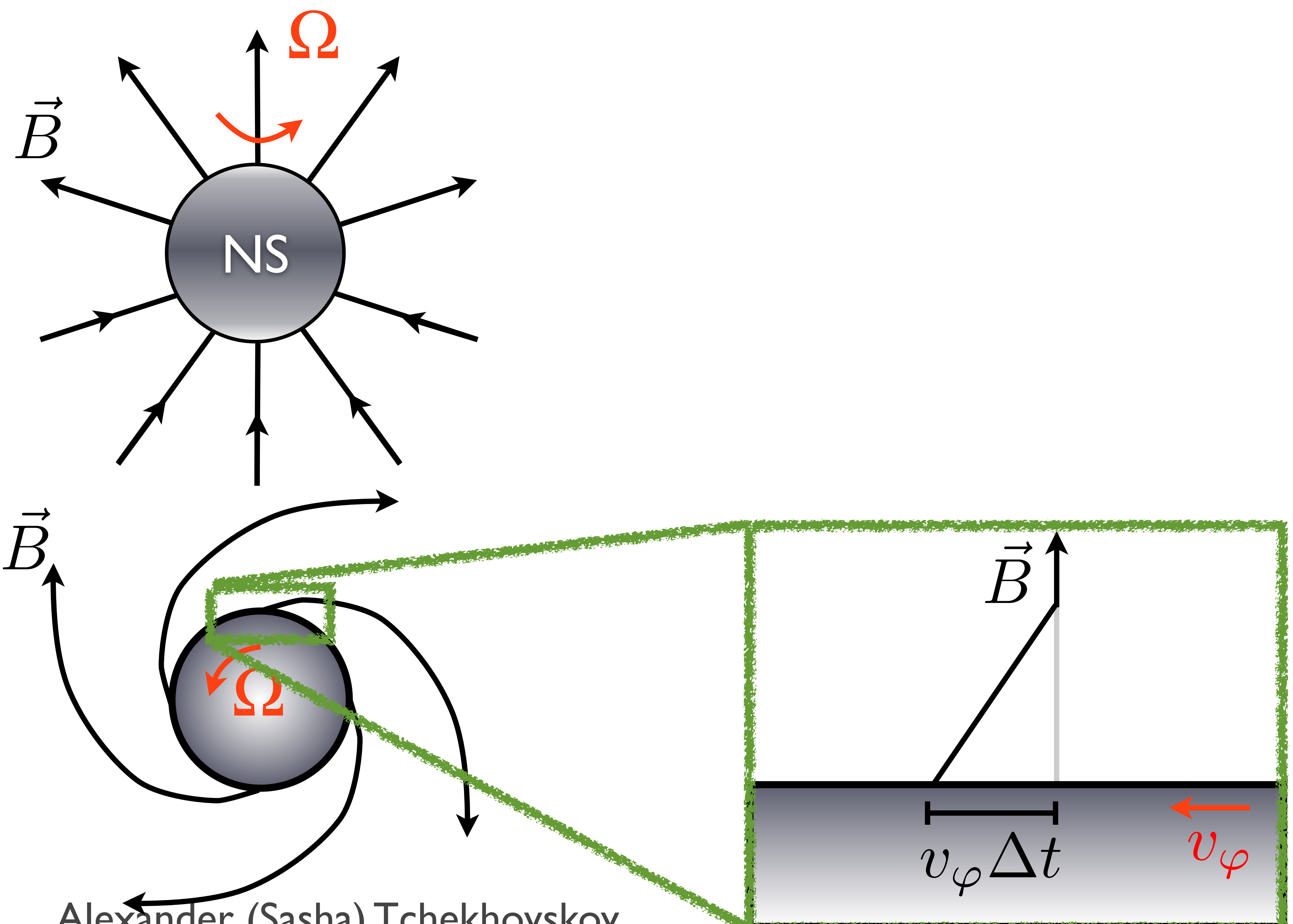

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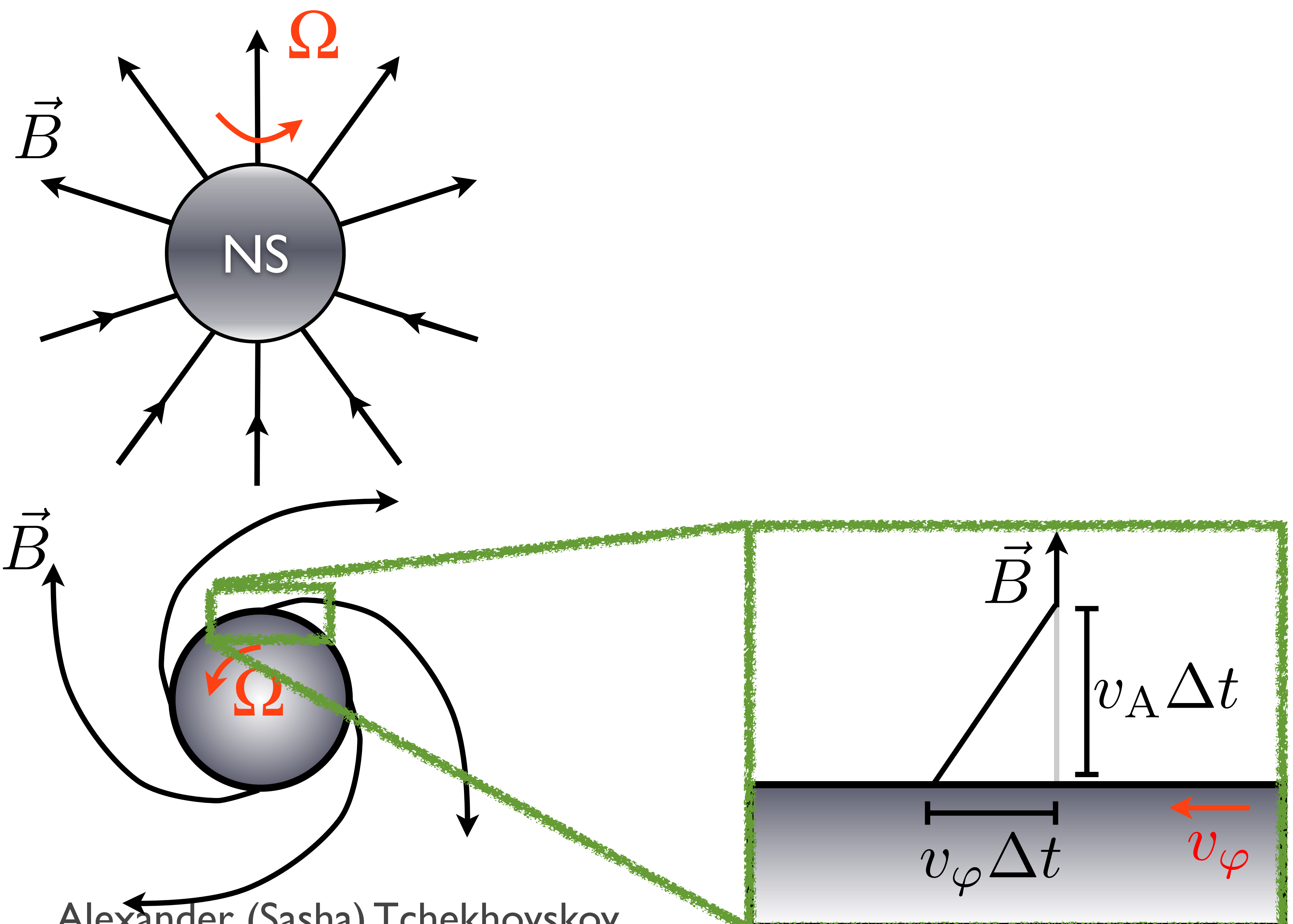
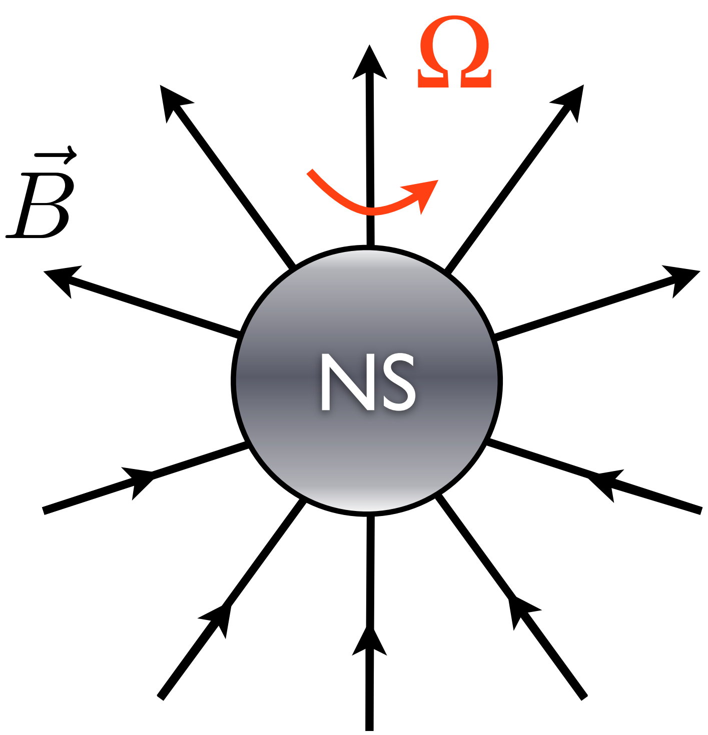
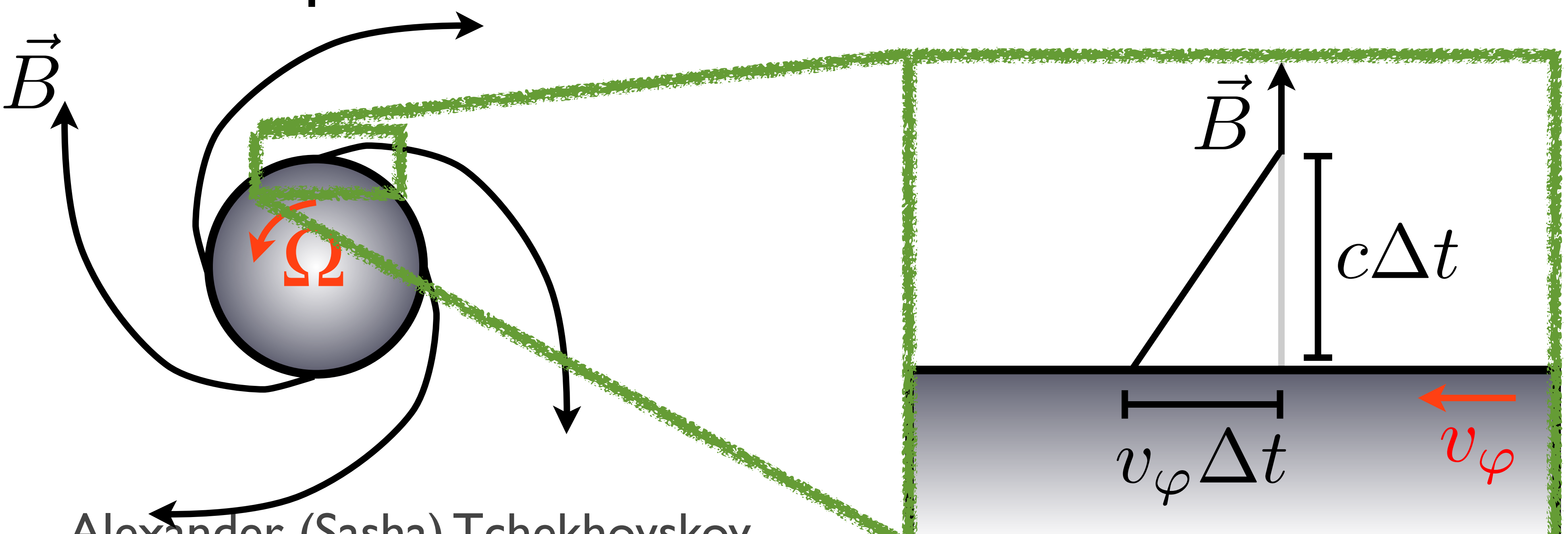


How do *force-free* Jets Accelerate?





Assume the jets are ***massless (force-free)*** for simplicity

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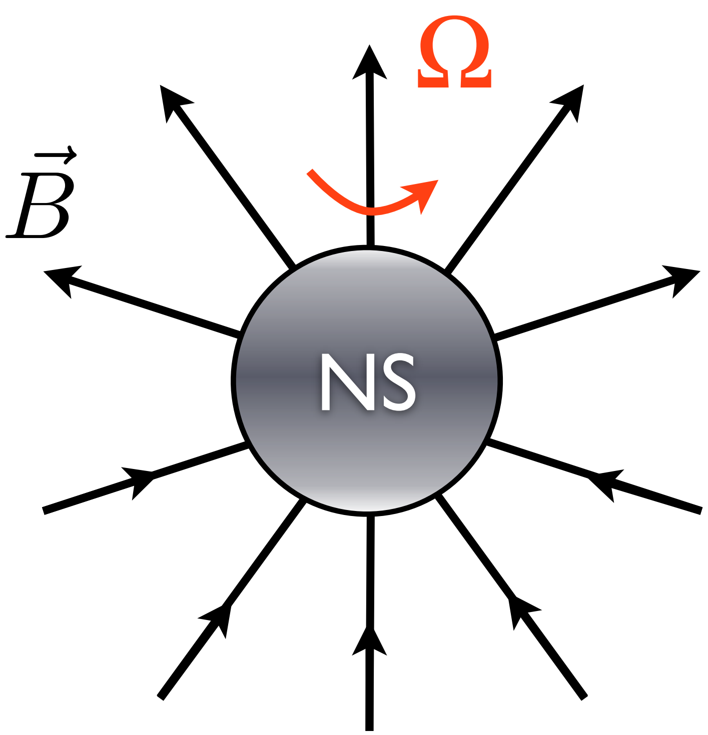
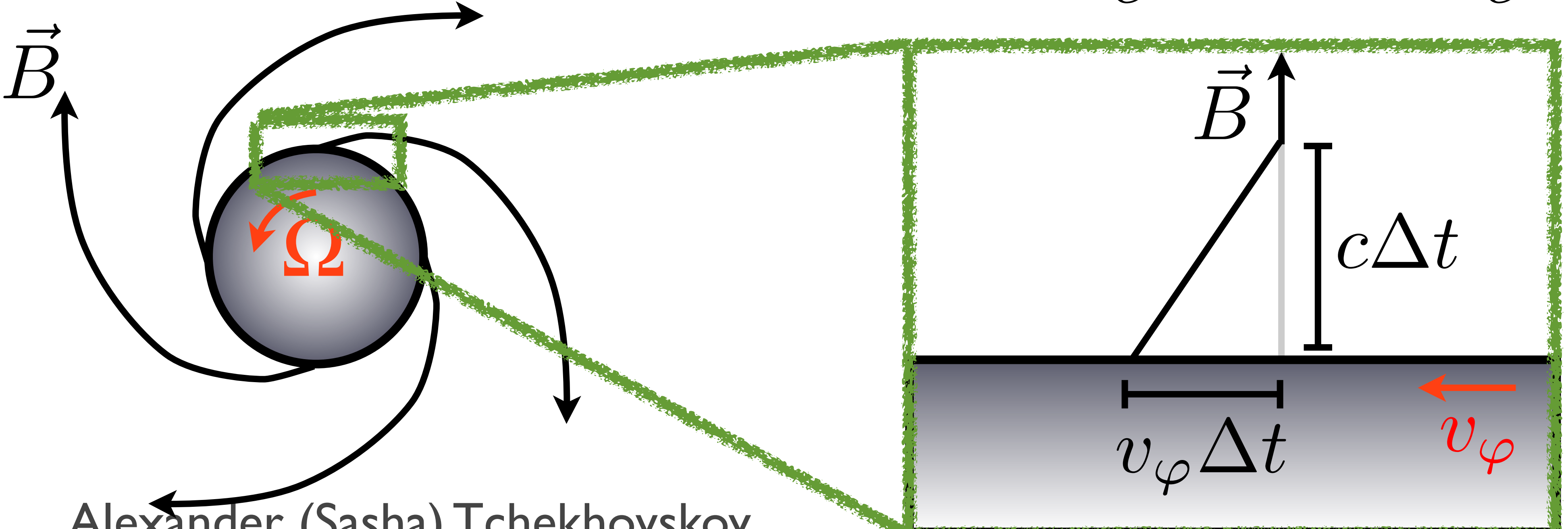


$$B_\varphi = -\frac{v_\varphi}{c} B_r = -\frac{\Omega R}{c} B_r$$



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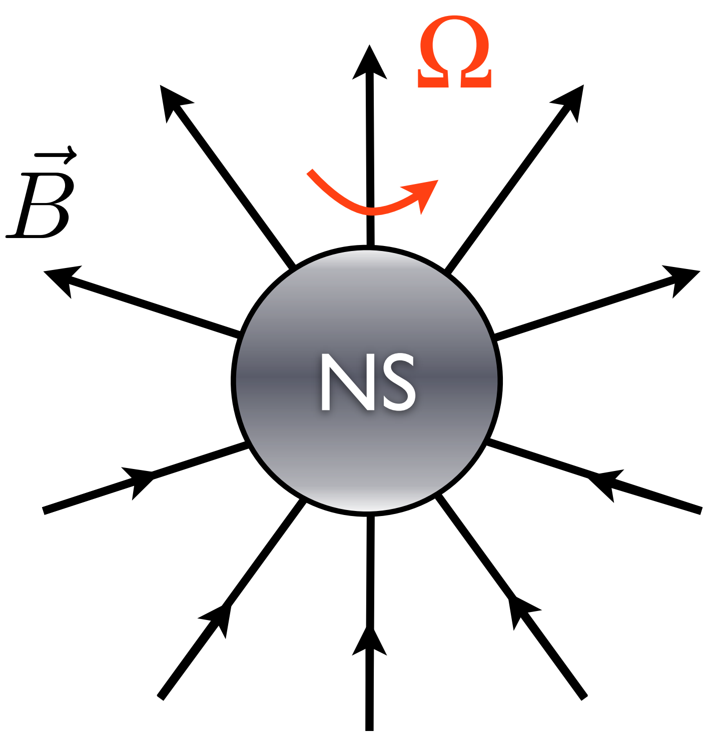

$$E = \left| -\frac{\vec{v}}{c} \times \vec{B} \right| = +\frac{\Omega R}{c} B_r$$

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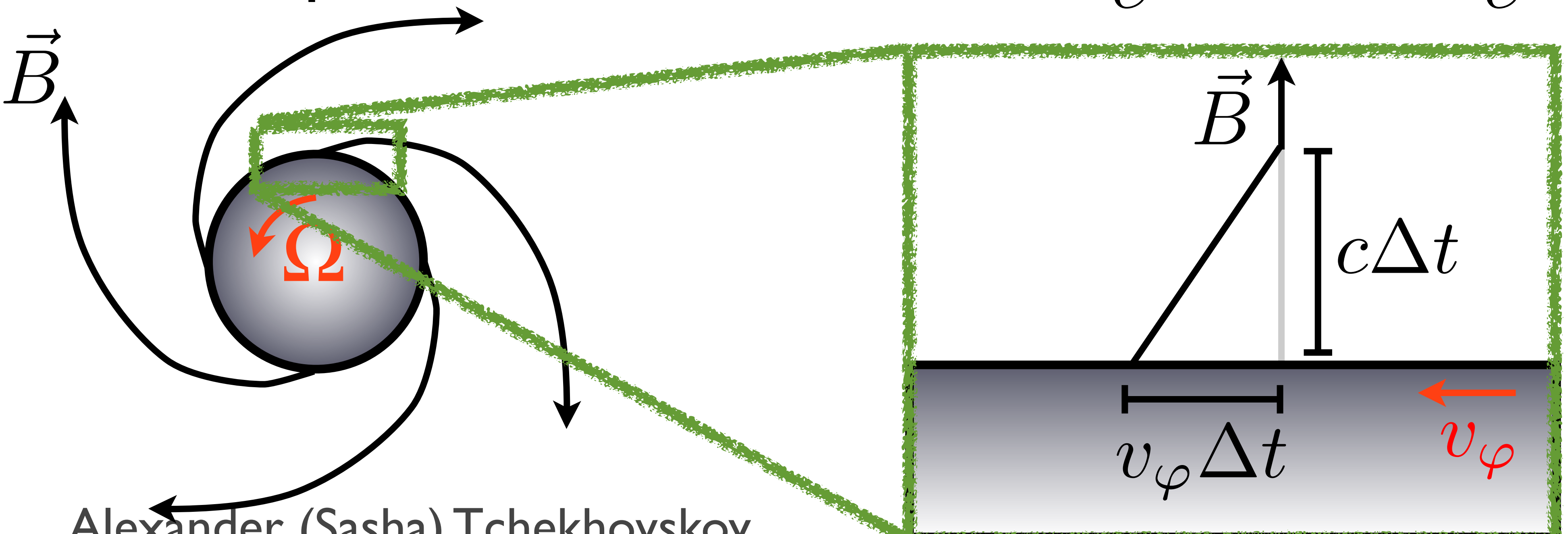

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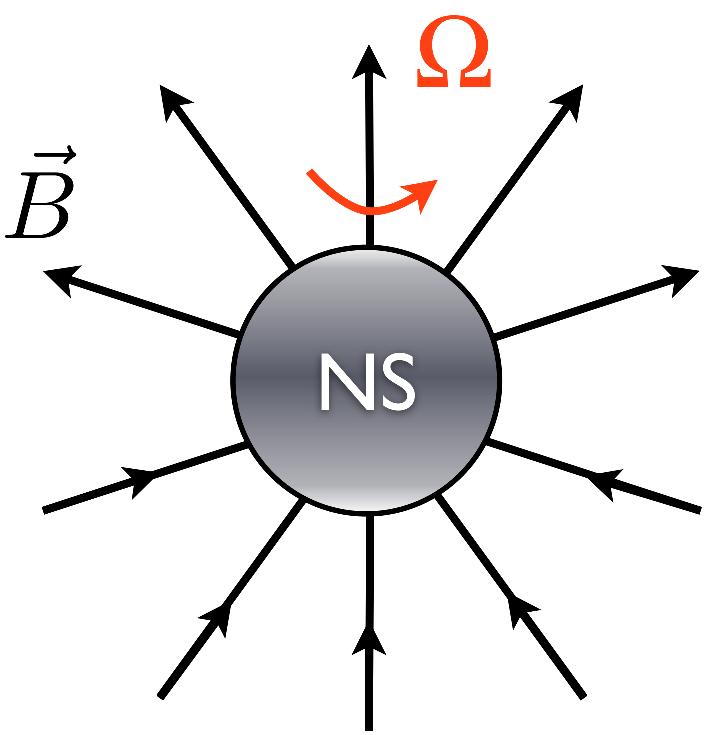

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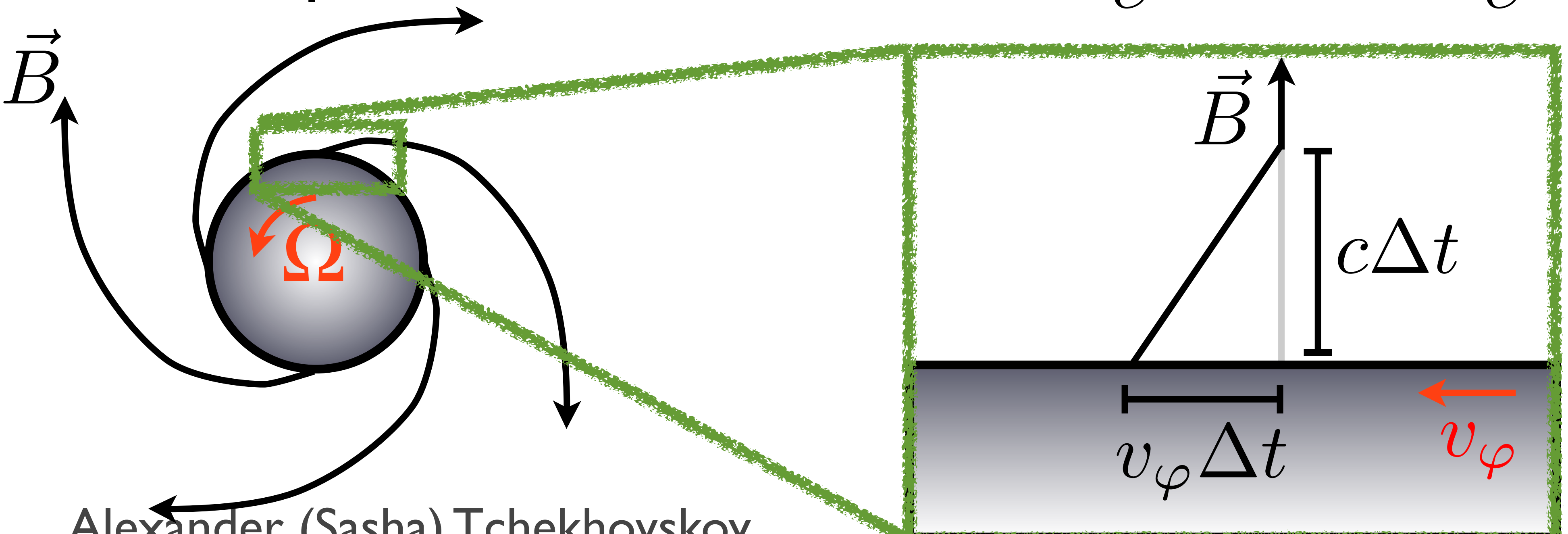

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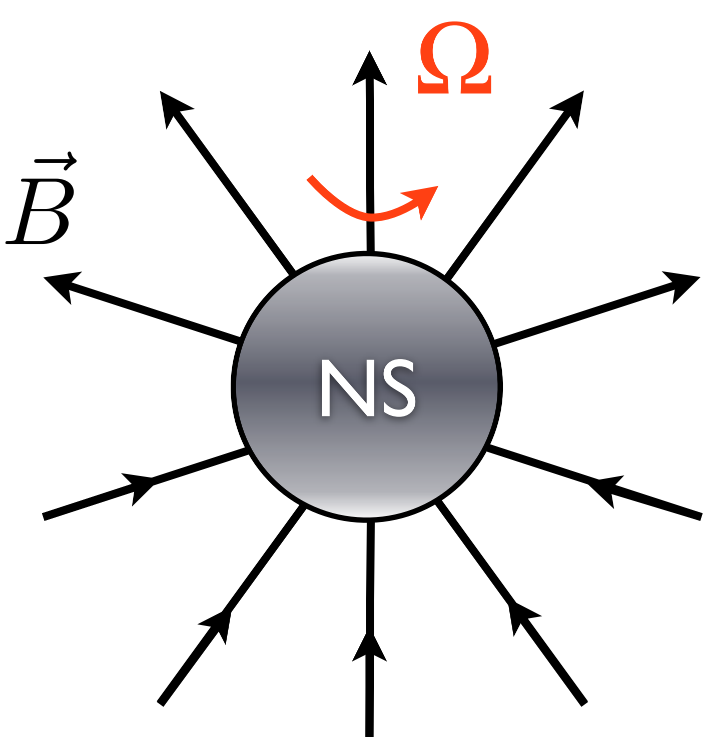

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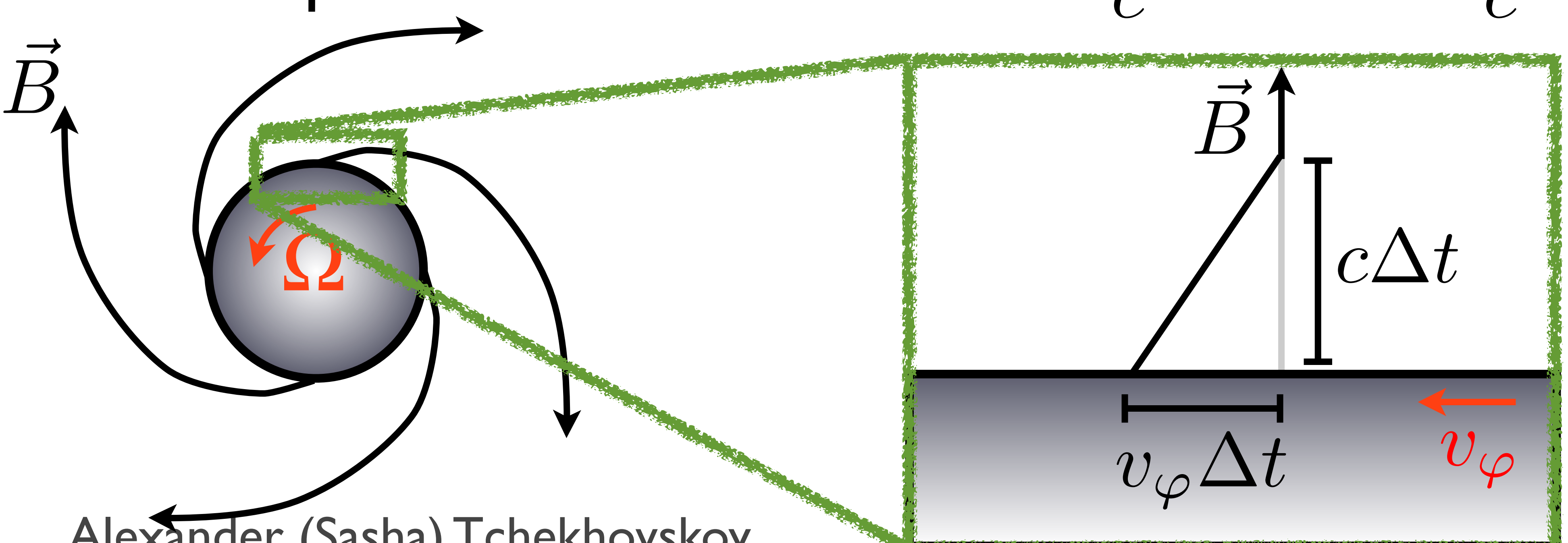

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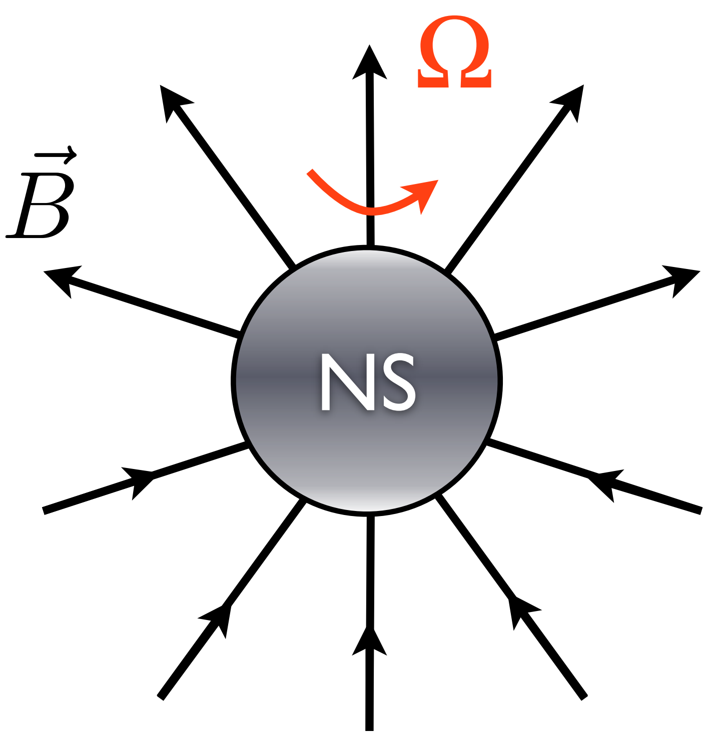

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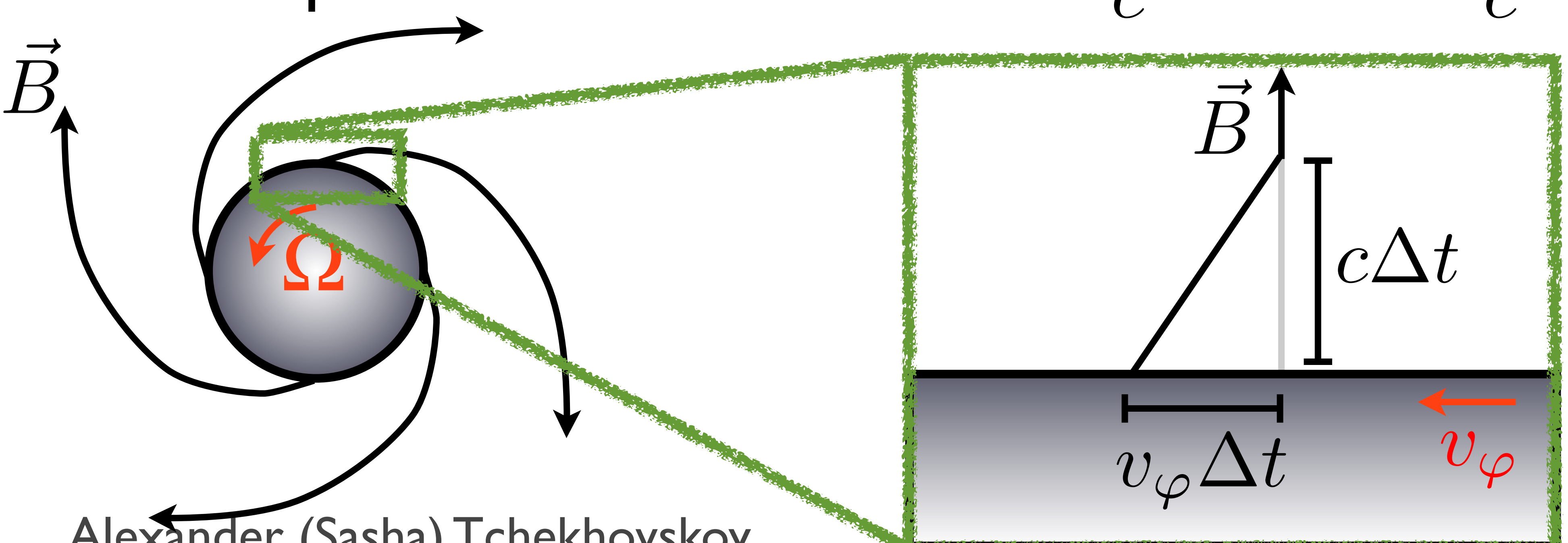

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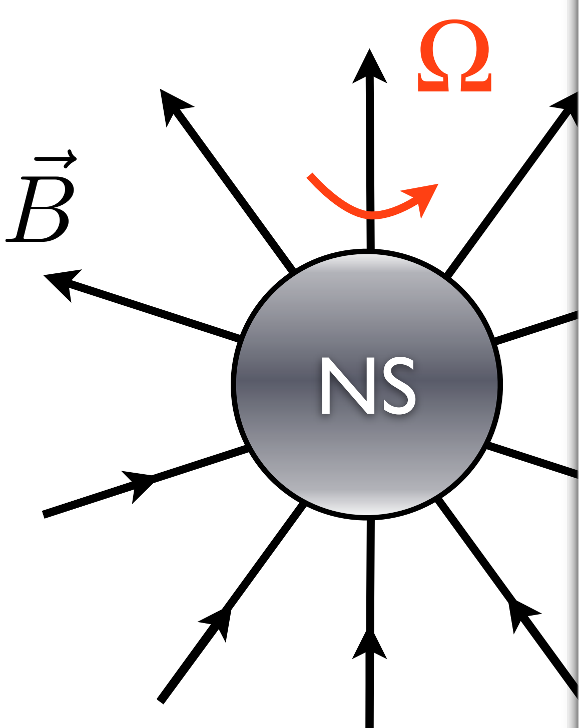

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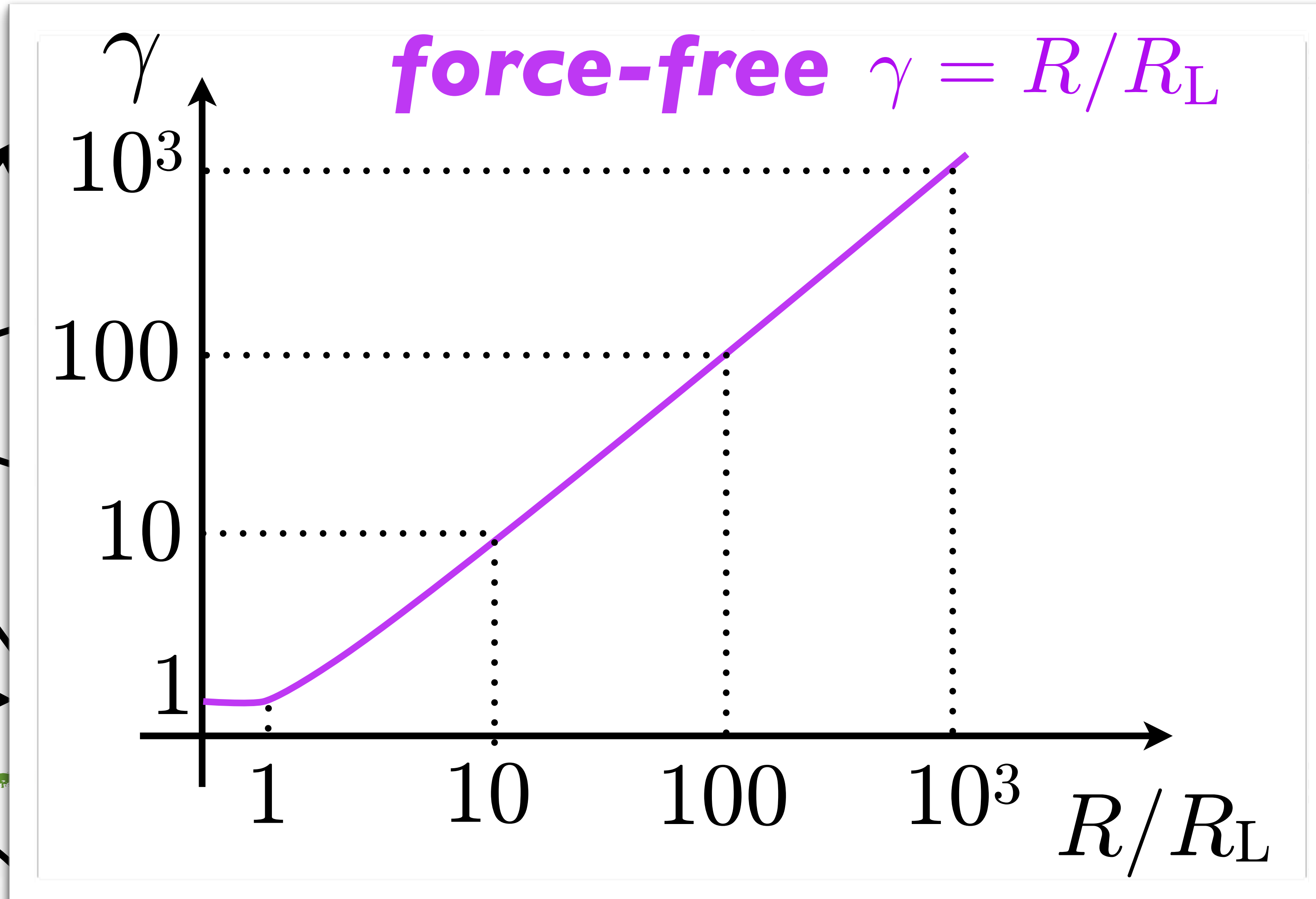

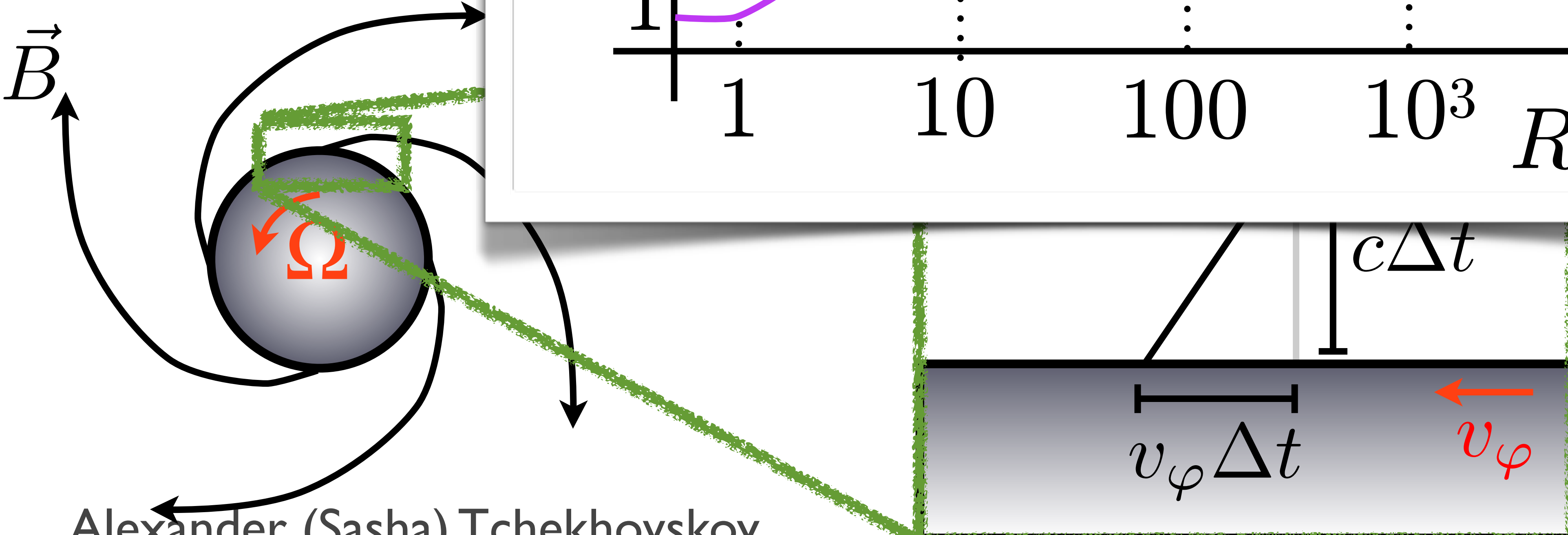

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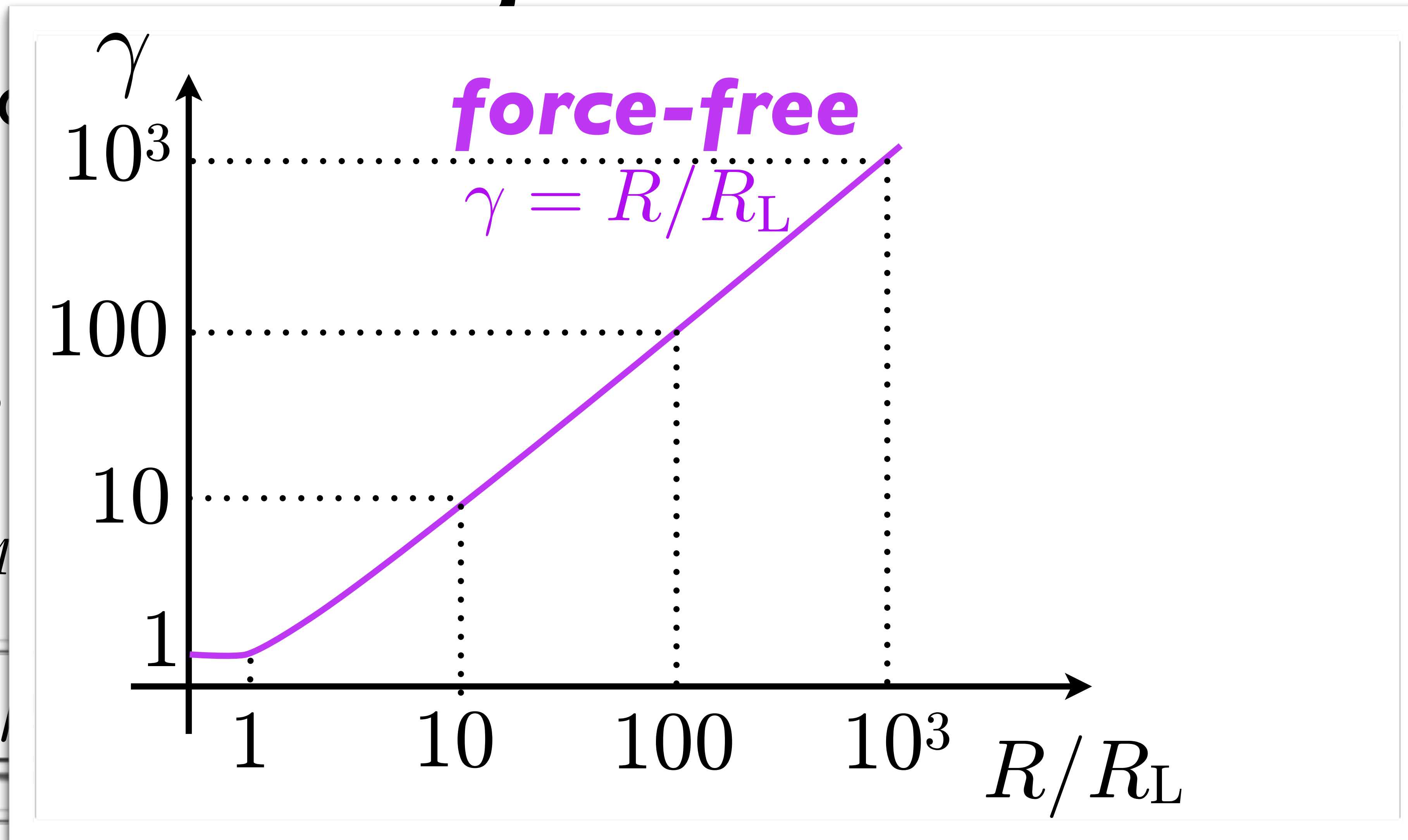

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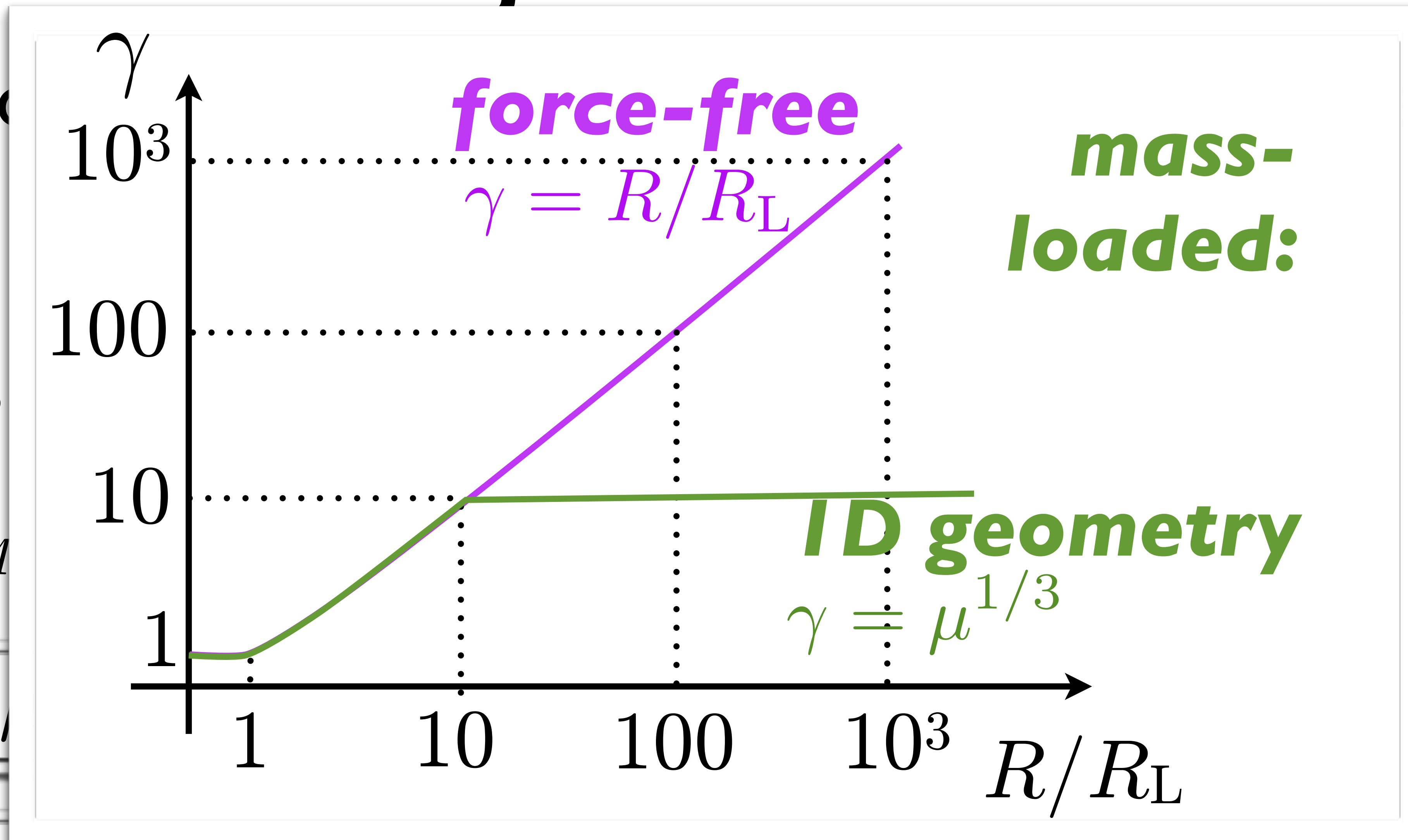

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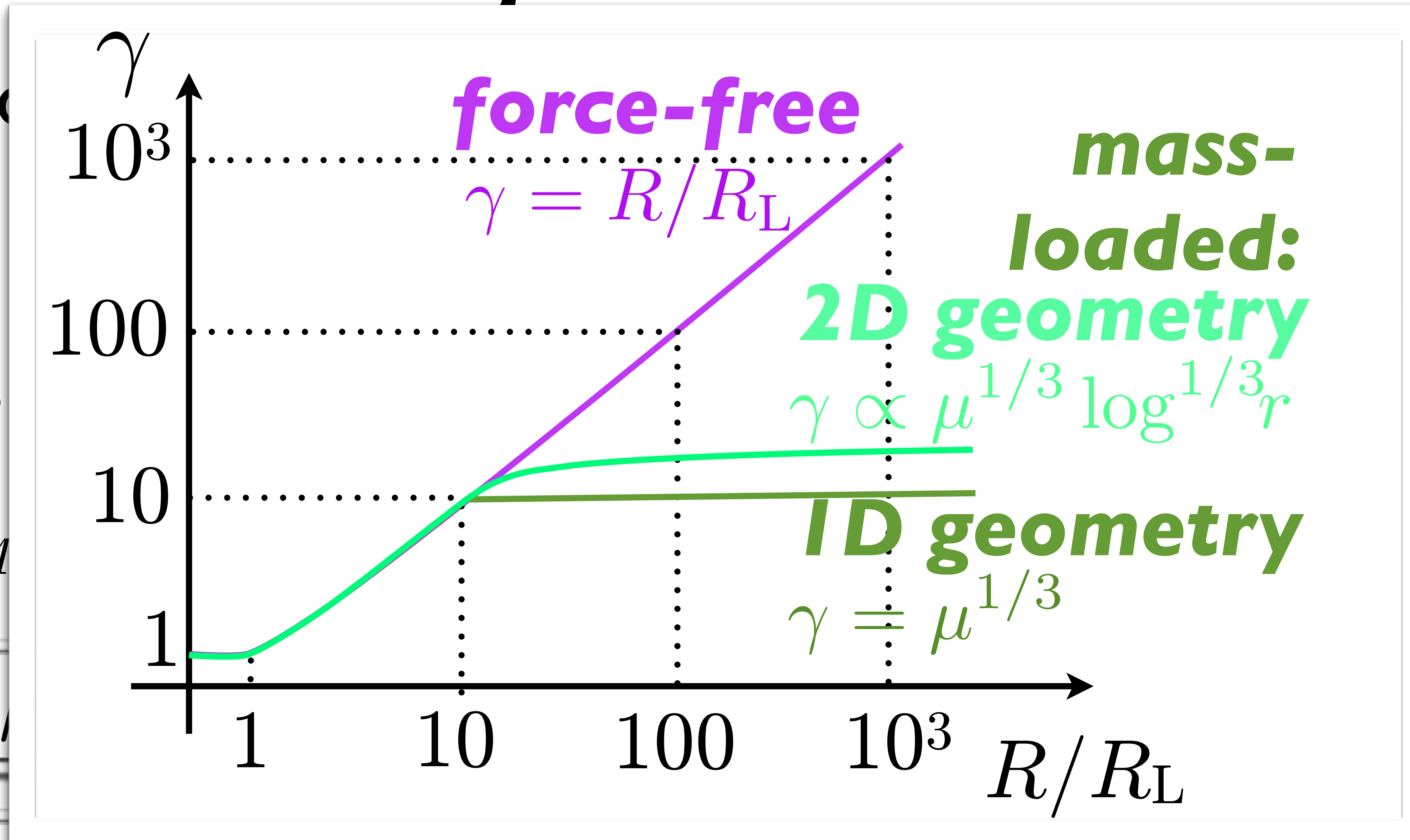

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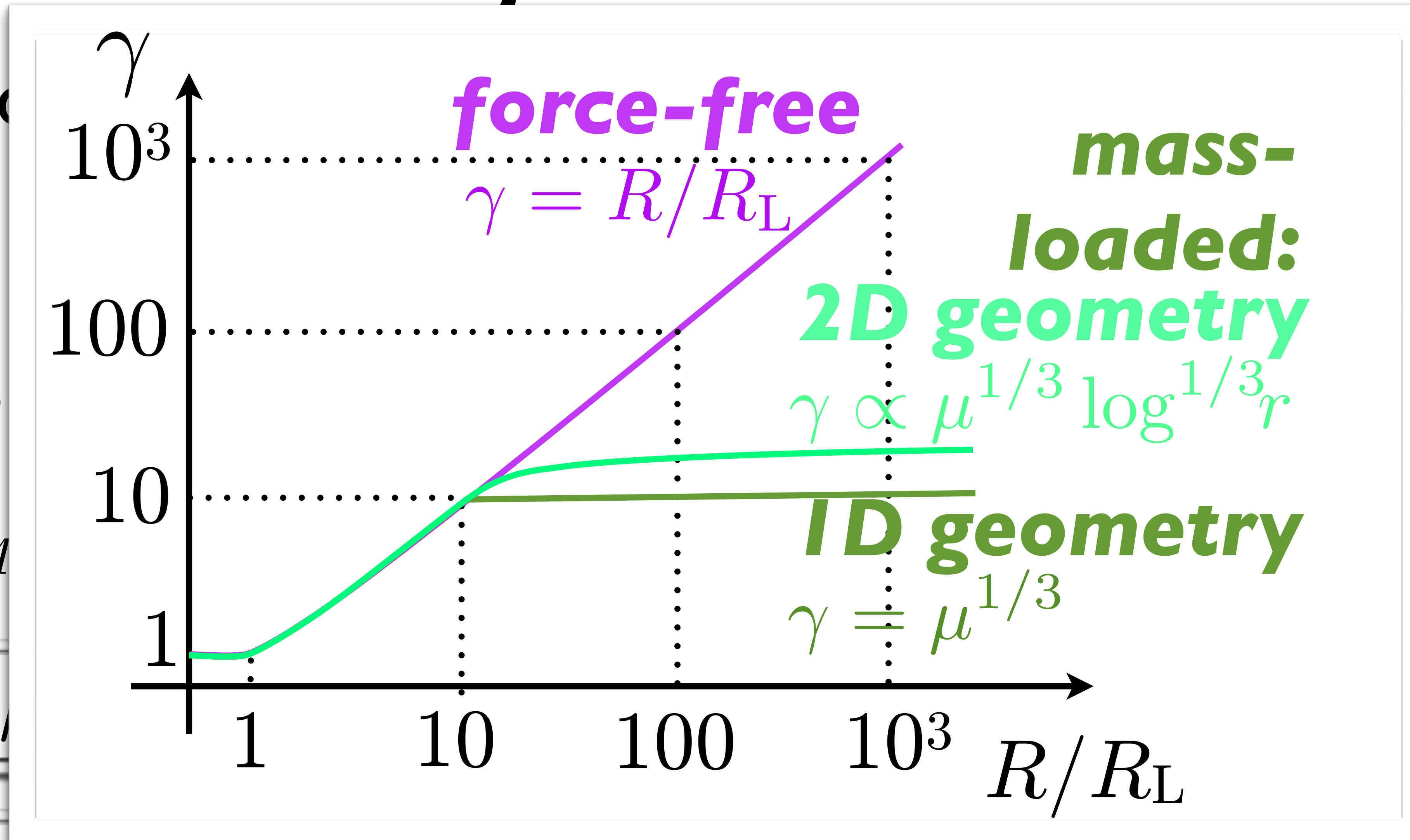

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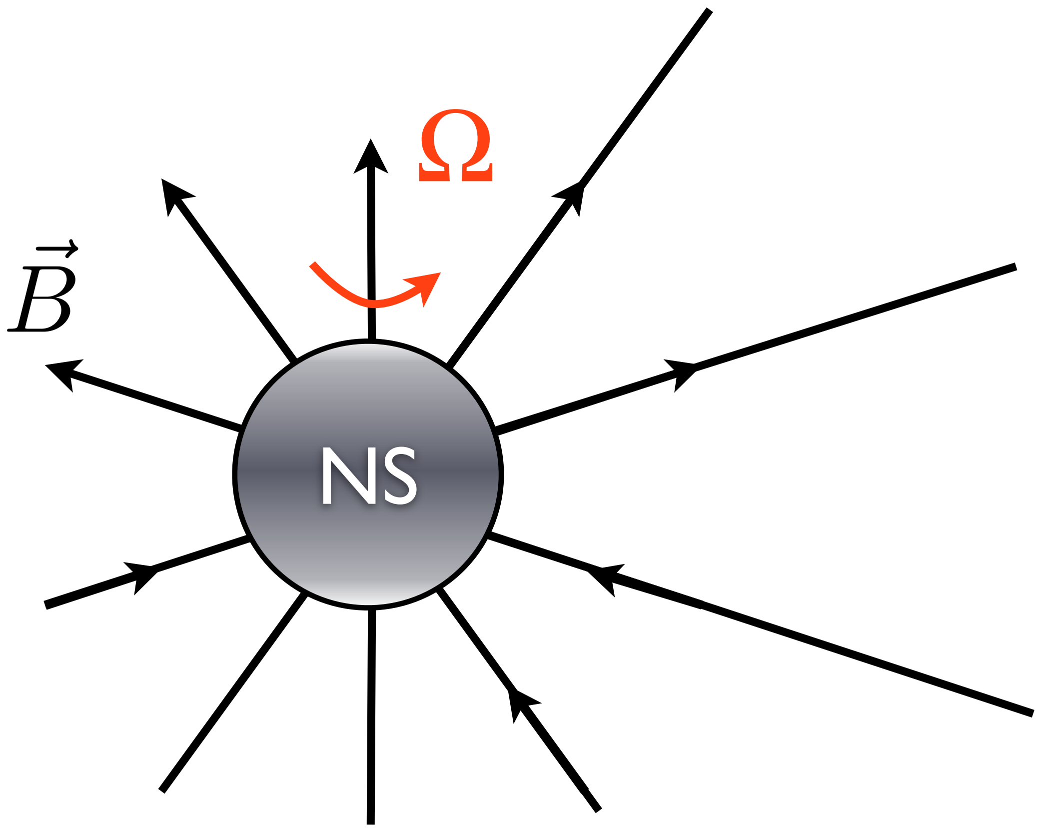

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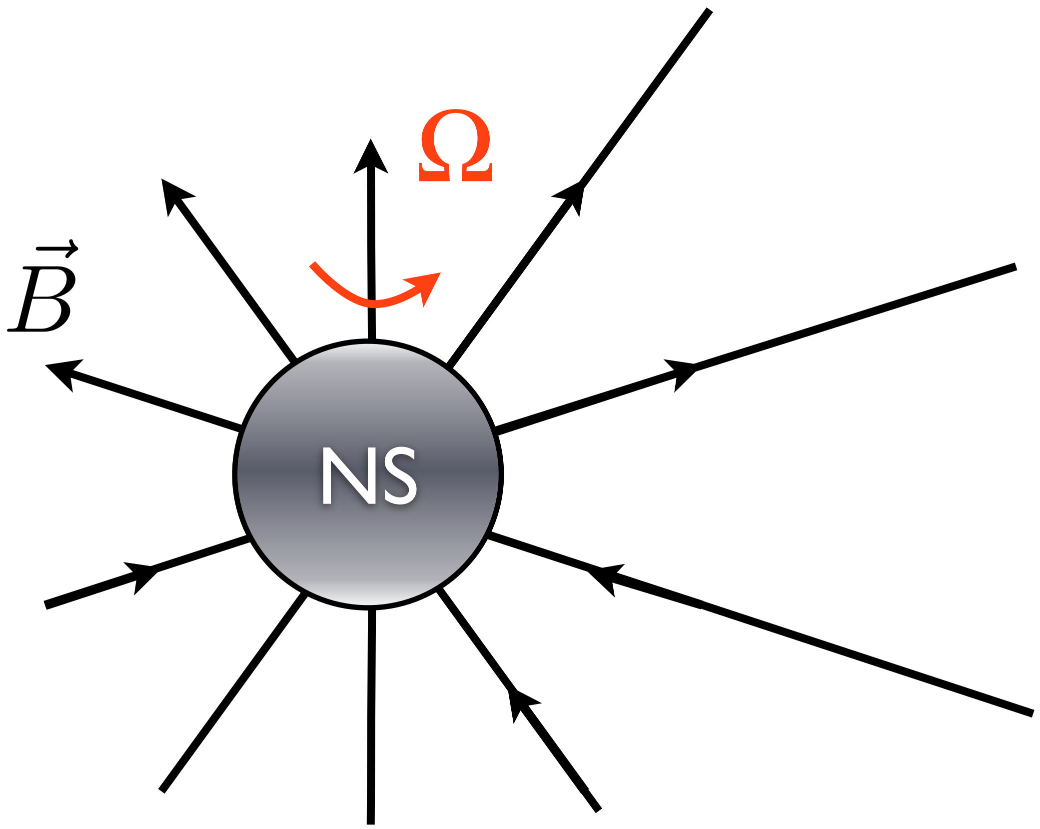

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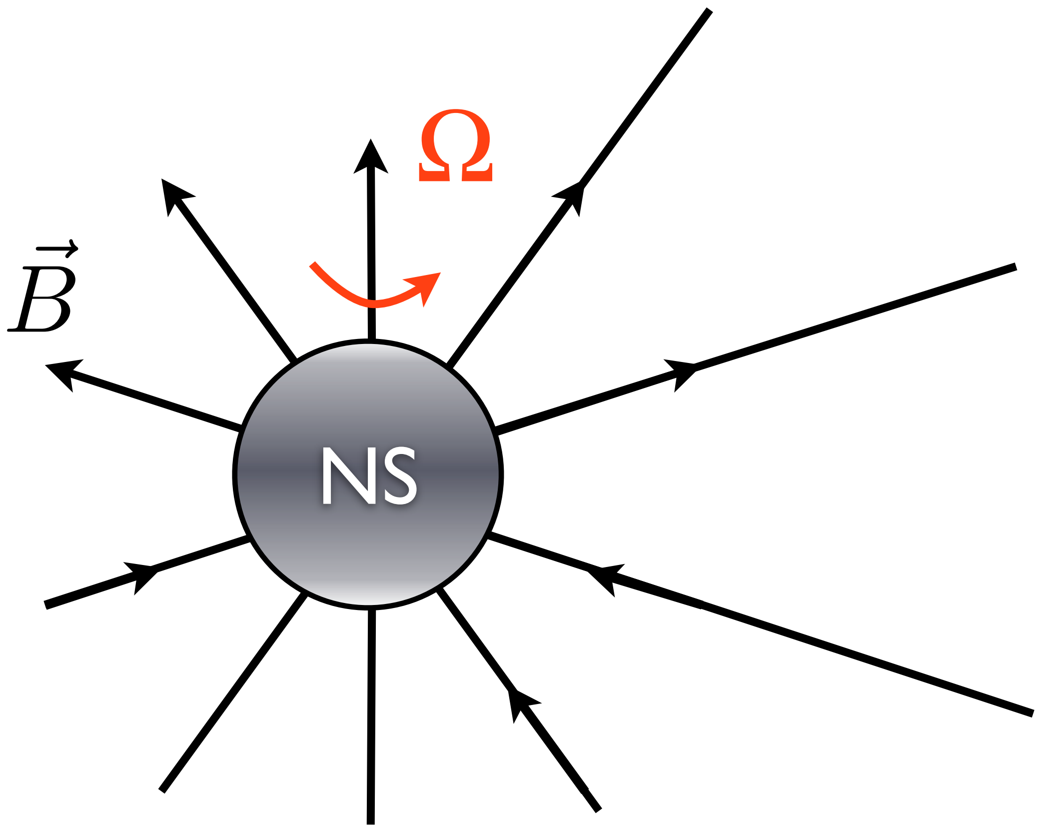

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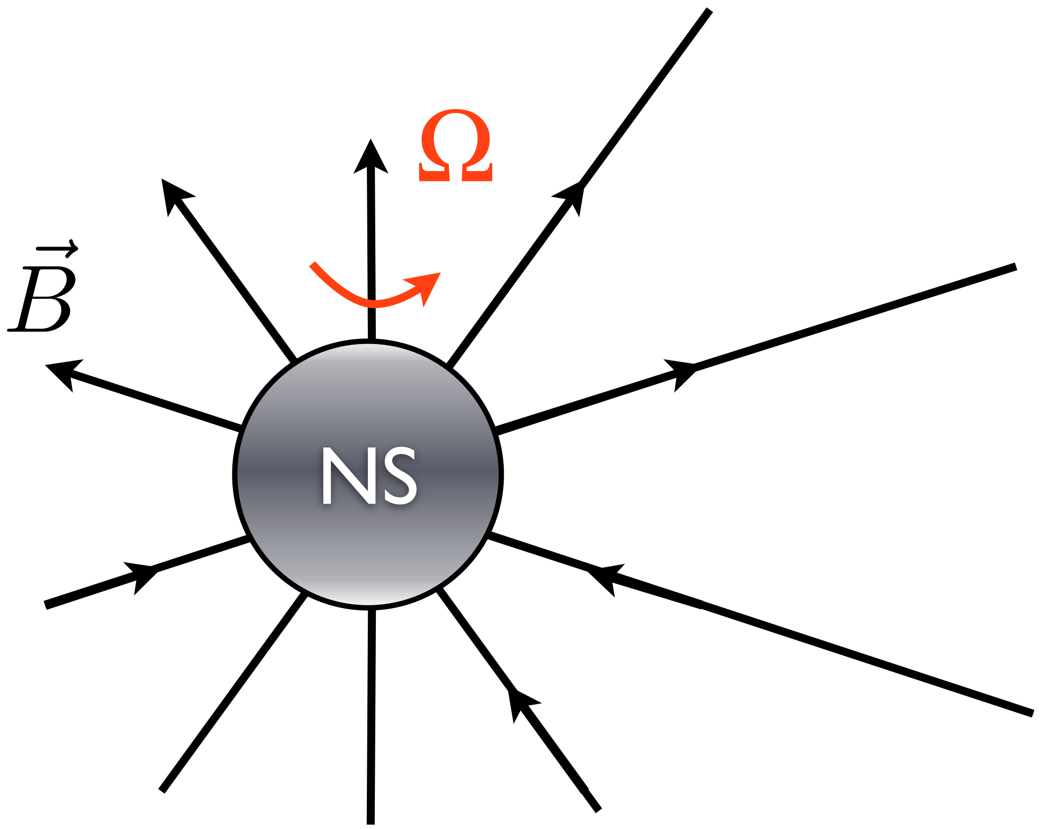

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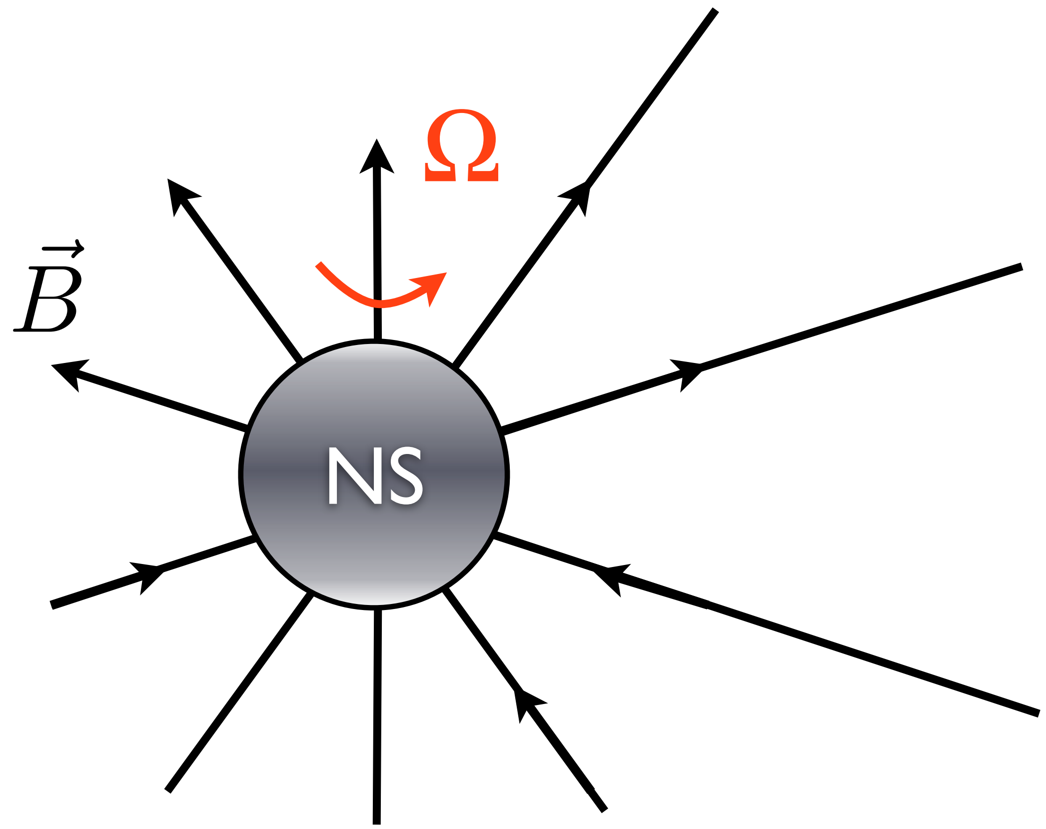

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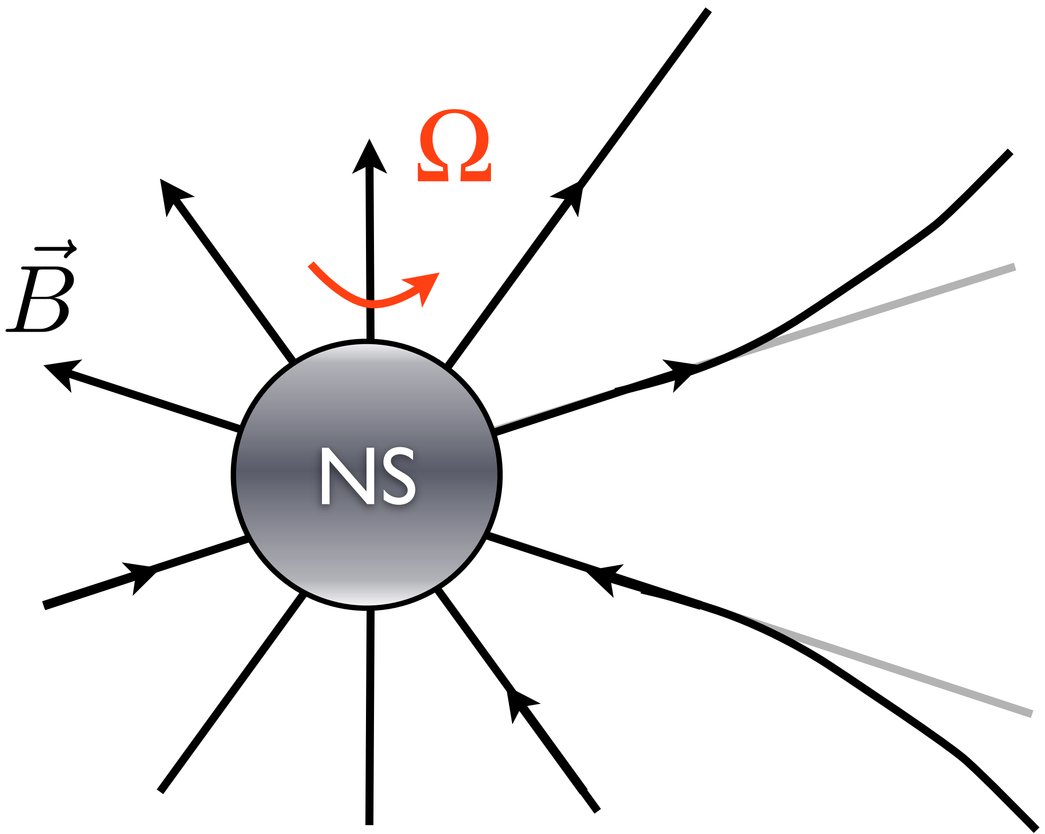

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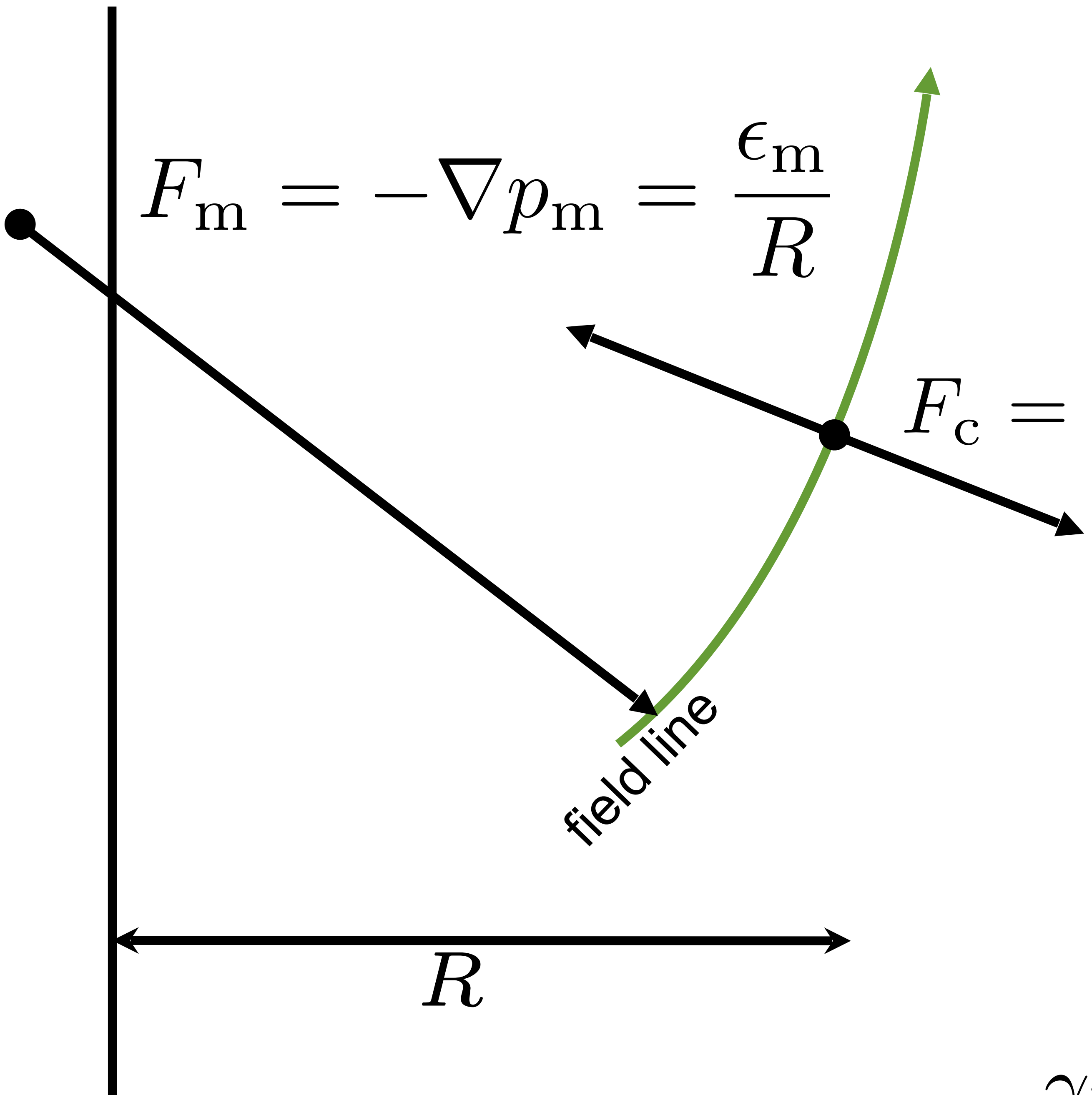
Force-balance across ***bent*** magnetic field lines, $B_\varphi^2 - E^2 \gg B_r^2$



$$F_\mathrm{m} = -\nabla p_\mathrm{m} = \frac{\epsilon_\mathrm{m}}{R}$$

$$F_\mathrm{c} = \frac{\epsilon_\mathrm{m}\gamma^2}{R_\mathrm{c}}$$

$$F_\mathrm{m} = F_\mathrm{c}$$

$$\frac{\epsilon_\mathrm{m}}{R} = \frac{\epsilon_\mathrm{m}\gamma^2}{R_c}$$

$$\gamma = \left(\frac{R_c}{R}\right)^{1/2}$$

Can combine both limits:

$$\frac{1}{\gamma^2} = \frac{1}{\gamma_1^2} + \frac{1}{\gamma_2^2}$$

$$\gamma_1 \approx \frac{\Omega R}{c} \qquad \gamma_2 \approx \left(\frac{R_c}{R}\right)^{1/2}$$

$$B_\varphi^2 - E^2 \ll B_r^2 \qquad B_\varphi^2 - E^2 \gg B_r^2$$

Alexander (Sasha) Tchekhovskoy

How do mass-loaded Jets Accelerate?

Conserved quantities along jets = ratios of conserved fluxes:

$$F_B = B_p$$

$$F_M = \gamma\rho v_p = \eta B_p$$

$$\Rightarrow \eta = \frac{F_M}{F_B} = \frac{\gamma\rho v_p}{B_p} = \text{const}$$

$$F_E = \underbrace{F_{EM}}_{=\frac{cEB_\varphi}{4\pi}} + \underbrace{F_{KE}}_{=\gamma F_M}$$

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$$\boxed{\frac{\gamma}{\mu} = 1 - \frac{\pi B_p R^2}{\Phi}}$$

In order to accelerate efficiently, need reduction in local field line density (Komissarov+09, AT+09)

Alexander (Sasha) Tchekhovskoy

Acceleration in a magnetic nozzle

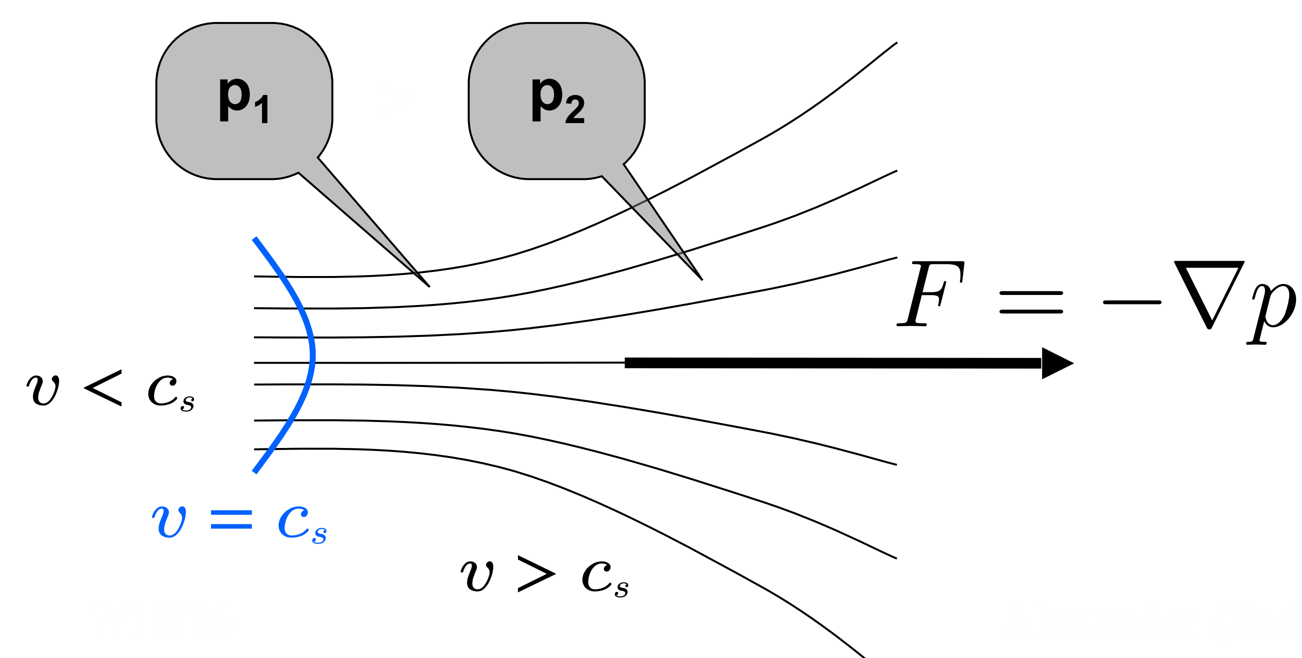
(Begelman & Li 1994, Komissarov 2009, AT+ 2009)

$$\boxed{\frac{\gamma}{\mu} = 1 - \frac{\pi B_p R^2}{\Phi}}$$

If $B_P(R) = \mathrm{const}$, no acceleration.

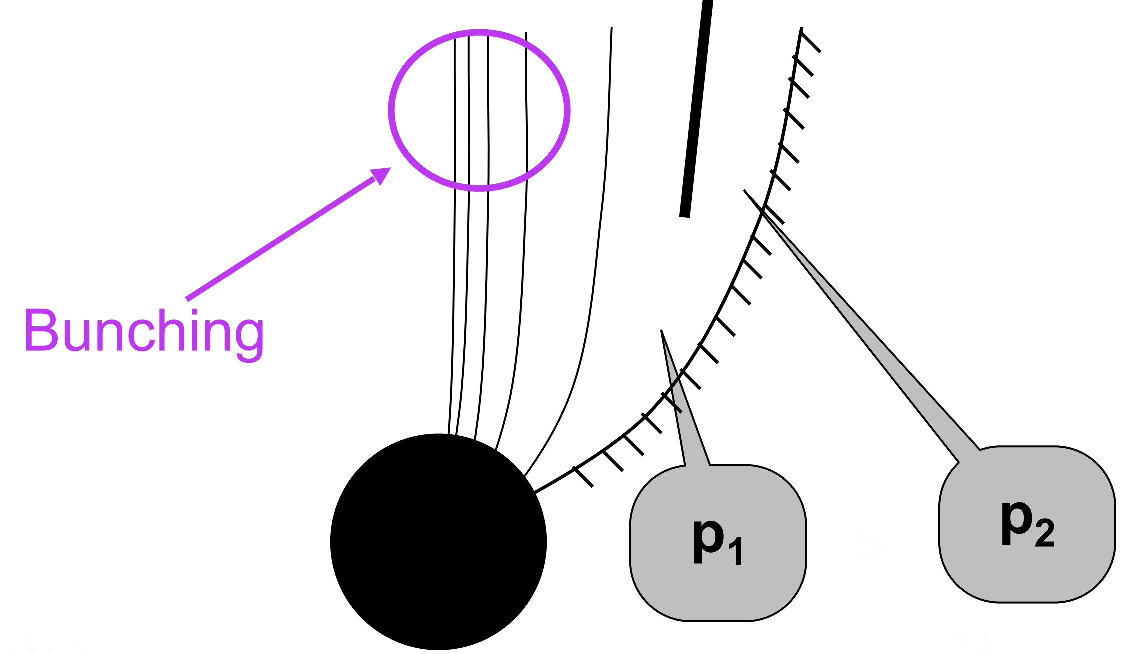
Need magnetic flux bunching toward jet axis.

Hydro: de Laval nozzle: flow opens up after sonic surface → pressure drops → ∇p accelerates flow:

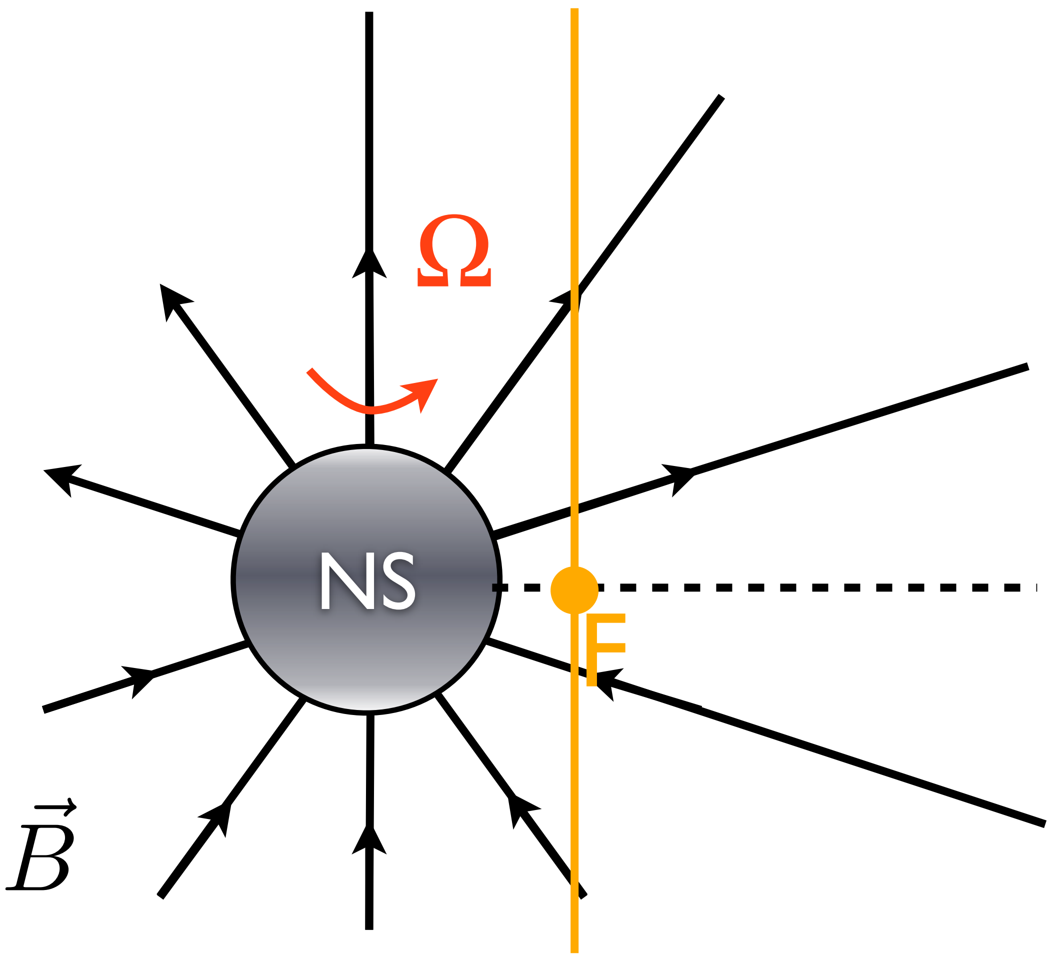


MHD: reduction in field line density as the rest of field lines bunch up at the jet axis.

$$F = -\nabla p$$



When Can Jets Accelerate?



- Communication is essential
- All signals travel inside the Mach cone ξ:

$$\xi = \frac{\gamma_{\mathrm{F}}}{\gamma} \approx \frac{\sigma^{1/2}}{\gamma}$$

- For communication across jet need $\theta \lesssim \xi$, so

$$\gamma\theta \lesssim \sigma^{1/2} = \left(\frac{\mu}{\gamma}\right)^{1/2}$$

- Thus:

$$\gamma \lesssim \frac{\mu^{1/3}}{\theta^{2/3}}$$

- Jets accelerate better near the axis

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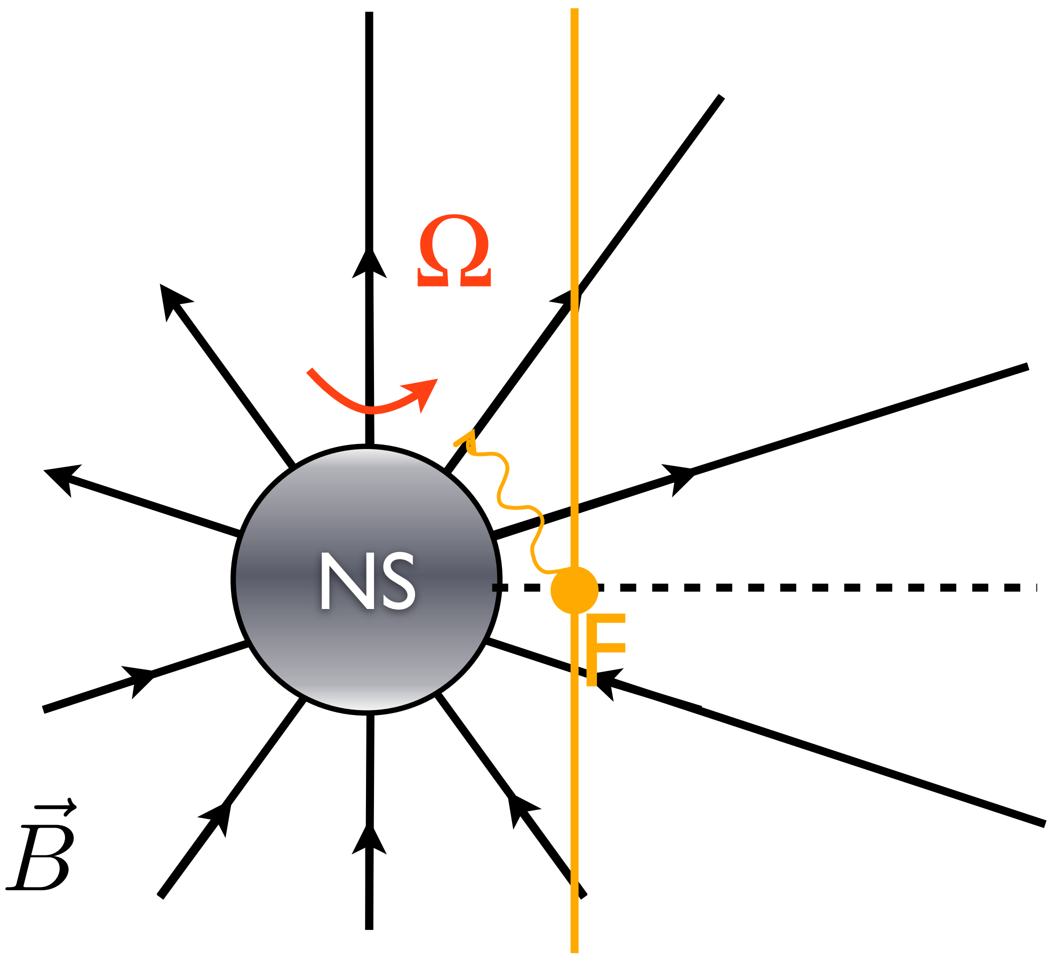

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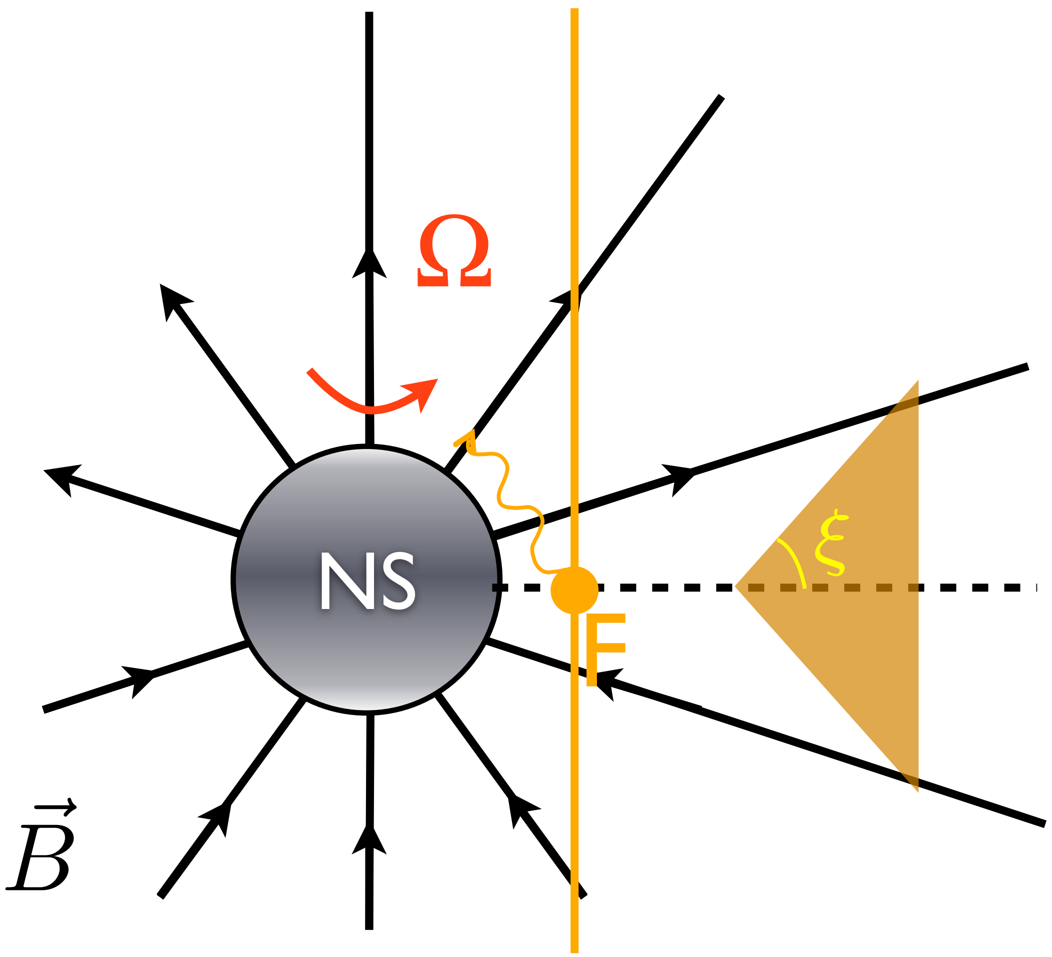

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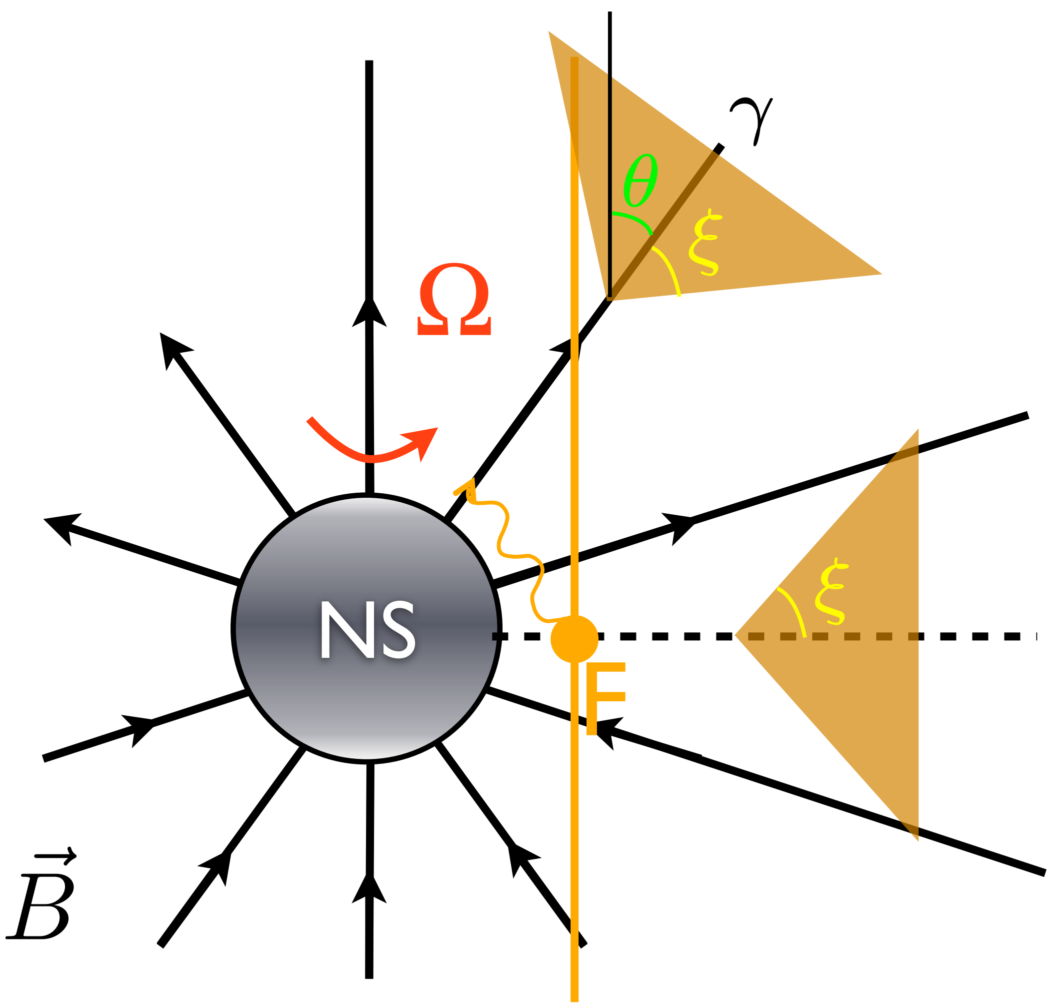

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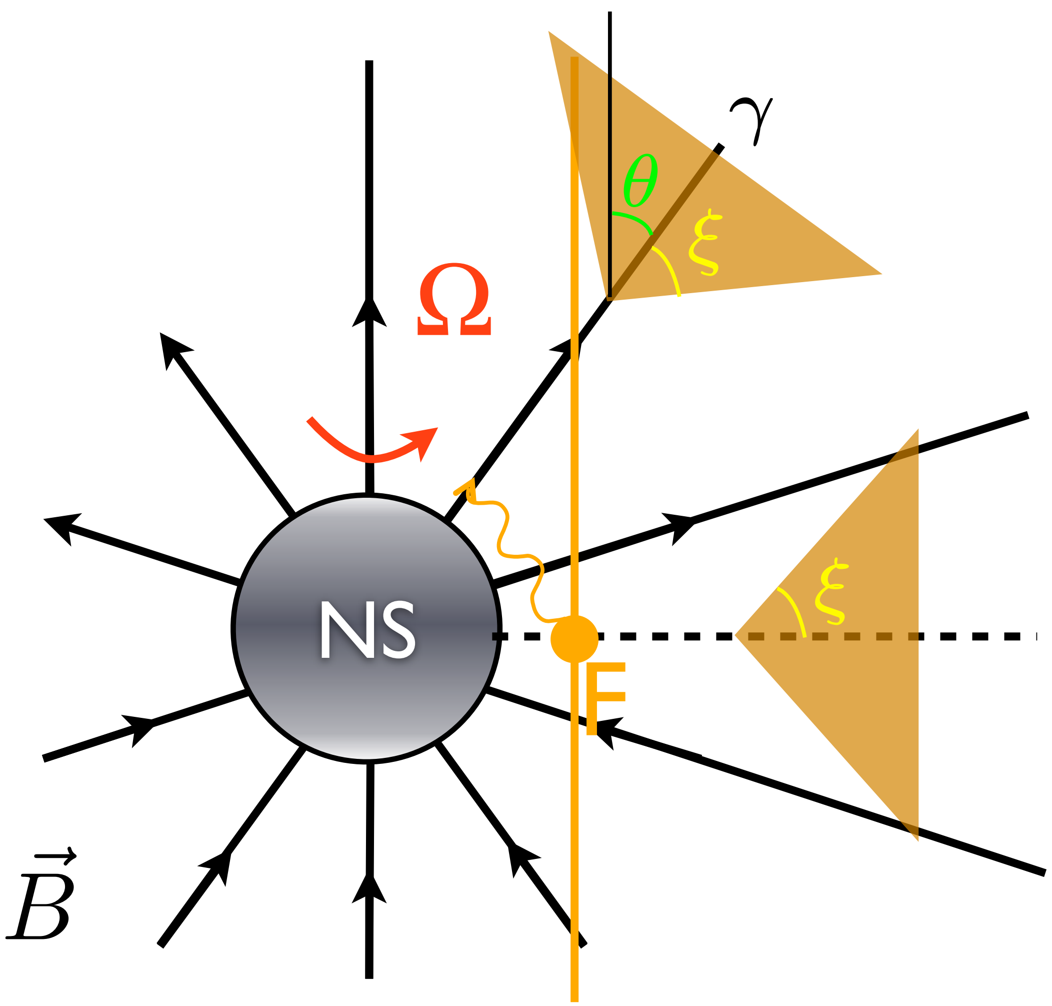
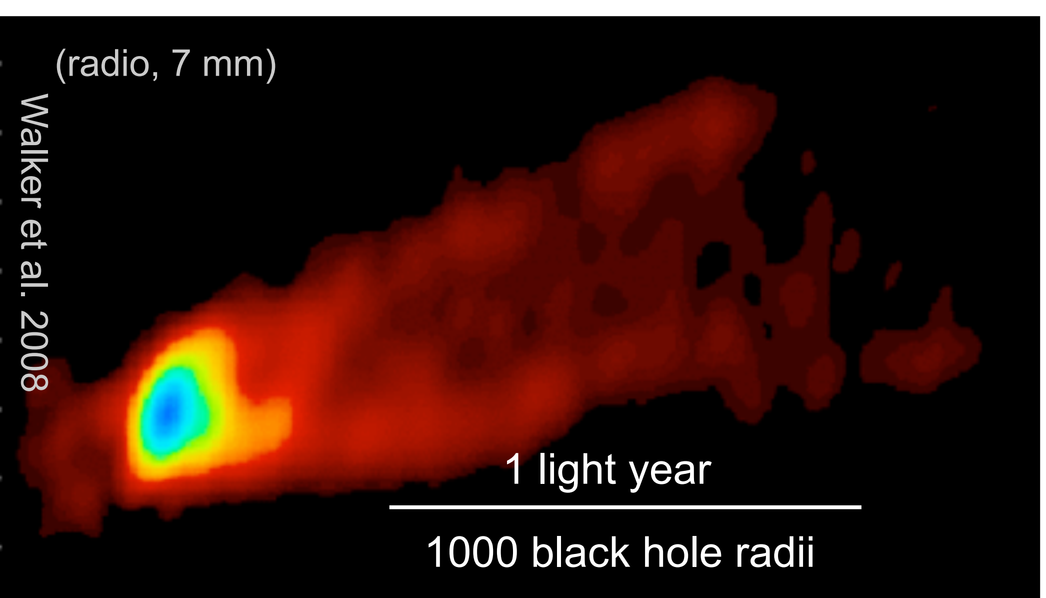


but, most jets are collimated:



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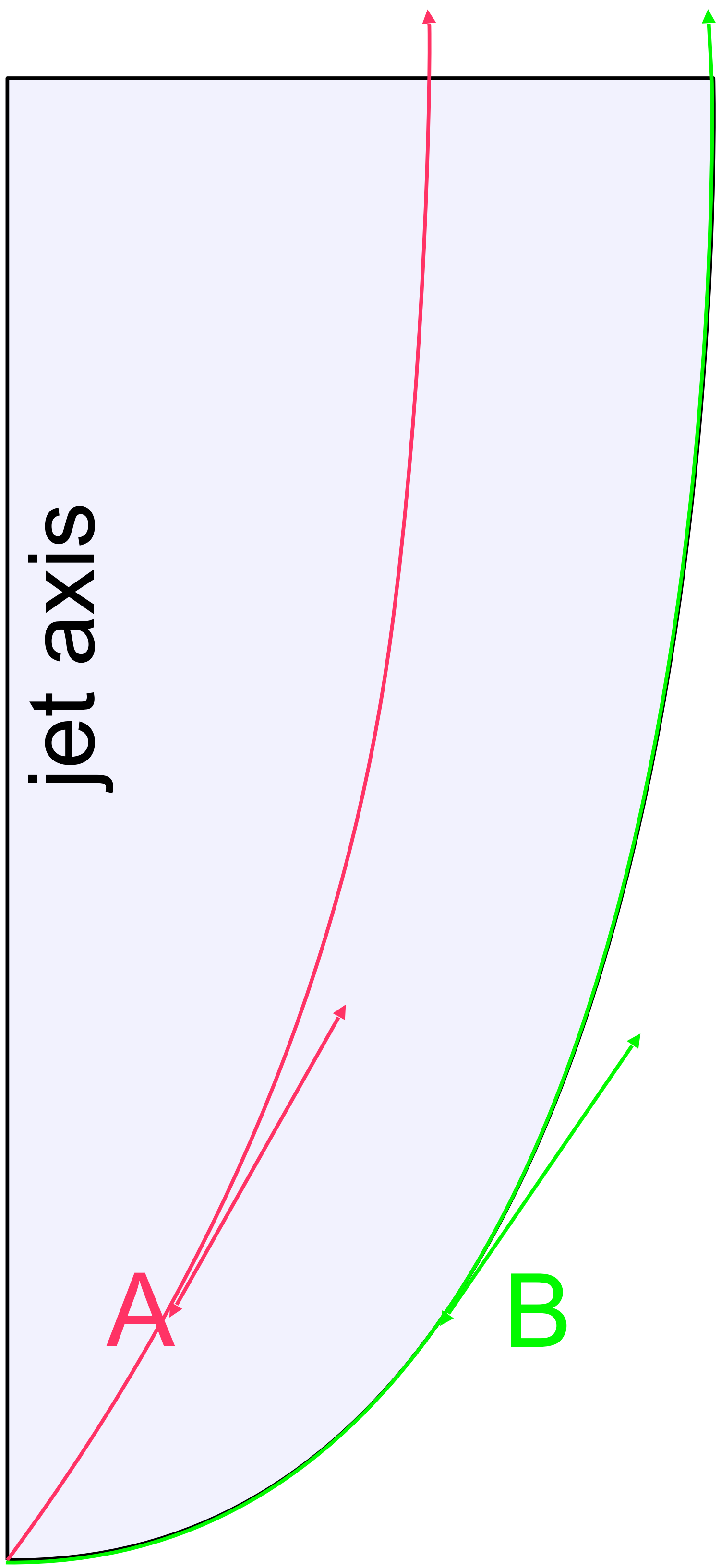

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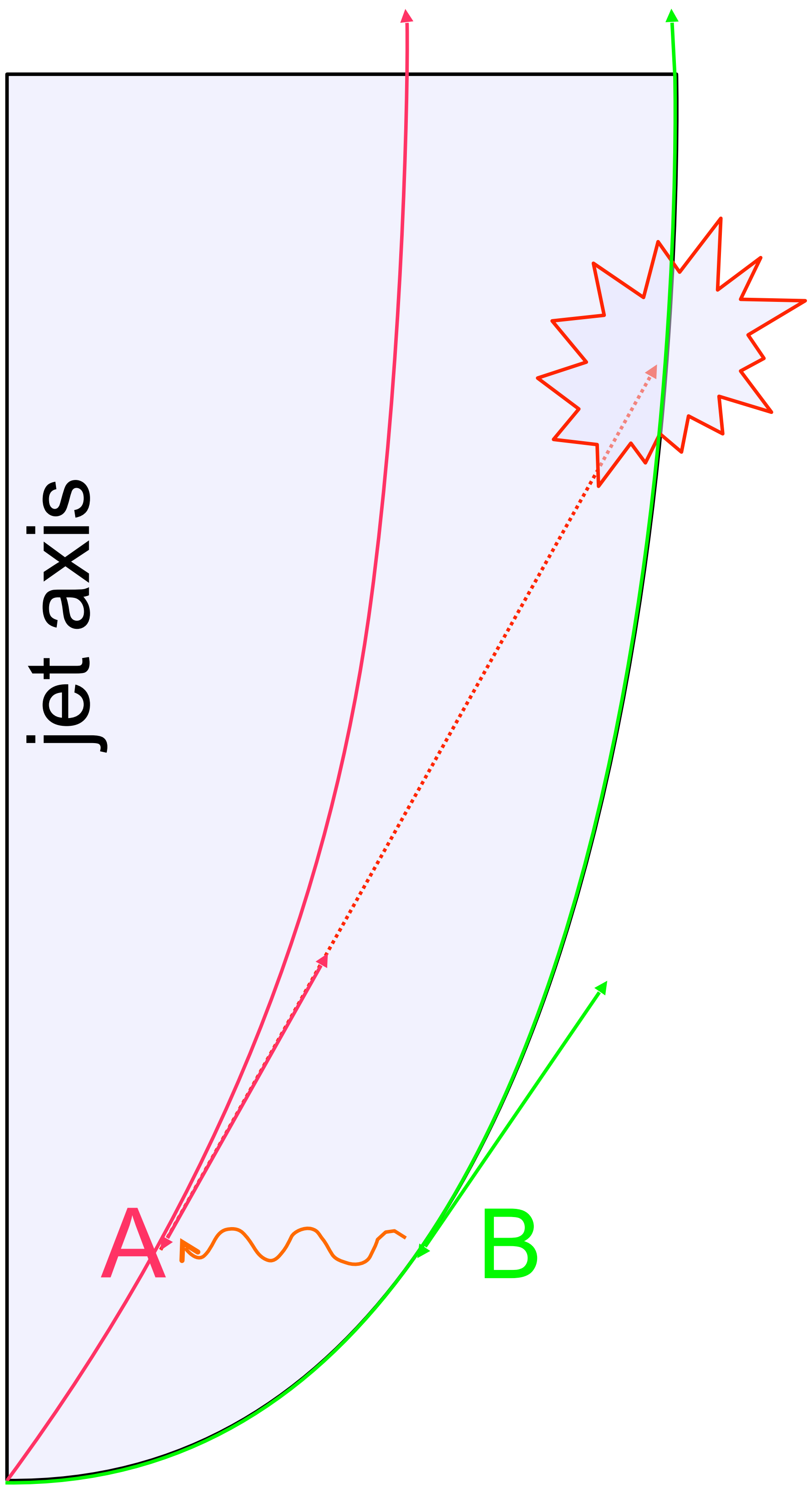

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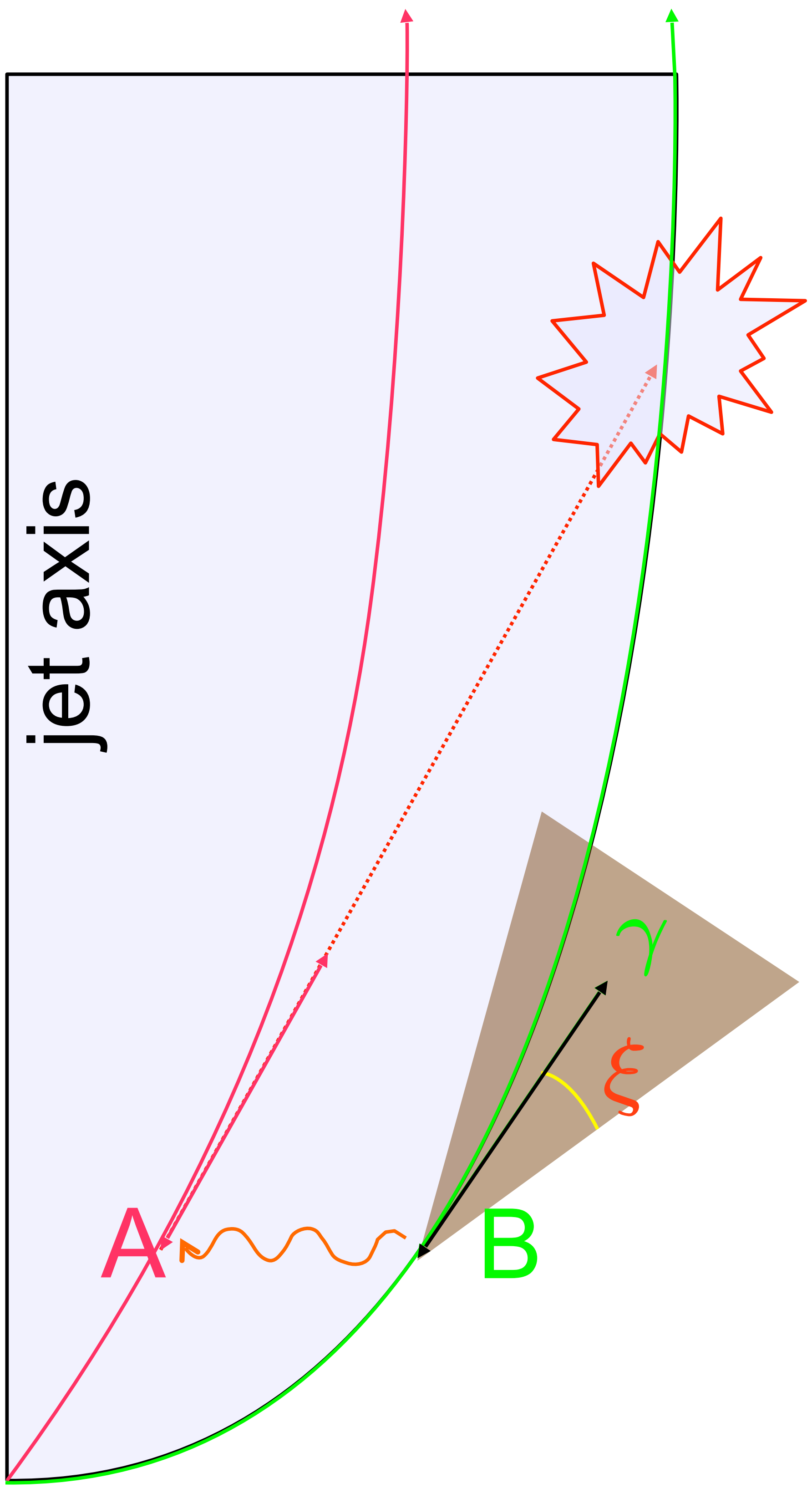

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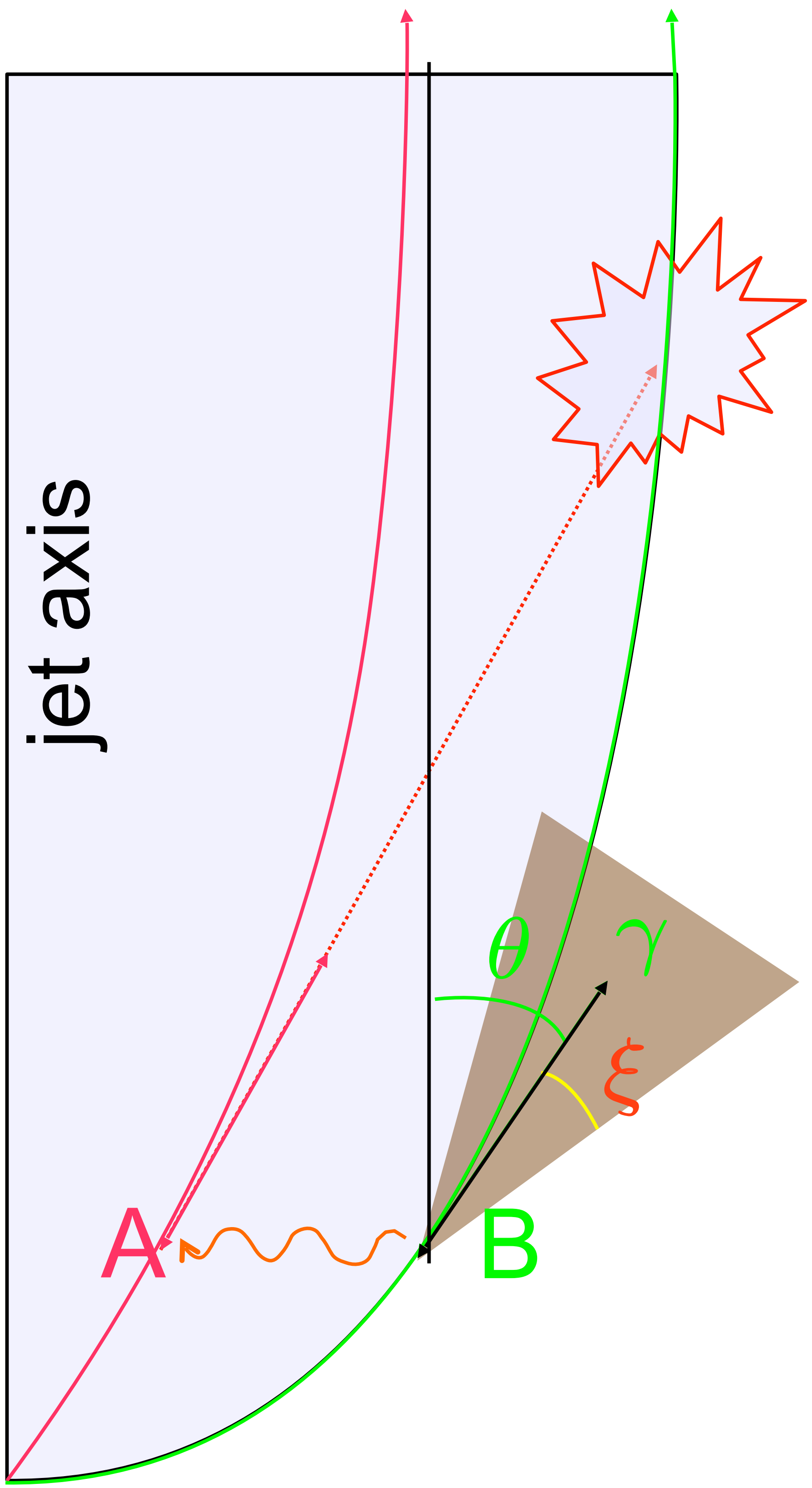

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- For communication across jet need $\theta \lesssim \xi$, so $\theta \lesssim \sigma^{1/2}/\gamma$
- Robust conclusion: $\gamma\theta \lesssim \sigma^{1/2}$
- Collimated jets accelerate efficiently

What Do We Observe?

- *Expect* in collimated jets: $\gamma\theta \lesssim \sigma^{1/2} \lesssim 1$
- Observe:
  - Active Galactic Nuclei: $\gamma\theta \sim 0.1{-}0.2$
  - Gamma-ray bursts (GRBs): $\gamma\theta \sim 10{-}100$
- Does it mean that GRB jets are unmagnetized?

GRB Jets: Problem Setup

Simulations of magnetized confined jets:

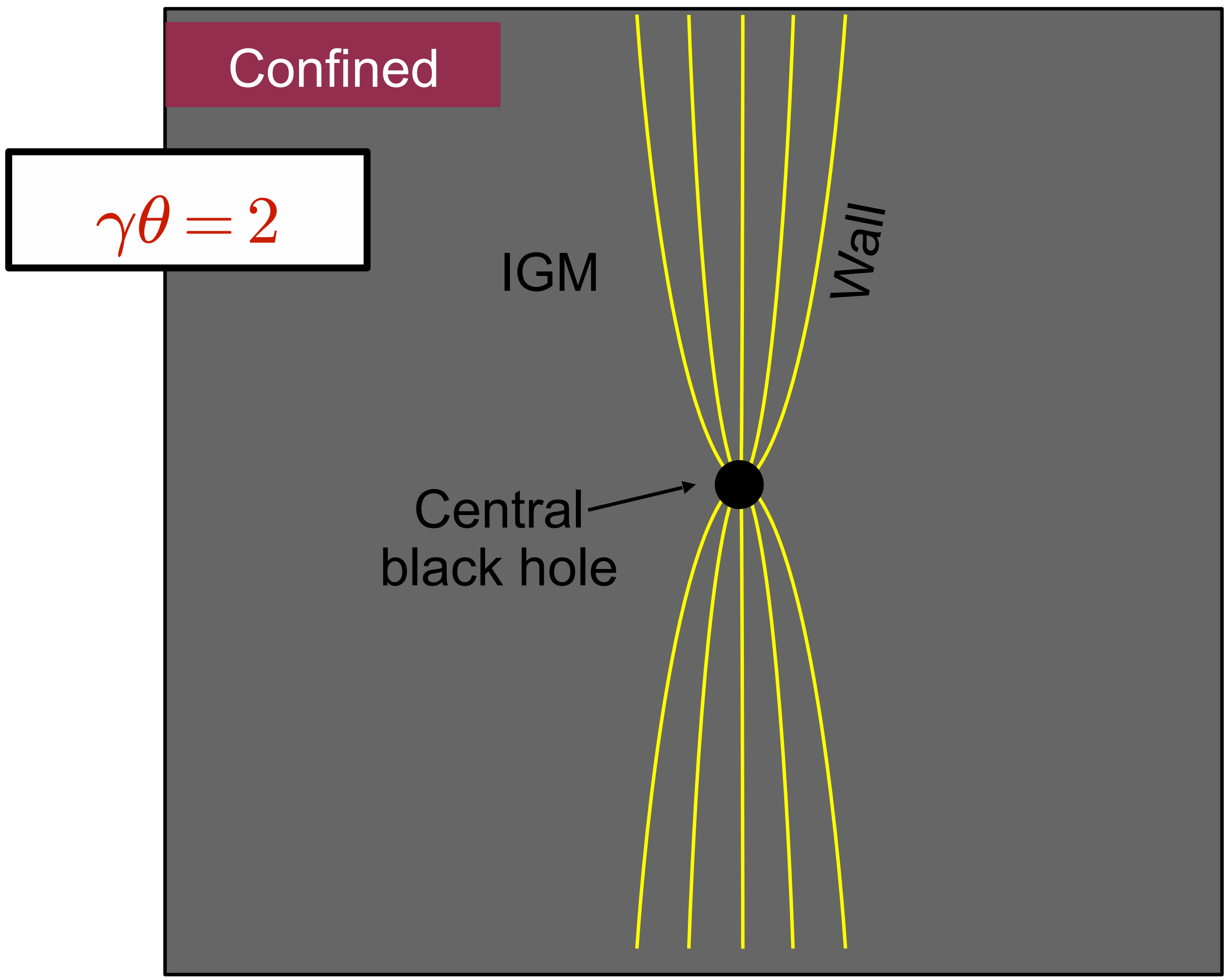
$\gamma\theta \lesssim 1$

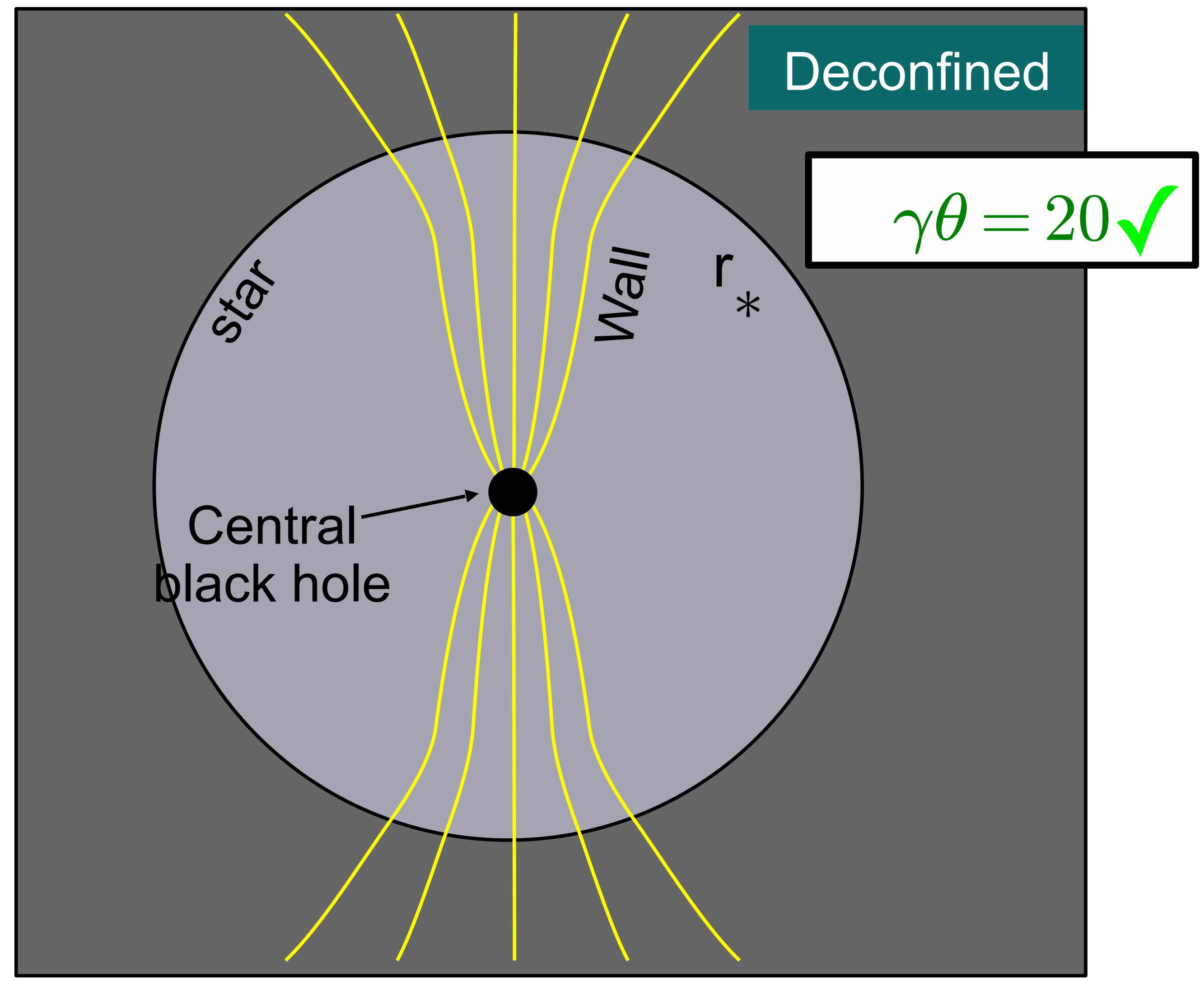
(Komissarov et al., MNRAS, 2009)

GRB jets are DEconfined:

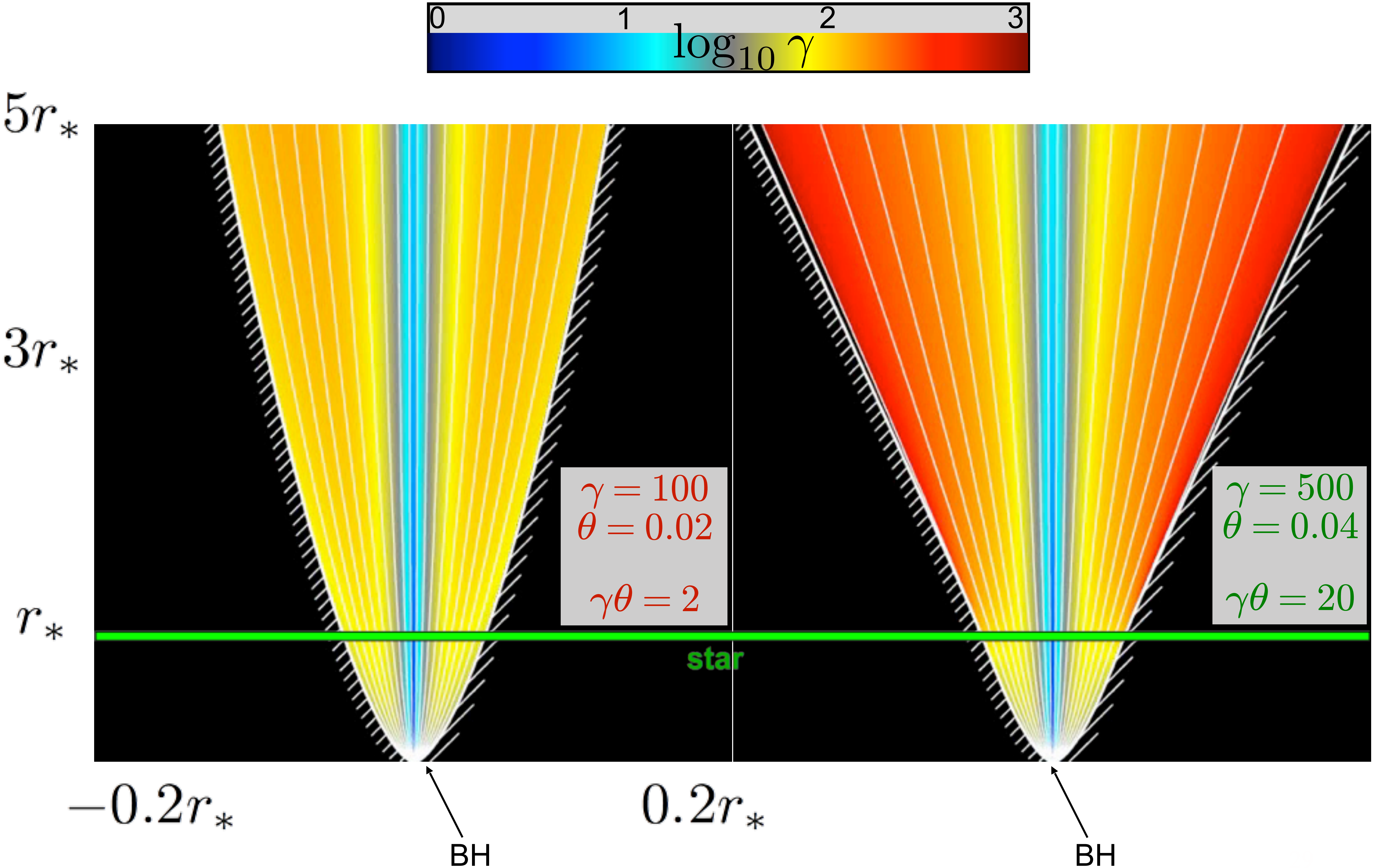
$\gamma\theta \gtrsim 10$

(Tchekhovskoy, Narayan, McKinney, New Astronomy, 2010)

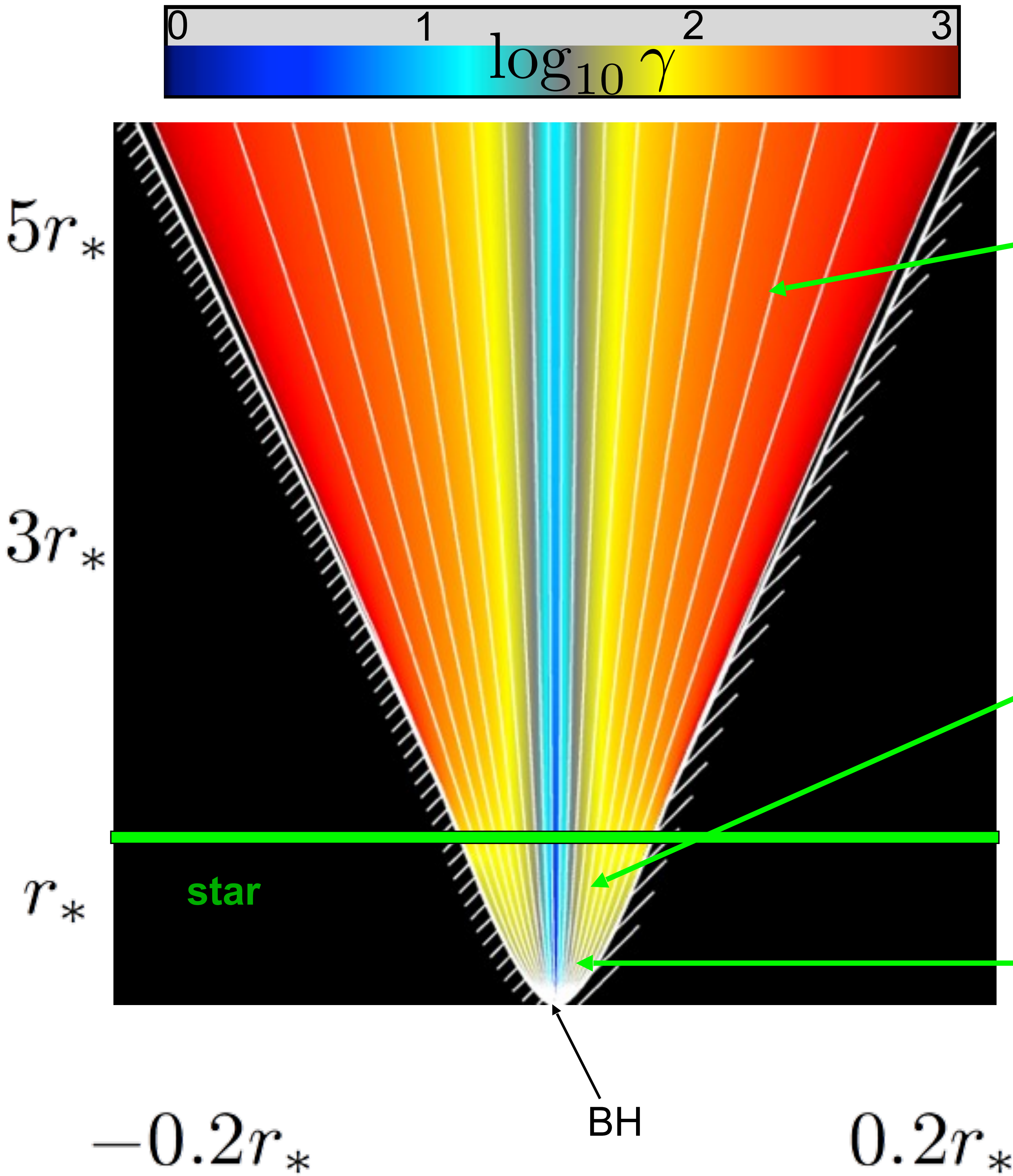




Confined vs. Deconfined



Jet Structure Summary



Fully unconfined jet:

$$\gamma\theta \simeq 20\sigma^{1/2}$$ (AT+ 2010)

Fully confined jet, large distance. Centrifugal force limits jet velocity (AT+ 2008):

$$\gamma \approx \left(\frac{R_c}{R}\right)^{1/2}$$

Fully confined jet, small distance. Linear increase:

$$\gamma \approx \Omega R/c$$ (Michel 1969)

Magnetic Summary

- Rotation + large-scale magnetic flux ➛ jets
- Black holes do not have their own magnetic flux, and rely on accretion disks for flux supply
- Jet power increases with rotational frequency squared and magnetic flux squared
- Jets naturally accelerate magnetically, but only collimating jets do so well
- Many jets are consistent with being powered magnetically, but other processes such as radiative driving can also be at play (see Jim Stone's lecture)

Homework

- Exercises with HARMPI code: fully parallel, 3D general relativistic MHD code
  - MONOPOLE_PROBLEM_1D
  - MONOPOLE_PROBLEM_2D
- Documentation and download at: https://github.com/atchekho/harmpi