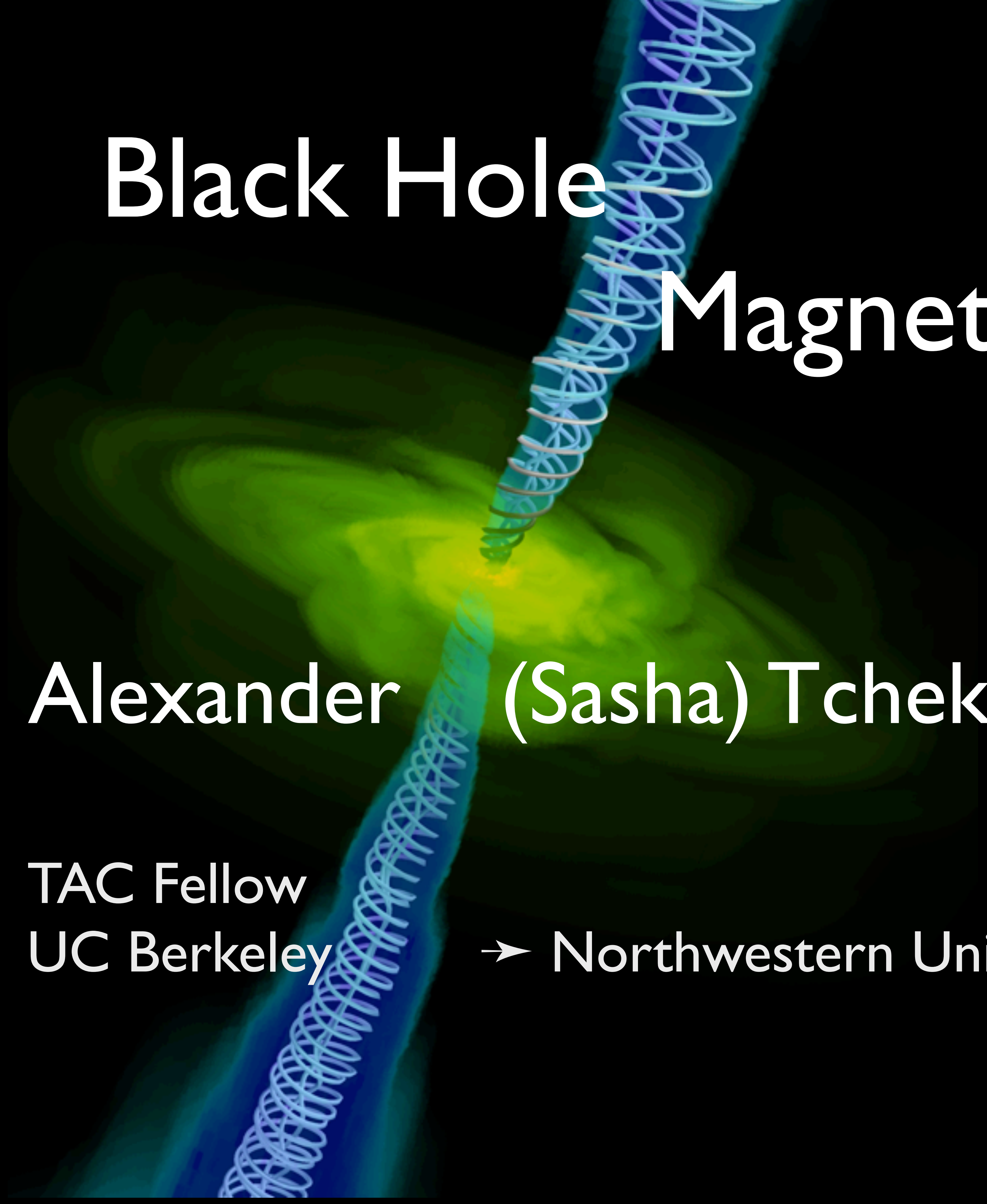


Black Hole Magnetospheres

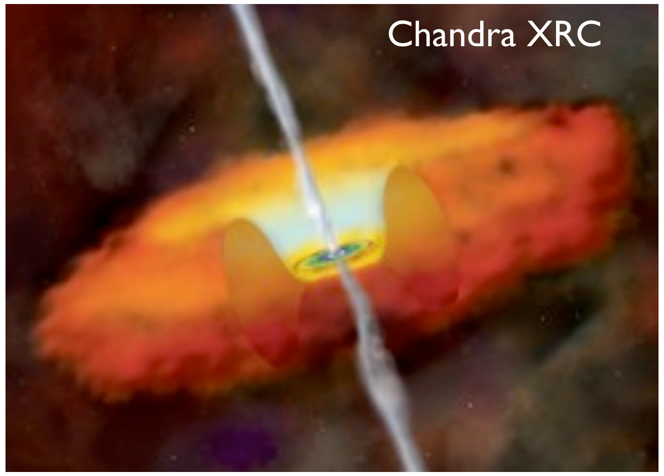
Alexander (Sasha) Tchekhovskoy

TAC Fellow
UC Berkeley ➛ Northwestern University

Black Holes Power Many Transients

Supermassive

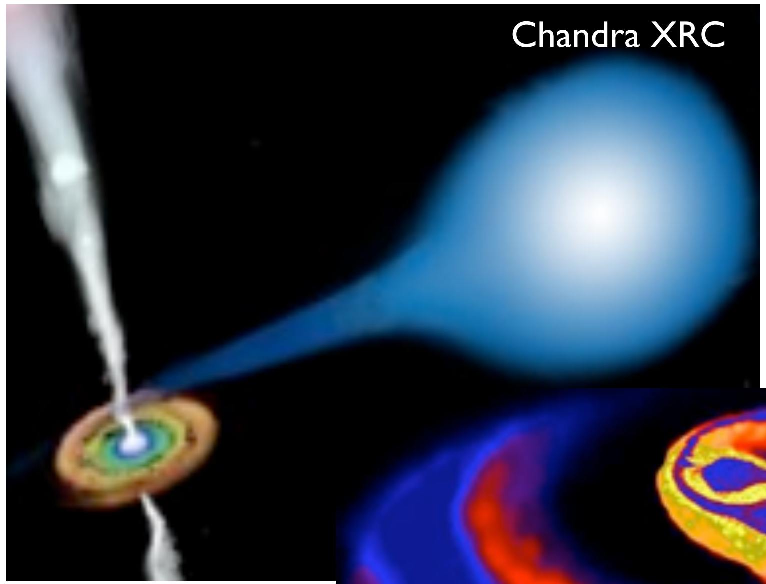
$M \sim 10^{6-10} M_\odot$



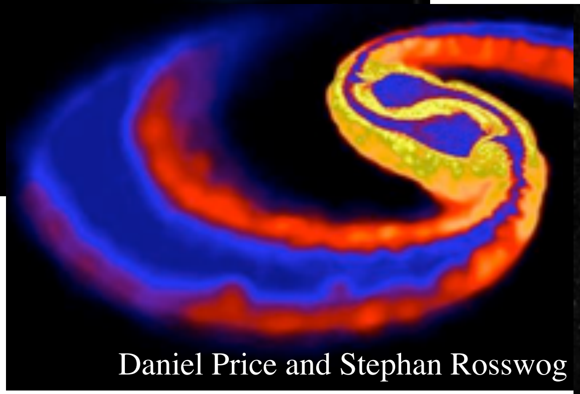
Quasars/AGN

Stellar-mass

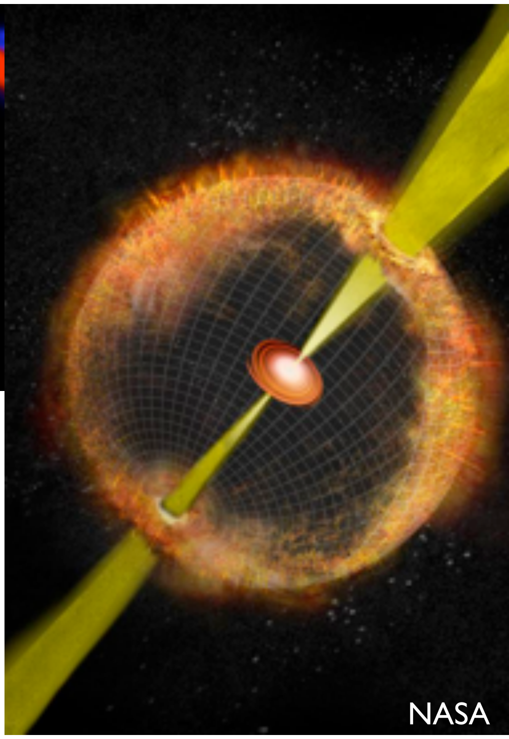
$M \sim \text{few}-10 M_\odot$



Black Hole Binaries


Daniel Price and Stephan Rosswog

Gamma-ray bursts


NASA

Black hole or Neutron star

(AT 2015)

Alexander (Sasha) Tchekhovskoy

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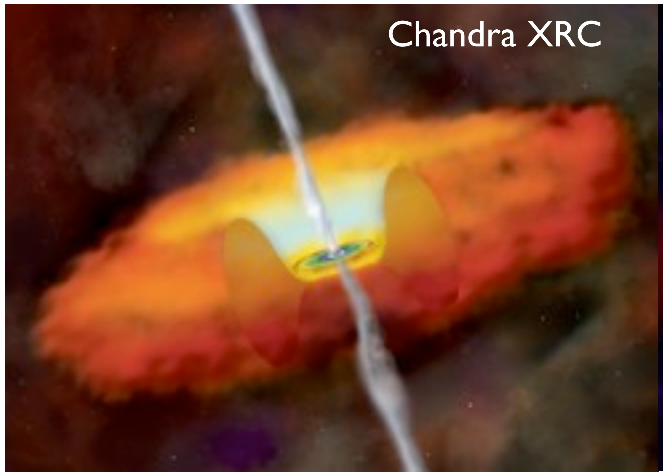
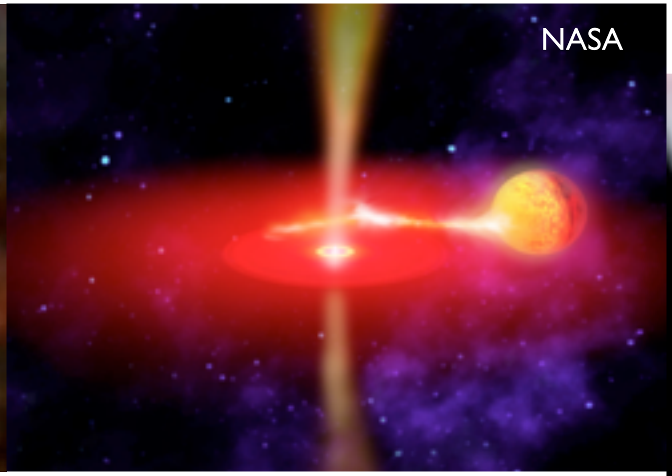


Quasars/AGN

Intermediate

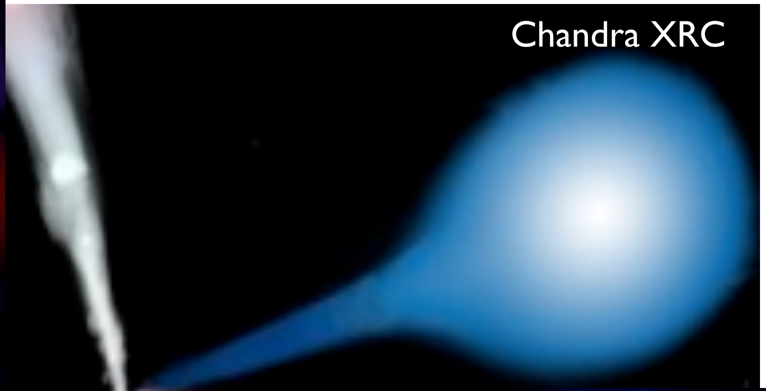
$M \sim 10^{2-5} M_\odot$



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

—— Stellar-mass ——

$M \sim \mathrm{few}{-}10 M_\odot$



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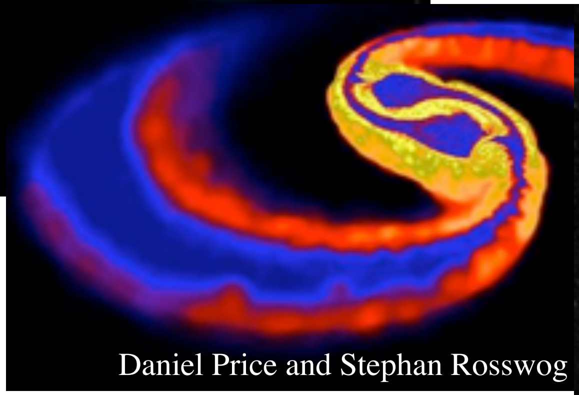

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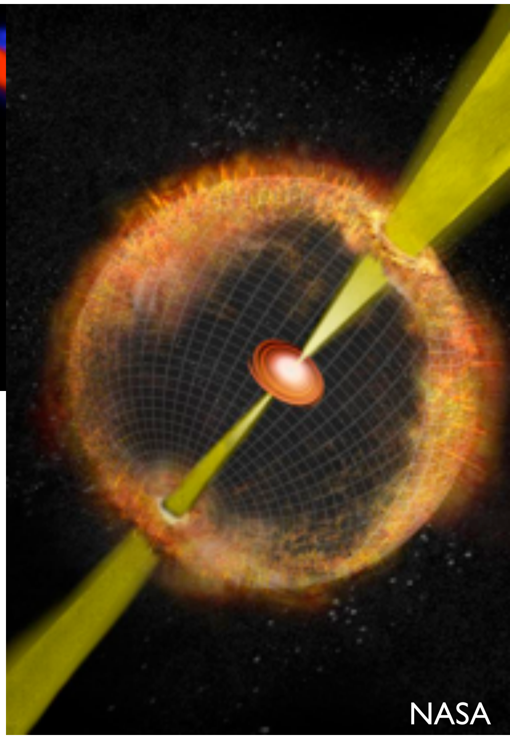

Black hole or Neutron star

(AT 2015)

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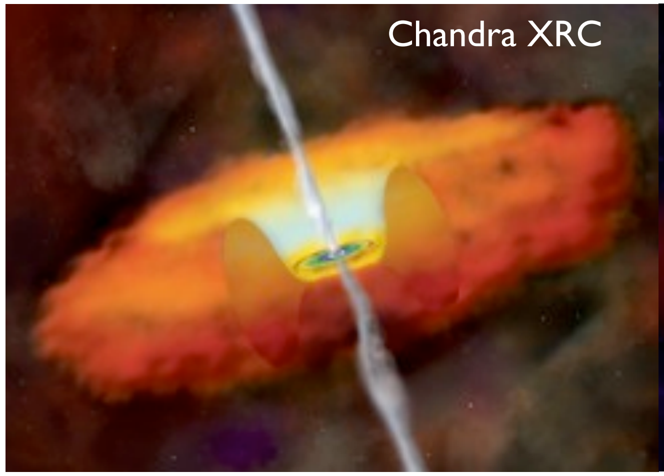
Chandra XRC

Quasars/AGN

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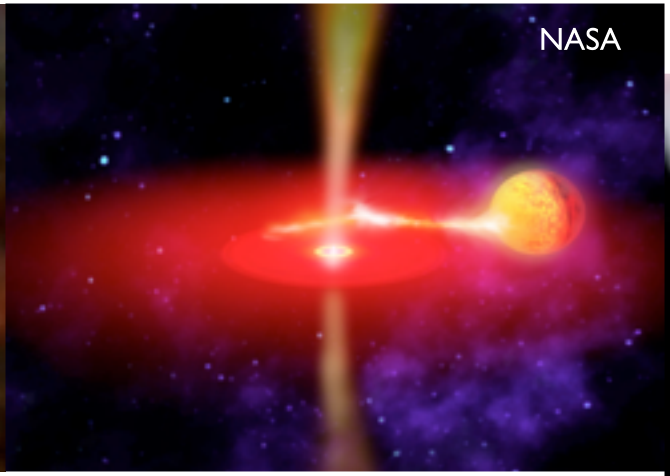
NASA

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

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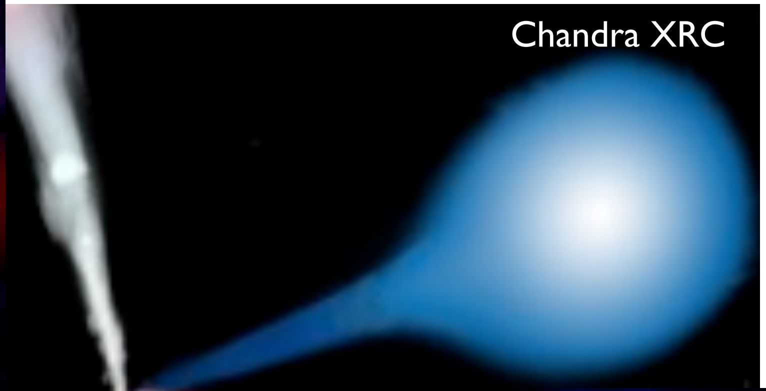
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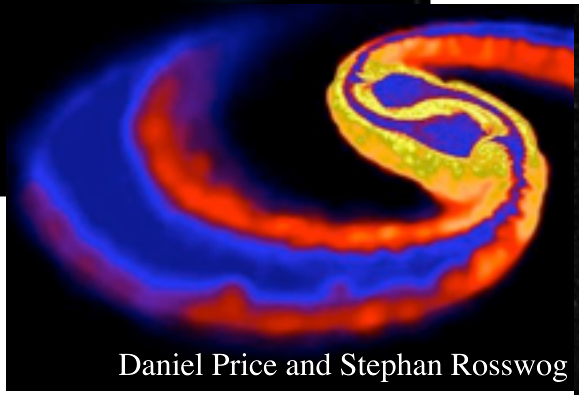
Black Hole Binaries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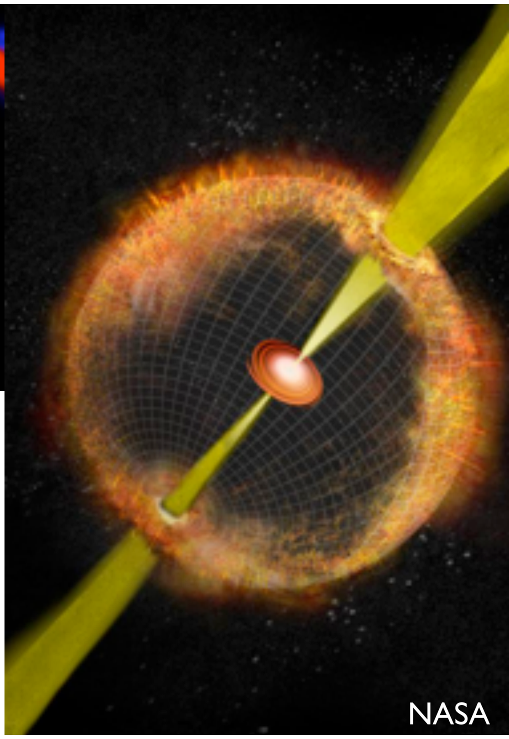
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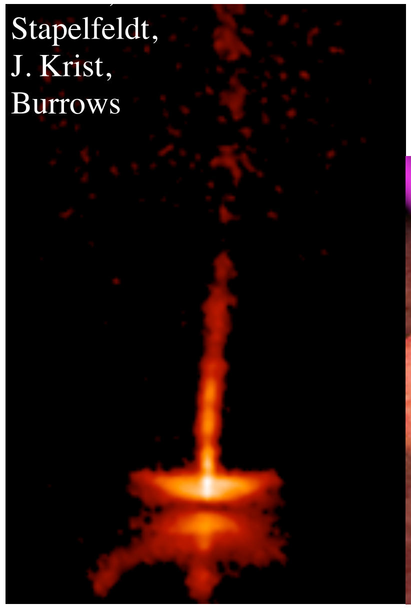
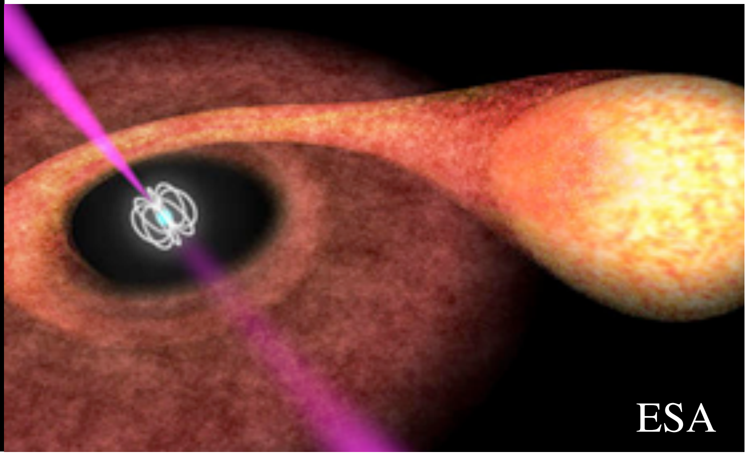

Stapelfeldt, J. Krist, Burrows

Stars


ESA

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

(AT 2015)

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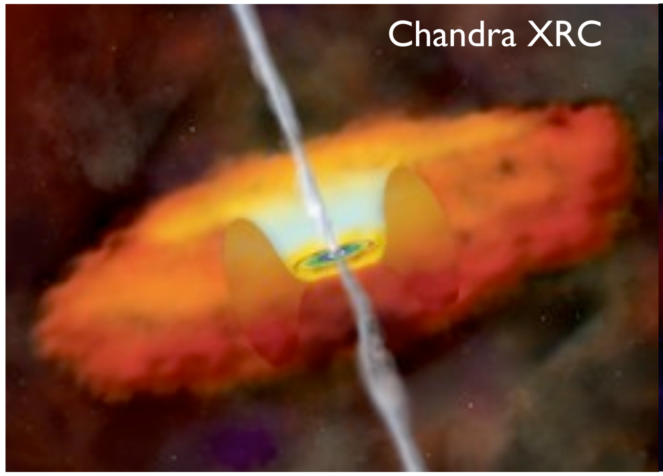
Chandra XRC

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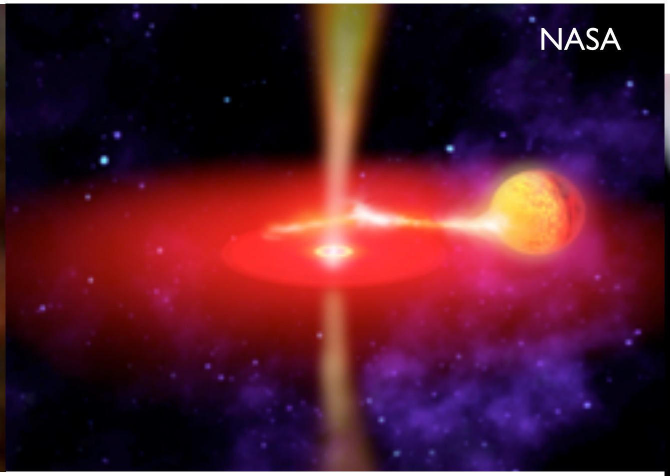
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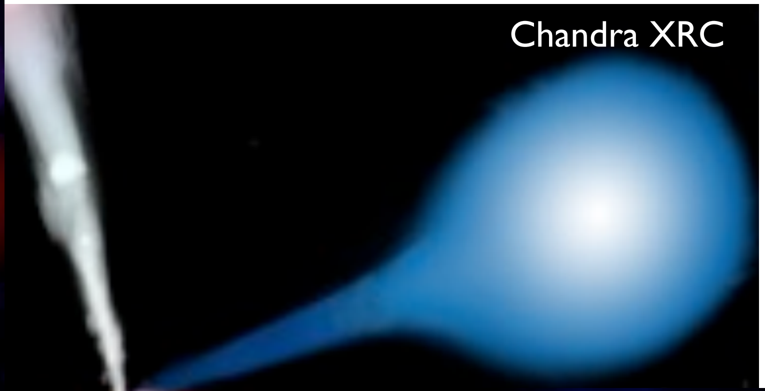
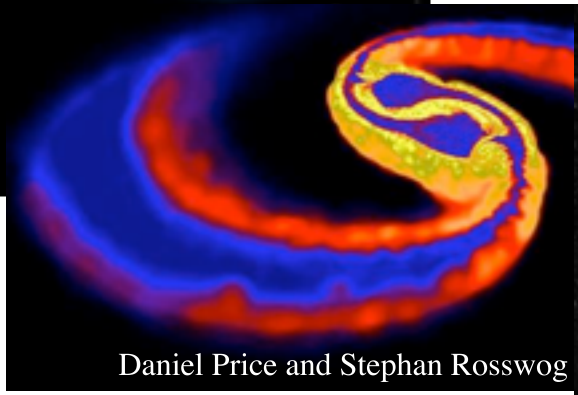
Intermediate-mass black holes/ultra-luminous X-ray sources?


Chandra XRC

Black Hole Binaries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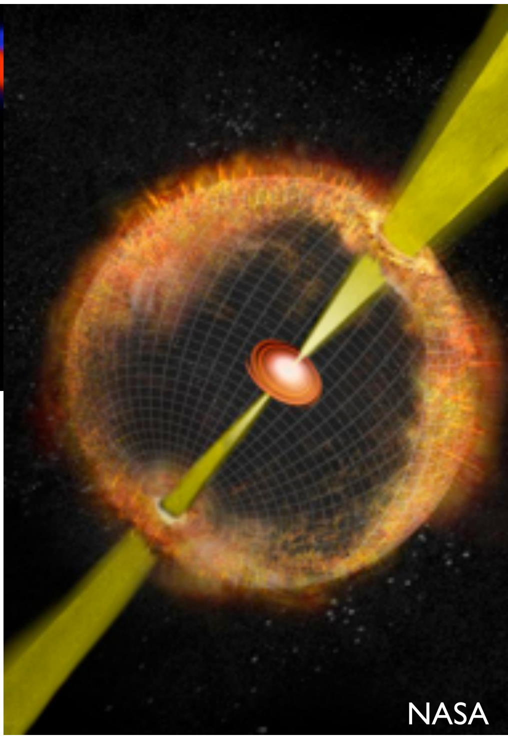
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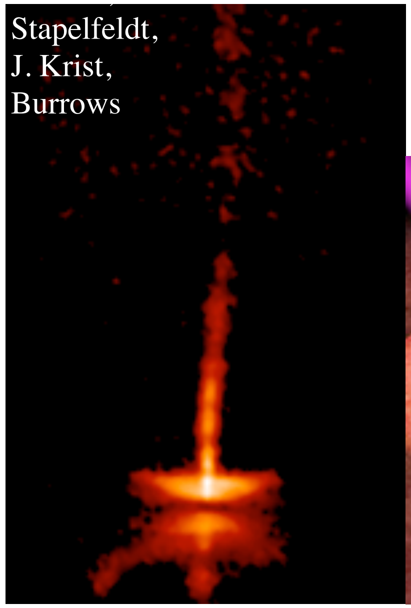
Black hole or Neutron star


Stapelfeldt, J. Krist, Burrows

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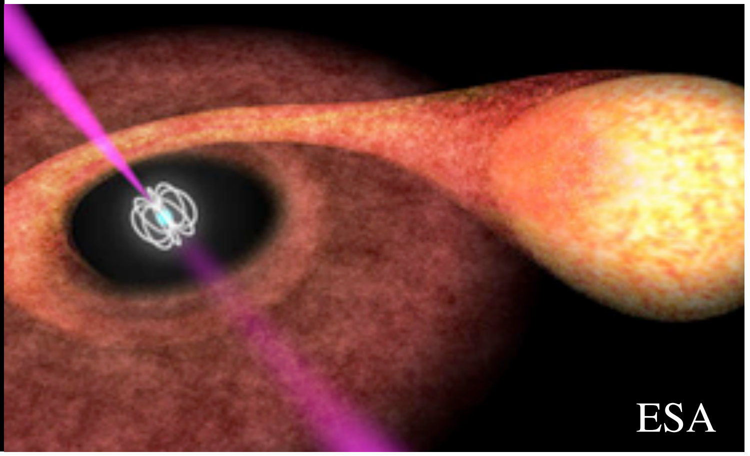
ESA

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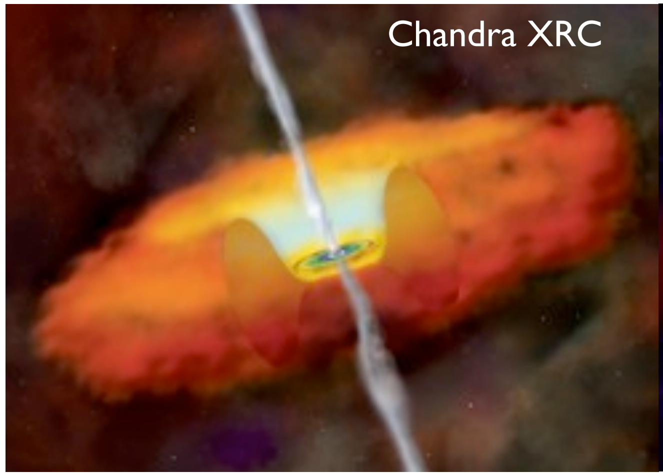
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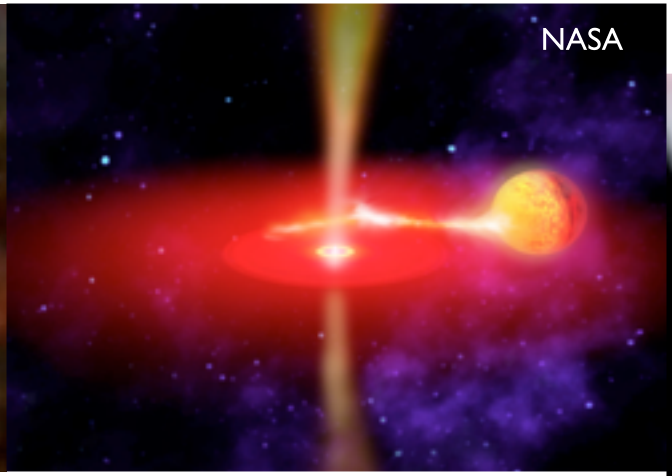
Quasars/AGN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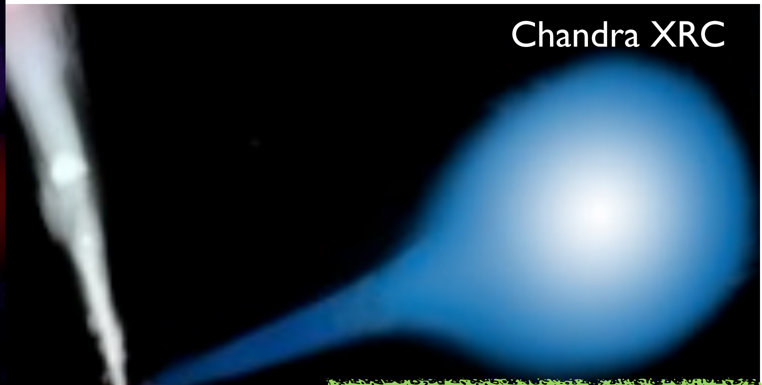
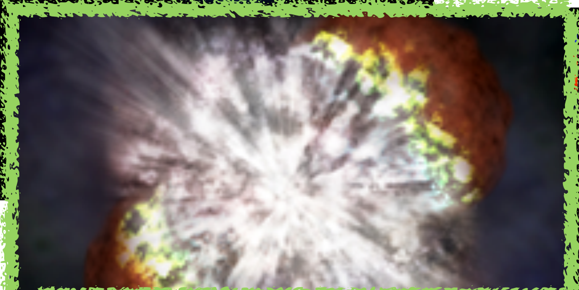
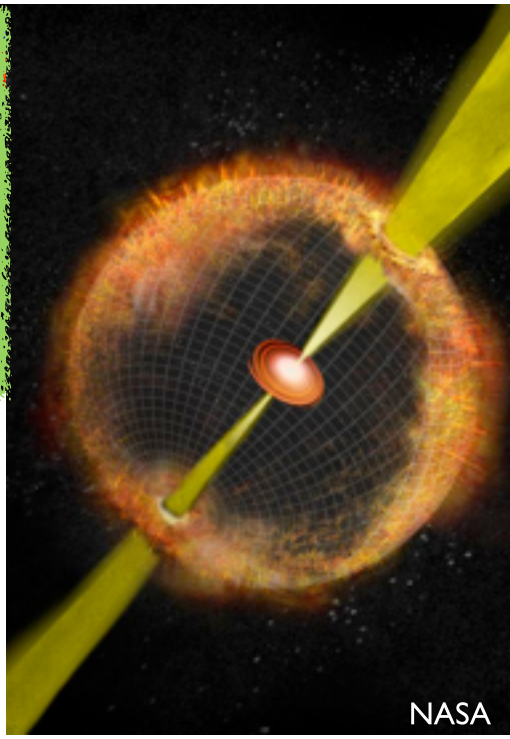

Chandra XRC

Black Hole Binaries



factories of heavy elements, "*kilonovae*"

bursts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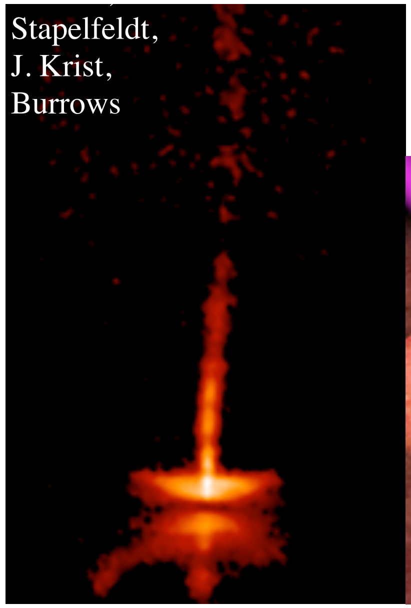
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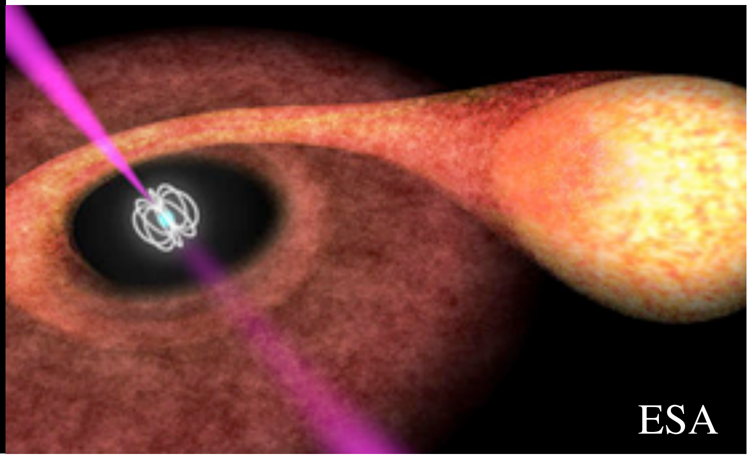
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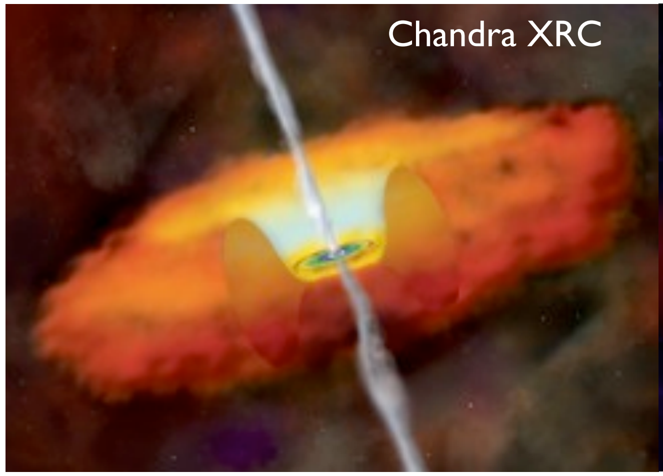

Chandra XRC

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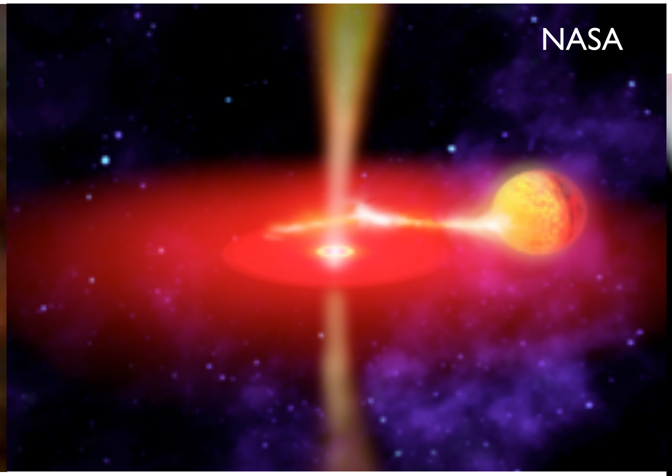

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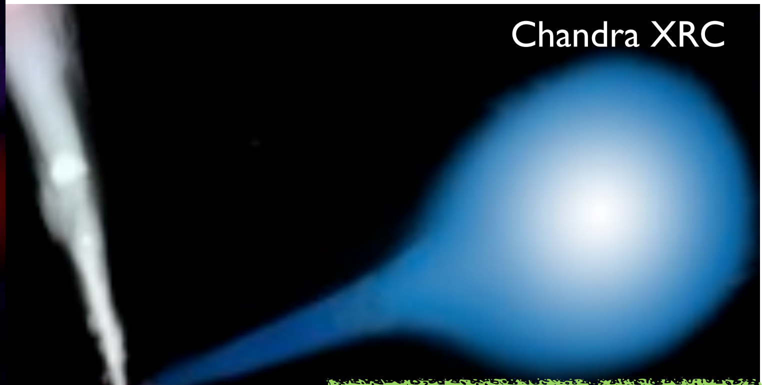

Chandra XRC

Black Hole Binaries

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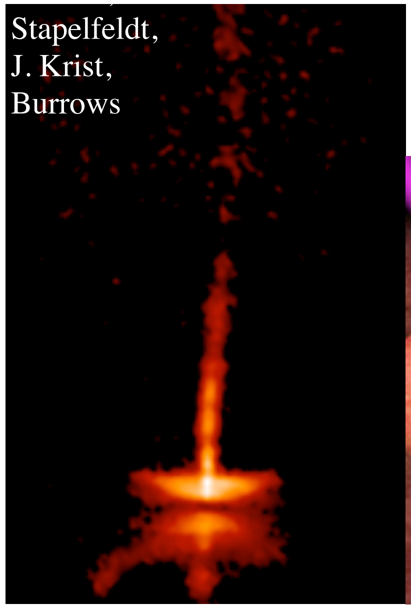
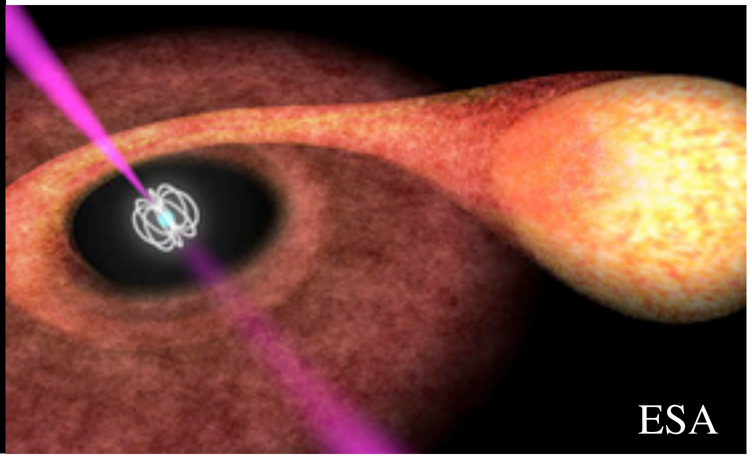
Neutron star



Stapelfeldt, J. Krist, Burrows

Stars



ESA

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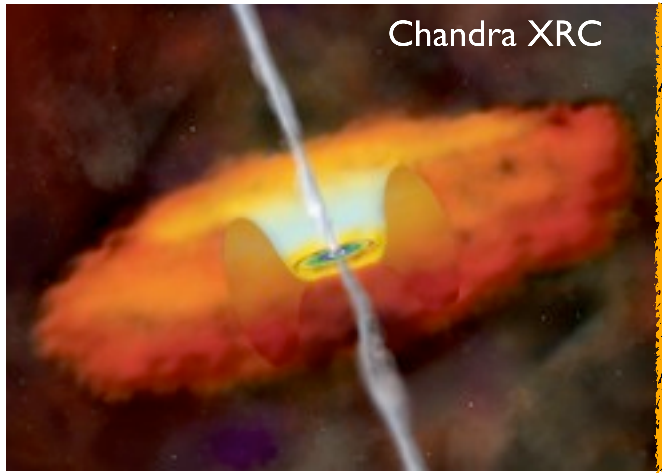

Quasars/AGN

turn out to be neutron stars

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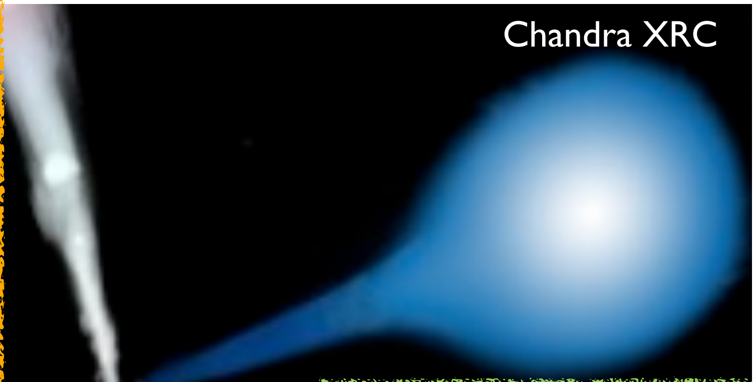

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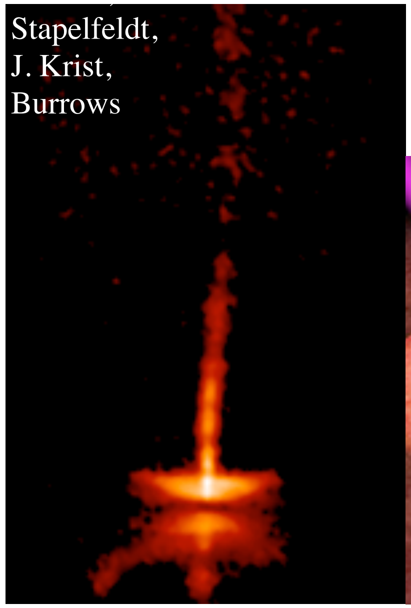

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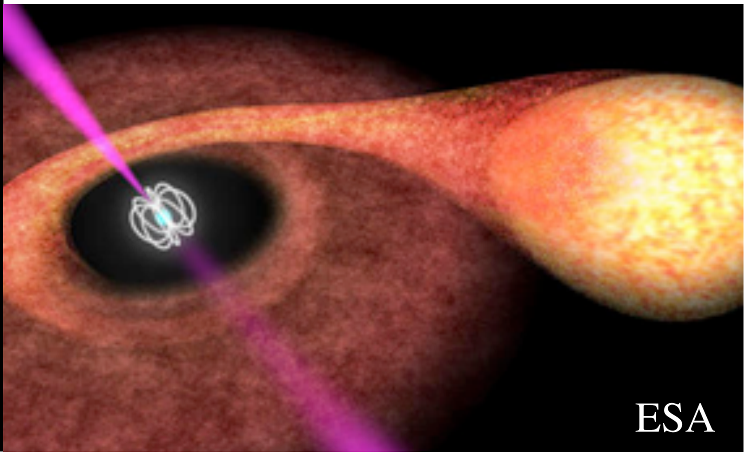

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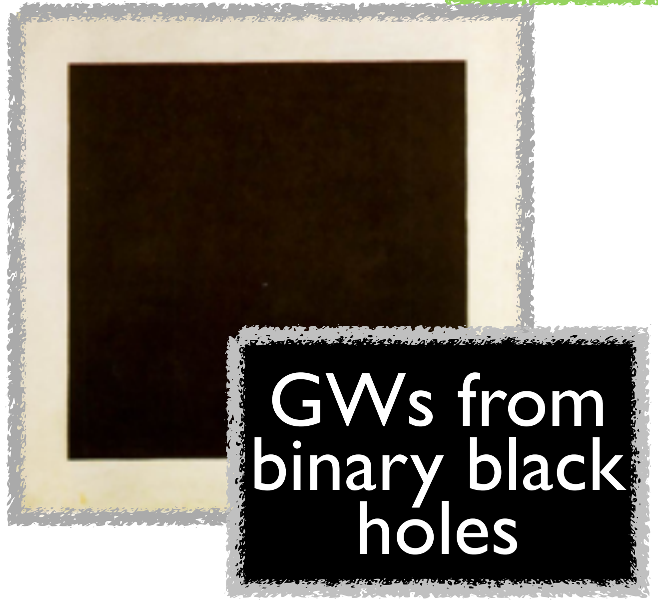

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NASA/CXC/M.Weiss

devour stars, launch jets

Quasars/AGN

ESA

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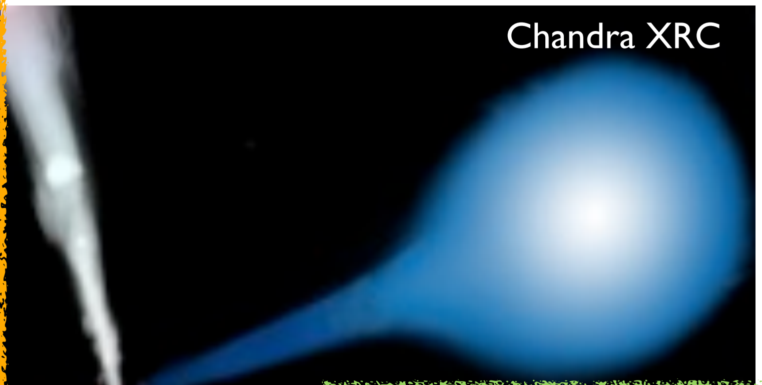

Chandra XRC

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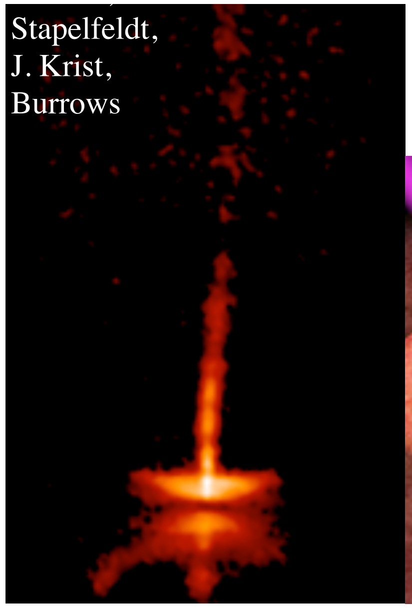

Stapelfeldt, J. Krist, Burrows

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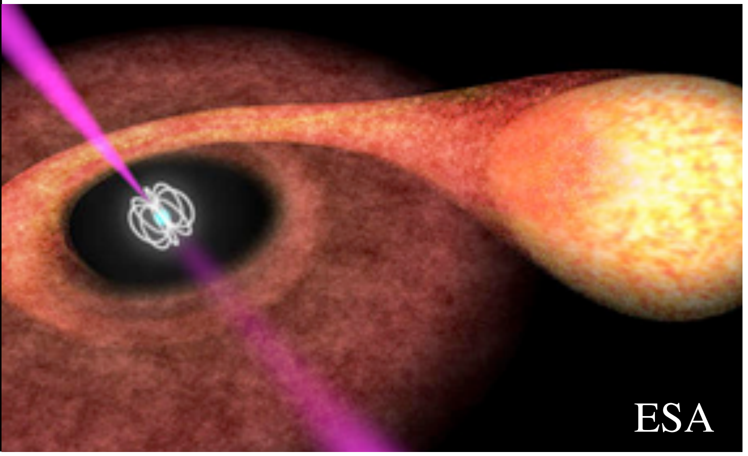

ESA

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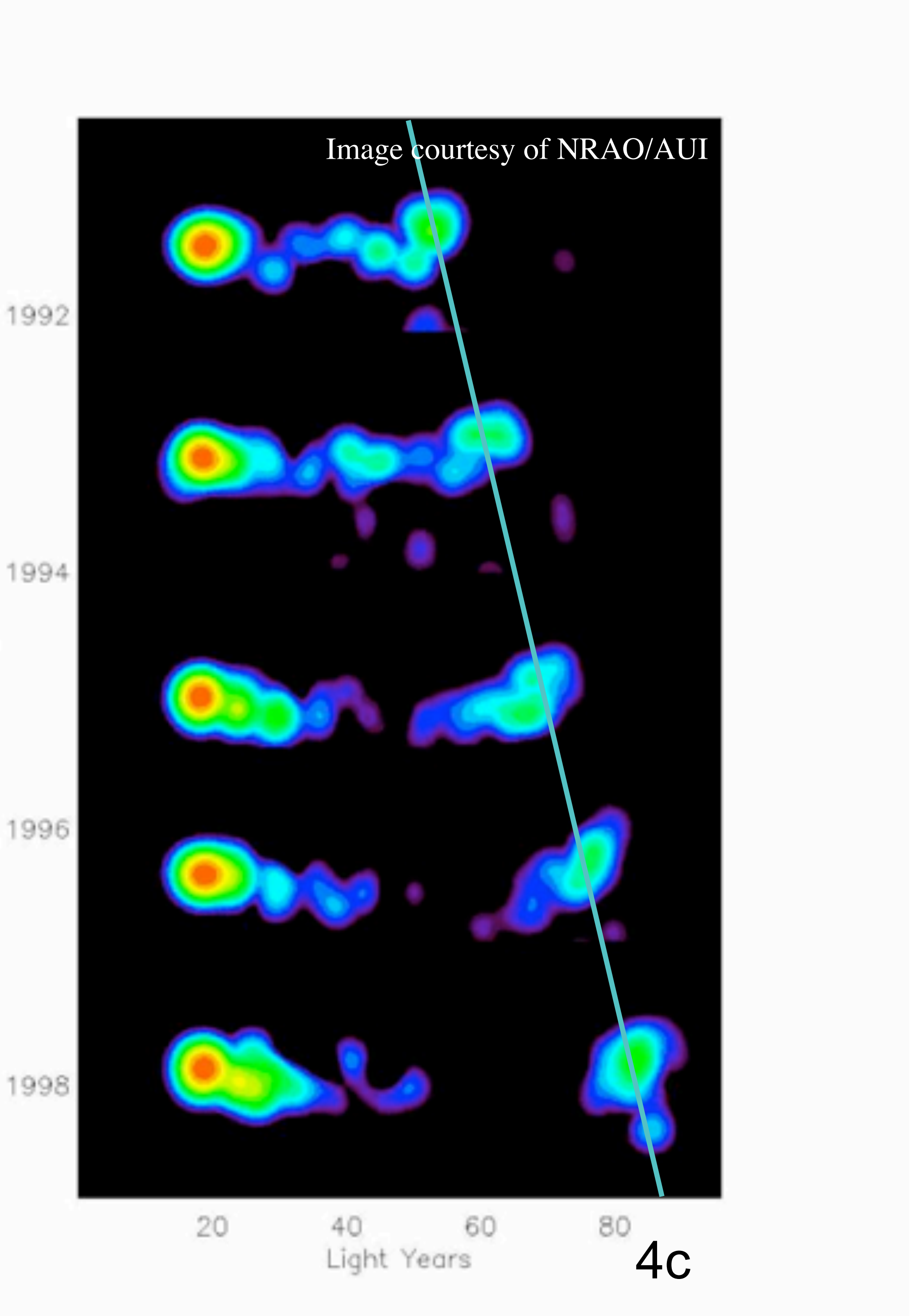
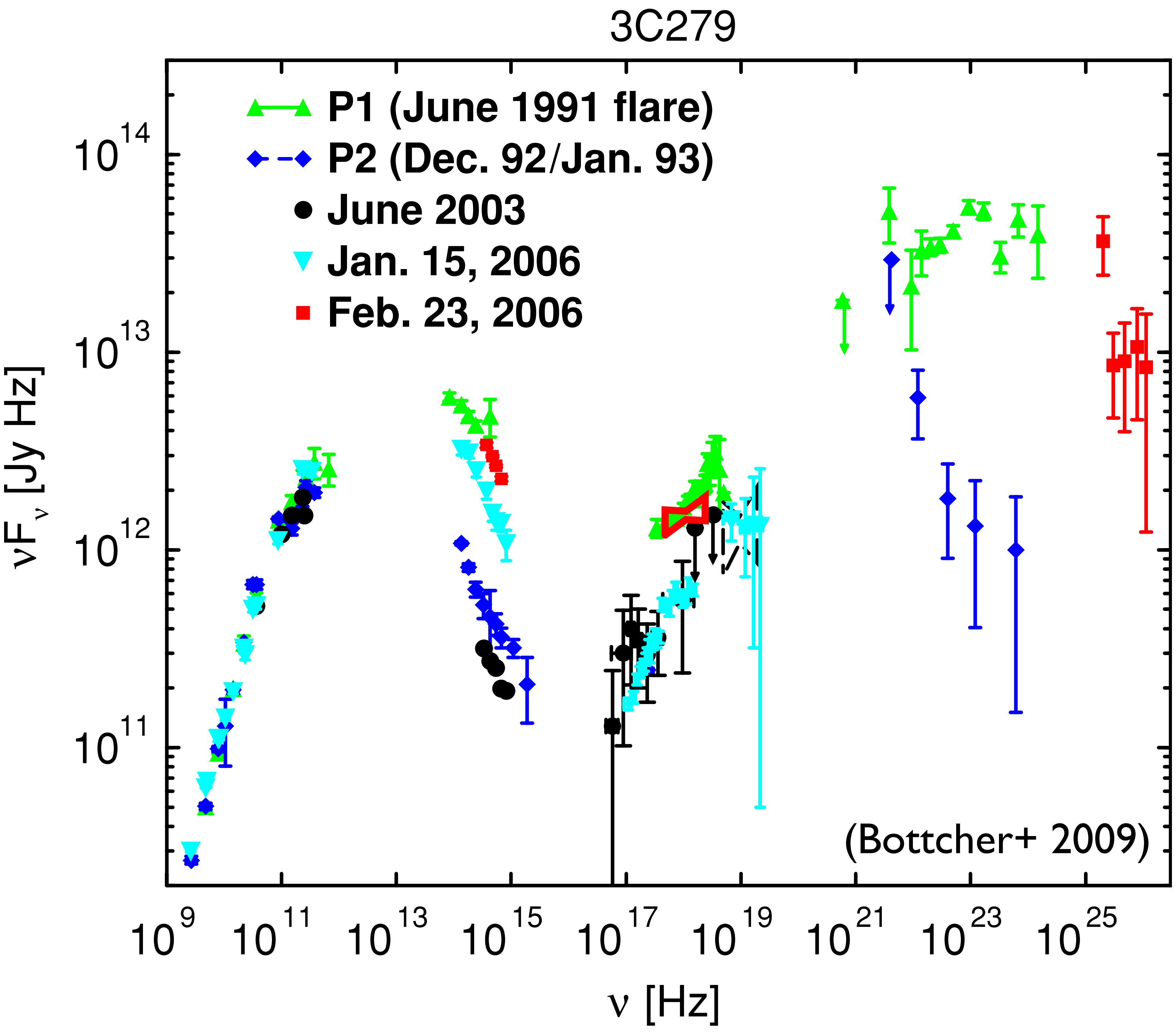
(AT 2015)

Jet Beaming Allows Observing Dim Sources

Active Galaxy with Jet Pointing at us: 3C279





$v \approx 0.997\, c$

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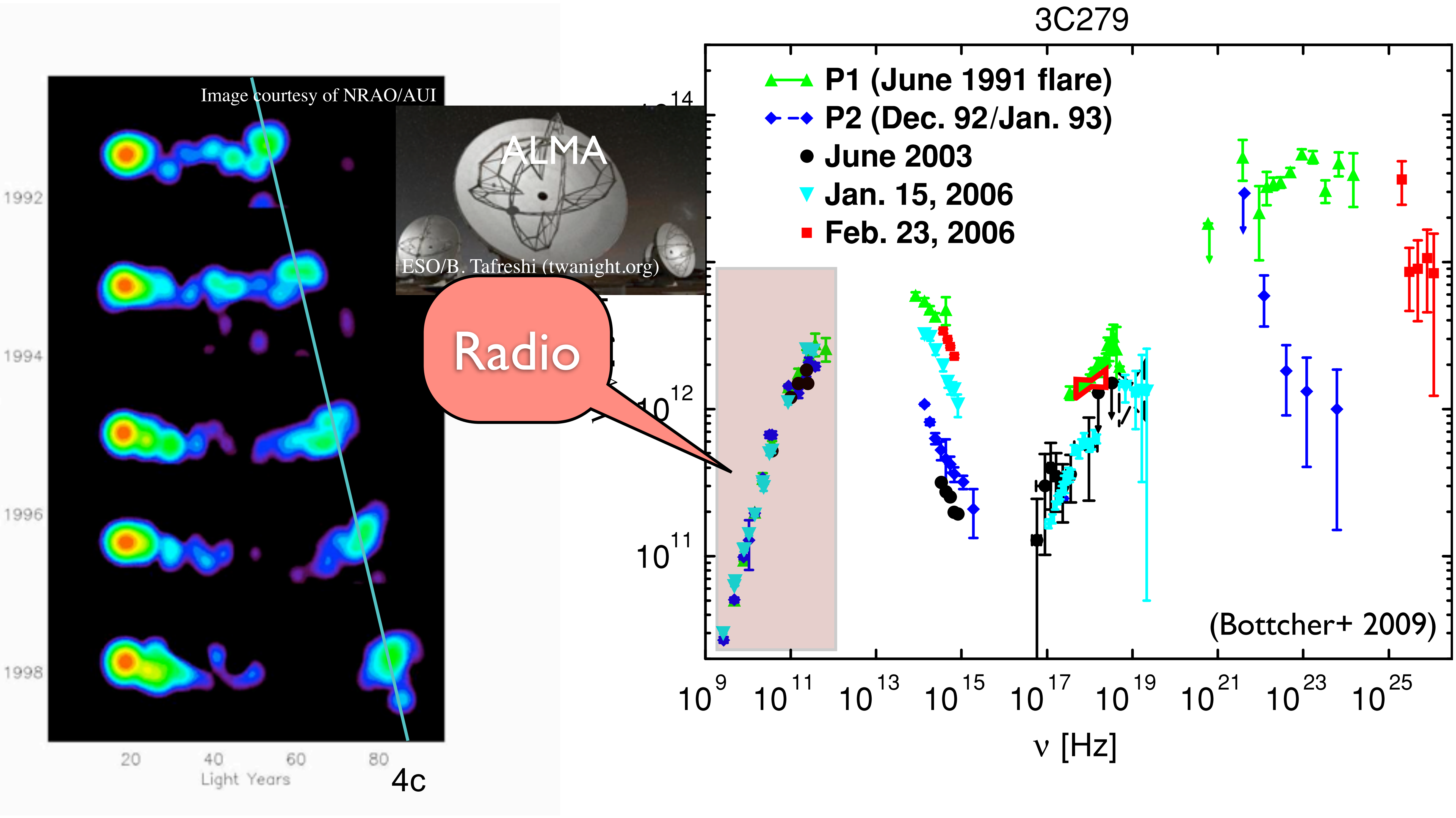

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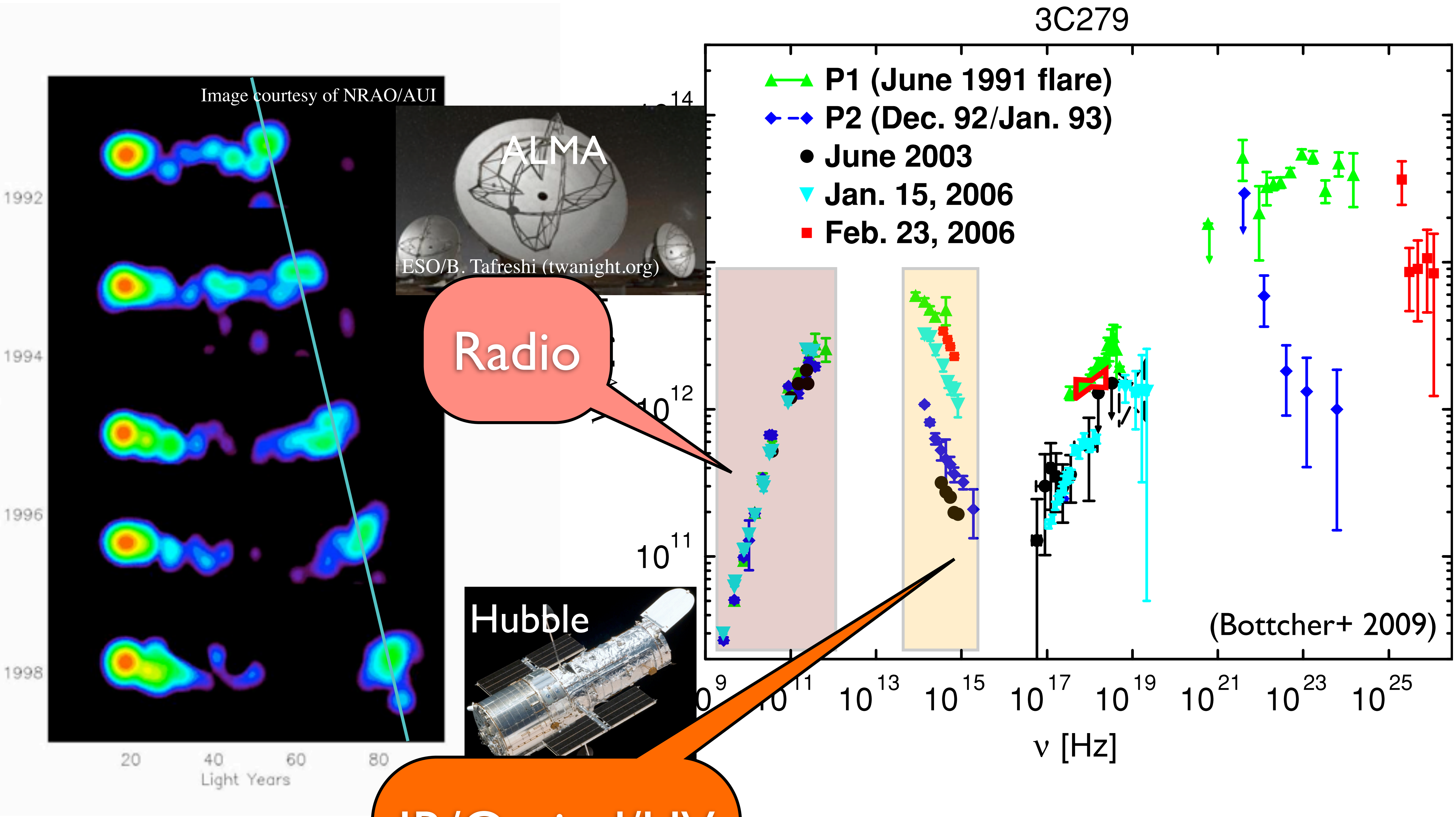

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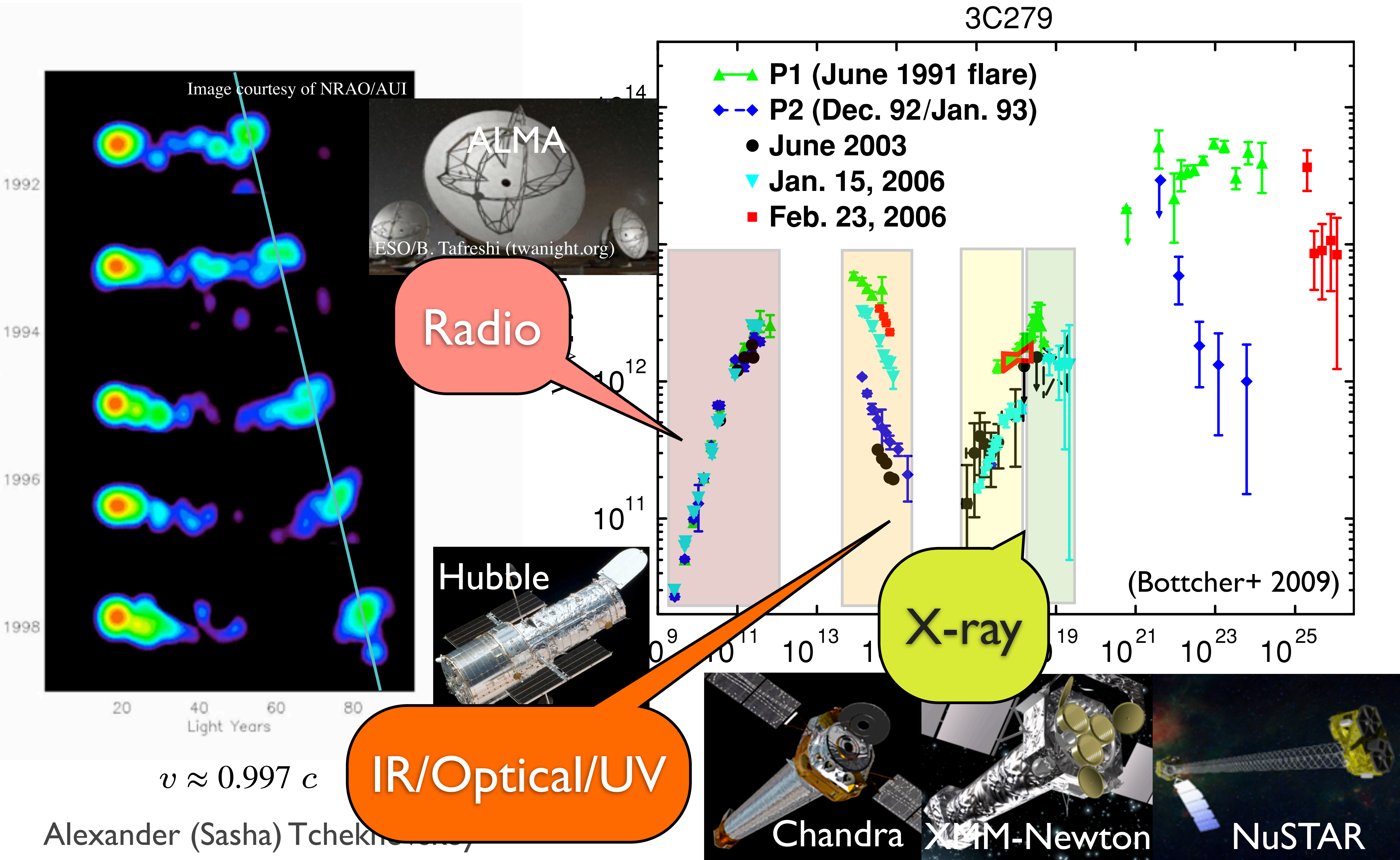

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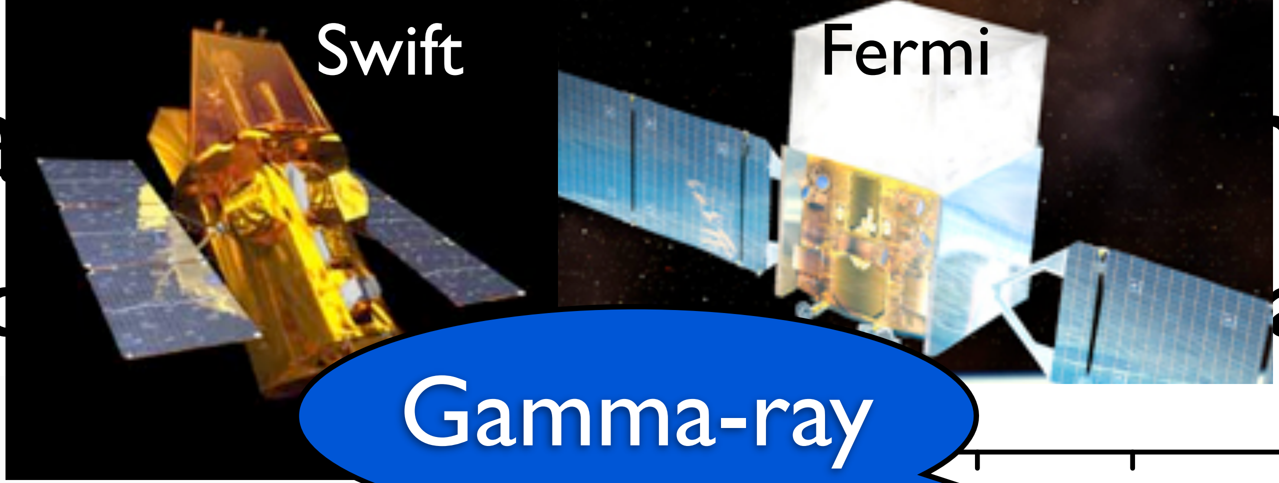
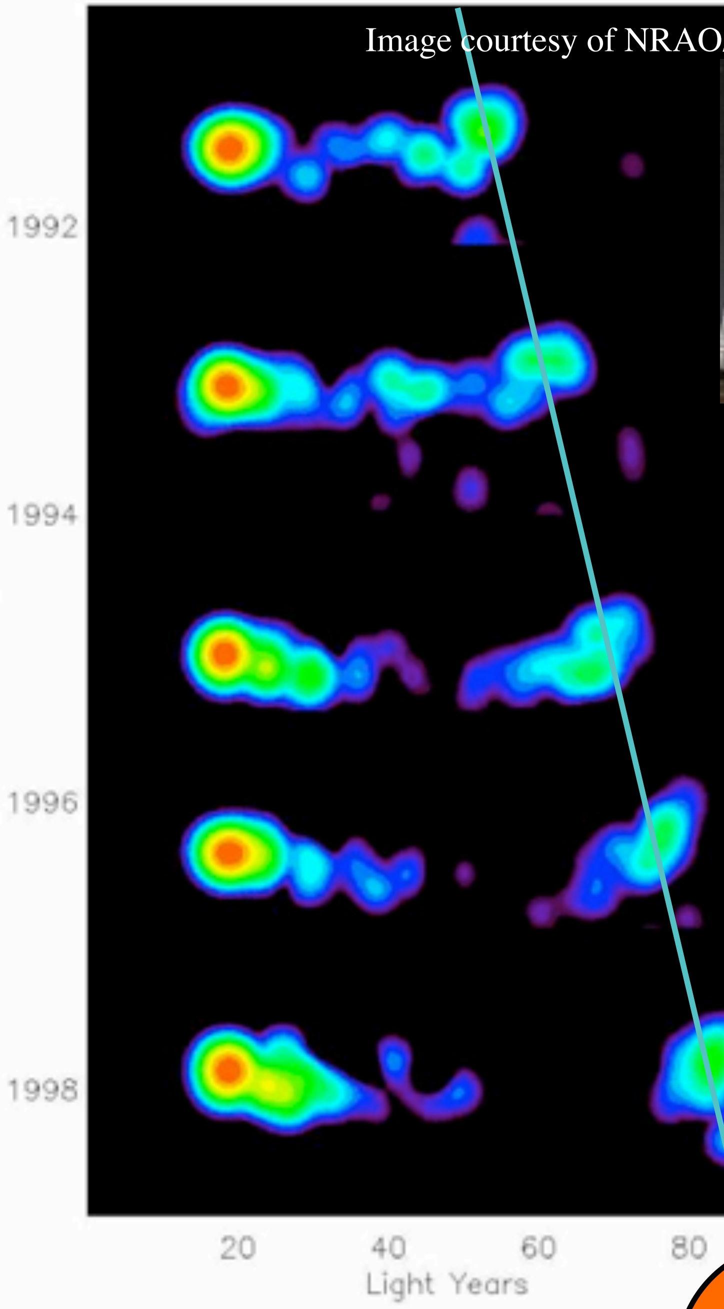
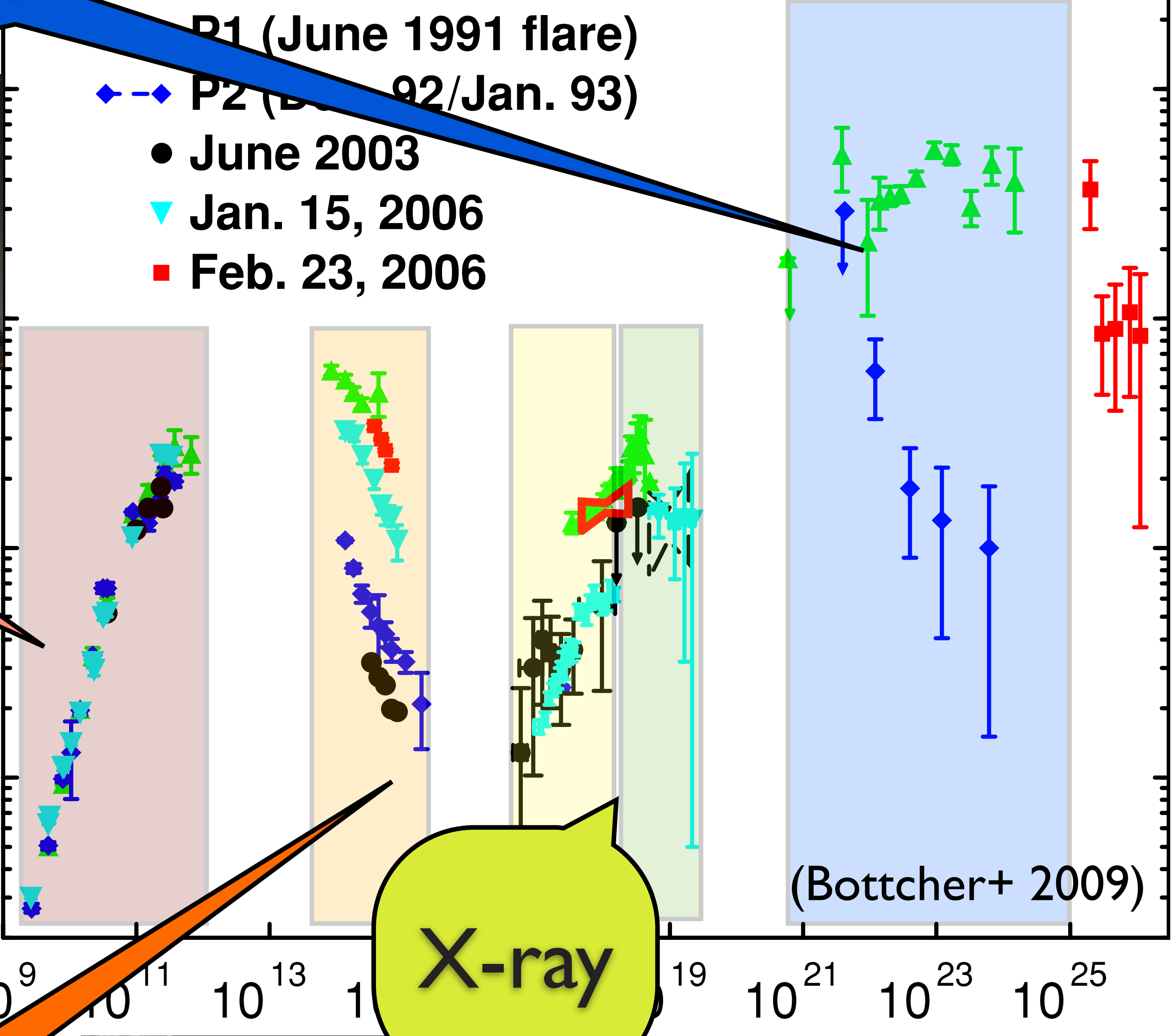


Gamma-ray

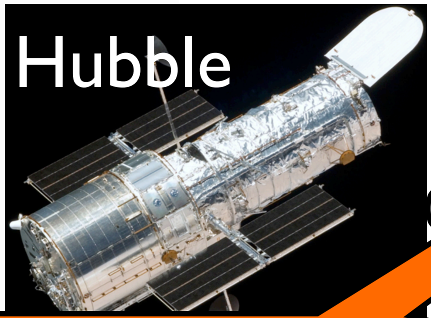


Radio



(Bottcher+ 2009)

X-ray



IR/Optical/UV

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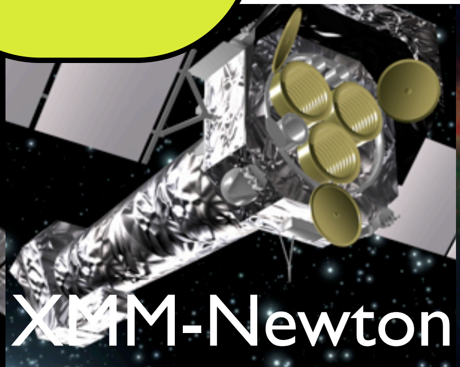
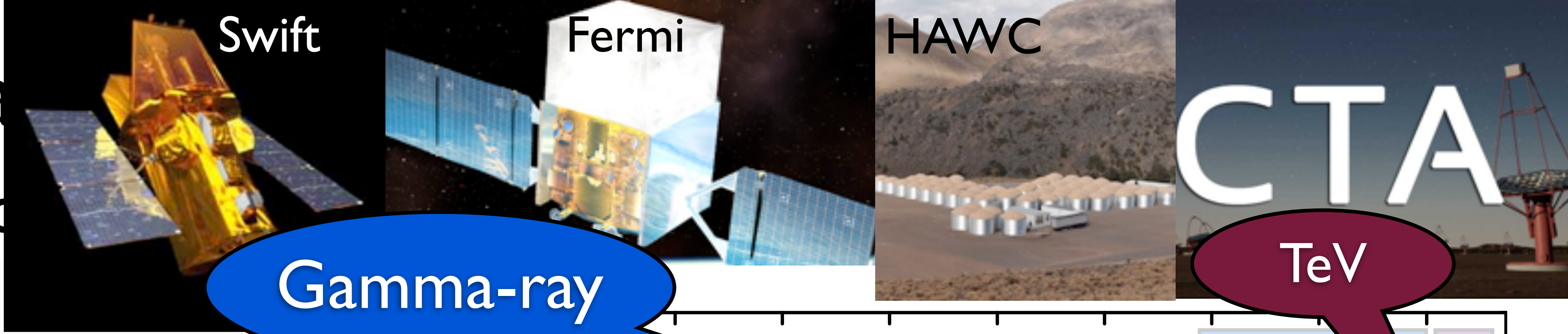


Alexander (Sasha) Tchek

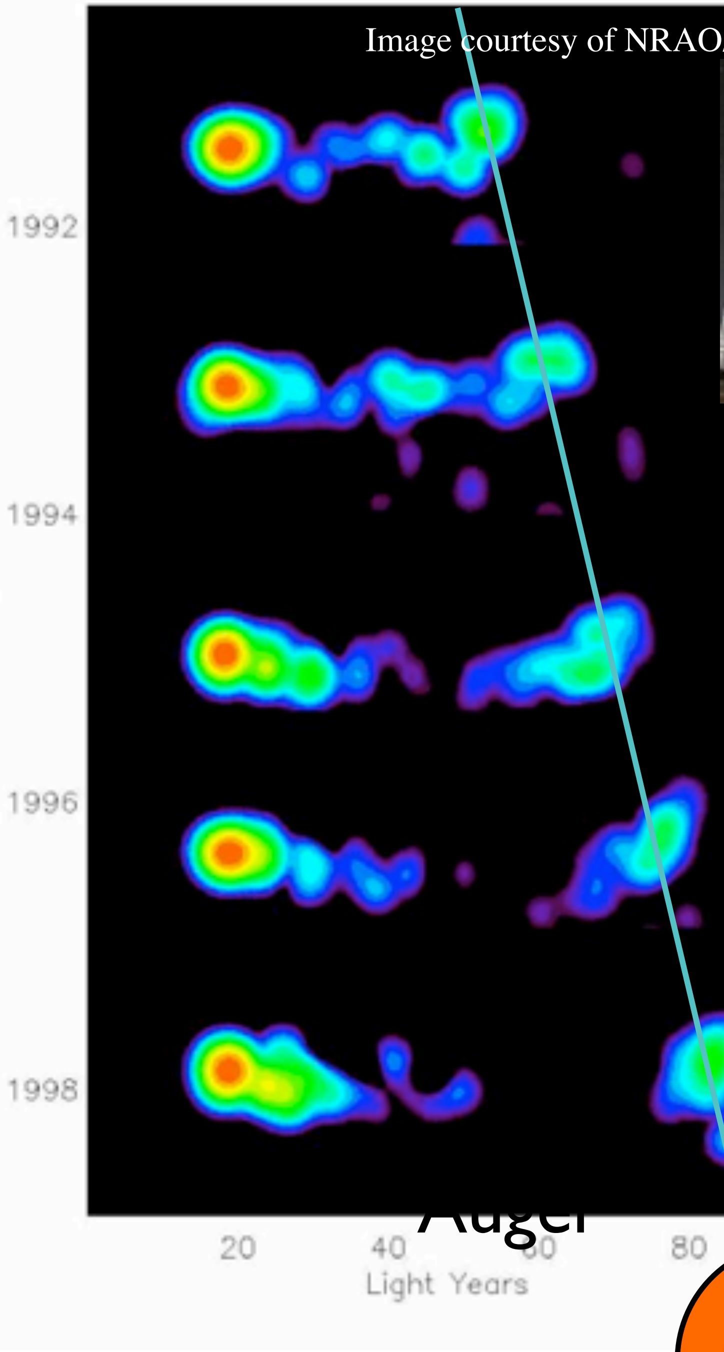
Jet Bea

Ac



Gamma-ray

TeV



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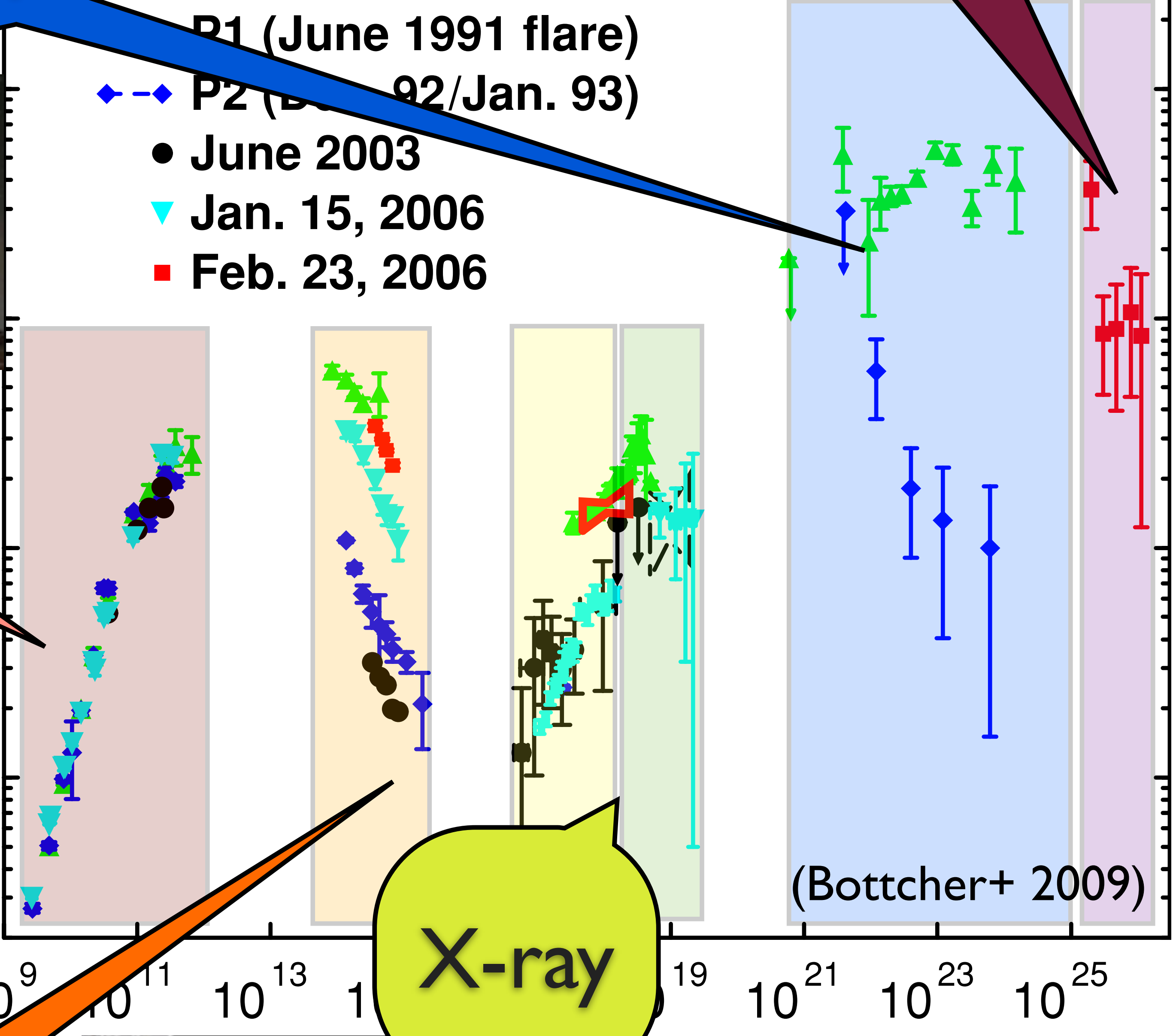

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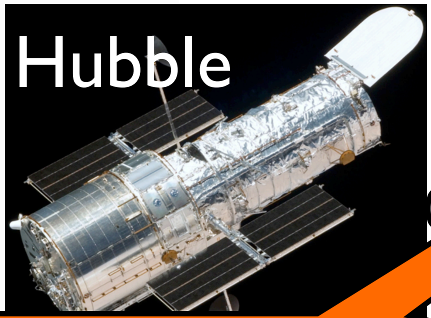


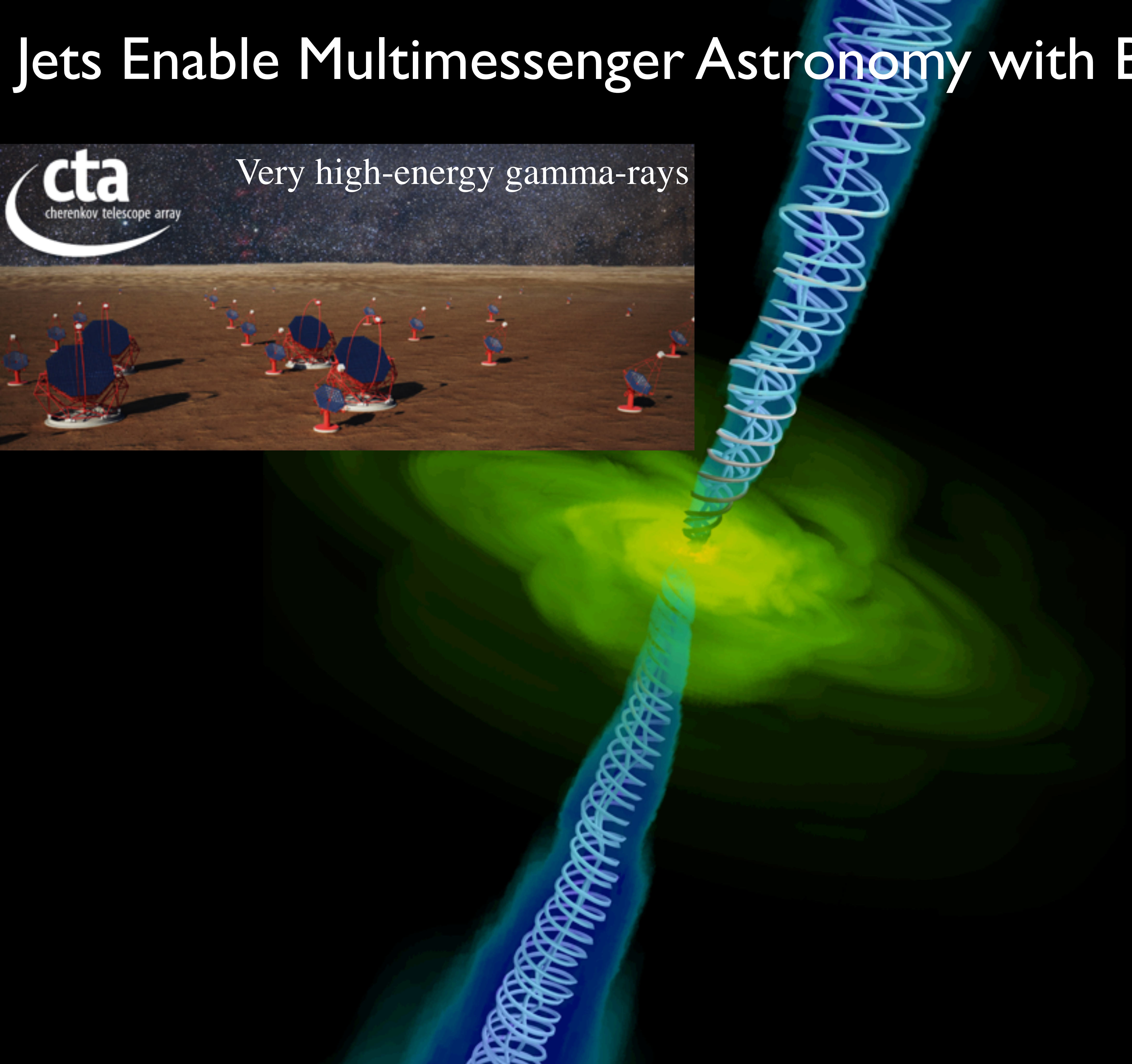
Auger

IR/Optical/UV

$v \approx 0.997\ c$

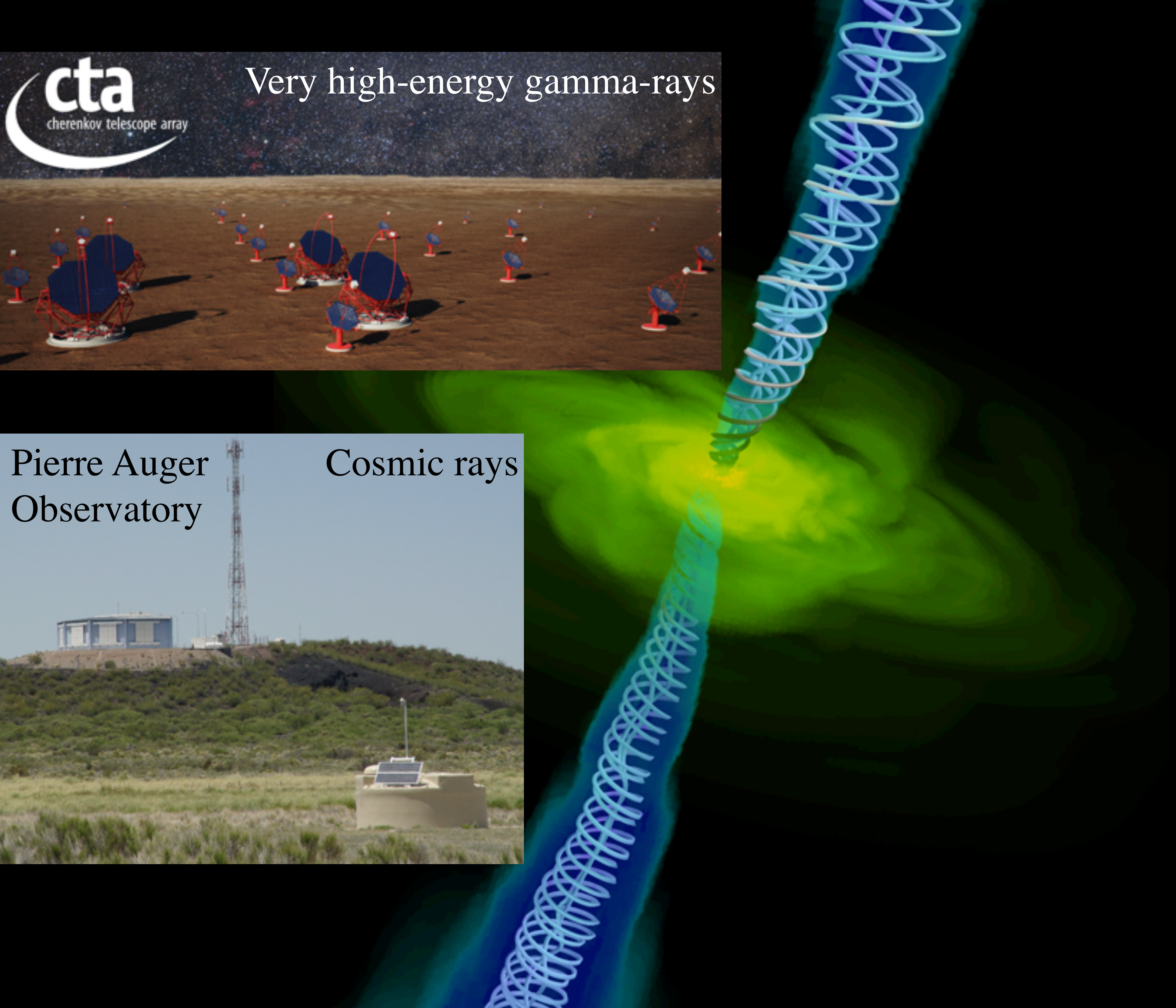
Alexander (Sasha) Tchek

Jets Enable Multimessenger Astronomy with Black Holes



Very high-energy gamma-rays

Jets Enable Multimessenger Astronomy with Black Holes



Very high-energy gamma-rays

Pierre Auger Observatory

Cosmic rays

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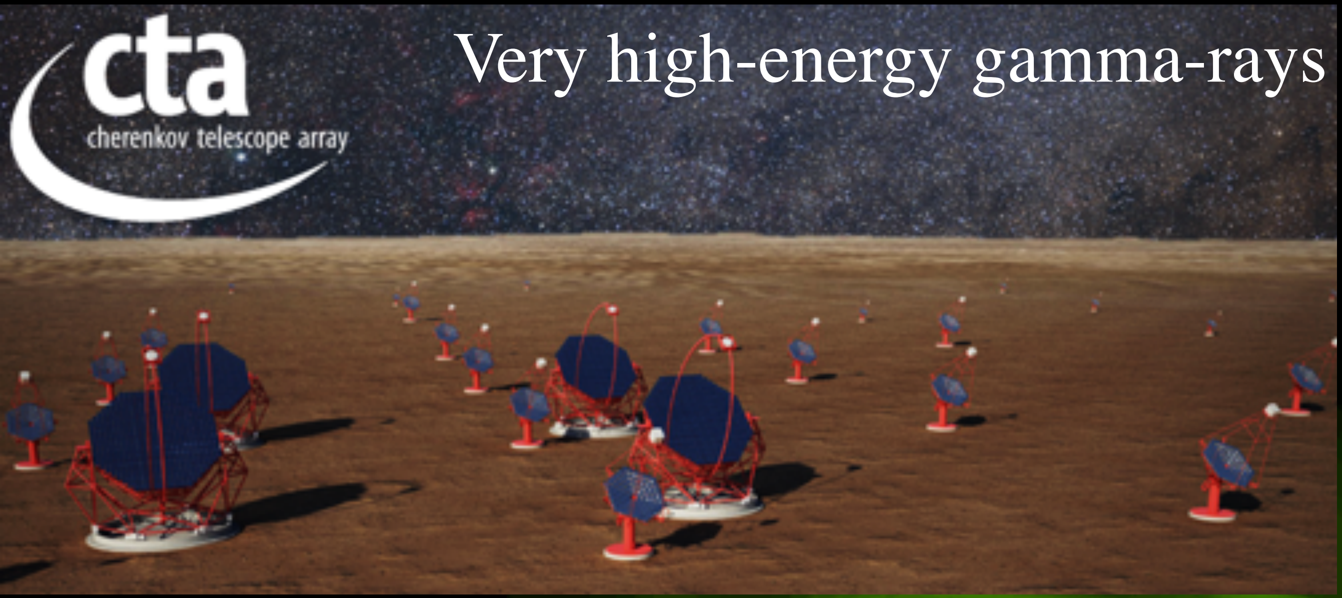

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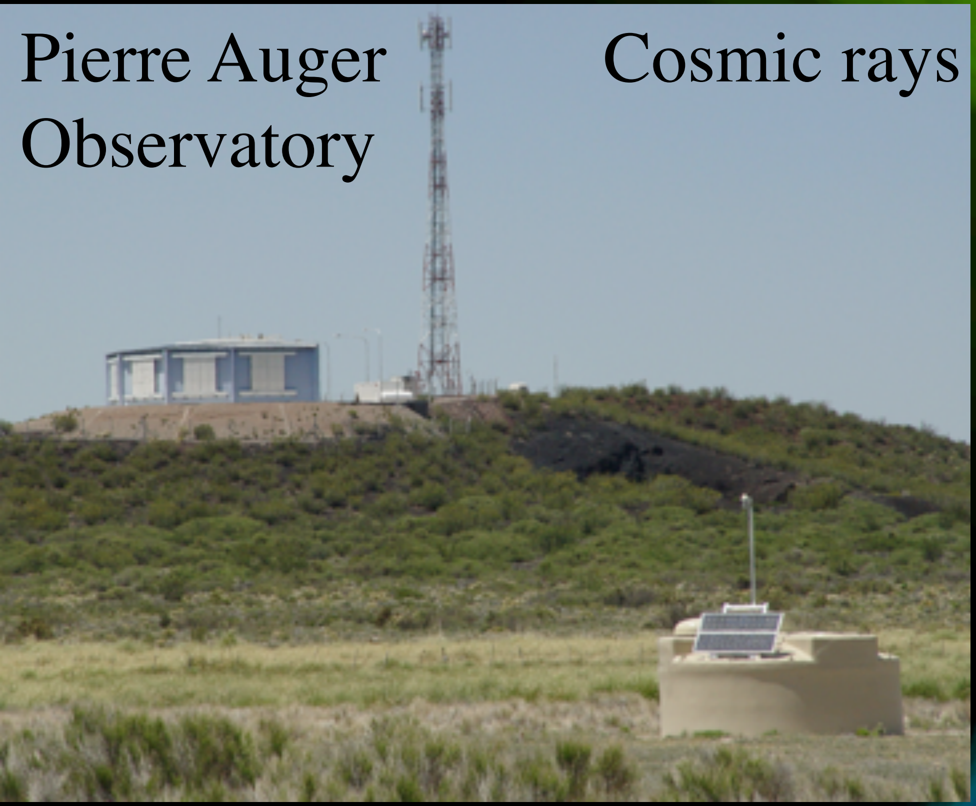
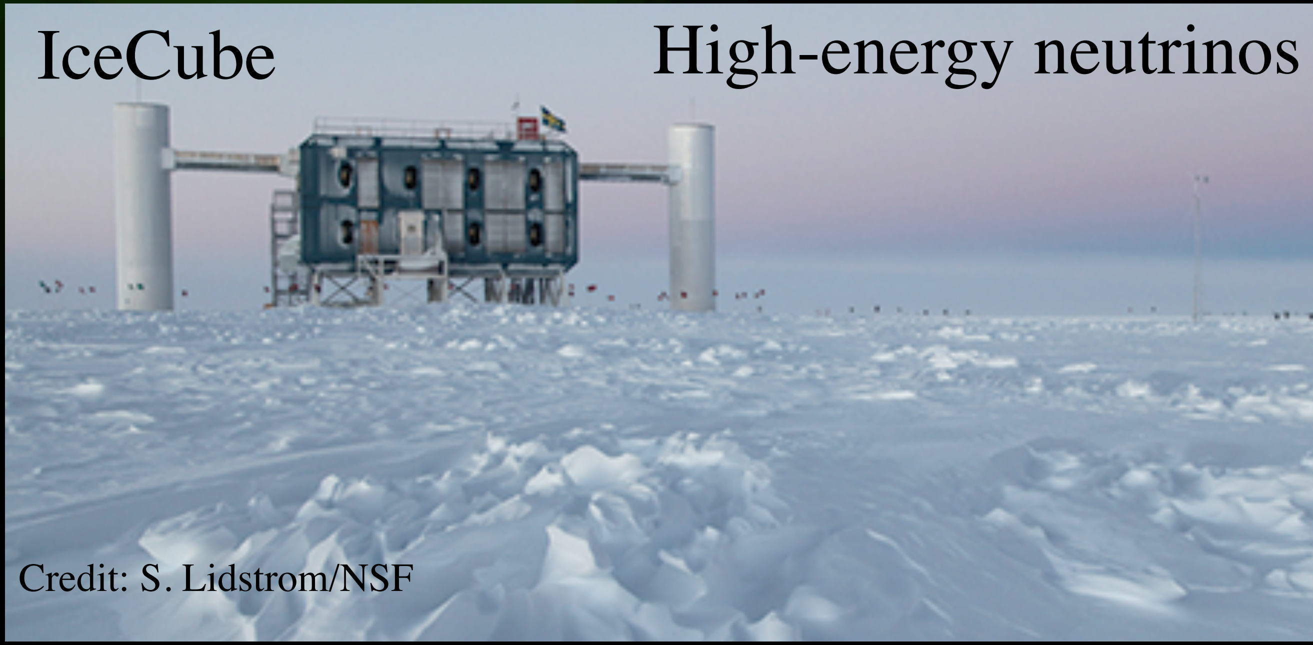


Pierre Auger Observatory

Cosmic rays



IceCube

High-energy neutrinos

Credit: S. Lidstrom/NSF

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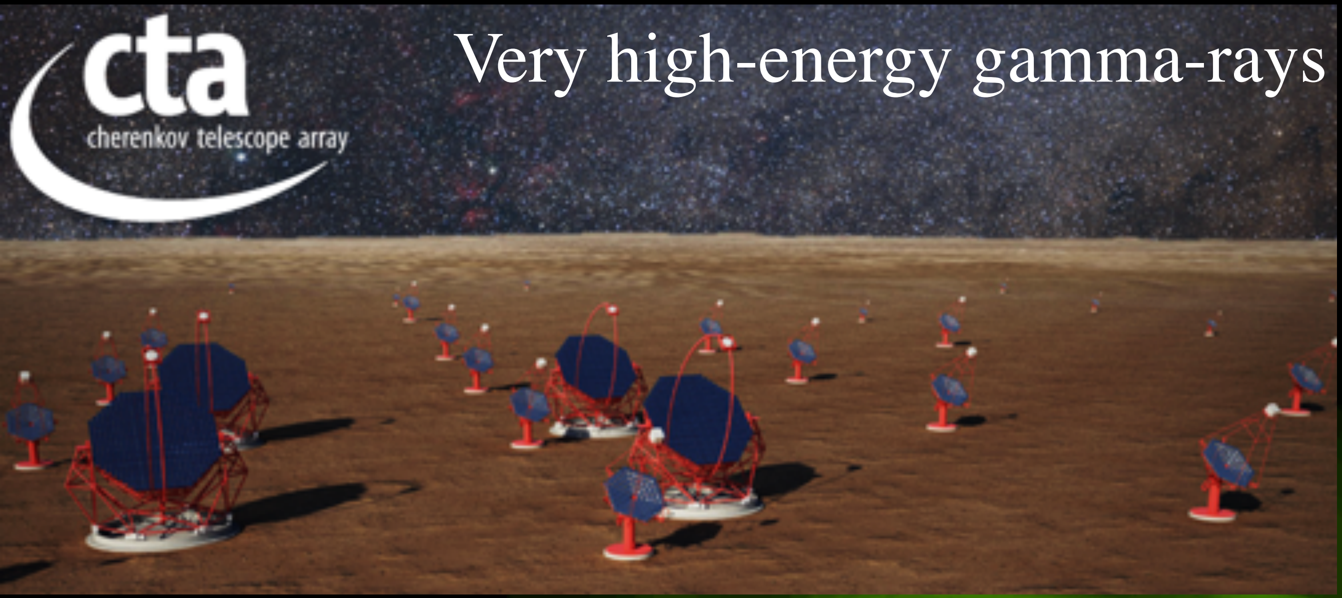
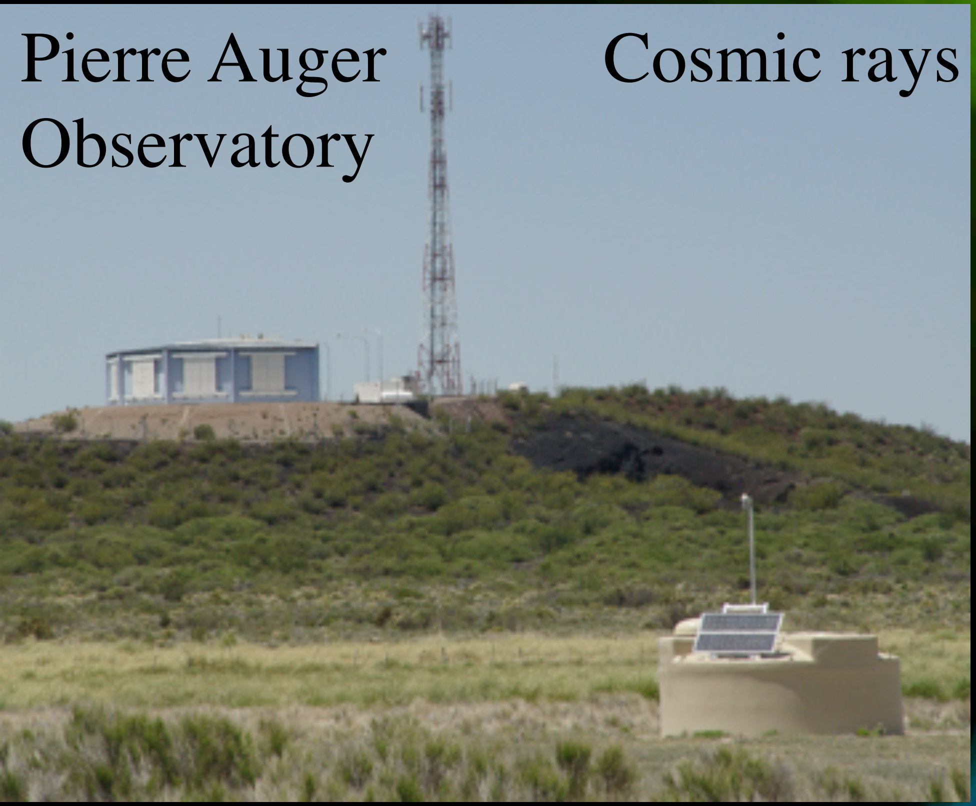


Very high-energy gamma-rays

LIGO

Gravitational Waves



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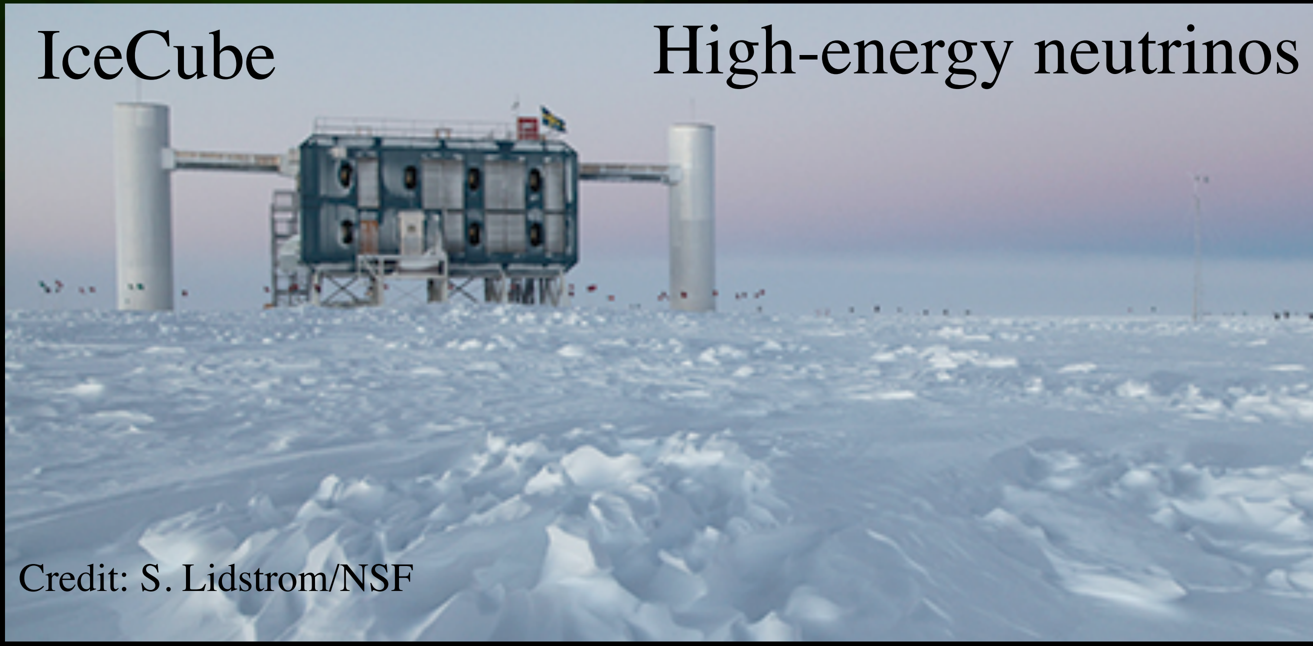

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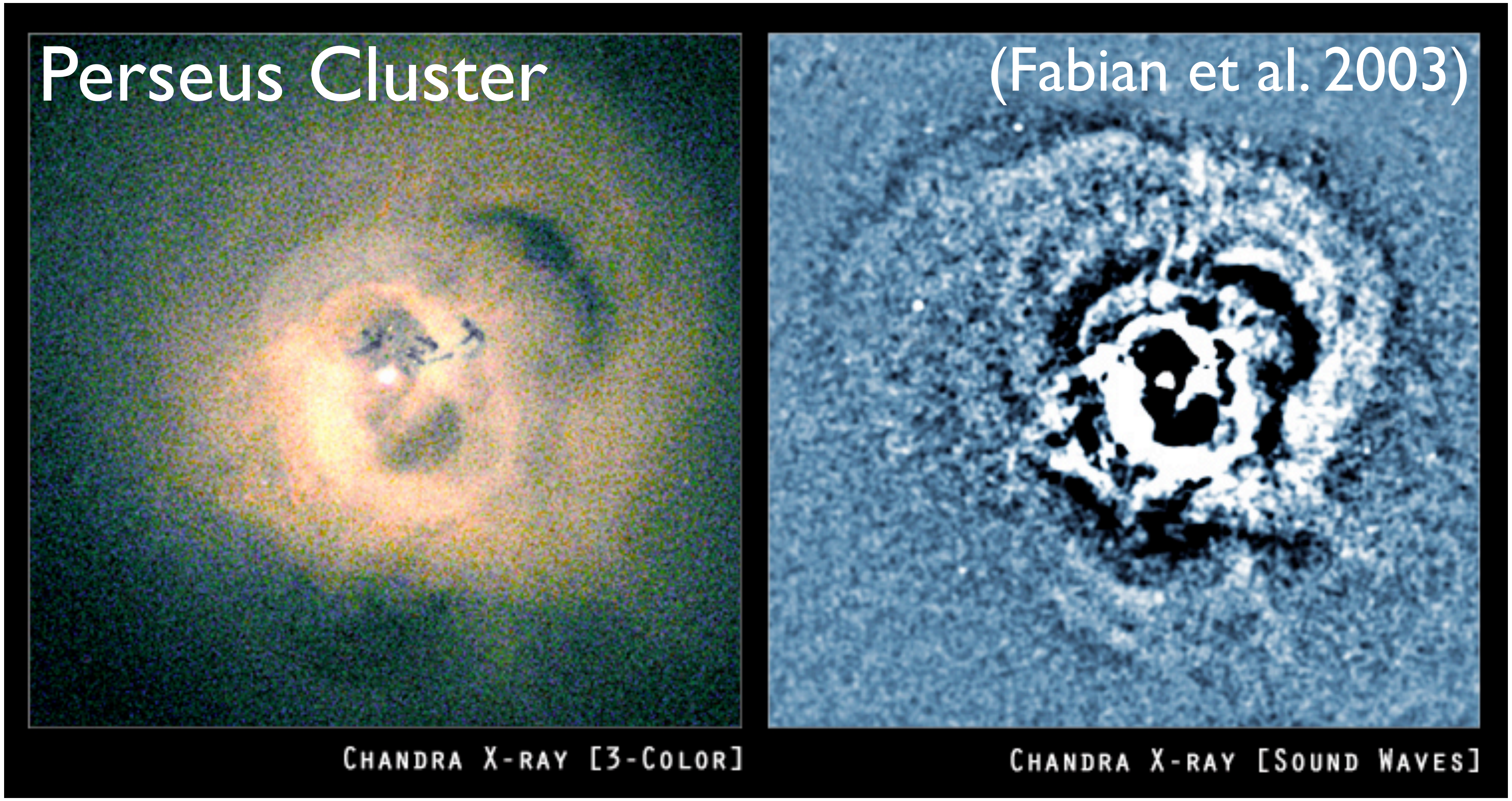
Jets Affect Galaxies/Clusters



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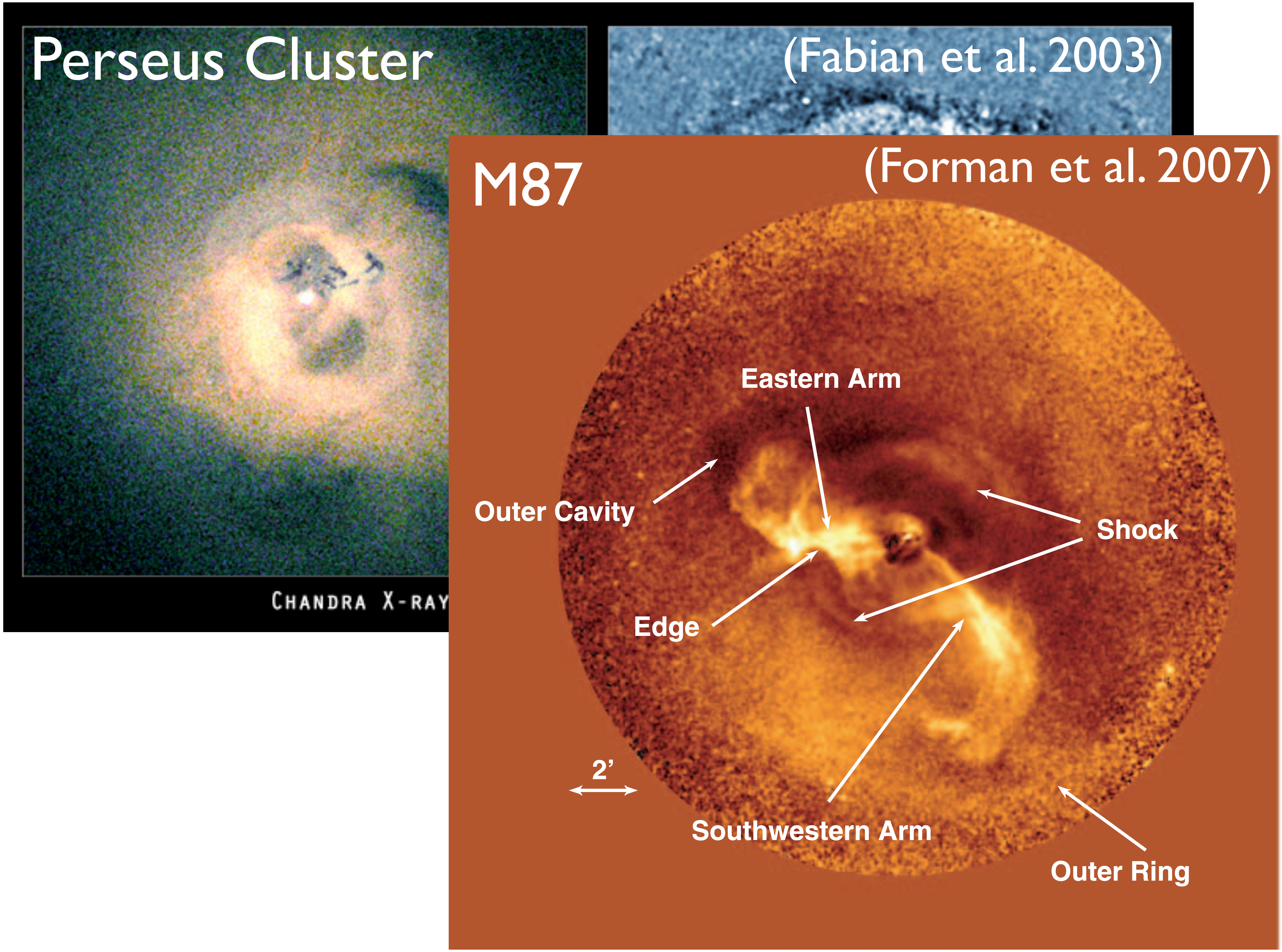

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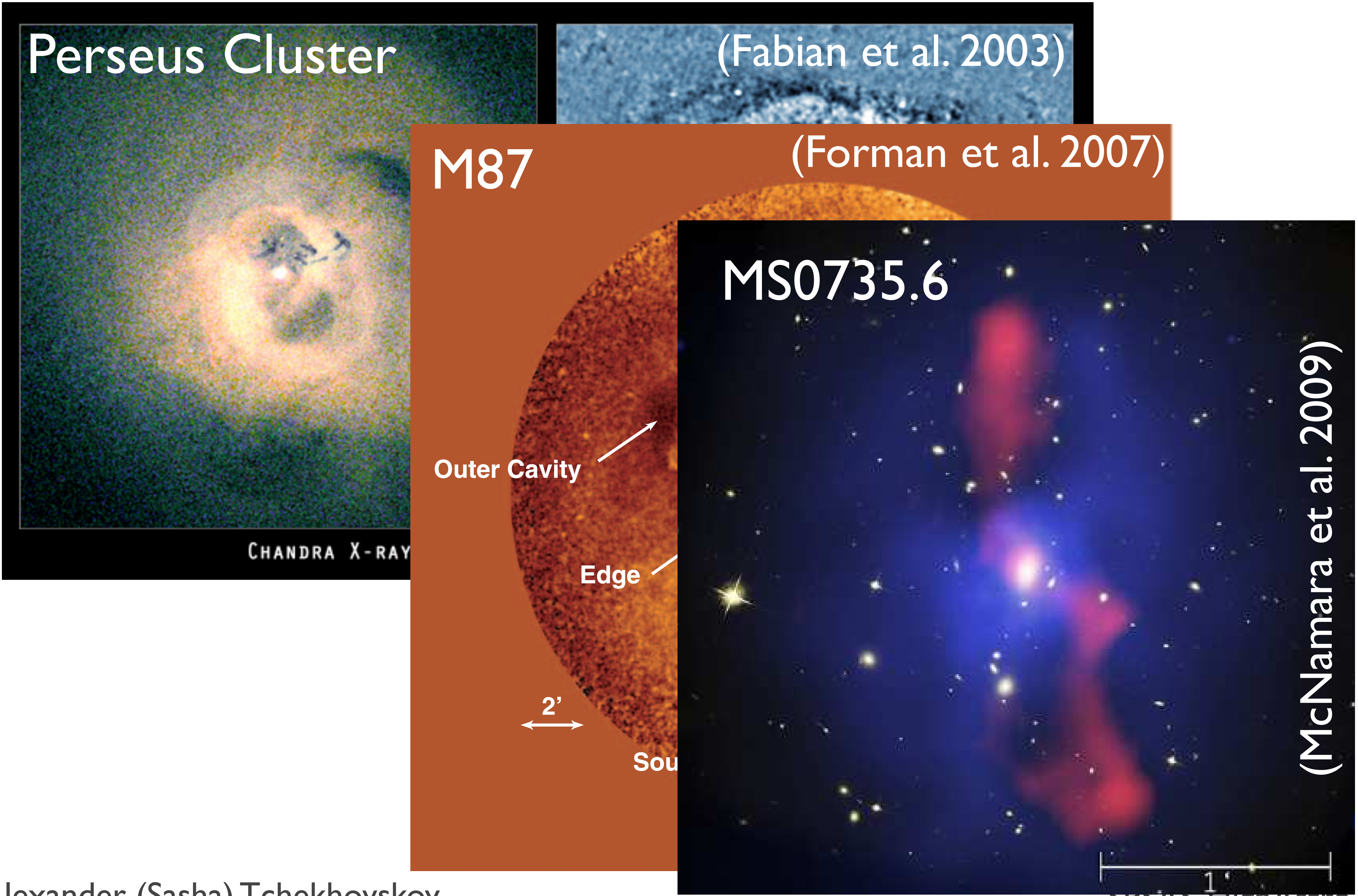
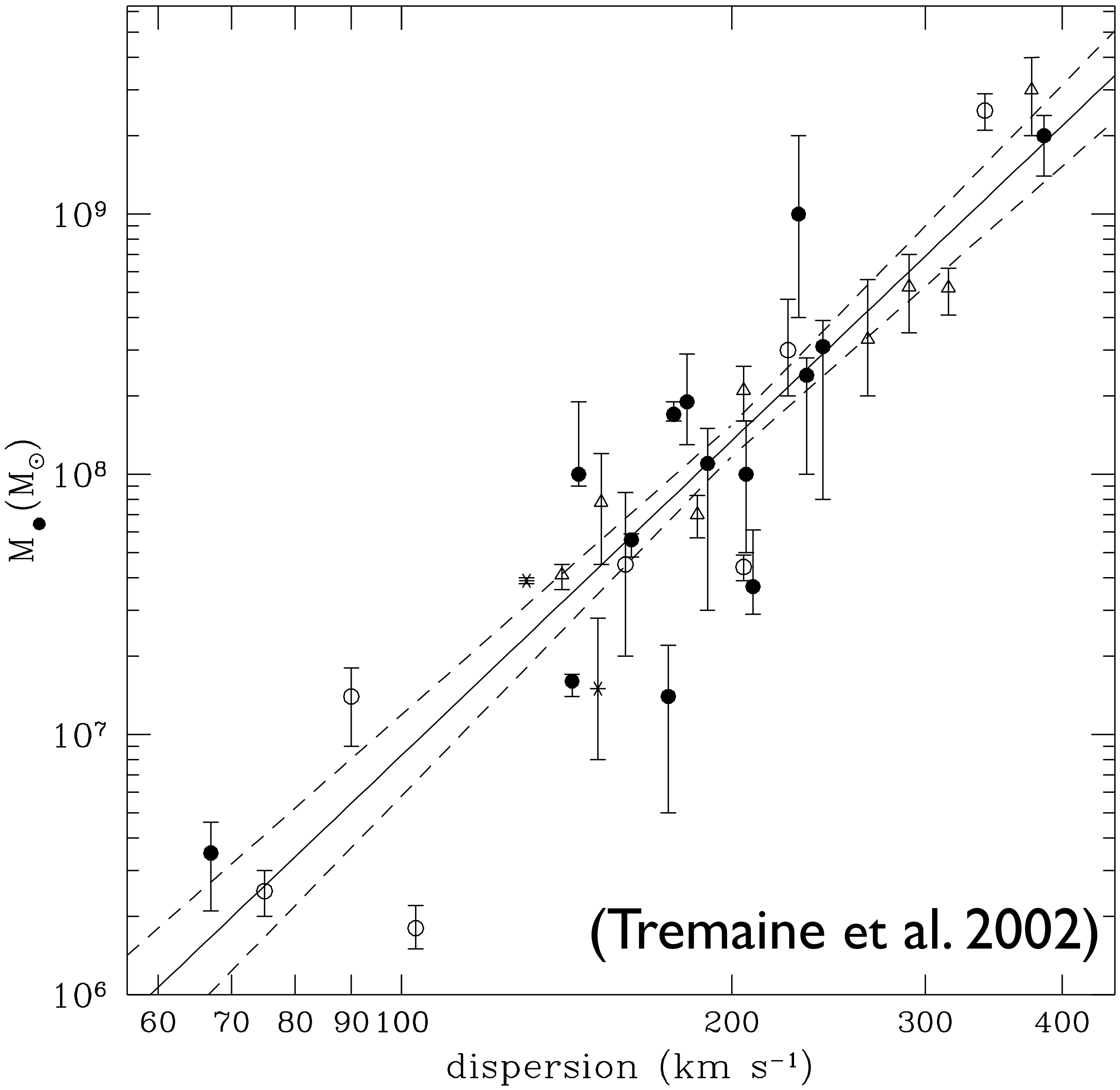


Jets Affect Galaxies/Clusters

"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?



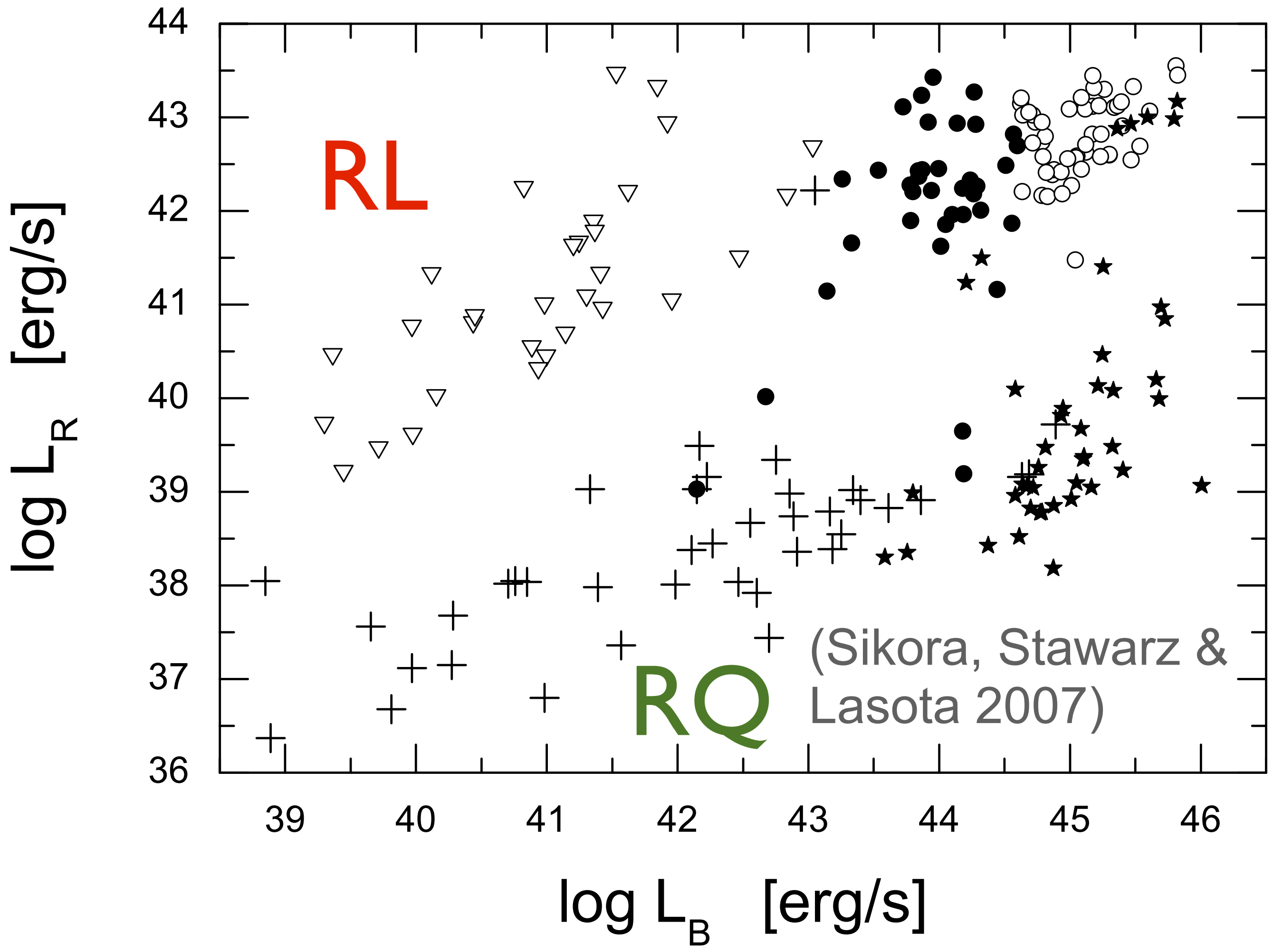
(Tremaine et al. 2002)

AGN Radio Loud/Quiet Dichotomy

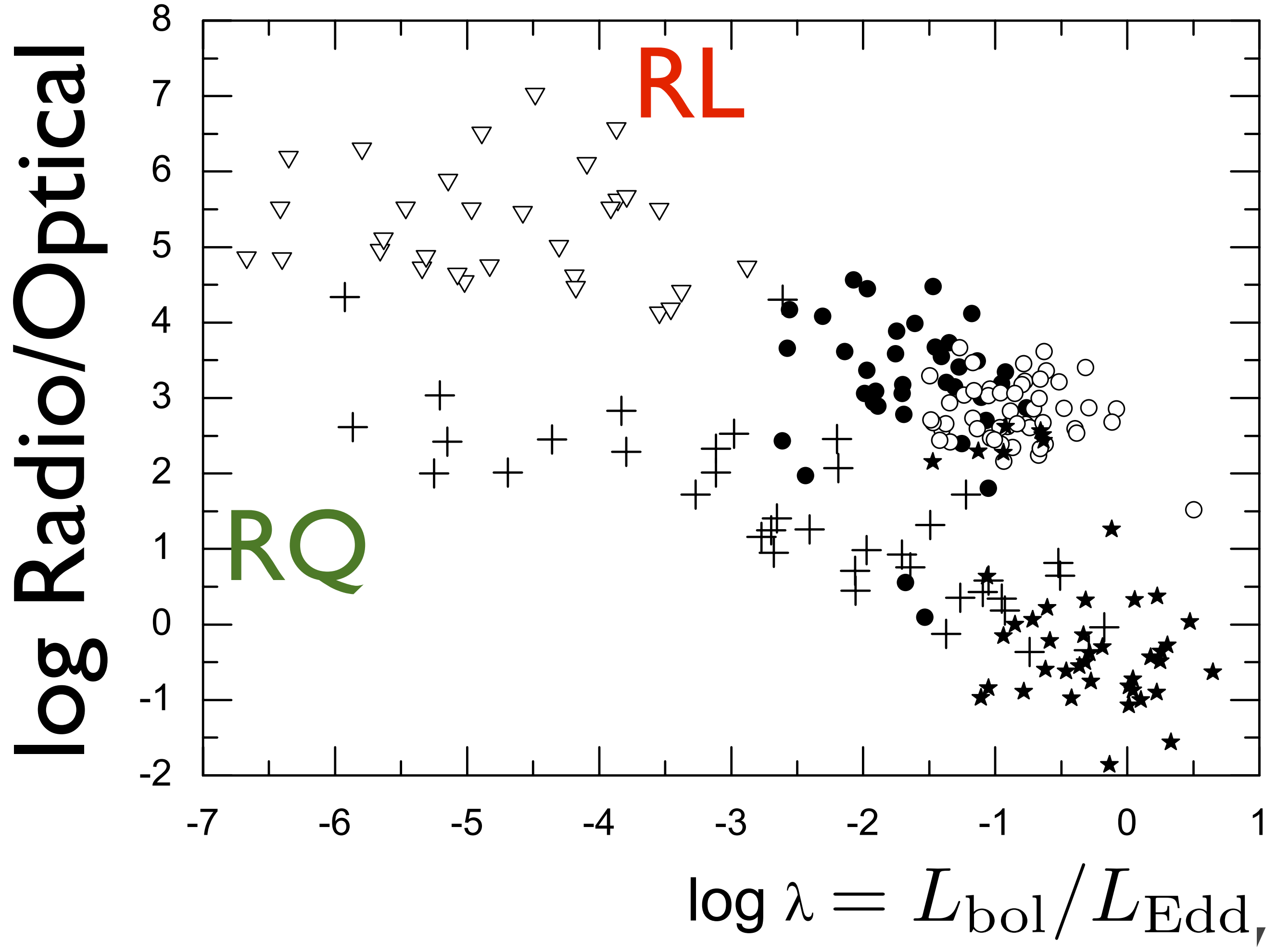
- Factor of 1000 difference in radio luminosity.
- There must be at least one other parameter in addition to M and $\dot{M}$:

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

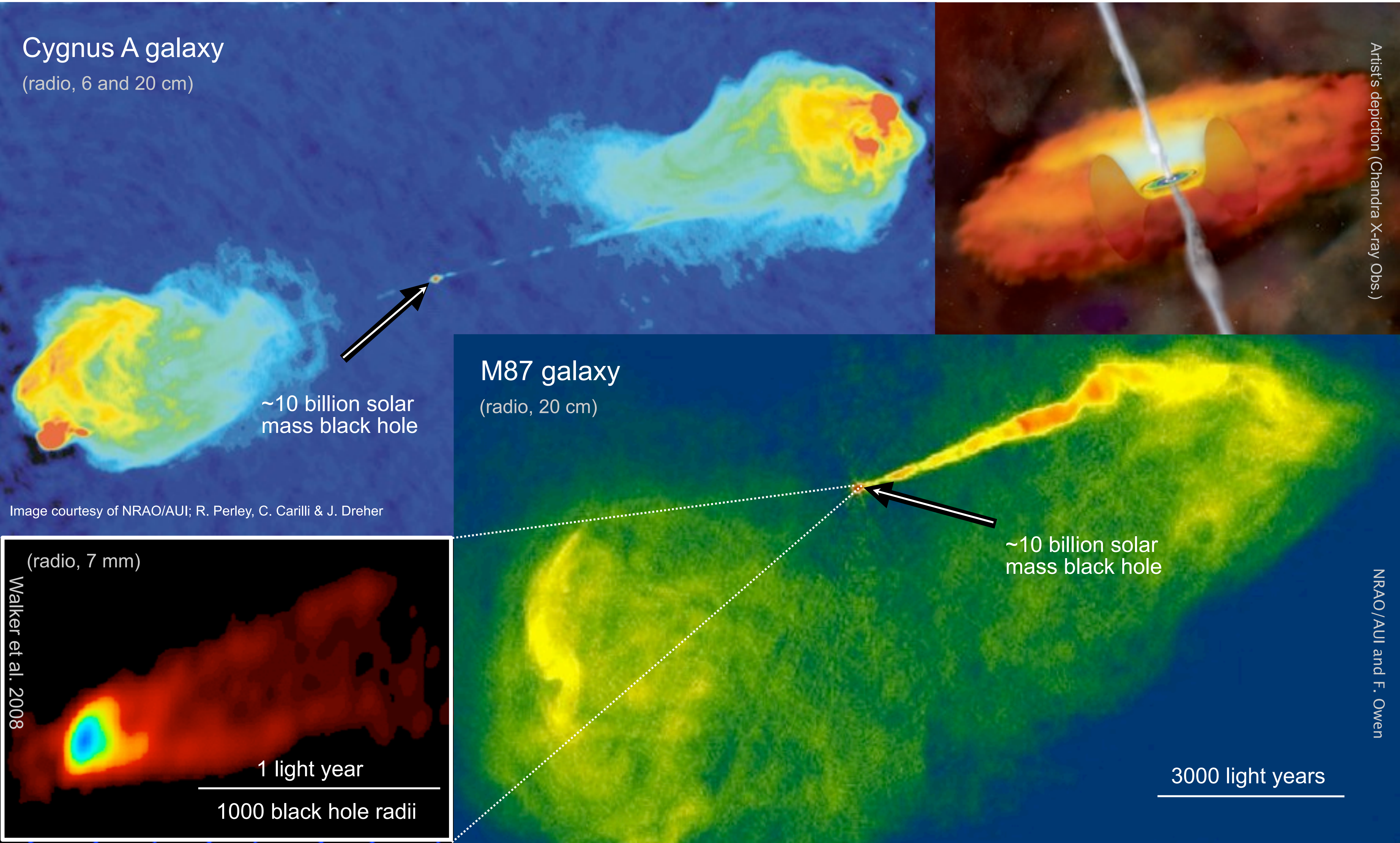
- Magnetic flux?
  Ambient medium? (Broderick & Fender 2012)
  BH spin? (Blandford 1990, Tchekhovskoy et al. 2010)



(Sikora, Stawarz & Lasota 2007)



Jets: Beautiful and Challenging



Cygnus A galaxy

(radio, 6 and 20 cm)

Image courtesy of NRAO/AUI; R. Perley, C. Carilli & J. Dreher

Artist's depiction (Chandra X-ray Obs.)

M87 galaxy

(radio, 20 cm)

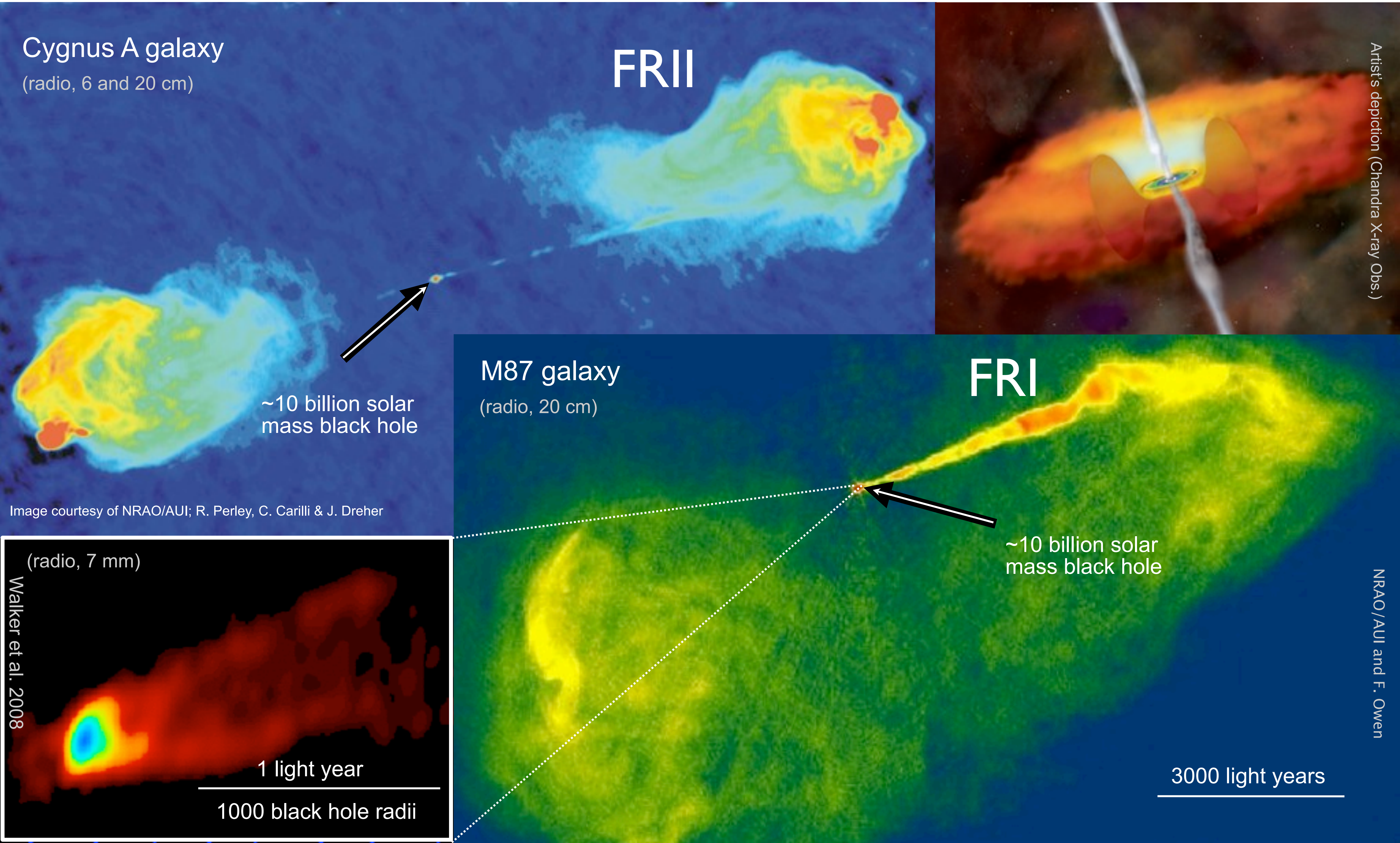
NRAO/AUI and F. Owen

(radio, 7 mm)

Walker et al. 2008

Jets: Beautiful and Challenging

FRI/FRII dichotomy (Fanaroff & Riley, 1974)



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NRAO/AUI and F. Owen

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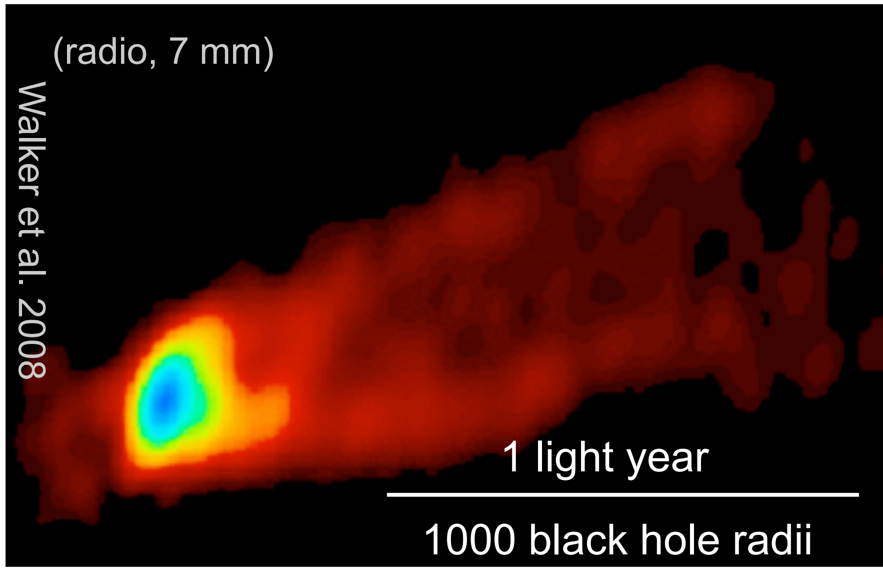
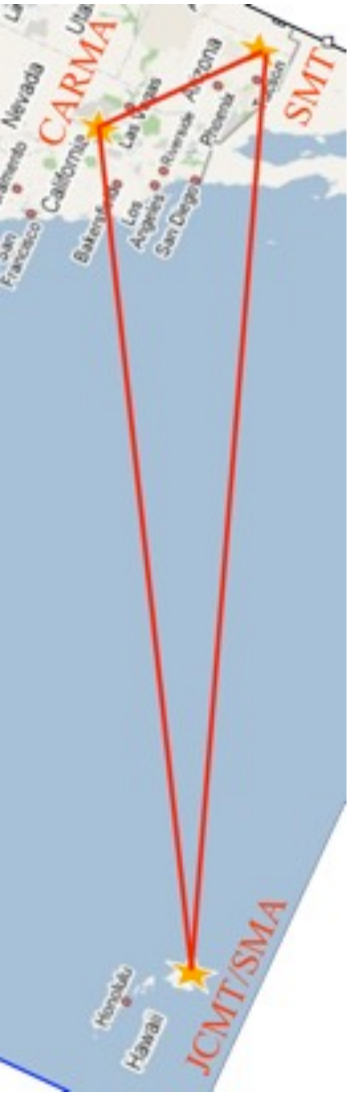
Walker et al. 2008

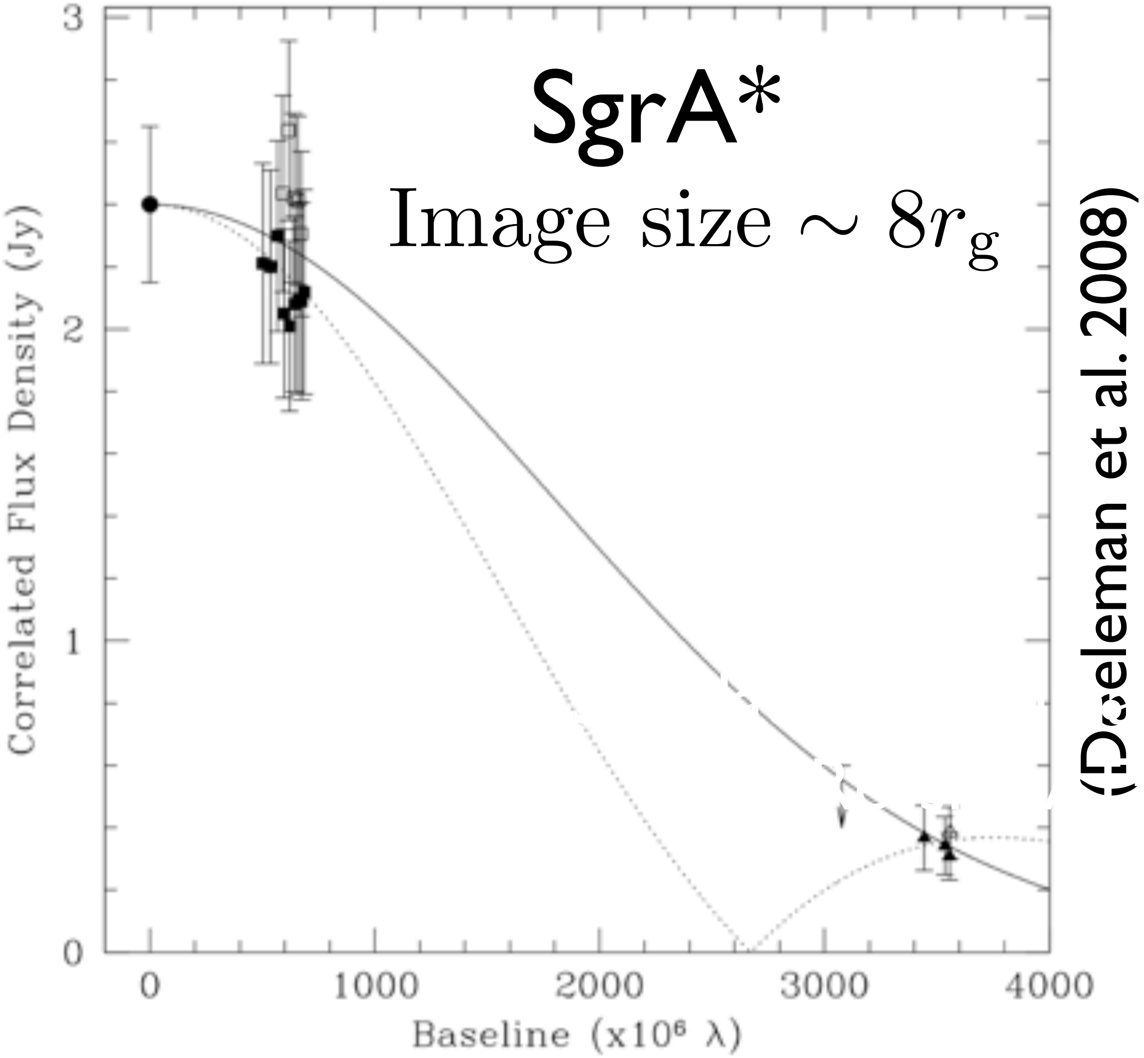
Event Horizon Telescope (*EHT*): VLBI images of Black Holes

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



Walker et al. 2008

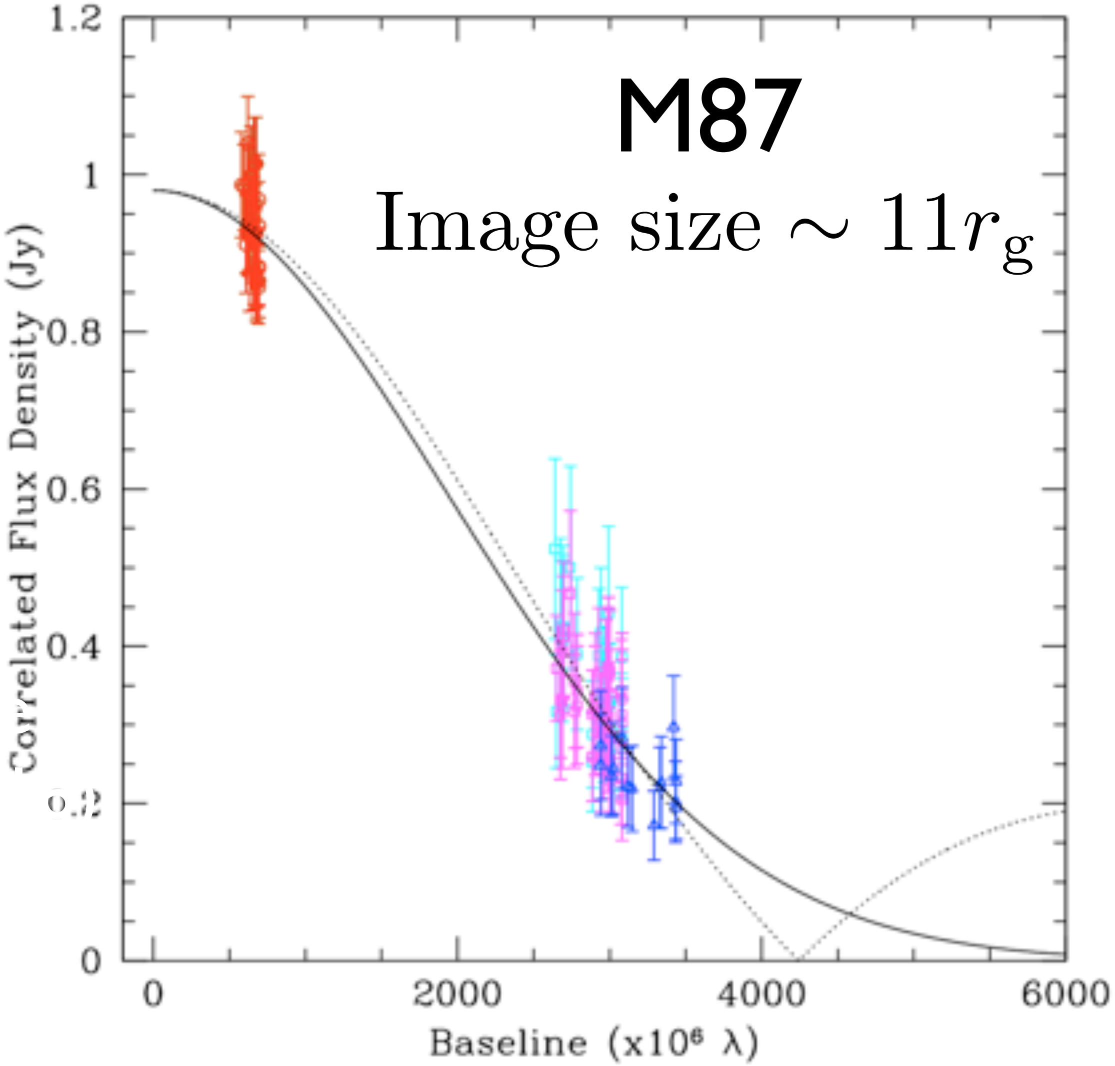




SgrA*

Image size $\sim 8r_{\rm g}$

(Doeleman et al. 2008)

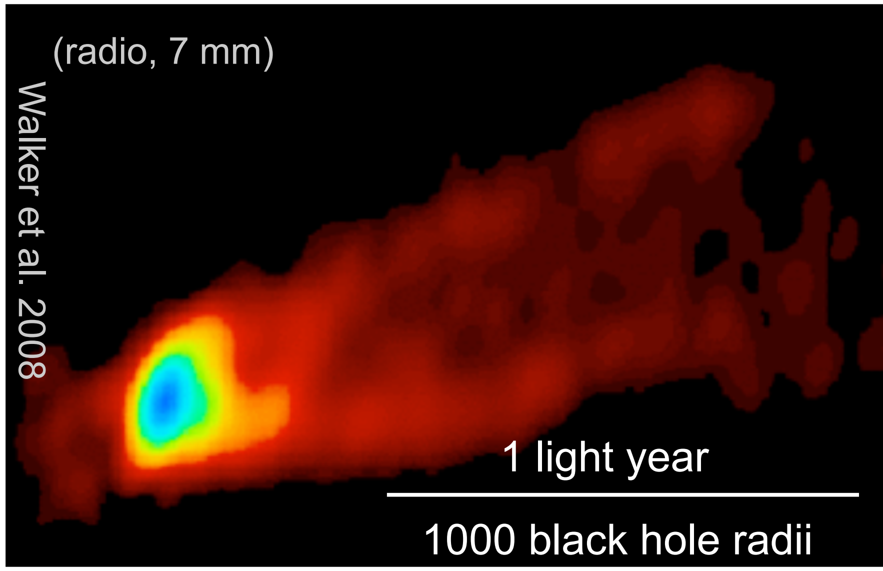


M87

Image size $\sim 11r_{\rm g}$

(Doeleman et al. 2012)

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



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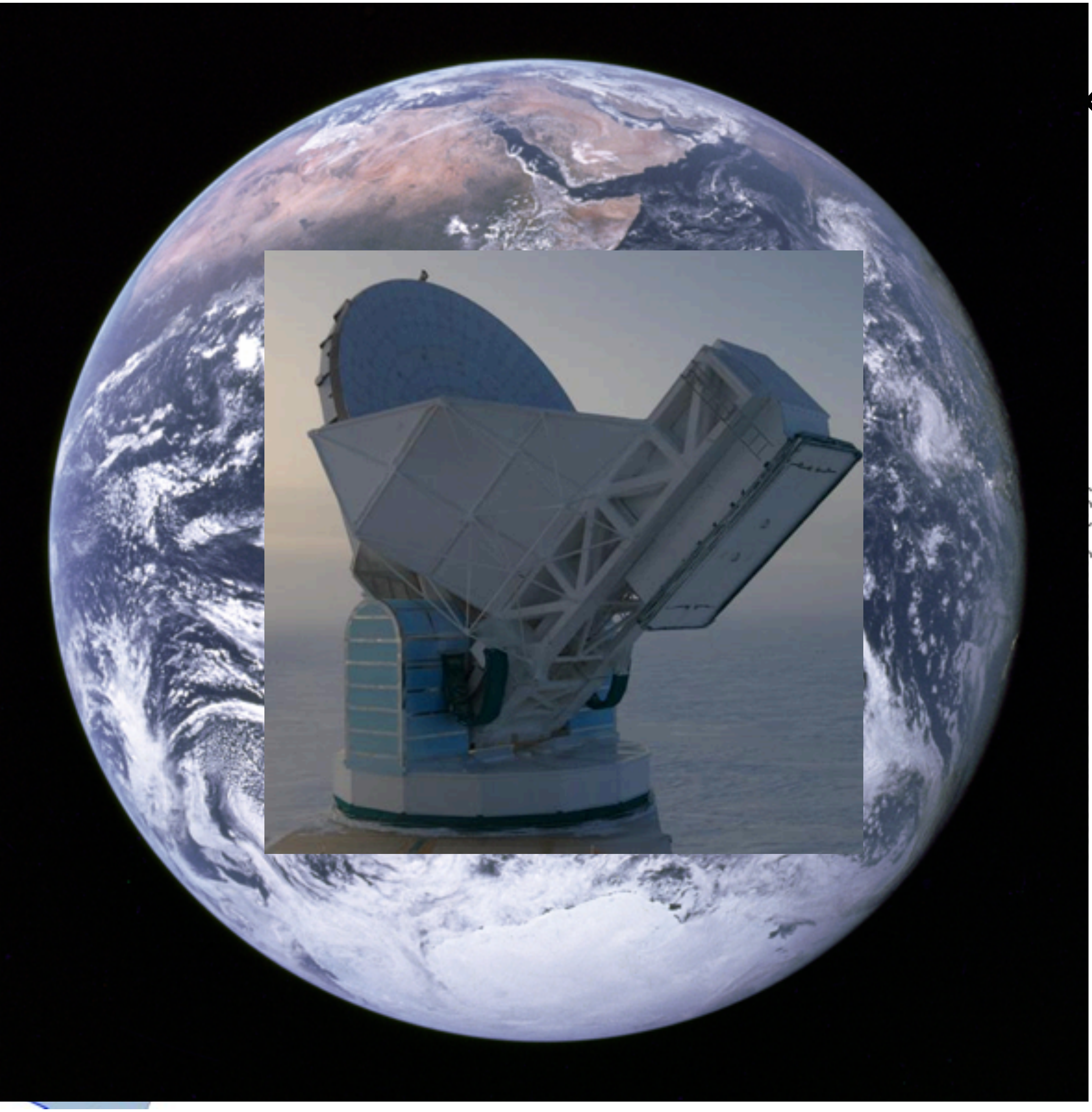

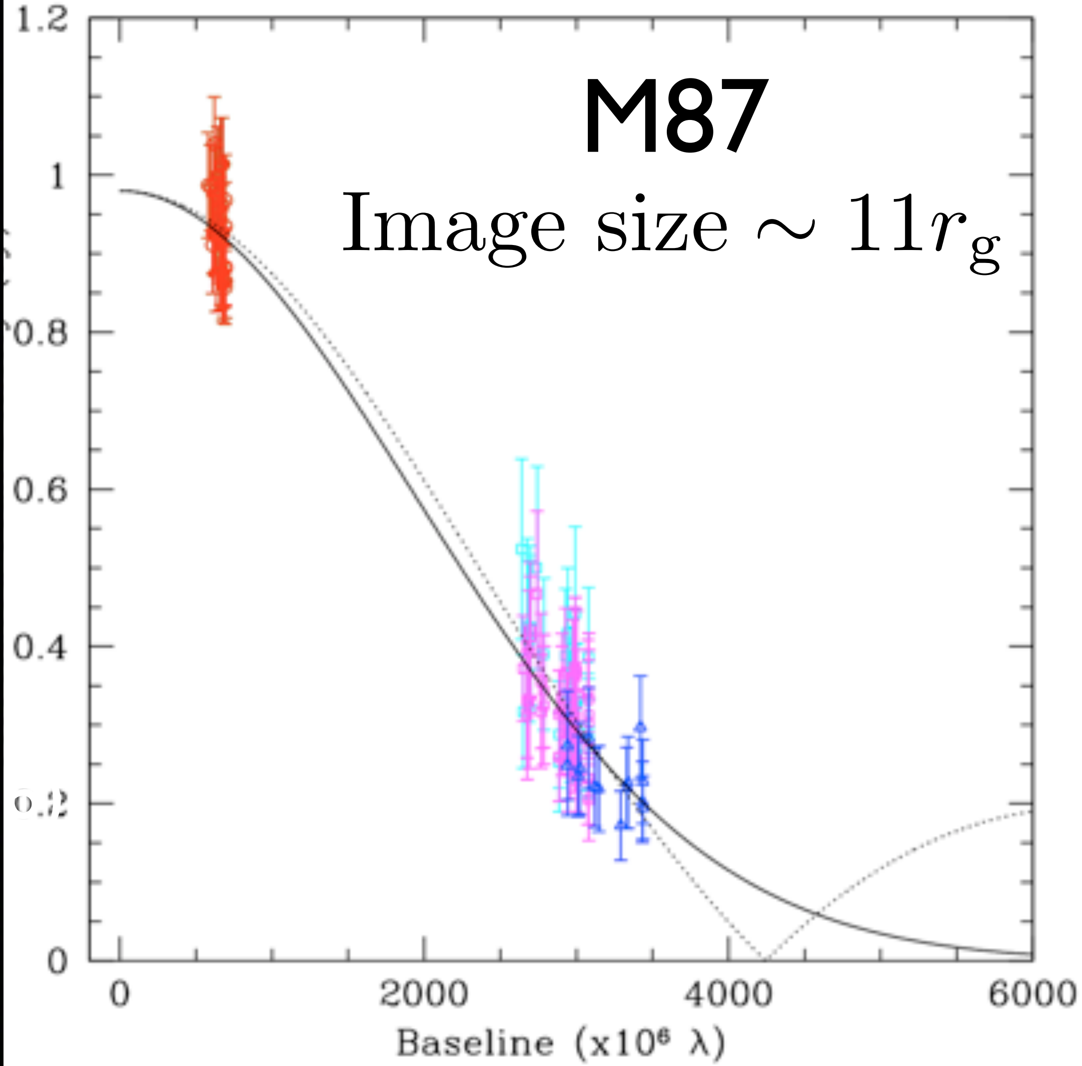

(Doeleman et al. 2012)

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

credit: event horizon telescope.org

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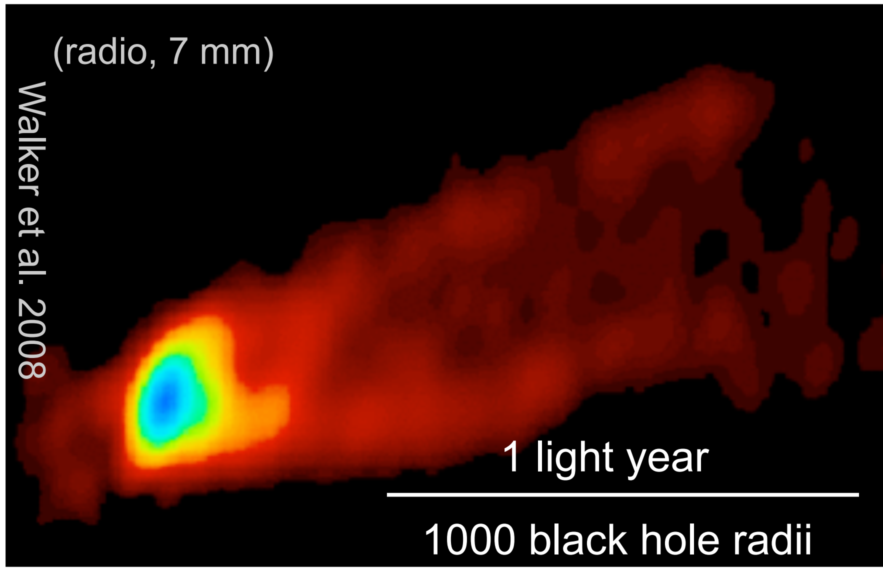
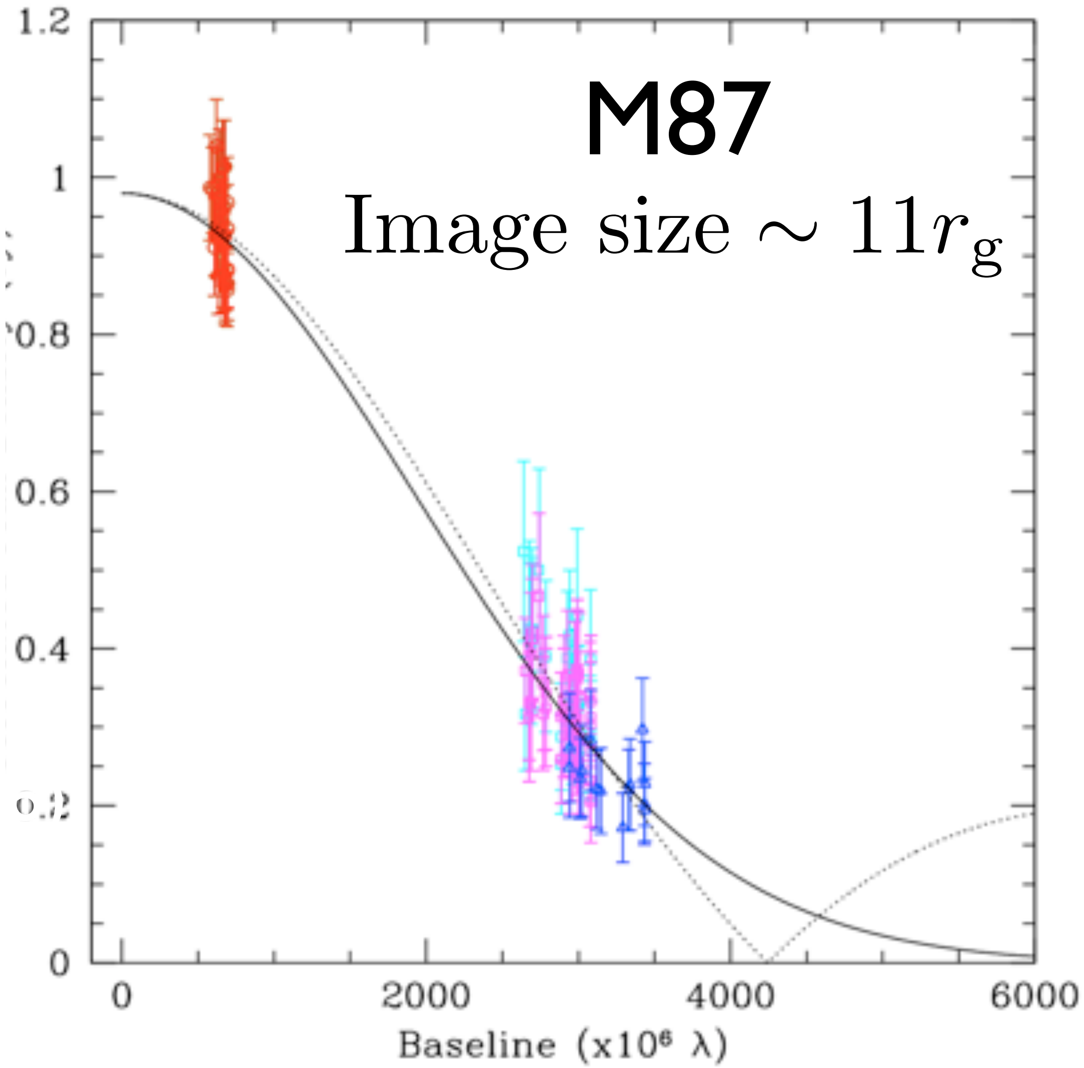
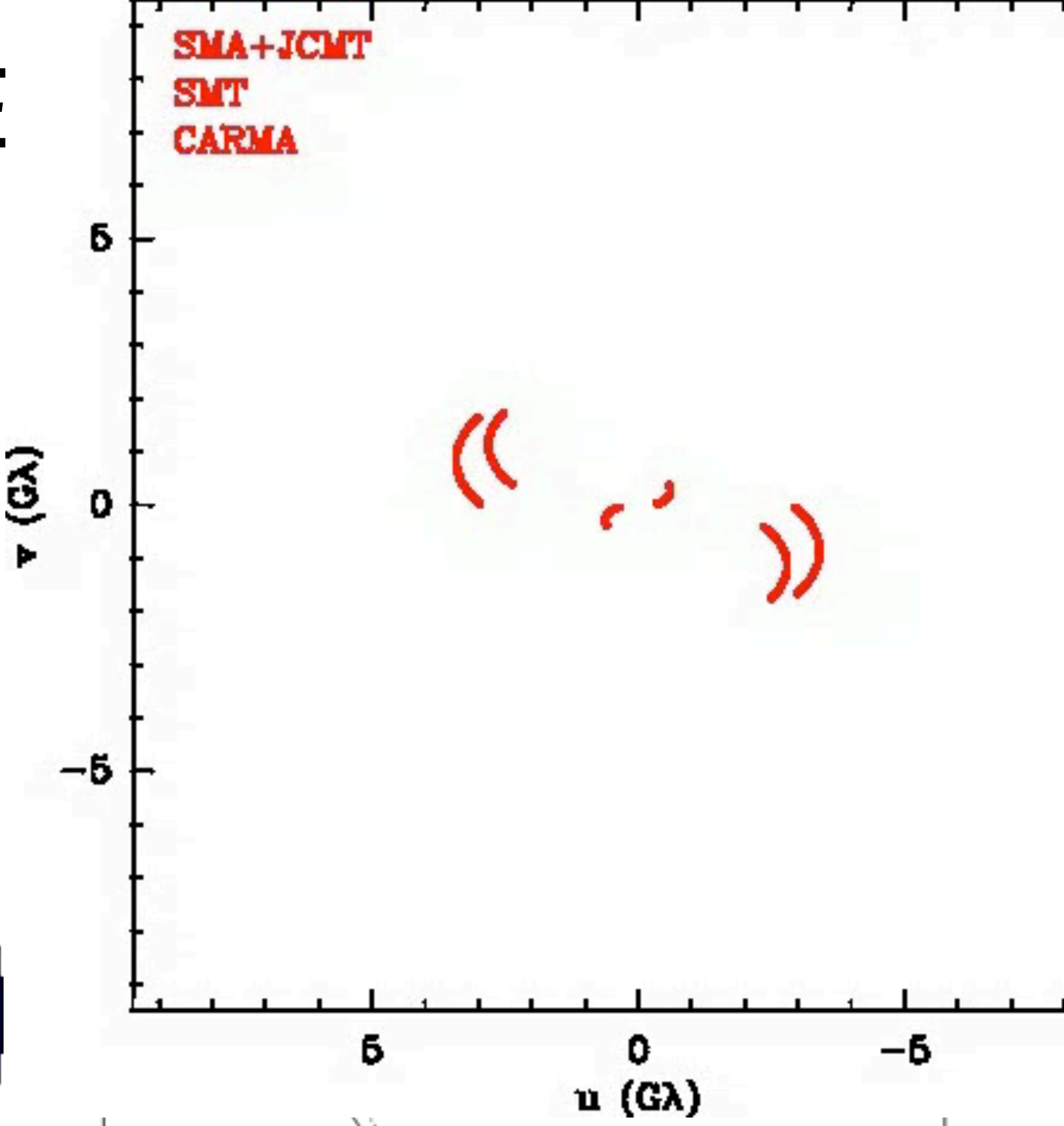


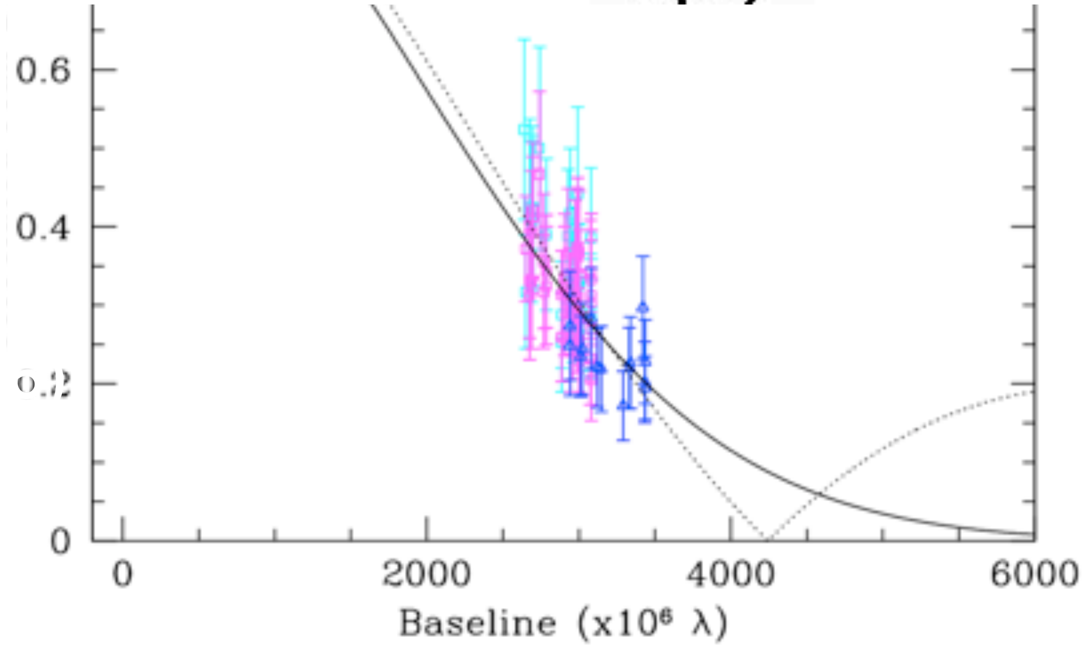


(Doeleman et al. 2012)

Event Horizon Telescope (E
VLBI images of Black Hol

credit:
event
horizon
telescope.org





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VLBI images of Black Hol

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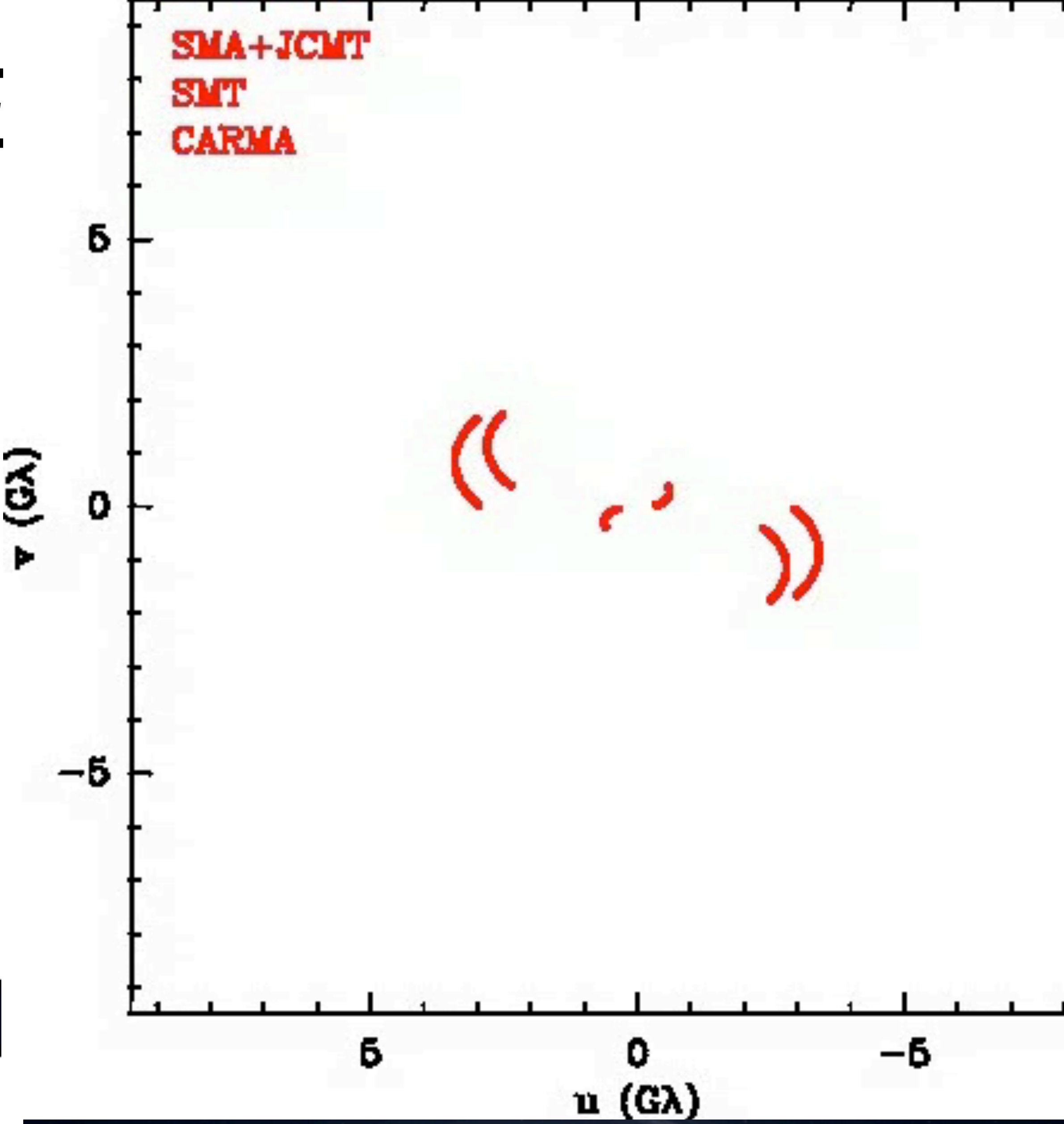
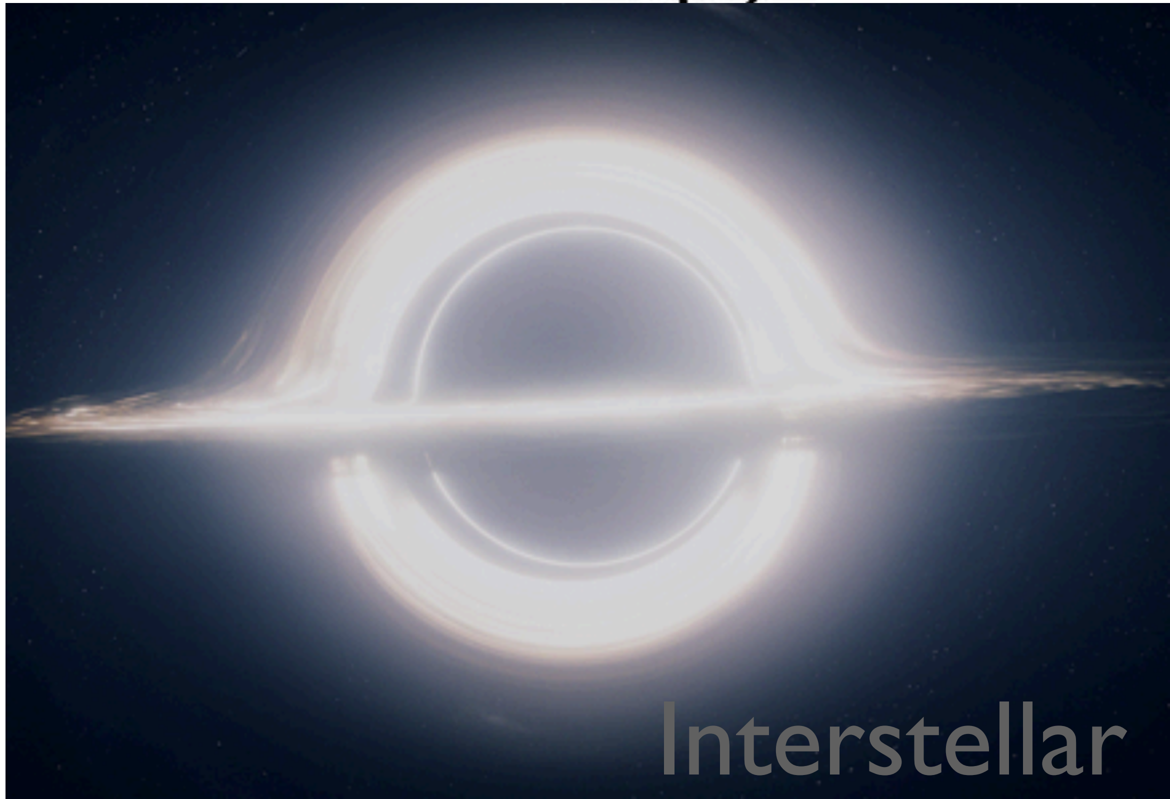
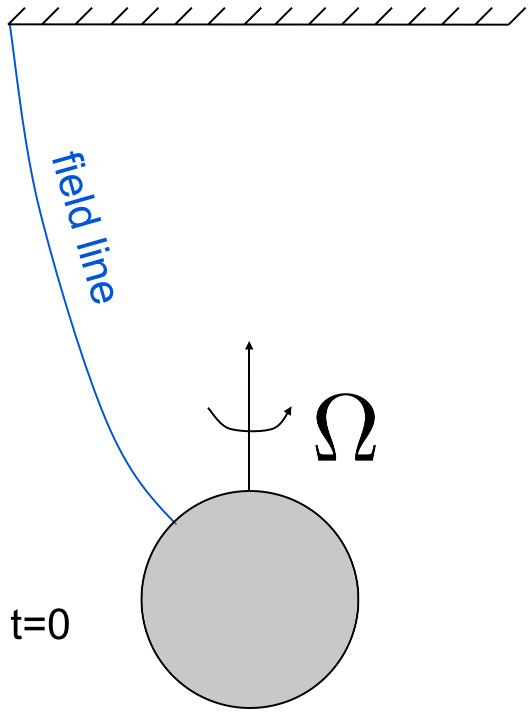


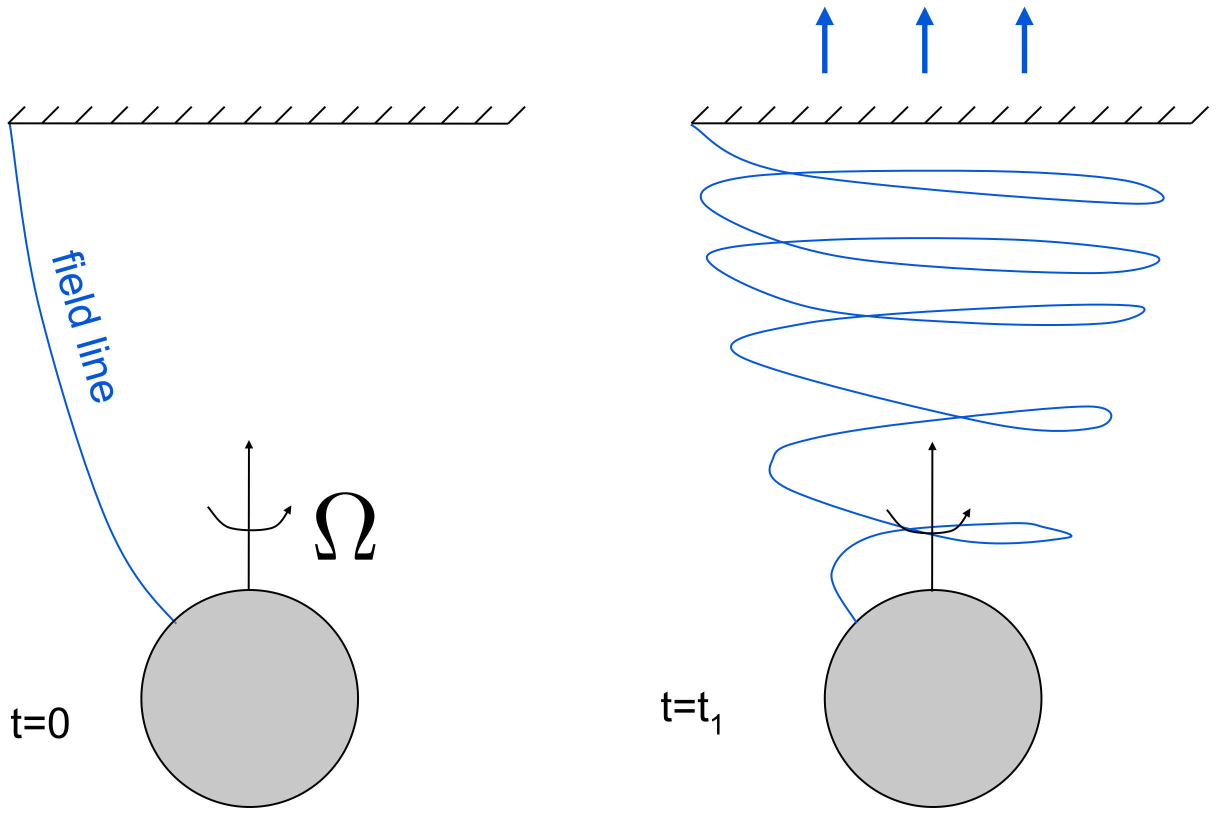


Jets 101



Jets 101

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



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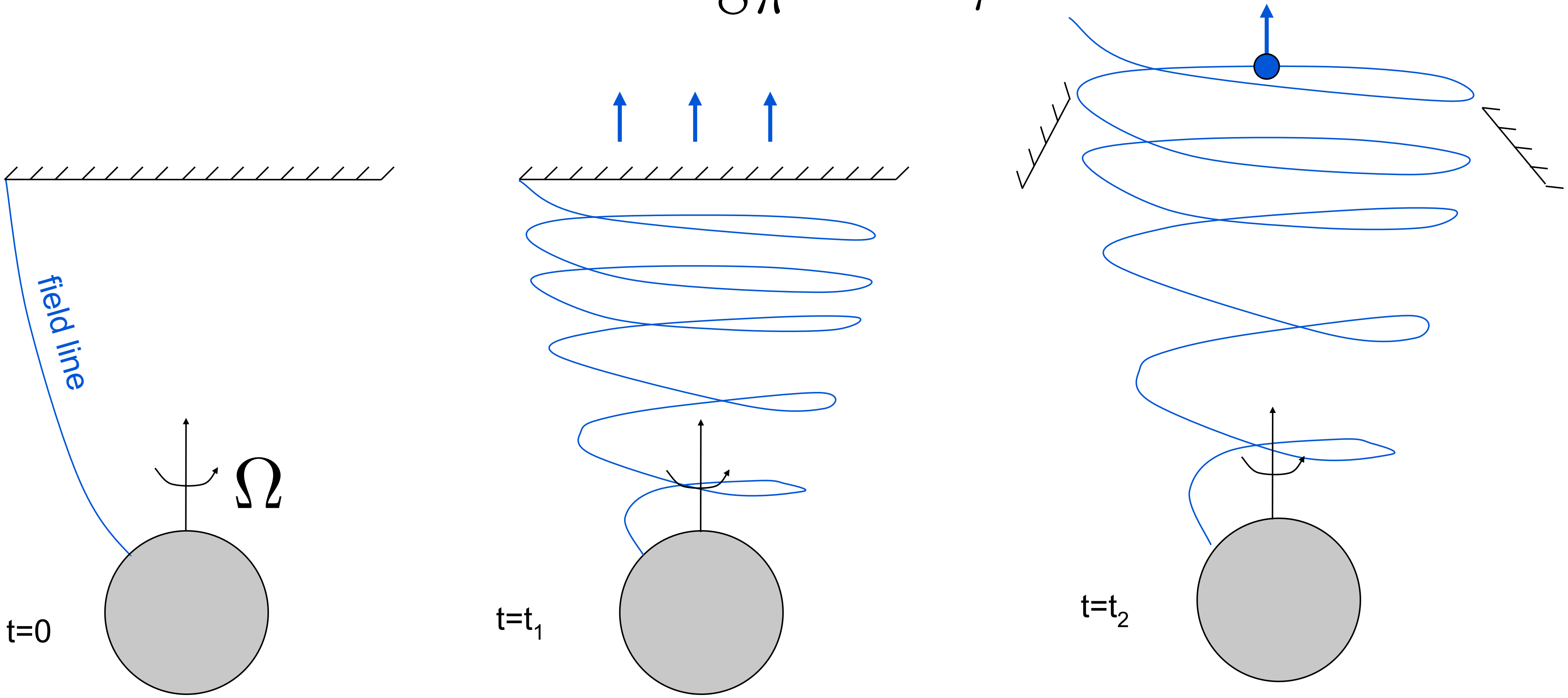
Field toroidally-dominated

$$B_\varphi \gg B_z$$



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

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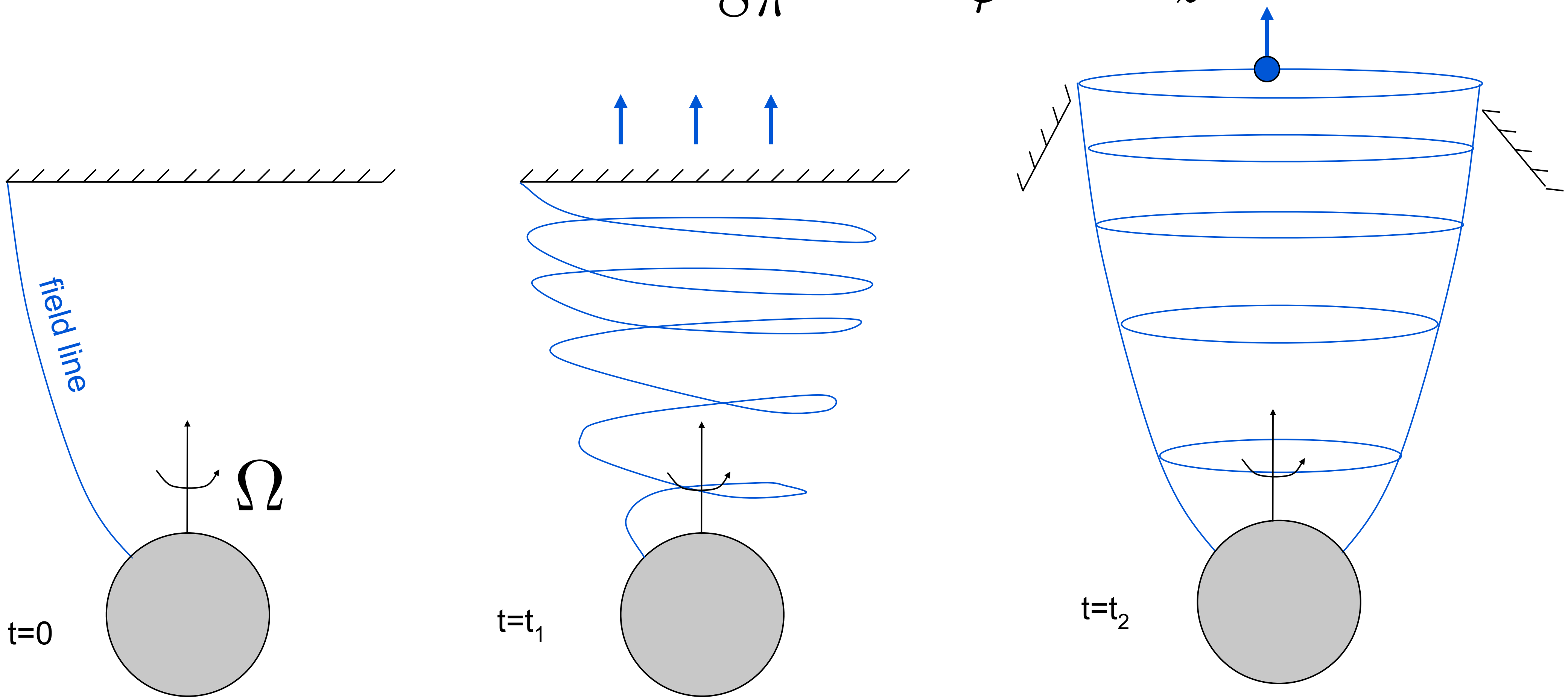

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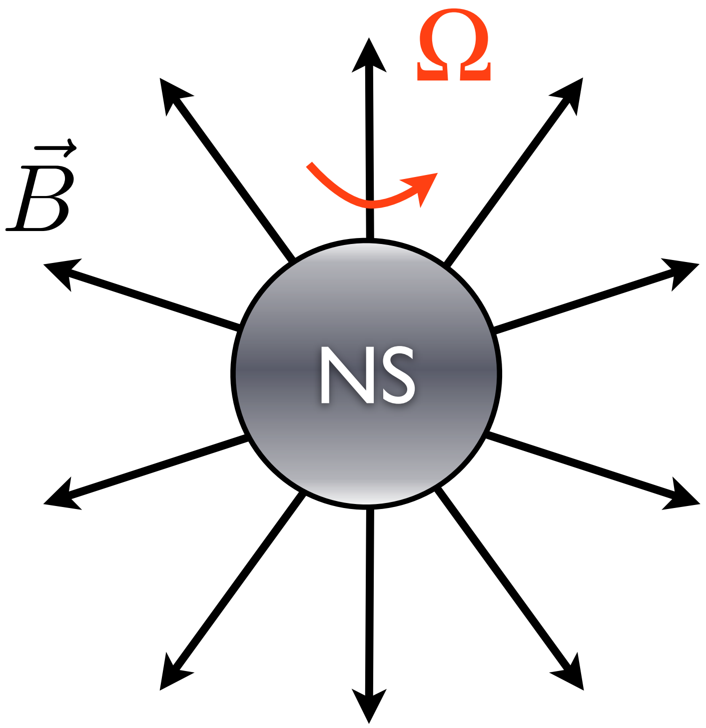
What Powers Outflow?



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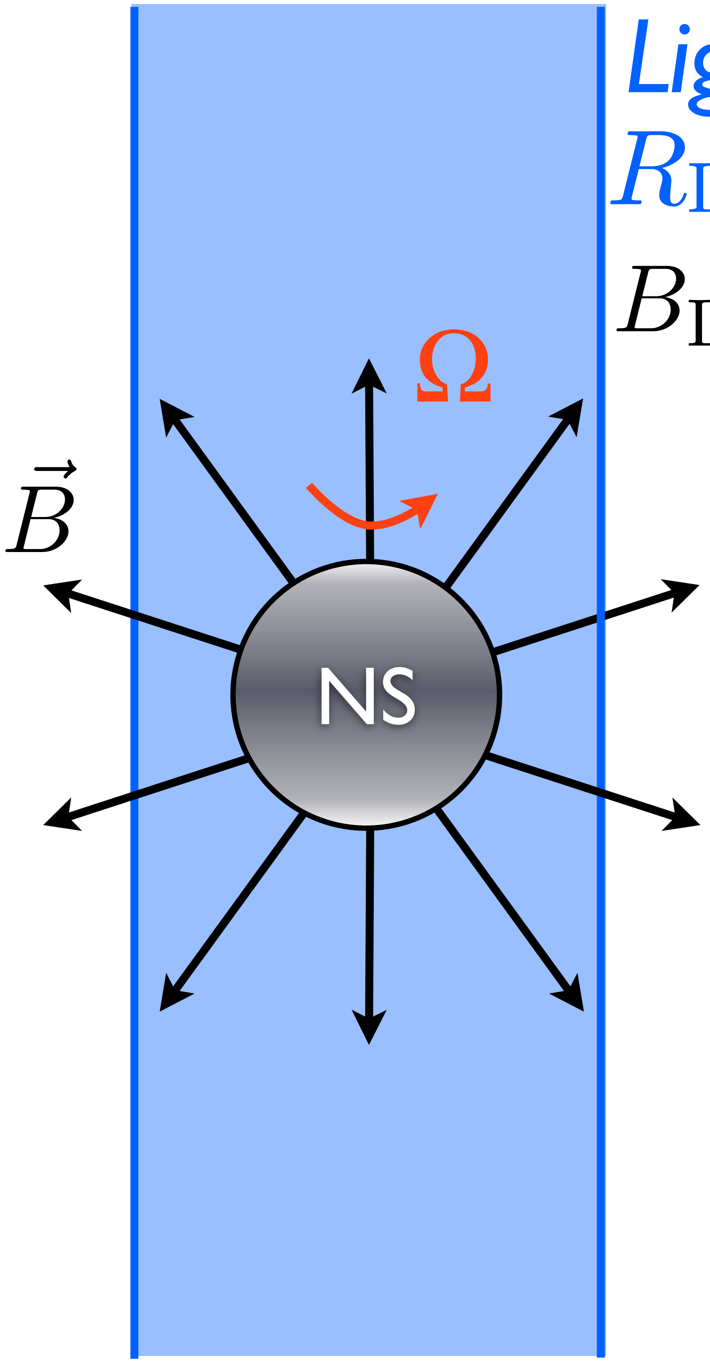

Light cylinder (LC):

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

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

- Flow separates from NS at LC

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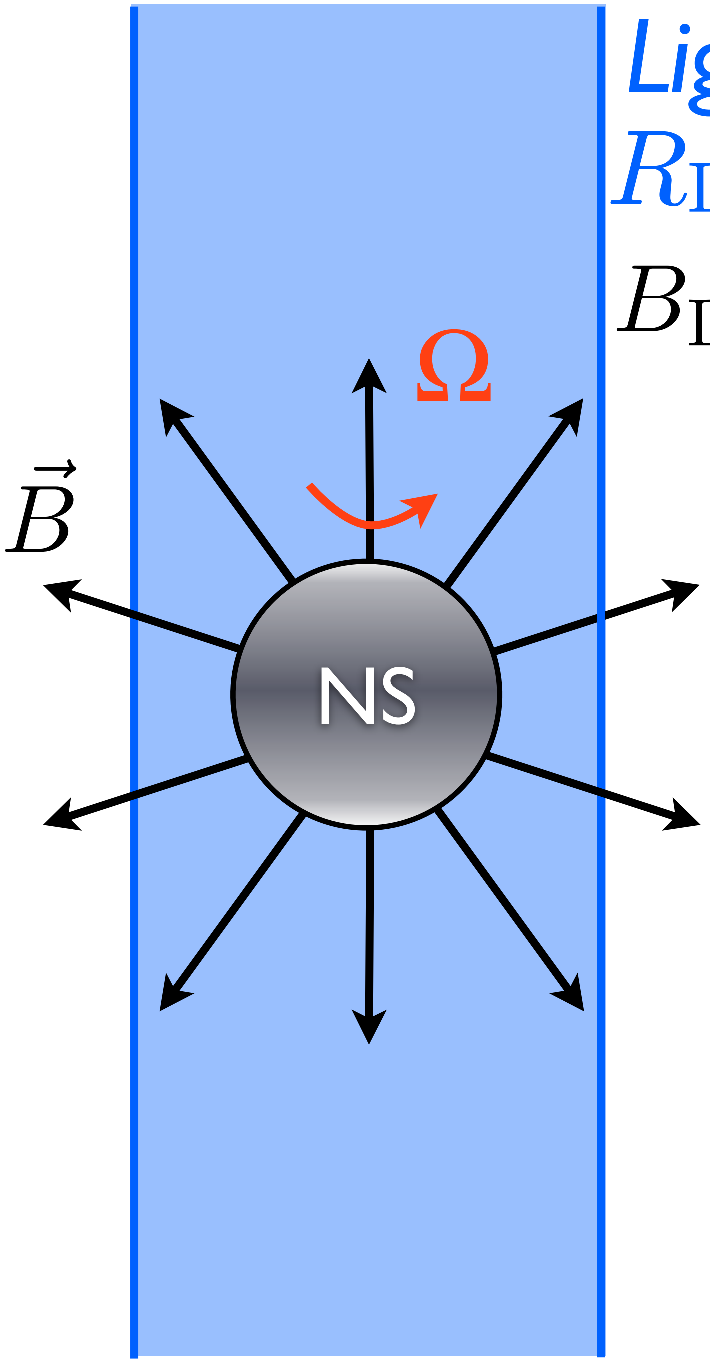

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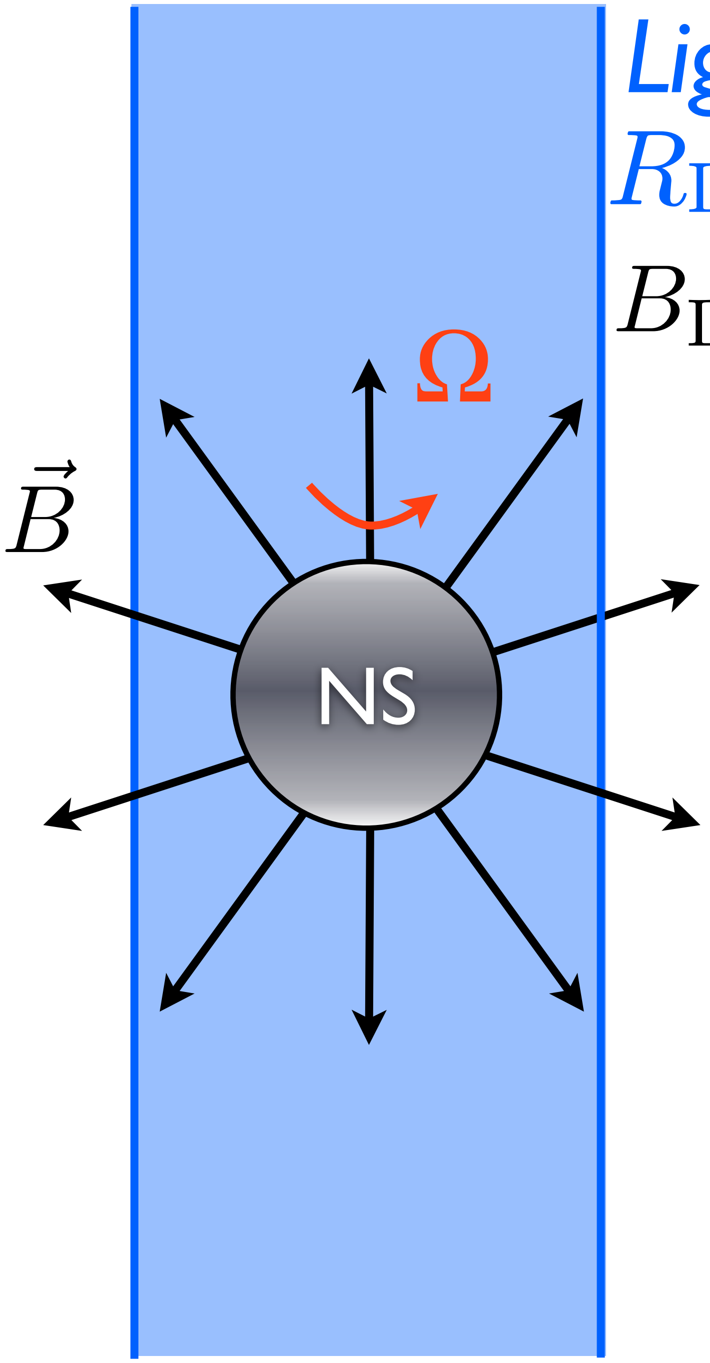

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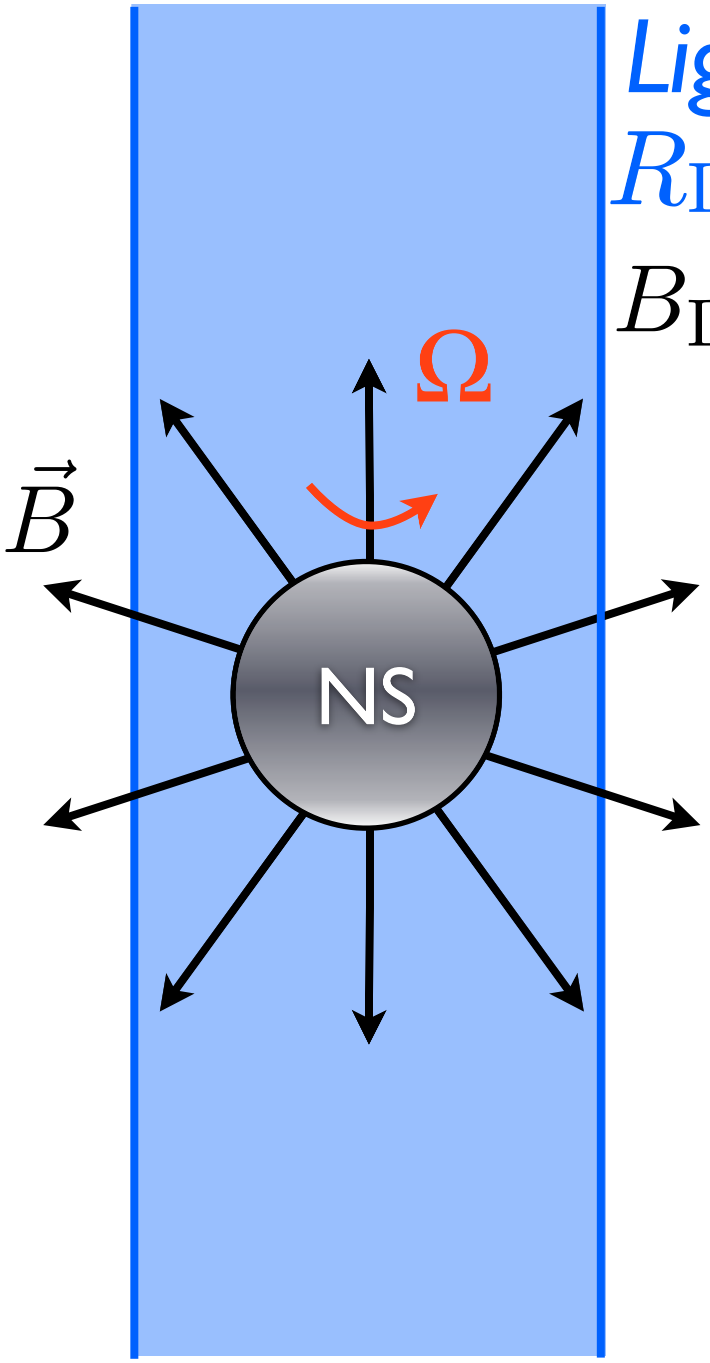

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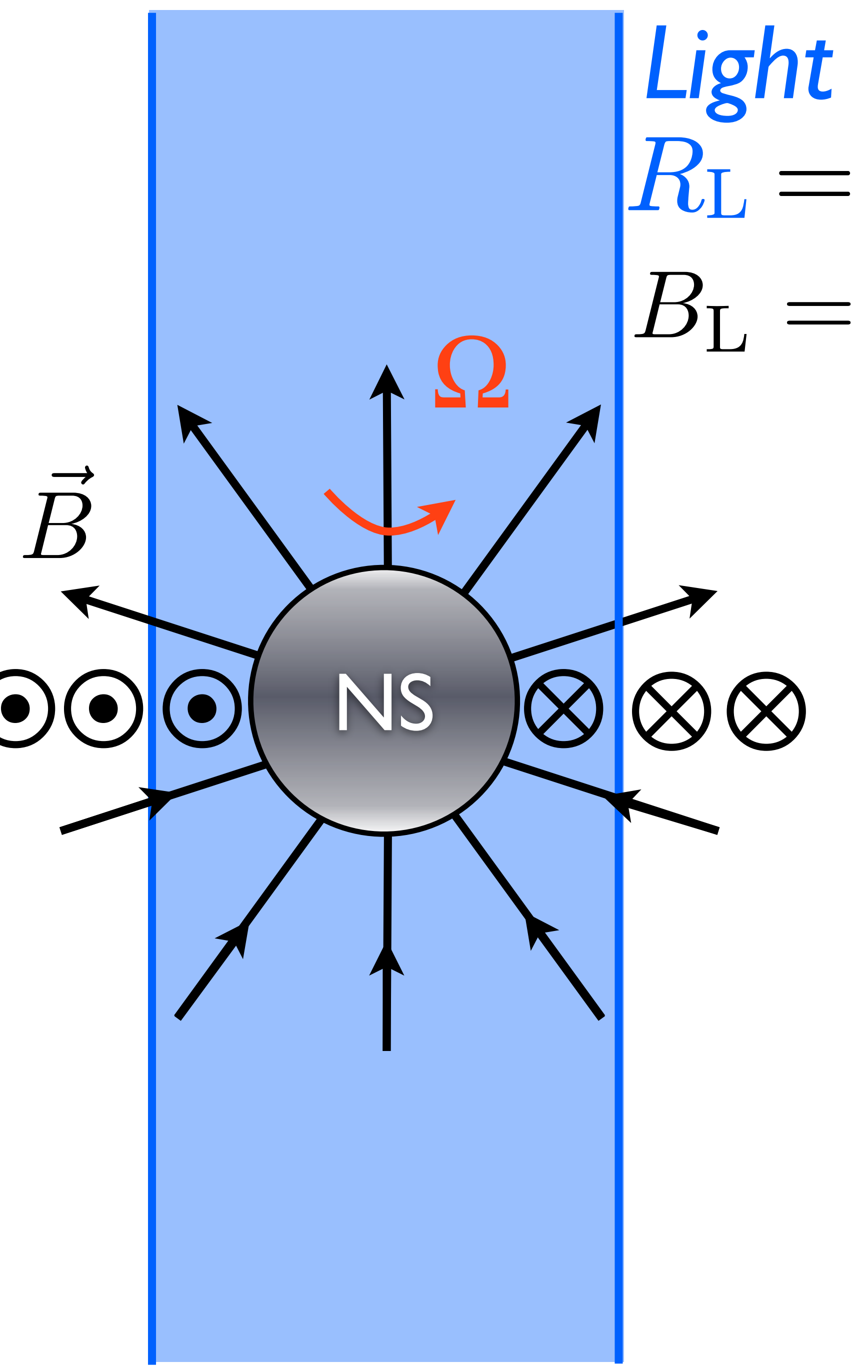

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- Split-monopole

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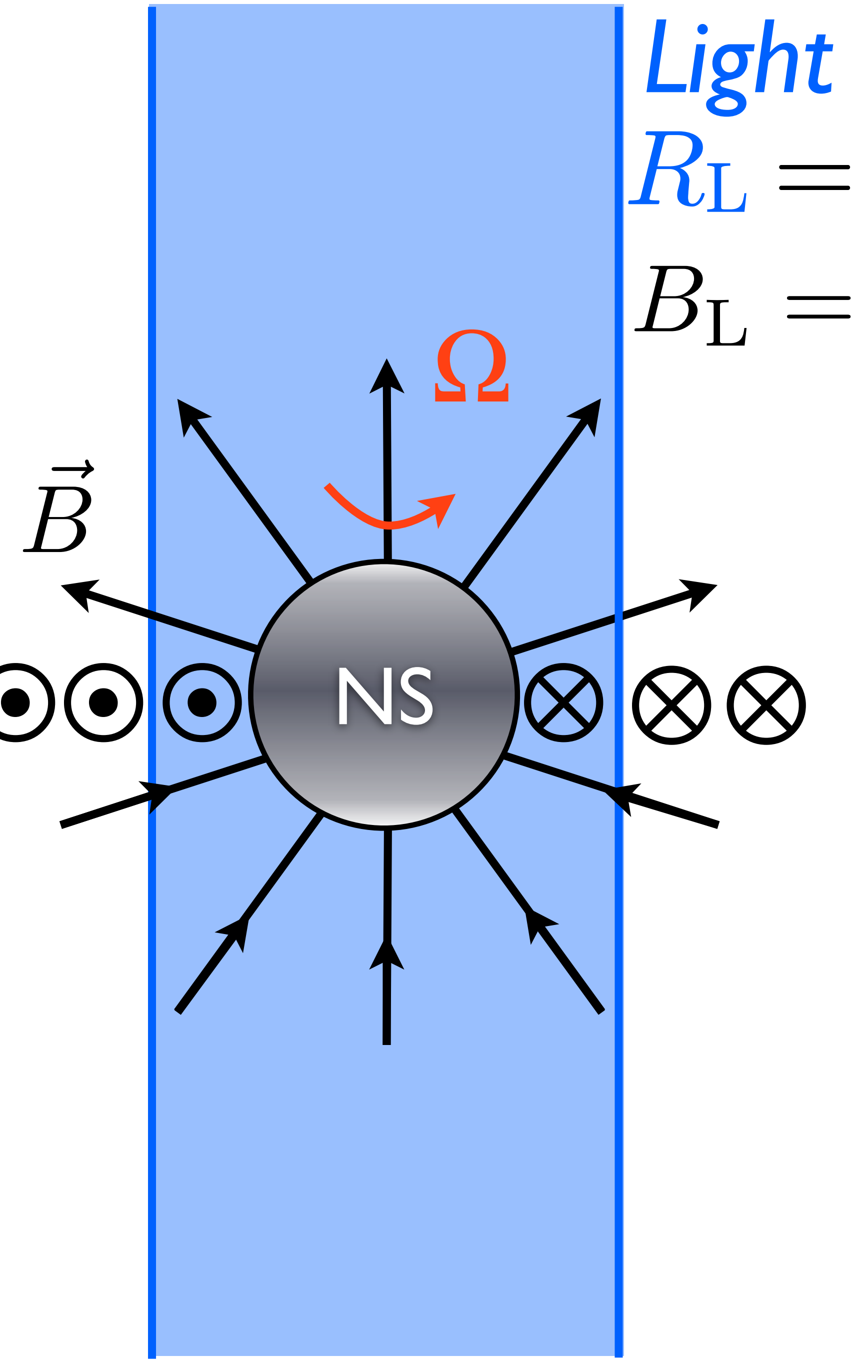

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- Split-monopole
- What about black holes?

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

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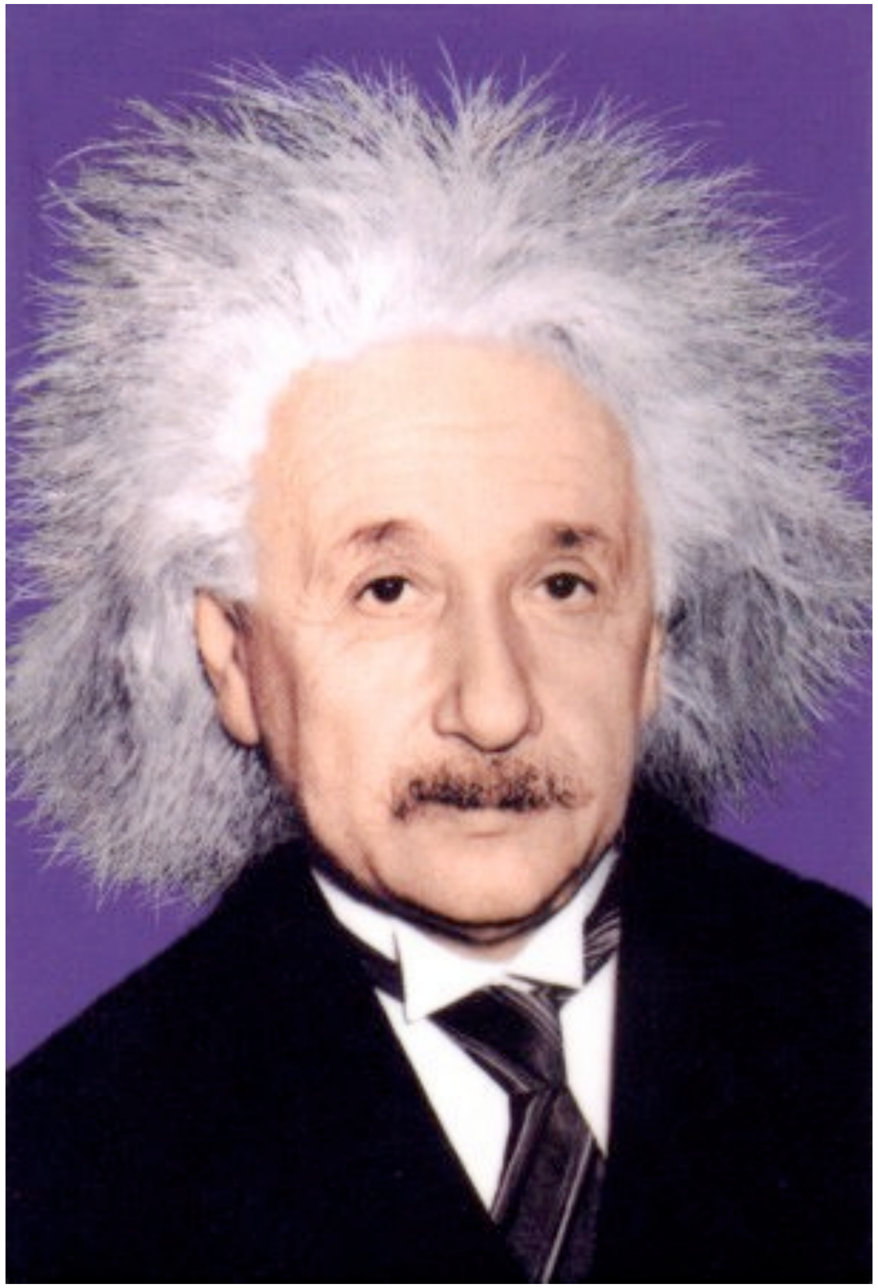
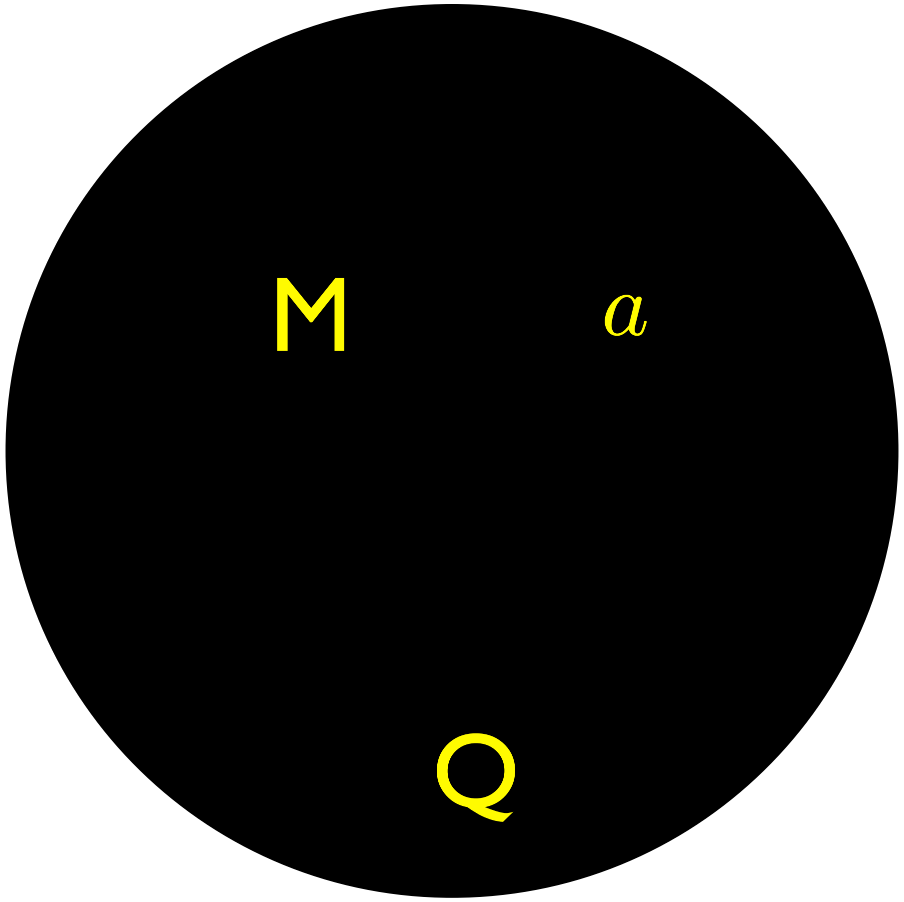
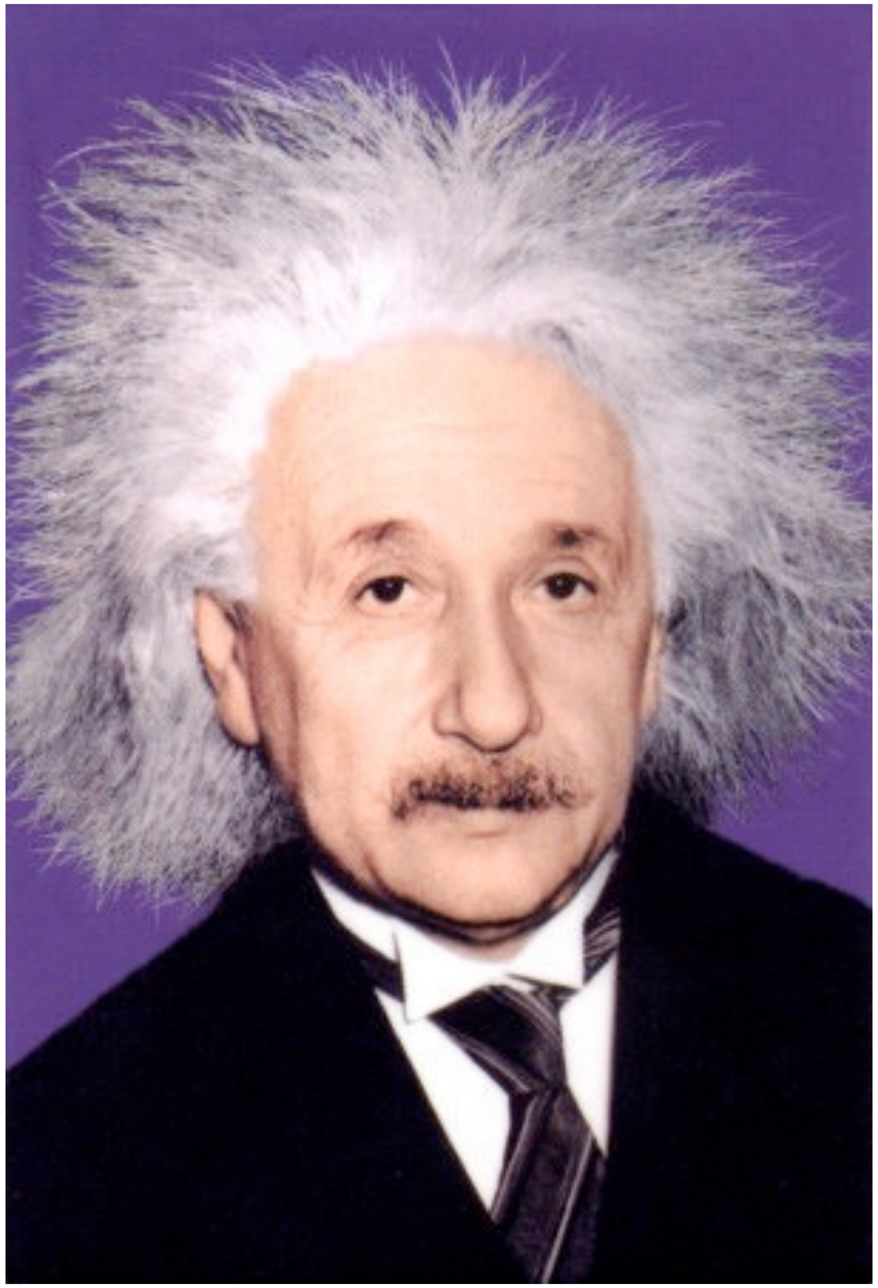


Einstein had a lot of hair!



Black Hole has **3** hairs!

Slide: R. Narayan



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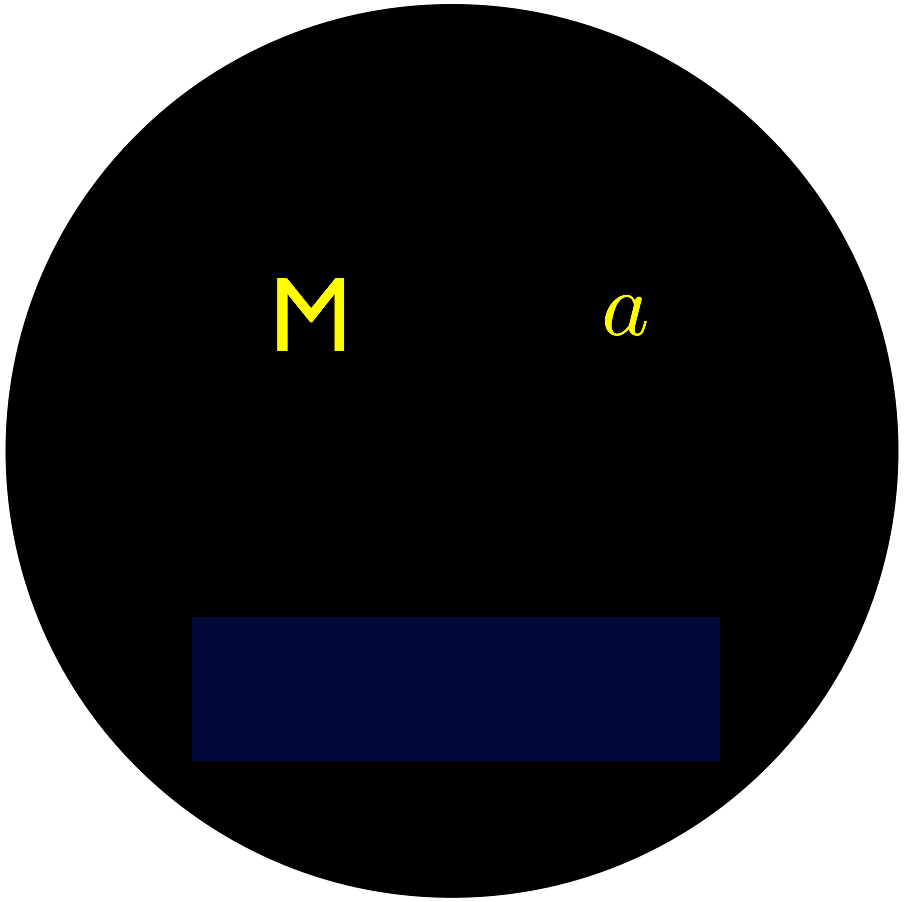
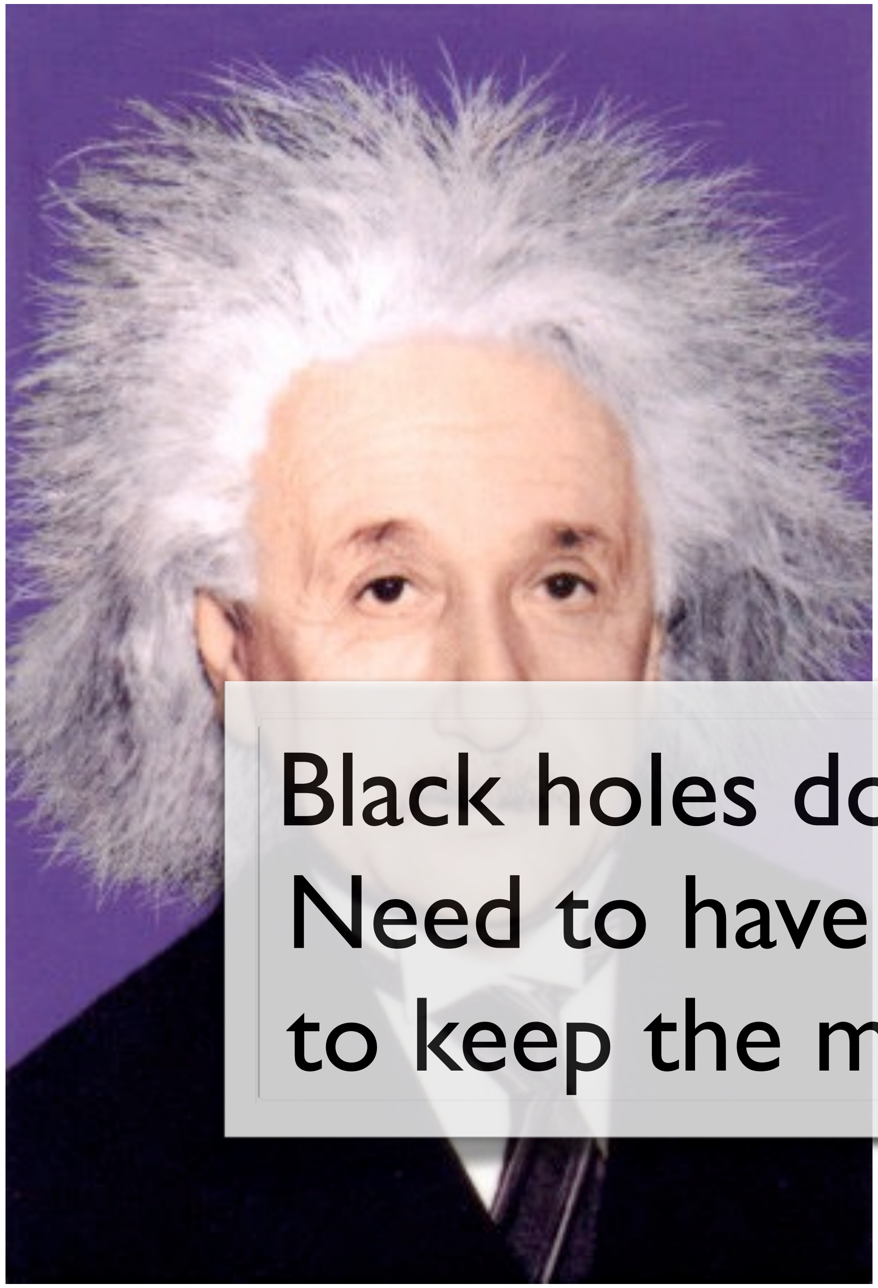
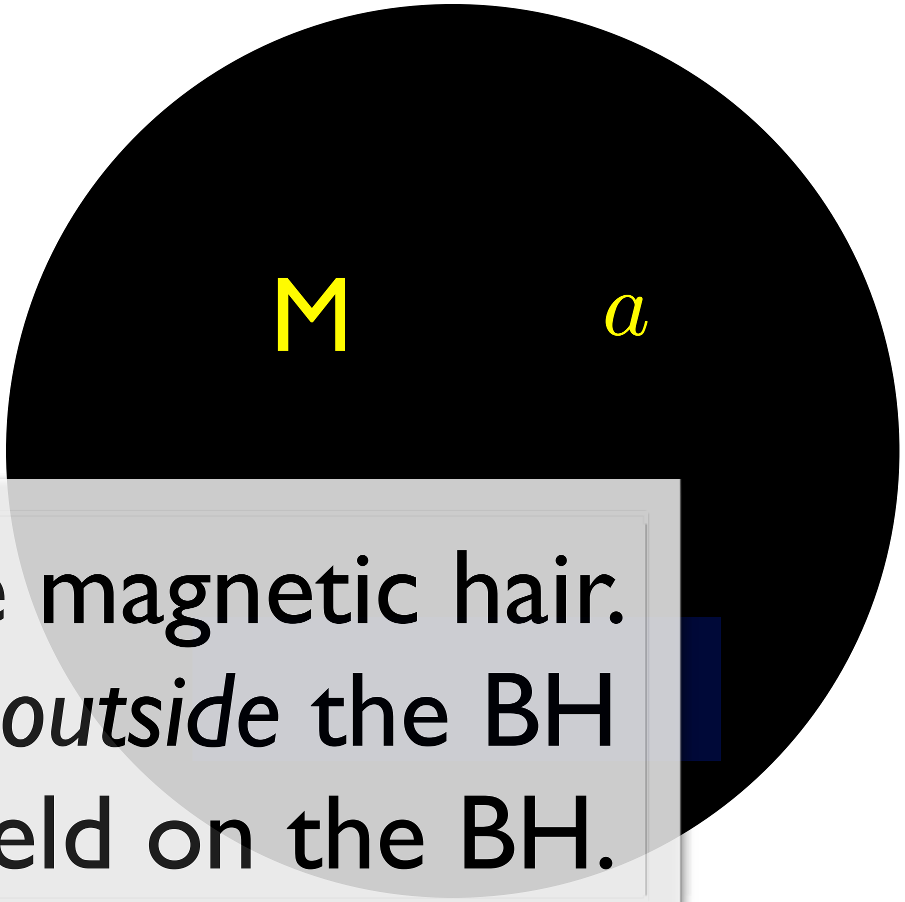


A **Black Hole** has only **2** hairs

Slide: R. Narayan



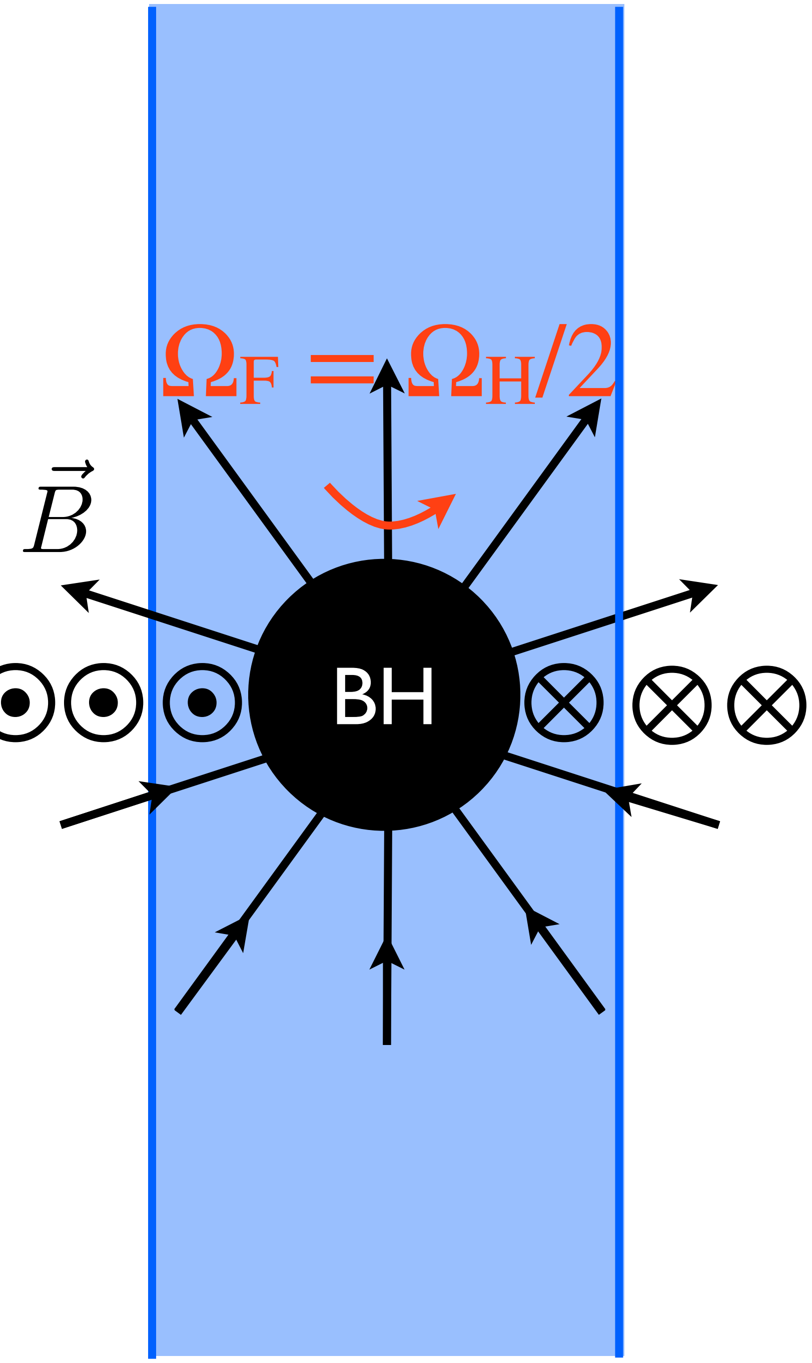


Black holes do not have magnetic hair. Need to have currents *outside* the BH to keep the magnetic field on the BH.

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:

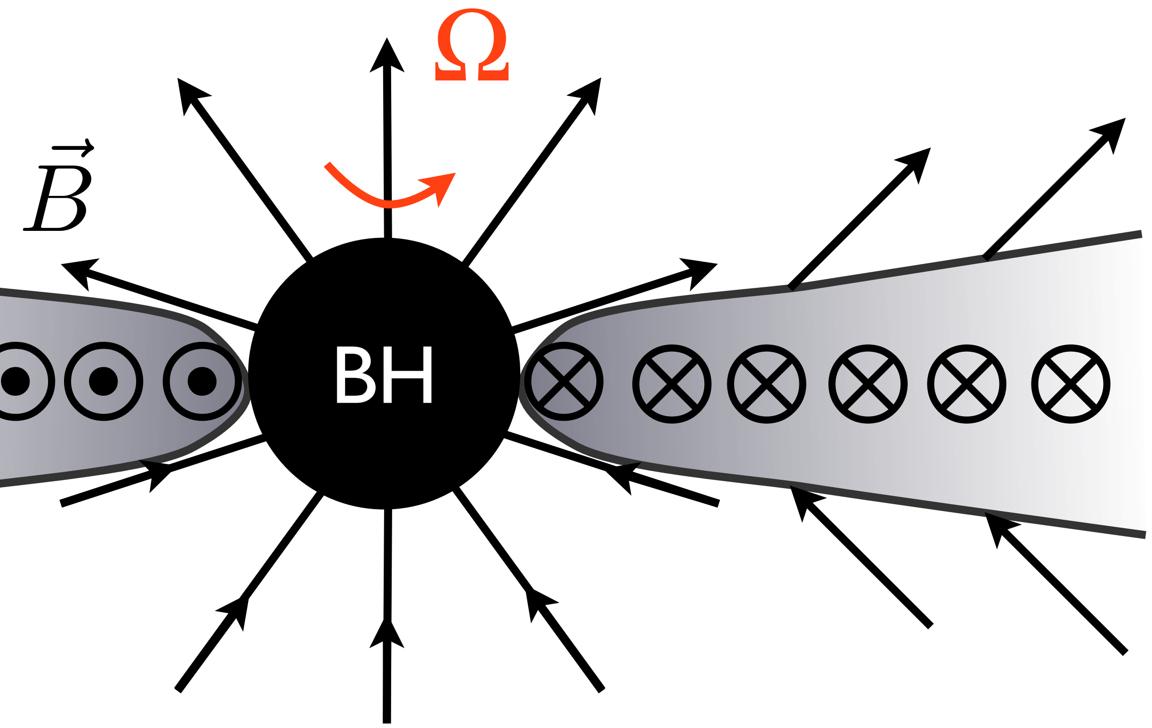
$$\Omega_{\rm F} = \Omega_{\rm H}/2$$

- Otherwise, behaves almost like a NS!

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

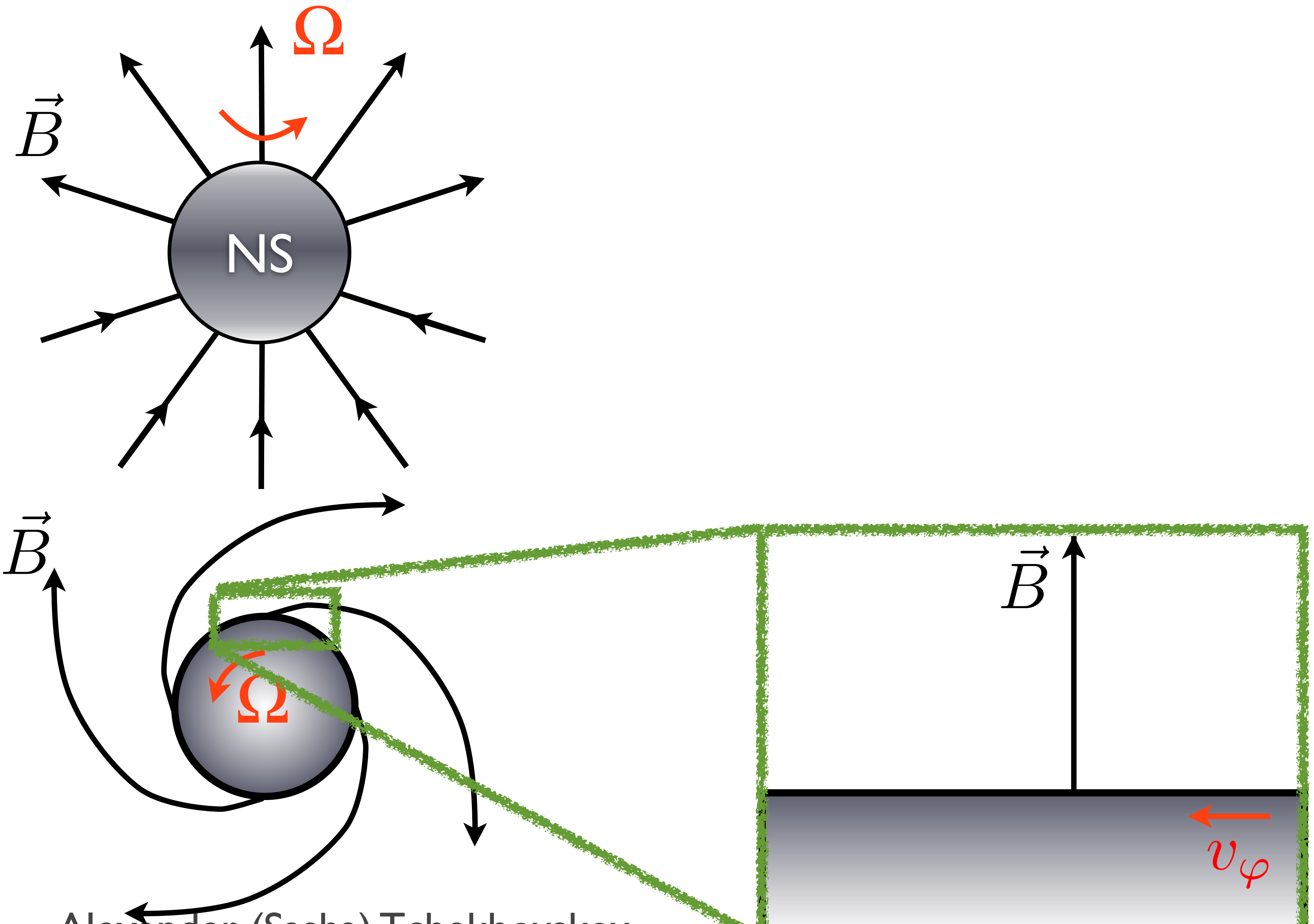
(~10% corrections for other field geometries, AT+10, AT15)

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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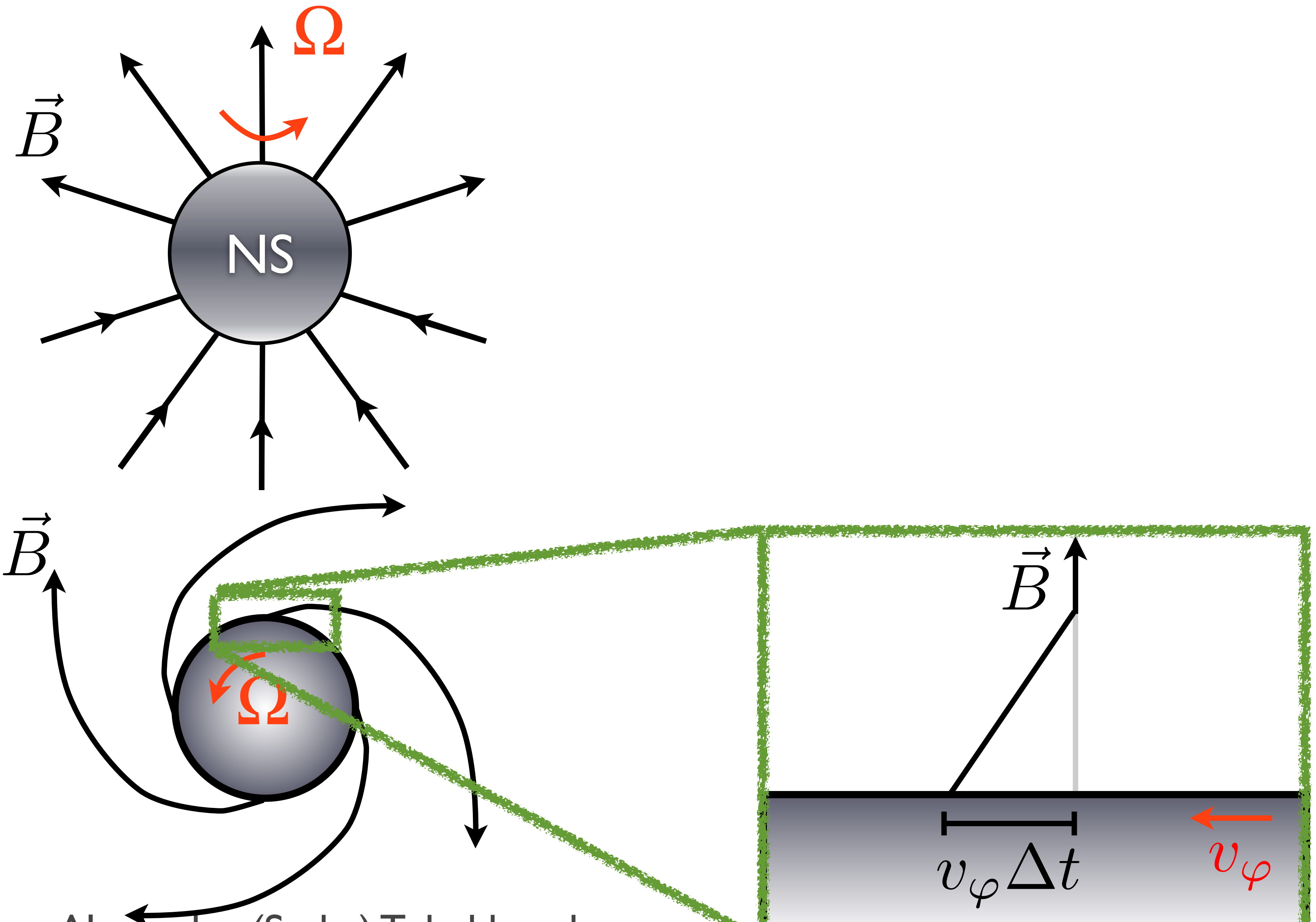

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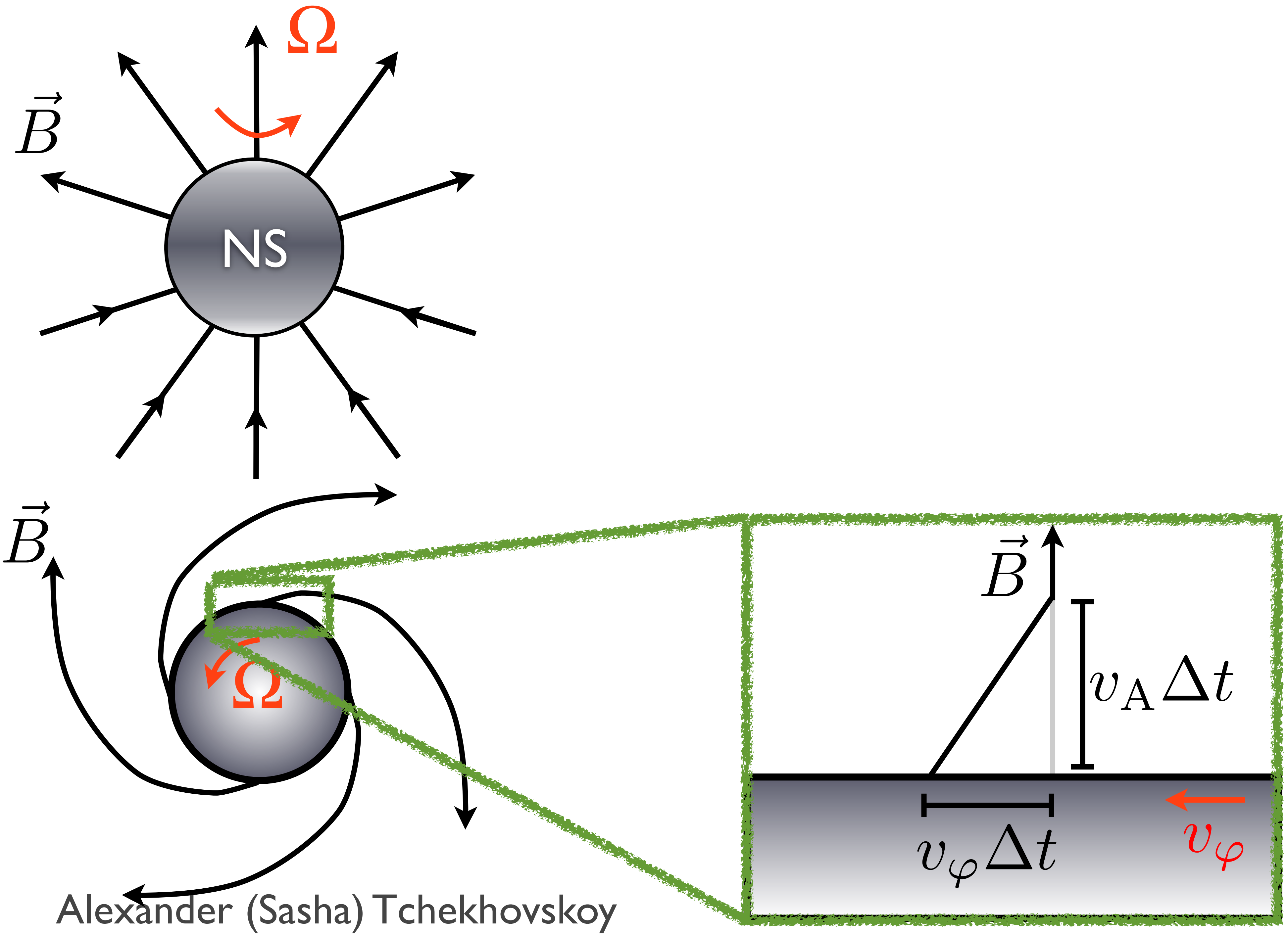
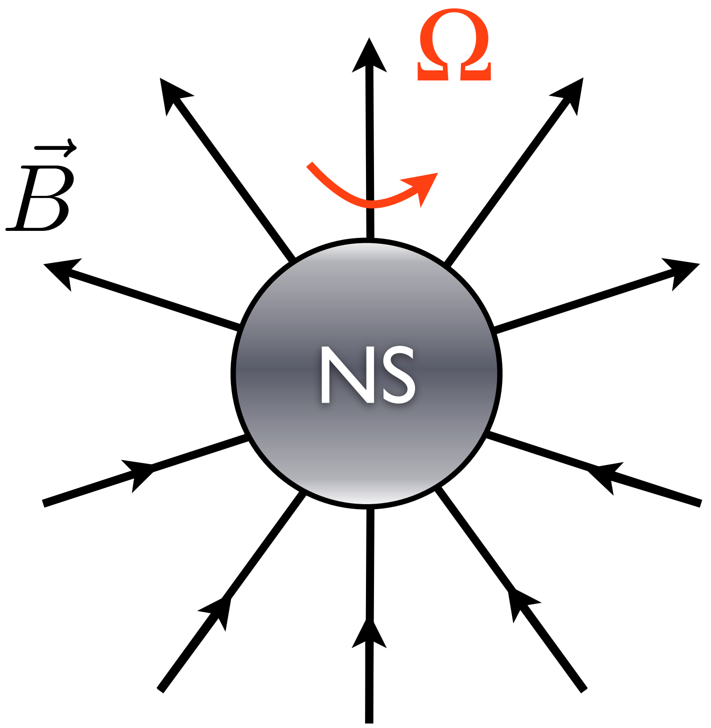
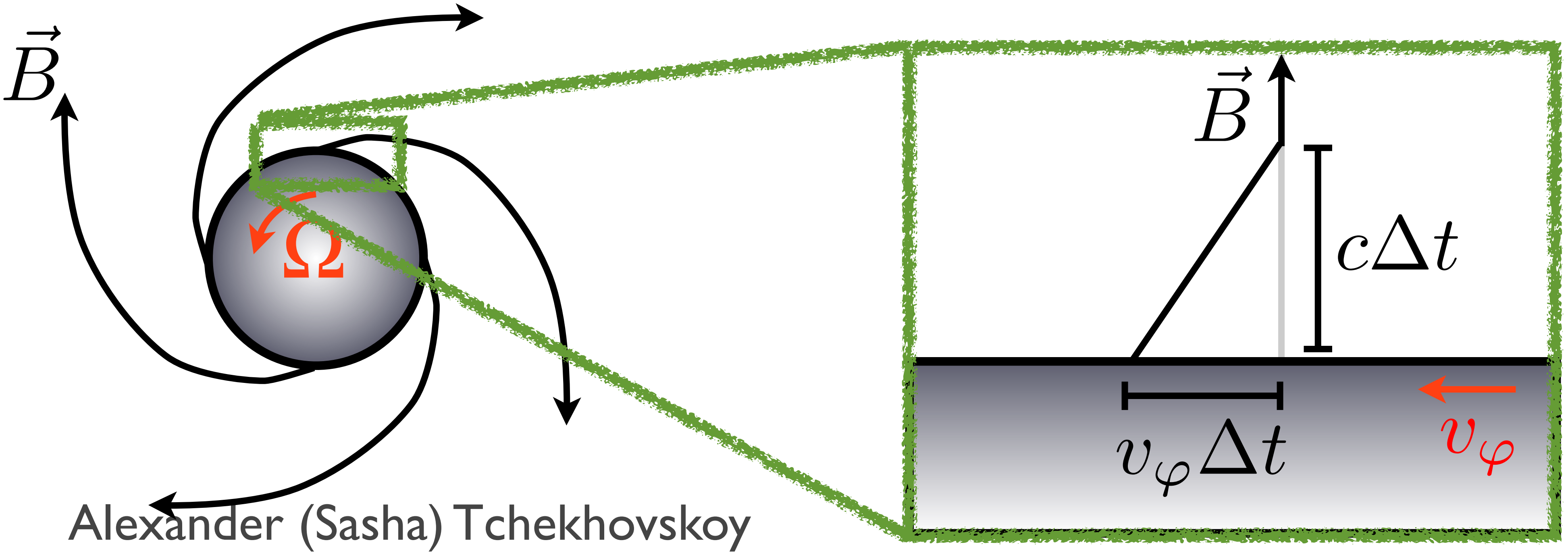


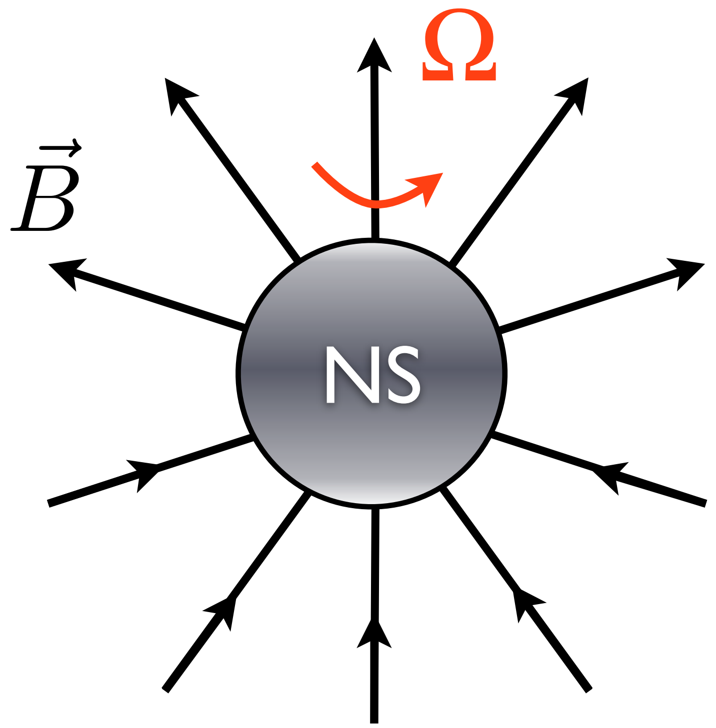
How do ***force-free*** Jets Accelerate?



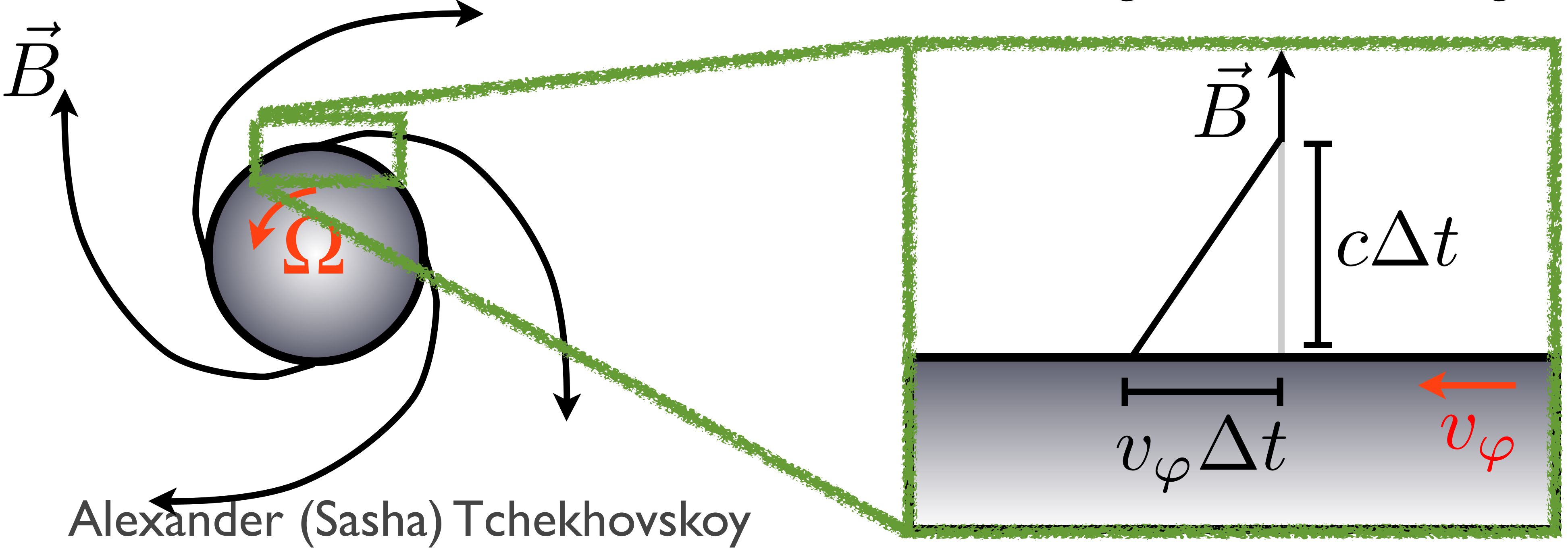


Assume the jets are ***massless (force-free)*** for simplicity

How do force-free Jets Accelerate?



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



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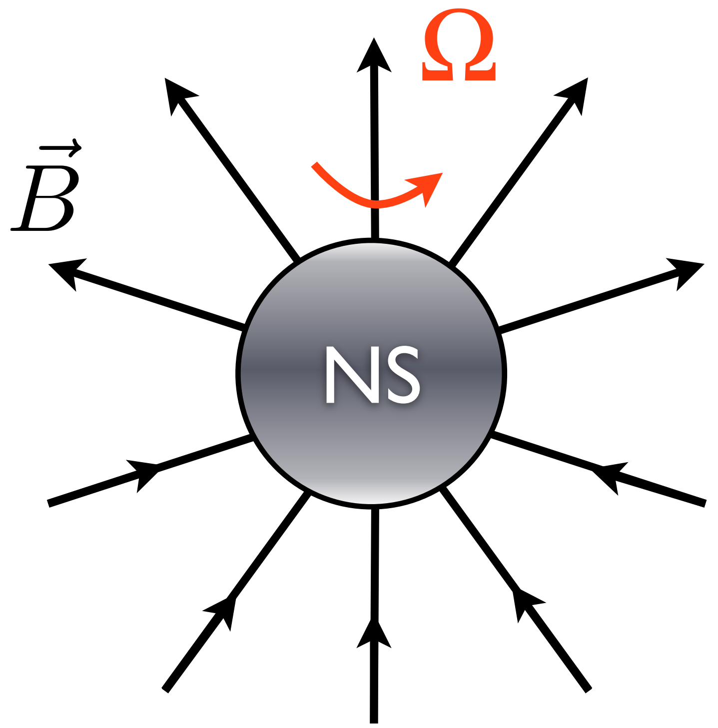
How do force-free Jets Accelerate?



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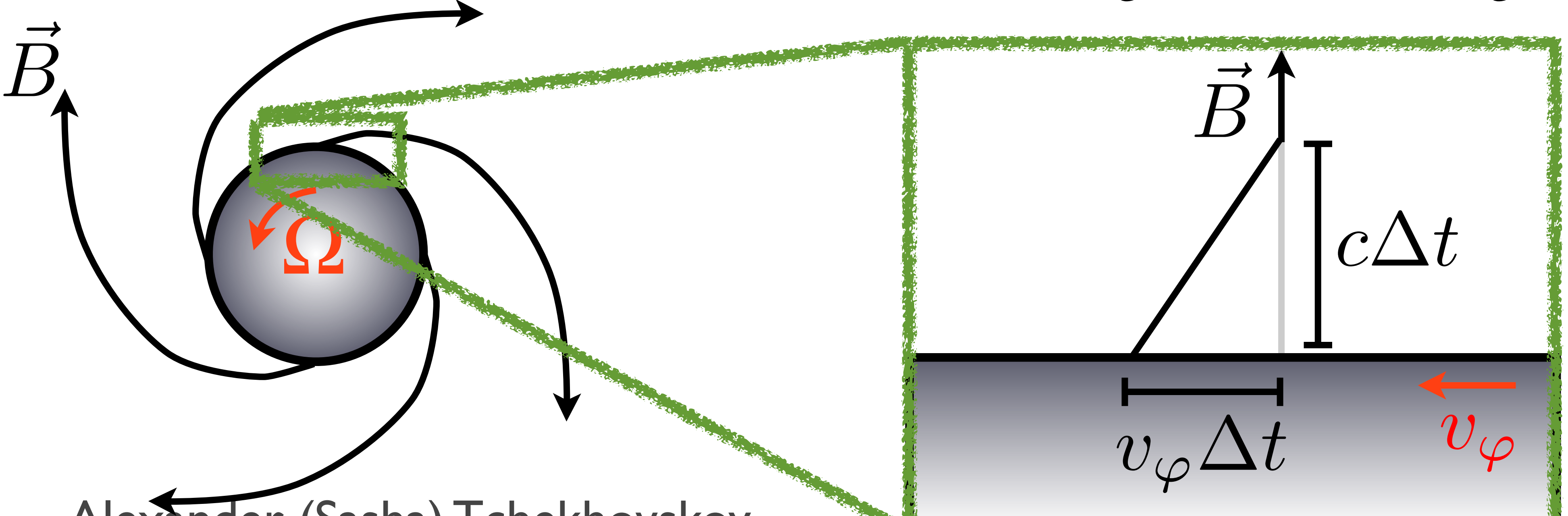

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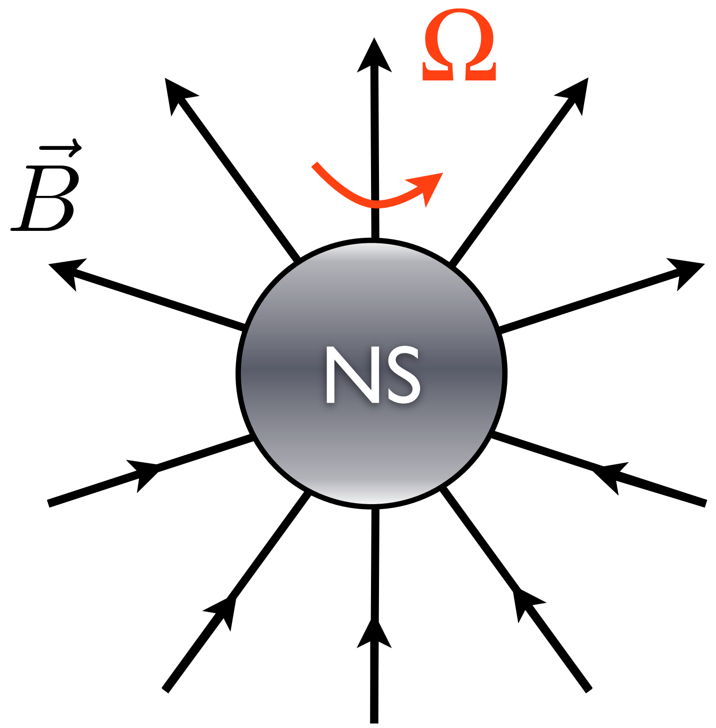

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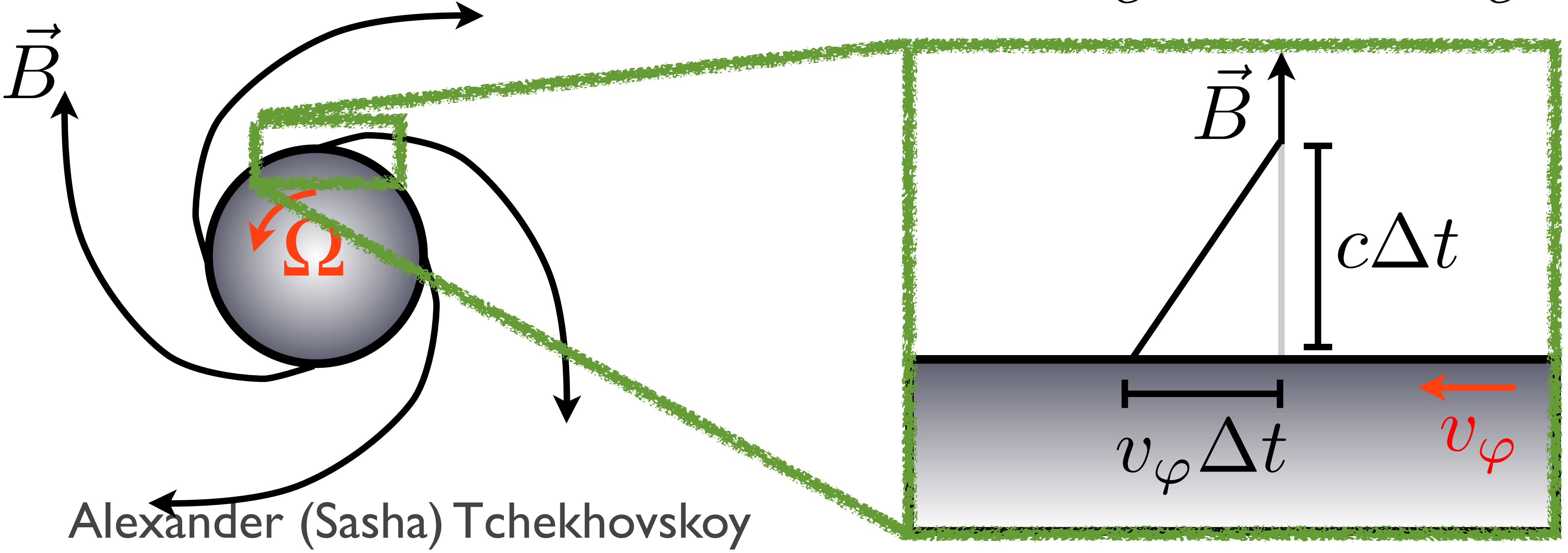

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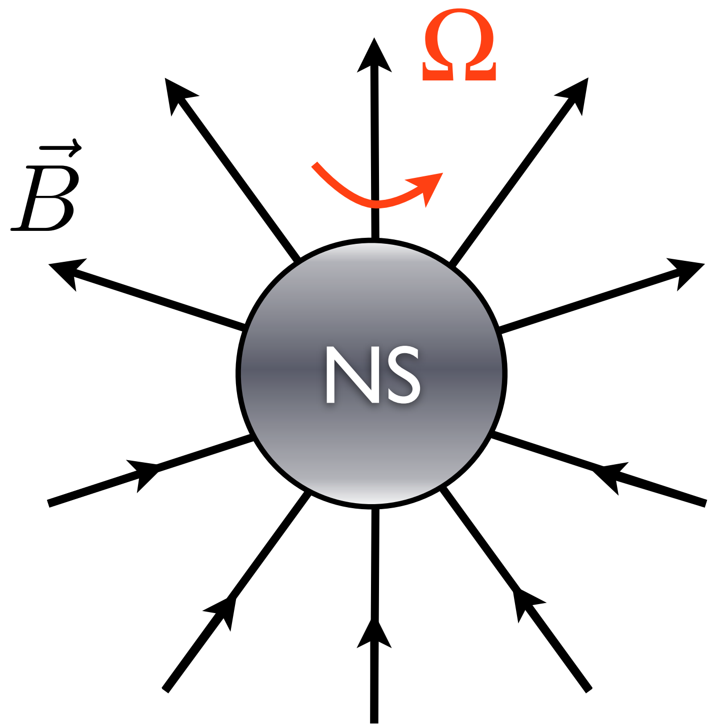

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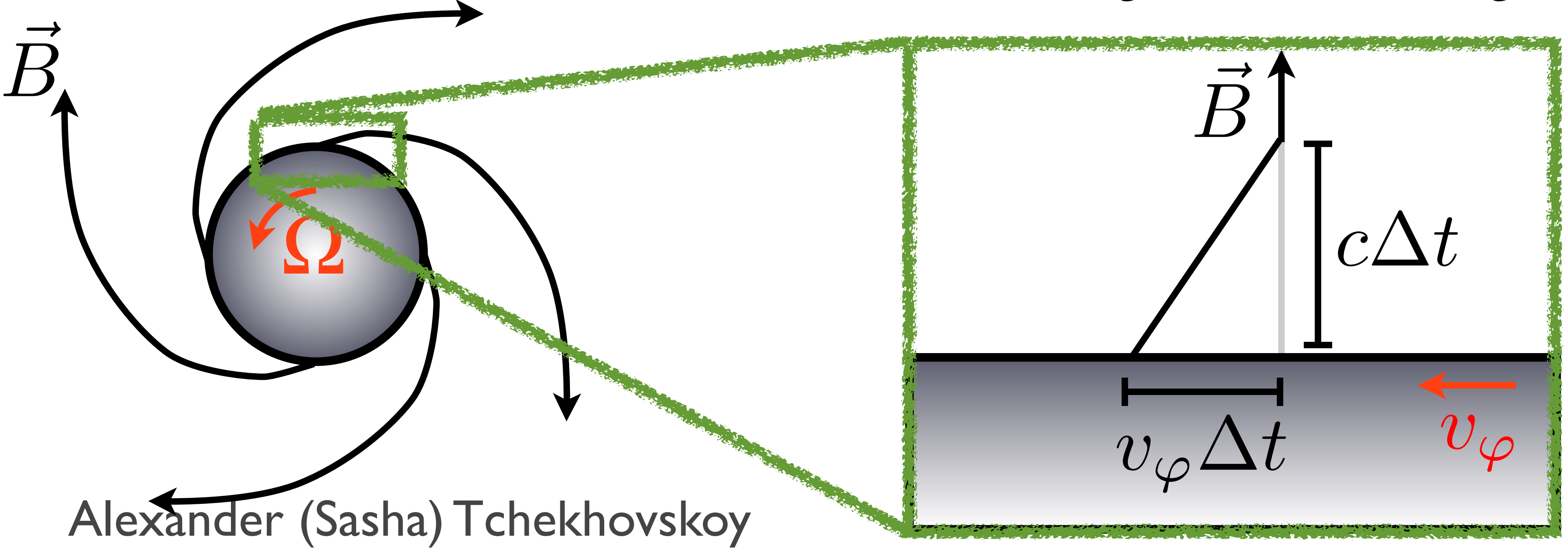

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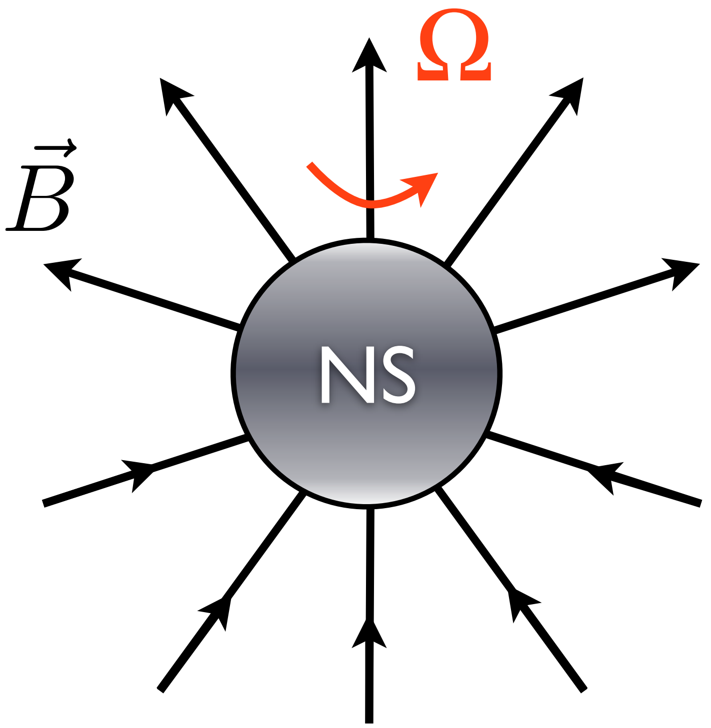

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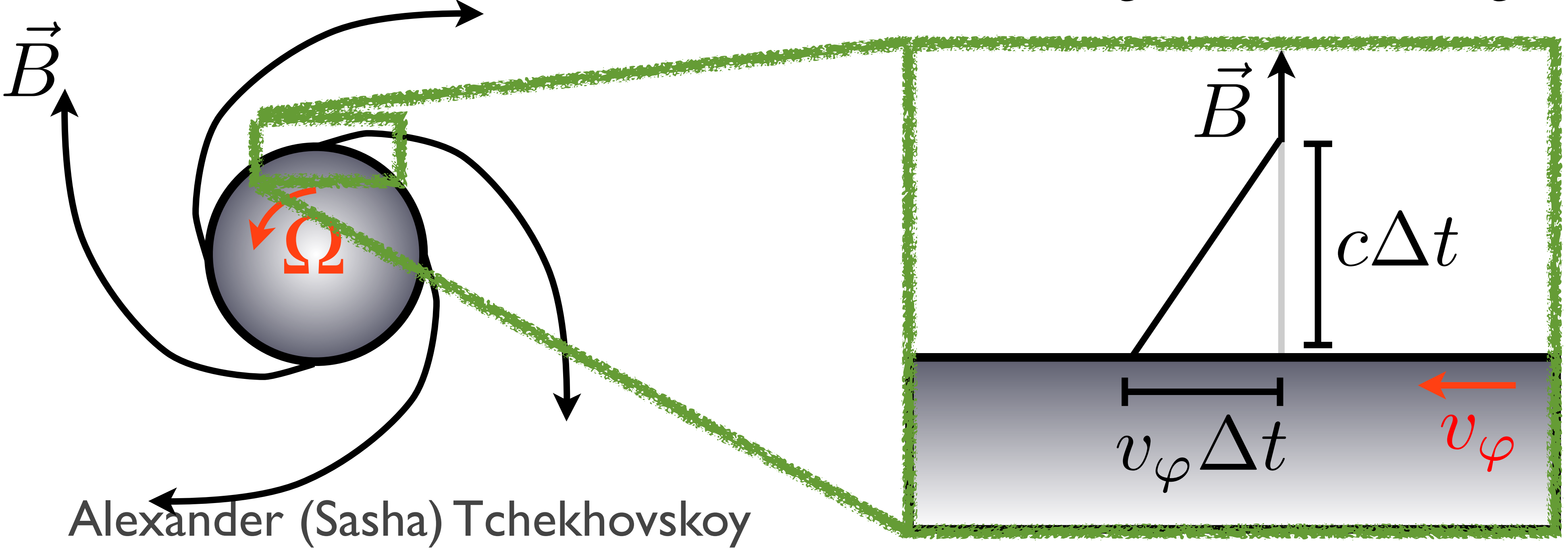

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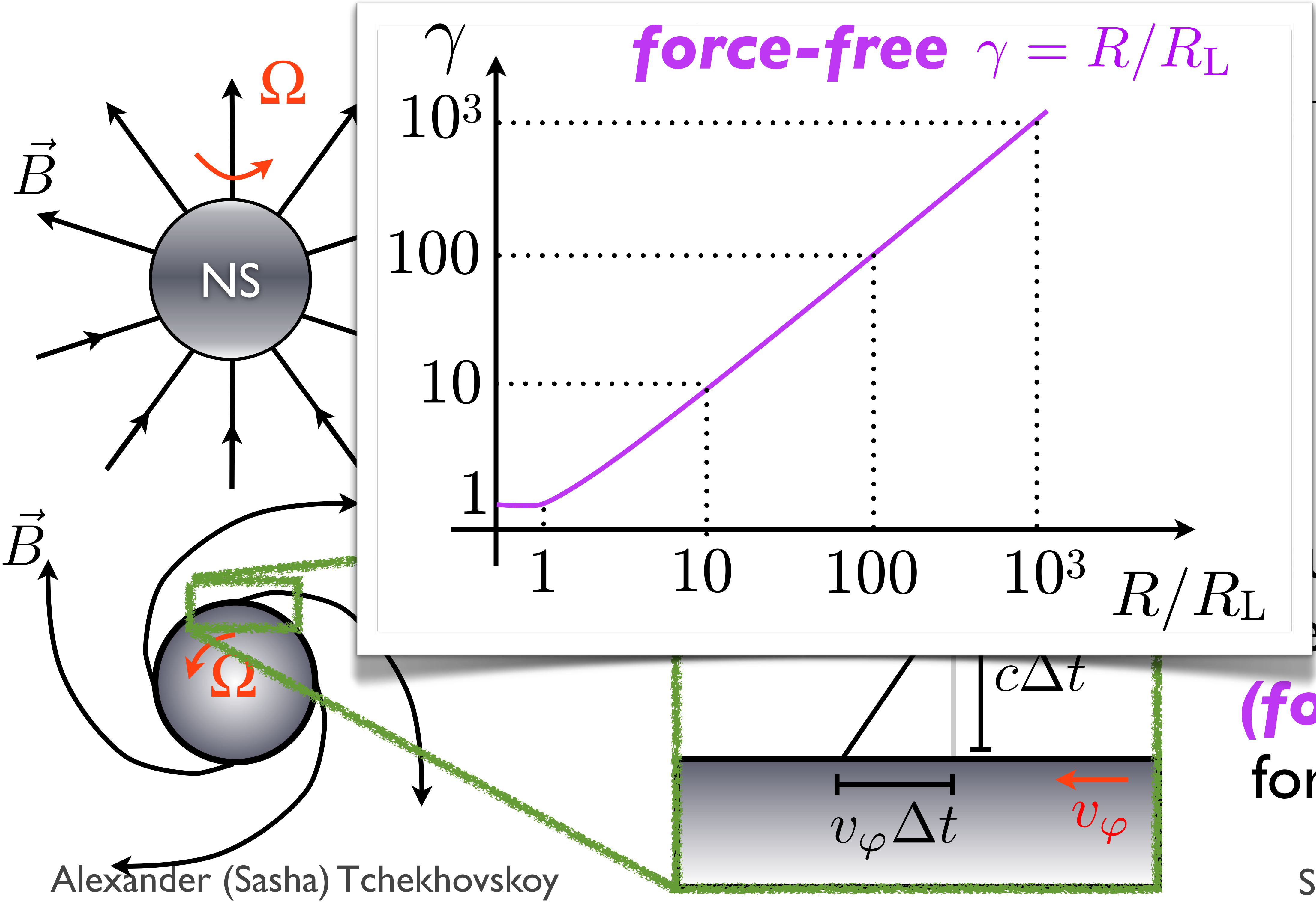

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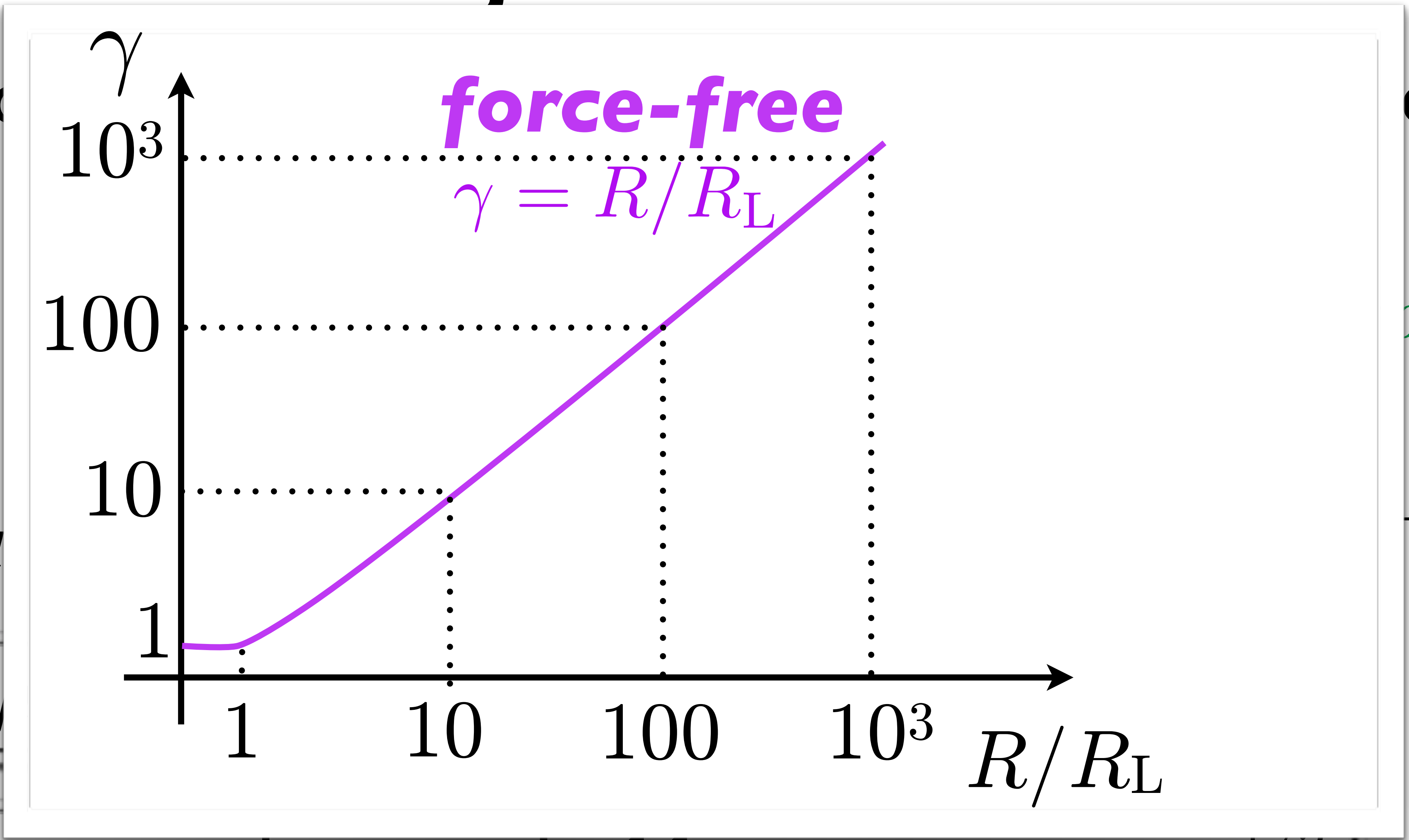

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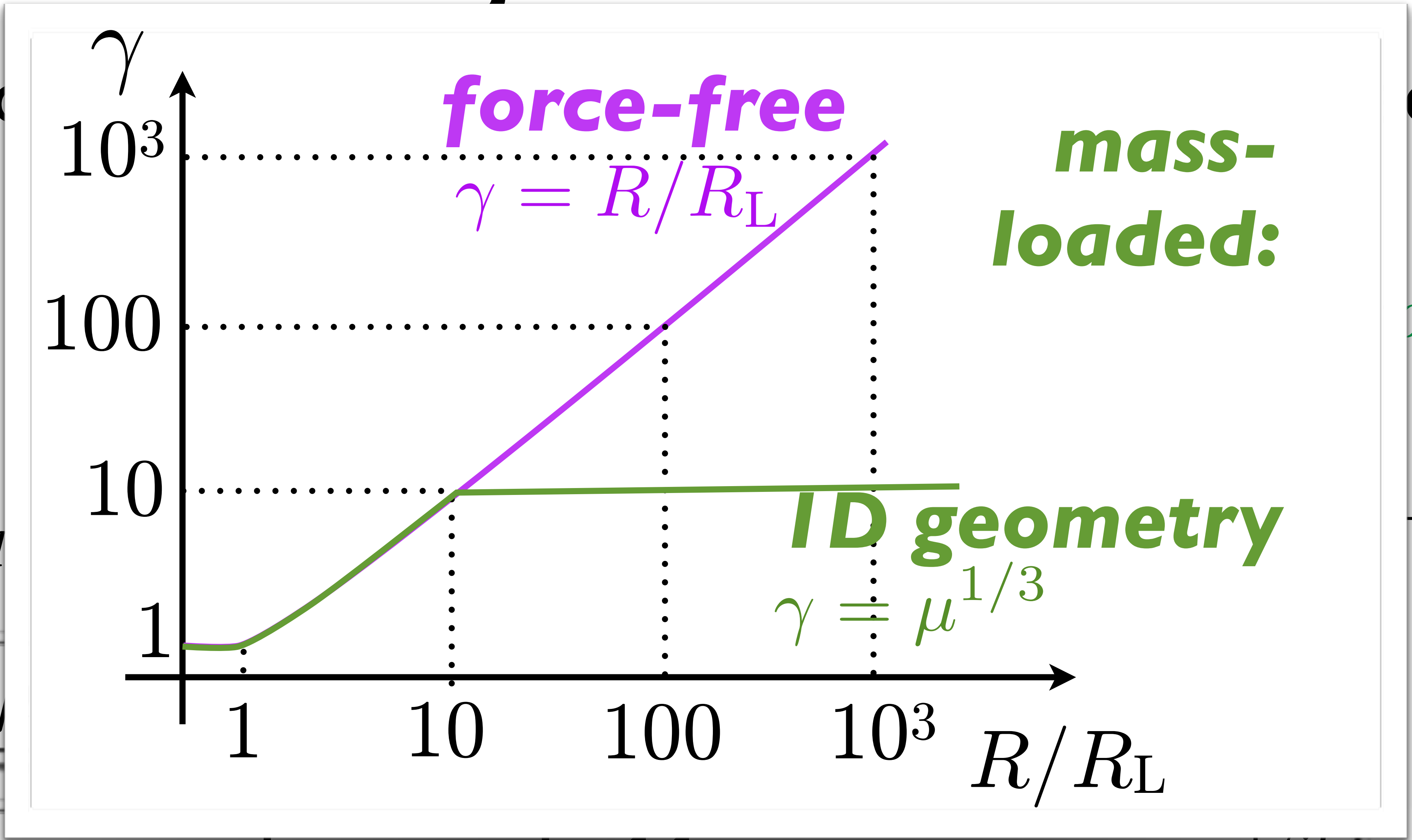

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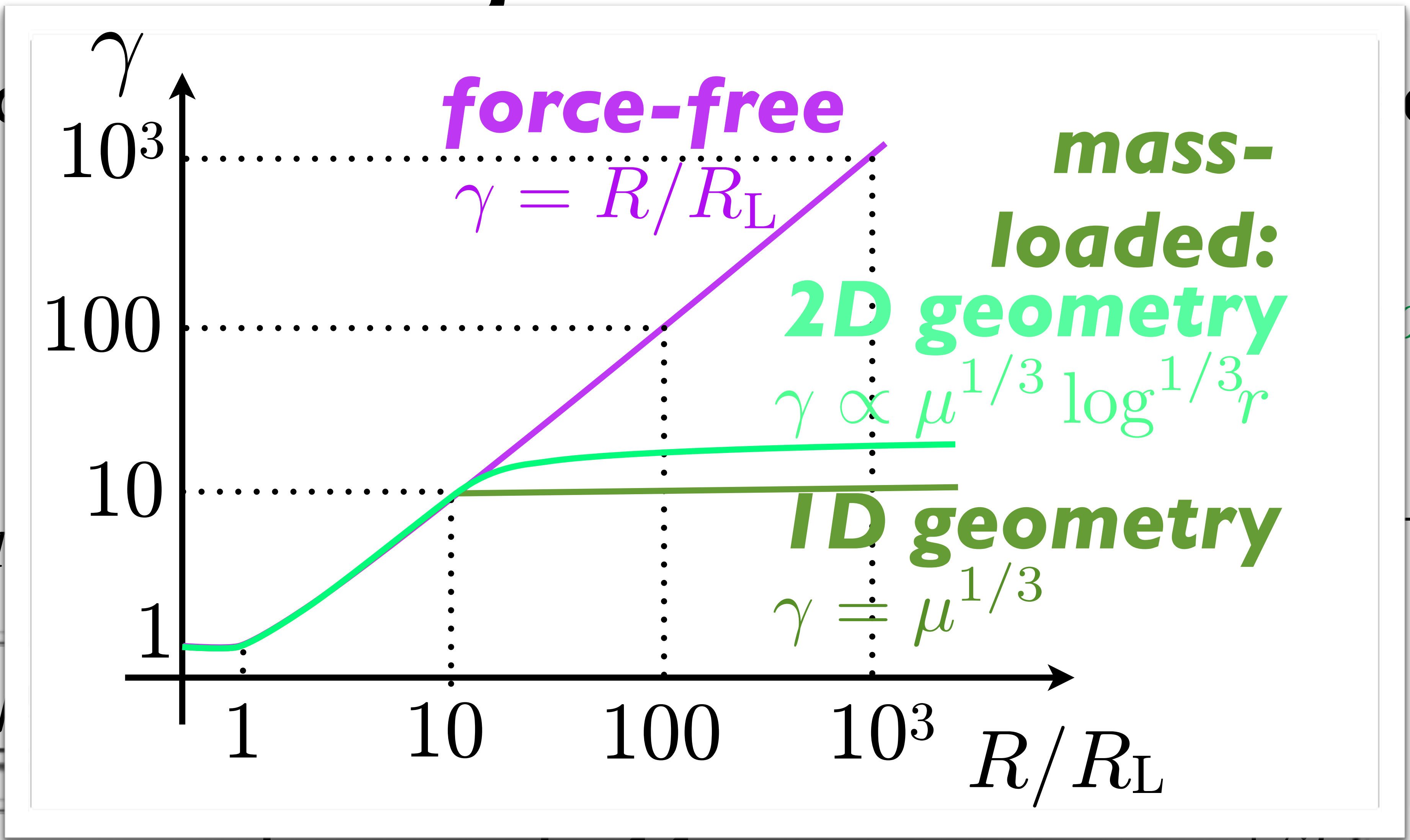

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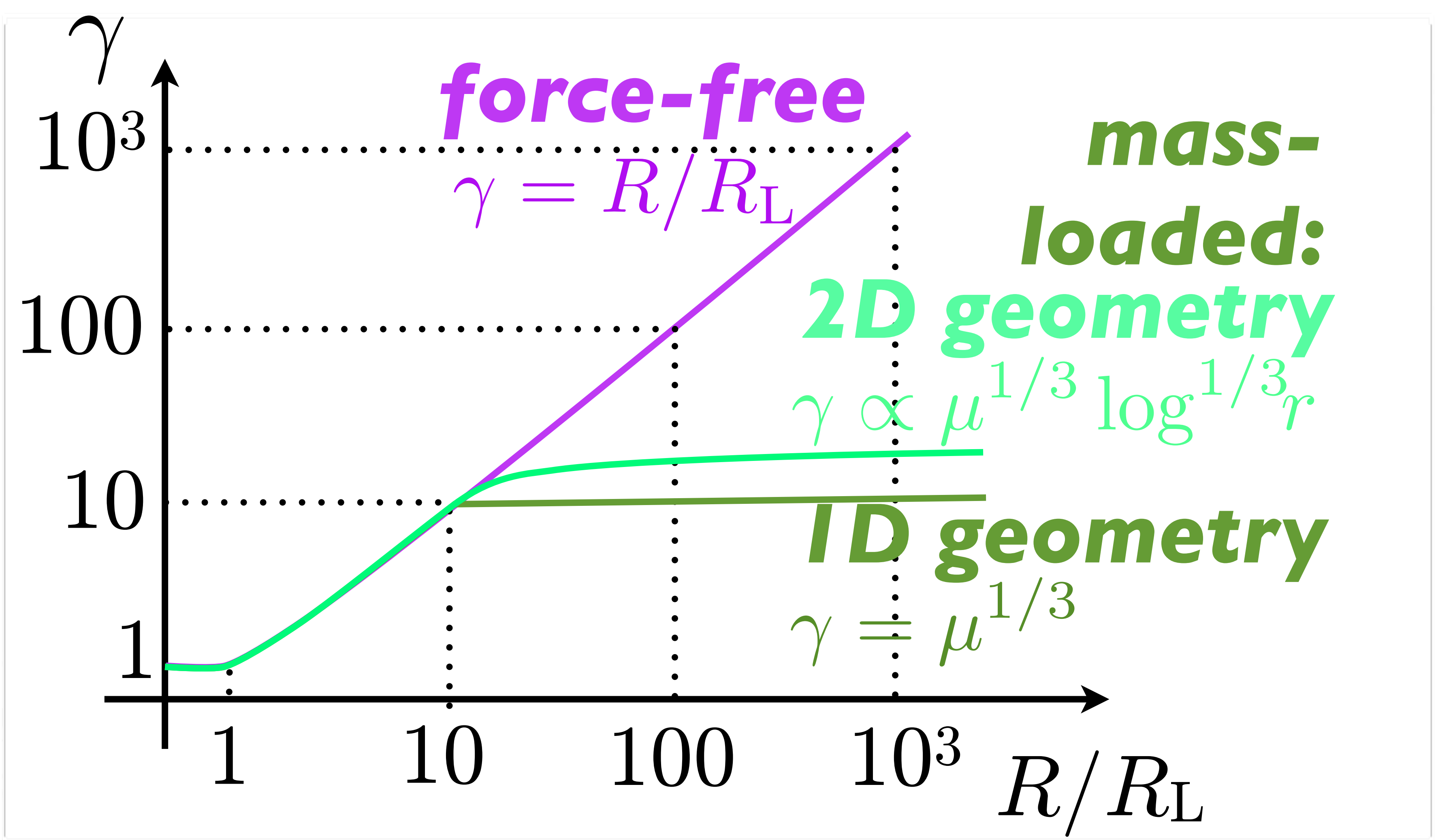

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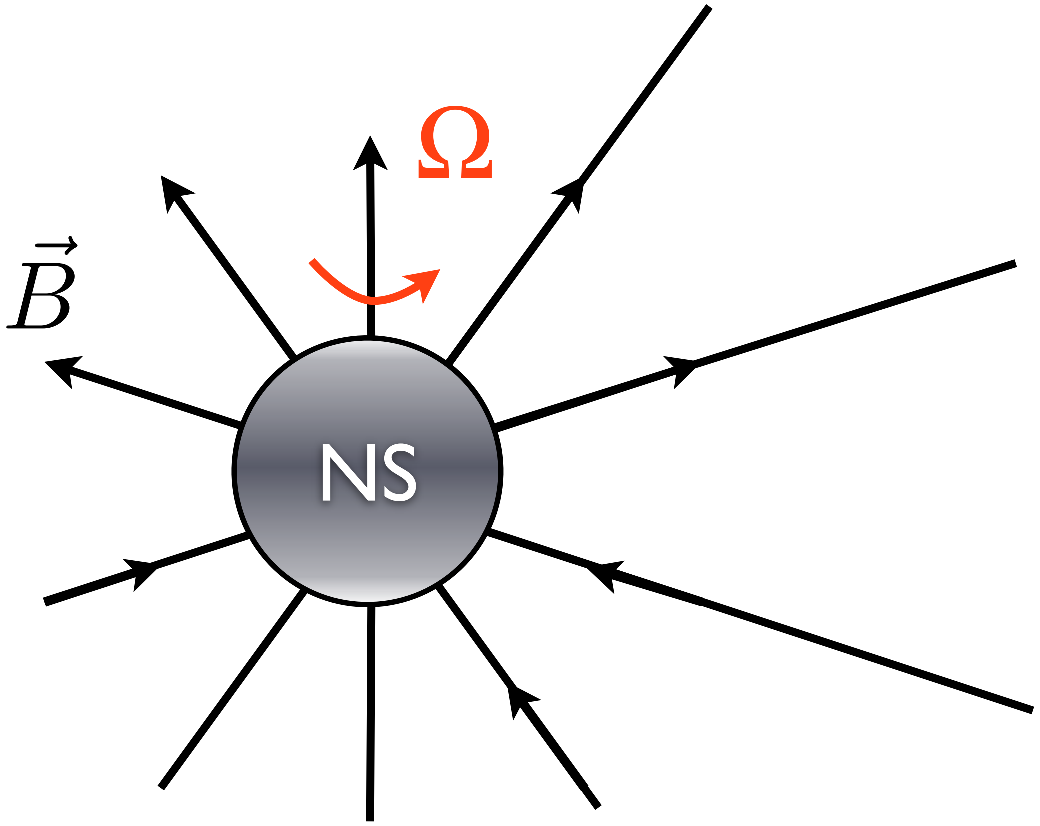

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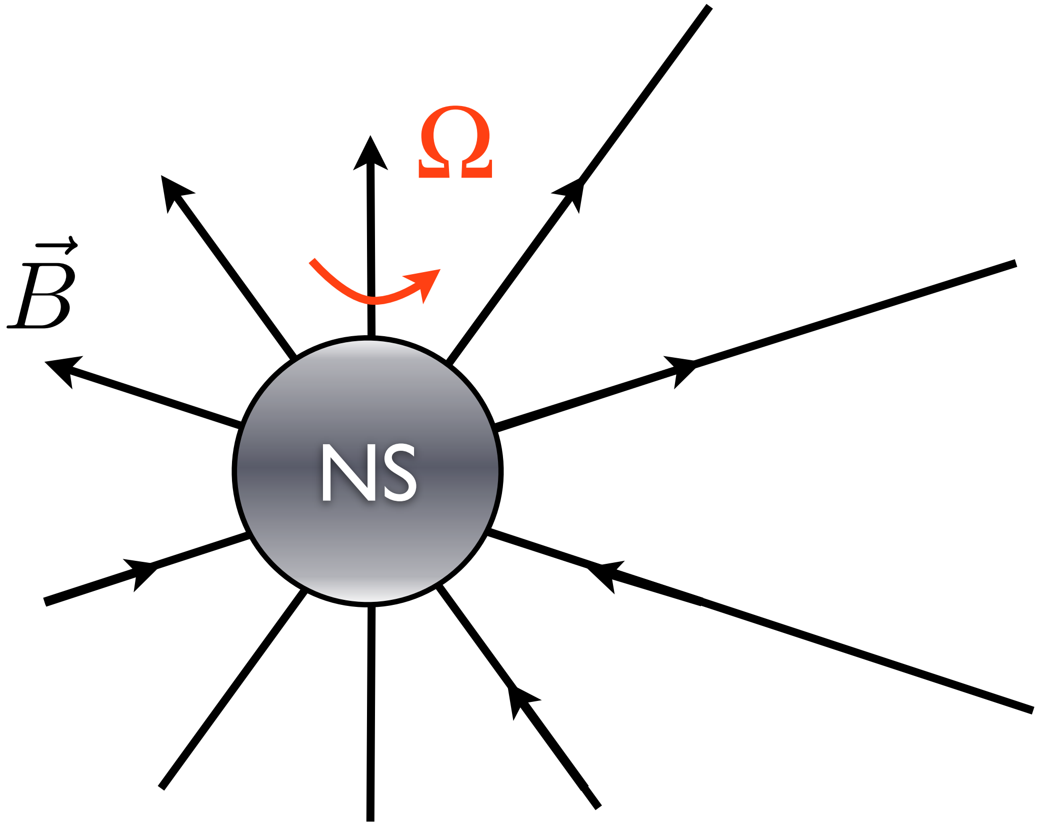

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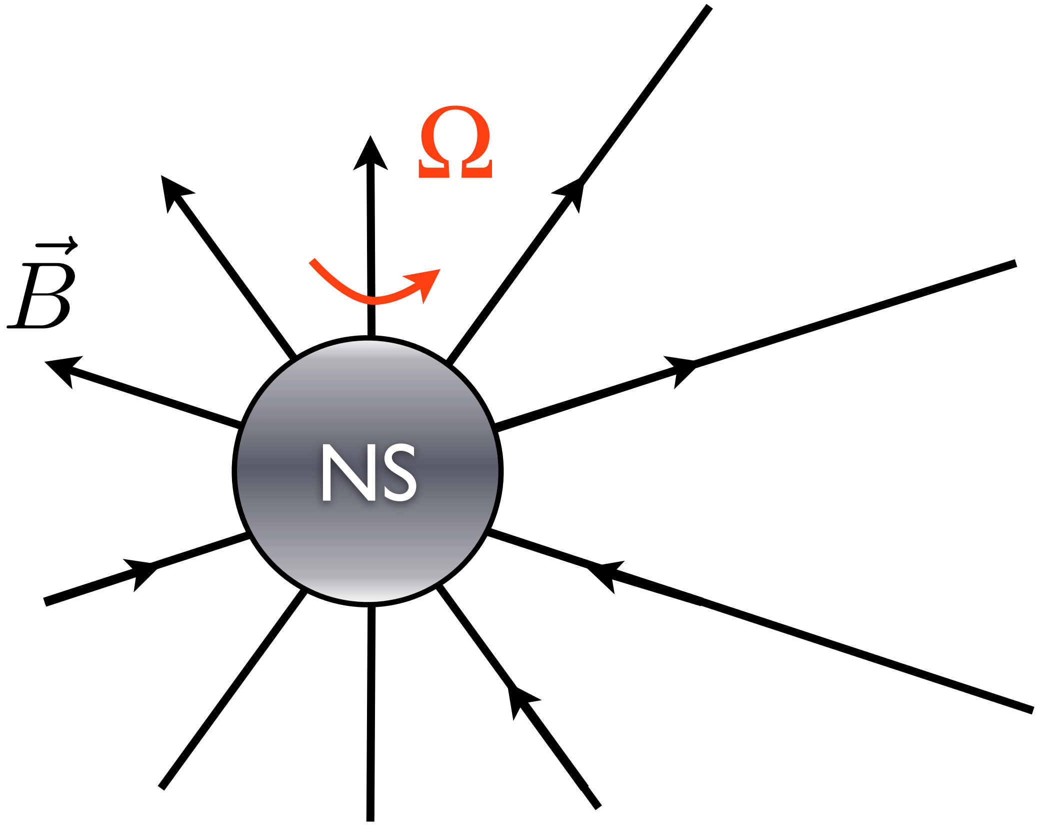

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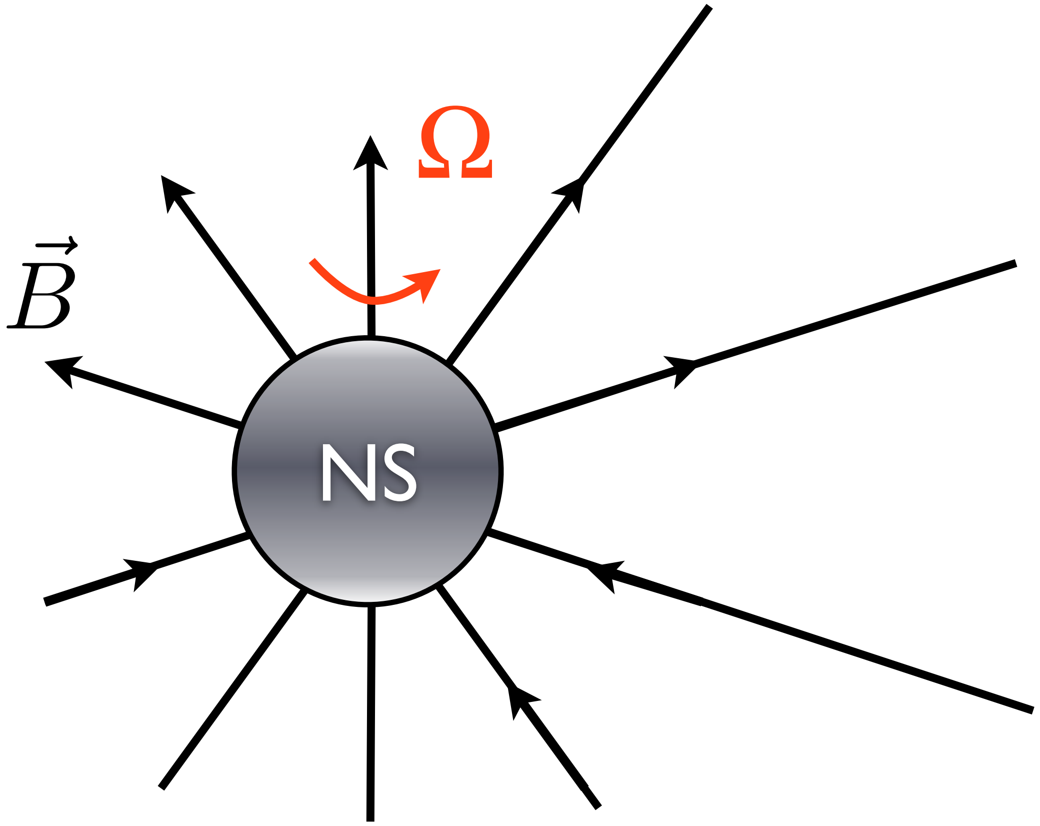

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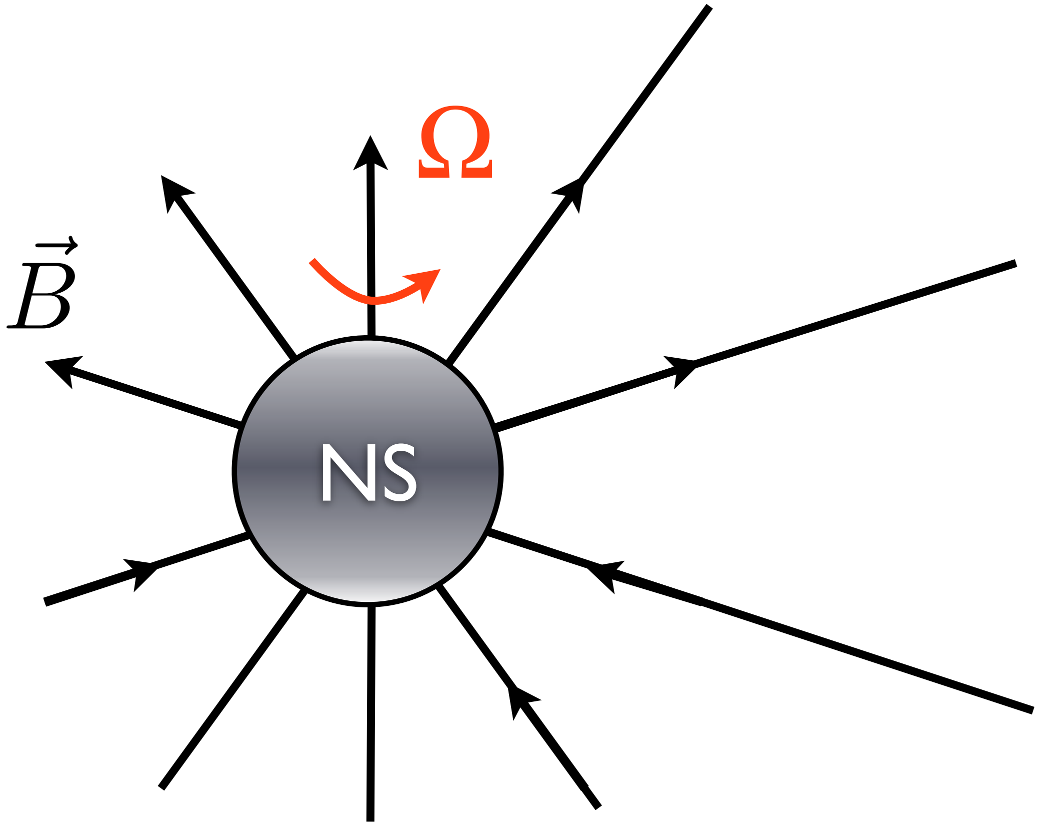

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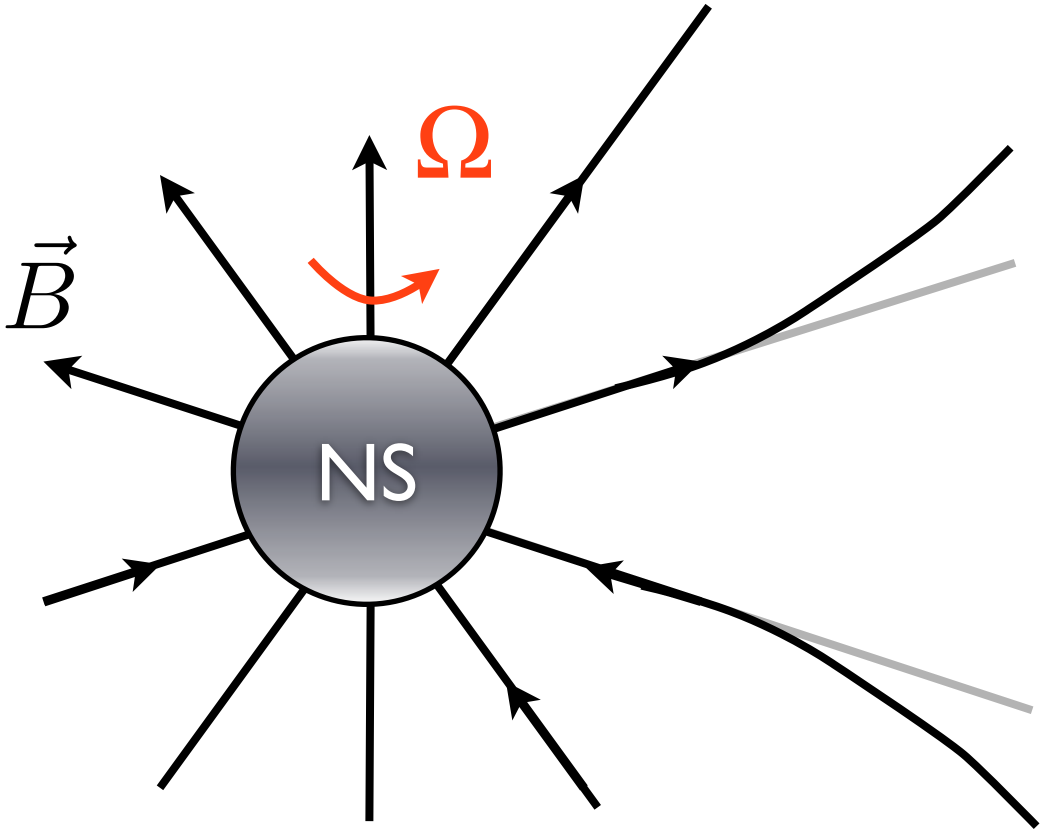

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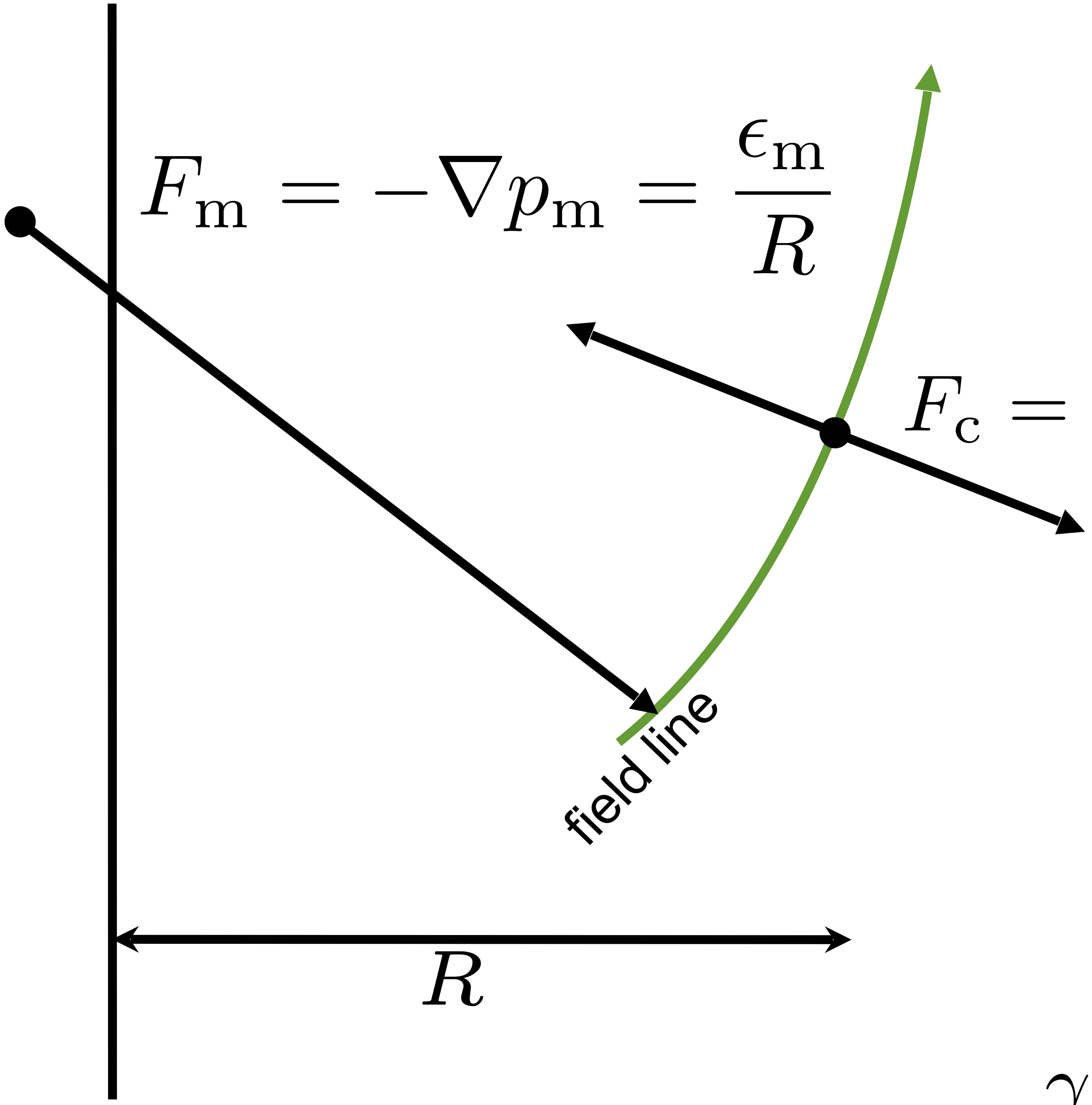
Why So Bad (2/2)?

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



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

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

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

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

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

Can combine both limits:

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

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

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

How do mass-loaded Jets Accelerate?

Conserved quantities along jets = ratios of conserved fluxes:

$$F_B = B_p$$

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

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

$$F_E = \underset{\substack{\| \\ \frac{cEB_\varphi}{4\pi}}}{F_{EM}} + \underset{\substack{\| \\ \gamma F_M}}{F_{KE}}$$

$$\Rightarrow \quad \mu = \frac{F_E}{F_M} = \gamma\frac{F_{EM}}{F_{KE}} + \gamma = \gamma(\sigma + 1)$$

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$$\| \; E = B_\varphi = \Omega R B_p/c$$

$$\frac{\Omega^2 R^2 B_p^2}{4\pi c}$$

How do mass-loaded Jets Accelerate?

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

$$F_E = F_{EM} + F_{KE} \qquad \Rightarrow \mu = \frac{F_E}{F_M}$$

$$\boxed{\Phi \equiv (\pi B_p R^2)_{\mathrm{F}}}$$

$$F_{EM} = \frac{cEB_\varphi}{4\pi} \quad \Big\|\ E = B_\varphi = \Omega R B_p/c \quad = \frac{\Omega^2 R^2 B_p^2}{4\pi c}$$

$$F_{KE} = \gamma F_M$$

$$\mu = \frac{\Omega^2}{4\pi^2\eta c}\pi B_p R^2 + \gamma = \frac{\mu}{\Phi}\pi B_p R^2 + \gamma$$

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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)

Acceleration in a magnetic nozzle

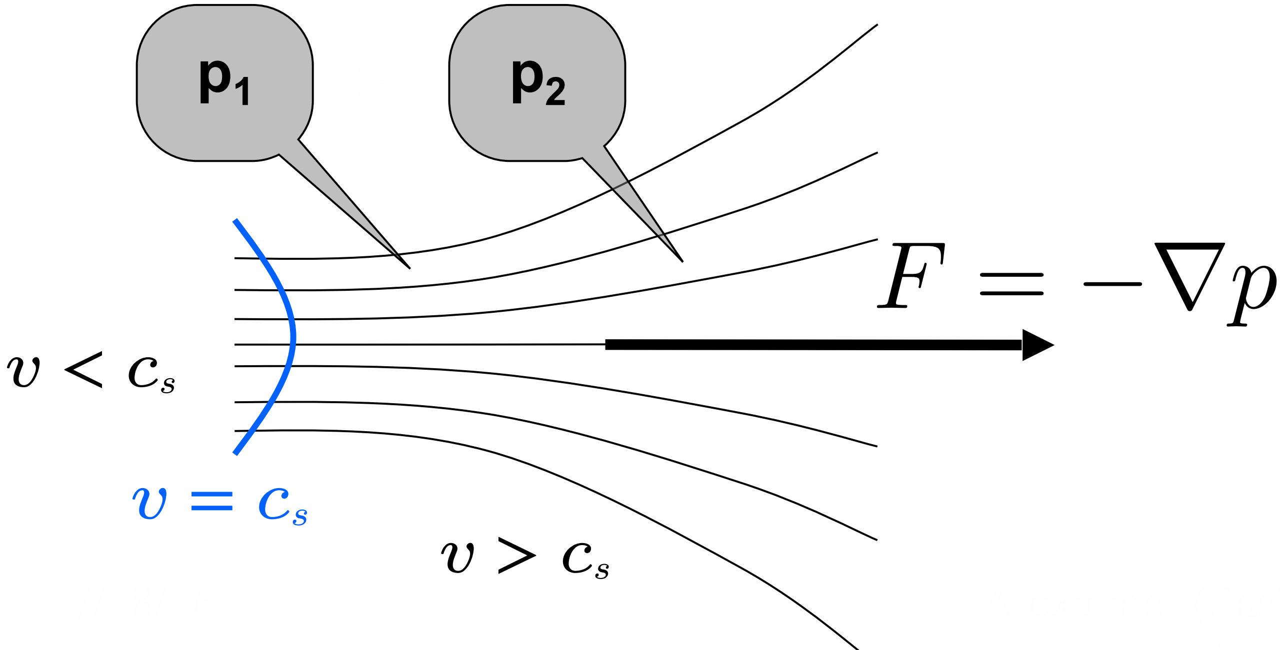
(Begelman & Li 1994, Komissarov 2009, AT+ 2009)

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

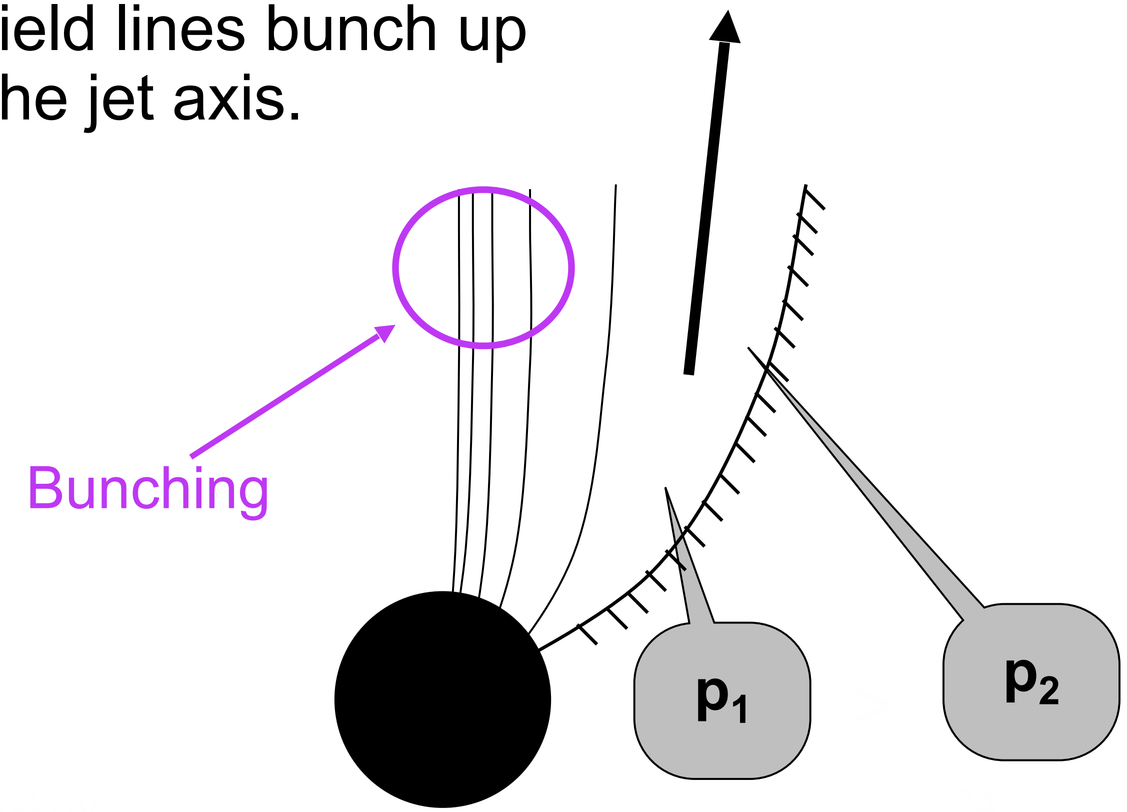
If $B_P(R) = \mathrm{const}$, no acceleration.

Need magnetic flux bunching toward jet axis.

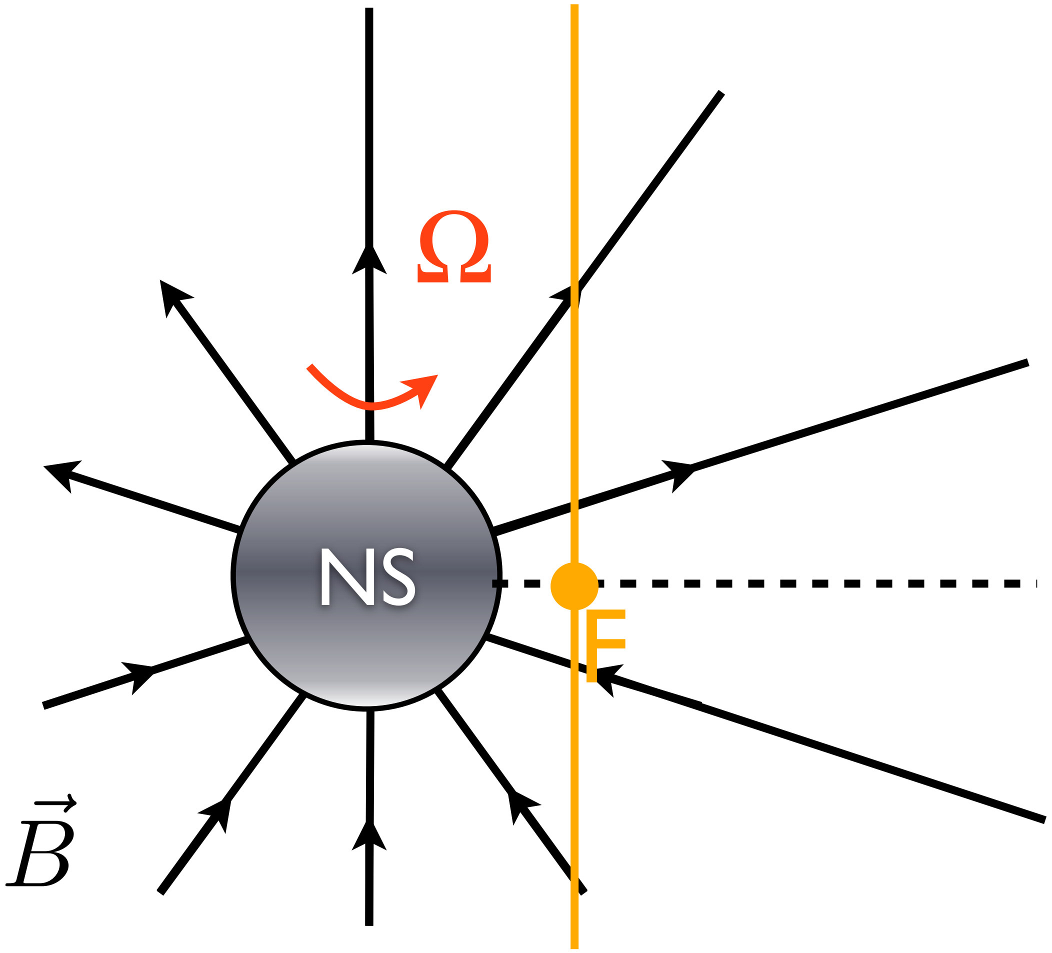
Hydro: de Laval nozzle: flow opens up after sonic surface → pressure drops → ∇p accelerates flow:



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



When Can Jets Accelerate?



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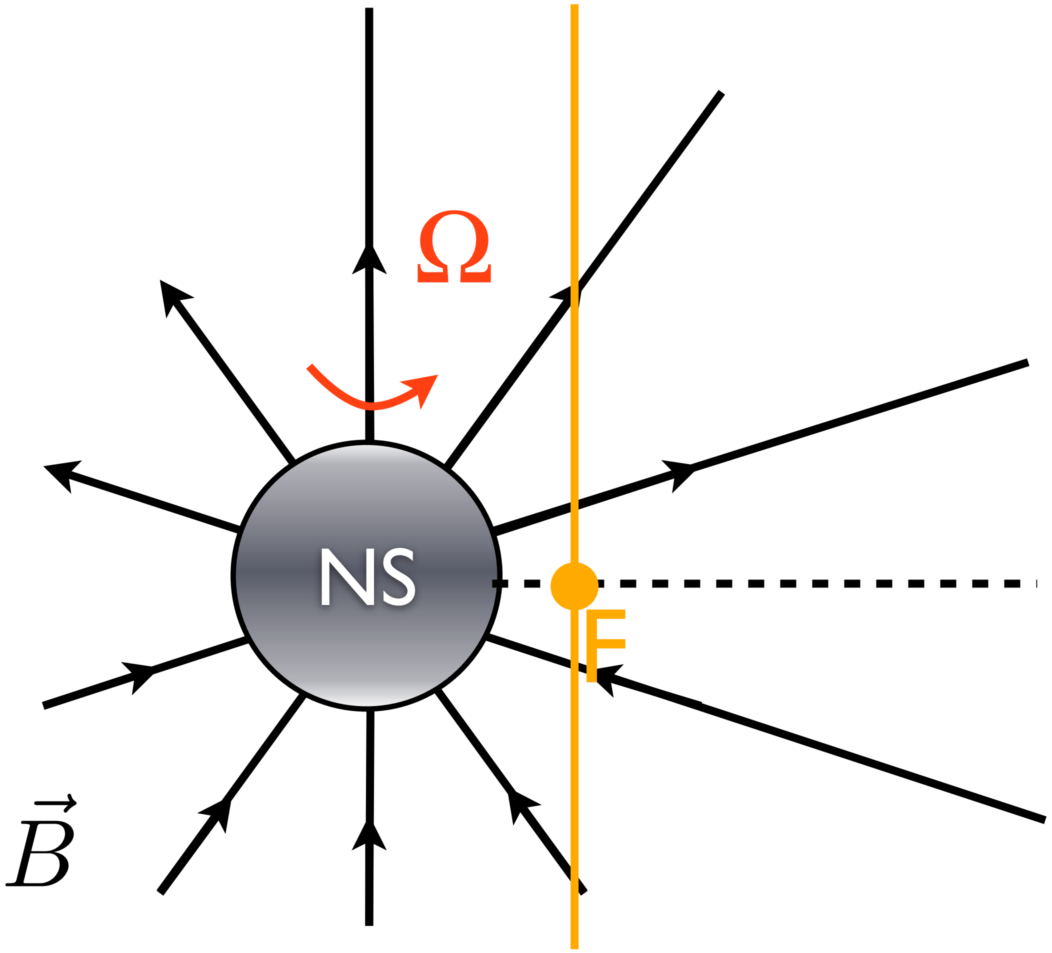

- Communication is essential

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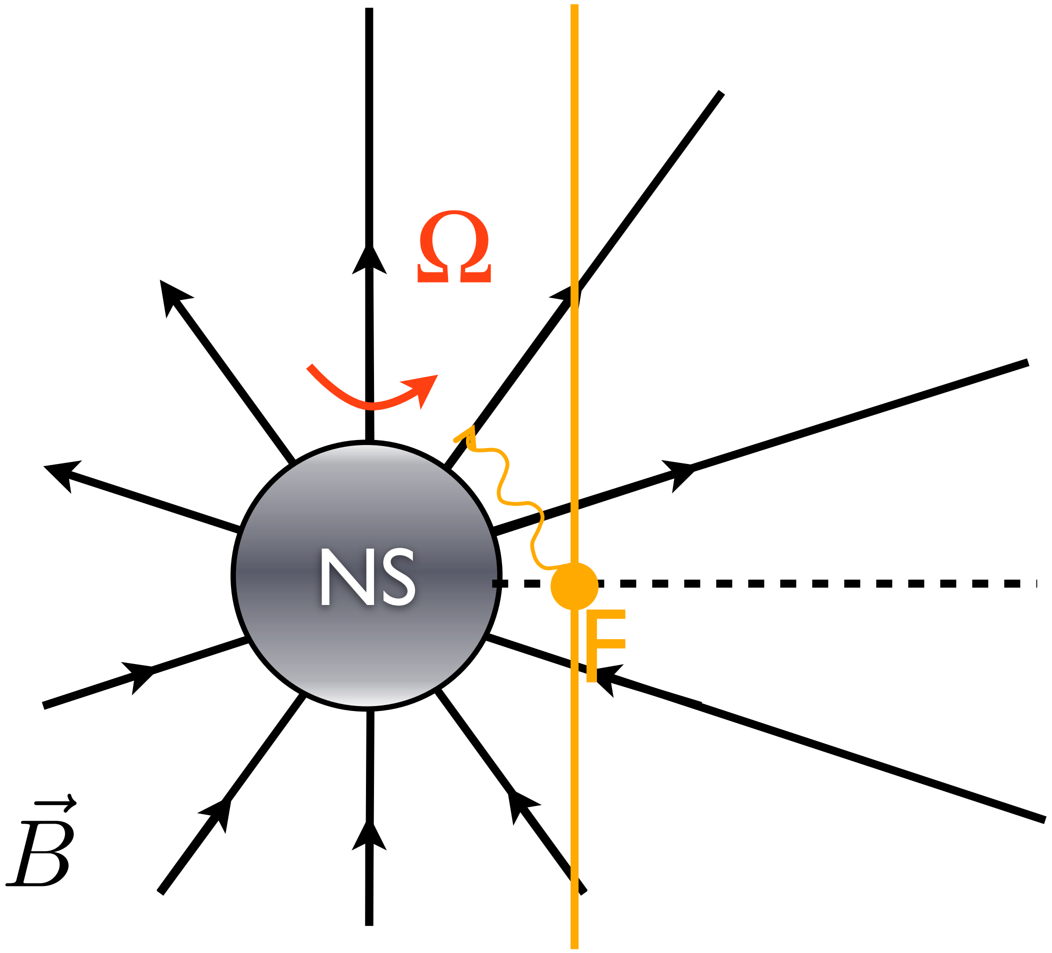

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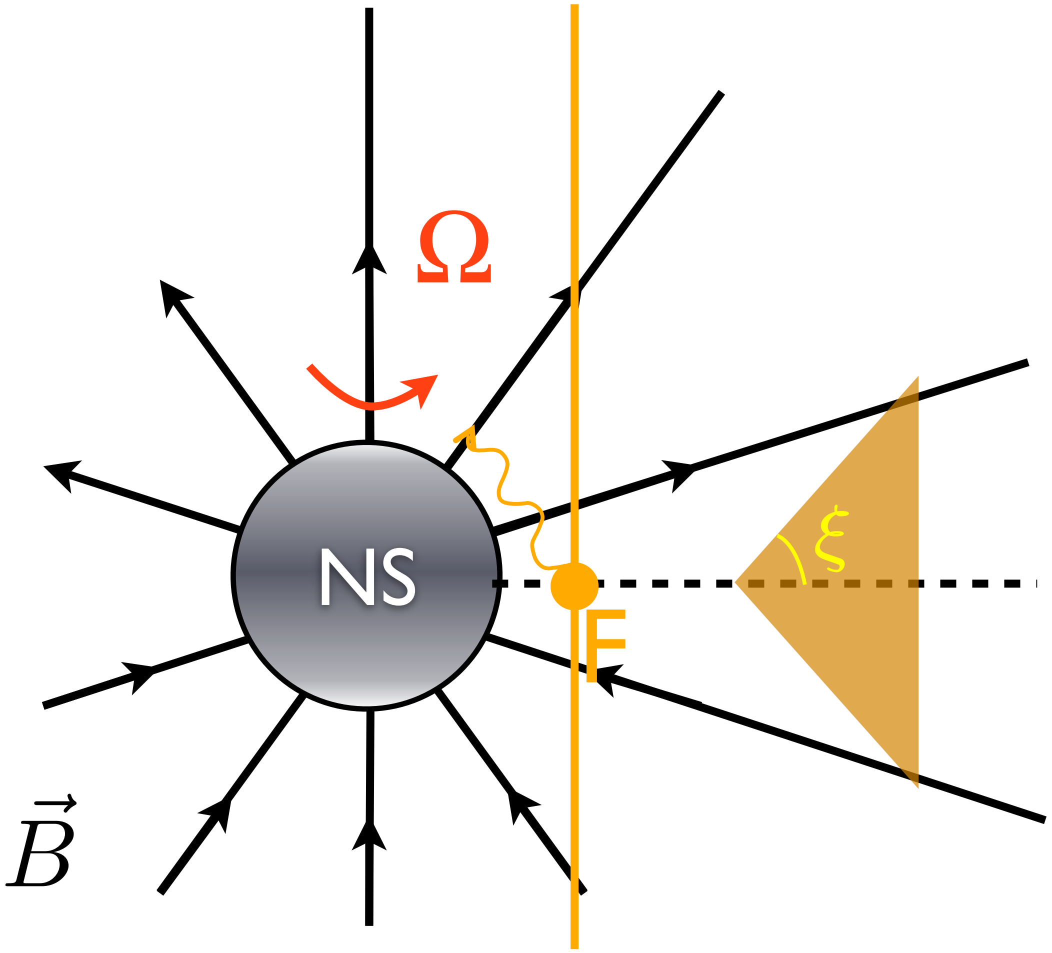

- Communication is essential
- All signals travel inside the Mach cone ξ:

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

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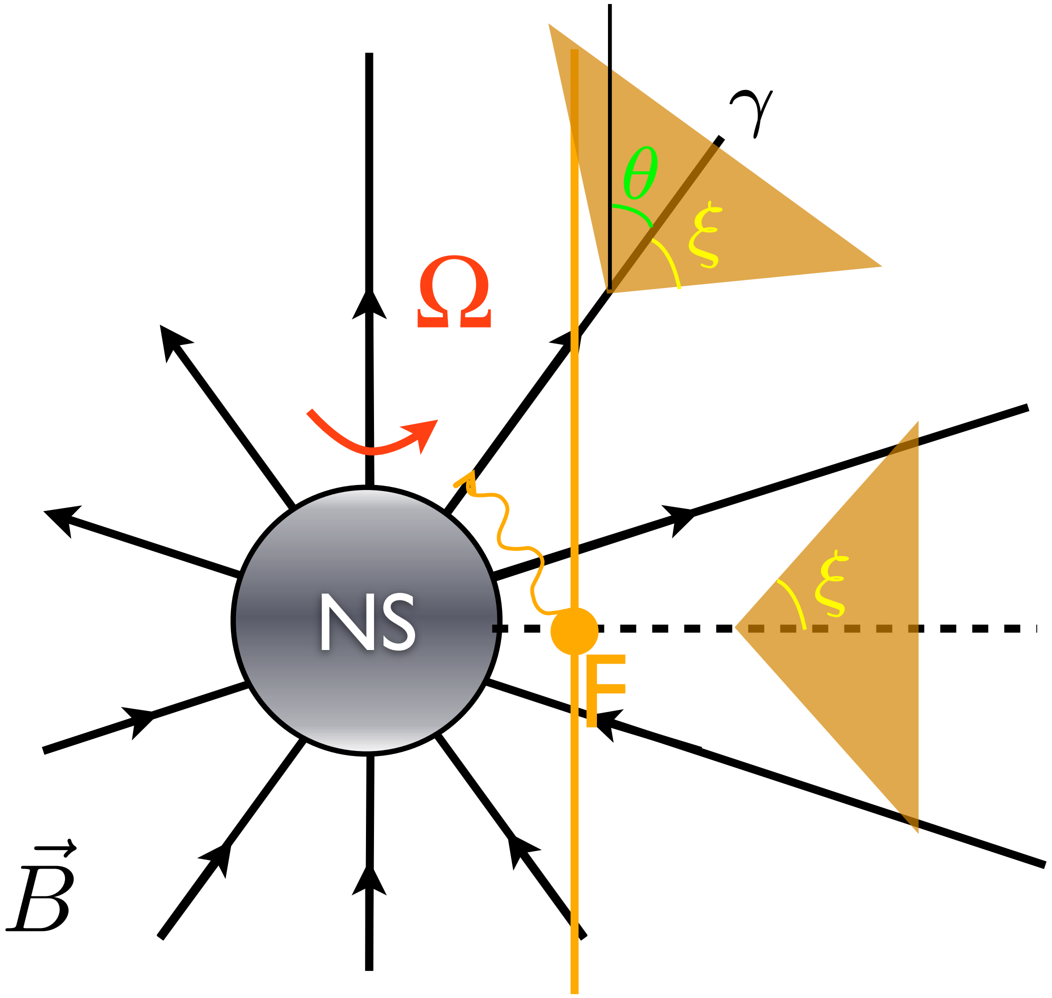

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$$\gamma\theta \lesssim \sigma^{1/2} = \left(\frac{\mu}{\gamma}\right)^{1/2}$$

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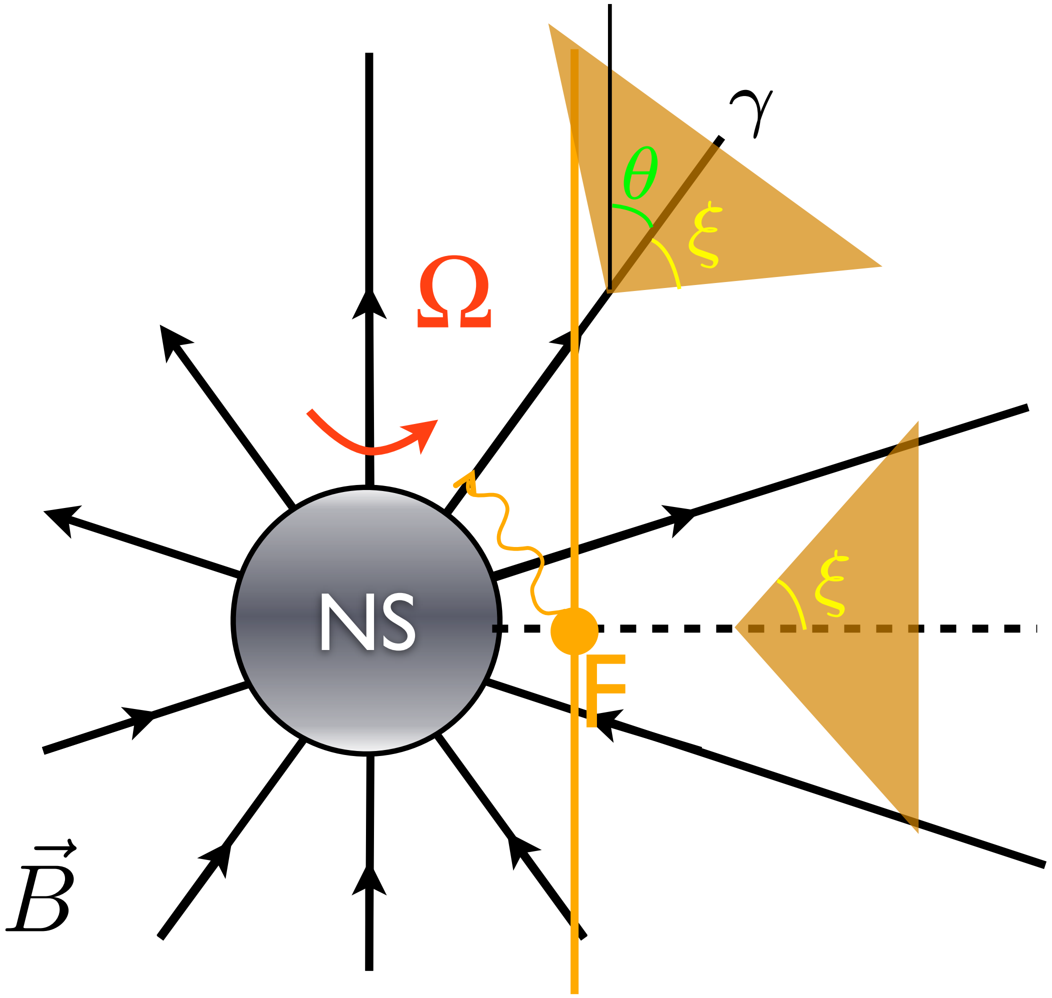

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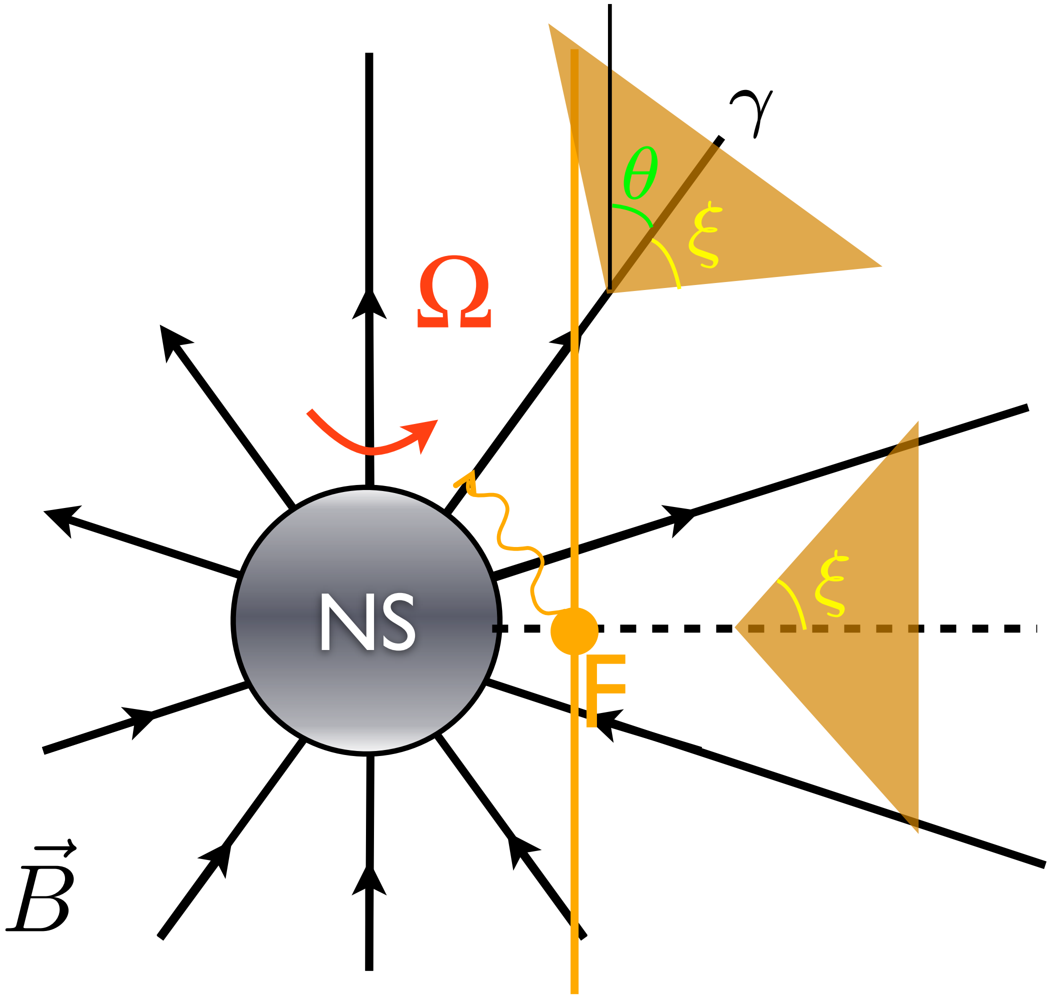

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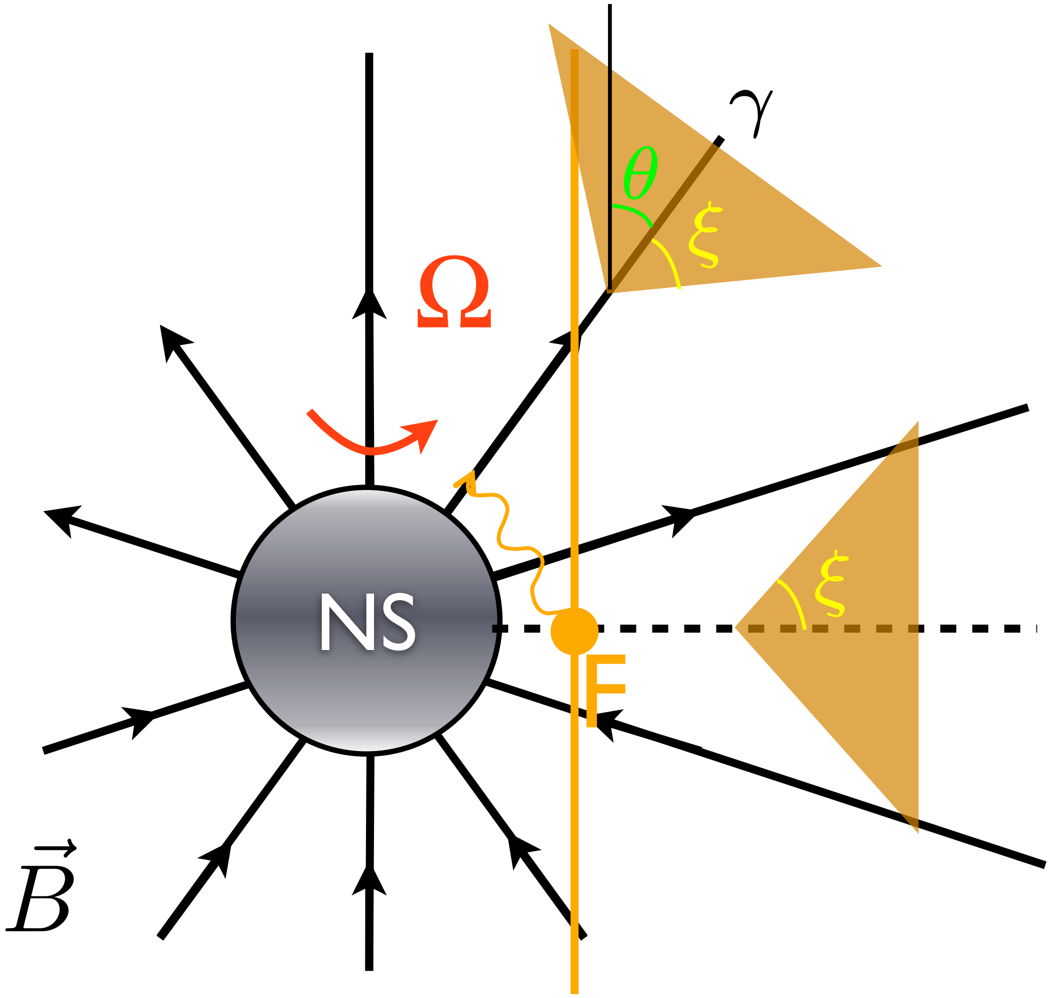
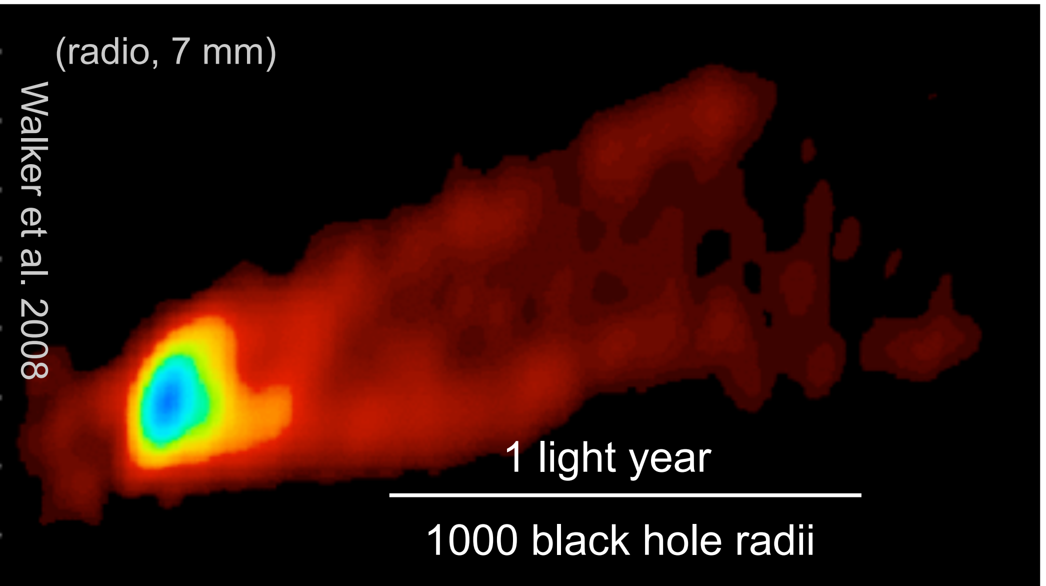
- Jets accelerate better near the axis

When Can Jets Accelerate?



but, most jets are collimated:



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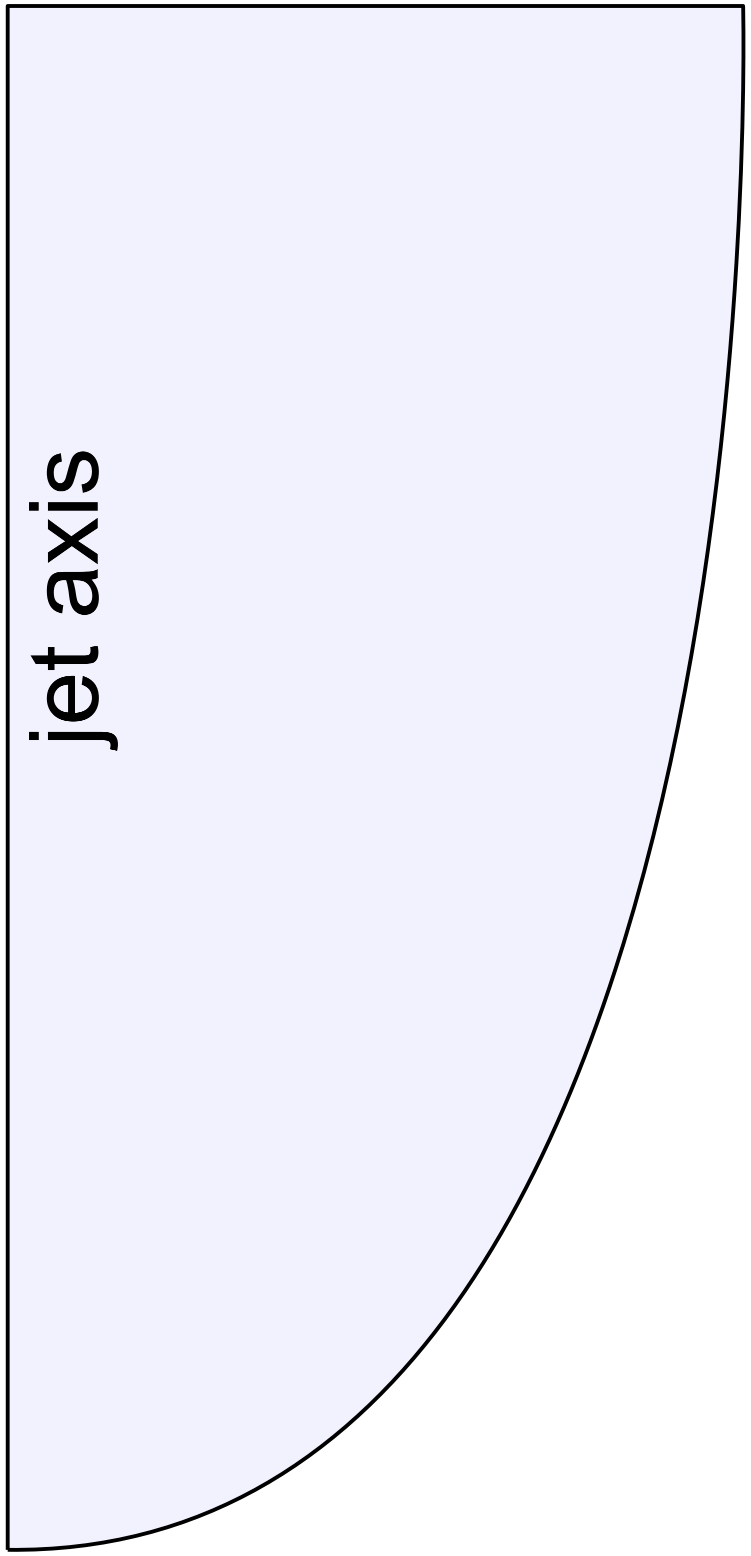
How Do Collimated Jets Accelerate?



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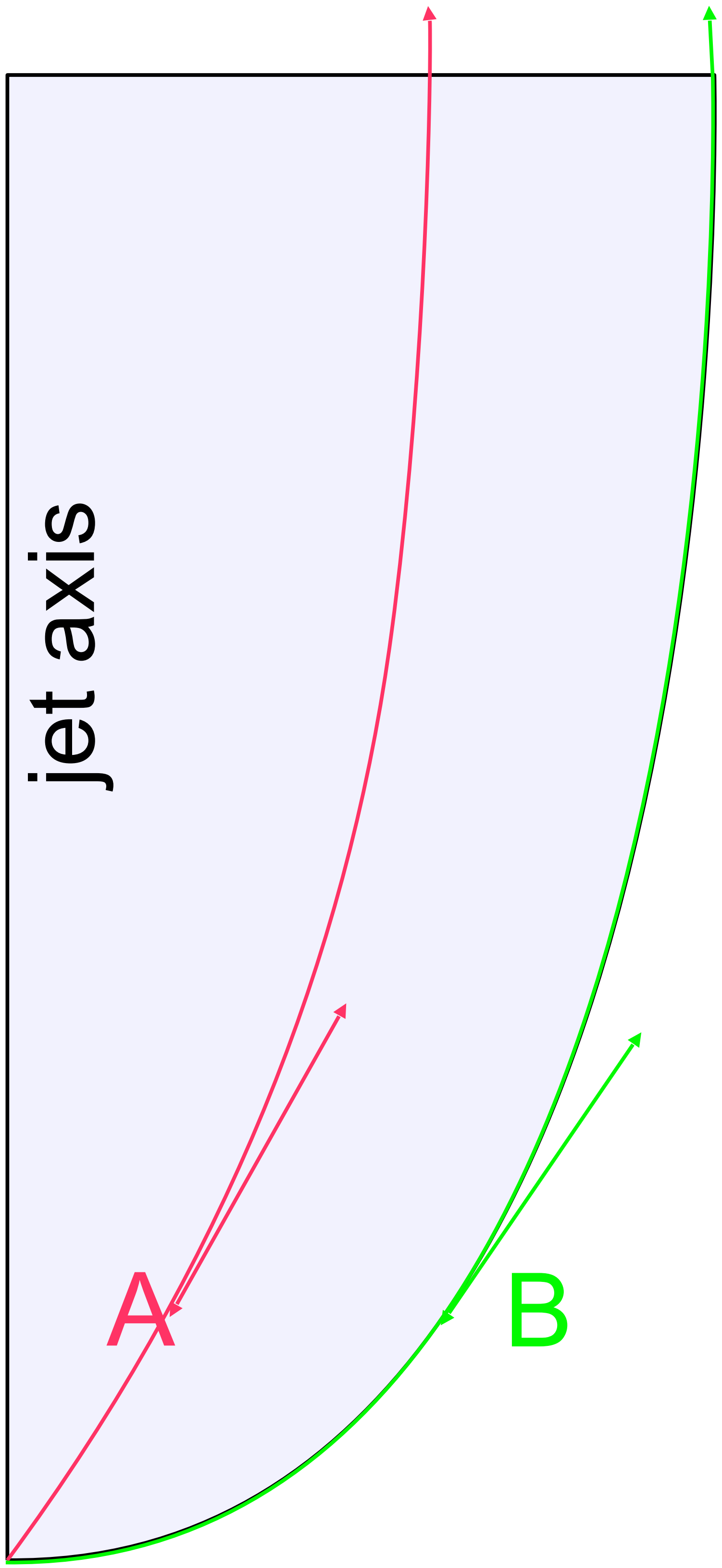
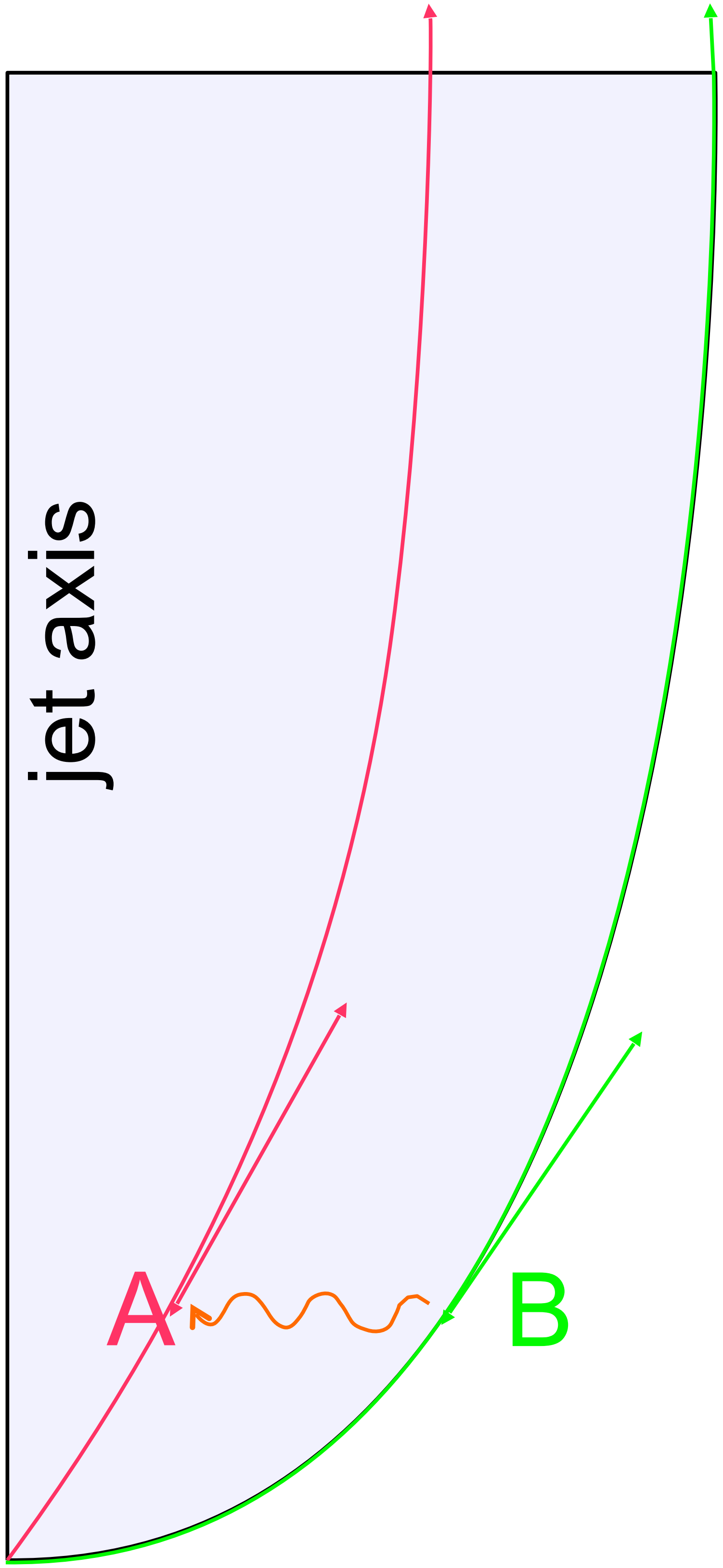


- **Communication** is essential

How Do Collimated Jets Accelerate?



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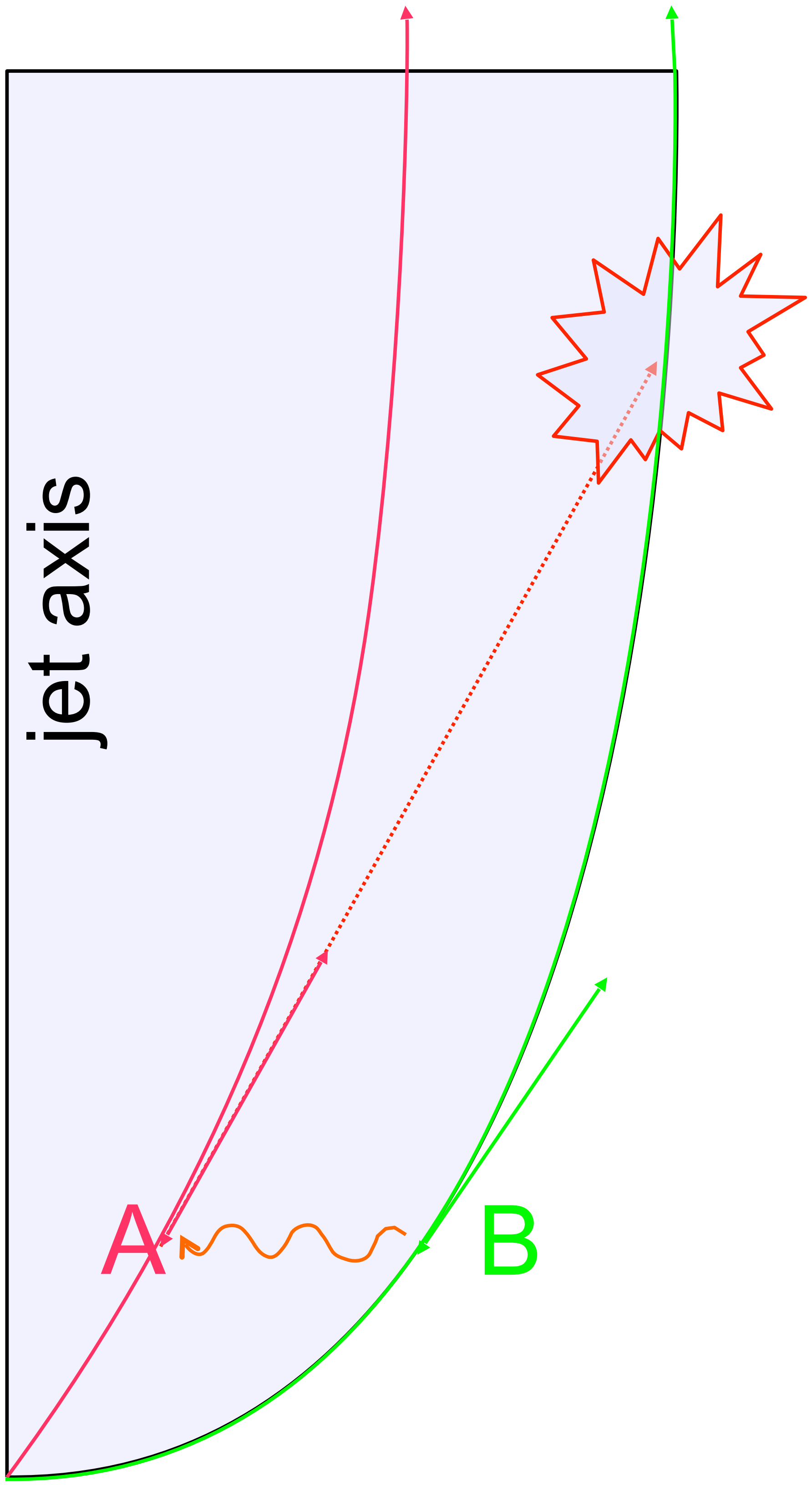

- Communication is essential to avoid collisions

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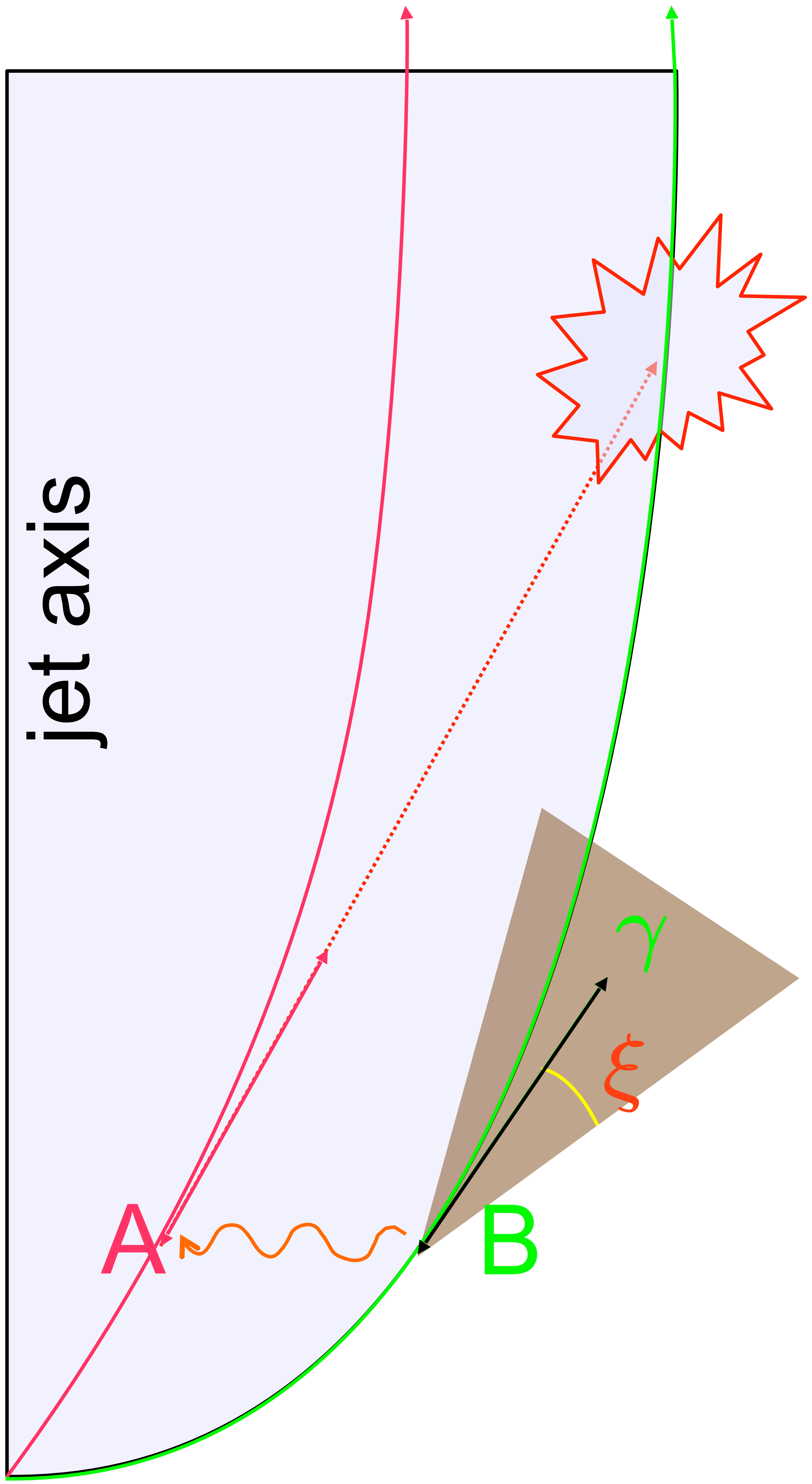

- Communication is essential to avoid collisions
- Jet boundary B needs to keep announcing its trajectory to the rest of the jet

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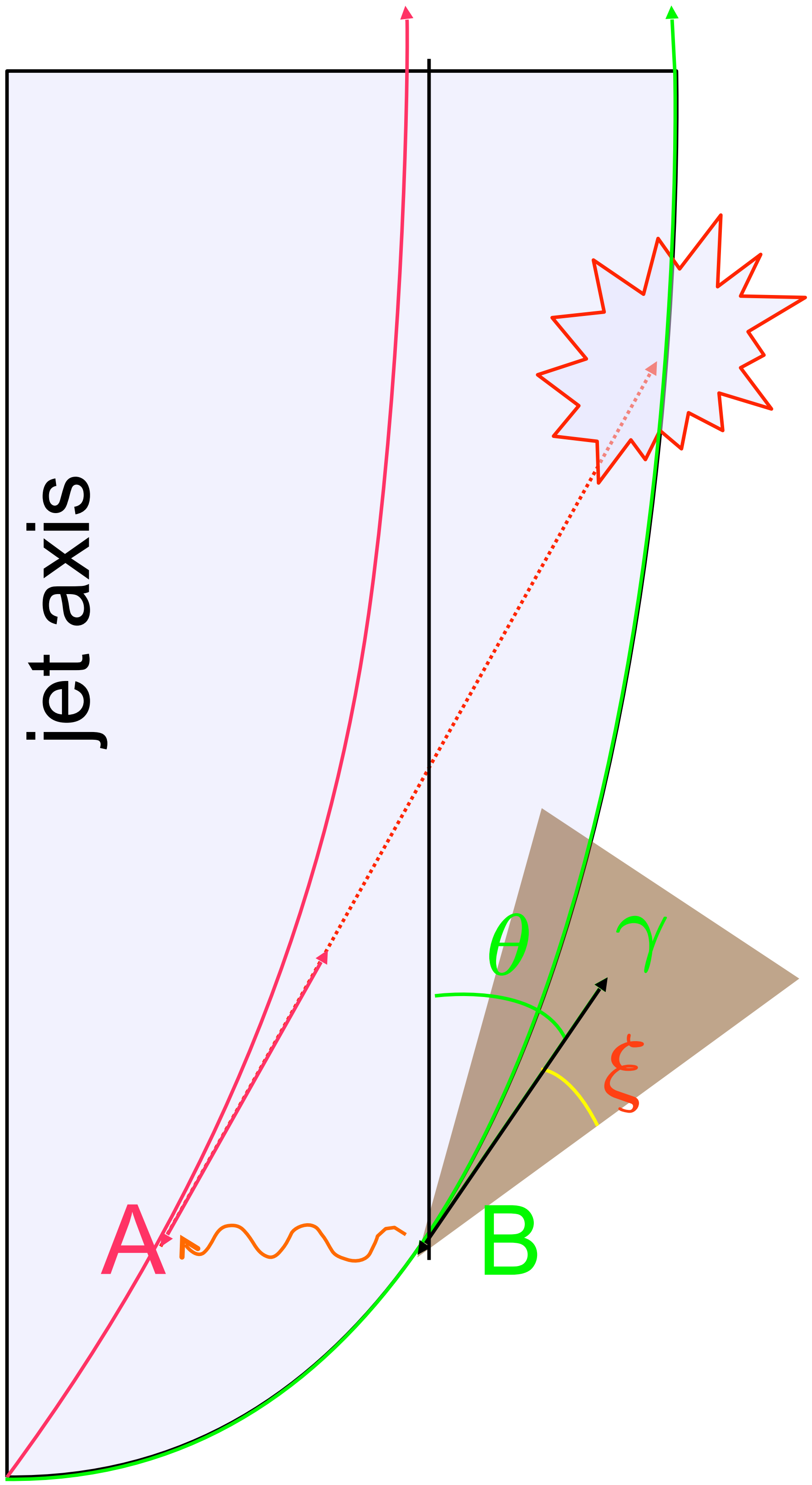


- Communication is essential to avoid collisions
- Jet boundary B needs to keep announcing its trajectory to the rest of the jet
- All signals travel inside Mach cone ξ:

$$\xi \le \frac{\gamma_F}{\gamma} = \frac{\sigma^{1/2}}{\gamma}$$

- 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:

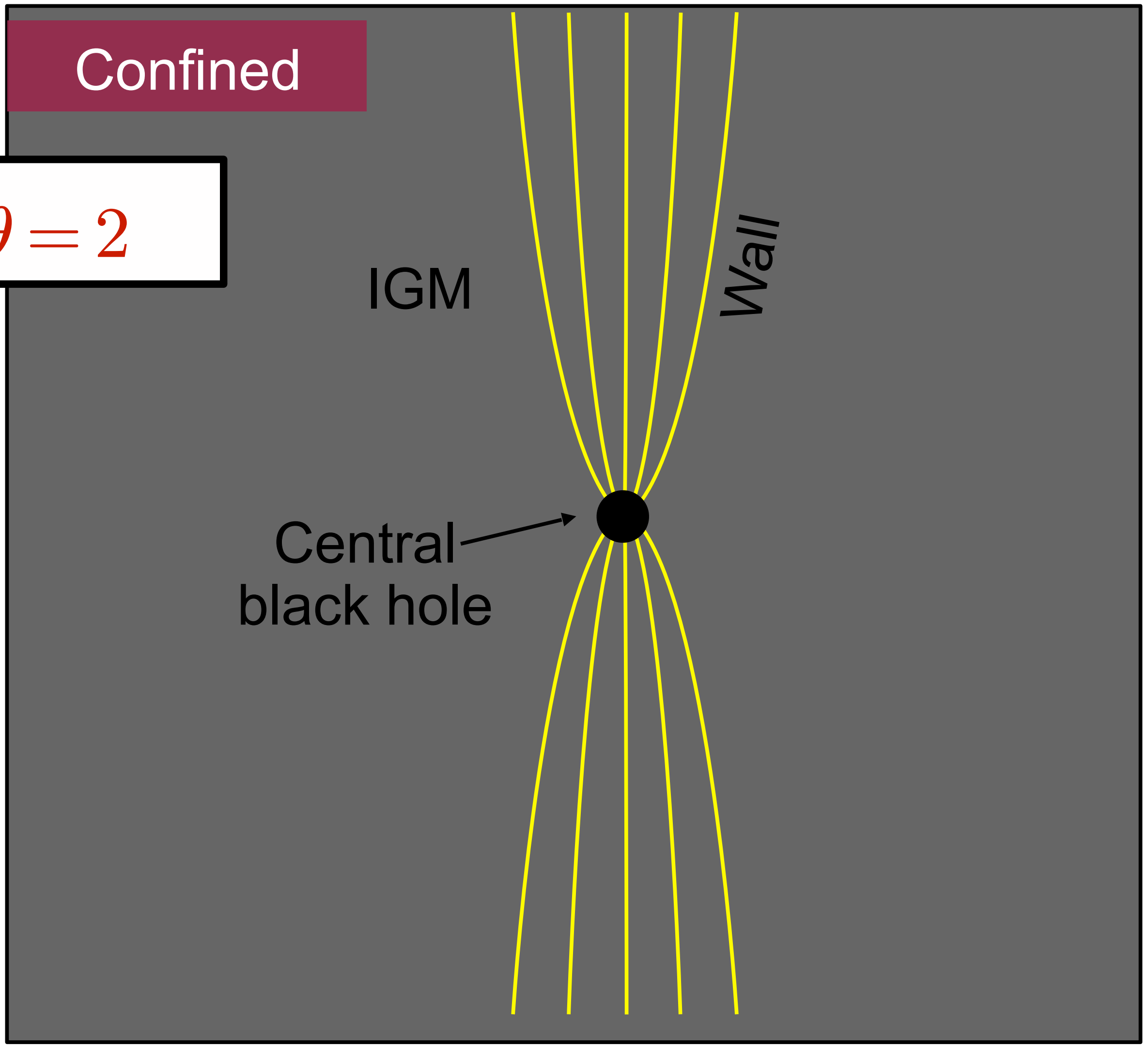
$\gamma\theta \lesssim 1$

(Komissarov et al., MNRAS, 2009)

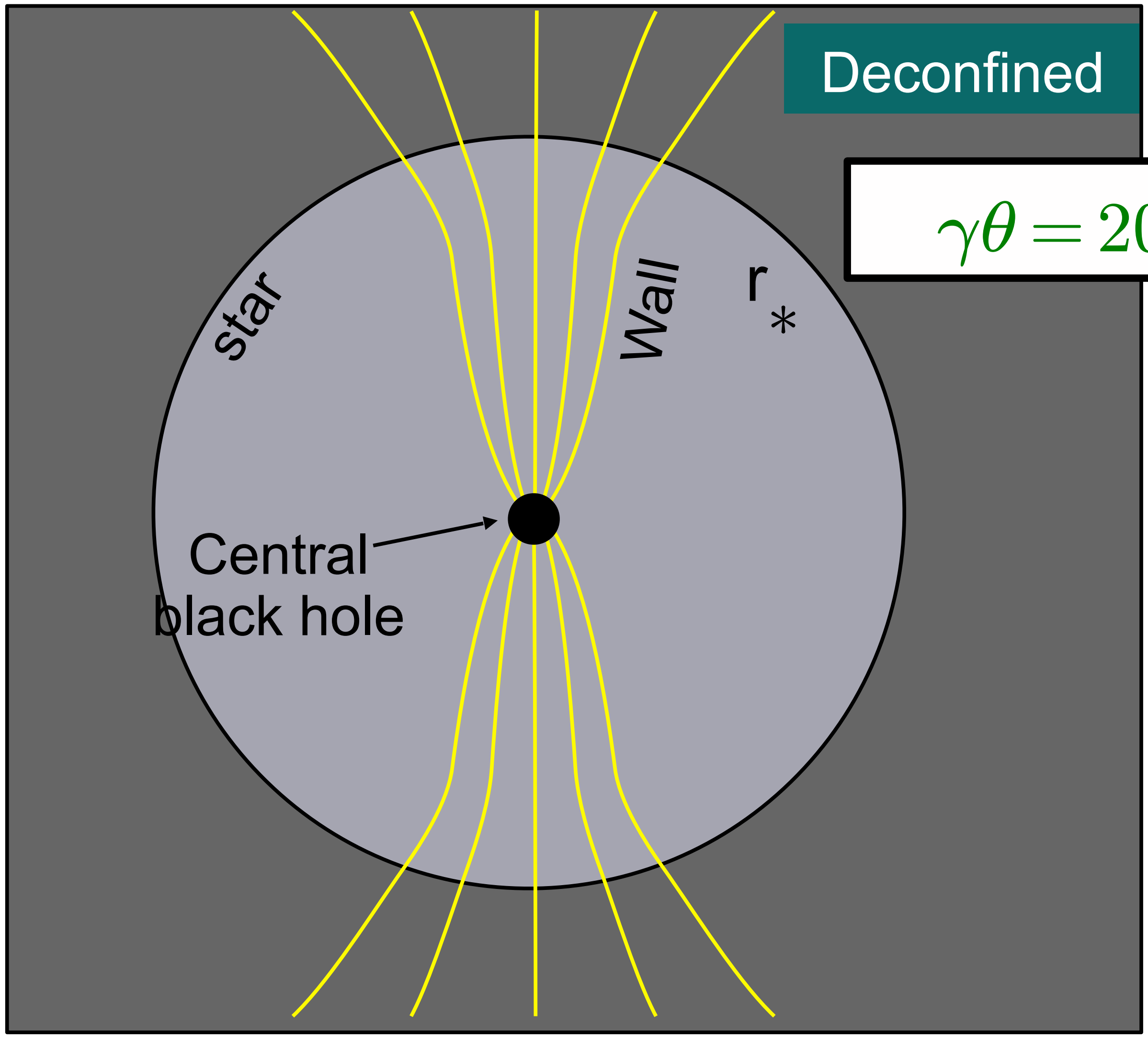
GRB jets are DEconfined:

$\gamma\theta \gtrsim 10$

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

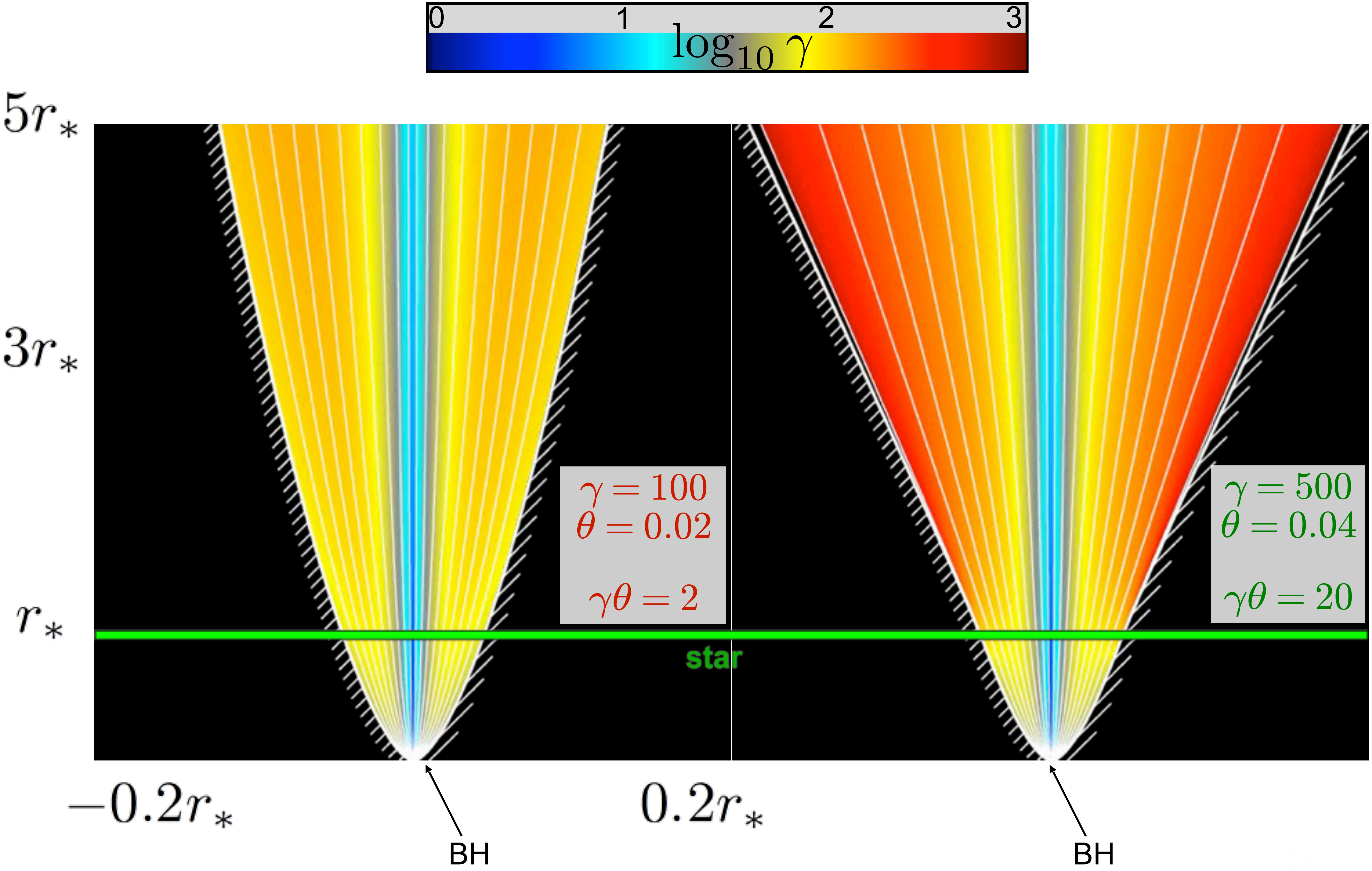


$\gamma\theta = 2$

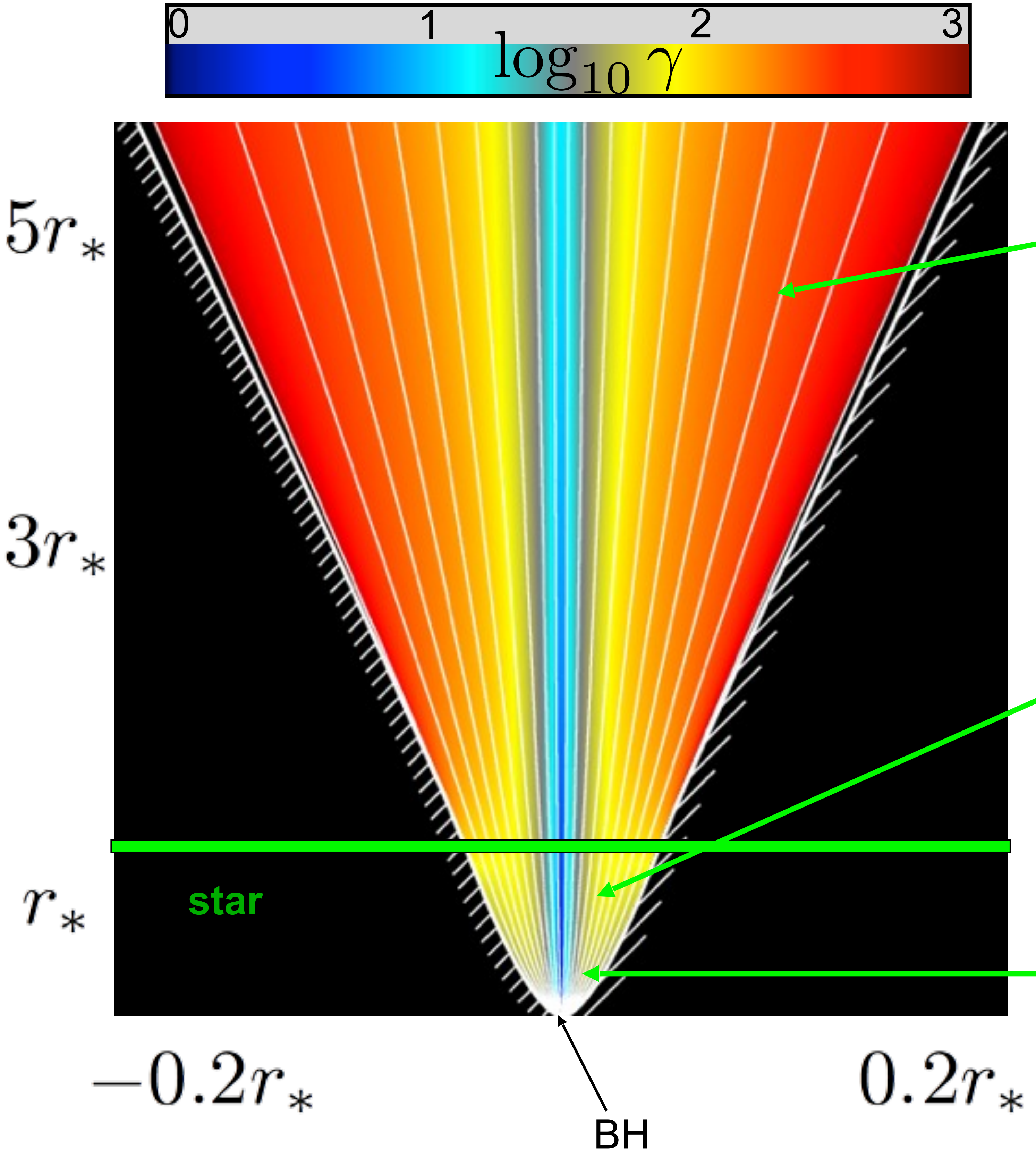


$\gamma\theta = 20$ ✓

Confined vs. Deconfined



Jet Structure Recap



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

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