Relativistic jets in the aftermath of compact binary coalescences

Theory and observations

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ECT* DTP/TALENT2024

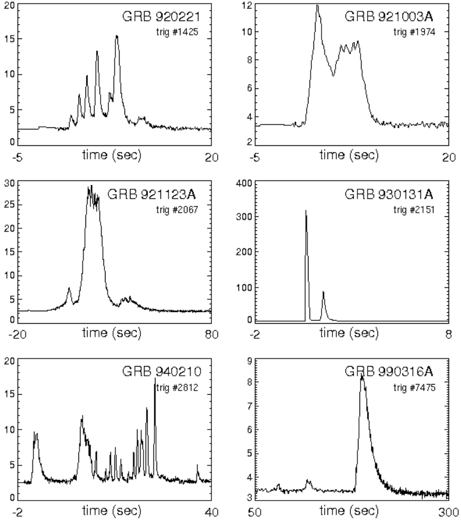
Preamble

Observational appearance of gamma-ray bursts

Some reviews and references:

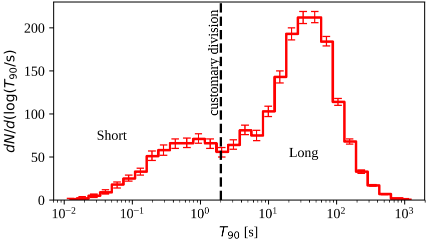
- Piran 2004
- Zhang 2018
- Kumar & Zhang 2015

Gamma-ray burst 'prompt emission'



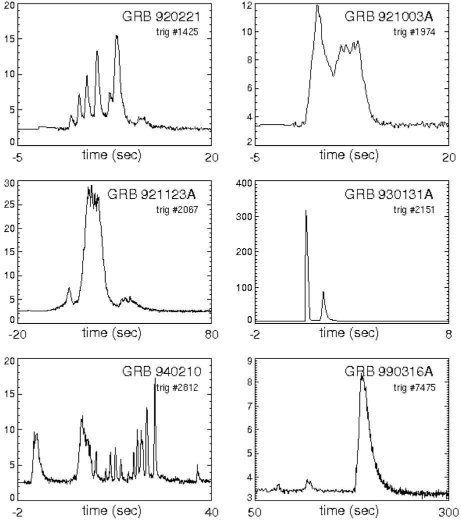
[Some CGRO/BATSE gamma-ray burst light curves]

Bimodal duration distribution



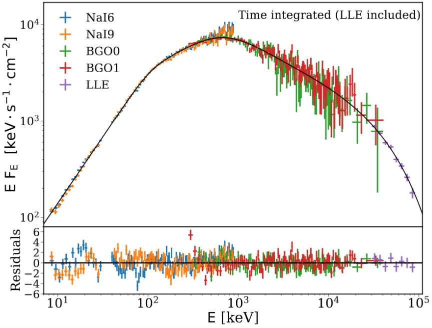
(CGRO/BATSE GRB duration data)

Gamma-ray burst 'prompt emission'



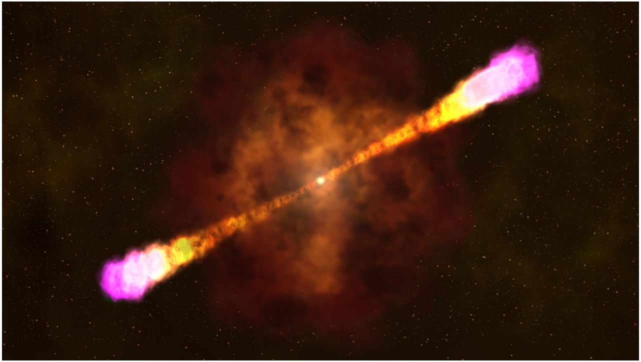
[Some CGRO/BATSE gamma-ray burst light curves]

A GRB spectrum



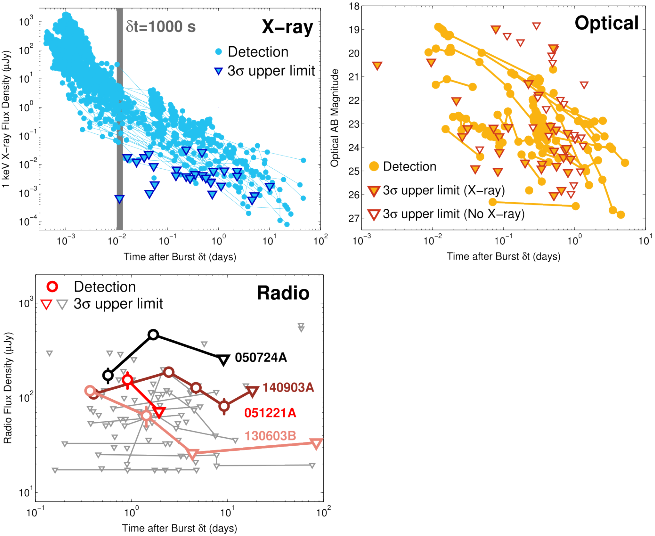
[Ravasio et al. 2018]

Relativistic jet



[Credit: NASA Goddard]

Gamma-ray burst ‘afterglow’



[Fong et al. 2015]

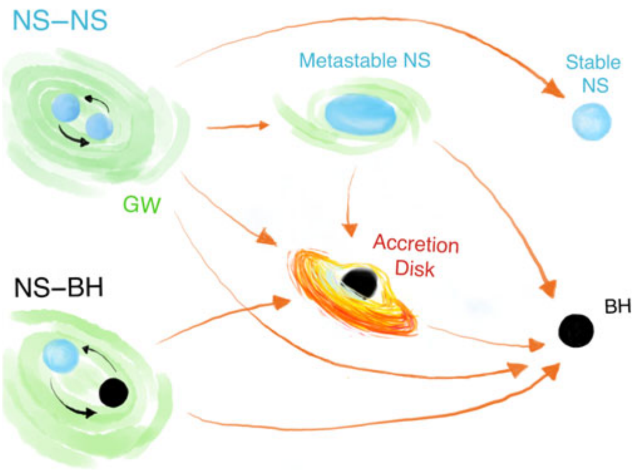
Part 1

What happens after a compact binary merger

Some reviews and references:

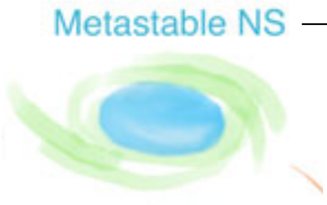
- Nakar 2020
- Meszaros et al. 2019
- Ascenzi et al. 2021
- Salafia et al. 2022

Compact binary merger outcomes



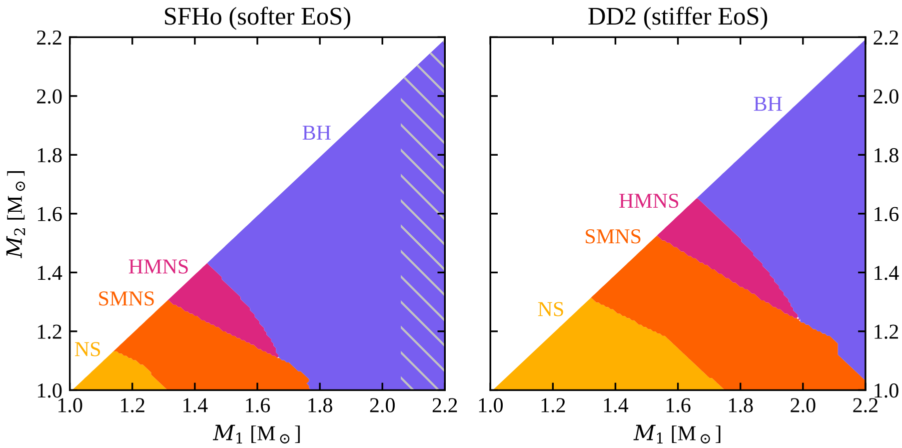
[Figure: Ascenzi+21]

Meta-stable neutron star remnants

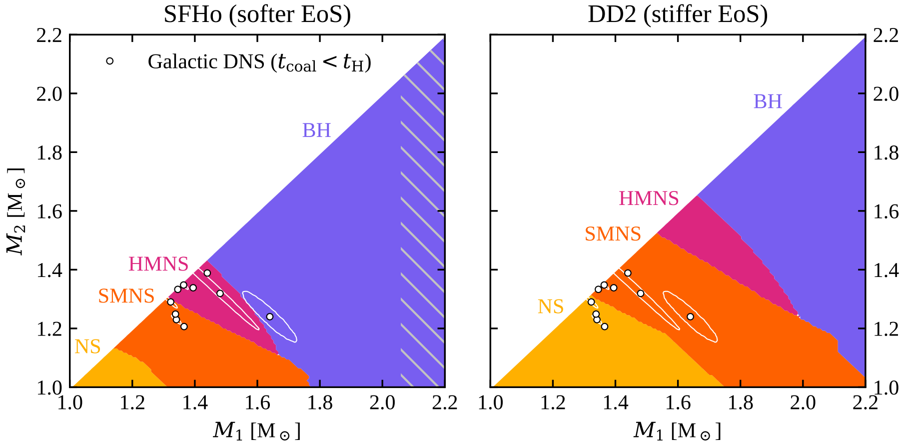


	hyper-massive (HMNS)	*vs*	supra-massive (SMNS)
supported by:	differential rotation		uniform rotation
collapse after:	viscous timescale $t_{BH} \lesssim 0.1$ s		spin-down timescale

NS-NS merger outcomes on M_1, M_2 plane

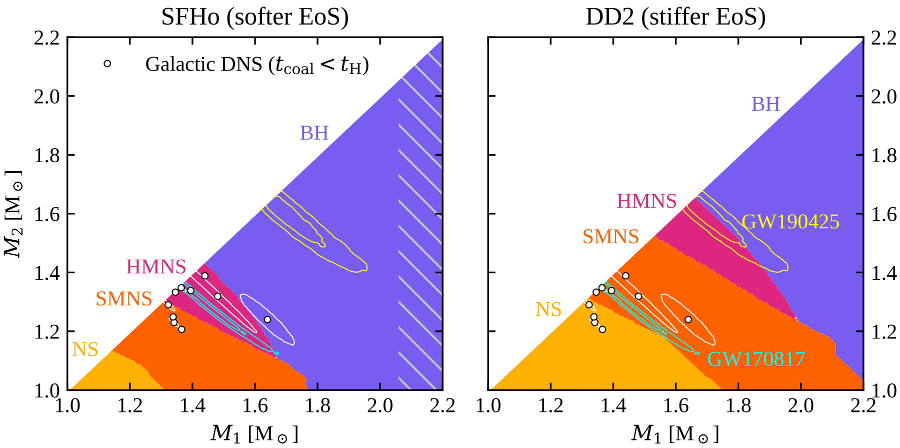


NS-NS merger outcomes on M_1, M_2 plane



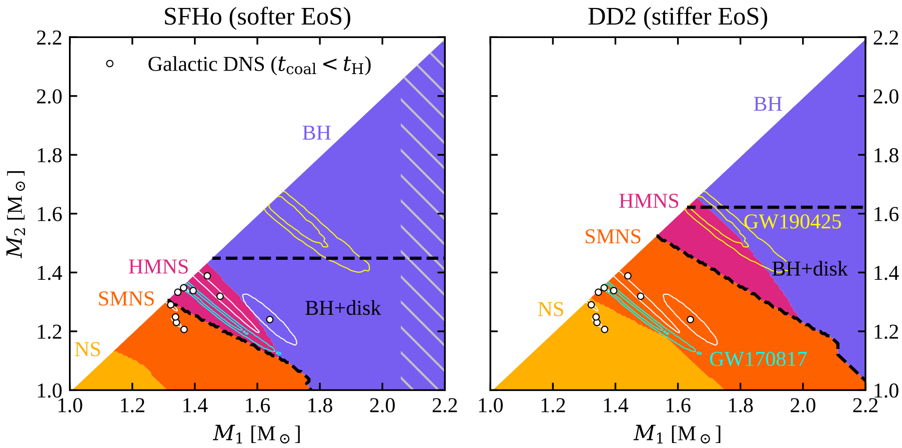
[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19]

NS-NS merger outcomes on M_1, M_2 plane



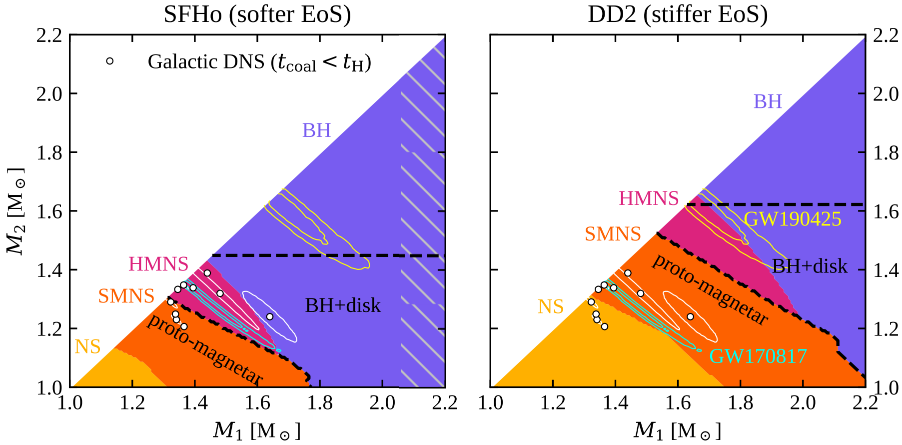
[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19; GW data: Abbott+19,20]

NS-NS merger outcomes on M_1, M_2 plane



[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19; GW data: Abbott+19,20]

NS-NS merger outcomes on M_1, M_2 plane

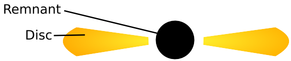


[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19; GW data: Abbott+19,20]

NS-NS and BH-NS post-merger

Outflow components

Non-thermal emission



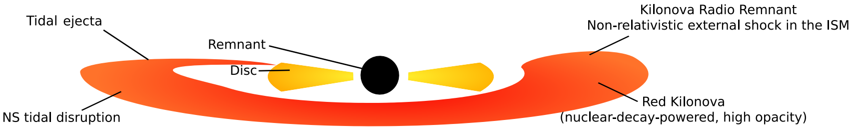
Launching mechanism

Thermal emission

NS-NS and BH-NS post-merger

Outflow components

Non-thermal emission



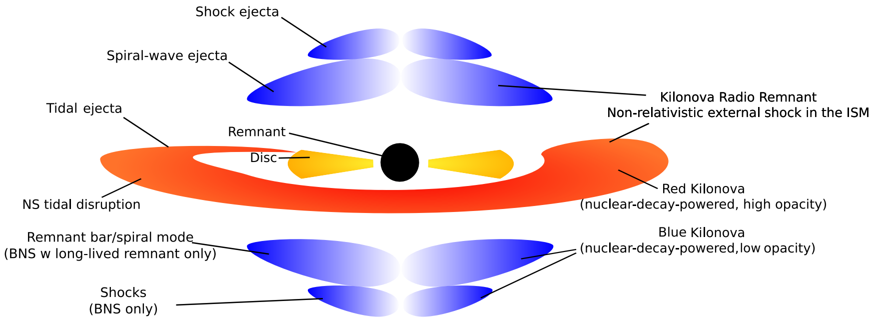
Launching mechanism

Thermal emission

NS-NS and BH-NS post-merger

Outflow components

Non-thermal emission



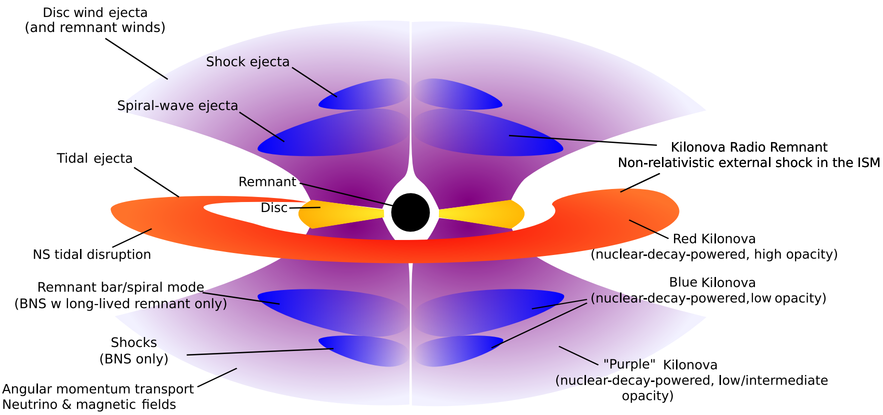
Launching mechanism

Thermal emission

NS-NS and BH-NS post-merger

Outflow components

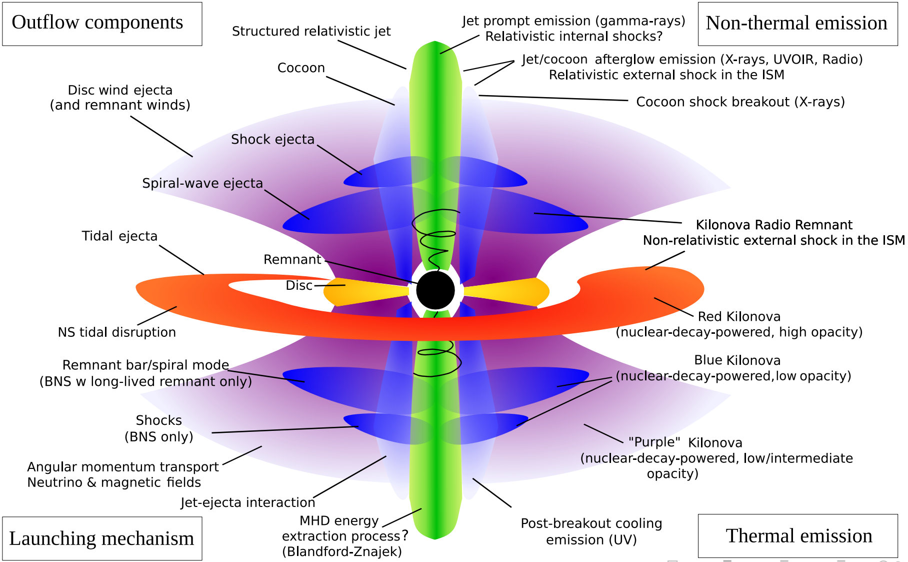
Non-thermal emission



Launching mechanism

Thermal emission

NS-NS and BH-NS post-merger



Part 2

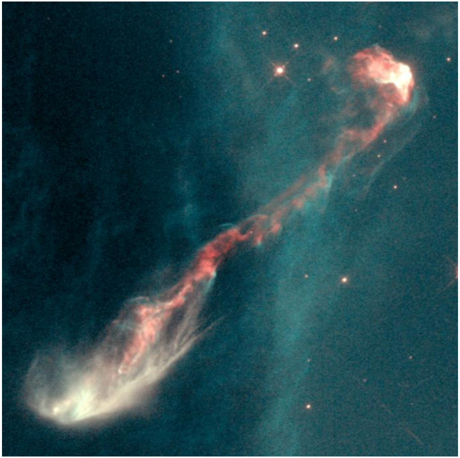
Jet launching

Some reviews and references:

- Tchekhovskoy et al. 2012
- Komissarov & Porth 2021
- Salafia & Giacomazzo 2021

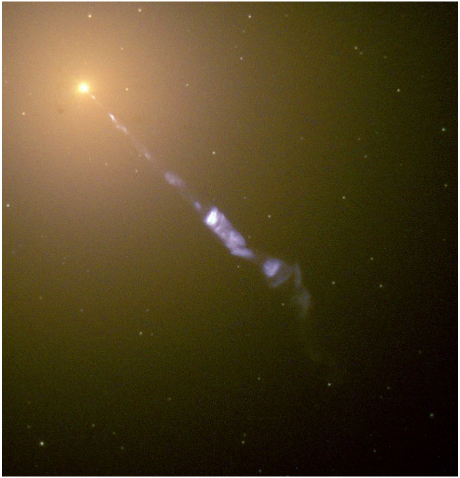
Astrophysical jets - 1

Proto-stellar jets



[HH47 jet, credit:NASA/ESA/STScI]

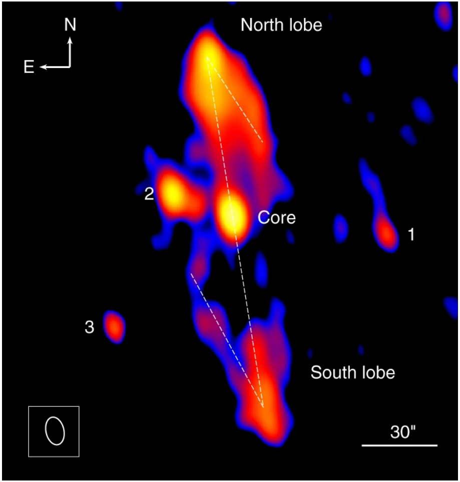
AGN jets



[M87 jet, credit:NASA/STScI/AURA]

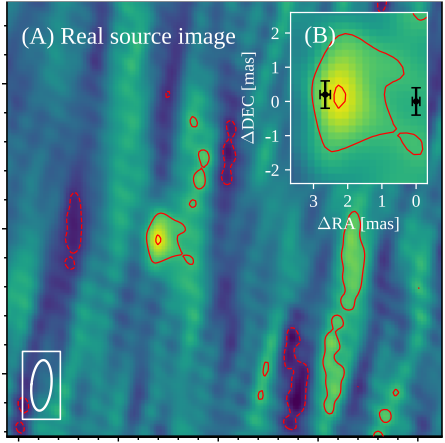
Astrophysical jets - 2

Microquasars



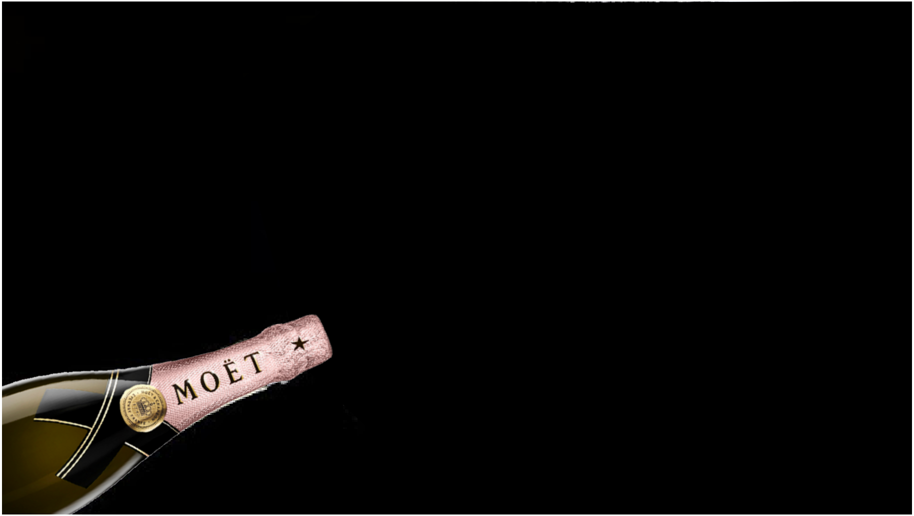
[GRS 1758-258, Marti et al. 2017]

Gamma-ray bursts

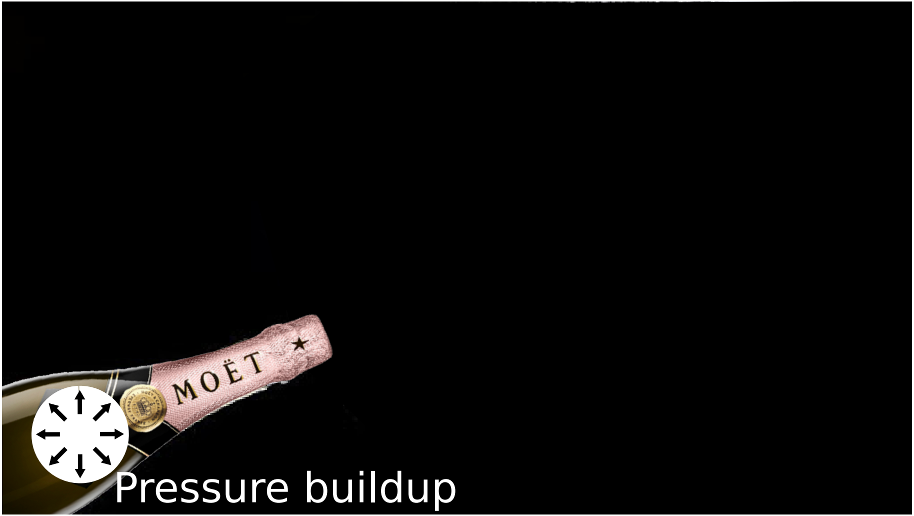


[GRB 170817A jet, Ghirlanda et al. 2019]

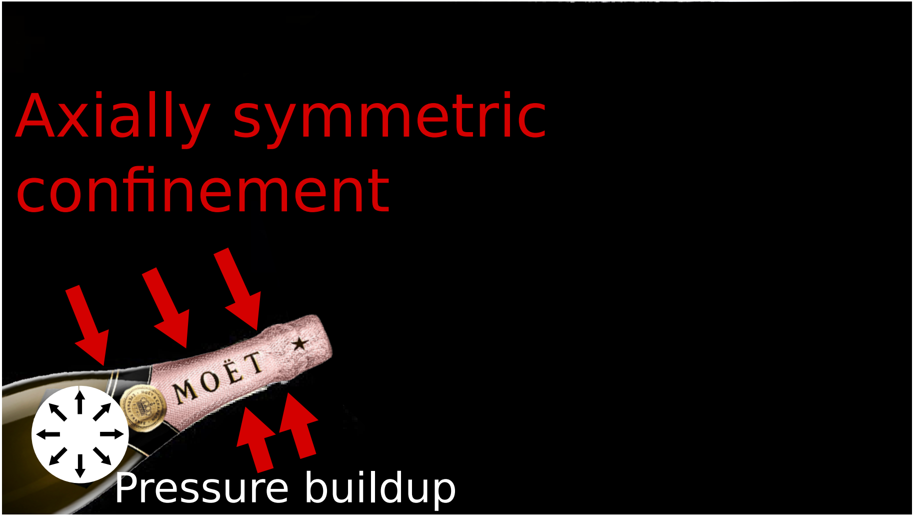
What it takes to make a jet



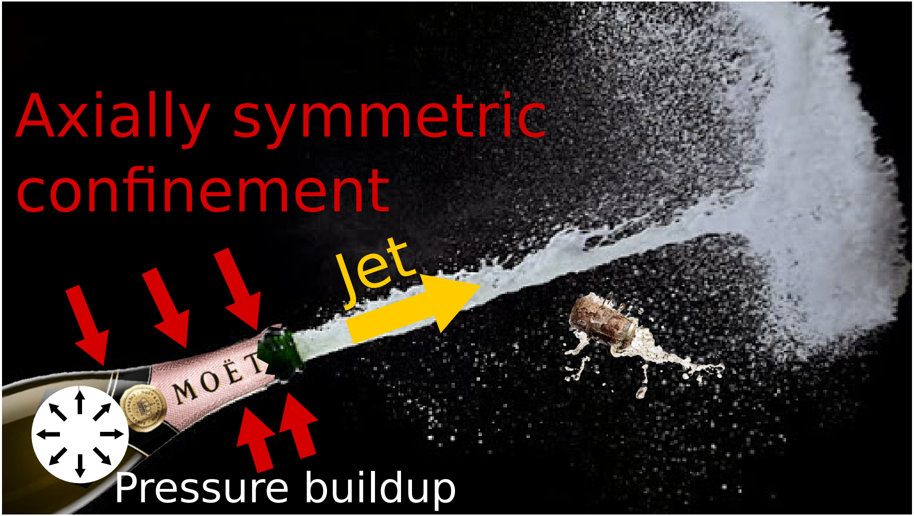
What it takes to make a jet



What it takes to make a jet



What it takes to make a jet



Astrophysical jets: basic ingredients

- Axisymmetry?
- Confinement?
- Pressure buildup?

Astrophysical jets: basic ingredients

- Axisymmetry? rotation, gravity
- Confinement?
- Pressure buildup?

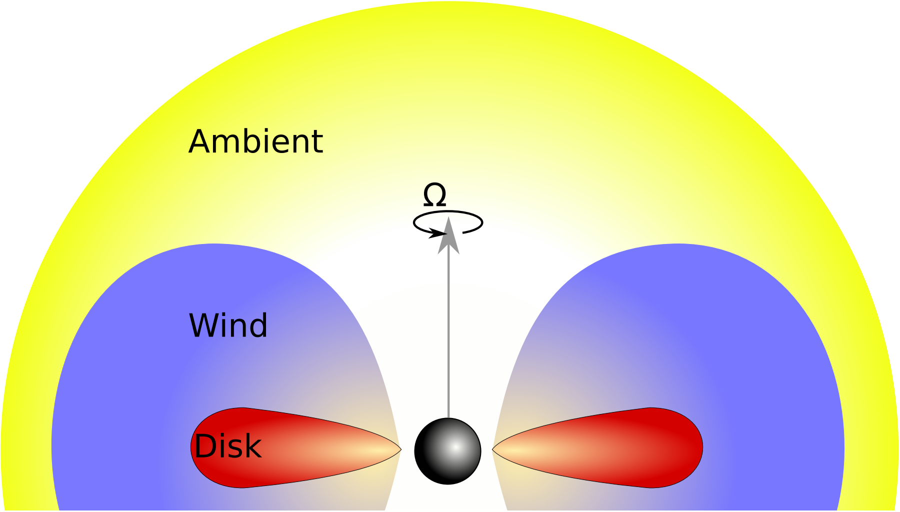
Astrophysical jets: basic ingredients

- Axisymmetry? rotation, gravity
- Confinement? pressure gradients, magnetic field
- Pressure buildup?

Astrophysical jets: basic ingredients

- Axisymmetry? rotation, gravity
- Confinement? pressure gradients, magnetic field
- Pressure buildup? Energy source?

Accretion on rotating compact object



Basic MagnetoHydroDynamics concepts

(good introduction:
H. C. Spruit 2013, "Essential magnetohydrodynamics for astrophysics")

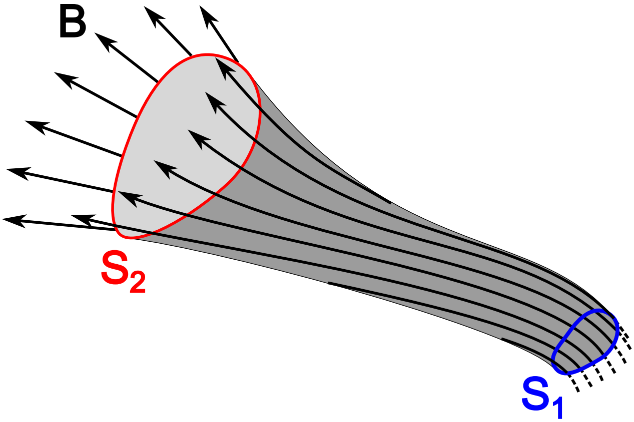
Ideal MHD fluid is

- perfectly conducting $\rightarrow E = 0$ (in fluid rest frame)
- magnetized:

  $\nabla \cdot B = 0 \rightarrow$ field lines always close
  Magnetic flux is conserved $\rightarrow$ "flux freezing"

Flux freezing

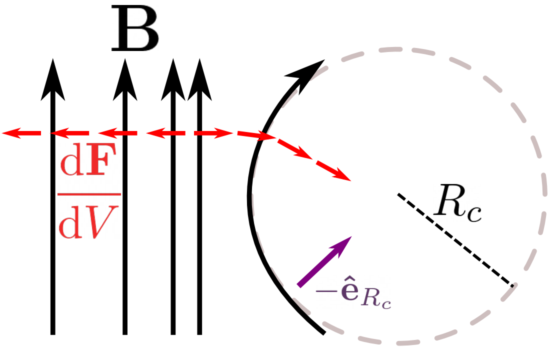
Magnetic field lines are “transported along with the fluid”



[attribution: Chetvorno, CC0 license]

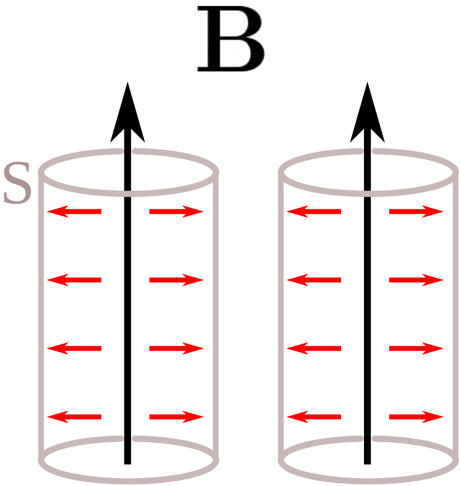
Lorentz force

$$\frac{\mathrm{d}\mathbf{F}}{\mathrm{d}V} = \frac{1}{4\pi}\mathbf{J}\times\mathbf{B} = \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} = -\frac{1}{8\pi}\nabla_\perp B^2 - \frac{B^2}{4\pi R_c}\hat{\mathbf{e}}_{R_c}$$



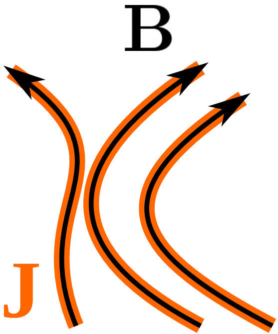
- always perpendicular to $\mathbf{B}$
- towards negative mag. energy density gradient ($\rightarrow$ equalize pressure)
- towards center of radius of curvature ($\rightarrow$ straighten lines)

Magnetic pressure



$$\frac{\mathrm{d}\mathbf{F}}{\mathrm{d}V} S \frac{\mathrm{d}\mathbf{F}}{\mathrm{d}A} = \mathbf{p}_{\mathrm{mag}} \qquad \left|\mathbf{p}_{\mathrm{mag}}\right| = \frac{B^2}{8\pi}$$

Force-free region

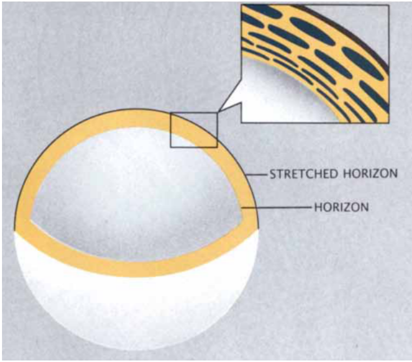


$$\mathbf{J} = \frac{1}{4\pi}(\nabla \times \mathbf{B}) \parallel \mathbf{B} \rightarrow \frac{\mathrm{d}\mathbf{F}}{\mathrm{d}V} = \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$

- Needs high magnetization (other forces $\ll$ Lorentz force)
- Minimum energy configuration (within the volume)
- Exterts stress on boundaries

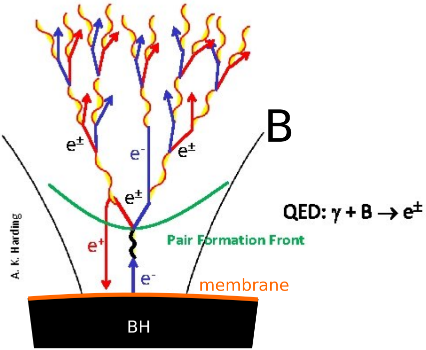
Kerr black hole magnetosphere

Membrane paradigm



[Price & Thorne 1988]

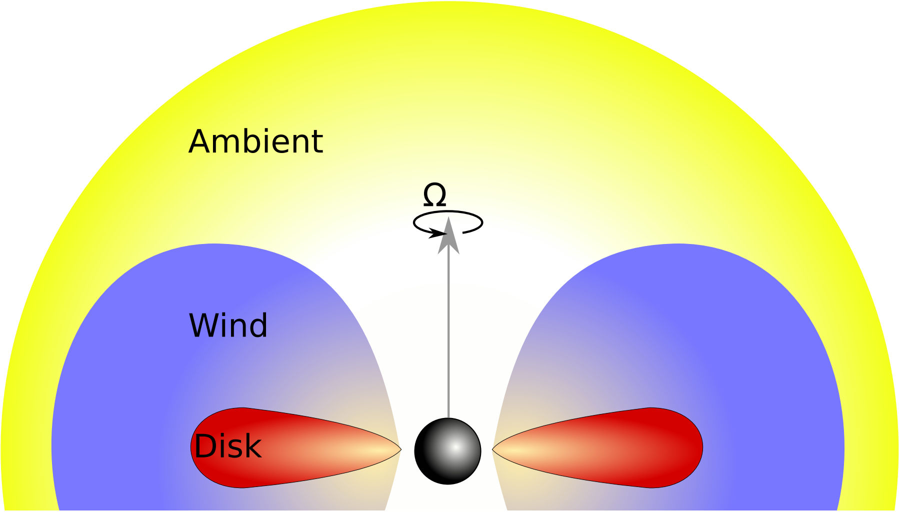
Vacuum breakdown



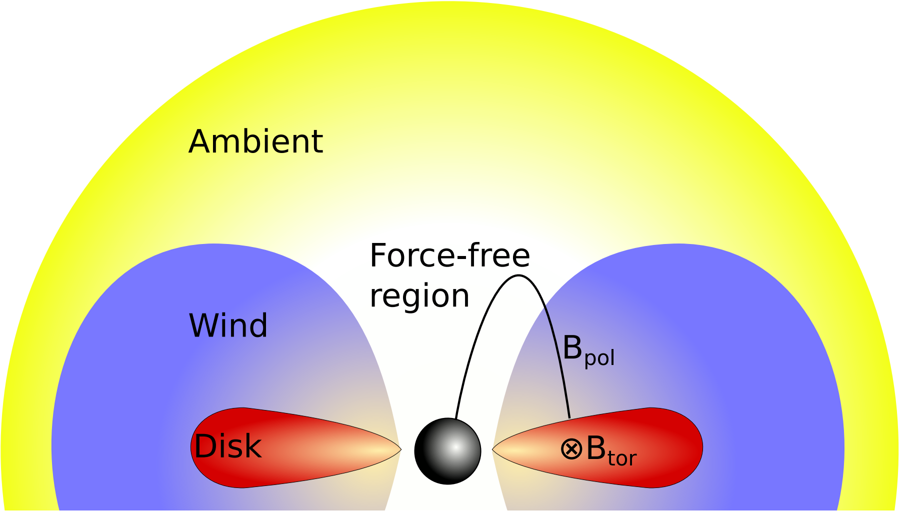
[Adapted from A. K. Harding]

[Blandford & Znajek 1977]

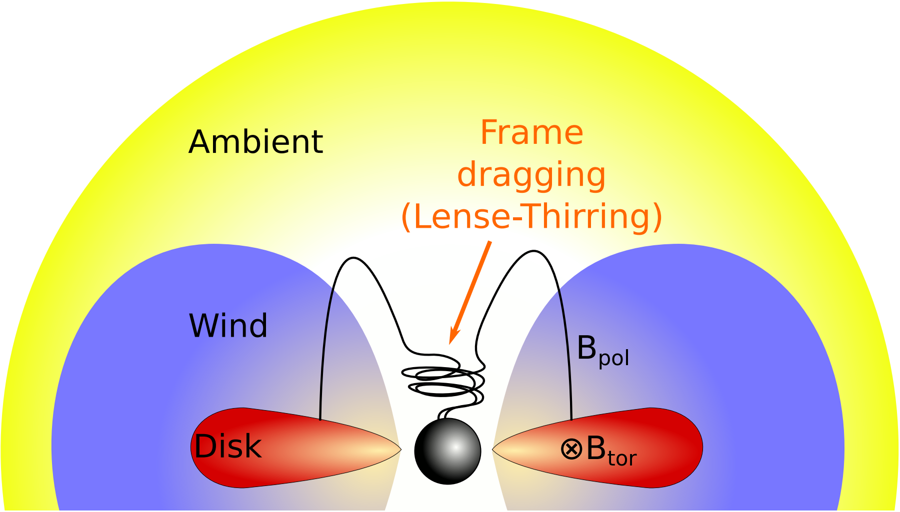
Accretion-driven jets - Blandford-Znajek process



Accretion-driven jets - Blandford-Znajek process

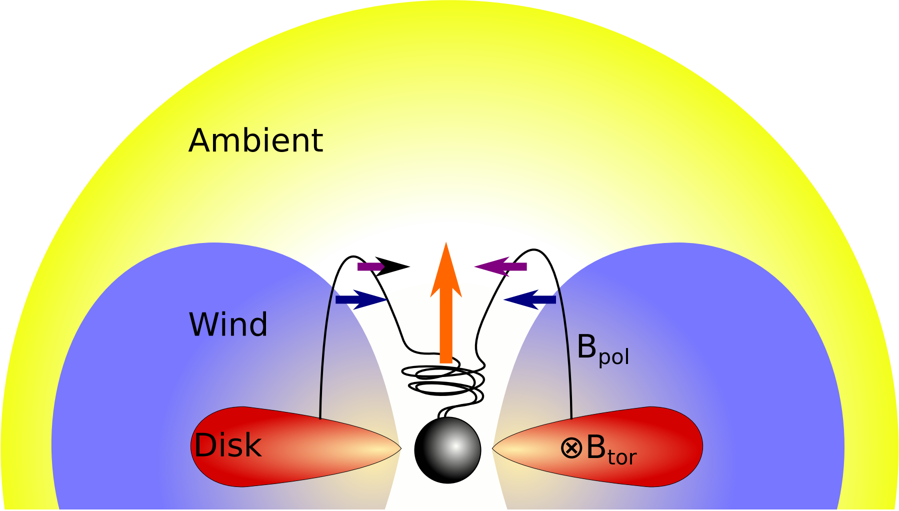


Accretion-driven jets - Blandford-Znajek process



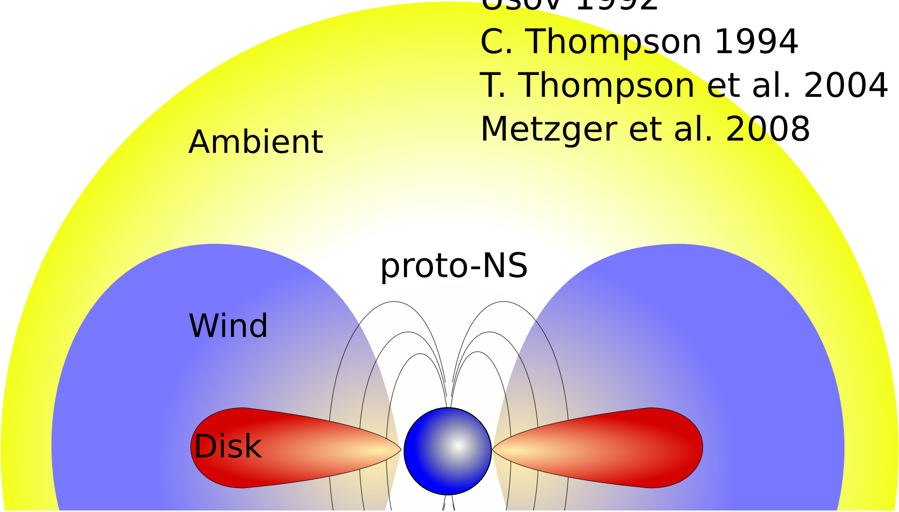
Accretion-driven jets - Blandford-Znajek process

Blandford & Znajek 1977



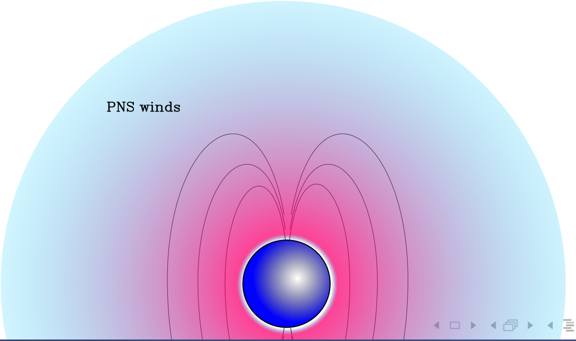
Accretion-driven jets - Blandford-Znajek process

Usov 1992
C. Thompson 1994
T. Thompson et al. 2004
Metzger et al. 2008



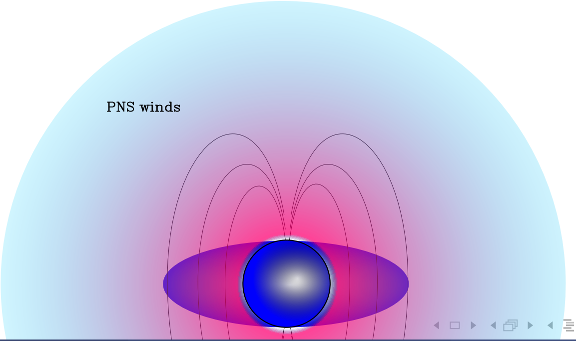
PNS jet-launching difficulties

- proto-NS is hot $\rightarrow$ high L_ν $\rightarrow$ ν-driven wind



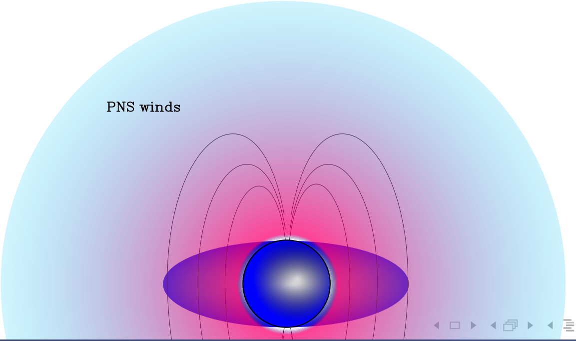
PNS jet-launching difficulties

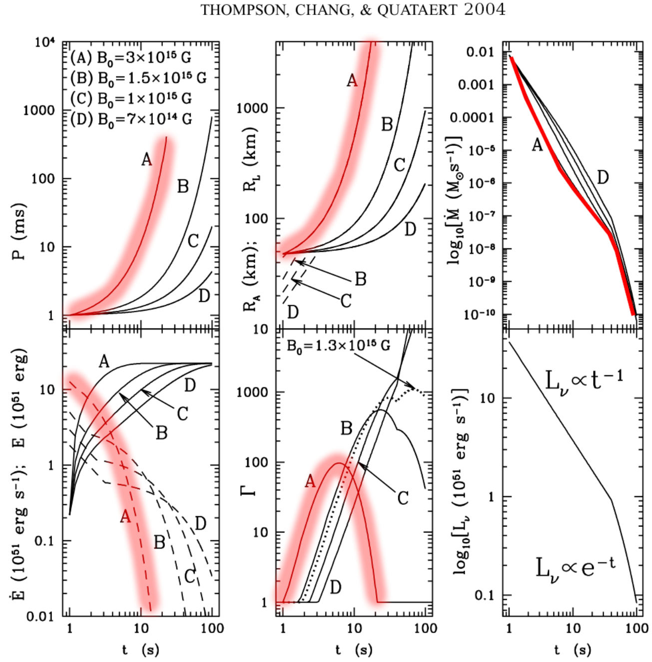
- proto-NS is hot $\rightarrow$ high L_ν $\rightarrow$ ν-driven wind
- differential rotation + magnetic field $\rightarrow$ magneto-centrifugal winds



PNS jet-launching difficulties

- proto-NS is hot $\rightarrow$ high $L_\nu \rightarrow \nu$-driven wind
- differential rotation + magnetic field $\rightarrow$ magneto-centrifugal winds
- 'baryon pollution' problem $\rightarrow$ low Γ





Early works optimistic.

Recent simulations reveal difficulties (e.g. Mösta et al. 2020, Soares et al. 2022).

Unsettled.

Blandford-Znajek luminosity

$$L_{\mathrm{jet,\,BZ}} \propto B_{\mathrm{pol}}^2 a_{\mathrm{BH}}^2$$

[Blandford & Znajek '77, see also Tchekhovskoy et al. '12]

Taps BH rotational energy

$\sigma = B^2/(4\pi\rho c^2)$ magnetization

$$\rho \propto \dot{M}$$

$$\rightarrow B^2 \tilde{\propto} \dot{M}$$

$$\rightarrow L_{\mathrm{jet,BZ}} = \eta_{\mathrm{BZ}}(a_{\mathrm{BH}}, ...)\dot{M}c^2$$

But η_{BZ} can be > 1

Blandford-Znajek efficiency

$\eta_{\rm BZ}$ depends on:

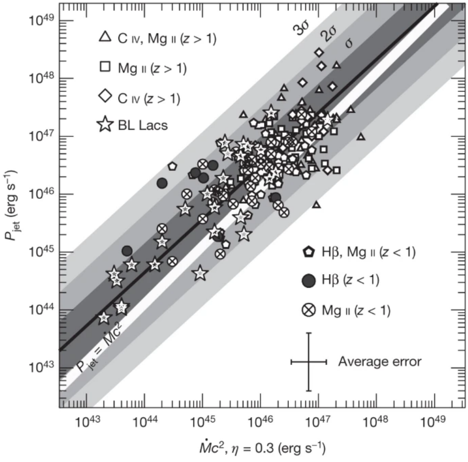
- BH spin, $a_{\rm BH}^2$
- disk magnetization, σ
- poloidal/toroidal field (only $B_{\rm pol}$ is used)
  [see Liska et al. 2020 for a recent discussion]
- extent of force-free region ("disk occultation effect")
  [Tchekhovskoy et al. 2010]

Maximum efficiency: Magnetically Arrested Disk, $\eta_{\rm BZ,MAD} \gtrsim 1$
[Bisnovatyi-Kogan & Ruzmaikin '74; Narayan et al.'03]

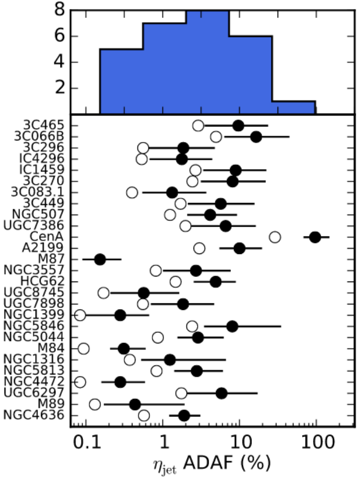
$\eta_{\rm BZ}$ as low as 10^{-3} if thick disk & predominantly toroidal B
[see Salafia & Giacomazzo 2020 for a recent discussion]

η_{BZ} in Active Galactic Nuclei

Figure 2: Jet power versus accretion power.

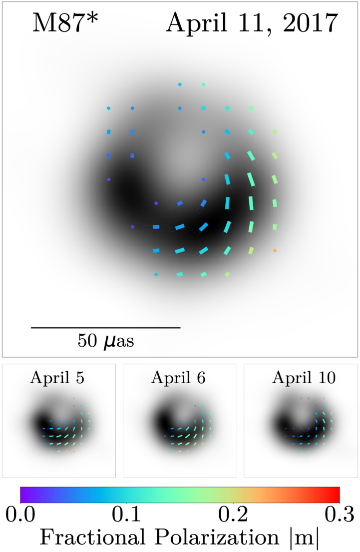


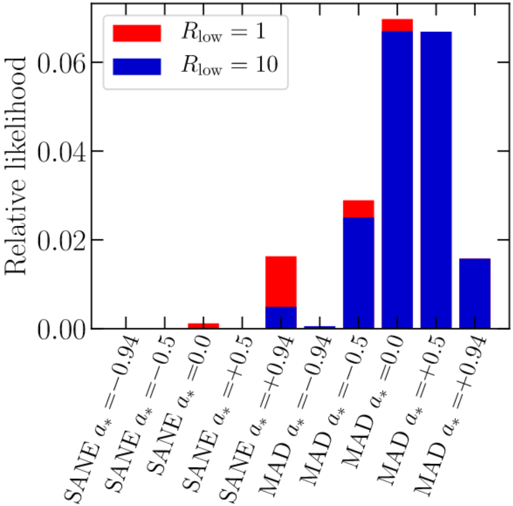
Ghisellini et al. 2014



Nemmen & Tchekhovskoy 2015

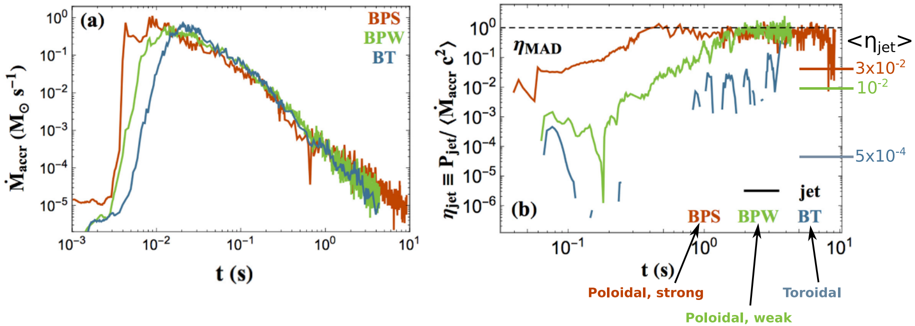
EHT polarimetry of M87 favours MAD over SANE





[EHT collaboration 2021]

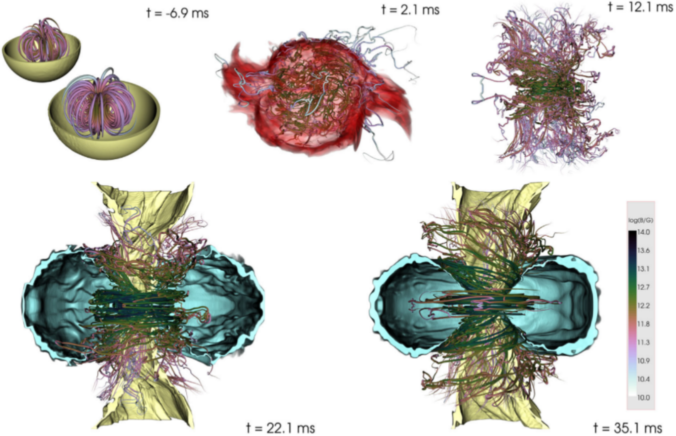
η_{BZ} in short gamma-ray bursts: B configuration



[Christie et al. 2019]

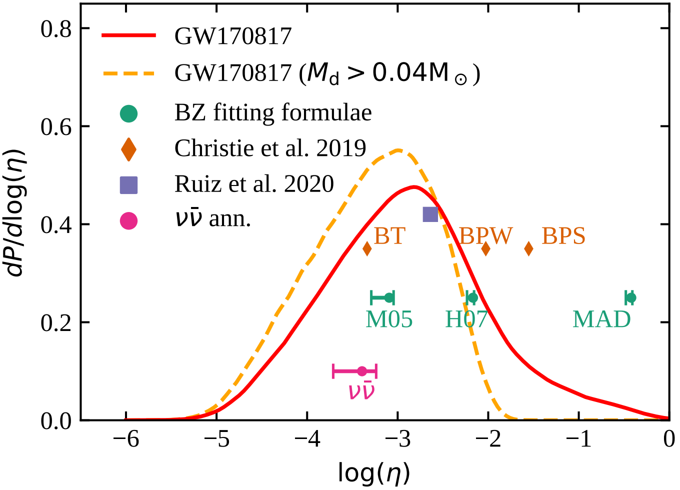
Expected B configuration in binary neutron star mergers

Dynamics + flux freezing → predominantly toroidal



[Kawamura et al. 2016]

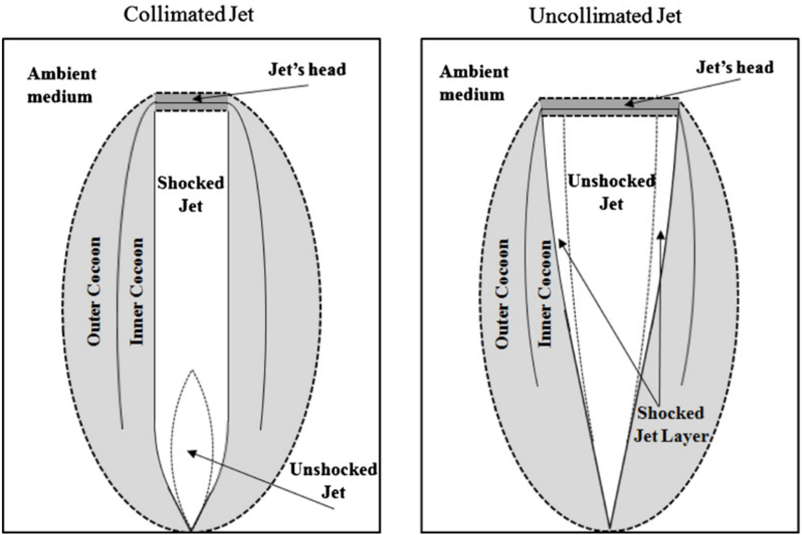
GW170817 accretion-to-jet efficiency



Part 3
Consequences of jet launch

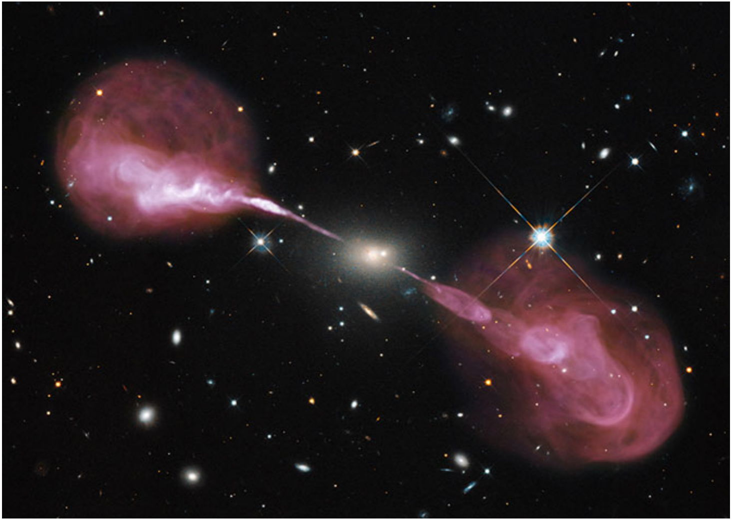
Some reviews and references:

- Salafia & Ghirlanda 2022
- Salafia et al. 2020



[Bromberg et al. 2011; see also Martì et al. 1995, Matzner 2003, Lazzati et al. 2019, Salafia et al. 2020, Hamidani et al. 2020]

Hercules A: a collimated extragalactic jet

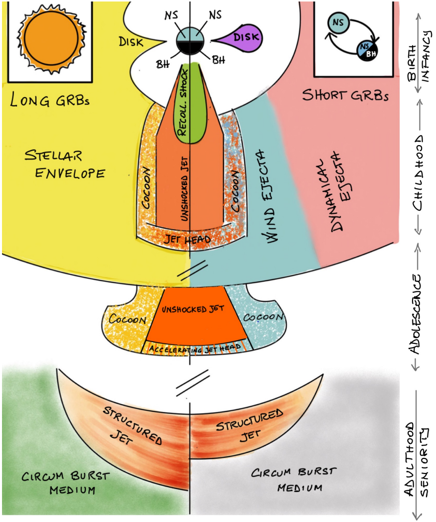


[NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)]

Hercules A: a collimated extragalactic jet

[X-ray: NASA/CXC/SAO, Optical: NASA/STScI, Radio: NSF/NRAO/VLA]

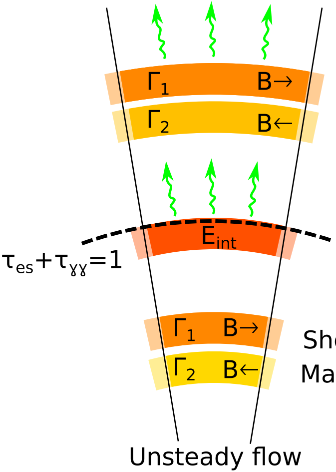
Jet propagation and breakout



← Salafia & Ghirlanda 2022

[Jet propagation and breakout: see e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

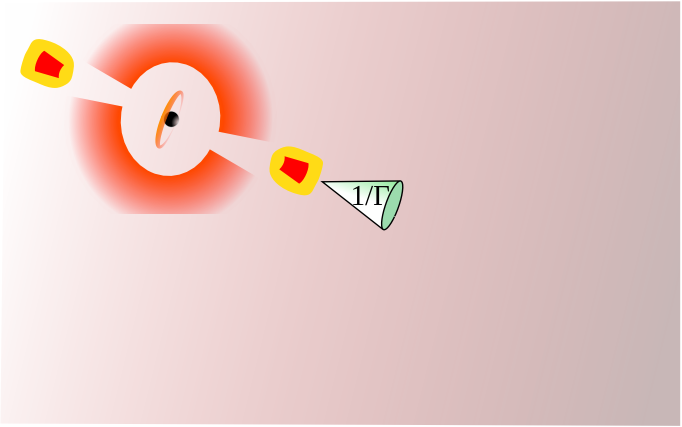
Jet ‘composition’ → prompt emission processes



Dissipation process	Energy conversion	Radius [cm]
Internal shocks (Collisionless) Magn. reconn. (Petschek)	$E_K \to E_{int} \to \gamma$ $E_B \to E_{int} \to \gamma$	$10^{13\text{-}16}$
Photospheric emission	$E_{int} \to \gamma$	$10^{12\text{-}13}$
Shocks (radiation-mediated) Magn. reconn. (Sweet-Parker)	$E_K \to E_{int}$ $E_B \to E_{int}$	$10^{7\text{-}12}$

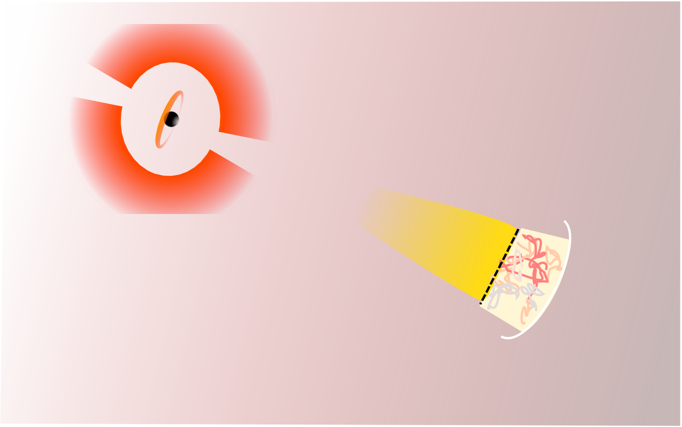
[Rees+94,05, Daigne+02, Drenkhahn+02, McKinney+12, Zhang+15, ...]

Afterglow mechanism: shock in interstellar medium



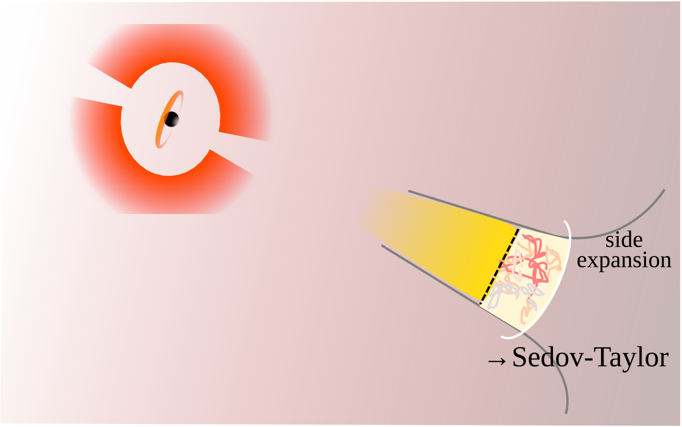
[Paczynski & Rhoads 1993, Meszaros & Rees 1997, Sari et al. 1998, Panaitescu & Kumar 2000, ...]

Afterglow mechanism: shock in interstellar medium



[Paczynski & Rhoads 1993, Meszaros & Rees 1997, Sari et al. 1998, Panaitescu & Kumar 2000, ...]

Afterglow mechanism: shock in interstellar medium



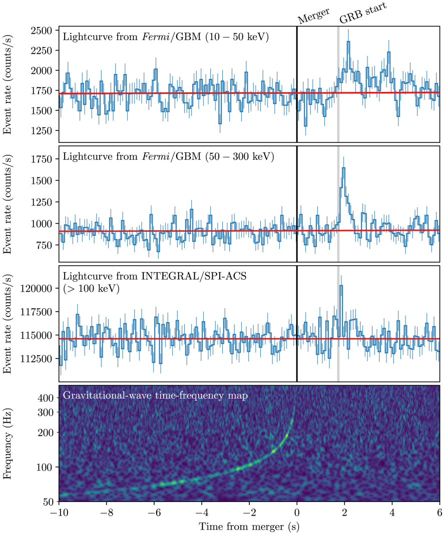
[Paczynski & Rhoads 1993, Meszaros & Rees 1997, Sari et al. 1998, Panaitescu & Kumar 2000, ...]

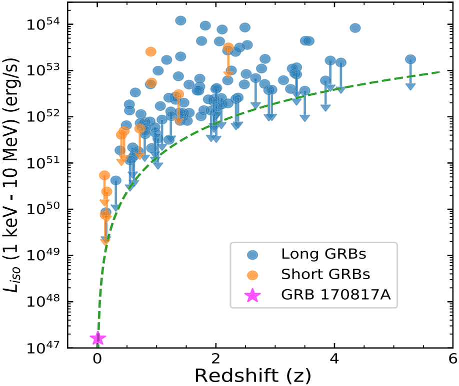
Part 4
Observations

Some reviews and references:

- Margutti & Chornock 2021
- Nakar 2020
- Metzger 2019

GW170817 & GRB170817A



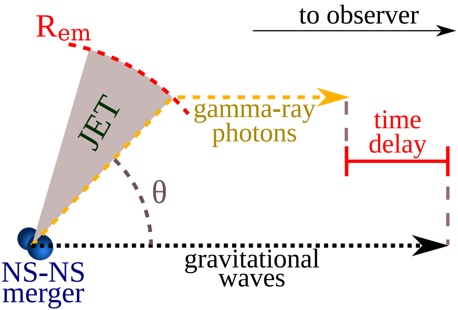


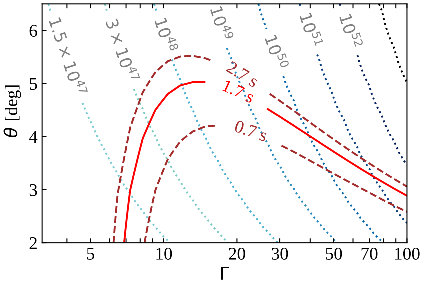
[Abbott et al. 2017 (ApJ, 484, 2)]

The 1.7 s GW-GRB delay

Decomposition $\Delta t_{\mathrm{GW-GRB}} = \Delta t_{\mathrm{j}} + \Delta t_{\mathrm{bo}} + \Delta t_{\gamma}$

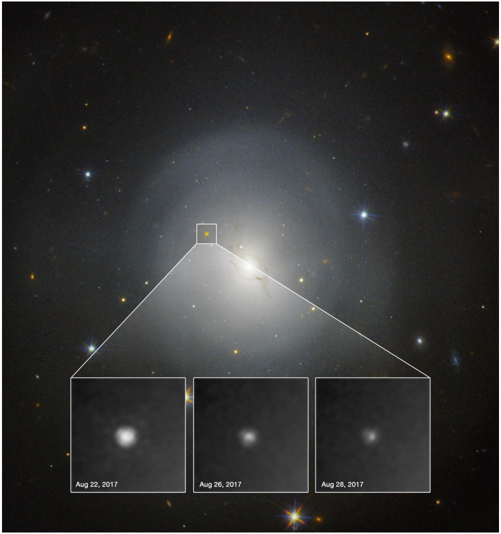
- Δt_{j}, time from merger to jet launch
- Δt_{bo}, jet breakout time
- Δt_{γ}, observer-frame time from breakout to gamma-ray production





[Salafia et al. 2018; see also Gill et al. 2019, Zhang 2019, Beniamini et al. 2020]

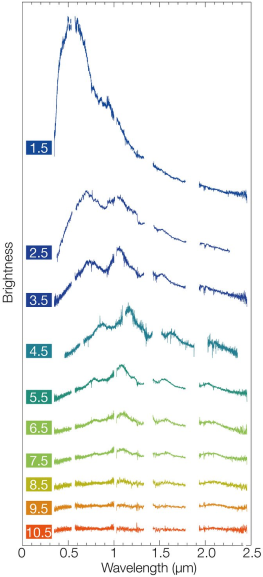
Galaxy NGC4993: a new transient



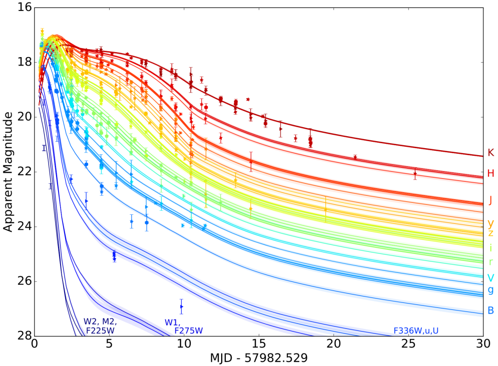
[Hubble Space Telescope, NASA and ESA]

- Massive, early-type galaxy
- $d_{\mathrm{L}} \sim 40\,\mathrm{Mpc}$, $z \sim 0.01$
- New fast-evolving transient

The AT2017gfo transient

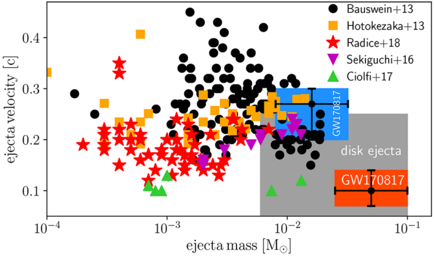


[Pian et al. 2017, Villar et al. 2018]

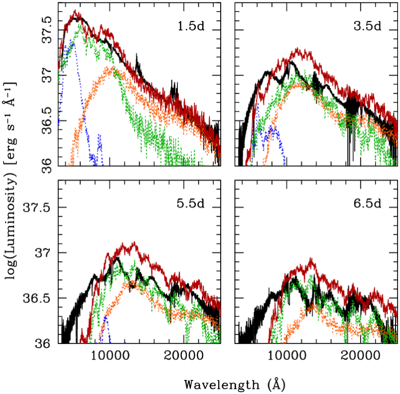


The AT2017gfo Kilonova

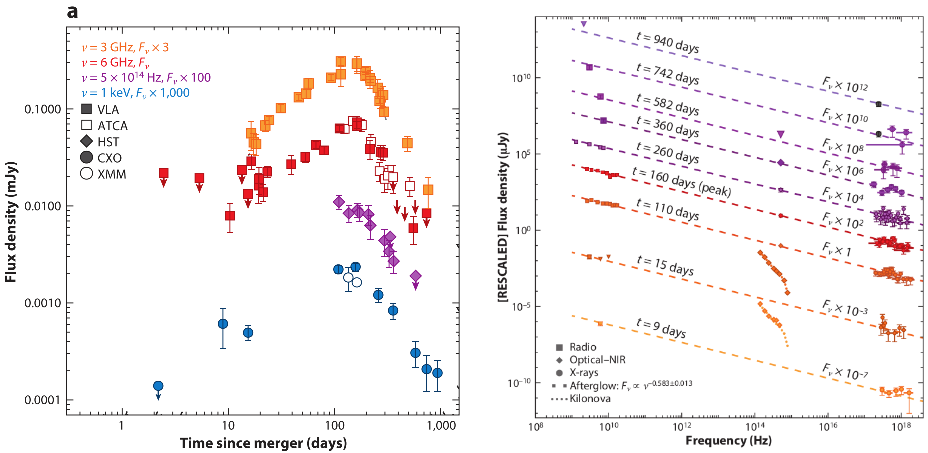
- fast color evolution & broad spectral features consistent with KN expectations
- at least two components with different opacities



[Siegel 2019]

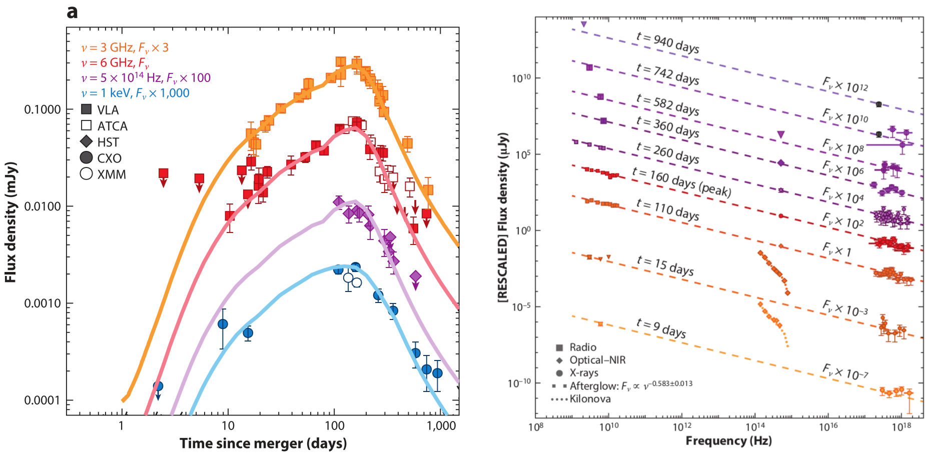


[Pian et al. 2017]



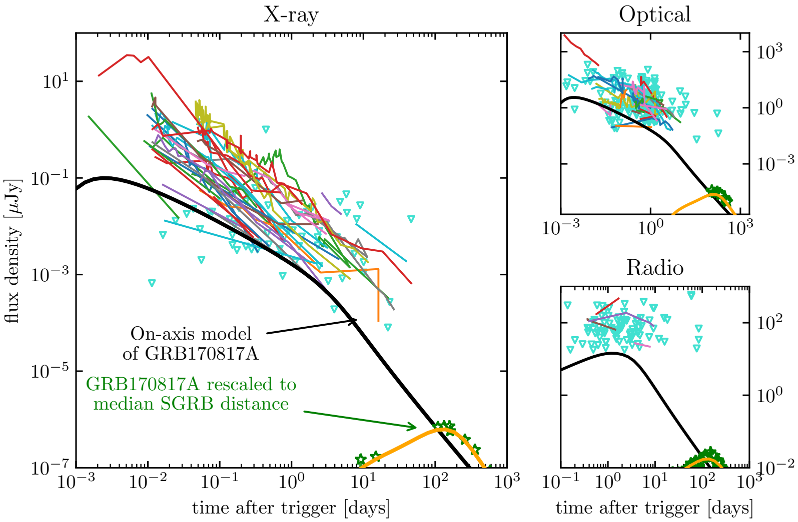
[Margutti & Chornock 2021]

Afterglow



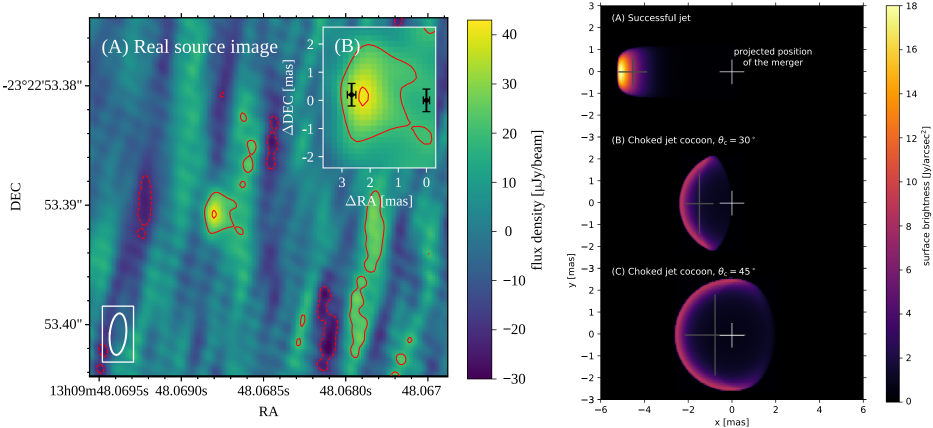
[Margutti & Chornock 2021]

Afterglow compared to known SGRBs



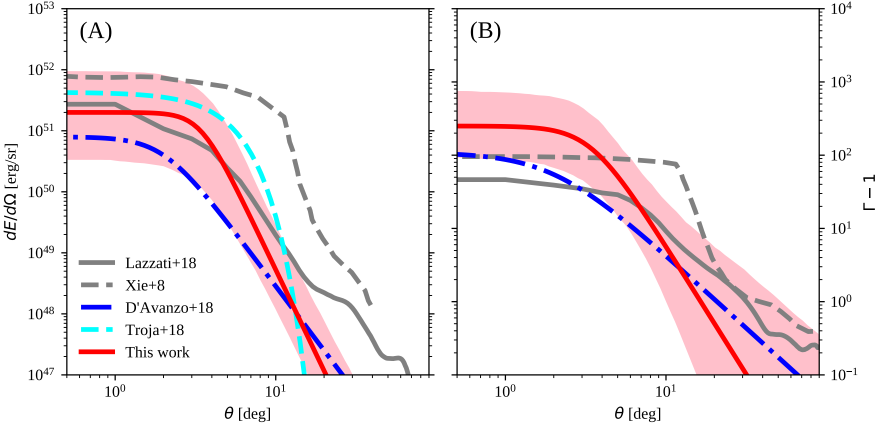
[Salafia et al. 2019]

‘Superluminal’ motion and compact image



(Ghirlanda, Salafia, et al. 2019)

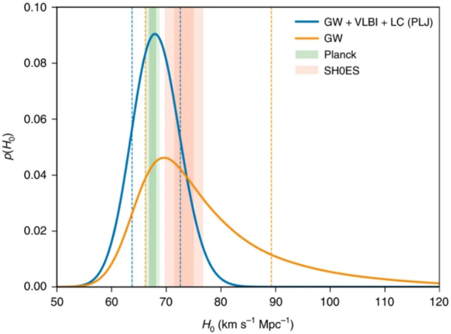
Inference on GW170817 jet energy profile



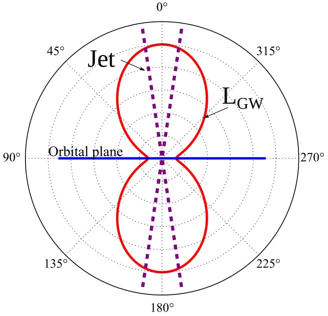
[Ghirlanda et al. 2019]

Enhanced standard siren H_0 measurement

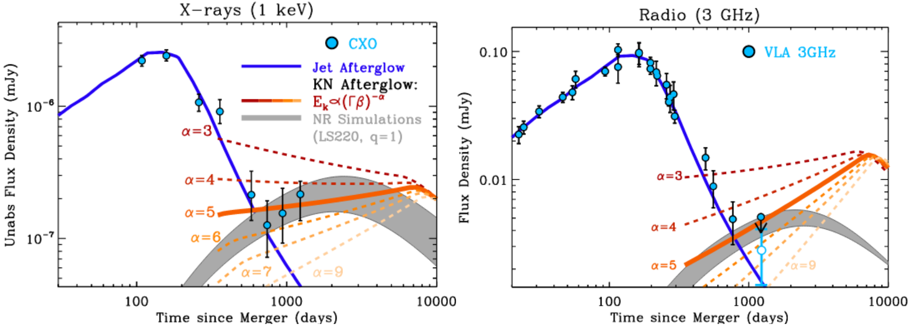
Fig. 2: Posterior distributions for H_0.



(Hotokezaka et al. 2019)

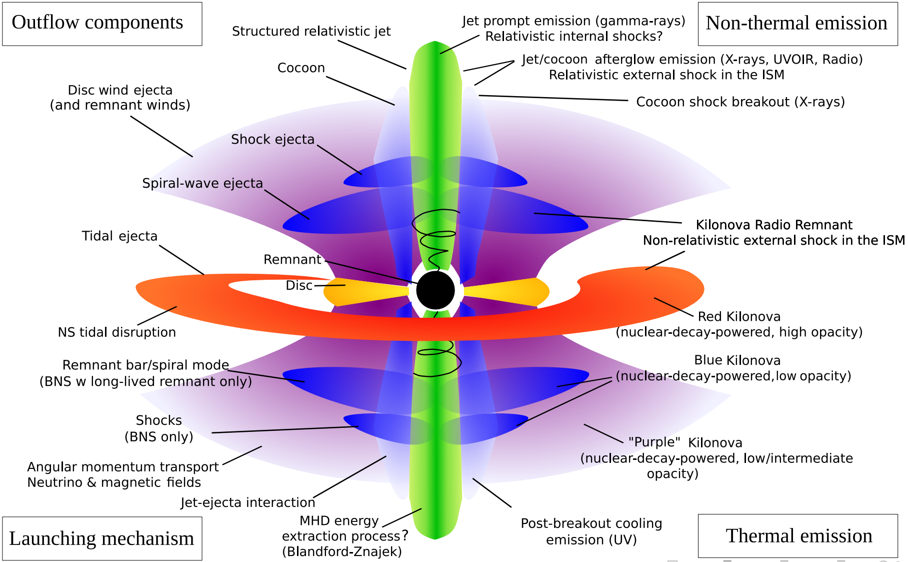


Late-time X-ray excess

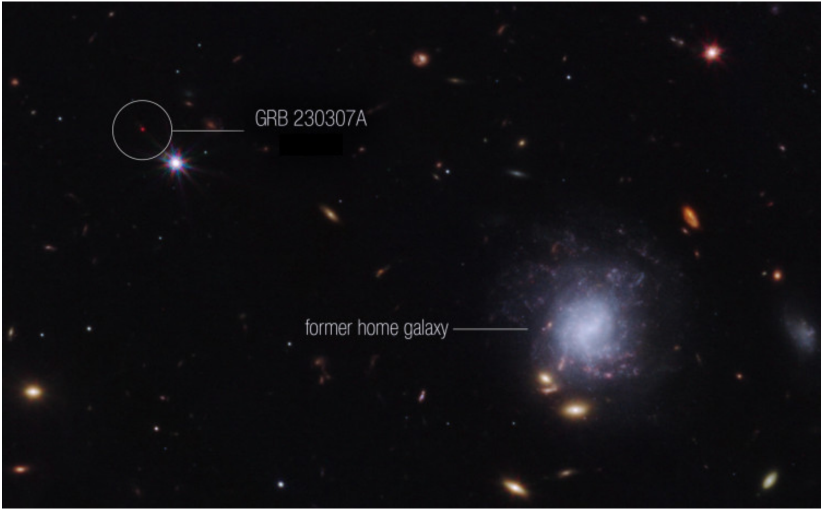


[Hajela et al. 2021]

NS-NS and BH-NS post-merger

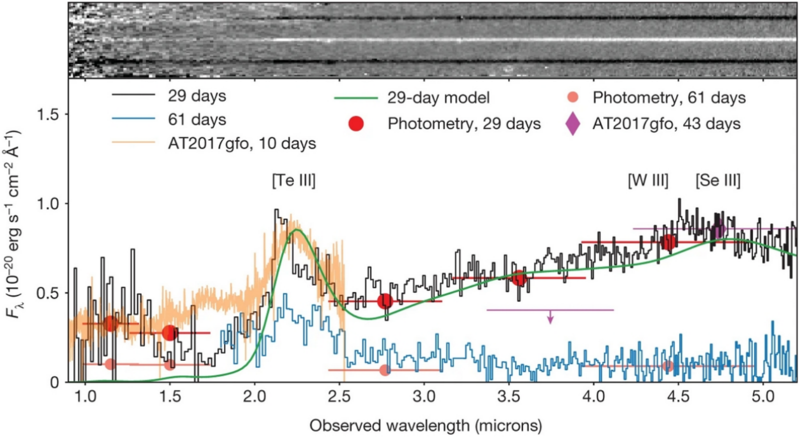


GRB 230307A: large galactic offset



[Levan et al. 2023]

GRB 230307A: evidence of KN in nebular phase



[Levan et al. 2023]

Summary 1

- Gamma-ray bursts produced in relativistic jets; some from aftermath of binary neutron star mergers
- Blandford-Znajek process (spinning BH + magnetized accretion disk) main jet-launching mechanism candidate
- proto-NS central engine not ruled out yet
- if jet driven by accretion, efficiency not very high: in Blandford-Znajek setting, this implies predominantly toroidal magnetic field right after merger;
- to produce observable emission,the jet must break out from the ejecta cloud. In doing so it is reshaped and it deposits part of its energy in a cocoon
- prompt emission mechanism not well understood: magnetic vs kinetic? sub-photospheric vs optically thin dissipation?
- afterglow produced in shock that arises as the jet expands into ISM;

Summary 2

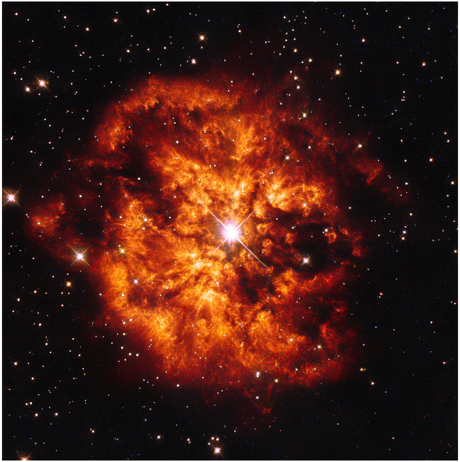
- GW170817 prompted huge improvement in understanding of GRB jets (e.g. superluminal motion confirmed relativistic and collimated nature; role of jet structure highlighted);
- GW-GRB delay in GW170817 may indicate long-lived neutron star, but may also be just dominated by propagation effects
- GW170817 jet is only known example of a clearly off-axis GRB jet

Thank you!

Backup slides

Gamma-ray burst progenitors

"Long" GRB

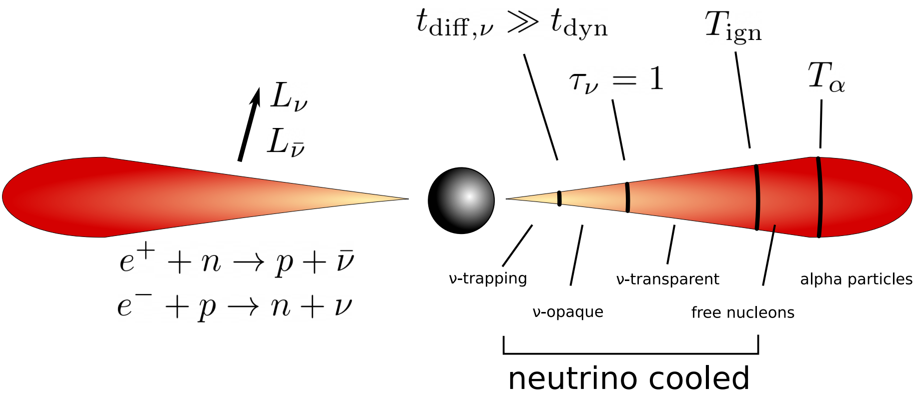


Core-collapse of massive star
[Woosley 1993]

"Short" GRB

Merger of neutron-star-harbouring compact binary
[Eichler et al. 1989]

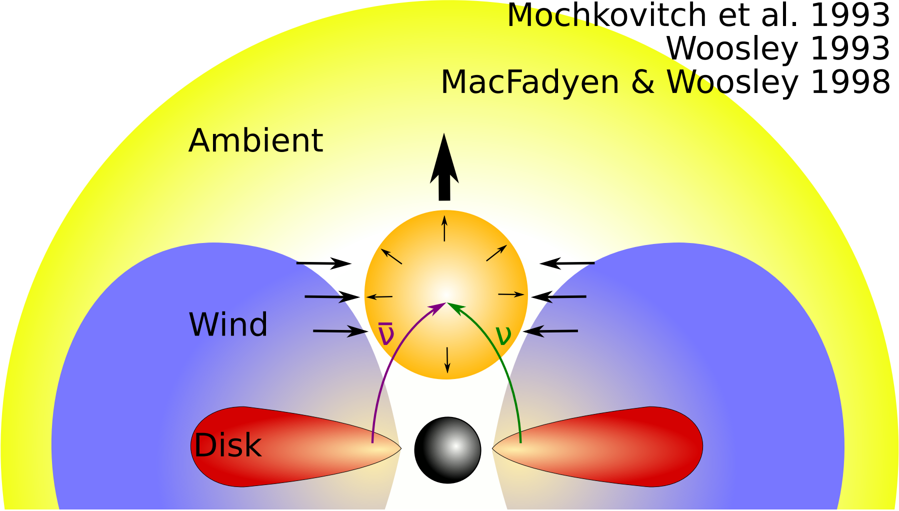
Neutrino-antineutrino annihilation process



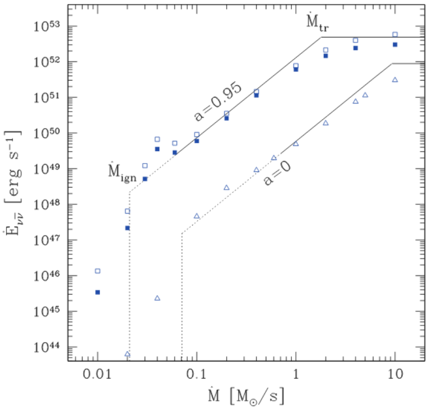
[Eichler et al. 1989, Mochkovitch et al. 1993, Chen & Beloborodov 2007]

Neutrino-antineutrino annihilation process

Eichler et al. 1989
Mochkovitch et al. 1993
Woosley 1993
MacFadyen & Woosley 1998



$\nu\bar{\nu}$ annihilation luminosity



$$L_{\rm jet,\nu\bar{\nu}} \propto r_{\rm ISCO}^{-24/5}\,\dot{M}^{9/4}\,M_{\rm BH}^{-3/2}$$

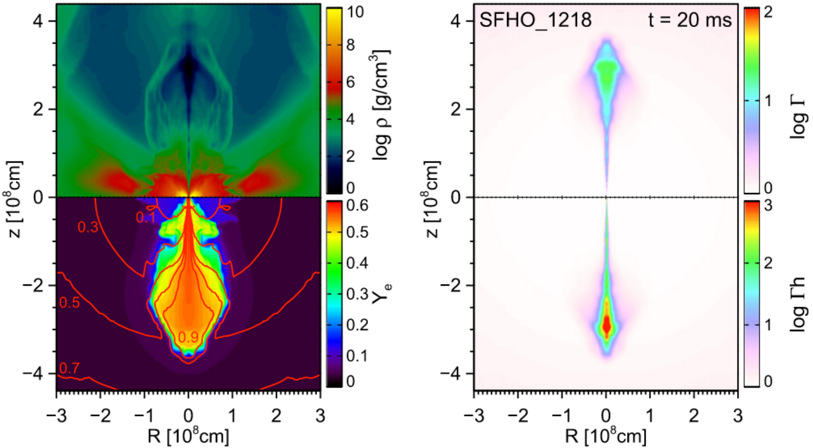
$$(\dot{M}_{\rm ign} < \dot{M} < \dot{M}_{\rm sat})$$

$$\dot{M}_{\rm ign} \sim \text{few} \times 10^{-2}\,{\rm M_\odot/s}$$

$$\dot{M}_{\rm sat} \sim \text{few} \times \,{\rm M_\odot/s}$$

[Zalamea & Beloborodov 2011 by GR ray tracing of ν & $\bar{\nu}$'s emitted according to neutrino-cooled accretion flow of Chen & Beloborodov 2007]

Global simulations of $\nu\bar{\nu}$ mechanism in short GRBs

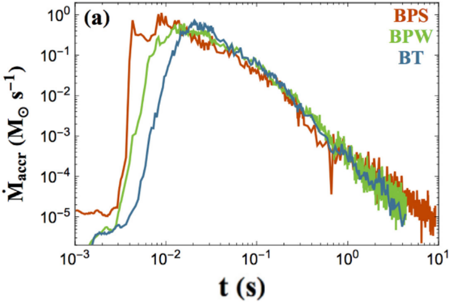


[Just et al. 2016]

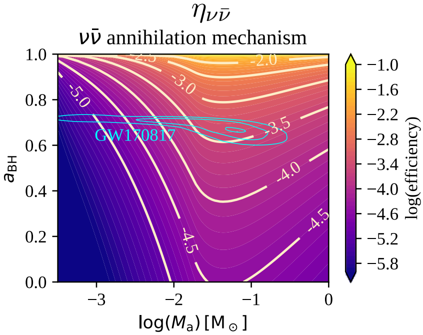
$\nu\bar{\nu}$ expected efficiency: short GRBs

Accretion rate time evolution:

$\dot{M} \propto t^{-2}$

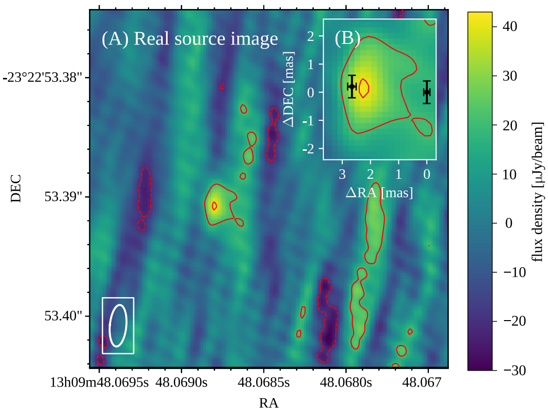


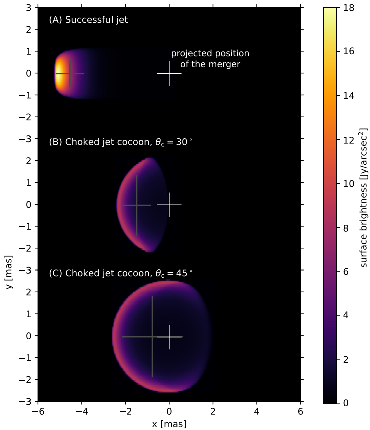
[Christie et al. 2019]



[Salafia & Giacomazzo 2020]

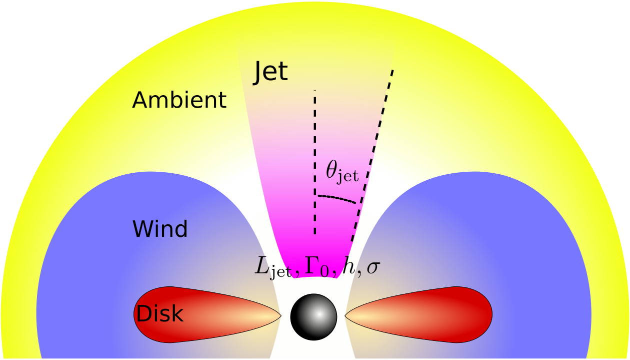
GW170817: solid off-axis jet evidence





[Mooley et al. 2018, Ghirlanda et al. 2019]

Jet properties at launch

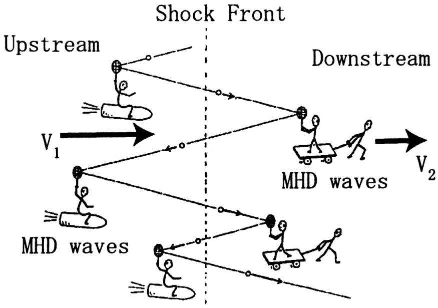


$$L_{\rm jet} = \pi\theta_{\rm jet}^2\beta_0 c\Gamma_0^2(h+\sigma)\rho c^2,\ h = 1 + \frac{e}{\rho c^2} + \frac{p}{\rho c^2},\ \sigma = \frac{B^2}{8\pi\rho c^2}$$

- Blandford-Znajek: $\sigma \gg h$ (Poynting-flux-dominated outflow)
- $\nu\bar{\nu}$ annihilation: $h \gg \sigma$ ("Fireball")

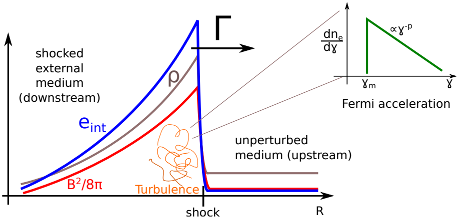
(note: reality much more nuanced)

Diffusive shock acceleration

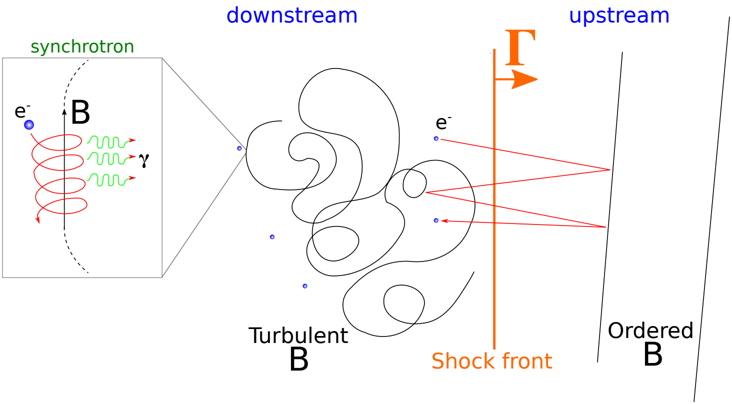


[Hoshino 2001, courtesy M. Scholer]

- collisionless shocks
- non-thermal particle pop. w. power law momentum distrib. (Fermi 1949)
- Need small-scale, random mag. field → turbulence



Synchrotron radiation



Inverse Compton radiation