Collapsars: Black Hole Properties, Magnetic Fields and r-process Nucleosynthesis

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ReFCO workshop, Warsaw

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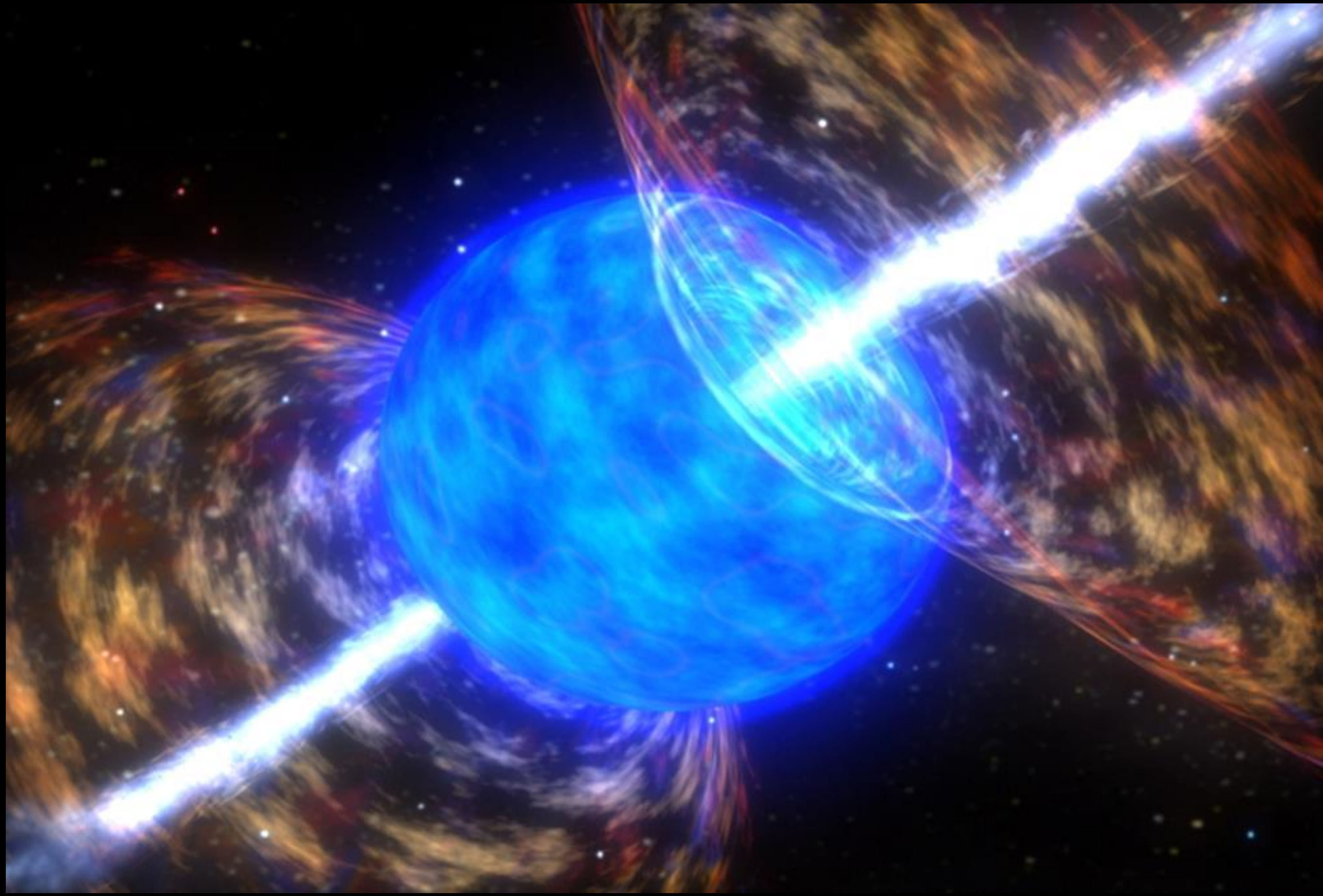
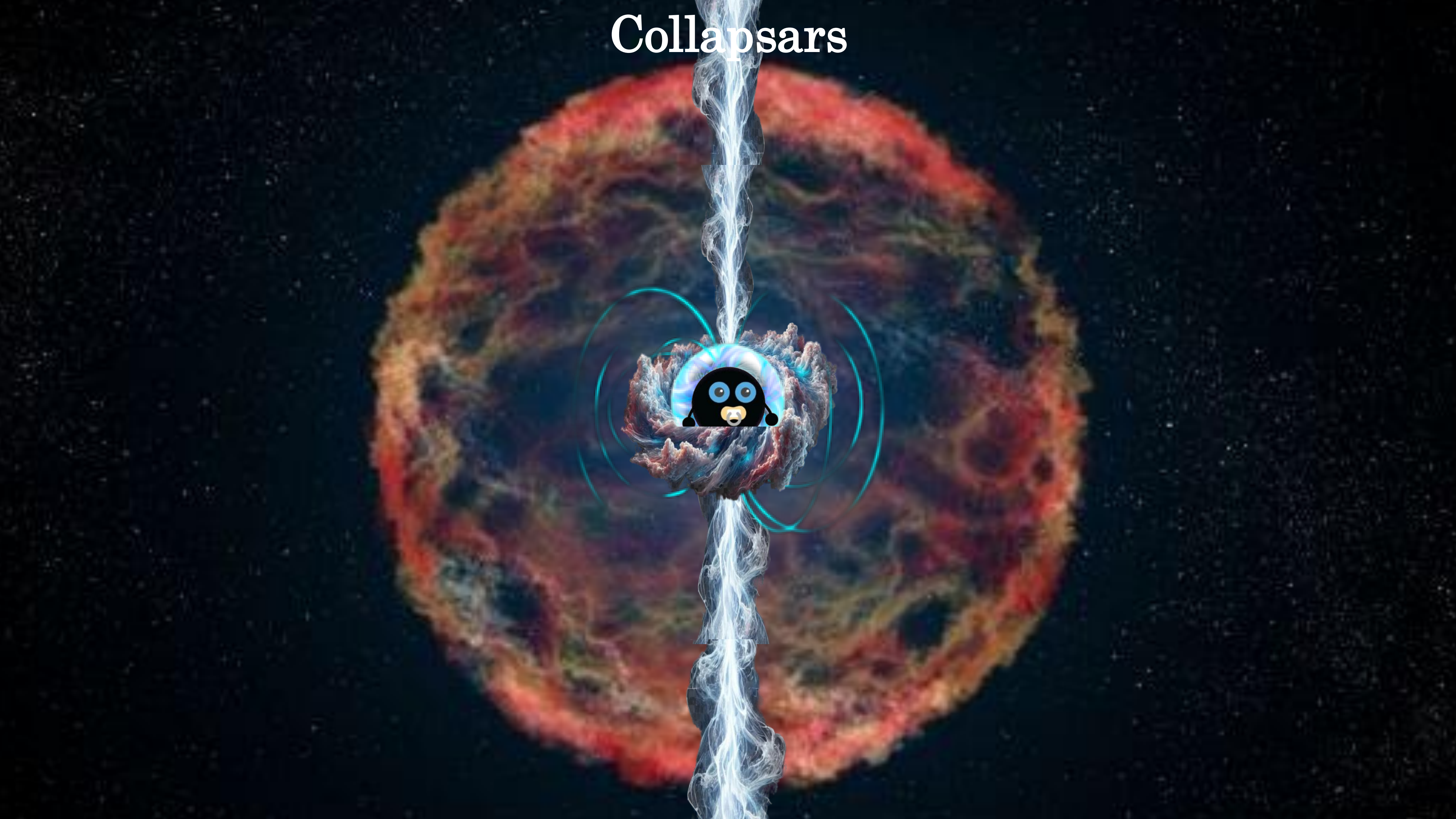
Collapsars

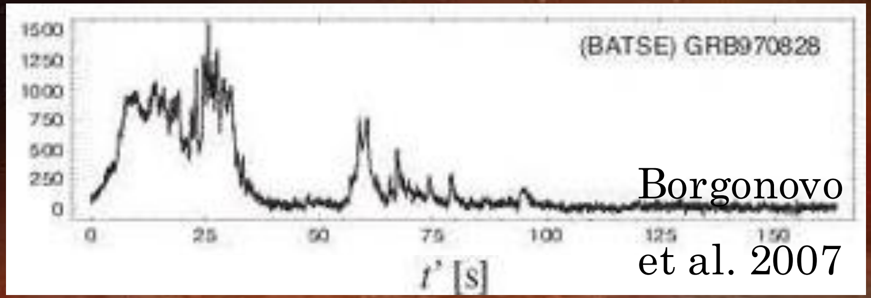
- Collapsars are progenitors of long GRBs (Woosley 1993)
- SN1998bw Ic-BL associated with GRB980425 (Iwamoto et al. 1998)
- First "collapsar" simulations (Woosley & MacFadyen 1999; Zhang et al. 2003)



Collapsars



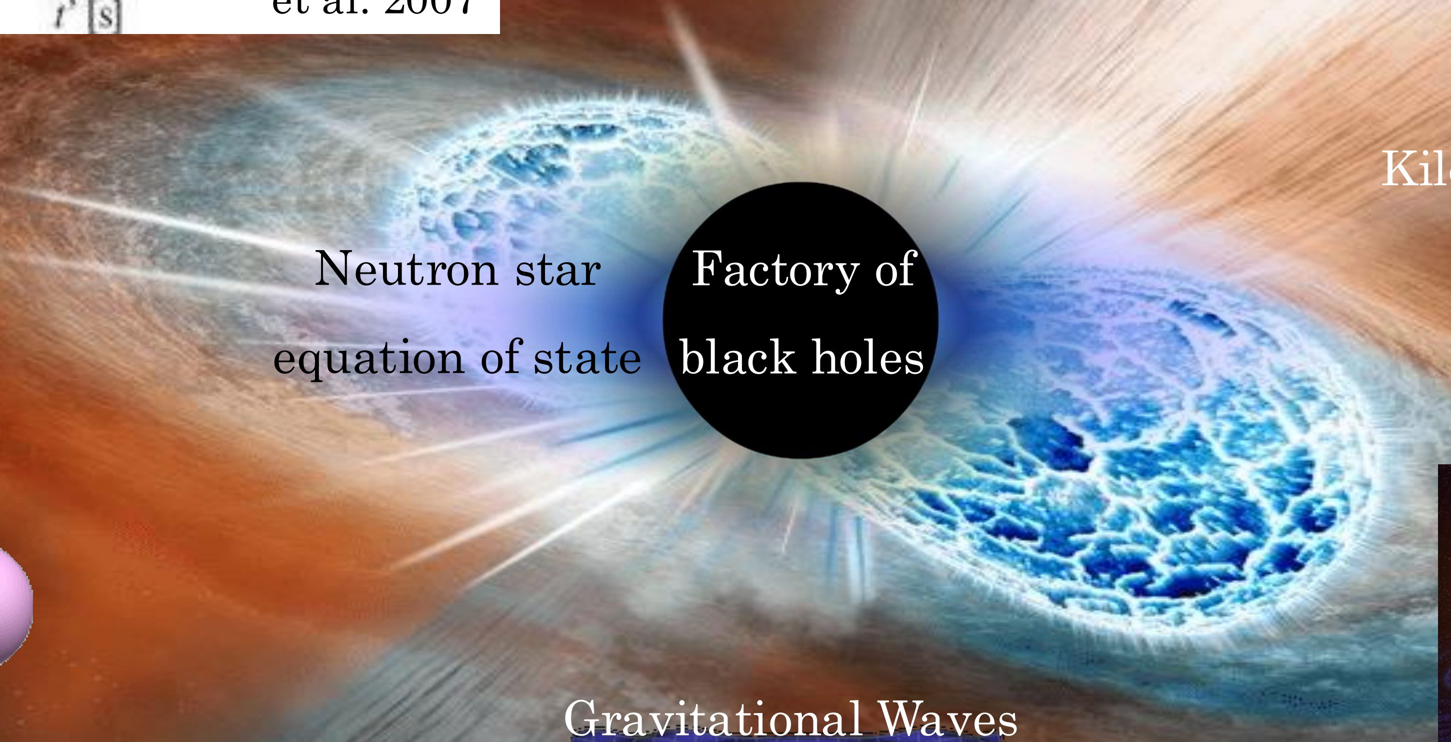
Plethora of Extreme Physics



Borgonovo et al. 2007

Jet labs

Kilonova → Heavy element nucleosynthesis



Neutron star equation of state

Factory of black holes

High-energy particles

Gravitational Waves

History of compact binaries

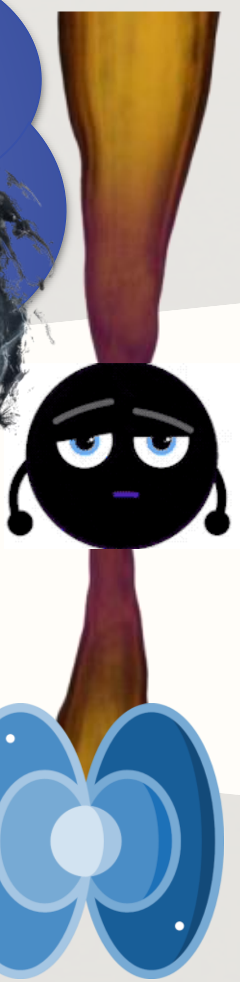
The Future of the Multi-messenger Universe

Gravity

LIGO-VIRGO-KAGRA 04/O5
Cosmic Explorer
Einstein Telescope
LISA

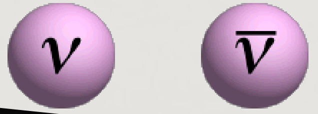
Electromagnetic

Rubin Observatory
Roman
JWST
WINTER
ULTRASAT
UVEX
SVOM

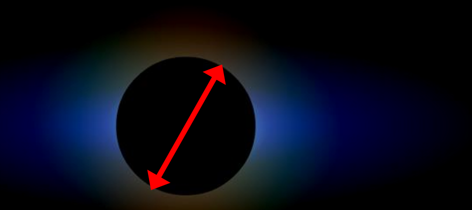


Particles

GCOS
IceCube-Gen2
Hyper-Kamiokande
DUNE
Grand10k

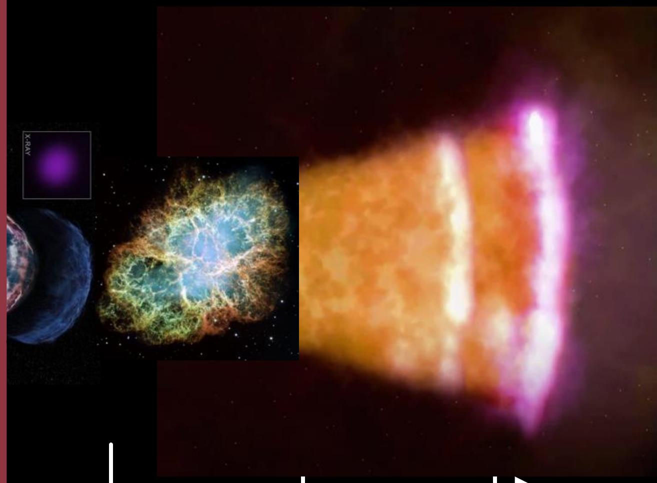


Scales of Transients



Challenge: 11 orders of magnitude in space and time between the black hole and the emission zone

Solution: 3D general-relativistic Magnetohydrodynamic+neutrino transport simulations from the black hole to photosphere



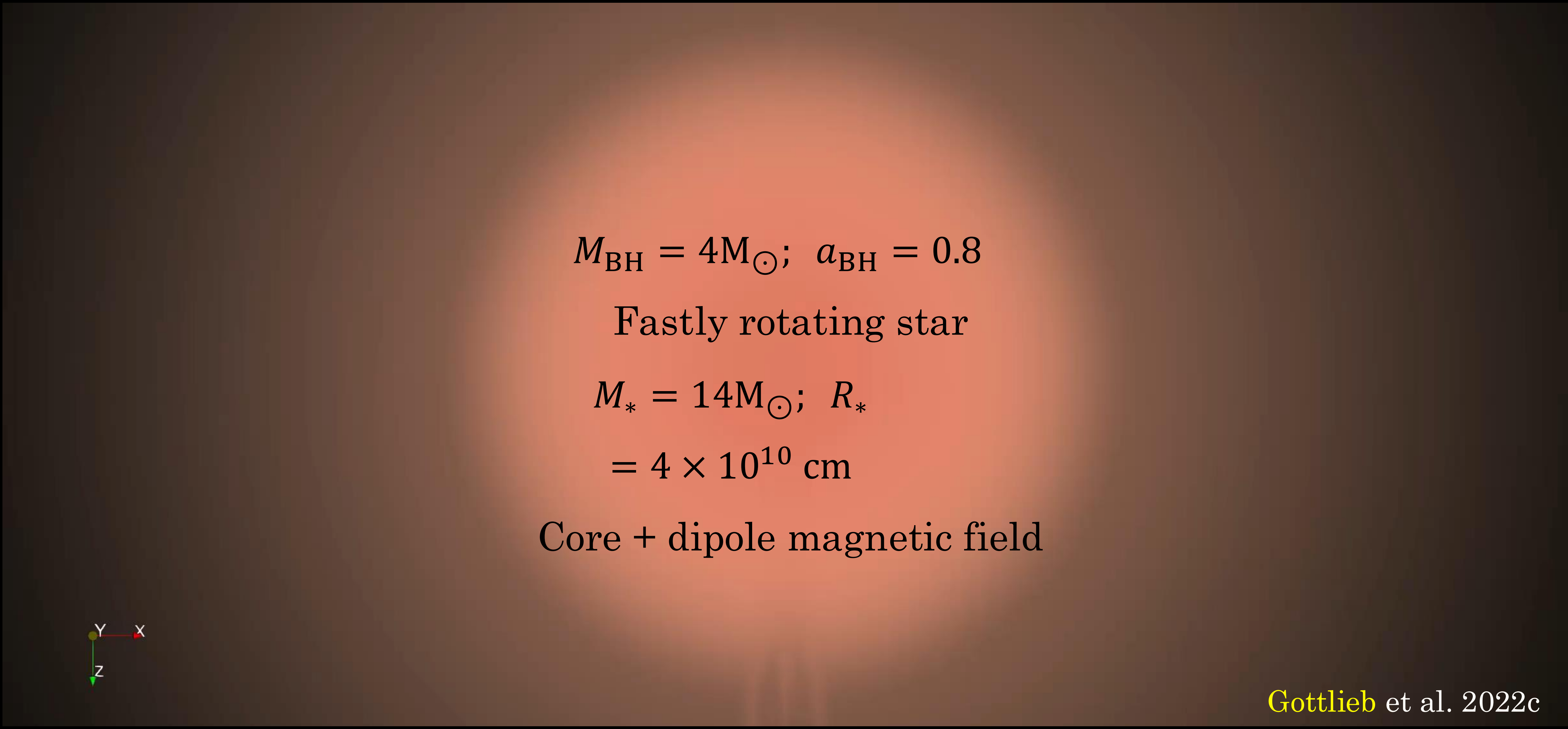
1 ms

week

1 year

1. Interpret observations from first-principles
2. Use observations to probe extreme physics
3. Predict new multi-messenger sources

Dancing Jets



$M_{\rm BH} = 4{\rm M}_\odot$; $a_{\rm BH} = 0.8$

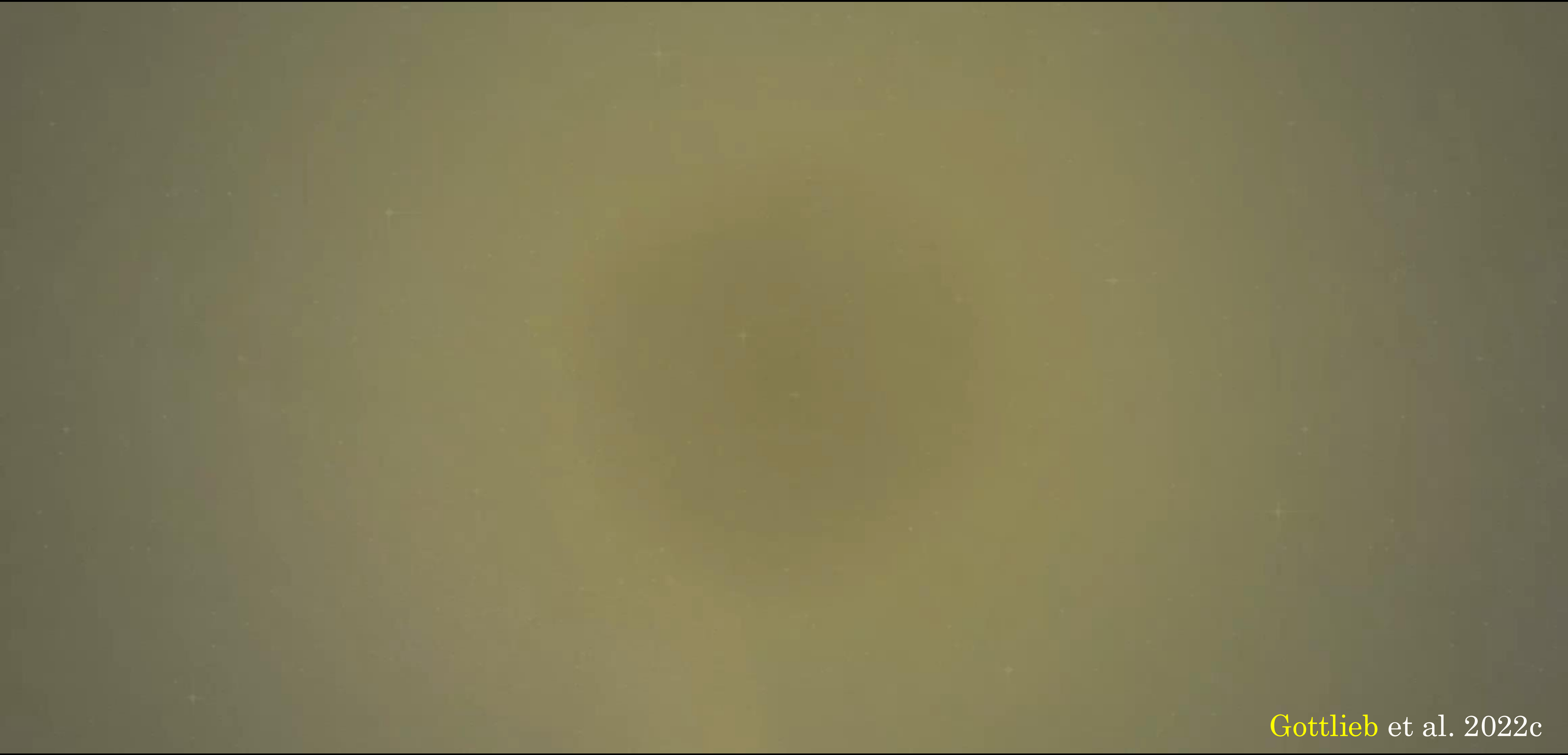
Fastly rotating star

$M_* = 14{\rm M}_\odot$; $R_* = 4 \times 10^{10}$ cm

Core + dipole magnetic field

Gottlieb et al. 2022c

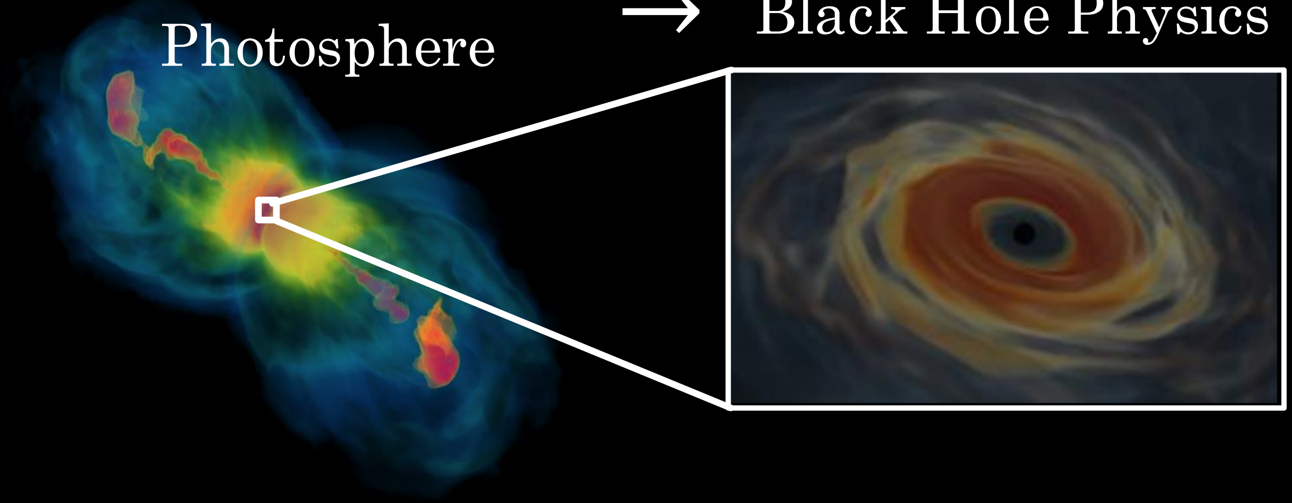
Dancing Jets

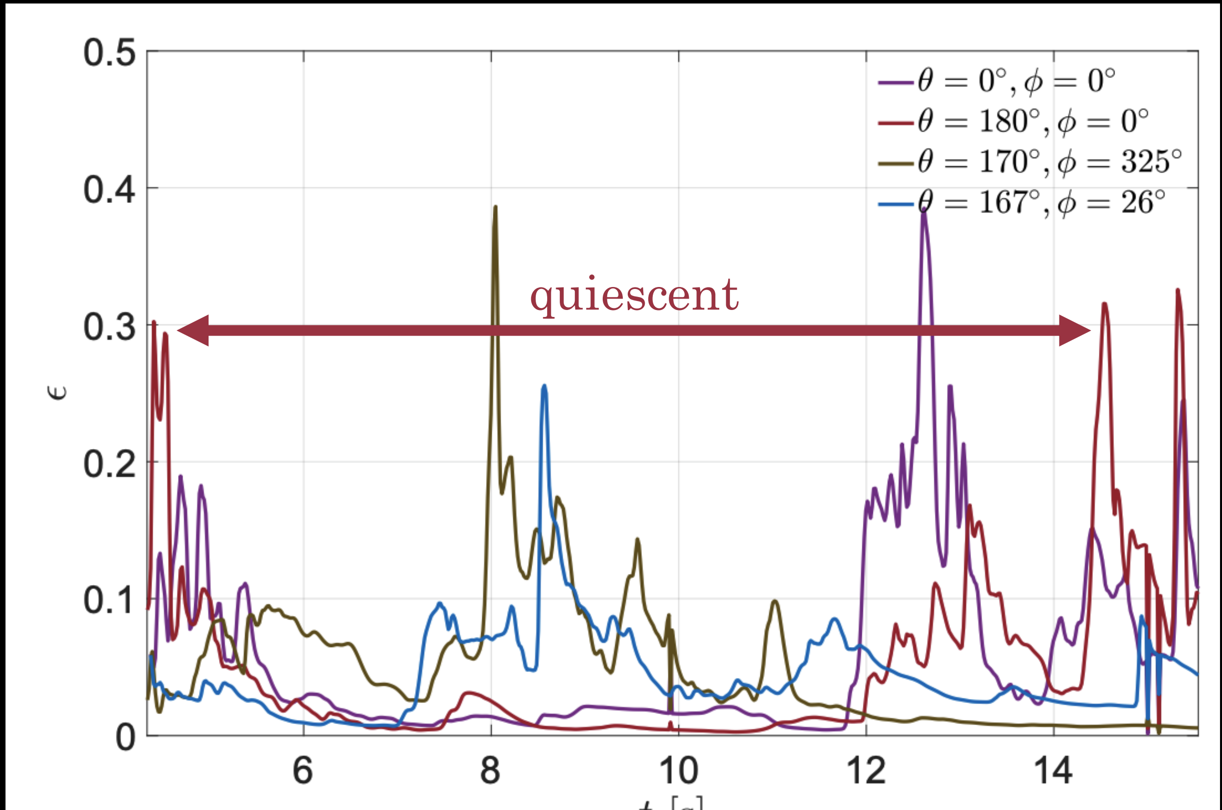


Gottlieb et al. 2022c

1. Interpret observations from first-principles: New Jet Physics

Observations from Photosphere → Black Hole Physics



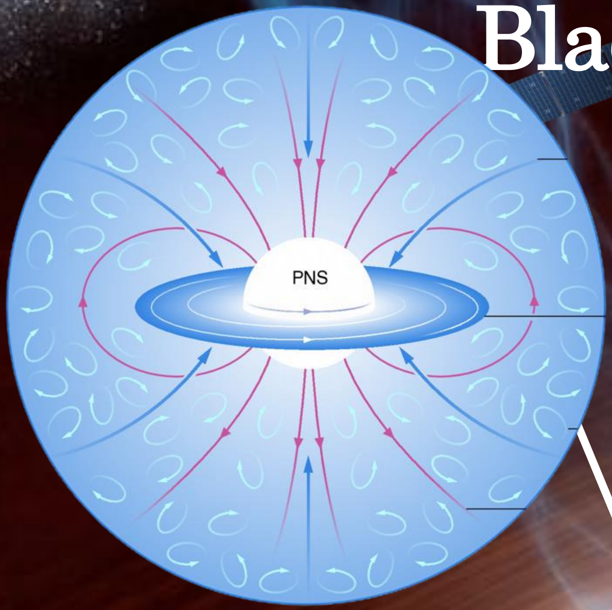


Gottlieb et al. 2022c

- ✓ Deciphering observations: quiescent times
- ❑ Wobbling imprint on GRB afterglows
- ❑ GRB emission mechanism

2. Use observations to probe extreme physics: Black Holes

- ✓ BH spin
- ✓ BH magnetic field
- ❑ BH kick
- ❑ BH mass
- ❑ Correlations

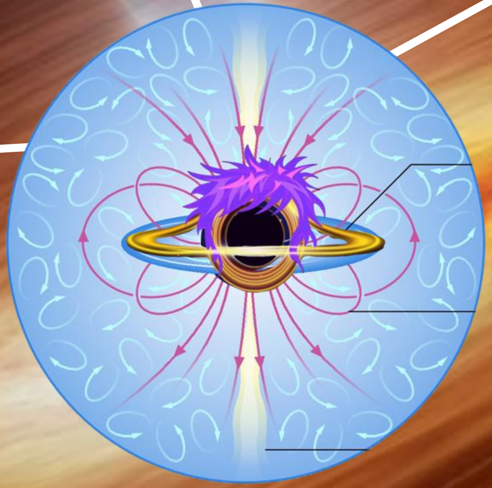


$$t_{bald} \sim 500 \frac{r_g}{c}$$

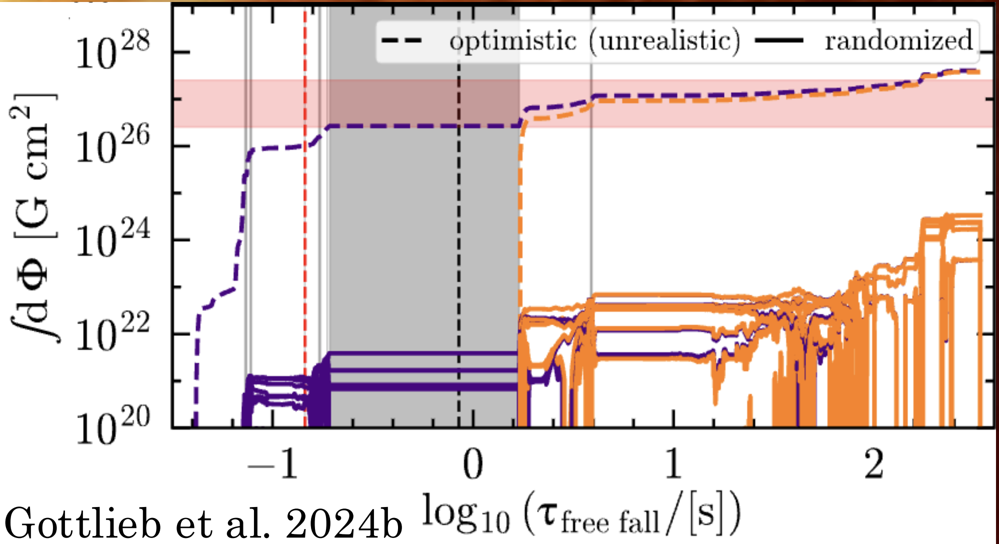
$$t_{visc} \sim 600 \left(\frac{0.1}{\alpha_{vis}}\right)\left(\frac{h/r}{0.3}\right)^{-2}\left[\frac{R_A(B, \dot{M}, R_{NS})}{3\, r_g}\right]^{1.5}\frac{r_g}{c}$$

Spin-down to $a \approx 0.1$
(Jacquemin-Ide, Gottlieb et al. 2023)

Black holes are born with $0.2 < a < 0.5$
(Gottlieb et al. 2023b)



Gottlieb et al. 2024b



Gottlieb et al. 2024b

But this requires extreme magnetic fields!

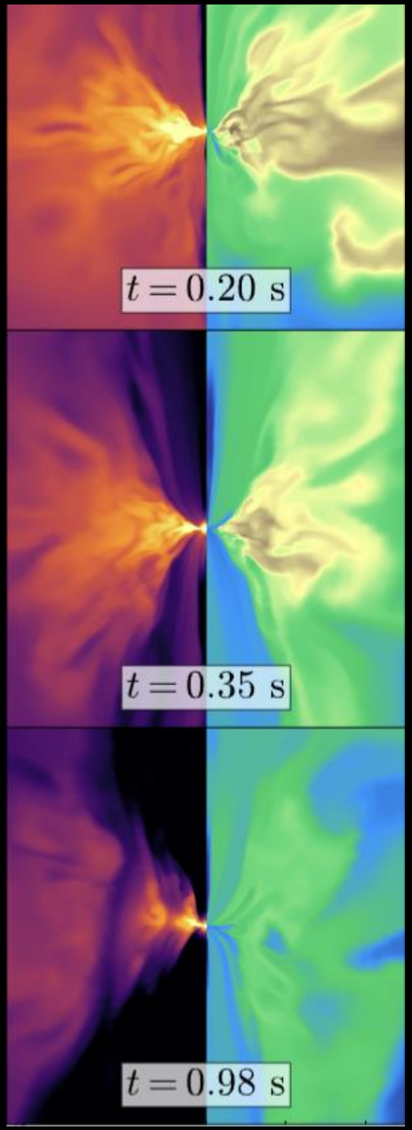
3. Predict new multi-messenger sources: Collapsar Kilonovae

Need for additional rare r-process generating events (Ji et al. 2016; Côté et al. 2019)

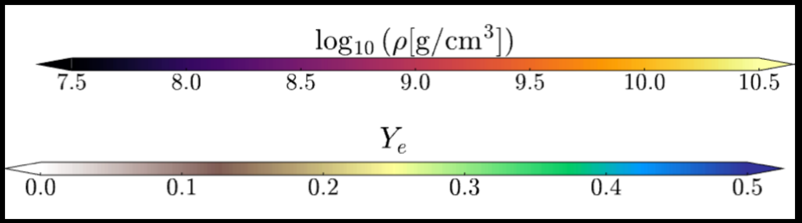
Recipe for expelling r-process elements from collapsing stars

1. Prepare a disk: $r_{\rm circ} > r_{\rm ISCO}$
2. Neutronize it: $\dot{M} > 0.07 \left(\frac{\alpha_{\rm eff}}{0.1}\right)^{\frac{5}{3}} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} M_\odot\ {\rm s}^{-1}$
3. Eject the neutron-rich gas: $\phi \equiv \frac{\Phi}{\sqrt{\dot{M} r_g^2 c}} > 10$

- ❑ r-process in realistic stars
- ❑ r-process yields
- ❑ Kilonova light curve

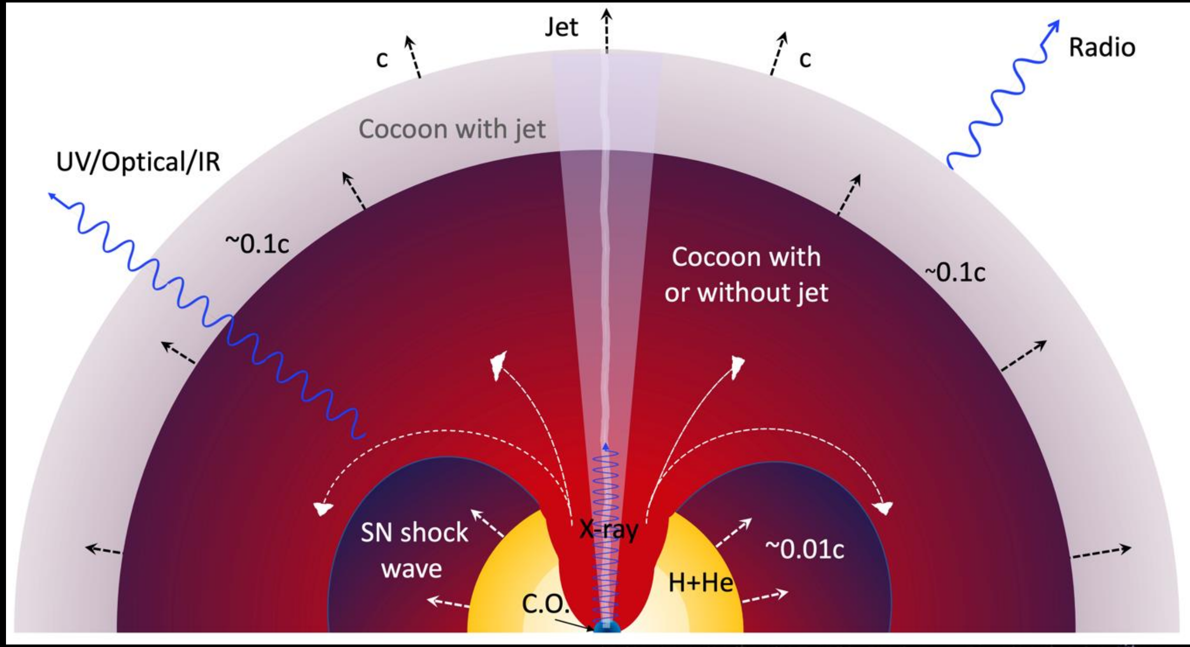


Issa, Gottlieb et al. 2024



3. Predict new multi-messenger sources: Variety of Fast Transients

Gottlieb et al. 2022b

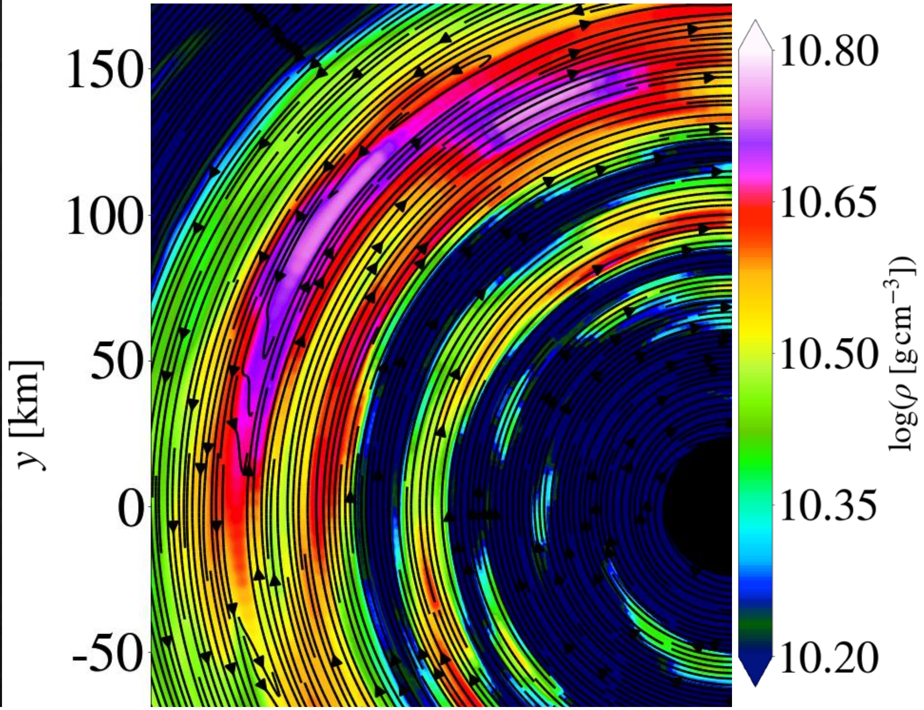


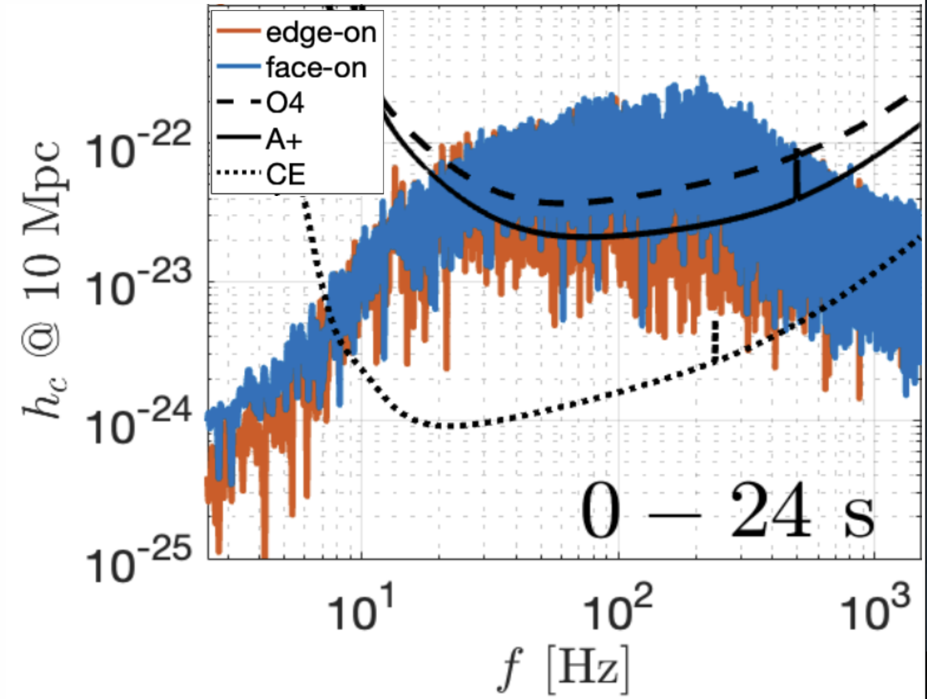
Jet-powered mildly-relativistic cocoons

Magnetic-driven disk mildly-relativistic outflows

Justin Bopp

Bopp & Gottlieb 2025





3. Predict new multi-messenger sources: Gravitational waves from Disks

$$f_{GW} = \frac{\tilde{m}\Omega}{2\pi} = \frac{\tilde{m}}{2\pi}\sqrt{\frac{GM_{BH}}{R_d^3}}$$

Gottlieb et al. 2024a

Collapsars

- Progenitors of long gamma-ray bursts
- Production sites of magnetars
- Production sites of black holes
- Potential sources of r-process elements
- Sources of a variety of transients
- Sources of gravitational waves