Title: Bridging Physics and Multi-messenger Observations of Black Hole-Powered Events

Speakers: Ore Gottlieb

Collection/Series: Strong Gravity

Subject: Strong Gravity

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Abstract:

With upcoming LIGO runs and new projects like LSST and ULTRASAT, black hole (BH)-powered multi-messenger events will be at the forefront of astrophysics. A major challenge in studying BH-powered explosions is the vast dynamical range between the BH and the emission site, which has hindered theoretical models from capturing the underlying physics from observations. Using 3D neutrino-general relativistic magnetohydrodynamic simulations, I will present the first such models, introducing an innovative model that now enables us to link GRB classes in mergers to their central engines and binary merger origins. For collapsing stars, I will demonstrate how our simulations open new frontiers in astrophysics, including a novel idea of how nascent BHs acquire their strong magnetic fields, heavy element nucleosynthesis in supernovae, the evolution of relativistic jets, new types of transients, and predictions of new vigorous, coherent, non-inspiral gravitational wave sources that may already be detectable by LIGO. These insights will be crucial for extracting the physics of transients from future gravitational wave and electromagnetic detections.

Bridging Physics and Multi-messenger Observations of Black Hole-Powered Events

Ore Gottlieb

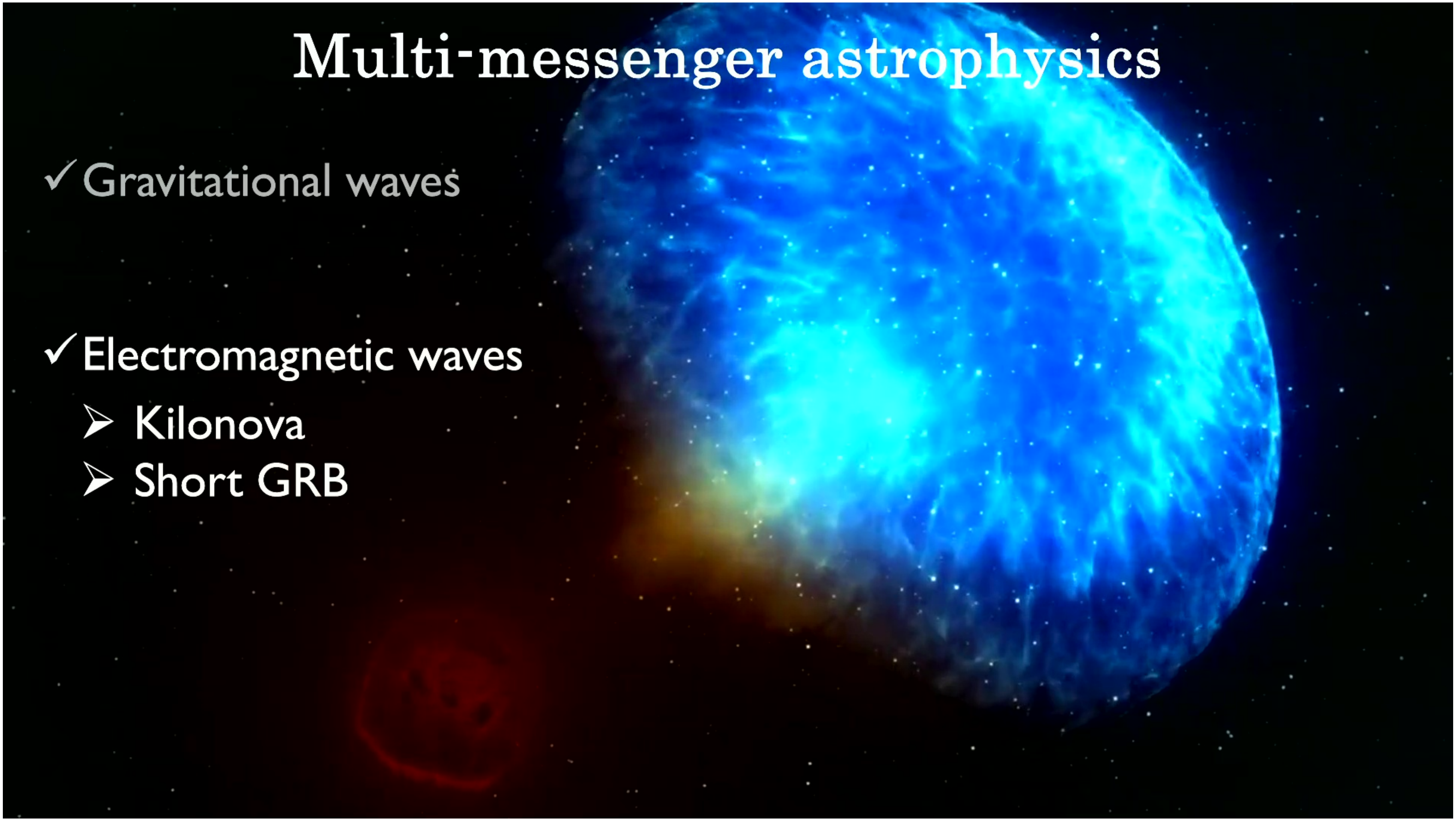
CCA, Flatiron Institute

Perimeter Institute 10/3/24

Multi-messenger astrophysics

✓ Gravitational waves

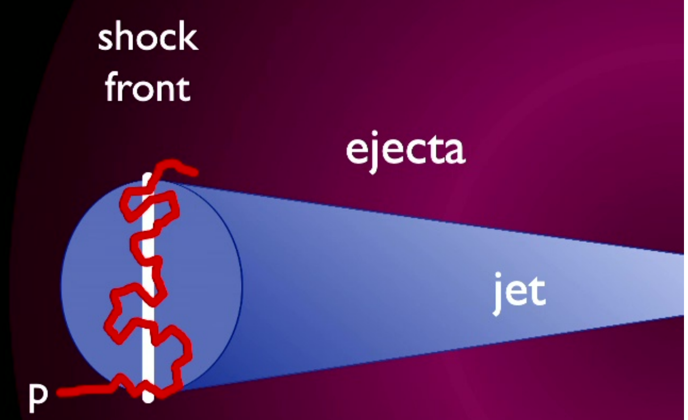
Multi-messenger astrophysics



- ✓ Gravitational waves
- ✓ Electromagnetic waves
  - ➢ Kilonova
  - ➢ Short GRB

Multi-messenger astrophysics

- ✓ Gravitational waves
- ✓ Electromagnetic waves
- ✓ Cosmic rays



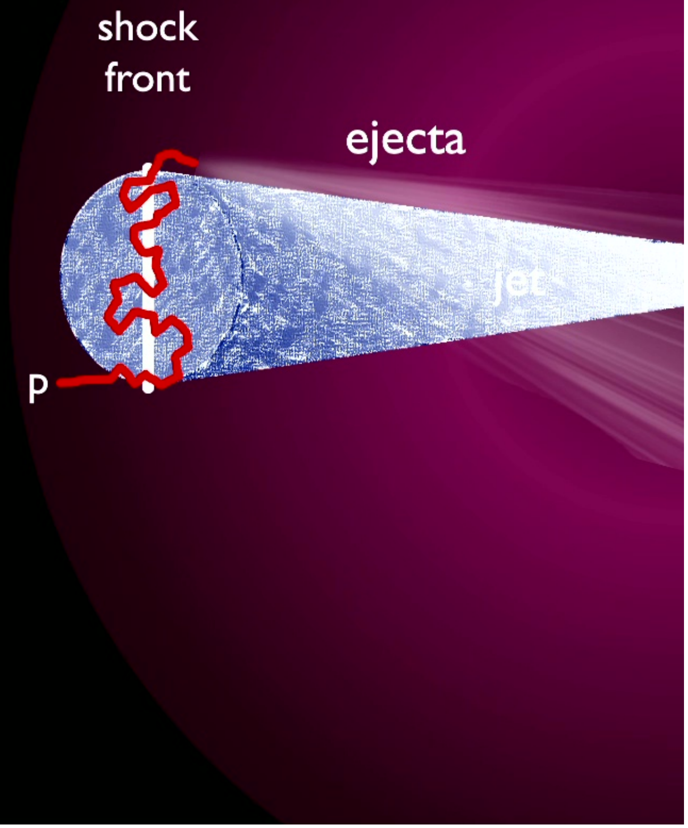
Multi-messenger astrophysics

✓ Gravitational waves

✓ Electromagnetic waves

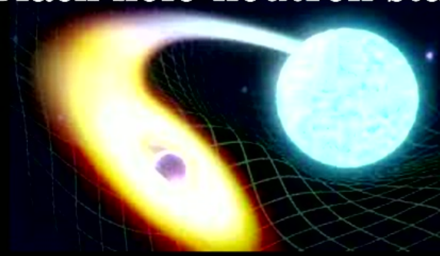
✓ Cosmic rays

✓ Neutrinos



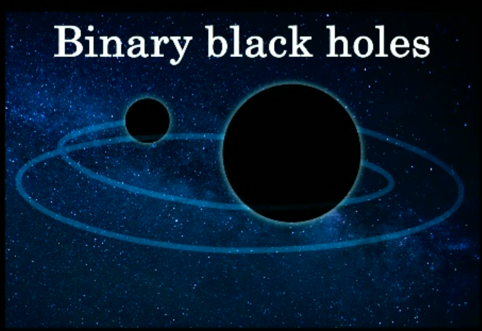
Stellar Black Holes

Black hole-neutron star



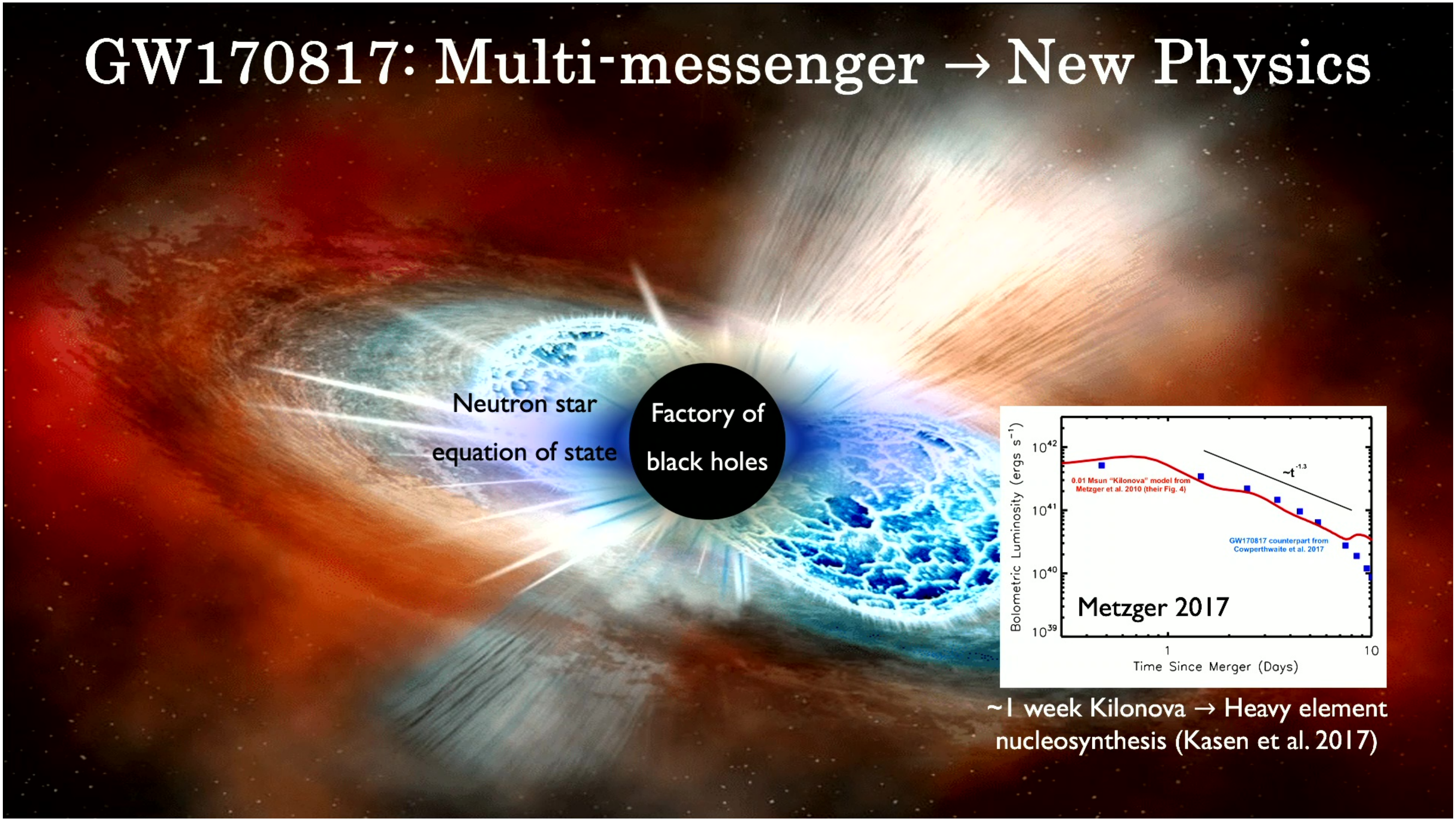
Unknown cataclysmic events

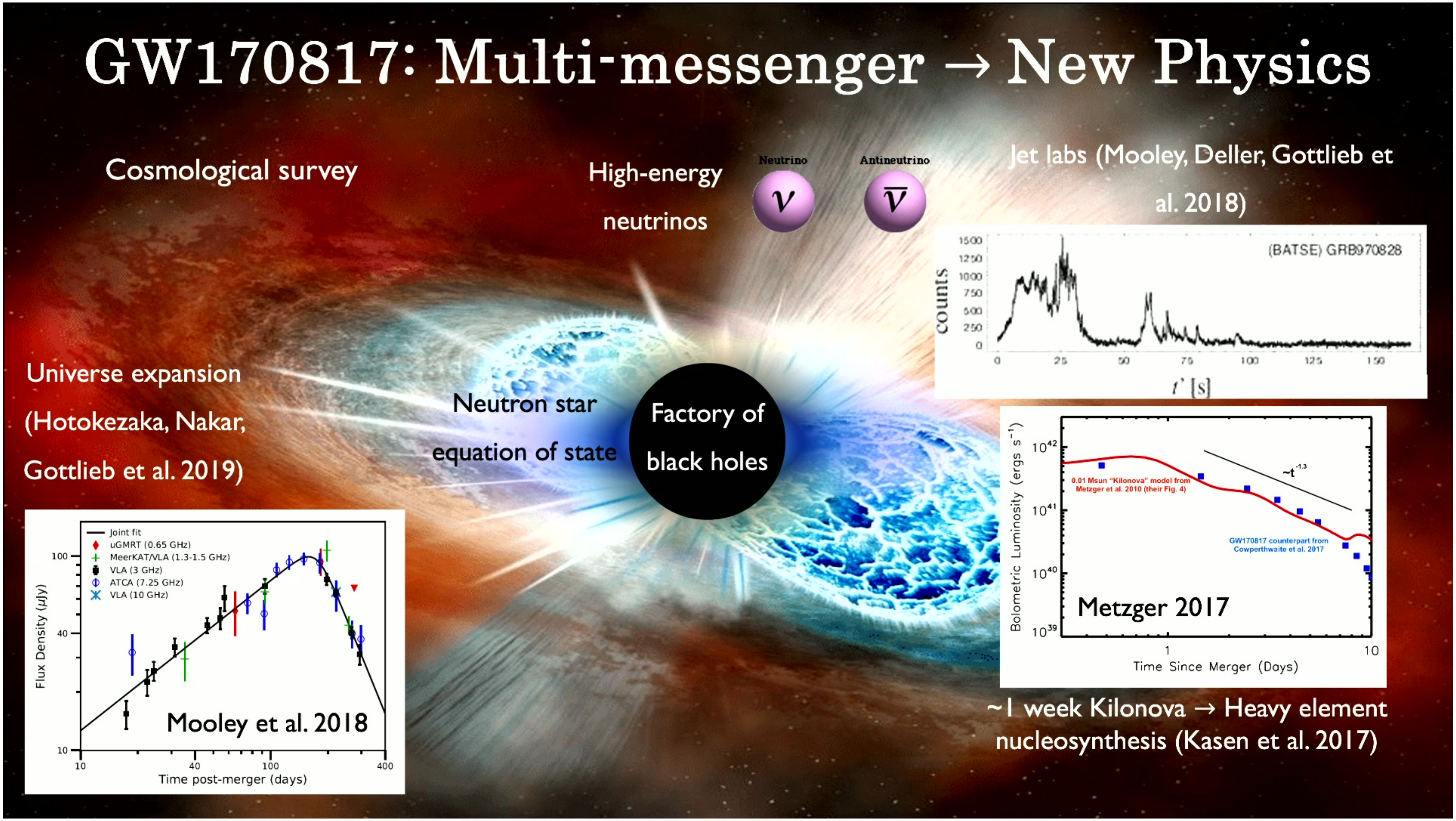
Binary black holes



Binary neutron stars

Supernovae


GW170817: Multi-messenger → New Physics
Neutron star
equation of state
Factory of
black holes
Bolometric Luminosity (ergs s^{-1})
10^{42}
10^{41}
10^{40}
10^{39}
1
10
Time Since Merger (Days)
$\sim t^{-1.3}$
0.01 Msun "Kilonova" model from Metzger et al. 2010 (their Fig. 4)
GW170817 counterpart from Cowperthwaite et al. 2017
Metzger 2017
~1 week Kilonova → Heavy element nucleosynthesis (Kasen et al. 2017)


GW170817: Multi-messenger → New Physics
Cosmological survey
High-energy neutrinos
Neutrino
Antineutrino
Jet labs (Mooley, Deller, Gottlieb et al. 2018)
(BATSE) GRB970828
counts
t' [s]
Universe expansion (Hotokezaka, Nakar, Gottlieb et al. 2019)
Neutron star equation of state
Factory of black holes
Bolometric Luminosity (ergs s⁻¹)
0.01 Msun "Kilonova" model from Metzger et al. 2010 (their Fig. 4)
GW170817 counterpart from Cowperthwaite et al. 2017
~t^-1.3
Metzger 2017
Time Since Merger (Days)
Joint fit
uGMRT (0.65 GHz)
MeerKAT/VLA (1.3-1.5 GHz)
VLA (3 GHz)
ATCA (7.25 GHz)
VLA (10 GHz)
Flux Density (μJy)
Mooley et al. 2018
Time post-merger (days)
~1 week Kilonova → Heavy element nucleosynthesis (Kasen et al. 2017)

Future of Multi-messenger Stellar Black Holes

Gravity

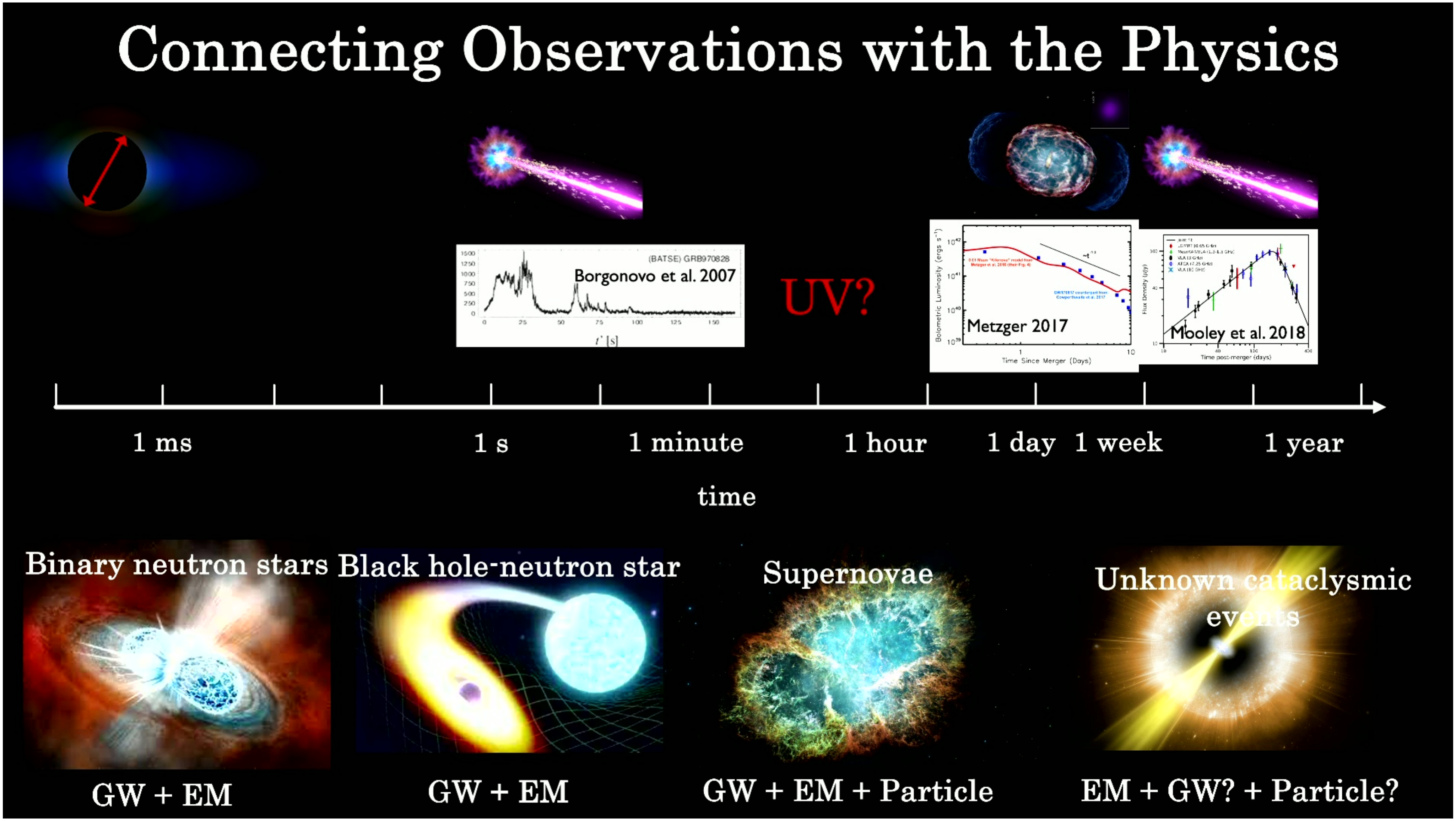
LIGO-VIRGO-KAGRA O4/O5
Cosmic Explorer
Einstein Telescope
LISA

Electromagnetic

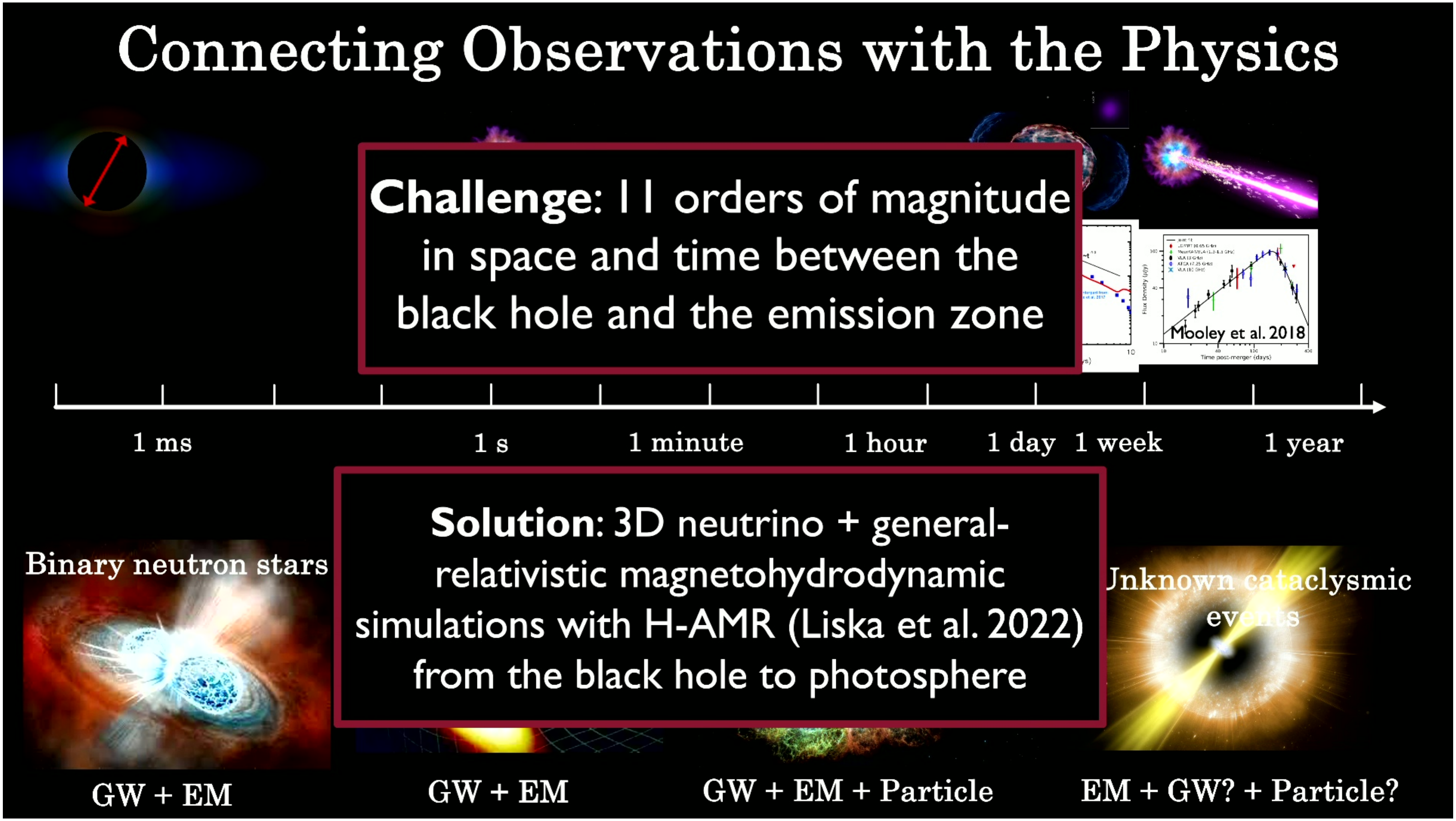
Rubin Observatory
ULTRASAT
UVEX
SVOM
ngVLA

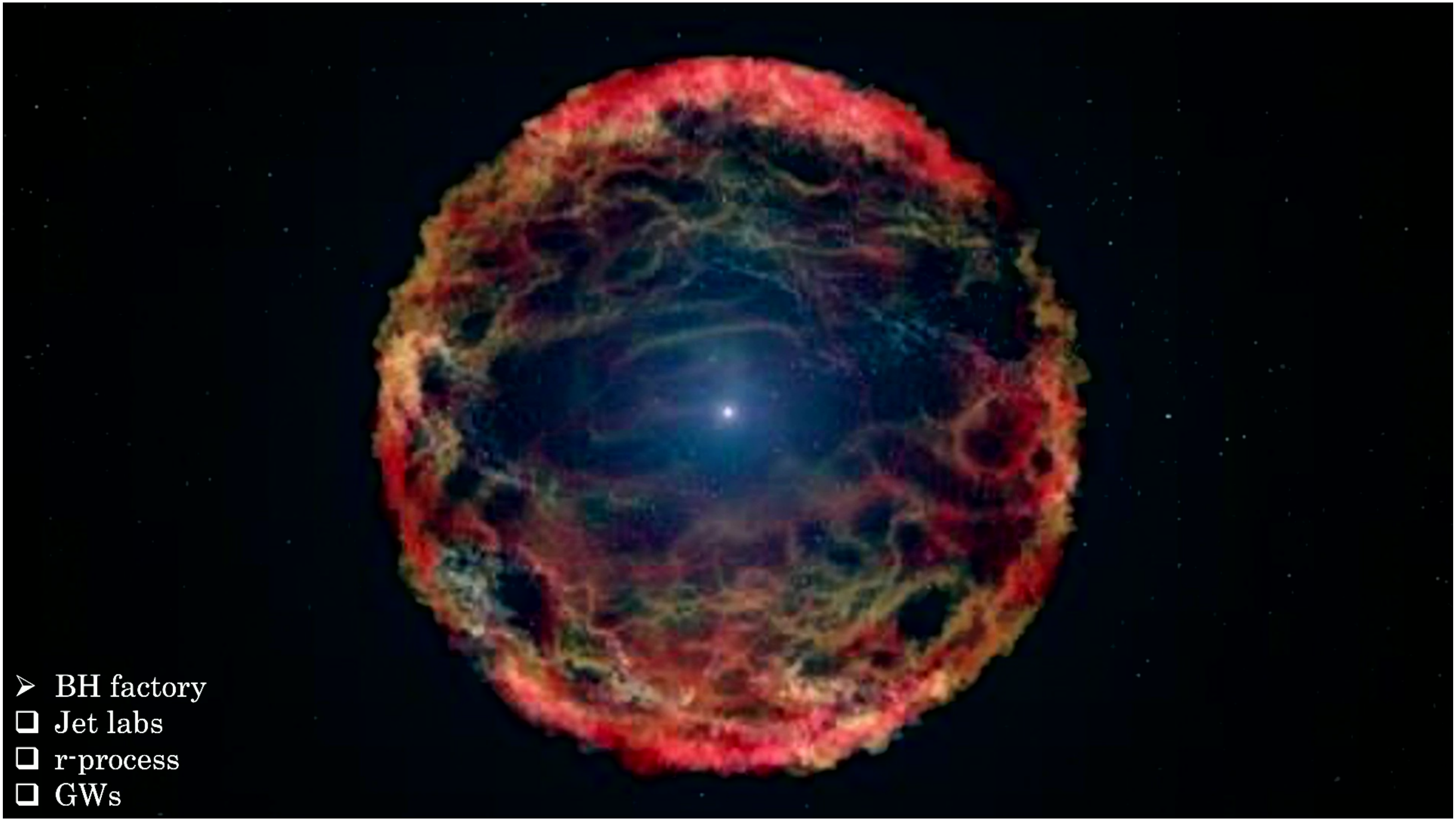
Particles

IceCube-Gen2
Hyper-Kamiokande
DUNE
Grand10k



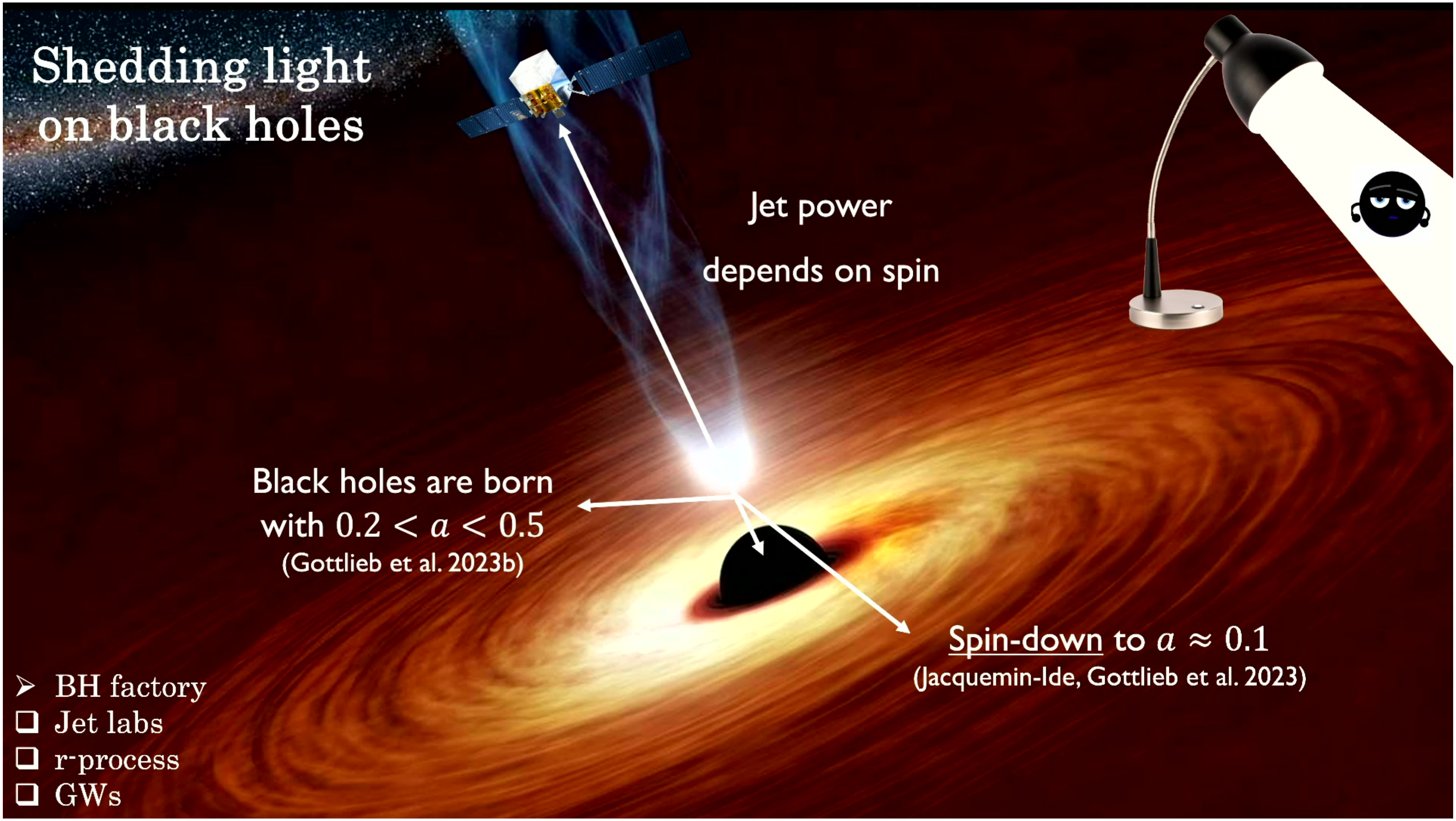
Connecting Observations with the Physics
Borgonovo et al. 2007
UV?
Metzger 2017
Mooley et al. 2018
1 ms
1 s
1 minute
1 hour
1 day
1 week
1 year
time
Binary neutron stars
Black hole-neutron star
Supernovae
Unknown cataclysmic events
GW + EM
GW + EM
GW + EM + Particle
EM + GW? + Particle?


Connecting Observations with the Physics
Challenge: 11 orders of magnitude in space and time between the black hole and the emission zone
Mooley et al. 2018
1 ms
1 s
1 minute
1 hour
1 day
1 week
1 year
Binary neutron stars
Solution: 3D neutrino + general-relativistic magnetohydrodynamic simulations with H-AMR (Liska et al. 2022) from the black hole to photosphere
Unknown cataclysmic events
GW + EM
GW + EM
GW + EM + Particle
EM + GW? + Particle?


➢ BH factory
❑ Jet labs
❑ r-process
❑ GWs

- Rotation (η_a)
- Strong B-fields (η_ϕ)

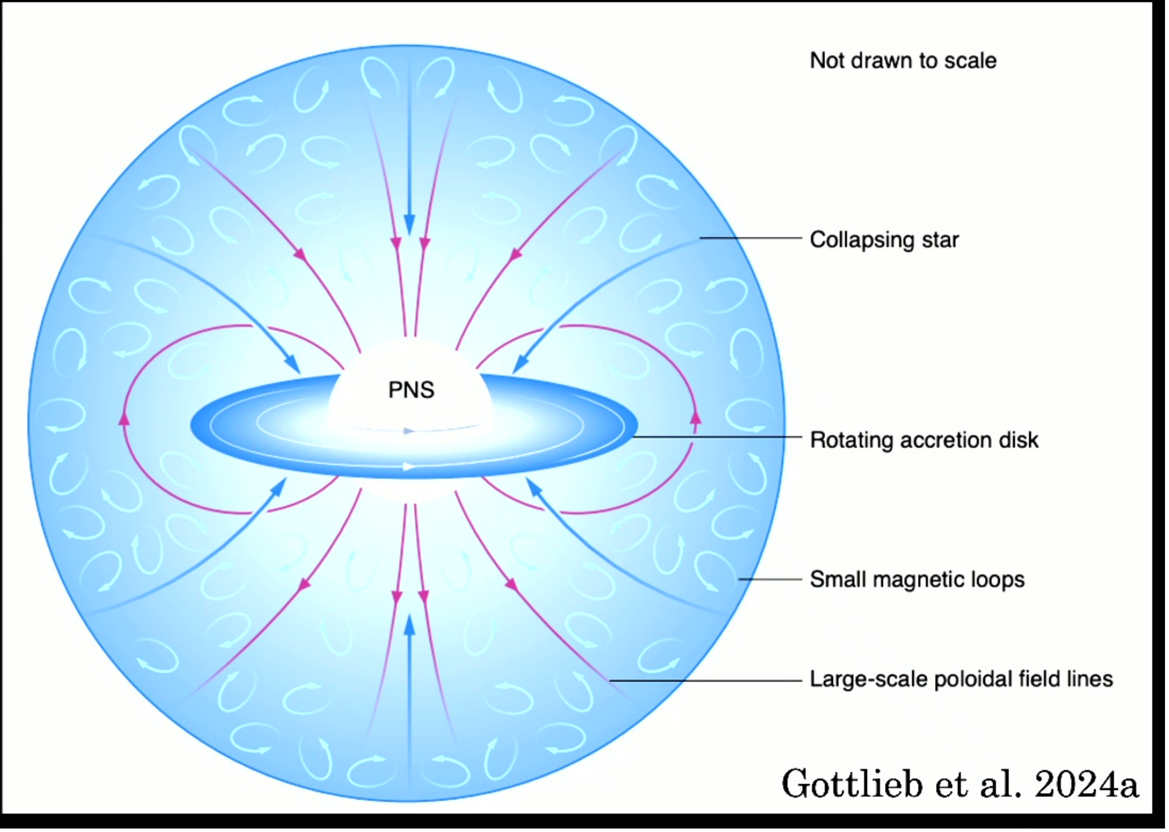
➢ BH factory
❑ Jet labs
❑ r-process
❑ GWs


Shedding light on black holes
Jet power depends on spin
Black holes are born with $0.2 < a < 0.5$
(Gottlieb et al. 2023b)
Spin-down to $a \approx 0.1$
(Jacquemin-Ide, Gottlieb et al. 2023)
➢ BH factory
❑ Jet labs
❑ r-process
❑ GWs

Origin of B-fields?

- Rapidly rotating models in MESA with $r_{circ} > r_{ISCO}$
- Tayler-Spruit (TS) dynamo
- Small scale random fields
- PNS field with $B \approx 10^{15}$ G

(Kaspi & Beloborodov 2017, Raynaud et al. 2020)



Gottlieb et al. 2024a

- ➢ BH factory
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- ❑ GWs

Origin of B-fields?

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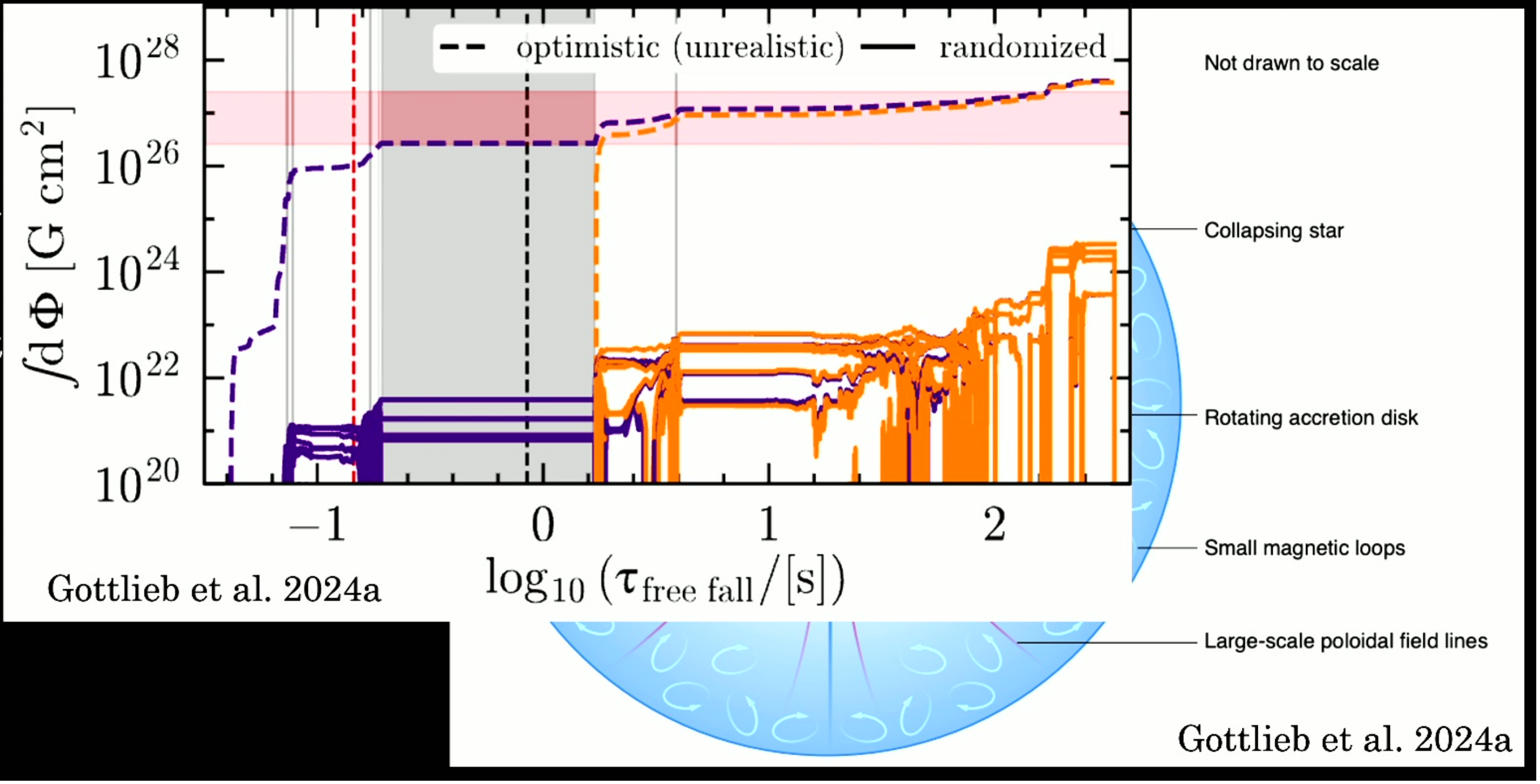
(Kaspi & Beloborodov



Gottlieb et al. 2024a

Gottlieb et al. 2024a

- ➢ BH factory
- ❑ Jet labs
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- ❑ GWs

She's got her mother's hair?

Black holes are balding (Most et al. 2024)

Can the black hole avoid balding?

$t_{bald} \sim 500 \frac{r_g}{c}$ (Bransgrove et al. 2021)

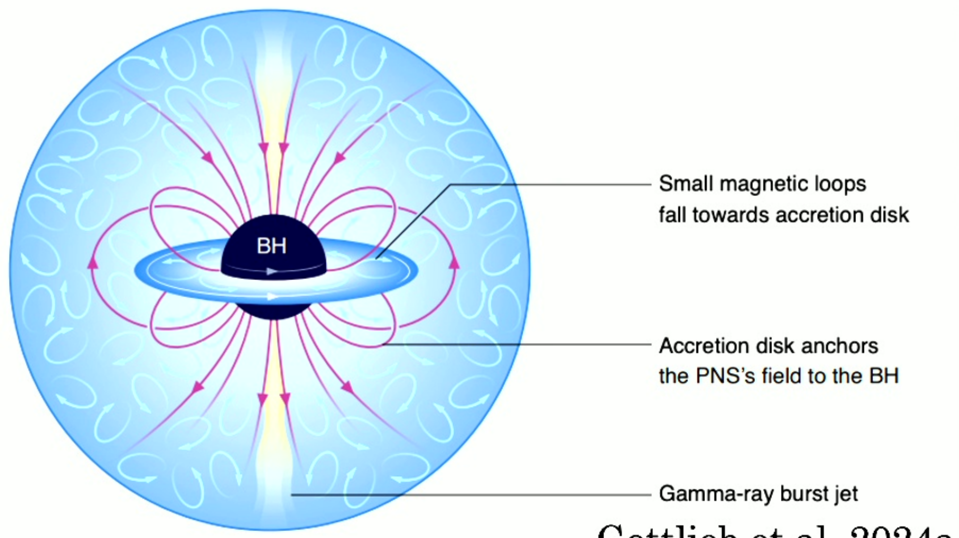
The PNS disk spreading from

$$R_A = 3 \left[\left(\frac{B}{10^{15}\ \mathrm{G}}\right)^2 \left(\frac{R_{NS}}{10\ \mathrm{km}}\right)^6 \left(\frac{\dot{M}}{M_\odot\ \mathrm{s}^{-1}}\right)^{-1} \right]^{2/7} \mathrm{km}$$

to the horizon on

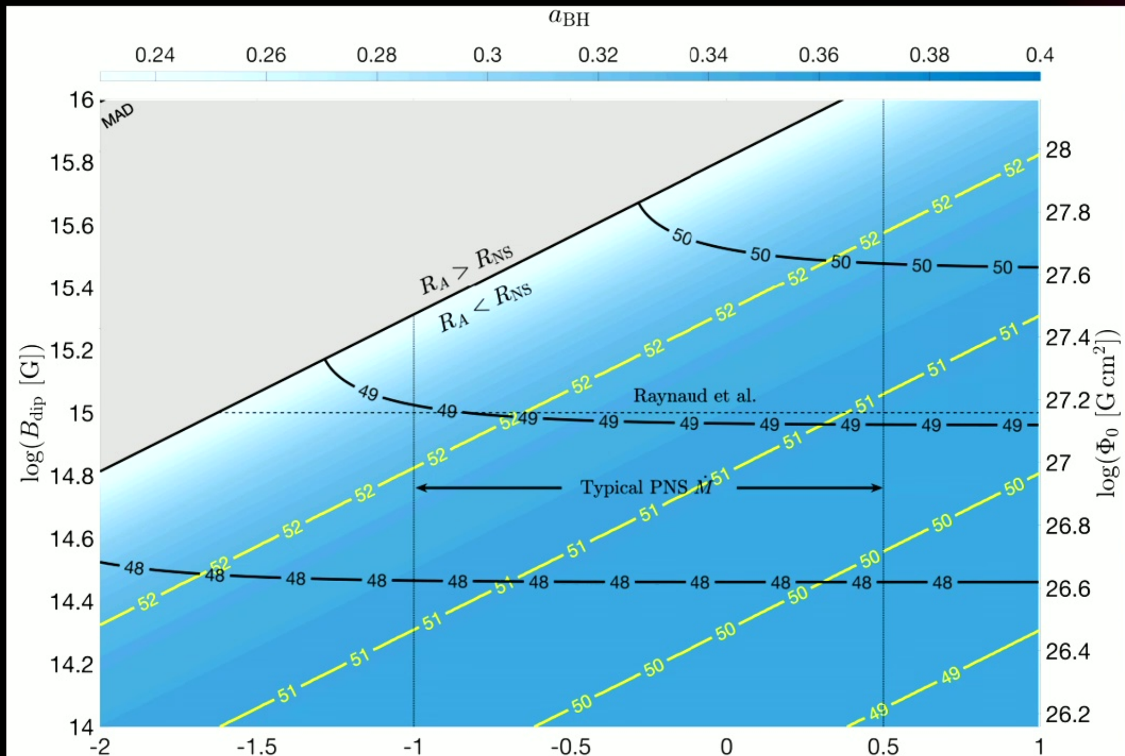
$$t_{visc} \sim 600 \left(\frac{0.1}{\alpha}\right) \left(\frac{h/r}{0.3}\right)^{-2} \left(\frac{R_A}{3\,r_g}\right)^{1.5} \frac{r_g}{c}$$

- ➢ BH factory
- ❑ Jet labs
- ❑ r-process
- ❑ GWs

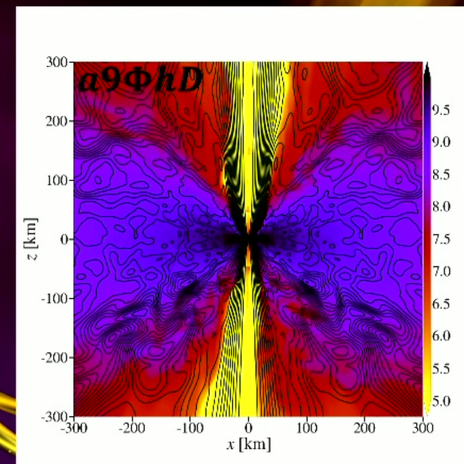


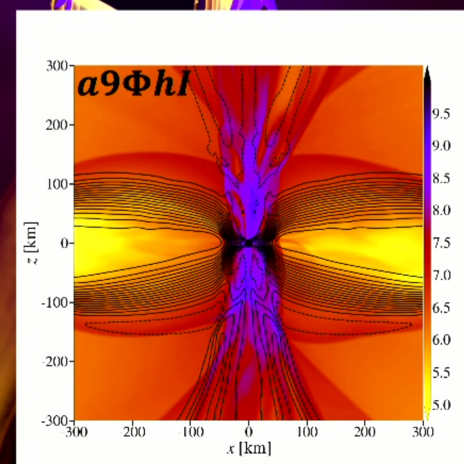
Gottlieb et al. 2024a

She's got her mother's hair!



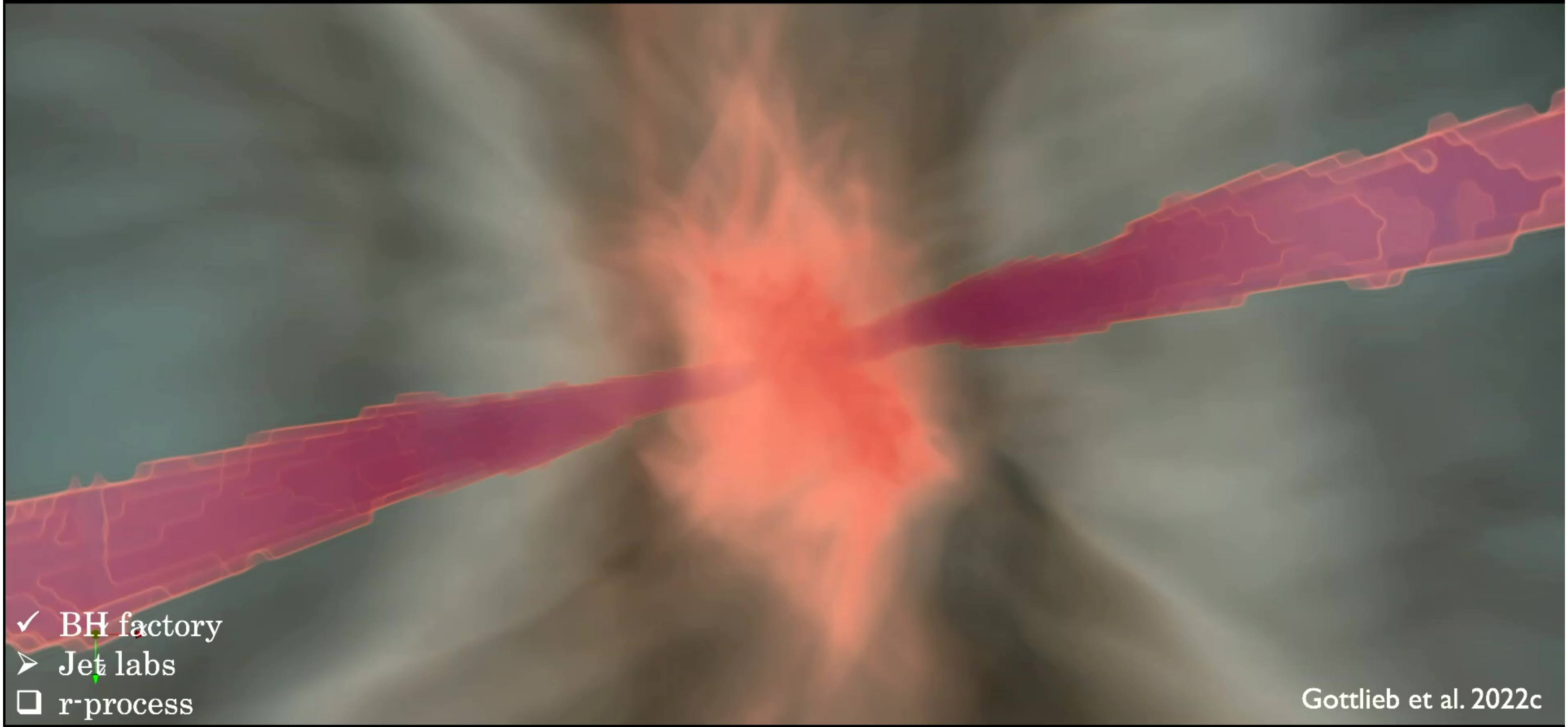
Gottlieb et al. 2024a





- ✓ BH factory
- ☐ Jet labs
- ☐ r-process
- ☐ GWs

Dancing jets



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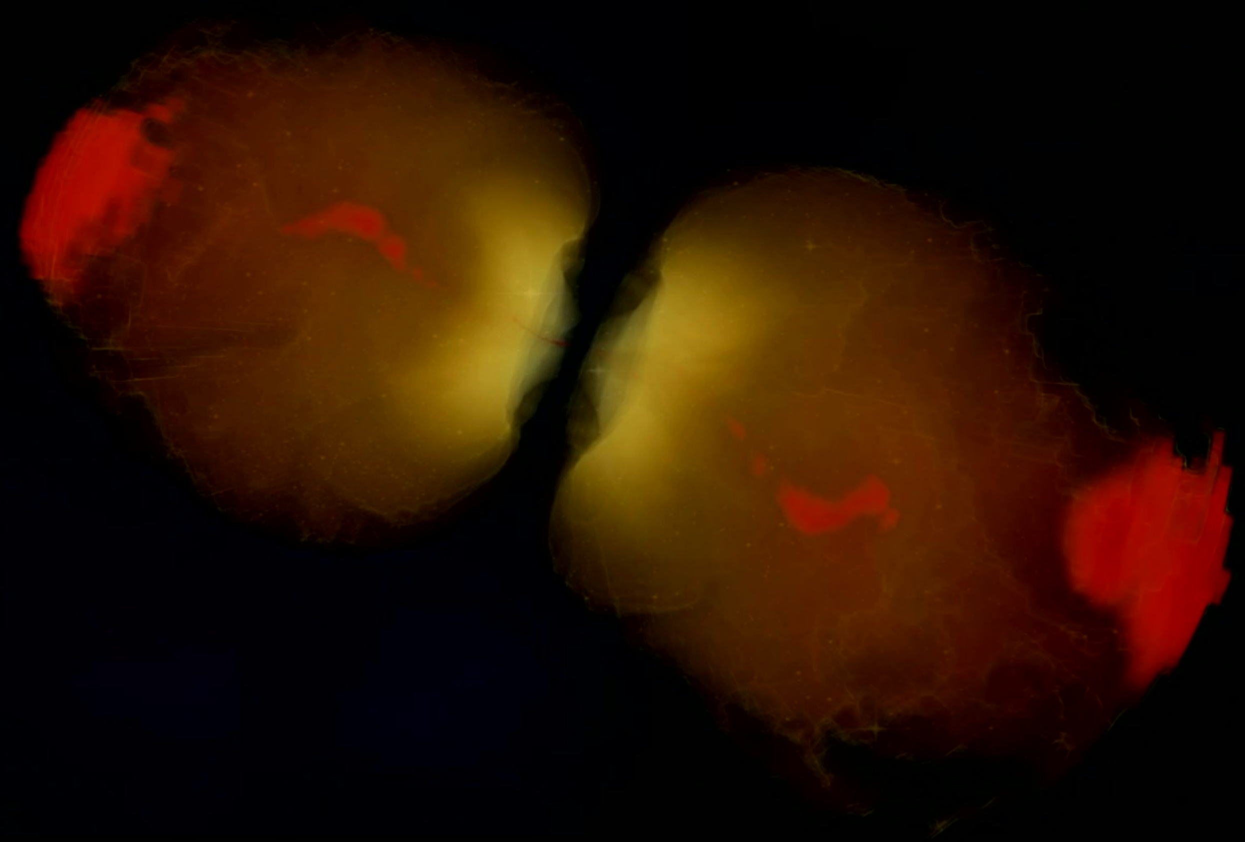
- ❑ r-process
- ❑ GWs

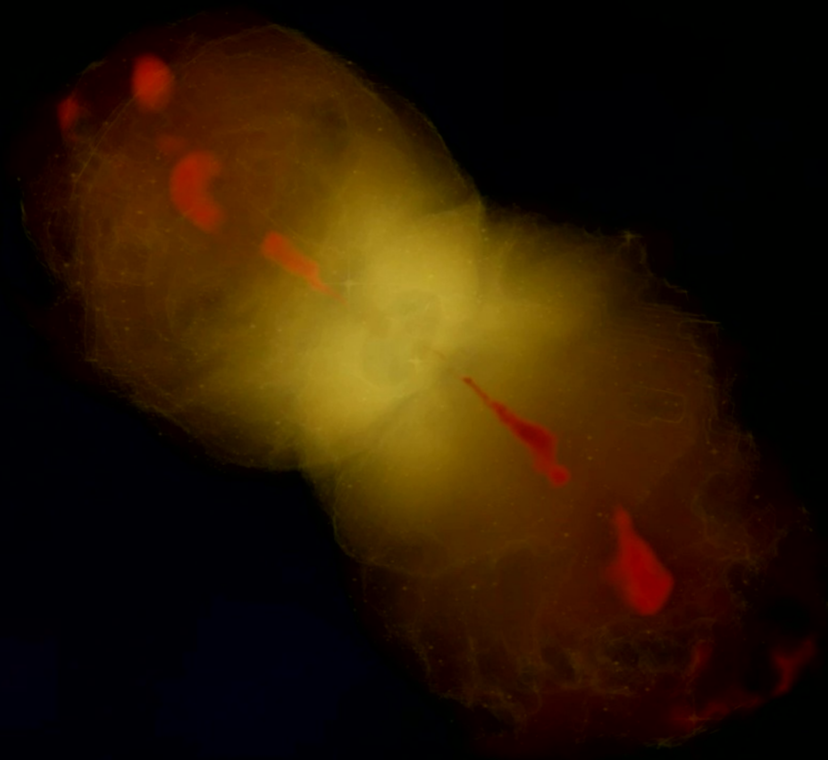
Dancing jets



- ✓ BH factory
- ➢ Jet labs
- ❑ r-process
- ❑ GWs

Gottlieb et al. 2022c

Dancing jets



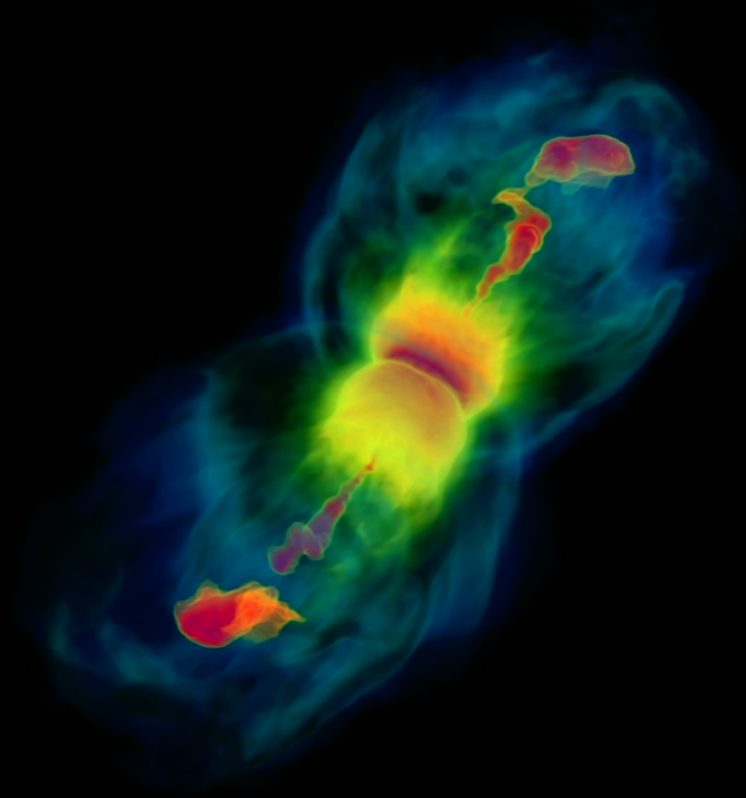
- ✓ BH factory
- ➢ Jet labs
- ❑ r-process
- ❑ GWs

Gottlieb et al. 2022c

New jet physics

- Wobbling implications:

➢ Low (intrinsic) GRB rate ~ ~~100~~ 10 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



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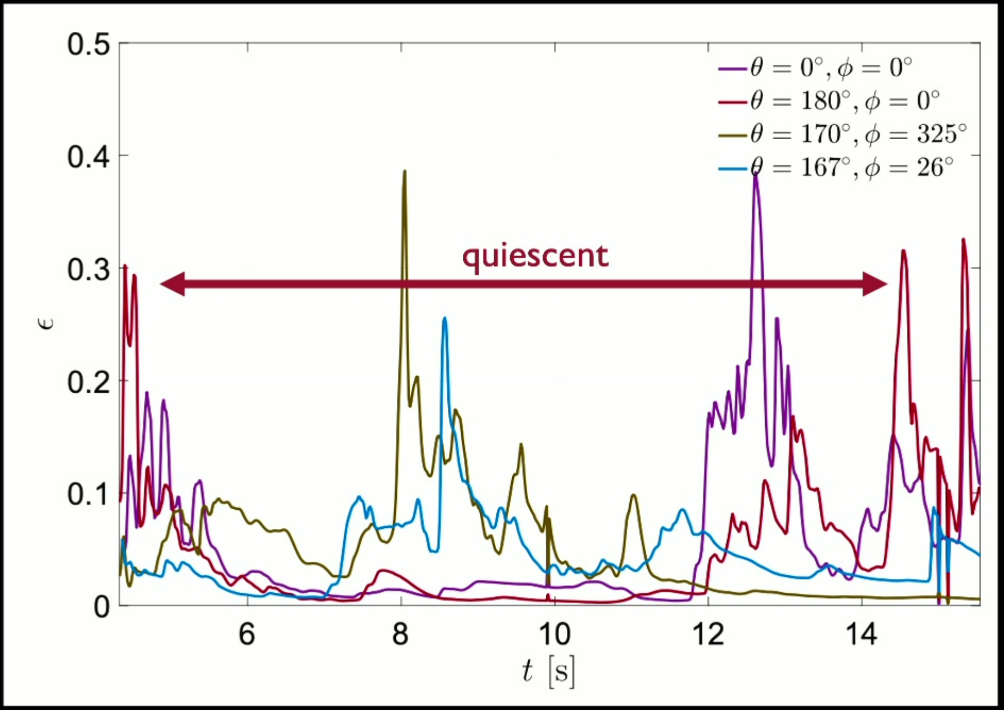
New jet physics

- Wobbling implications:

➢ Low (intrinsic) GRB rate ~ ~~100~~ 10 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

➢ Quiescent times



✓ BH factory
✓ Jet labs
❑ r-process
❑ GWs

New jet physics

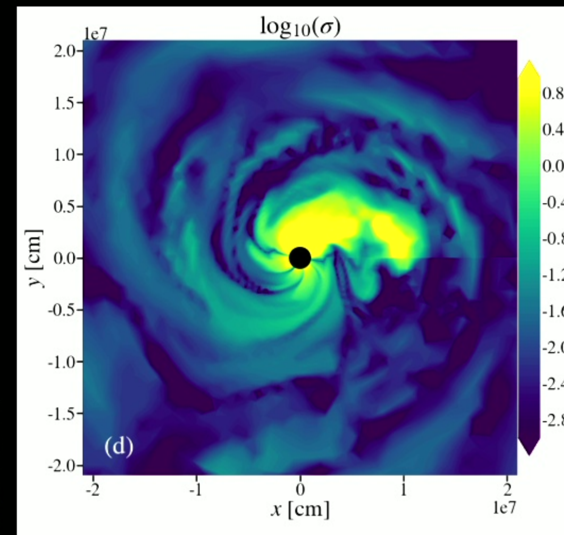
- Wobbling implications:

➢ Low (intrinsic) GRB rate ~ ~~100~~ 10 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

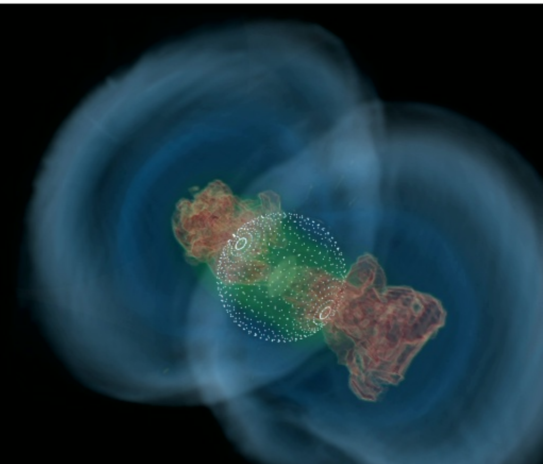
➢ Quiescent times

- New EM transients

➢ Zero spin black holes power outflows



Justin Bopp



Bopp & Gottlieb, in prep.

✓ BH factory
✓ Jet labs
❑ r-process
❑ GWs

Heavy element nucleosynthesis

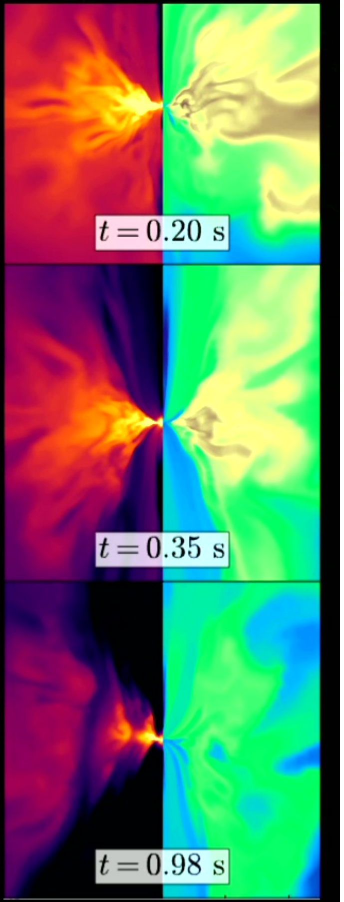
Recipe for expelling r-process elements from collapsing stars?

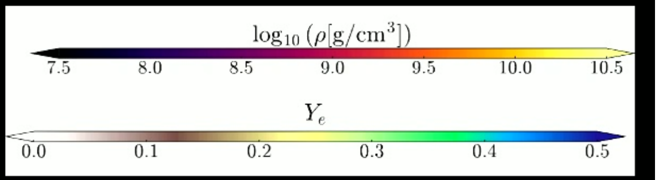
1. Prepare a disk: $r_{\rm circ} > r_{\rm ISCO}$

2. Make it neutron-rich: $\mathrm{t_{cool}} < t_{\rm acc}$; or: $\dot{M} > K_{\rm ign} \left(\frac{\alpha_{\rm eff}}{0.1}\right)^{\frac{5}{3}} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} \mathrm{M_\odot\ s^{-1}}$

3. Eject the neutron-rich gas requires: $\phi \equiv \frac{\Phi}{\sqrt{\dot{M} r_g^2 c}} > 10$

Danat Issa





- ✓ BH factory
- ✓ Jet labs
- ➢ r-process
- ❑ GWs

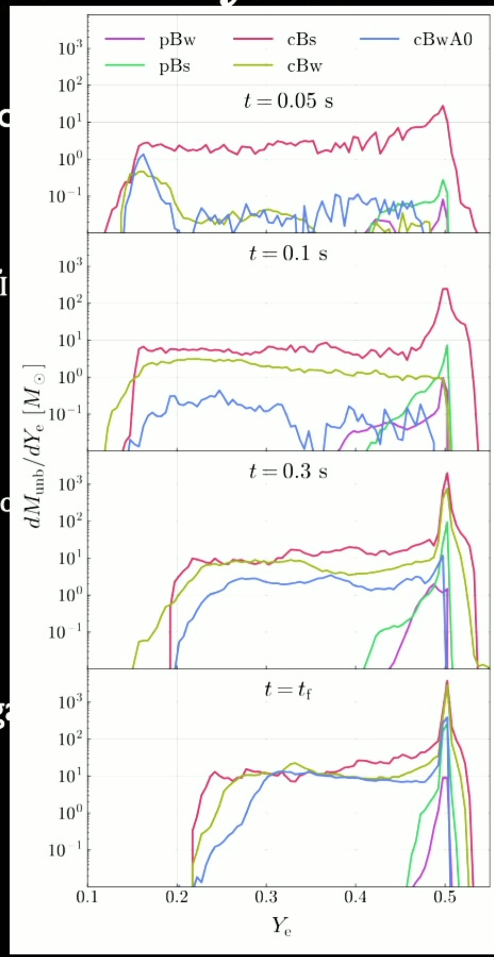
Heavy element nucleosynthesis

Recipe for expelling r-proc… …ars?

1. Prepare a disk: $r_{\rm circ} > r_{\rm I}$…

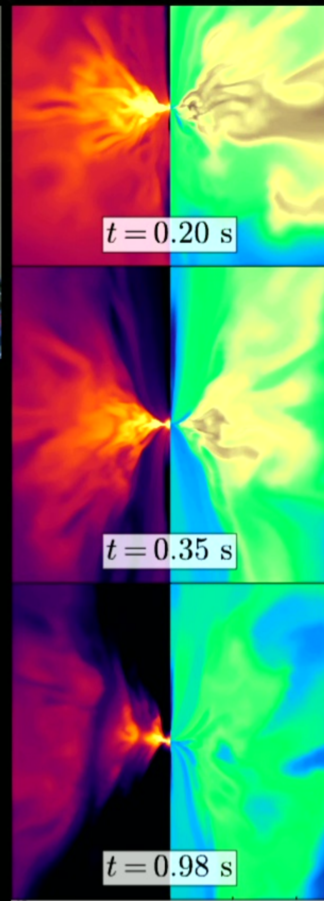
2. Make it neutron-rich: $t_{\rm co}$… $\left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}}\ {\rm M_\odot\ s^{-1}}$

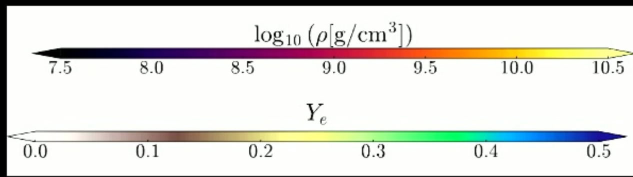
3. Eject the neutron-rich g…



Issa, Gottlieb et al. in prep.

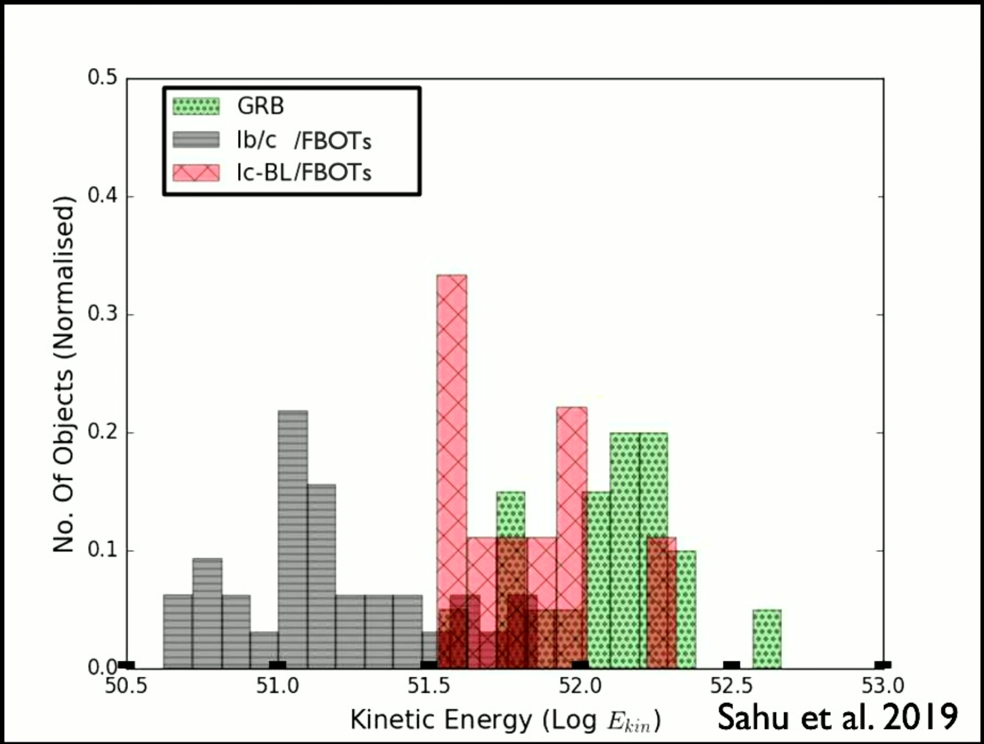
Danat Issa





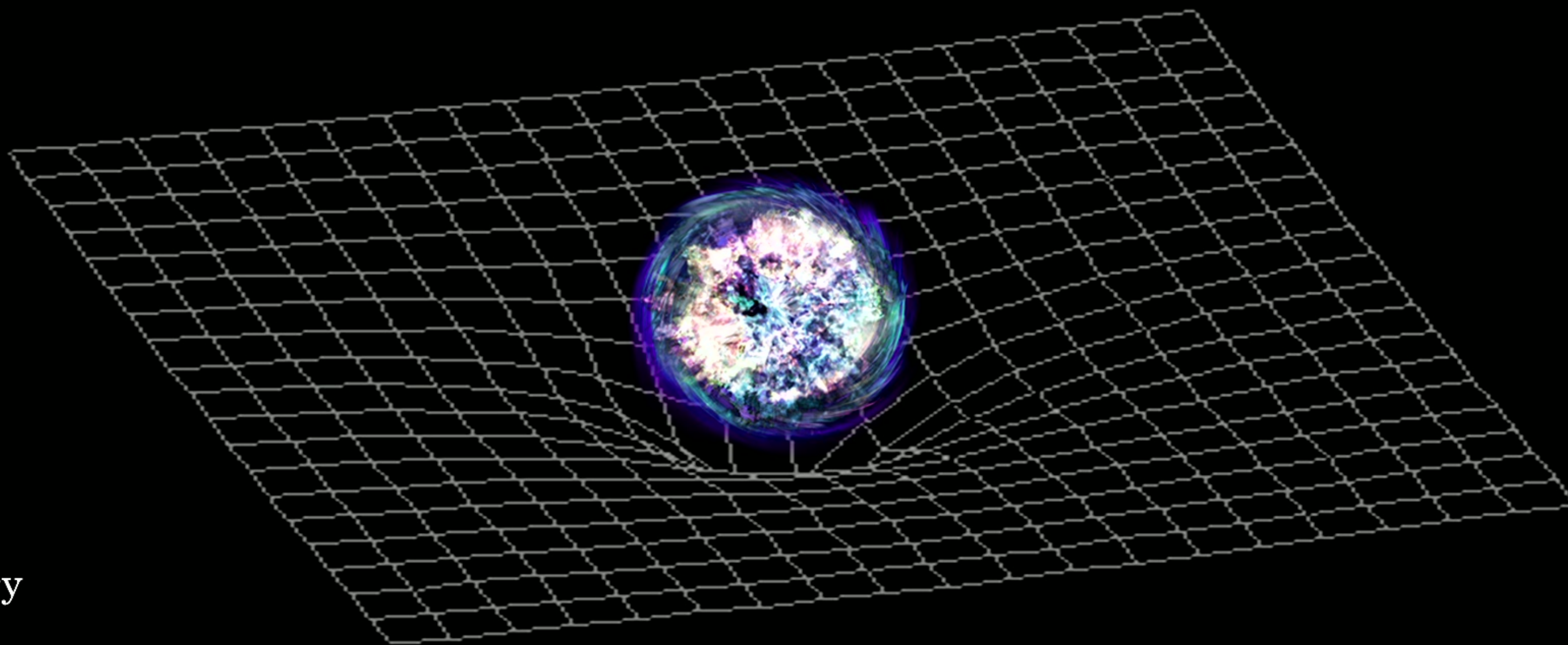
- ✓ BH factory
- ✓ Jet labs
- ➢ r-process
- ❑ GWs

Gravitational waves from collapsars



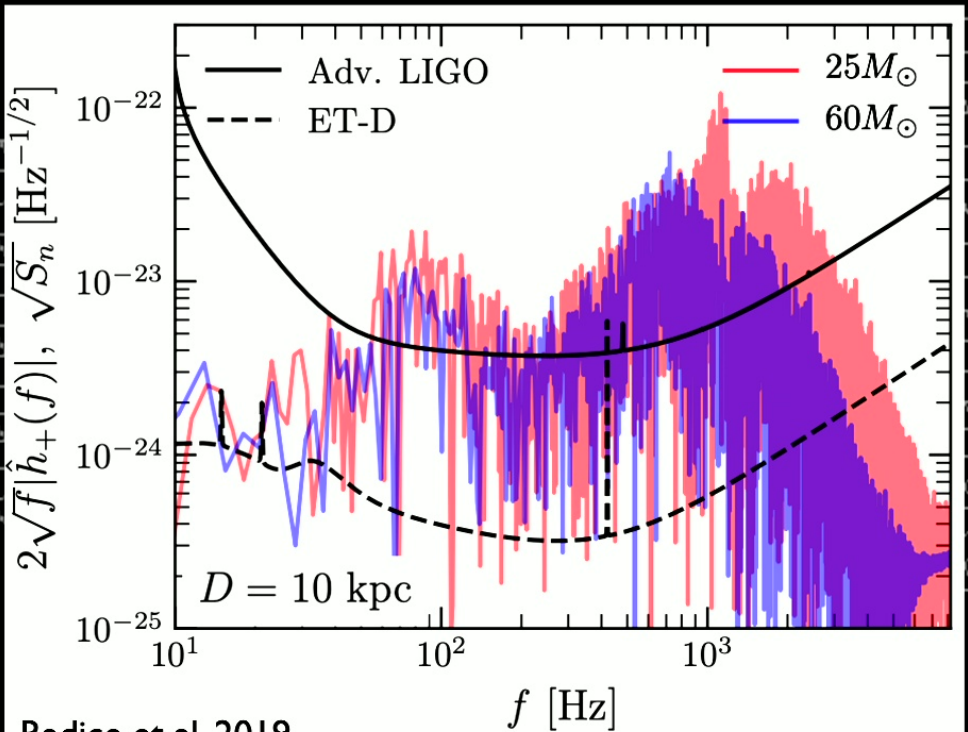
- ✓ BH factory
- ✓ Jet labs
- ✓ r-process
- ➢ GWs

Stochastic gravitational waves



- ✓ BH factory
- ✓ Jet labs
- ✓ r-process
- ➢ GWs

Stochastic gravitational waves



Radice et al. 2019

- ✓ BH factory
- ✓ Jet labs
- ✓ r-process
- ➢ GWs

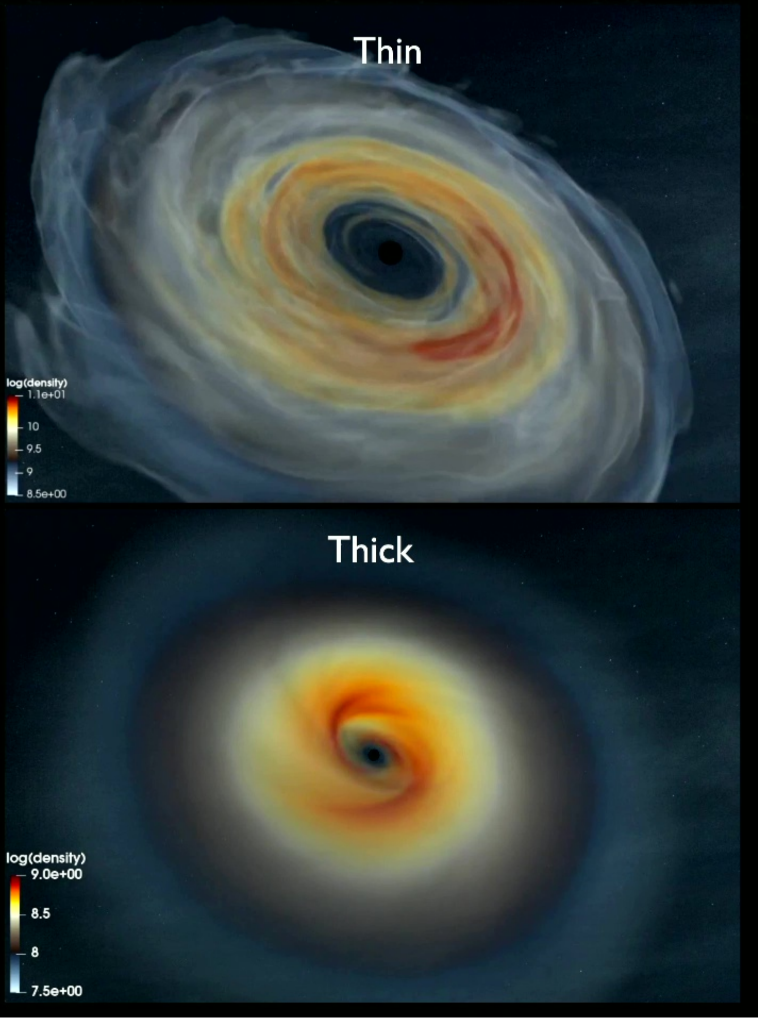
Disk-powered GWs: Thin vs. Thick

Analytic models → Numerical models

First-principles collapsar simulations

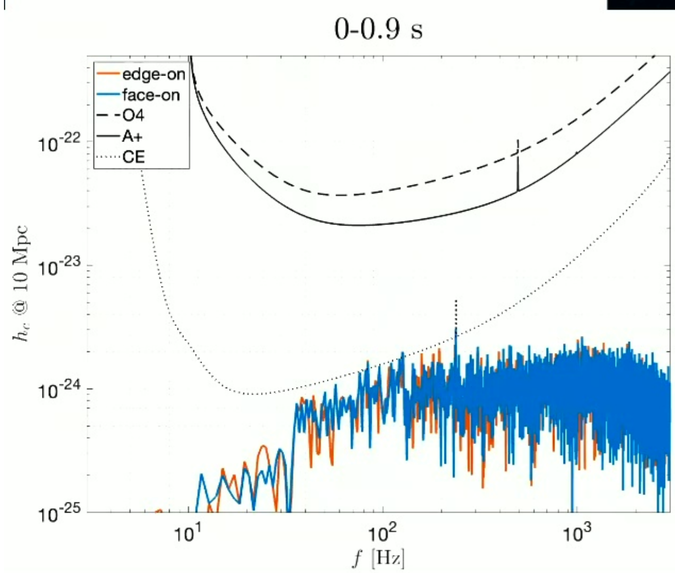
Thin disks:

- Denser → Stronger GWs
- Denser → Instabilities $\left(Q_T = \frac{\Omega c_s}{\pi G \Sigma_d}\right)$
- Compact → Coherent GWs

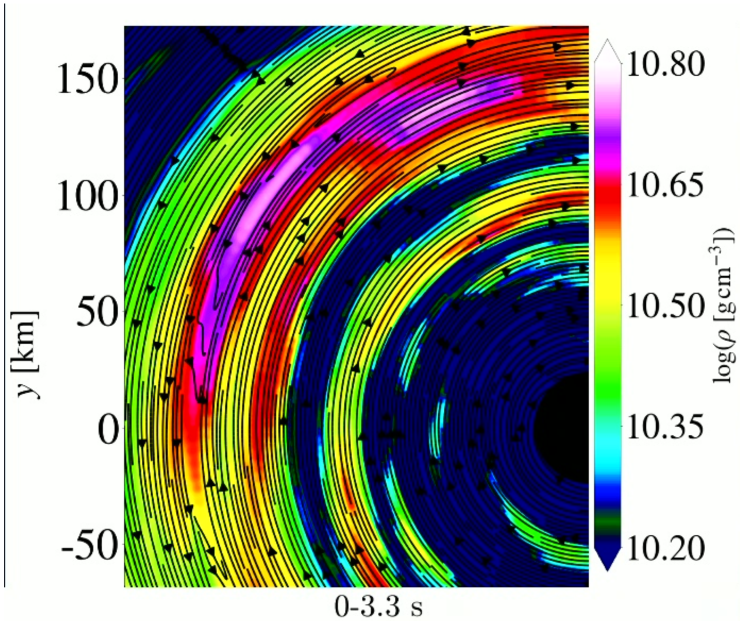


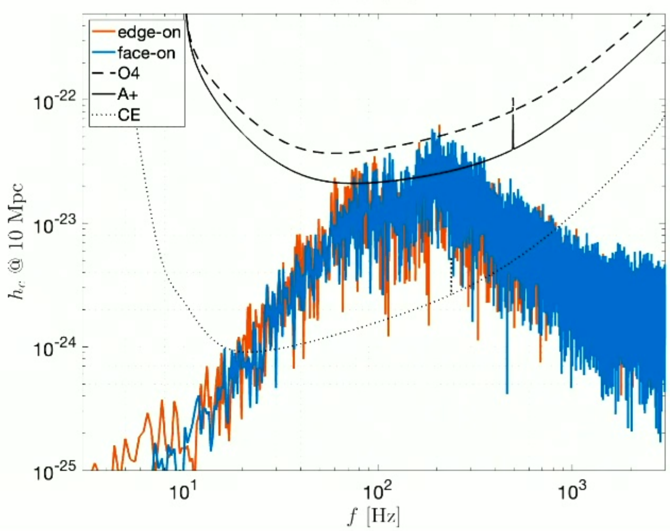
✓ BH factory
✓ Jet labs
✓ r-process
➢ GWs

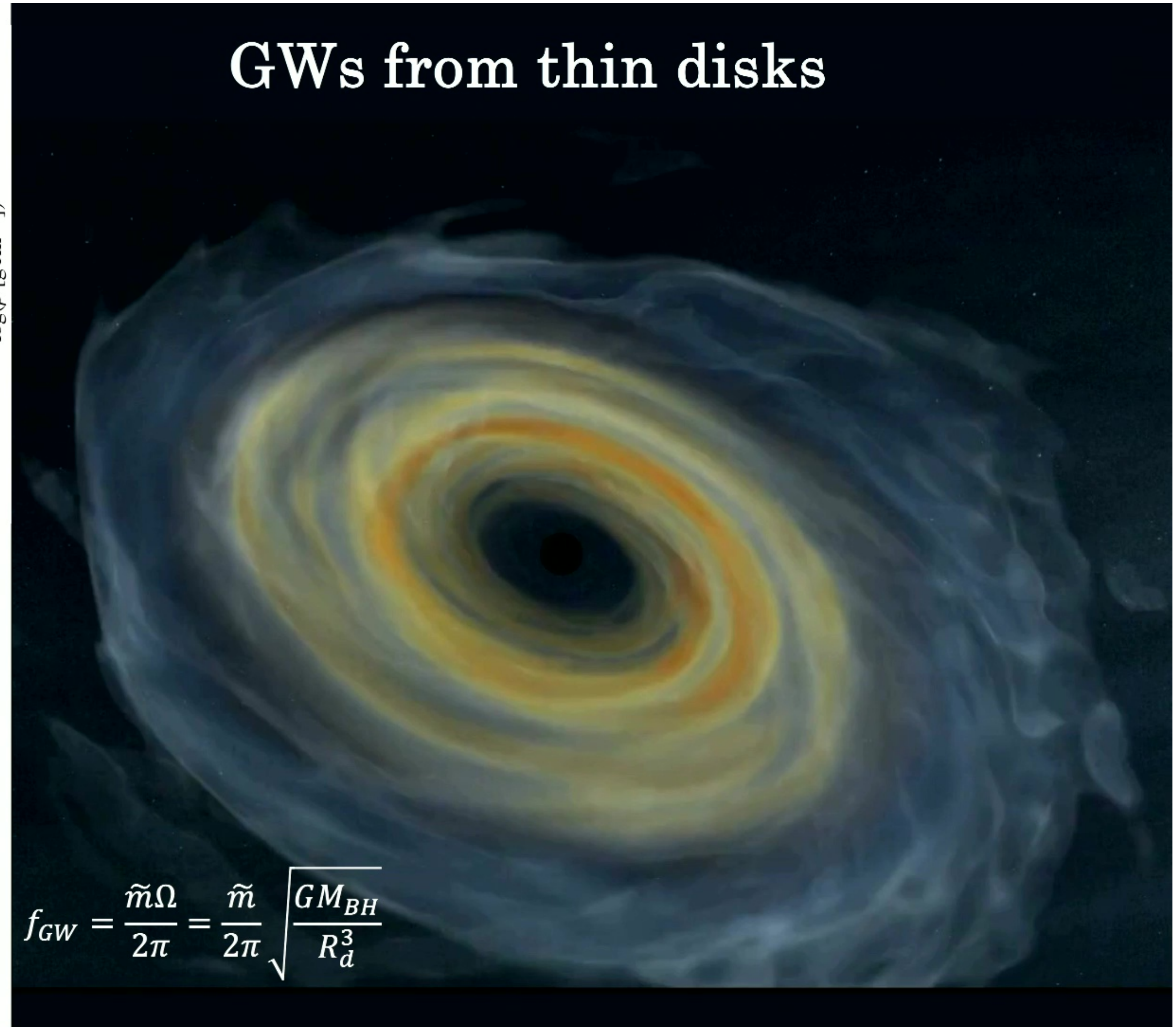
GWs from thin disks



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


150
100
50
0
-50
y [km]
10.80
10.65
10.50
10.35
10.20
log(ρ [g cm^-3])
0-3.3 s


edge-on
face-on
O4
A+
CE
10^-22
10^-23
10^-24
10^-25
h_c @ 10 Mpc
10^1
10^2
10^3
f [Hz]


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

Detection prospects

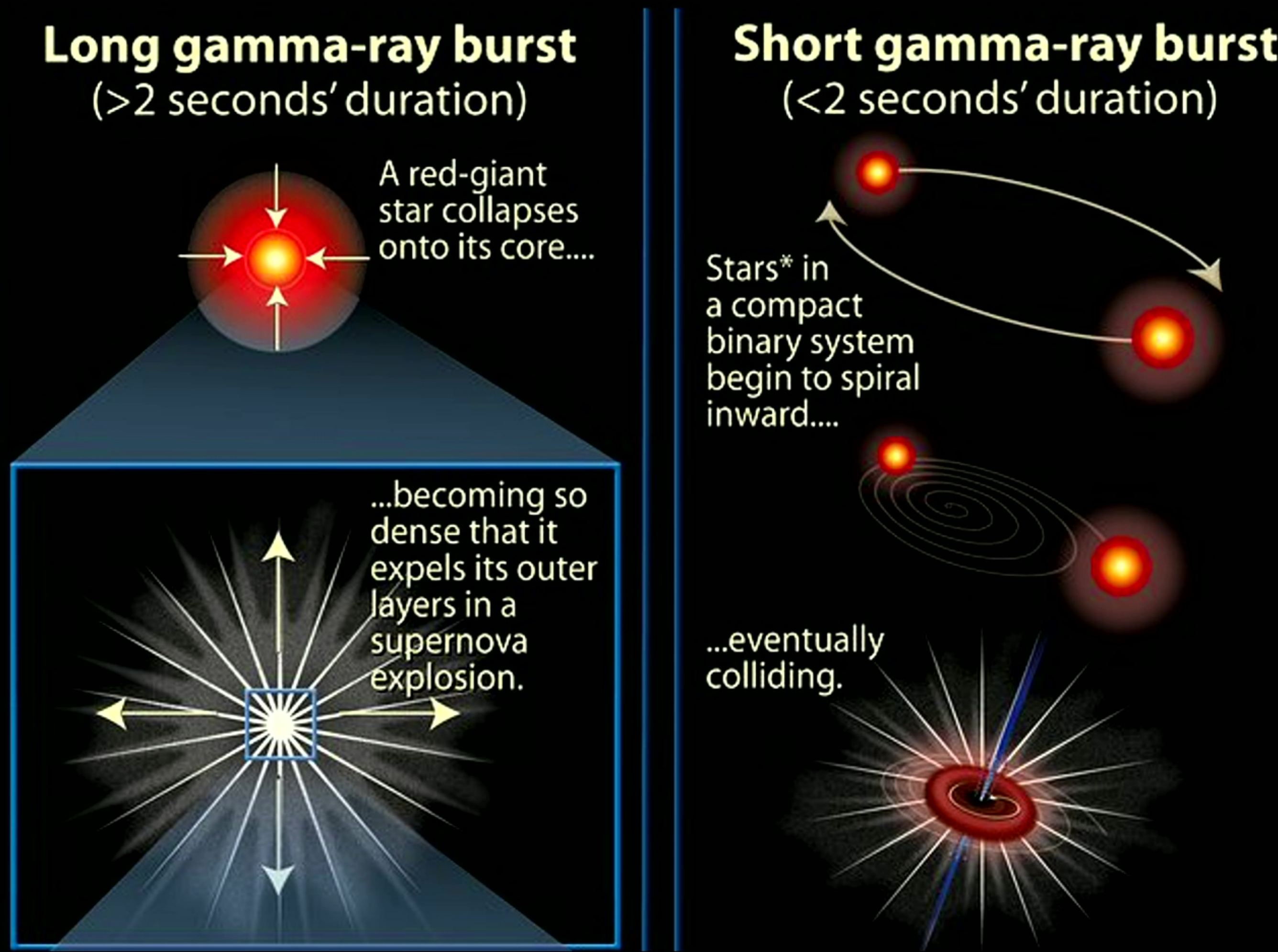
- GRB rate translates to: $N_{\mathrm{LIGO}} \sim 0.1\, \varrho_{20}^{-3}\ \mathrm{yr}^{-1}$ $N_{\mathrm{CE}} \sim 10^{0.5}\, \varrho_{20}^{-3}\ \mathrm{yr}^{-1}$
- SN Ib/c rate translates to: $N_{\mathrm{LIGO}} \sim 10\, \varrho_{20}^{-3}\ \mathrm{yr}^{-1}$ $N_{\mathrm{CE}} \sim 10^{2.5}\, \varrho_{20}^{-3}\ \mathrm{yr}^{-1}$
- Multi-messenger signals with GRBs/cocoon emission/Type Ib/c emission
- Time and space localization enables targeted search for GWs
- Disk GWs are > 100 stronger than CCSN GWs + coherent – easier to form templates
- **Collapsar disks are the most promising burst-type GW sources to date**

✓ BH factory
✓ Jet labs
✓ r-process
✓ GWs

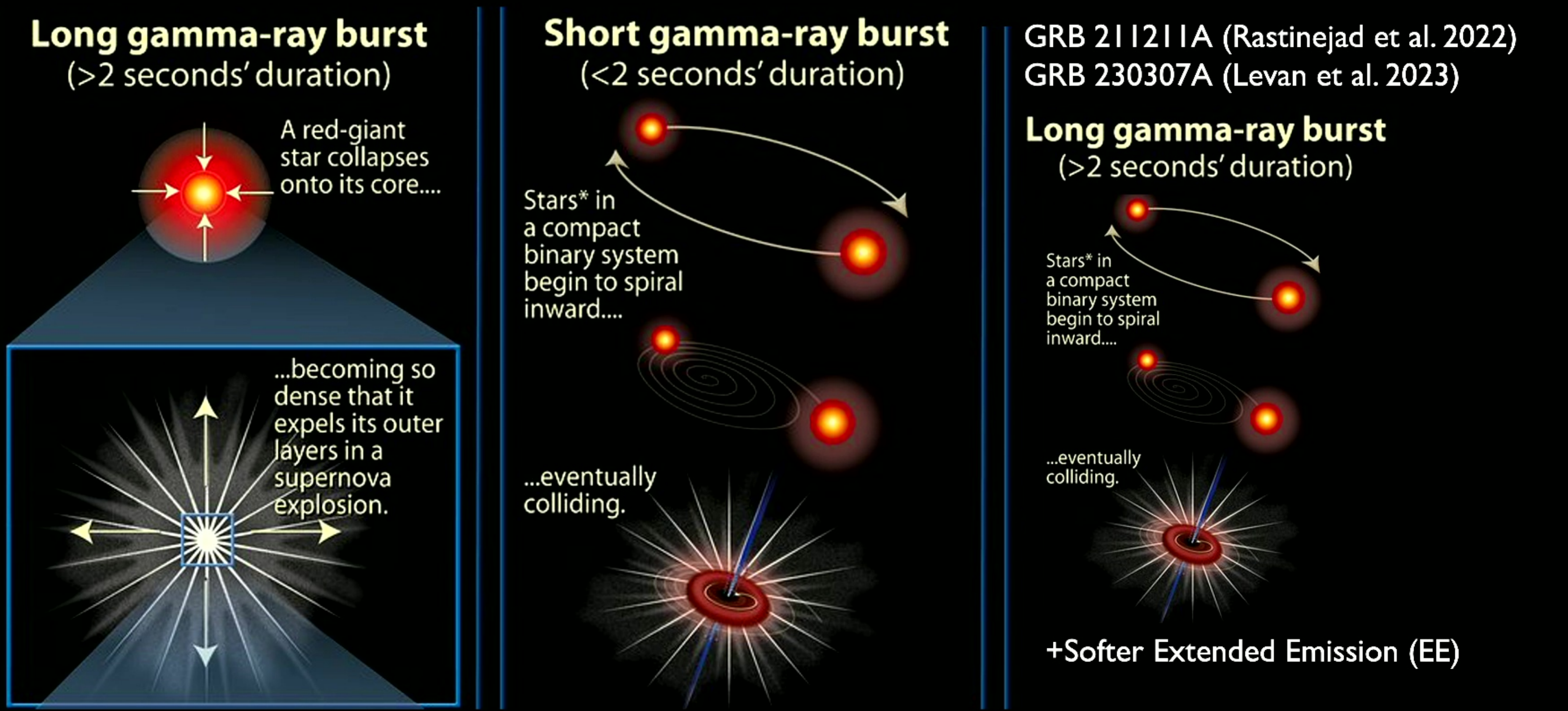
Collapsars

- Black holes are born moderately-spinning, obtaining their field from the PNS
- Such BHs promptly power a BZ-jet that matches GRB observations
- Jets wobble
- Non-spinning BHs power new transients or explain existing ones?
- Collapsars can produce r-process elements
- Collapsar disks are the most promising non-inspiral GWs in LIGO

Types of GRBs



Types of GRBs



Jet launching

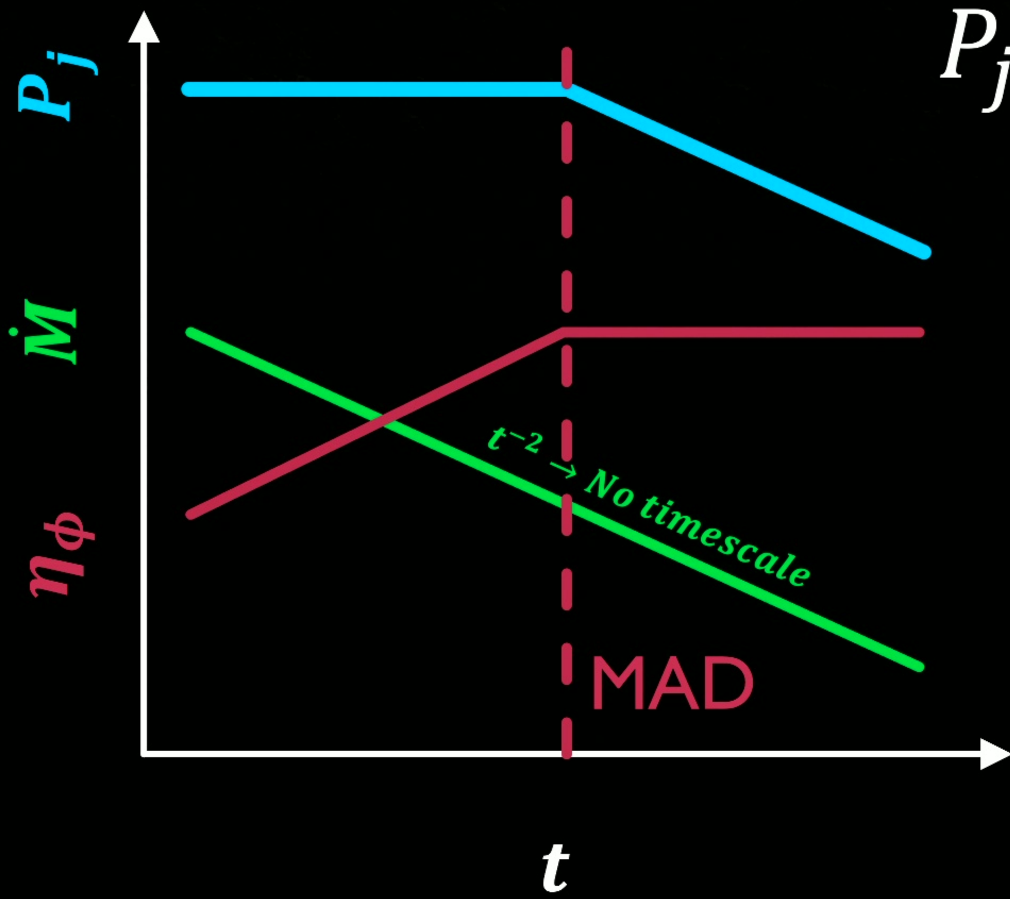
$$P_j = \dot{M} c^2 \eta_a(a) \eta_\phi(\phi)$$

$\dot{M}$ – Mass accretion rate

η_a – Spin efficiency

η_ϕ – Field efficiency

Compact binary GRBs (cbGRBs)



$$P_j = \dot{M} c^2 \eta_a(a) \eta_\phi(\phi)$$

$$\eta_a(a) \approx 1$$

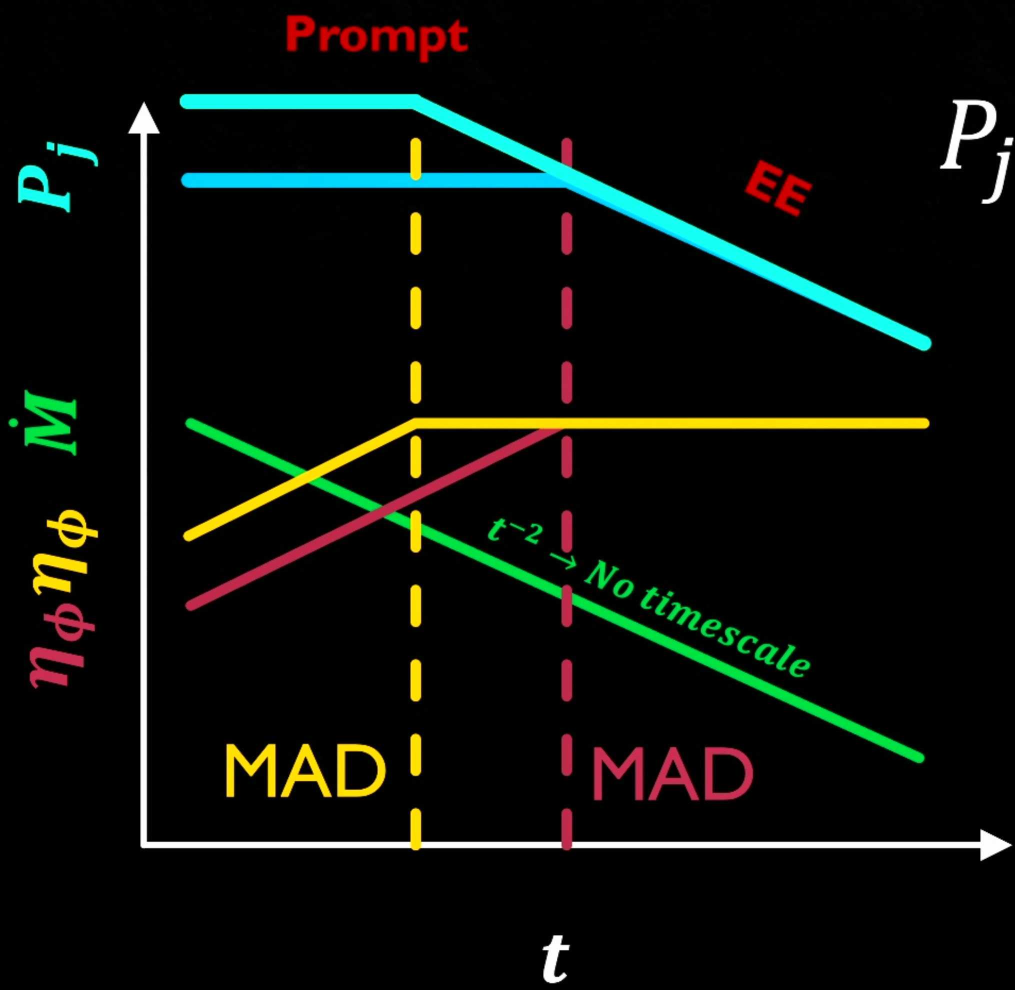
$$\rightarrow P_j \sim \dot{M} \eta_\phi$$

$$\dot{M} \sim \frac{r_h}{r_{disk}} \frac{M}{t_{vis}} \sim t^{-2}$$

$$P_j \sim \text{const.}$$

$$\rightarrow \eta_\phi \sim P_j \dot{M}^{-1} \sim t^2$$

Compact binary GRBs (cbGRBs)



$$P_j = \dot{M}c^2\eta_a(a)\eta_\phi(\phi)$$

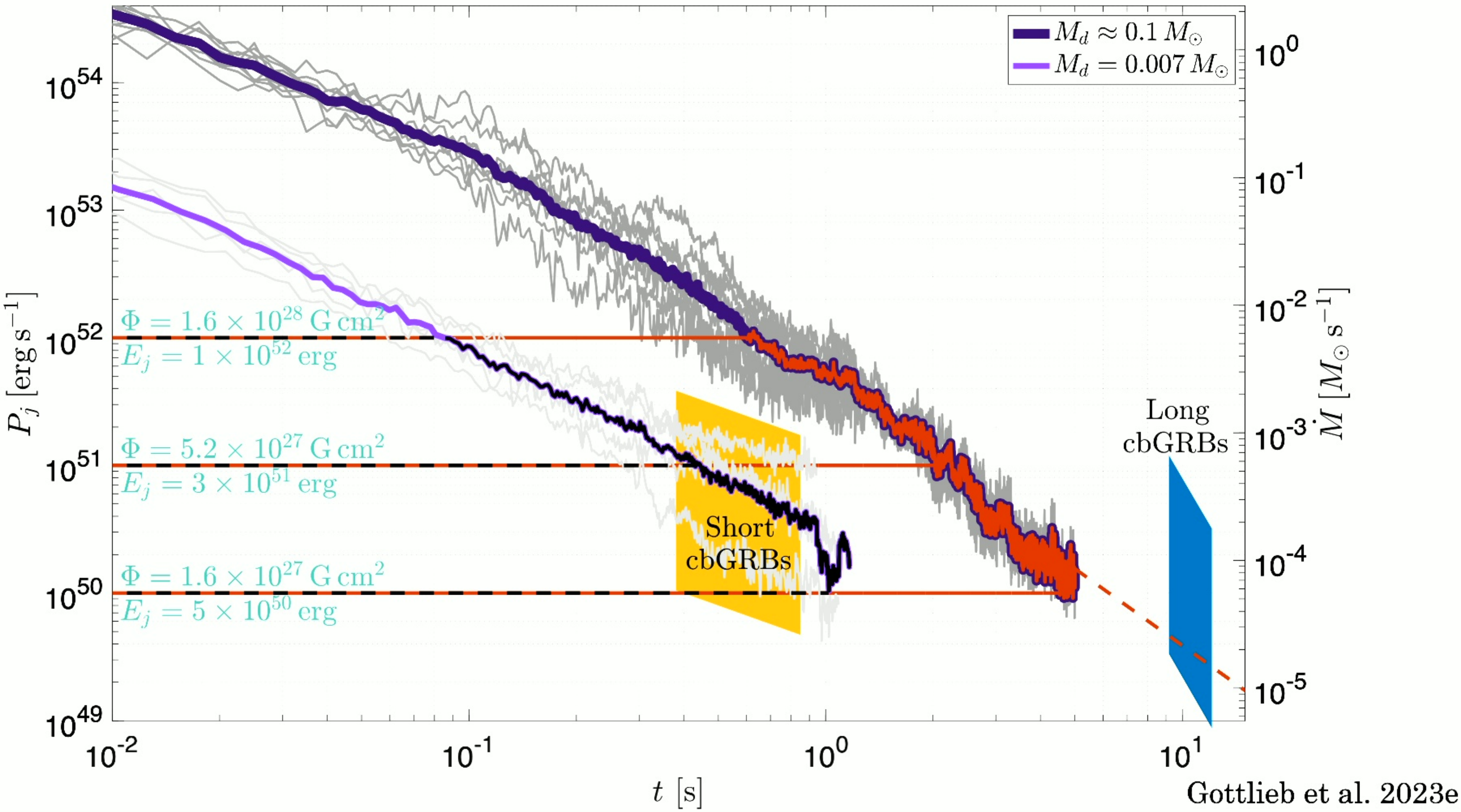
$$\eta_a(a) \approx 1$$

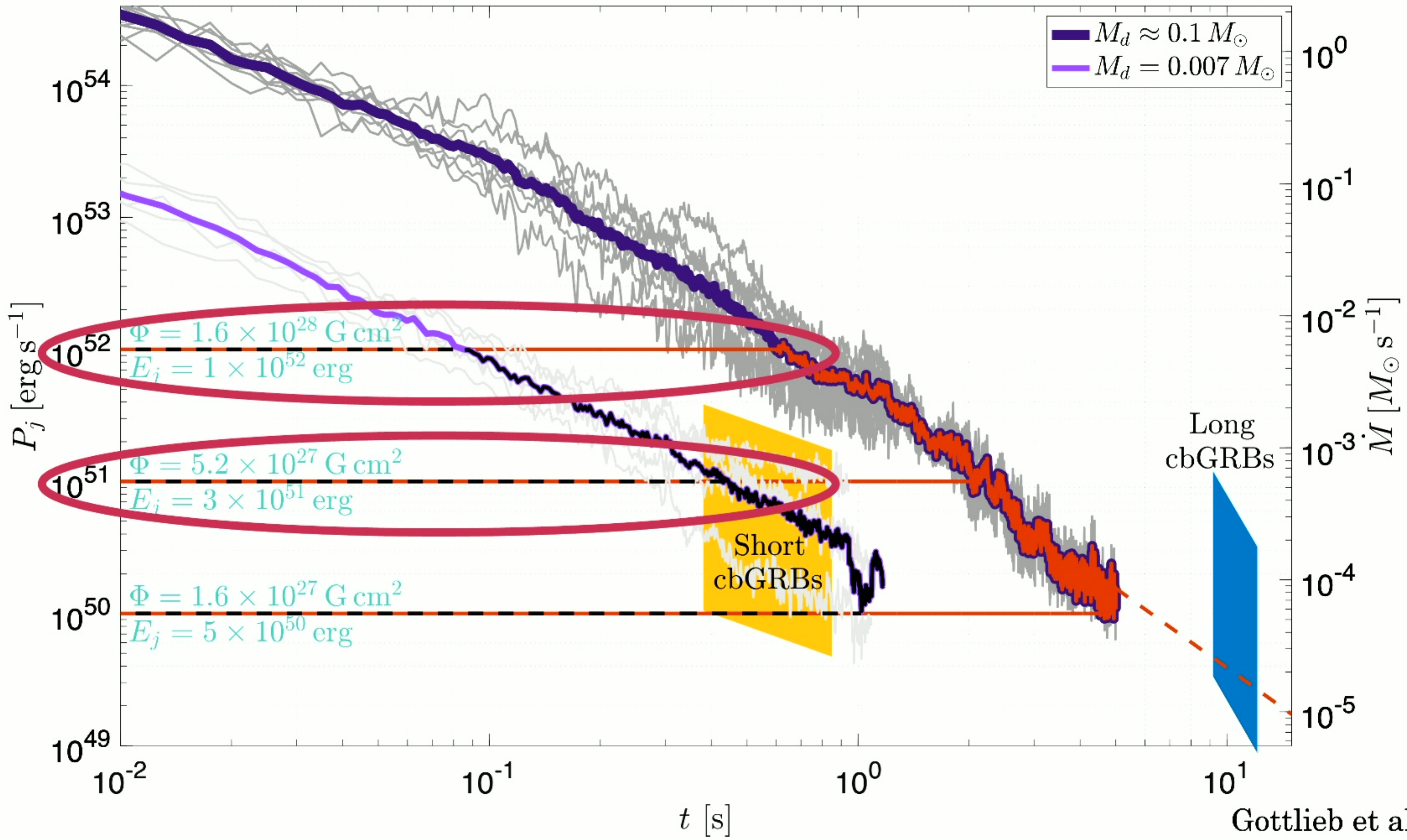
$$\to P_j \sim \dot{M}\eta_\phi$$

$$\dot{M} \sim \frac{r_h}{r_{disk}}\frac{M}{t_{vis}} \sim t^{-2}$$

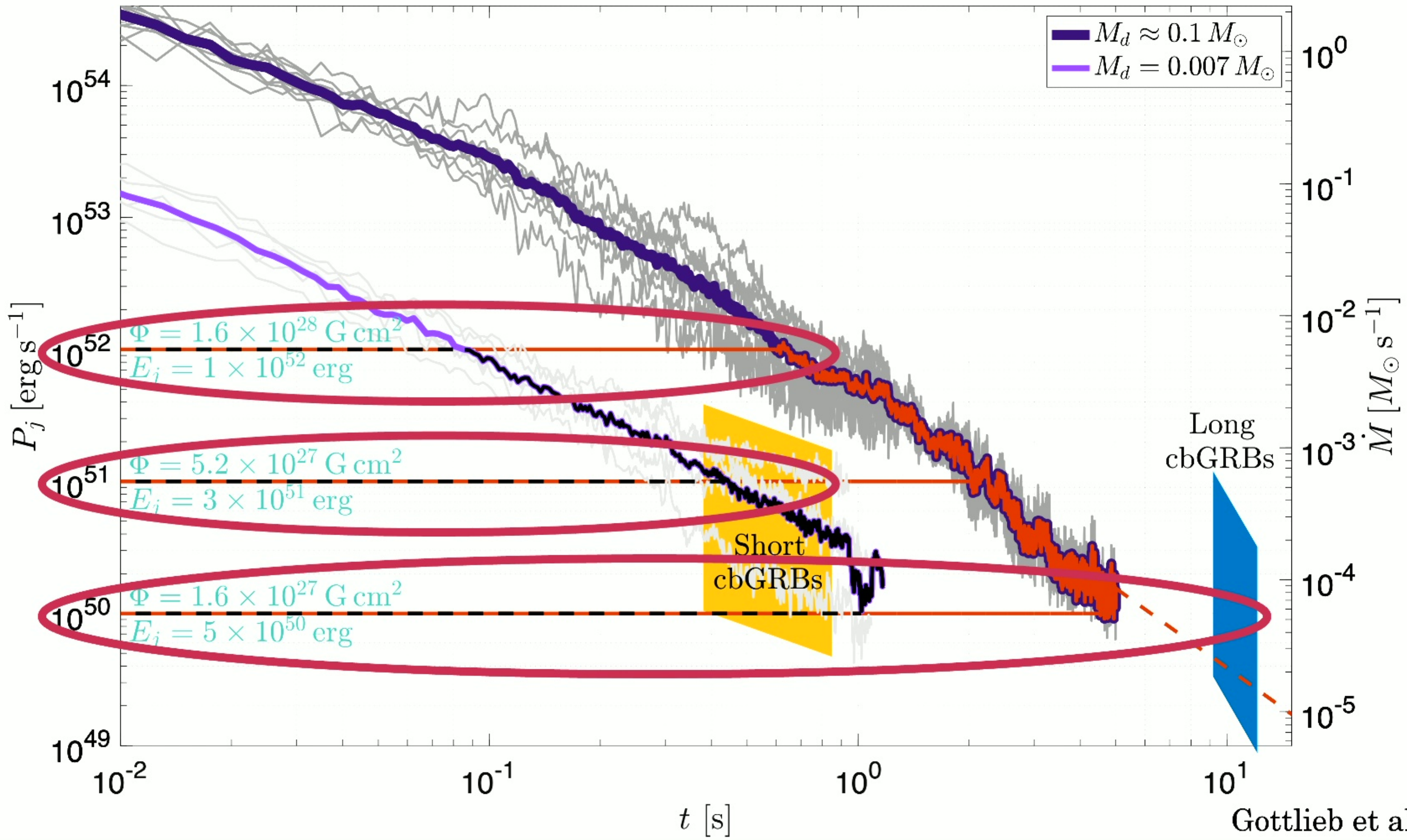
$$P_j \sim \text{const.}$$

$$\to \eta_\phi \sim P_j\dot{M}^{-1} \sim t^2$$

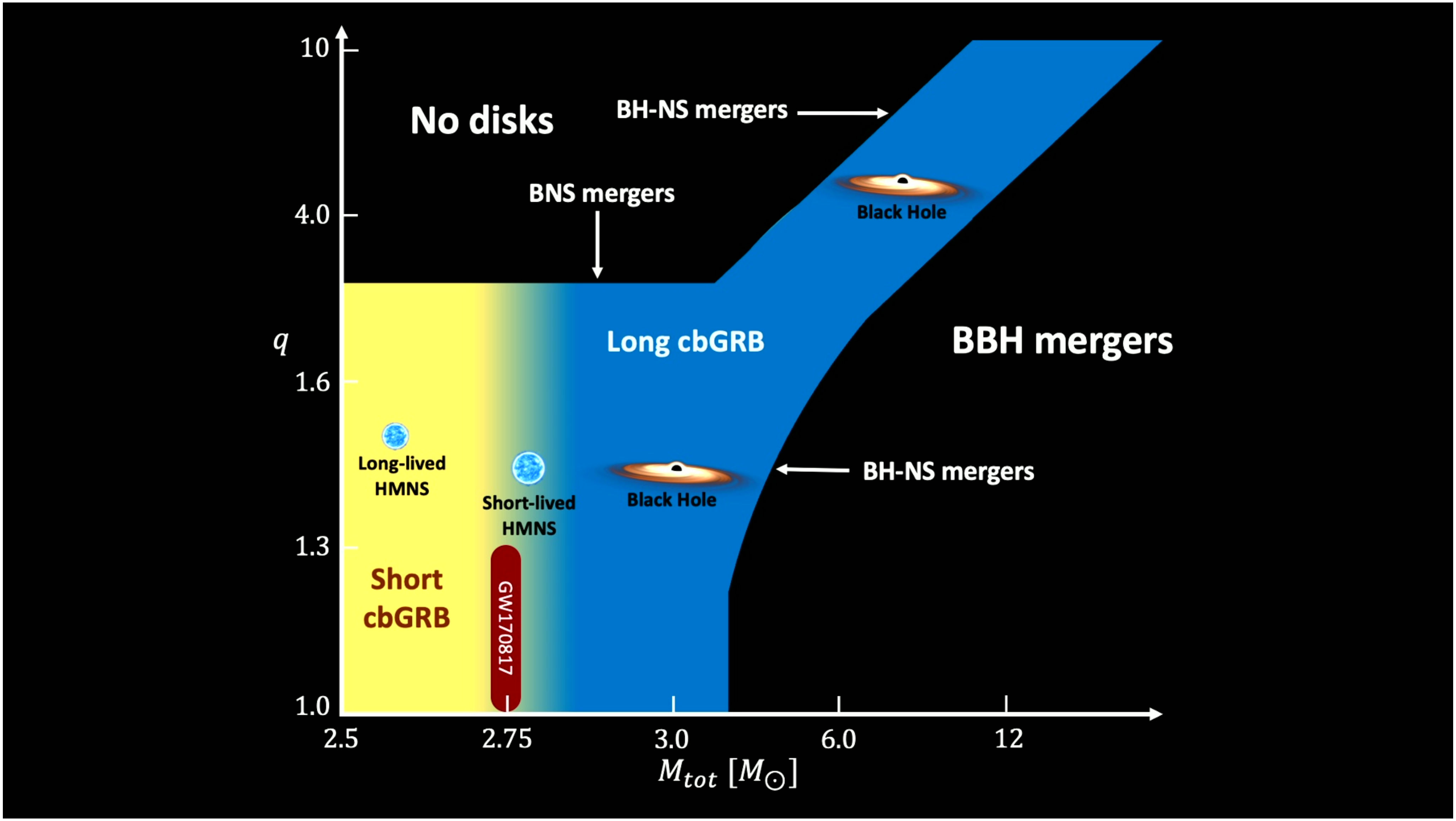

$M_d \approx 0.1\, M_\odot$
$M_d = 0.007\, M_\odot$
$\Phi = 1.6 \times 10^{28}$ G cm^2
$E_j = 1 \times 10^{52}$ erg
$\Phi = 5.2 \times 10^{27}$ G cm^2
$E_j = 3 \times 10^{51}$ erg
$\Phi = 1.6 \times 10^{27}$ G cm^2
$E_j = 5 \times 10^{50}$ erg
Short cbGRBs
Long cbGRBs
P_j [erg s^{-1}]
$\dot{M}$ [$M_\odot$ s^{-1}]
t [s]
10^{54}
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-2}
10^{-1}
10^{0}
10^{1}
Gottlieb et al. 2023e



Gottlieb et al. 2023e

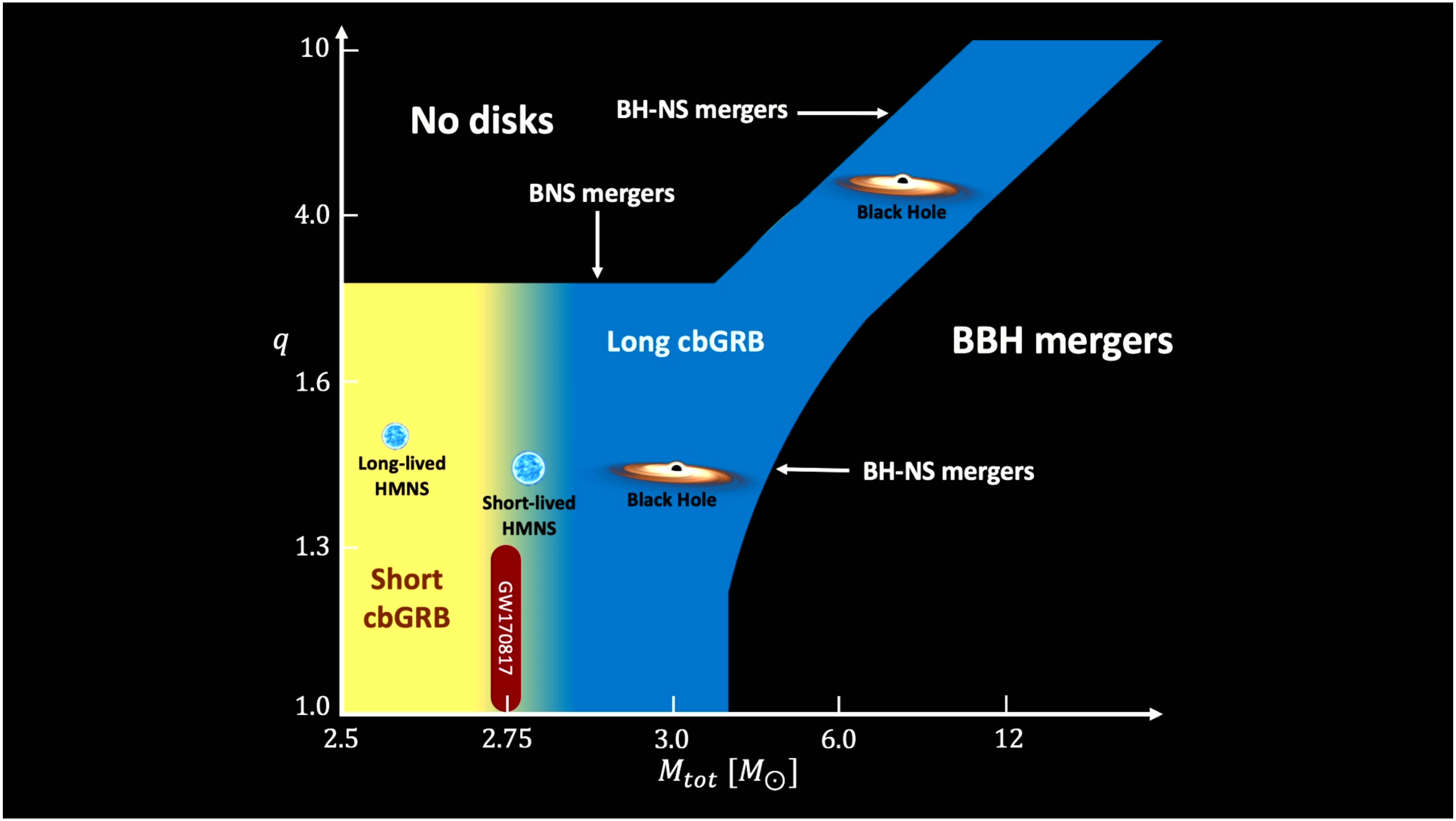


Gottlieb et al. 2023e

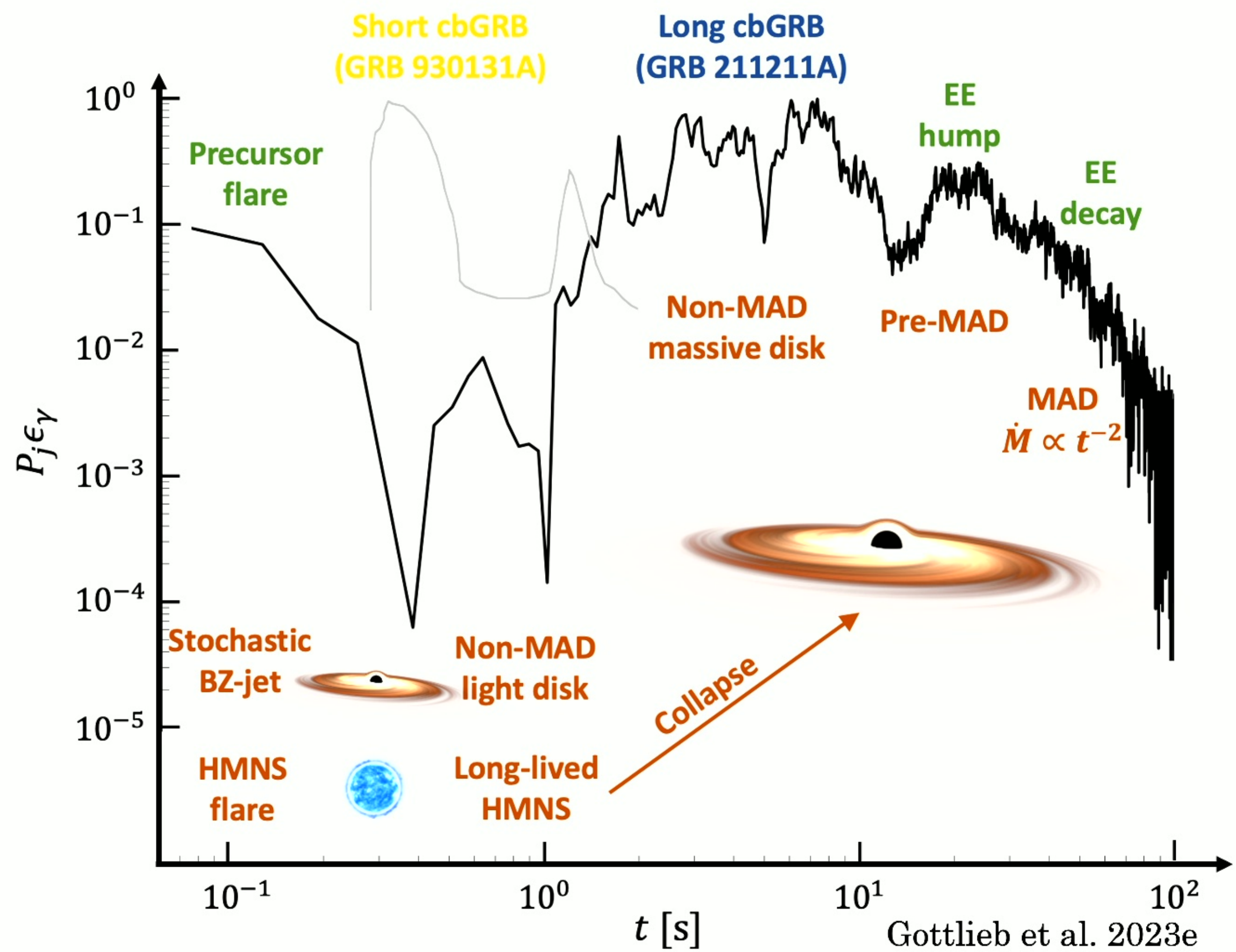

10
4.0
1.6
1.3
1.0
q
No disks
BH-NS mergers
BNS mergers
Black Hole
Long cbGRB
BBH mergers
Long-lived HMNS
Short-lived HMNS
Black Hole
BH-NS mergers
Short cbGRB
GW170817
2.5
2.75
3.0
6.0
12
$M_{tot}\ [M_\odot]$

Unified picture for the origin of compact binary GRBs

- Transition to MAD marks the GRB duration and EE onset
- Unequal mass BNS & some BH-NS mergers inevitably power long cbGRBs
- BHs with less massive disks or HMNSs power standard short cbGRBs?
- Generalizing for a unified model of GRBs + kilonovae



10
4.0
1.6
1.3
1.0
q
No disks
BH-NS mergers
BNS mergers
Black Hole
Long cbGRB
BBH mergers
Long-lived HMNS
Short-lived HMNS
Black Hole
BH-NS mergers
Short cbGRB
GW170817
2.5
2.75
3.0
6.0
12
M_{tot} [$M_\odot$]


Short cbGRB
(GRB 930131A)
Long cbGRB
(GRB 211211A)
EE
hump
EE
decay
Precursor
flare
Non-MAD
massive disk
Pre-MAD
MAD
$\dot{M} \propto t^{-2}$
Stochastic
BZ-jet
Non-MAD
light disk
Collapse
HMNS
flare
Long-lived
HMNS
$P_j \epsilon_\gamma$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
10^0
10^1
10^2
t [s]
Gottlieb et al. 2023e