Title: Electromagnetic signatures from neutron star mergers and supermassive binary black holes

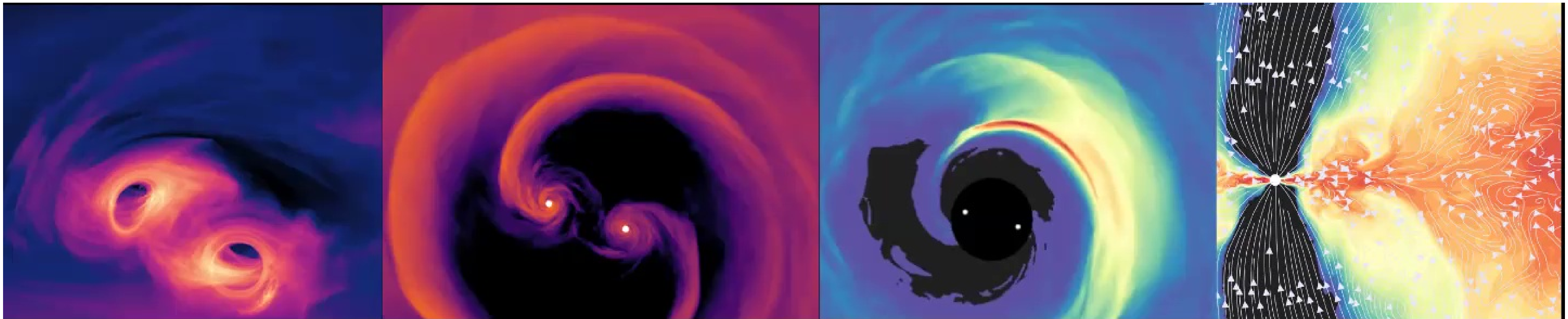
Speakers: Luciano Combi

Series: Strong Gravity

Date: November 18, 2021 - 1:00 PM

URL: https://pirsa.org/21110032

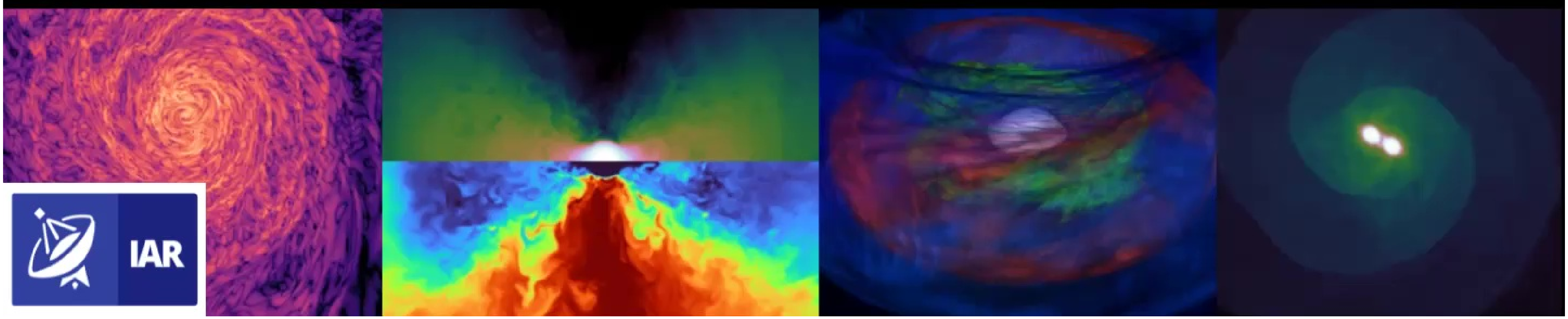
Abstract: Mergers of compact objects are among the most violent events in the Universe. At close separations, compact binaries emit gravitational waves, releasing enormous amounts of energy until they merge. When matter is present in the system, the event might be accompanied by electromagnetic emission, which can span the entire electromagnetic spectrum. Multi-messenger observations by gravitational-wave detectors and electromagnetic telescopes have opened a new avenue to understand the nature of spacetime and its interaction with matter. In this talk, I will discuss recent efforts to connect first-principle calculations with the electromagnetic radiation emitted in compact binary mergers through general-relativistic magnetohydrodynamic simulations. In particular, I will focus on the relativistic outflows produced in binary neutron star systems and on electromagnetic signatures of supermassive binary black-hole mergers.



# Electromagnetic signatures from mergers of compact binaries

Luciano Combi (IAR, Argentina)

*Strong Gravity Seminar, Perimeter Institute, 18/11/2021*



# Overview of this talk

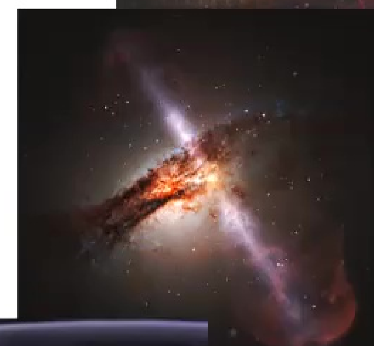
The presentation will be divided in two parts

## 1 - Supermassive black hole binaries

In collaboration with M. Campanelli (RIT), J. Krolik (JHU), S. Noble (NASA), F. Lopez Armengol (RIT), E. Gutierrez (IAR) +

## 2 - Binary neutron star mergers

In collaboration with D. Siegel (PI/Guelph)



# Overview of this talk

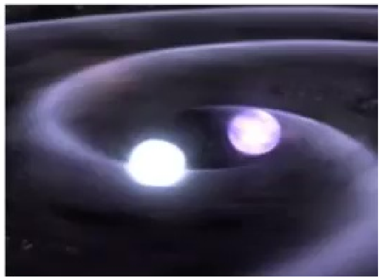
I will discuss two multi-messenger systems
at very different scales:

1 - **Supermassive black hole binaries** $(M \sim 10^6 - 10^9\, M_\odot)$
**GW** : ~nHz/mHz . Detection with Pulsar Timing Array / LISA
**EM** : AGN-like accretion disk and jets
**Neutrinos**: high-energy neutrinos?
No confirmed sources yet! (few candidates)

R ~ 0.001 pc


2 - **Binary neutron star mergers** $( M \sim 2M_\odot )$
**GW** : ~Hz/kHz. Detection with LIGO/Virgo/Karga
**EM** : Thermal transient, afterglow, short GRB...
**Neutrinos**: nuclear neutrinos?
Existence confirmed by LIGO/VIRGO + EM telescopes

R ~50 Km



# Supermassive black hole binaries

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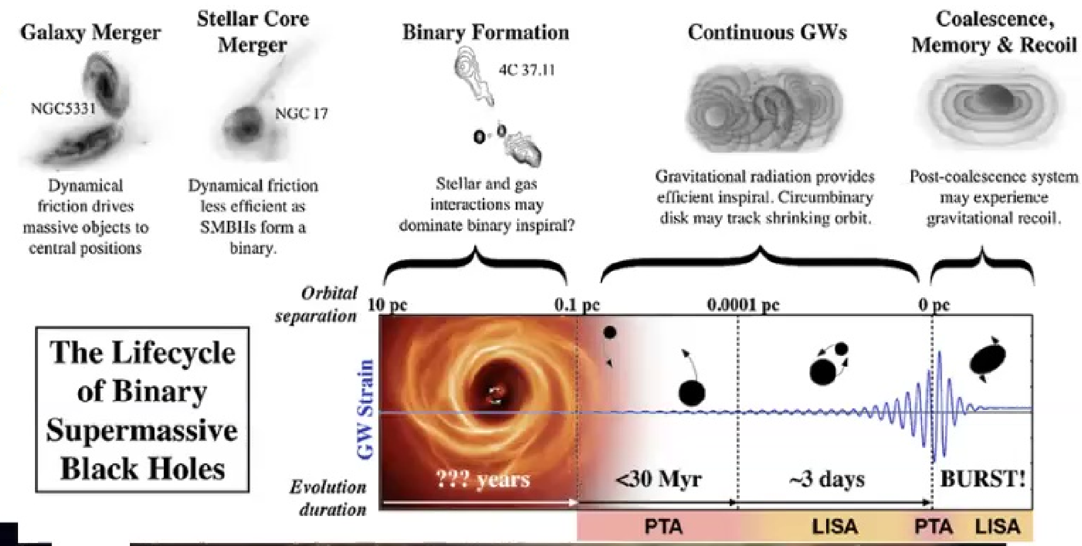
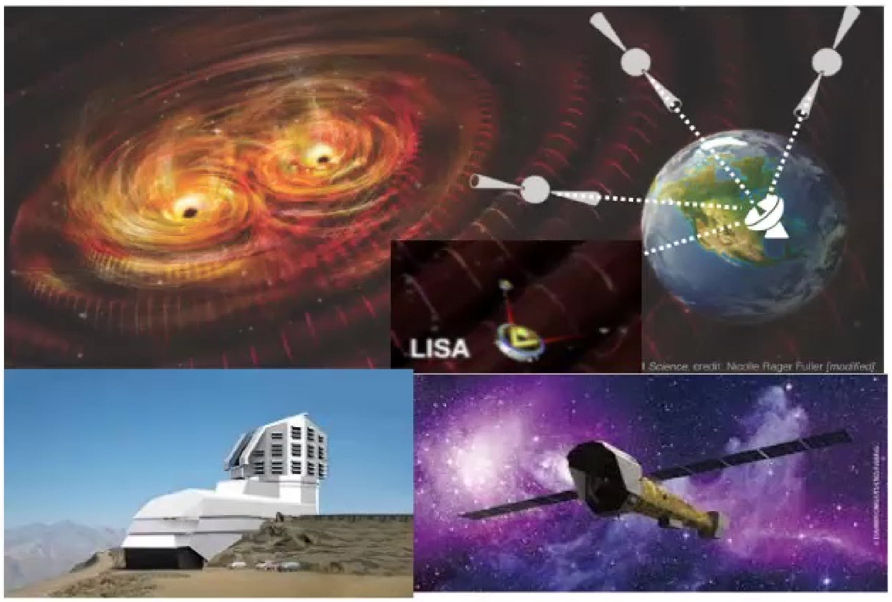



# Supermassive black hole binaries

## A GW multi-messenger system

GW detection: LISA / PTA




EM detection: SDSS-V,LSST, Athena, ...

- ❑ Contrary to stellar-mass black holes, supermassive BBH should evolve in gas-rich environments.
- ❑ If they accrete at similar rates as AGN, they should be detectable via **electromagnetic waves.**

**Challenge:**

How do we distinguish supermassive binaries from conventional AGNs looking at EM? **Find unique EM signatures such as variability and spectral features**

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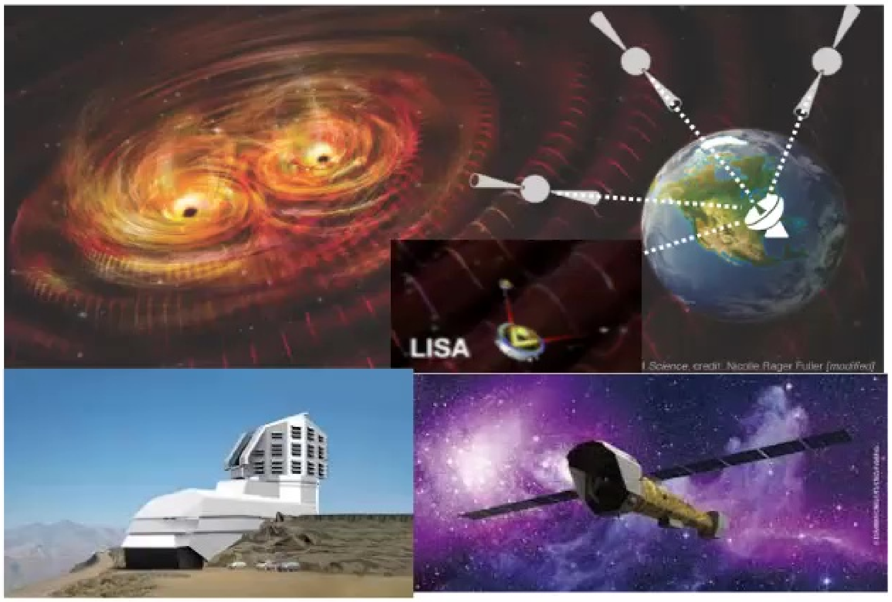


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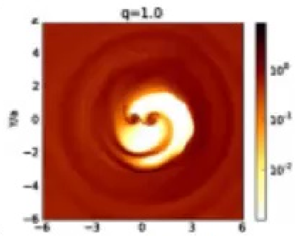
# Different strategies and techniques depending on what aspect of the system we want to investigate

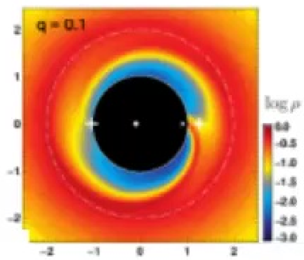
## Strategy & Techniques

Adapted from S. Noble's slides

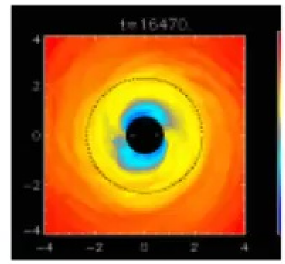
Hopkins, Hernquist, Di Matteo, Springel++



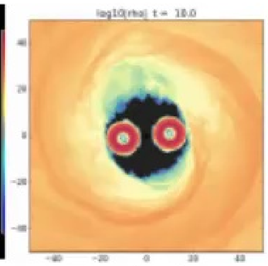

Ryan&Dittman (2021)
Farris++ (2014), D'Orazio++ (2013-15)
Muñoz ++ (2017-2019)
Moody++ (2019)



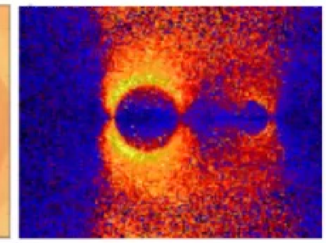

Shi & Krolik (2014-2016)



Noble++2012–15
Noble++2020-in-prep
Lopez Armengol++2020-



Bowen++(2018)
LC++ (2021a,2021b)
Lopez Armengol, LC++ (2021)



elly++2017
old++2014

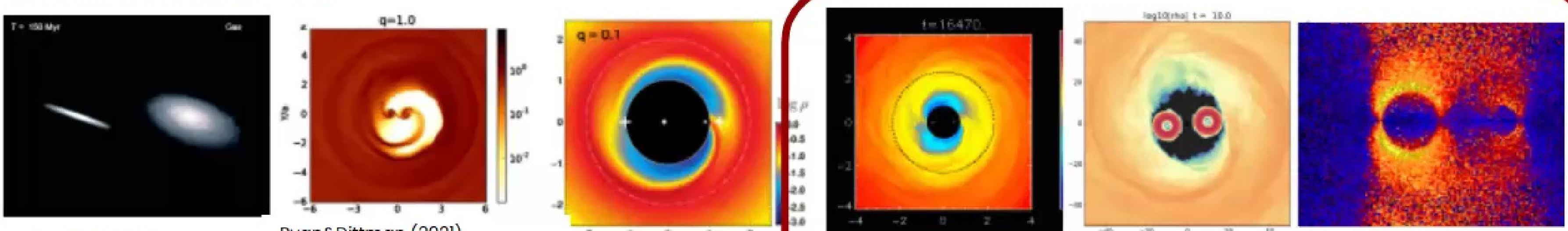
| | | | | |
|---|---|---|---|---|
| Matter: | Viscous Hydro. | MHD | GR MHD | GR MHD |
| Gravity: | Newtonian | Newtonian | Post-Newtonian | Numerical Relativity |

Different strategies and techniques depending on what aspect of the system we want to investigate

I will focus on this part

Adapted from S. Noble's slides

## Strategy & Techniques

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| **Matter:** | **Viscous Hydro.** | **MHD** | **GR MHD** | **GR MHD** |
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- ❑ System is highly non-linear : we need **simulations** to study it
- ❑ Close separations : GR effects are important.
- ❑ Different timescales: circumbinary disk - accretion around binary
  mini-disk - accretion around black holes

# Investigating accretion close to merger and their EM observables

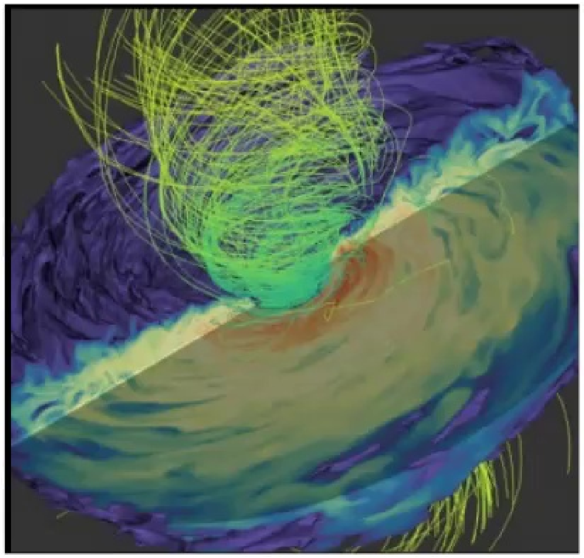
At close separation (<~ 20 rg) inspiral is relatively fast. We need GRMHD simulations.

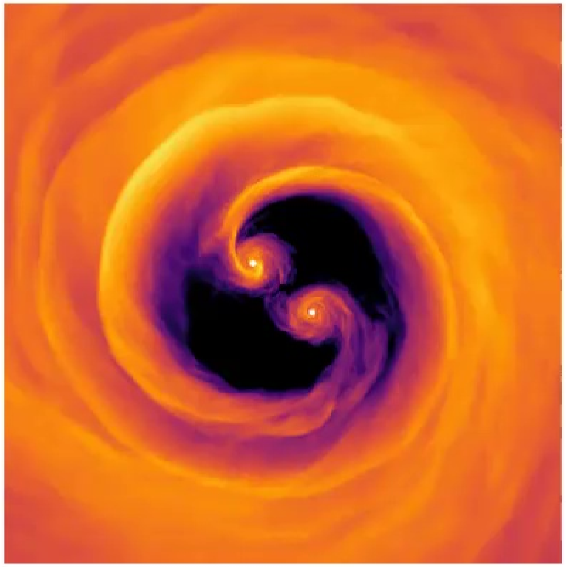
## Key questions:

*How much accretion is there in this stage?
*How does spin affect accretion?
*What are the variability signatures?
*Are there imprints of the binary variability in the jet emission?

**This is the focus of our work**

(LC+PRD 2021, LC+2021 ApJ (submitted), Armengol, LC+ 2021 ApJ, Gutierrez. LC +2021 (in prep)





Our goal is to investigate accretion onto *spinning* supermassive binary black holes close to merger and produce concrete EM predictions.

# Methods

We follow these steps:

1) Model approximate spacetime metric for spinning BBHs

2) ***Long-term*** *(>100 orbits)* GRMHD simulations of circumbinary disk accretion.

3) GRMHD simulation resolving physics near the black holes to analyze **mini-disk accretion**.

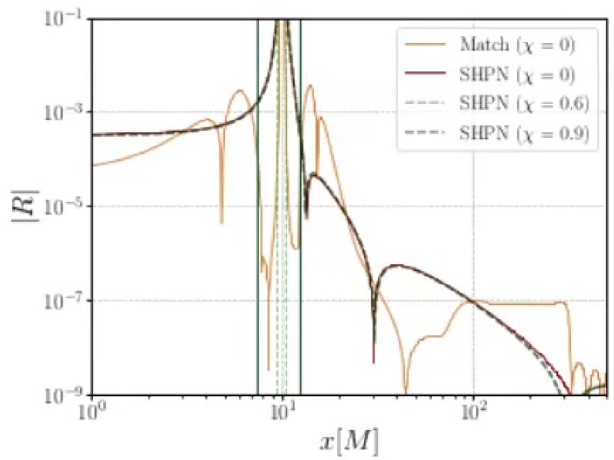
4) Use ray-tracing to obtain EM observables.

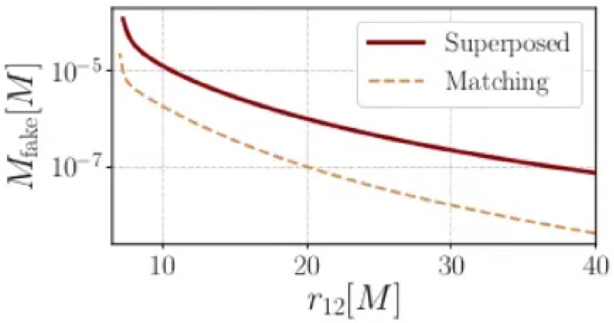
# Approximate analytical spacetime of a binary black hole system.

Instead of solving Einstein's equation numerically, we build an approximate metric describing a spinning binary black hole through a boosted superposition:

$$g_{ab} = \eta_{ab} + M_1 \mathcal{H}^1_{ab}(\vec{x}_1, \vec{v}_1) + M_2 \mathcal{H}^2_{ab}(\vec{x}_2, \vec{v}_2),$$

1. The metric uses **Post-Newtonian trajectories.**
2. Well-defined at every point in space, even at the BH horizon. Good enough for separations > 15 M, in the inspiral regime.




**We use this metric as a background spacetime for MHD simulations**

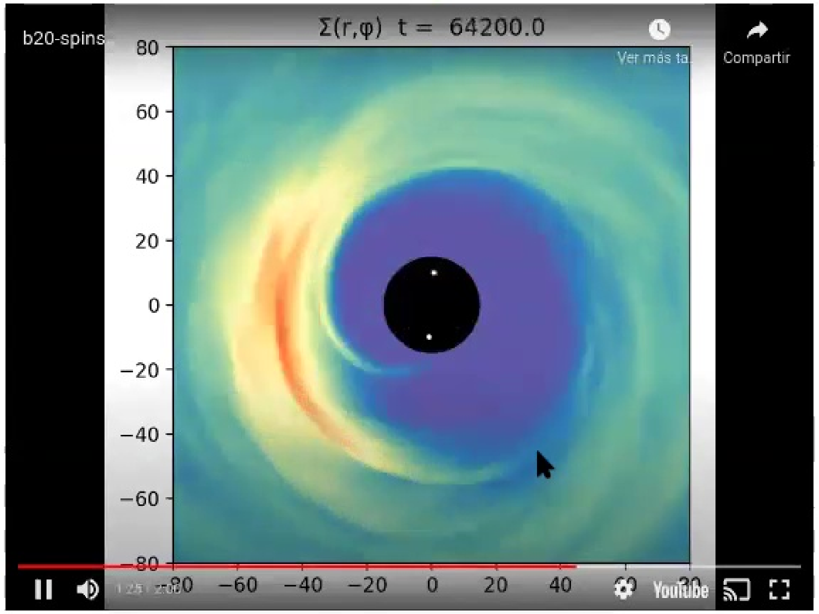
**REF:** LC et al, Phys. Rev. D 104, 044041 (2021)

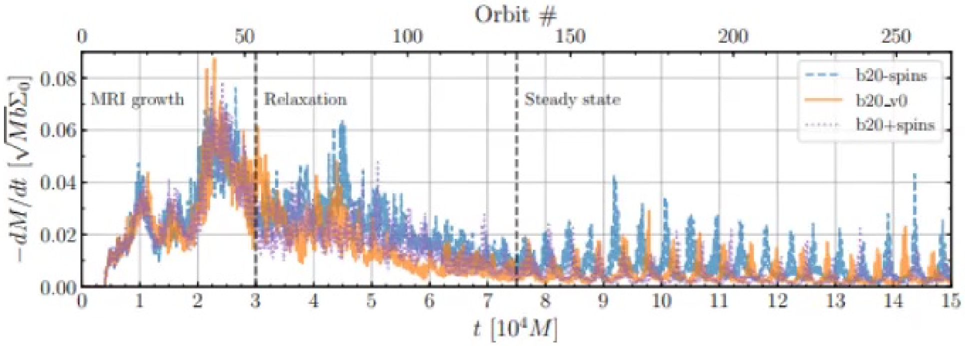
# Long-term simulation of circumbinary disk: the influence of spins

## Full 3D GRMHD simulations with the finite-volume code **Harm3D**

Allows us to analyze the circumbinary region of the system for many orbits and effects of spin

1. We found that the system enters steady state only after ~150 orbits
2. Accretion rate into the cavity is decreased (enhanced) for aligned (anti-aligned) spins of a = 0.9 M. This is due to the influence of frame-dragging on the streams.
3. Bulk properties in the circumbinary disk are not affected by spin as expected.




**REF:** Armengol, LC, et al, ApJ 913 (1), 16 (2021)

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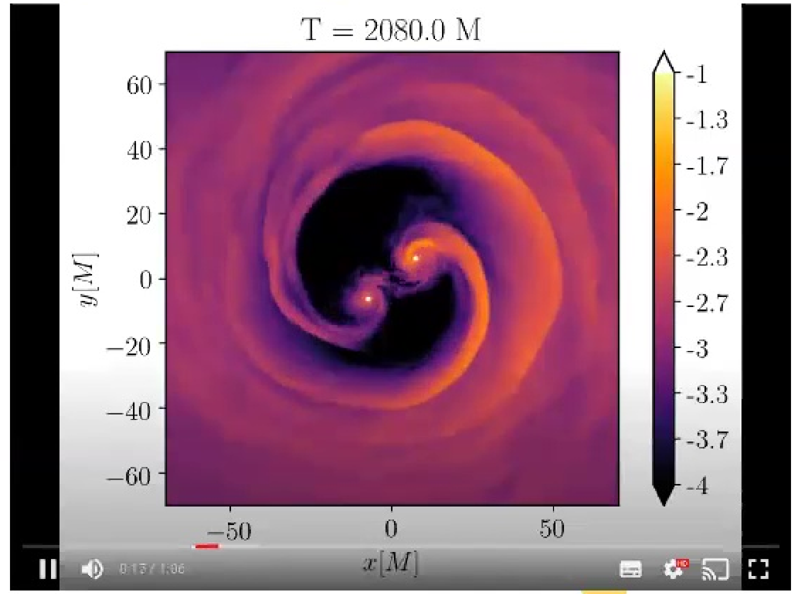


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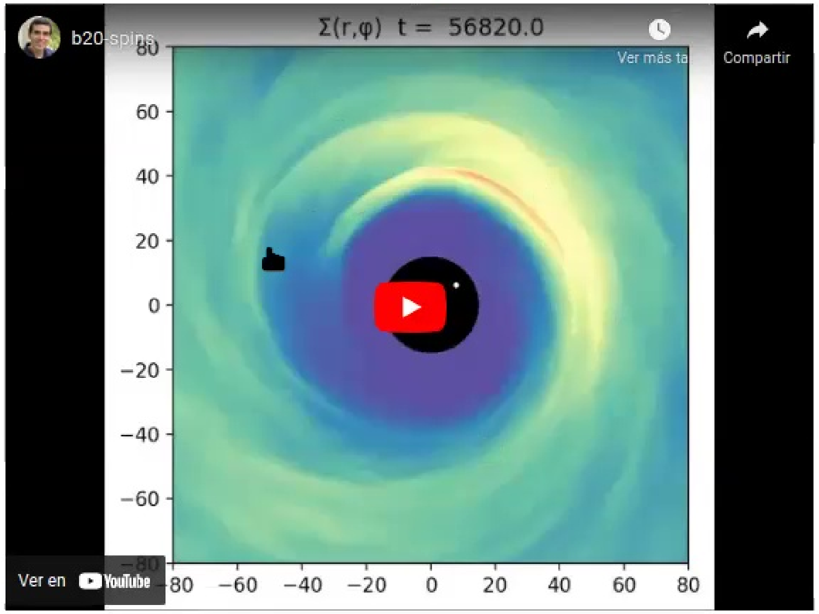


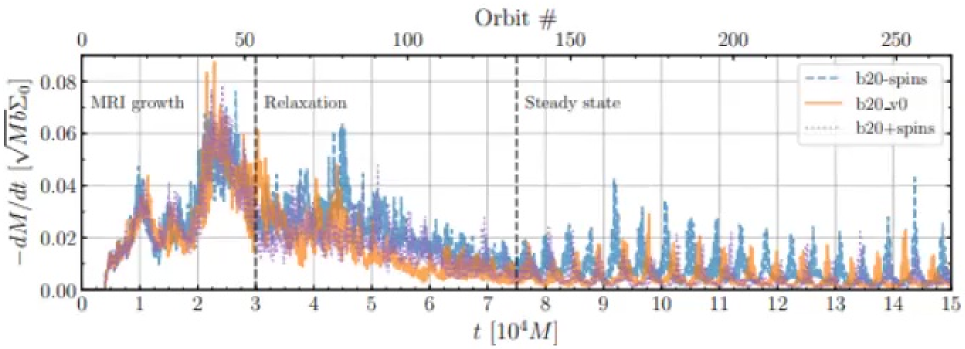


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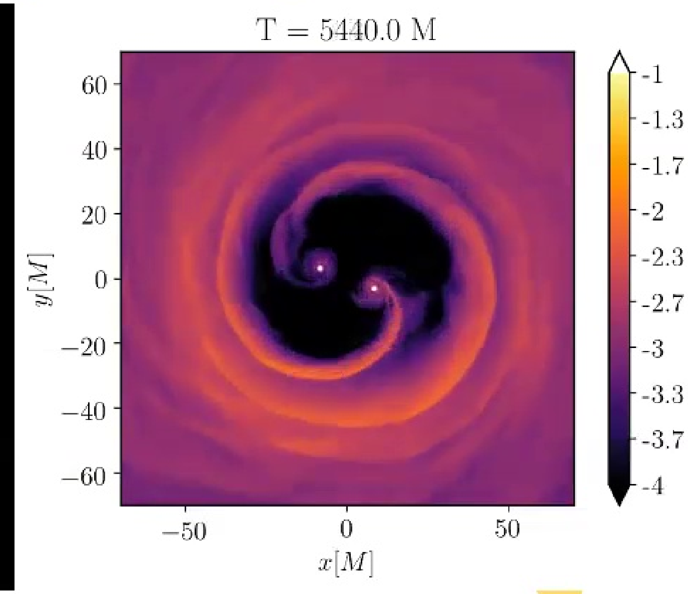


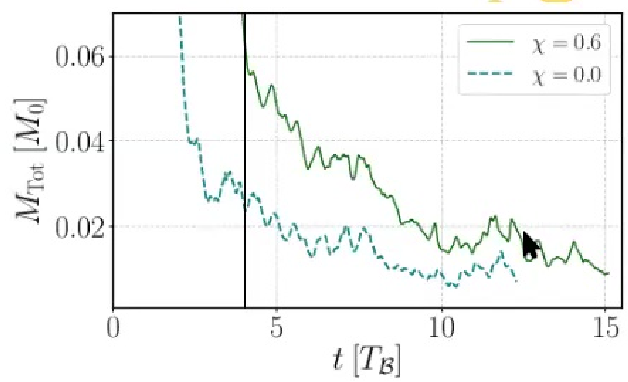

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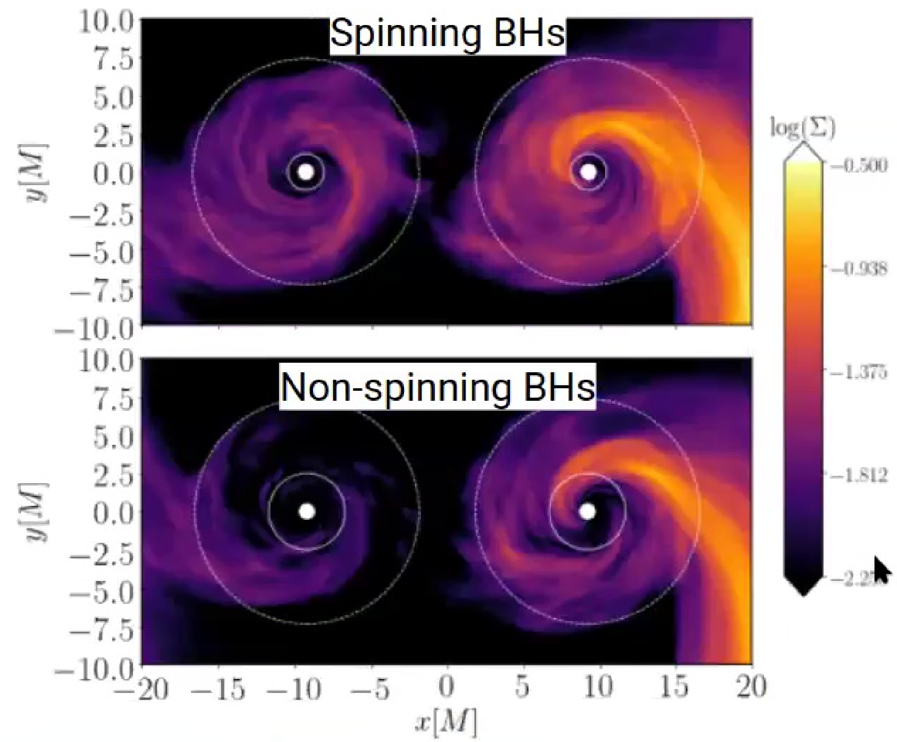


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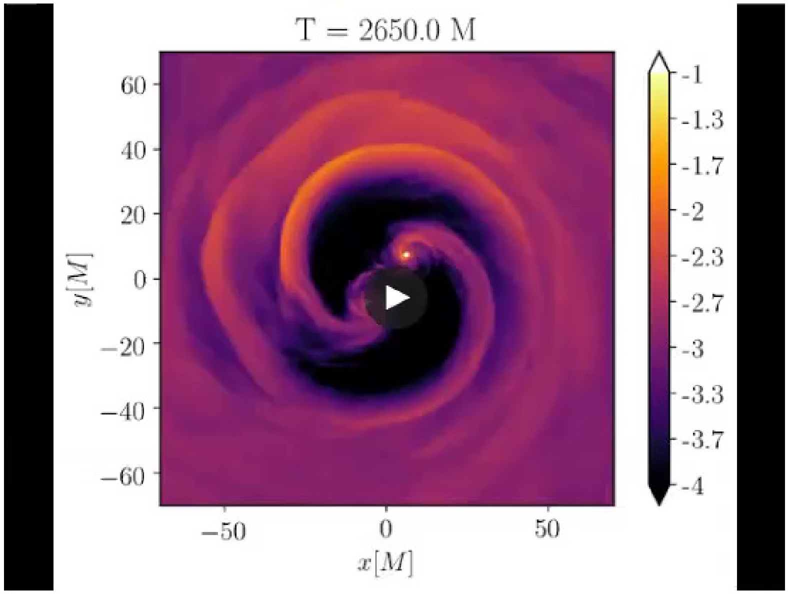


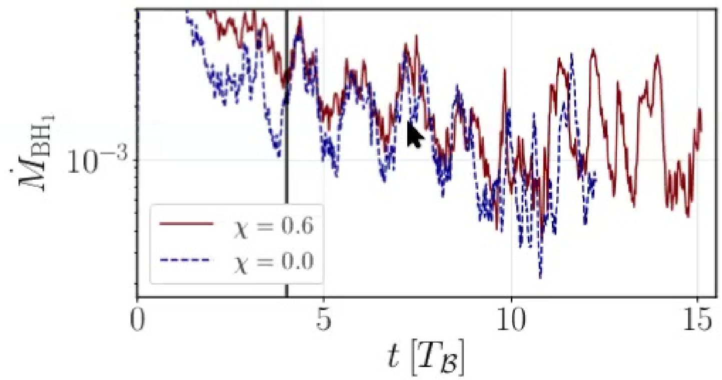


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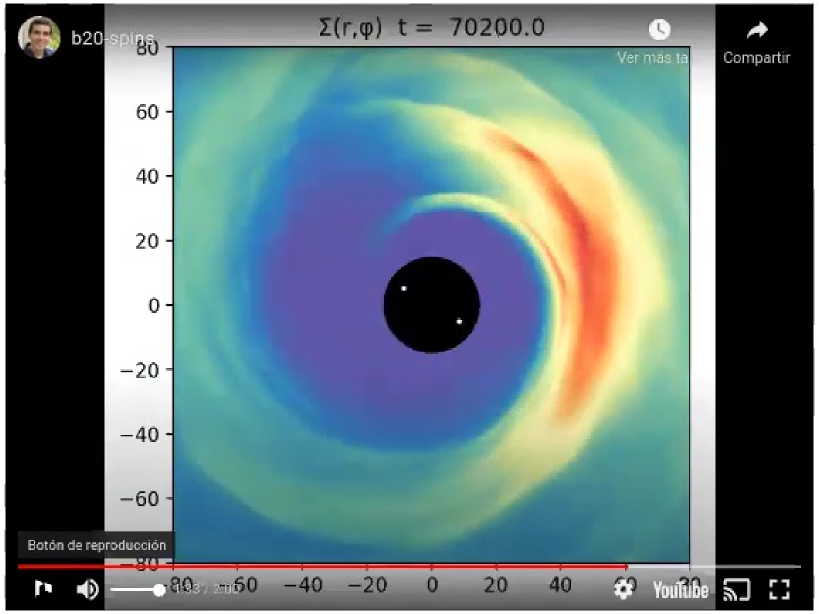


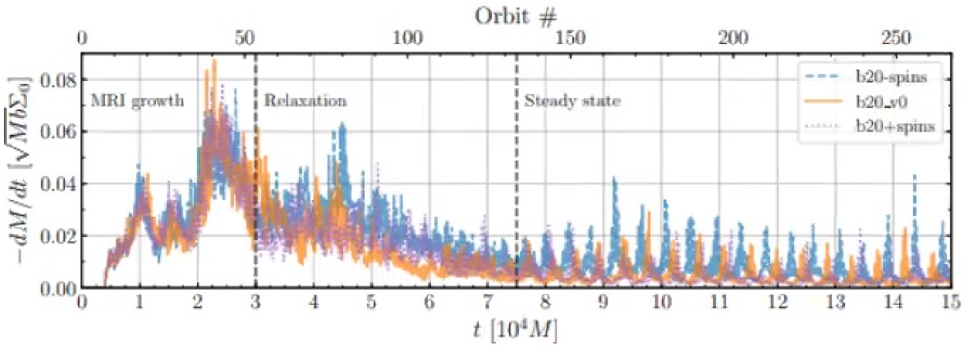


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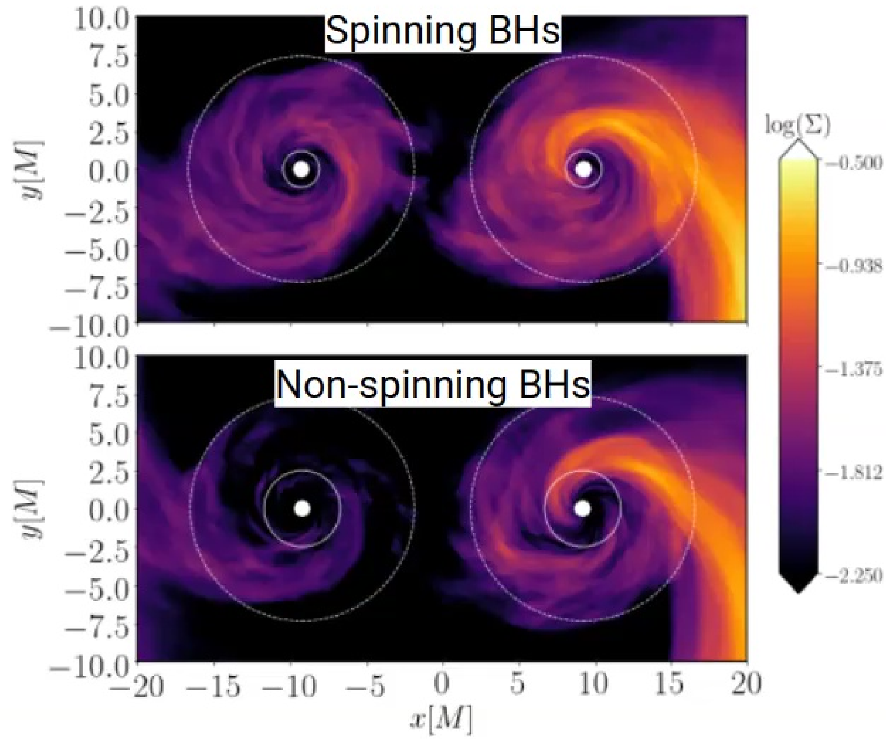


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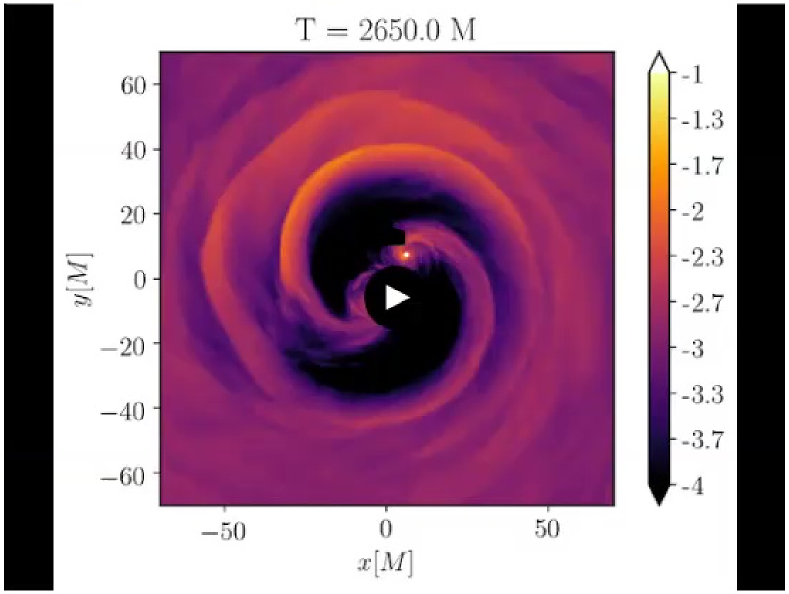


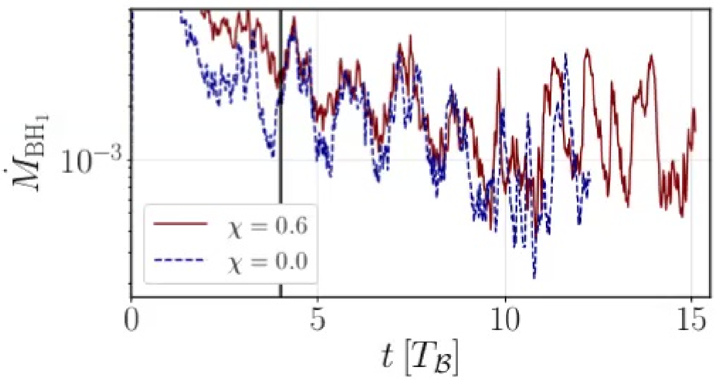


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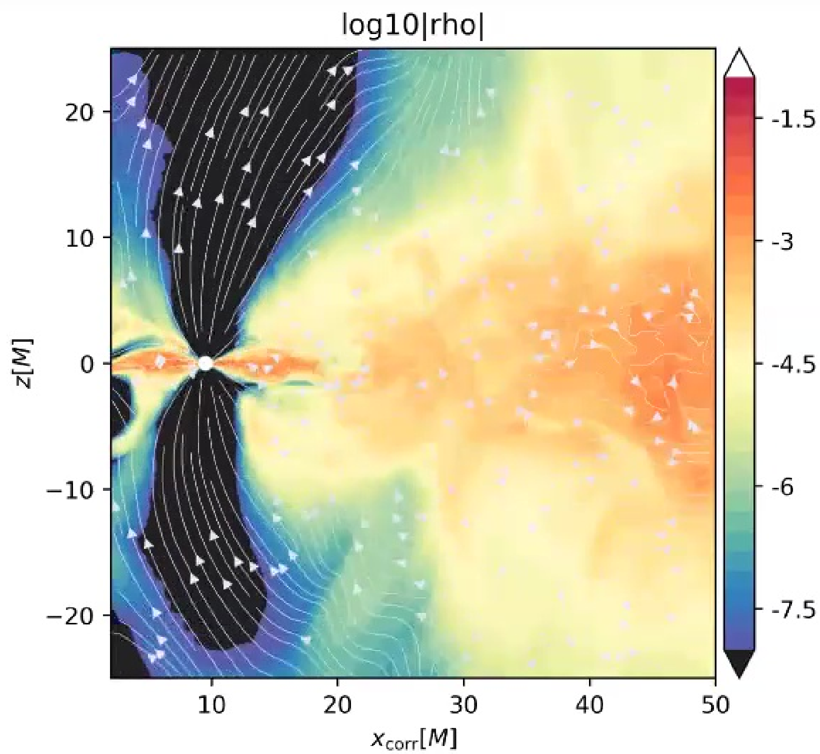


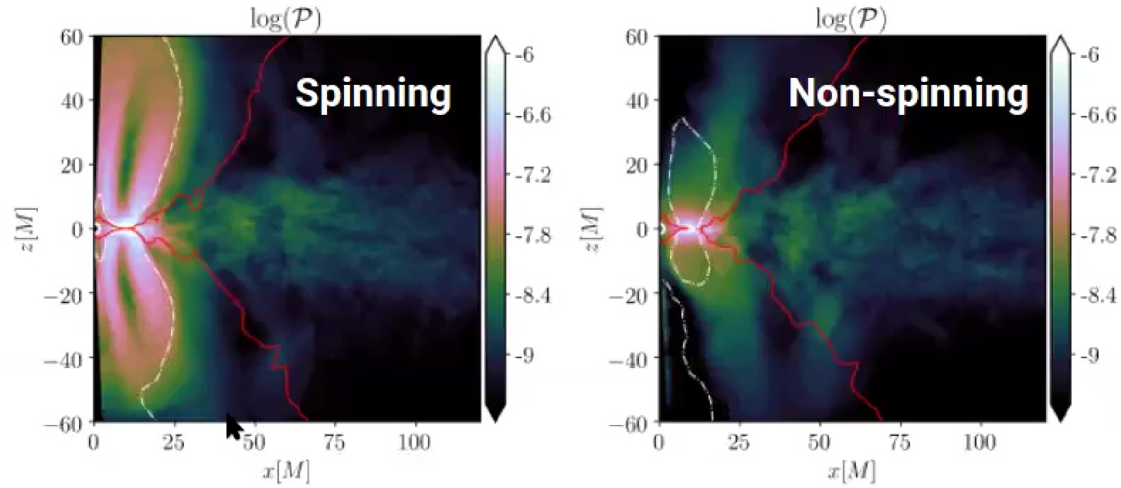


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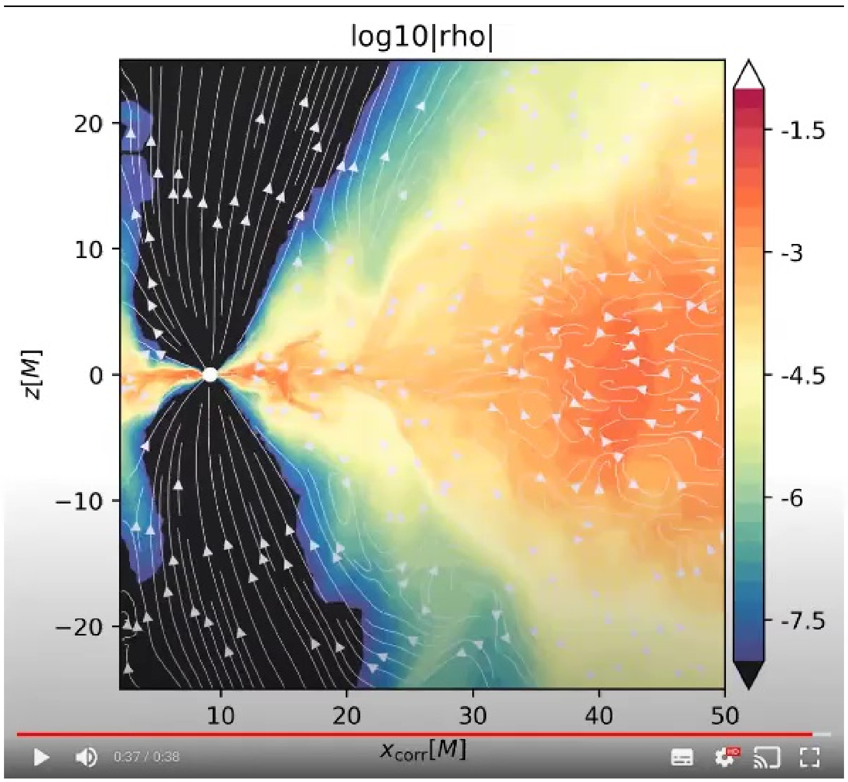


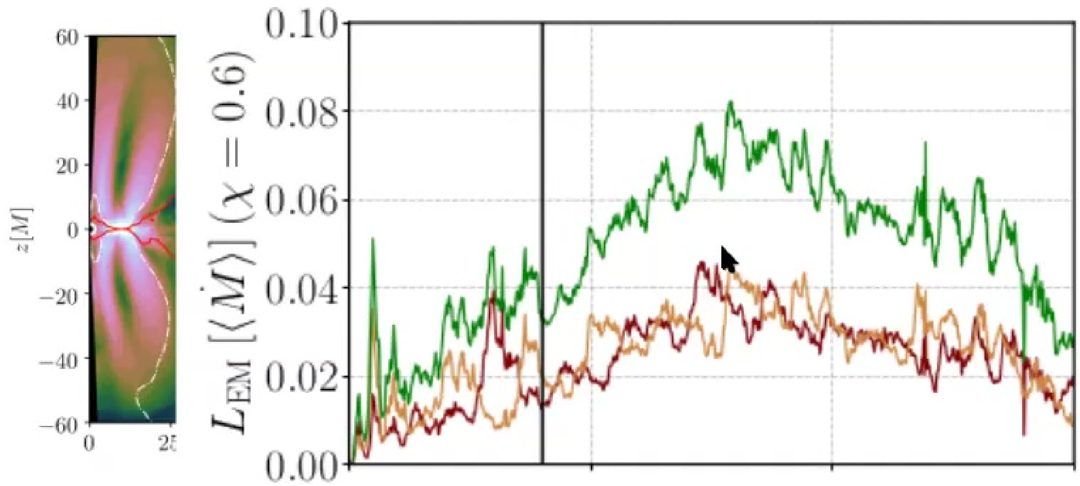


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## **Electromagnetic predictions** through ray-tracing of GRMHD simulations

(**REF**: Gutiérrez, LC, Noble et al, in prep (2021))

Camera-to-source approach

Geodesic equation

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0,$$

Radiative transport equation

$$\frac{dI}{d\lambda} = j - \alpha I$$

Low-accretion rate systems **(Opt. thin)**

High-accretion rate systems **(Opt. thick)**

**We use the code Bothros (Noble+ 2017, dAscoli+ 2018)**

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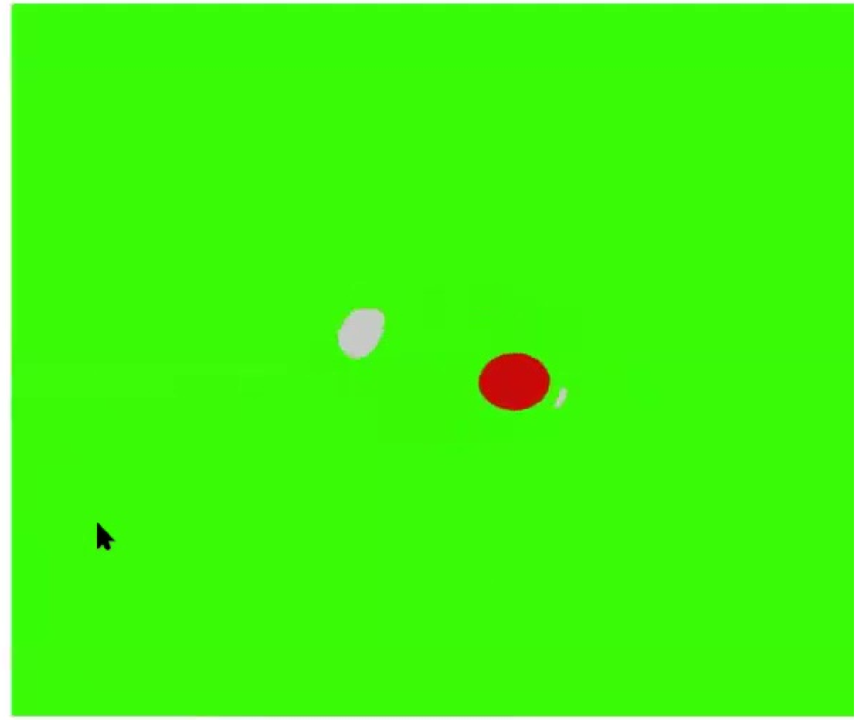

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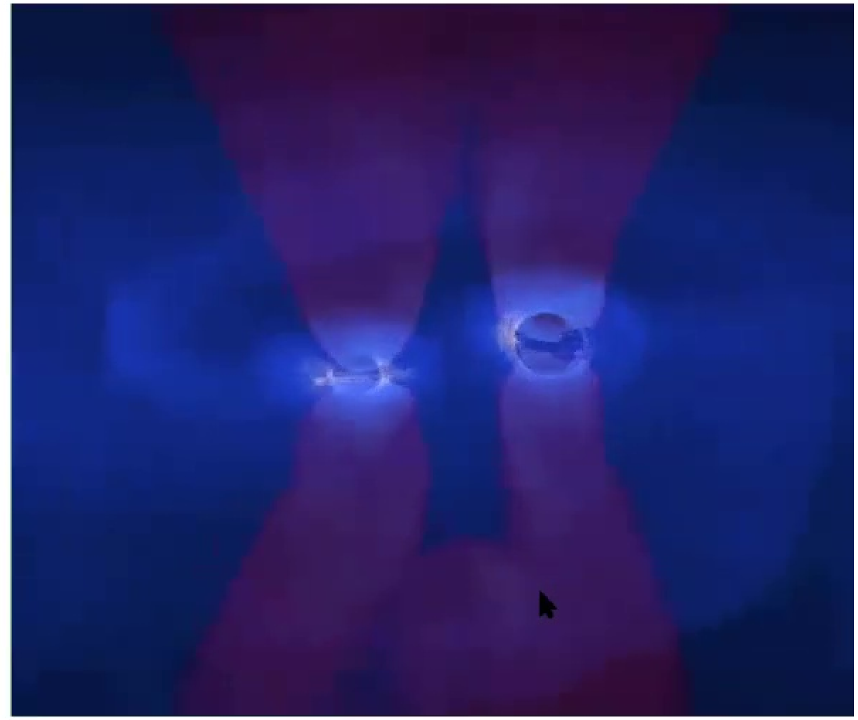

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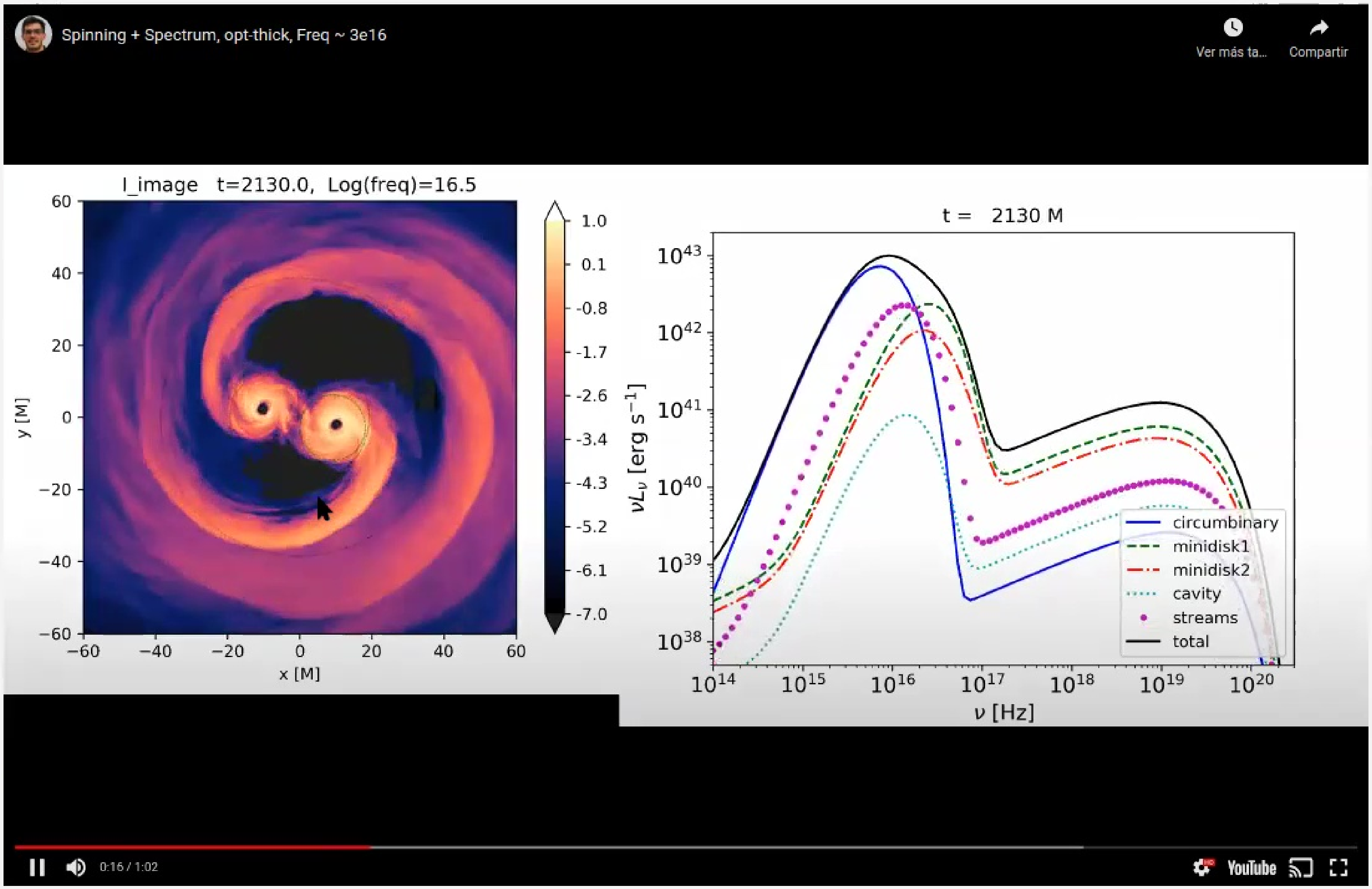
# **Optically Thick Emission**




Face-On

Spinning (a=0.6)

**Data from Combi+ (2021)**

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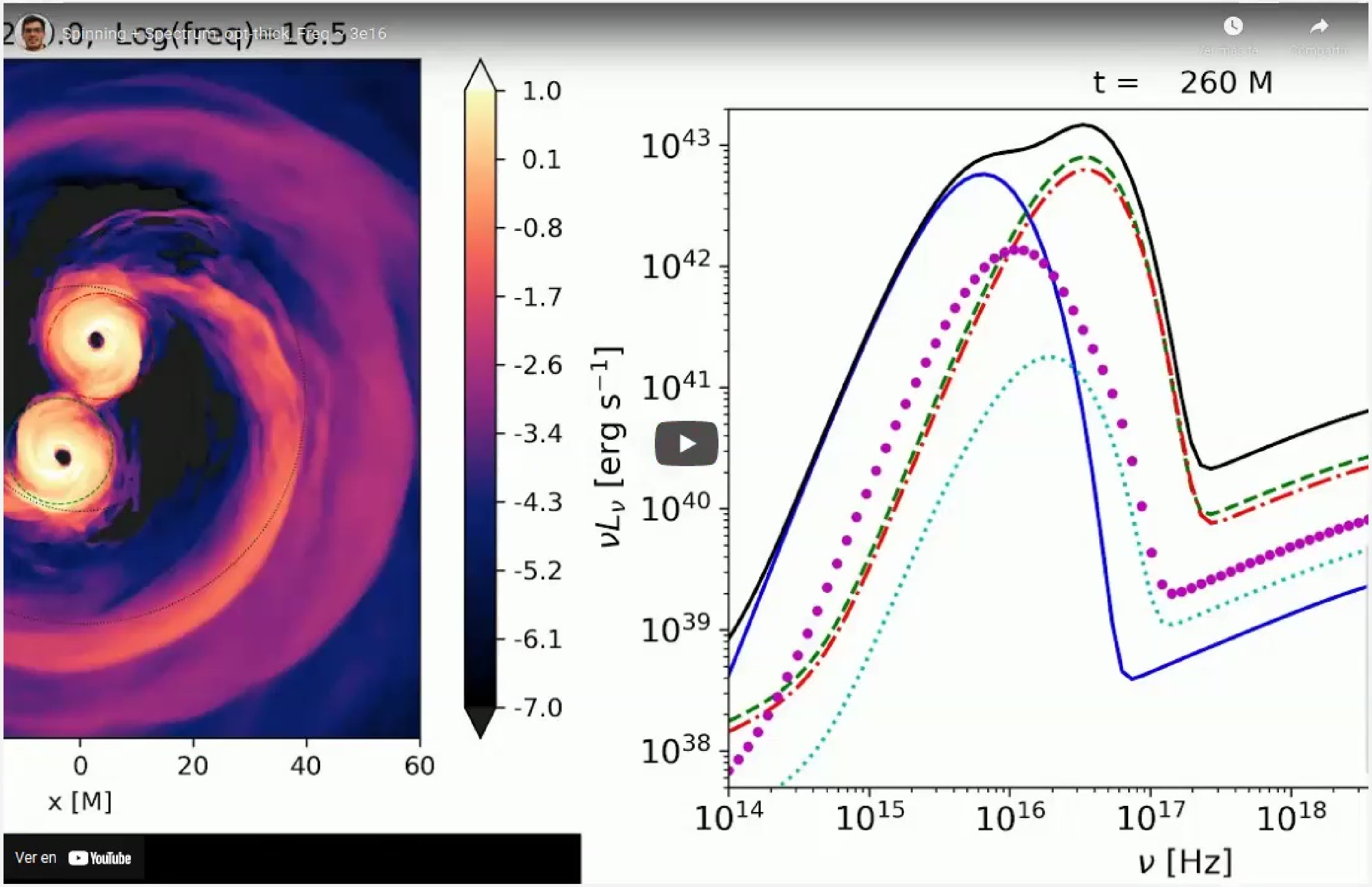
**Data from Combi+ (2021)**

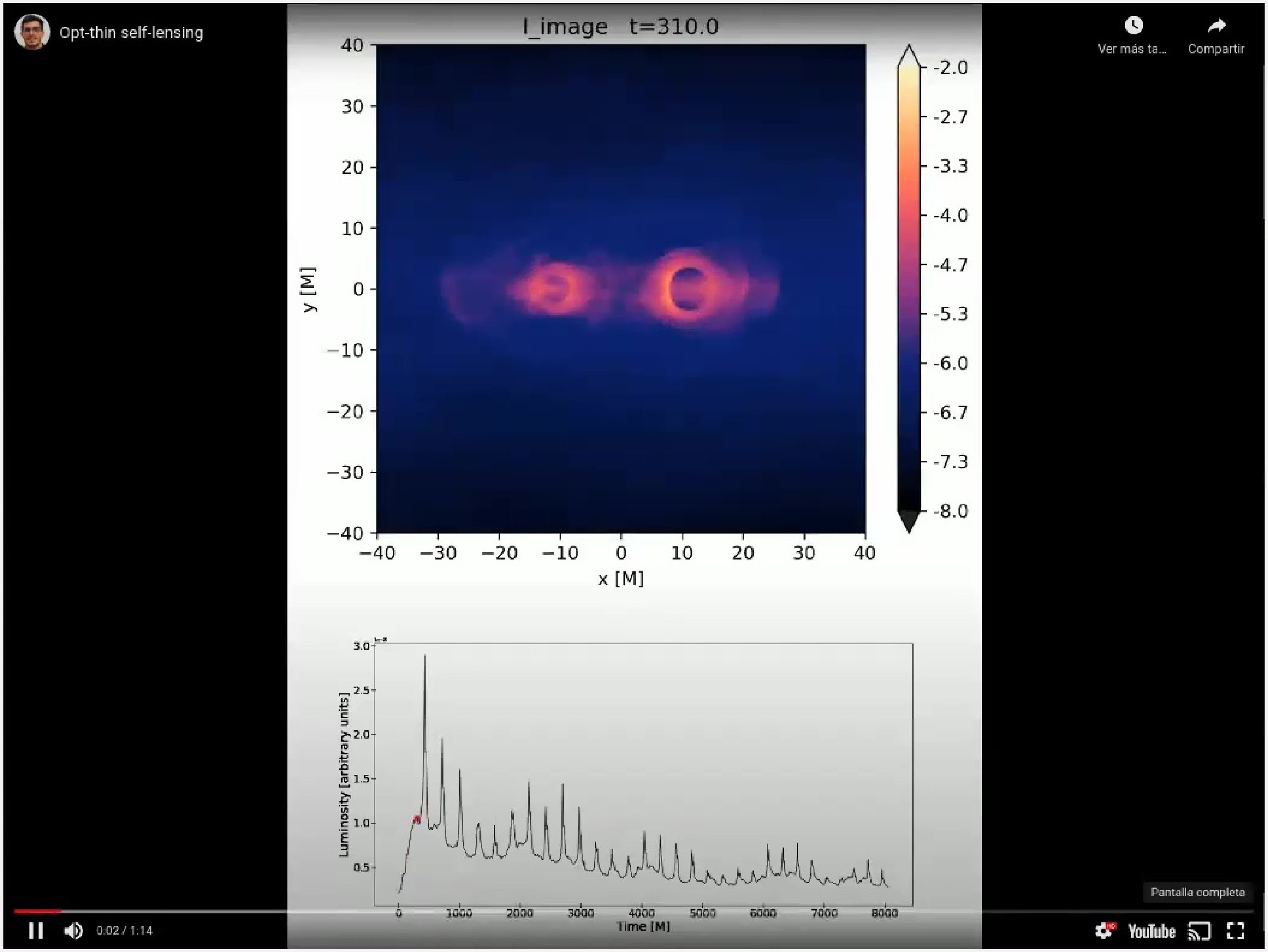


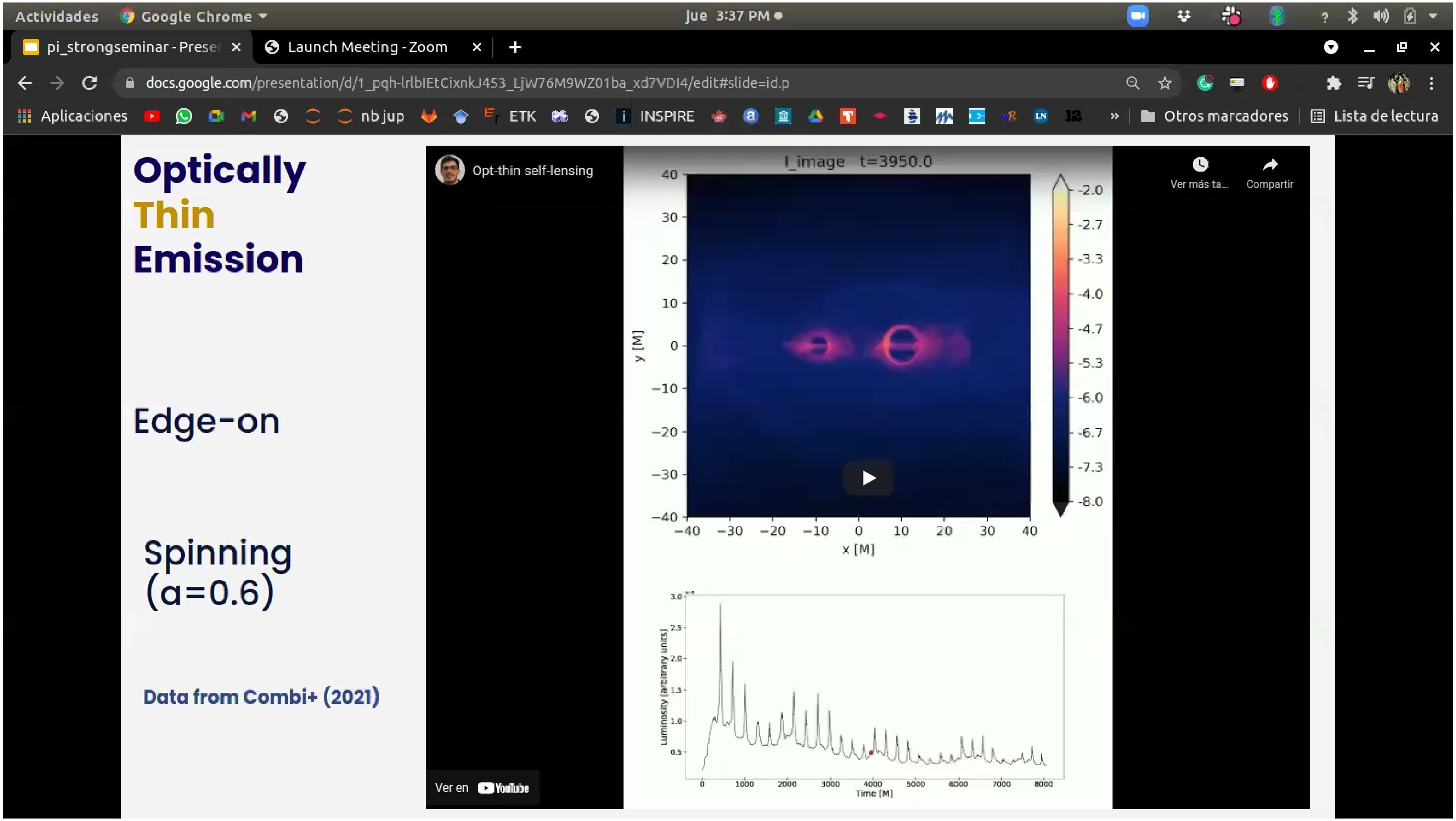
# **Optically Thin Emission**

Edge-on

Spinning (a=0.6)

**Data from Combi+ (2021)**




Optically
Thin
Emission
Edge-on
Spinning
(a=0.6)
Data from Combi+ (2021)
Opt-thin self-lensing
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y [M]
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# PART II:

# GRMHD simulations of neutron star mergers

## Observables from the dynamical ejecta and post-merger phase

# **Electromagnetic predictions** through ray-tracing of GRMHD simulations

(**REF**: Gutiérrez, LC, Noble et al, in prep (2021))

Camera-to-source approach

Geodesic equation

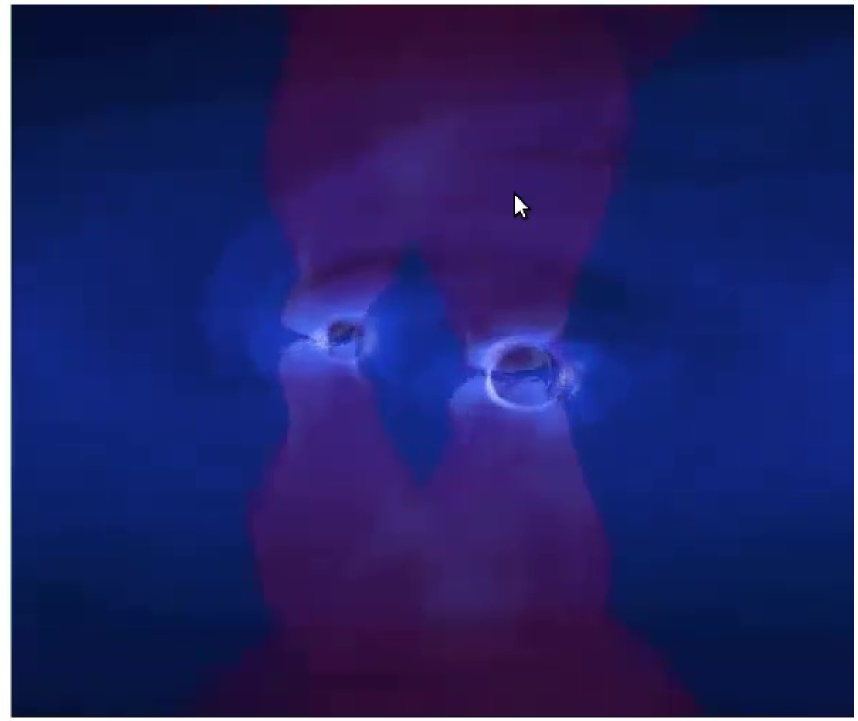
$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0,$$

Radiative transport equation

$$\frac{dI}{d\lambda} = j - \alpha I$$

Low-accretion rate systems **(Opt. thin)**

High-accretion rate systems **(Opt. thick)**



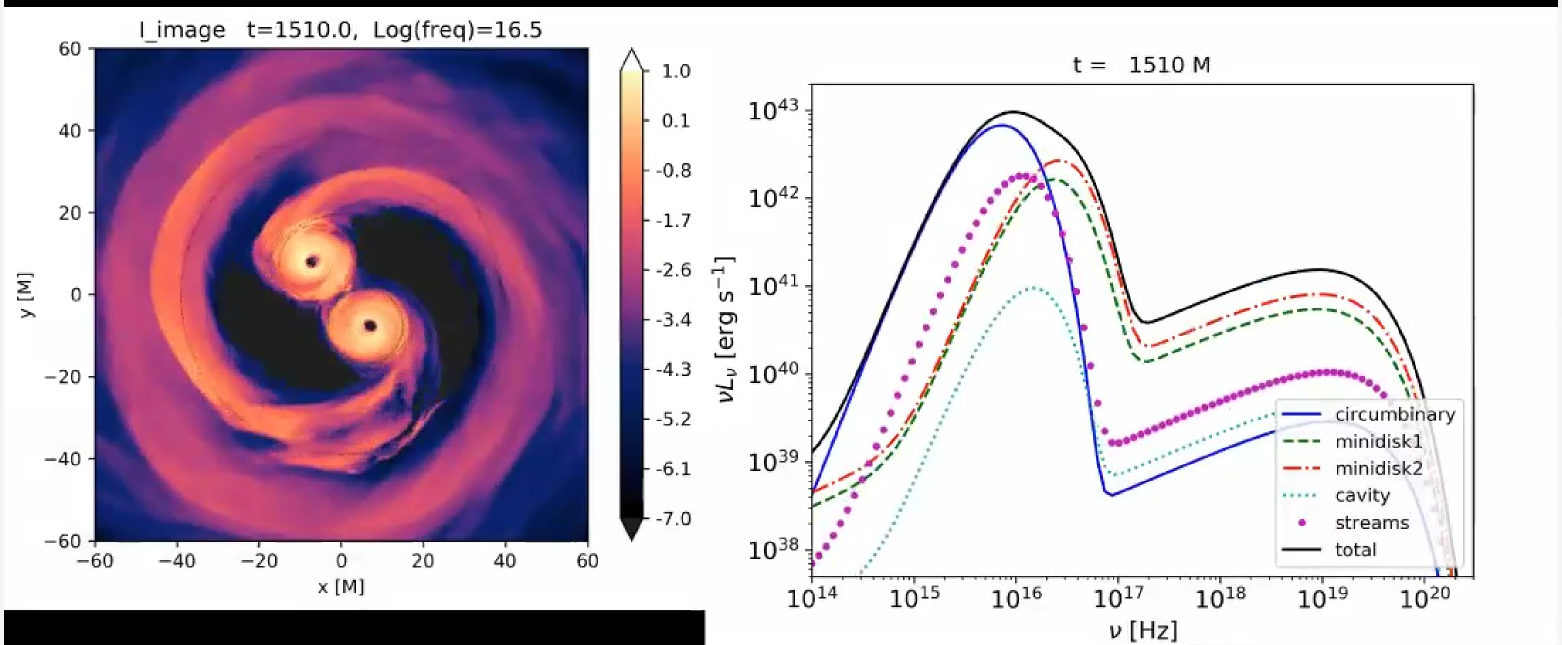
`We use the code Bothros (Noble+ 2017, dAscoli+ 2018)`

# Optically Thick Emission

Face-On

Spinning (a=0.6)

**Data from Combi+ (2021)**

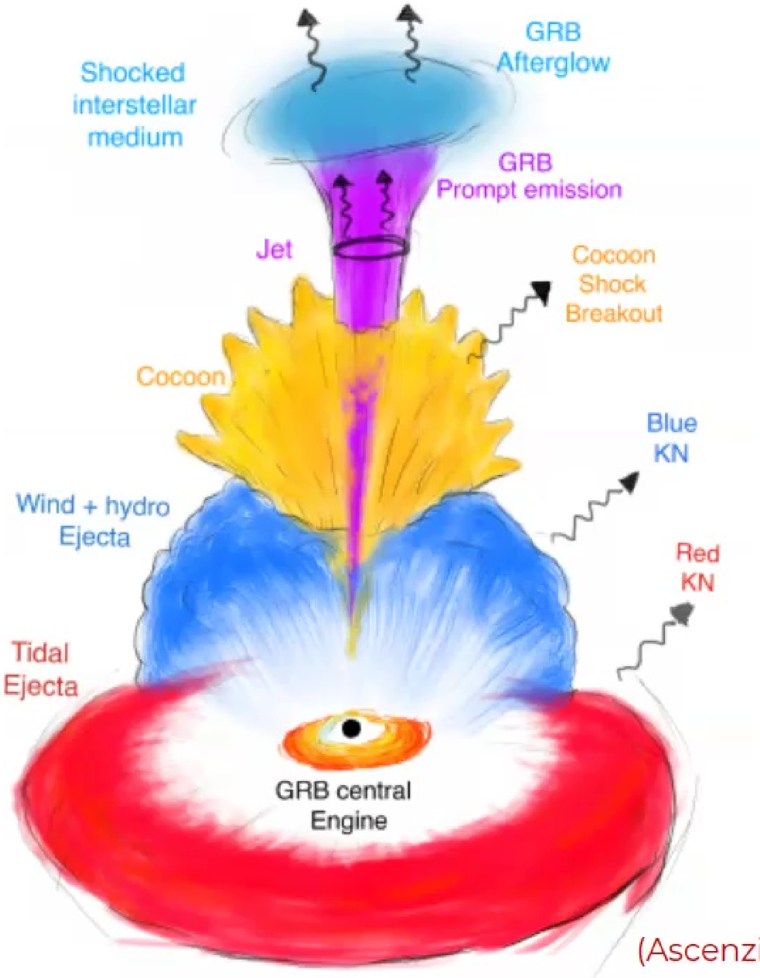


# PART II:

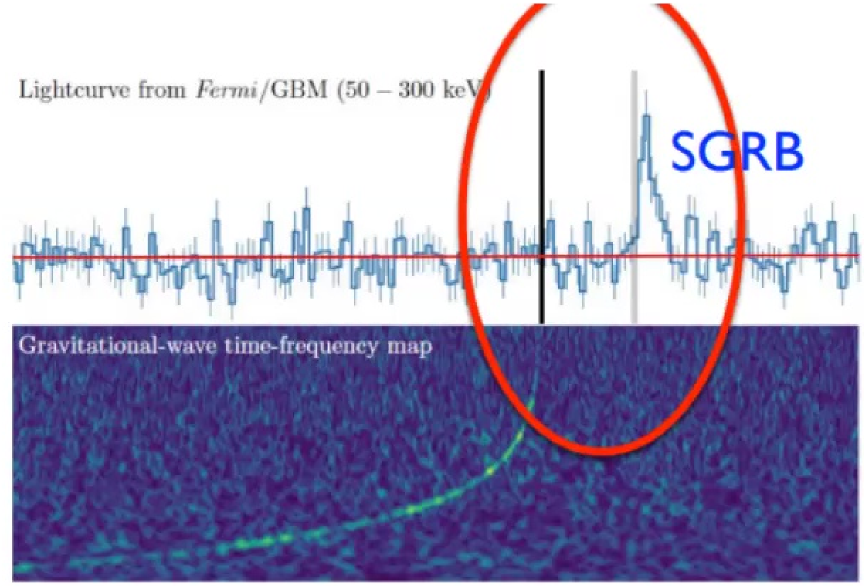
# GRMHD simulations of neutron star mergers

## Observables from the dynamical ejecta and post-merger phase

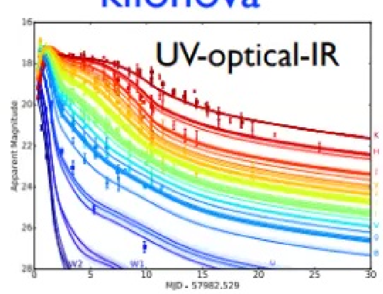
# Fireworks from GW170817



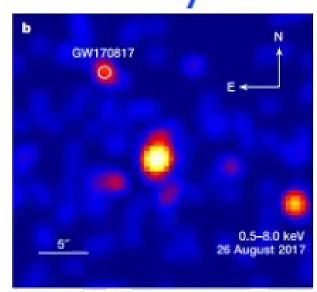

(Ascenzi+21)



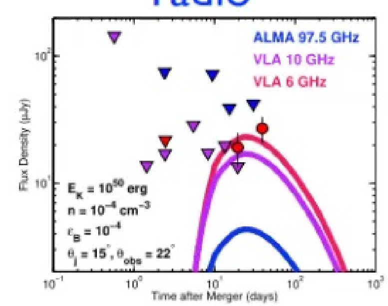

kilonova



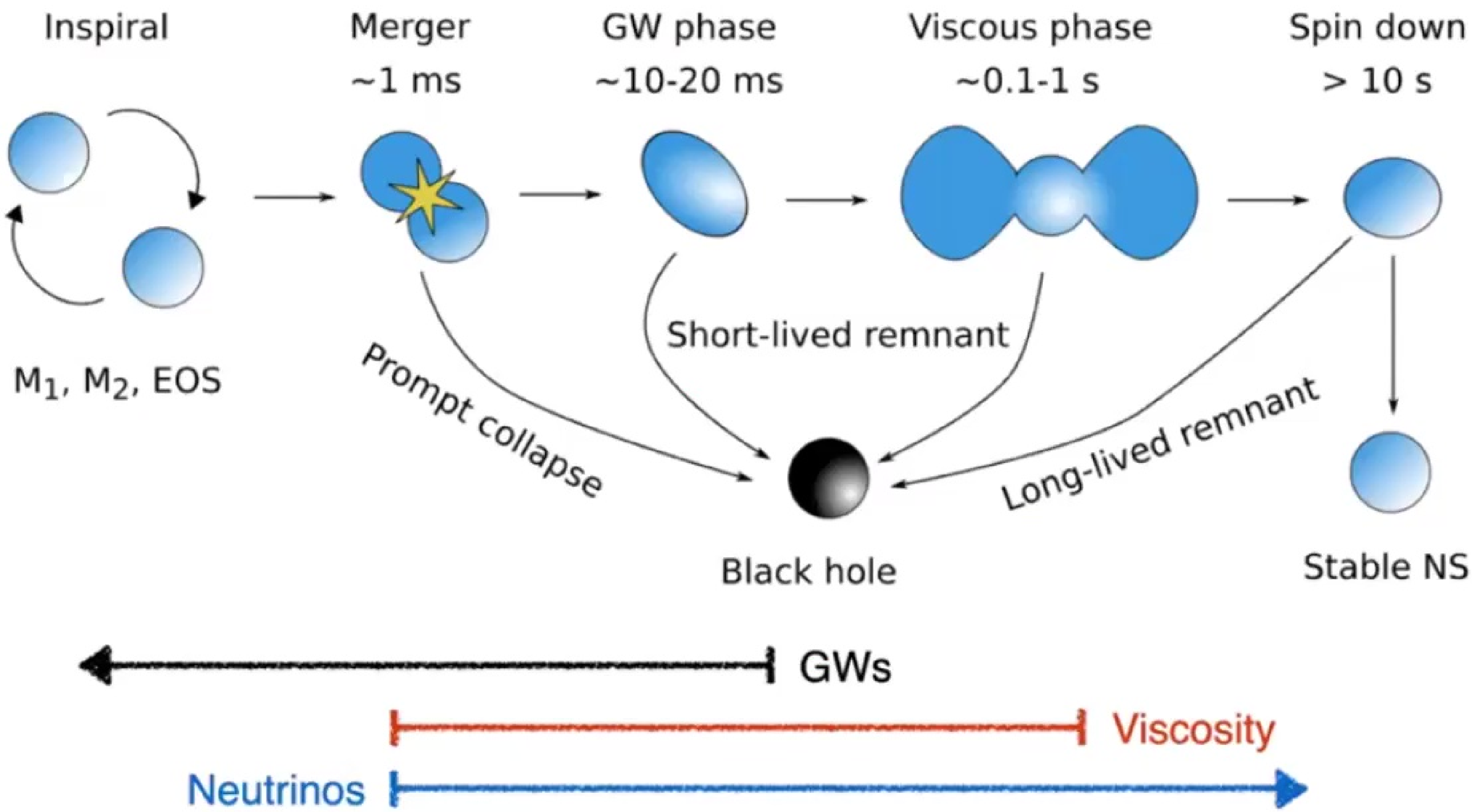

X-rays




radio

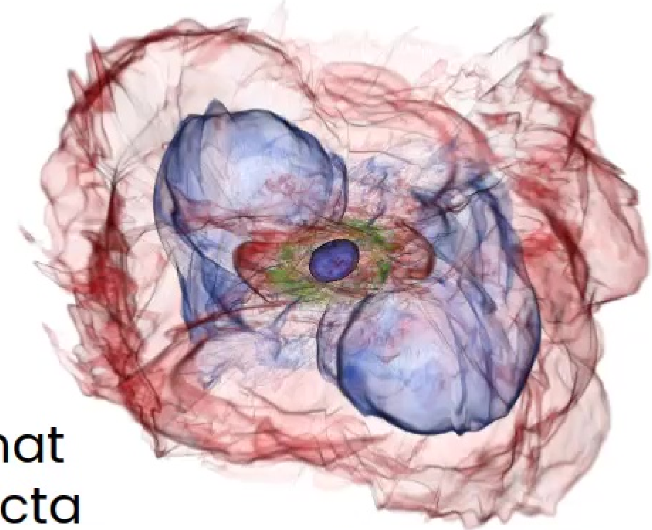


# Phases of the merger and types of ejecta



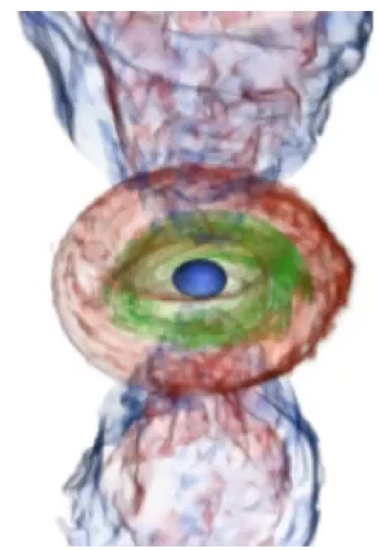

(Radice+20)

Investigating observables signatures from dynamical and post-merger ejecta only possible through simulations.



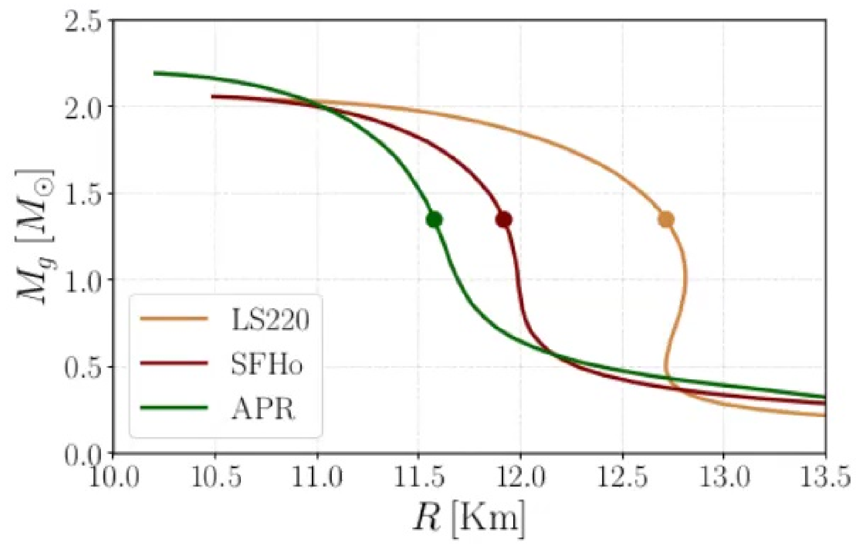
## Open questions:

1) What is the nature KN precursors?
2) How do KN ejecta give rise to radio emission that would allow independent measurement of ejecta masses?
3) How do remnants collapse? (relevant for EOS constraints based on EM data)
4) Non-linear hydrodynamics and mass ejection: fully self-consistent treatment of all ejection mechanisms
5) What is the dominant site of the r-process? first comprehensive nucleosynthesis analysis from mergers

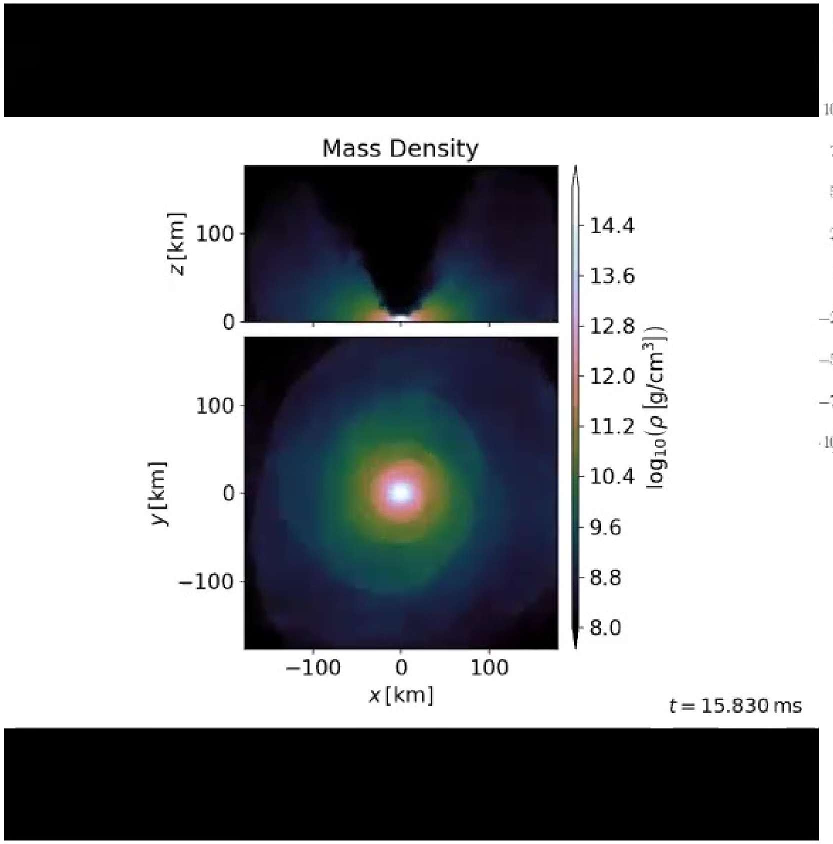


**In this work**
(Combi & Siegel 2021, in prep)**:**

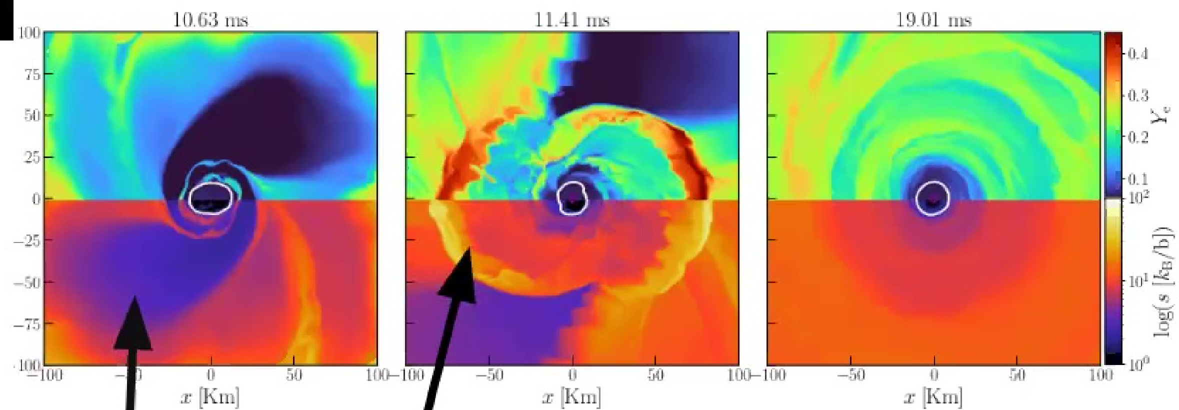
- ❑ We simulate equal-mass BNS using three different **realistic nuclear equations of state** (SFHo, APR4, LS220).
- ❑ We use an approximate scheme for **neutrino transport** (M0).
- ❑ We evolve the BNS with magnetic fields (buried in the star, Binit ~10^15 G)
- ❑ We use tracer particles to analyze the ejecta and use a nuclear reaction network to compute nucleosynthesis



# Characterizing the dynamical ejecta: electron fraction

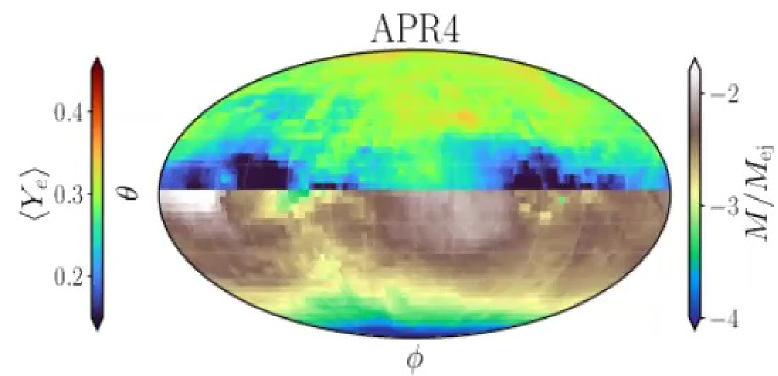



If EOS is soft, then shock breakthrough reprocesses tidal ejected material to higher Ye on a preferential direction.



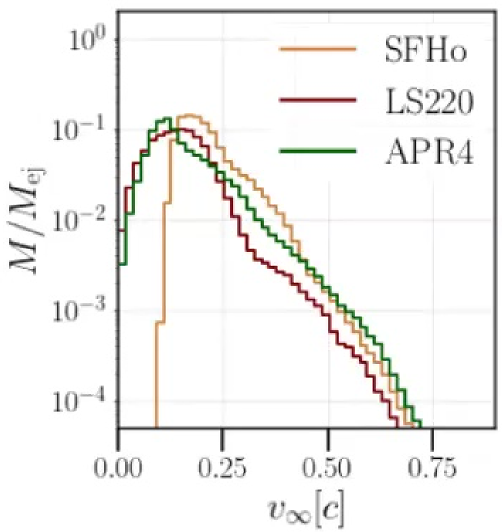

Tidal

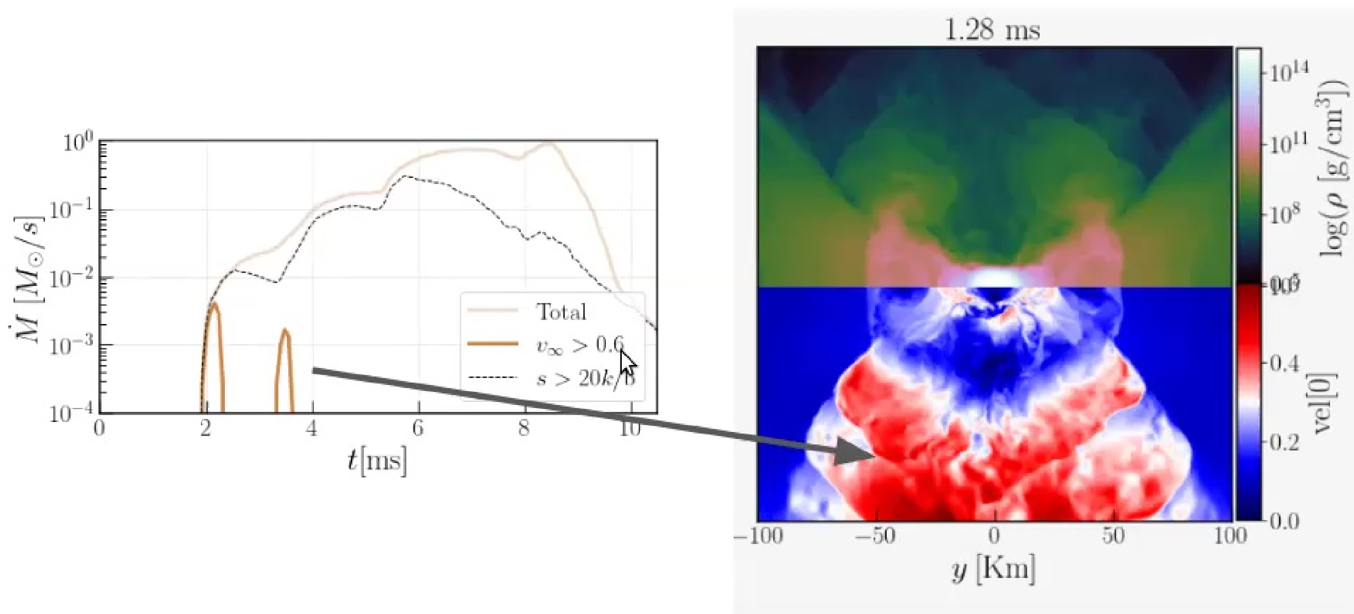
Shock-heated



# Characterizing the dynamical ejecta: fast ejecta

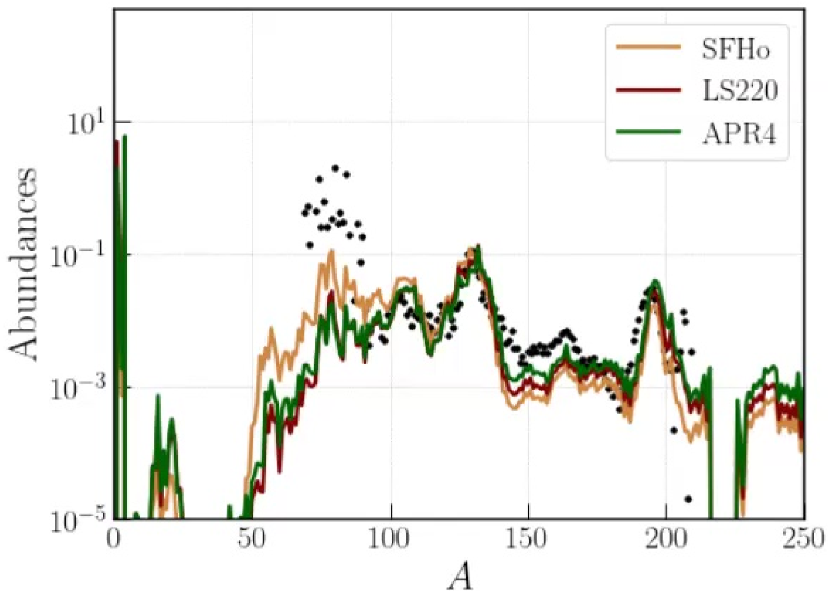
If EOS is soft, first two strong bounces generate fast ejecta

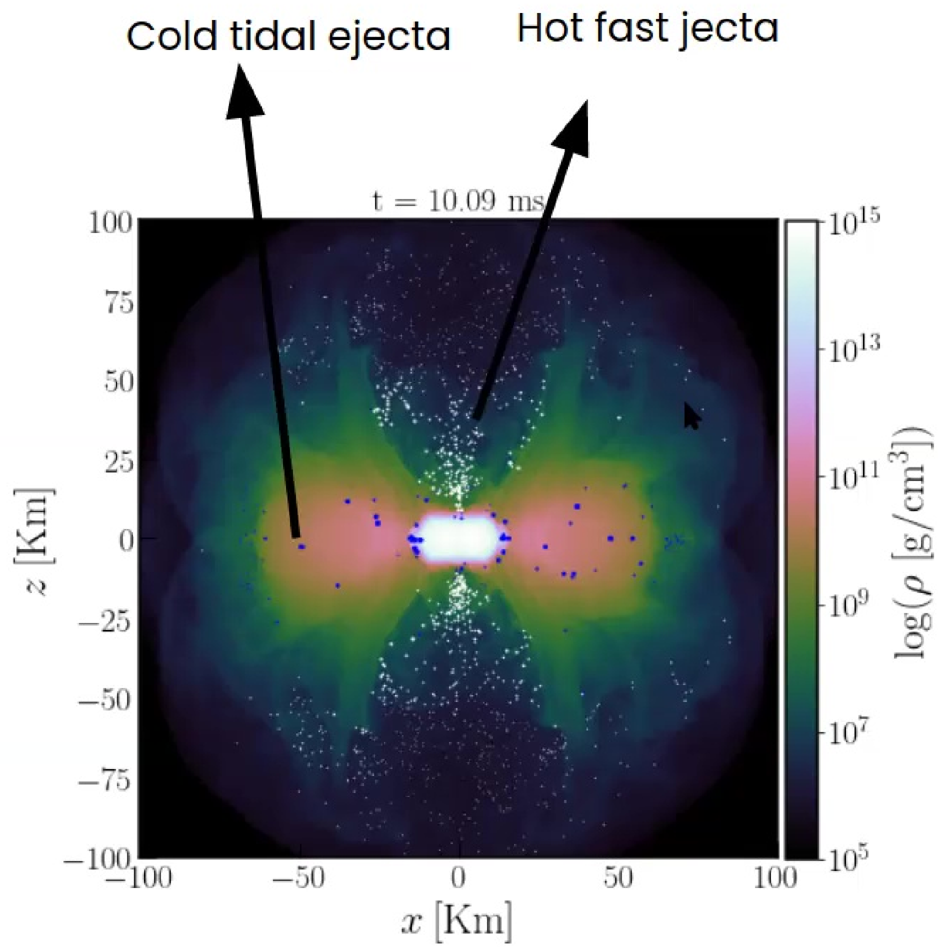


# Nucleosynthesis analysis

We use tracer particles to sample the different parts of the ejecta. Then we use these as initial data for our nuclear reaction network `SkyNet` to compute the nuclear products

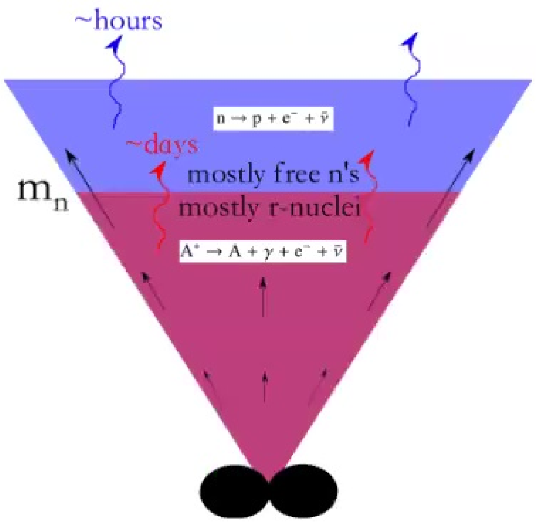


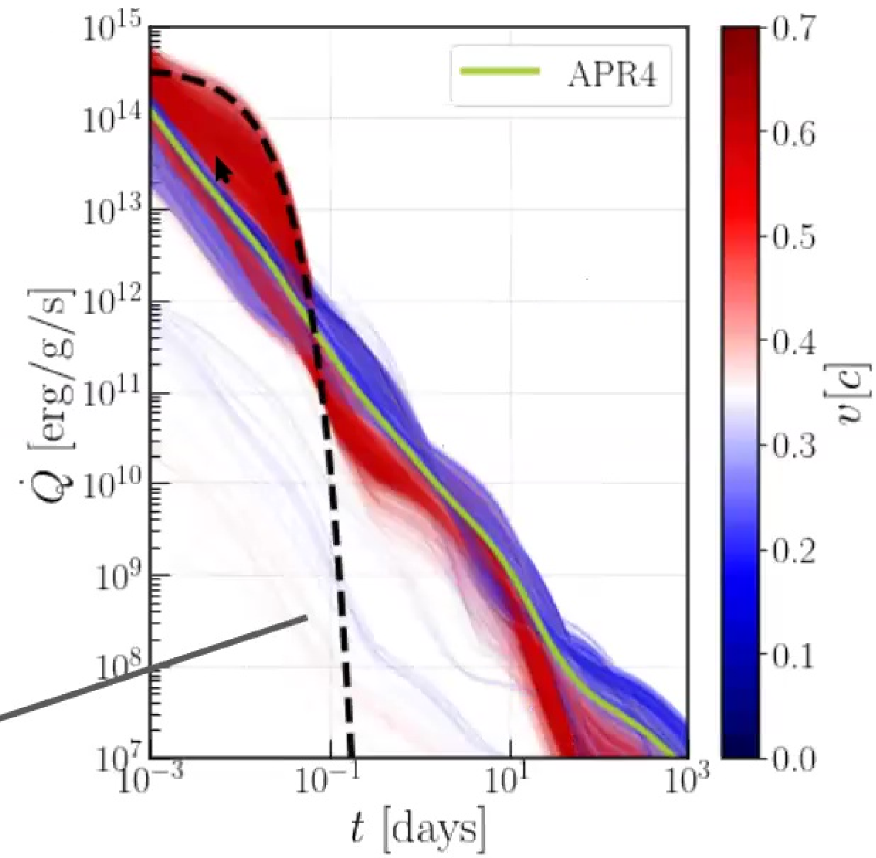
# Free neutrons production: early UV emission?

From `SkyNet` we can obtain the fraction of the ejecta that results in free neutrons (~5 * 10^-5 Msun)

*Free neutrons can then produce an early UV transient (Metzger+2015)*

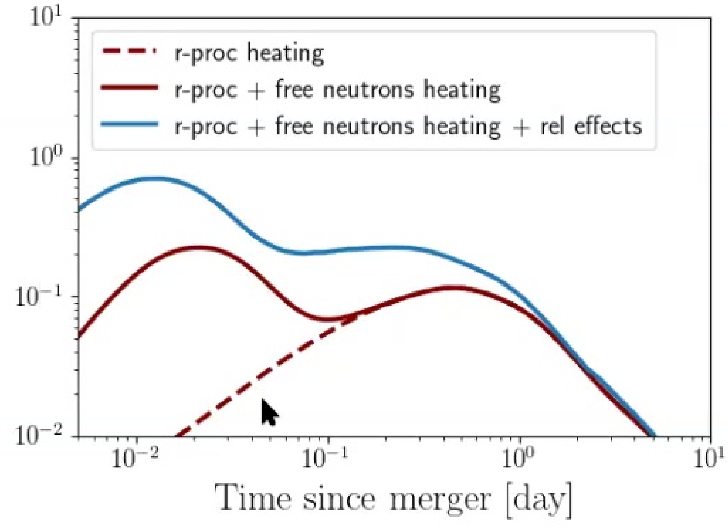


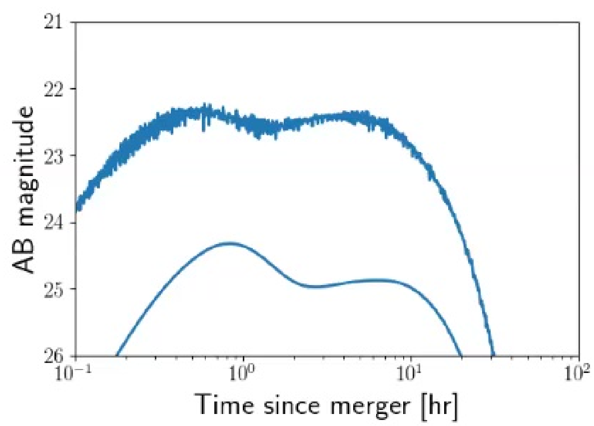

Dashed curve: Kulkarni 2005

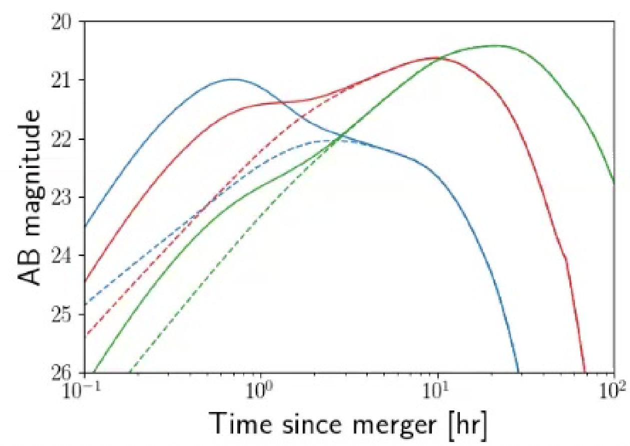


# Kilonova emission from simulation ejecta

- Including **free neutron heating** enhance the total luminosity by ~ 1 of magnitude in the first few hours of the merger.
- Including relativistic effects (Doppler, time of flight, beaming) enhance the lightcurve ~ 2 orders of magnitude in the UV.
- **Next step!** Check afterglow radio emission from this fast ejecta (in progress)



# Takeaways

❖ GRMHD simulations of spinning SMBBHs

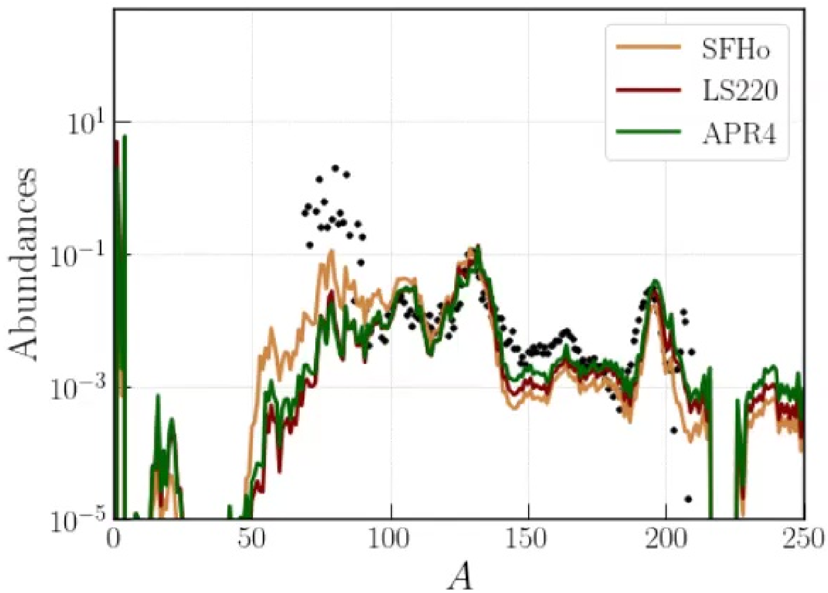
- We performed simulations of accretion onto spinning and non-spinning black holes.
- BHs have an accretion variability that is imparted by the circumbinary disk.
- Spinning BHs have more massive mini-disks.
- This variability is then reflected on the Poynting flux and radiation emission (computed using ray tracing)

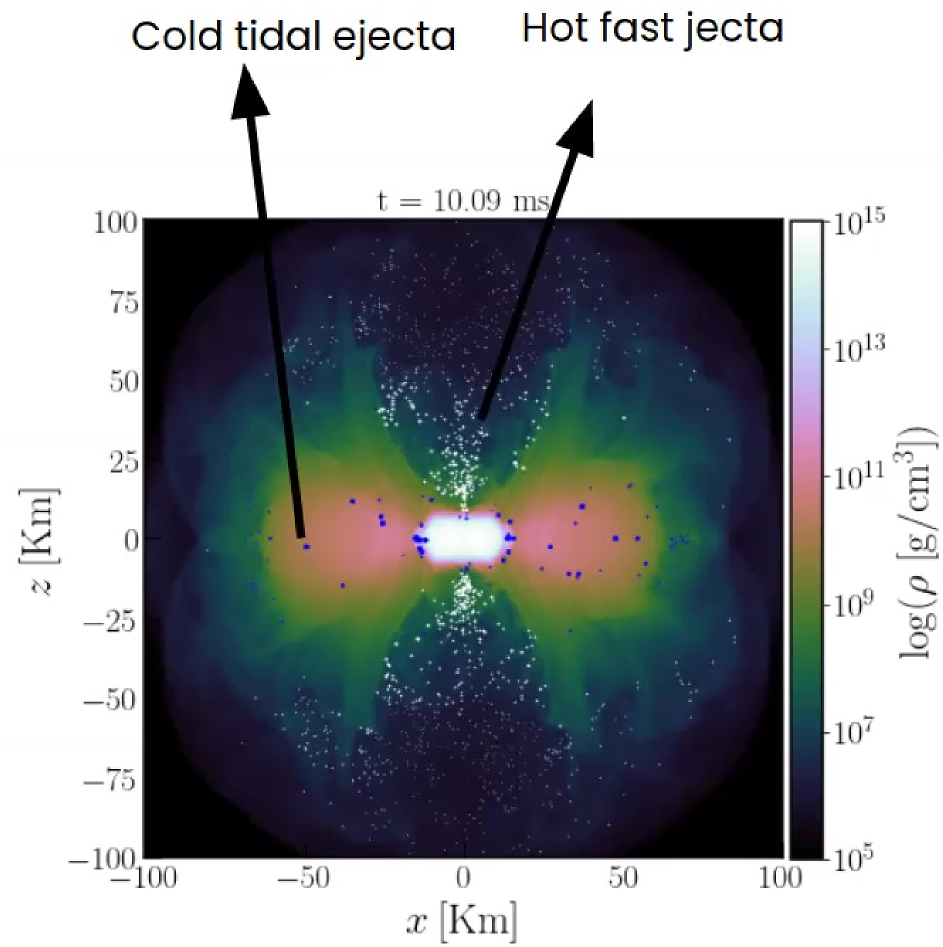
❖ GRMHD simulations of BNS with weak interactions

- We performed simulations of BNS with n**eutrino transport and magnetic fields**.
- We analyze the mechanisms and precursor signals from the dynamical ejecta self-consistently.
- Found **enhanced early emission due to neutron heating** +relativistic effects.
- Currently working on post-merger evolution and properties of outflows. Studying the interplay of neutrino cooling and absorption and magnetic fields

# Nucleosynthesis analysis

We use tracer particles to sample the different parts of the ejecta. Then we use these as initial data for our nuclear reaction network `SkyNet` to compute the nuclear products



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