Planetary Tidal Disruption Events as a Driver of Extreme Stellar Variability

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Outline

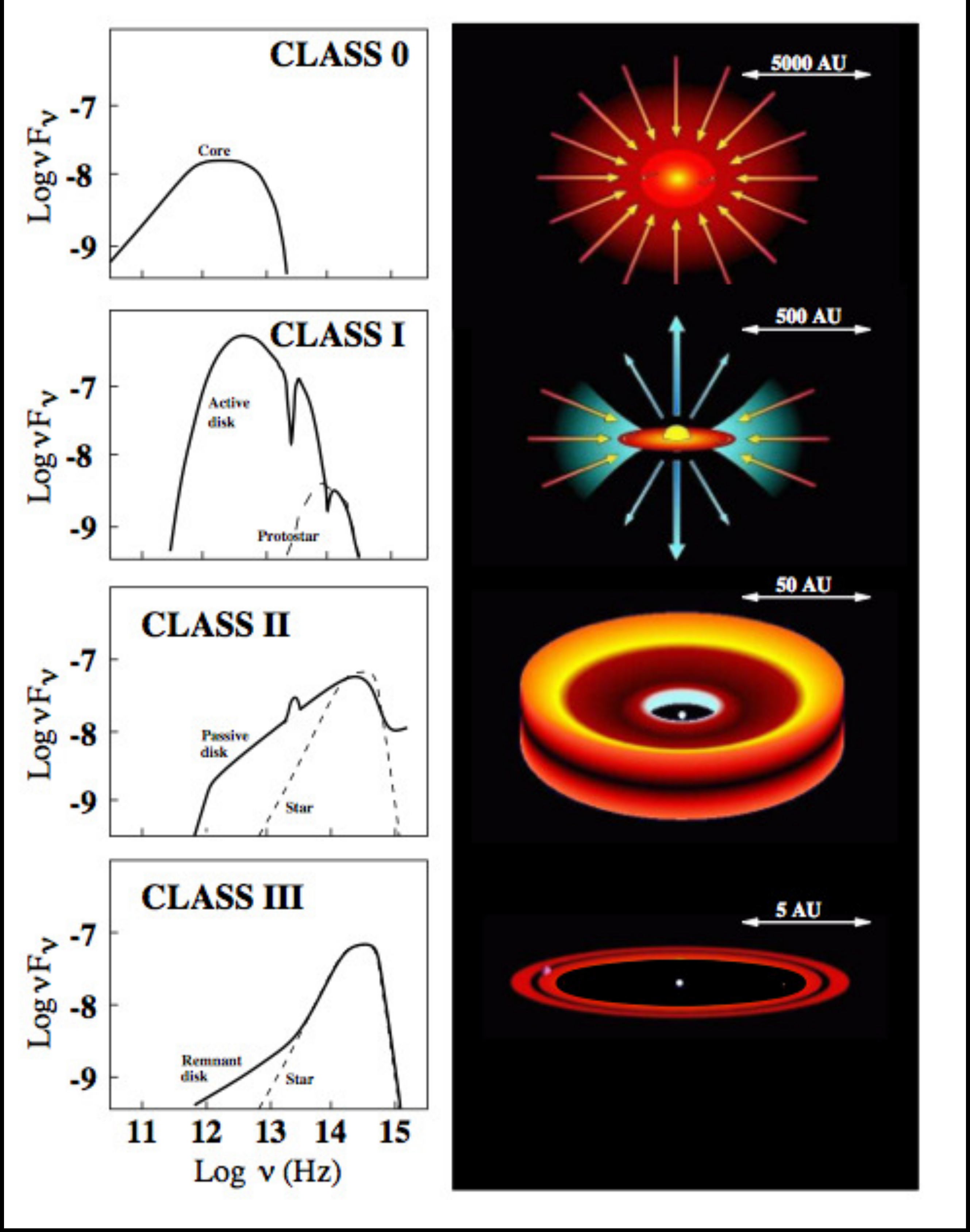
1. YSO Variability: FUors vs. EXors

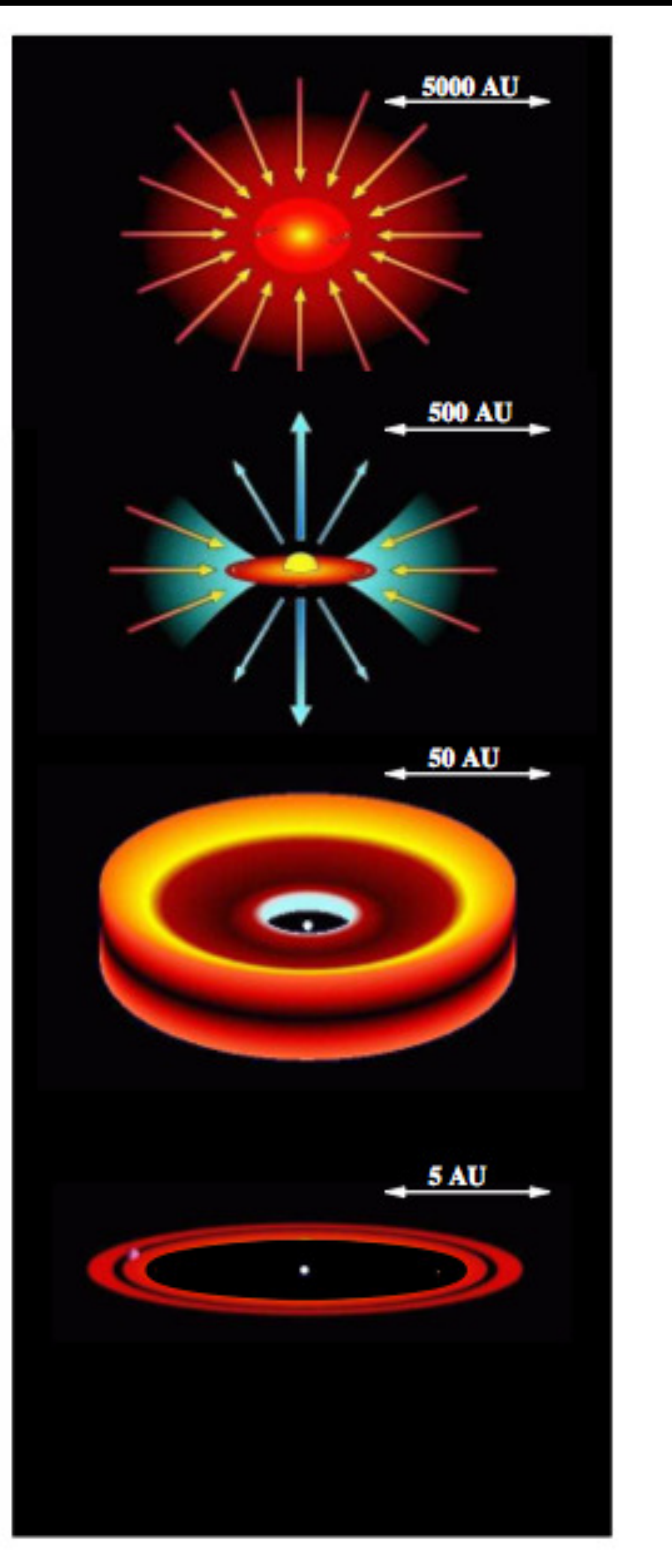
2. The Observational Anomaly: The "WIT" Class -> *VVV-WIT-13*

3. Physical Hypothesis: Planetary Tidal Disruption Events / Numerical Modeling (Hydrodynamics)

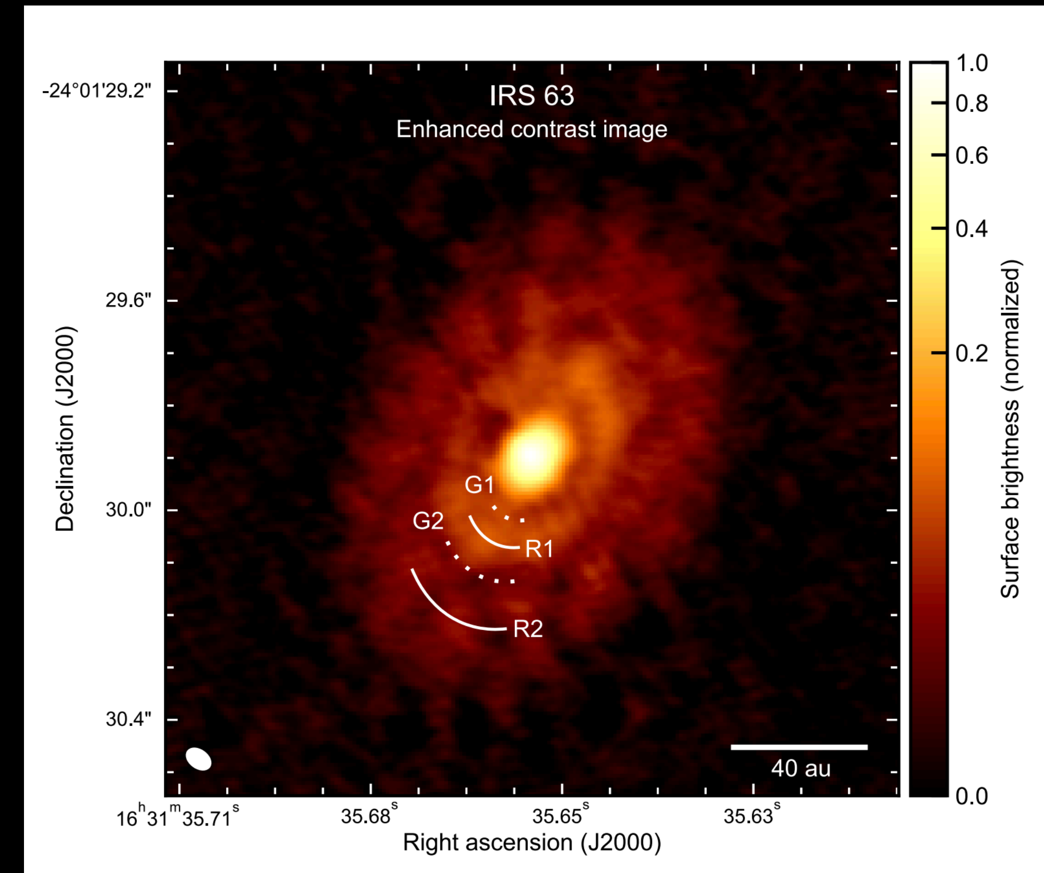
T Tauri Stars and the "Standard" Variability

- **Class 0/I** (Protostars): Dominated by a massive envelope => mass flow toward the center
- **Class II** (Classical T Tauri): Envelope dissipated; star is visible with infrared excess from a disk environment
- **Class III** (Weak-line T Tauri): Disk almost entirely dissipated, leaving only debris or planets



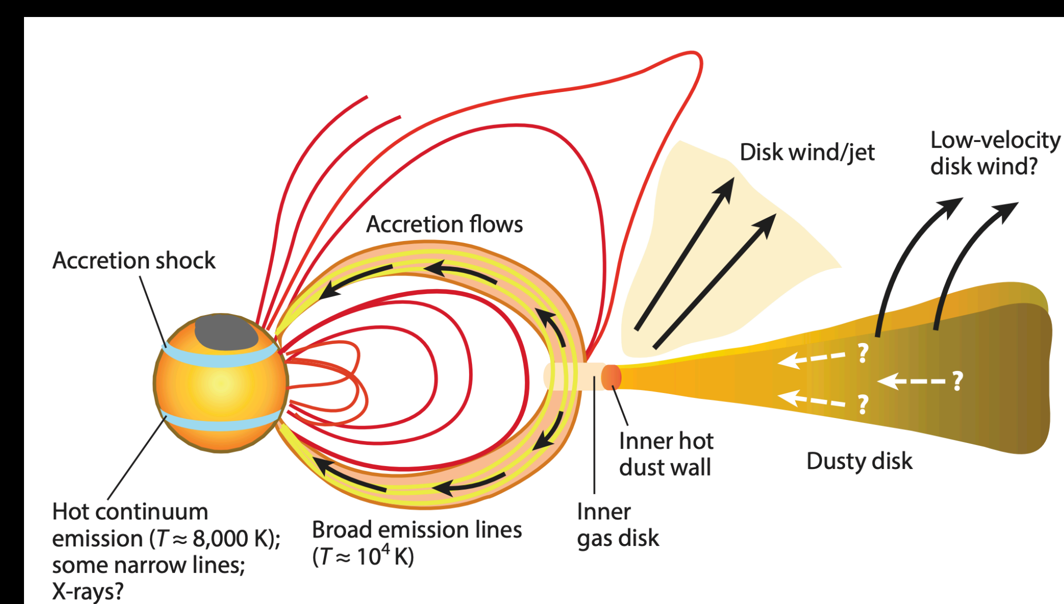


Early planet formation



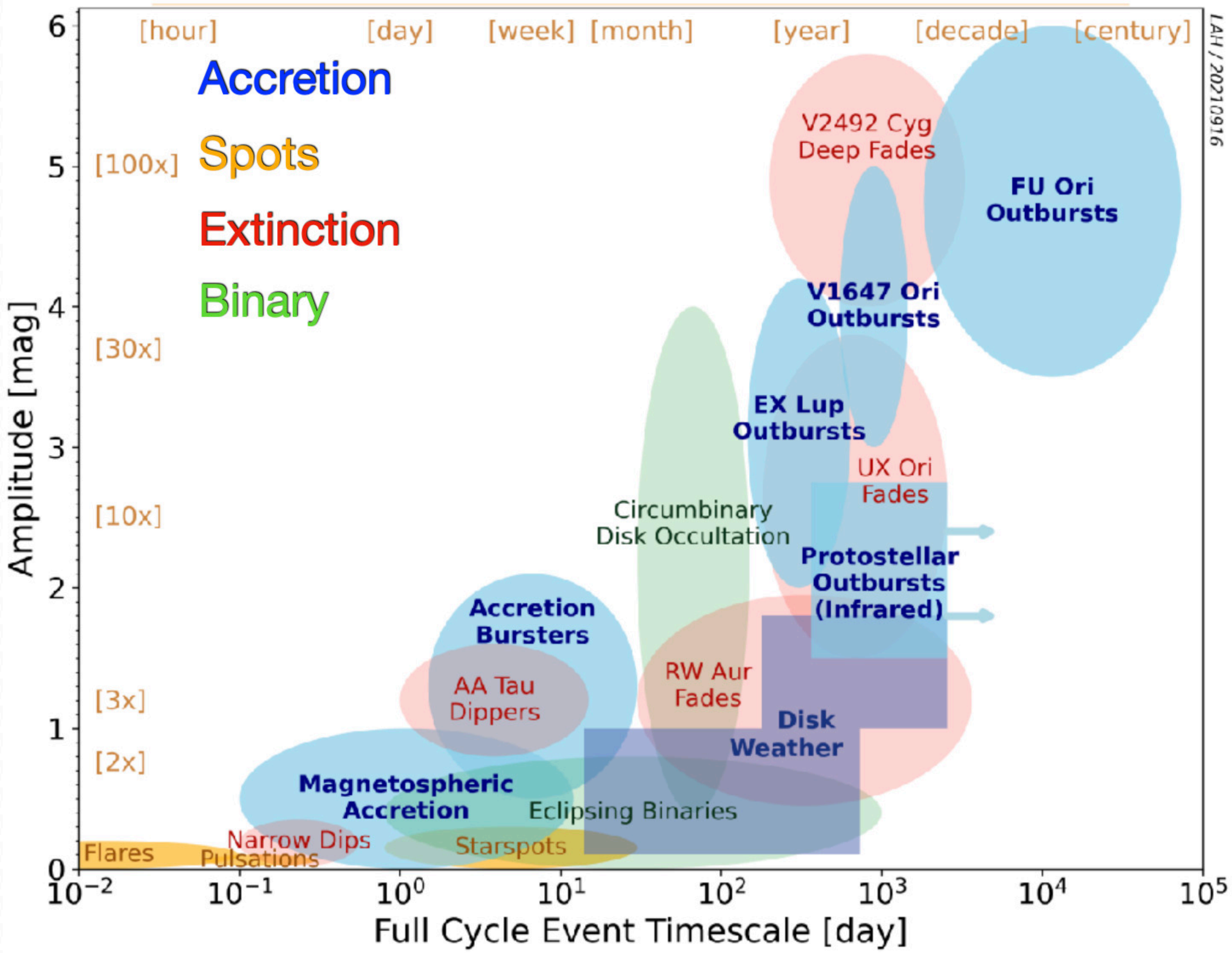
Segura-Cox+2020

Assumed Sources of Variability: Driven by magnetic fields, star rotation, dust occultations, and accretion



Hartman+2016

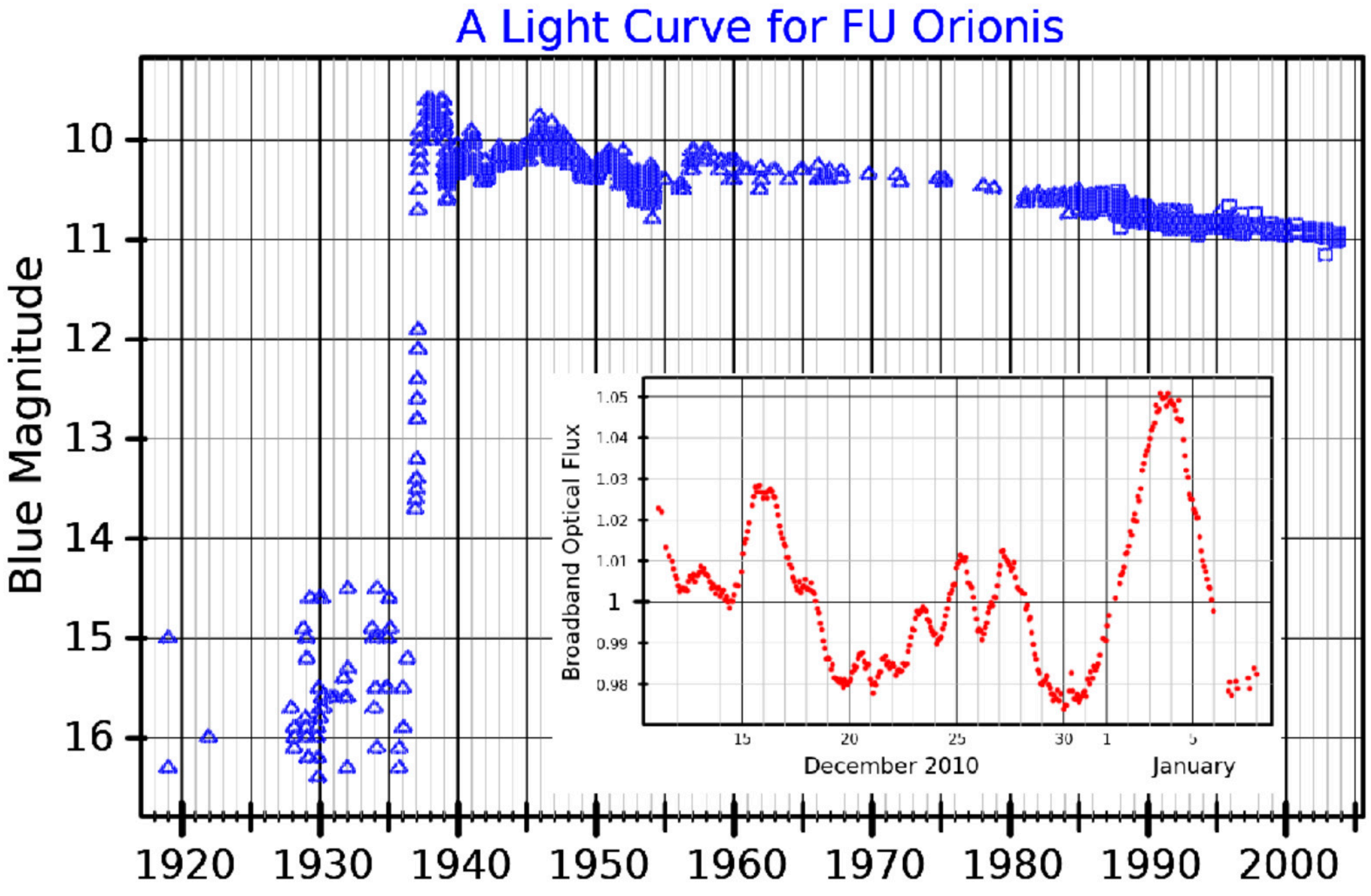
Young stars are variable stars

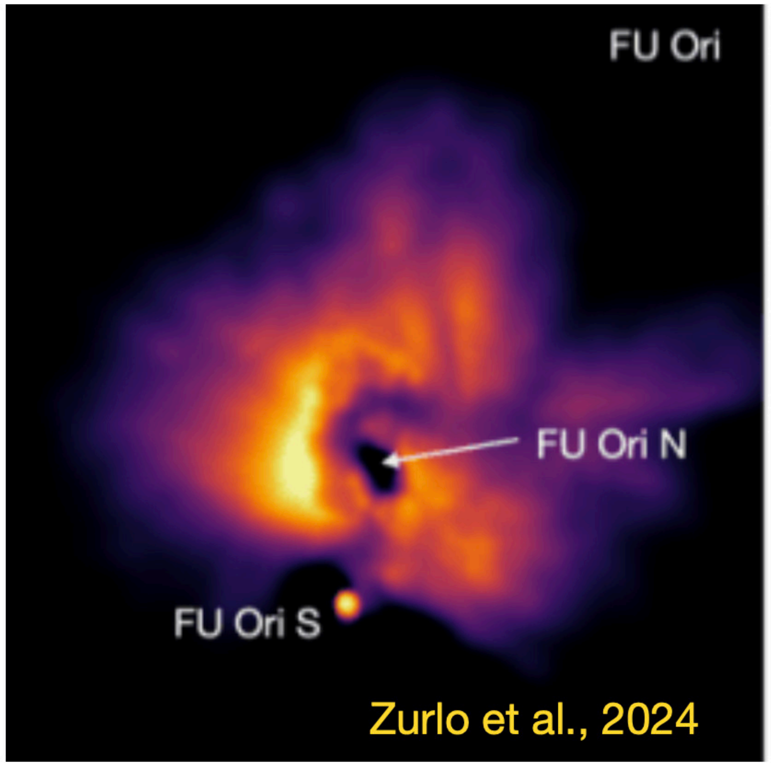


Extreme Outbursts: FUors

The Archetype: FU Orionis

- **FU Orionis** a T Tauri star located in the Orion Molecular Cloud
- **In 1936**, the luminosity increased 250-times (6 magnitudes) in just one year
- **The Aftermath**: It did not fade. It has remained in a high-brightness "plateau" for nearly 90 years
- **The FUor class** is the category of long-duration, high-accretion outbursts defined by this archetype star (FU Orionis)

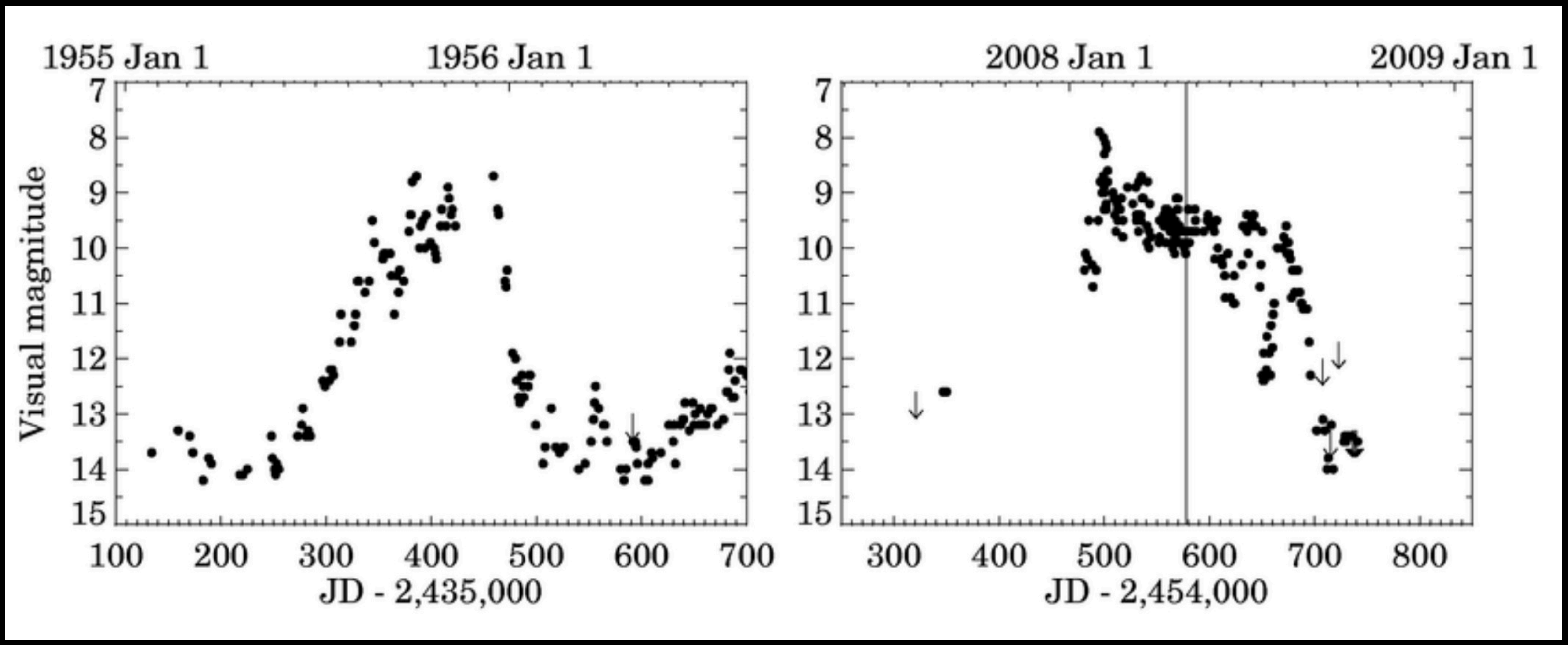

A Light Curve for FU Orionis
Blue Magnitude
10
11
12
13
14
15
16
1920
1930
1940
1950
1960
1970
1980
1990
2000
Broadband Optical Flux
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
15
20
25
30
1
5
December 2010
January


FU Ori
FU Ori N
FU Ori S
Zurlo et al., 2024

Extreme Outbursts: EXors

The Archetype: EX Lupi

- **EX Lupi** a T Tauri star located in the Lupus (The Wolf) constellation
- Unlike the long-duration FUors, EX Lupi exhibits repetitive outbursts separated by quiescent periods.
- Events are short-lived, typically lasting months to ~ 1 year.



outburst of EX Lupi in 1955-56 outburst in 2008

P. Abrahám et al., Nature (2009)

Comparison of Eruptive YSO Classes: FUors vs. EXors

Feature	FU Orionis (FUors) | "The Marathoner"	EX Lupi (EXors) | "The Sprinter"
Archetype	FU Orionis	EX Lupi
Duration	Decades to Centuries	Months to ~1–2 Years
Recurrence	None observed (Single event)	Repetitive (Every few years)
Accretion Rate ($\dot{M}$)	Extreme ($\sim 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$)	High ($\sim 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$)
Brightness (ΔMag)	High ($\Delta V \approx$ 4–6 mag)	Moderate ($\Delta V \approx$ 2–4 mag)
Spectrum	Absorption (Cool Supergiant-like)	Emission (Hot gas, Brγ)
Trigger	Massive Disk Instability	Minor Disk Instability

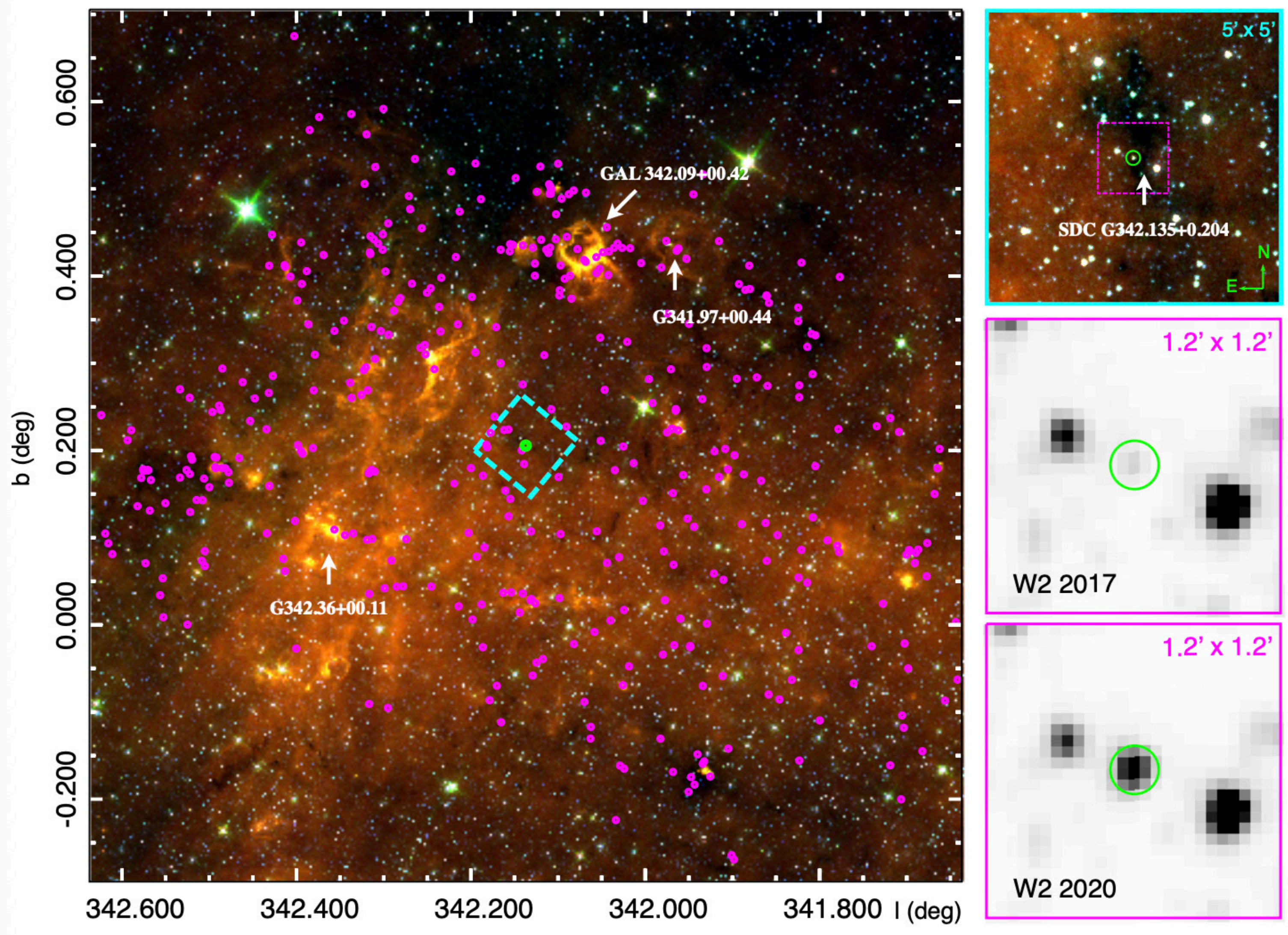
Key Takeaway: Standard outbursts are either long and intense (FUors) or short and repetitive (EXors). VVV-WIT-13 fits neither.

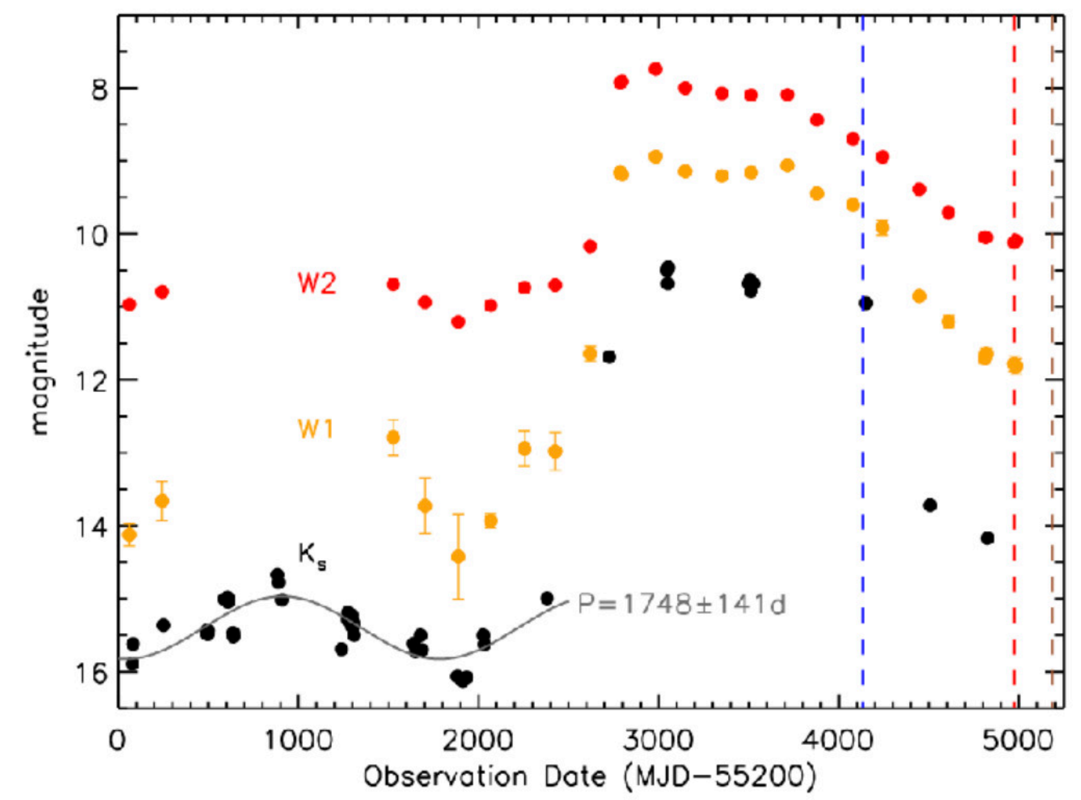
The "What Is This" (WIT) Class

Classification: "WIT" stands for "What Is This?" – a designation for objects that defy standard variable classes

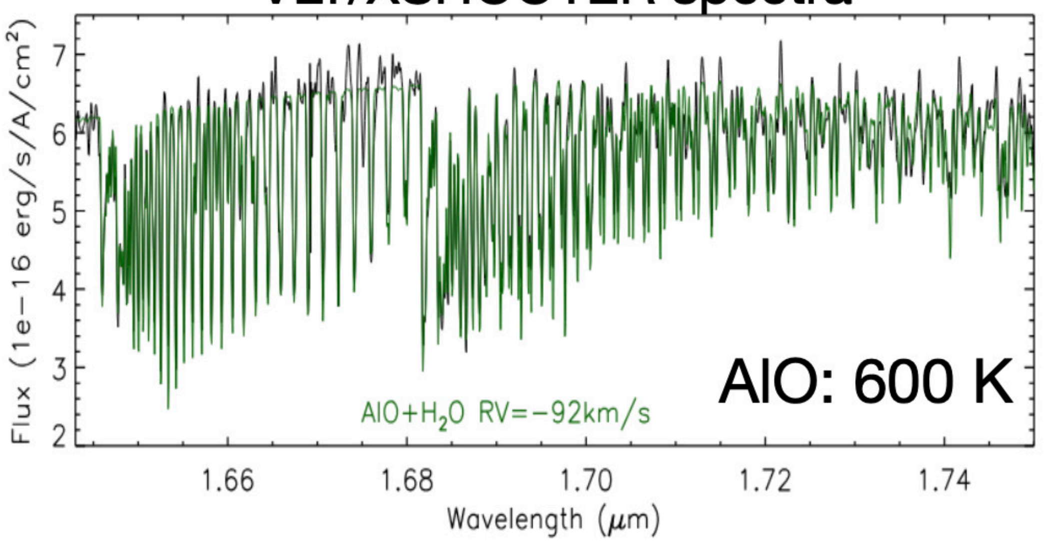
- Object: **VVV-WIT-13** (from the "VISTA Variables in the Via Lactea" survey) Zhen Guo et al., 2025

VVV-WIT-13: an infrared outbursting YSO





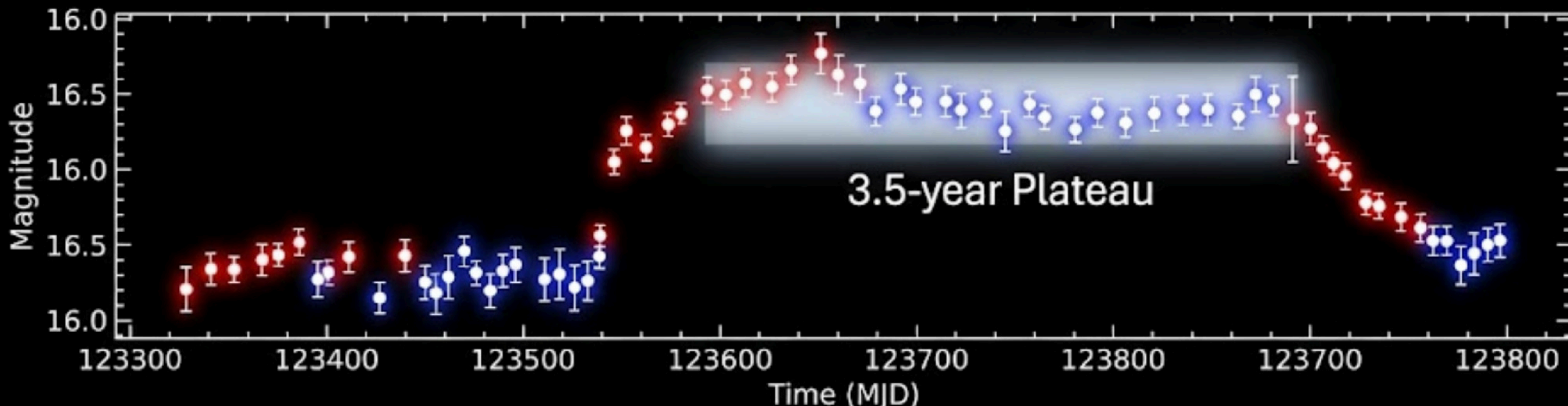
VLT/XSHOOTER spectra



Guo, Montesinos, Morris, Kurtev, Borissova, et al., accepted

1. The Discovery & Light Curve Anomaly

- **Object**: VVV-WIT-13 (“What Is This?”).
- **Pre-outburst**: Faint YSO ($K_s \sim 16.5$ mag), standard low variability.
- **The 2016 Outburst**: Massive brightening ($\Delta K_s \approx 5.7$ mag).
- **The Problem:** Stable **3.5-year plateau**.
  - Too short for FUor (decades).
  - Too long & flat for EXor (~1 year).



The “Impossible” Light Curve (Guo et al. 2025)

The Timescale Problem (Duration):

- **Standard EXor**: Events are short-lived, typically lasting from a few months up to 1 year. They are "sprinters."
- **VVV-WIT-13**: The outburst lasted 3.5 years. This is significantly longer than the typical viscous timescale for the small inner-disk instabilities that trigger EXors.

The Light Curve Shape (Profile):

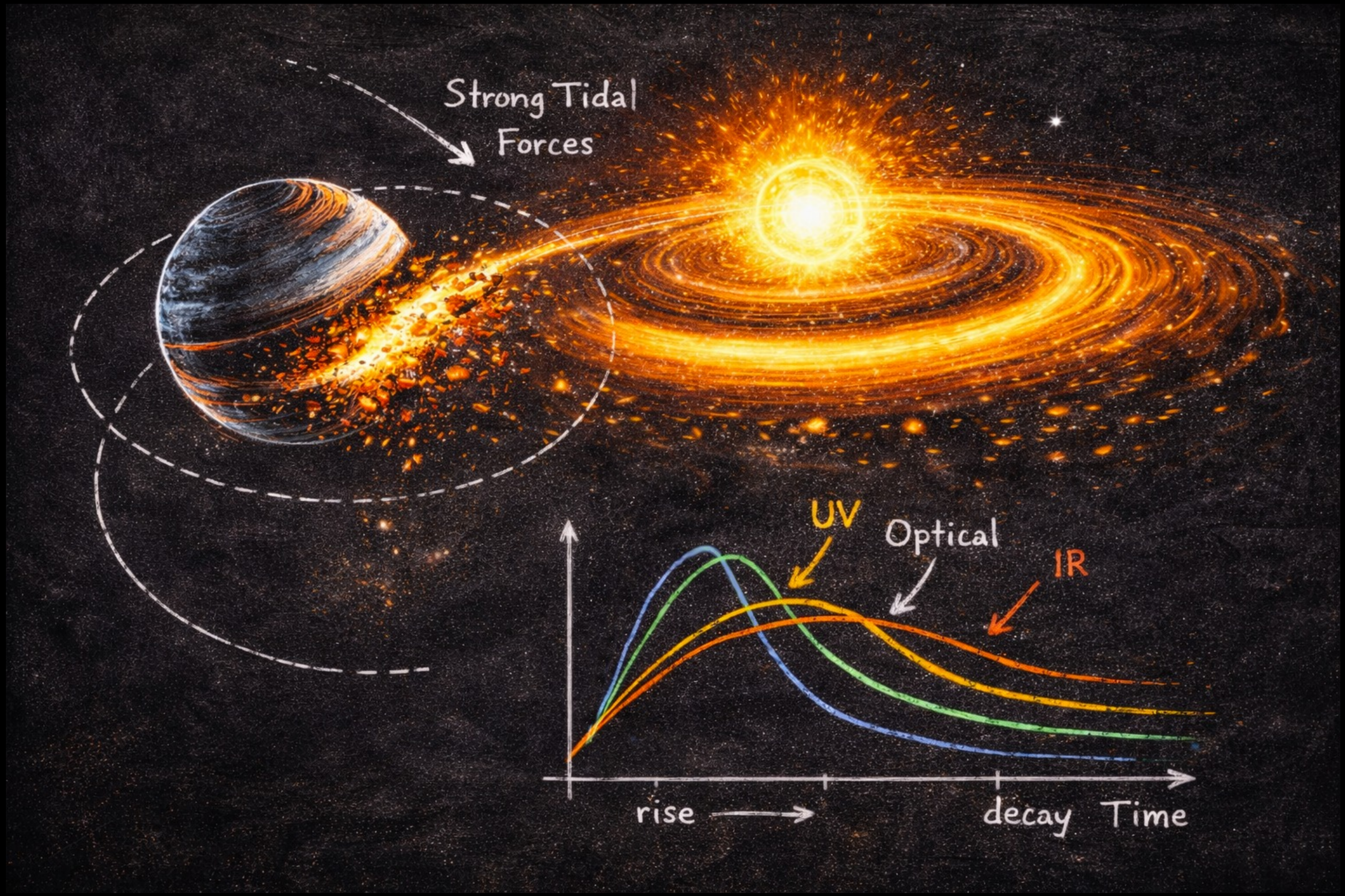
- **Standard EXor:** The light curve usually looks like a triangle or a spike. It rises fast, reaches a sharp peak, and immediately starts to decay.
- **VVV-WIT-13**: It showed a flat-top plateau. The brightness stayed constant for years. This "box-shaped" profile implies a sustained, stable feeding mechanism, not a sudden instability that drains quickly.

The Spectral Signature (Temperature)

- **Standard EXor**: The spectrum is dominated by Emission Lines => hot accretion shock where gas crashes onto the star at free-fall speeds ($T > 10,000$ K)
- **VVV-WIT-13**: The spectrum is dominated by Absorption Lines (CO, AlO) => low temp, like an expanded "photosphere", The gas is dense enough to be optically thick and cool enough to form molecules.

So… What Is This?

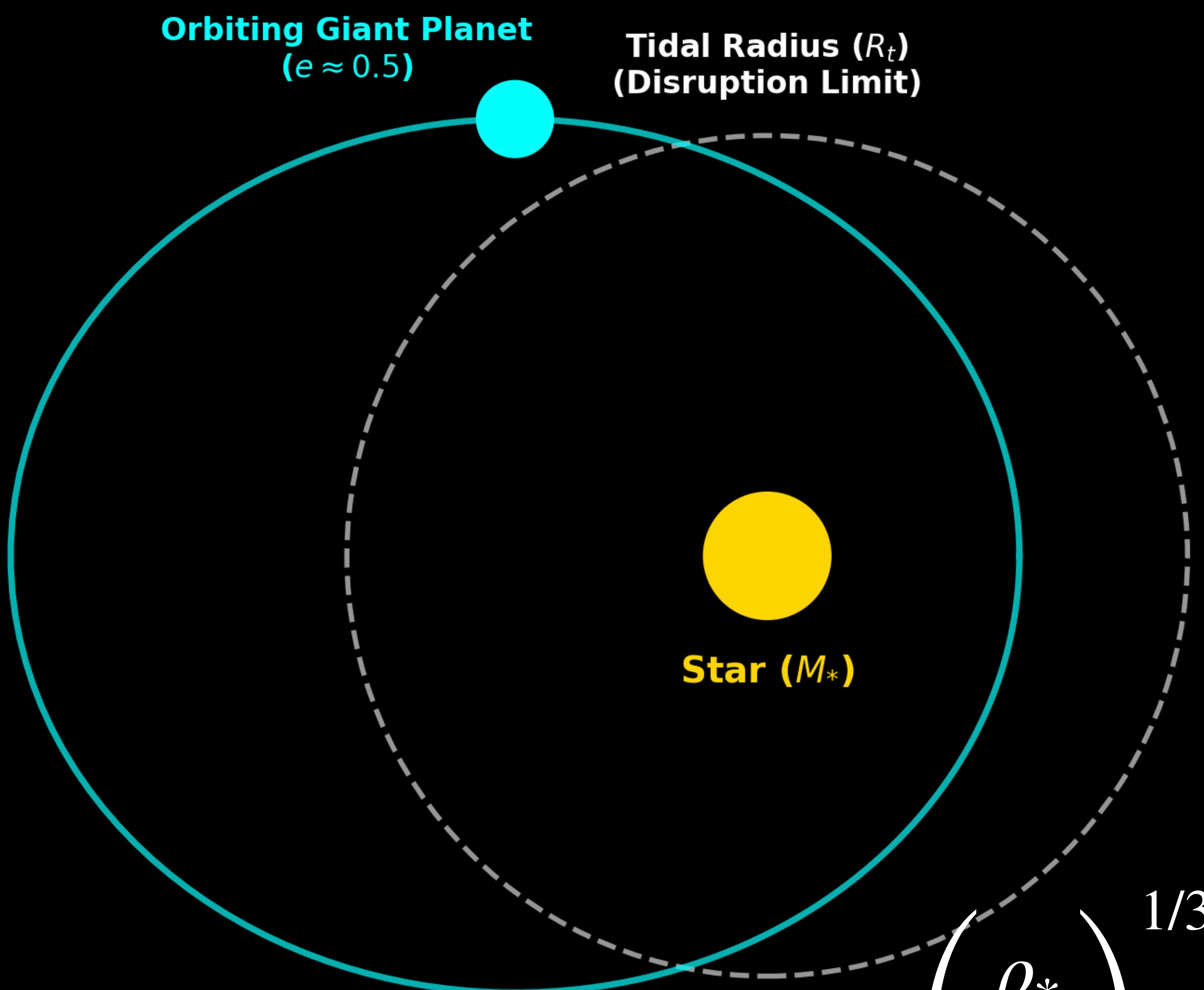
Proposed scenario: Planetary Tidal Disruption



To explain this anomaly, we propose a Planetary Tidal Disruption. Imagine a Jupiter-mass planet or Brown Dwarf on an eccentric orbit. It passes too close to the star—inside the tidal radius—and gets torn apart…

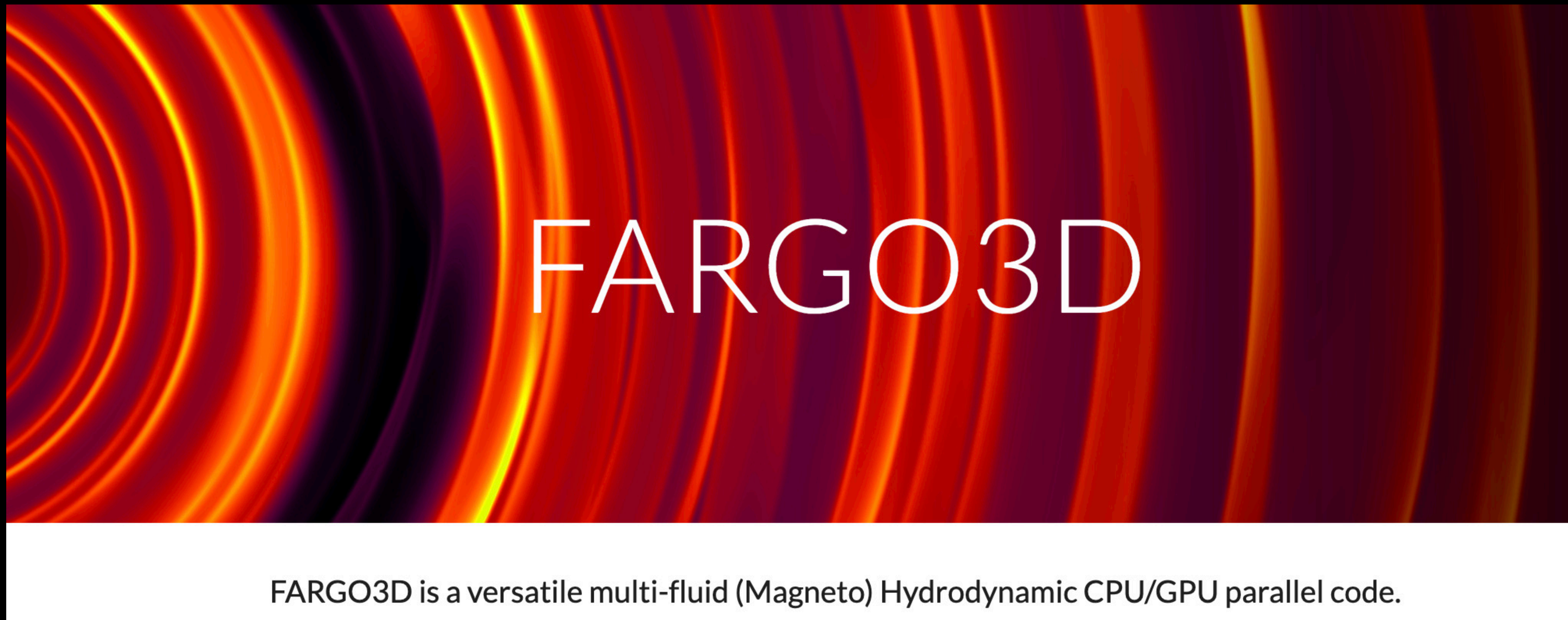
The physics of a Tidal Disruption Event

- A Young Stellar Object (YSO) hosting a companion (Jupiter mass planet)
- The companion follows a moderately eccentric orbit. The white dashed circle marks the Roche limit (where the star's gravity overcomes the planet's internal cohesion)
- As the planet passes through this "destruction zone" it is shredded by tidal forces. **Gravitational potential energy is eventually converted into radiation**



$$R_R = kR_* \left(\frac{\rho_*}{\rho_p}\right)^{1/3}$$

$$\Delta E = \frac{GM_*M_p}{2a} \frac{e^2}{1-e^2}$$



Benitez-Llambay, P. & Masset, F. 2016

Solves Navier-Stokes and continuity equations for a gaseous disk subject to the gravity of the central object and embedded planets

We need an energy equation to capture the TDE thermal evolution: non-stationary energy equation

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot (\epsilon \mathbf{v}) = -P(\nabla \cdot \mathbf{v}) + Q_v^+ - Q^-$$

Q_ν^+: Viscous heating rate (source).

Q^-: Radiative cooling rate (sink).

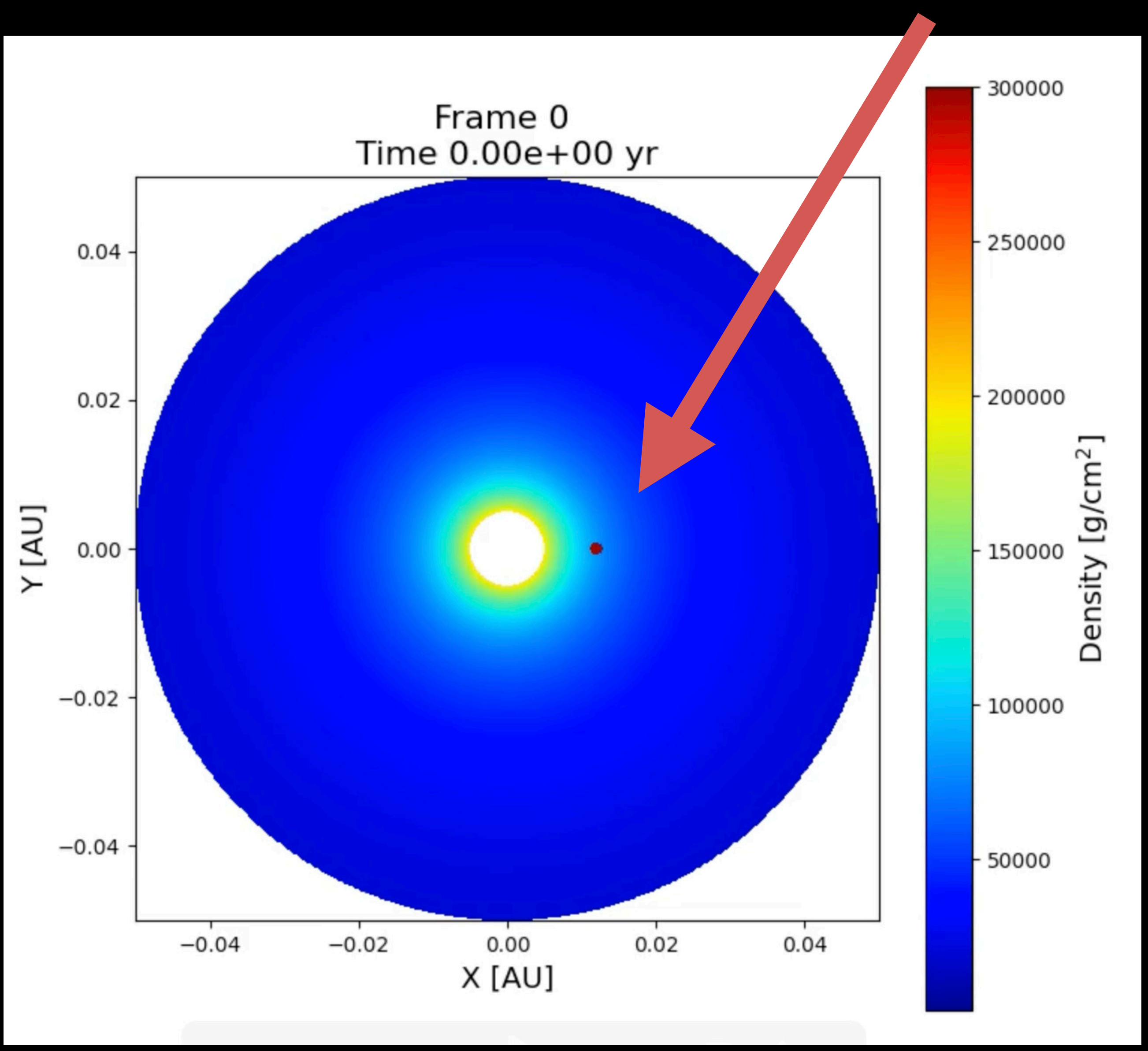
$$Q^- = \frac{2\sigma_{SB} T_{mid}^4}{\tau_{eff}}$$

We adopt a realistic Rosseland-mean opacity following Bell & Lin (1994) for the dust/molecular regimes, smoothly transitioning to Kramers opacity and electron scattering at high temperatures.

Initial conditions

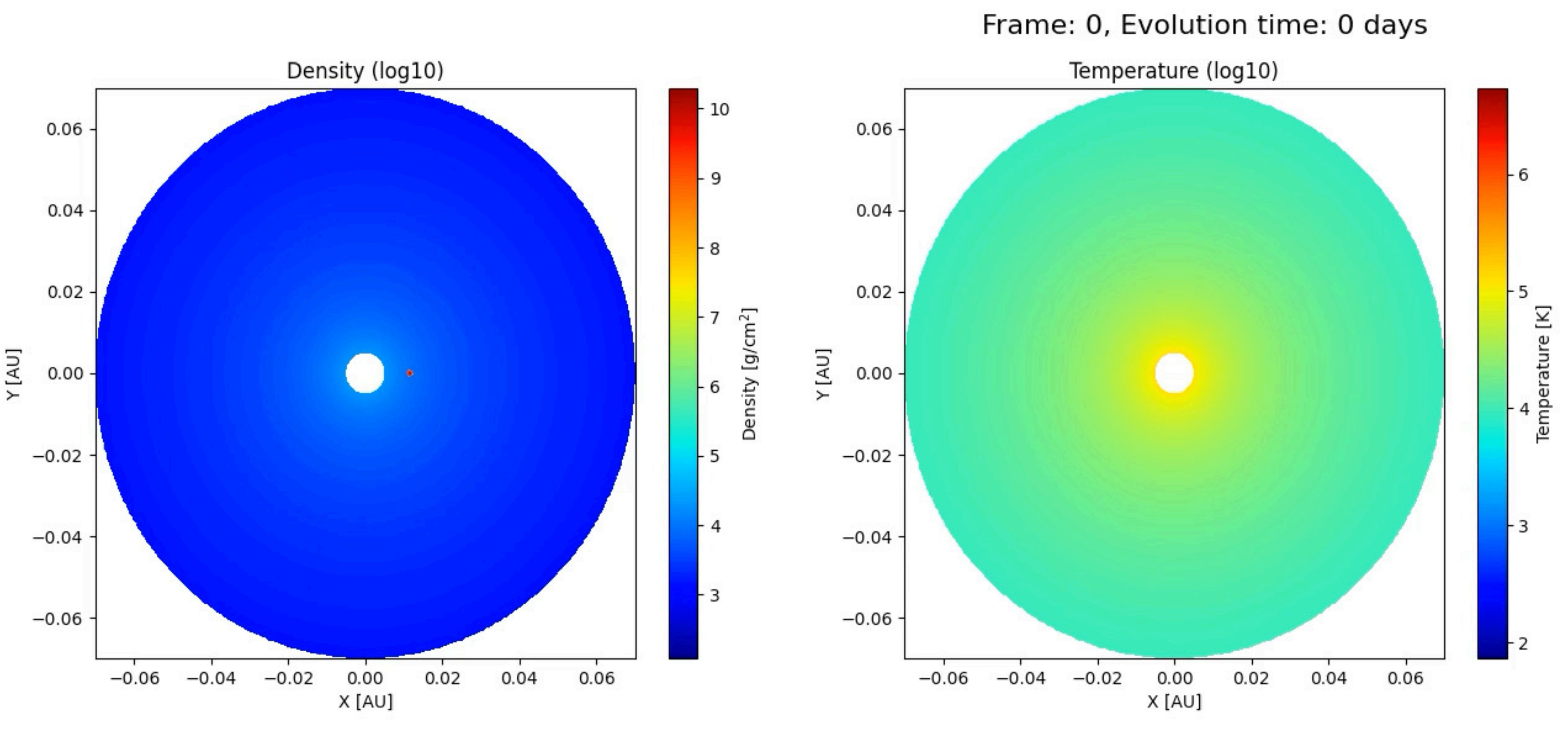
$$\Sigma(r,\phi) = \Sigma_0 \left(\frac{r}{R_0}\right)^{-p} + \Delta\Sigma_{\rm clump}$$

$$\Delta\Sigma_{\rm clump}(r,\phi) = A\exp\left(-\frac{d^2}{2\sigma^2}\right) \quad \text{for} \quad d \leq R_H$$



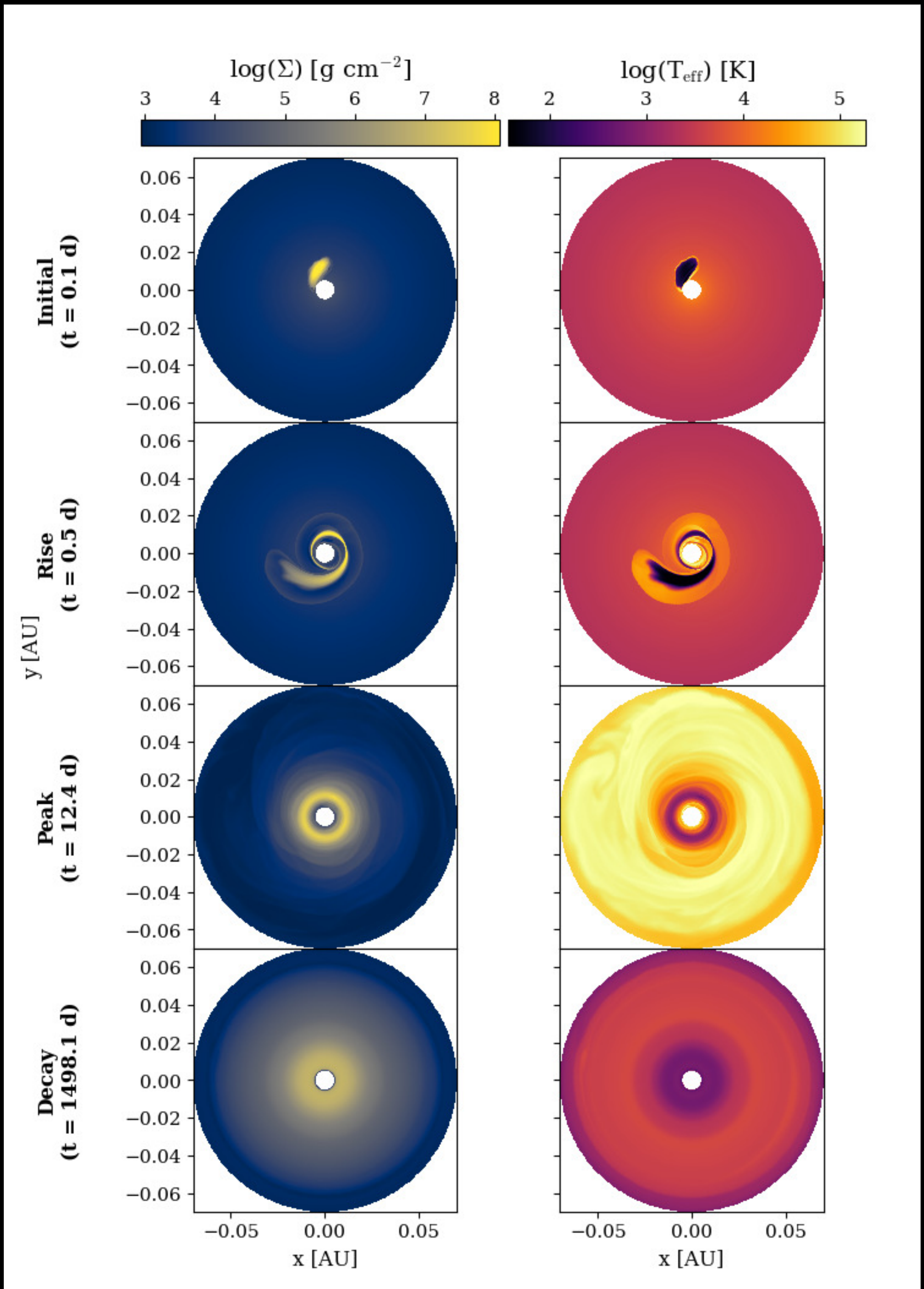
$$v_\phi = \sqrt{\frac{GM_*}{a}\frac{1+e}{1-e}}$$

Numerical Simulations (2D): FARGO3D code



Animation link: movie

Results:

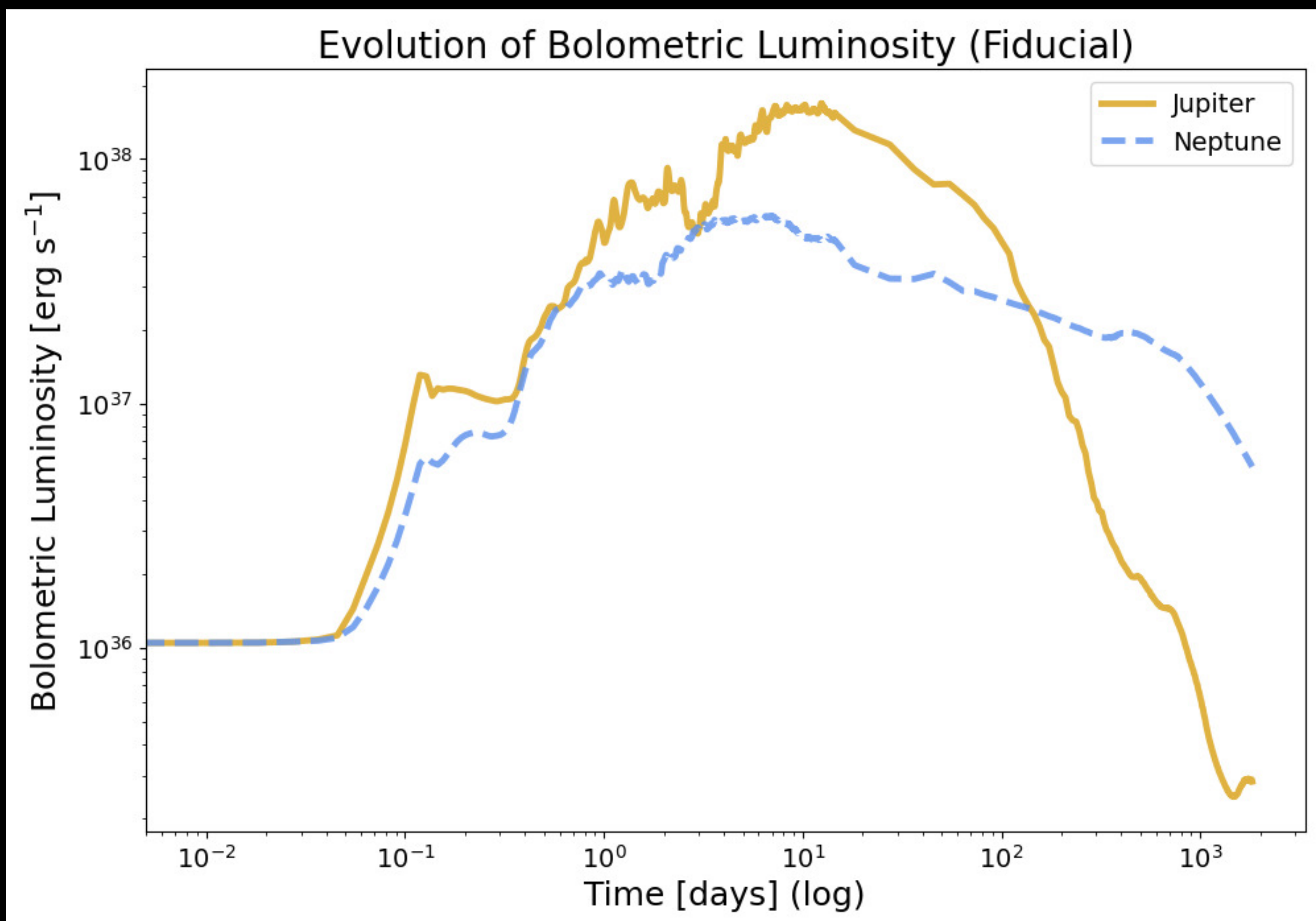


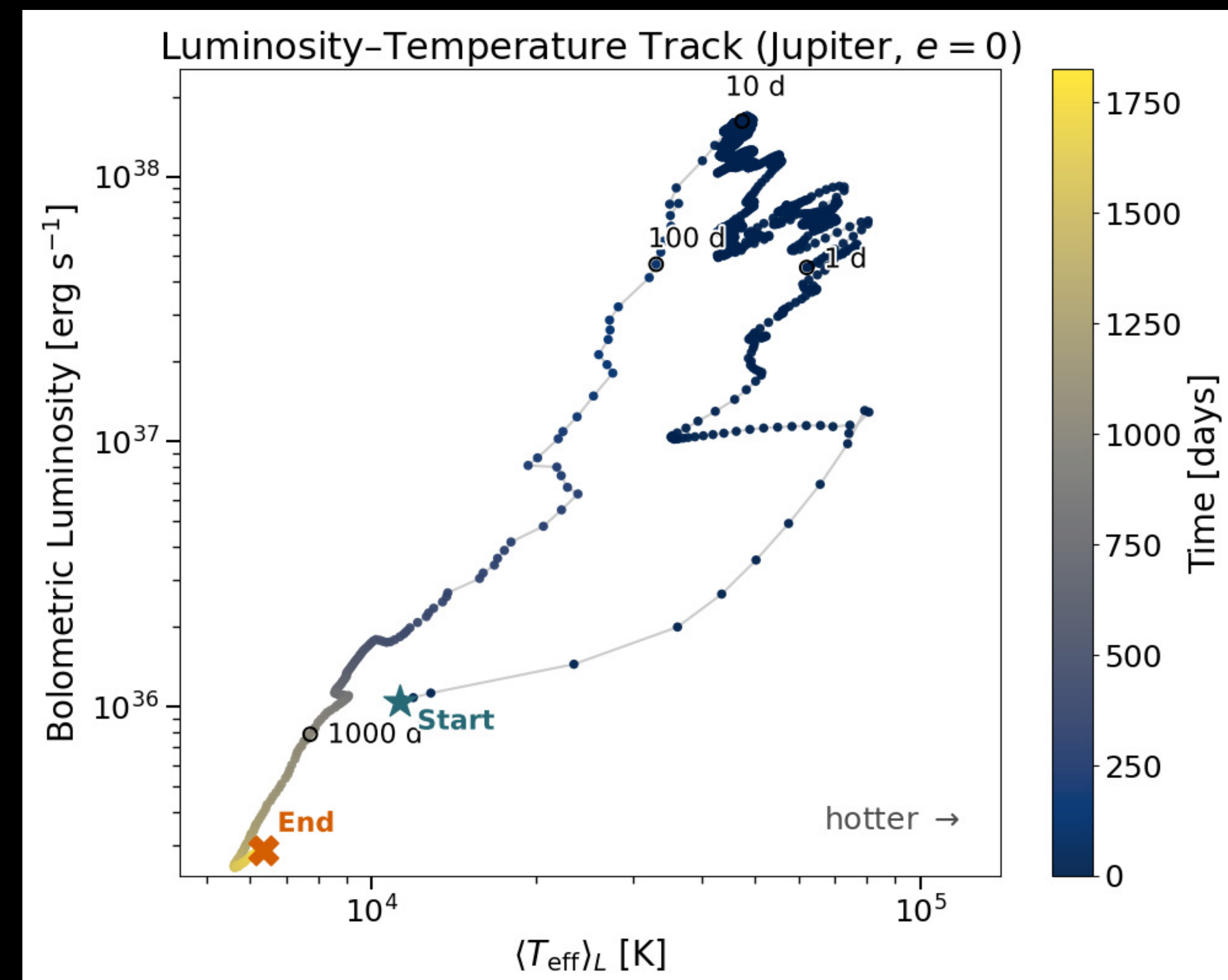
From the simulation we can compute the light curves

$$L_{\lambda_b}(t) = 2\int_A \pi B_{\lambda_b}\big(T_{\rm eff}(r,\phi,t)\big)\ \mathrm{d}A$$

$L_{\text{peak}} \sim 10^{38}\,\text{erg s}^{-1}$!

Light curves (bolometric)





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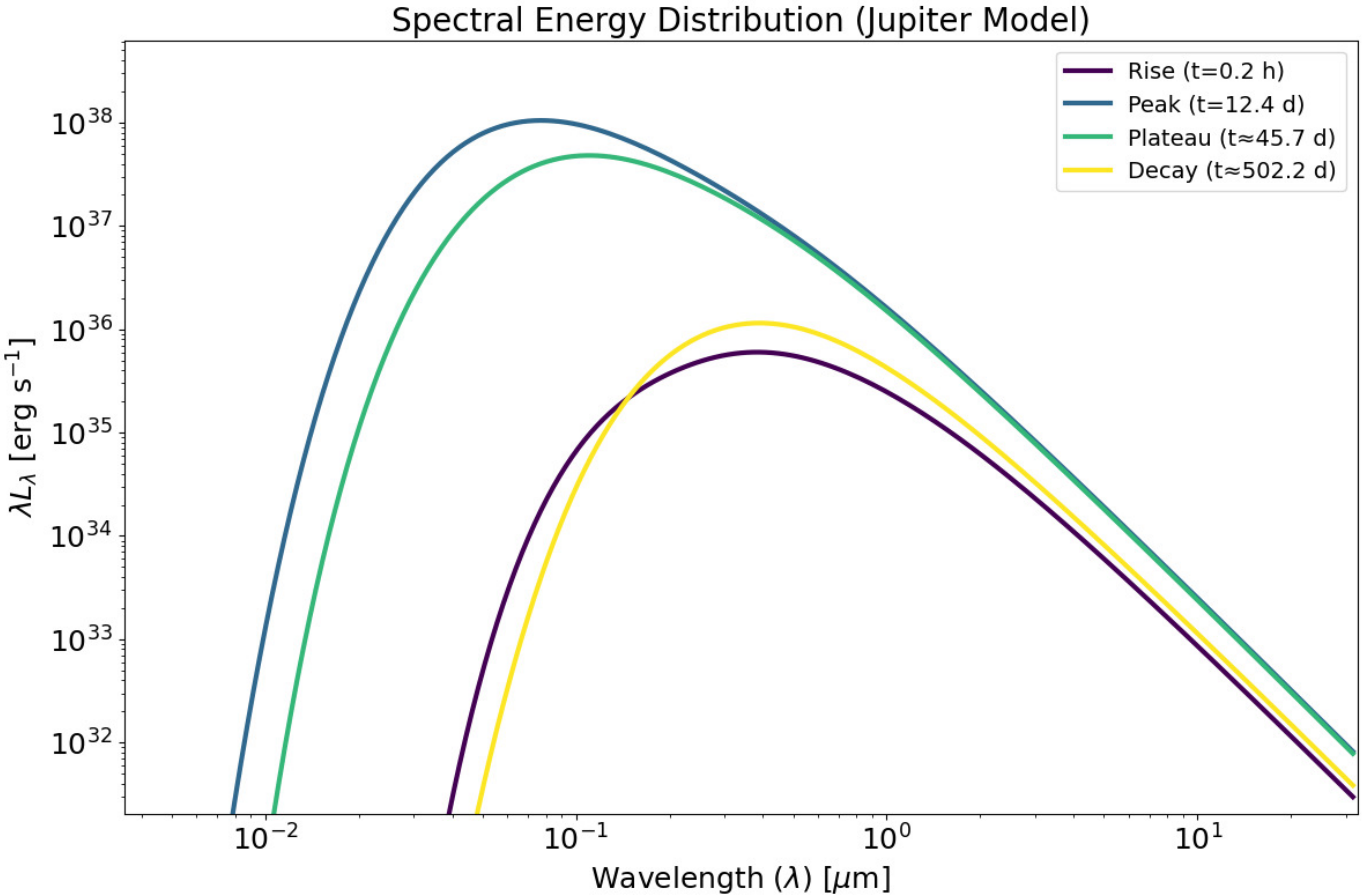
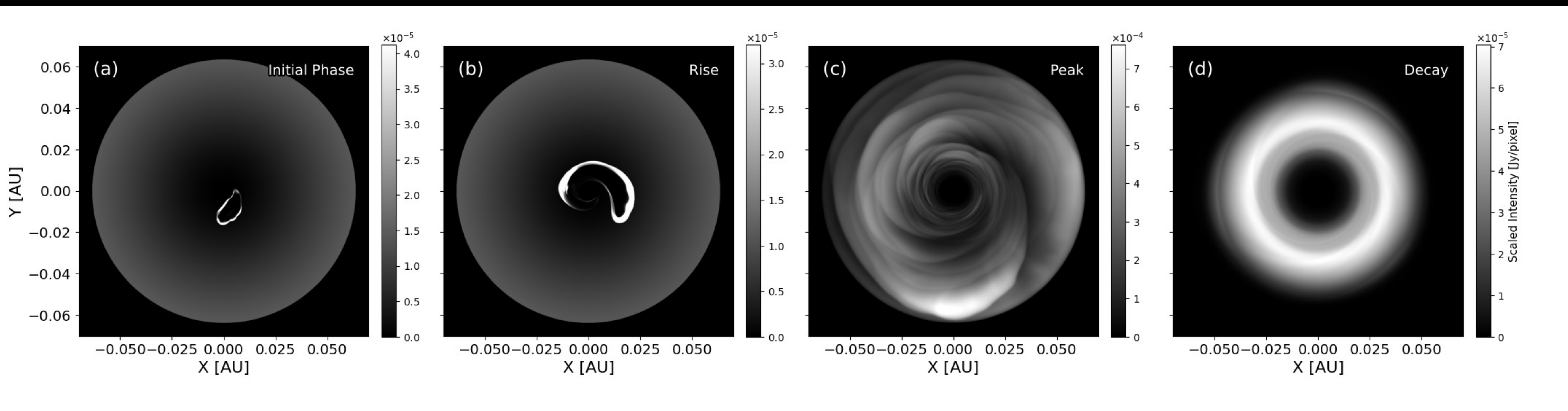


Spectral Energy Distribution (Jupiter Model)
Rise (t=0.2 h)
Peak (t=12.4 d)
Plateau (t≈45.7 d)
Decay (t≈502.2 d)
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
λL_λ [erg s^{-1}]
10^{-2}
10^{-1}
10^{0}
10^{1}
Wavelength (λ) [μm]

Radiative transfer calculations

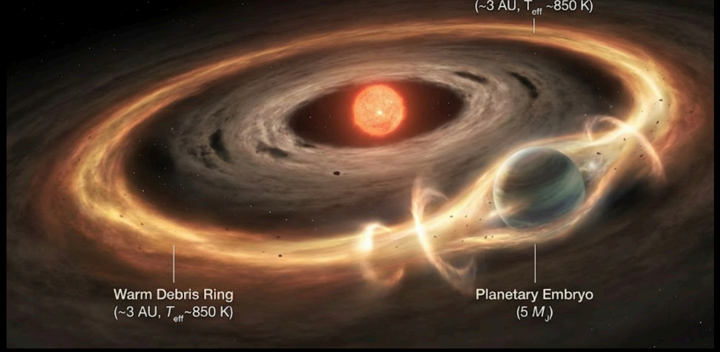
RADMC-3D (Dullemond et al. 2012)

t=0.1 d t=0.5 d t=12.4 d t=1500 d



Synthetic imaging of a Jupiter TDE at λ = 1.0 μm

Proposed scenario for WIT-13:



The outburst is powered by the tidal disruption of a massive planetary embryo

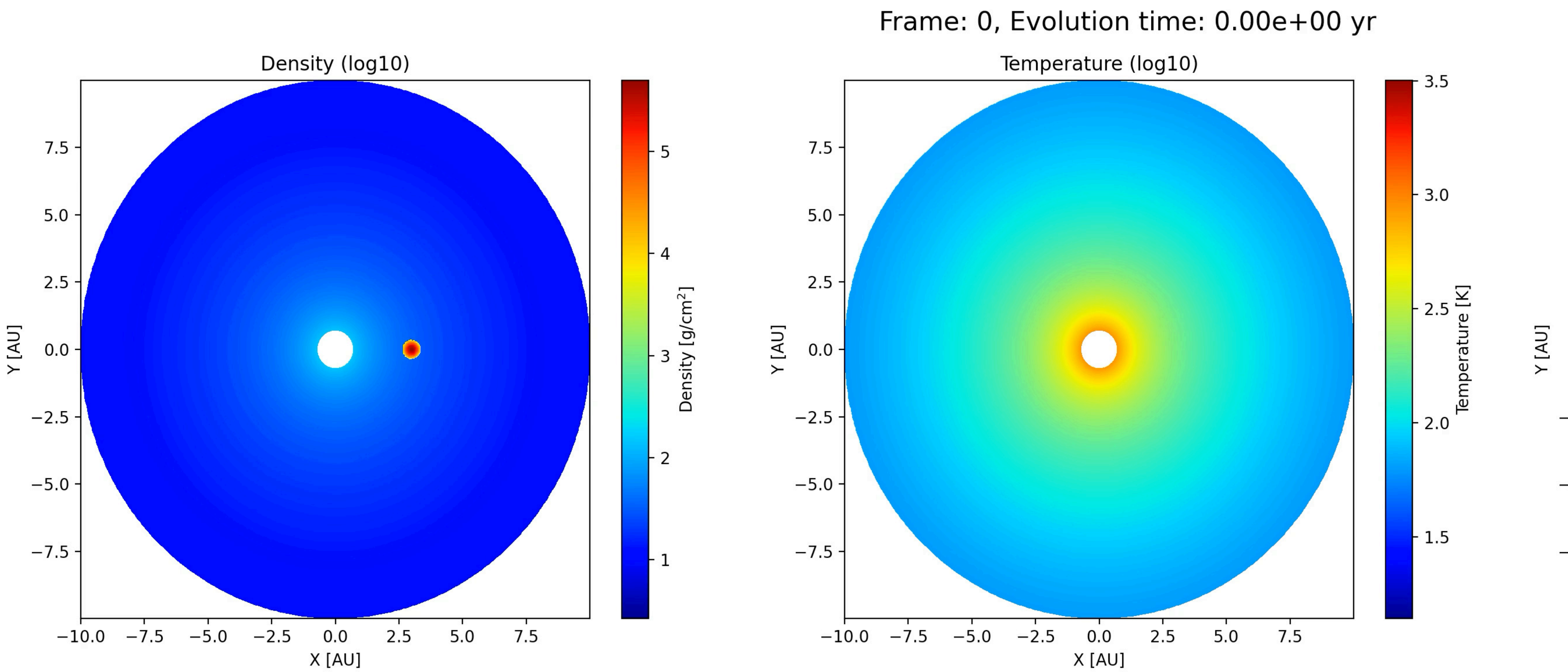
Observation	Value	Method / Constraint
Outburst Duration	~ 2000 - 3000 days	Light curve morphology (Intermediate)
Peak Luminosity (L_{bol})	~ 55 $L_{\odot}$	Derived assuming high extinction ($A_V = 17$)
Visual Extinction (A_V)	~ 17 mag	Estimated from pre-outburst colors

larger mid-infrared amplitude (a bright “ring”?)

Best model parameter

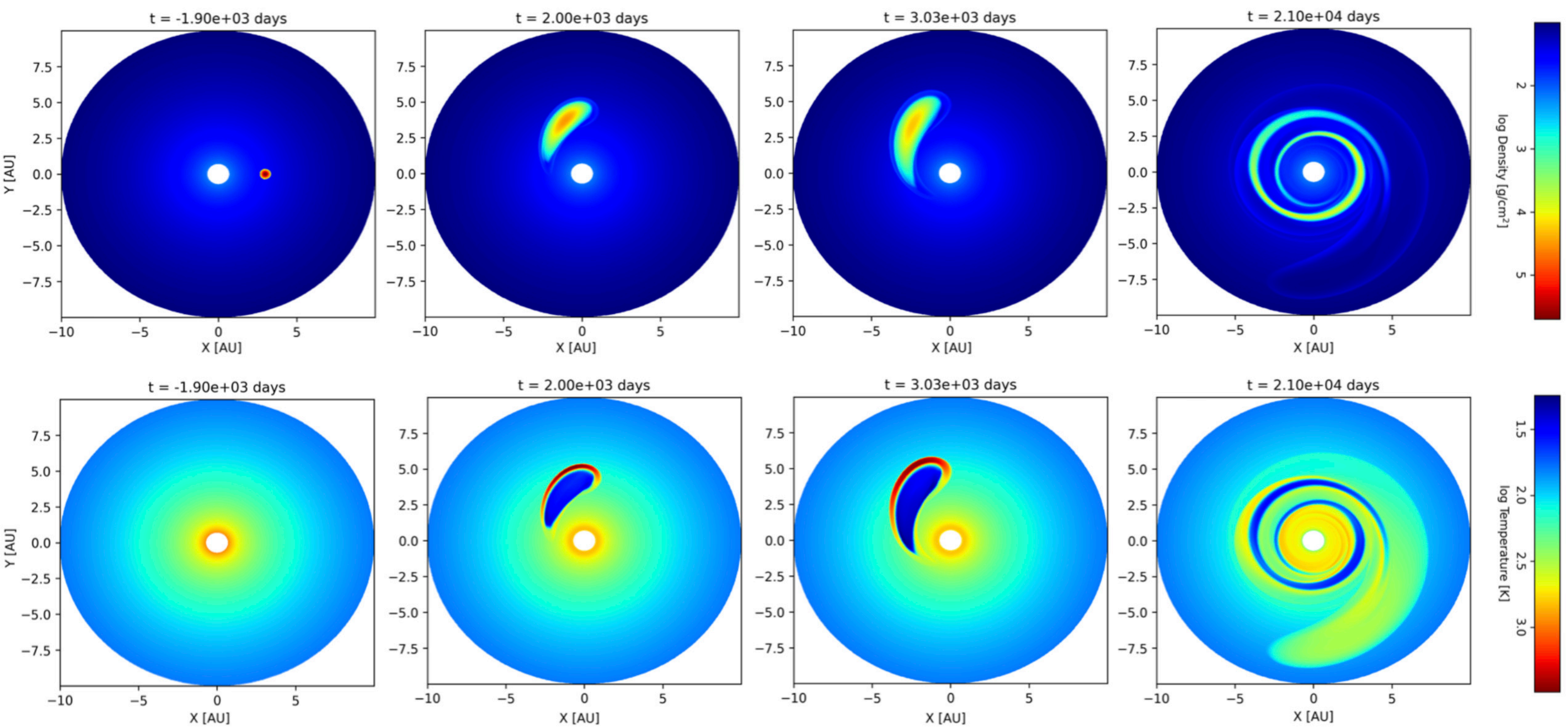
Model Parameter	Value / Description
Progenitor Object	Giant Planet Embryo
Progenitor Mass (M_p)	5 M_J
Disruption Distance (R_{dis})	~ 3 au
Host Star Mass (M_*)	0.4 - 0.6 $M_\odot$
Simulation Code	FARGO3D (2D Hydro)

Simulation results WIT-13

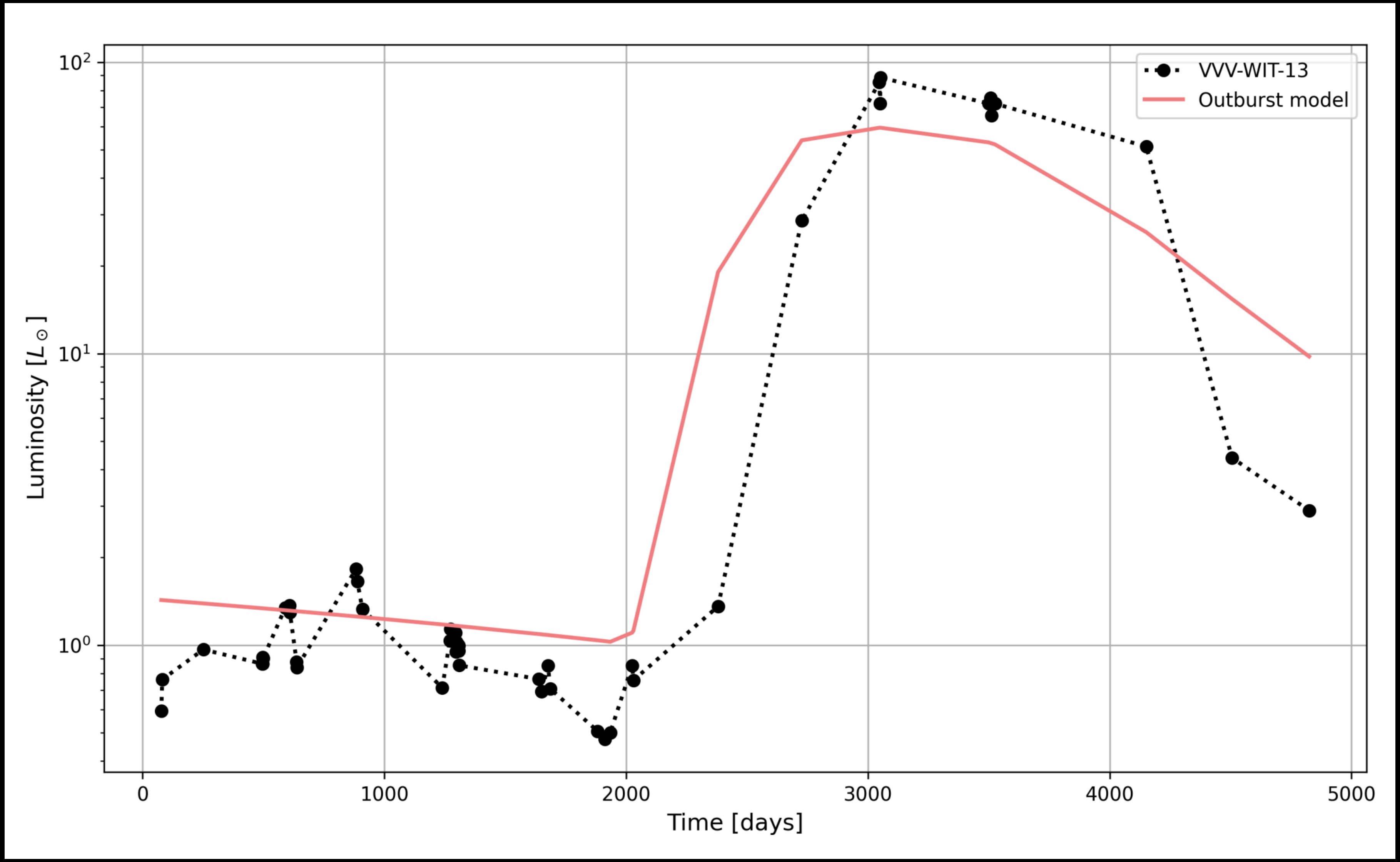


Animation link: movie

Simulation results WIT-13



Comparison with VVV-WIT-13



If confirmed, VVV-WIT-13 would represent the first real-time observation of a planetary disruption in a young disk

Conclusions

- Tidal disruption of planetary embryos is physically viable. It predicts a distinct observational signature —depending on planet parameters: mass, composition, eccentricity
- We applied this model to VVV-WIT-13. e.g., Explains its anomalously cold spectrum and light curve very well
- Planetary Tidal Disruptions represent a potential new class of stellar variability
- Upcoming large-scale surveys of Eruptive YSOs will allow us to constrain the occurrence rate of these events

Gaia Science Alert, ZTF Alerce, Vera Rubin Telescope in the future

Děkuji za pozornost

Thank you for your attention

Gracias por su atención