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Properties and signatures of IMBH-TDEs in MOCCA Star Cluster Models

Tracing tidal disruption events as electromagnetic signatures of intermediate-mass black holes formed in dense star clusters

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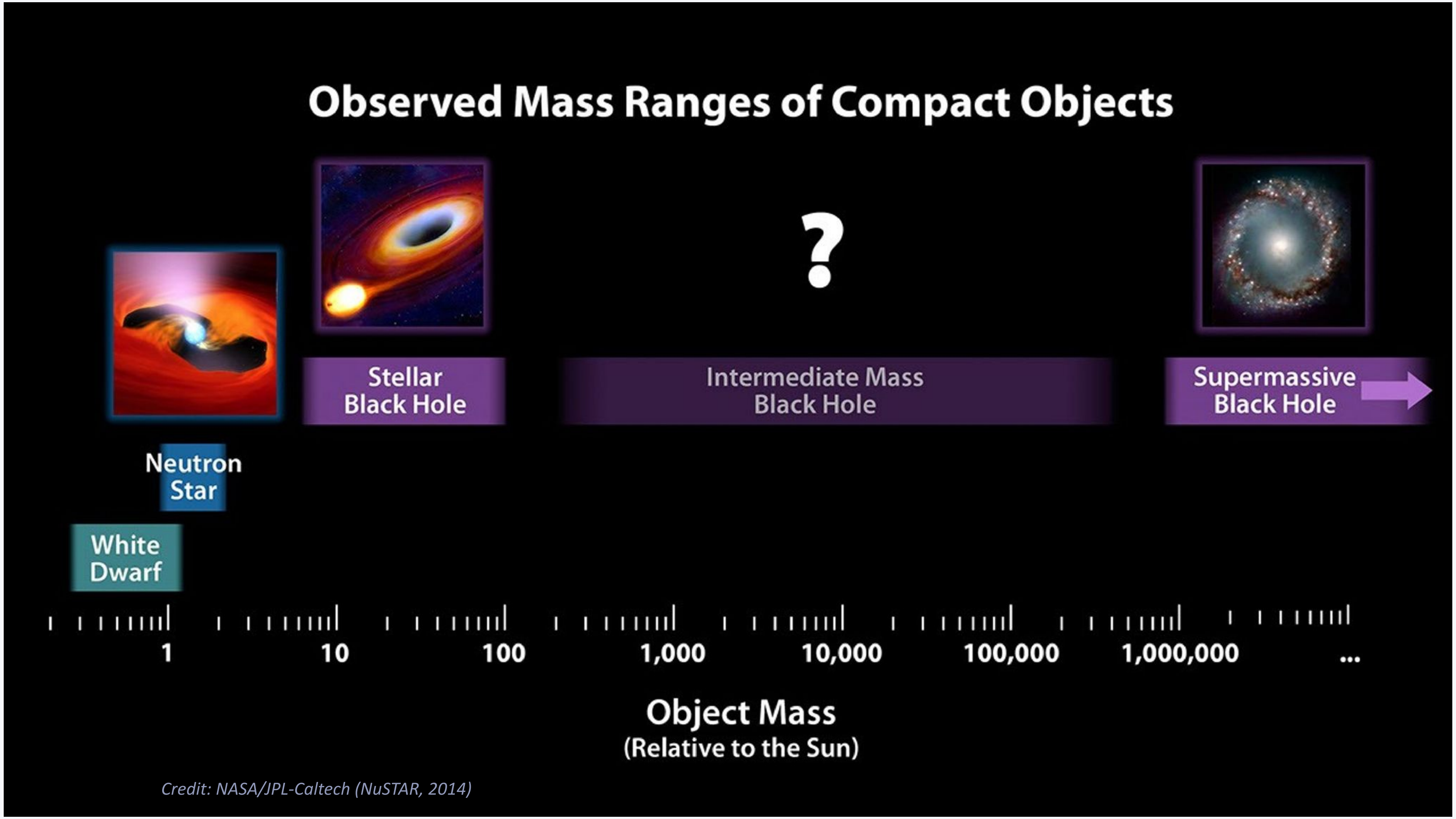
OVERVIEW

Roadmap

1	**The Background**	What tidal disruption events are, what intermediate-mass black holes are, and why TDEs are the way to find them
2	**The Evidence**	Real IMBH–TDE candidates observed to date - including two with well-sampled light curves
3	**Method**	How IMBHs form in dense star clusters, the MOCCA code, and the pipeline from cluster dynamics to a light curve
4	**Result & outlook**	Growth histories, TDE rates, synthetic LSST light curves, and what comes next

The intermediate-mass black hole gap



Why intermediate-mass black holes stay hidden

No steady fuel supply

Dense star clusters are largely gas-poor, so IMBHs rarely sustain AGN-like accretion — no persistent electromagnetic beacon to search for.

Dynamical masses are contested

Averaged velocity-dispersion claims (e.g. 47 Tuc) are frequently degenerate with dense stellar-mass remnant populations — though individual fast-moving stars, as in ω Cen, can settle the question.

A transient window is needed

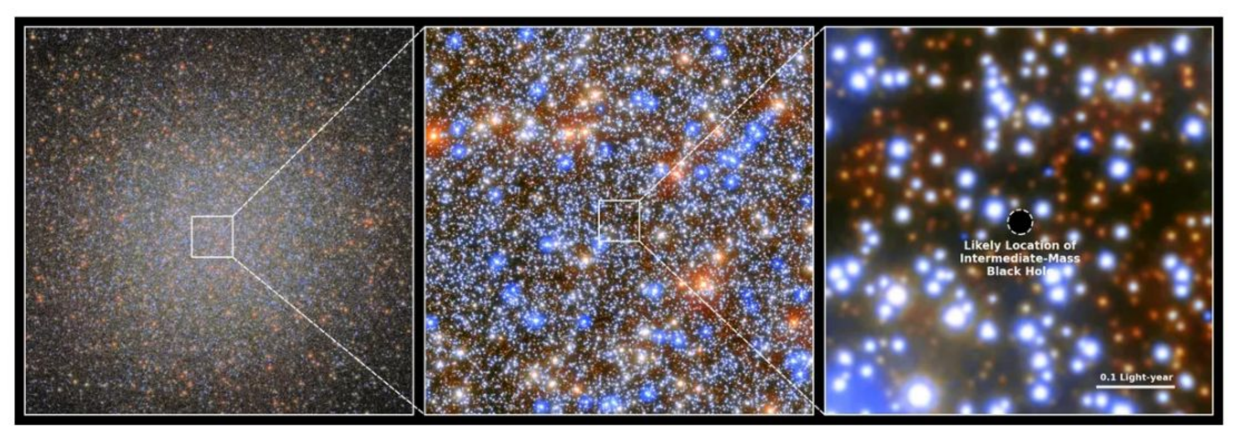
A star that wanders close enough to be tidally disrupted briefly lights up an otherwise quiescent IMBH — a one-off, self-luminous signpost.

This is exactly what a tidal disruption event (TDE) provides.

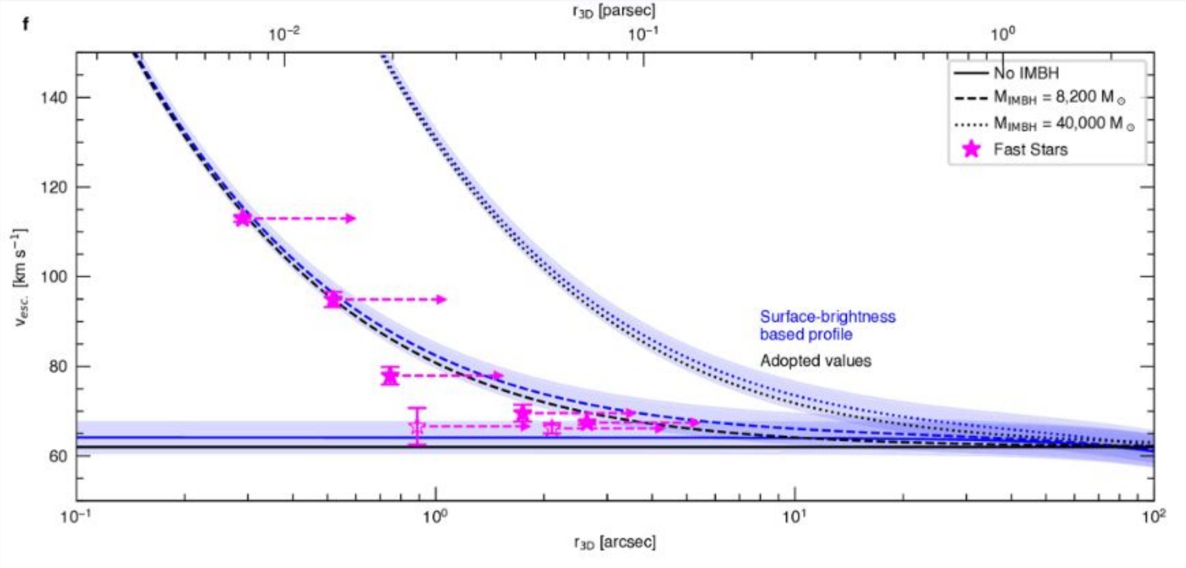
THE EVIDENCE

IMBH in ω Centauri — the strongest detection to date

- 1.4 million proper-motion measurements across 20 years of HST data - the oMEGACat catalogue (Häberle et al. 2024)
- Seven stars in the central 0.08 pc move faster than the cluster's own escape velocity
- Their orbits require a compact object of M_IMBH ≳ 8,200 M☉ - a firm lower limit, from kinematics alone



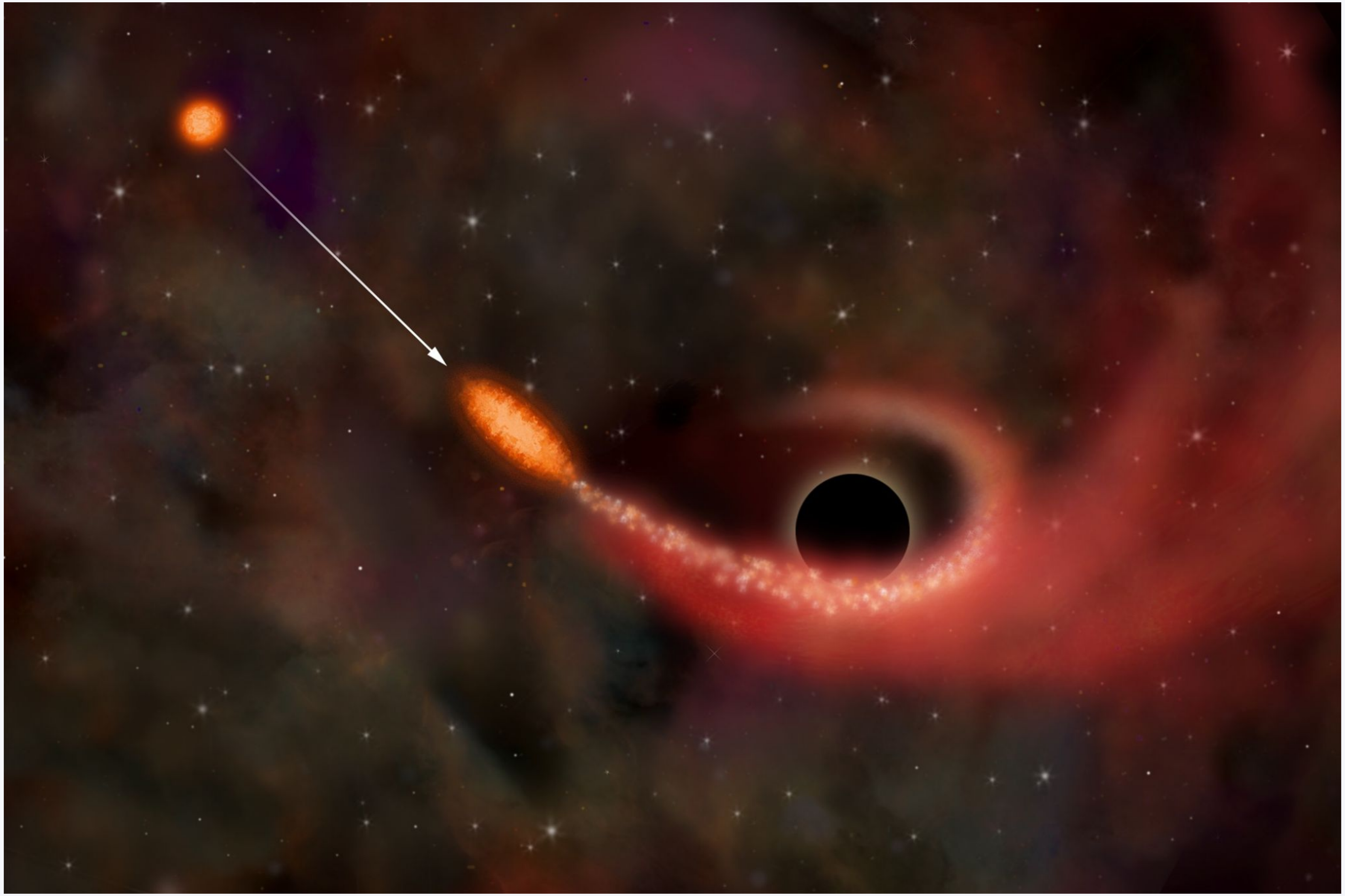
Successive HST zooms into ω Cen's core, down to the likely IMBH location.



The seven fast stars (magenta) sit above the no-IMBH escape-velocity curve, tracking the M_IMBH ≈ 8,200 M☉ model. Credit: Häberle et al. (2024), Nature 631, 285–288.

ω Cen is likely the stripped nucleus of a dwarf galaxy the Milky Way once swallowed — and this result needed 20 years of archival HST data on one specific, nearby cluster. Most clusters will never have that; a less data-hungry signature like a TDE flare is what makes a systematic search possible.

TDEs: Tidal disruption events

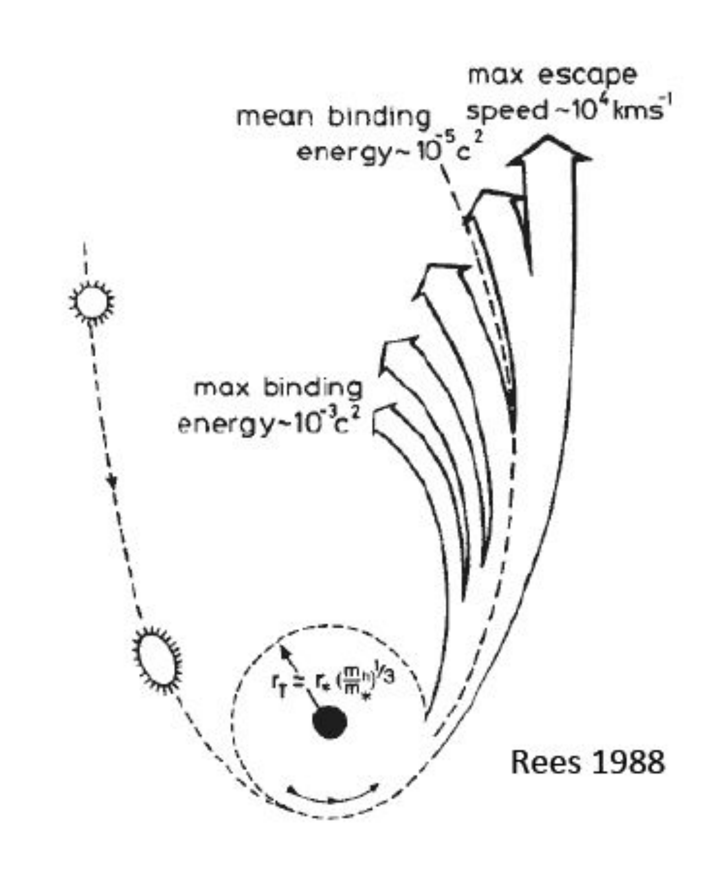


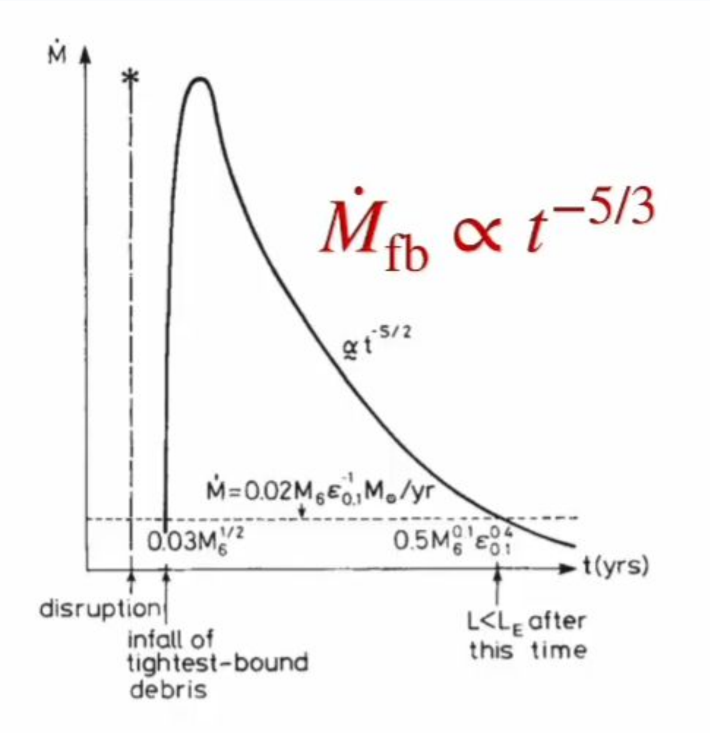
Credit:
NASA/JPL-Caltech

TDEs: The Classical Model

A star passing within the tidal radius *r_t* of a black hole is stretched and torn apart by the differential gravitational force.

- Star scattered onto a near-parabolic orbit (loss cone)
- Pericentre radius < tidal radius → disruption
- ~50% bound, ~50% unbound debris
- Quick circularization & accretion → the flare
- $\dot{M}fb \propto t^{-5/3}$ (fallback rate decay) (timescale: months - years)
- Multicolor BB disk → UV / soft X-ray

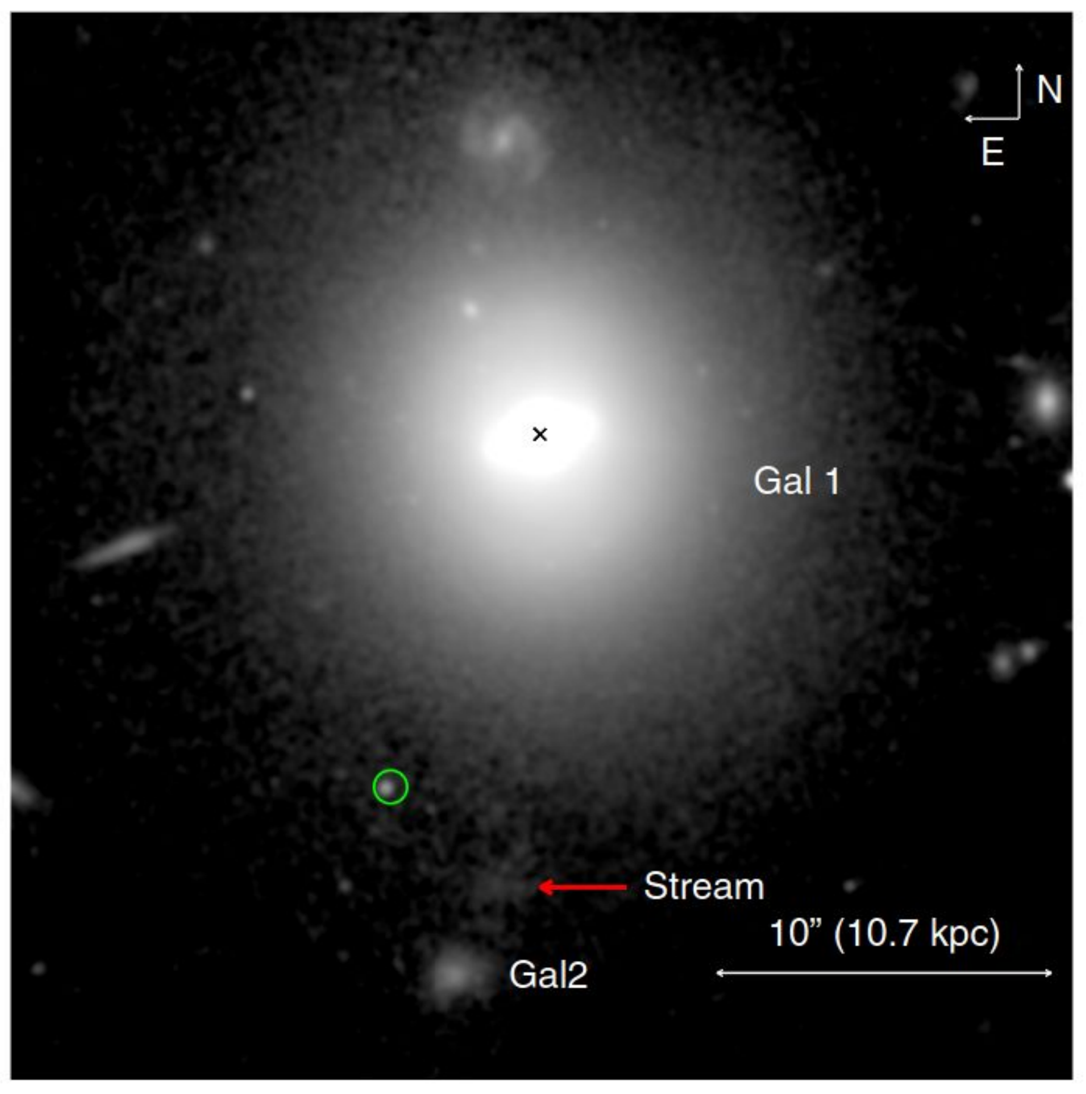


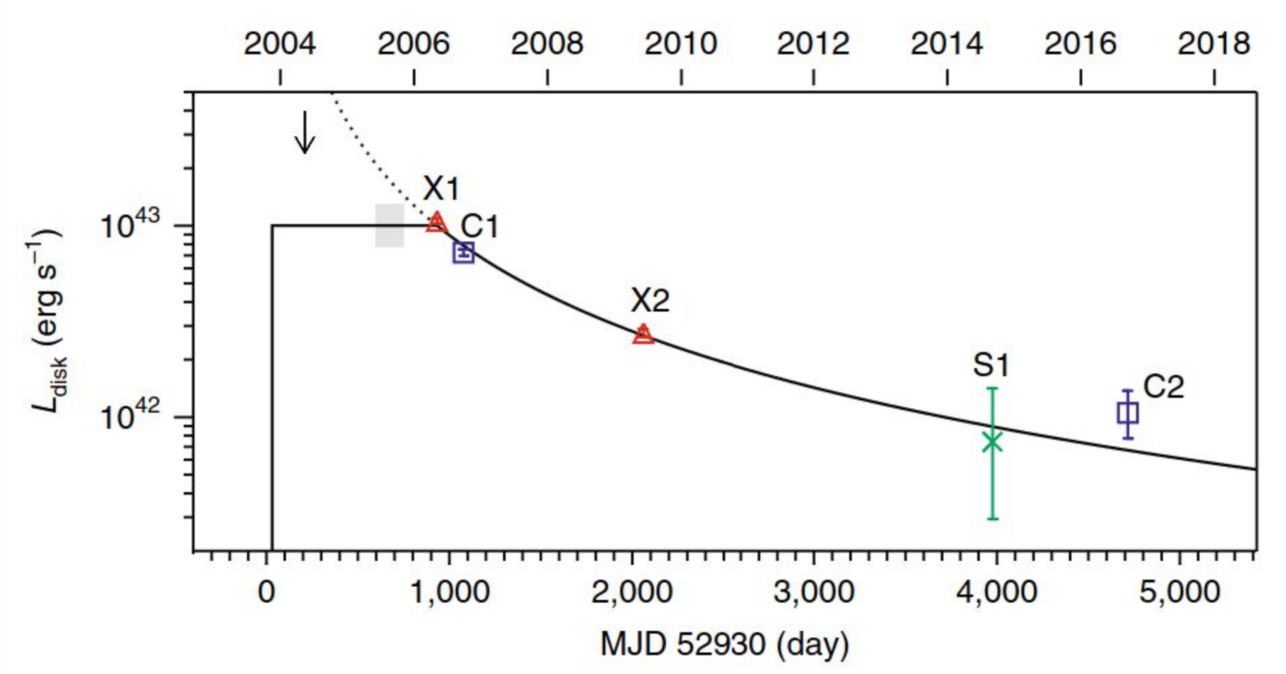


Credit: Rees (1988), Nature 333, 523

THE EVIDENCE

IMBH-TDE Candidate: 3XMM J215022.4–055108

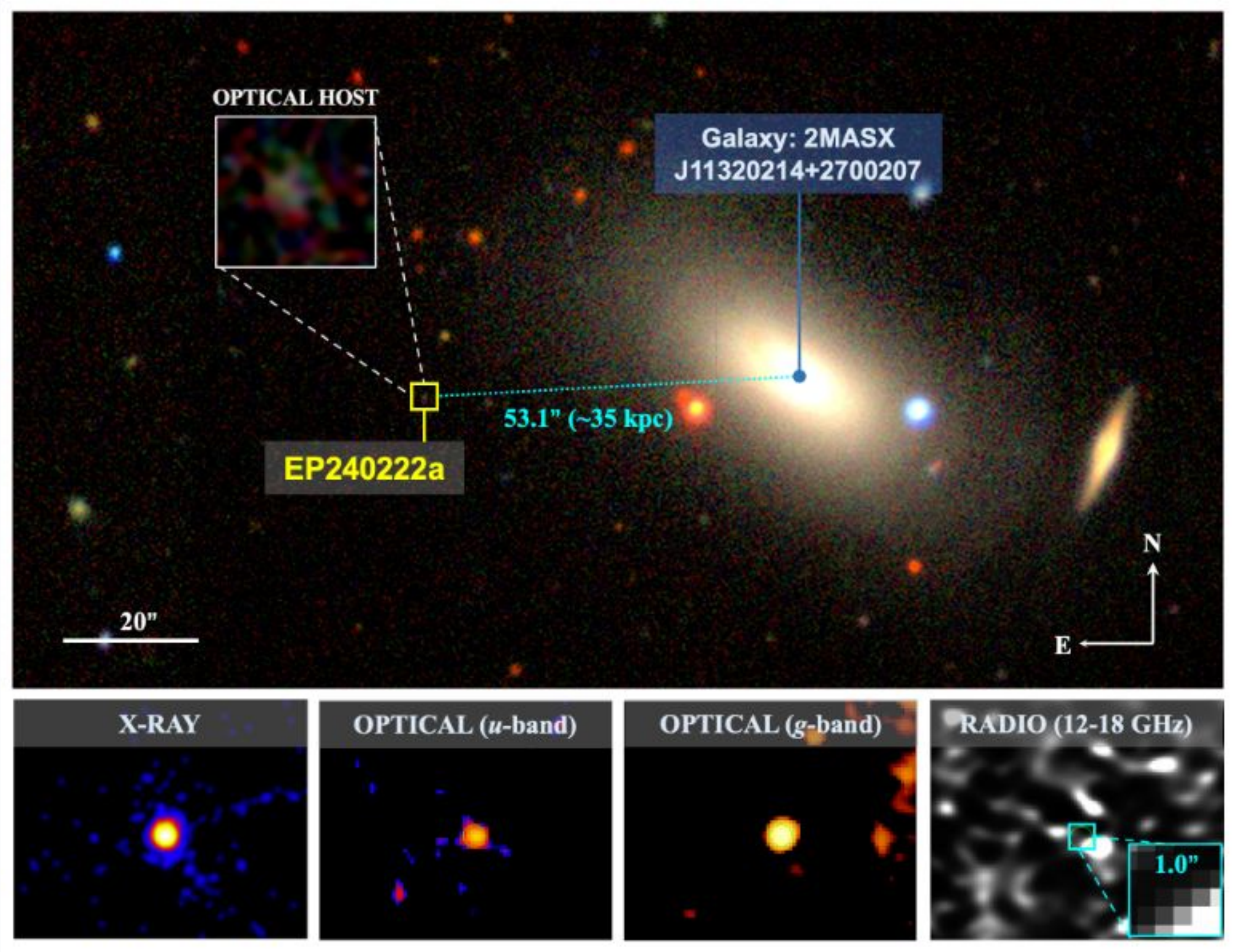


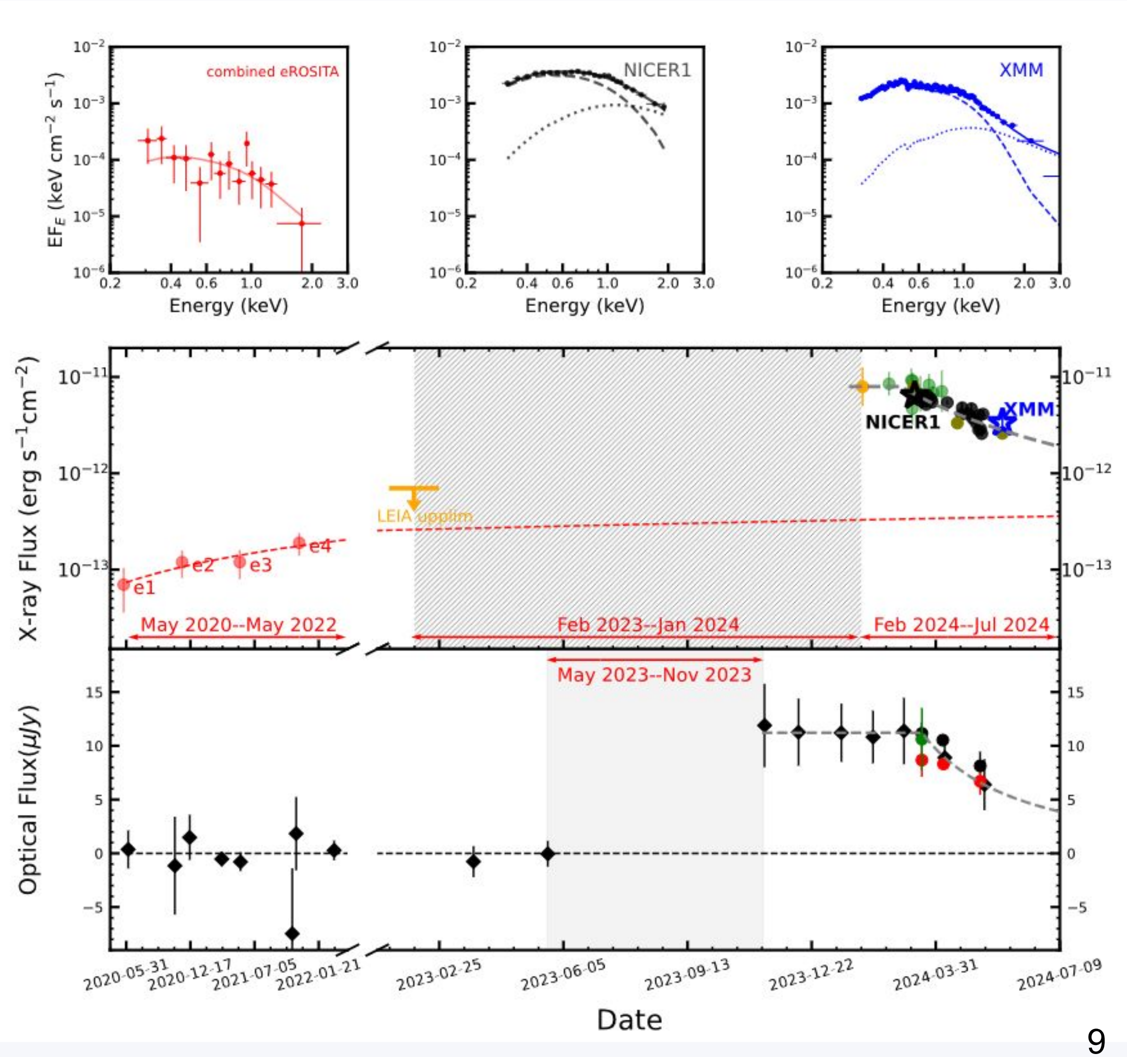


Credit: Lin et al. (2018), Nature Astronomy 2, 656 - Figure 2

THE EVIDENCE

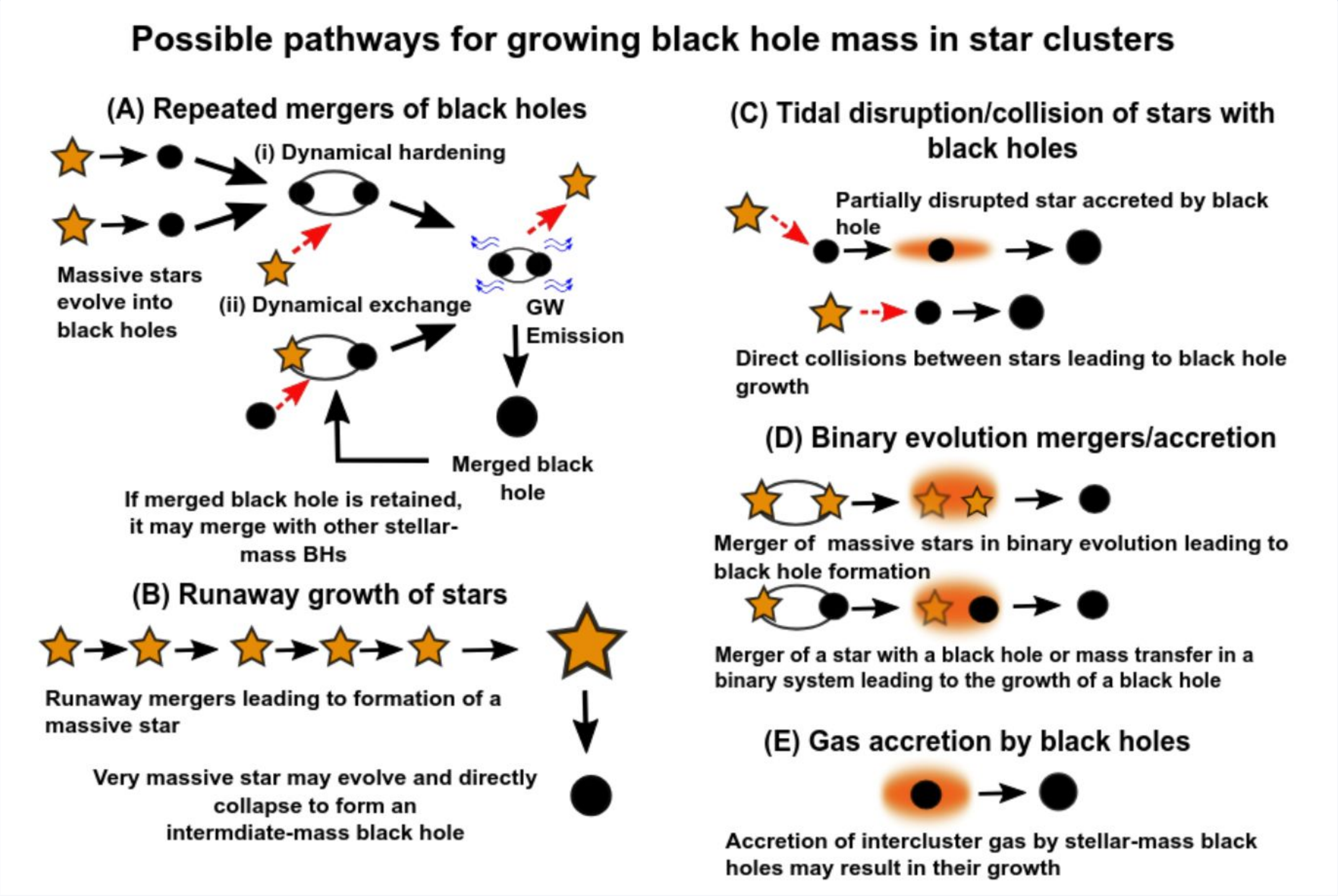
EP240222a: An IMBH-TDE





Credit: Jin et al. (2025), arXiv:2501.09580

How do IMBHs grow inside dense star clusters?



Credit: Askar, Baldassare & Mezcua (2024), arXiv:2311.12118

METHODOLOGY

The aim, and the approach

Aim

Identify observable electromagnetic signatures of tidal disruption events (TDEs) around intermediate-mass black holes (IMBHs) forming self-consistently in dense star clusters, and assess their detectability with LSST.

DYNAMICS

MOCCA (MOnte Carlo Cluster simulAtor)

Self-consistent star-cluster evolution: two-body relaxation, stellar & binary evolution (SSE/BSE), and strong encounters tracked over a full Hubble time.

DEBRIS PHYSICS

STARS_library fallback rates

Numerically tabulated mass fallback rates (Law-Smith et al. 2020), scaled to IMBH masses for each disruption event.

EMISSION

Slim-disk light-curve model

Tang et al. (2024) wind–disk framework converts fallback rate into a multi-band bolometric and LSST light curve.

The MOCCA Code

MOnte Carlo Cluster simulAtor: code to evolve realistic star clusters

Developed at **CAMK**

Based on a Hénon's Monte Carlo method → further improved by **Jerzy Stodółkiewicz** (1982; 1983; 1987) and **Mirek Giersz**

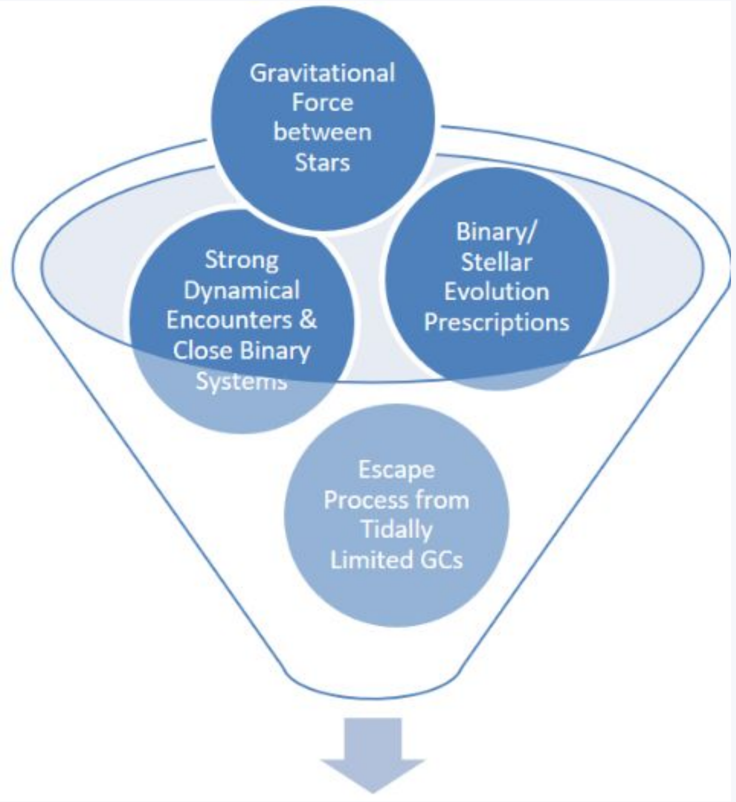
Includes key physics:

- Stellar & binary evolution (SSE/BSE + updates)
- Few-body integrator for close encounters
- Realistic treatment for escapers in a tidal field

Validated against direct N-body simulations

Can simulate realistic clusters in **days to weeks** → enabling large grids of models exploring the initial parameter space

MOCCA-Survey Database I, II, III (Askar et al. 2017; Hypki et al. 2022; Maliszewski et al. 2022; Giersz et al. 2025; Wiktorowicz et al. 2025)



MOCCA

https://moccacode.net/

MOCCA cluster models

Initial conditions

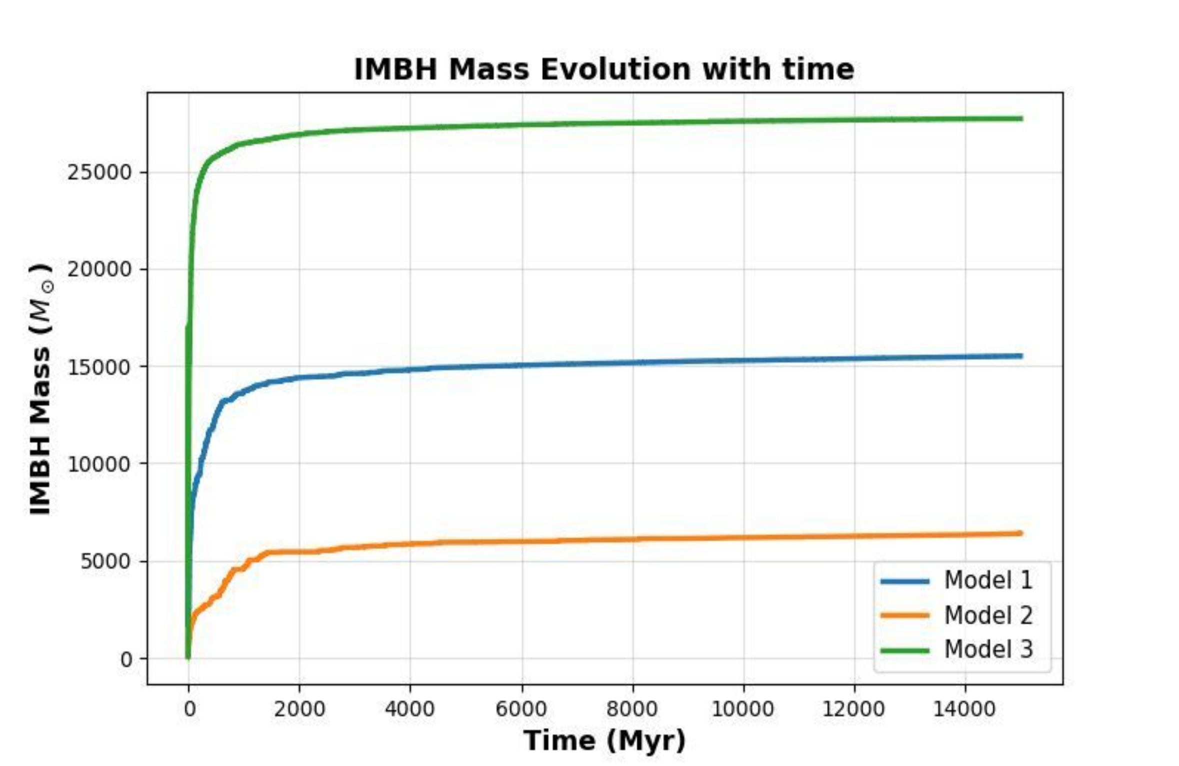
Total stars (N)	2×10^6
Total cluster mass	1.29×10^6 M☉
Concentration (W_0)	King model, {5, 8}
IMF	Kroupa (2001), 0.08–150 M☉
Metallicity (Z)	0.0005
Binary fraction	0.10
Stellar evolution	SSE / BSE (Hurley)

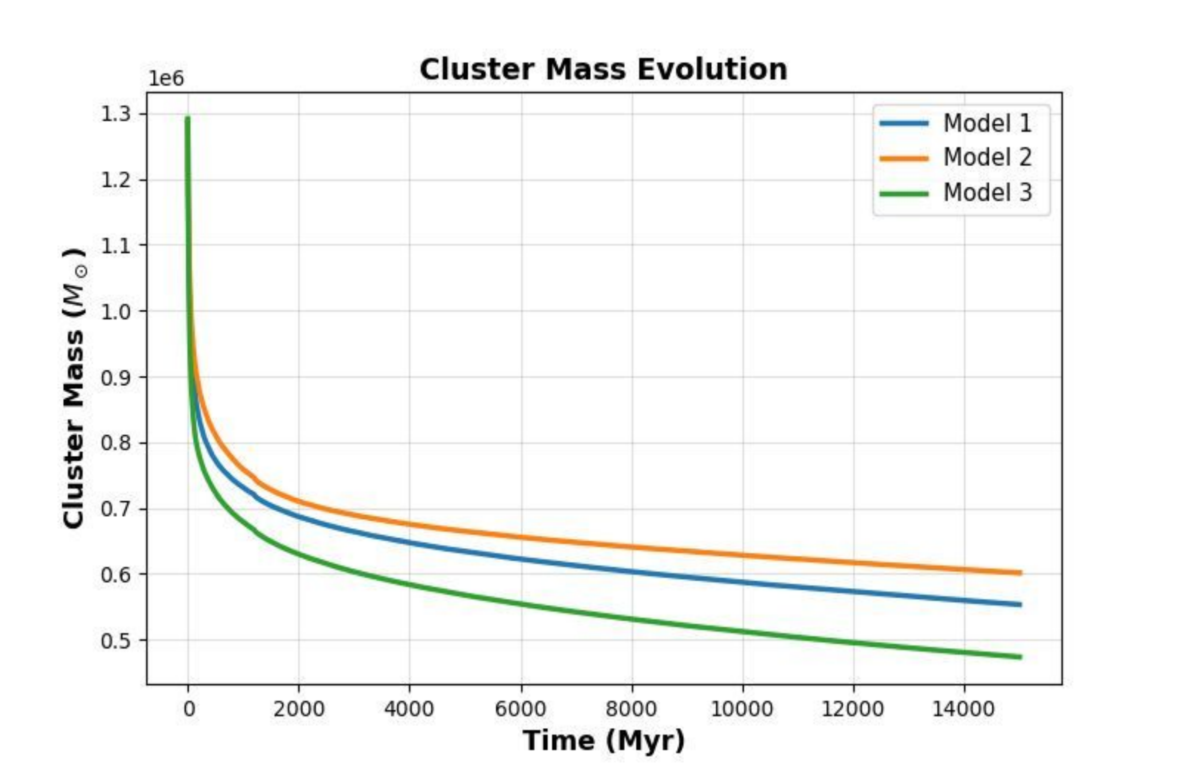
Present-day (14 Gyr) model outcomes

Model	M_BH [M☉]	r_h,0 [pc]	M_cl [M☉]	r_h [pc]	r_hl [pc]
Model 1	15,404	0.50	572,940	4.97	2.39
Model 2	6,301	1.00	617,170	5.26	2.44
Model 3	27,641	0.25	495,420	5.62	2.82

Compact, denser clusters (smaller r_h,0) produce the most massive IMBHs - tighter cores drive more frequent strong encounters and mergers, growing Model 3's black hole to ≈27,000 M☉ by 14 Gyr.

IMBH growth and cluster mass loss over 14 Gyr





Rapid early growth (< 1 Gyr) from runaway stellar and BH interactions, then a slow, steady climb as the cluster loses mass through relaxation-driven evaporation and stellar evolution.

METHODOLOGY

From a close encounter to a light curve

Tidal disruption condition

$r_t \gtrsim r_g$ (disruption occurs outside the horizon)

$r_t \approx R\star \, (M_{BH} / M\star)^{1/3}$ $r_g = G \, M_{BH} / c^2$

Event selection

TDEs are drawn from the , representative of present-day, observable disruption events for a cluster at its current evolutionary stage.

Modelling pipeline

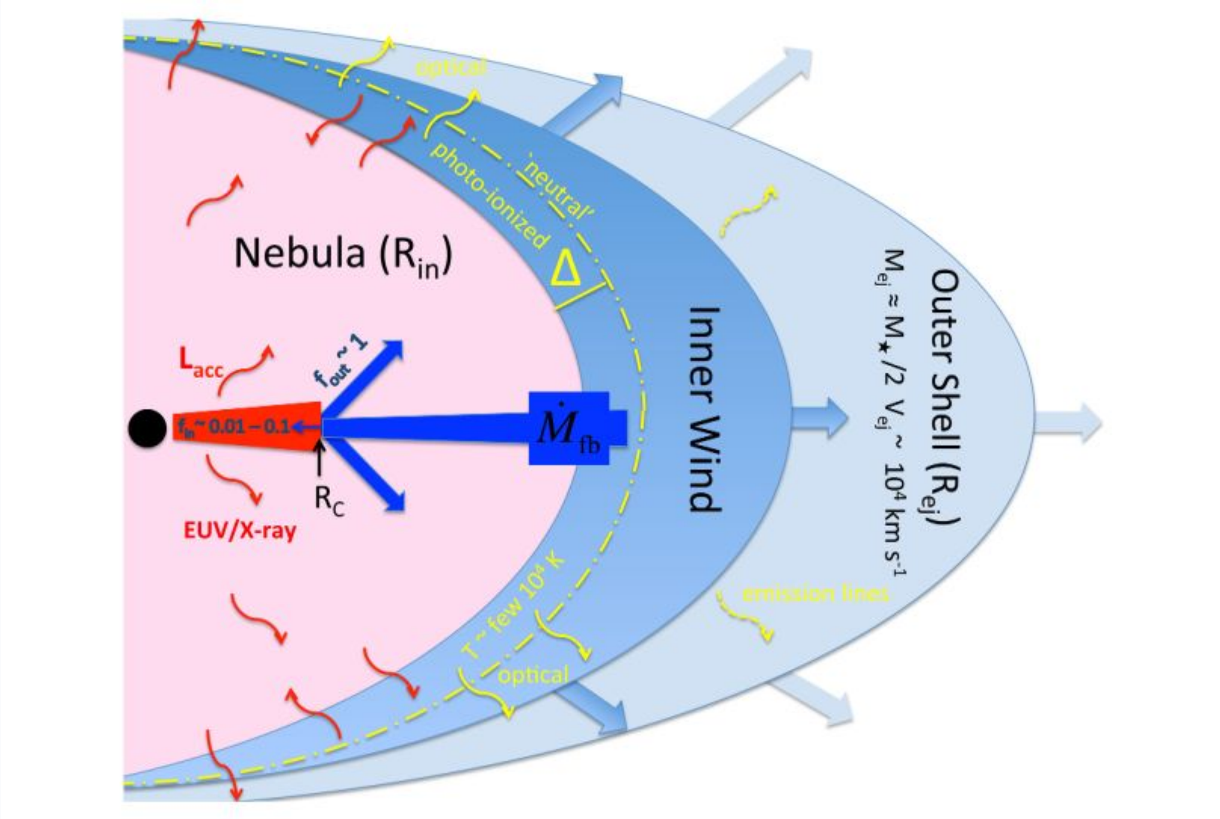
MOCCA simulation → STARS_library fallback rate → Slim-disk light curve → LSST multi-band photometry

Fallback rates from Law-Smith et al. (2020), tabulated by stellar structure and scaled to each IMBH mass.

Tang et al. (2024) wind–disk decomposition sets photospheric radius, temperature, and bolometric luminosity.

Present-day cluster luminosity (FSPS) is combined with LSST 5σ depths to test point-source and flare detectability.

From fallback rate to emission: the disk + wind split



A fraction of the fallback accretes through a compact disk; the rest launches an optically thick wind that reprocesses the disk's X-rays into the optical/UV flare we actually observe.

Credit: Metzger & Stone (2016), MNRAS 461, 948, Fig. 1

Following Tang et al. (2024)

DISK ACCRETION RATE

$\dot{M}_\bullet = (1 - f_{out})\, \dot{M}_{fb}$

the fraction of fallback that actually reaches the black hole

WIND OUTFLOW RATE

$\dot{M}_{out} = f_{out}\, \dot{M}_{fb}$

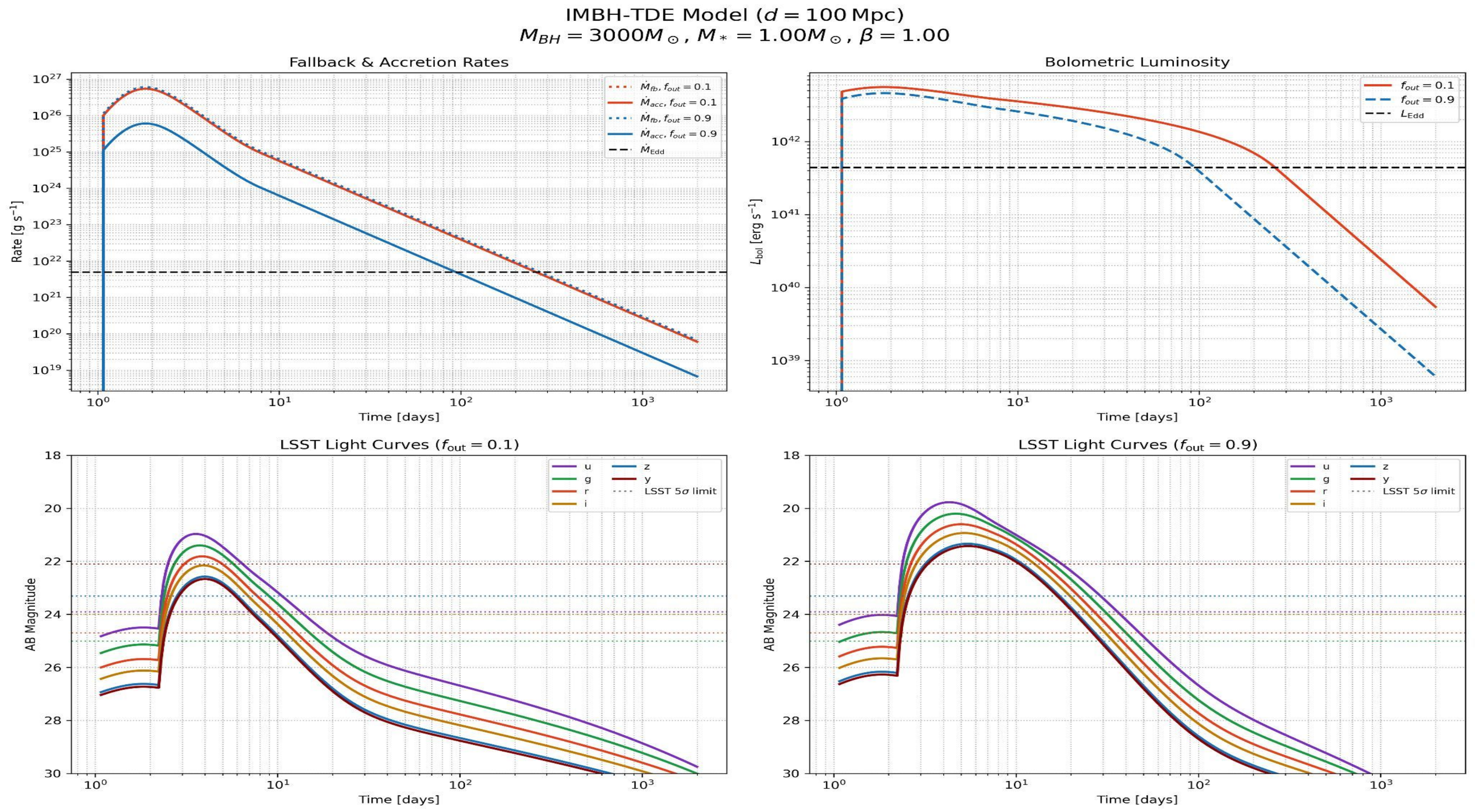
the rest launches the wind — this is the f_out = 0.1 vs 0.9 split shown on every light-curve slide

WIND PHOTOSPHERE LUMINOSITY

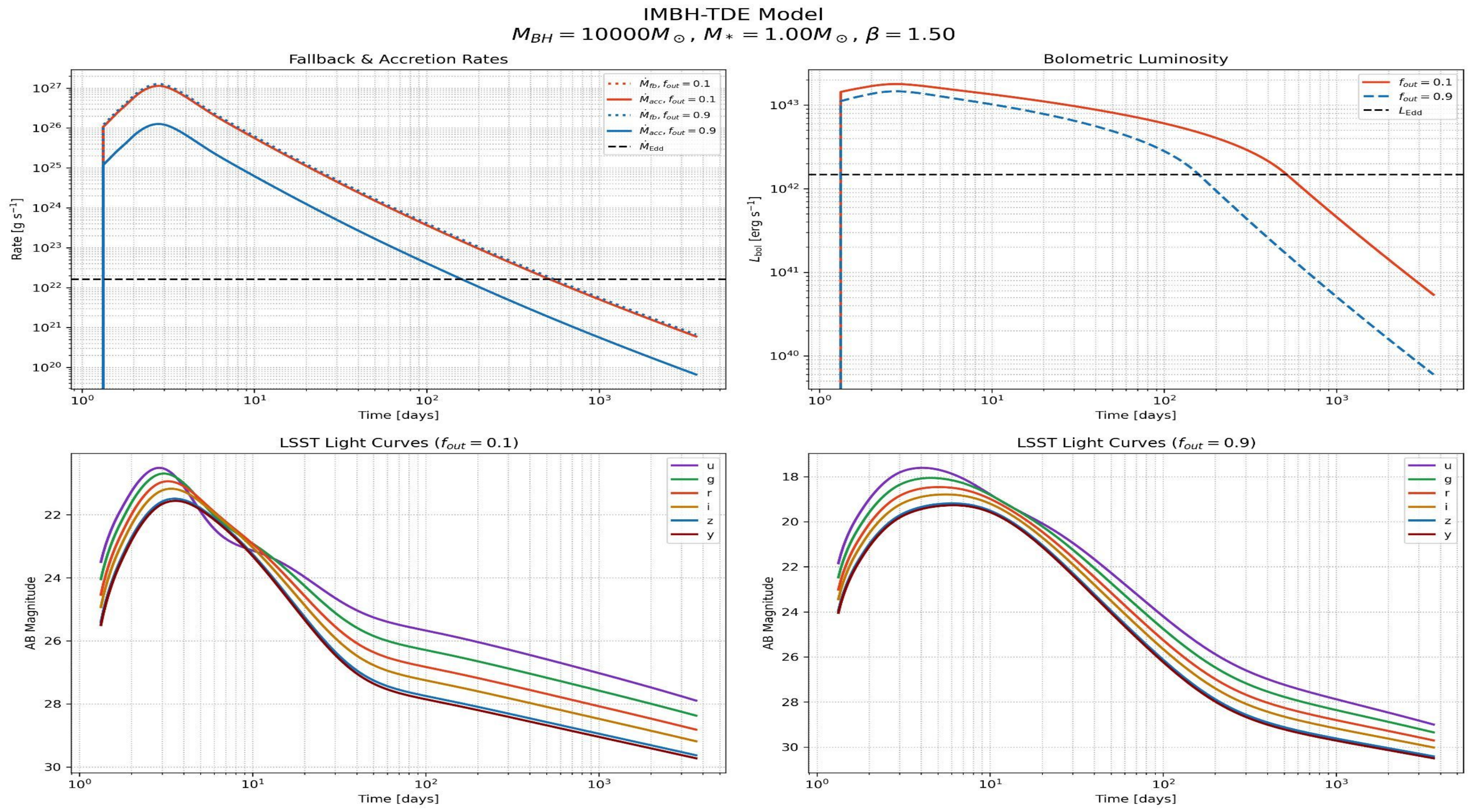
$L_\nu = 4\pi^2 R_{ph}^{\,2}\, B_\nu(T_{ph})$

reprocessed emission escapes here — sets the observed color and peak brightness

Representative light curve - grazing encounter (β = 1.0)



Representative light curve - deep plunge (β = 1.5)



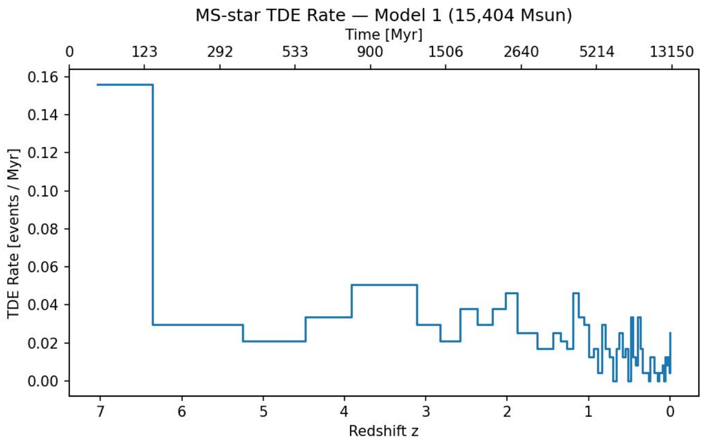
RESULT — RATES

PRELIMINARY

How the TDE rate evolves over cosmic time

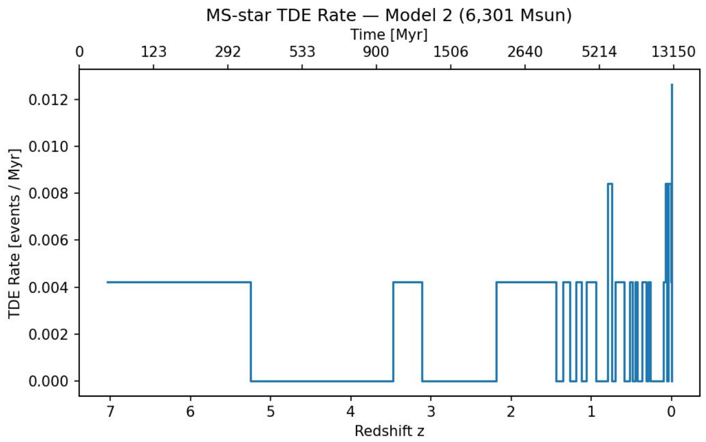
MS-star TDE rate history for each model, from the validated β = r_t/r_p disruption criterion.

Model 1 15,404 M☉



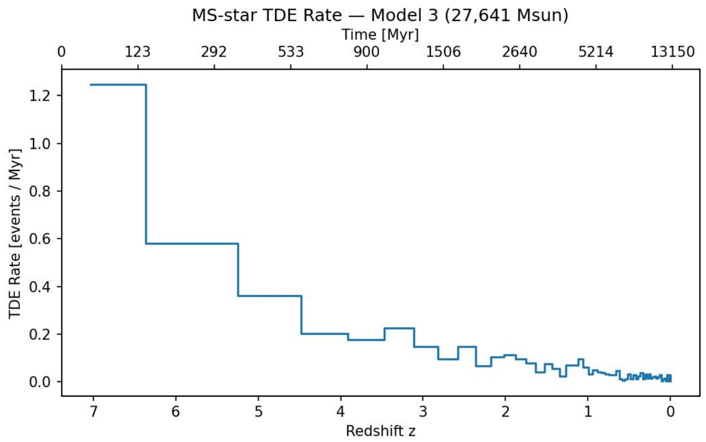
20.93 Gyr^{-1}

Model 2 6,301 M☉



2.86 Gyr^{-1}

Model 3 27,641 M☉



85.14 Gyr^{-1}

All three show a decline from an early peak as the loss cone empties over 13 Gyr - clearest for the two higher-mass models (1 and 3); the lowest-mass Model 2 shows a much noisier, more intermittent pattern, reflecting sparser event statistics.

THE CONCISE CONCLUSION

Key takeaways

- **Real IMBH–TDE candidates exist — 3XMM J215022.4−055108 (~17,500 M☉) and EP240222a — within our modelled mass range, direct observational anchors for this pipeline**
- **Deeper plunges (β = 1.5) are brighter and stay detectable longer than grazing encounters (β = 1.0)**
- **LSST's depth should make these events detectable well beyond the host cluster's own reach**
- **A realistic path to growing the IMBH–TDE sample beyond today's handful of candidates**
- **Next step: Rate estimates for transient sky surveys**

Thank You