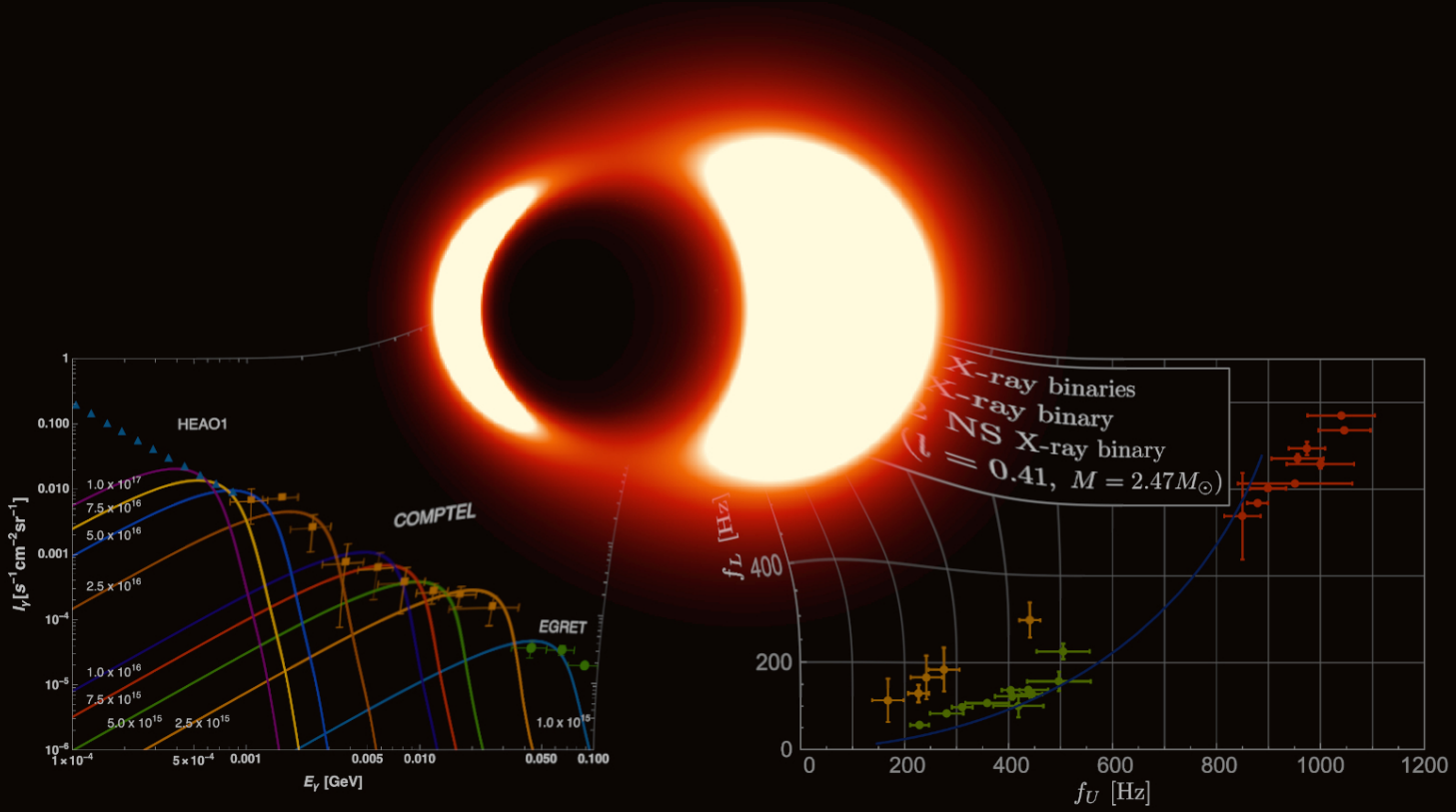
Black holes as probes for new physics



Jens Boos
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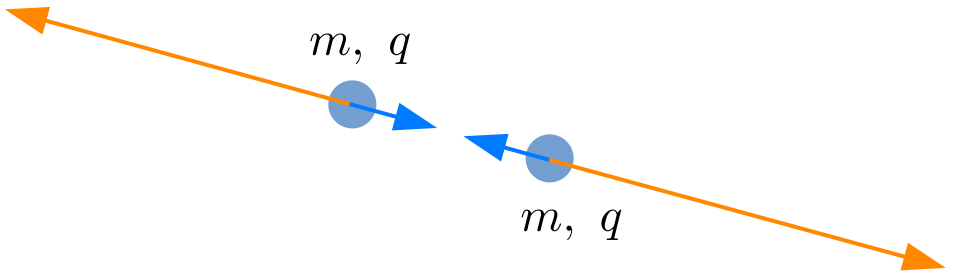
Karlsruhe Institute of Technology

Institute for Theoretical Physics

YIG Prep Pro

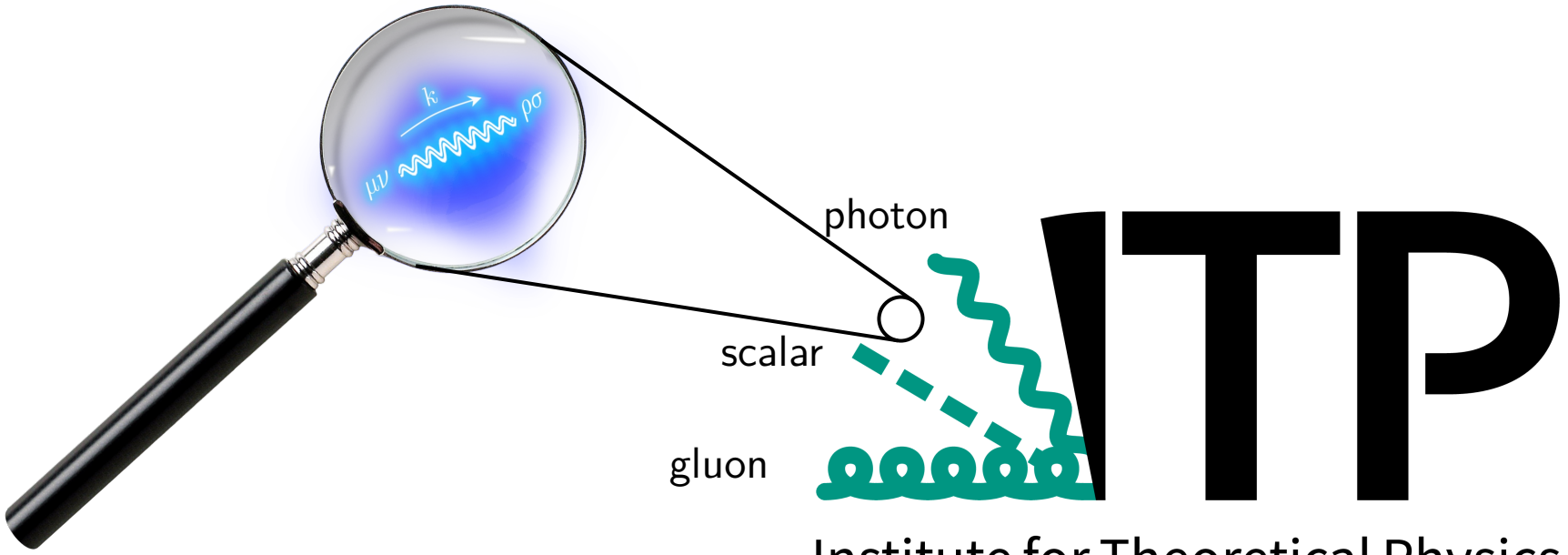
Karlsruher Institut für Technologie

Gravity is a very weak force.



$$\left|\frac{F_{\text{grav}}}{F_{\text{em}}}\right| = 4\pi\epsilon_0 G\left(\frac{m}{q}\right)^2 \sim 2\times 10^{-43}\left(\frac{m}{511\,\text{keV}/c^2}\right)^2\left(\frac{q}{e}\right)^{-2}$$

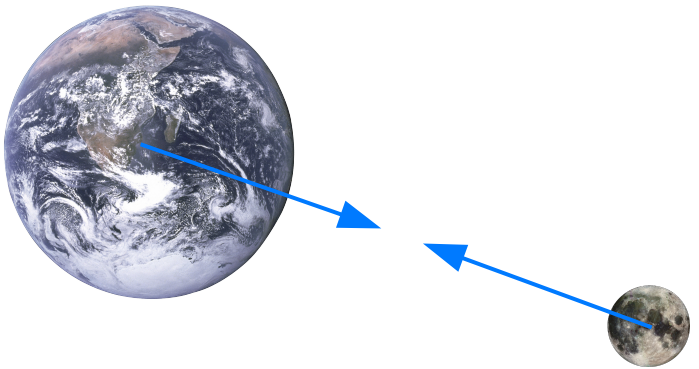
Gravity is a very weak force.



ITP

Institute for Theoretical Physics

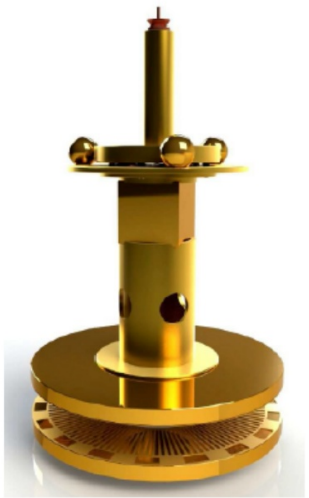
Gravity is relevant at macroscopic scales.

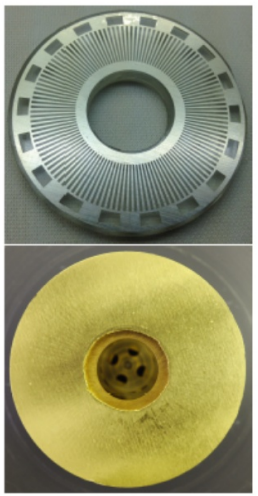


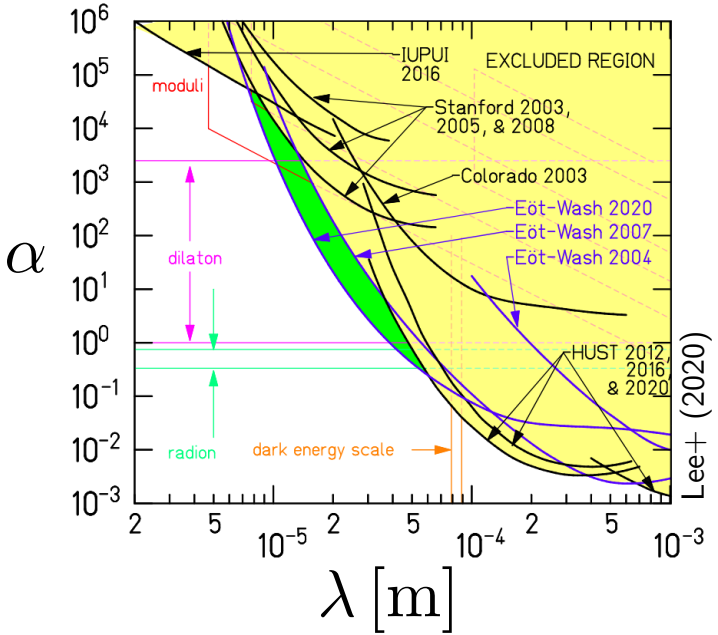
$$\left| \frac{F_{\text{grav}}}{F_{\text{em}}} \right| \ggg 1$$

Is Newton enough?

Eötvös-type experiments **confirm** Newton's law to distances of $\mathcal{O}(50\,\mu\mathrm{m})$ for $\mathcal{O}(\mathrm{kg})$ masses:







$$V = -\frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

Small masses (linear theory) and slow masses (non-relativistic). Beyond: need **general relativity**.

Example: perihelion shift of Mercury

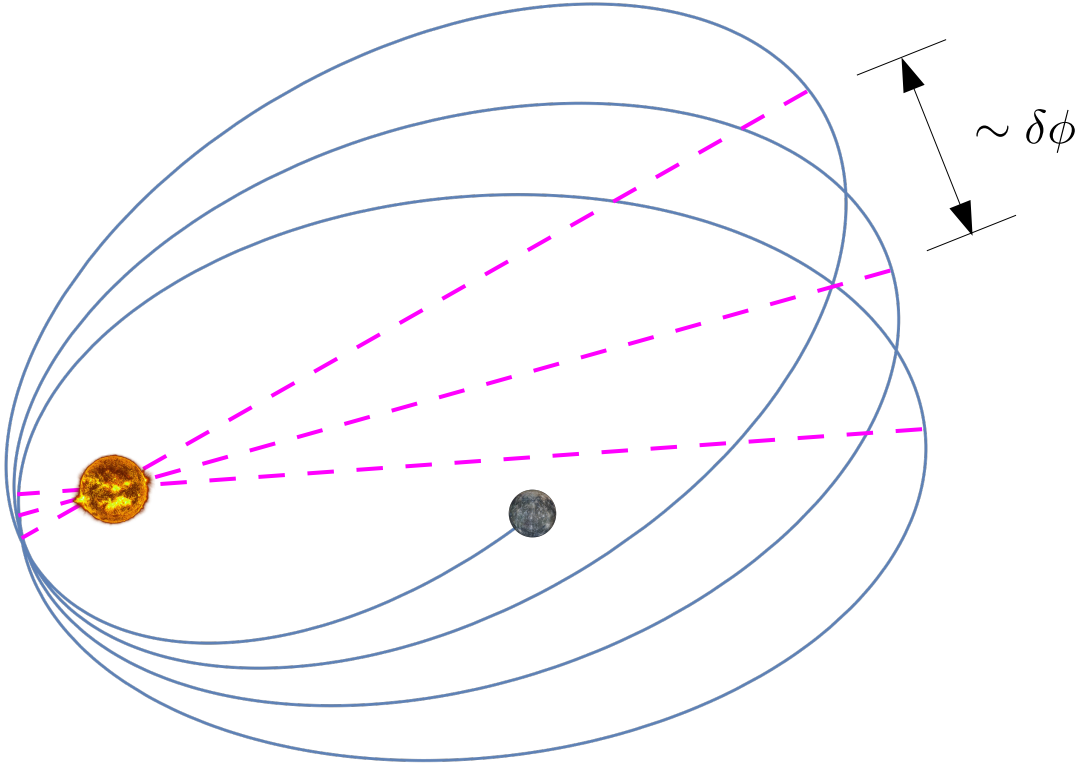
Mercury **perihelion shift** $\delta\phi$ cannot be described by Newtonian mechanics.

$$\delta\phi \approx 42.98''/\text{century}$$

Bertrand's theorem: central potentials like

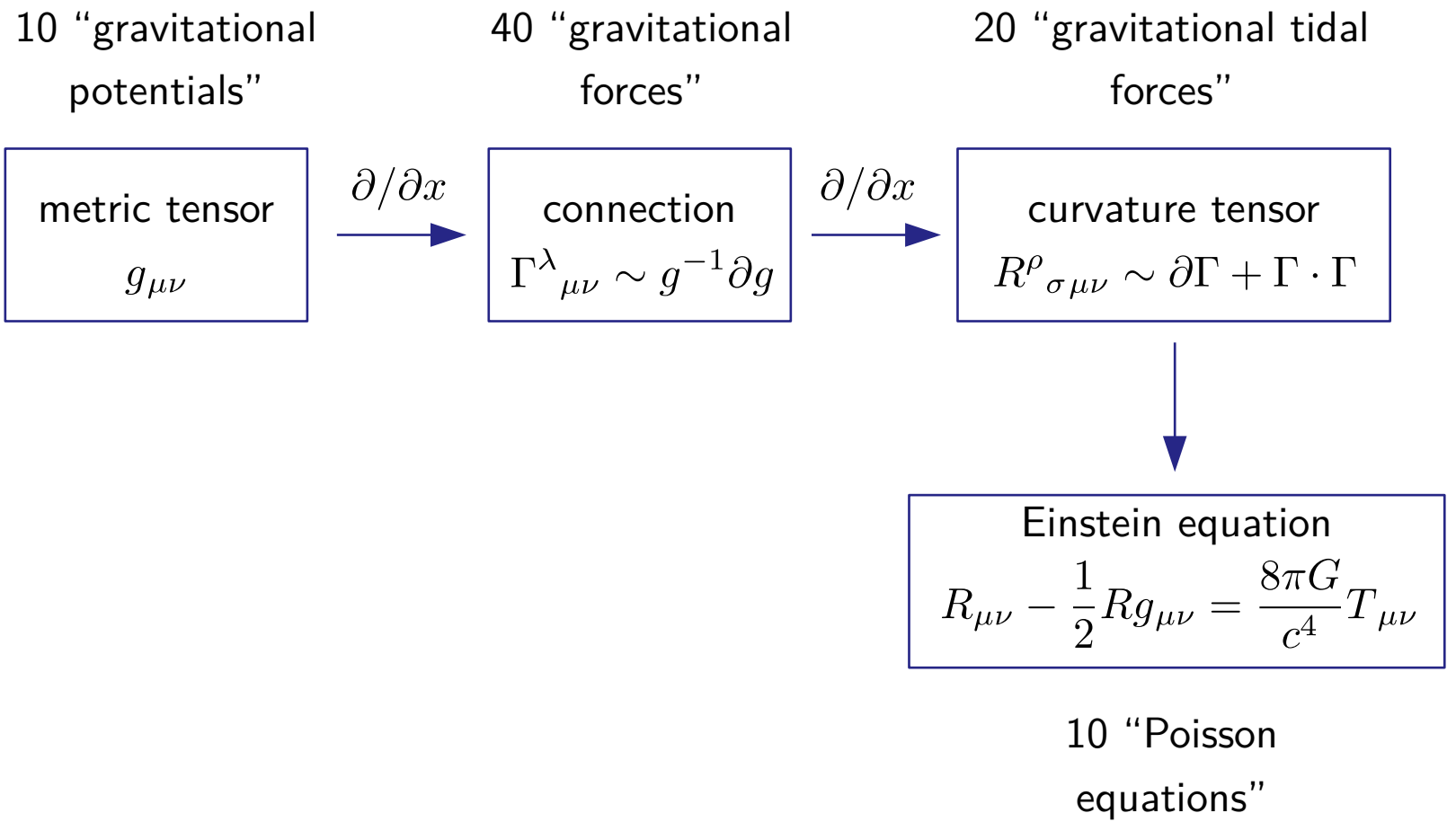
$$V = \frac{c_1}{r} + c_2 r^2$$

generate closed orbits, no others.



Important: Taking into account other planetary bodies cannot explain the precession.

General relativity in a nutshell



Solar System Tests of General Relativity

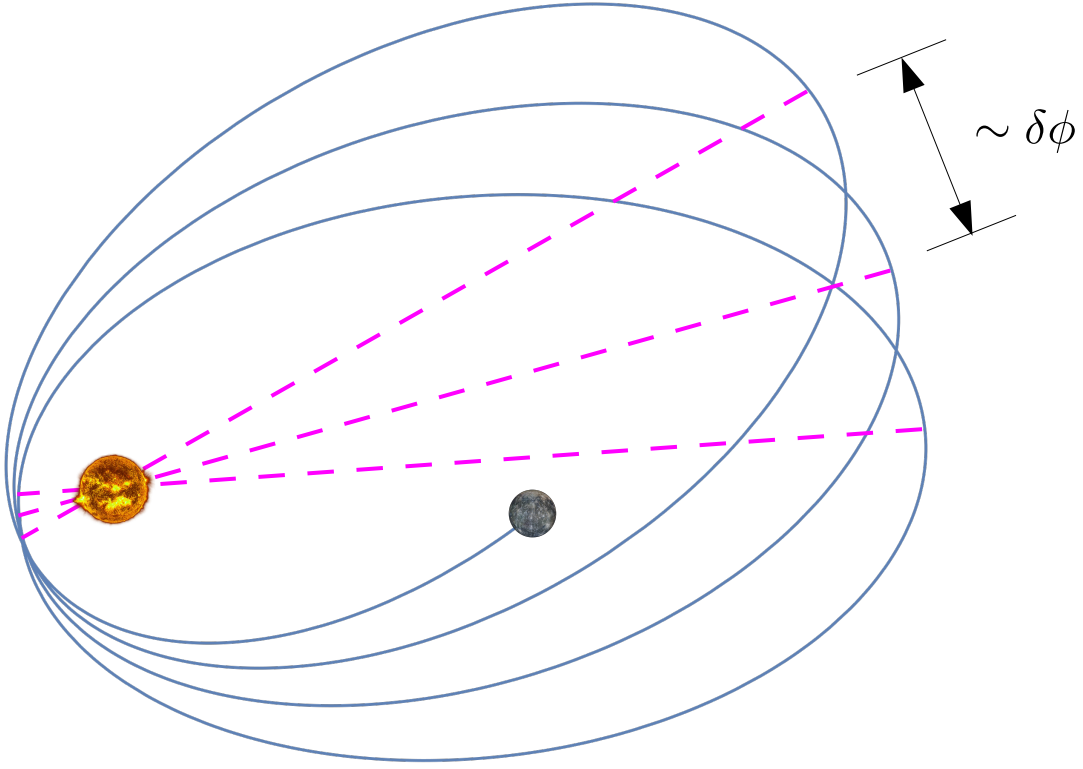
Jens Boos, KIT

General relativity explains the perihelion shift.

Mercury's **perihelion shift** is described accurately via geodesics:

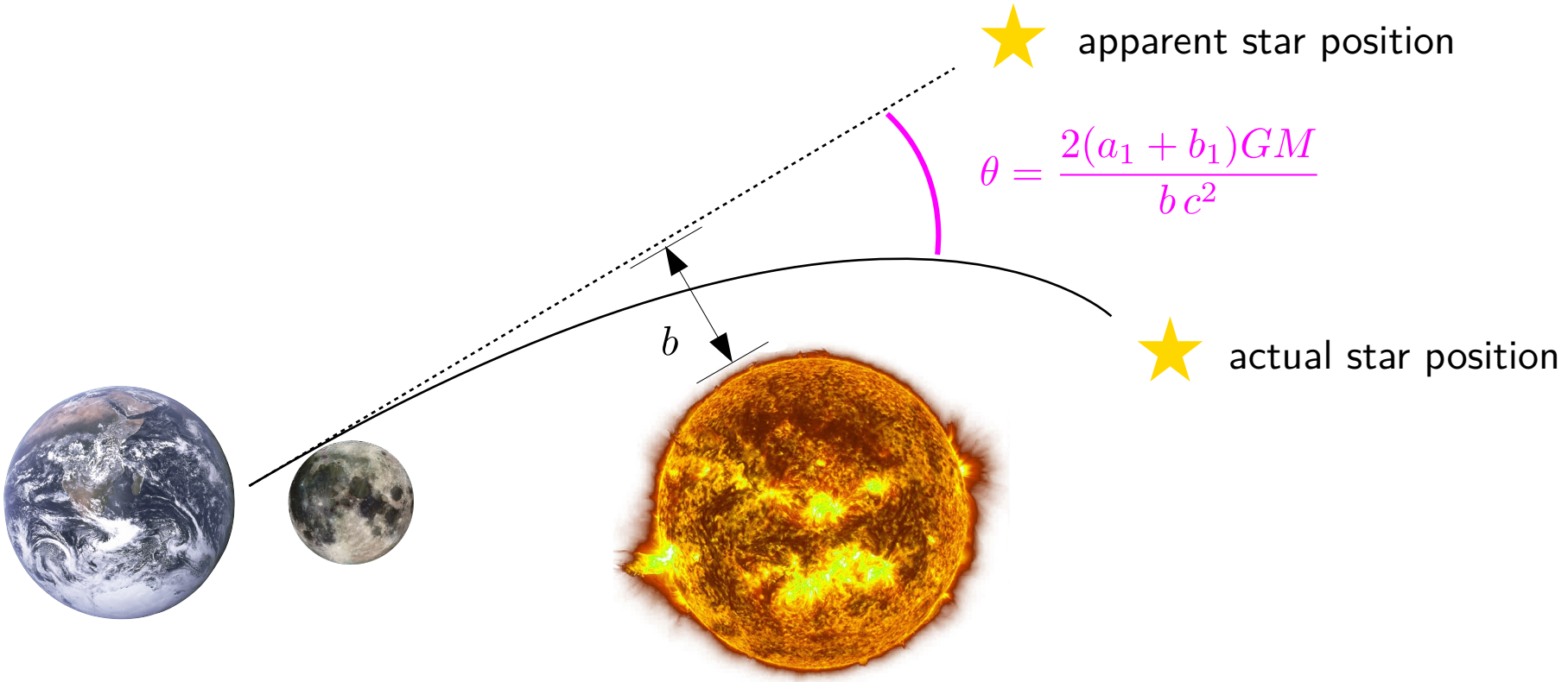
$$\dot{r}^2 = E^2 - V_{\text{eff}}\,,$$
$$V_{\text{eff}} = \left(1 + \frac{L^2}{r^2}\right)\left(1 - \frac{2GM}{r}\right)$$

$$-\frac{2GML^2}{r^3}$$

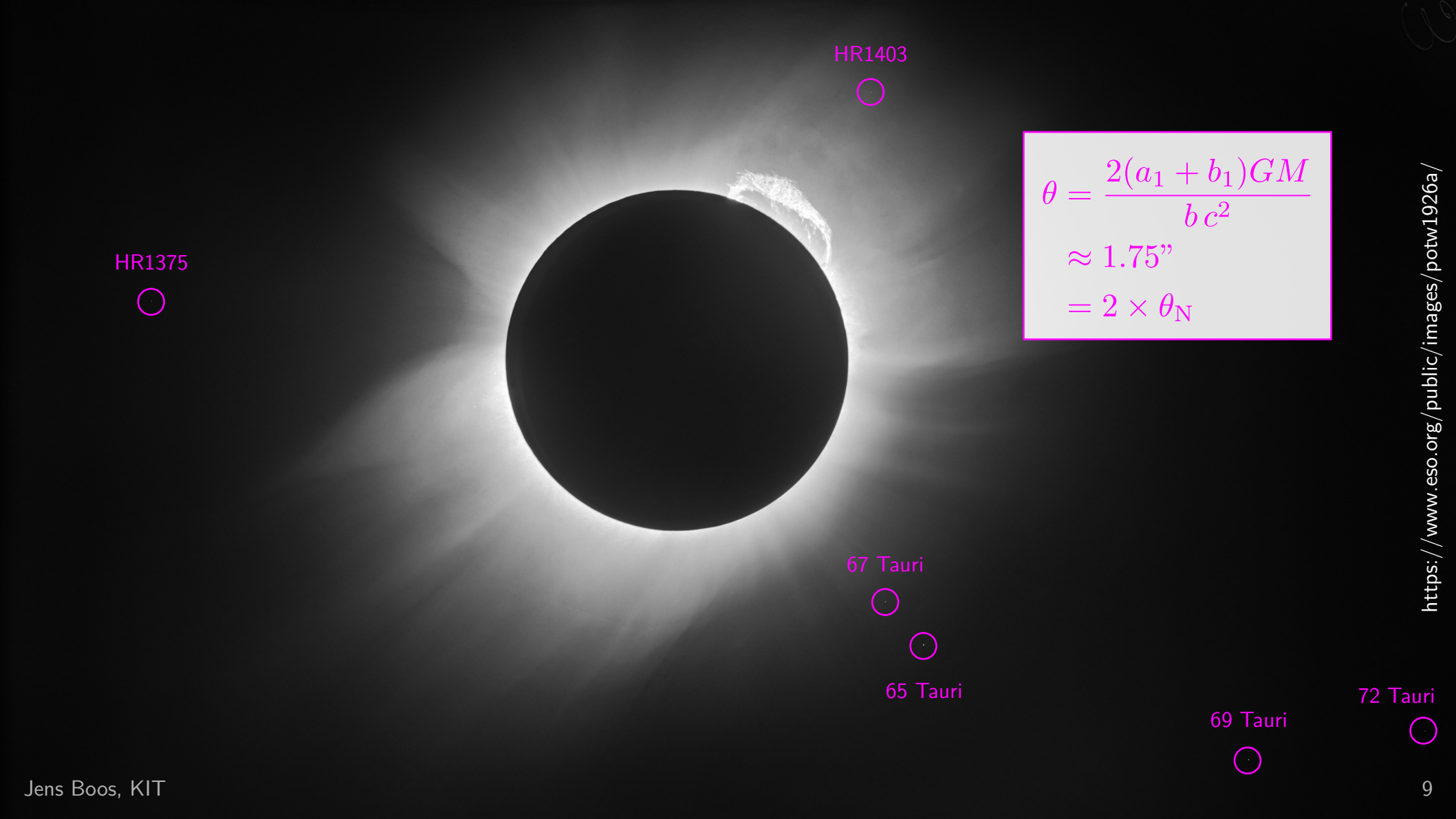


This deviation from Bertrand's theorem gives the observed $\delta\phi = \dfrac{6\pi GM}{a(1-e^2)c^2} \approx 42.98''/\text{century}.$

General relativity also bends light the right amount.



$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -\left(1 - \frac{2a_1 GM}{r}\right)\mathrm{d}t^2 + \left(1 + \frac{2b_1 GM}{r} + \ldots\right)\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$



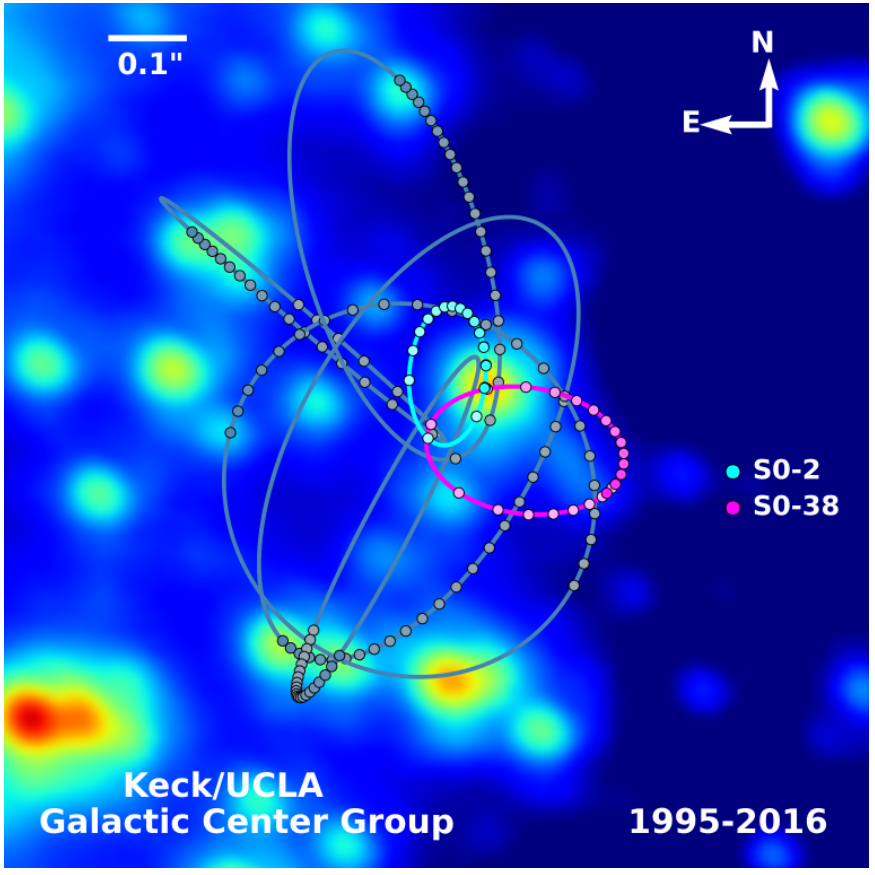
$$\theta = \frac{2(a_1 + b_1)GM}{b\,c^2}$$
$$\approx 1.75”$$
$$= 2 \times \theta_{\mathrm{N}}$$

https://www.eso.org/public/images/potw1926a/

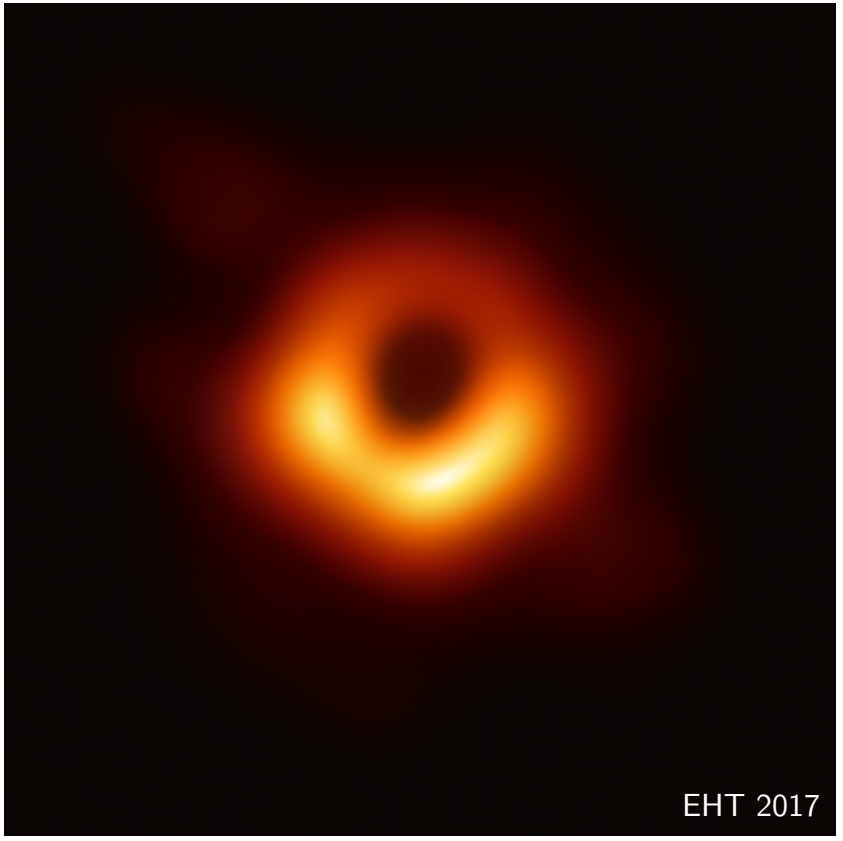
Strong Field Tests of General Relativity

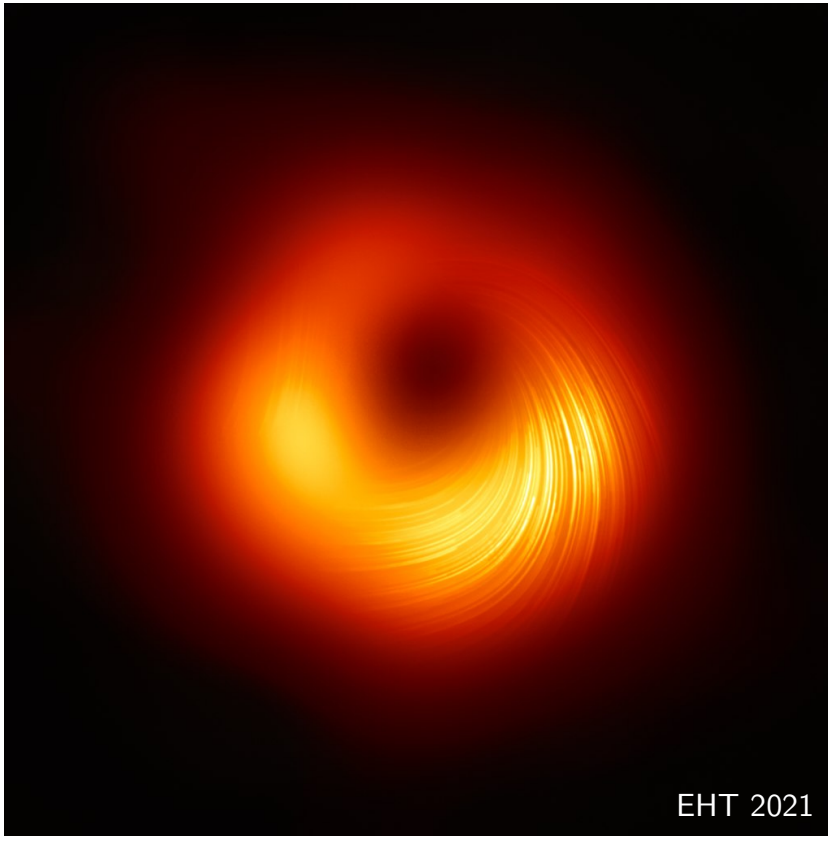
Jens Boos, KIT

Orbits around Sagittarius A* in the galactic center (IR observations)

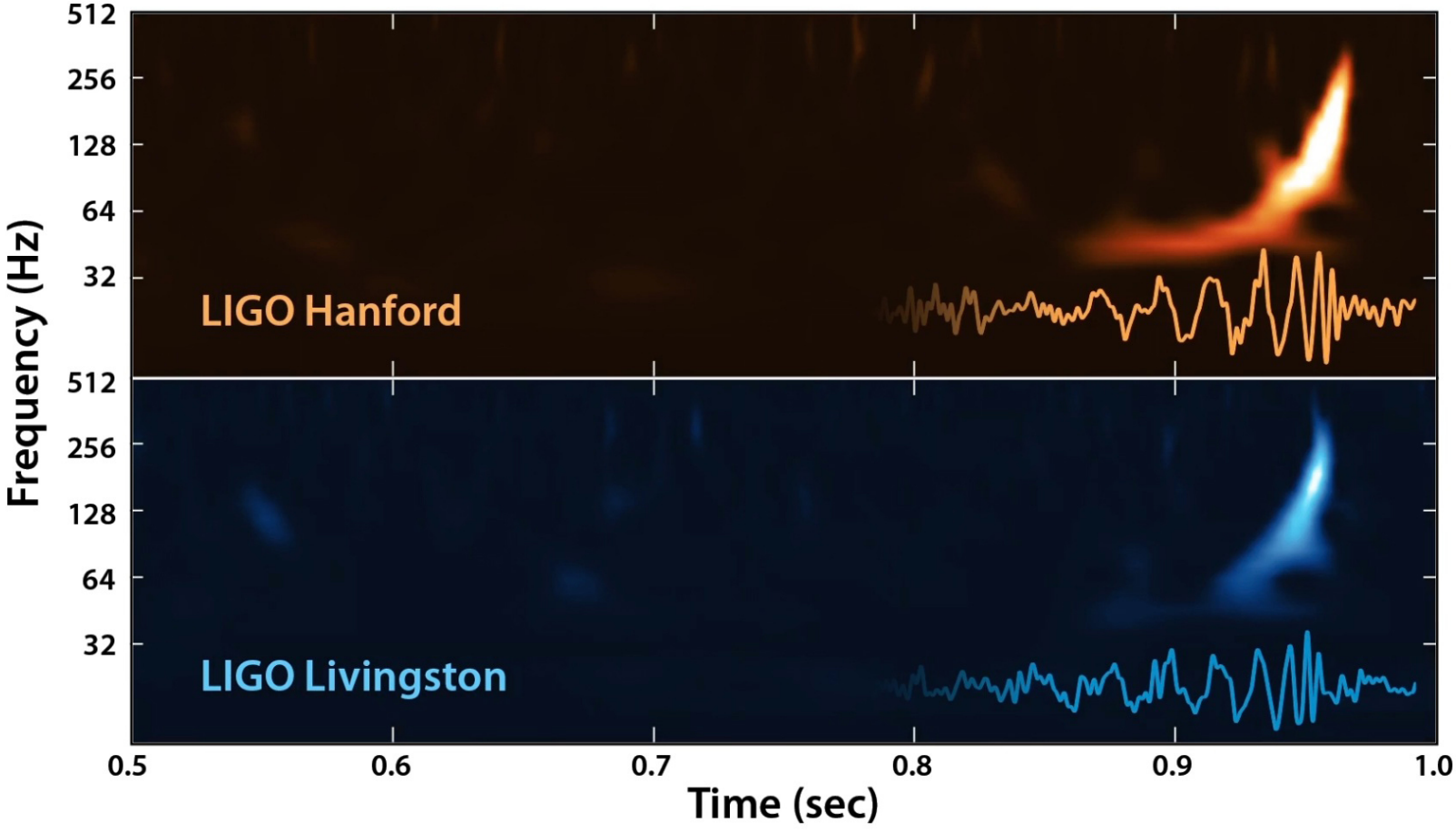


“Pictures” of Messier 87* in microwaves (radio astronomy)

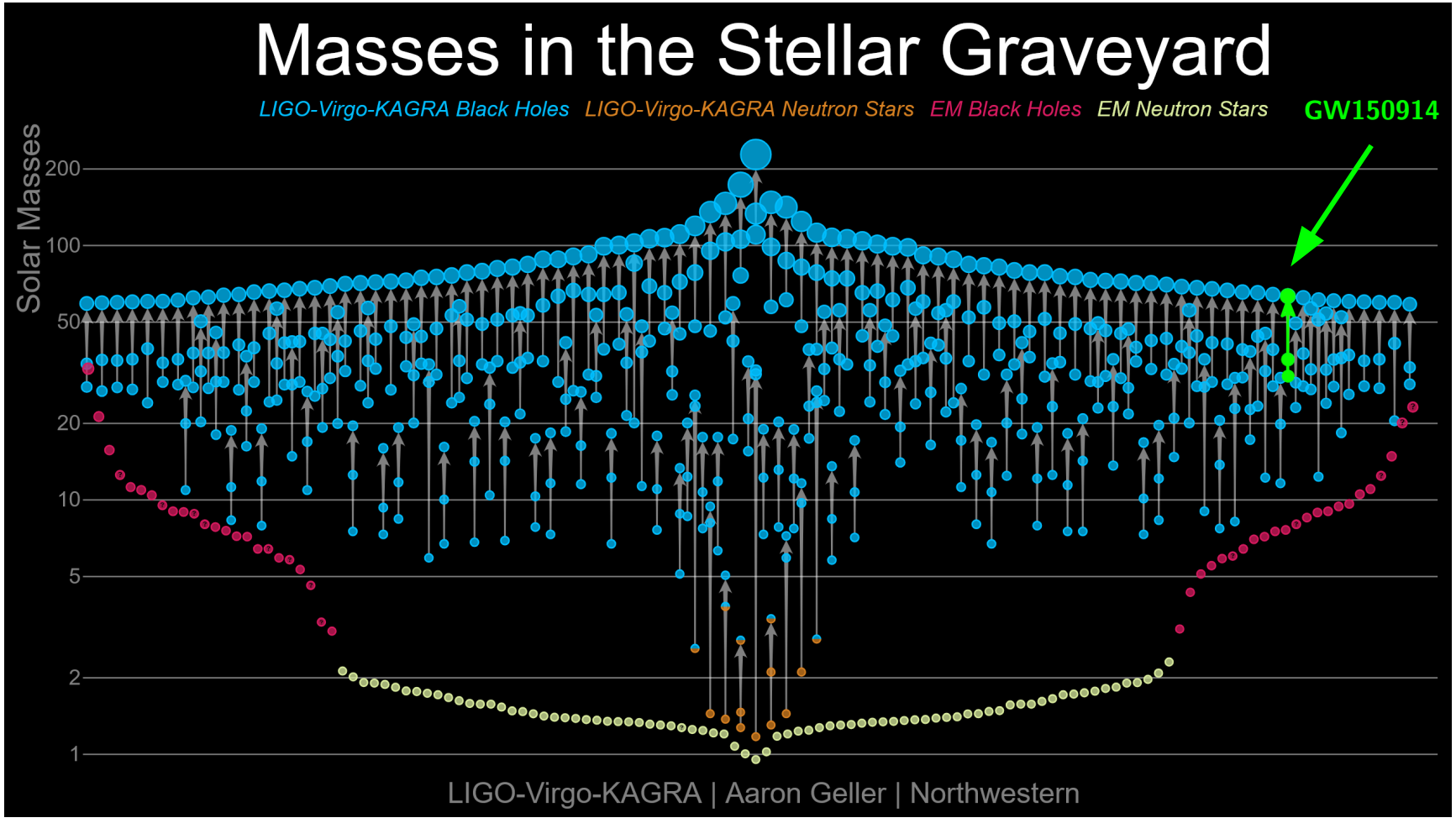




First-ever direct detection of gravitational waves (GW150914)

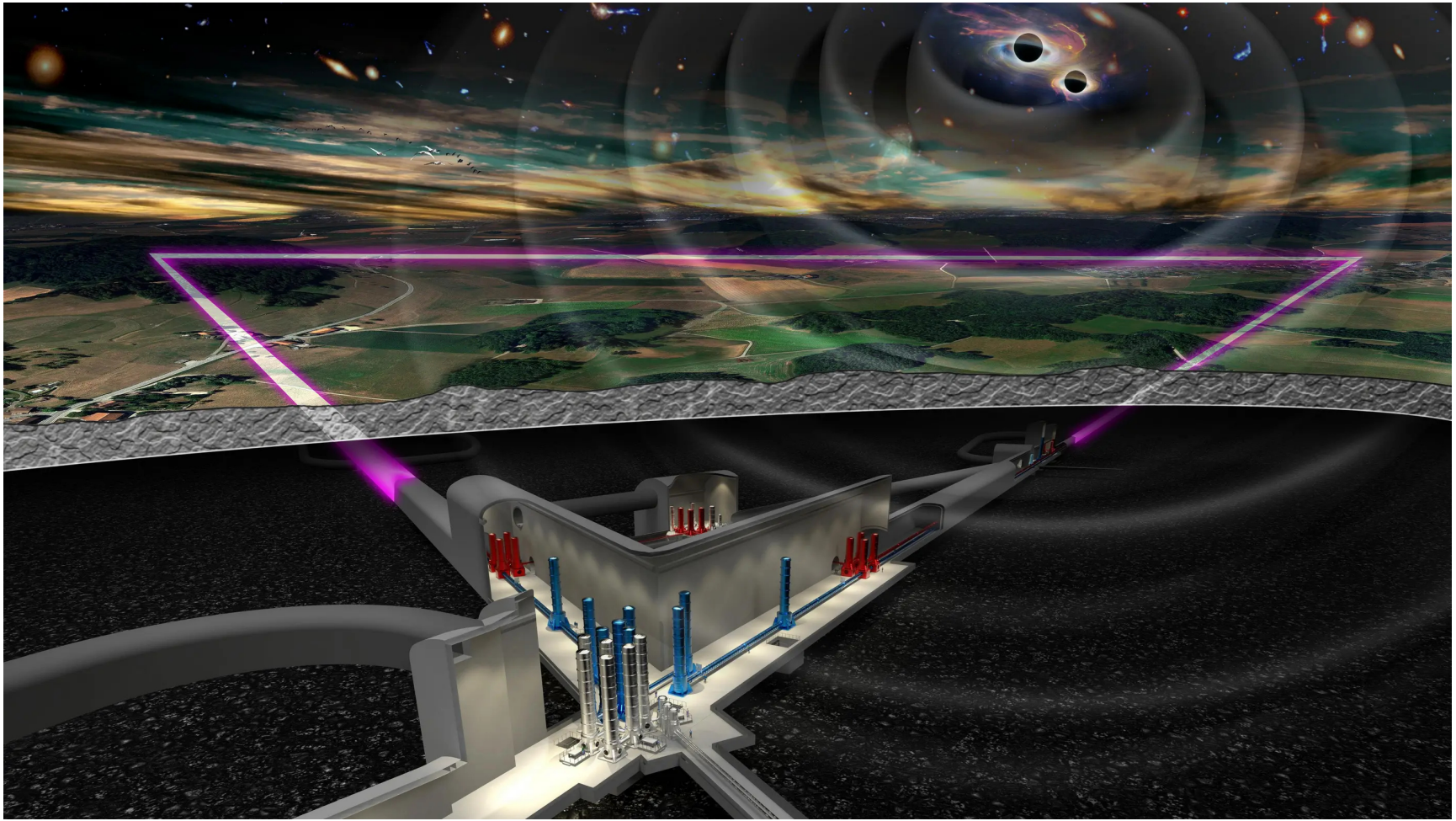


And many many more since then:



https://ligo.northwestern.edu/media/mass-plot/index.html

Even more expected with help of the Einstein Telescope!



So, black holes appear to exist.

But there is a key problem!

Black holes

Einstein equation
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$
→ vacuum Einstein equation
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 0$$
→ solve for $g_{\mu\nu}$

The general, static, spherically symmetric vacuum solution is the **Schwarzschild black hole**:

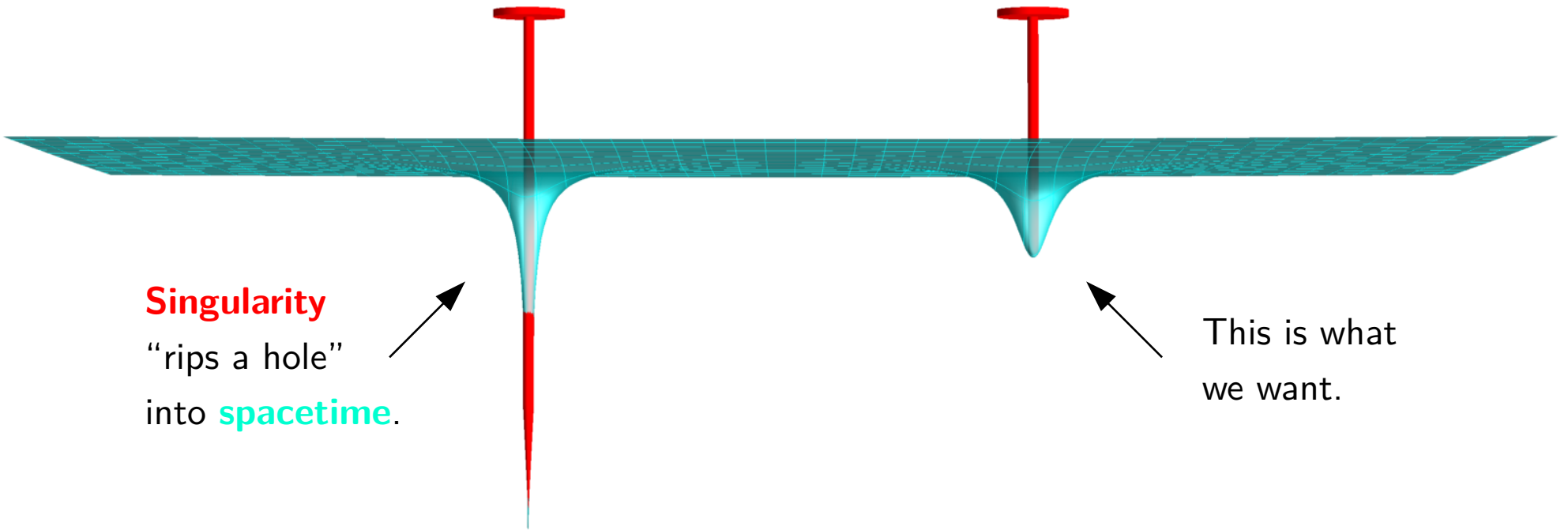
$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -\underbrace{\left(1 - \frac{2GM}{rc^2}\right) c^2 \mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1 - \frac{2GM}{rc^2}}}_{\text{nontrivial causal structure}} + \underbrace{r^2 \left(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\varphi^2\right)}_{\text{spherical part}}$$

Two important locations: $r = \frac{2GM}{c^2}$ (event horizon), and $r = 0$ (singularity).

Why are singularities a problem?

At $r = 0$, the tidal forces become infinite: $R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} \sim \frac{(GM)^2}{r^6} \to \infty$

This **breaks** the theory.



Singularity
"rips a hole"
into **spacetime**.

This is what
we want.

Roadblock: perturbative non-renormalizability

Why don't we just expand around flat spacetime,

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{m_{\mathrm{Pl}}} h_{\mu\nu} \,,$$

and try to renormalize this theory "as usual?"

$$S = \frac{1}{2\kappa} \int \mathrm{d}^4X \sqrt{-g} \left[R \; + \sum_{k,l,m} c_k R^l \nabla^m R^{k-l-m} \right]$$

Negative mass dimension of $\kappa = \dfrac{8\pi G}{c^4} = \dfrac{1}{m_{\mathrm{Pl}}^2}$ gives superficial degree of divergence $D = 2(1 + L)$.

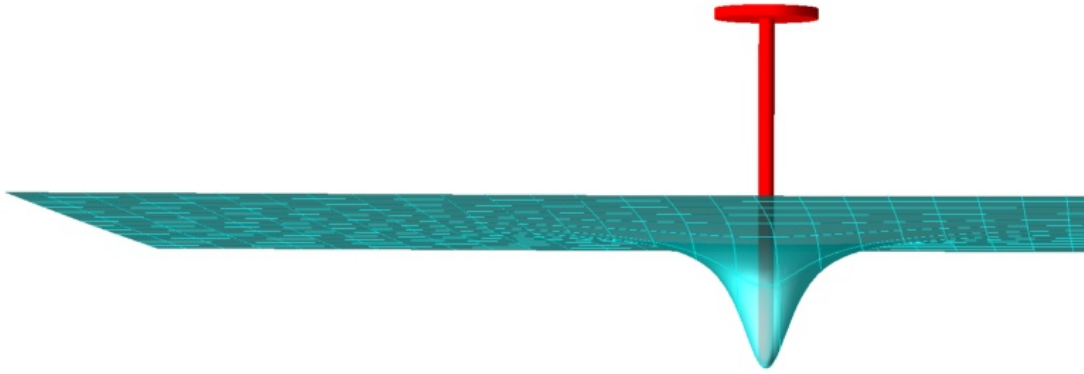
An infinite tower of renormalization conditions is required ⟶ high-energy predictability is lost.

Is “new physics” needed to resolve this problem?

Phenomenological approach: non-singular black holes.

A smooth black hole model with a **regulator**:
(Hayward 2006)

$$f(r) = 1 - \frac{2GM}{r} \;\to\; 1 - \frac{2GMr^2}{r^3 + 2GM\ell^2}$$



$$\mathcal{R} \sim \frac{1}{\ell^2}$$

Generic properties across a wide range of parametrizations:

- Universal (M-independent) behavior at $r = 0$.
- Satisfies the "limiting curvature conjecture." (Markov 1982+1984, Polchinski 1989, Mukhanov & Brandenberger 1992)
- This form is expected from vacuum polarization. (Israel & Poisson 1988, Balbinot & Poisson 1990)
- Can be reproduced by renormalization group improvement. (Bonanno & Reuter 2000)
- Horizon "vanishes" if regulator is larger than critical threshold.

Goal: constrain this parameter ℓ by observations! (Does not have to be Planck scale.)

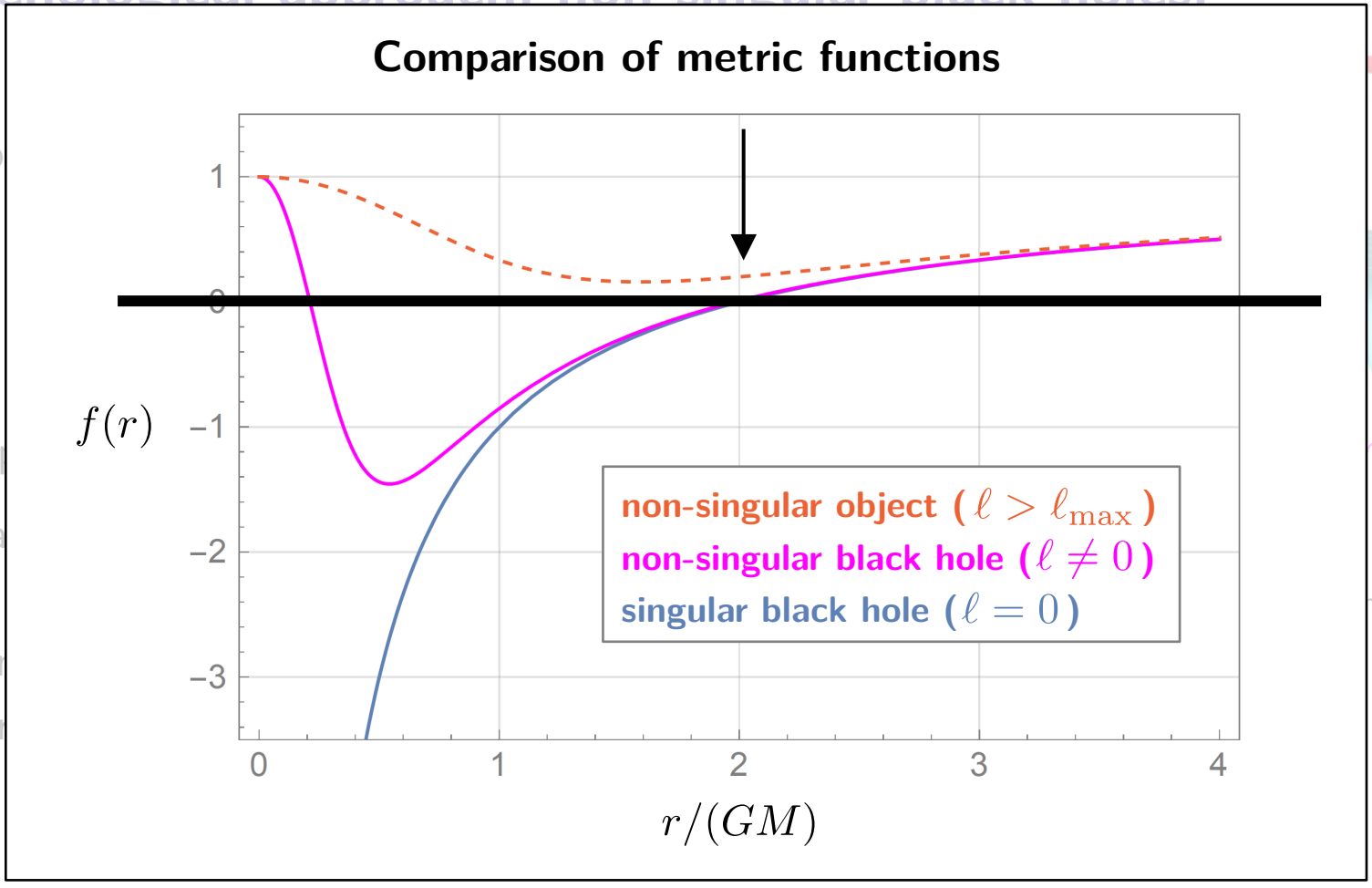
Phenomenological approach: non-singular black holes

A smooth b
(Hayward 2006)

$f(r) =$

Generic pro

- Universa
- Satisfies
- This for
- Can be
- Horizon



$\sim \frac{1}{\ell^2}$

ndenberger 1992)

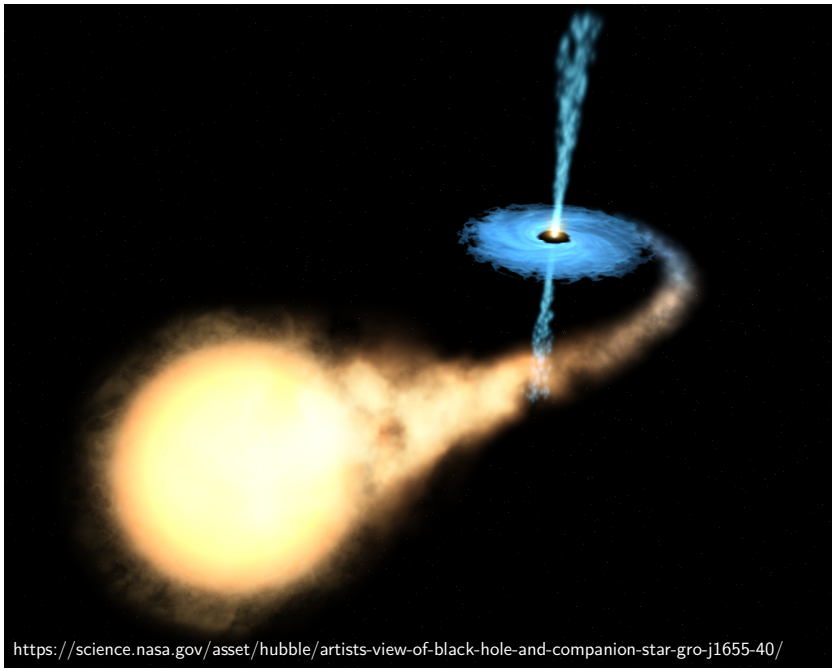
Observational Scenarios

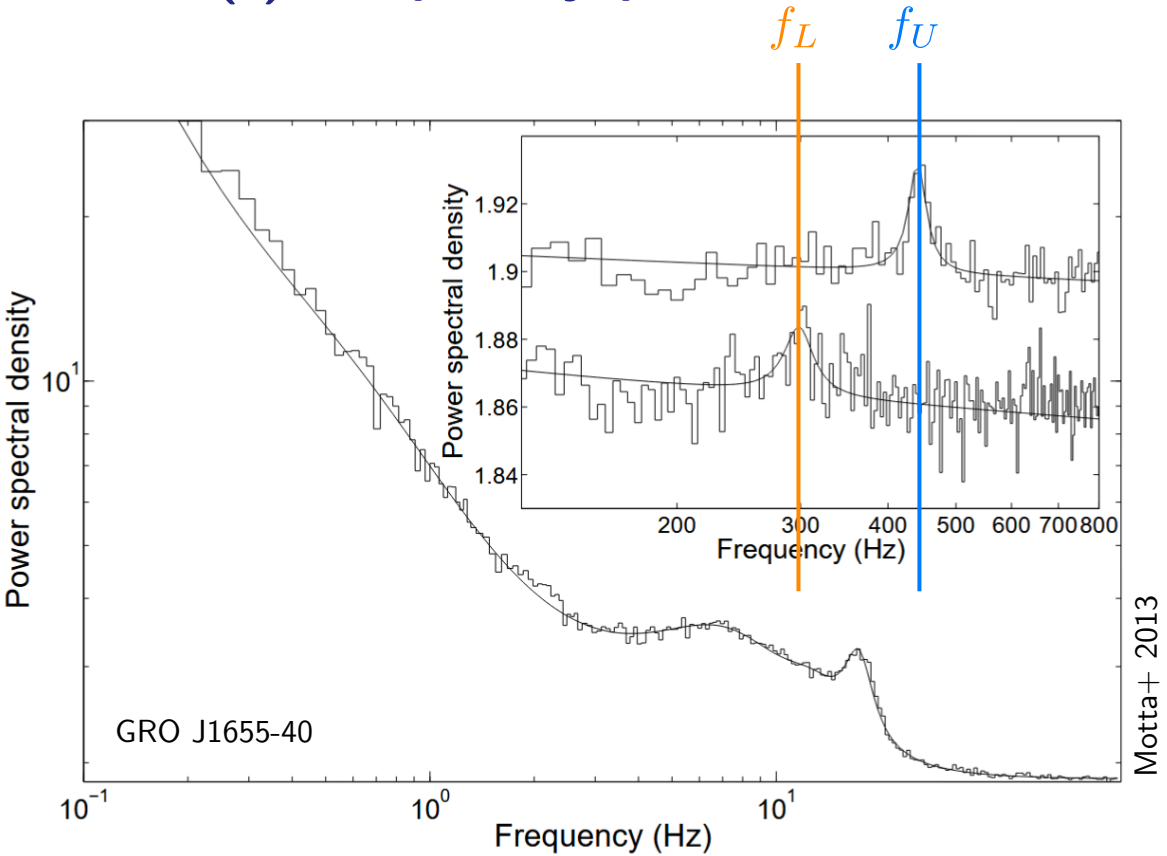
Scenario #1

Quasi-periodic oscillations

JB & Felix Wunsch,
Novel very-high-frequency quasi-periodic oscillations of compact, non-singular objects
to appear in JCAP (2026), 2510.00986 [gr-qc].

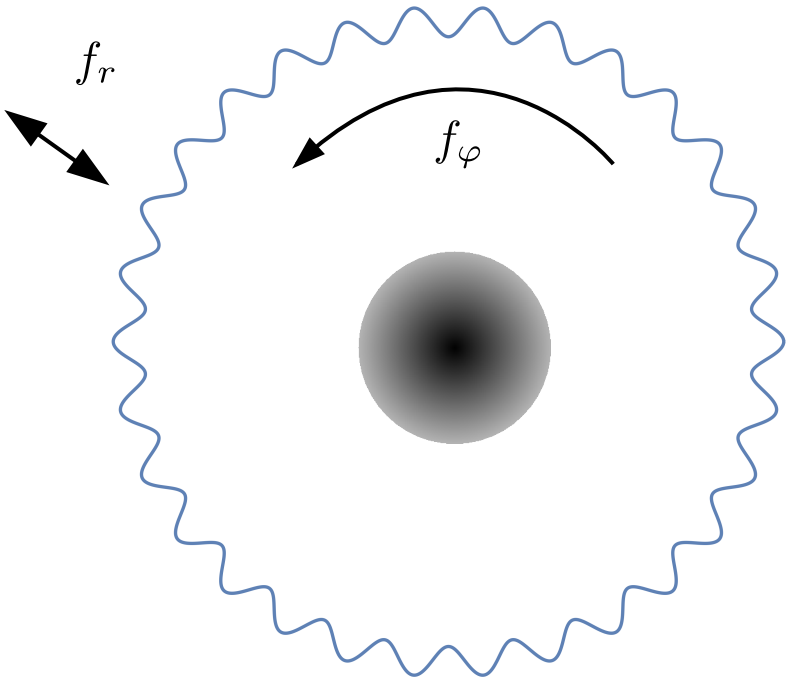
X-ray binary spectra feature discrete (!) frequency pairs.





Transient black hole binary Nova Scorpii 1994 = **black hole** & low-mass companion star.

Oscillations from orbital properties of infalling matter (1/2)



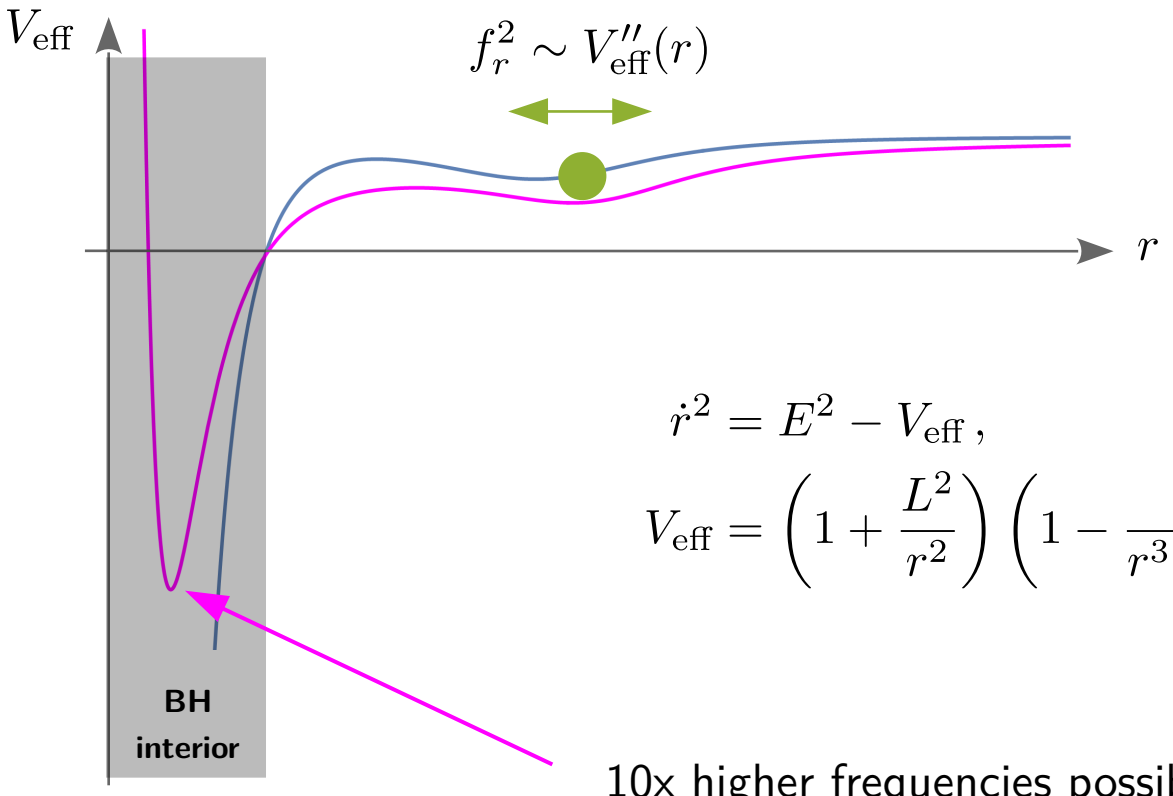
Relativistic precession model

(Stella & Vietri 1998)

Keplerian frequency $f_{\mathrm{U}} = f_\varphi$

periastron precession $f_{\mathrm{L}} = f_\varphi - f_r$

Oscillations from orbital properties of infalling matter (2/2)



$$\dot{r}^2 = E^2 - V_{\rm eff}\,,$$

$$V_{\rm eff} = \left(1 + \frac{L^2}{r^2}\right)\left(1 - \frac{2GMr^2}{r^3 + 2GM\ell^2}\right)\,.$$

10x higher frequencies possible,
provided there is no horizon.

$$\Leftrightarrow \quad \ell > \ell_{\rm max} \sim \frac{2GM}{c^2}$$

Oscillations from orbital properties (2/2)

$f_r \sim V''_{\text{eff}}(r)$

Exact expressions

$$f_\varphi^2 = \left(\frac{1}{4\pi GM}\right)^2 \frac{\rho^3 - 2l^2}{2(\rho^3 + l^2)^2}\,,$$

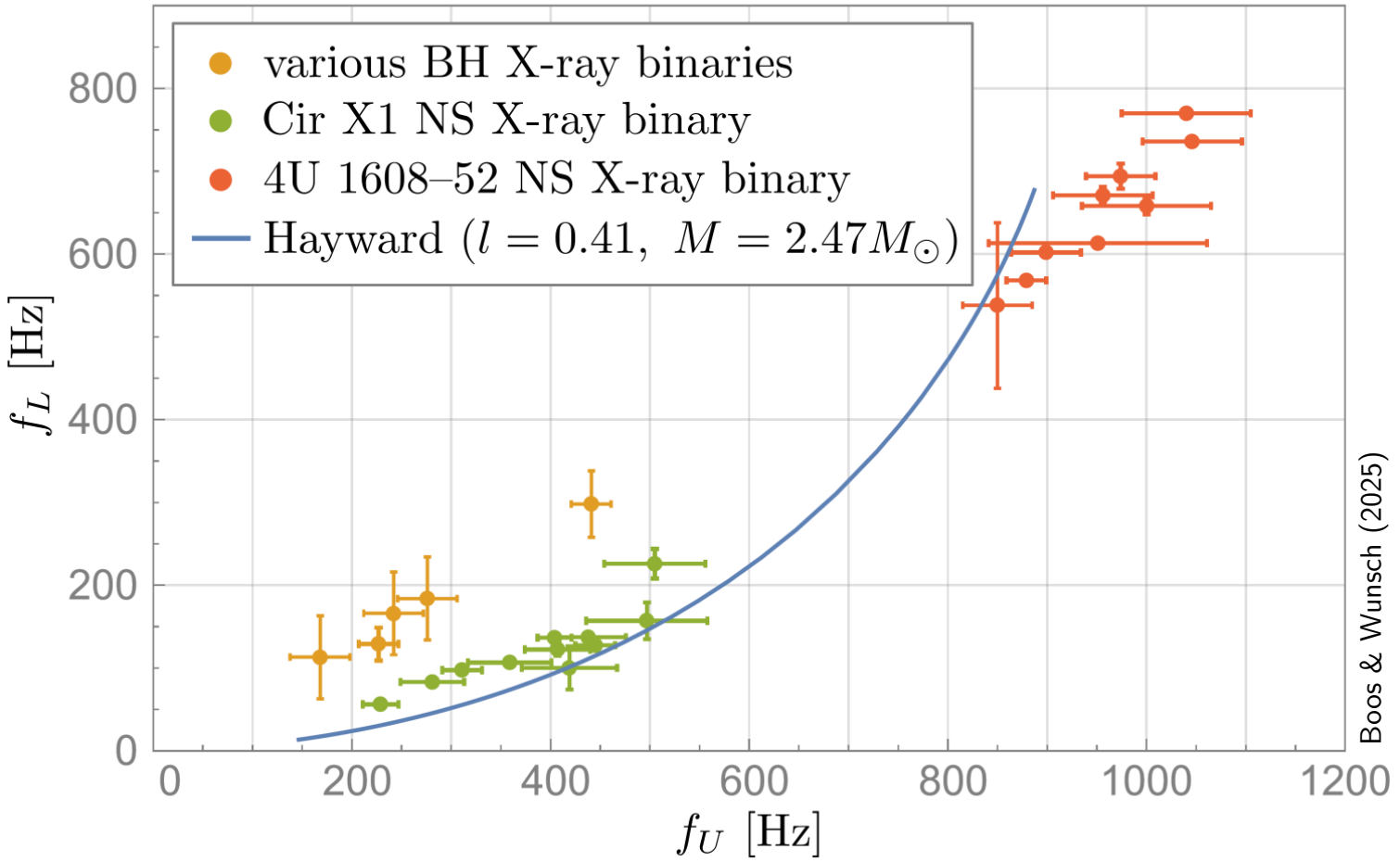
$$f_r^2 = \left(\frac{1}{4\pi GM}\right)^2 \left[\frac{3L^2}{\rho^4} - \frac{9\rho^4(L^2+\rho^2)}{(\rho^3+l^2)^3} + \frac{3\rho(L^2+3\rho^2)}{(\rho^3+l^2)^2} - \frac{1}{\rho^3+l^2}\right],$$

$$L^2 = (2GM)^2 \frac{\rho^7 - 2l^3\rho^4}{\rho^5(2\rho-3) + 2l^6 + 4l^3\rho^3}\,, \quad l = \frac{\ell}{2GM}\,, \quad \rho = \frac{r}{2GM}\,.$$

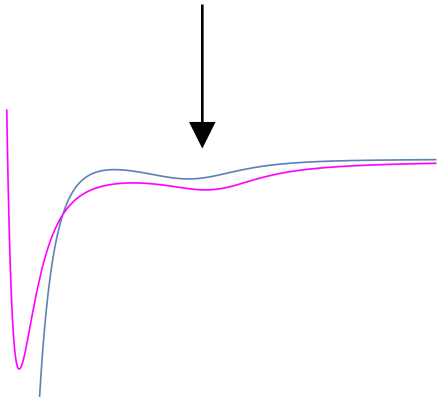
10x higher frequencies possible,
provided there is no horizon.

$$\Leftrightarrow \quad \ell > \ell_{\max} \sim \frac{2GM}{c^2}$$

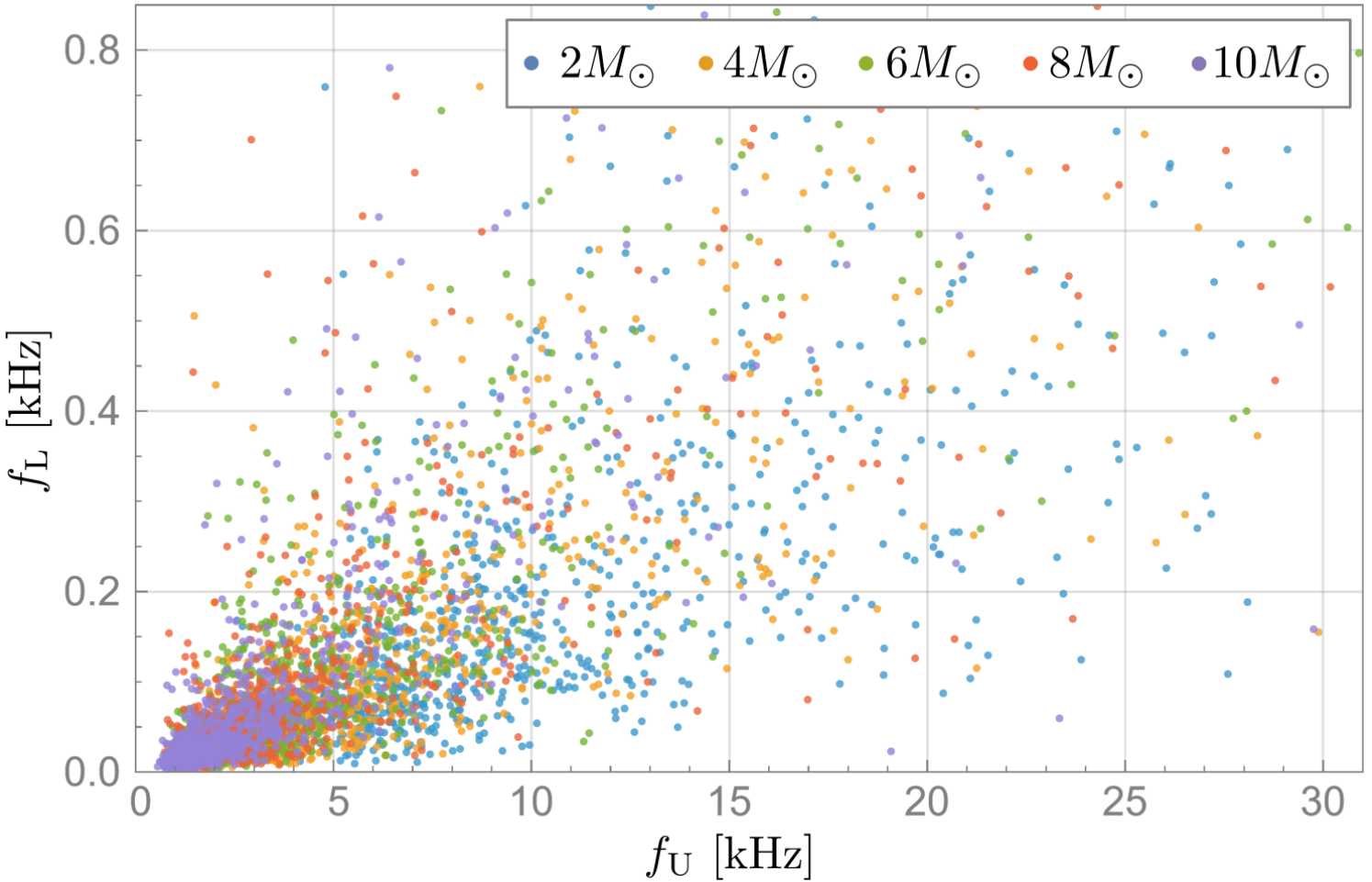
High-frequency quasi-periodic oscillations



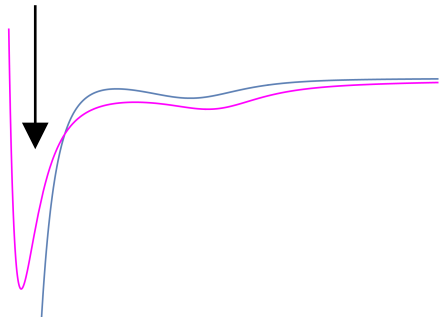
Boos & Wunsch (2025)



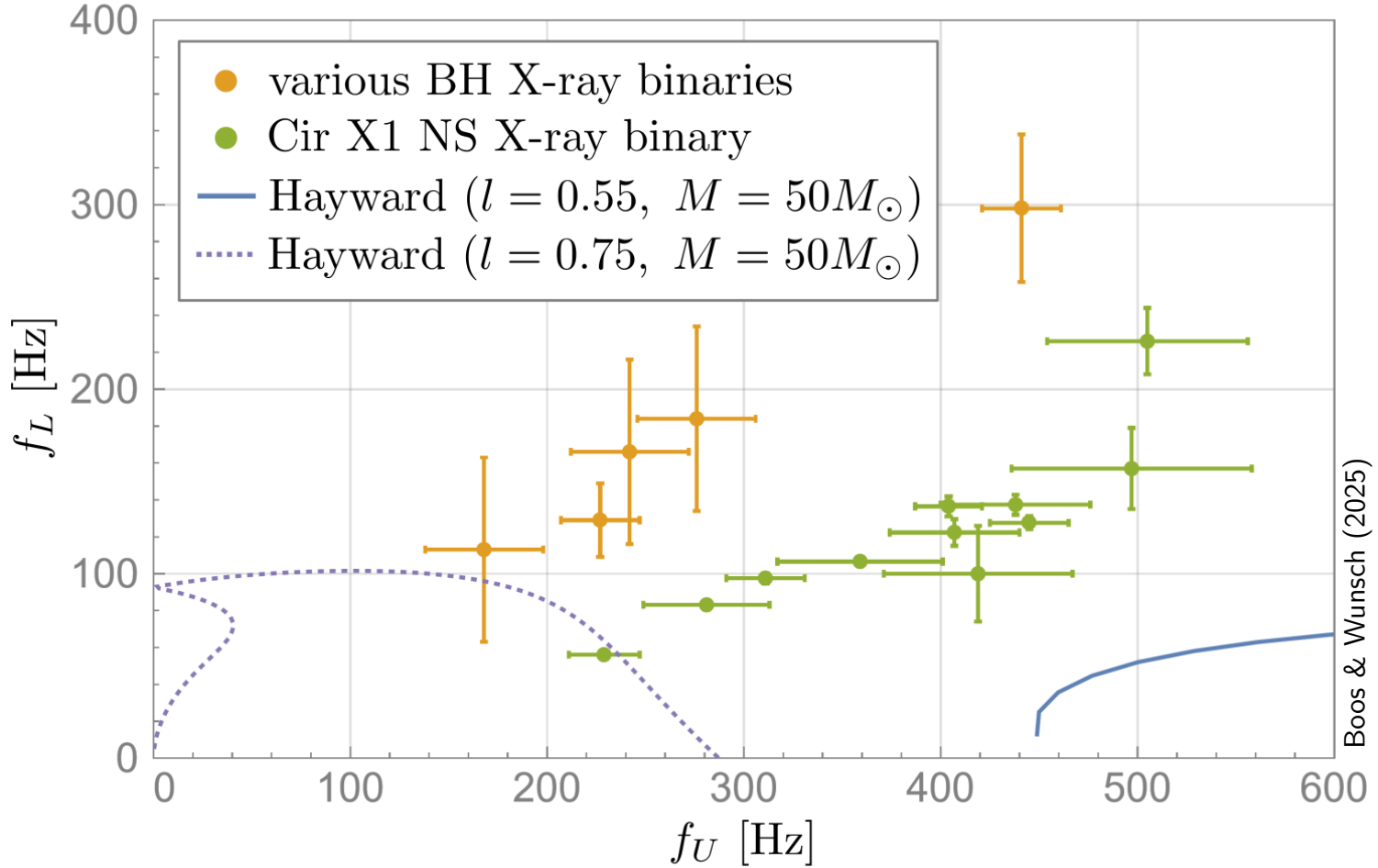
Very-high-frequency quasi-periodic oscillations (1/2)

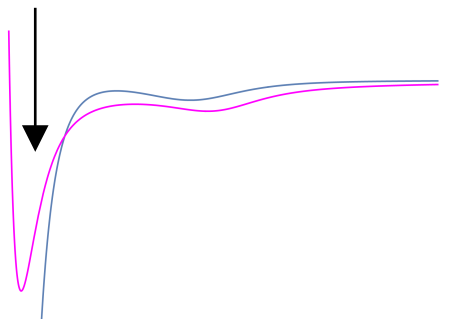


Boos & Wunsch (2025)



Very-high-frequency quasi-periodic oscillations (2/2)





Boos & Wunsch (2025)

Result: Quasi-periodic oscillations probe noisy environments

First surprise:

$\frac{\ell}{2GM} \sim 0.1 \ldots 0.3$ is often compatible with observed QPO's for NS and BH X-ray binaries.

Gives $\mathcal{O}(\%)$ deviations in frequencies, but limited by frequency resolution.

Drawback: noisy environment prohibits a 1:1 identification with new physics.

Open question: is there universality in this regulator?

New result:

Very-high frequency kHz QPO's (currently below time resolution at 1ms) as probes for horizons.

Better: no environment!

Scenario #2

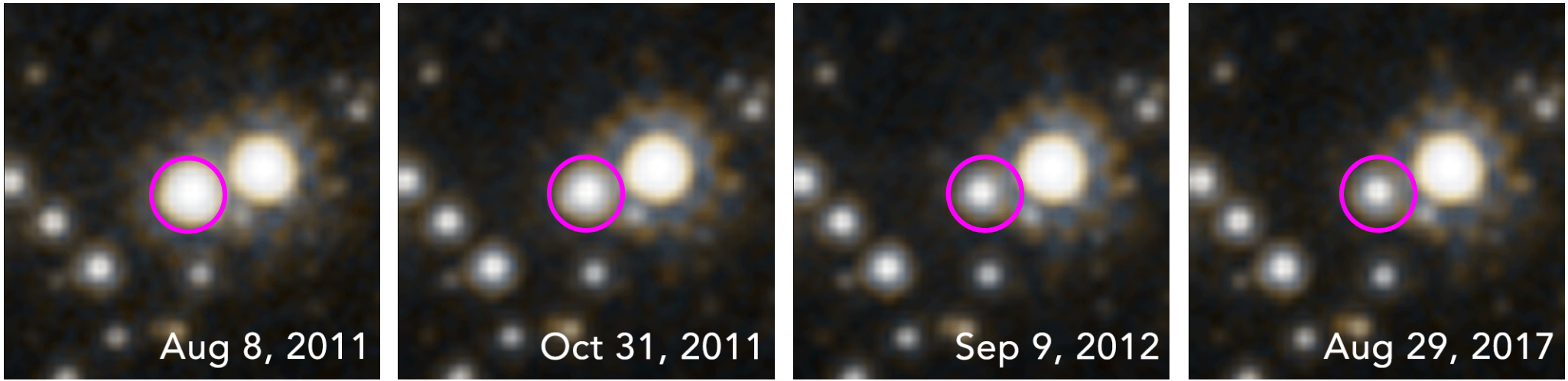
Microlensing of isolated black holes

JB & Hao Hu,

Microlensing of non-singular black holes at finite size: A ray tracing approach

Phys. Rev. D **113**, 024065 (2026), 2510.10282 [gr-qc].

In 2022, a “rogue” black hole was discovered.

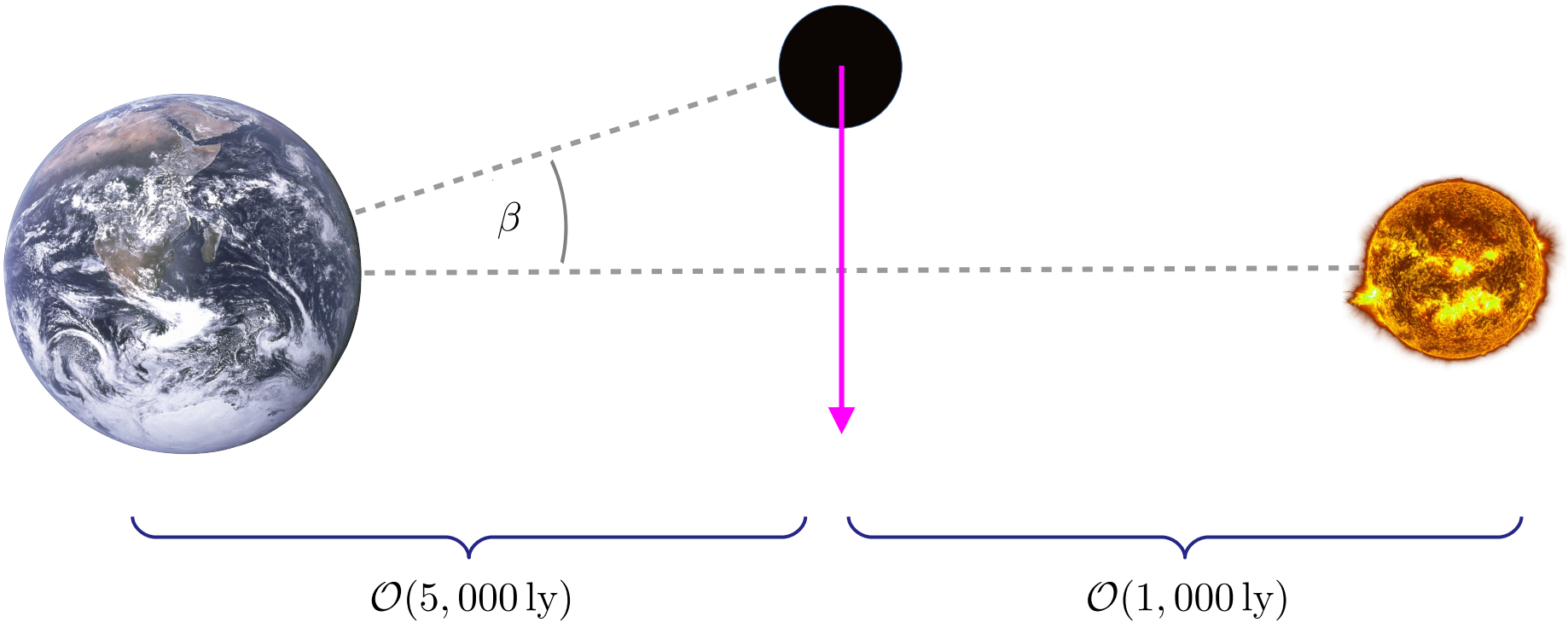


This dataset is called OGLE-2011-BLG-0462/MOA-2011-BLG-191.

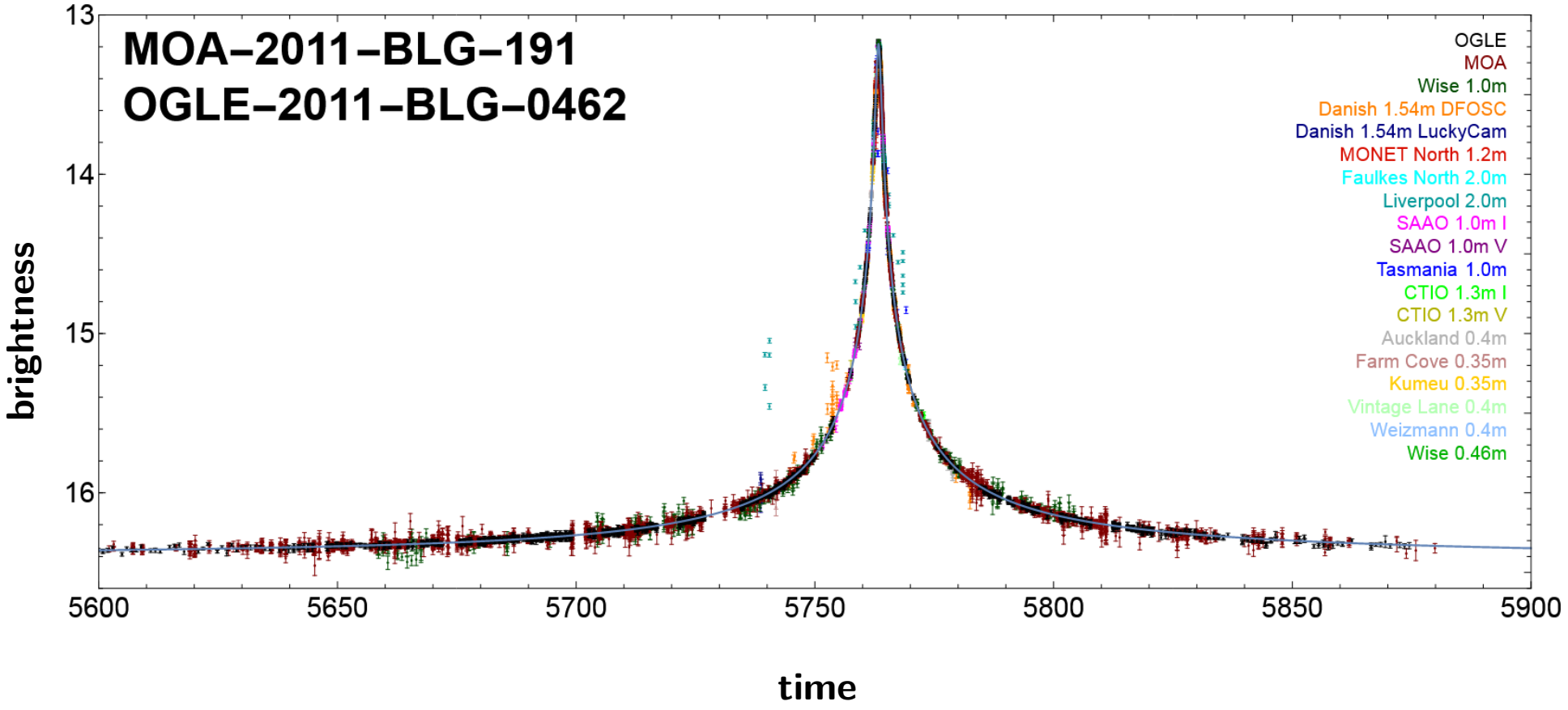
It describes the **variation of brightness** of a background star under passage of a **black hole**.

This black hole is **isolated**: no accretion disks, no noisy environments. Ideal testing environment!

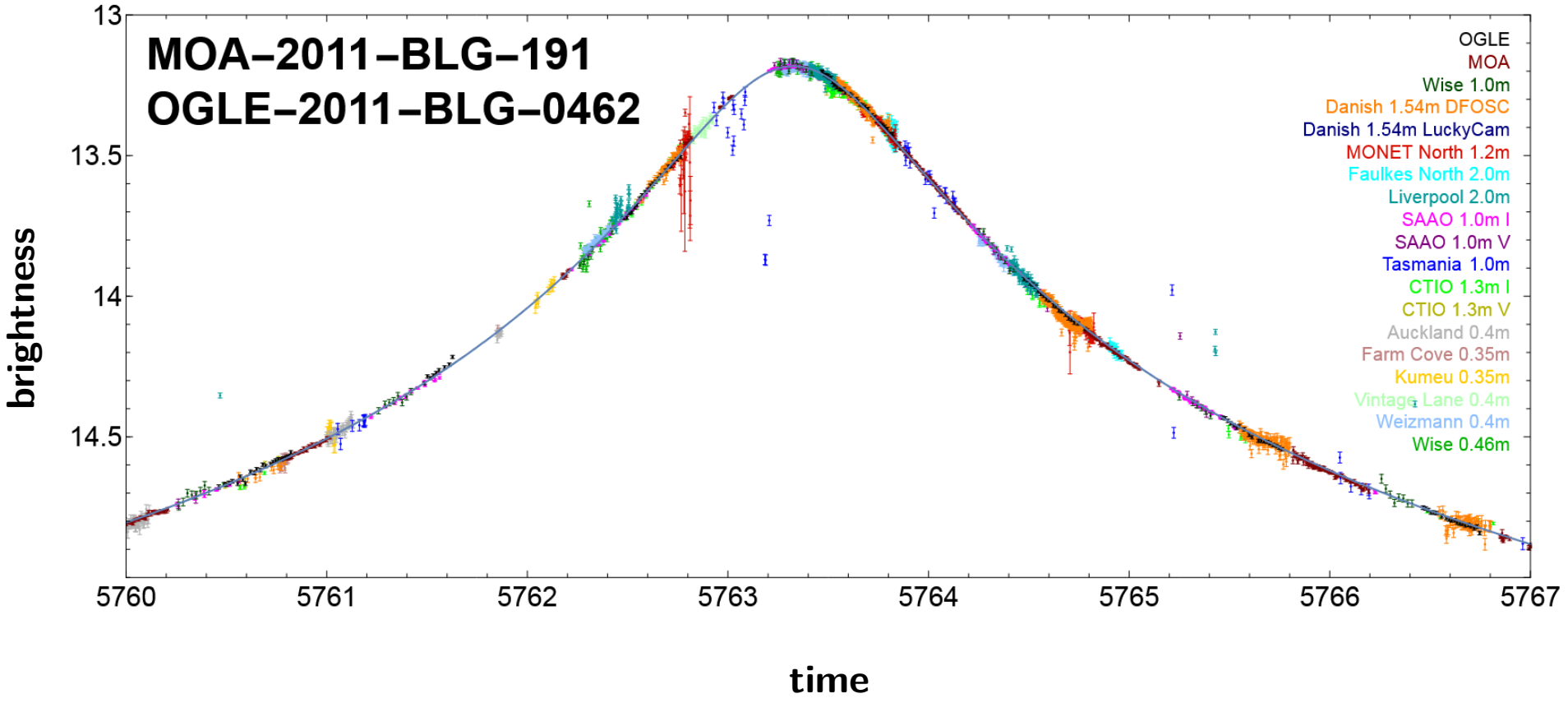
Geometrical setup: a black hole crosses the line of sight



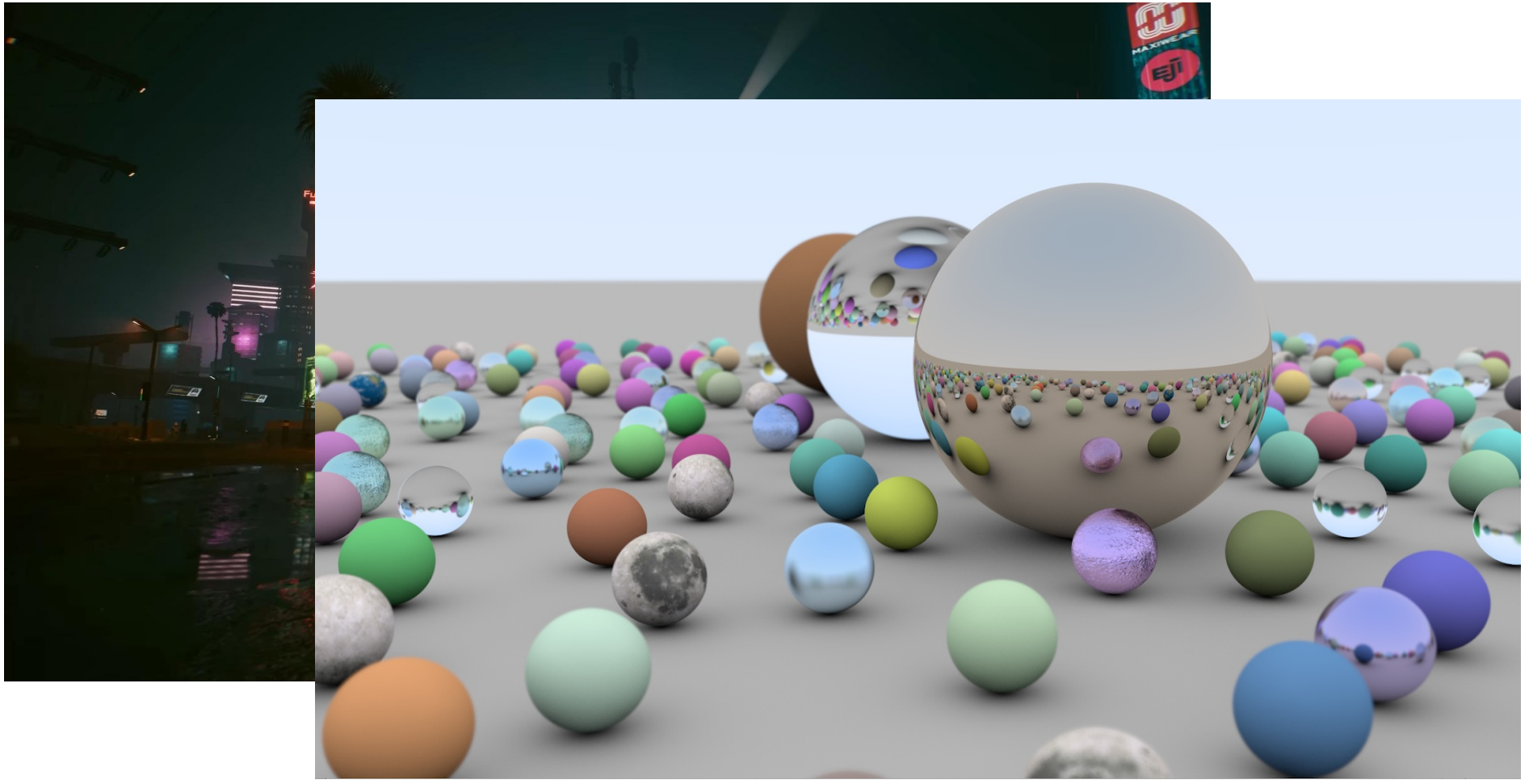
Recorded brightness curve



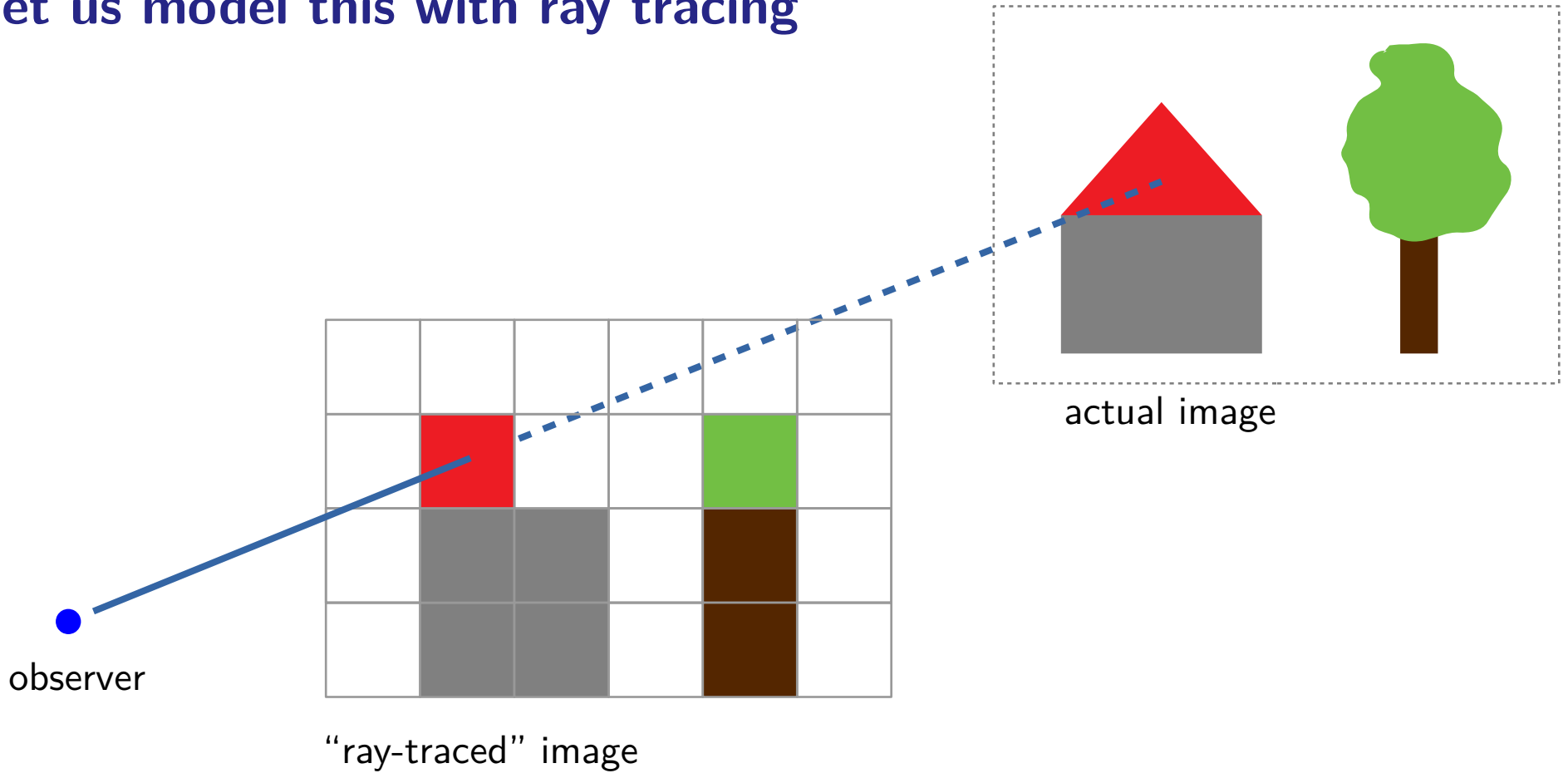
Recorded brightness curve (zoomed in)

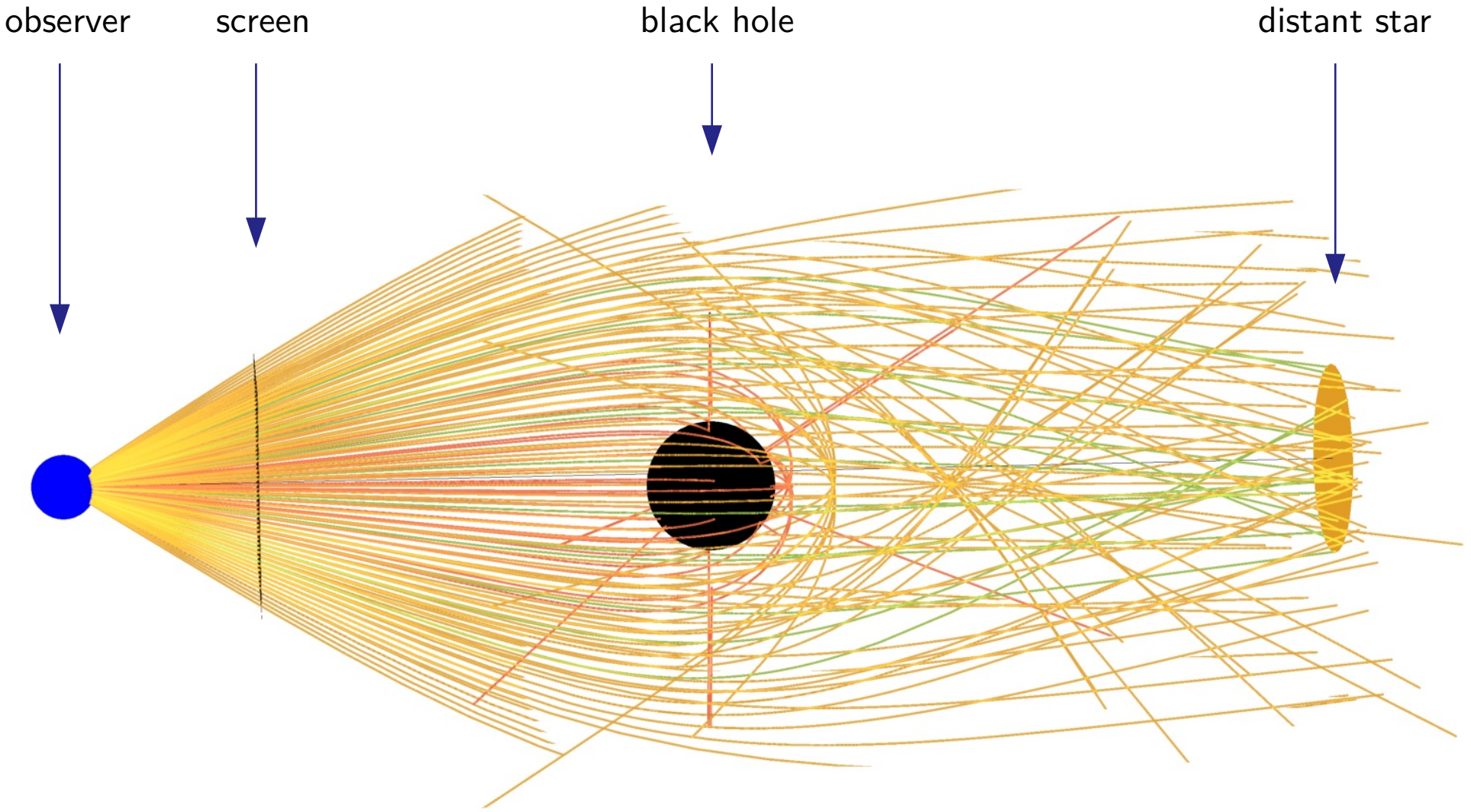


Let us model this with ray tracing



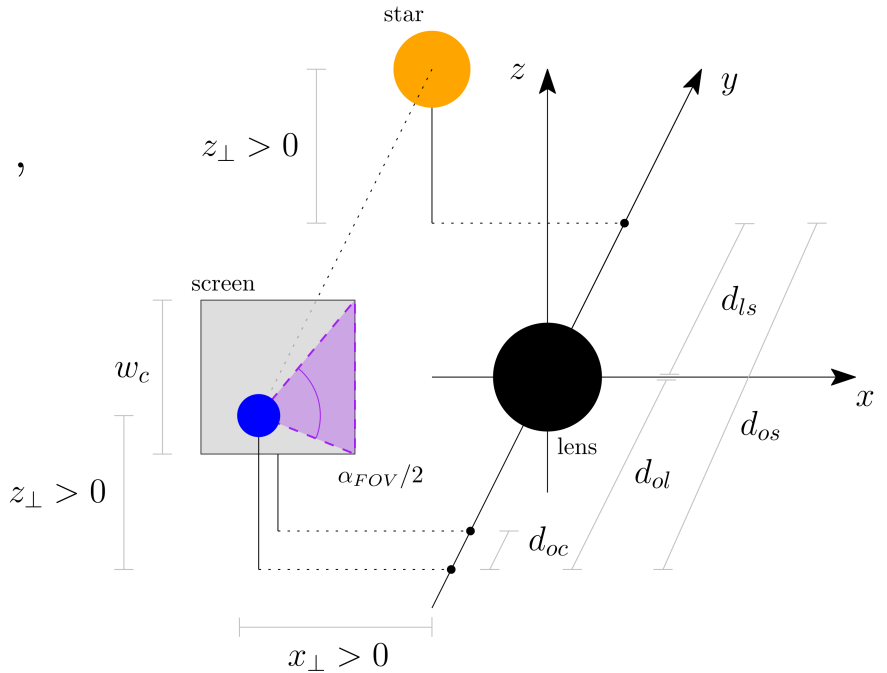
Let us model this with ray tracing

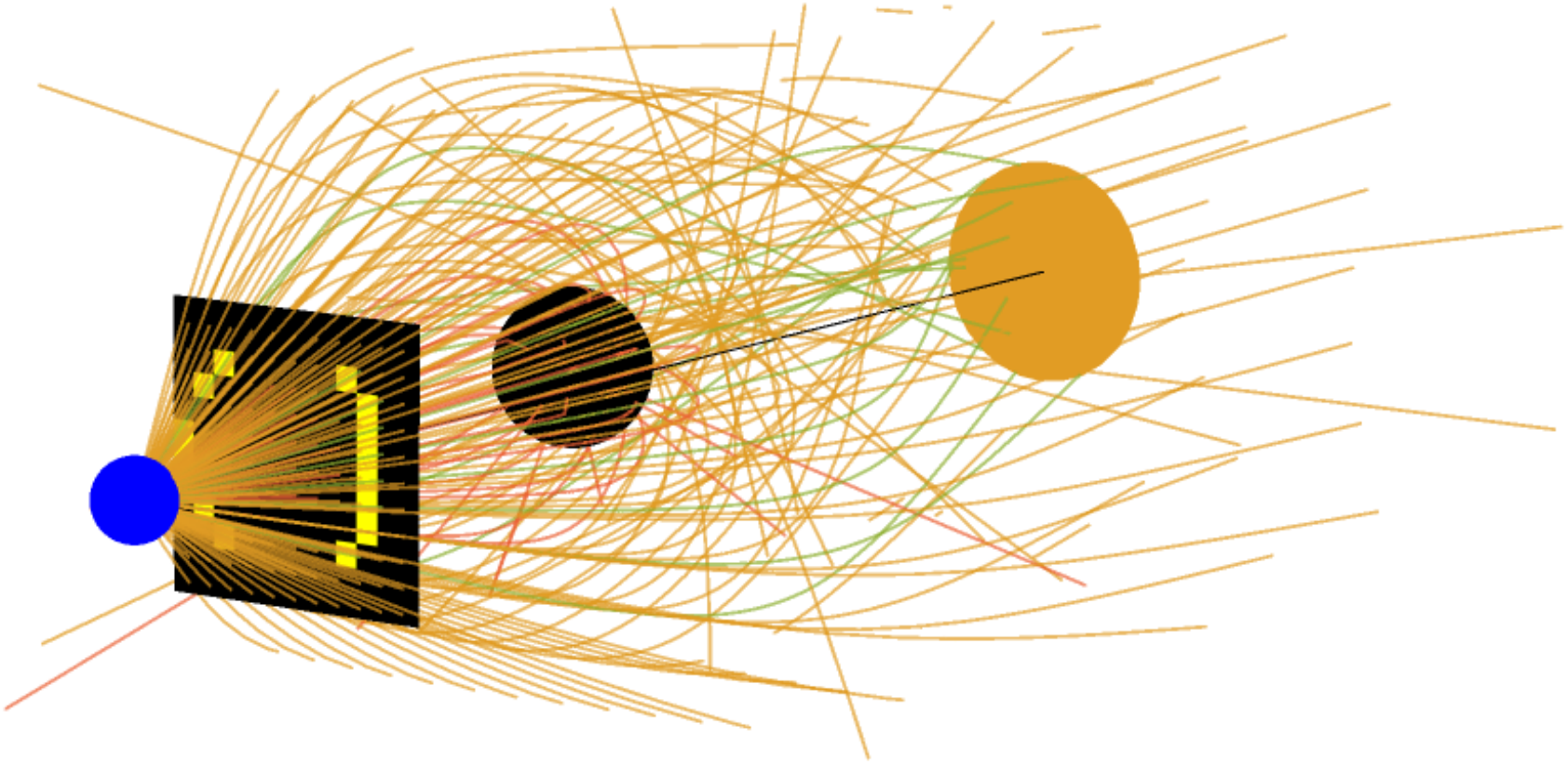


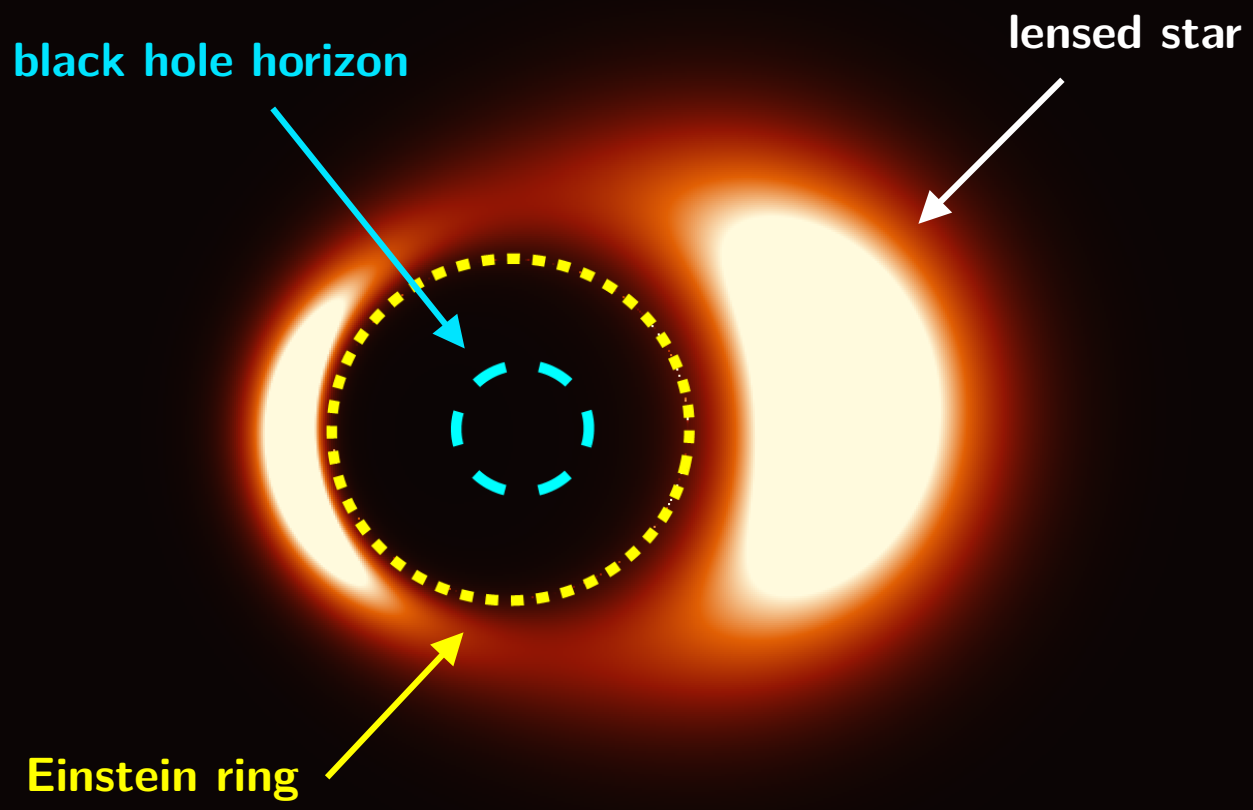

observer
screen
black hole
distant star

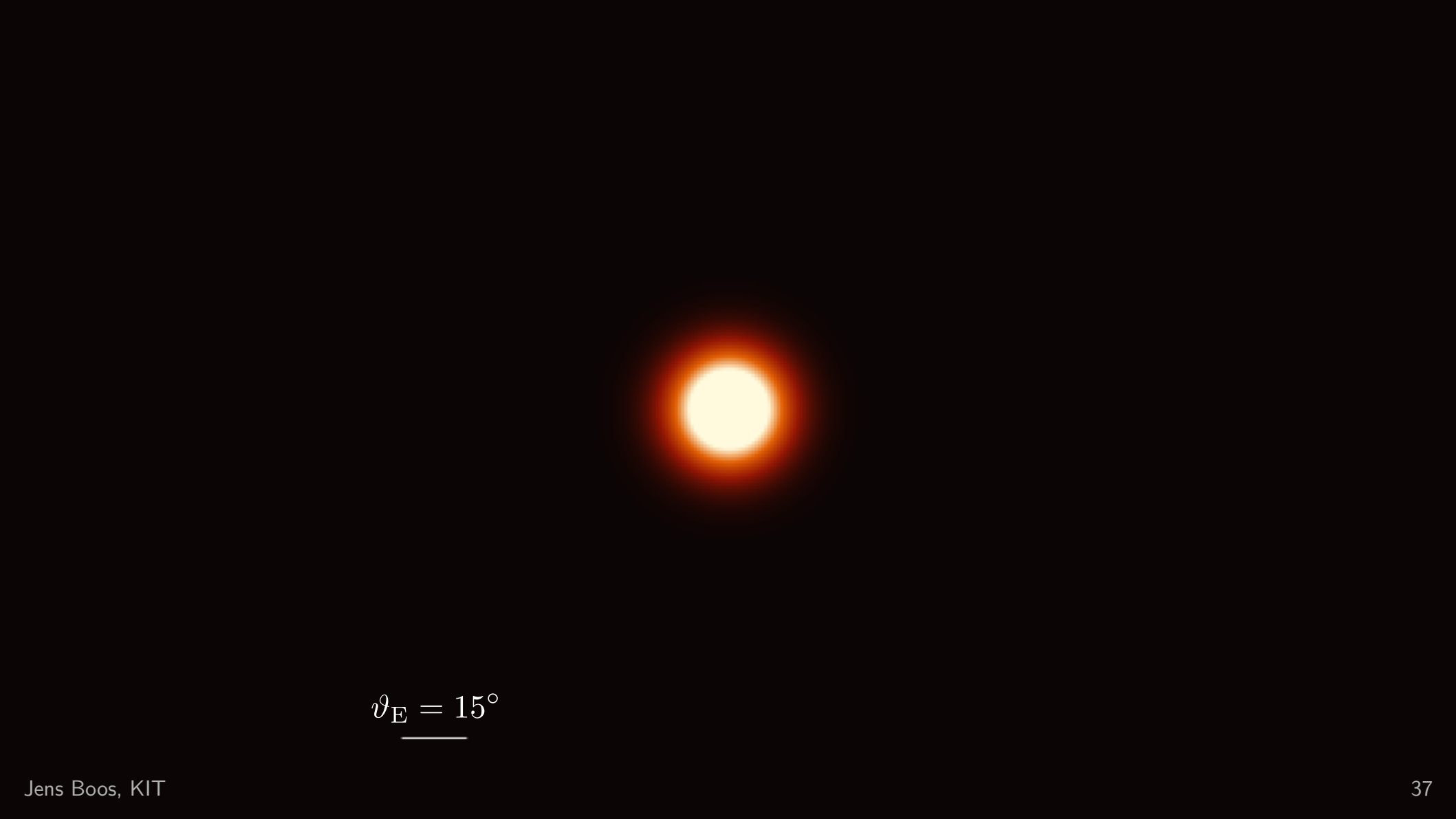
Evolution equations and geometrical parameters

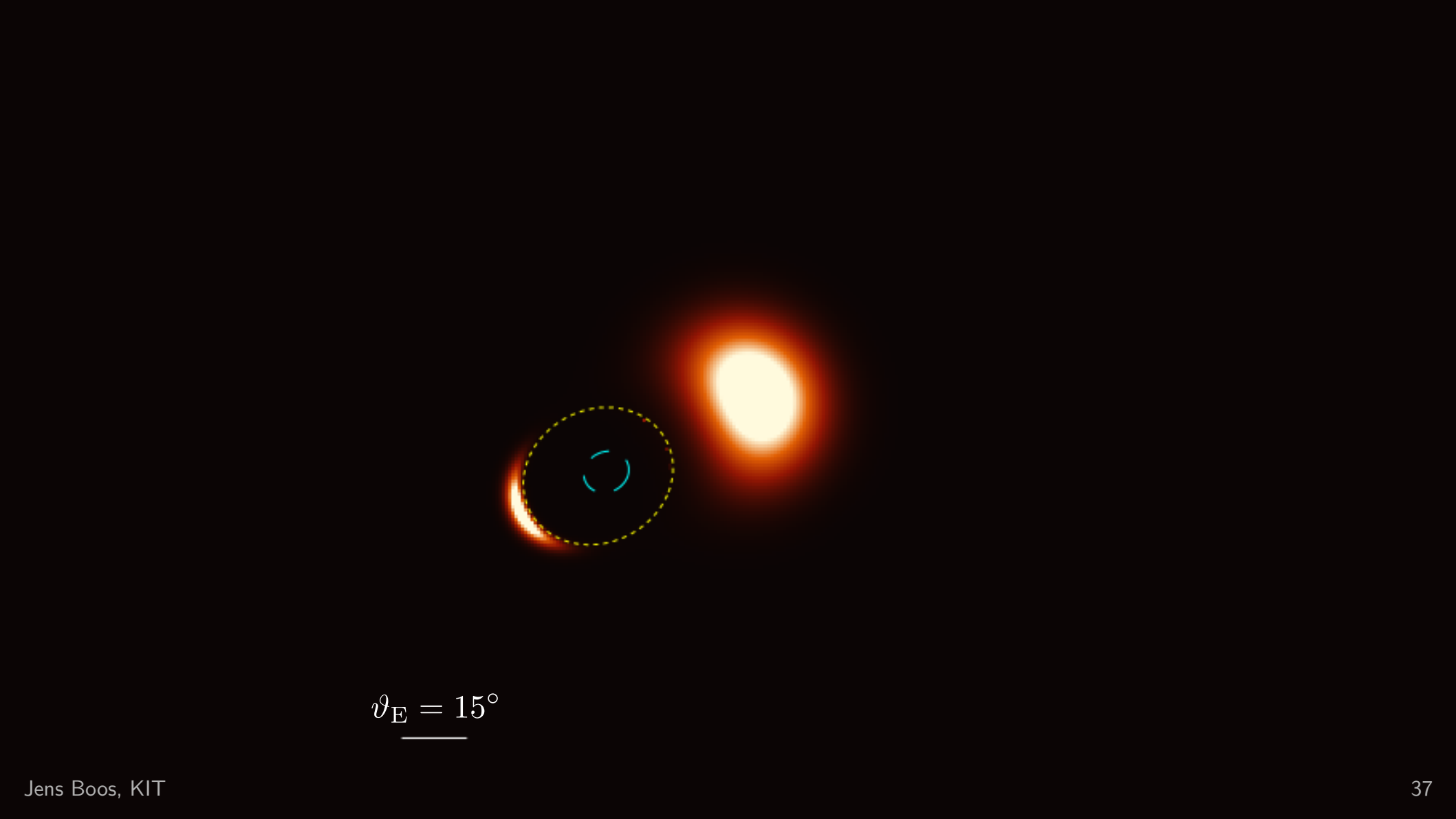
$$
\begin{cases}
\ddot{r} = \dfrac{B'}{2B}\dot{r}^2 - \dfrac{B}{2}\left[\dfrac{A'}{A^2} - 2CC'\dot{\theta}^2 - \dfrac{2C'L_1^2}{C^3\sin^2\theta}\right], \\
\ddot{\theta} = -\dfrac{2C'\dot{\theta}\dot{r}}{C} + \cos\theta\dfrac{L_1^2}{C^4\sin^3\theta}, \\
\dot{\varphi} = \dfrac{L_1}{C^2\sin^2\theta}, \\
\dot{I} = n(r,\theta,\varphi),
\end{cases}
$$

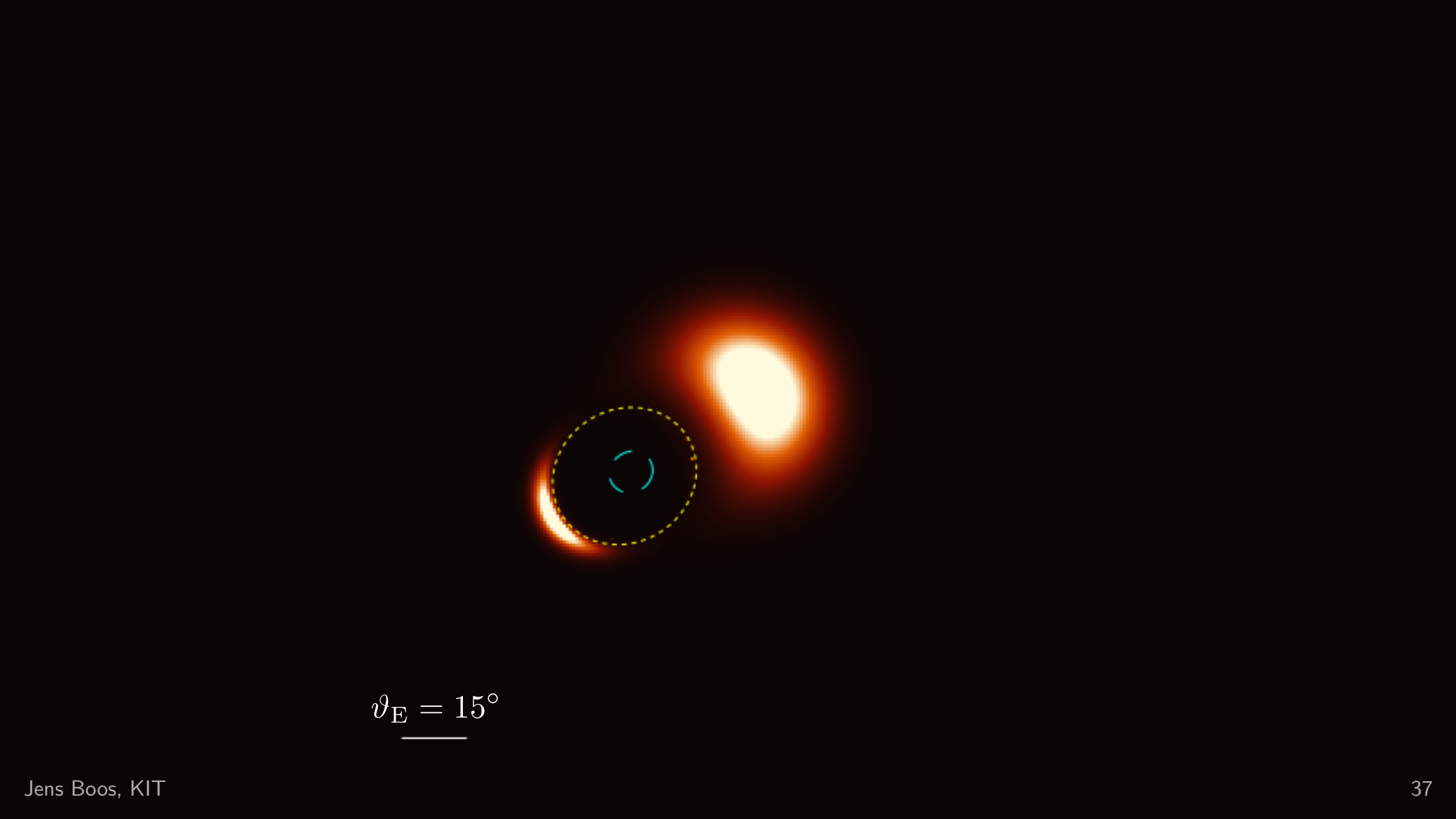


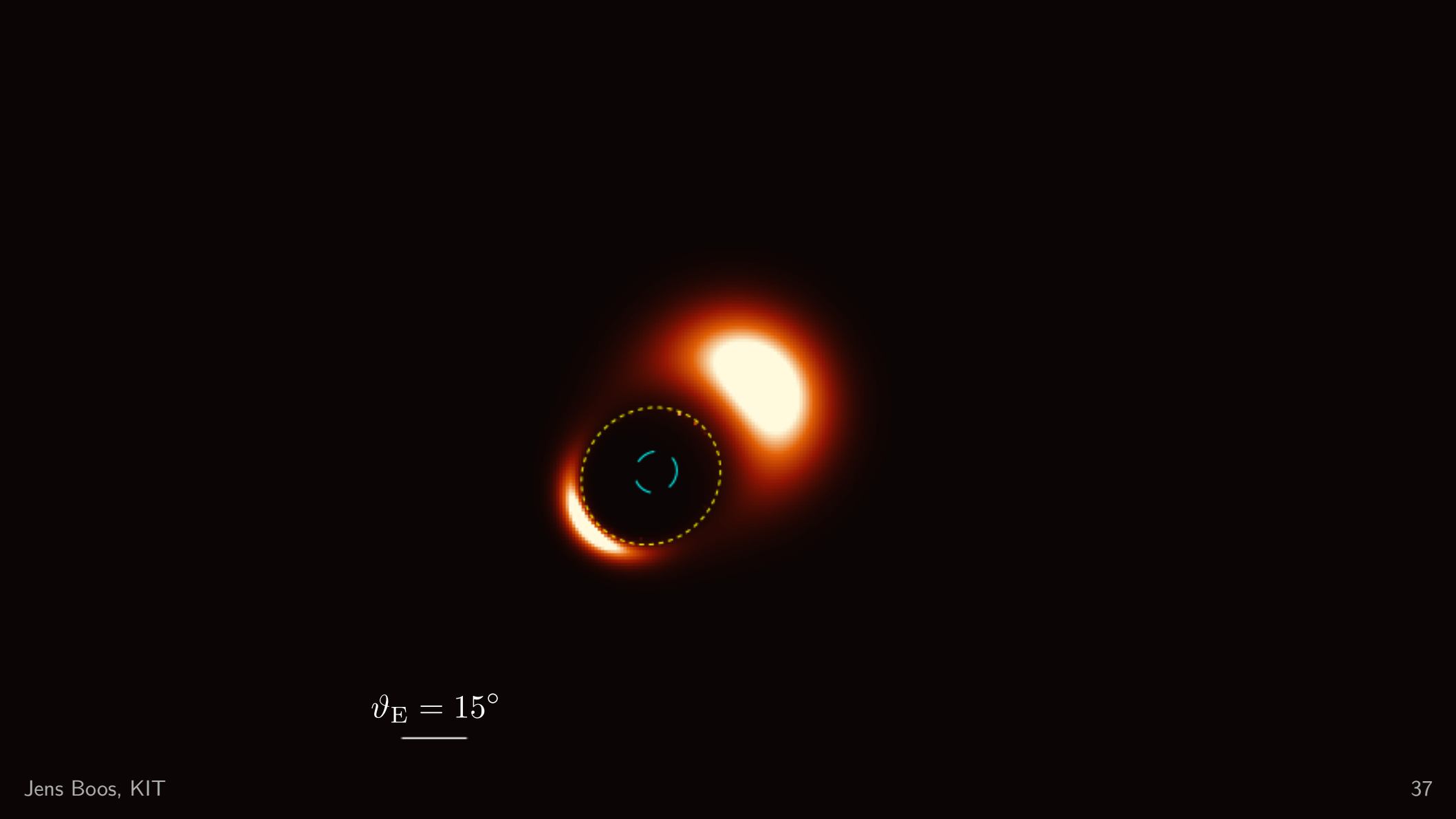



black hole horizon
lensed star
Einstein ring

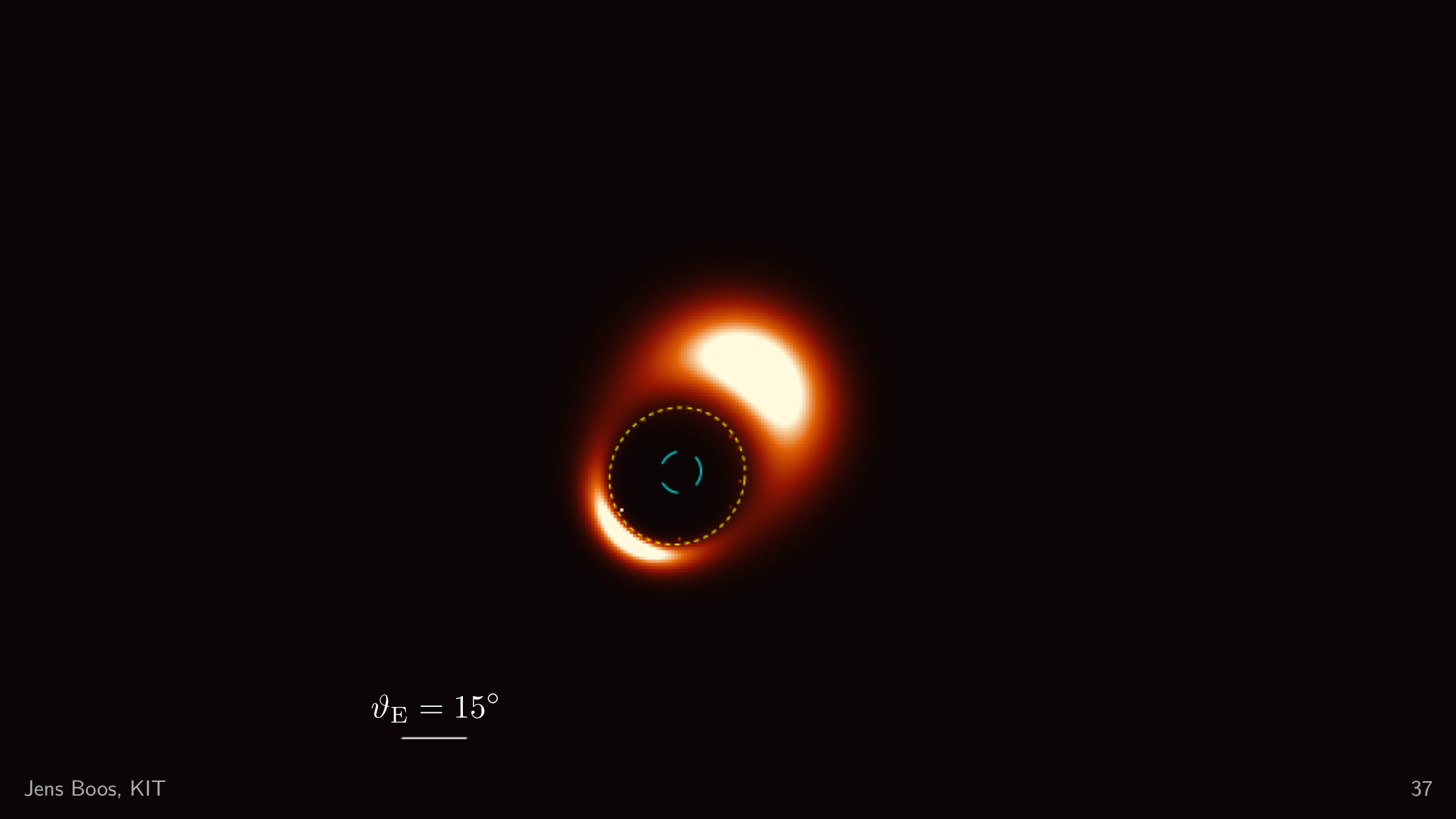

$\vartheta_{\mathrm{E}} = 15^{\circ}$


$\vartheta_{\mathrm{E}} = 15^{\circ}$

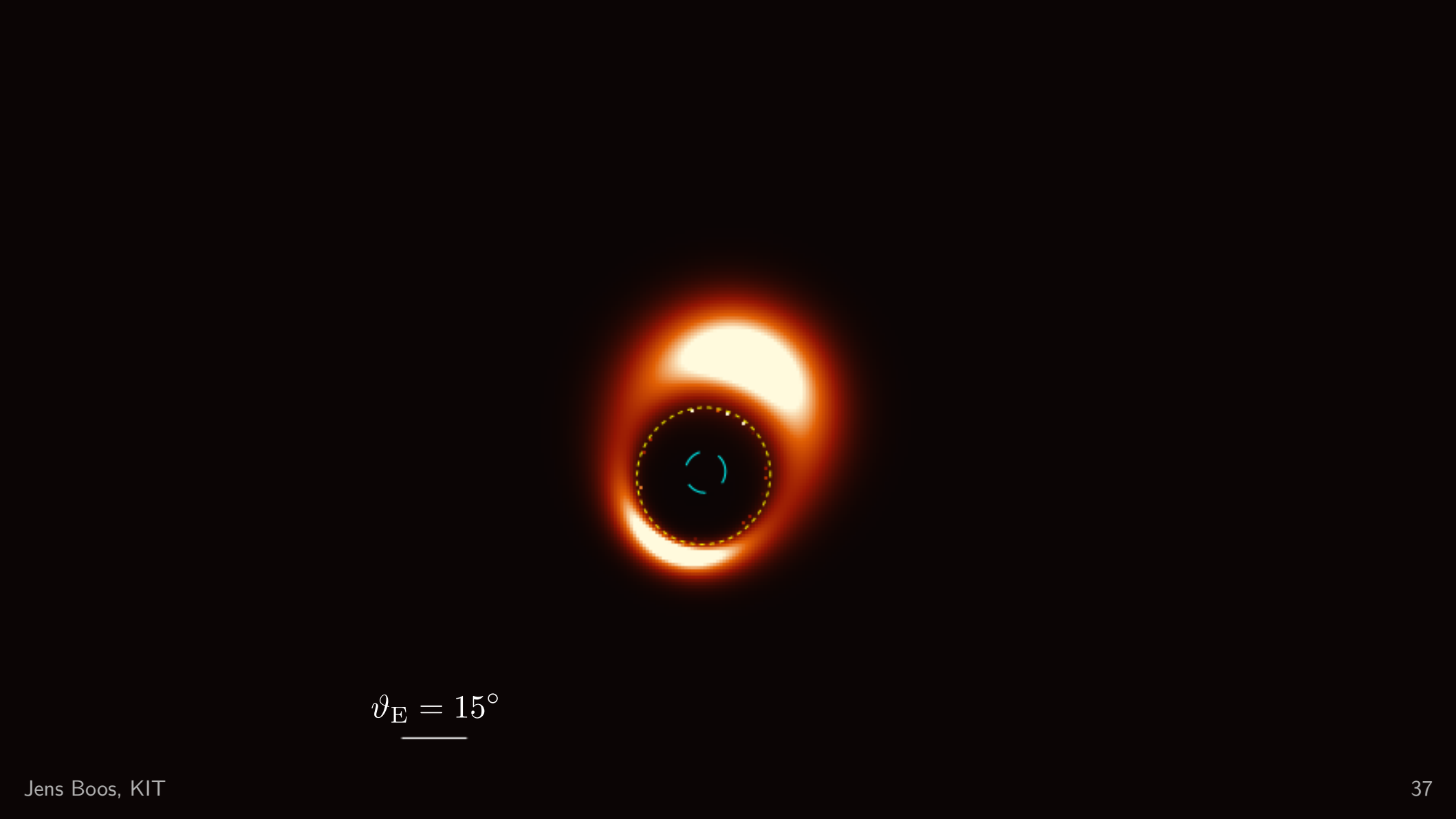

$\vartheta_{\mathrm{E}} = 15^{\circ}$



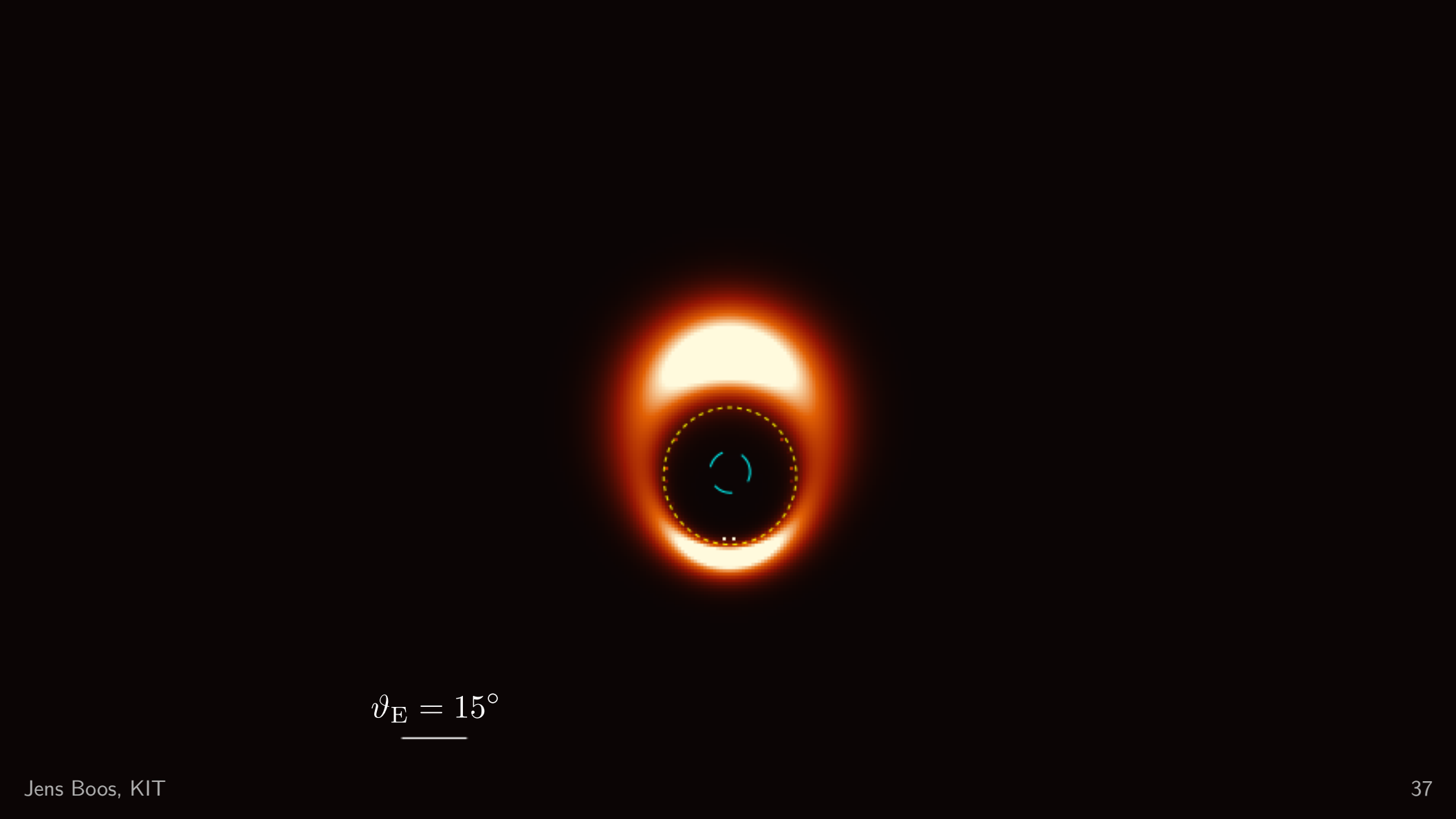
$\vartheta_{\mathrm{E}} = 15^{\circ}$



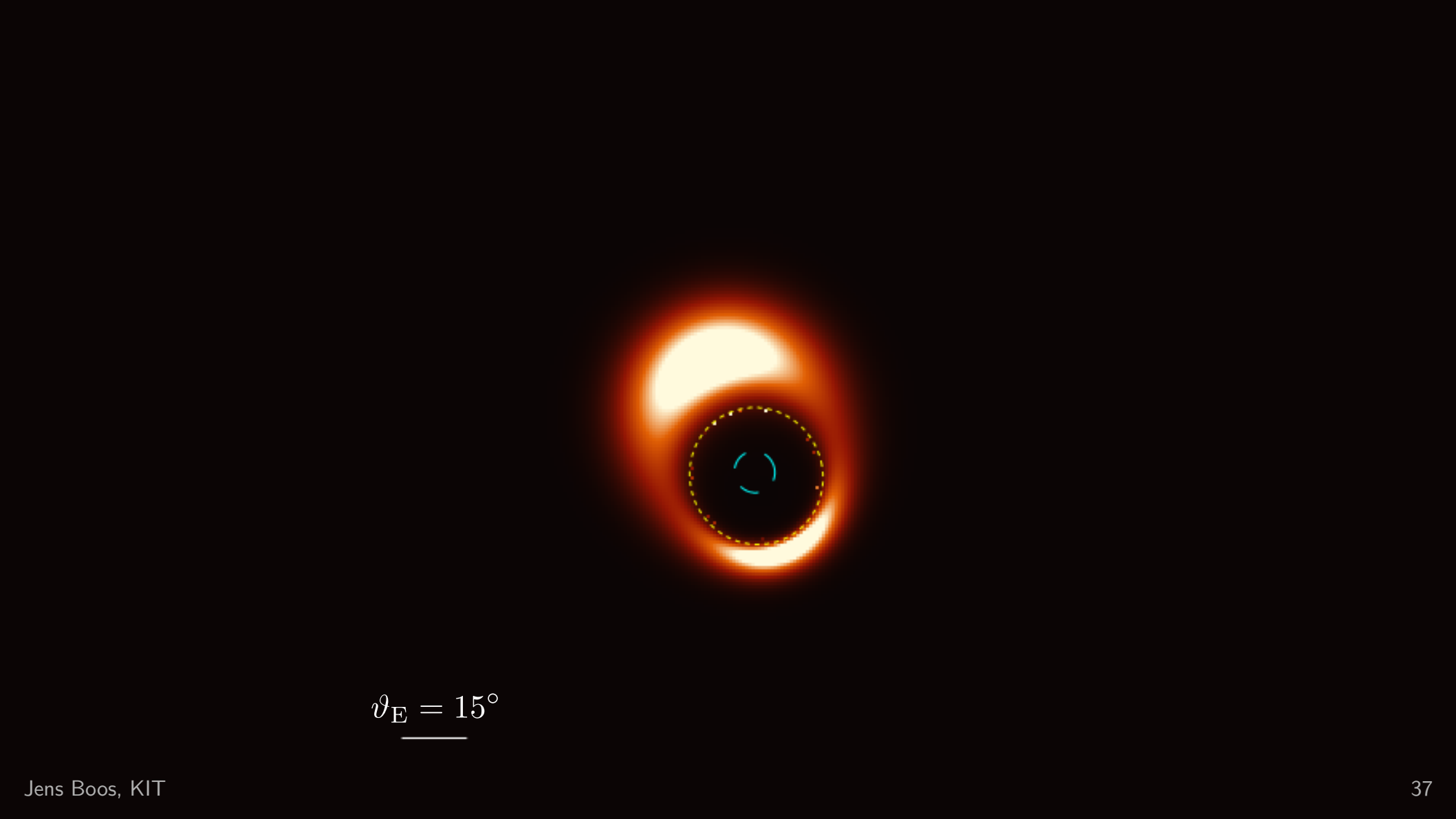
$\vartheta_{\mathrm{E}} = 15^{\circ}$



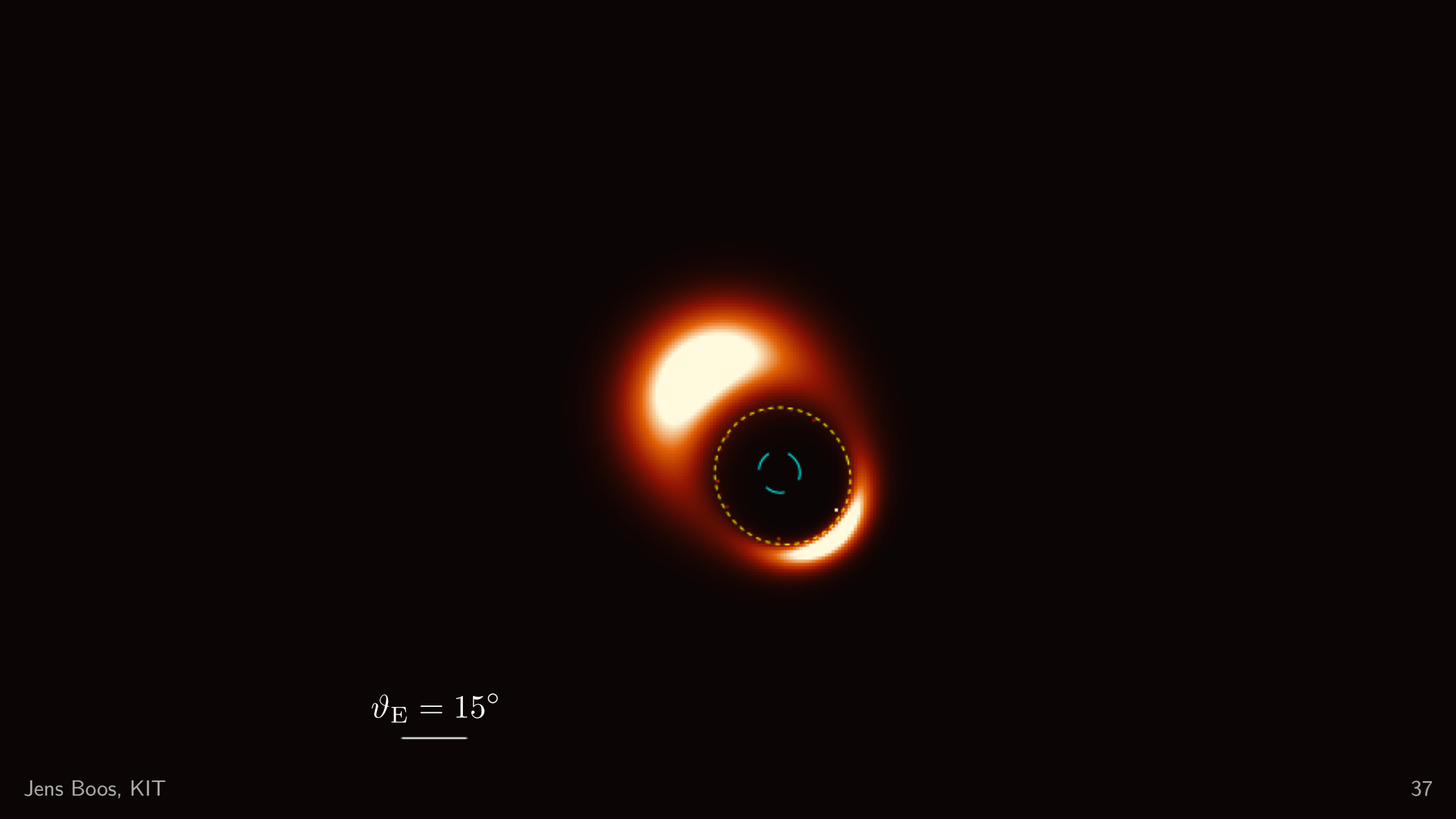
$\vartheta_{\mathrm{E}} = 15^{\circ}$



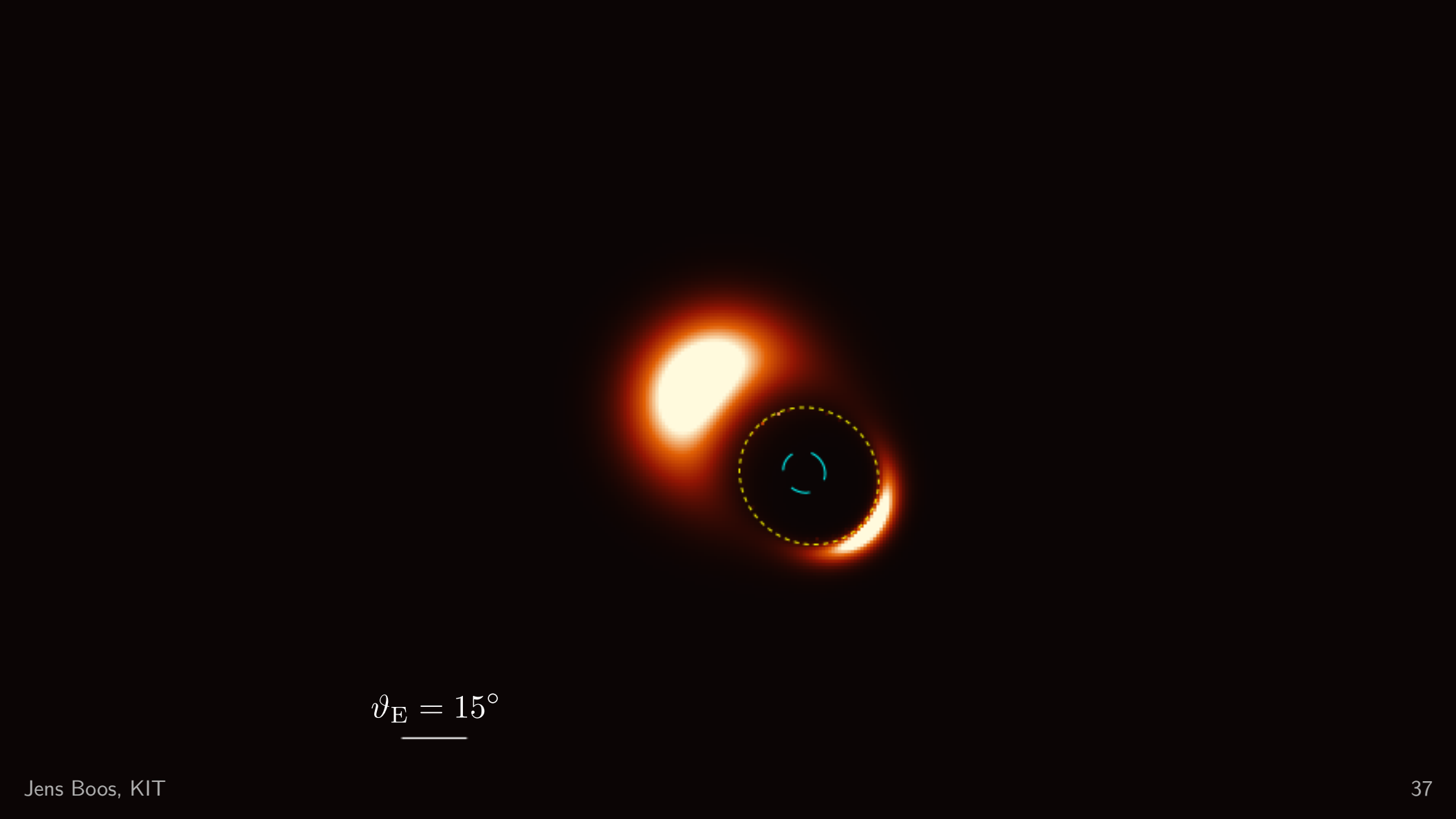
$\vartheta_{\mathrm{E}} = 15^{\circ}$



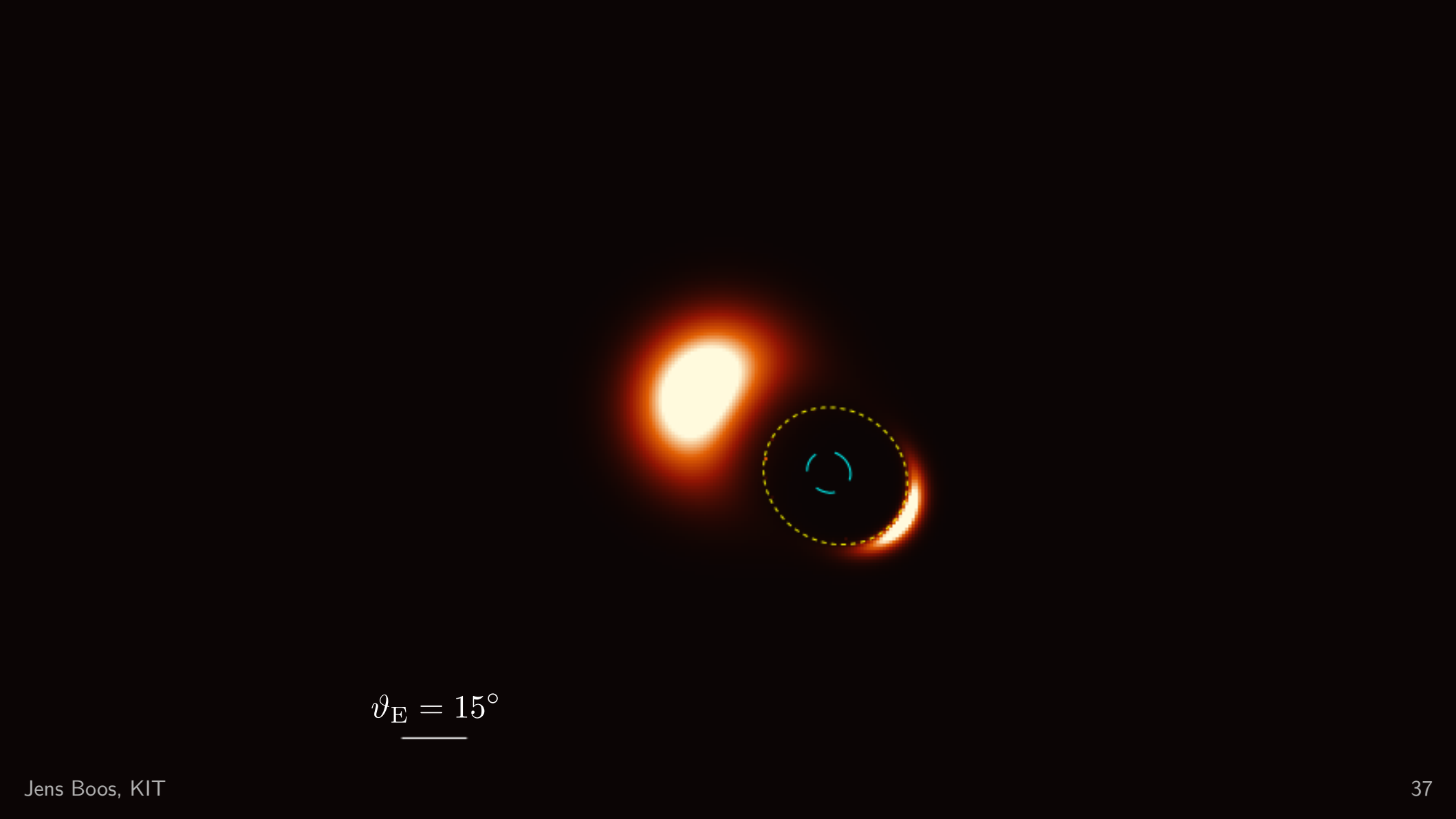
$\vartheta_{\mathrm{E}} = 15^{\circ}$



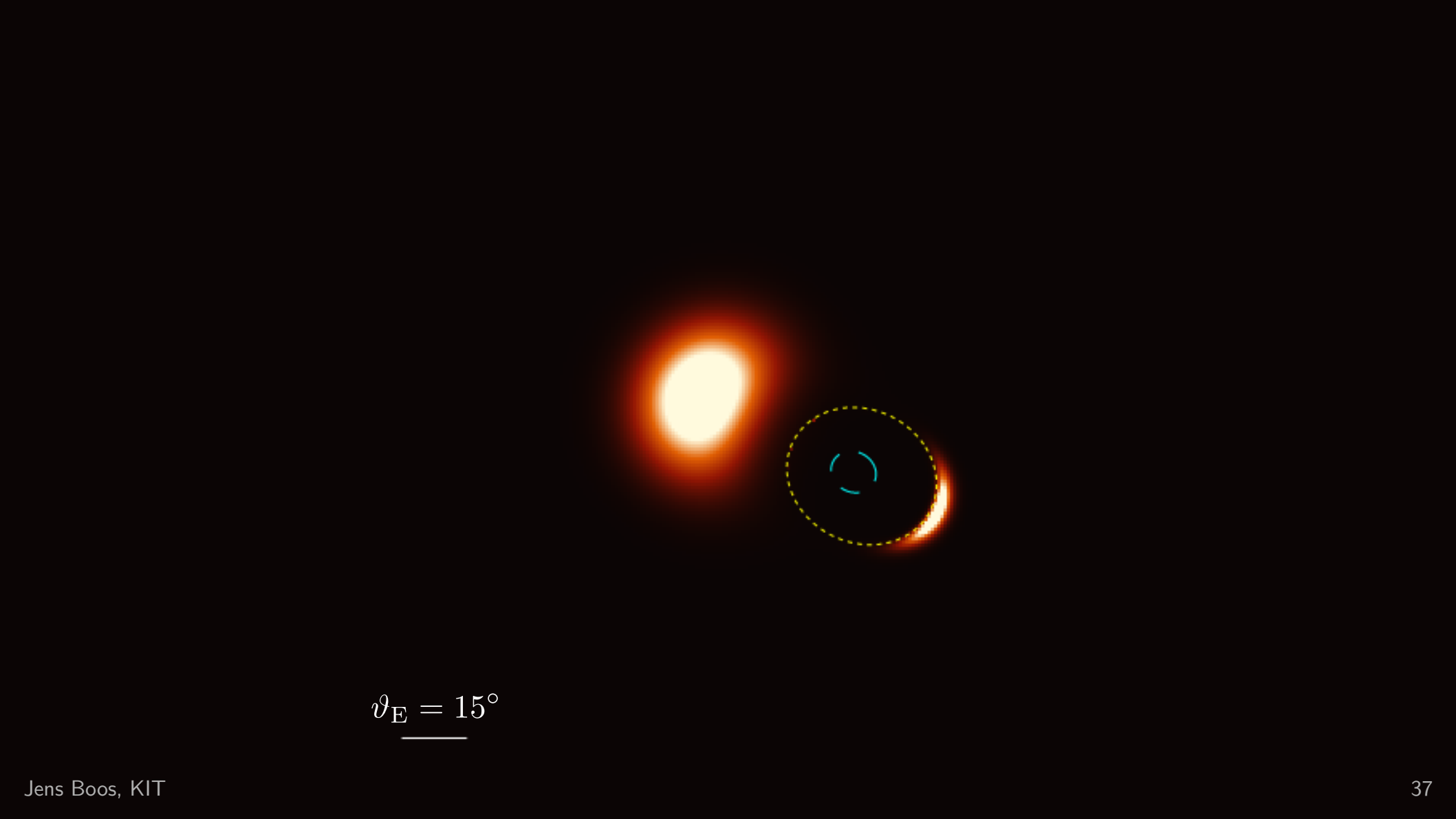
$\vartheta_{\mathrm{E}} = 15^{\circ}$



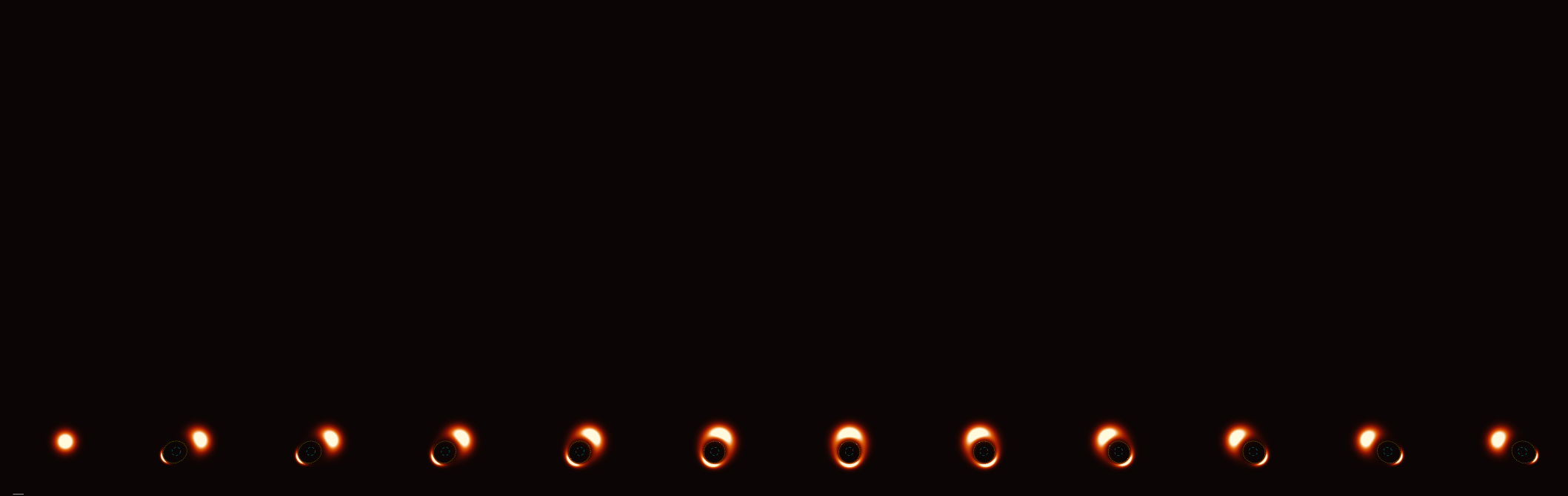
$\vartheta_{\mathrm{E}} = 15^{\circ}$

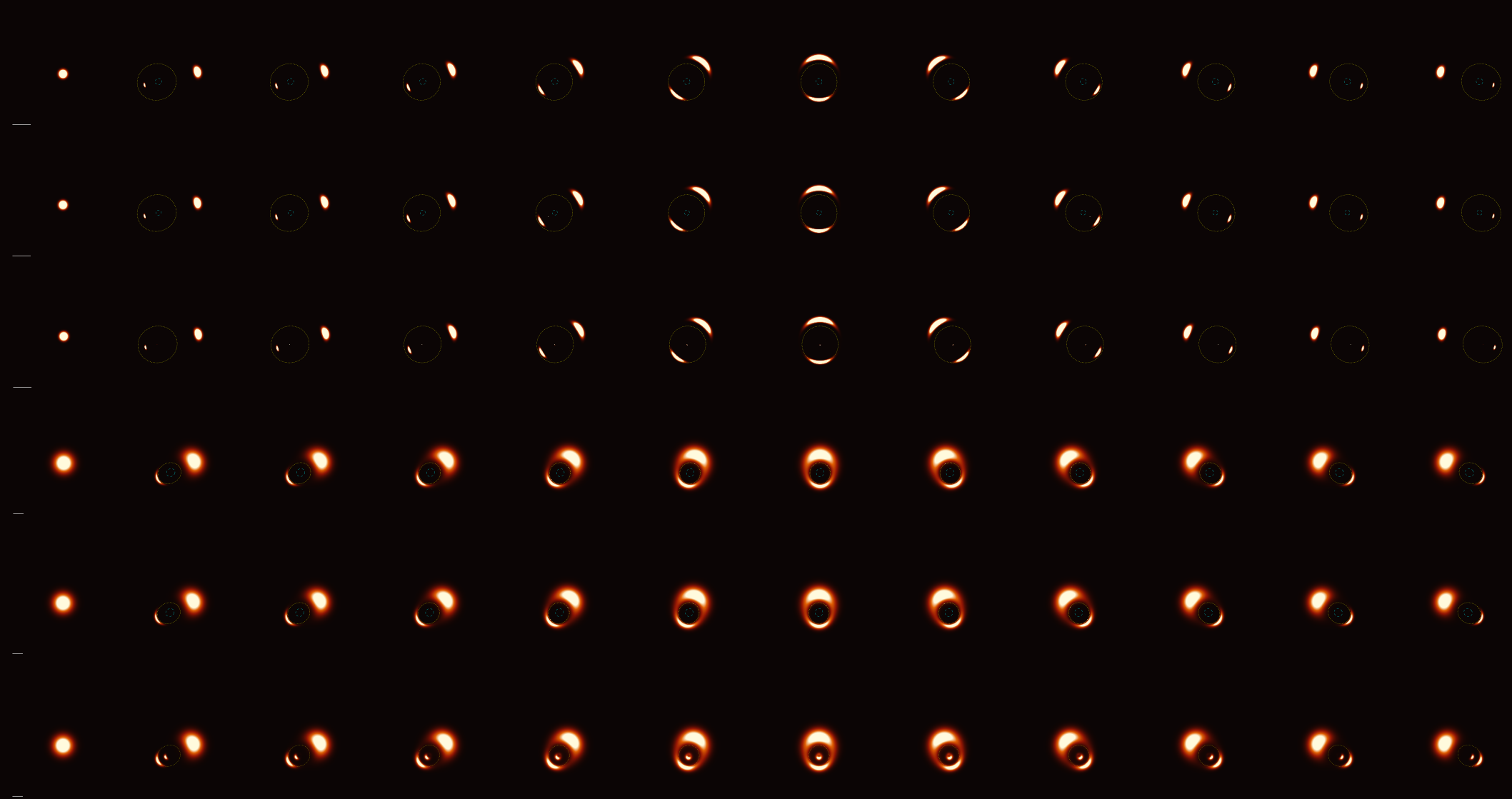


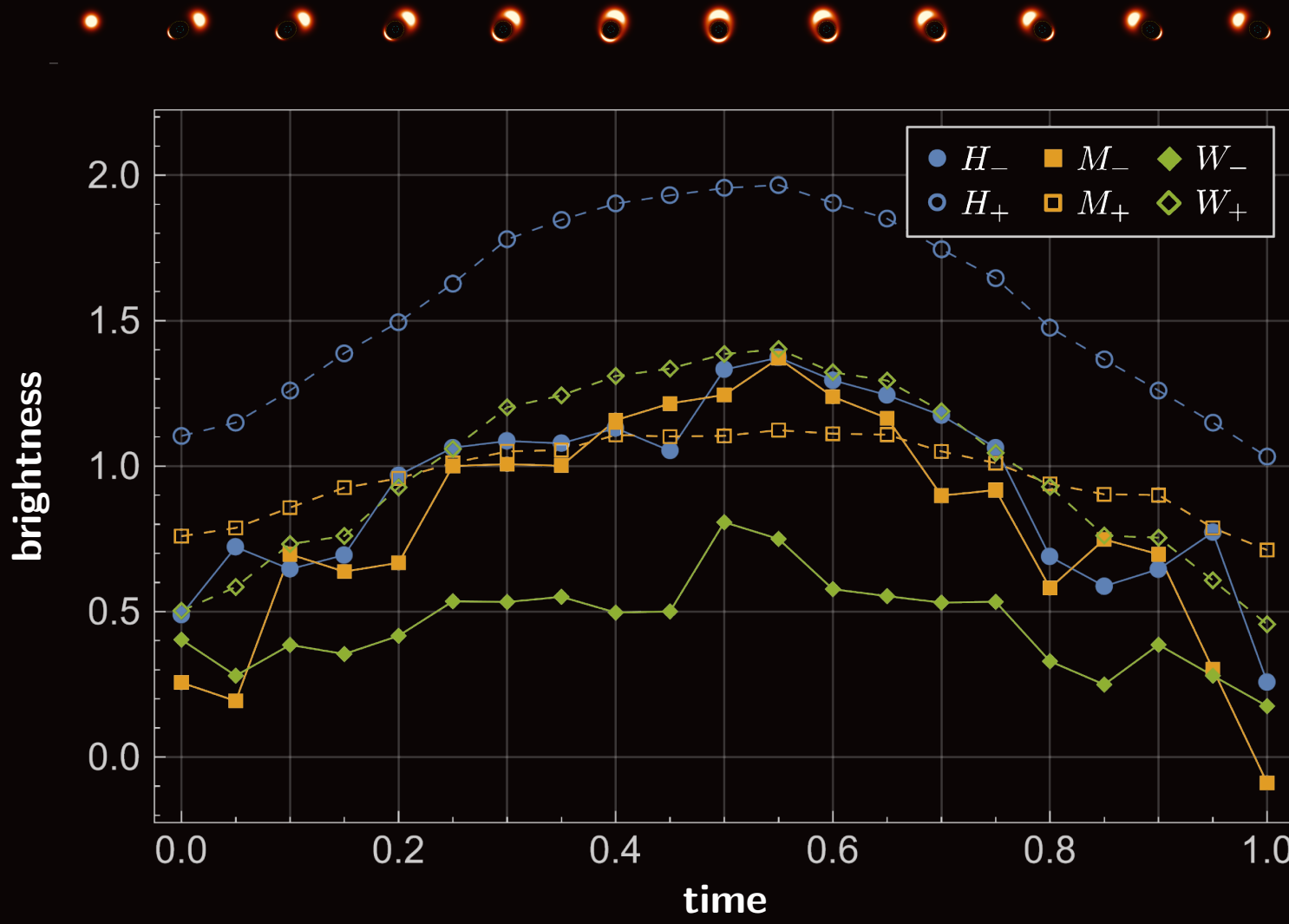
$\vartheta_{\mathrm{E}} = 15^{\circ}$



$\vartheta_{\mathrm{E}} = 15^{\circ}$






H_-
M_-
W_-
H_+
M_+
W_+
brightness
time
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0
Boos & Hu (2025)

Comparison to parametrized post-Newtonian framework (4th order):

Total brightness enhancement:

$$\delta = \frac{15\pi}{16} \times \left(\frac{\ell}{GM}\right)^2 \times \left(\frac{\vartheta_\bullet}{\vartheta_\mathrm{E}}\right)^3 \times \frac{1}{\beta}$$

This is very sensitive to geometrical setup:

$$\delta = \left(\frac{\ell}{GM}\right)^2 \times \frac{2+\beta_\mathrm{min}^2}{\beta_\mathrm{min}\sqrt{4+\beta_\mathrm{min}^2}} \times \begin{cases} 1.9 \times 10^{-24} & \text{OGLE-2011-BLG-0462} \\ 2.0 \times 10^{-2} & \text{numerical setup} \end{cases}$$

Strong dependence on angle β between lens and star. Statistics important! (Ongoing work...)

Result: New physics enhances microlensing intensity

Regulator enhances magnification:

Non-singular models decrease the curvature of the time-delay surface.

Numerical modeling:

Finite-size effects and horizonless "exotic" cases require numerical treatment.

Realistic scenarios:

Magnification is extremely sensitive to minimal source-lens angle.

A statistical analysis is warranted.

Drawback: Quadratically suppressed in $\ell/(2GM)$. Are there domains when $\ell/(2GM) \sim 0.5$?

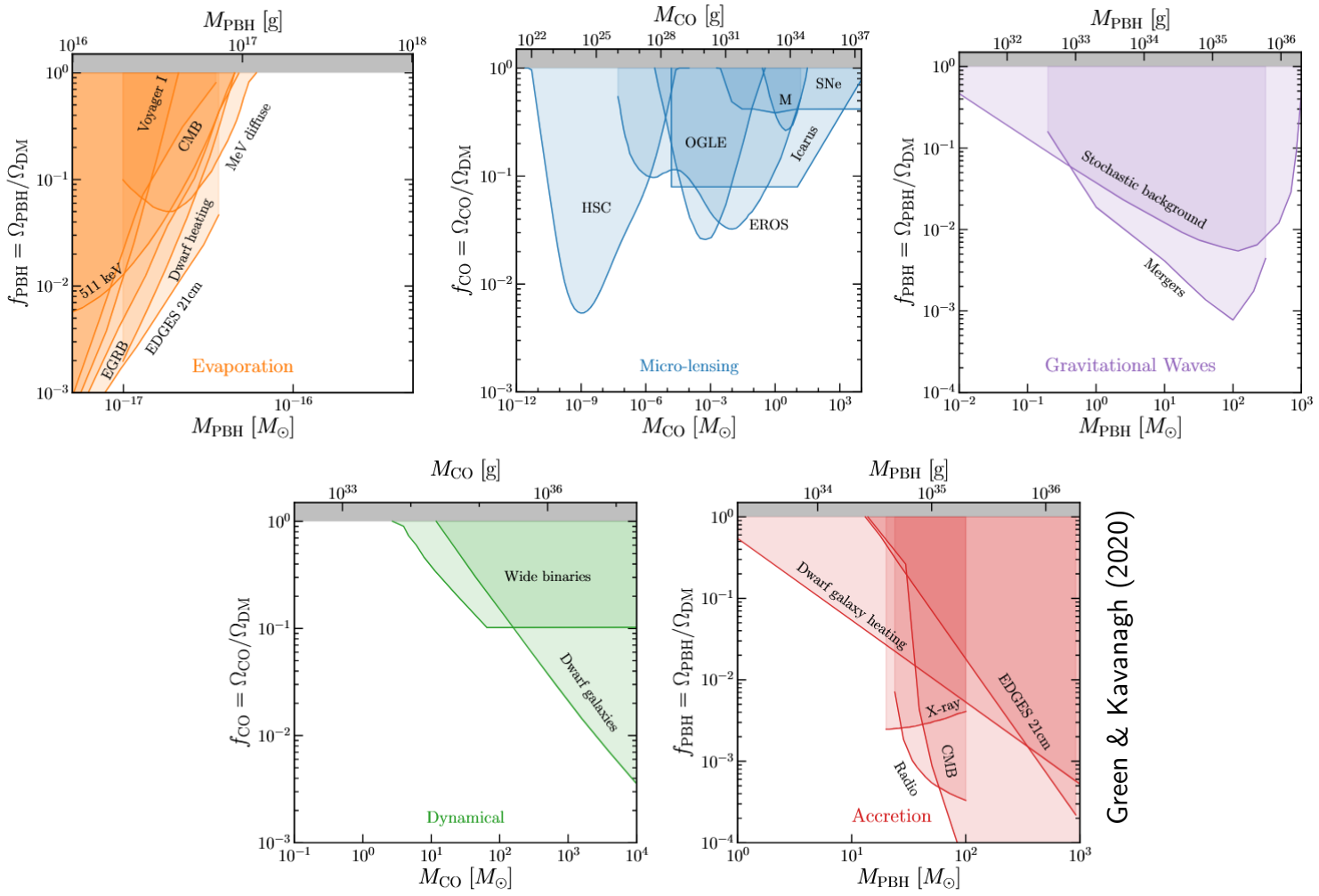
Scenario #3

Low-mass black holes as (part of) dark matter

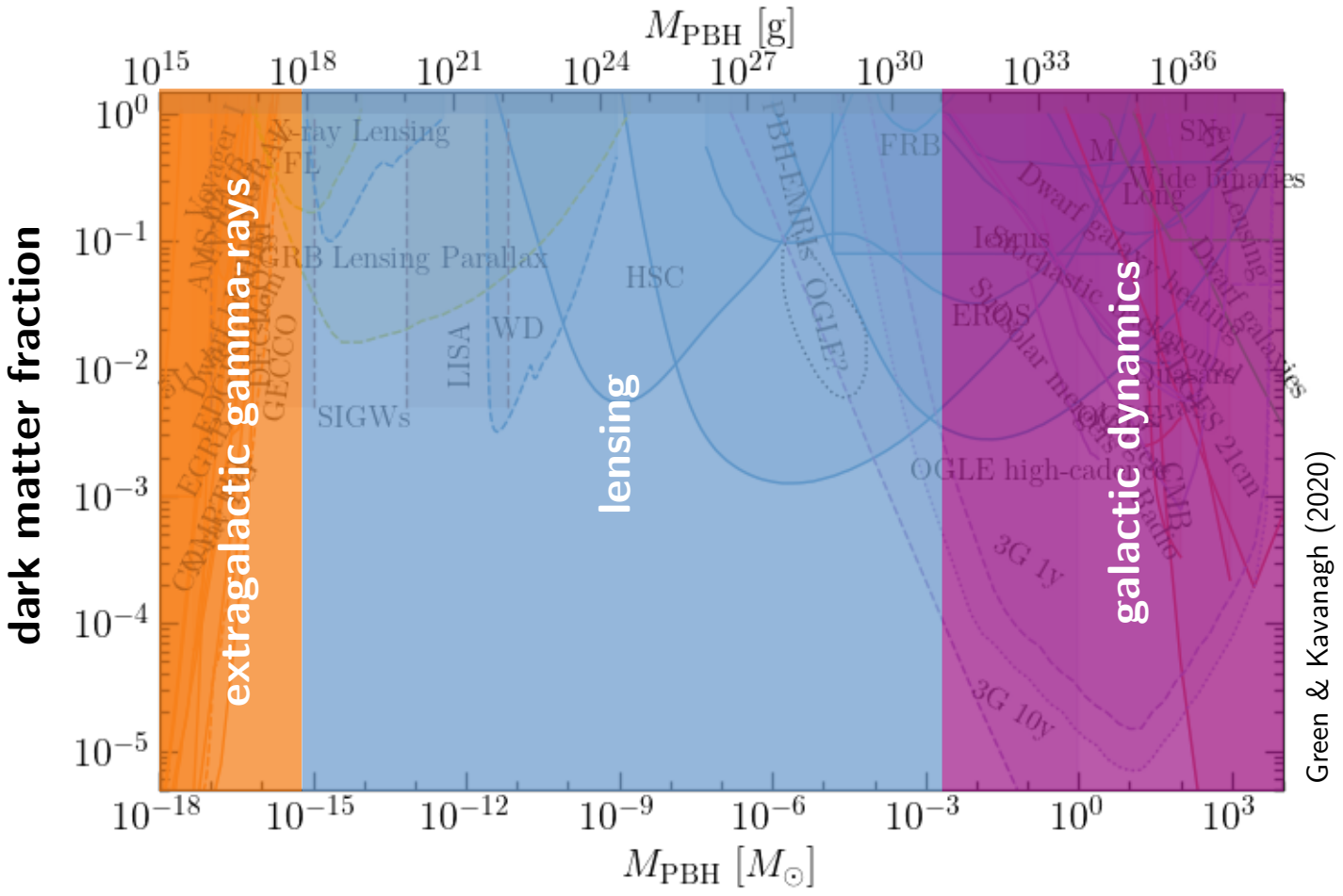


JB & Christoph Borschensky;
JB & Arif Gündoğdu & Marek Hartenfels;
work in progress

Constraints on low-mass black holes



Constraints on low-mass black holes



Black holes evaporate

Associated Hawking temperature:

$$T_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G k_{\mathrm{B}}} \frac{1}{M} \approx 1.2 \left(\frac{10^{26}\mathrm{g}}{M} \right) \mathrm{K}$$

Calculate from first principles:

$$T_{\mathrm{H}} = \frac{\hbar c}{4\pi\, k_B} \left. \frac{\partial f}{\partial r} \right|_{r=r_{\mathrm{h}}} \quad \text{with} \quad f(r_h) = 0\,.$$

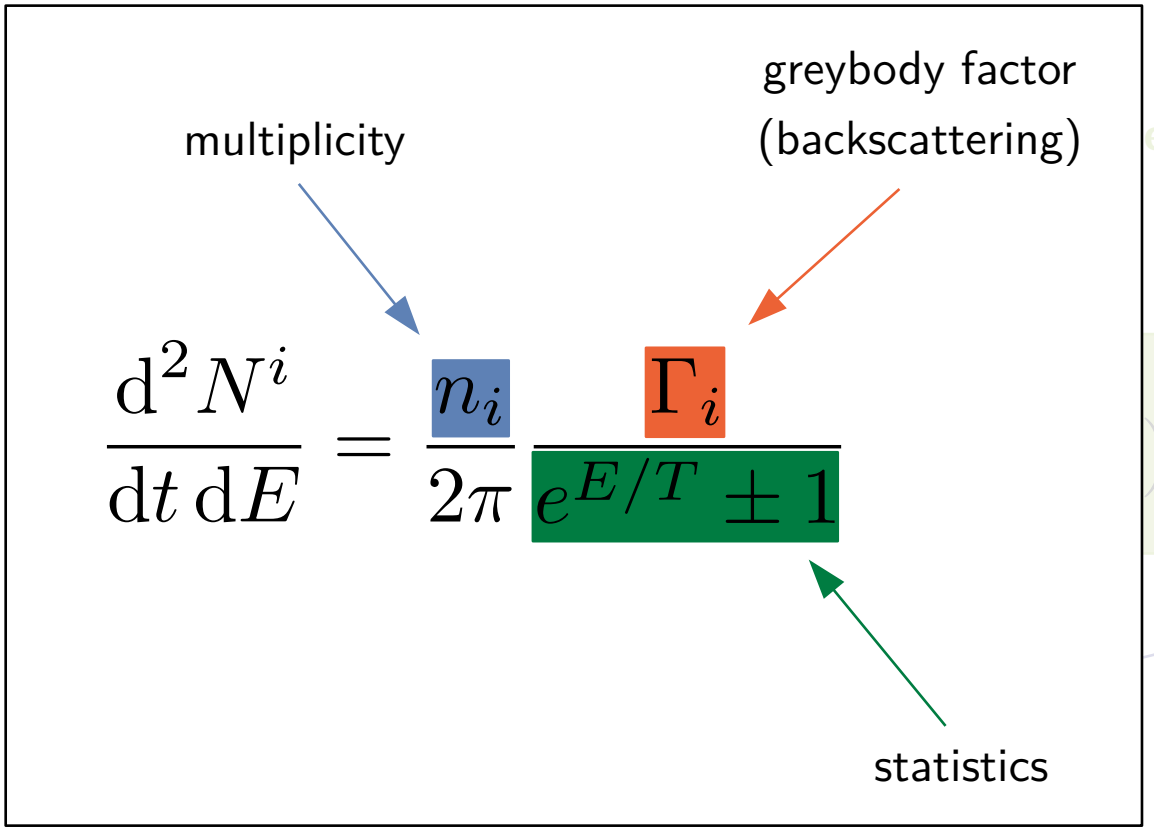
As the temperature increases, more and more modes can be evaporated efficiently.

Mass loss formula

can compute

$$\frac{\mathrm{d}M}{\mathrm{d}t} = (-1) \sum_i \int_0^\infty \mathrm{d}E\, E \frac{\mathrm{d}^2 N^i}{\mathrm{d}t\, \mathrm{d}E}(M, E)$$

Mass loss formula

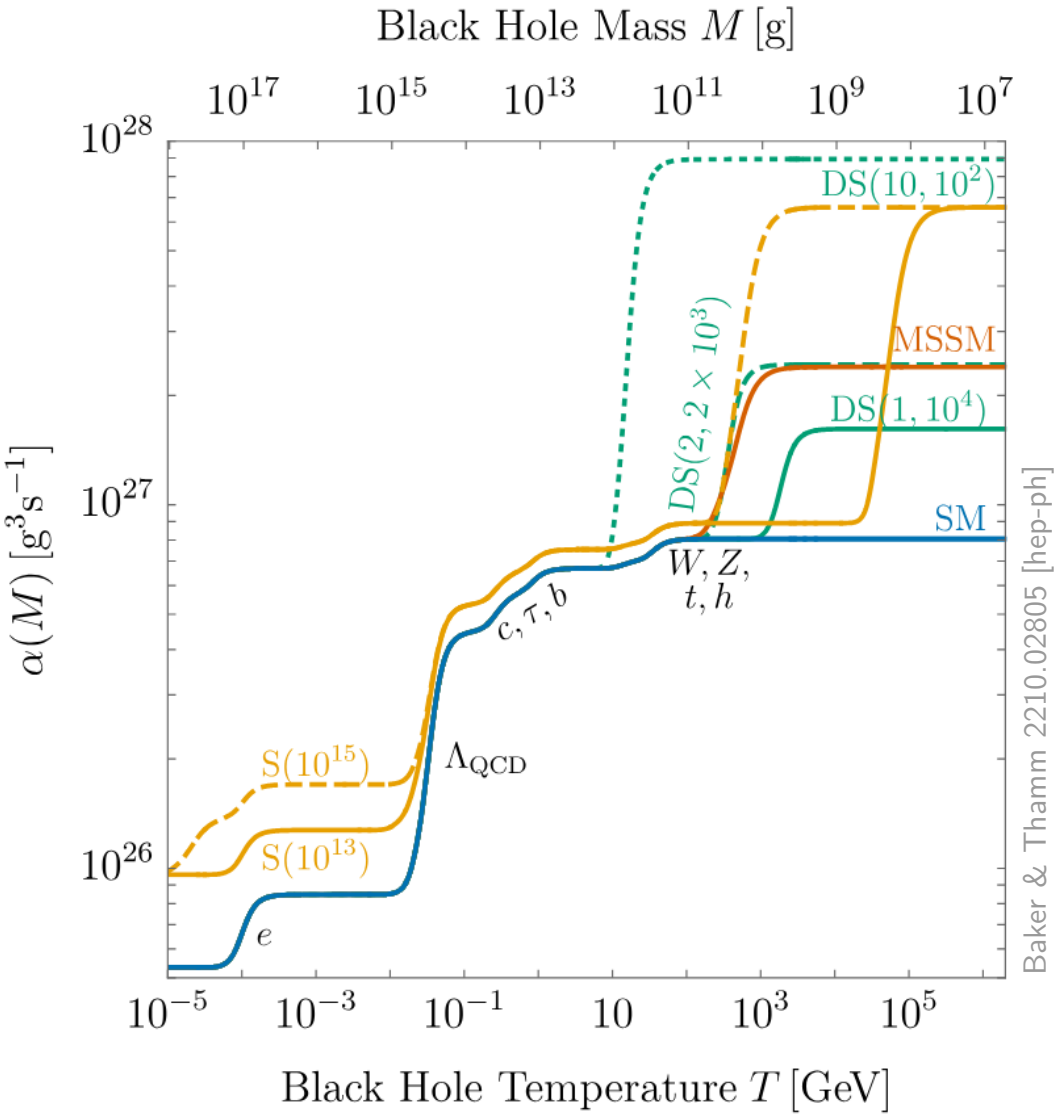


Mass loss formula

can compute

$$\frac{\mathrm{d}M}{\mathrm{d}t} = (-1) \sum_i \underbrace{\int_0^\infty \mathrm{d}E\, E \frac{\mathrm{d}^2 N^i}{\mathrm{d}t\, \mathrm{d}E}(M, E)}$$

how does this look like?


Black Hole Mass M [g]
10^{17}
10^{15}
10^{13}
10^{11}
10^{9}
10^{7}
10^{28}
10^{27}
10^{26}
$\alpha(M)$ [g^{3}s^{-1}]
DS$(10, 10^2)$
DS$(2, 2 \times 10^3)$
MSSM
DS$(1, 10^4)$
SM
$W, Z,$
t, h
c, τ, b
$\Lambda_{\rm QCD}$
S(10^{15})
S(10^{13})
e
10^{-5}
10^{-3}
10^{-1}
10
10^{3}
10^{5}
Black Hole Temperature T [GeV]
Baker & Thamm 2210.02805 [hep-ph]

The dark matter connection

Propagate black holes through cosmic history until recombination.

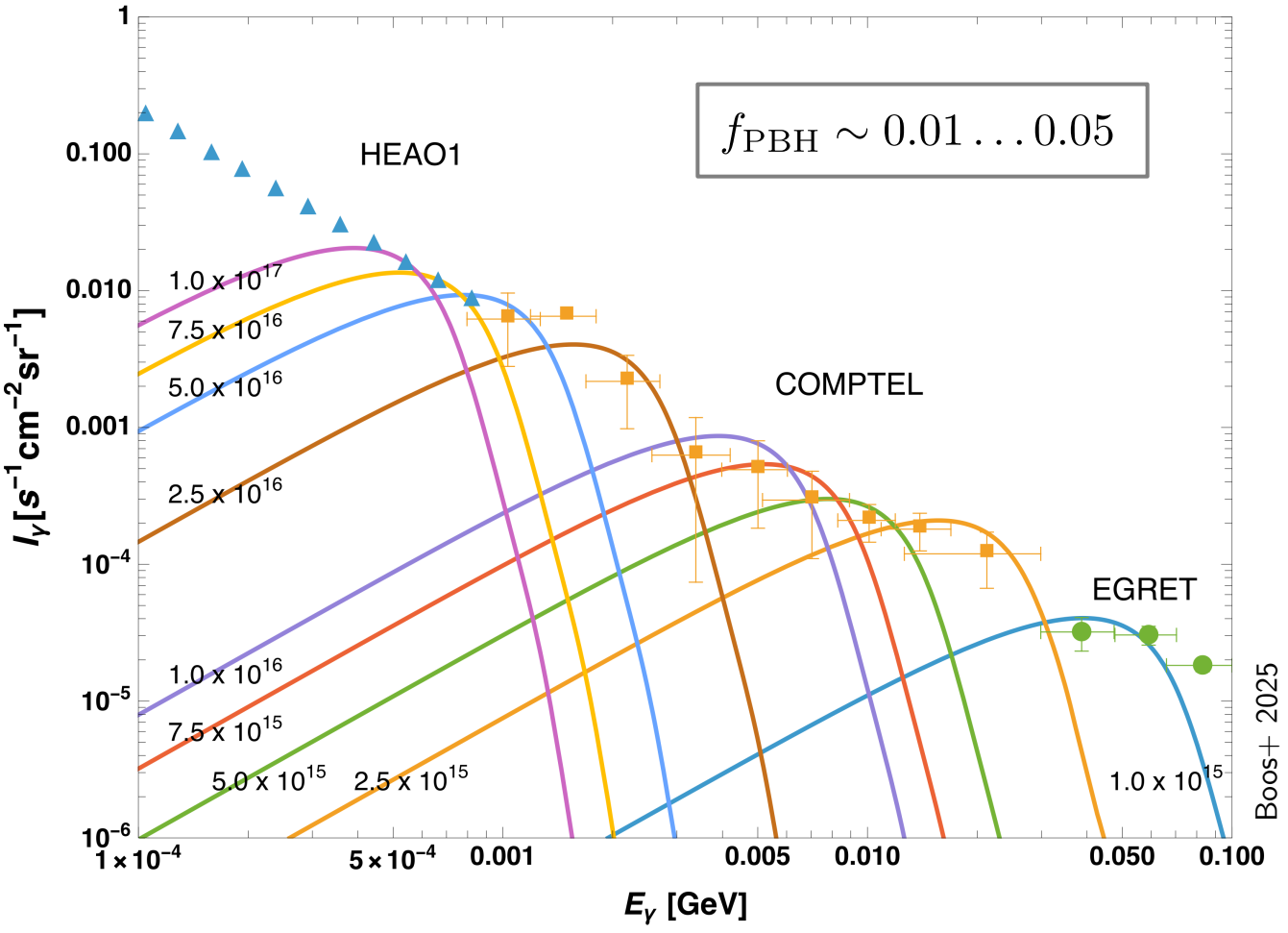
$$n_{\gamma,0}(E_{\gamma,0}) = n_{\mathrm{PBH}}(t_0) E_{\gamma,0} \int_0^{z_\star} \frac{z}{H(z)} \left.\frac{\mathrm{d}^2 N^\gamma}{\mathrm{d}t\,\mathrm{d}E}\right|_{E_\gamma=(1+z)E_{\gamma,0}}$$

Obtain maximal dark matter fraction:

$$f_{\mathrm{PBH}} = \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{dm}}} = \frac{n_{\mathrm{PBH}}(t_0) M}{\rho_{\mathrm{c0}} \Omega_{\mathrm{dm}}}$$

dark matter relic density

Constraining modified models with gamma-ray fluxes



Summary

Summary: amplifiers are needed.





Thank you to my group members and to the Young Investigator Group Program @ KIT.

Scenarios studied to date:

- **Time-variability** in QPO's can rise through astrophysical noise.
- Geometric amplifier via **small angle** lensing.
- **Accumulation** of small deviations over cosmic timescales.

Phenomenology needs input from astrophysics and particle physics!

Thank you for your attention.