

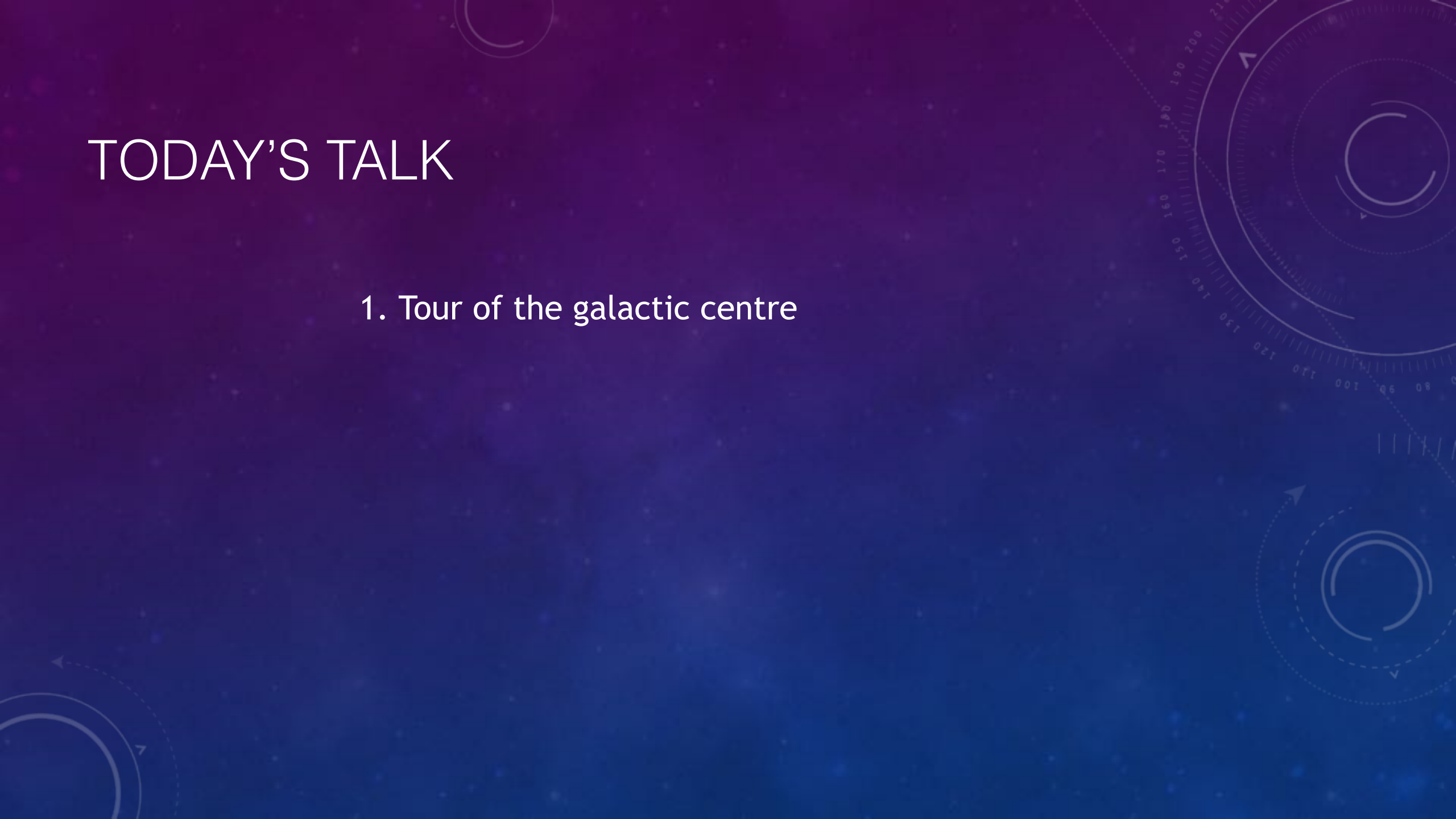
THE SPAGHETTIFICATION OF STARS BY SUPERMASSIVE BLACK HOLES

UNDERSTANDING ONE OF NATURE'S MOST EXTREME EVENTS

DR. ANDREW MUMMERY

TODAY'S TALK

1. Tour of the galactic centre



TODAY'S TALK

1. Tour of the galactic centre
2. What is spaghettification?

TODAY'S TALK

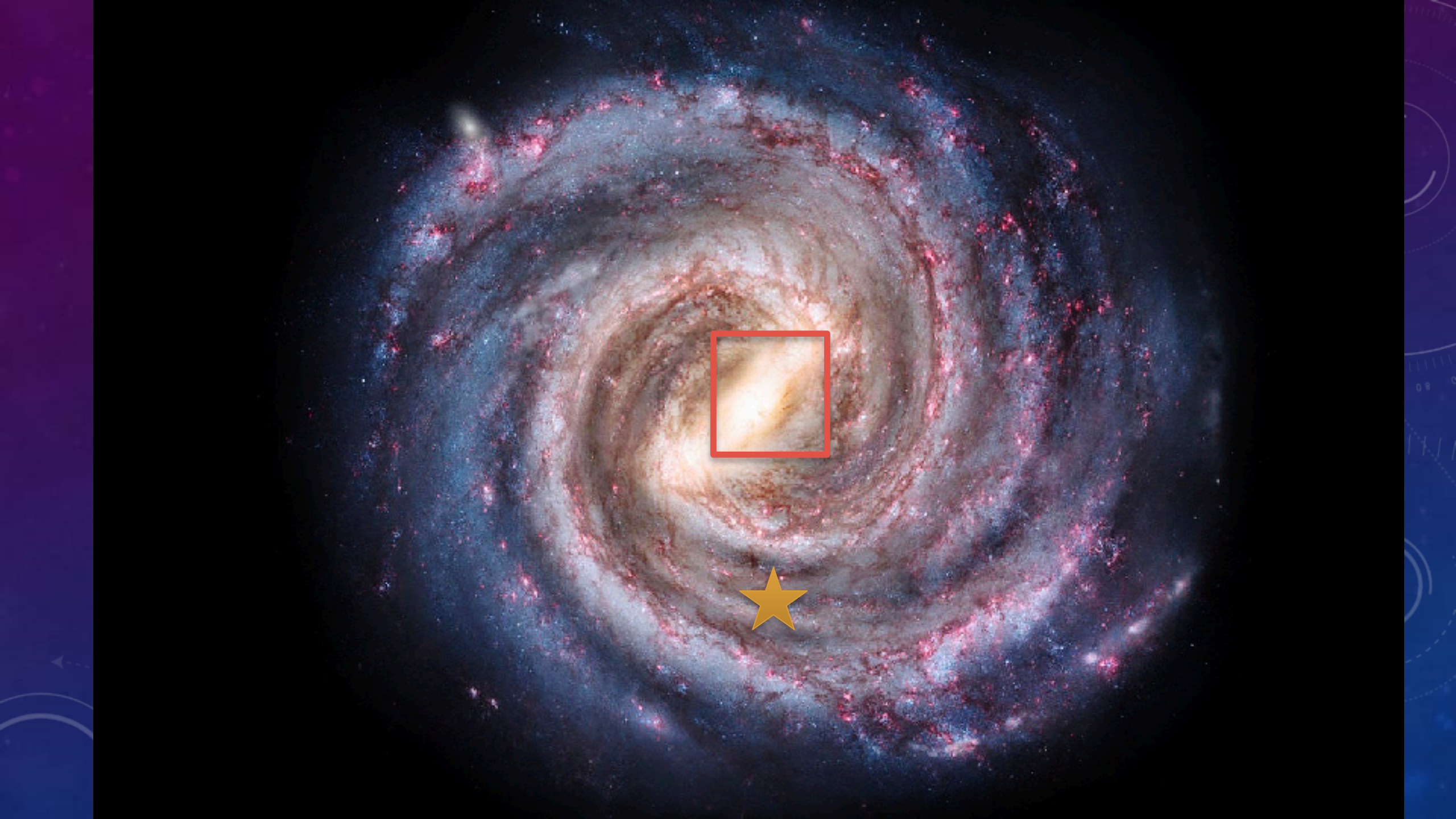
1. Tour of the galactic centre
2. What is spaghettification?
3. Observing “spaghettified” stars

TODAY'S TALK

1. Tour of the galactic centre
2. What is spaghettification?
3. Observing “spaghettified” stars
4. Understanding what we observe



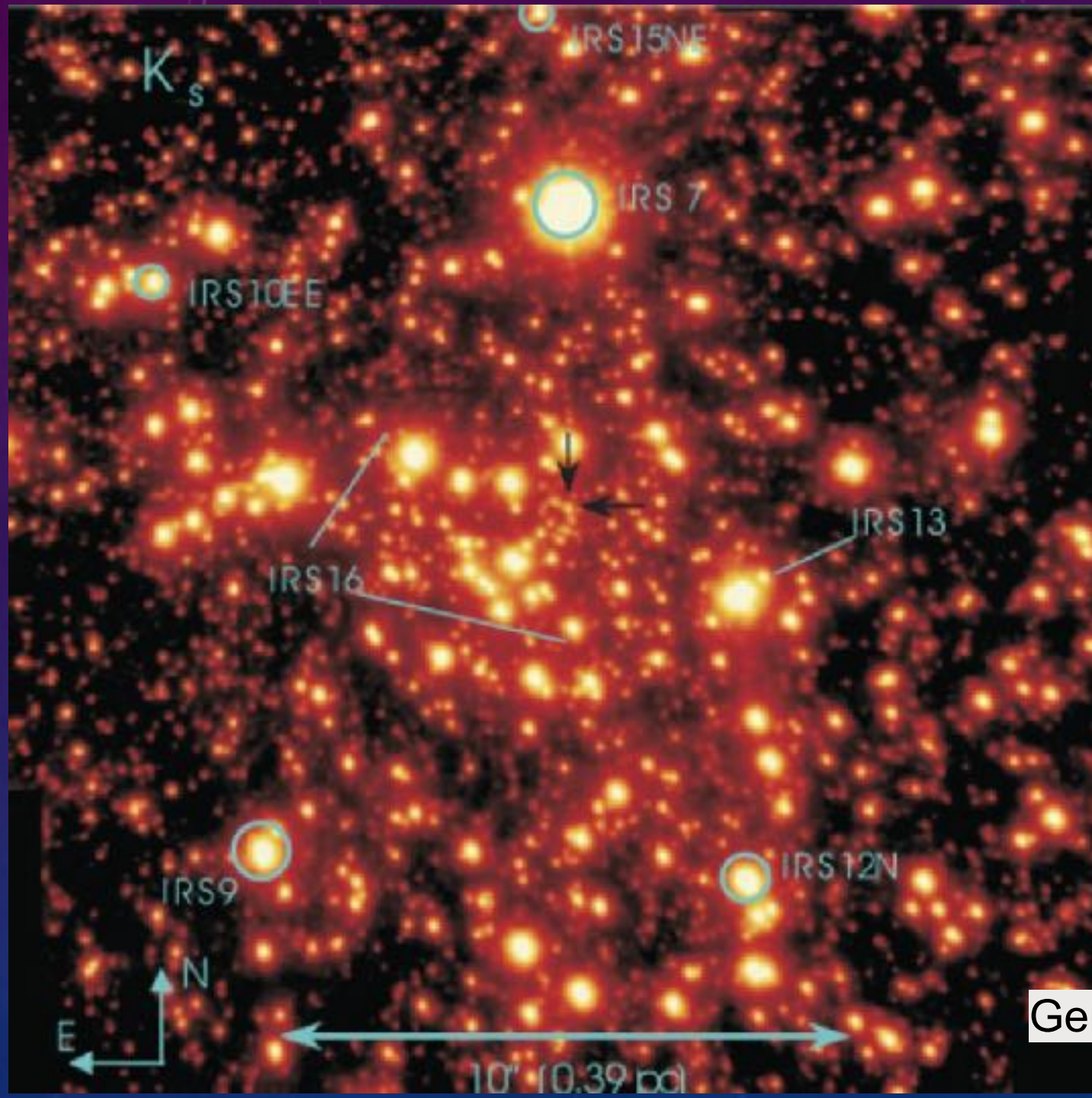






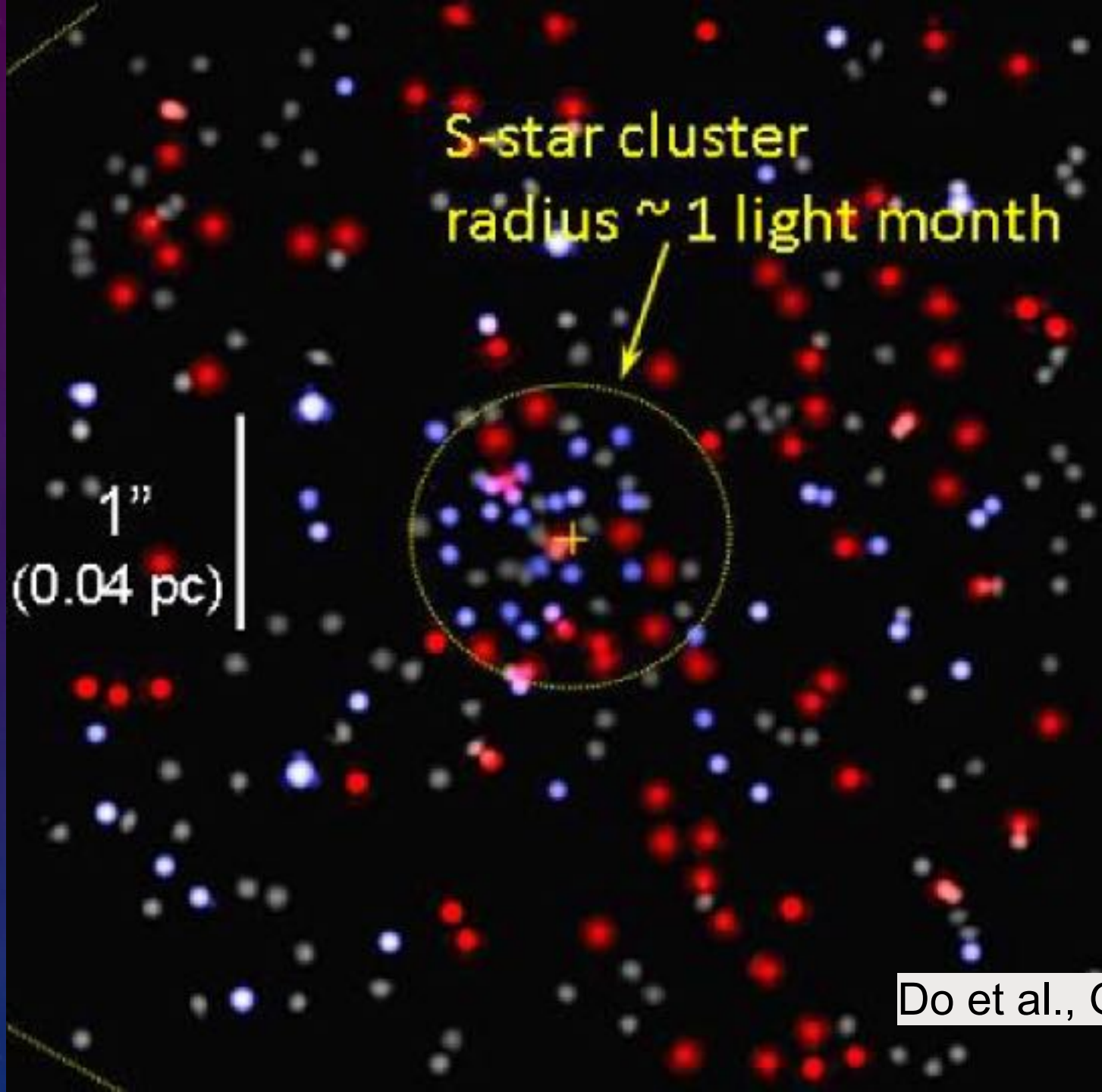


Schoedel et al. 150" x 150"



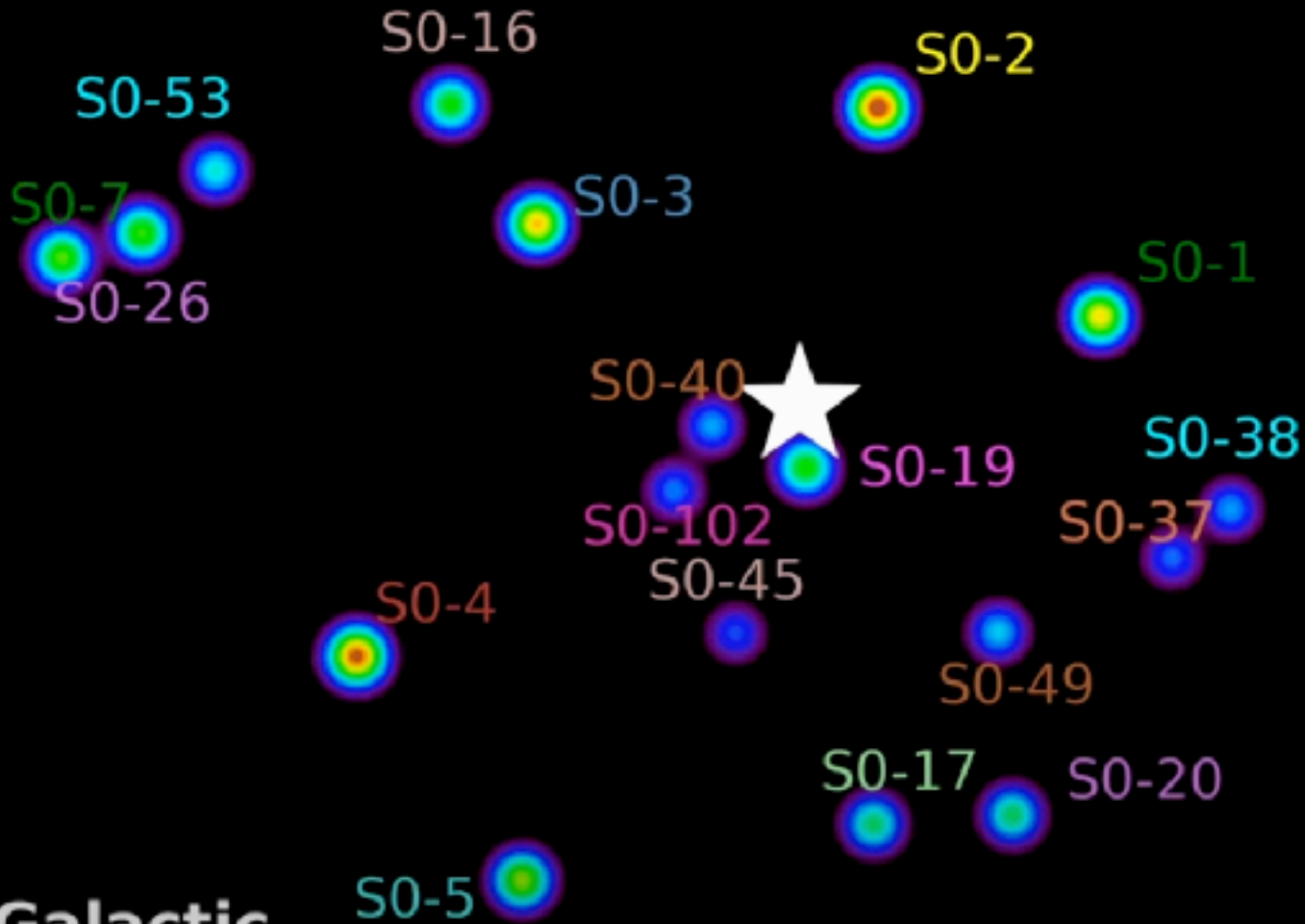
Genzel et al. $20'' \times 20''$





Do et al., Genzel et al. 5"x5"

1995.5



Keck/UCLA Galactic
Center Group

0.1"

Pause (k)

Genzel et al.

2018.7

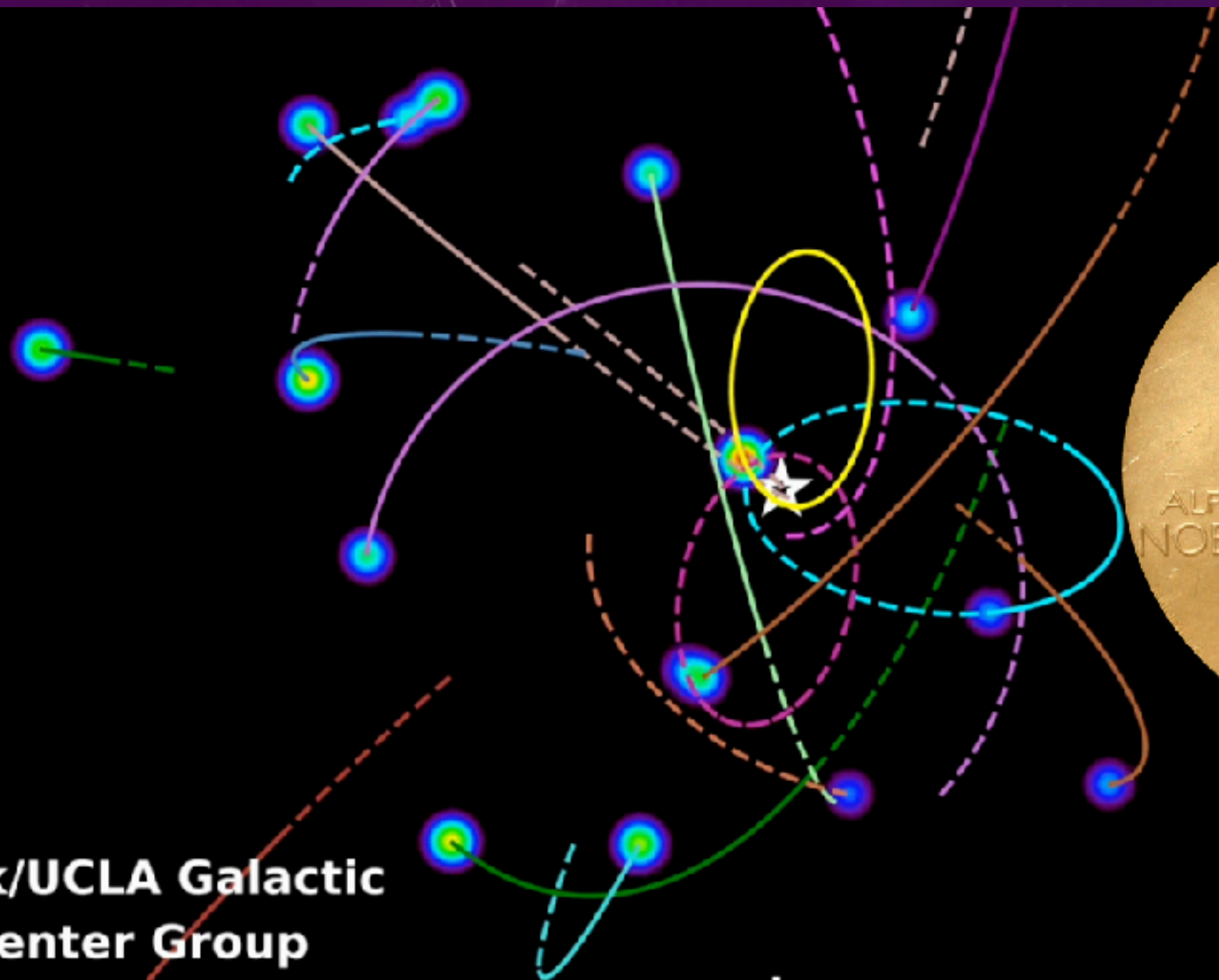


2020

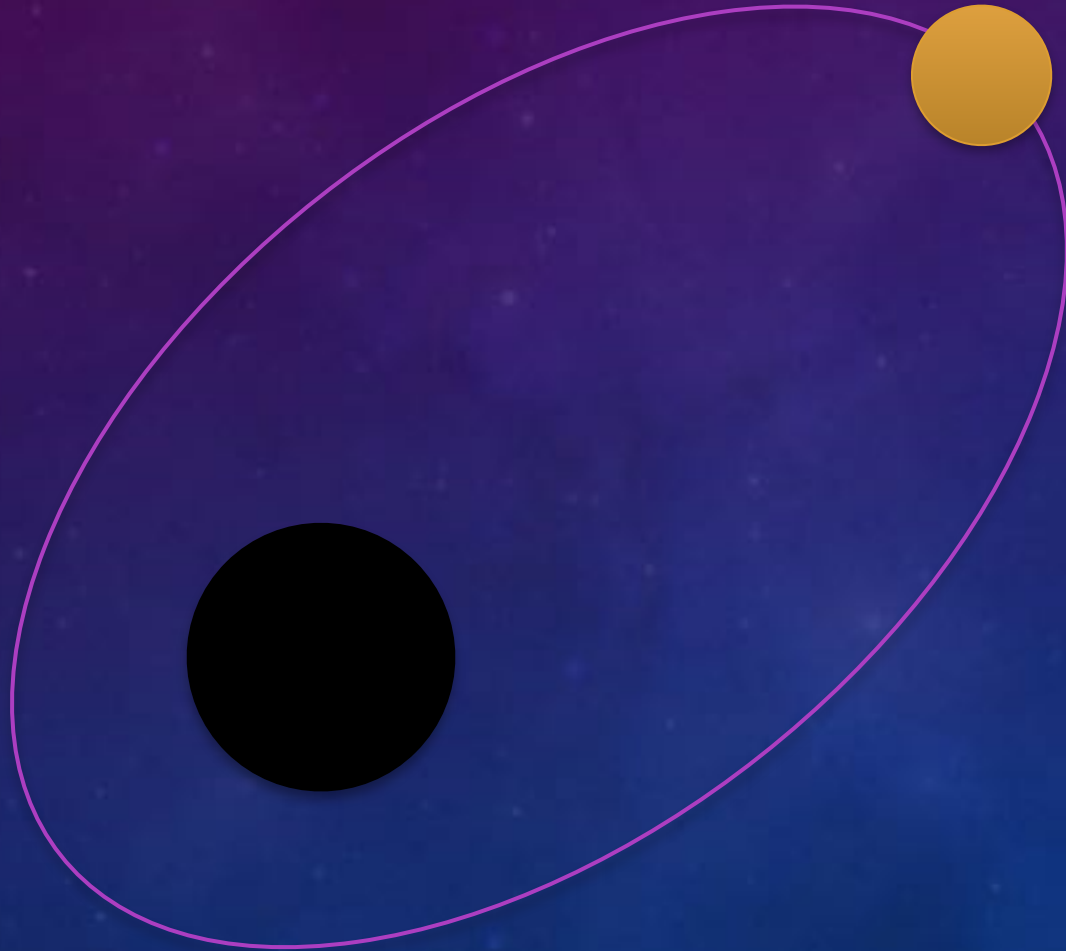
0.1"

Genzel et al.

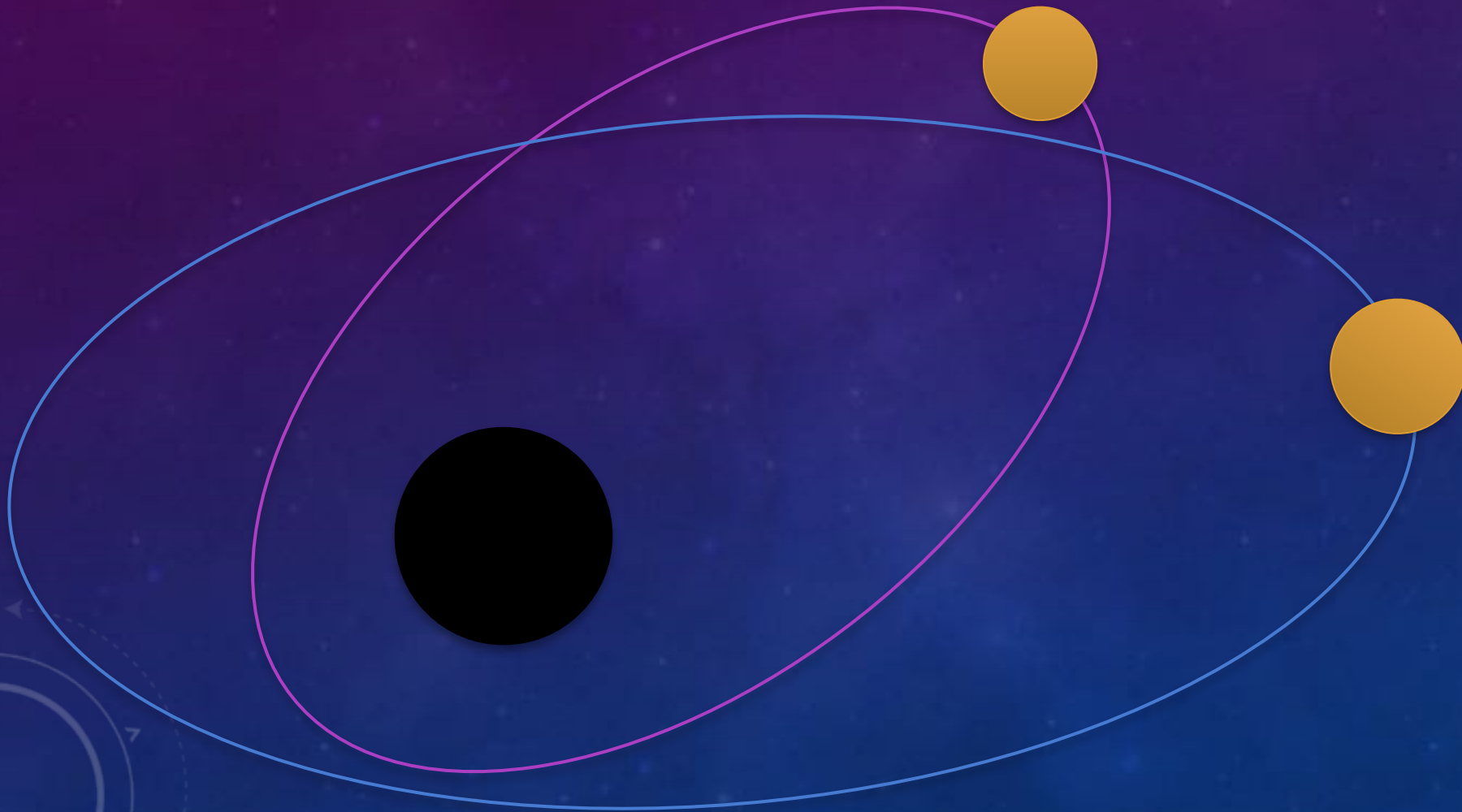
Keck/UCLA Galactic
Center Group



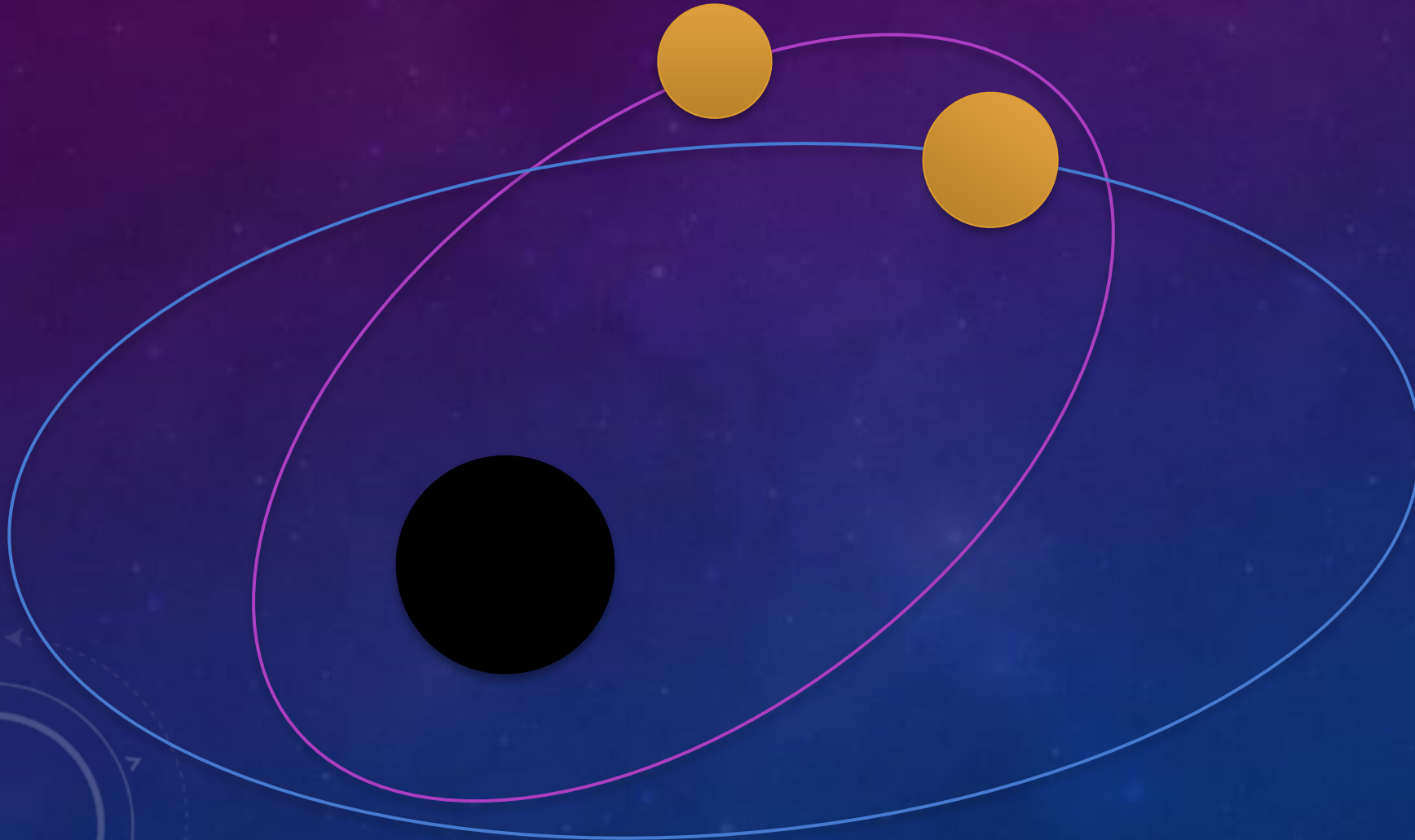
N-BODY INTERACTIONS



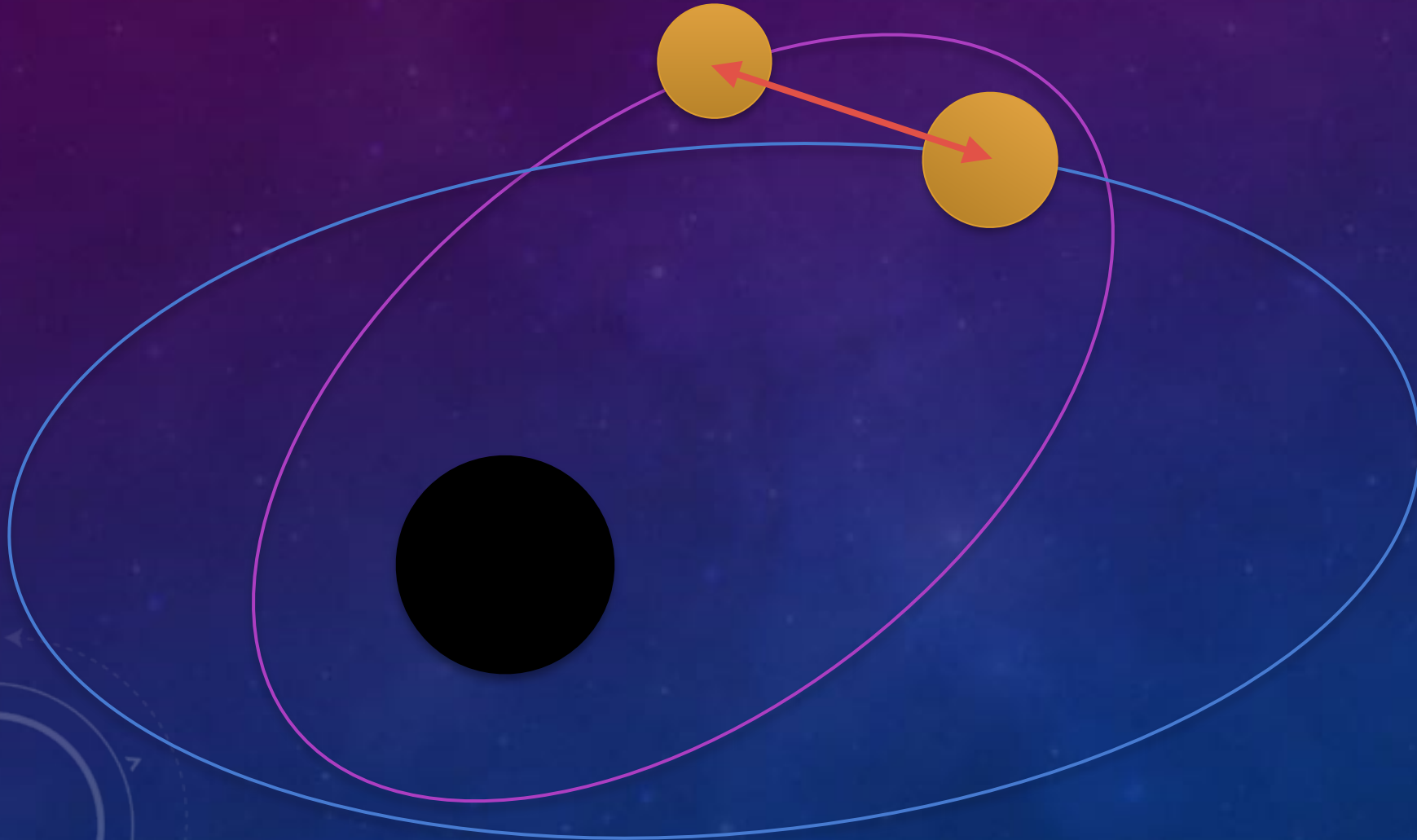
N-BODY INTERACTIONS



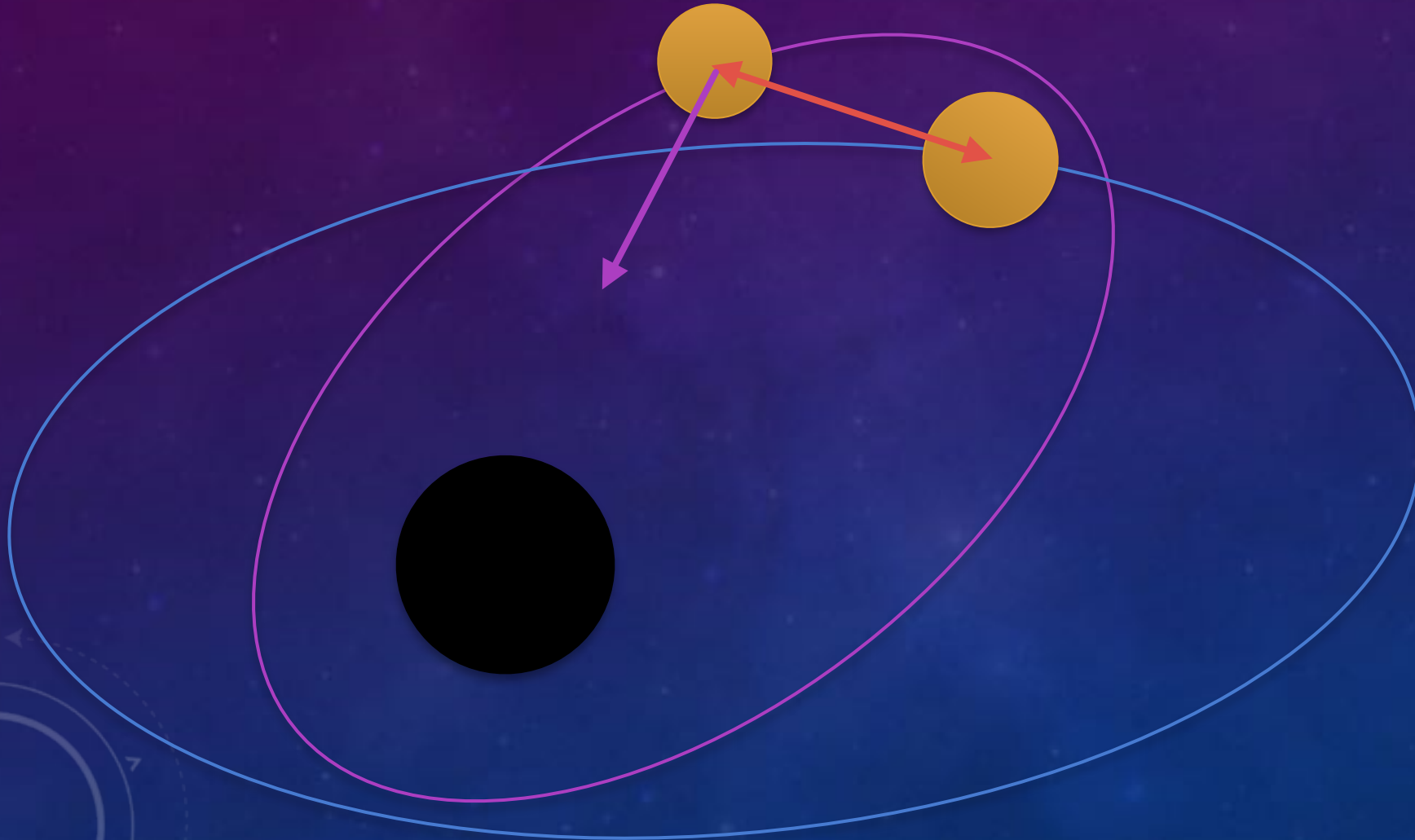
N-BODY INTERACTIONS



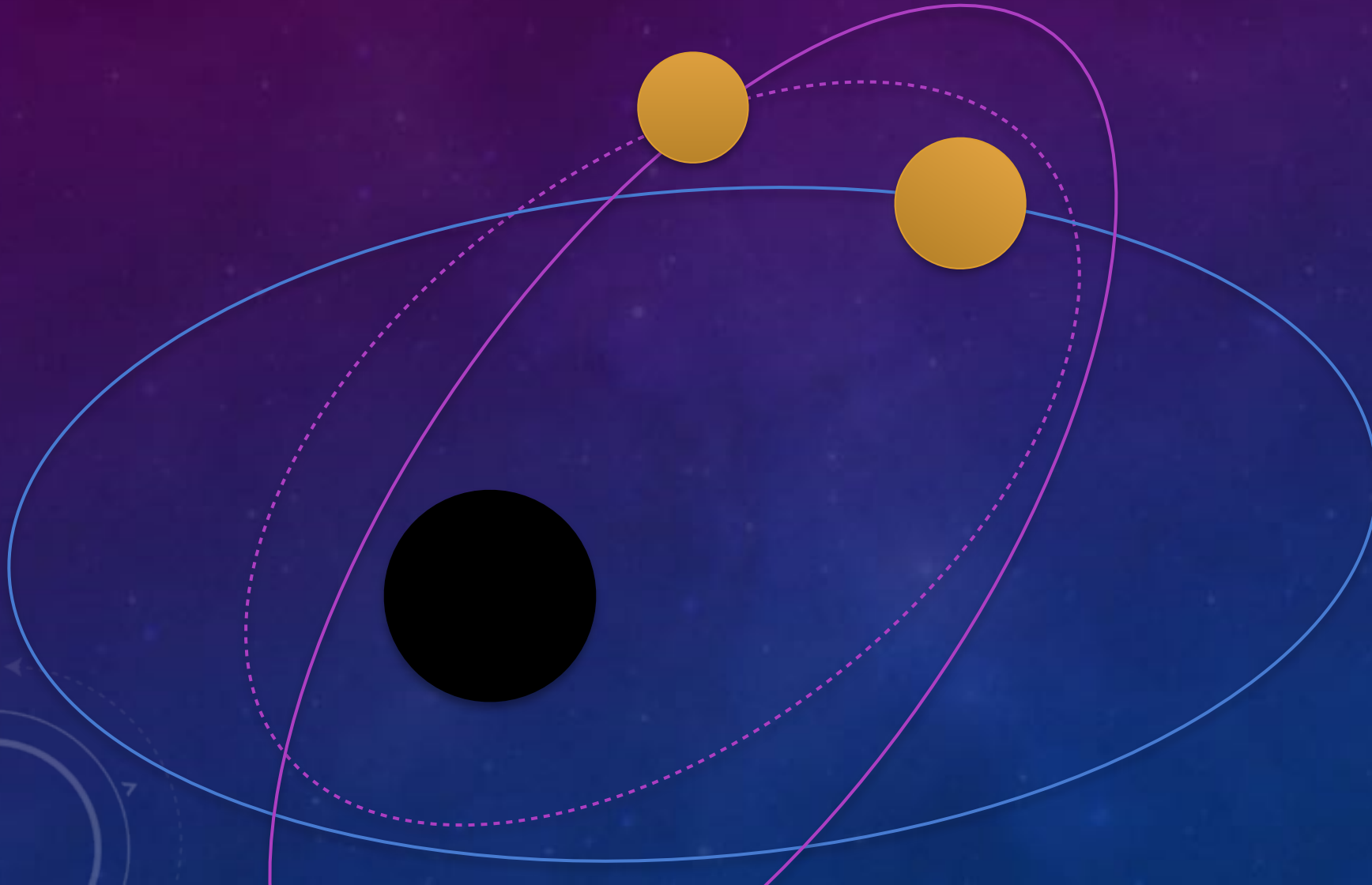
N-BODY INTERACTIONS



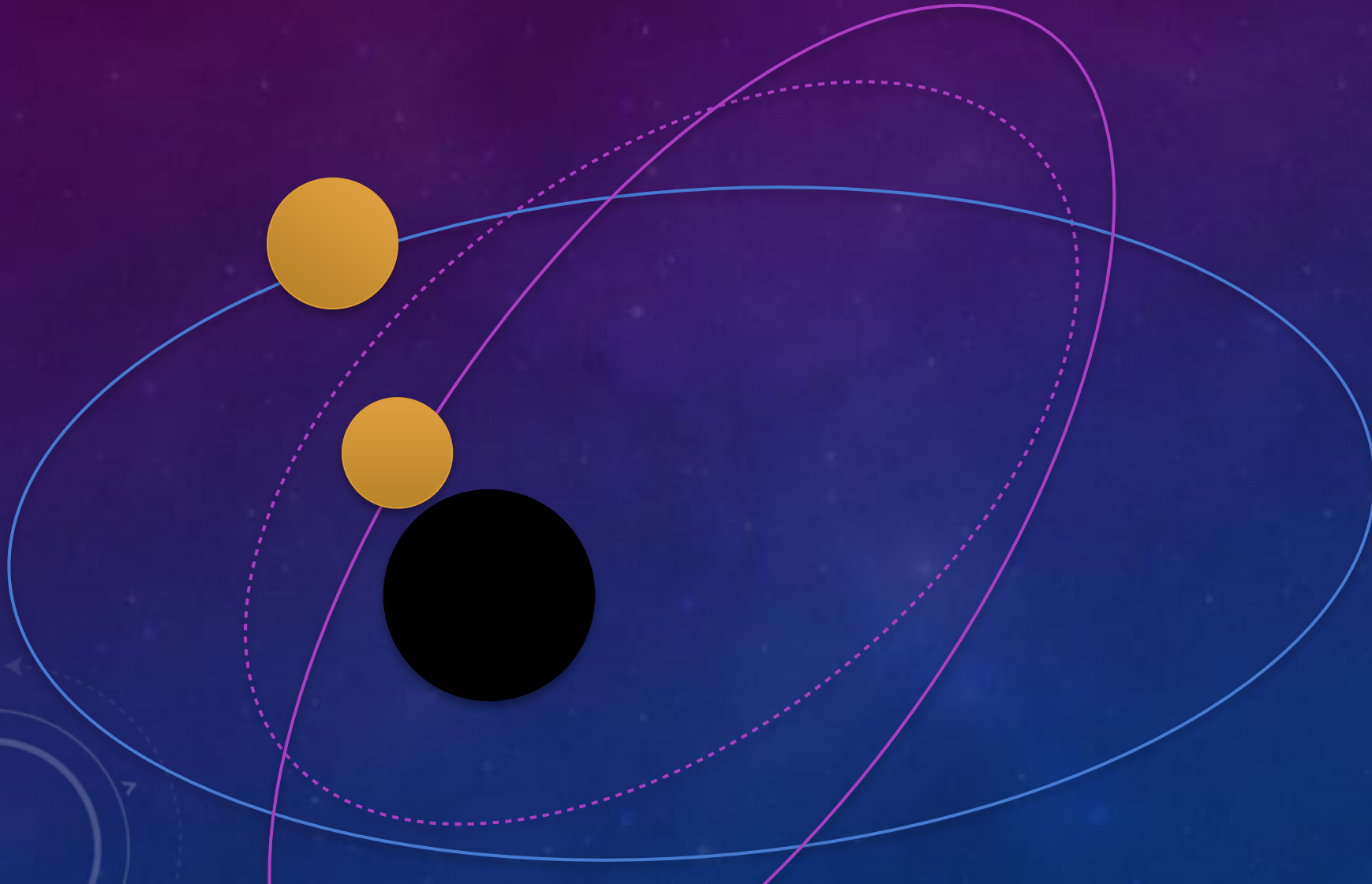
N-BODY INTERACTIONS



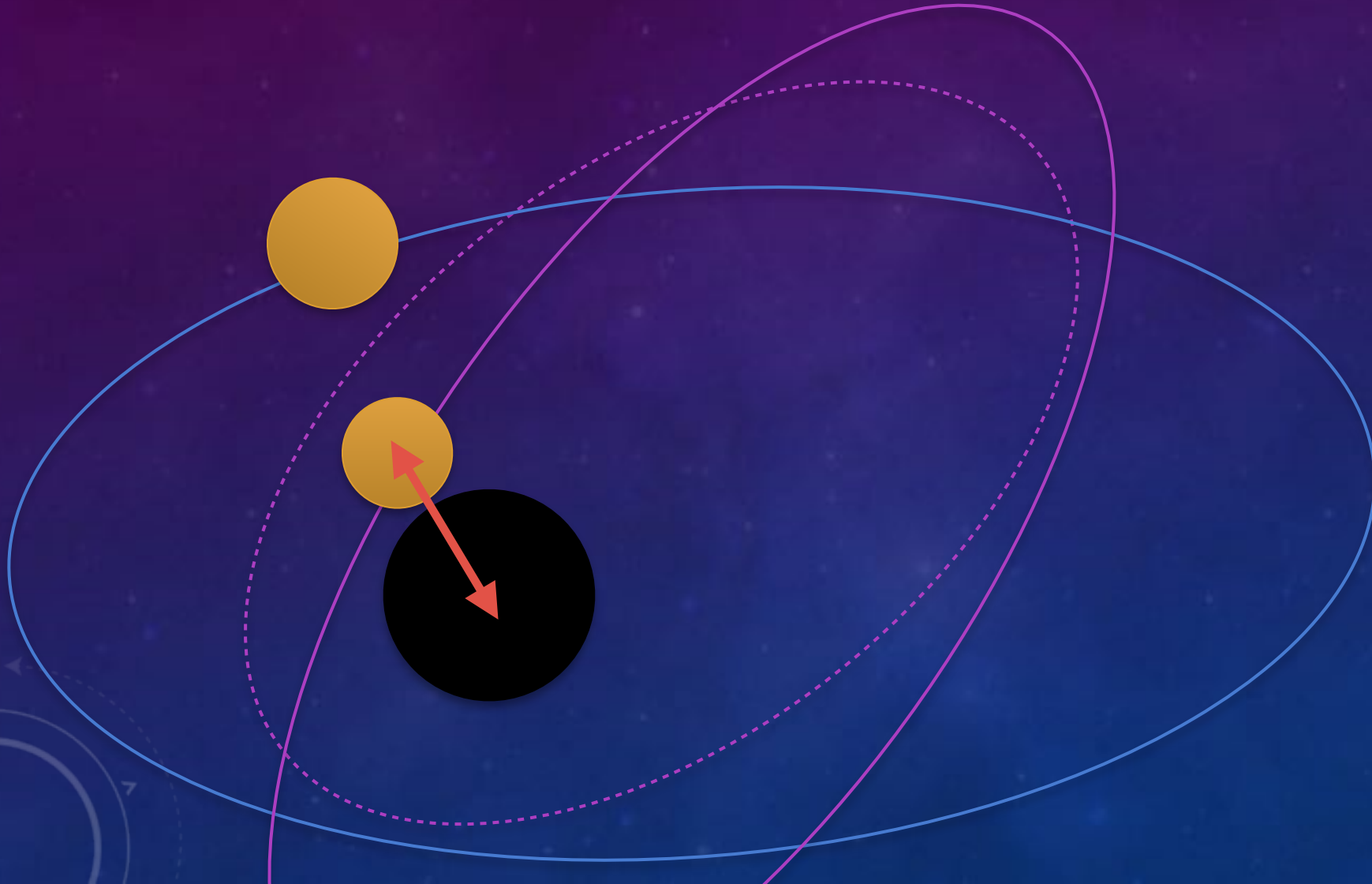
N-BODY INTERACTIONS



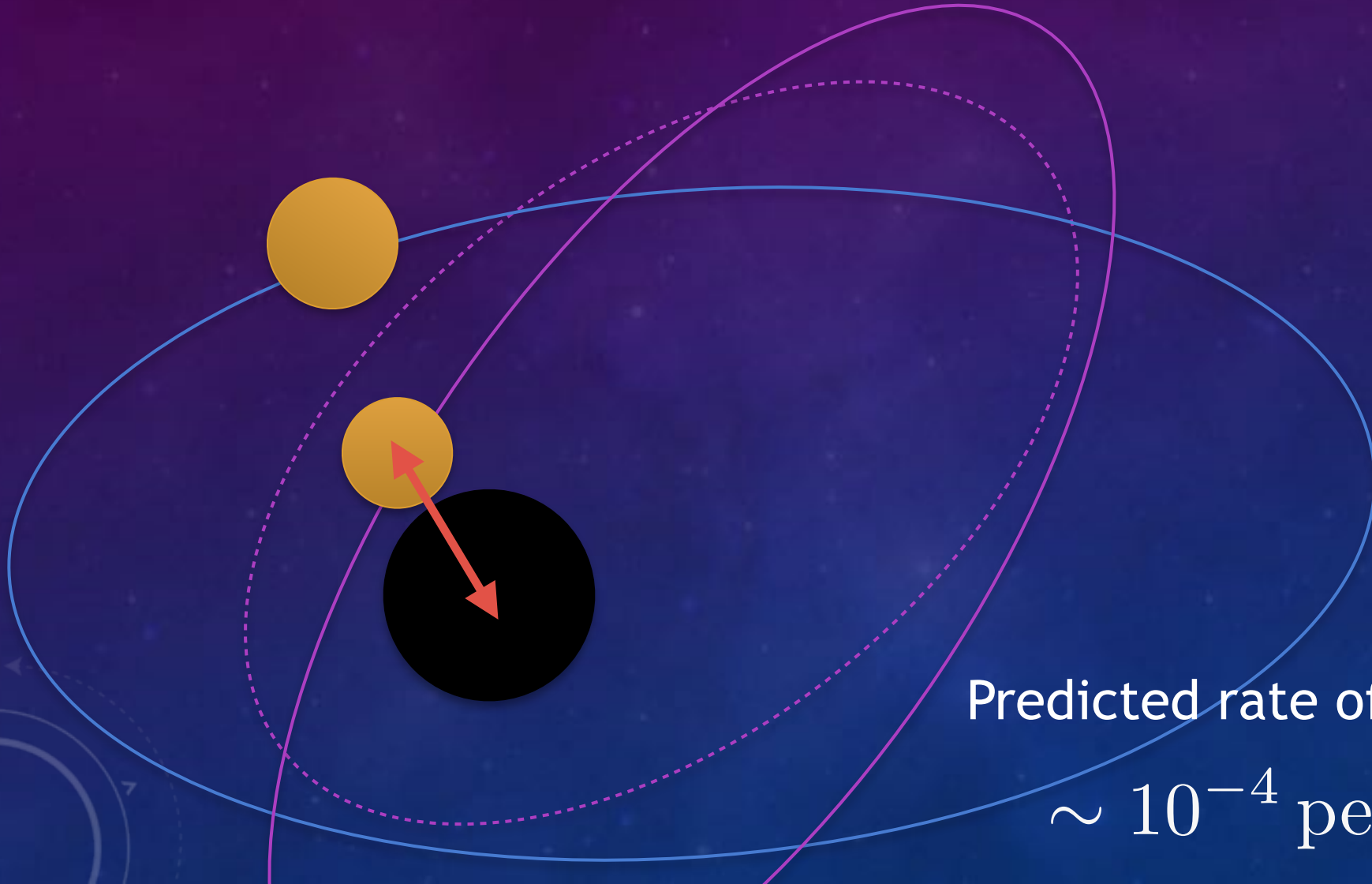
N-BODY INTERACTIONS



N-BODY INTERACTIONS



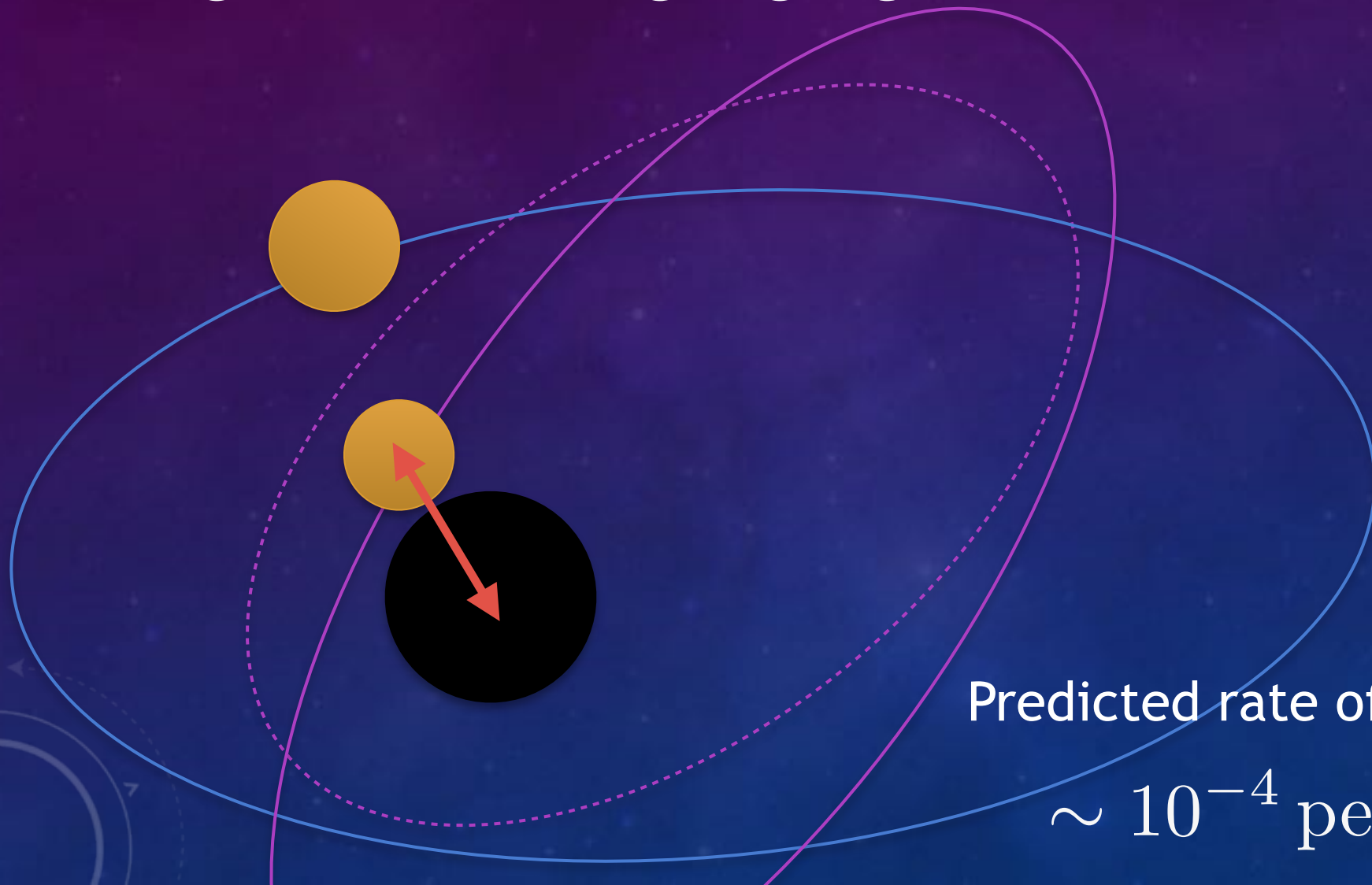
N-BODY INTERACTIONS



Predicted rate of close encounters:

$\sim 10^{-4}$ per galaxy per year

N-BODY INTERACTIONS



Oxford!

Predicted rate of close encounters:

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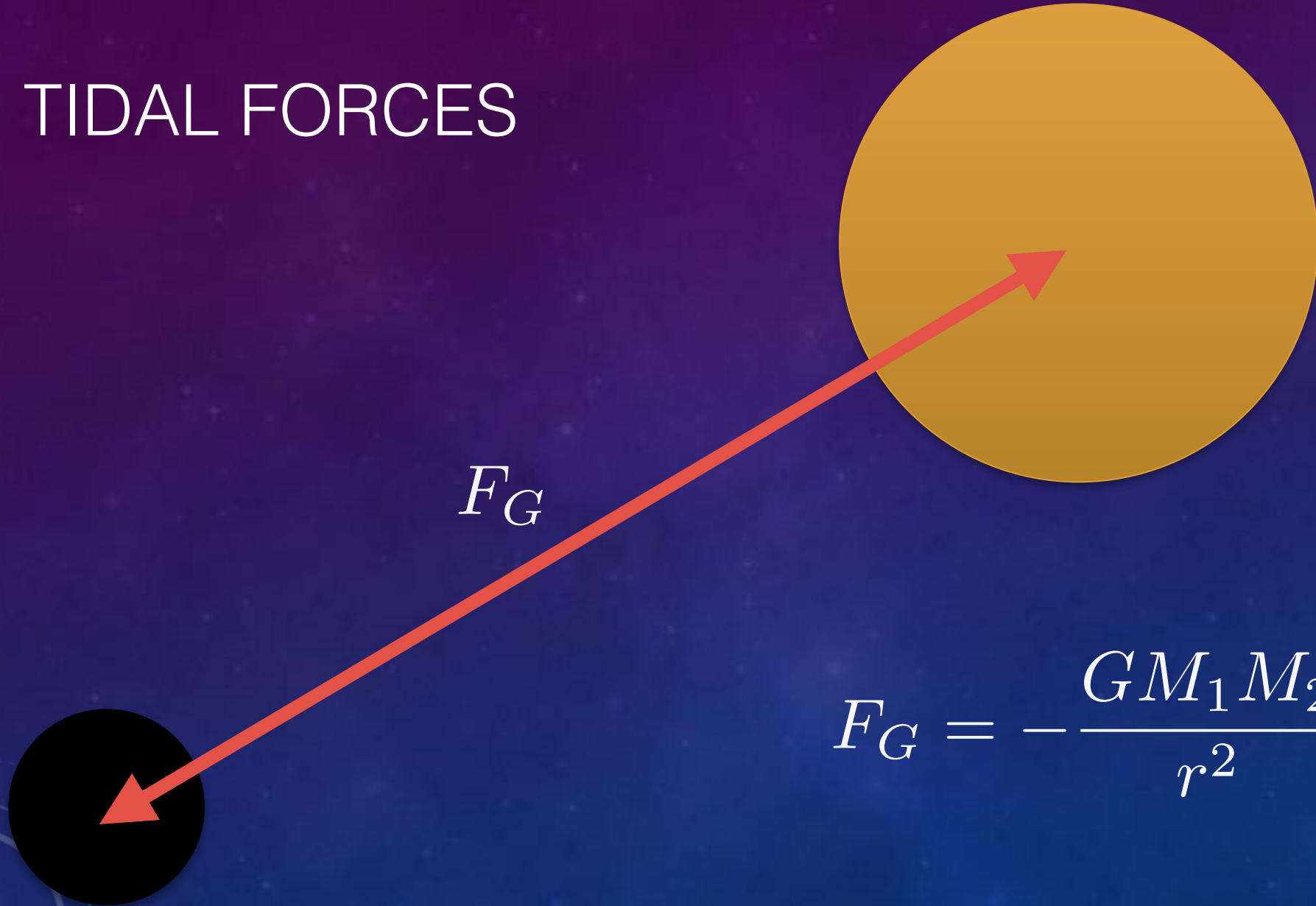
TIDAL FORCES



TIDAL FORCES

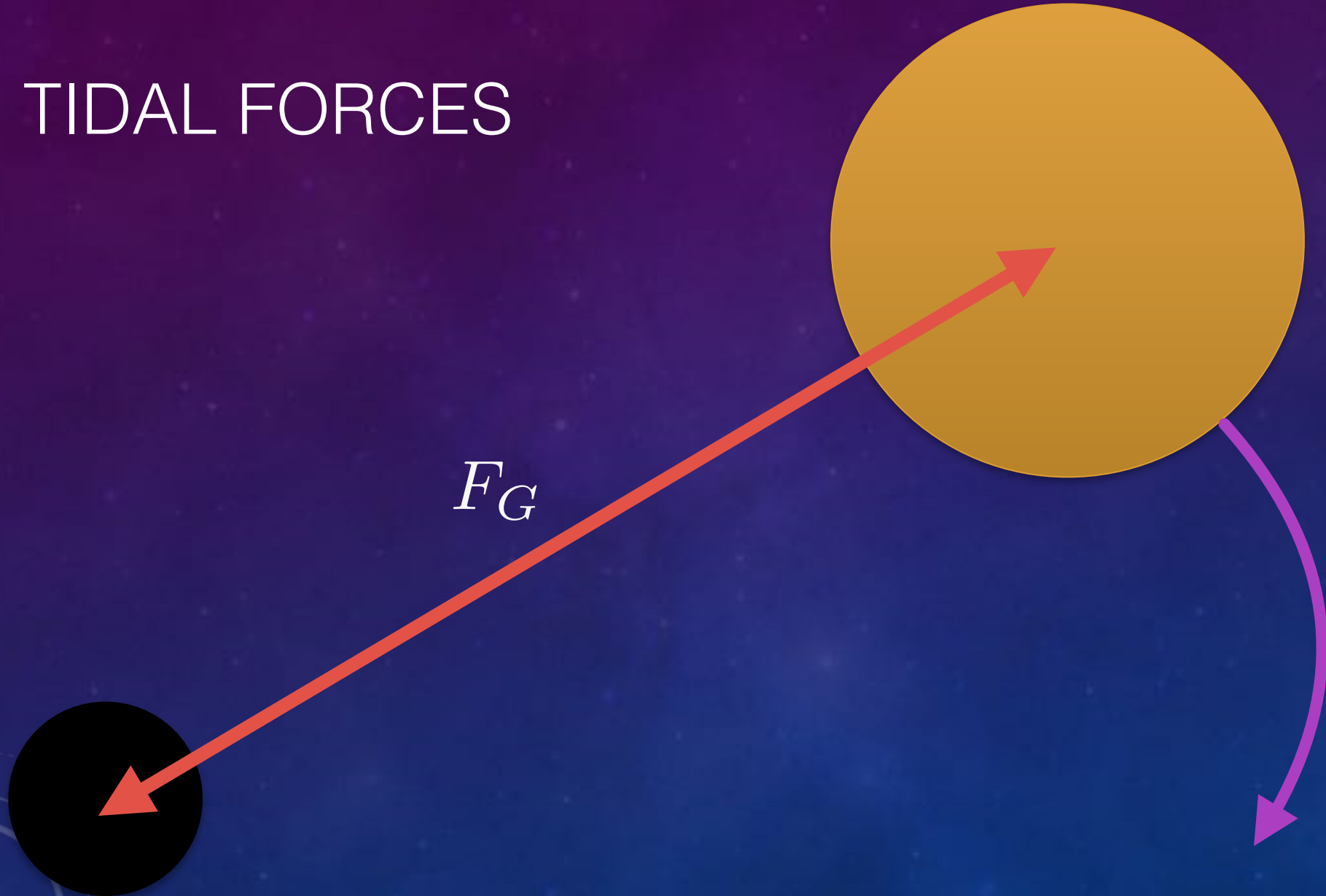


TIDAL FORCES

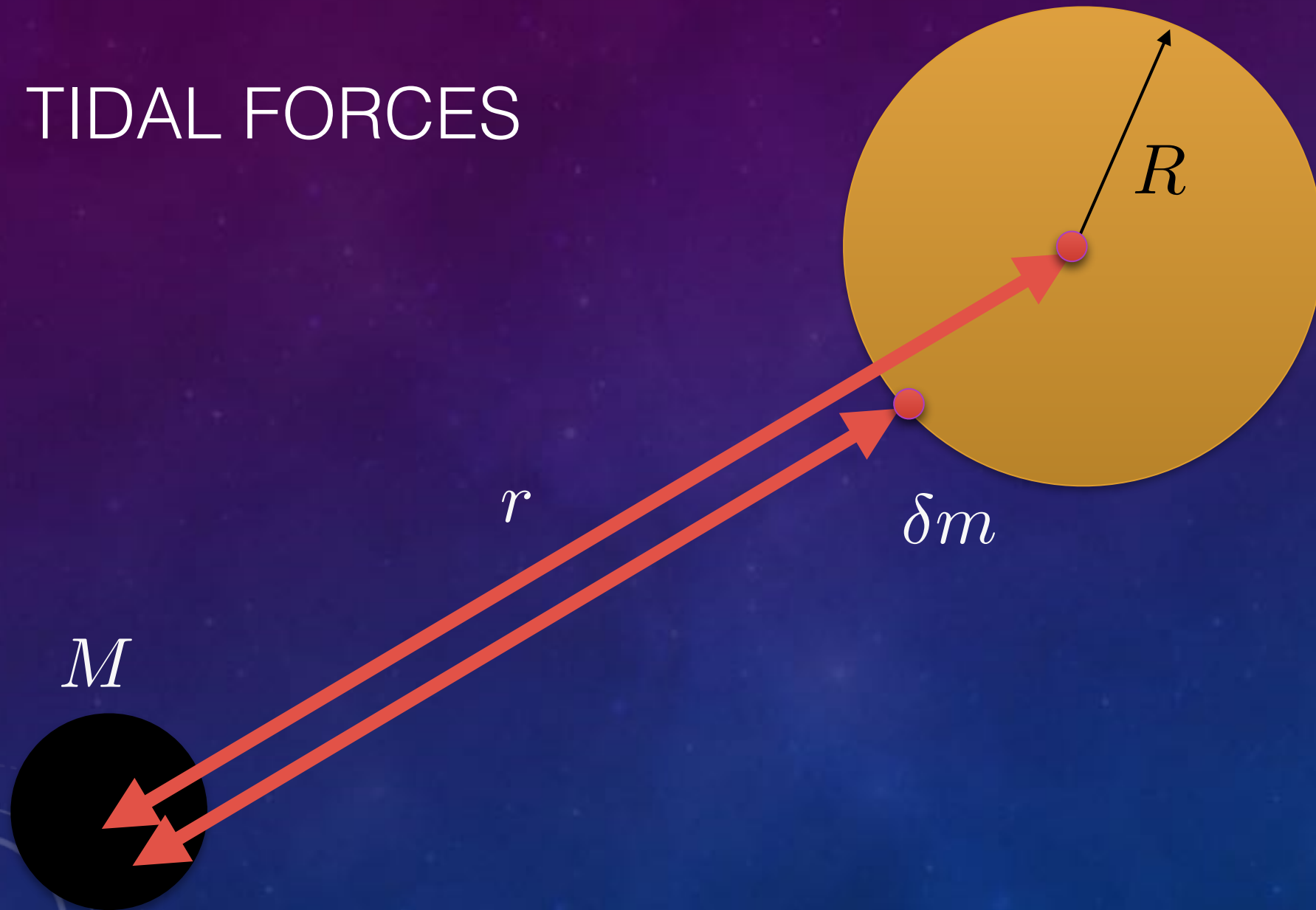


$$F_G = -\frac{GM_1M_2}{r^2}$$

TIDAL FORCES

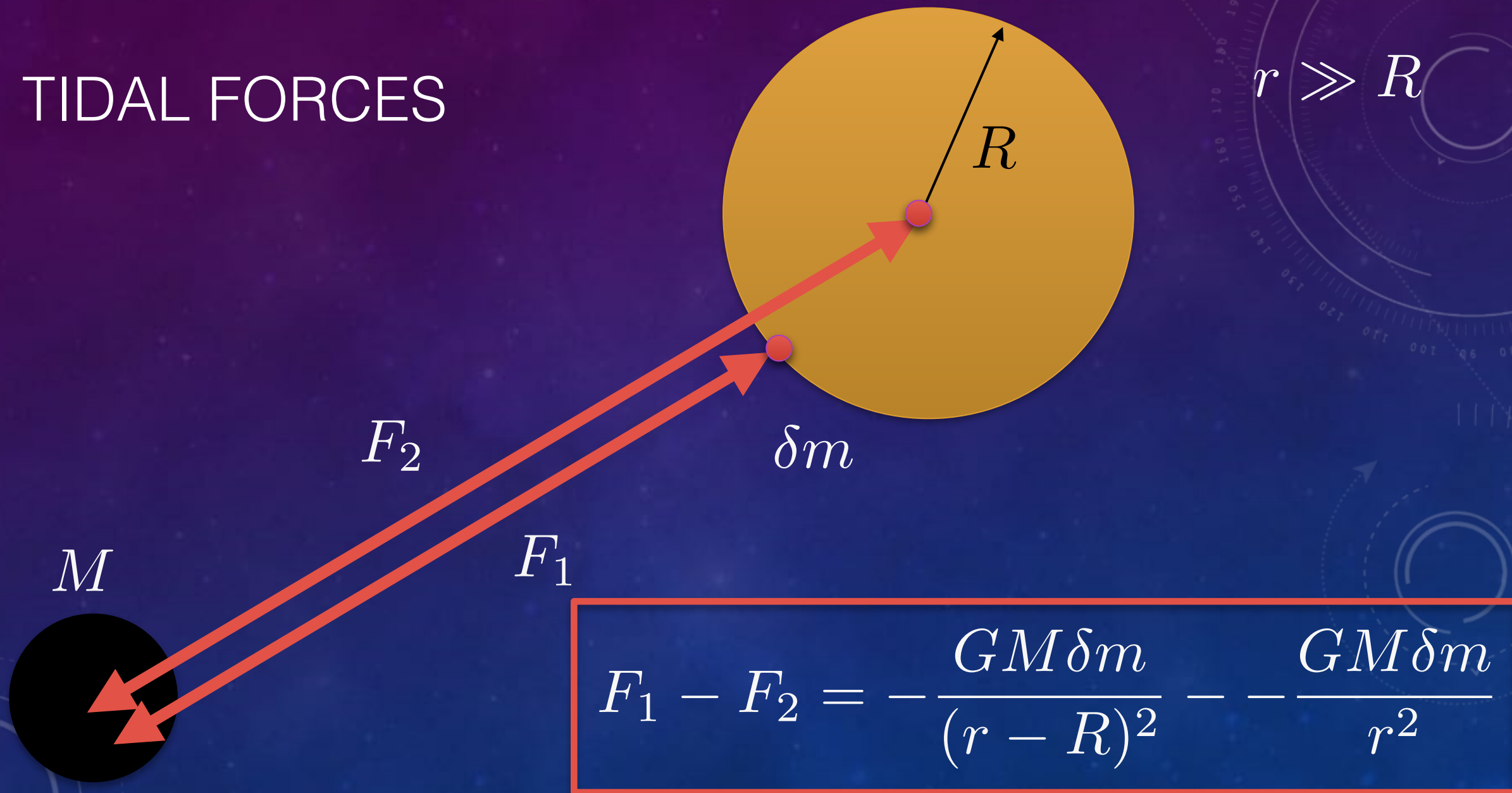


TIDAL FORCES



$$r \gg R$$

TIDAL FORCES



TIDAL FORCES

$r \gg R$

$$F_1 - F_2 = -\frac{GM\delta m}{r^2} \left(1 - \frac{R}{r}\right)^{-2} \approx -\frac{GM\delta m}{r^2}$$

TIDAL FORCES

$r \gg R$

$$F_1 - F_2 = -\frac{GM\delta m}{r^2} \left(1 - \frac{R}{r}\right)^{-2} - -\frac{GM\delta m}{r^2}$$

$$F_1 - F_2 \approx -\frac{GM\delta m}{r^2} \left(1 + 2\frac{R}{r}\right) - -\frac{GM\delta m}{r^2}$$

TIDAL FORCES

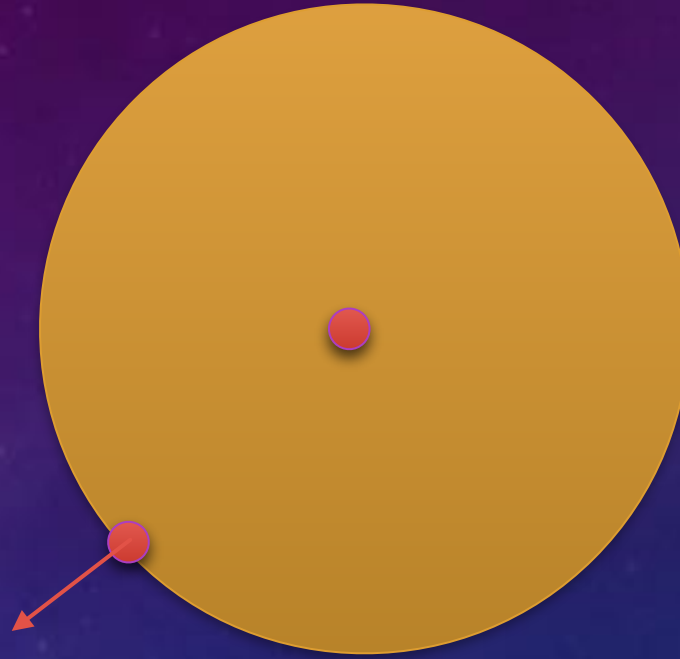
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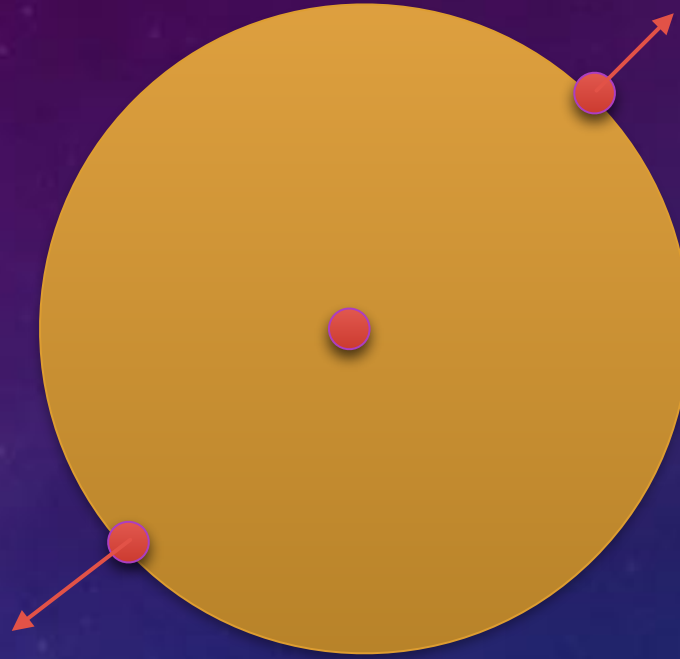
$$F_1 - F_2 \approx -\frac{GM\delta m}{r^2} \left(1 + 2\frac{R}{r}\right) - -\frac{GM\delta m}{r^2}$$

$$F_1 - F_2 \approx -\frac{2GM\delta m R}{r^3}$$

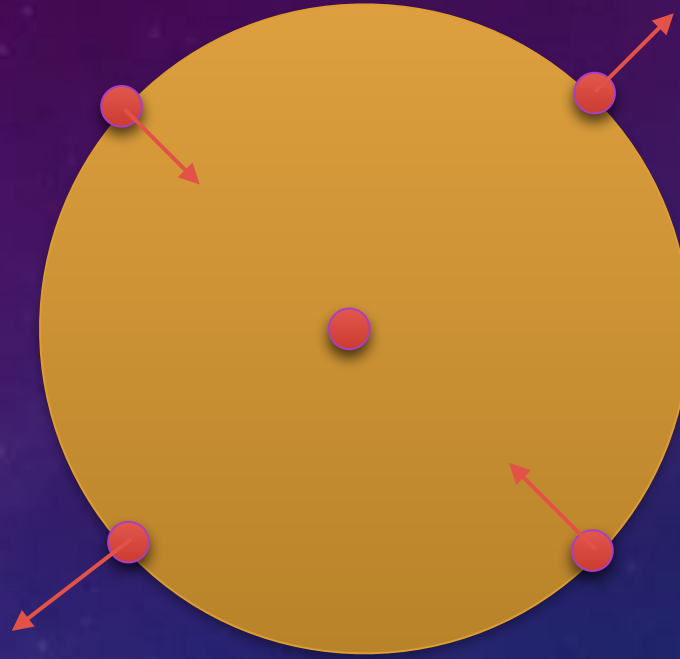
TIDAL FORCES



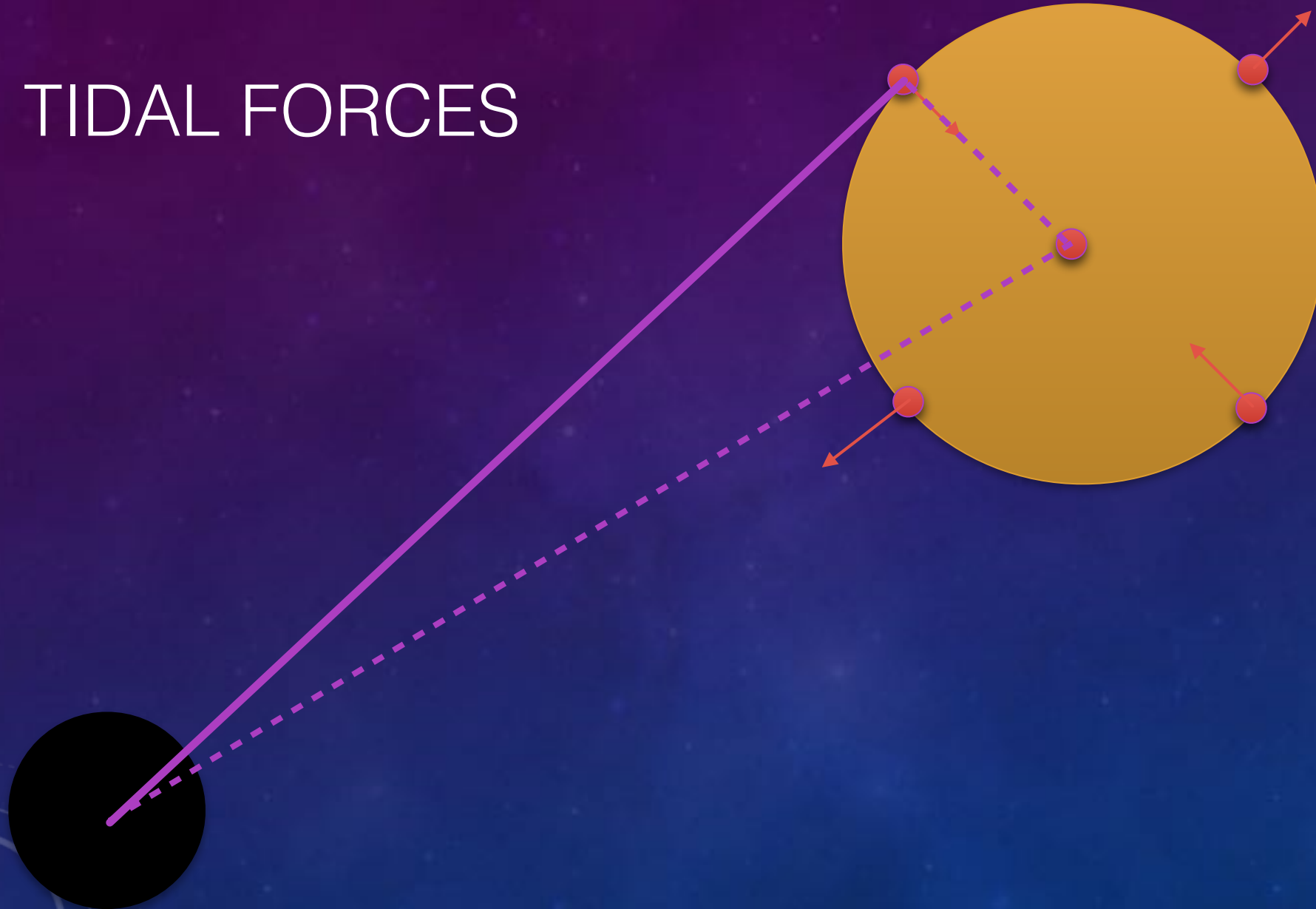
TIDAL FORCES



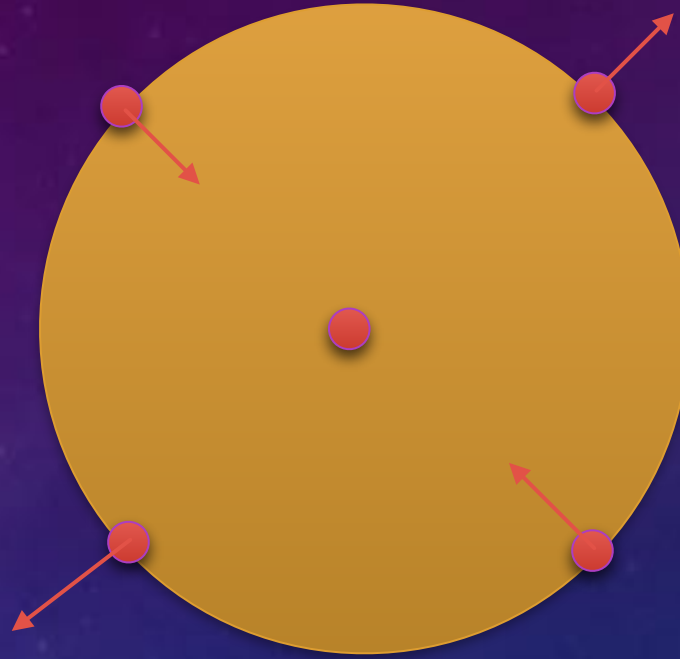
TIDAL FORCES



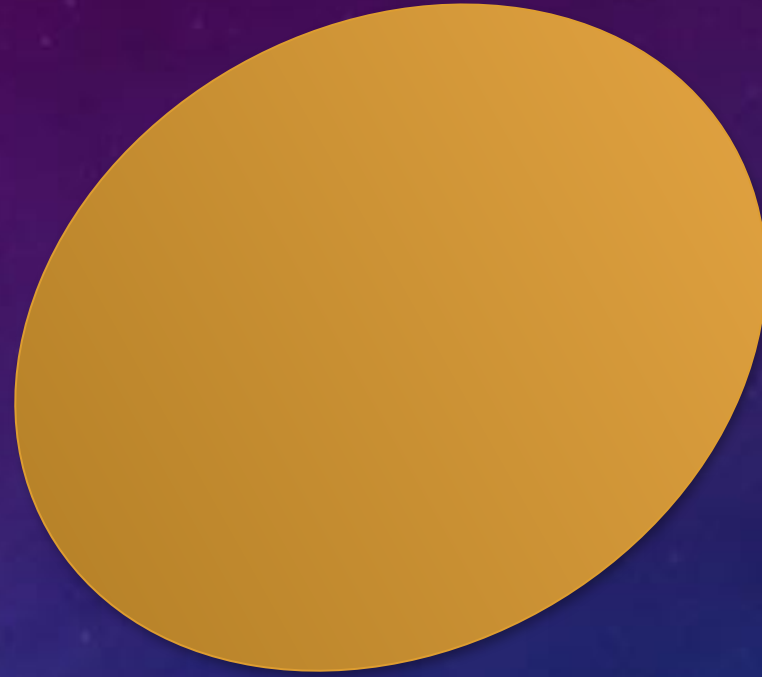
TIDAL FORCES



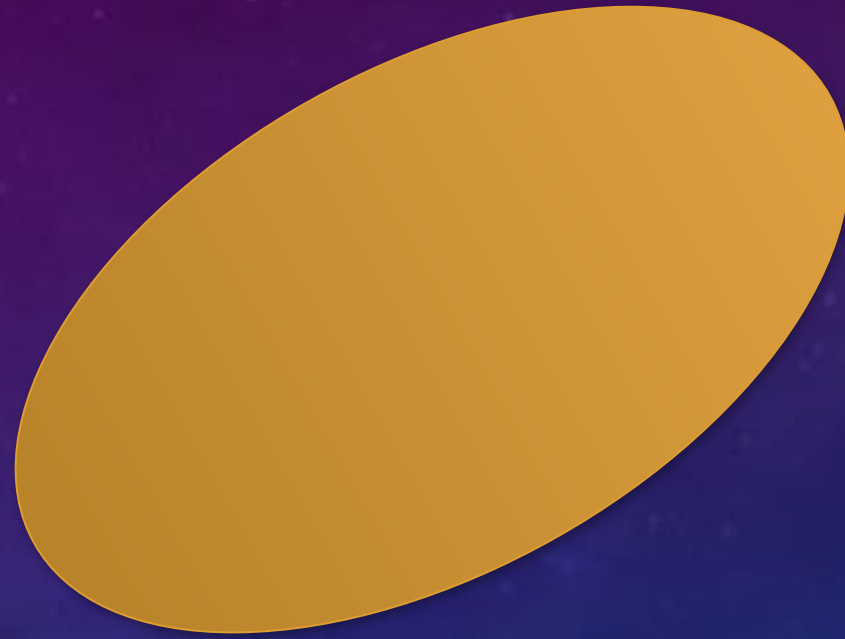
TIDAL FORCES



TIDAL FORCES



TIDAL FORCES



TIDAL FORCES



TIDAL FORCES



TIDAL FORCES



TIDAL FORCES



TIDAL FORCES



For the supermassive black holes in the centre of galaxies, this can completely destroy the star!



TIDAL DISRUPTION

$$F_T \approx \frac{GM_{\text{BH}}M_{\star}R_{\star}}{r^3}$$

TIDAL DISRUPTION

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TIDAL DISRUPTION

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$$F_{\text{self}} = F_T \rightarrow r_T \approx R_{\star} \left(\frac{M_{\text{BH}}}{M_{\star}} \right)^{1/3} \simeq 70 \times 10^6 \text{ km}$$

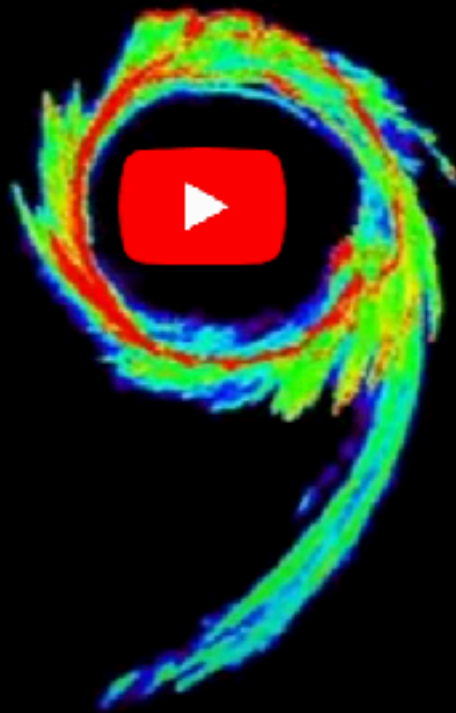
(For the sun about our SMBH)

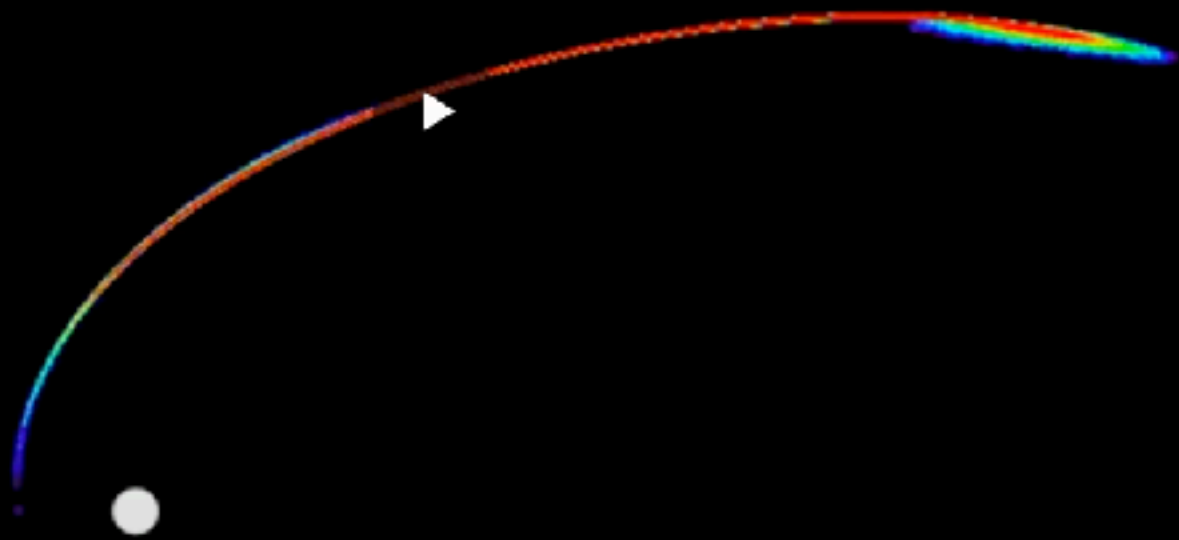
TIDAL DISRUPTION

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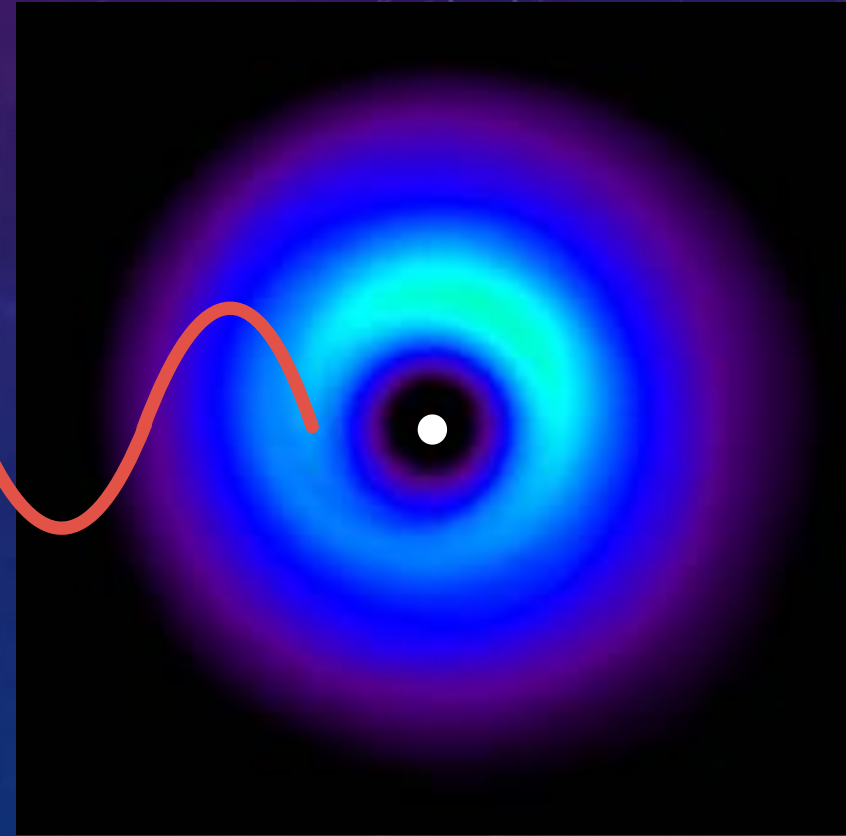
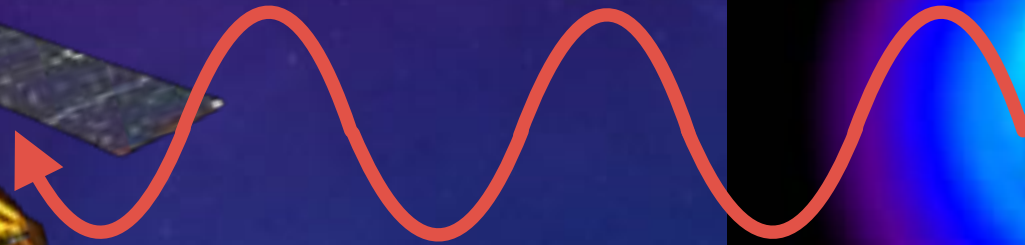
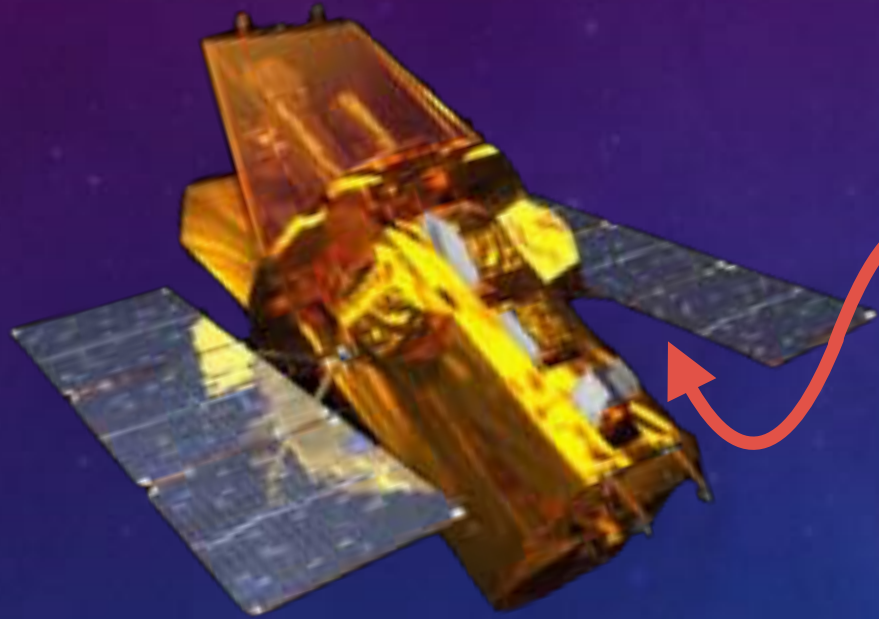
$$R_{\text{BH}} = \frac{2GM_{\text{BH}}}{c^2} \simeq 3 \times 10^6 \text{ km}$$

(For the sun about our SMBH)



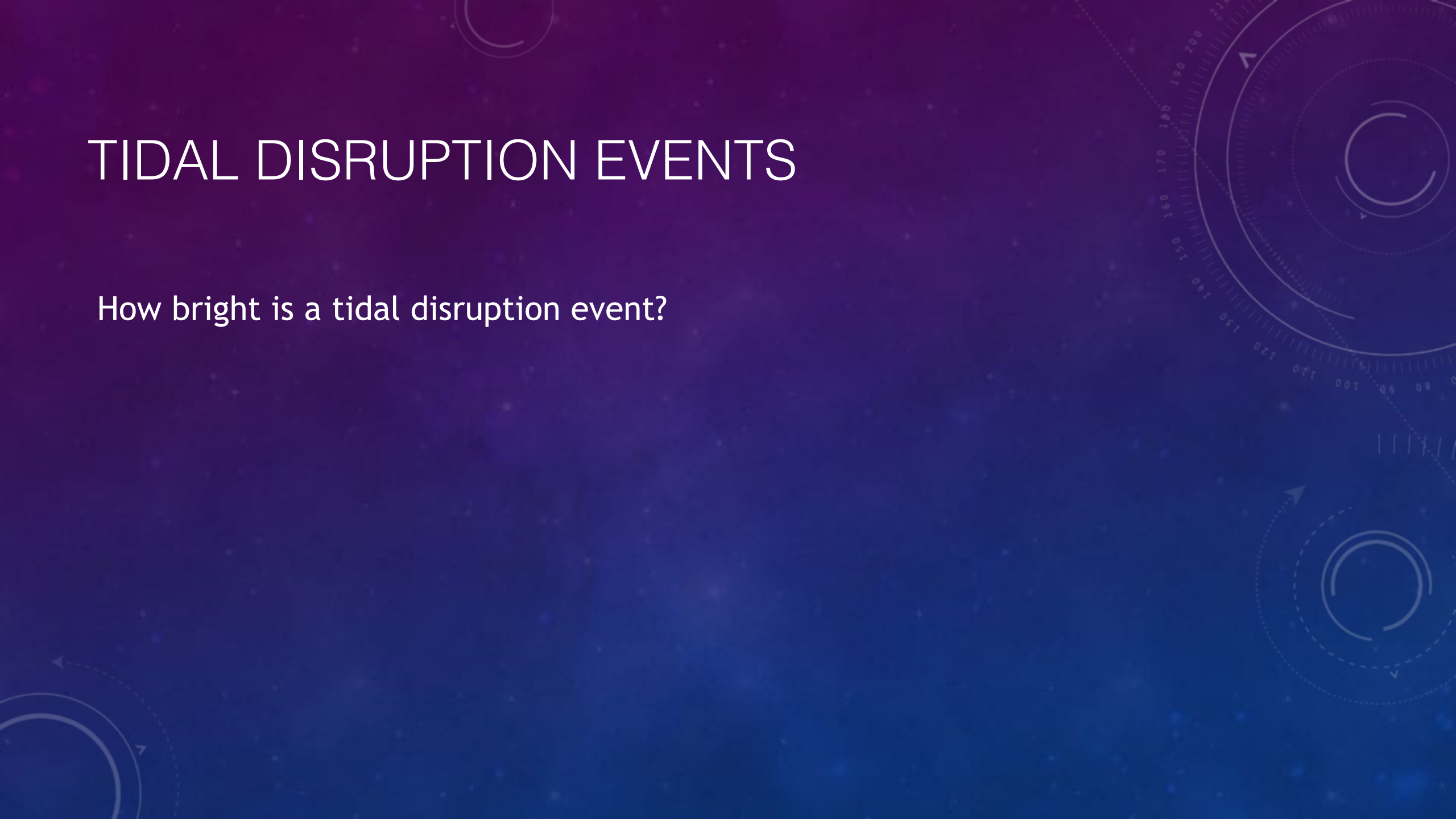


TIDAL DISRUPTION EVENTS



TIDAL DISRUPTION EVENTS

How bright is a tidal disruption event?



TIDAL DISRUPTION EVENTS

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$$L_{\star} \sim \frac{\epsilon_{\text{nuc}} M_{\star} c^2}{t_{\star}}$$

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$$L_{\star} \sim \frac{\epsilon_{\text{nuc}} M_{\star} c^2}{t_{\star}}$$

$$L_{\text{TDE}} \sim \frac{\epsilon_{\text{acc}} M_{\star} c^2}{t_{\text{TDE}}}$$

TIDAL DISRUPTION EVENTS

How bright is a tidal disruption event?

$$L_{\star} \sim \frac{\epsilon_{\text{nuc}} M_{\star} c^2}{t_{\star}} \quad L_{\text{TDE}} \sim \frac{\epsilon_{\text{acc}} M_{\star} c^2}{t_{\text{TDE}}}$$

$$L_{\text{TDE}} \sim L_{\star} \left(\frac{t_{\star}}{t_{\text{TDE}}} \right)$$

TIDAL DISRUPTION EVENTS

How bright is a tidal disruption event?

$$L_{\star} \sim \frac{\epsilon_{\text{nuc}} M_{\star} c^2}{t_{\star}} \quad L_{\text{TDE}} \sim \frac{\epsilon_{\text{acc}} M_{\star} c^2}{t_{\text{TDE}}}$$

$$L_{\text{TDE}} \sim L_{\star} \left(\frac{t_{\star}}{t_{\text{TDE}}} \right) \sim 10^{10} L_{\star}$$

TIDAL DISRUPTION EVENTS

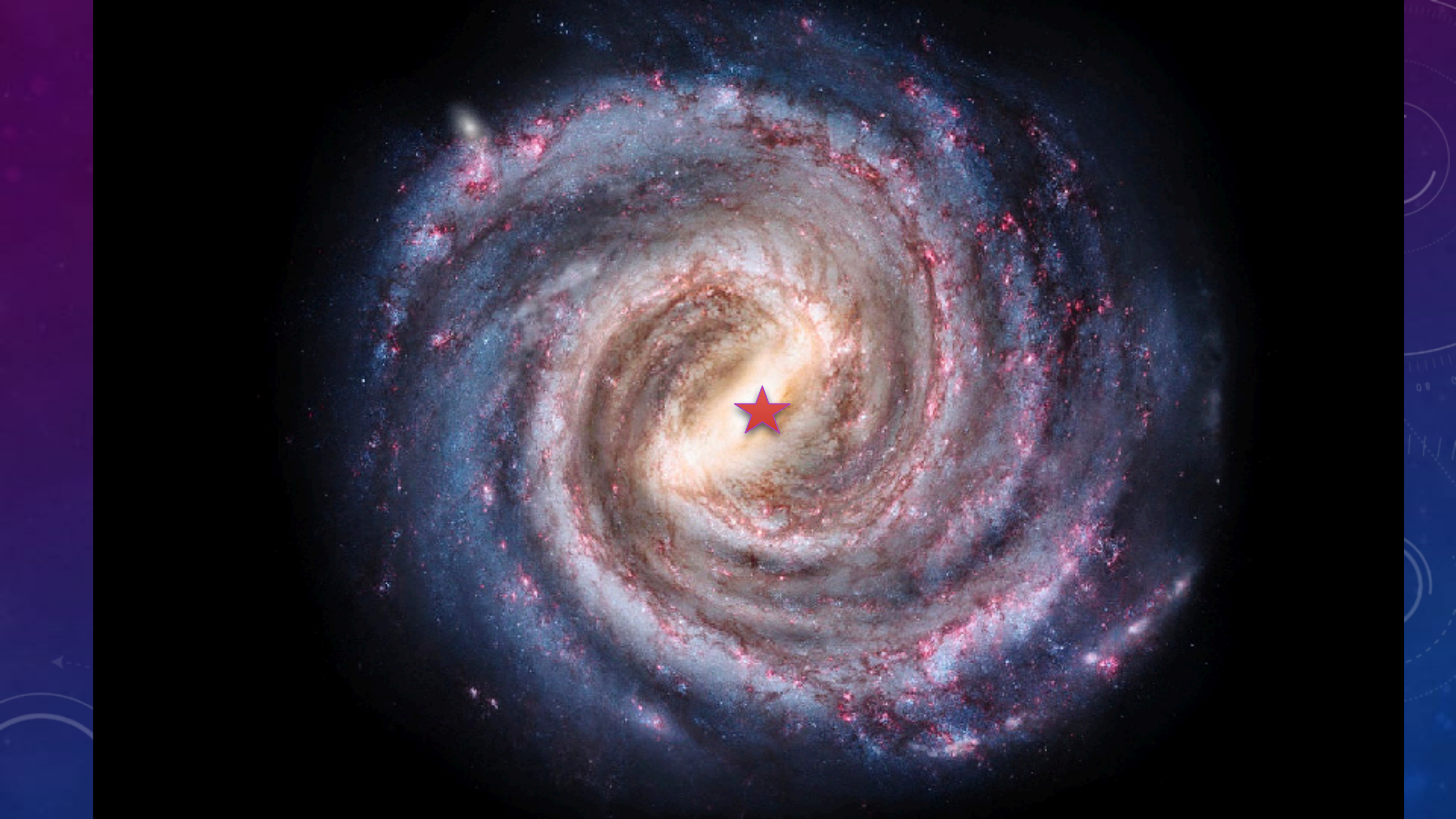
How bright is a tidal disruption event?

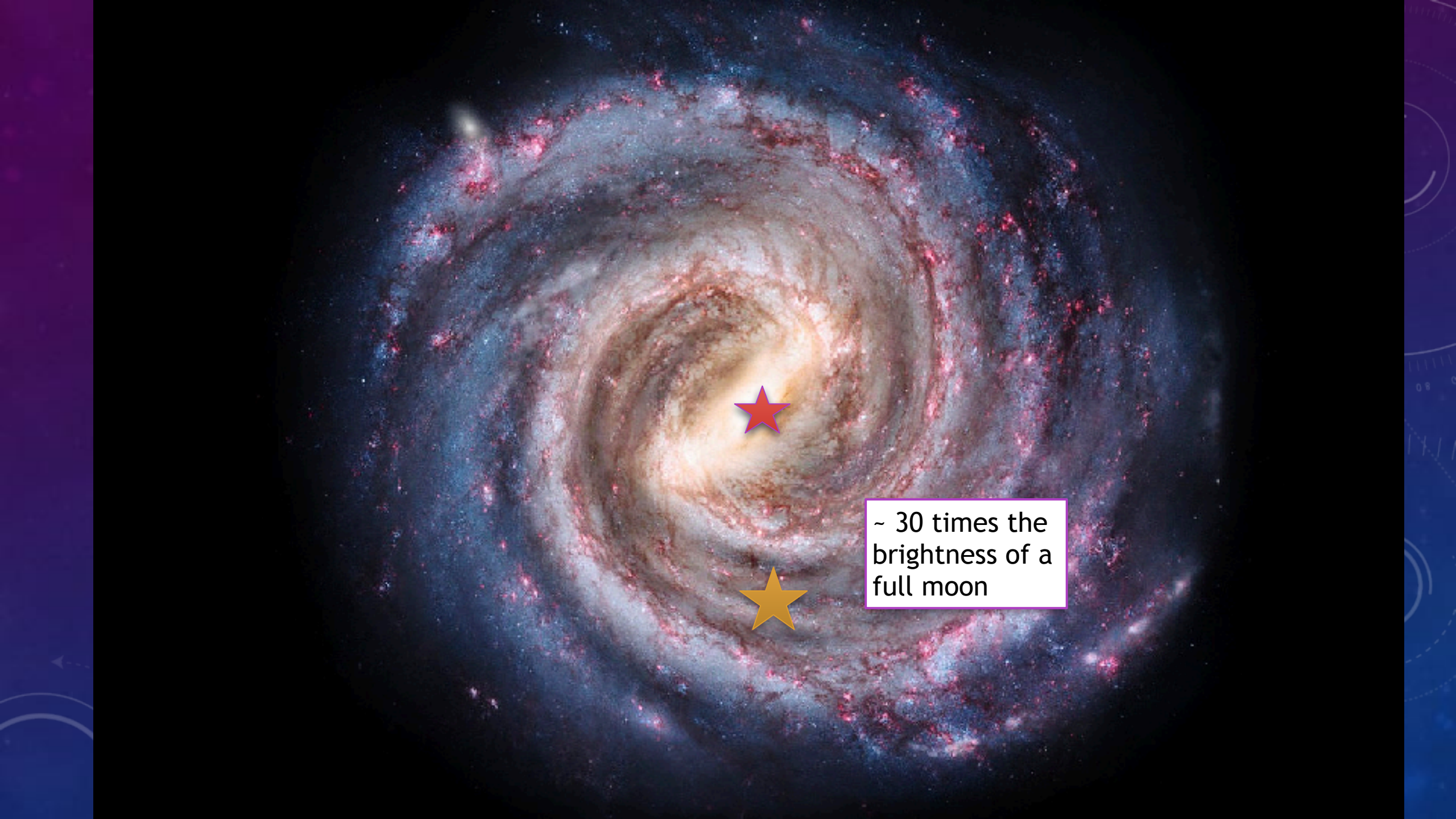
$$L_{\text{TDE}} \sim L_{\star} \left(\frac{t_{\star}}{t_{\text{TDE}}} \right) \sim 10^{10} L_{\star}$$

Very... the luminosity of the entire milky way is

$$L_{\text{MW}} \sim 10^{10} L_{\odot}$$



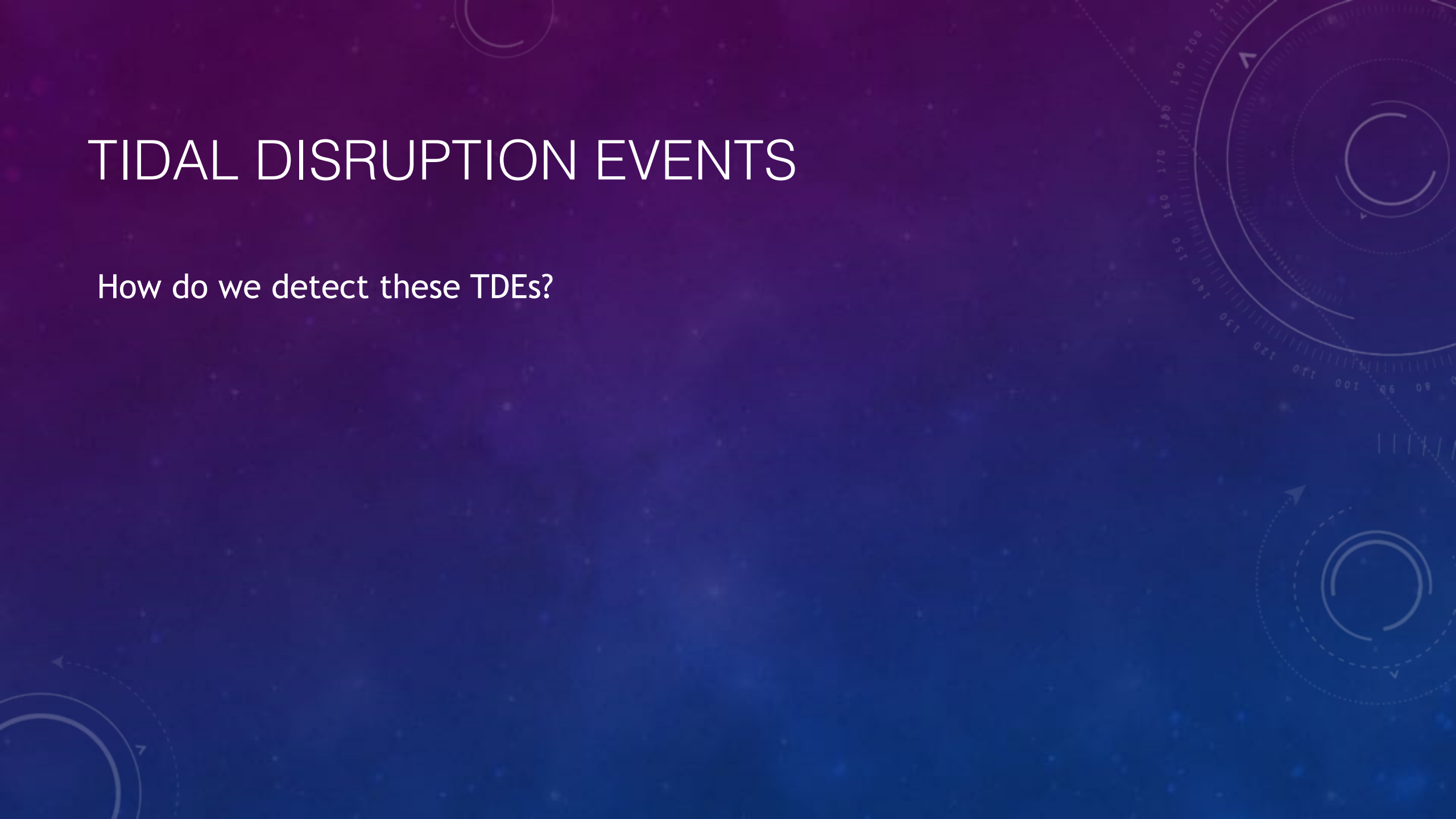




~ 30 times the
brightness of a
full moon

TIDAL DISRUPTION EVENTS

How do we detect these TDEs?



TIDAL DISRUPTION EVENTS

How do we detect these TDEs? Sit, watch the whole sky, and wait.

TIDAL DISRUPTION EVENTS

How do we detect these TDEs? Sit, watch the whole sky, and wait.

The logo for the ASAS-SN project, featuring the text "ASAS-SN" in a bold, white, sans-serif font. The text is centered on a black rectangular background. A bright, multi-pointed starburst effect is positioned behind the hyphen, creating a glowing point of light that extends across the background.

ASAS-SN

TIDAL DISRUPTION EVENTS

How do we detect these TDEs? Sit, watch the whole sky, and wait.

All Sky Automated Search for SuperNovae

The logo for the All Sky Automated Search for SuperNovae (ASAS-SN) project. It features the text "ASAS-SN" in a bold, white, sans-serif font. The "S" in "SN" is significantly larger and more prominent than the other letters. A bright, multi-pointed starburst or lens flare effect is centered behind the "S" in "SN", creating a glowing point of light with radiating lines. The background of the logo area is black, which makes the white text and starburst stand out sharply.

TIDAL DISRUPTION EVENTS

All Sky Automated Search for SuperNovae



ASAS SN

TIDAL DISRUPTION EVENTS

The All Sky Automated Search for SuperNovae find their first objects in the early 2010's

TIDAL DISRUPTION EVENTS

The All Sky Automated Search for SuperNovae find their first objects in the early 2010's

About ~thirty now confirmed to exist

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Two we will talk about today: ASASSN-14li and ASASSN-15lh

TIDAL DISRUPTION EVENTS

The All Sky Automated Search for SuperNovae find their first objects in the early 2010's

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Discovered by ASASSN

TIDAL DISRUPTION EVENTS

The All Sky Automated Search for SuperNovae find their first objects in the early 2010's

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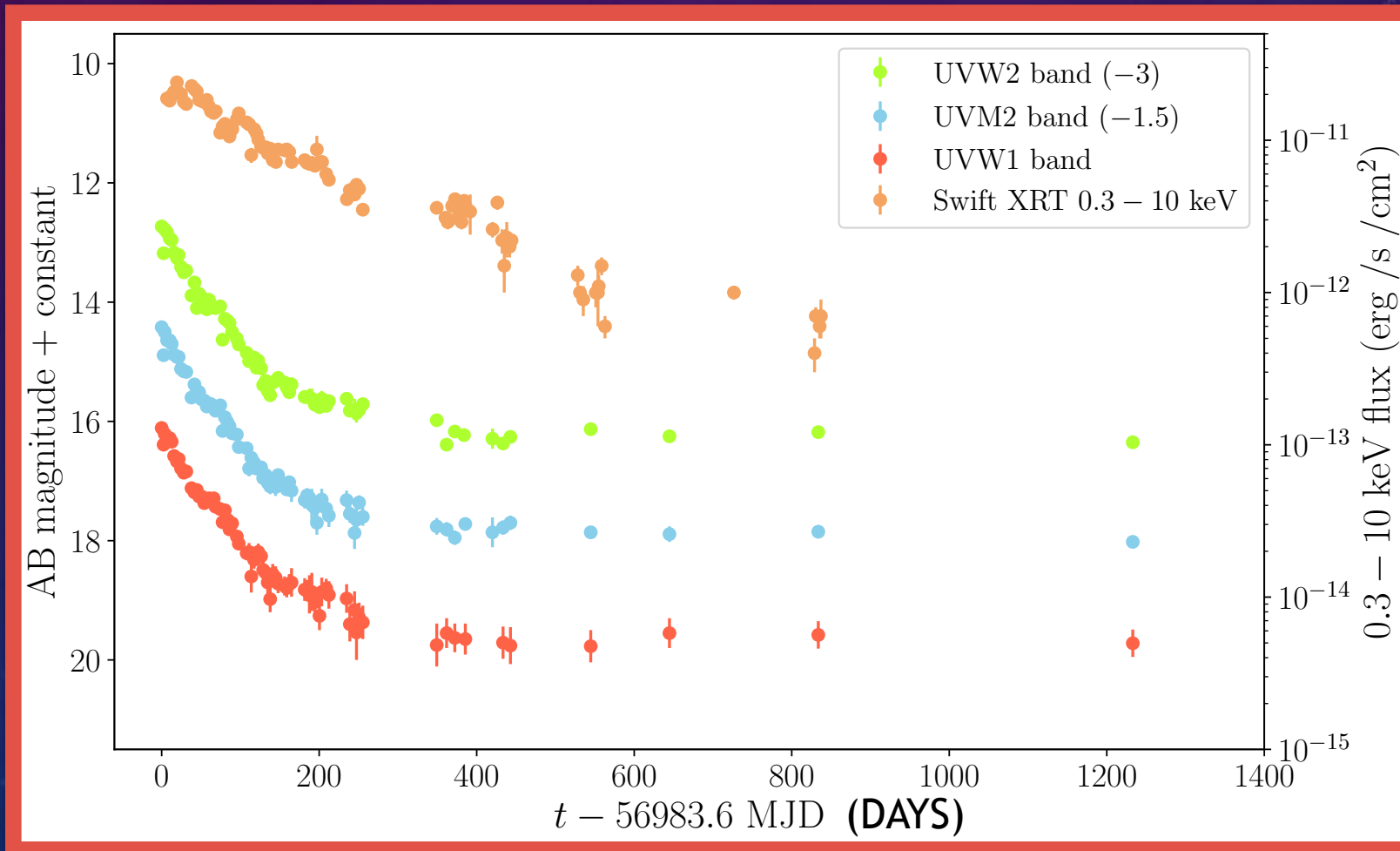
Two we will talk about today: ASASSN-14li and ASASSN-15lh

Discovered by ASASSN

The 321st object found in 2014

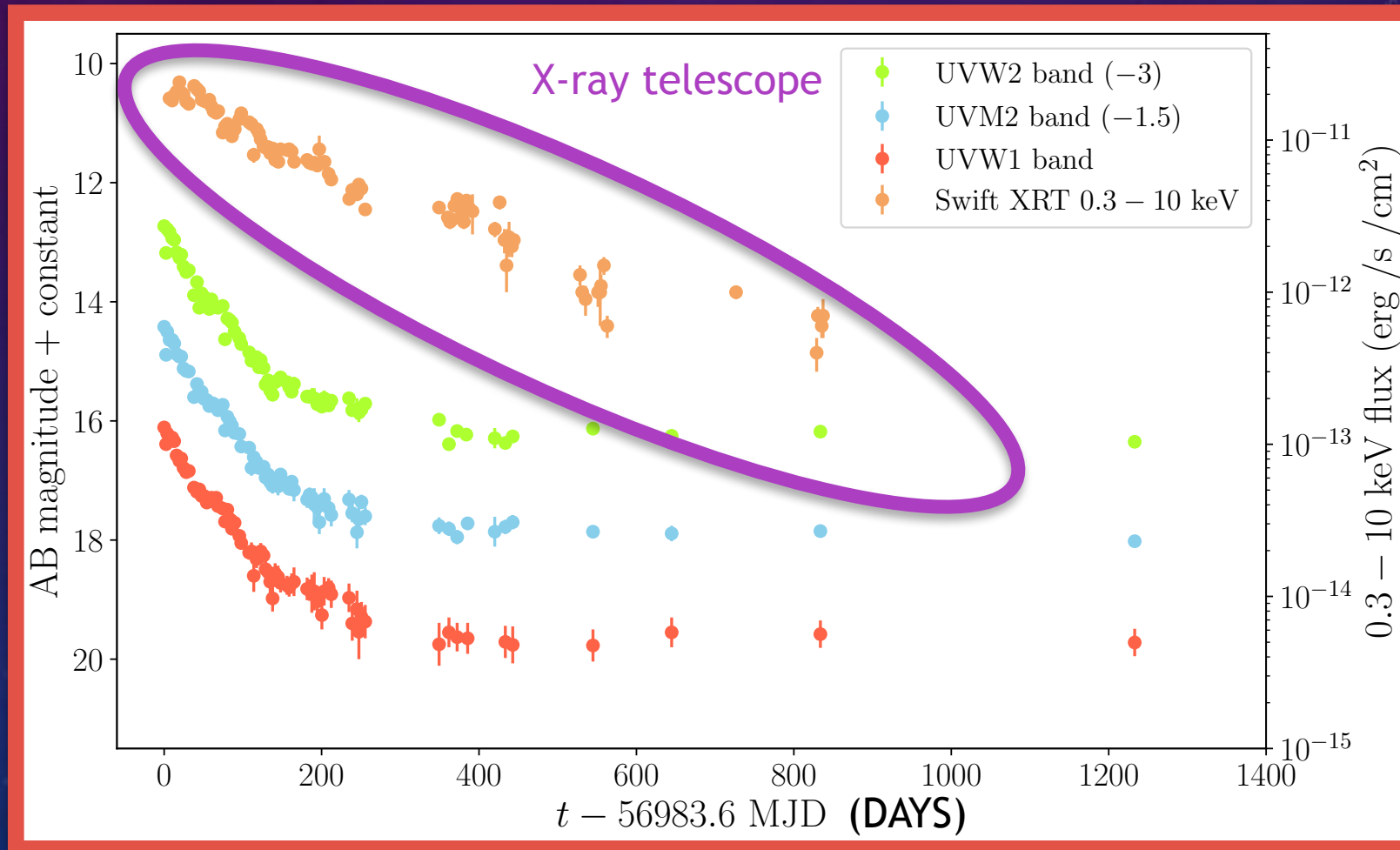
TIDAL DISRUPTION EVENTS

ASASSN-14li



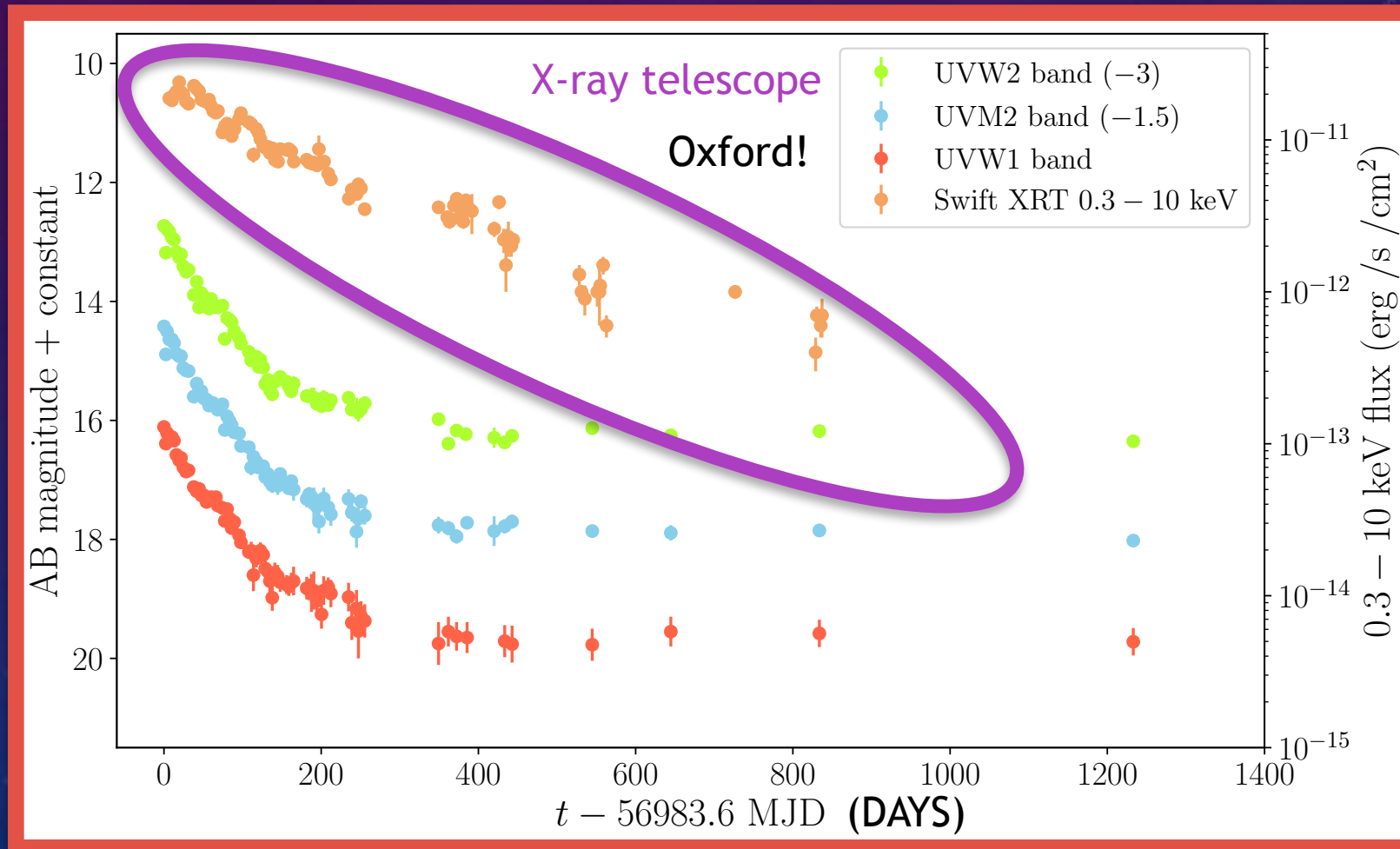
TIDAL DISRUPTION EVENTS

ASASSN-14li



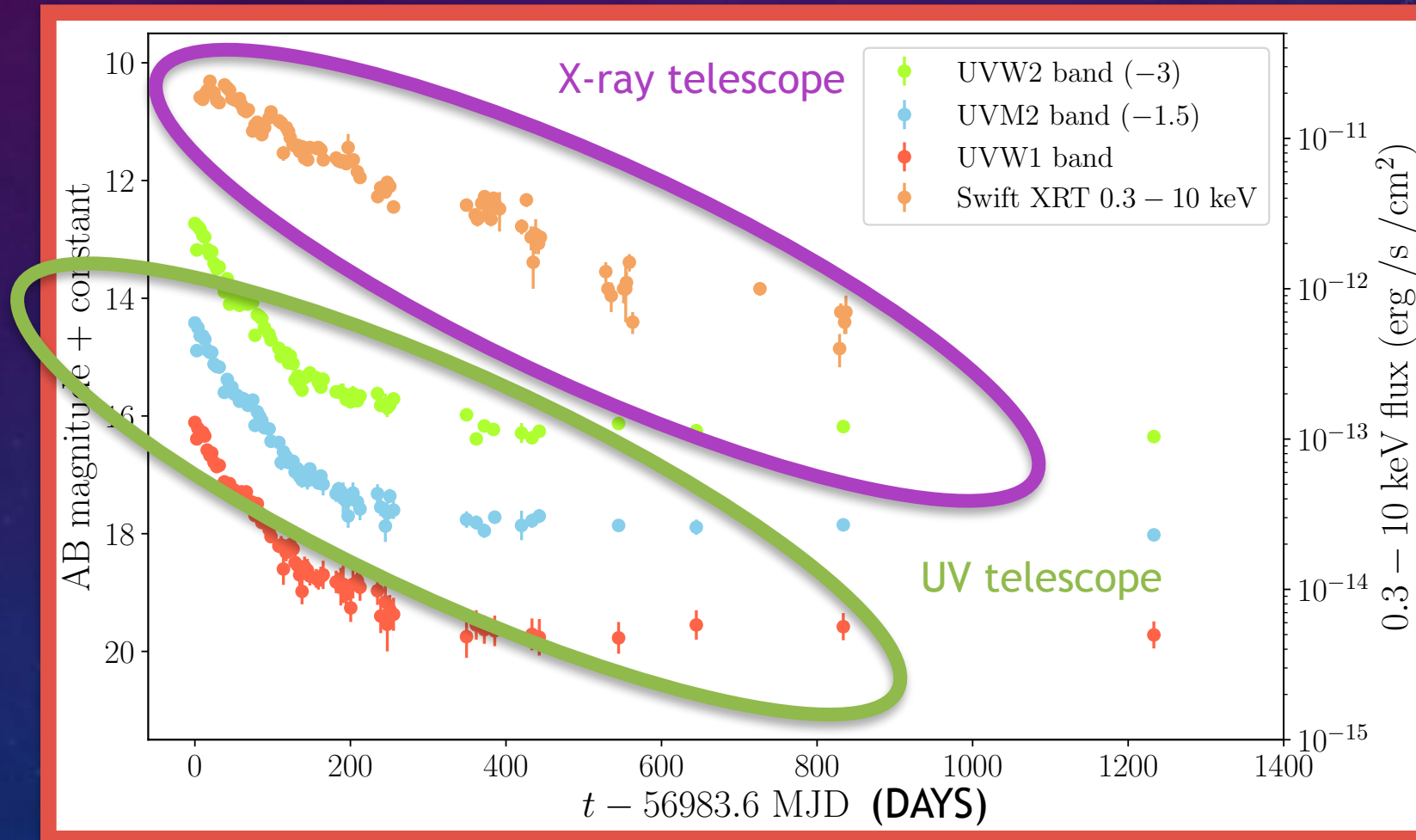
TIDAL DISRUPTION EVENTS

ASASSN-14li



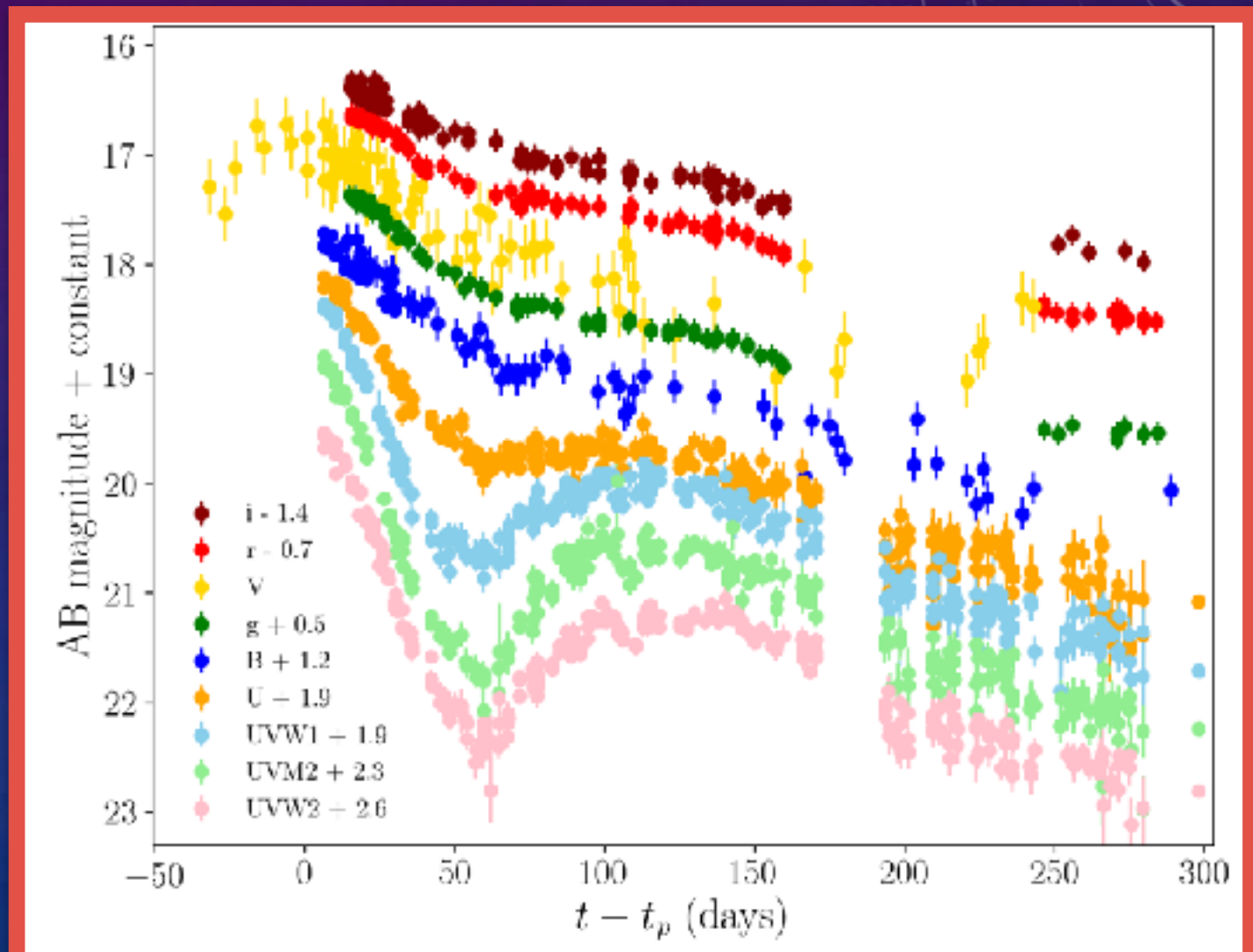
TIDAL DISRUPTION EVENTS

ASASSN-14li



TIDAL DISRUPTION EVENTS

ASASSN-15lh



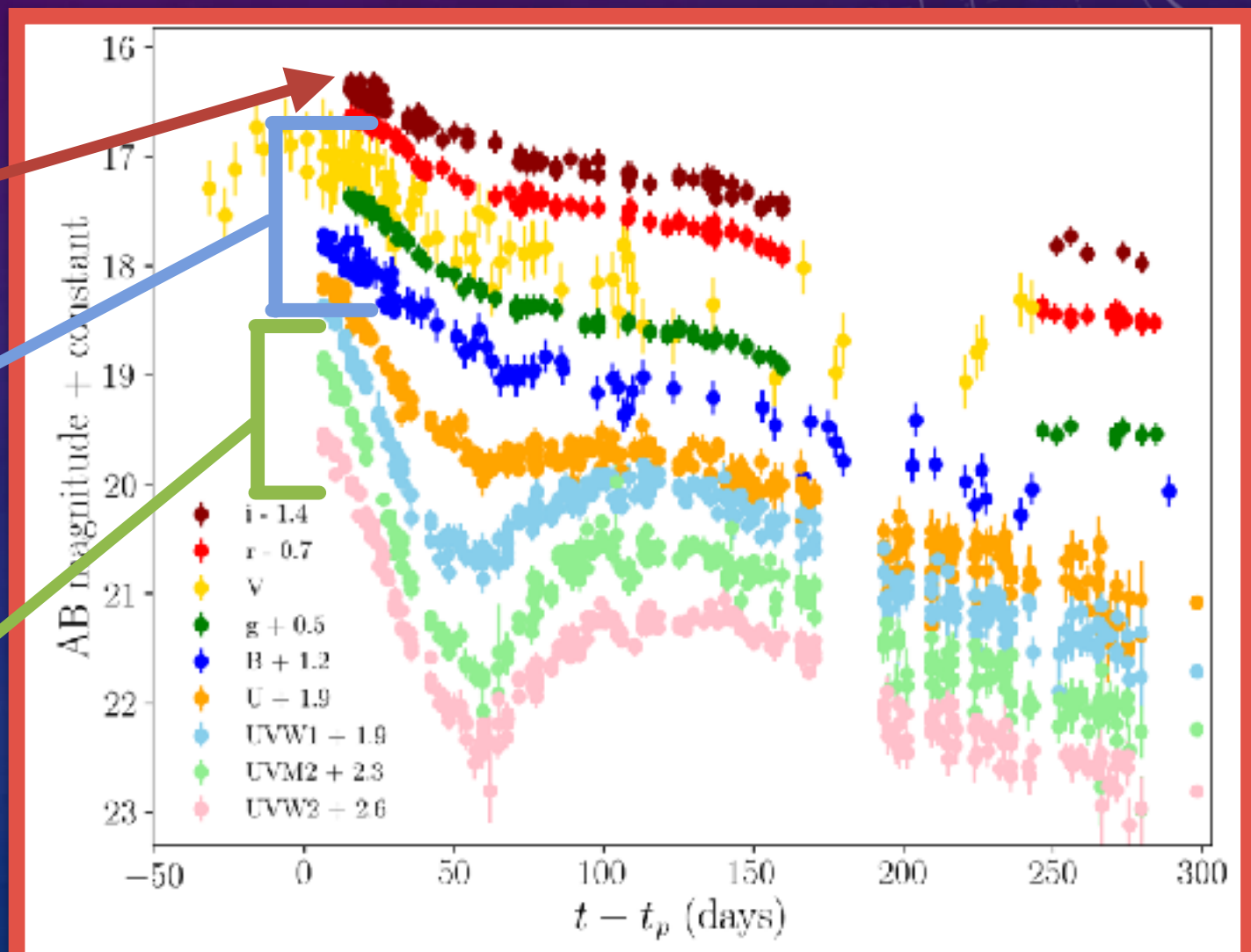
TIDAL DISRUPTION EVENTS

ASASSN-15lh

Infrared data

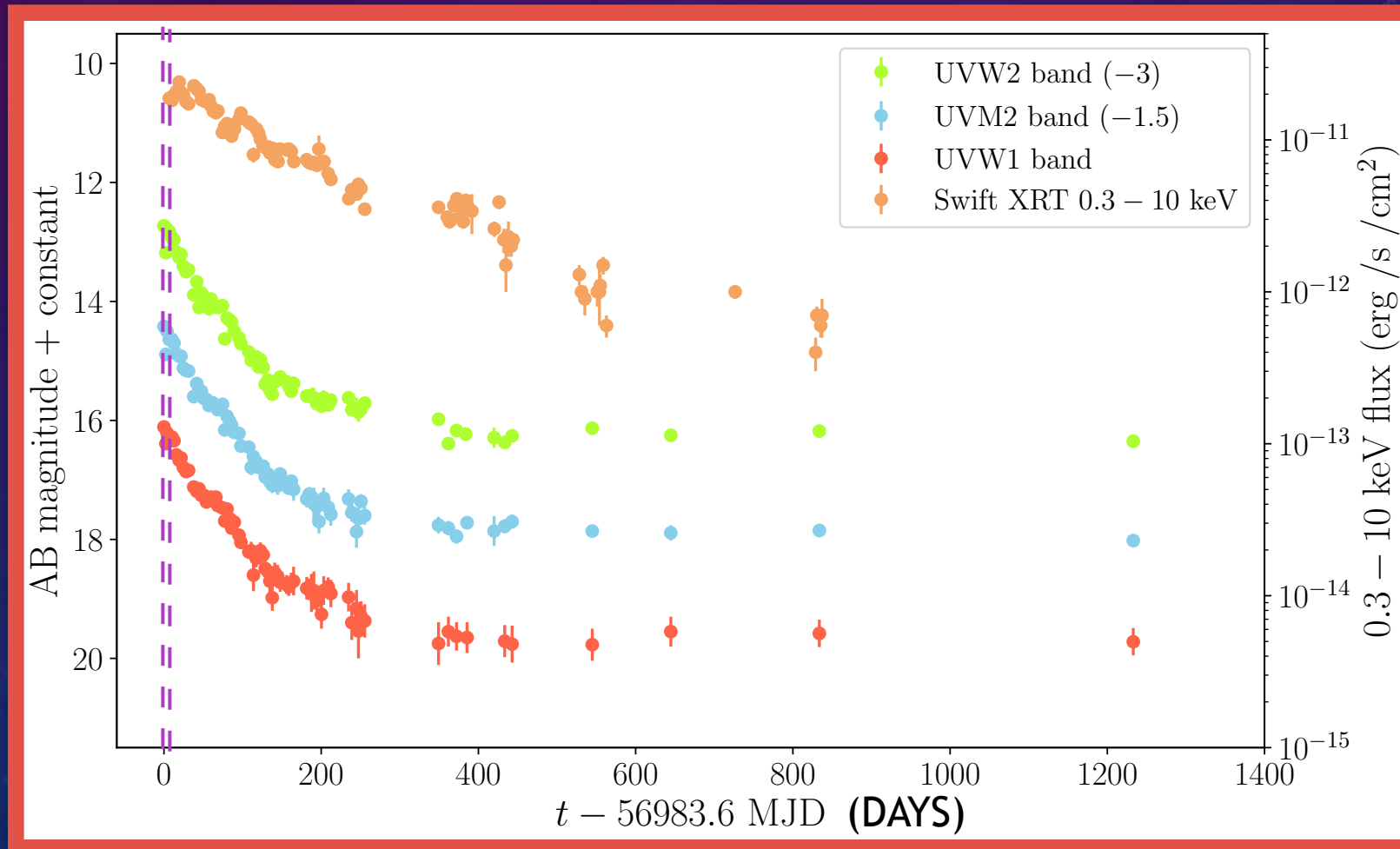
Optical data

UV data

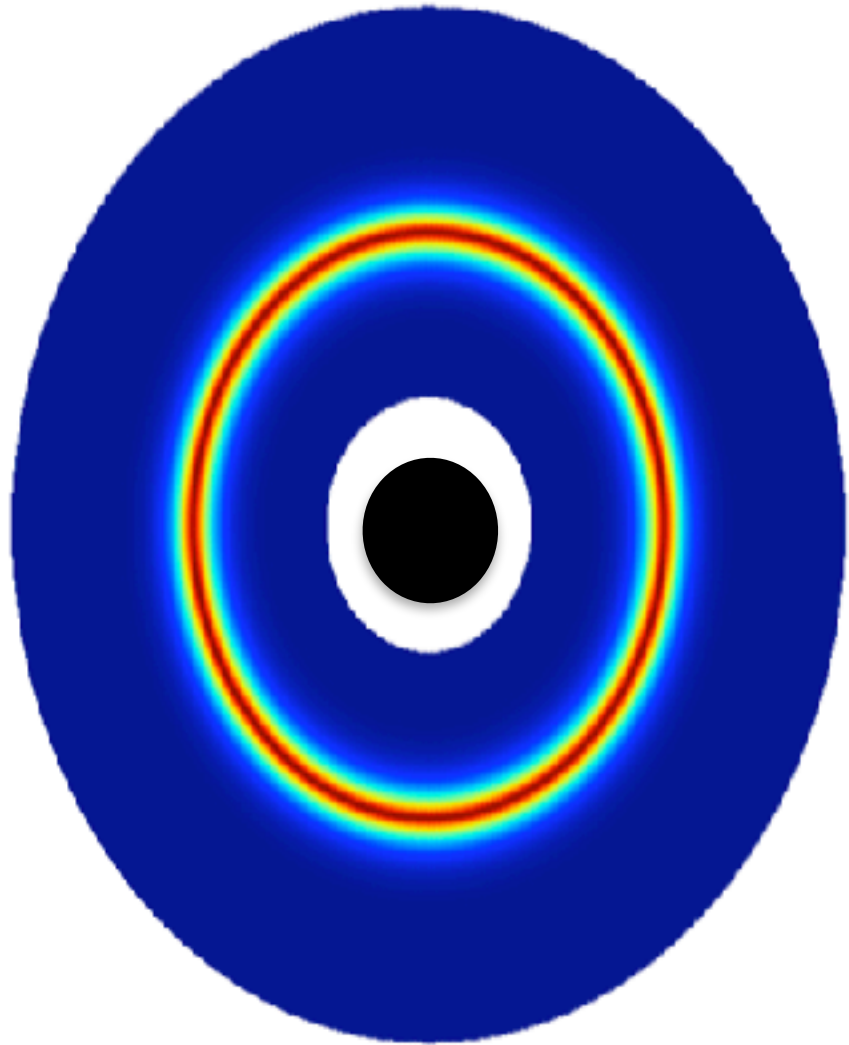


TIDAL DISRUPTION EVENTS

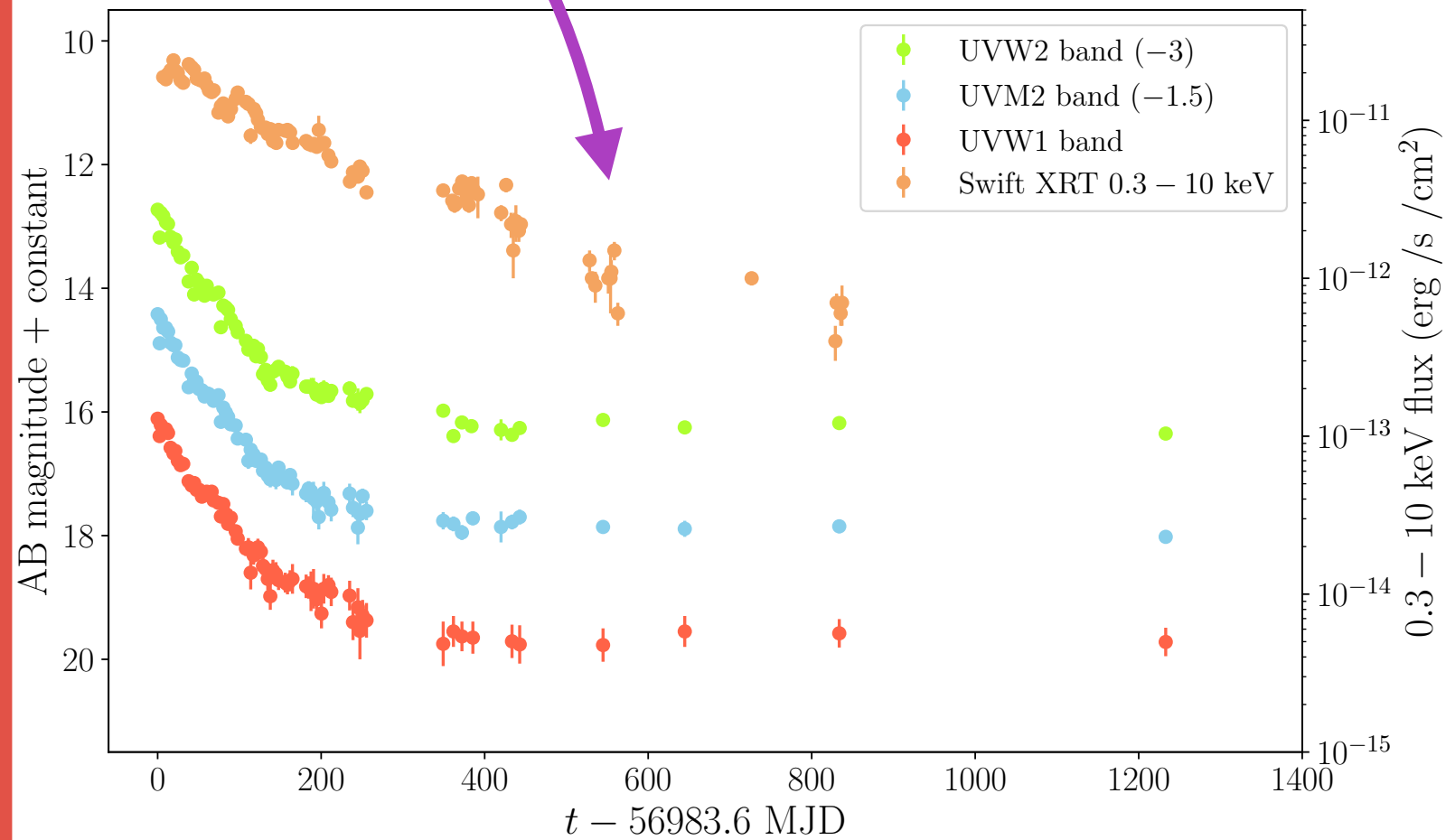
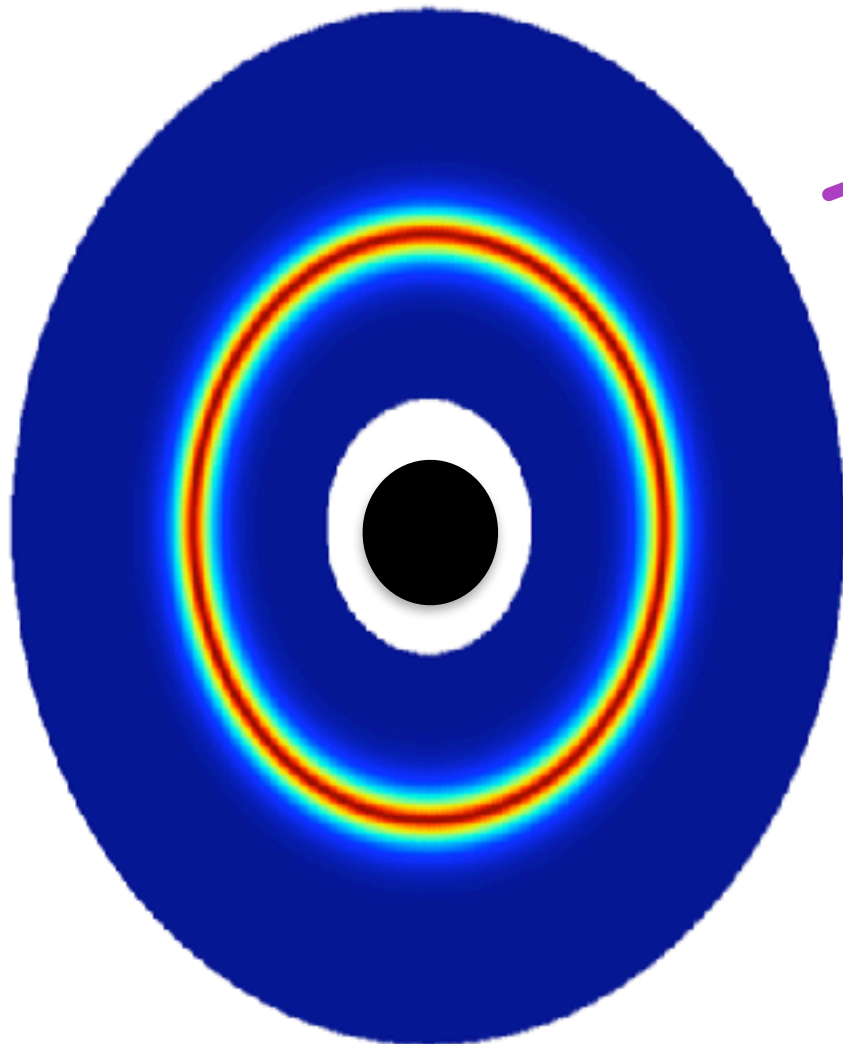
ASASSN-14li



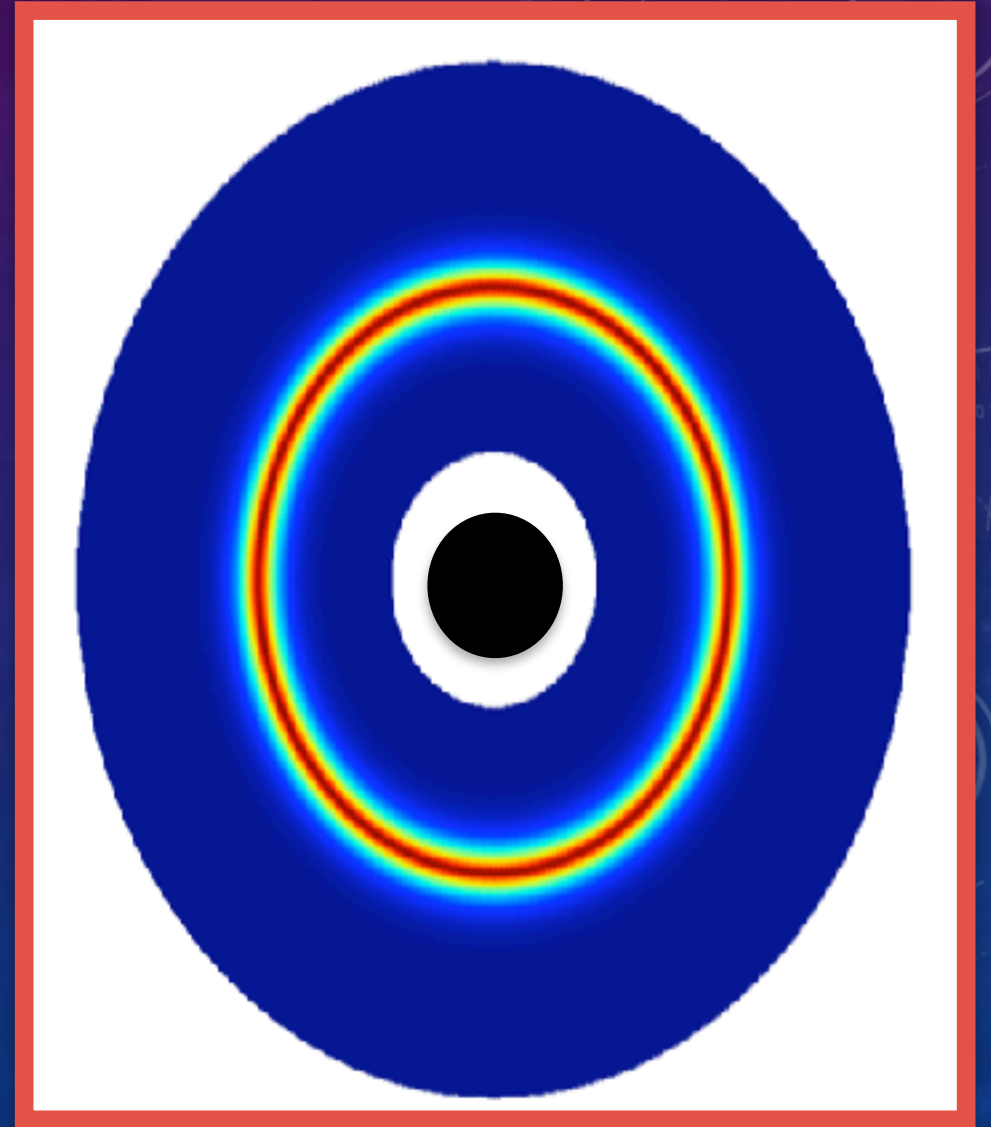
THE PROBLEM



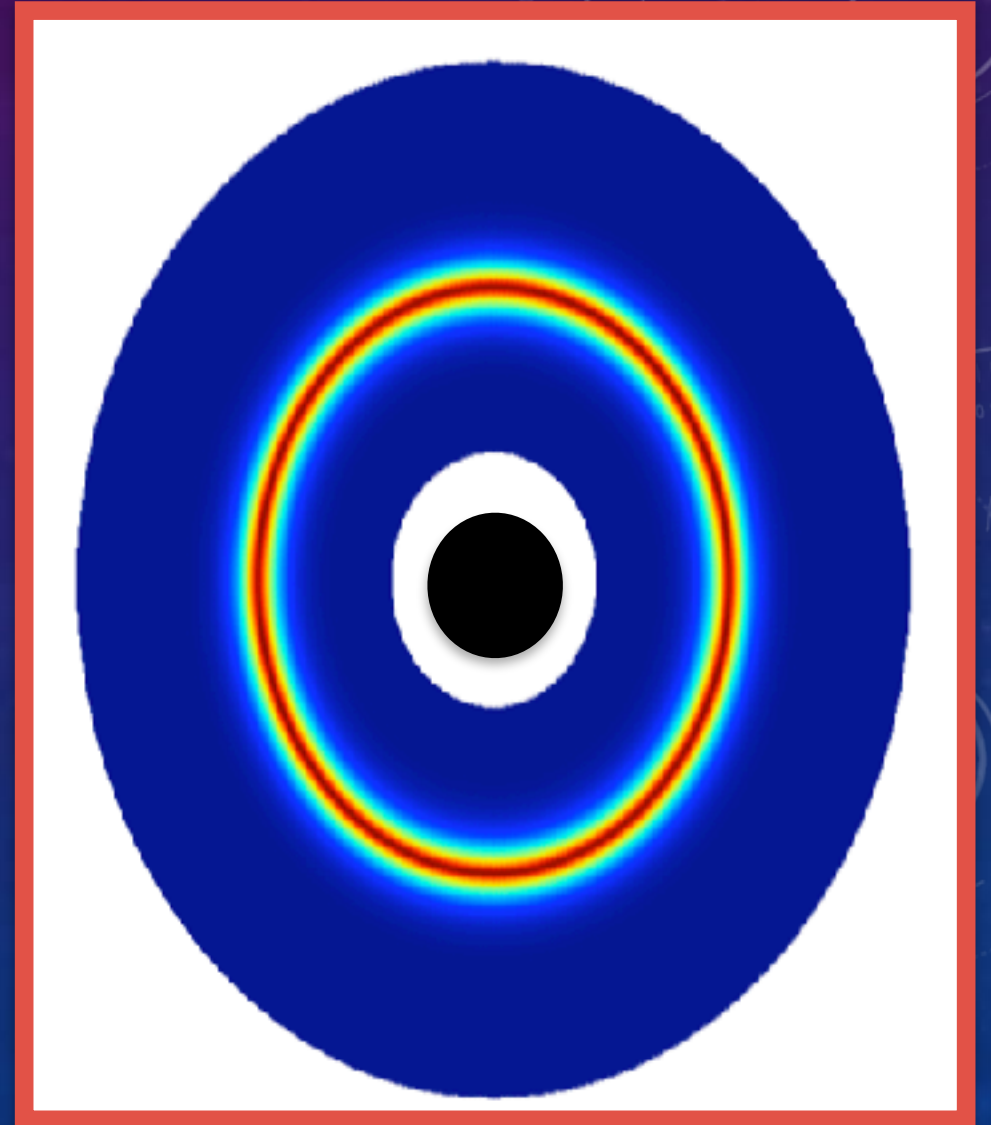
THE PROBLEM



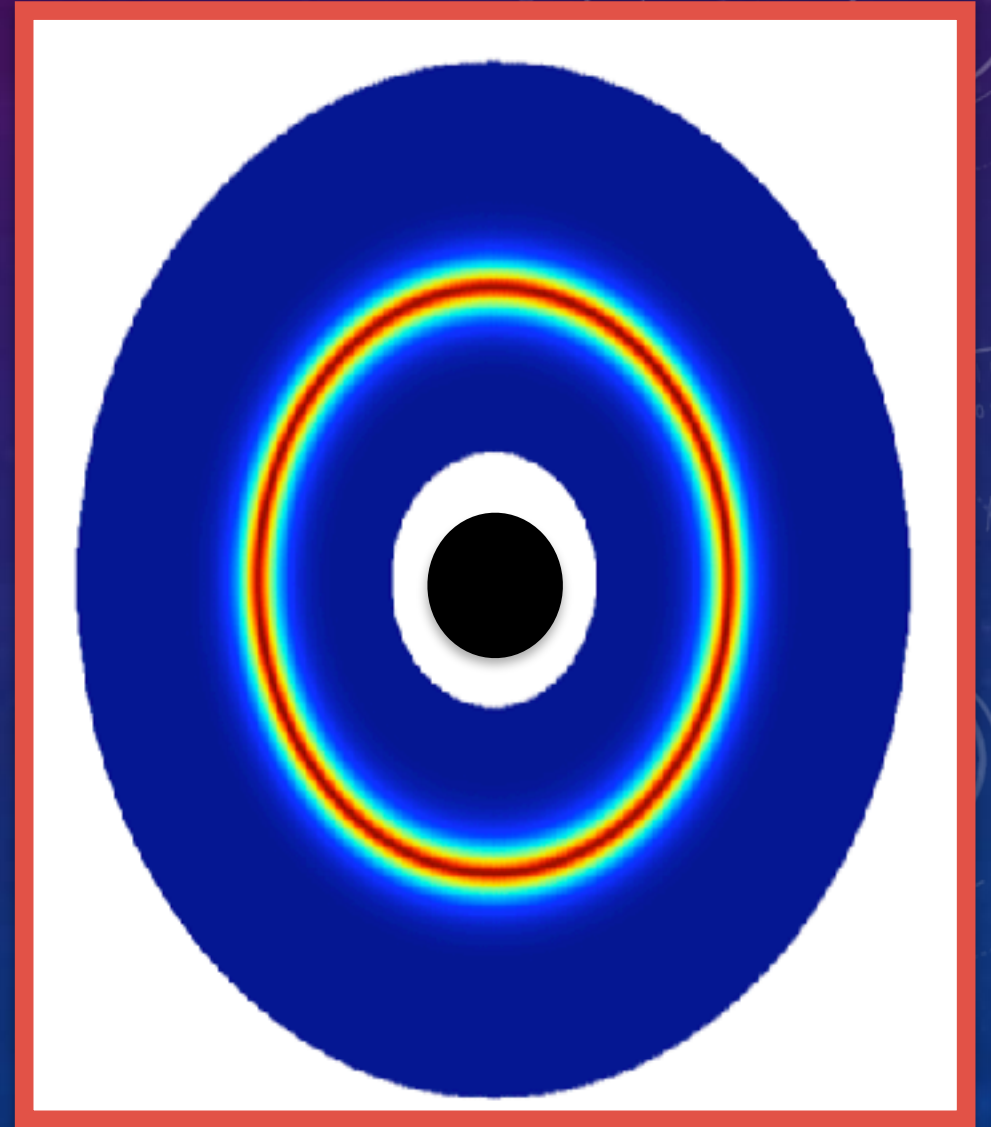
FLUID DYNAMICS IN GENERAL RELATIVITY



FLUID DYNAMICS IN GENERAL RELATIVITY

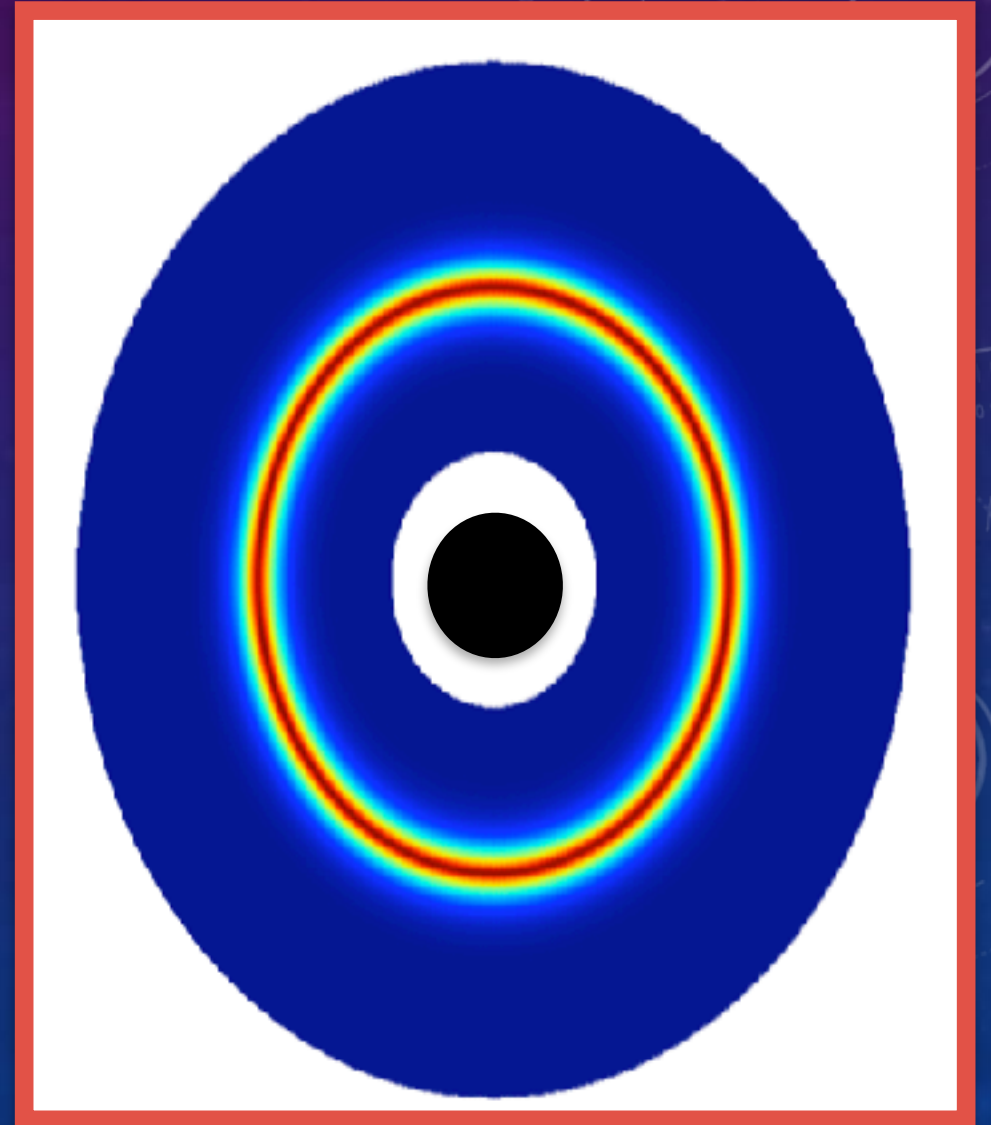


FLUID DYNAMICS IN GENERAL RELATIVITY



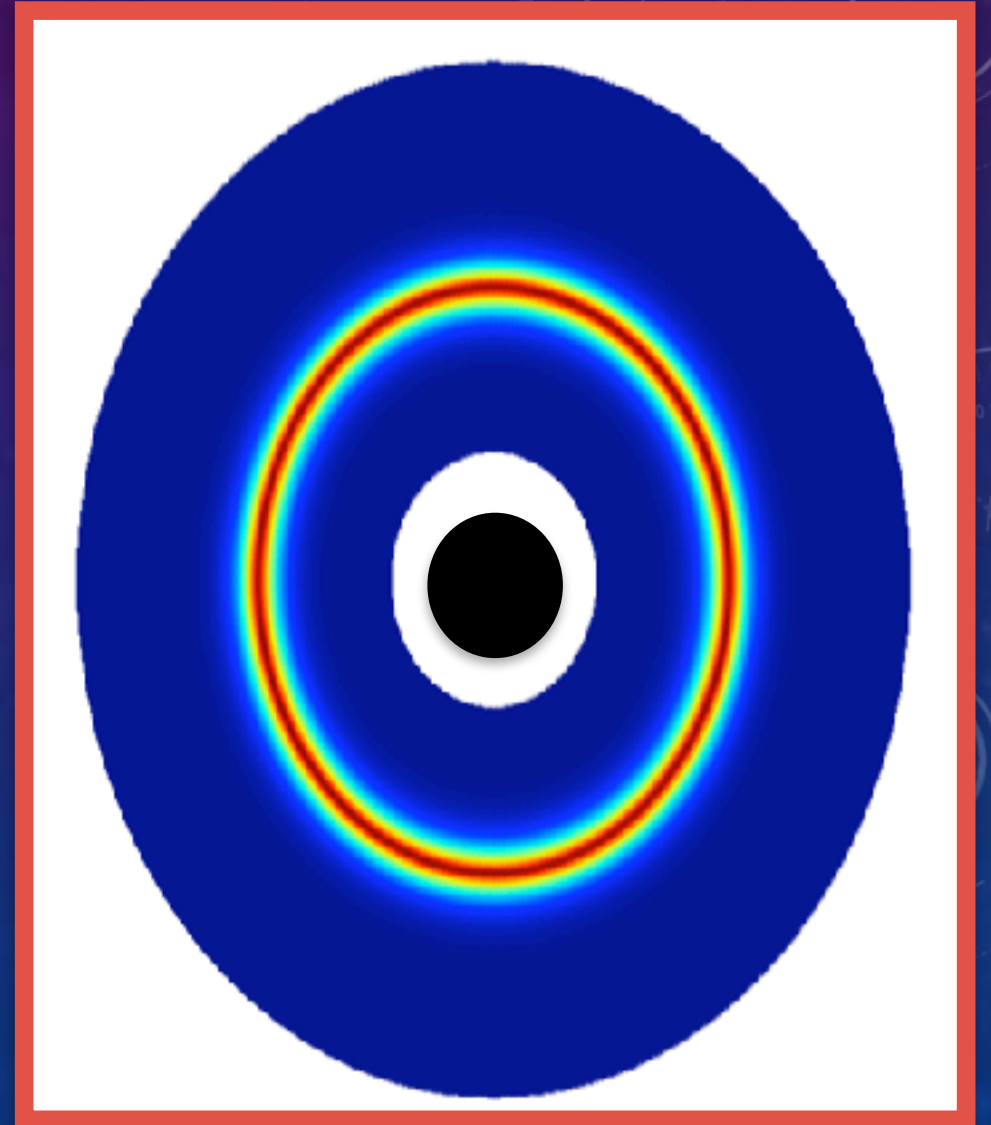
FLUID DYNAMICS IN GENERAL RELATIVITY

1. Conserve mass



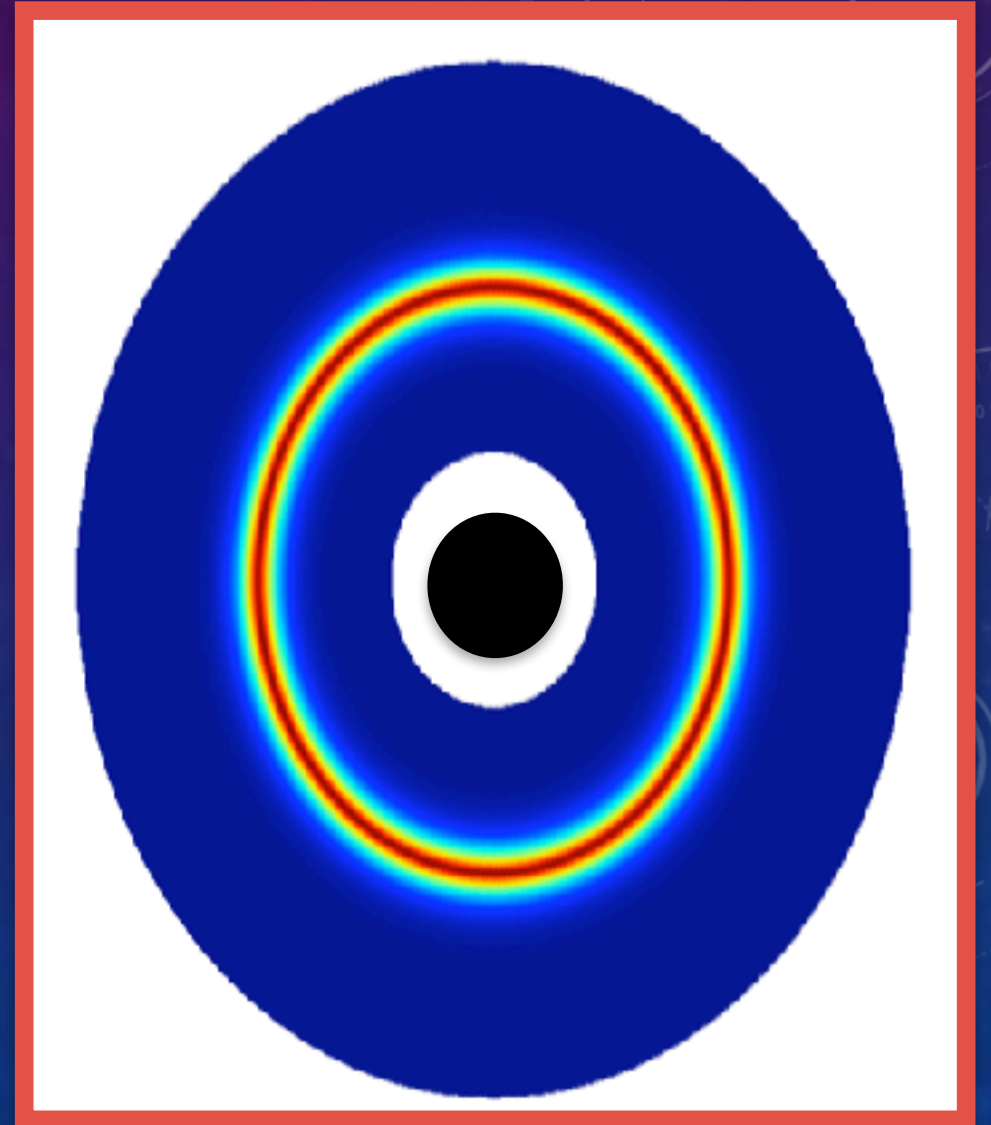
FLUID DYNAMICS IN GENERAL RELATIVITY

1. Conserve mass
2. Conserve angular momentum



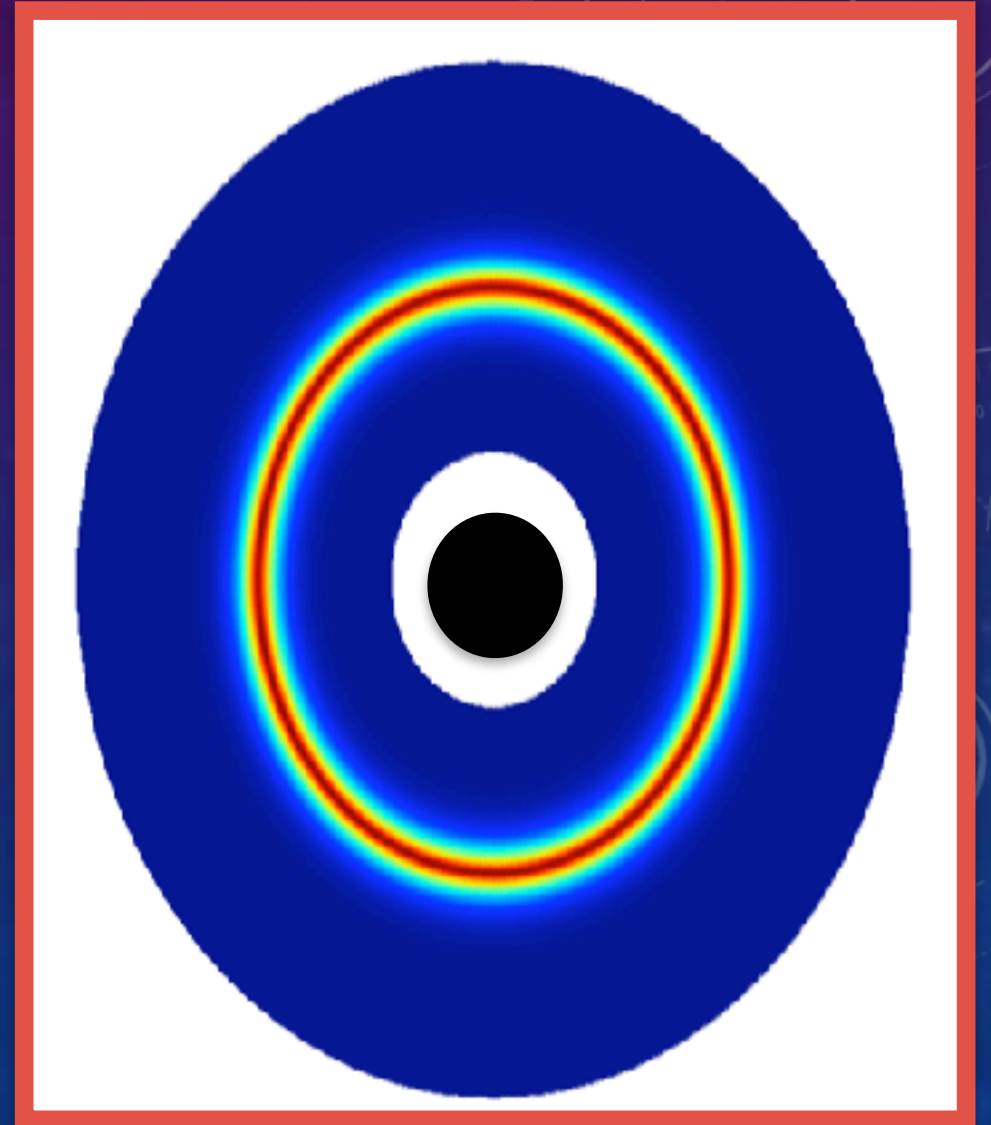
FLUID DYNAMICS IN GENERAL RELATIVITY

1. Conserve mass
2. Conserve angular momentum
3. Conserve energy



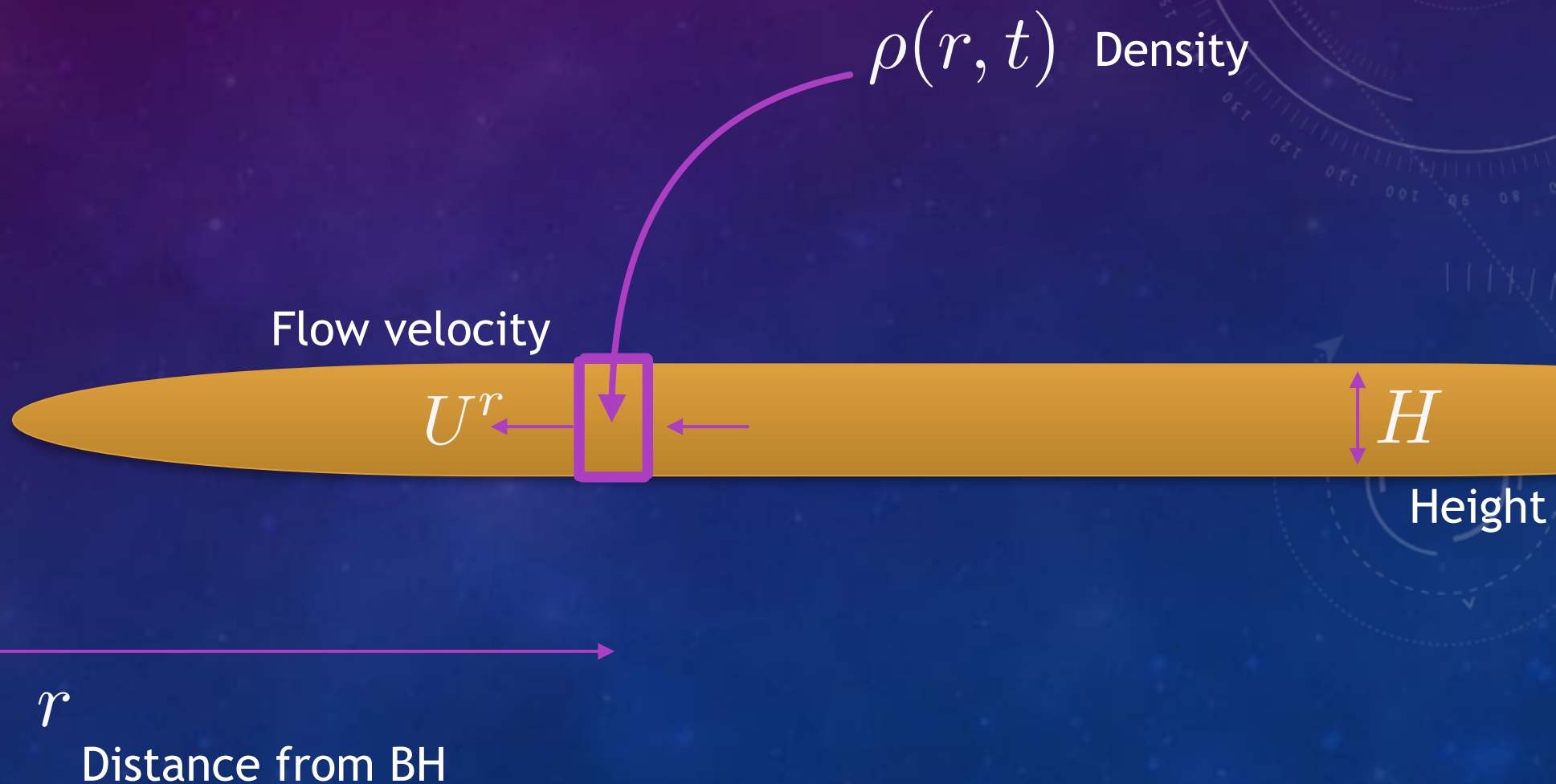
FLUID DYNAMICS IN GENERAL RELATIVITY

1. Conserve mass
2. Conserve angular momentum
3. Conserve energy
4. See what we get



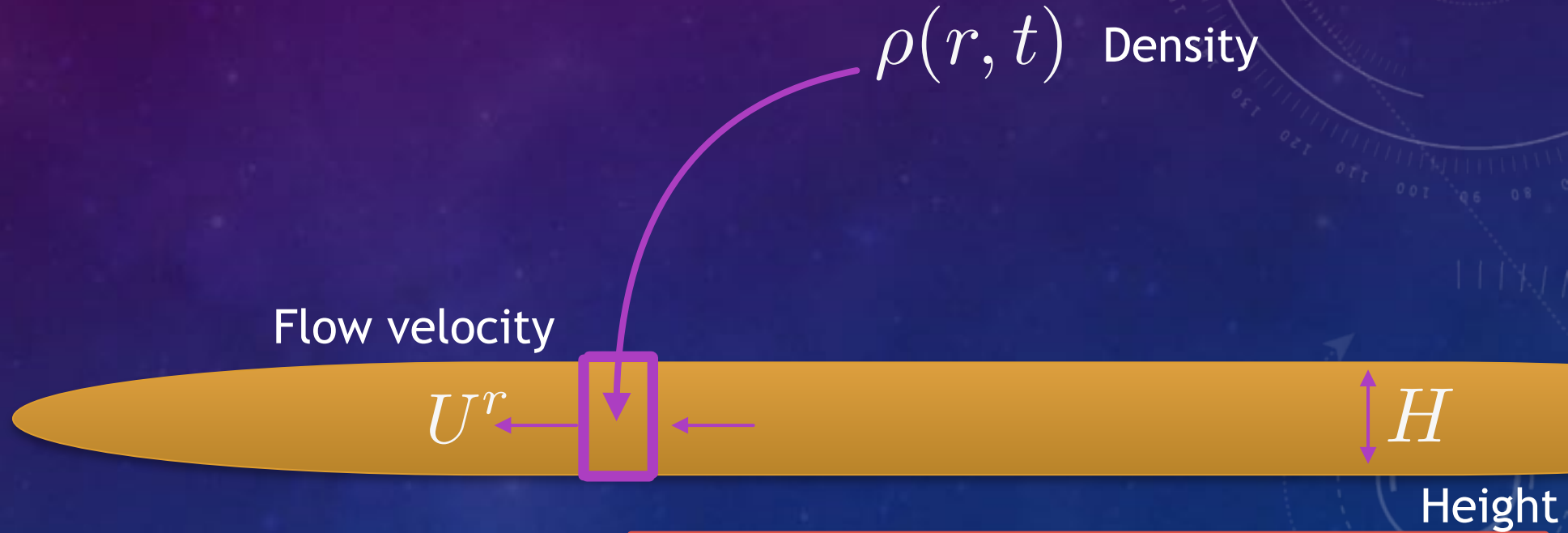
FLUID DYNAMICS IN GENERAL RELATIVITY

Mass conservation



FLUID DYNAMICS IN GENERAL RELATIVITY

Mass conservation



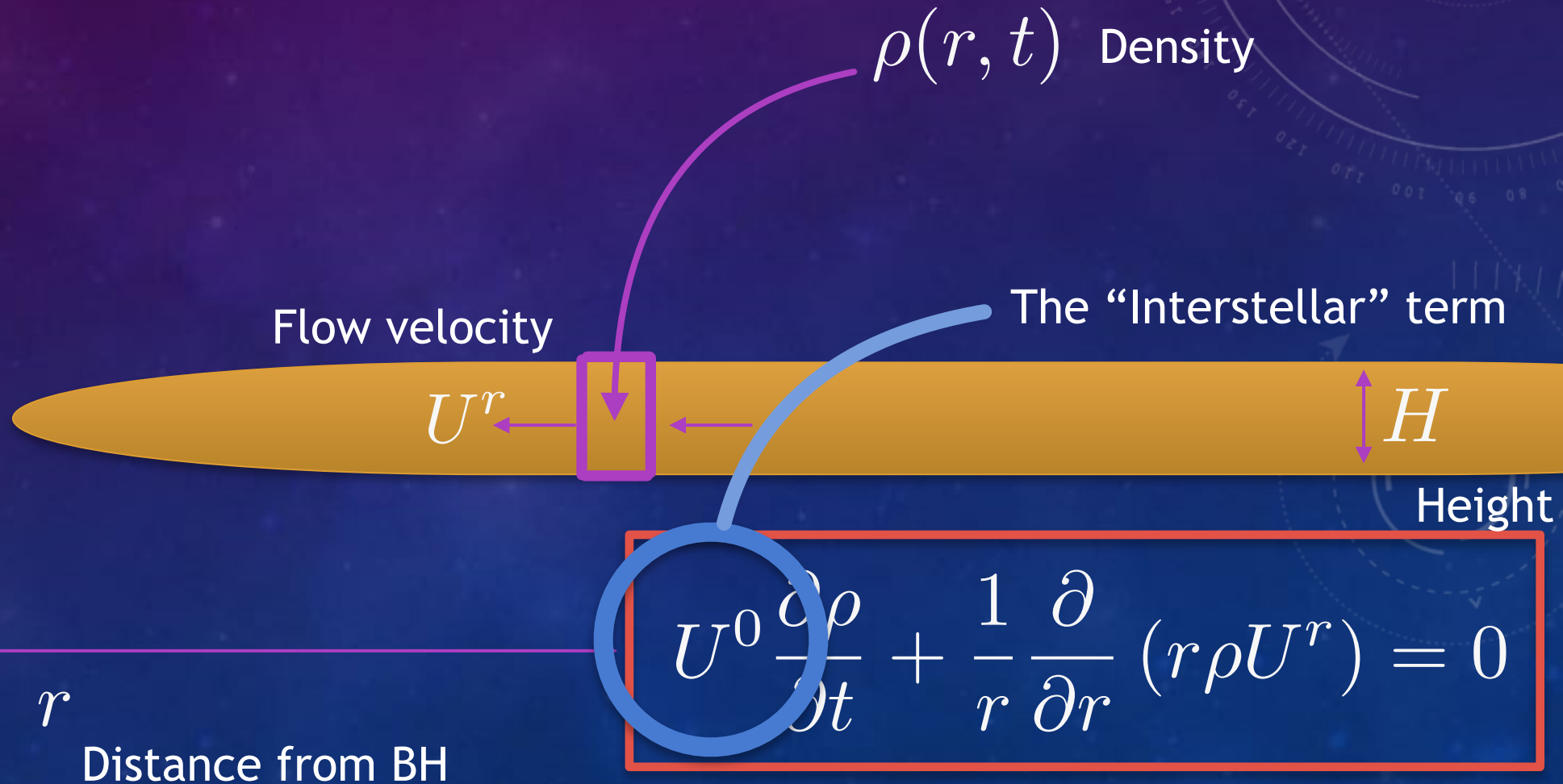
$$U^0 \frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho U^r) = 0$$

r

Distance from BH

FLUID DYNAMICS IN GENERAL RELATIVITY

Mass conservation



FLUID DYNAMICS IN GENERAL RELATIVITY

Angular momentum conservation



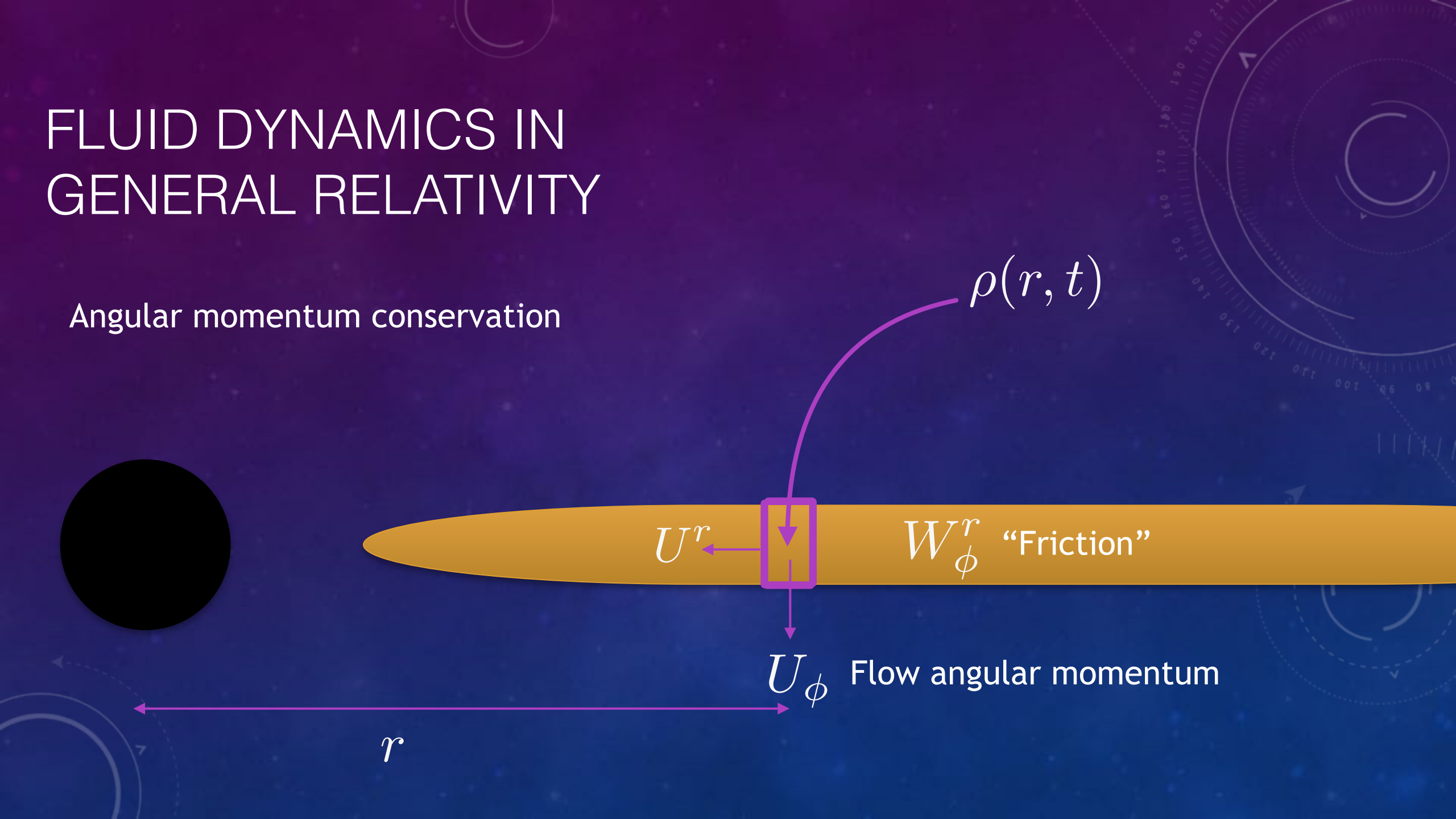
U^r

W_ϕ^r "Friction"

U_ϕ Flow angular momentum

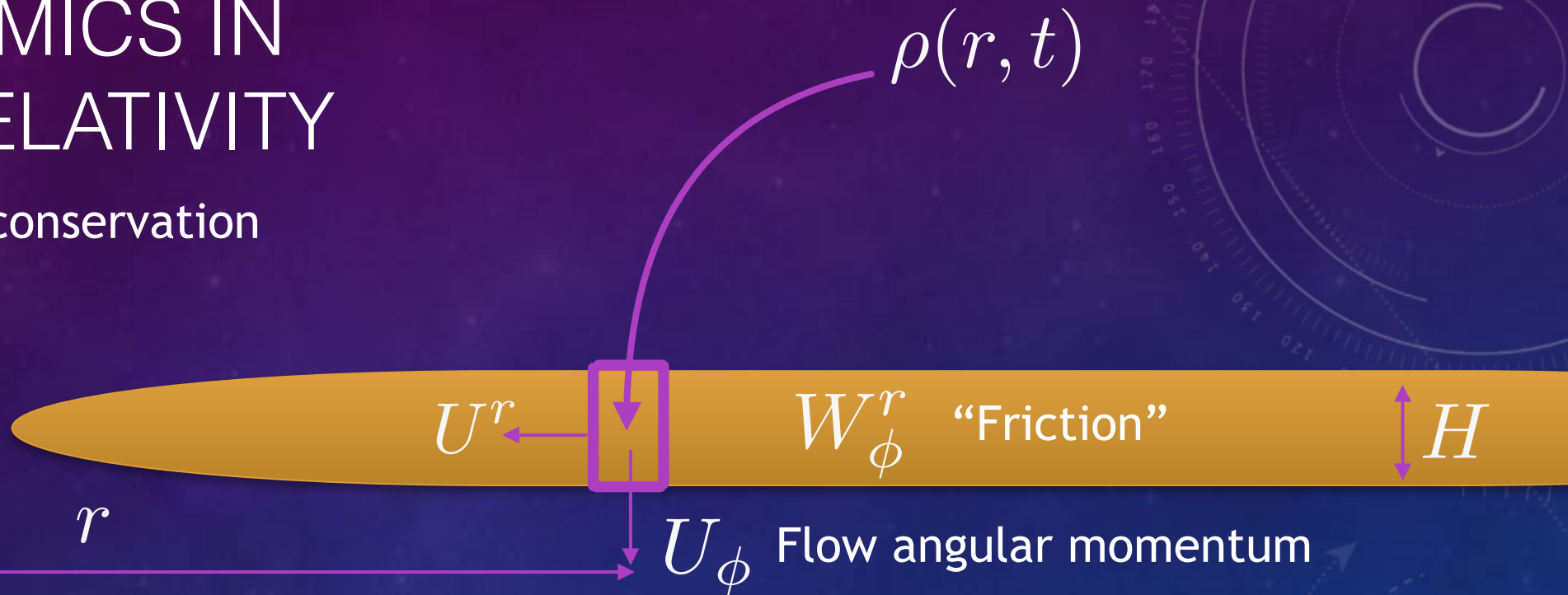
$\rho(r, t)$

r



FLUID DYNAMICS IN GENERAL RELATIVITY

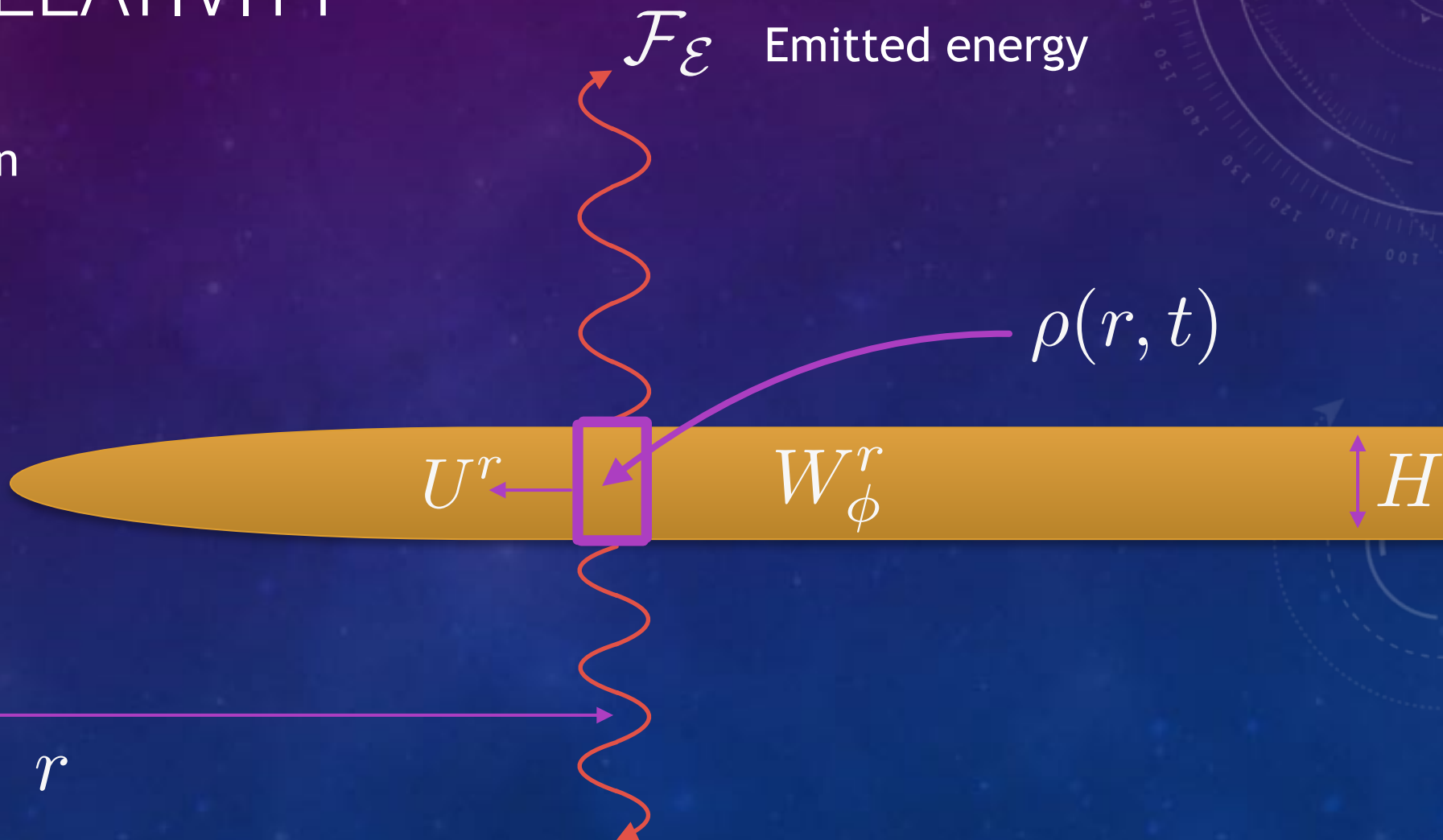
Angular momentum conservation



$$U_\phi \left[U^0 \frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho U^r) \right] + \rho U^r \frac{\partial U_\phi}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho W_\phi^r) + \frac{1}{H} U_\phi \mathcal{F}_\varepsilon = 0$$

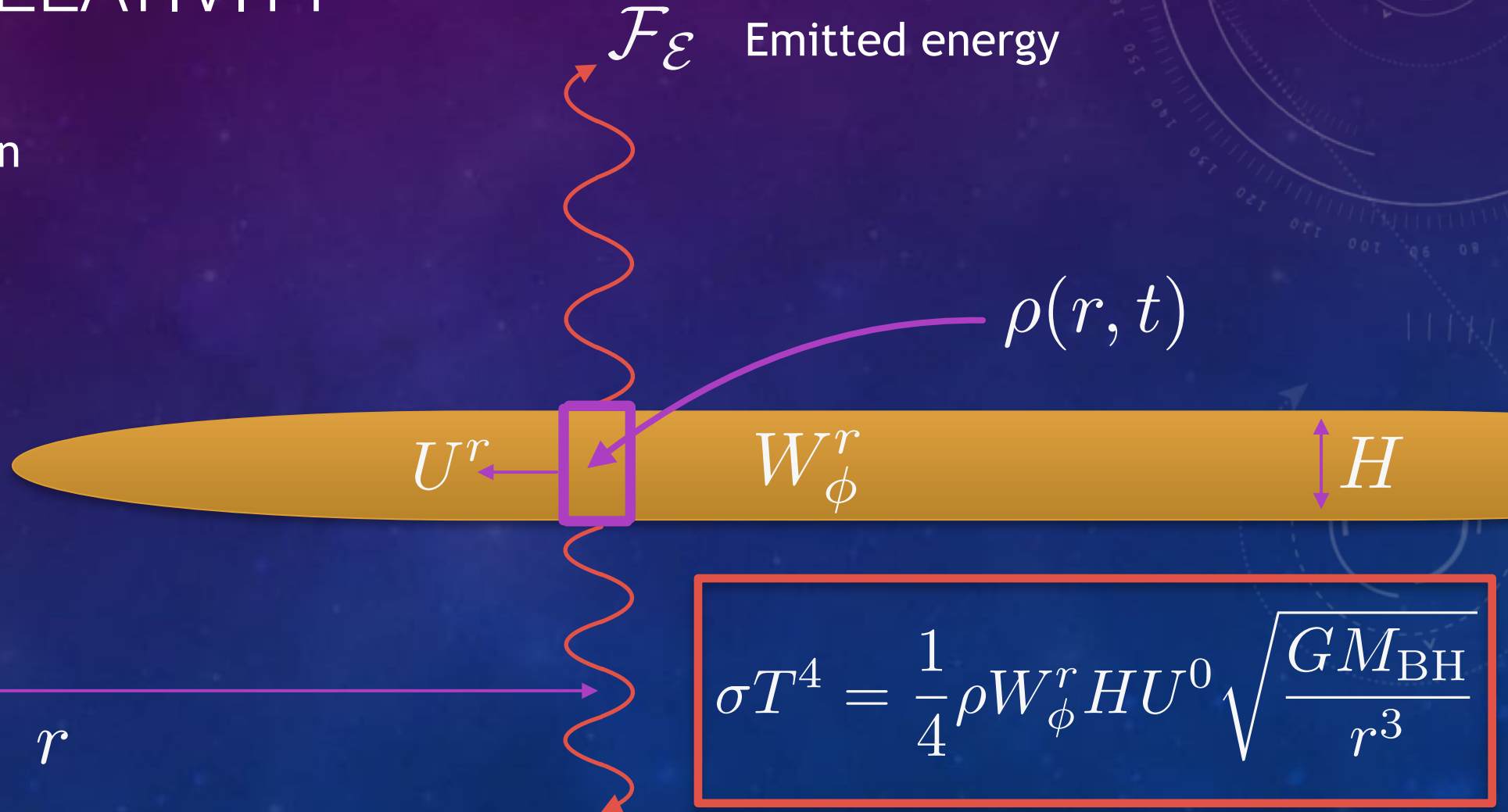
FLUID DYNAMICS IN GENERAL RELATIVITY

Energy conservation



FLUID DYNAMICS IN GENERAL RELATIVITY

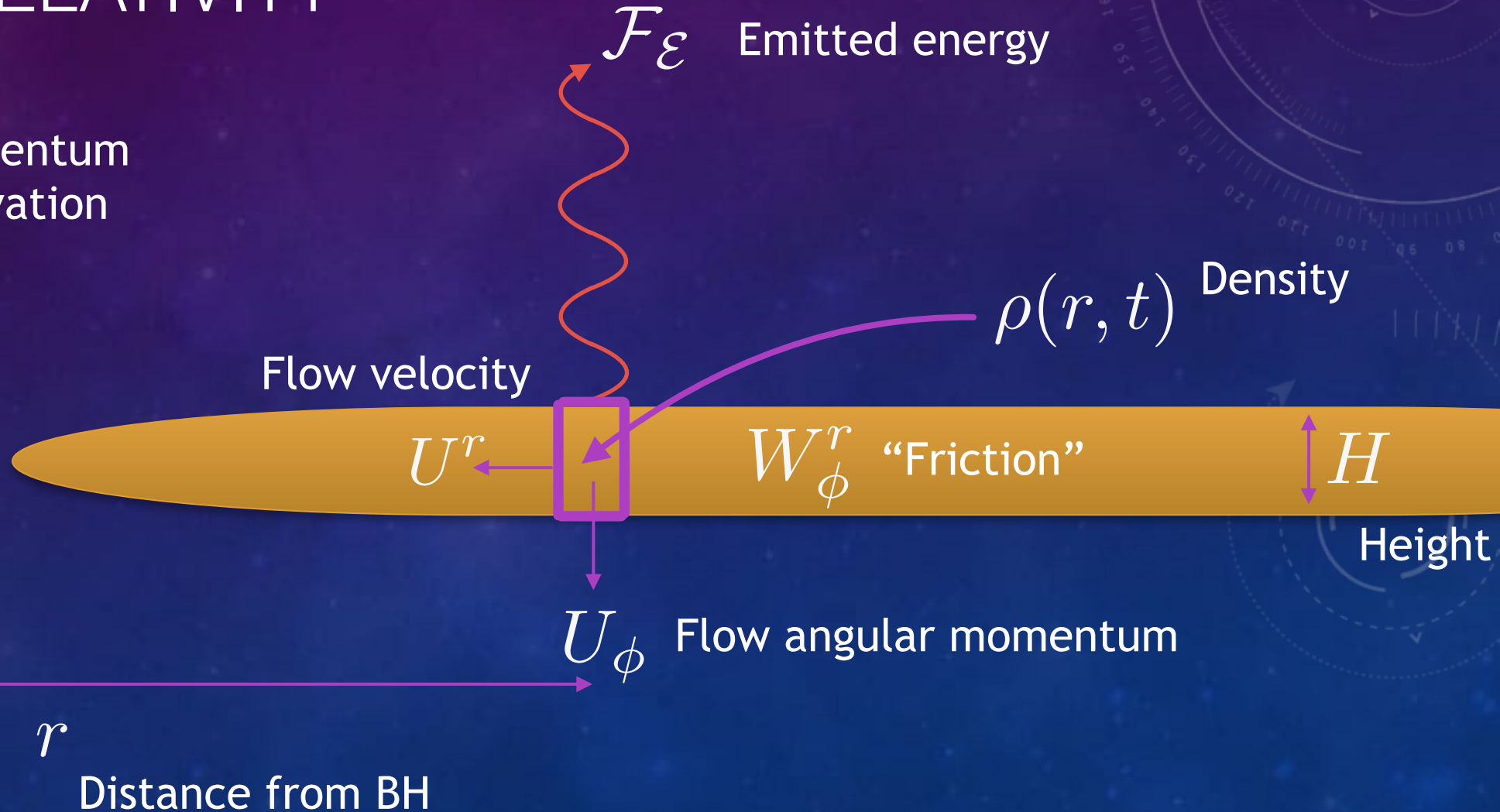
Energy conservation



$$\sigma T^4 = \frac{1}{4} \rho W_\phi^r H U^0 \sqrt{\frac{GM_{\text{BH}}}{r^3}}$$

FLUID DYNAMICS IN GENERAL RELATIVITY

Mass, Angular momentum
and Energy conservation

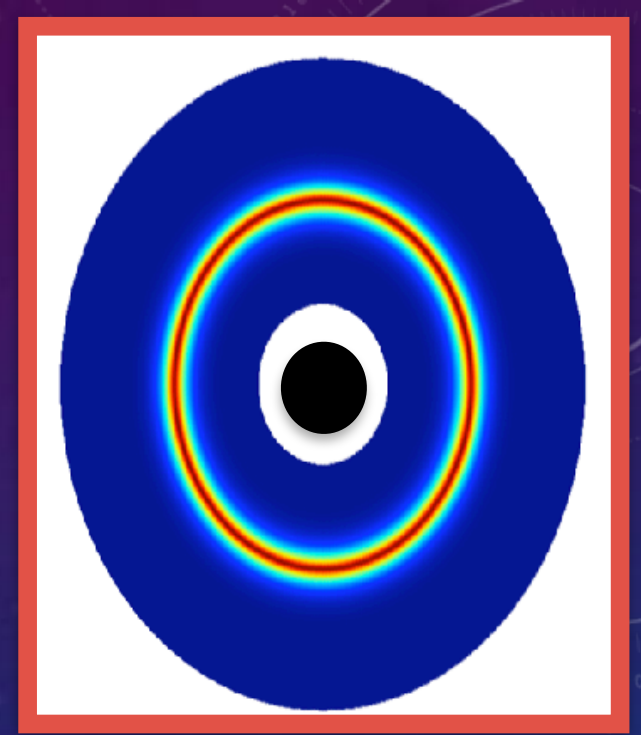


FLUID DYNAMICS IN GENERAL RELATIVITY

Mass, Angular momentum and Energy conservation

$$\frac{\partial \rho}{\partial t} = \frac{1}{rU^0} \frac{\partial}{\partial r} \left[\frac{U^0}{U_\phi'} \frac{\partial}{\partial r} \left(\frac{r\rho W_\phi^r}{U^0} \right) \right]$$

$$\sigma T^4 = \frac{1}{4} \rho W_\phi^r H U^0 \sqrt{\frac{GM_{\text{BH}}}{r^3}}$$



FLUID DYNAMICS IN GENERAL RELATIVITY

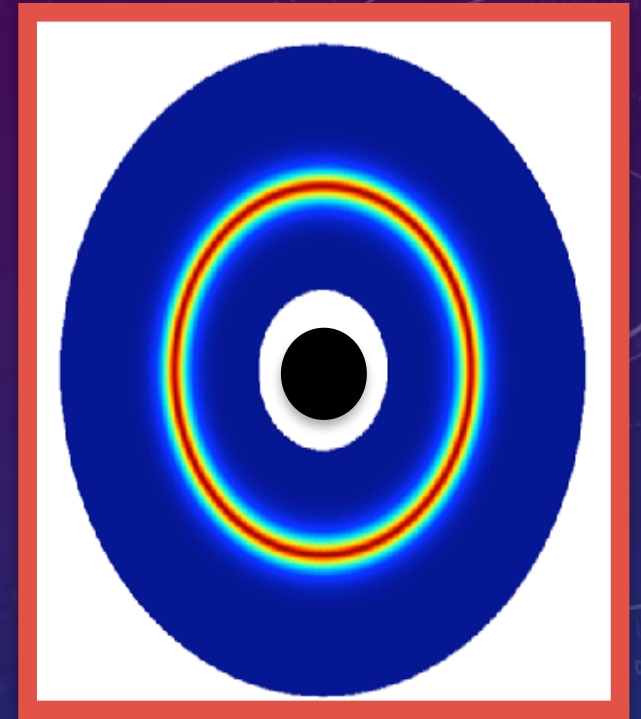
Mass, Angular momentum and Energy conservation

$$\sigma T^4 = \frac{1}{4} \rho W_{\phi}^r H U^0 \sqrt{\frac{GM_{\text{BH}}}{r^3}}$$

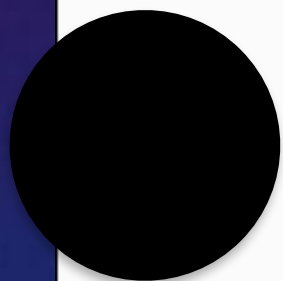
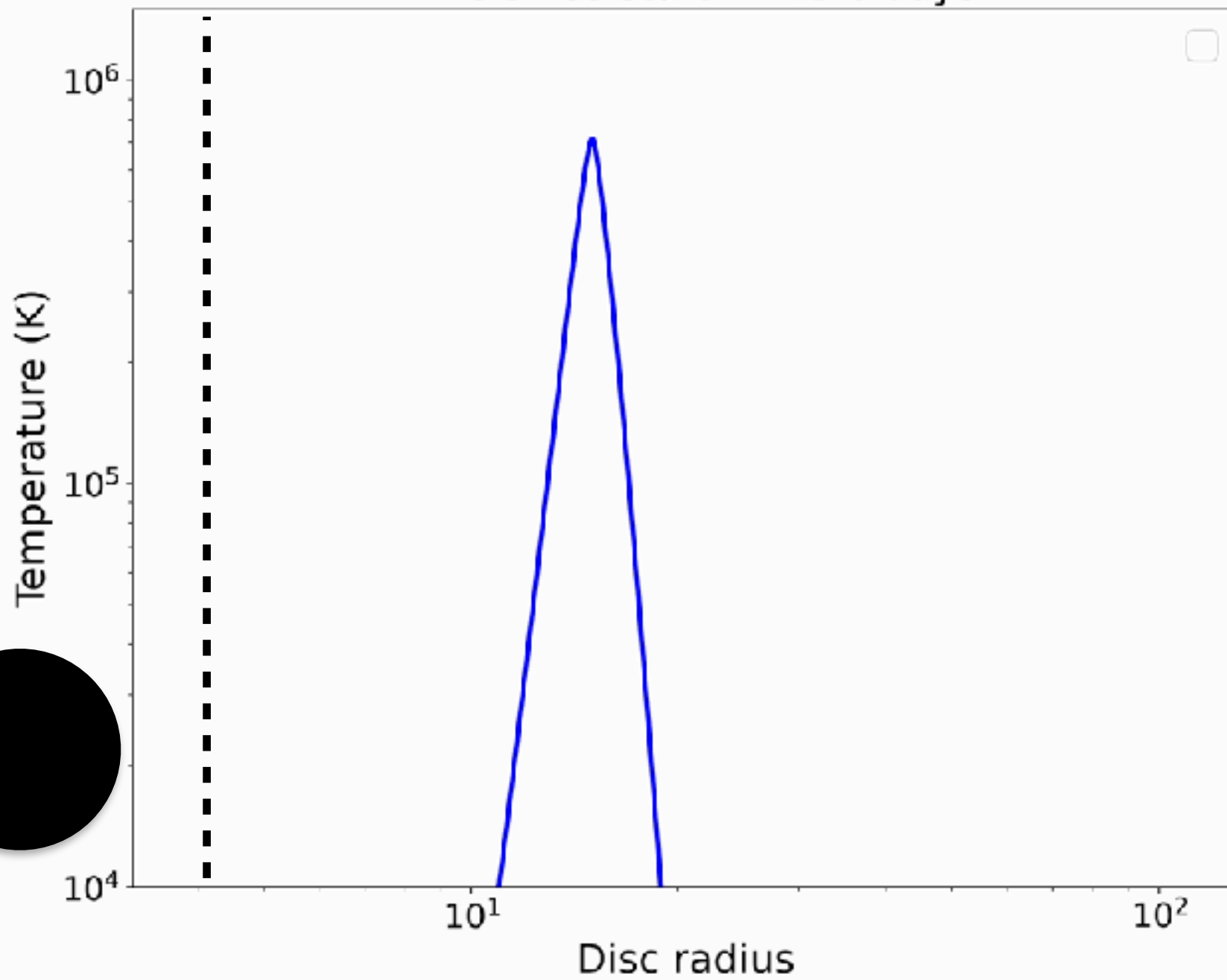
$$B_{\nu}(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

B_{ν} = Brightness

ν = Frequency

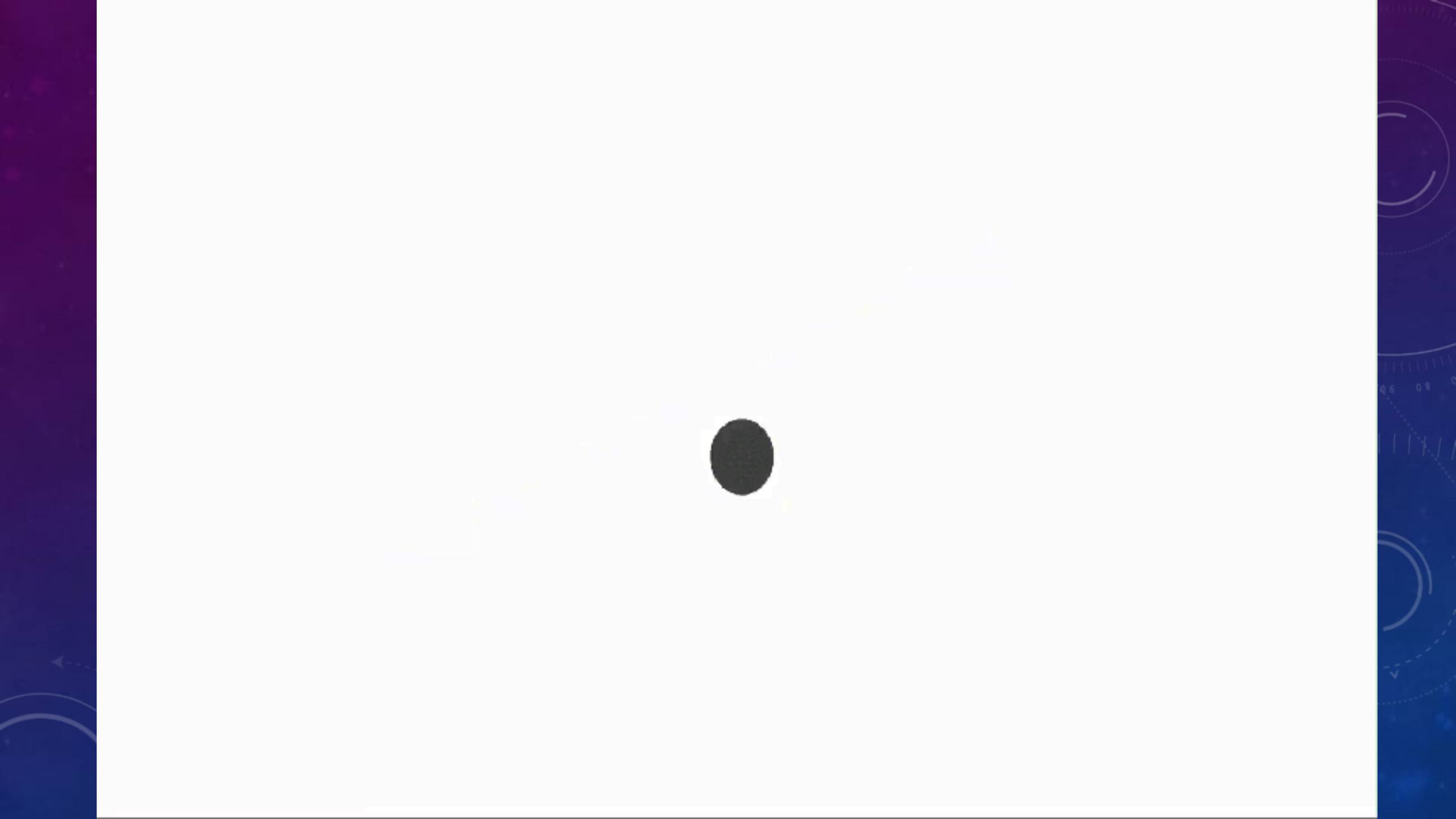


Time since start = -43.6 days

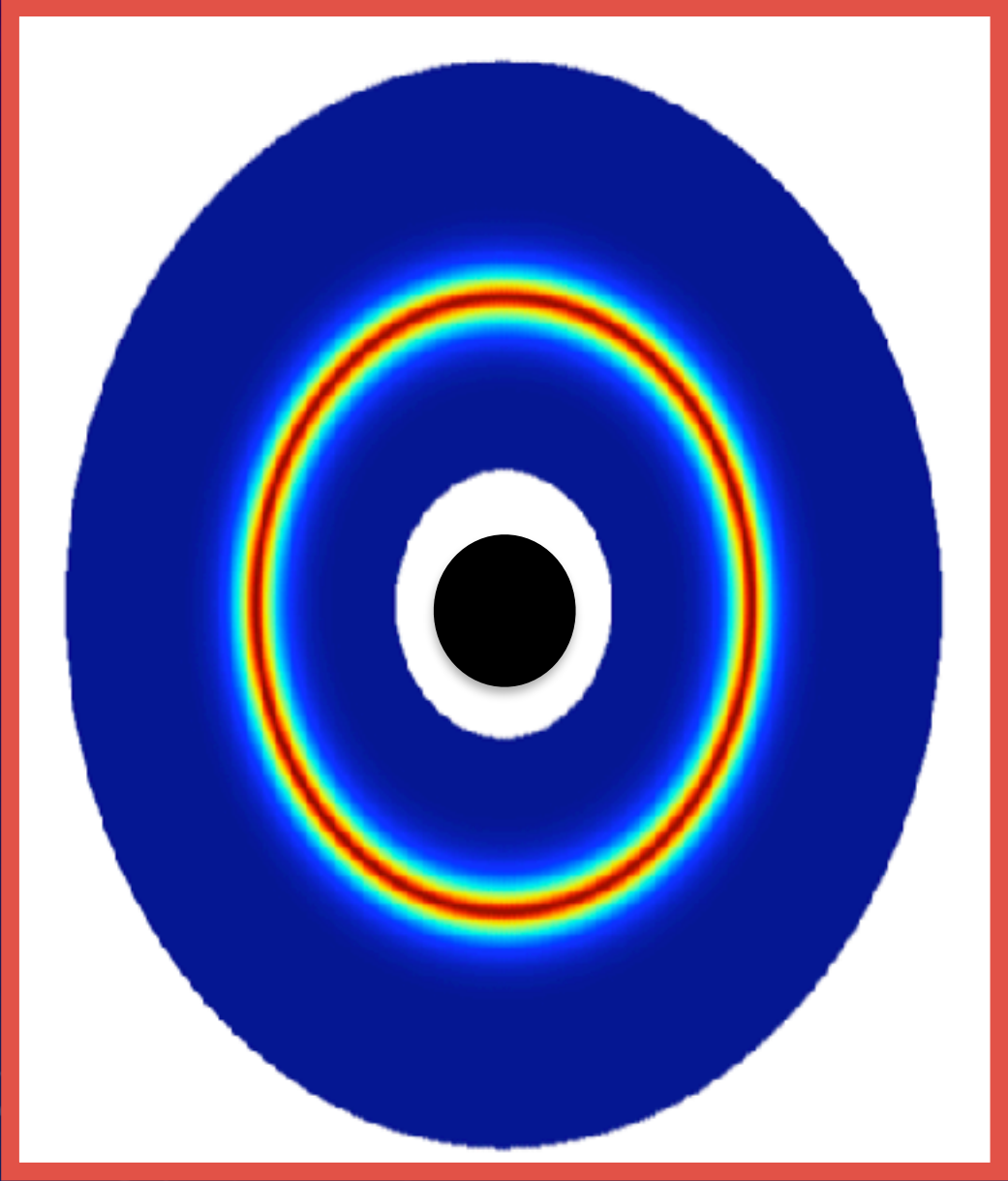


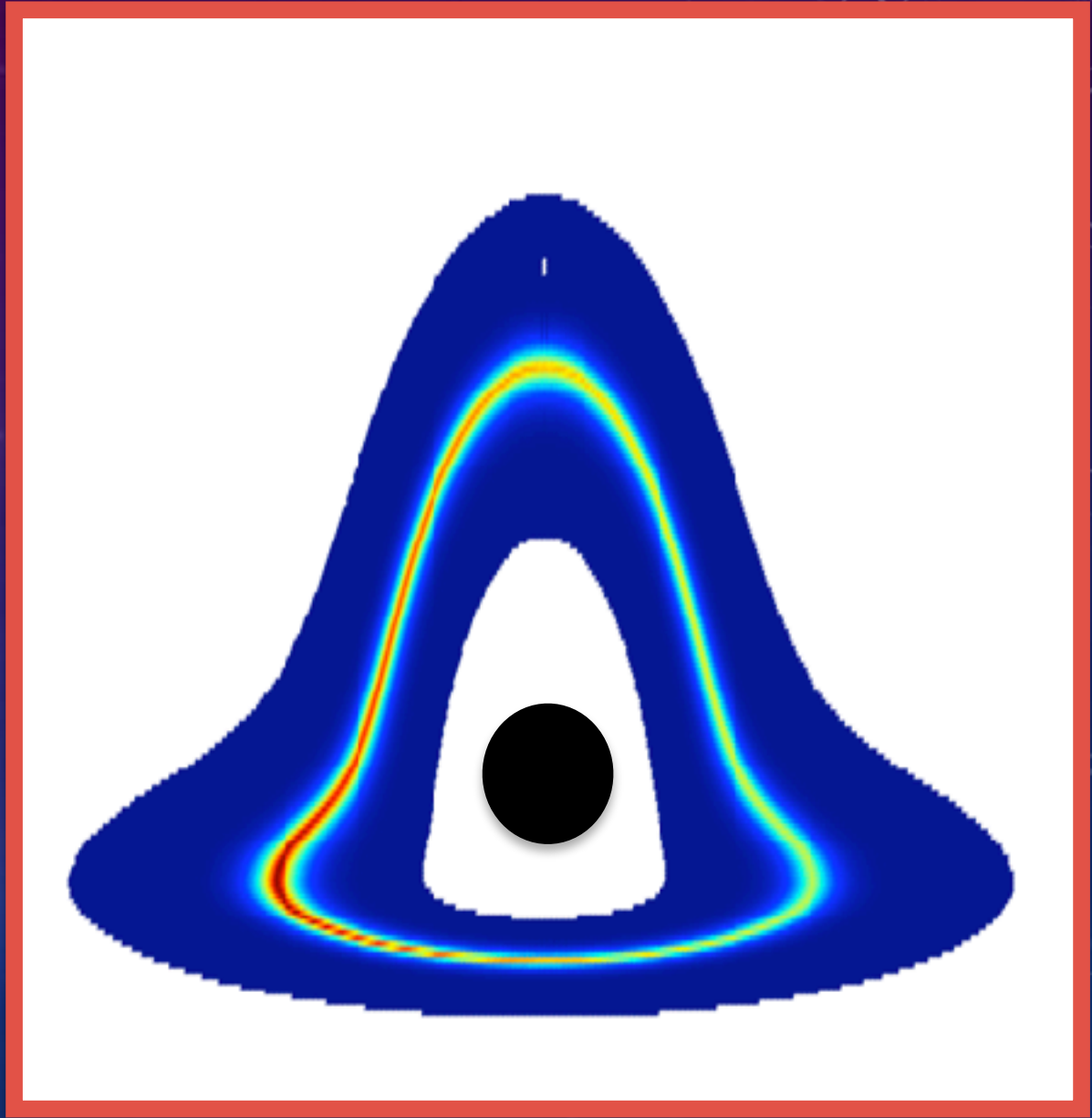
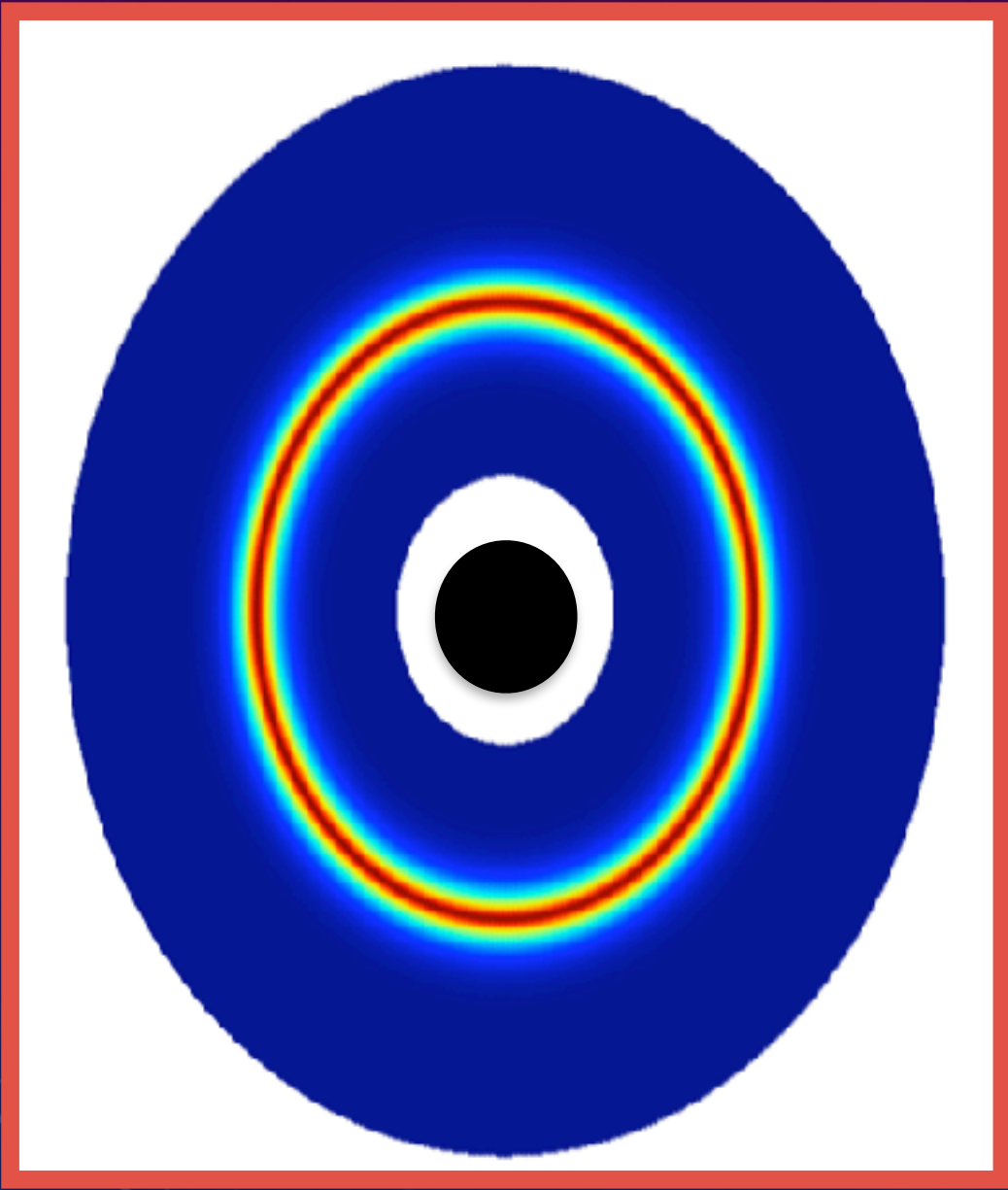
GRAVITATIONAL LENSING



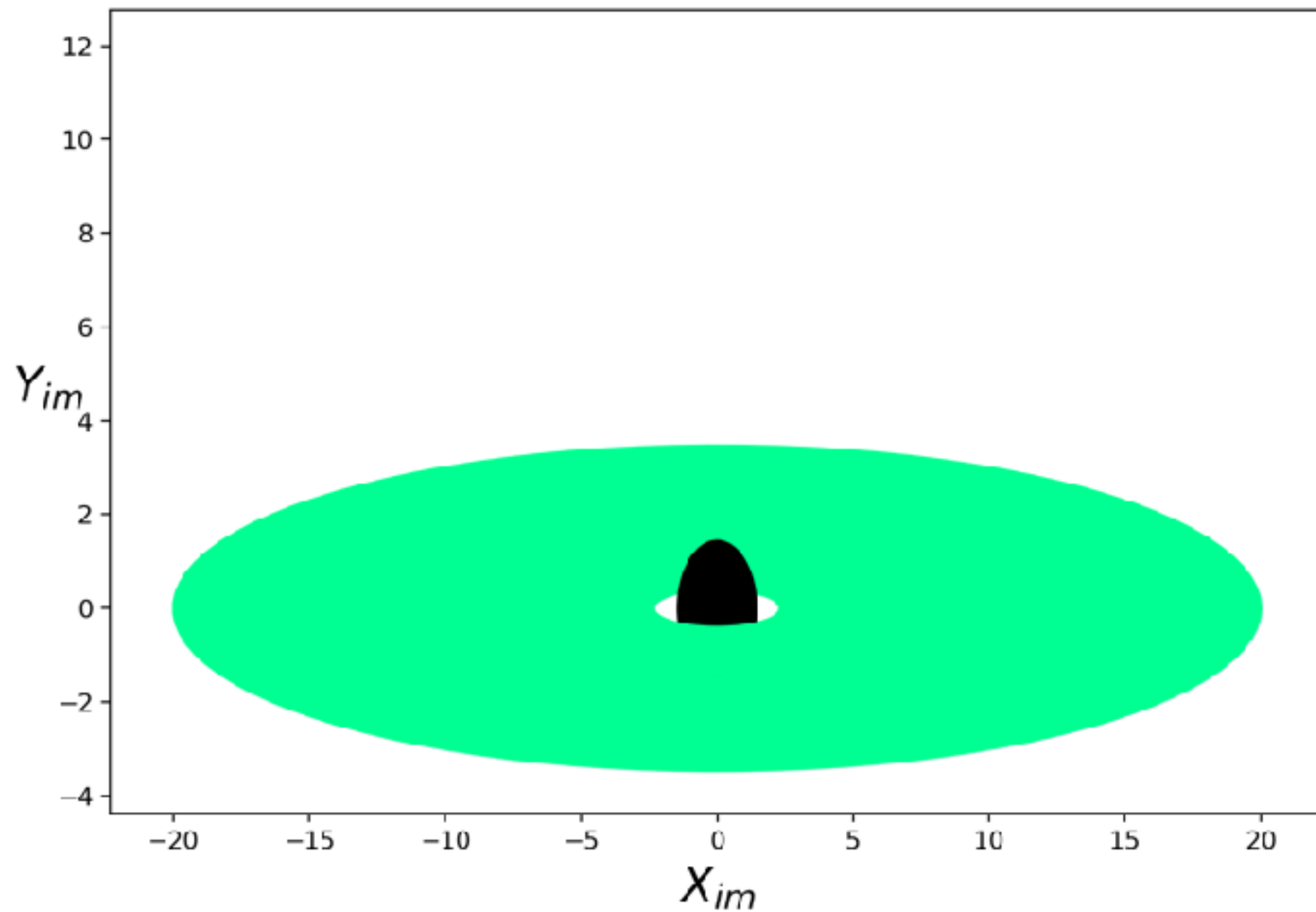




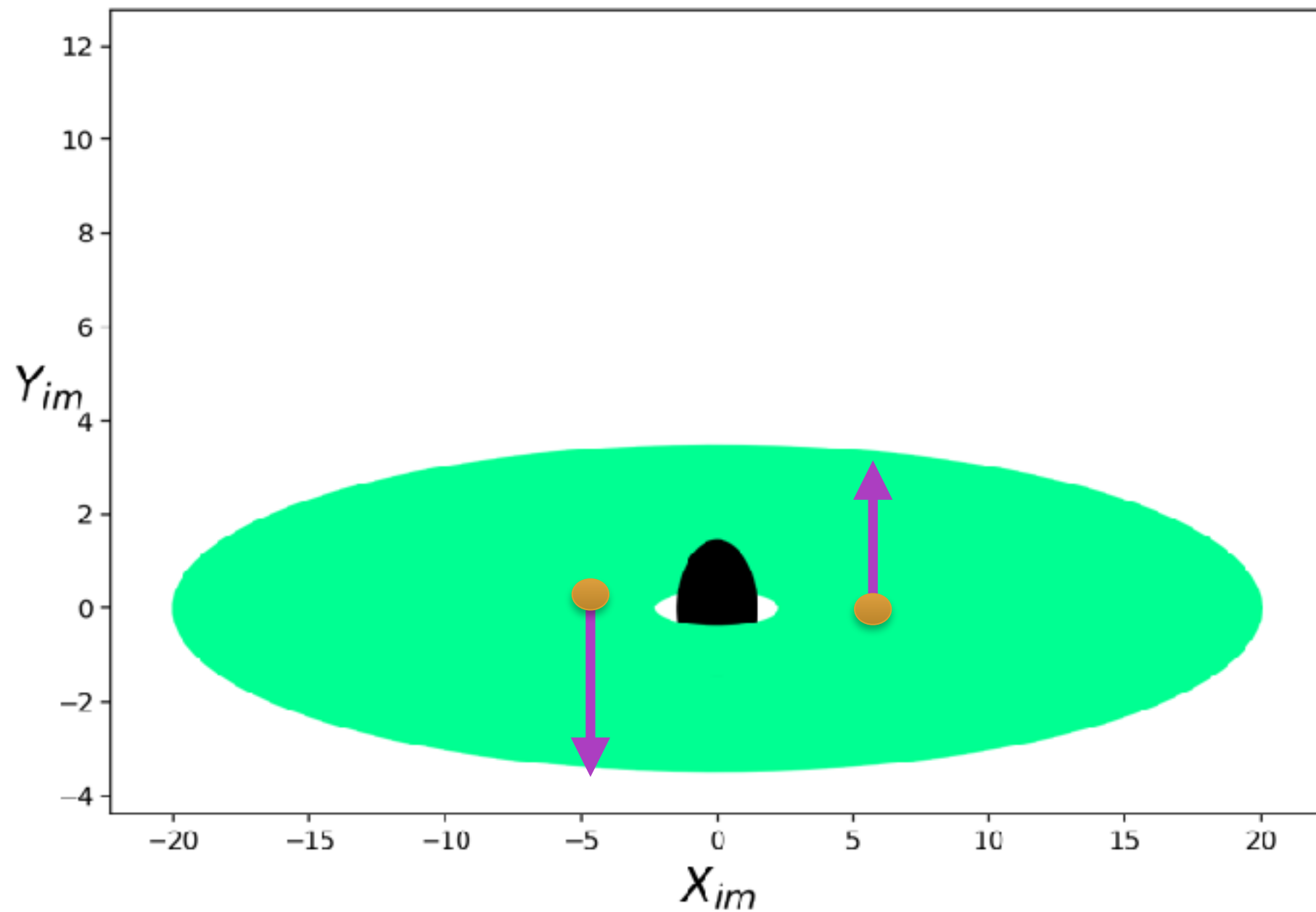




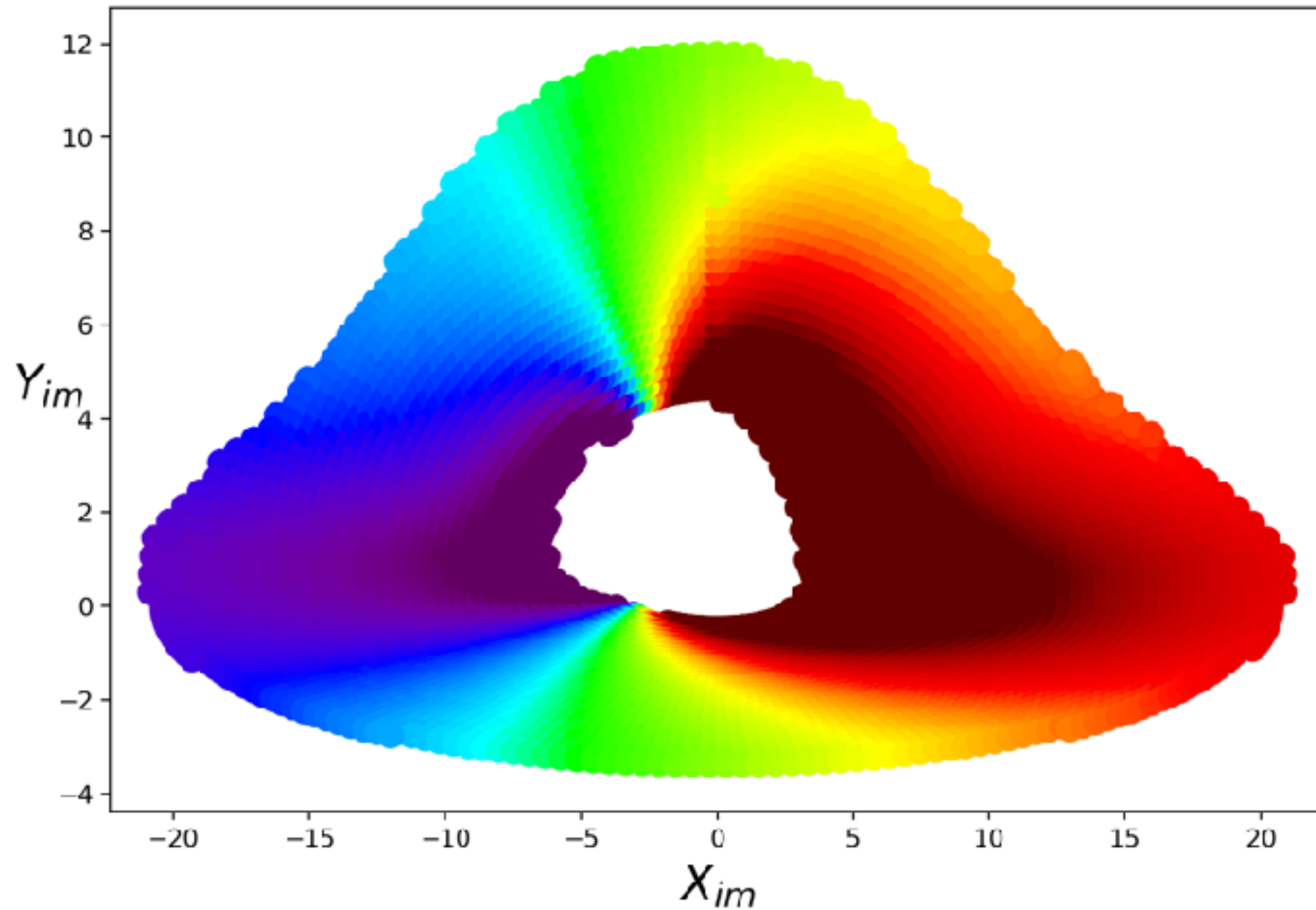
'Newtonian' Universe

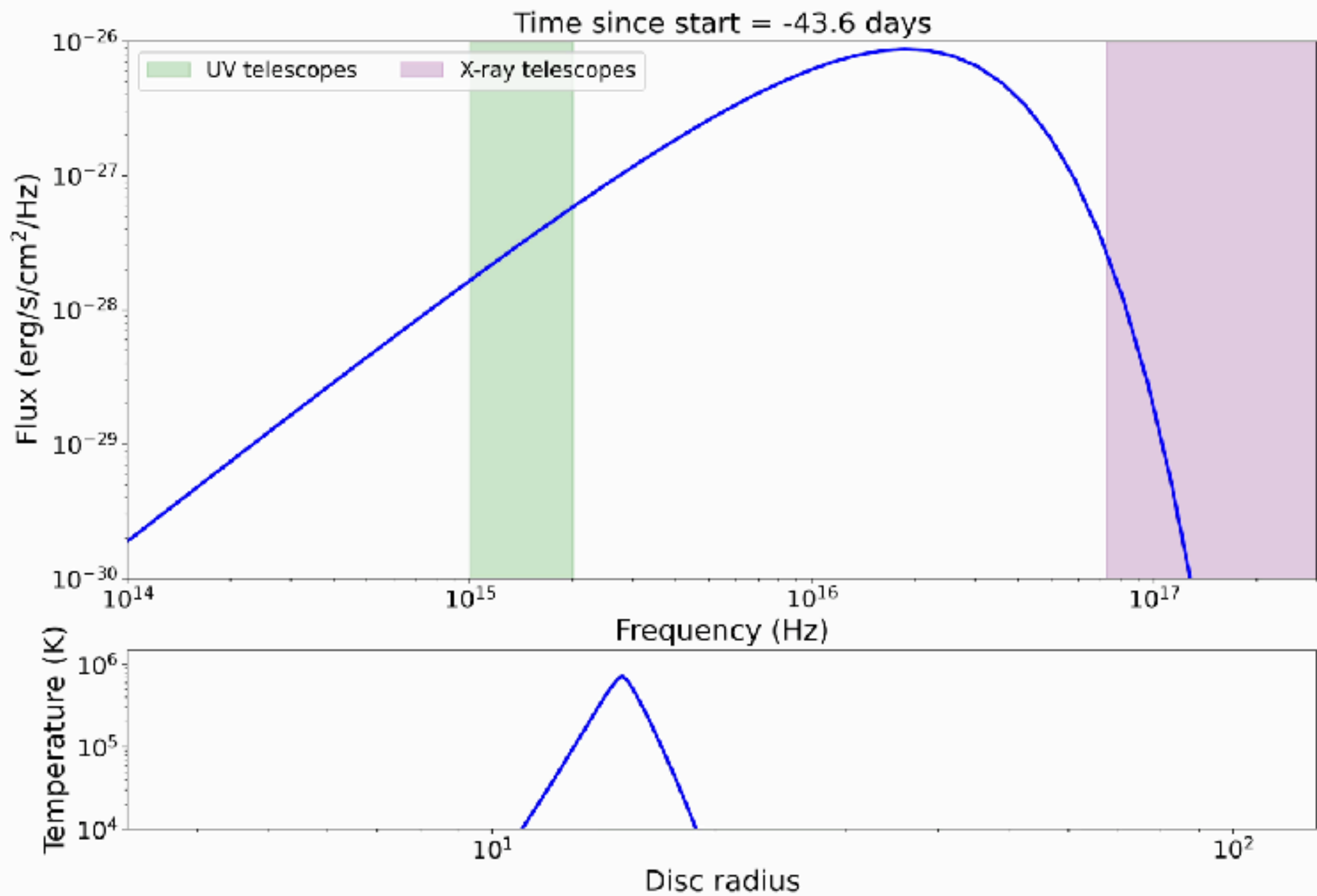


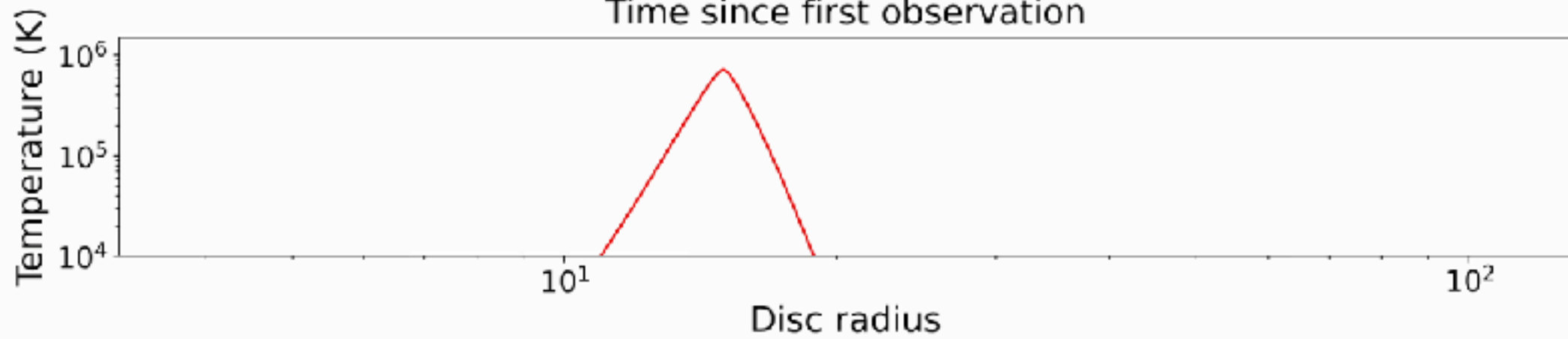
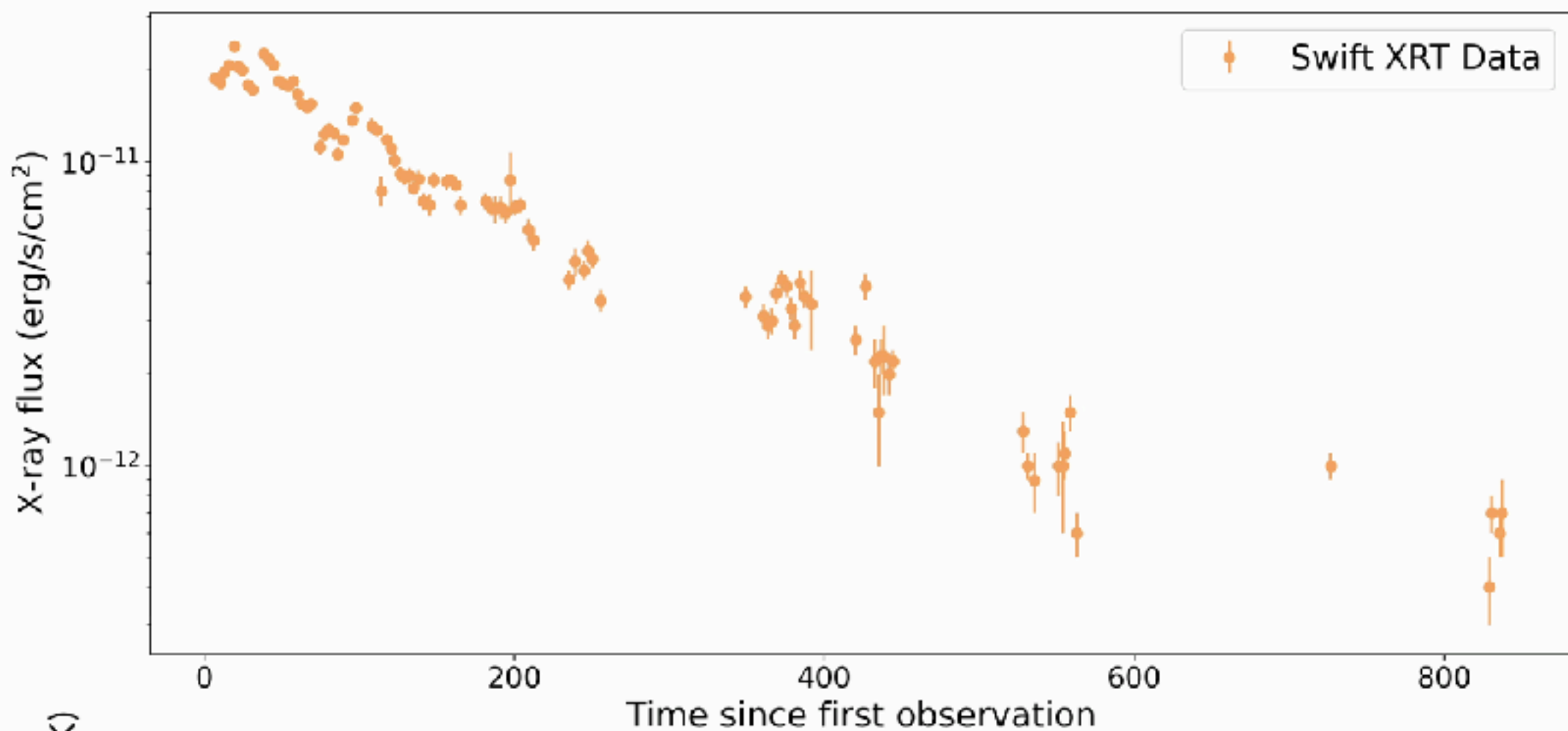
'Newtonian' Universe

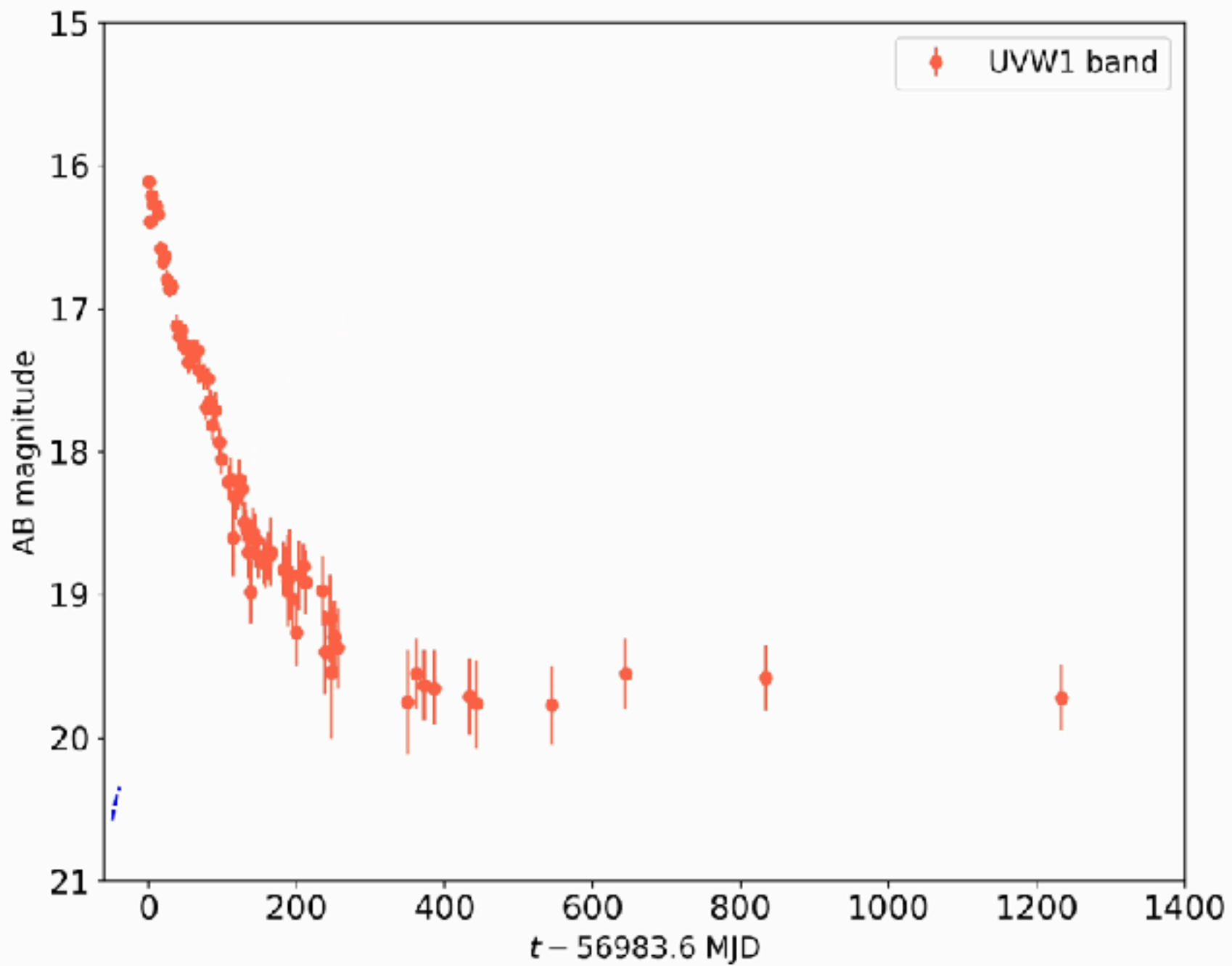


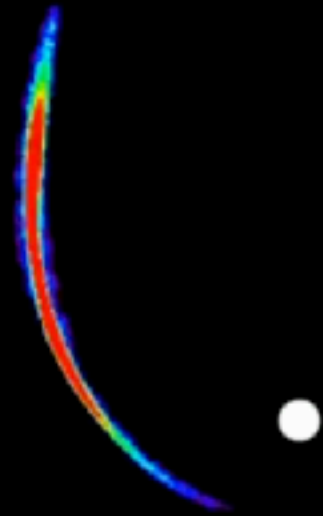
General Relativistic Universe

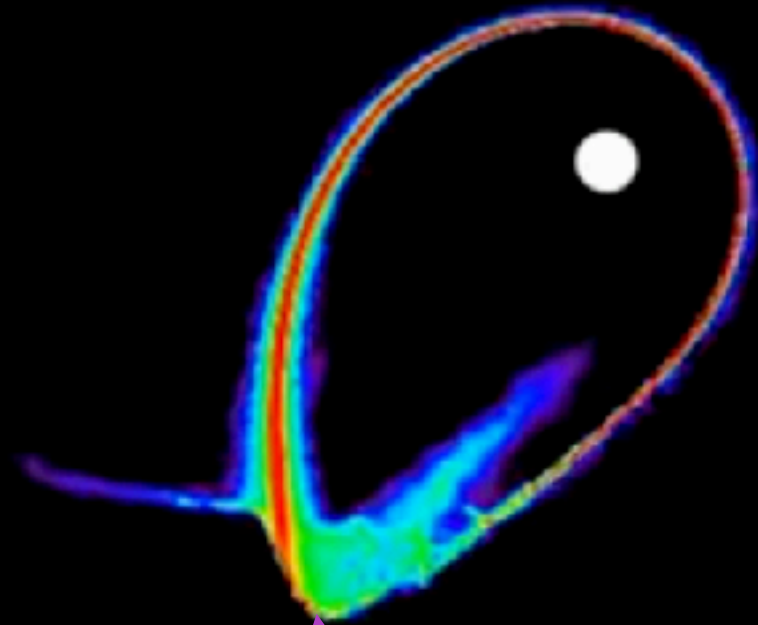




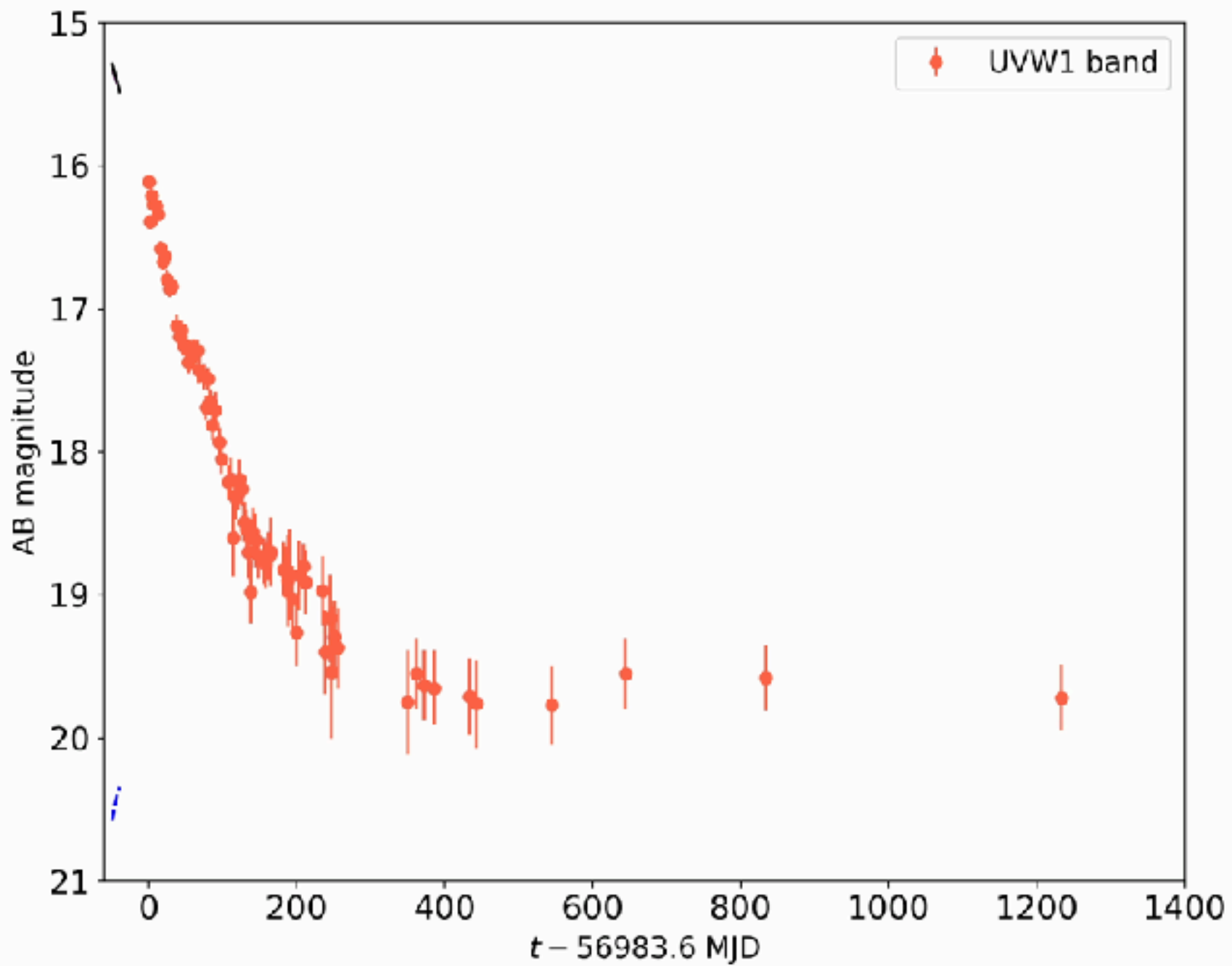




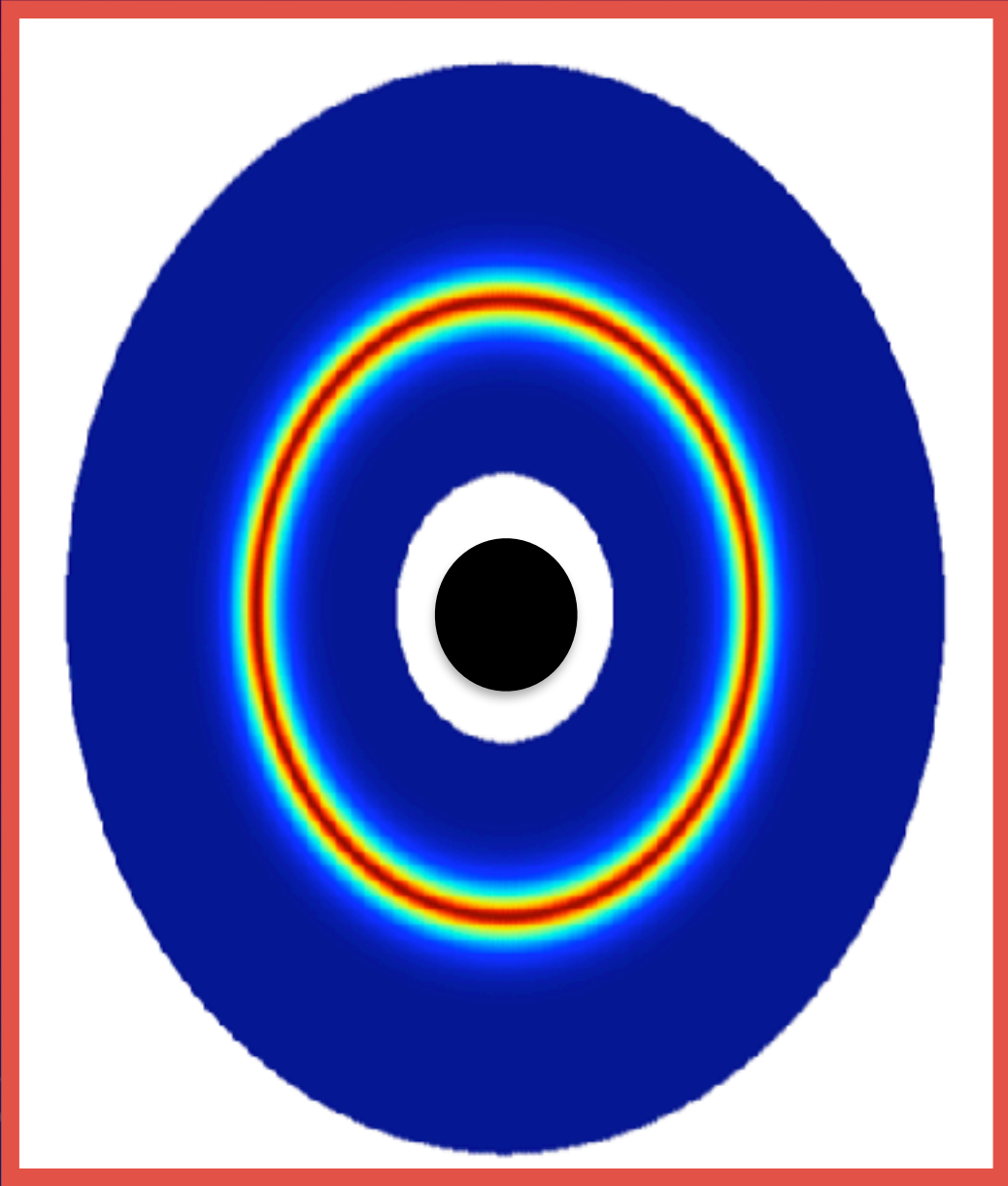




Shocks → Light

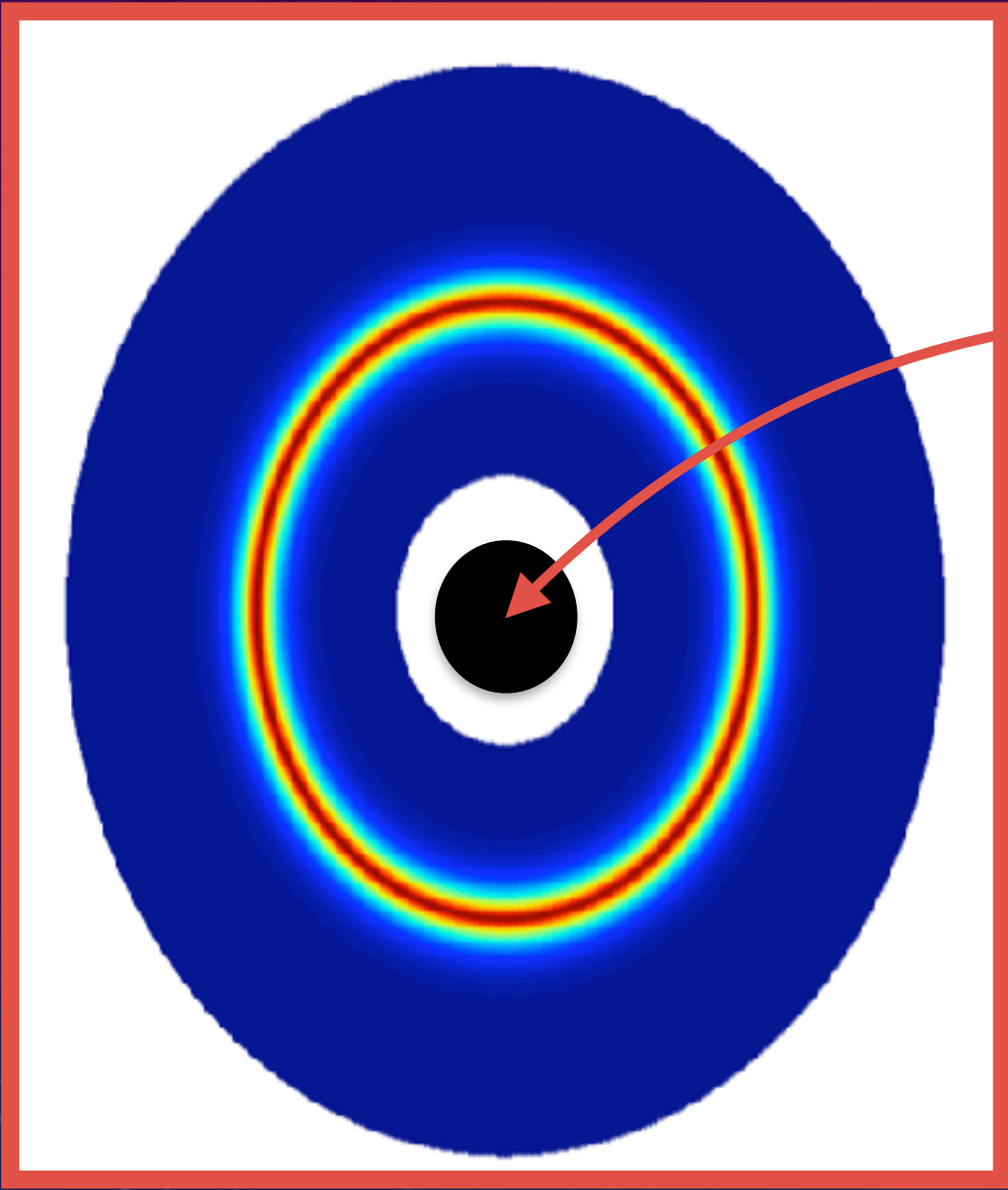


ASASSN-14li



ASASSN-14li

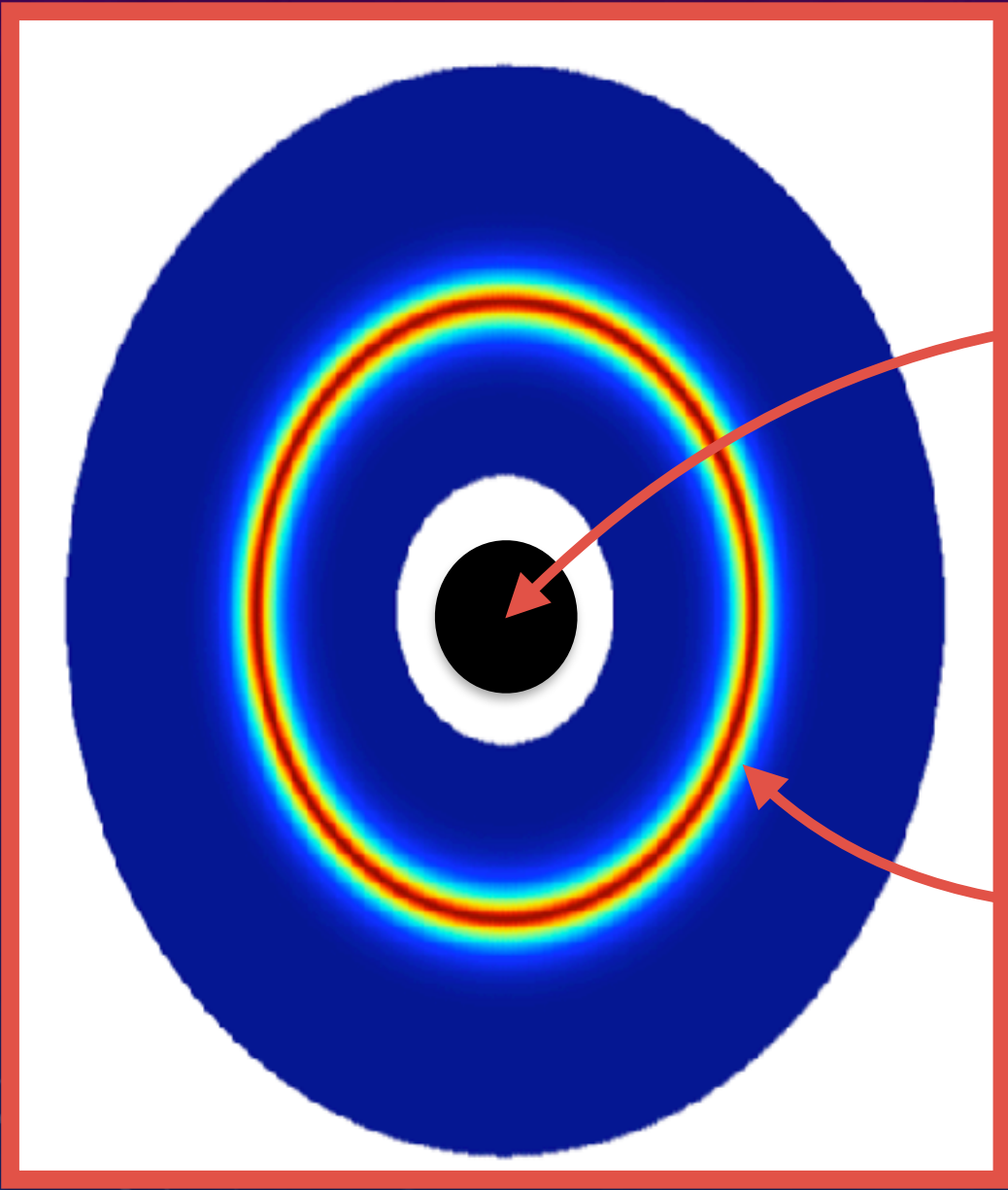
$$M_{\text{BH}} \simeq 2 \times 10^6 M_{\odot}$$



ASASSN-14li

$$M_{\text{BH}} \simeq 2 \times 10^6 M_{\odot}$$

$$M_{\text{disc}} \simeq 0.05 M_{\odot}$$

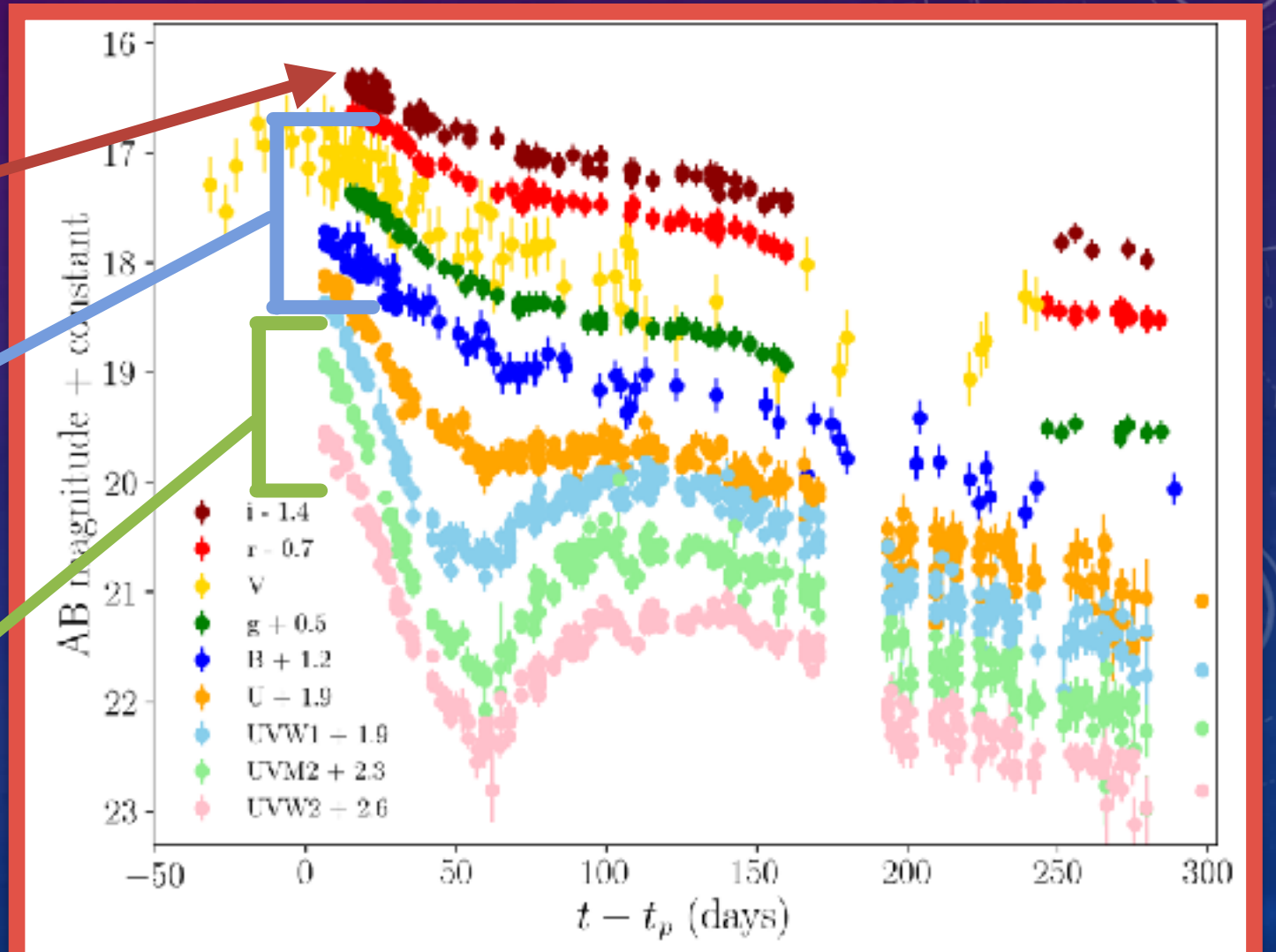


ASASSN-15lh

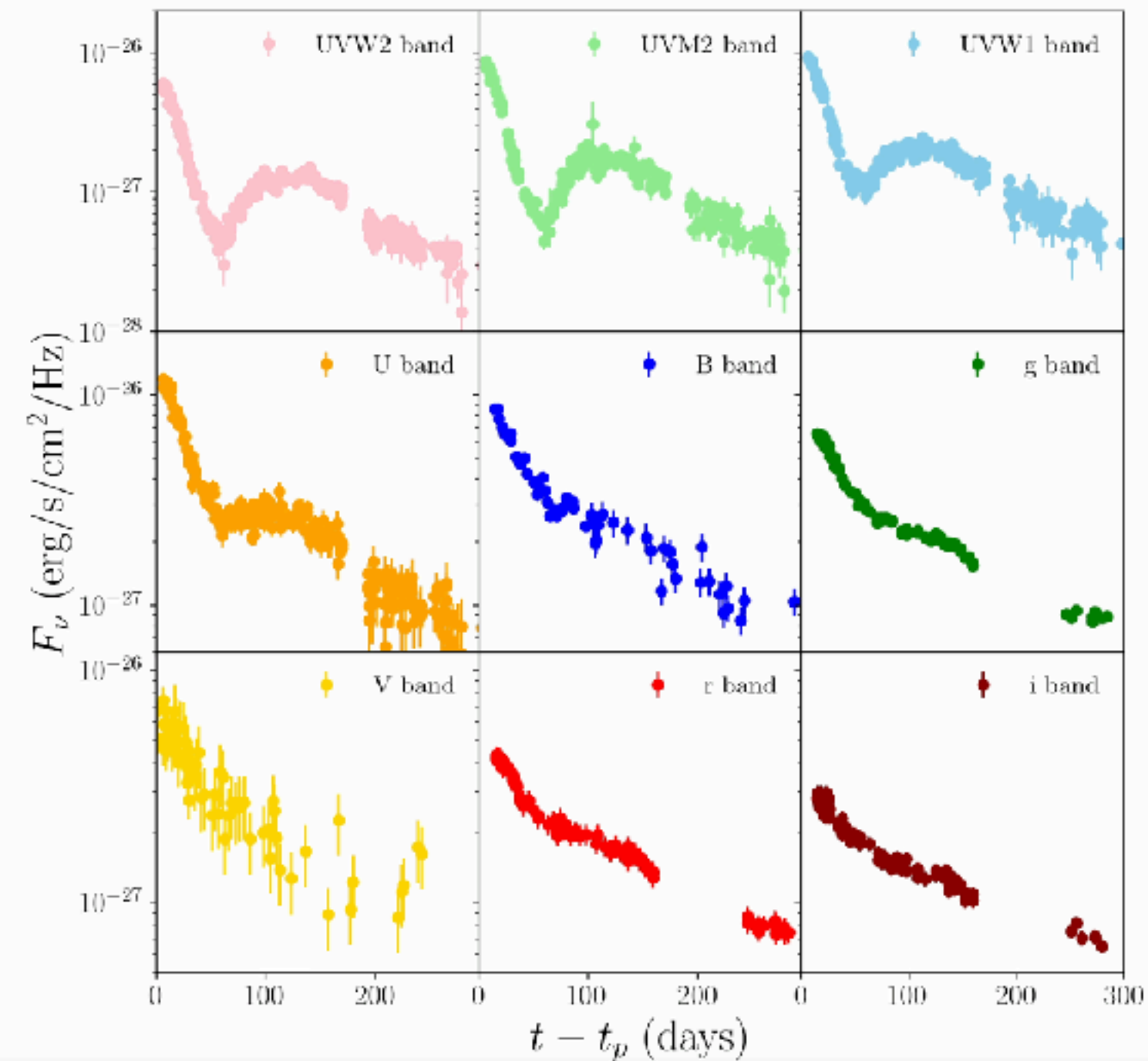
Infrared data

Optical data

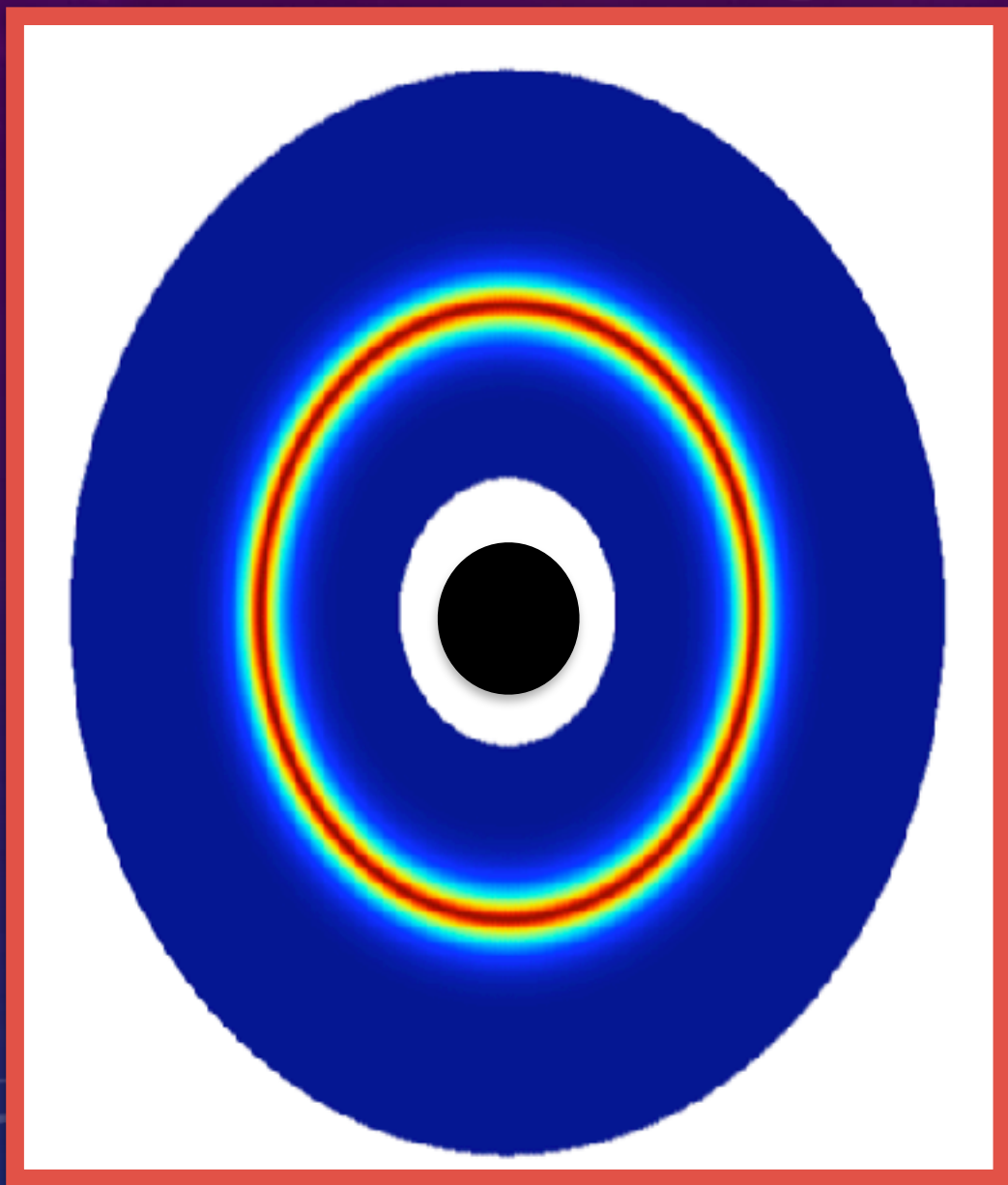
UV data



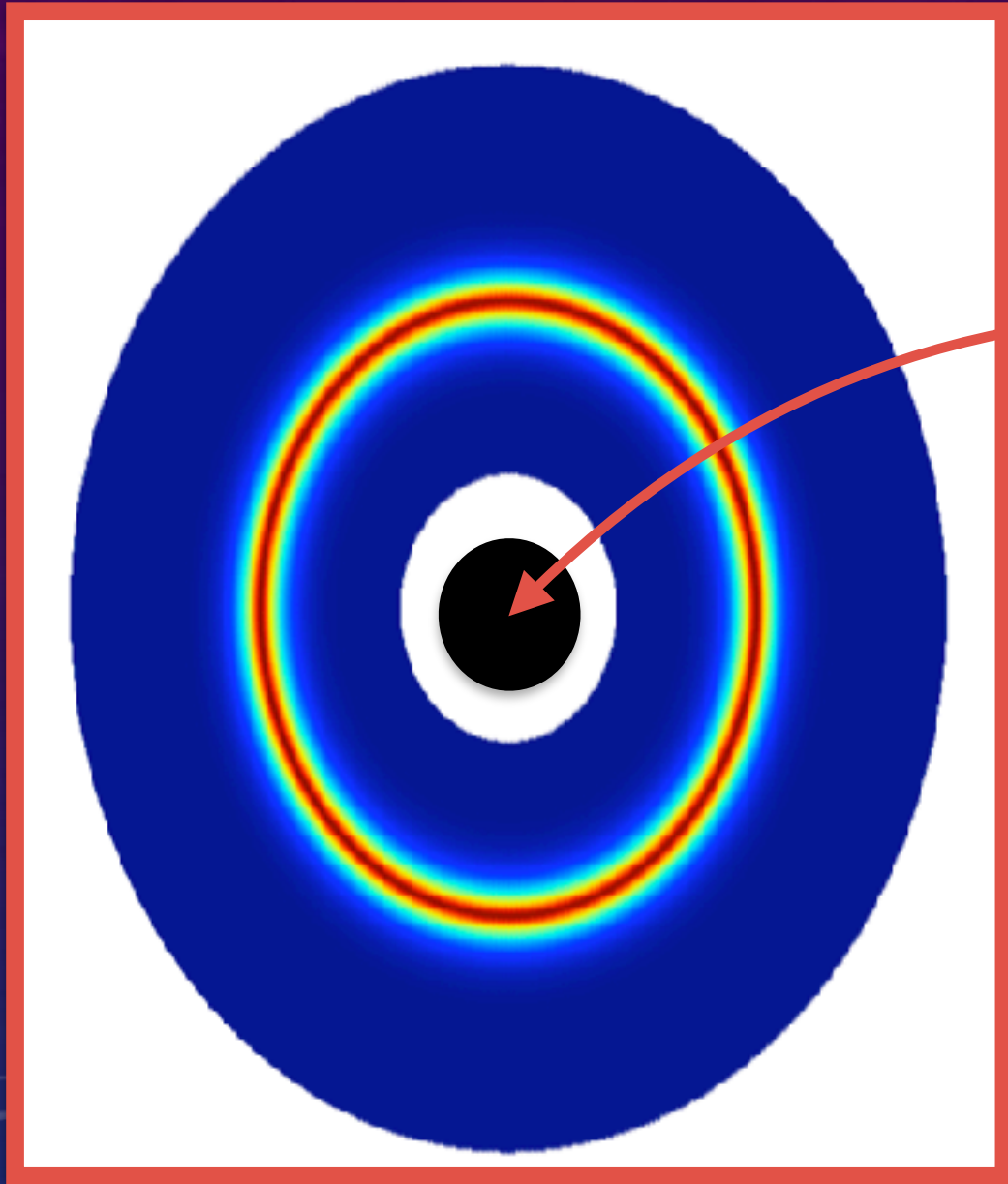
ASASSN-15lh



ASASSN-15lh



ASASSN-15lh

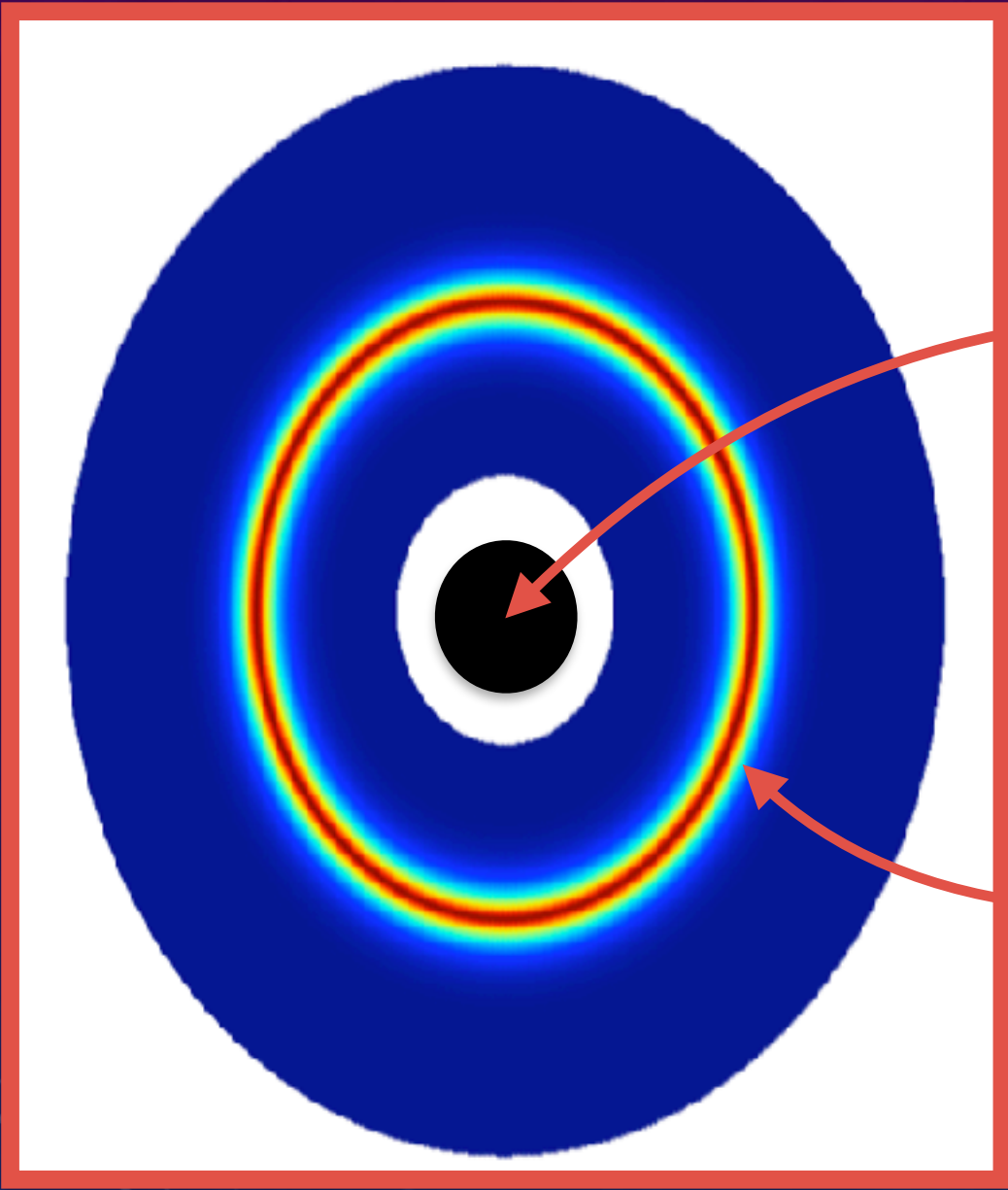


$$M_{\text{BH}} \simeq 1 \times 10^9 M_{\odot}$$

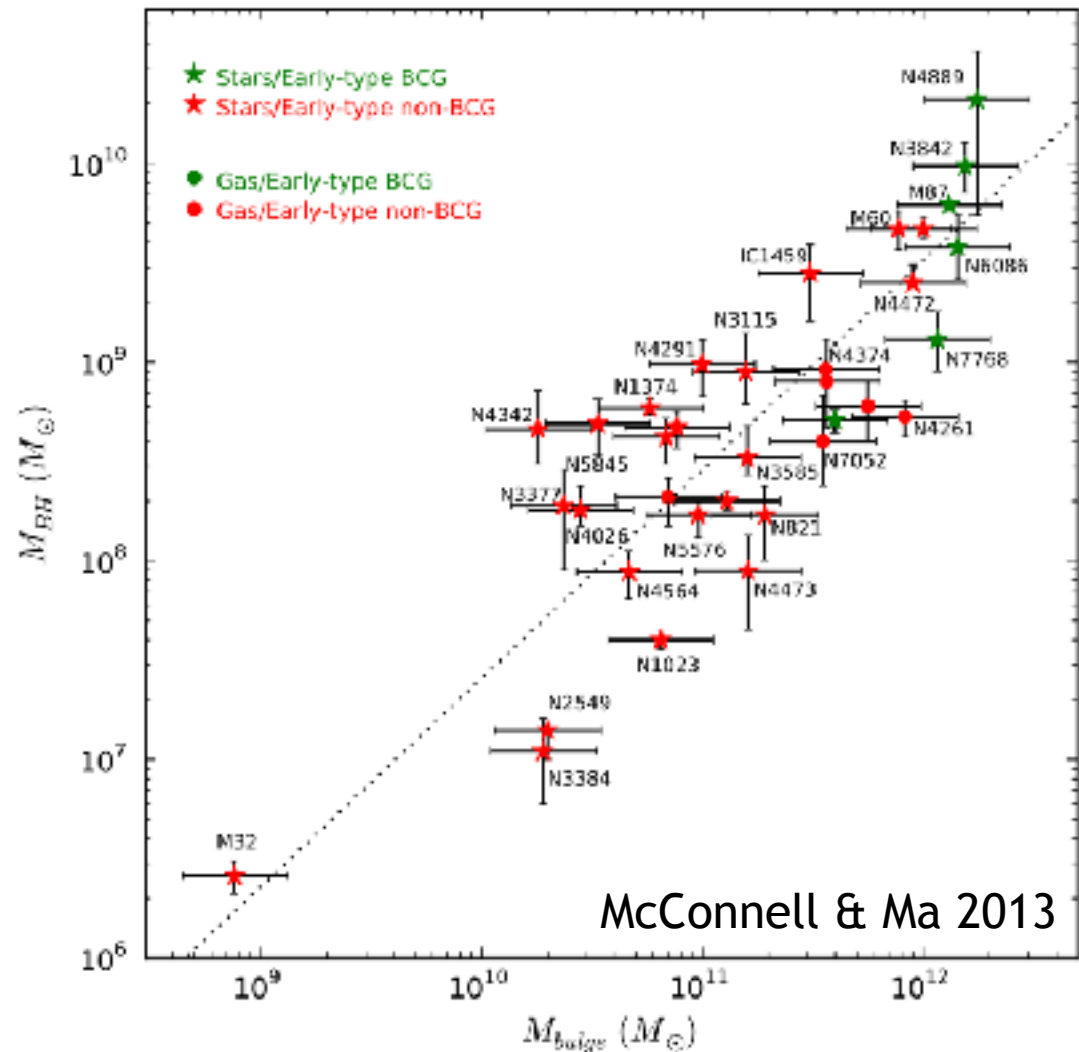
ASASSN-15lh

$$M_{\text{BH}} \simeq 1 \times 10^9 M_{\odot}$$

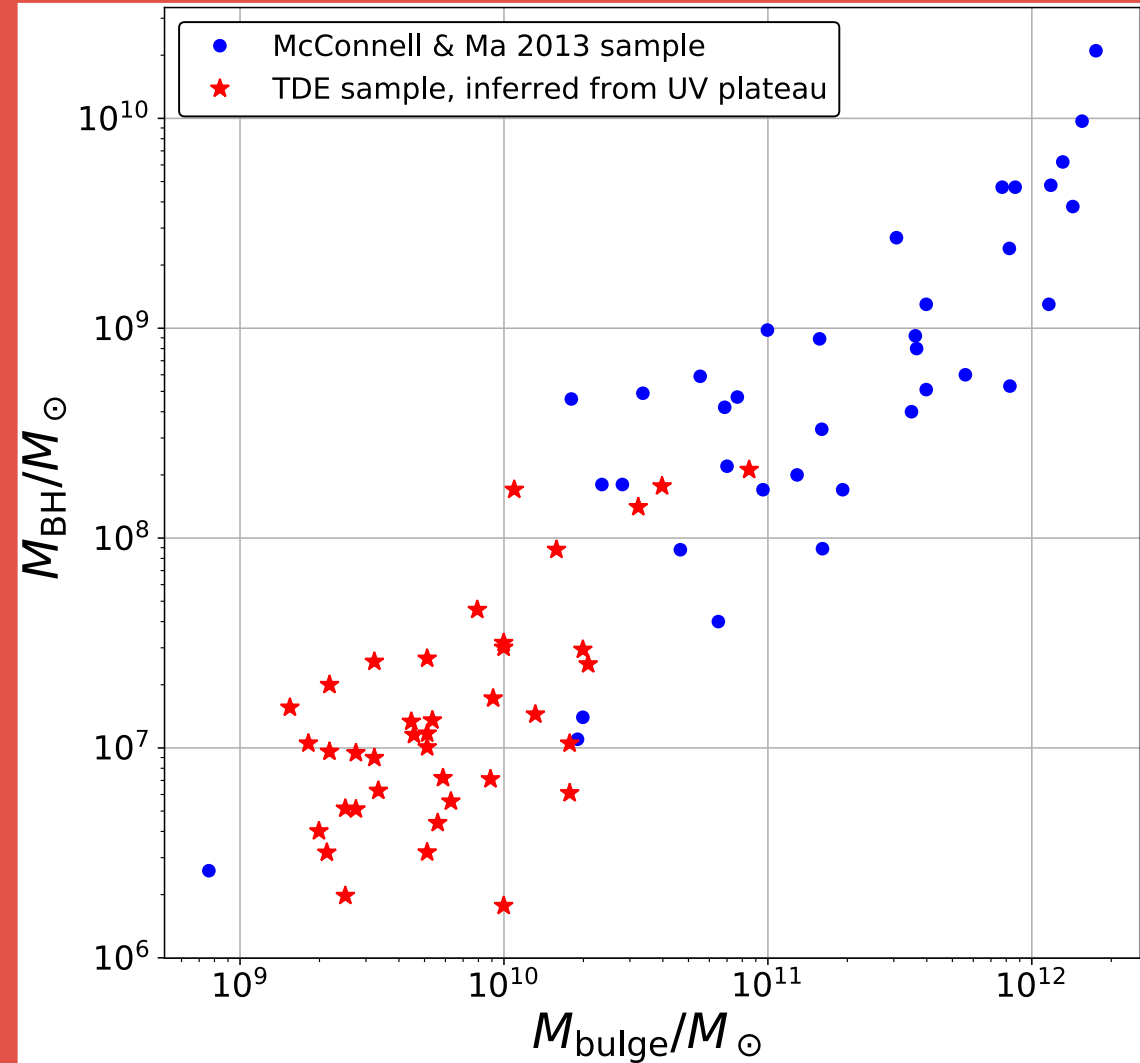
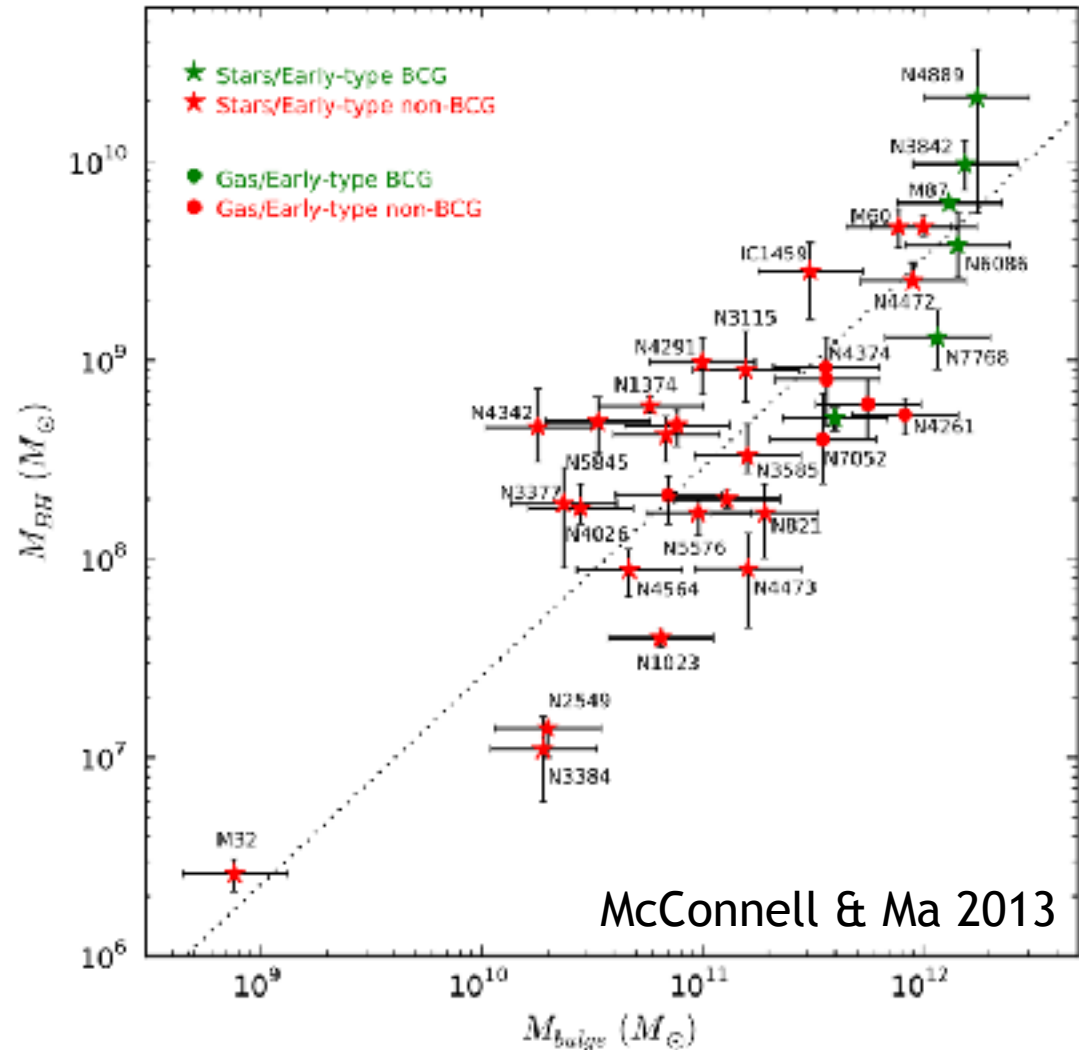
$$M_{\text{disc}} \simeq 0.1 M_{\odot}$$



WEIGHING SUPERMASSIVE BLACK HOLES



WEIGHING SUPERMASSIVE BLACK HOLES



TODAY'S TALK

1. Spaghettification occurs due to the extreme tidal forces near to black holes
2. Stellar Spaghettification produces emission observable at cosmological distances
3. Understanding these events allows us to weigh supermassive black holes