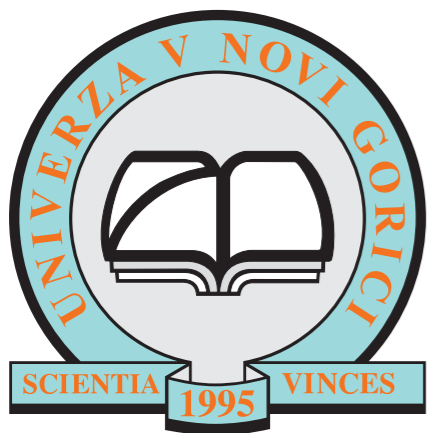


# Relativnost v astronomiji

---

Andreja Gomboc  
Fakulteta za naravoslovje  
Univerza v Novi Gorici

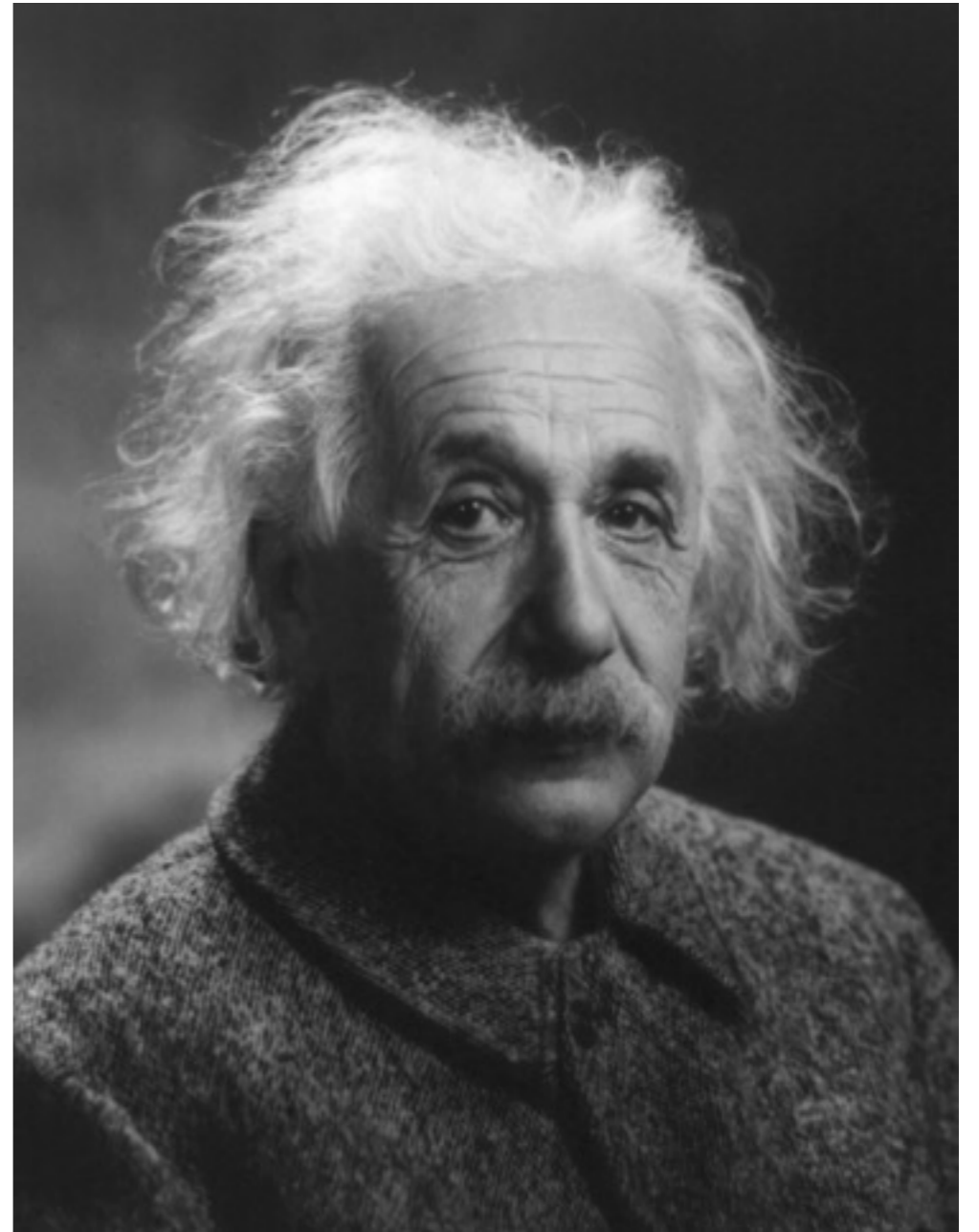


5. februar 2016, Sprehod skozi vesolje, ŠC Srečka Kosovela, Sežana

# relativnost

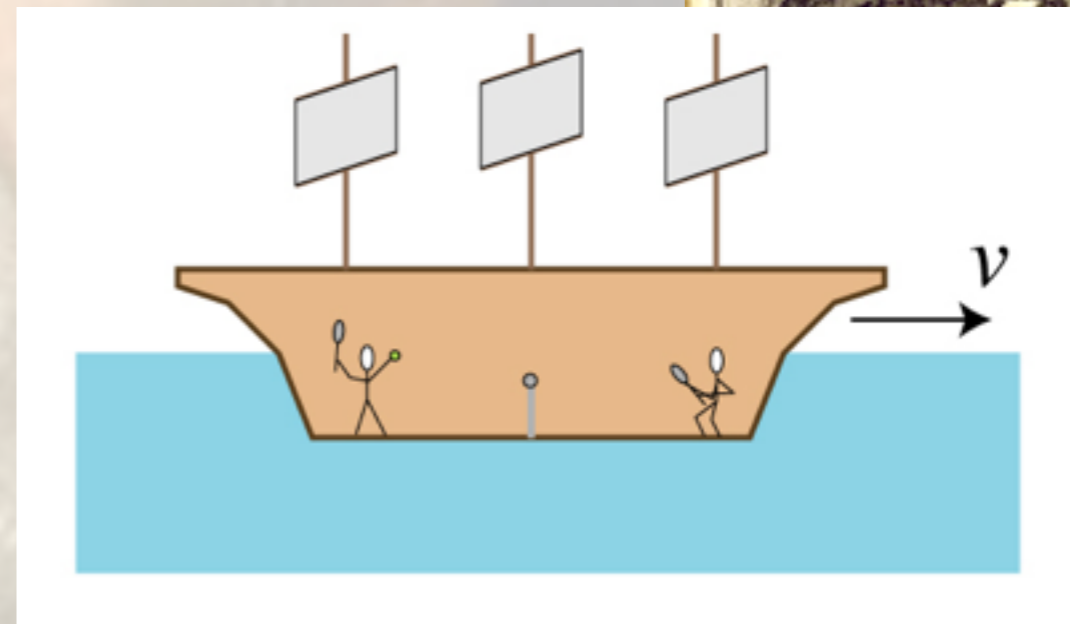
---

- Albert Einstein - oče relativnosti?



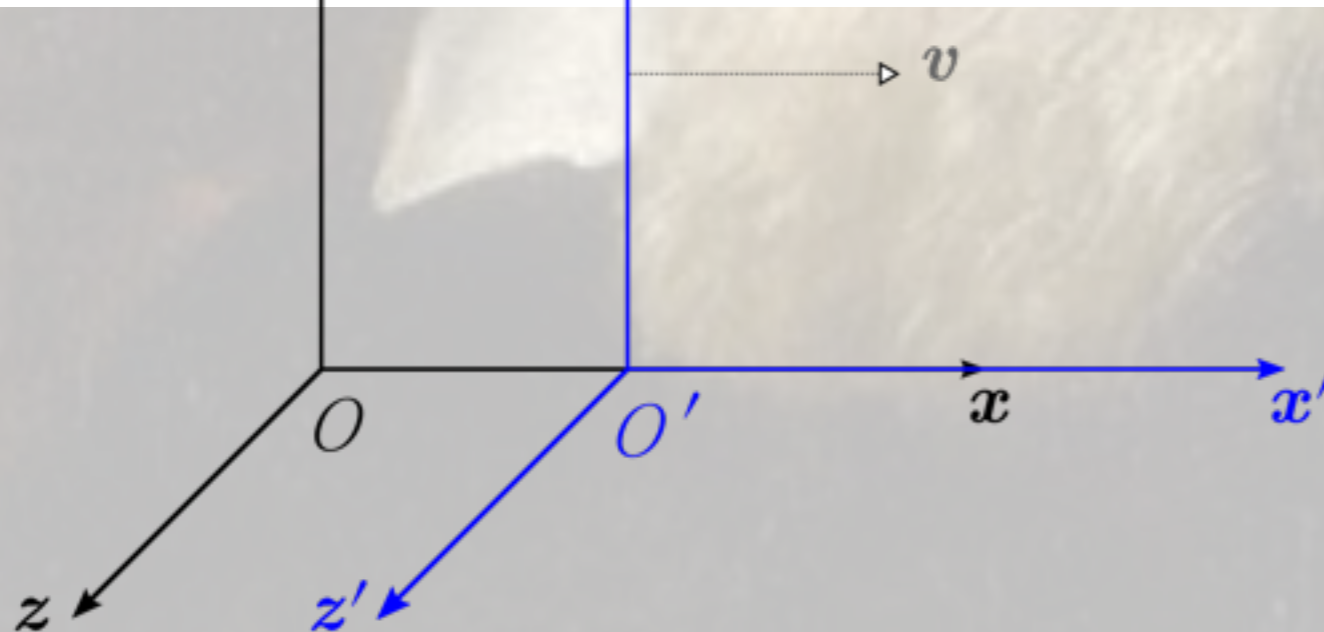
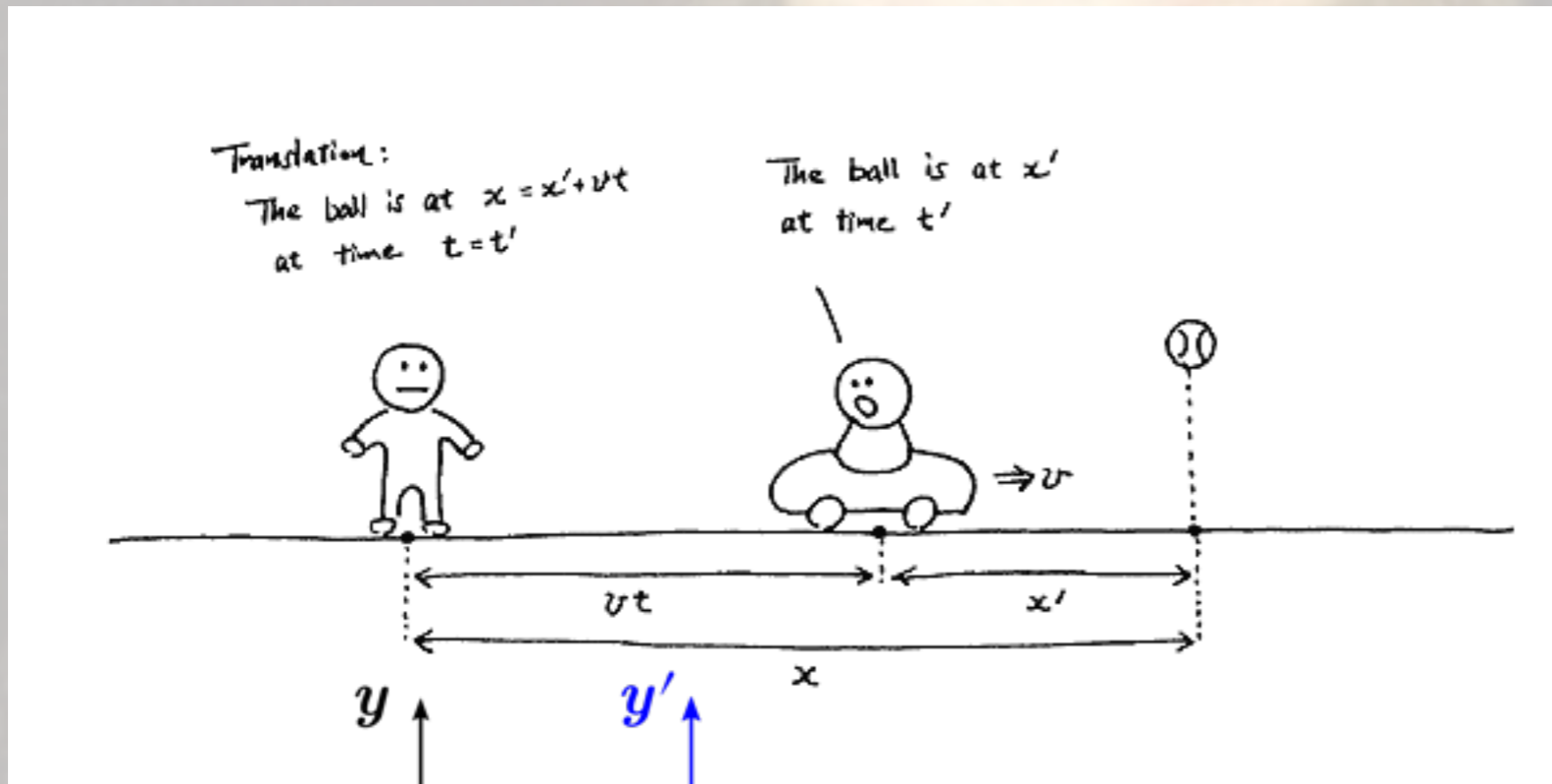
# relativnost in Galileo Galilej

Galileo (1632): "Dialog o dveh glavnih sistemih sveta" obravnana opazovanja gibanja, ki jih naredijo ljudje pod palubo ladje, ki ne vidijo zunanosti:



"Naj se ladja giblje s kakršnokoli hitrostjo, le da je gibanje enakomerno in brez zanašanj sem in tja. Ne boste opazili nobene razlike v naštetih pojavih, niti ne boste mogli iz njih ugotoviti ali se ladja giblje ali miruje. "

# Galilejeve transformacije



$$x' = x - vt$$

$$y' = y$$

$$z' = z$$

$$t' = t$$

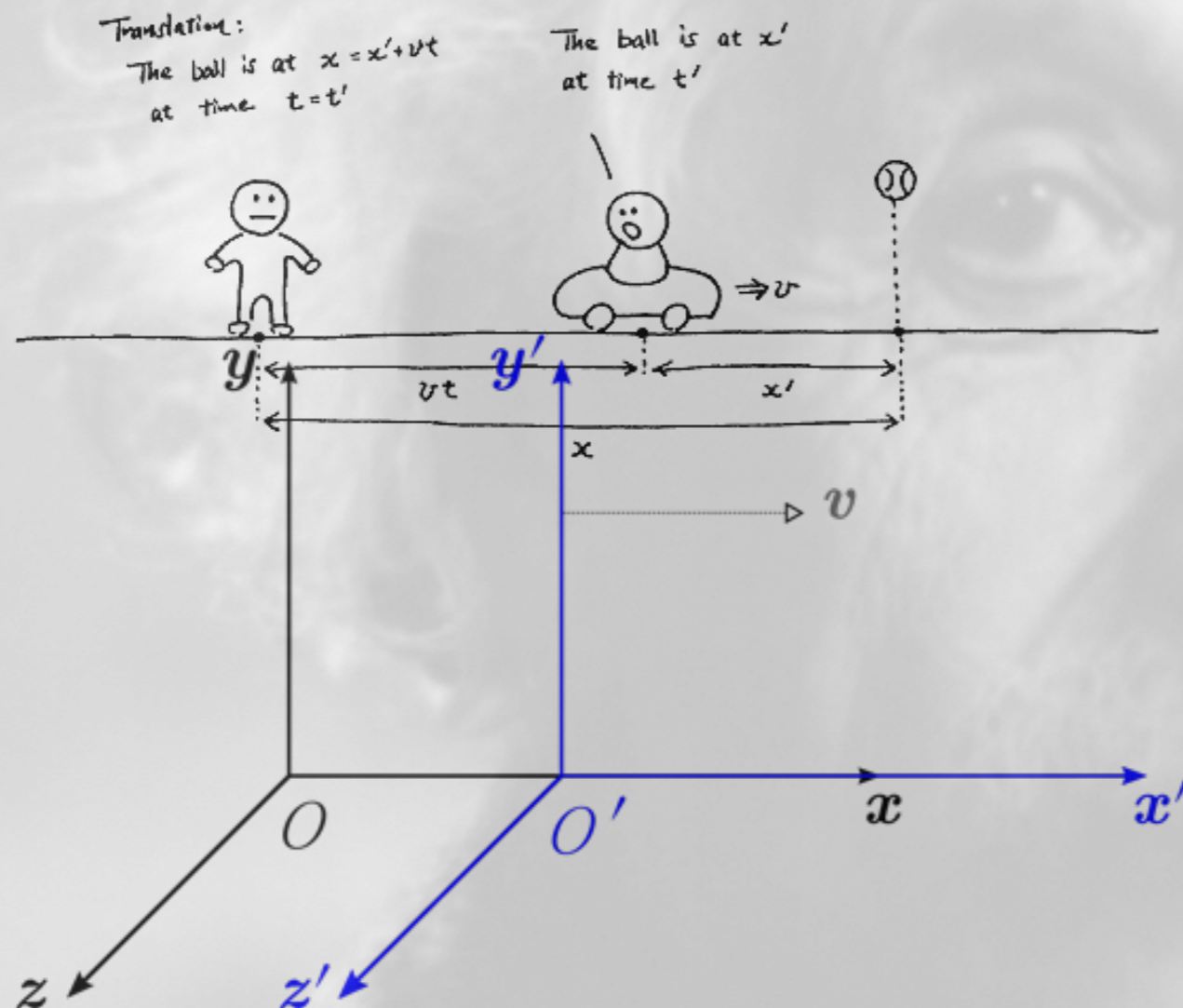
# relativnost in Albert Einstein

---

- hitrost svetlobe:  $c = 300.000 \text{ km/s}$
- posebna teorija relativnosti (1905):
  - relativnost gibanja, ko se  $v$  približuje  $c$
- **posebna teorija relativnosti** v Einsteinovi formulaciji sloni na dveh osnovnih načelih:
- **načelo relativnosti** – zakoni narave imajo v vseh inercialnih sistemih enako obliko. Vsi inercialni sistemi so med seboj enakovredni.
- **načelo o hitrosti svetlobe** – hitrost svetlobe v praznem prostoru je v vseh inercialnih sistemih konstantna.
- Implicitno privzame ta teorija tudi načelo o homogenosti časa in o homogenosti in izotropnosti prostora.

# inercialni sistem

- nepospešeni sistem (ne zavira, se ne vrti ipd.)
- prostorčas: 4 dimenzije (čas + 3 prostorske):  $t, x, y, z$

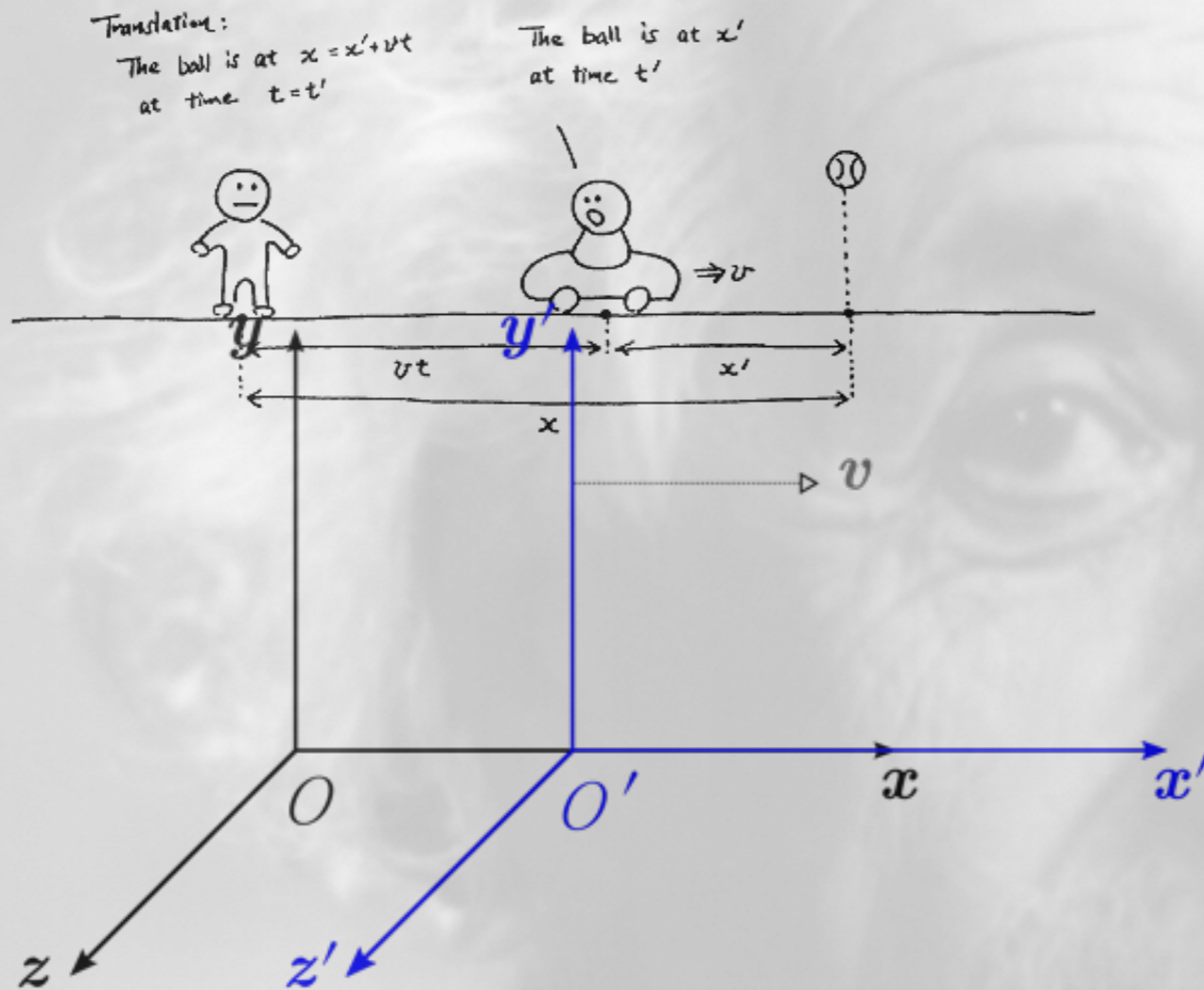


$$\beta = v/c$$

Lorentzov faktor:

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

# Lorentzove transformacije



$$x' = \gamma(x - vt)$$

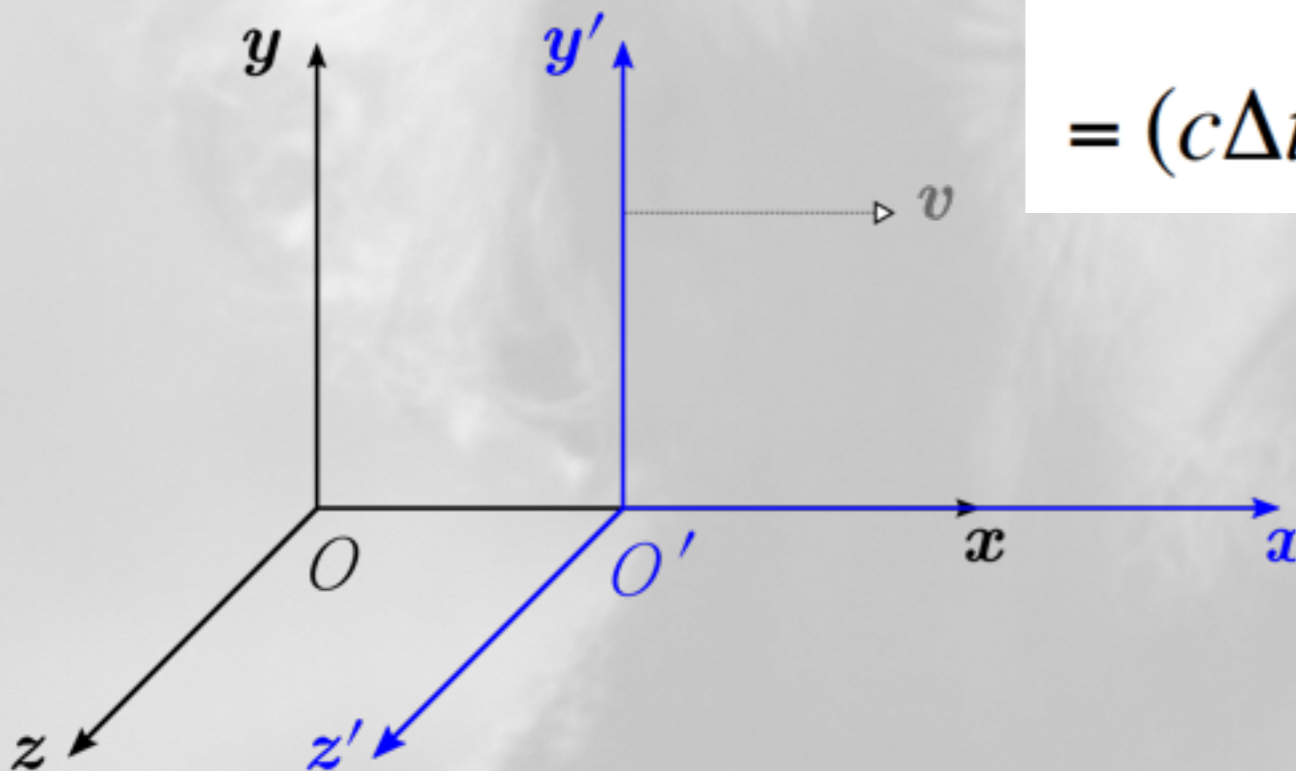
$$y' = y$$

$$z' = z$$

$$t' = \gamma\left(t - \frac{v}{c^2}x\right)$$

# čas - 4. koordinata

- 4 koordinate napišemo v vektor četverec:  $(ct, x, y, z)$
- sprememba položaja:  $(c\Delta t, \Delta x, \Delta y, \Delta z)$
- skalarni produkt četverca s samim sabo je invarianten na Lorentzove transformacije:



$$\begin{aligned}\Delta s^2 &= (c\Delta t)^2 - \Delta x^2 - \Delta y^2 - \Delta z^2 = \\ &= (c\Delta t')^2 - \Delta x'^2 - \Delta y'^2 - \Delta z'^2 = \Delta s'^2\end{aligned}$$



# podaljšanje časa

$S'$  ... lastni sistem (se giblje z delcem)

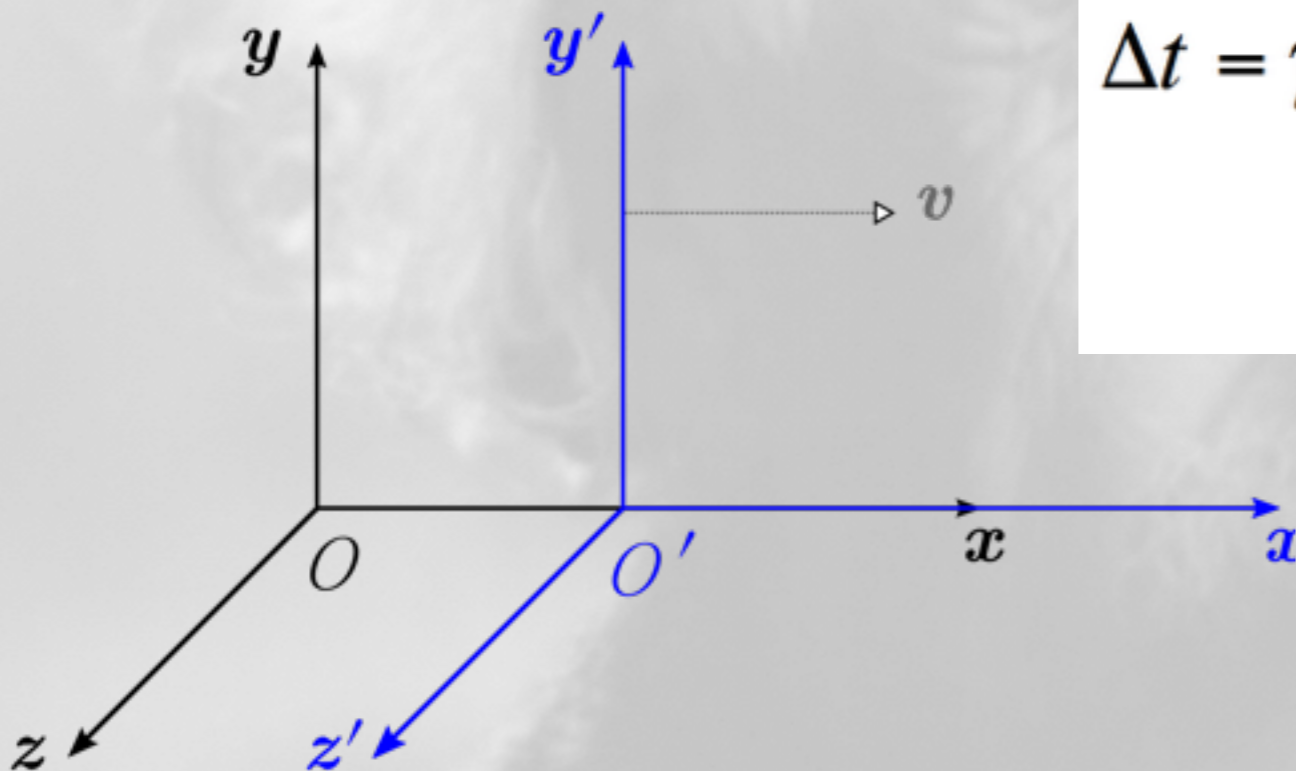
v sistemu  $S'$  delec torej miruje:  $\Delta x = 0, \Delta y = 0, \Delta z = 0$

$$\Delta s^2 = \Delta s'^2 = (c\Delta t')^2 = c^2 \Delta \tau^2$$

$t'$  ... lastni čas, označimo tudi s  $\tau$

V sistemu  $S$ , ki se giblje z  $v$  glede na  $S'$ , velja po Lorentzovi transformaciji:

$$\Delta t = \gamma \Delta \tau = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \Delta \tau$$



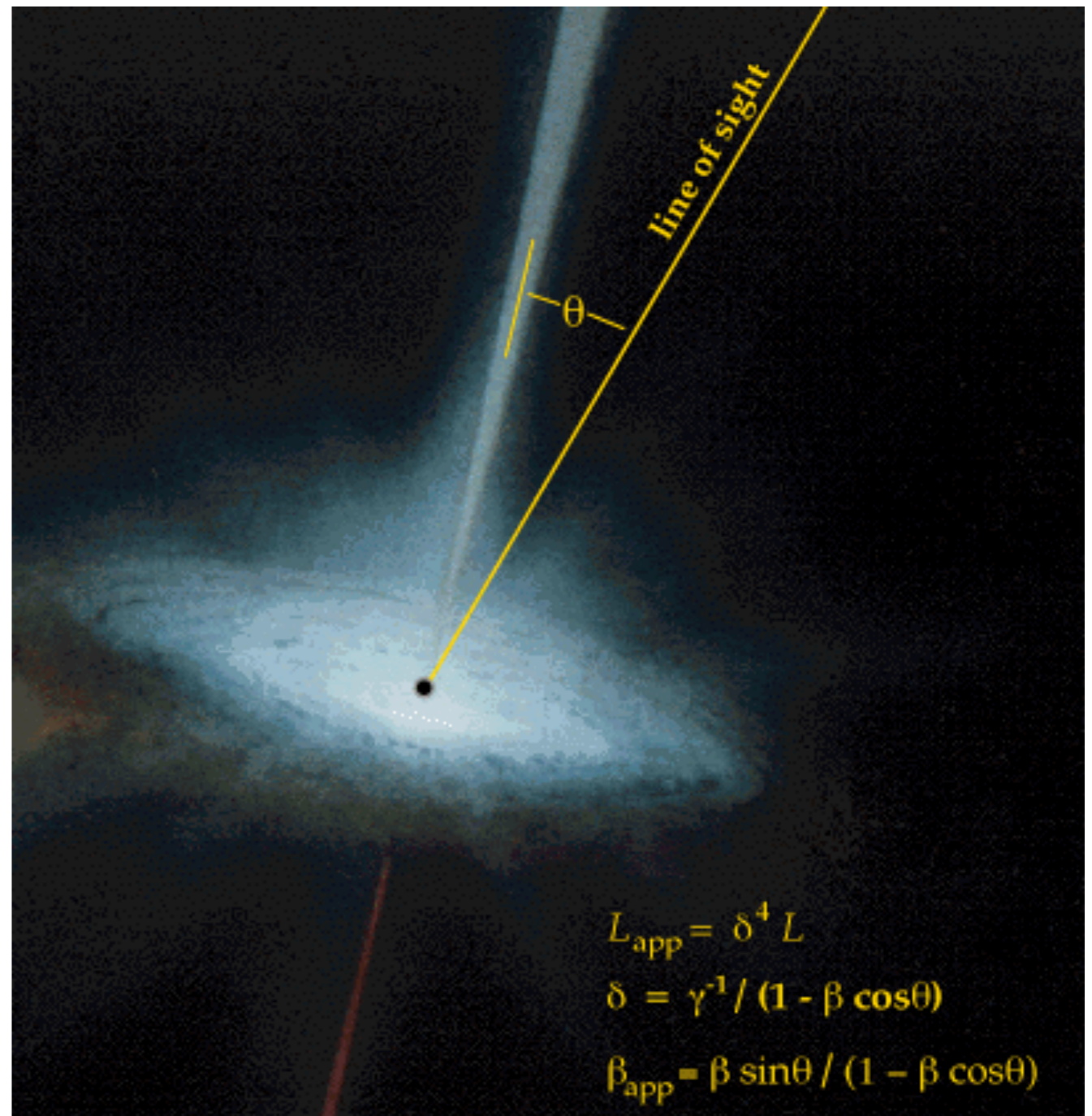
Primer iz fizike osnovnih delcev:

mioni imajo v mirovanju:  $\tau_0 = 2,2 \cdot 10^{-6} \text{ s}$

ko se gibljejo z  $\gamma=29,3$ :  $\tau_1 = 64,3 \cdot 10^{-6} \text{ s}$

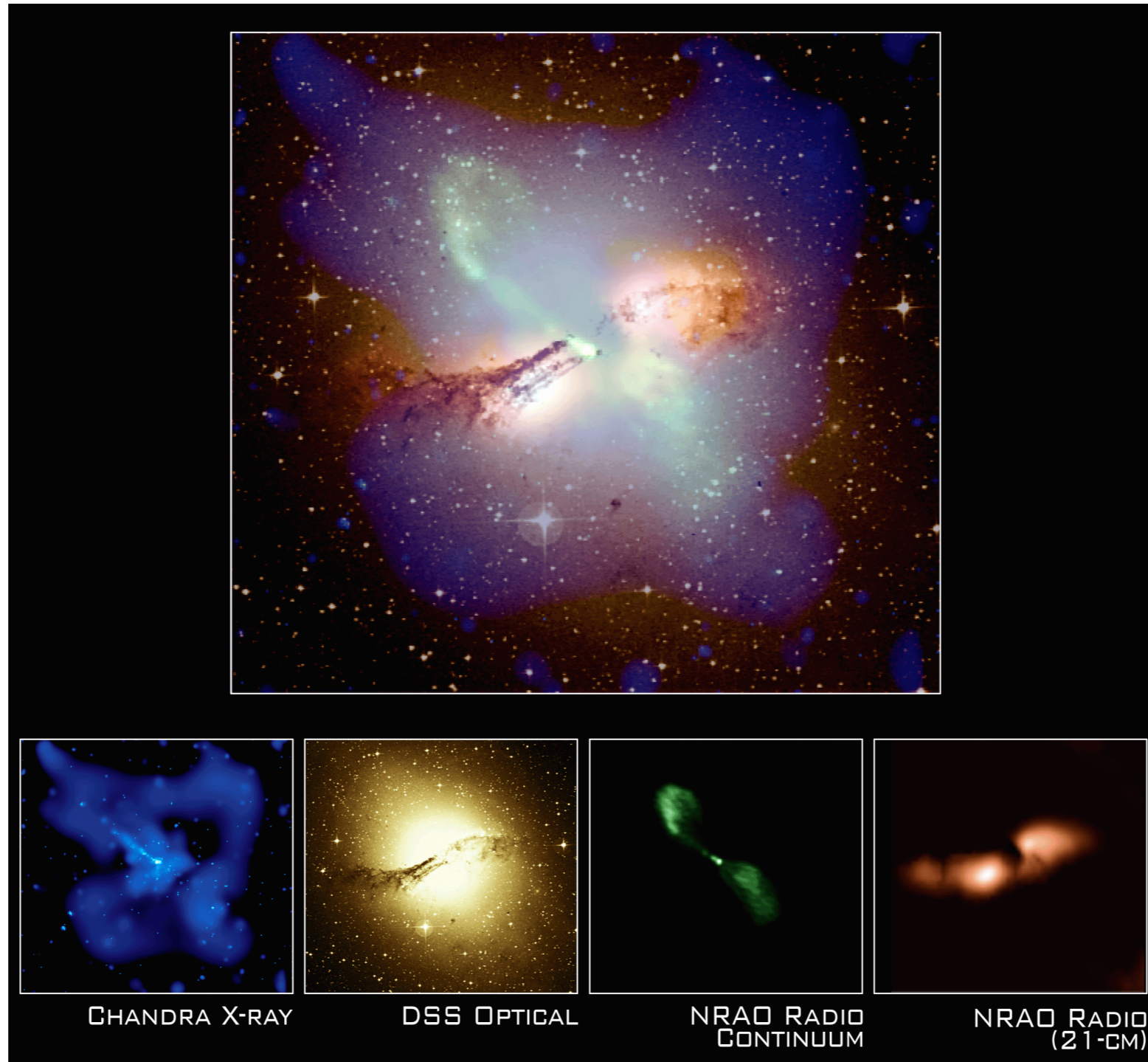
# primer v astronomiji: nadsvetlobno gibanje

- curek usmerjen skoraj proti nam



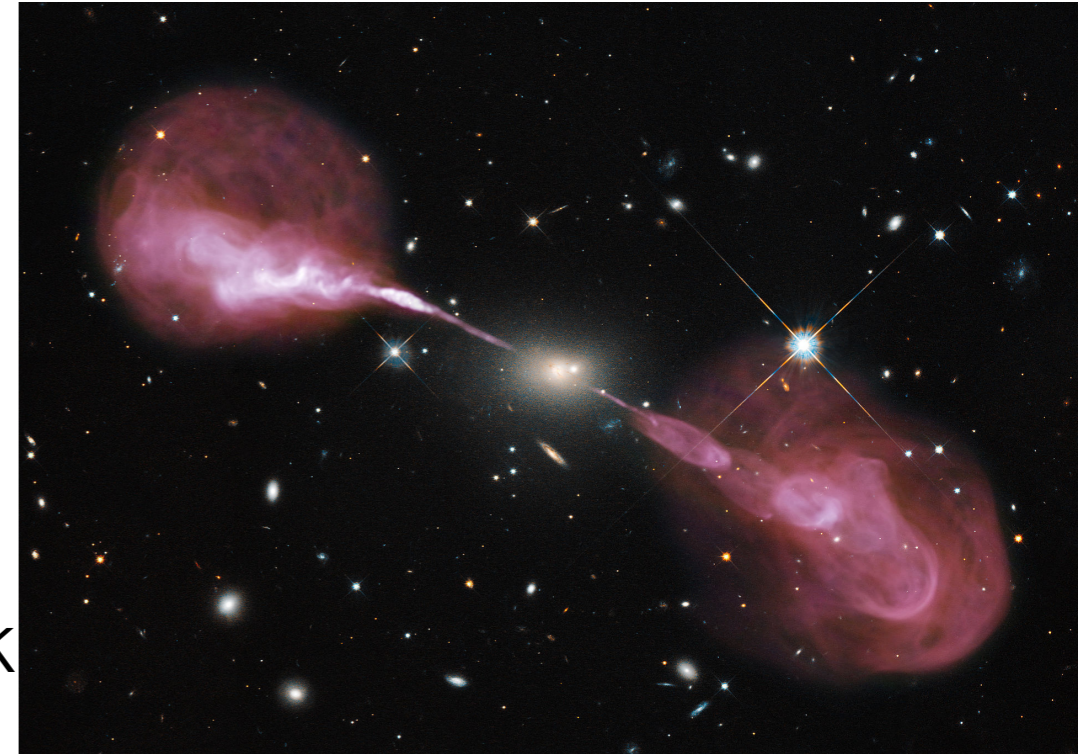
# aktivna galaktična jedra

---



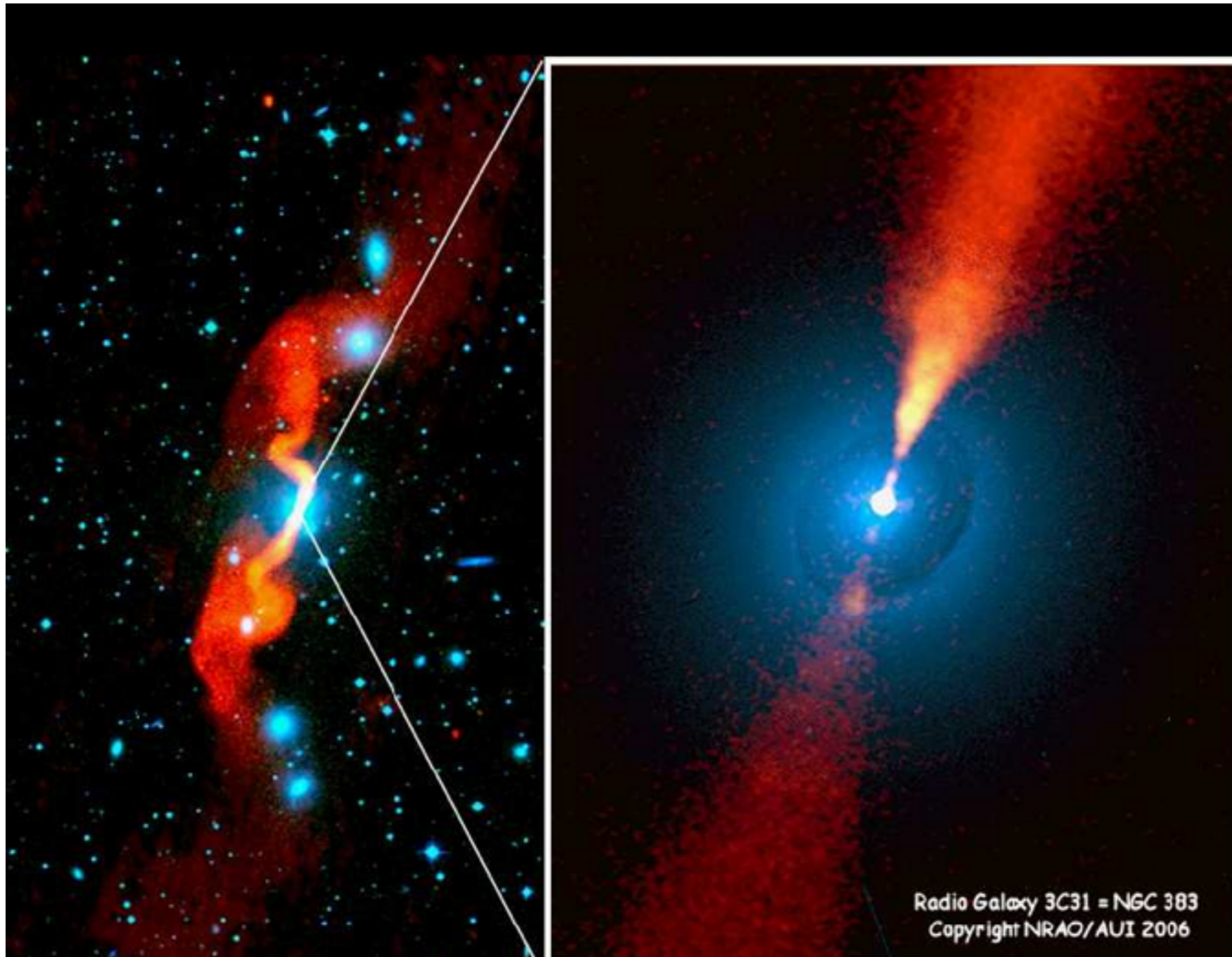
# aktivna galaktična jedra

- ogromen izsev v središču galaksije  
 $L \sim 10^{40} \text{ W} \sim 25 \text{ bilijonov Sonc} \sim$   
 $\sim 250 \text{ običajnih galaksij}$
- iz majhnega območja
- curki snovi dolgi milijone sv. let
- model: supermasivna črna luknja + disk

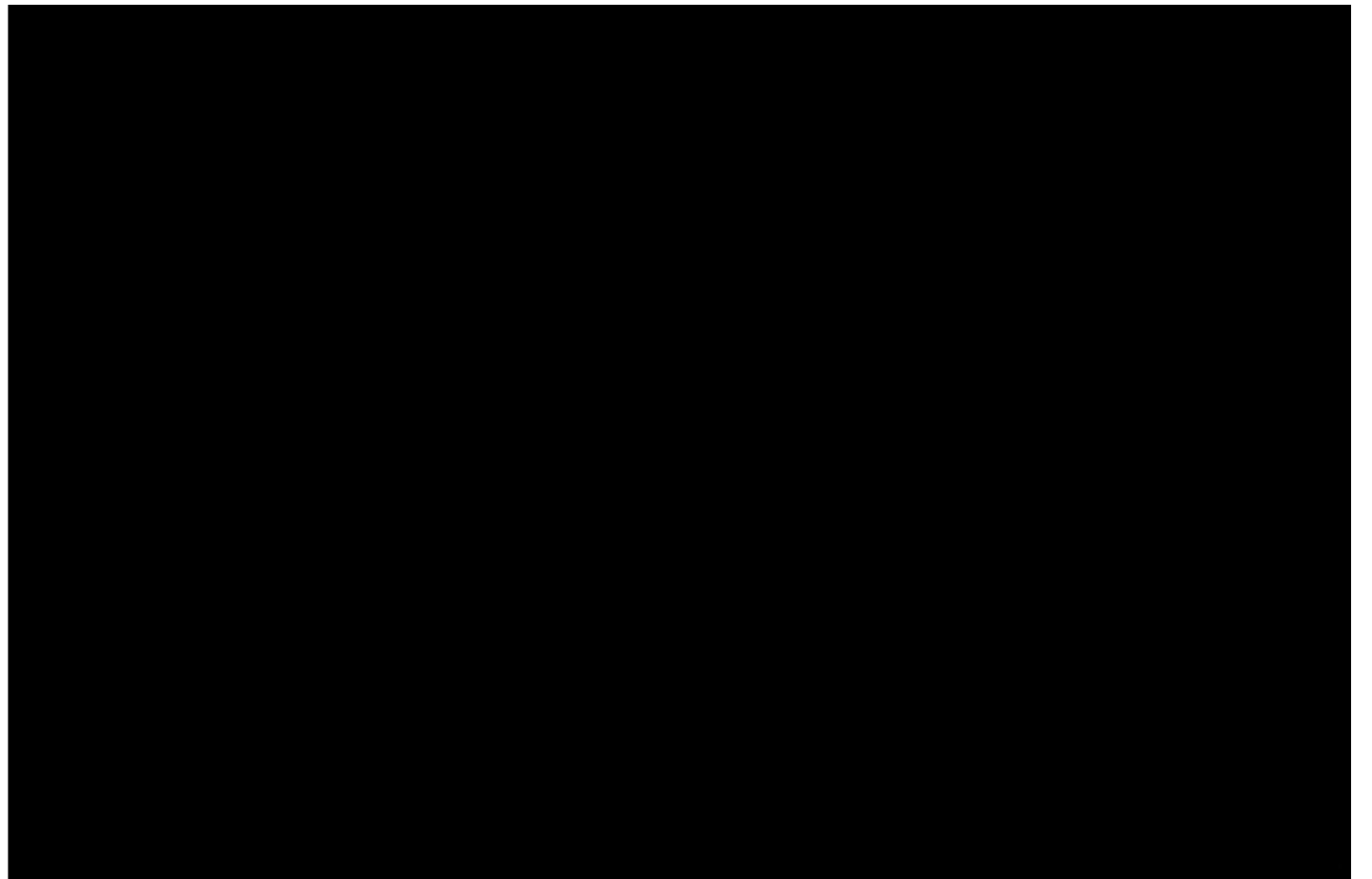
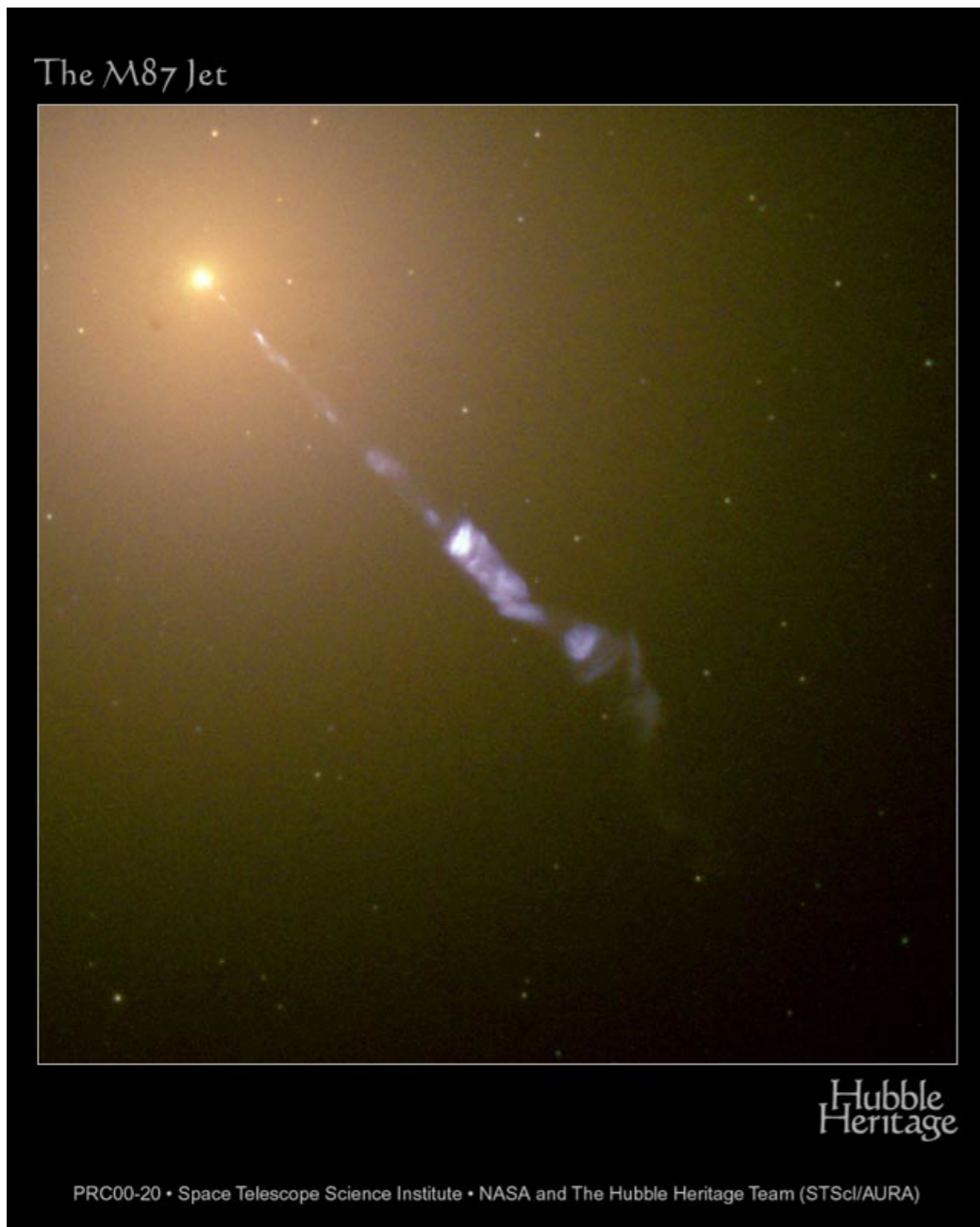


# curki snovi in energije

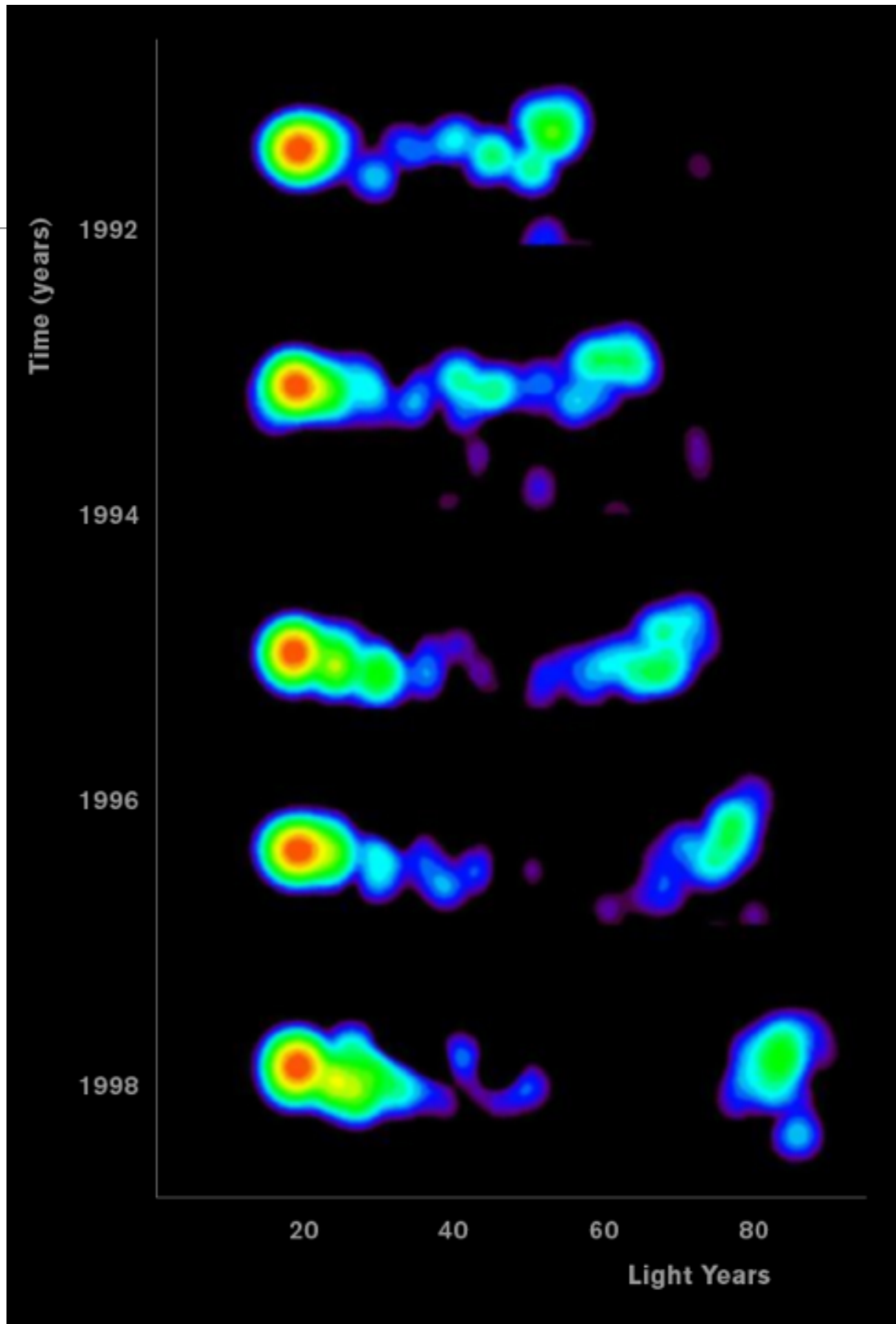
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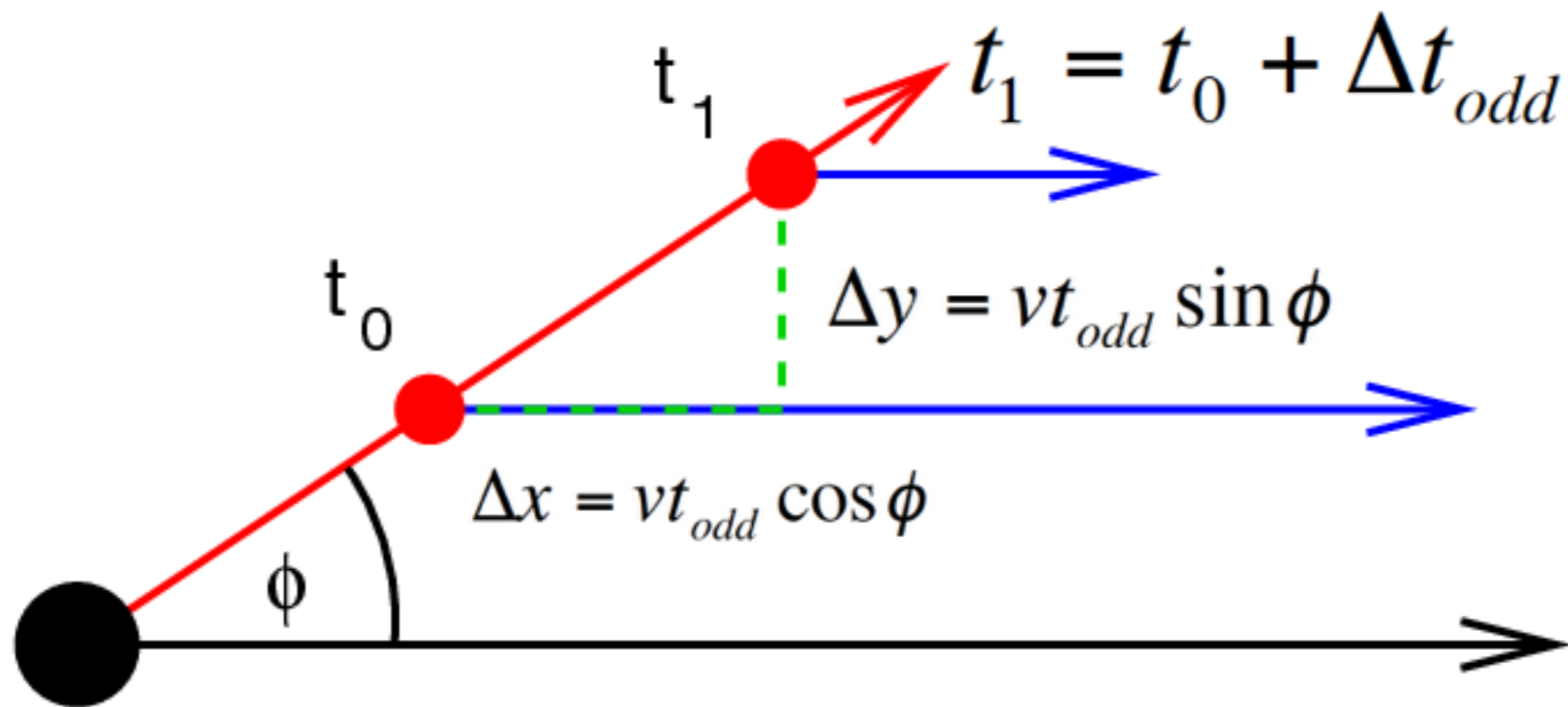


# M 87



3C 279





$$t_0^{pr} = t_0 + \frac{D}{c}$$

$$t_1^{pr} = t_1 + \frac{(D - v\Delta t_{odd} \cos \phi)}{c}$$

$$\Delta t^{pr} = \Delta t^{odd} \left(1 - \frac{v}{c} \cos \phi\right)$$



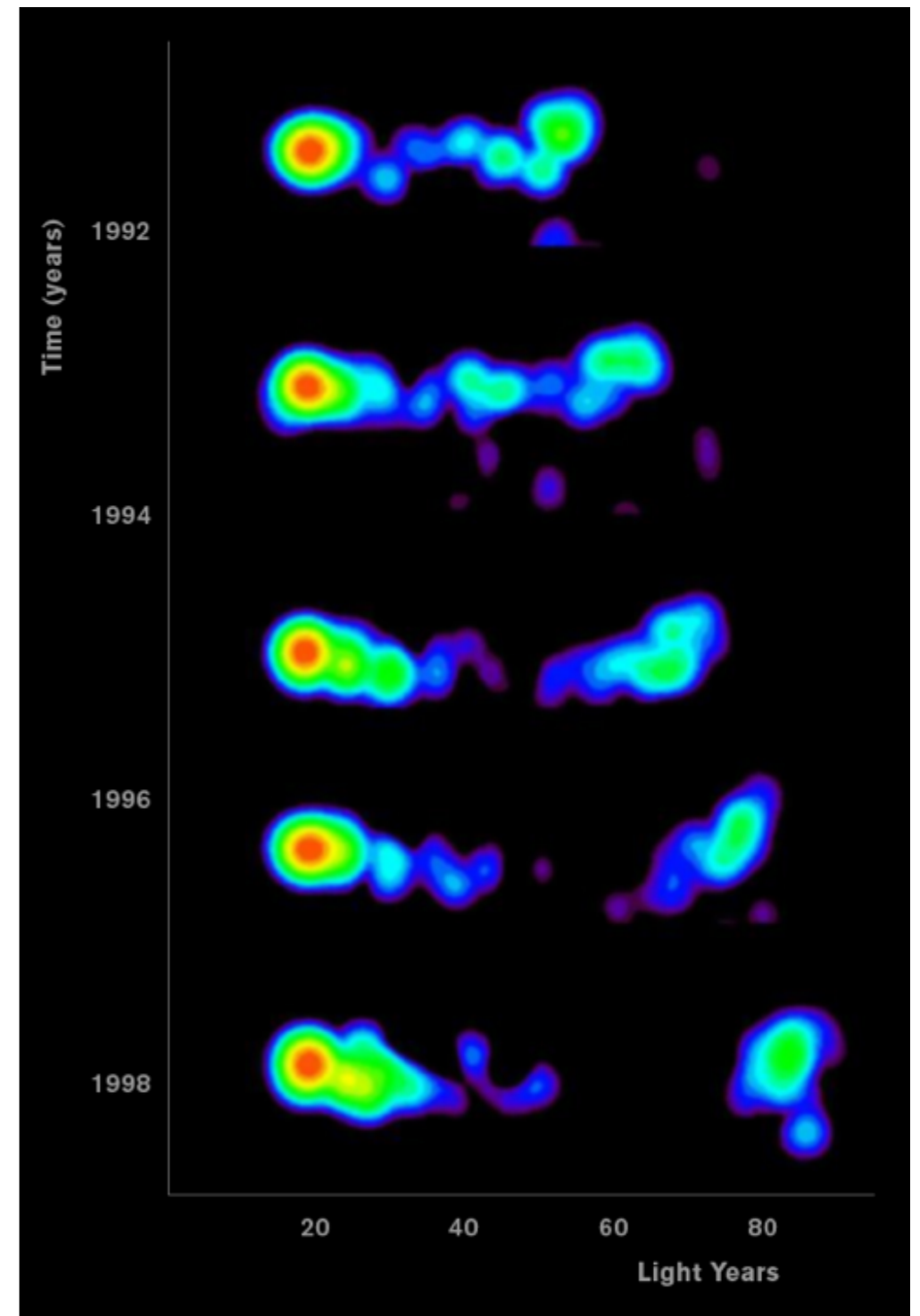
navidezna hitrost v prečni smeri

---

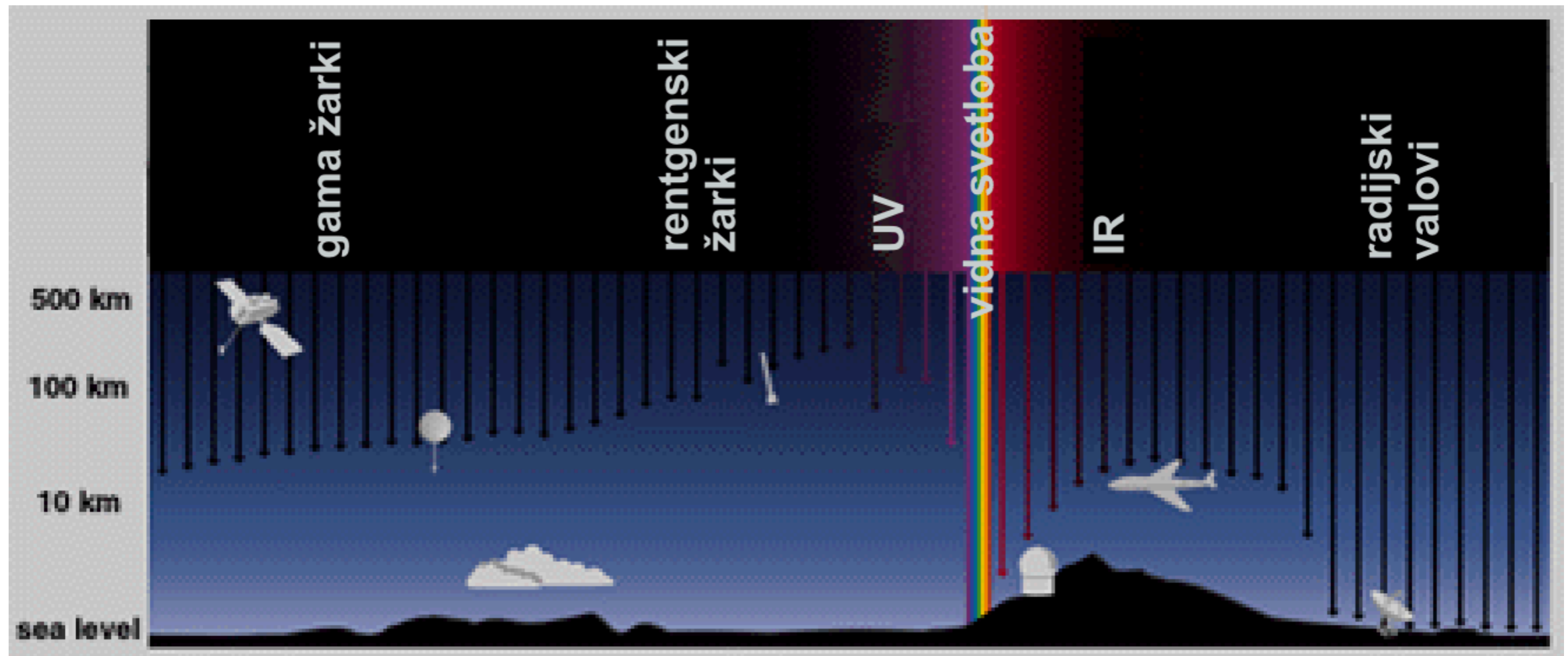
$$v_{prav}^{navidezna} = \frac{\beta \sin \phi}{1 - \beta \cos \phi}$$

$$\beta = \cos \phi$$

$$v_{prav-max}^{navidezna} = \gamma \beta c$$



# izbruhi sevanja gama - Gamma Ray Bursts (GRBs)

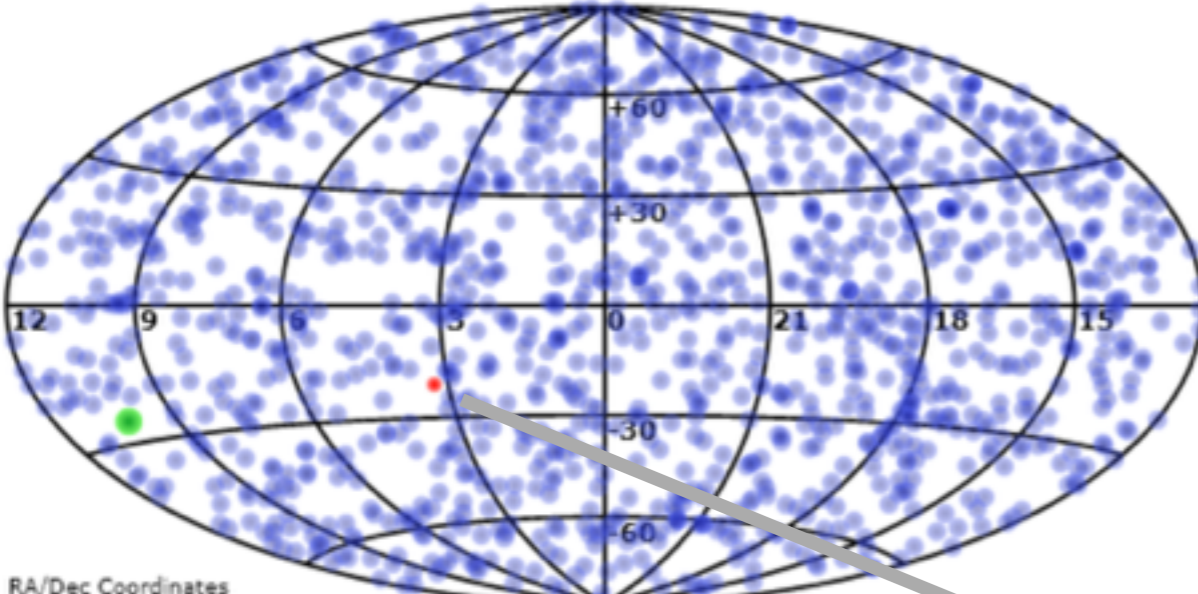


sateliti za sevanje gama:

- Fermi, INTEGRAL
- Swift - posebej za GRBje

# detekcija izbruhov sevanja gama

## GAMMA-RAY BURST REAL-TIME SKY MAP



**Burst ID:** GRB 100904A  
**Burst date:** 2010/09/04  
**Burst time (UTC):** 01:33:43  
**Detecting mission:** Swift

**Burst summary:** This burst had a two-peaked structure and lasted about 30 seconds. Because of a Sun constraint the telescope was not able to slew to observe with the XRT/UVOT. The proximity of the burst to the Sun prevents such observations until

Click the GRB to learn more...

Burst ID	Date	Time	Mission
GRB 20150513A	2015/05/13	20:31:19	Swift
GRB 20150502A	2015/05/02	11:30:42	Swift
GRB 20150428A	2015/04/28	03:12:03	Swift
GRB 20150424A	2015/04/24	07:42:56	Swift

Select Mission: All Bursts

**About**  
Welcome to the Gamma-ray Burst Real-time Sky Map. This web application is designed to give up to the minute updates on [gamma-ray burst](#) events reported by the various gamma-ray burst detecting satellites.

**Glossary**  
[A](#) | [B](#) | [C](#) | [D](#) | [E](#) | [G](#) | [K](#) | [L](#) | [M](#) | [P](#) | [R](#) | [S](#) | [T](#) | [U](#) | [X](#) | [Z](#)

**GRB Raw Data**

**RA/Dec Coordinates**  
● Burst < 7 days old ● Burst > 7 days old ● Burst > 60 days old ● Selected burst

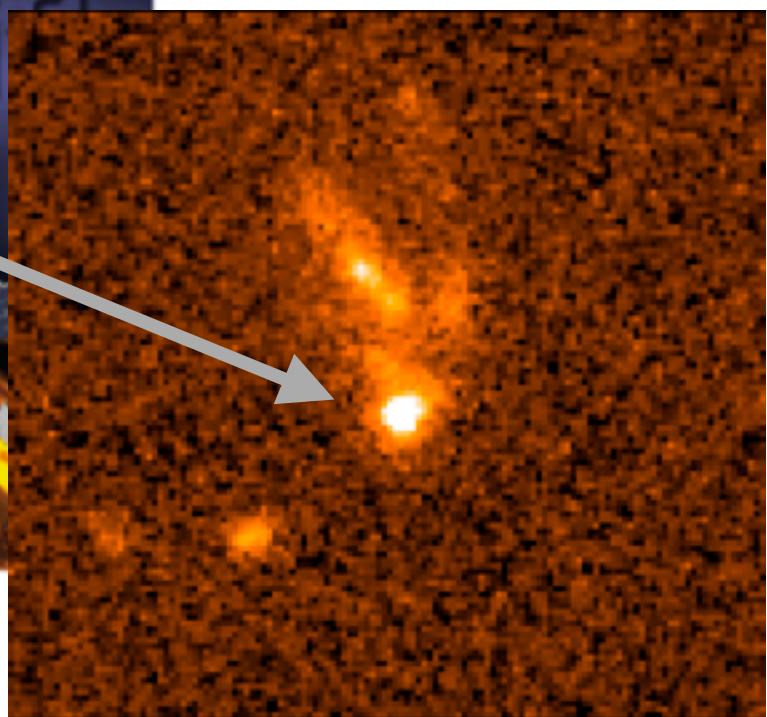
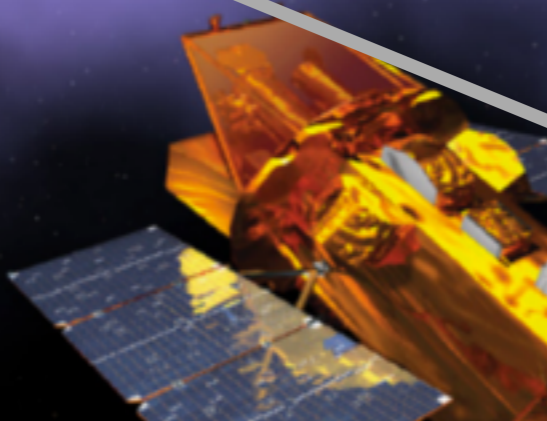
**GRB ID:** GRB 20150424A  
**Galactic Coordinates**  
Longitude: 23.57° Latitude: 263.59°  
Right Ascension: 10:09:14 Declination: -26:38:47  
Constellation: Hydra

**Burst Details**

Star Field

Swift

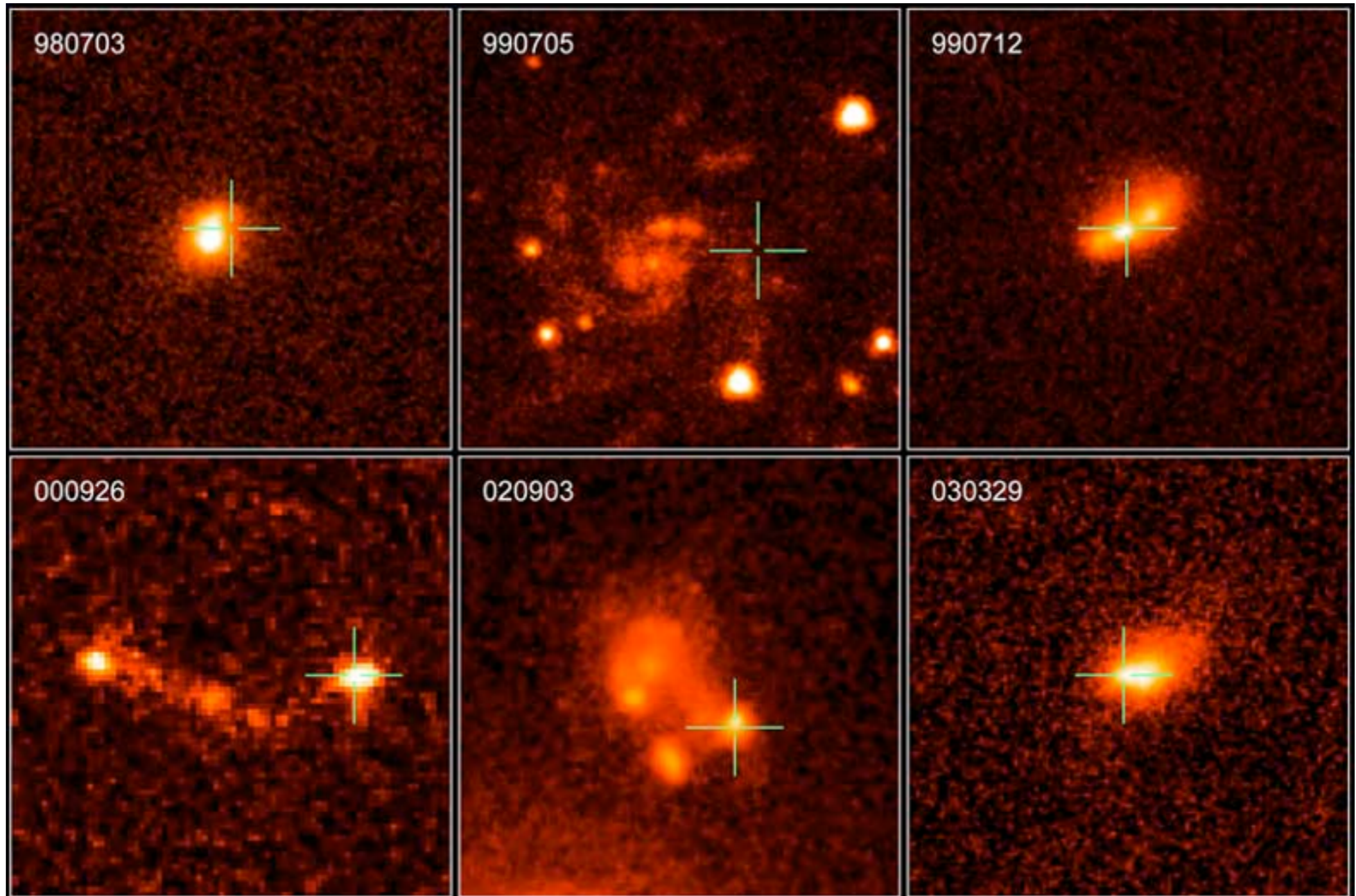
Print Preview



# galaksije gostiteljice

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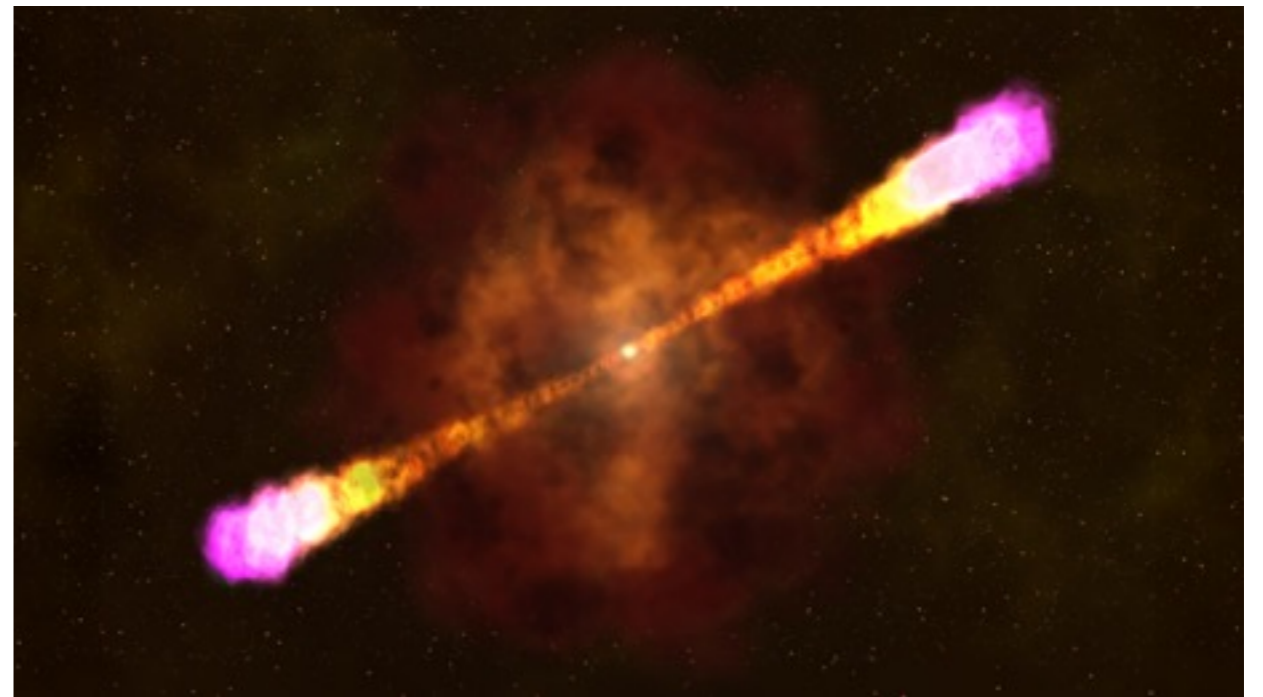
YYMMDD



# energija

---

- kozmološki rdeči premik  $\Rightarrow$  oddaljenost  $\Rightarrow$  energija!
- $E_{\text{iso}} \sim 10^{42} - 10^{48} \text{ J } (\sim M_{\text{sc}}^2)$
- neizotropna eksplozija
- $E_{\text{beaming corrected}} \sim 10^{40} - 10^{46} \text{ J}$

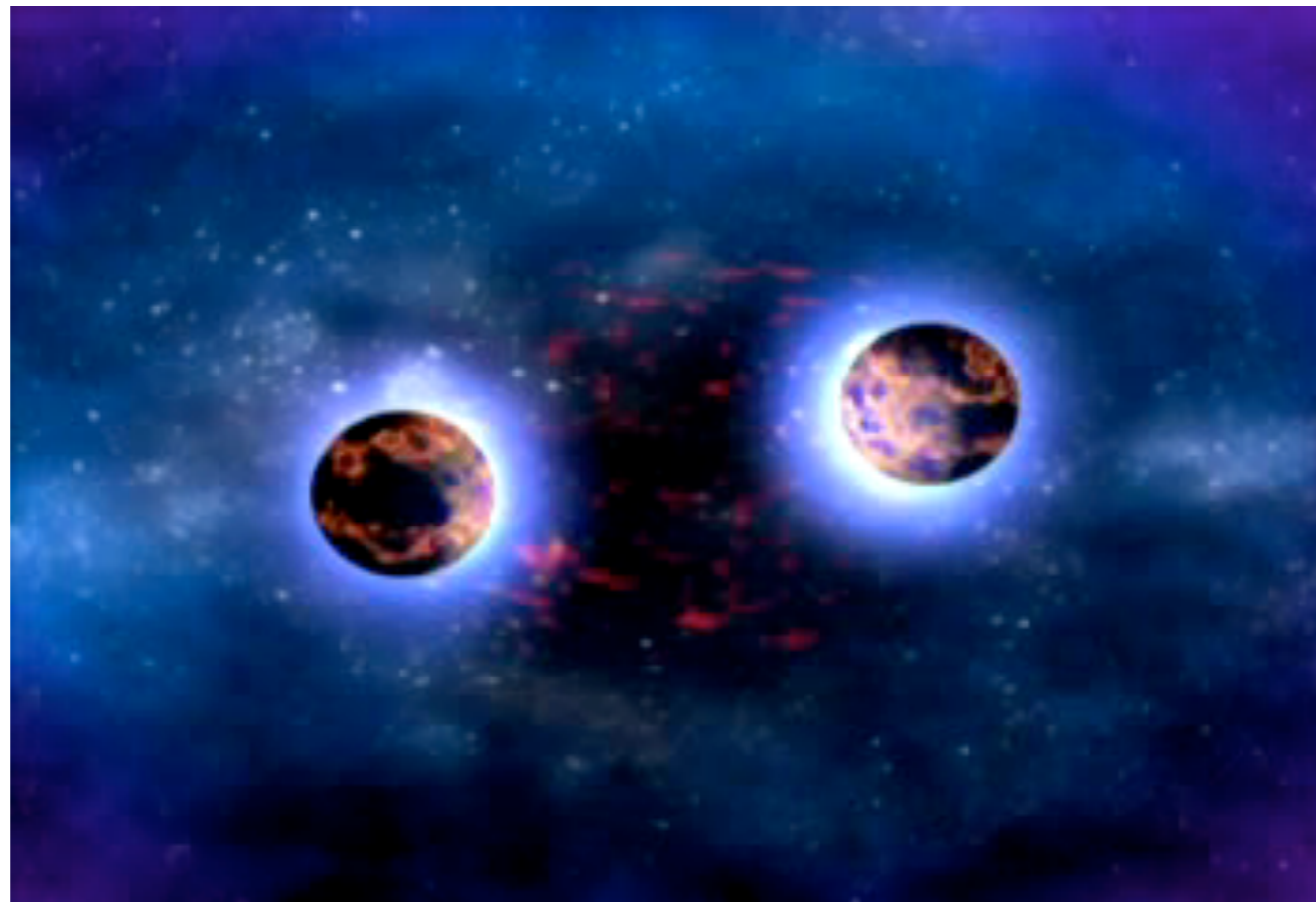


ilustracija: NASA

# model zlitja nevtronskih zvezd

---

- kratki ( $t < 2$  s) izbruhi sevanja gama



animacija: NASA

# model kolapsarja

---

- dolgi ( $t > 2$  s) izbruhi sevanja gama



animacija: NASA

opazovanja: GRB-supernova povezava

# “follow-up” opazovanja zasijev

---

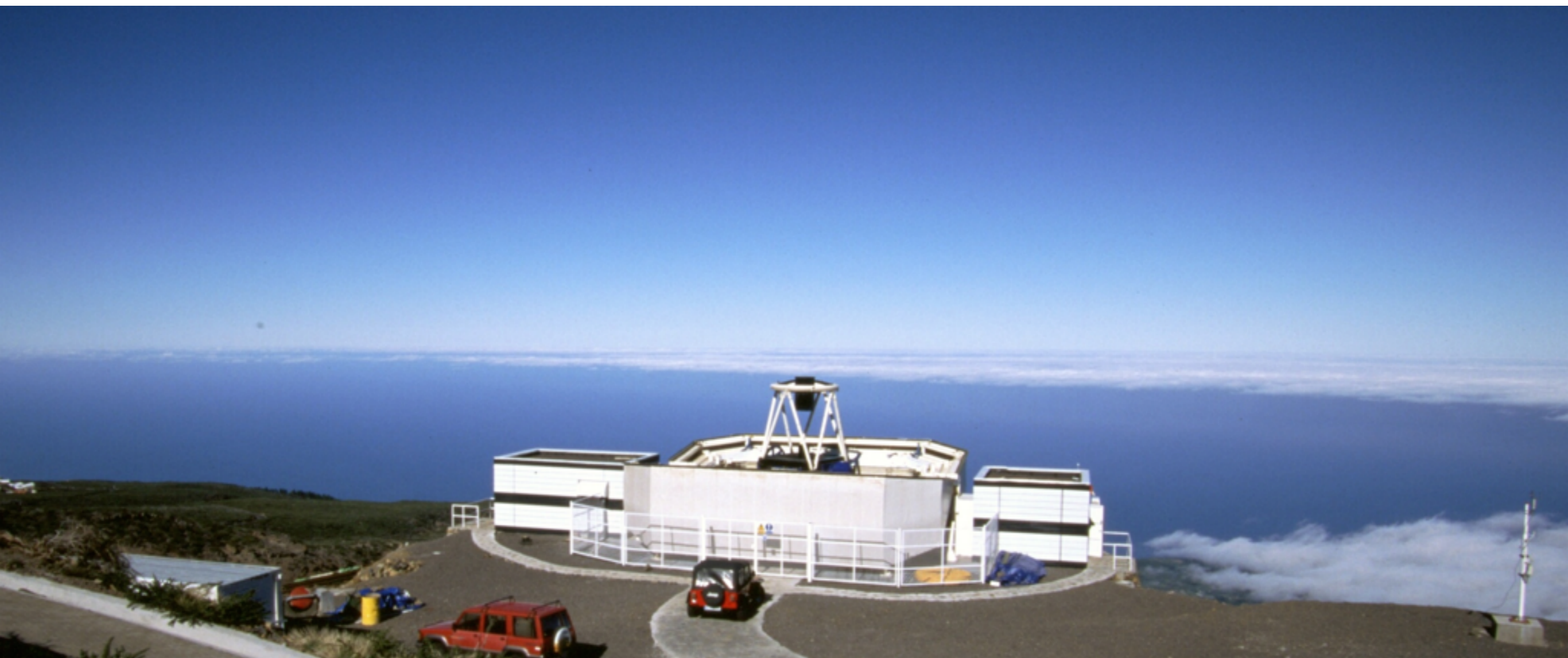
- rentgenska, UV, vidna, IR, radijska svetloba
- mreža robotskih optičnih teleskopov:



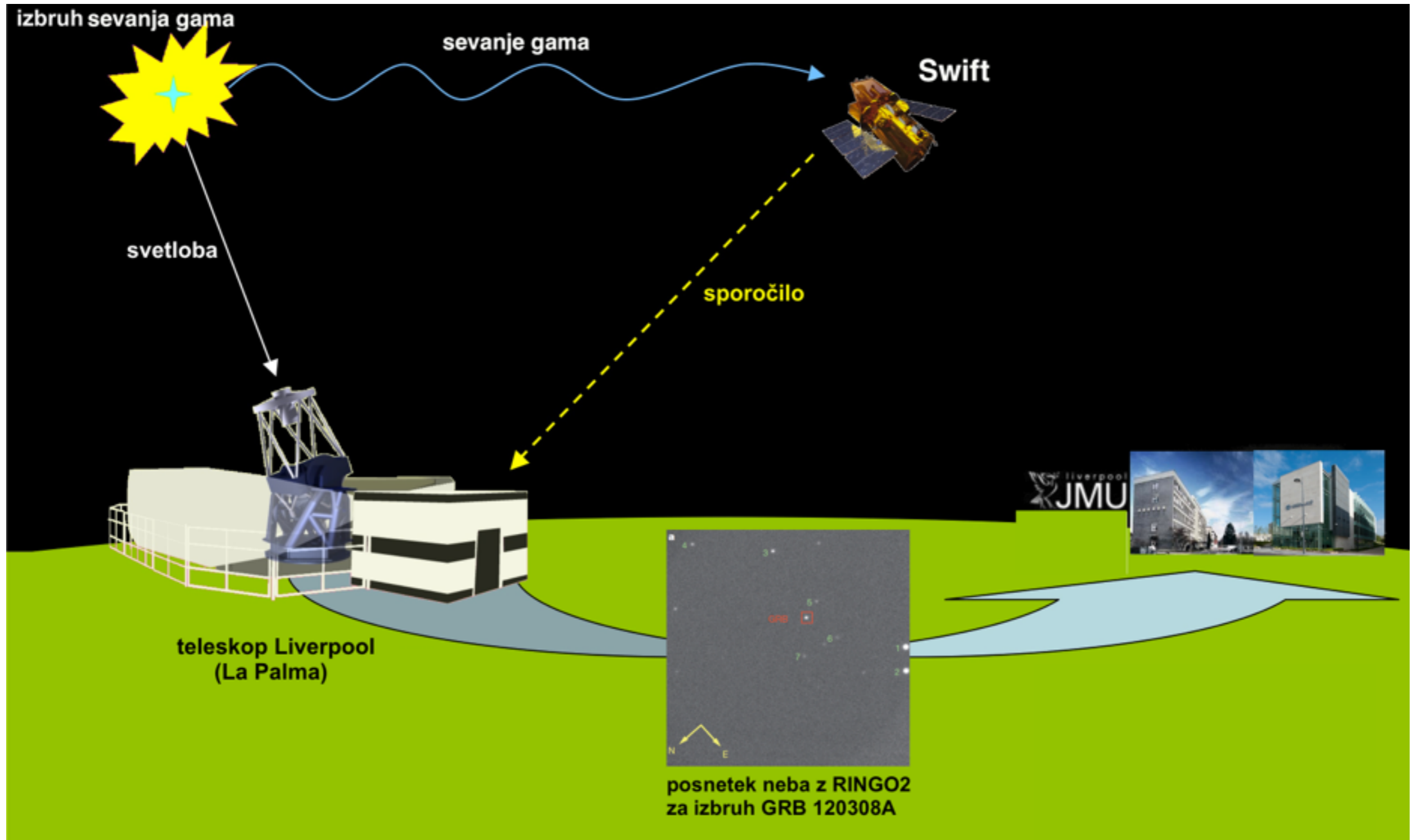


# teleskop Liverpool, La Palma, kanarsko otočje

---

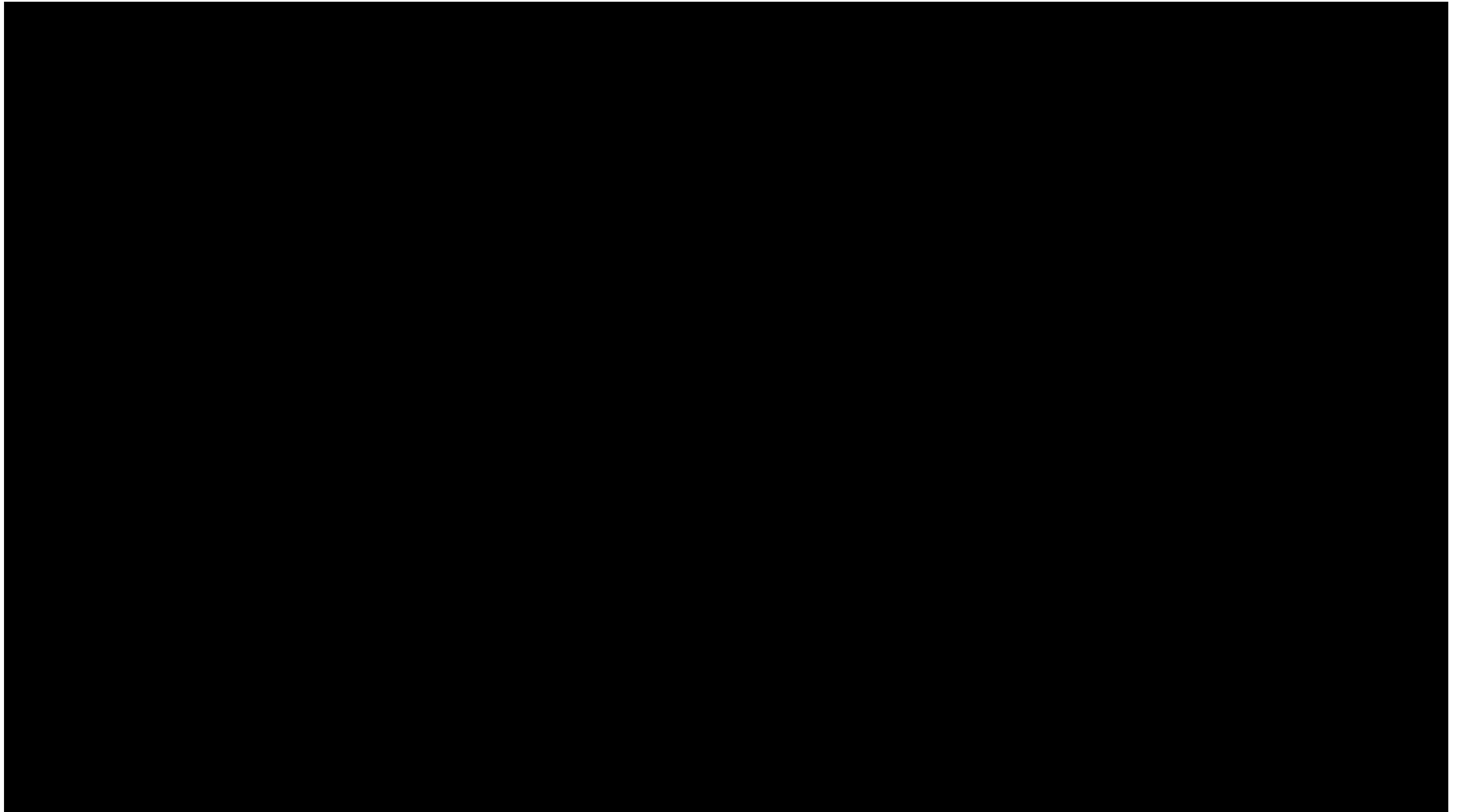


# avtomatski odziv in opazovanja



teoretična slika

---



animacija: NASA

# trajanje izbruhov

v sistemu curka traja izbruh  $dt'$

v sistemu, ki miruje, glede na "zvezdo", traja

$$dt^* = \gamma dt'$$

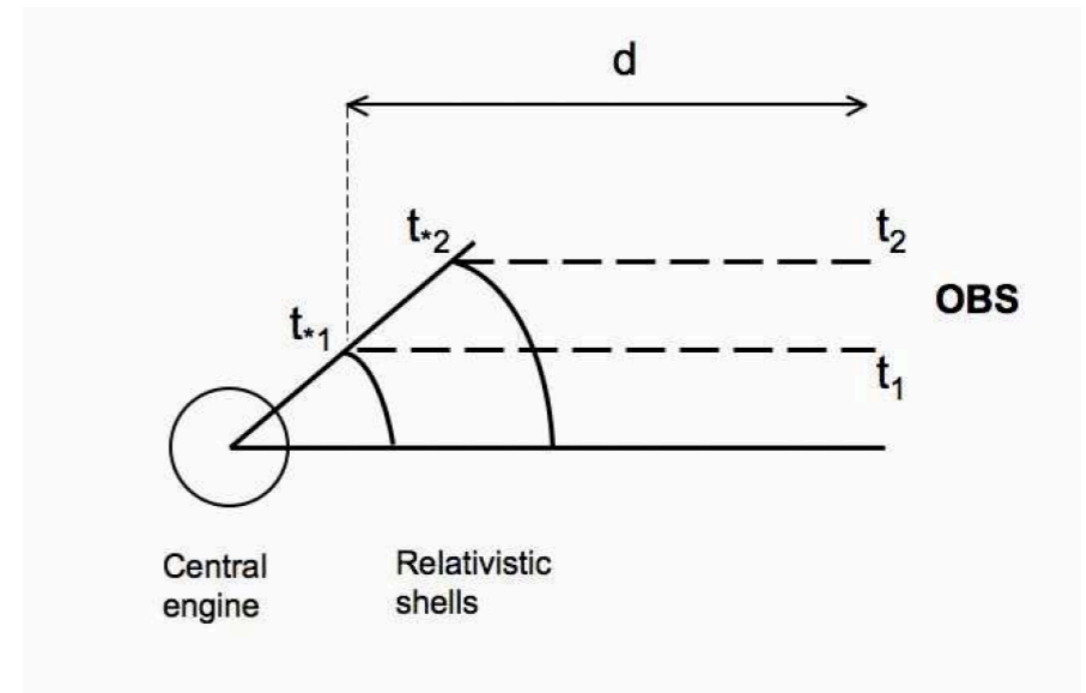
podaljšanje časa

Čurek se giblje proti nam pod kotom  $\theta$ .

Čas med prihodom dveh fotonov:

$$dt = dt^* (1 - \beta \cos \theta)$$

nadsvetlobno gibanje



---

$$\gamma^2 = 1/(1-\beta^2):$$

$$\text{za } \gamma \gg 1, \beta \approx 1: \gamma^2 = 1/(1-\beta)(1+\beta) \approx 1/2(1-\beta)$$

$$\text{za } \theta \ll 1 \text{ oz. } \cos \theta \approx 1:$$

$$dt = dt^* (1 - \beta \cos \theta) \approx \gamma dt' (1 - \beta)$$

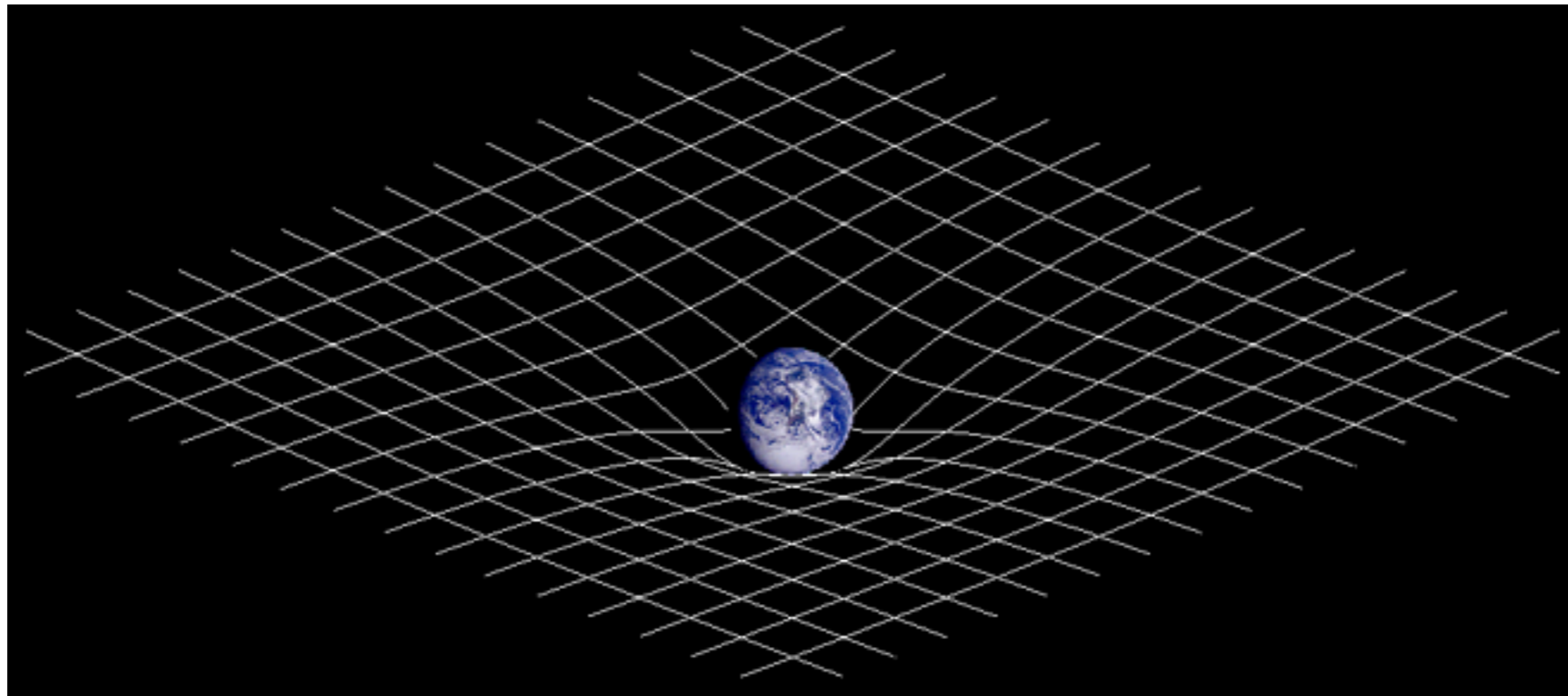
$$dt \approx dt' / 2\gamma$$

Če  $\gamma \approx 100$  in izmerimo trajanje  $dt = 1$  s, pomeni, da je izbruh v sistemu curka trajal 200 s.

# splošna teorija relativnosti

---

- ukrivljanje prostorčasa



# zgodovina

1915: Albert Einstein

1916: Karl Schwarzschild

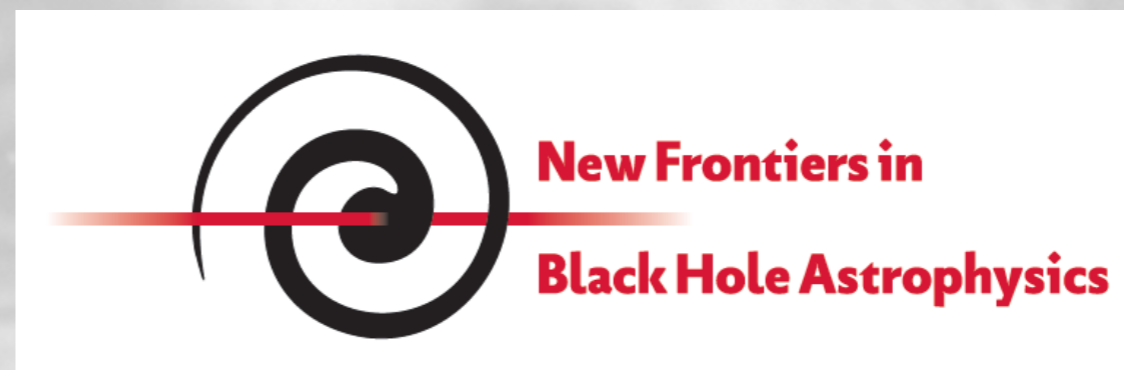
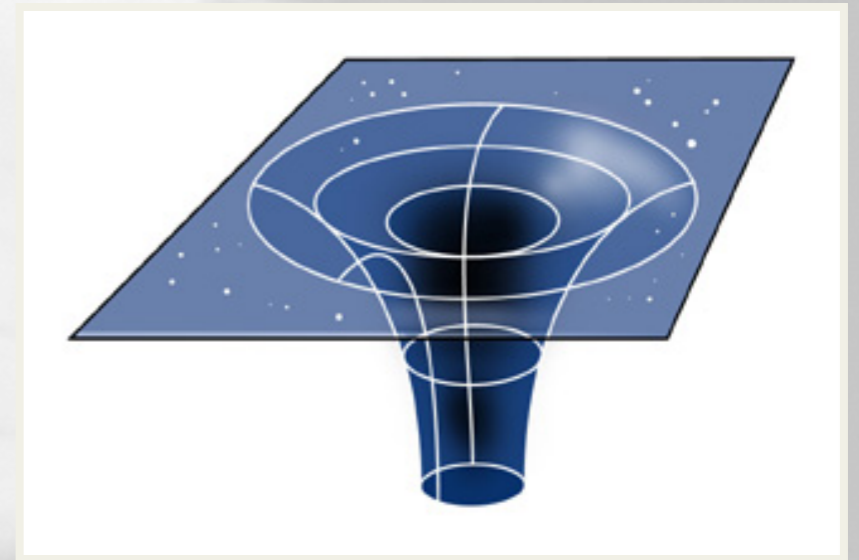
rešitev enačb splošne teorije relativnosti:  
črne luknje

IAU Simpozij

12.-16. september 2016

Ljubljana

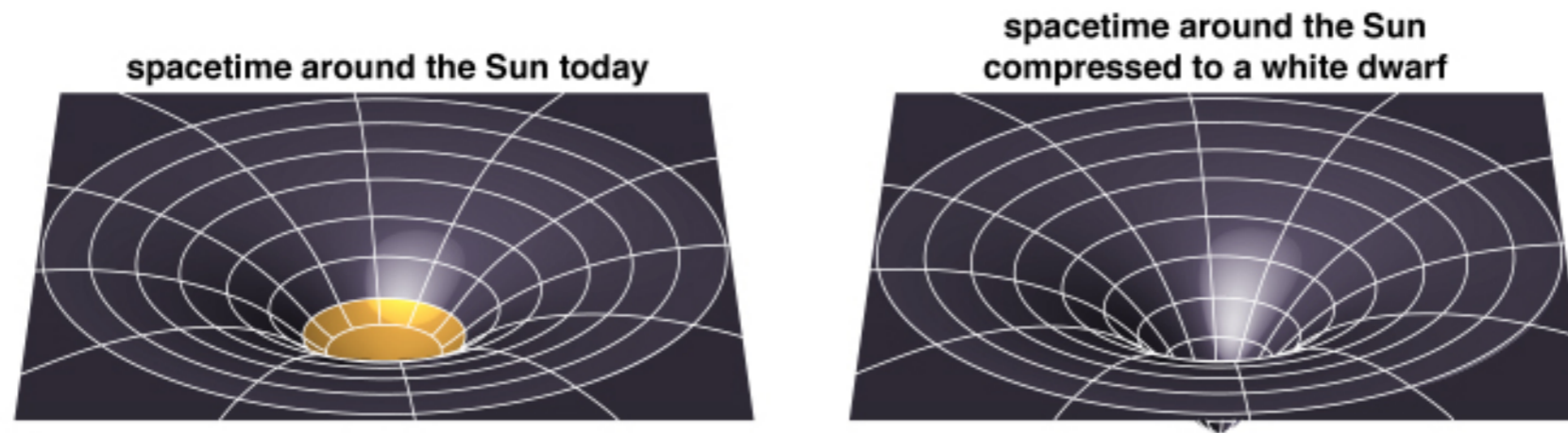
[www.blackholes2016.si](http://www.blackholes2016.si)



$$r_{Sch} = \frac{2GM}{c^2}$$

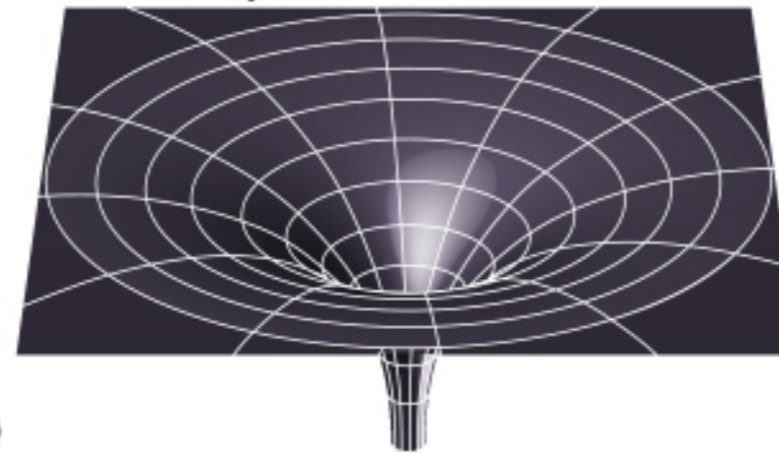
Schwarzschildov polmer - horizont

Sonce:  $r_{Sch}=3$  km



(a)

spacetime around the Sun compressed to a black hole

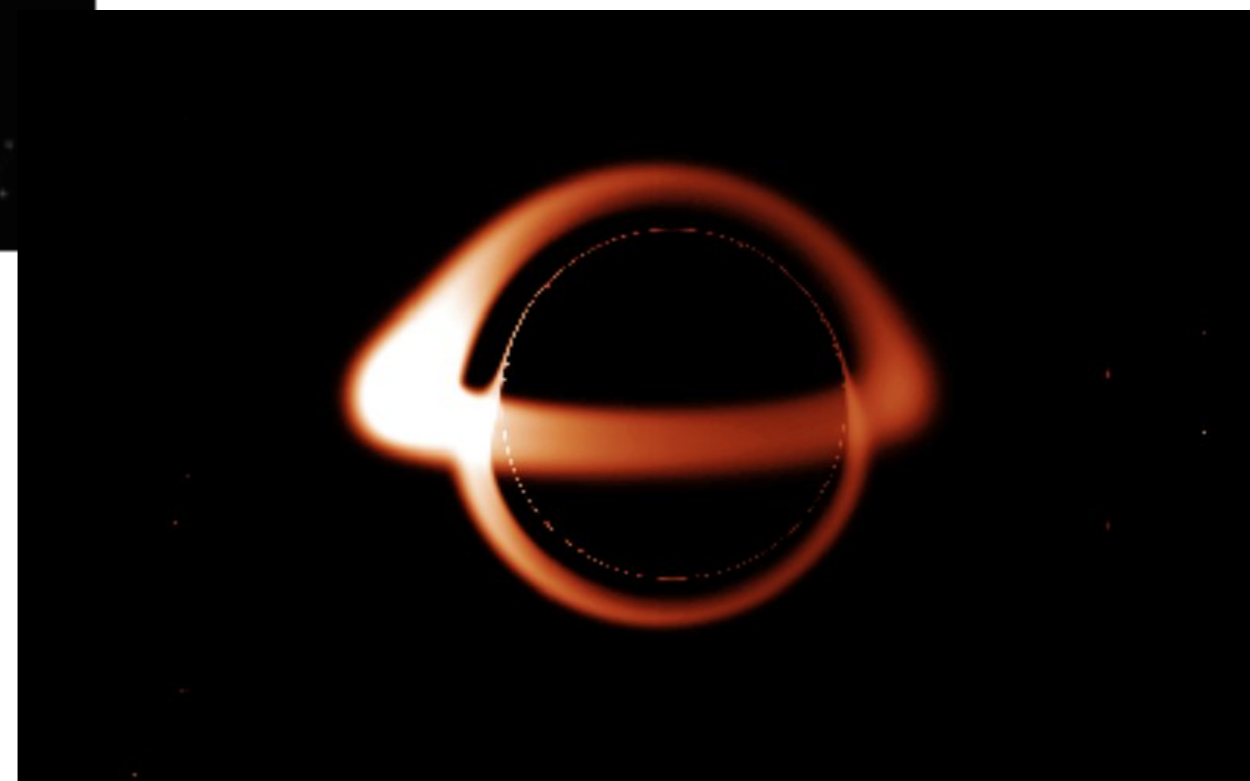
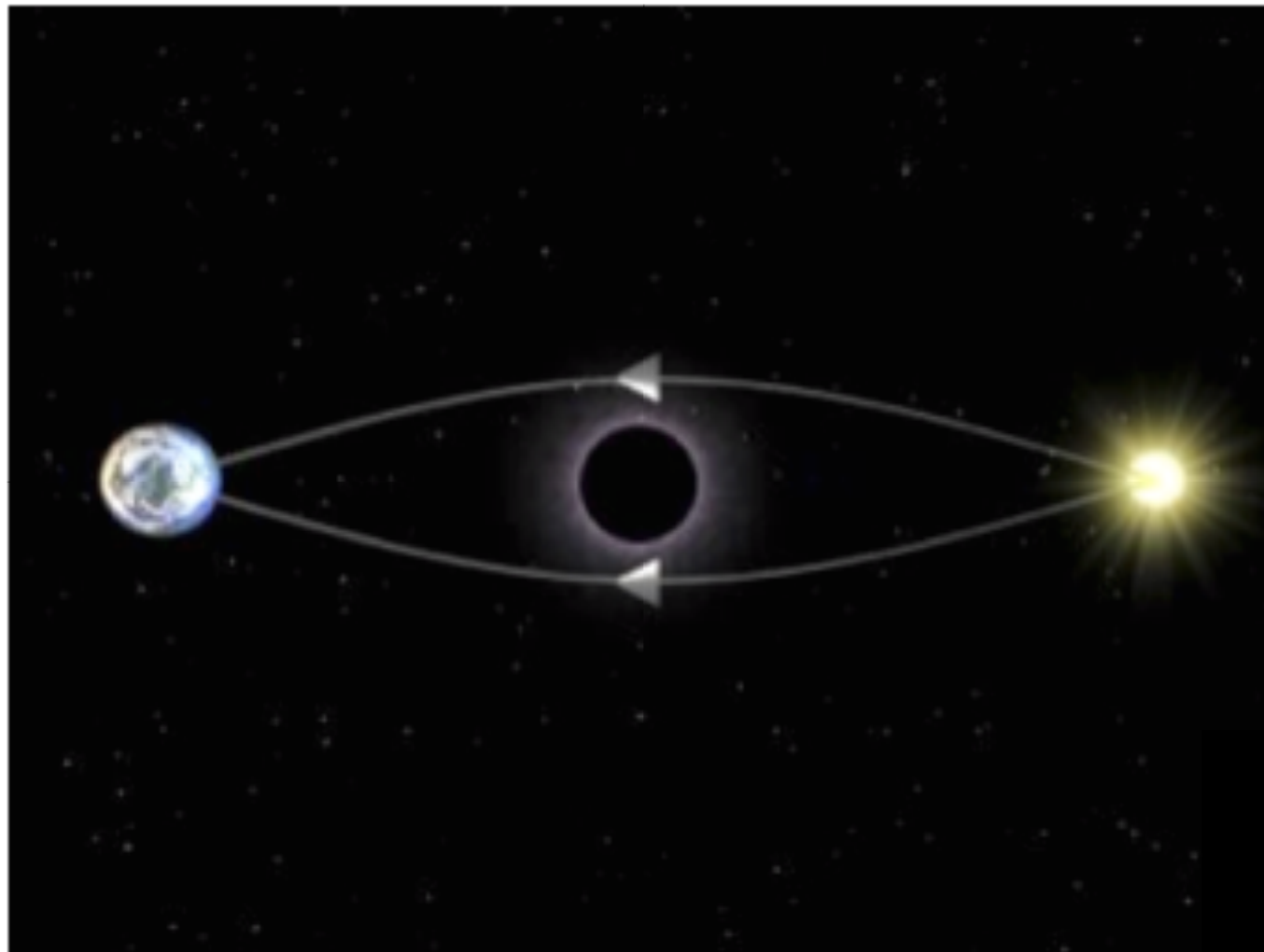


(b)



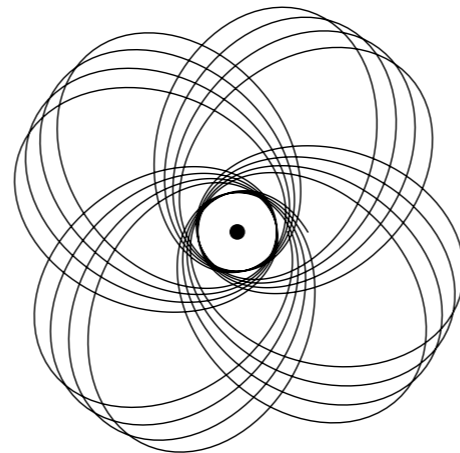
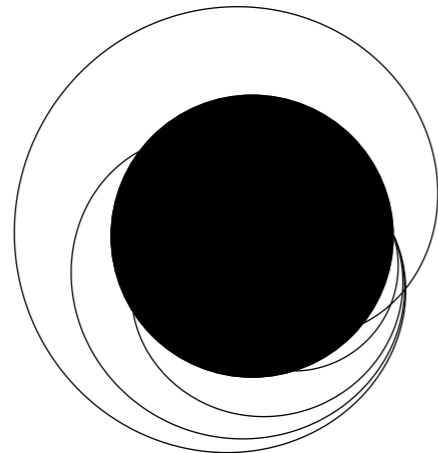
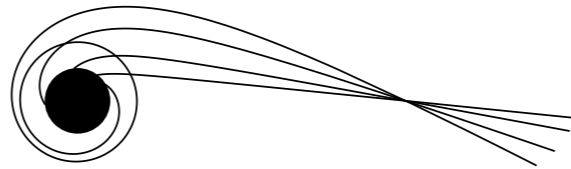
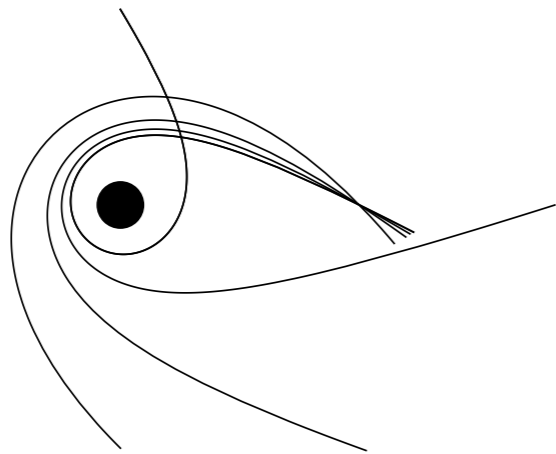
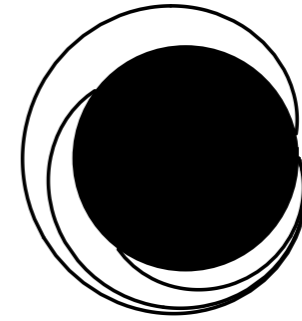
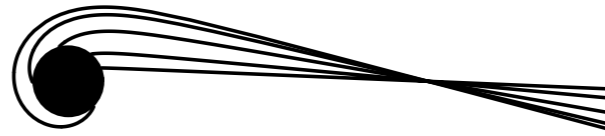
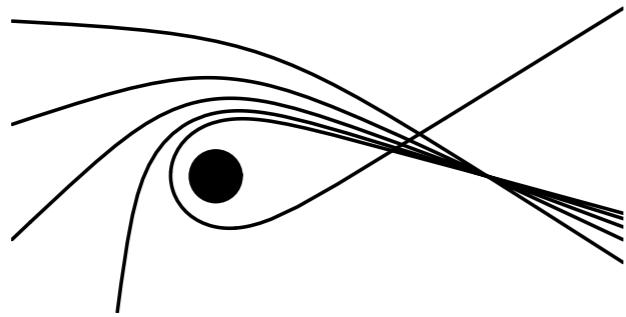
# gravitacijsko lečenje svetlobe

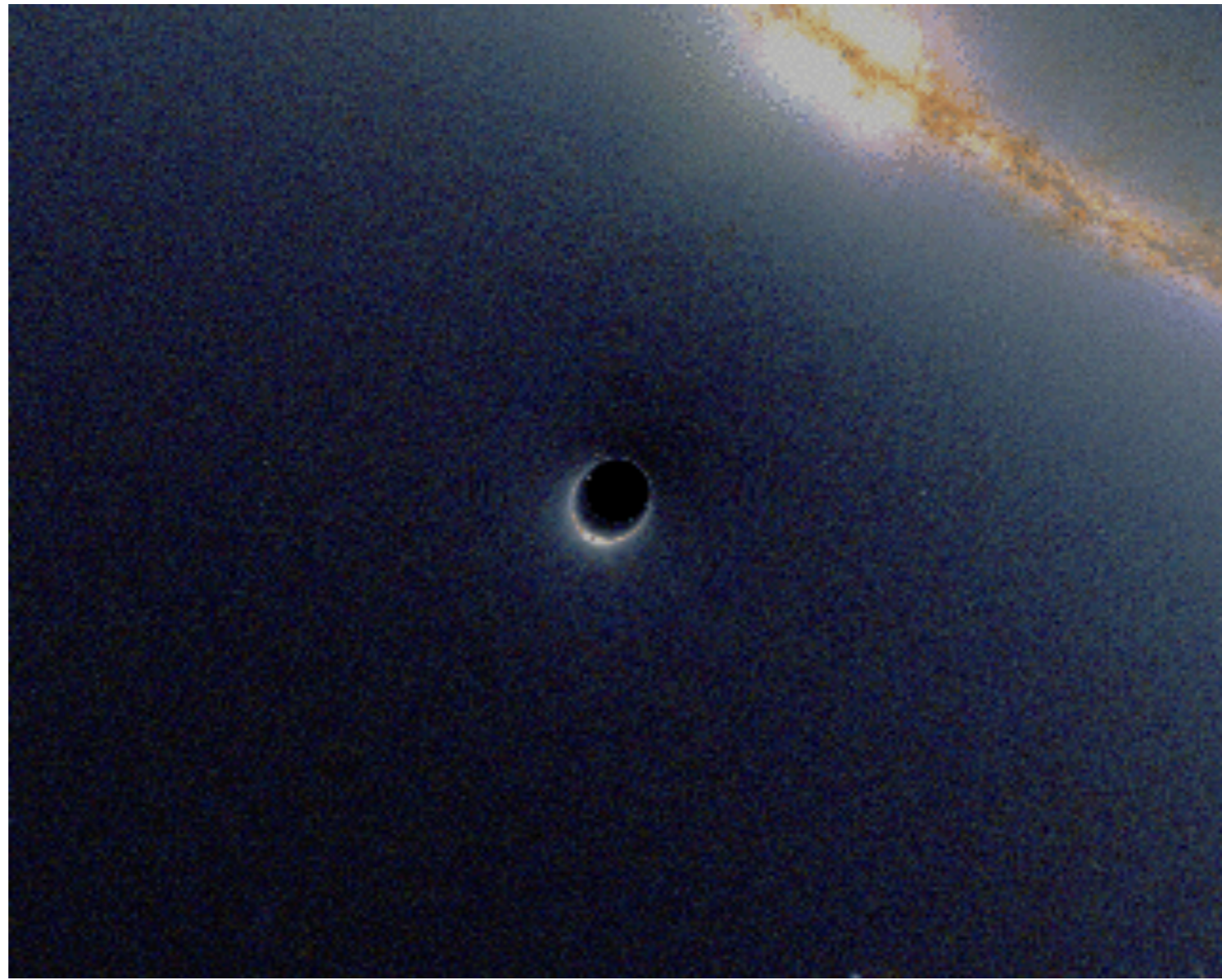
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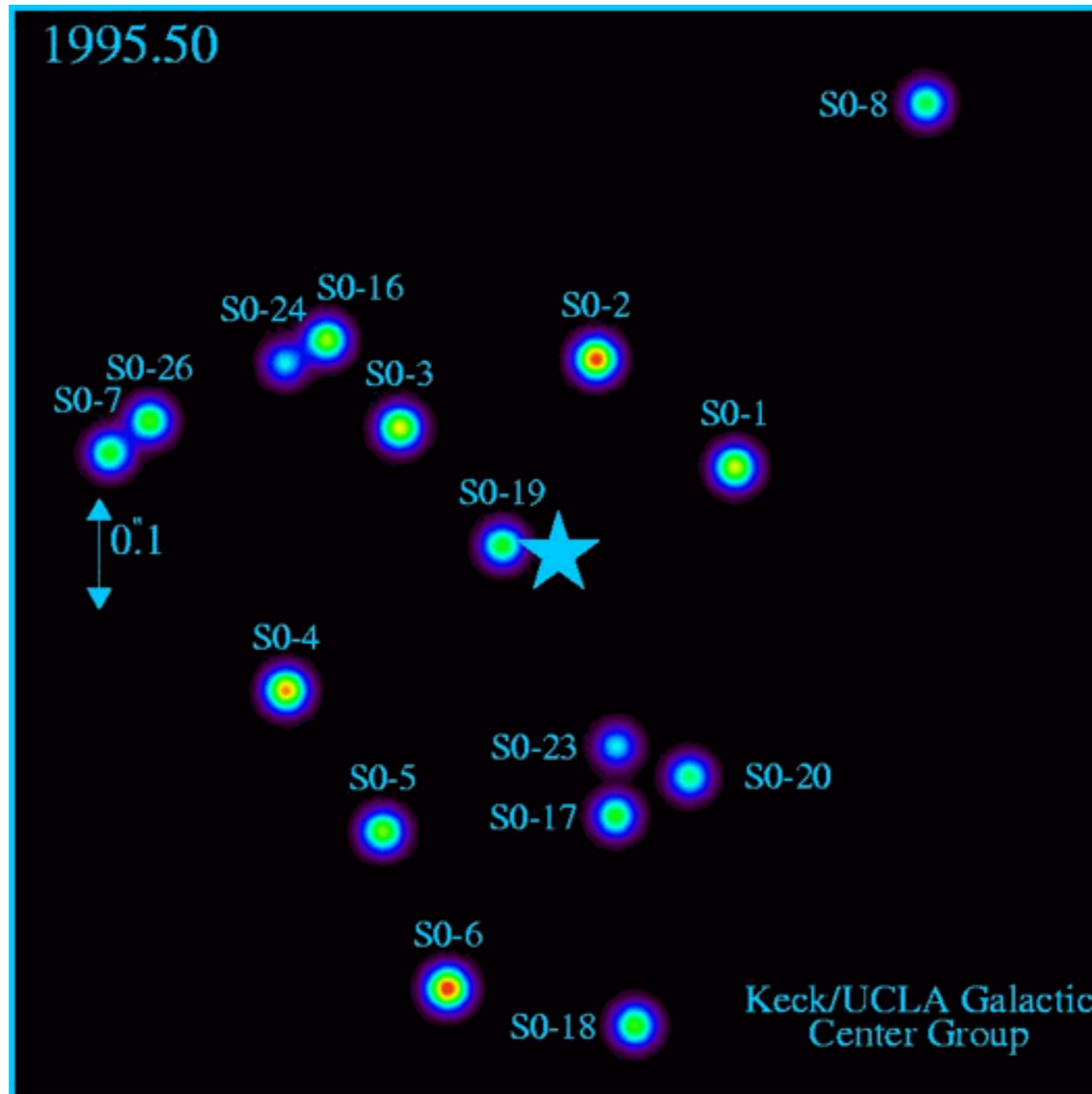
# tirnice svetlobe

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# zvezde v središču naše Galaksije



# plimska sila

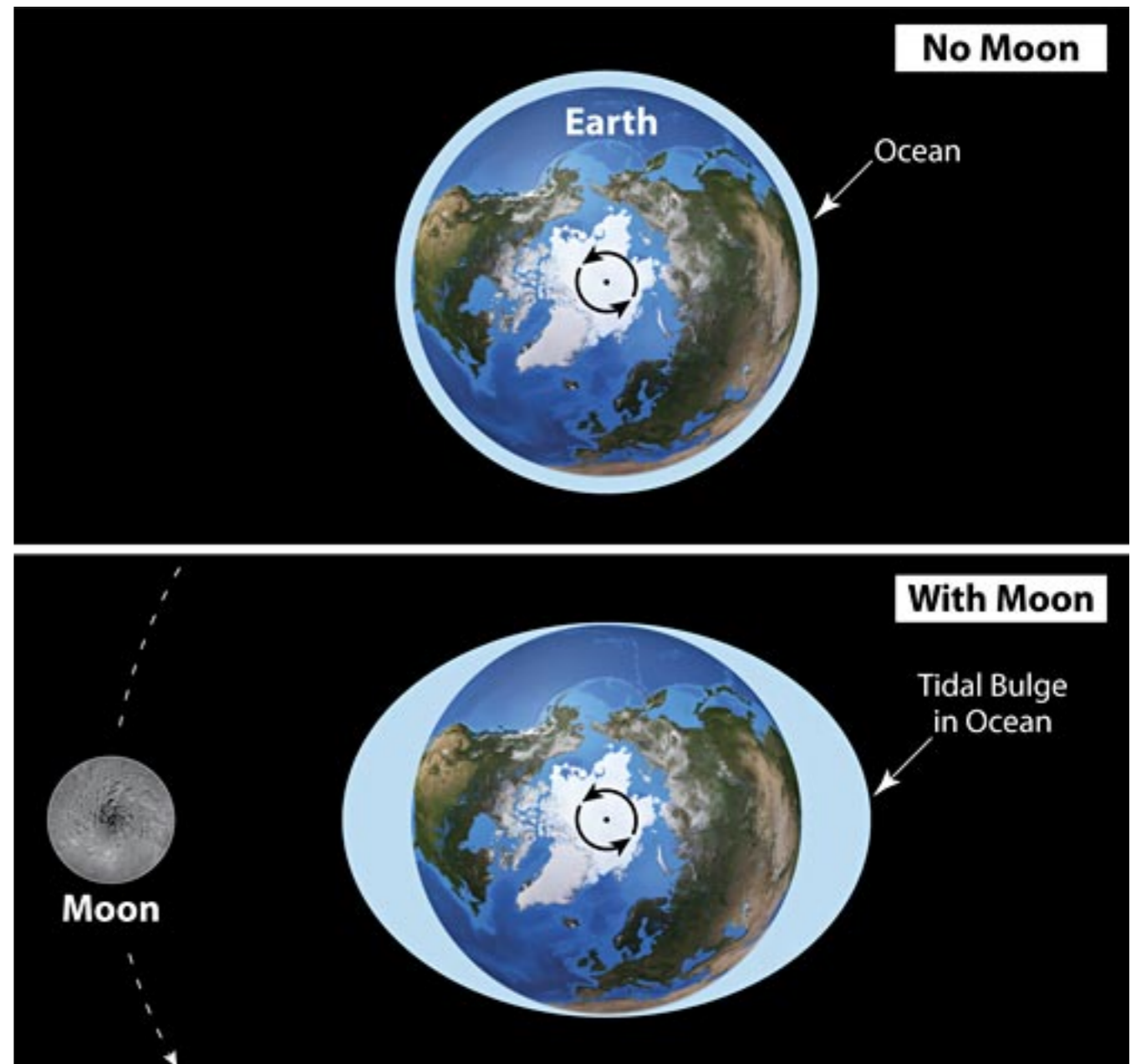
- plima - Zemlja-Luna:
- Zemlja=zvezda
- Luna=črna luknja
- gravitacijska sila:

$$F_g = -\frac{Gm_1m_2}{r^2}$$

- plimska sila:  $\propto \frac{m_1m_2}{r^3}$

$$r_{Sch} = \frac{2GM}{c^2}$$

- na horizontu:  $\frac{M}{M^3} \propto \frac{1}{M^2}$



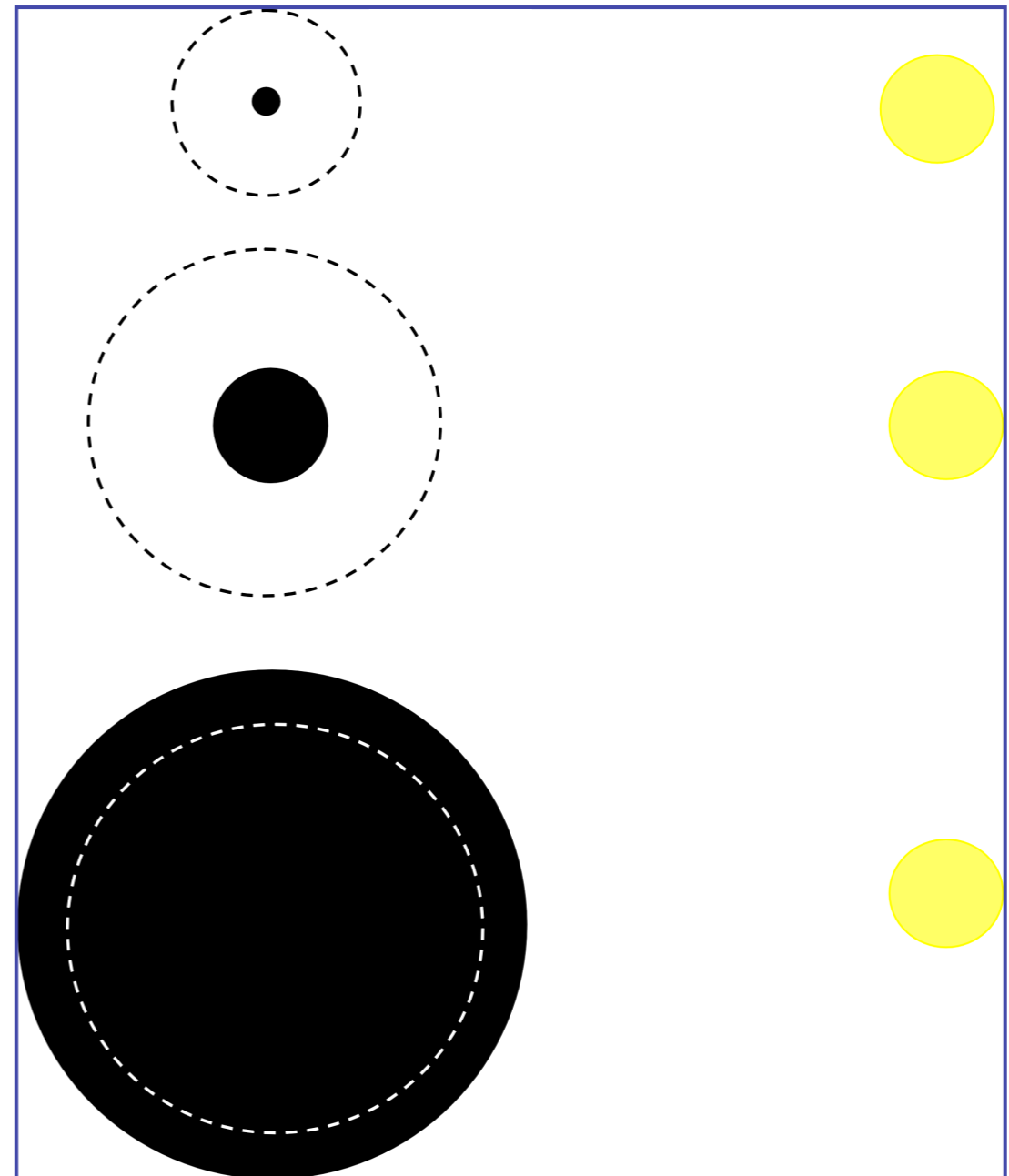
majhne črne luknje so bolj nevarne kot velike

# kaj se zgodi z zvezdo?

---

$$R_T \approx R_\star (M_{\text{BH}}/M_\star)^{1/3}$$

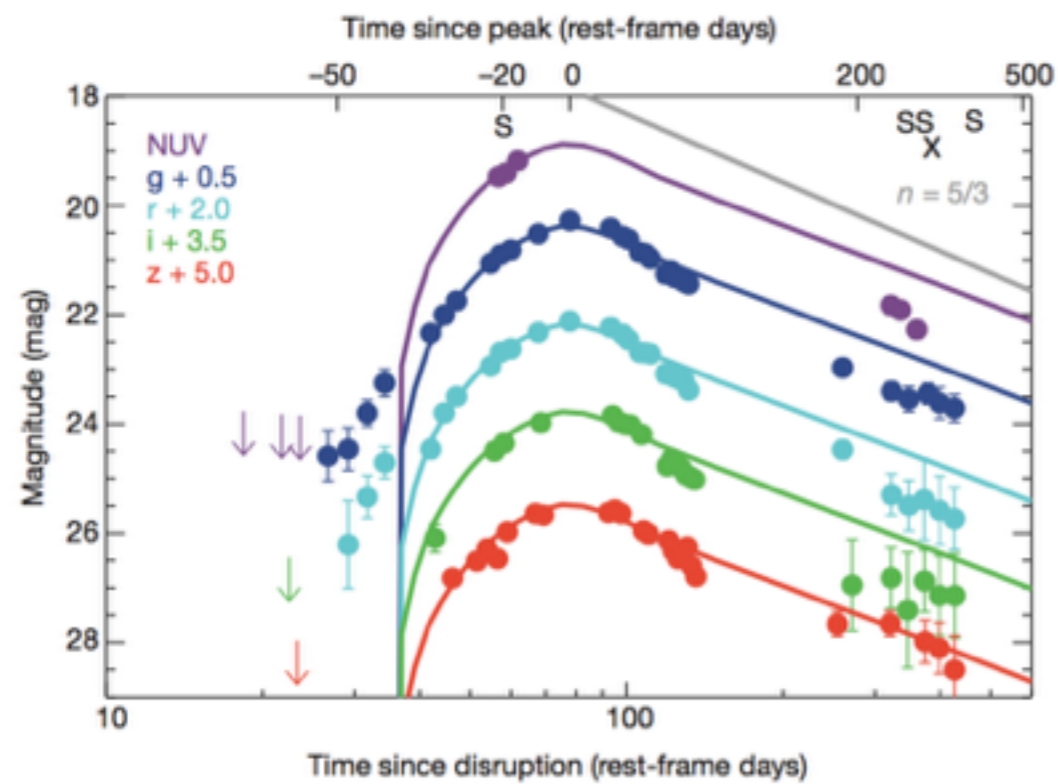
- $M_{\text{č.l.}} < 10.000 M_\text{S}$
- $M_{\text{č.l.}} \sim \text{milijon } M_\text{S}$
- $M_{\text{č.l.}} > 100 \text{ milijonov } M_\text{S}$



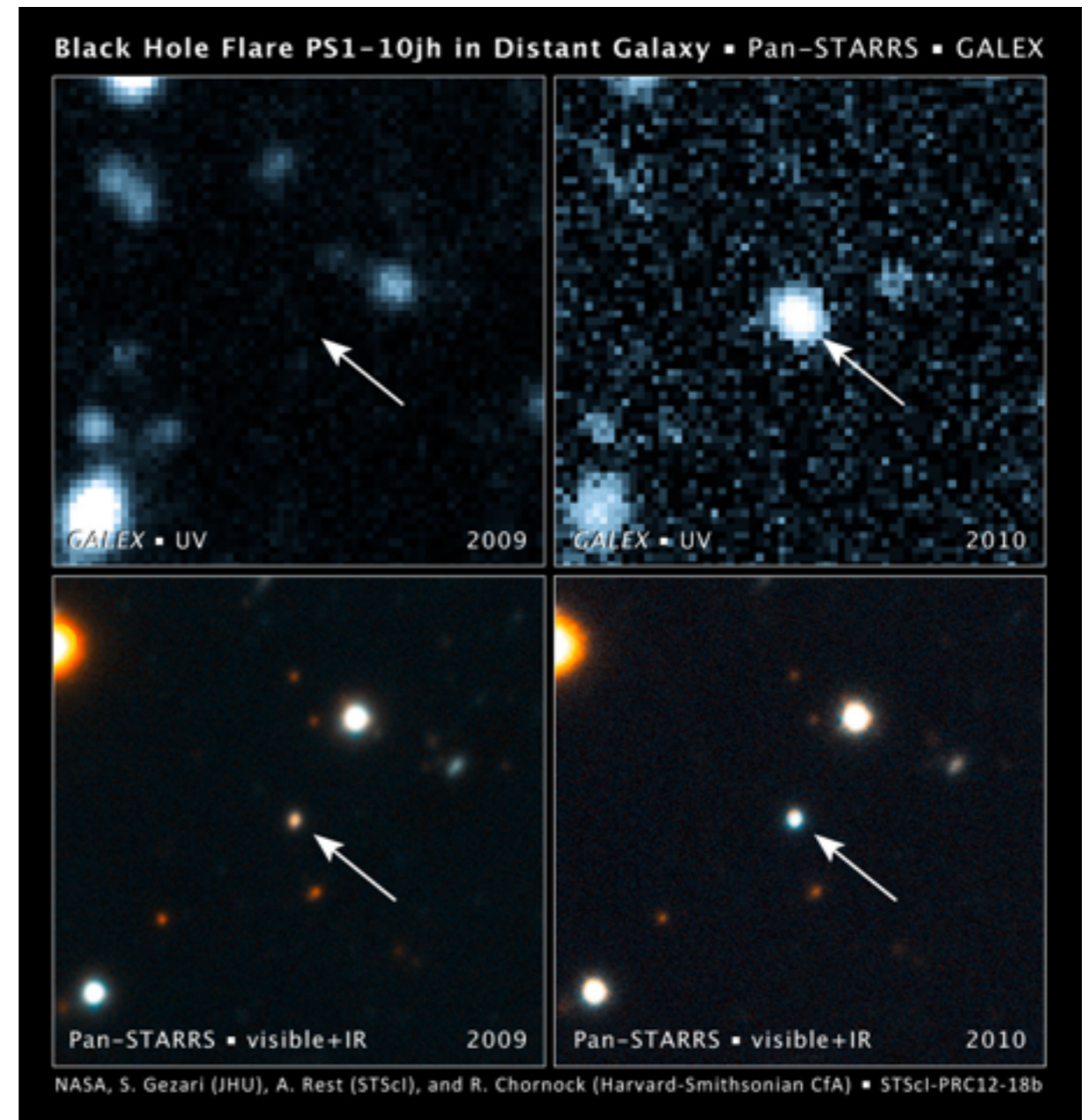


# opazovanja plimskih bliščev

- Pan-STARRS: PS1-10jh



Gezari et al., 2012







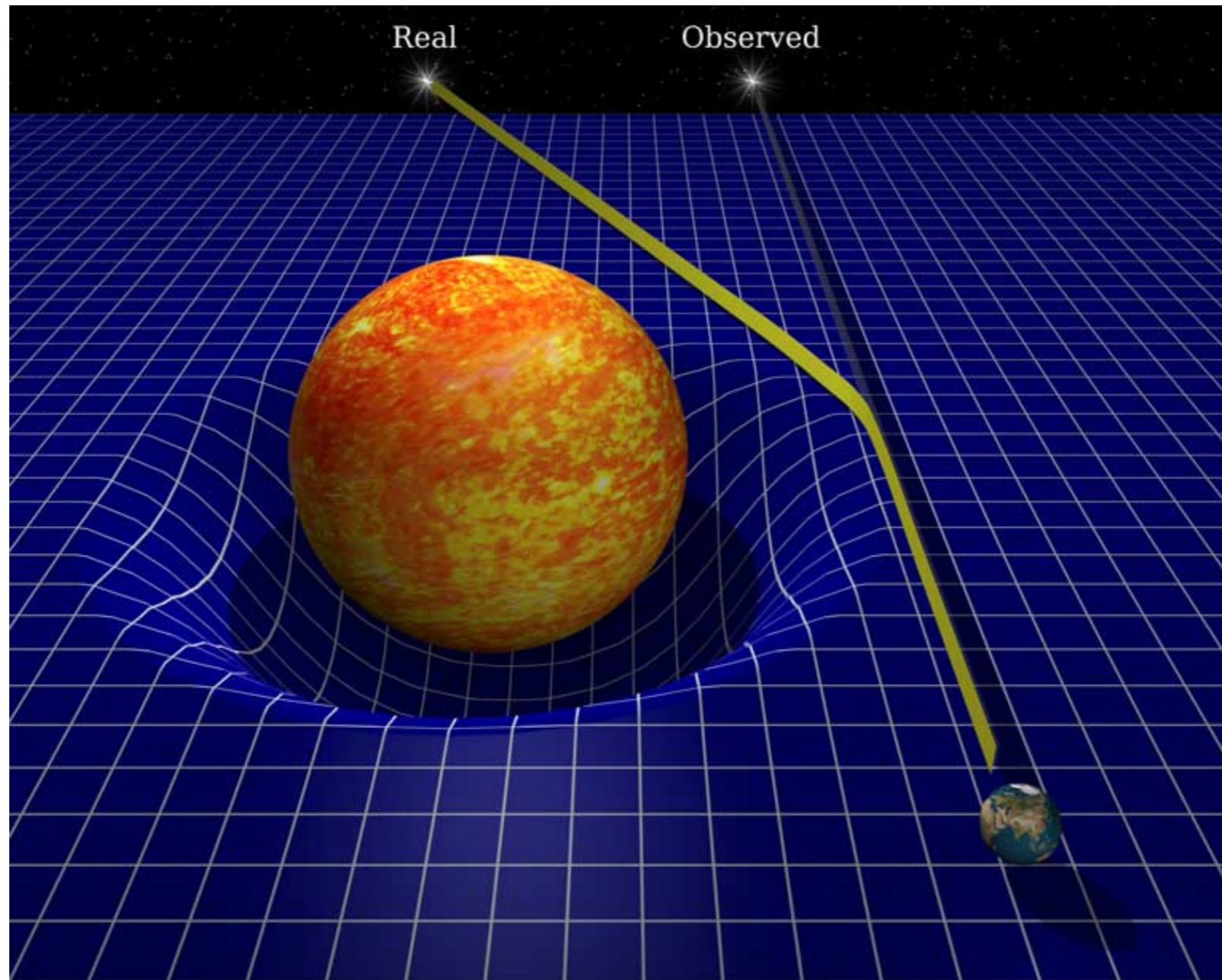
# čas ob padanju v črno luknjo

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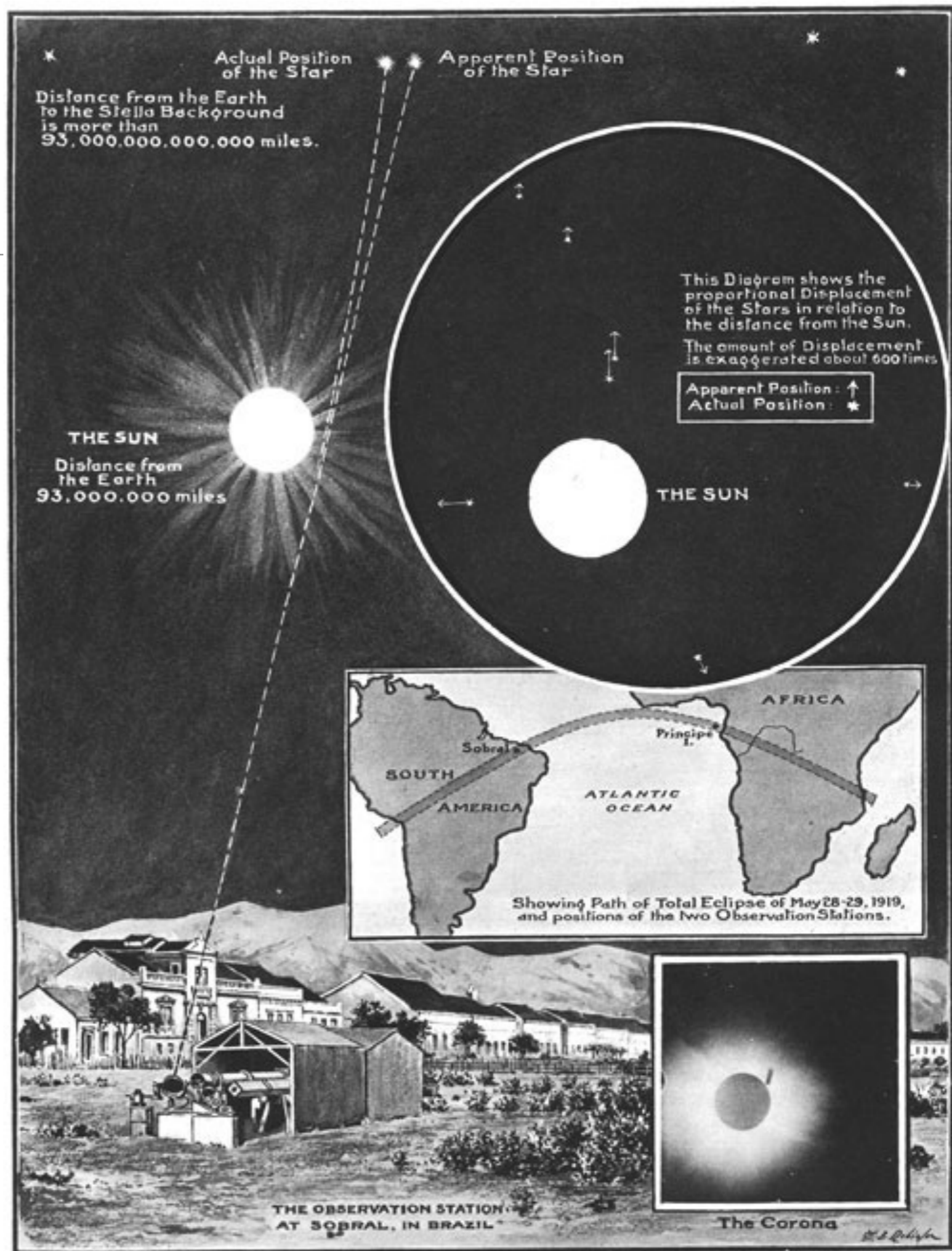


# gravitacijsko lečenje svetlobe

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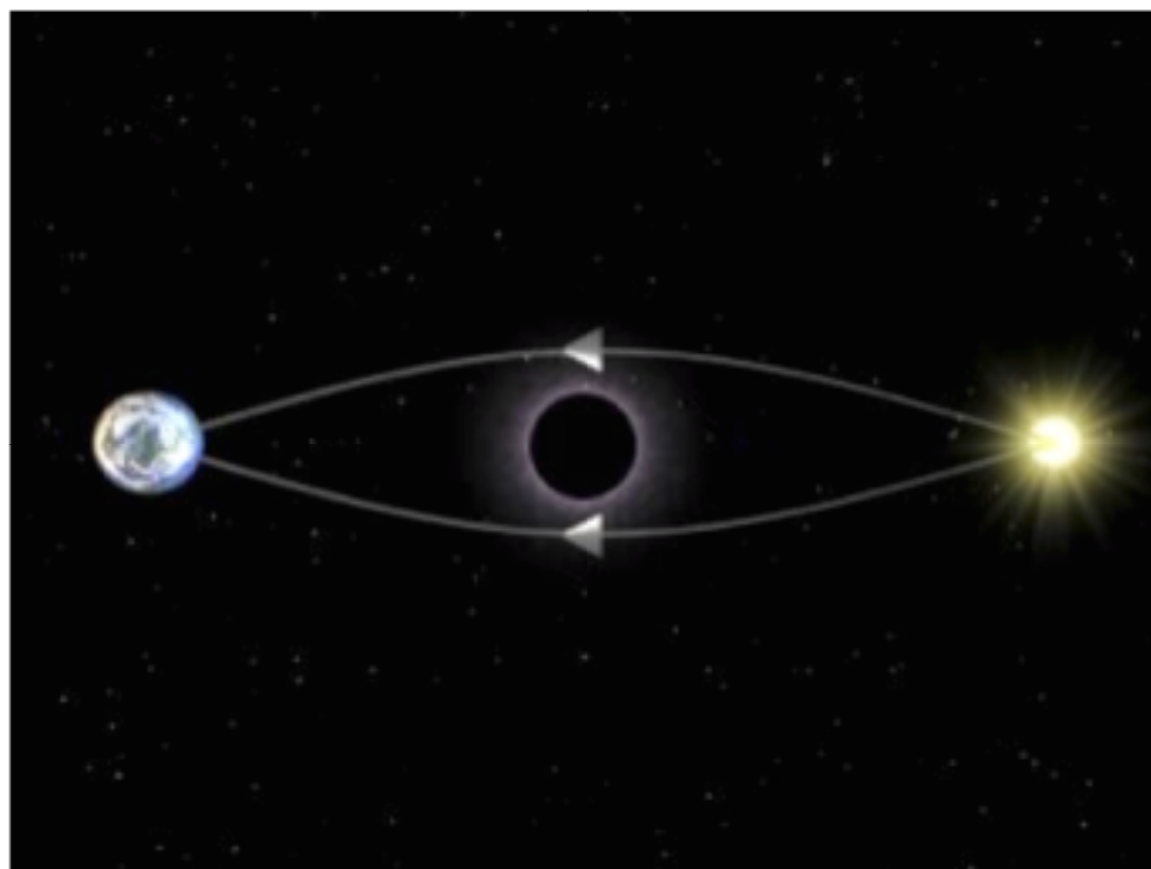


# Einstein 1919: Eddington

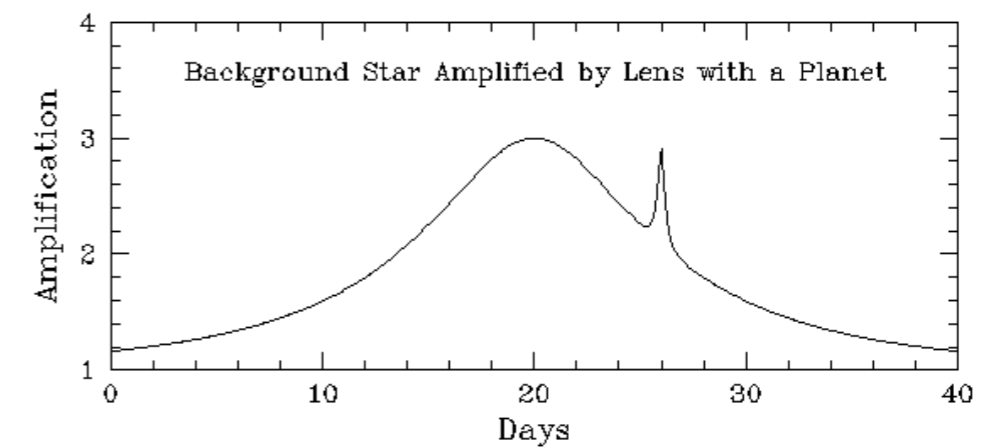
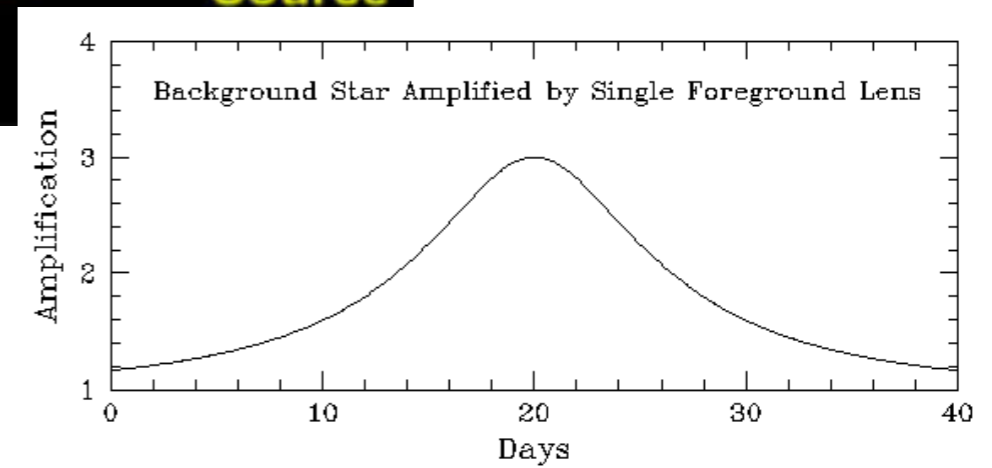
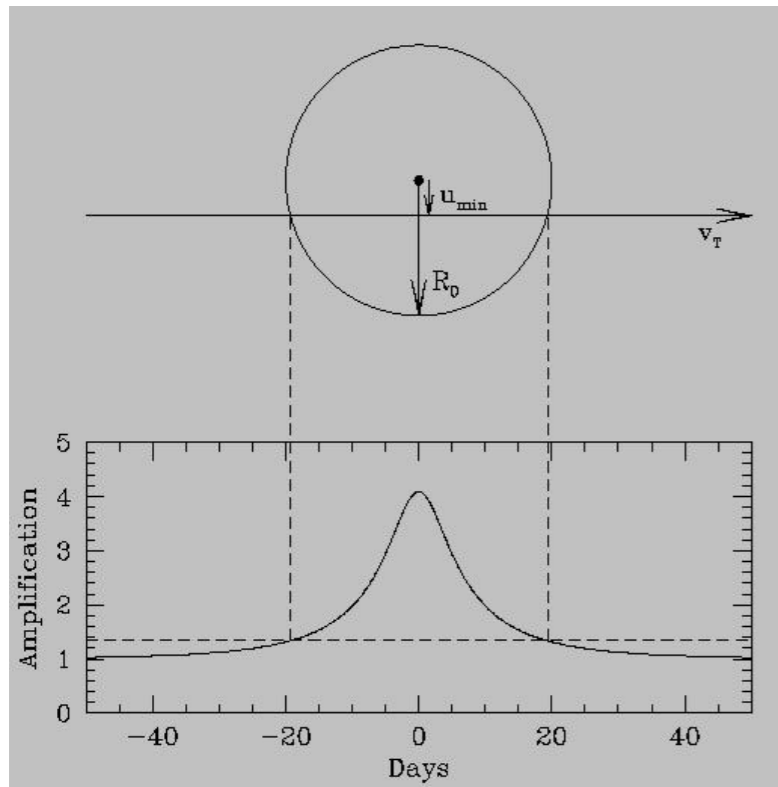
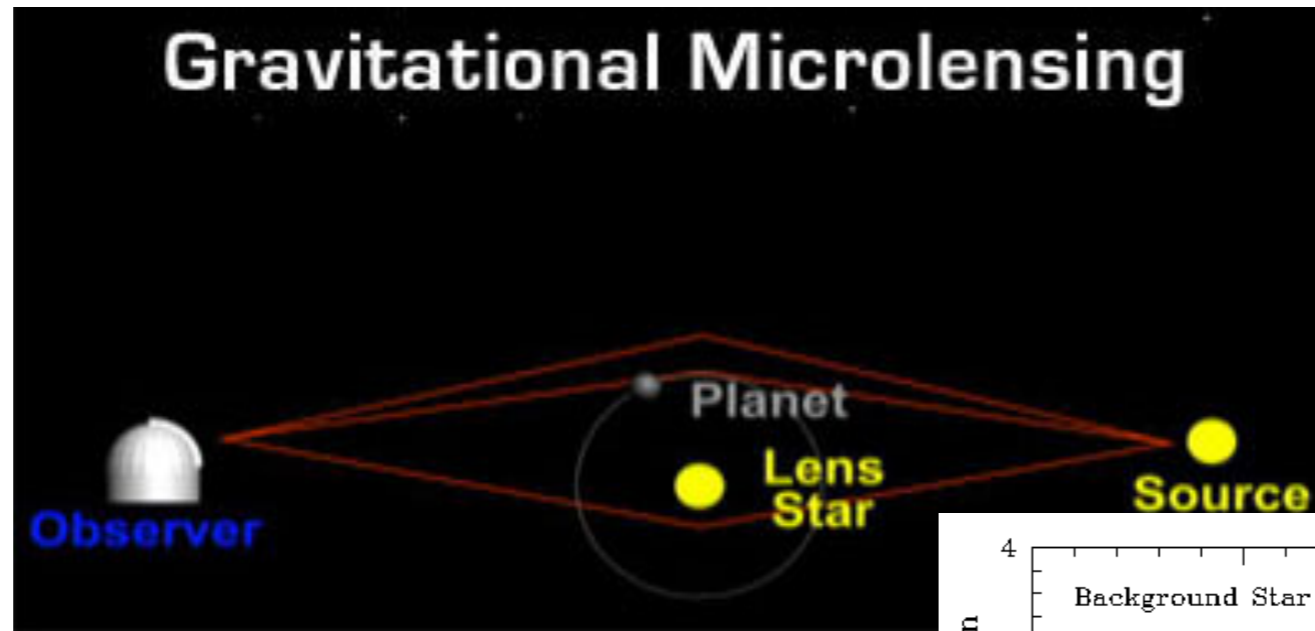


# gravitacijsko mikrolečenje in eksoplaneti

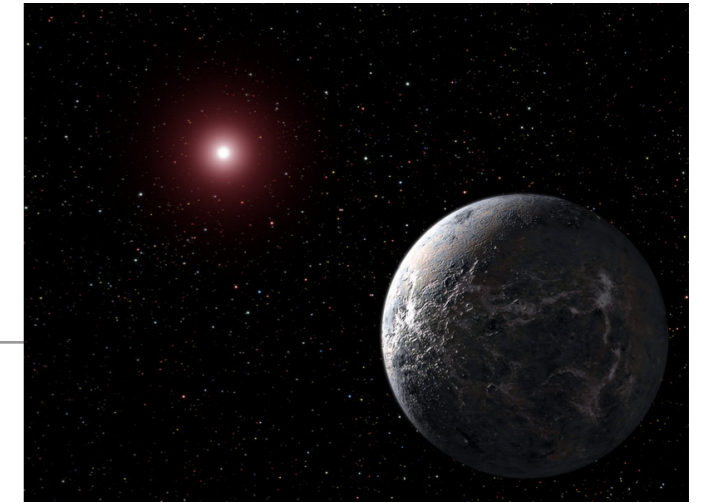
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# gravitacijsko mikrolečenje in eksoplaneti



# eksoplaneti



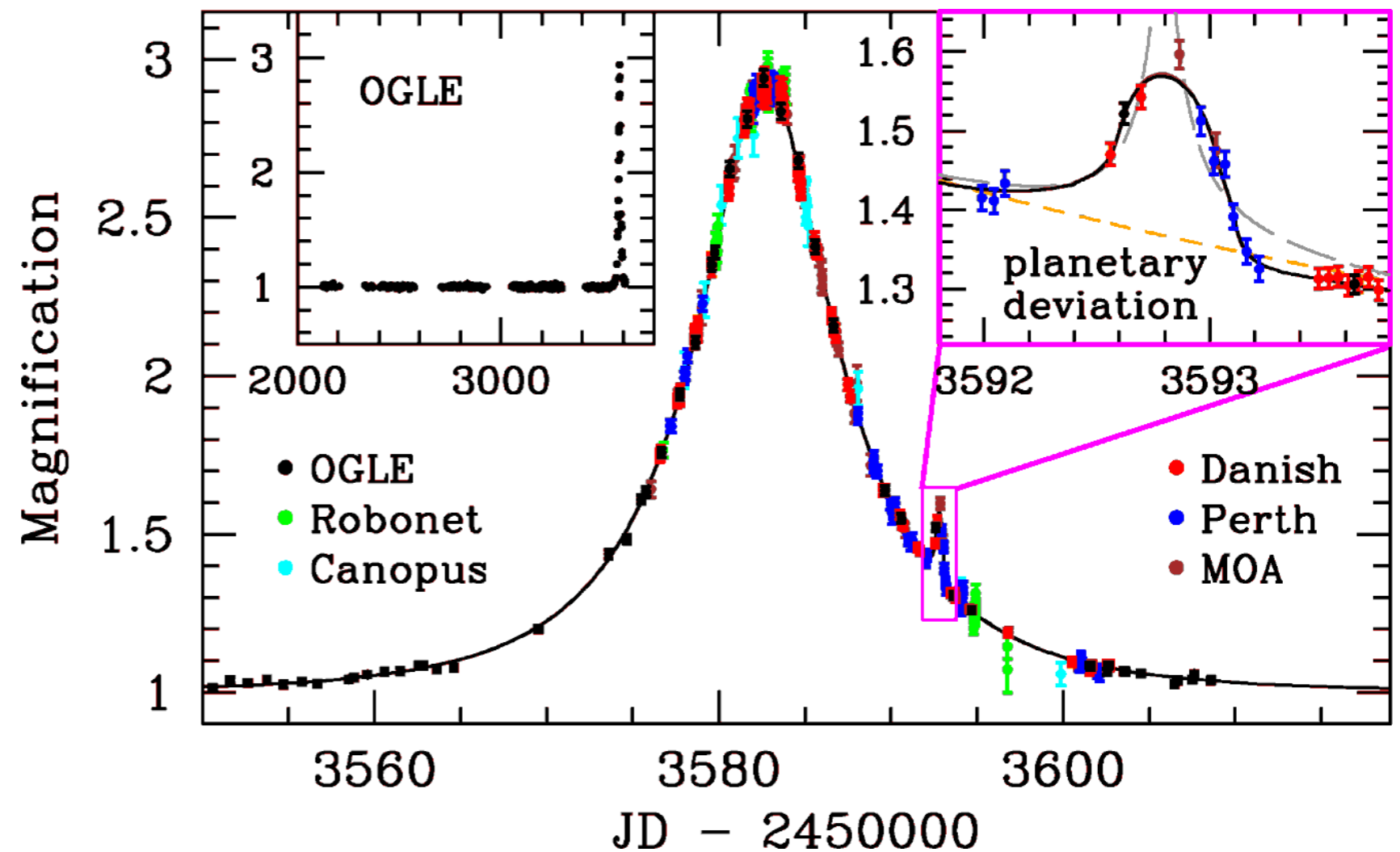
OGLE-2005-BLG-390Lb

5.5  $M_{\text{Zemlje}}$  – okrog “običajne” zvezde

2.6 a.e., 21.000 sv. let proti središču Galaksije

najhladnejši?

-220° C



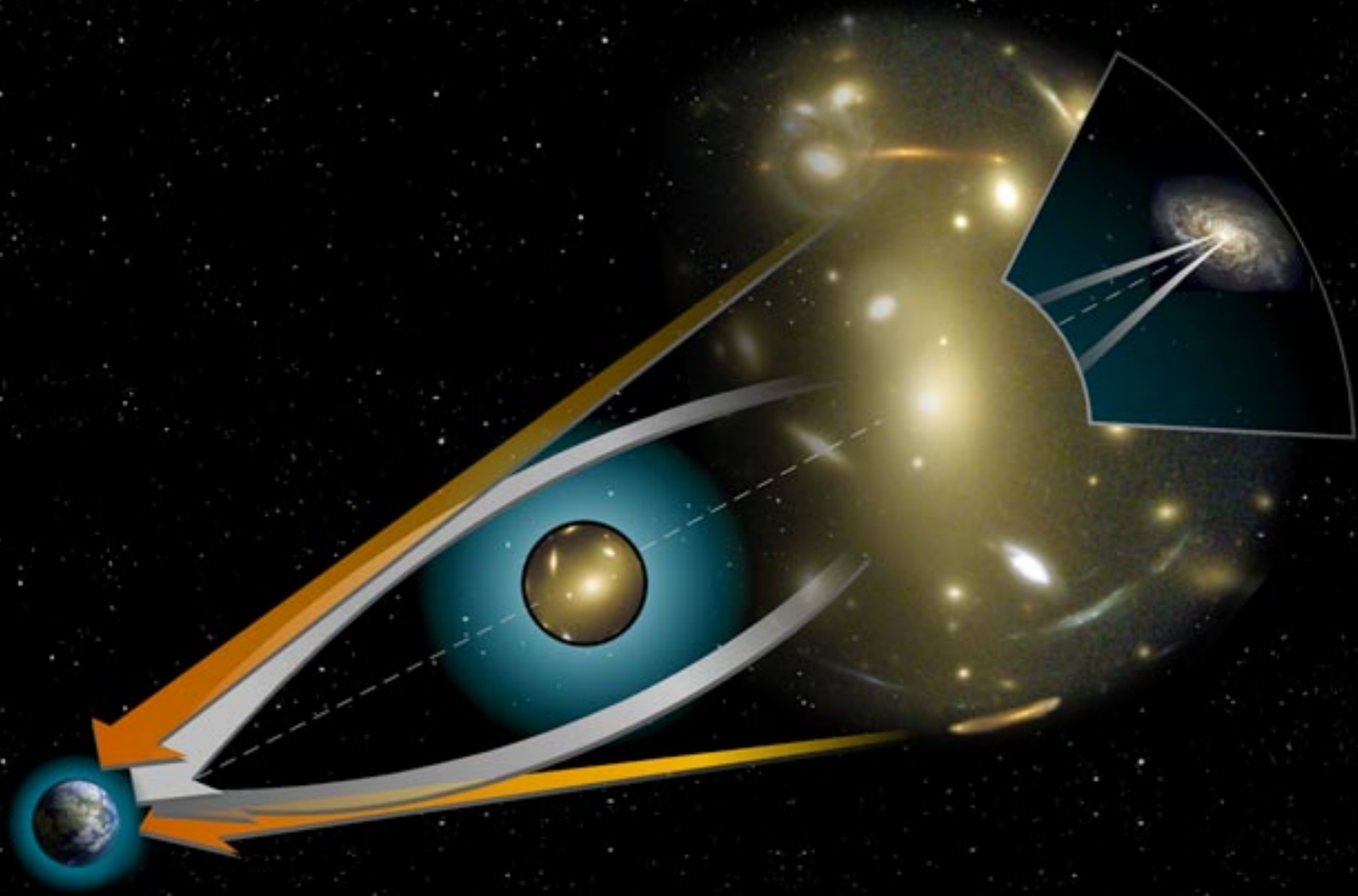
# gravitacijsko lečenje in jate galaksij

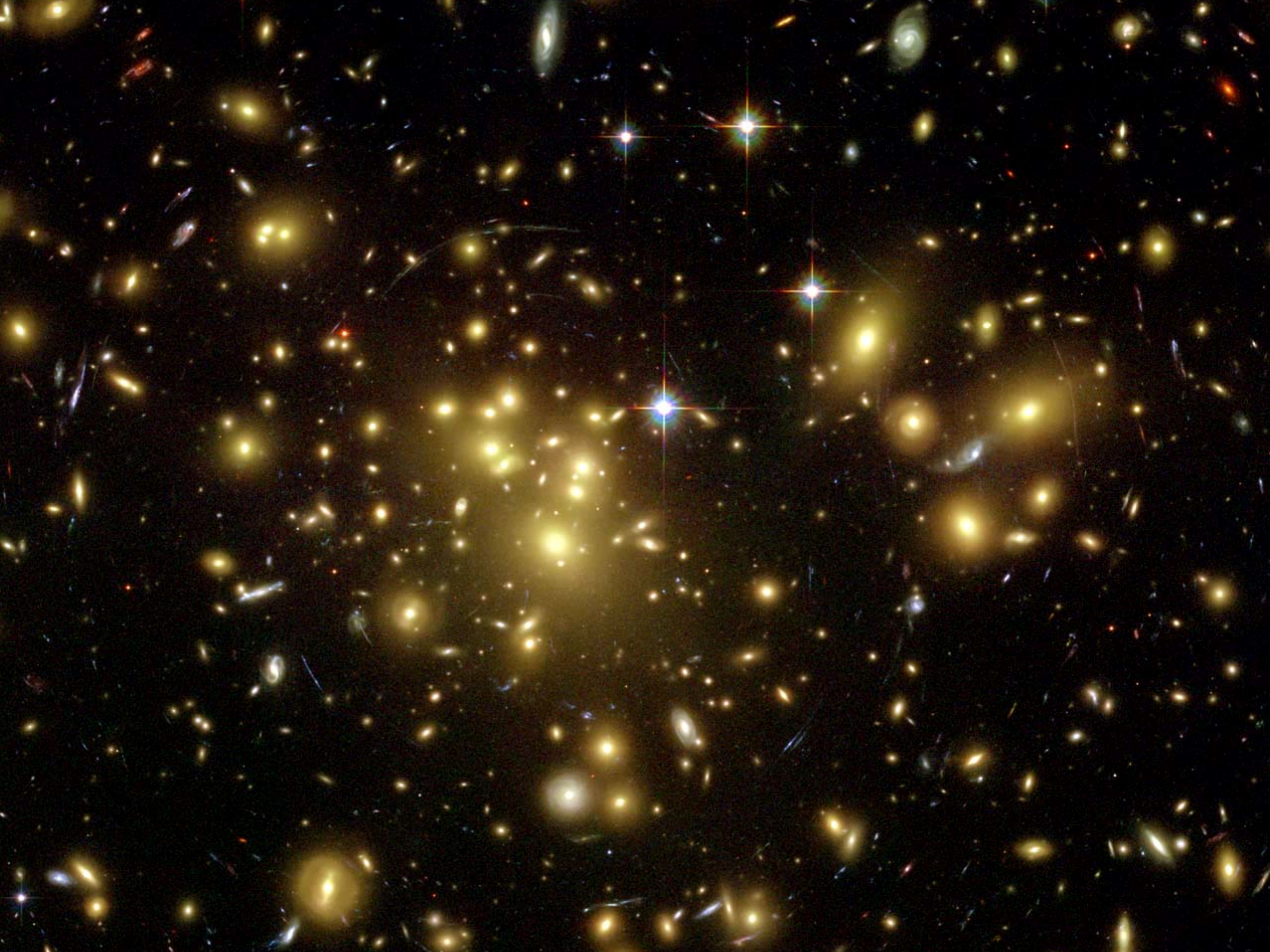
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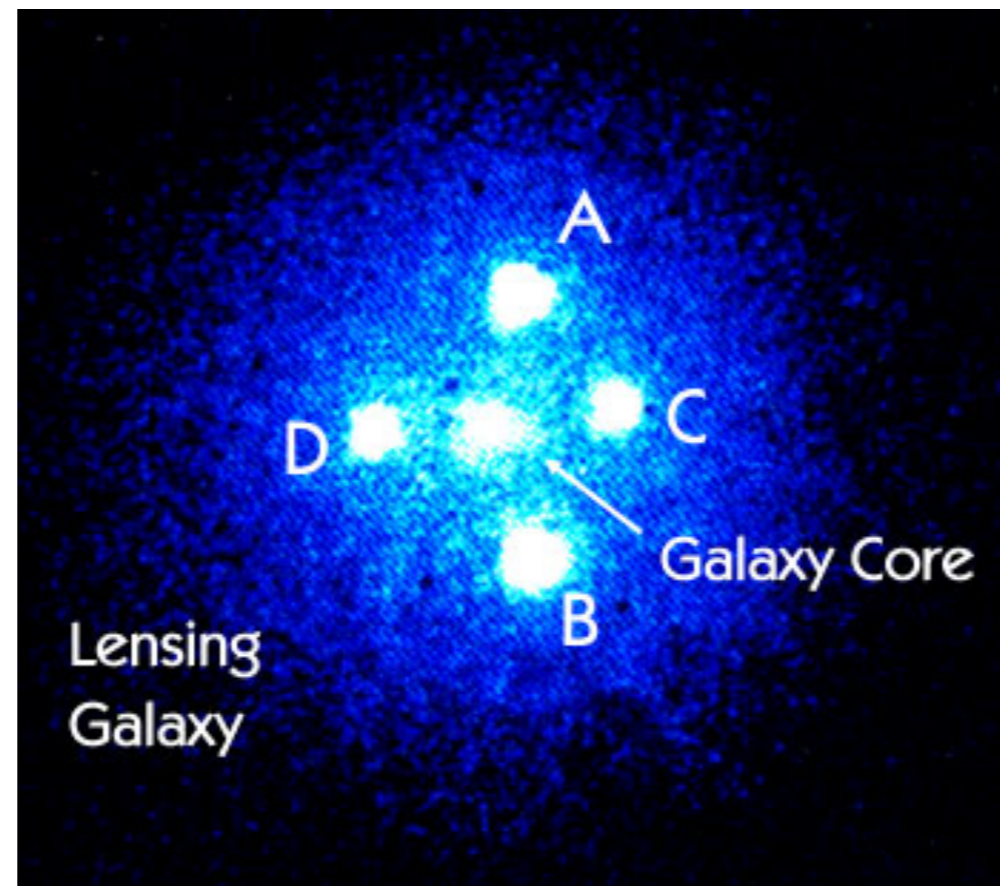
- jate galaksij

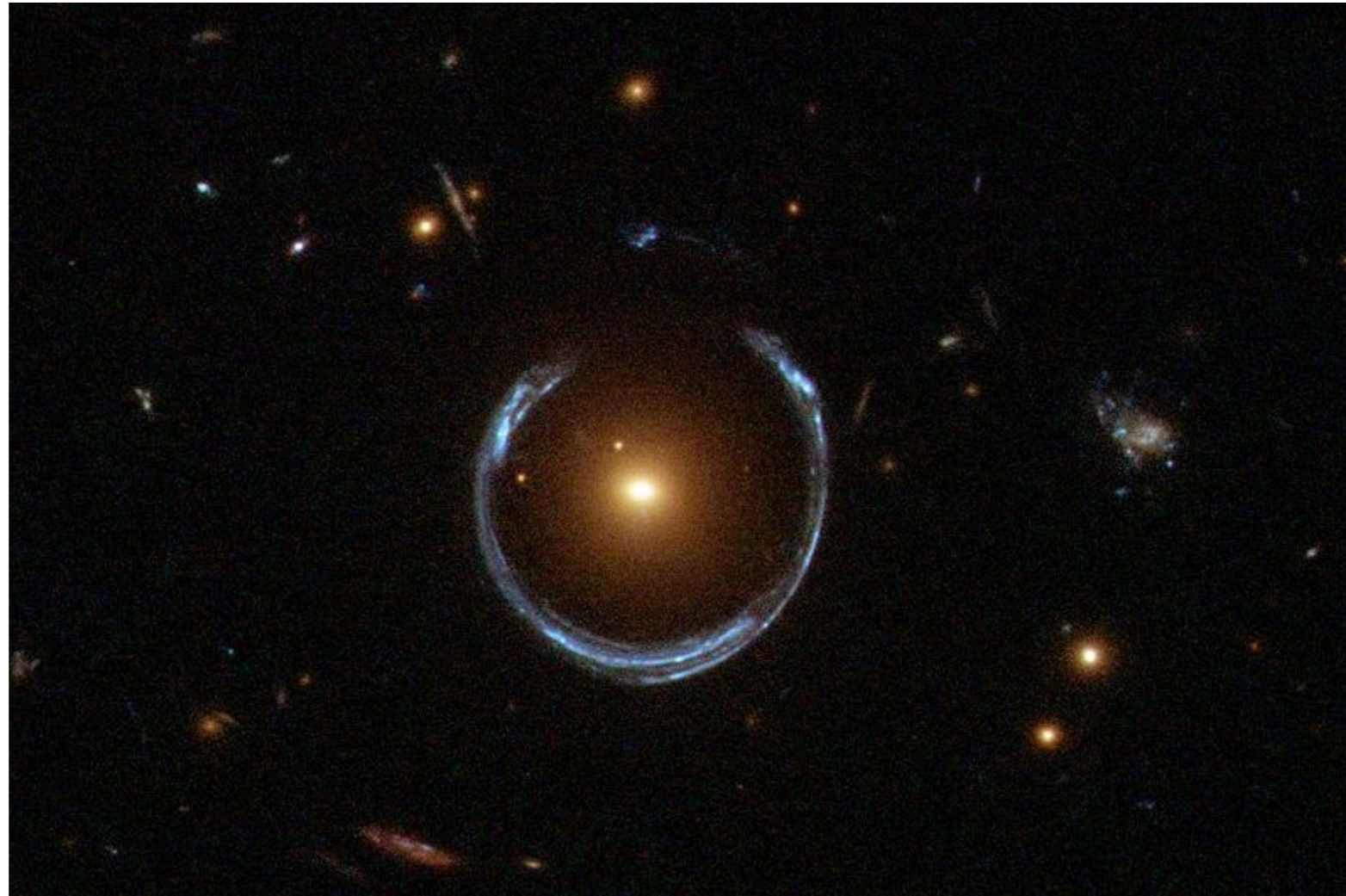










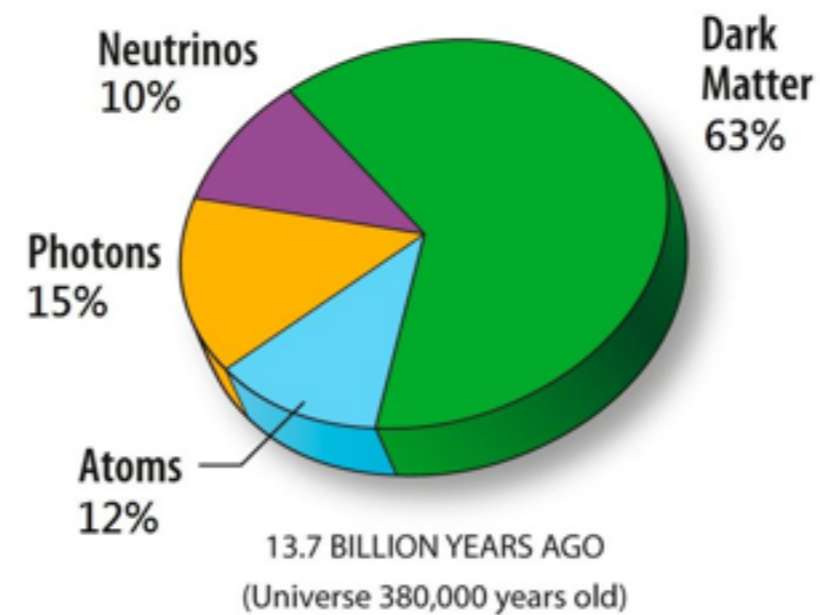
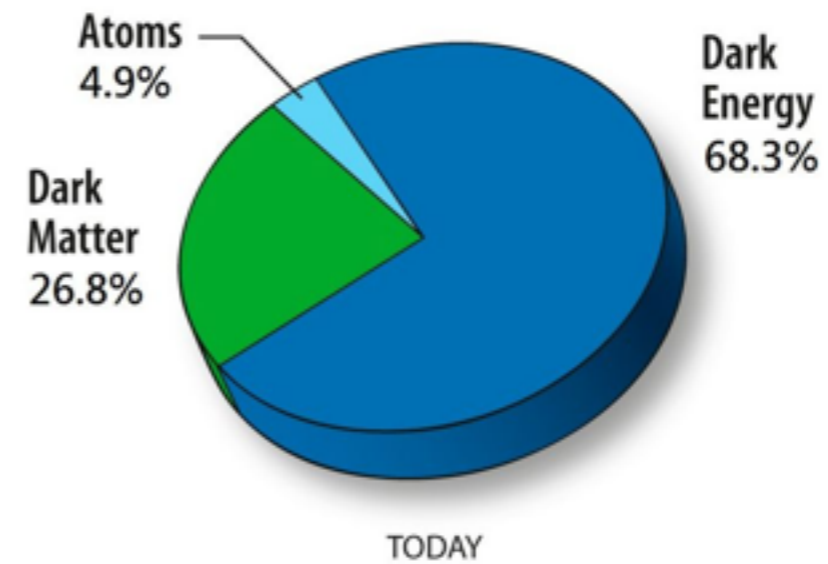




# temna snov

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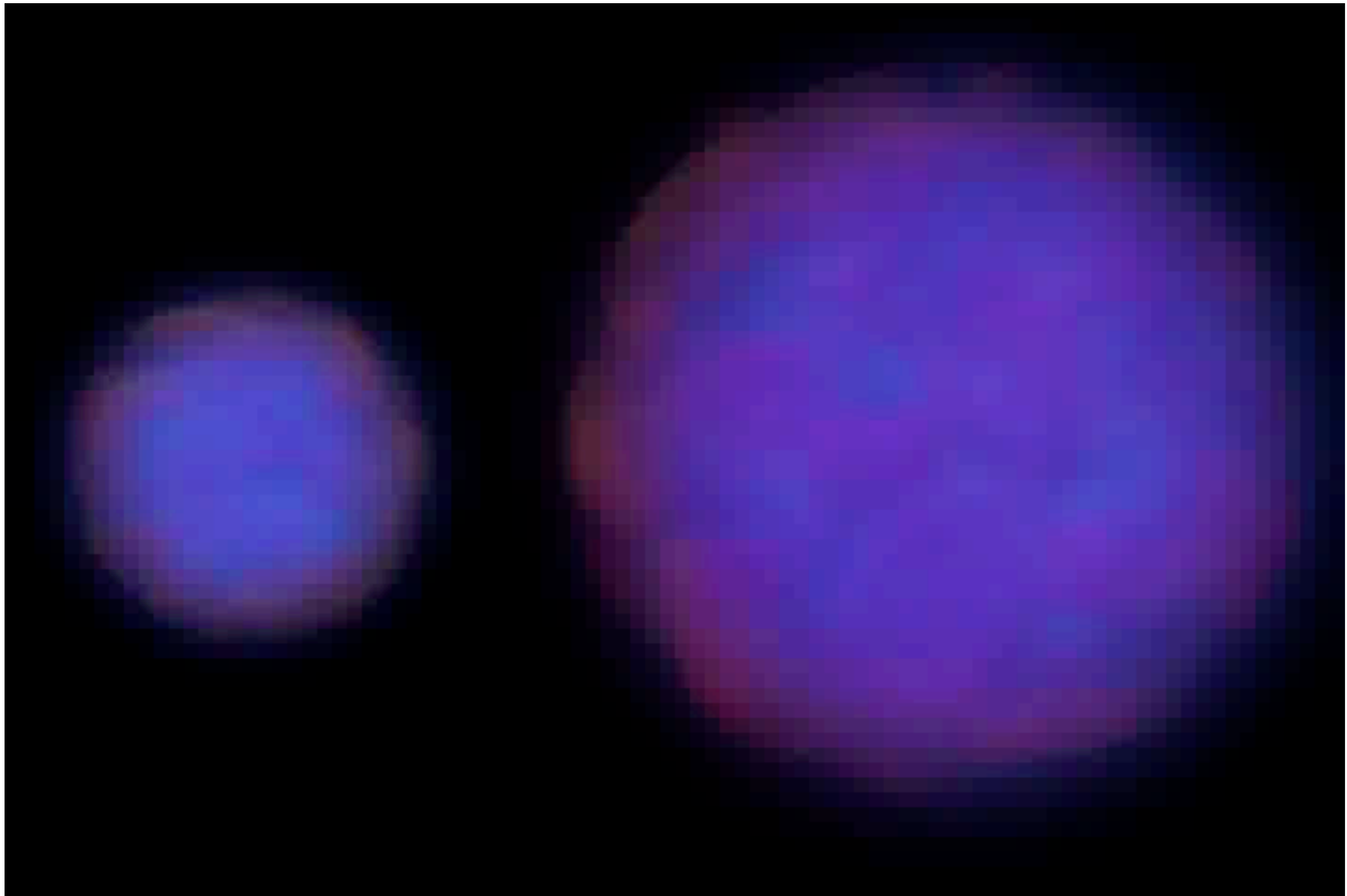
- sestava vesolja



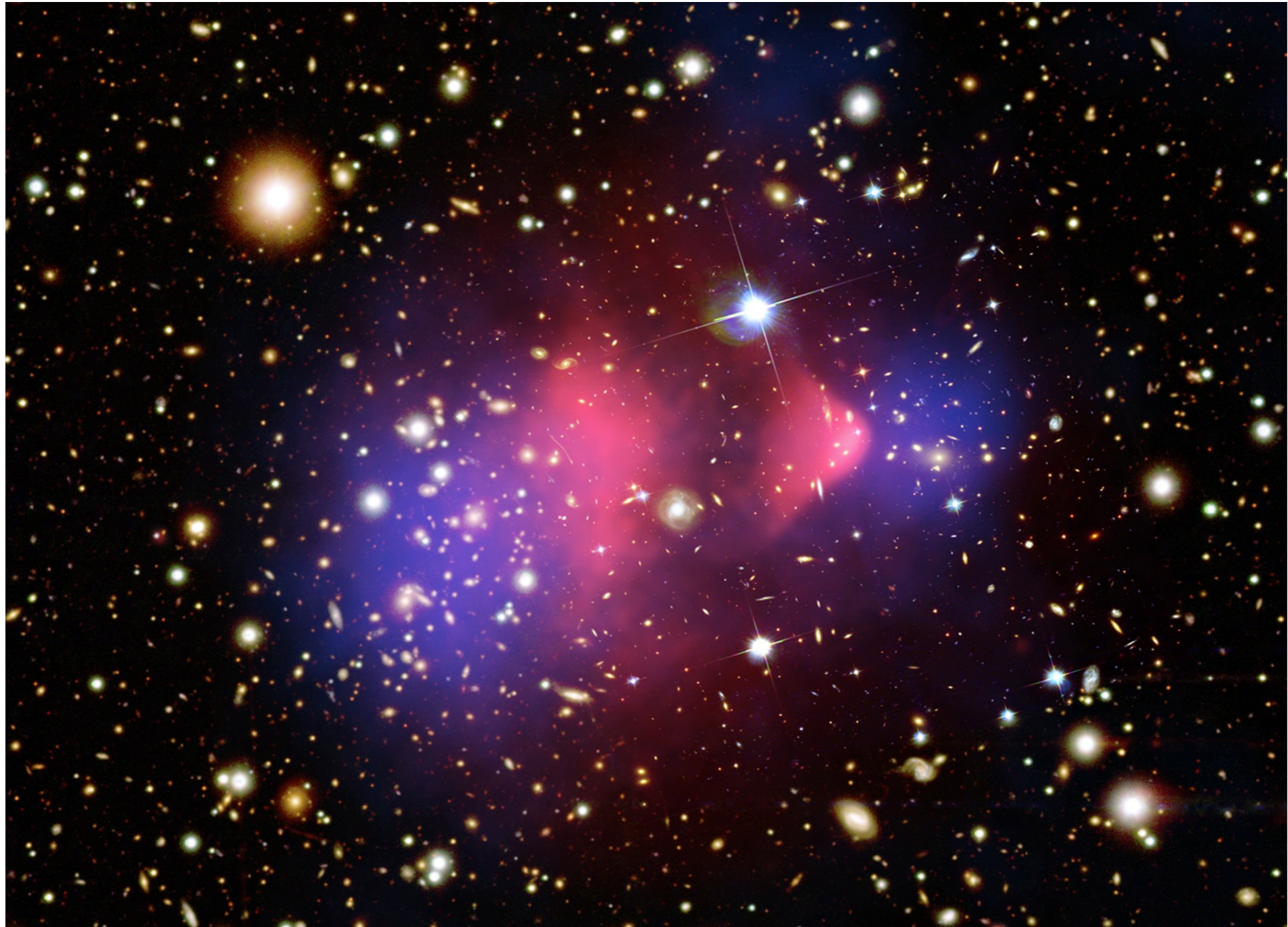
# trki jat galaksij

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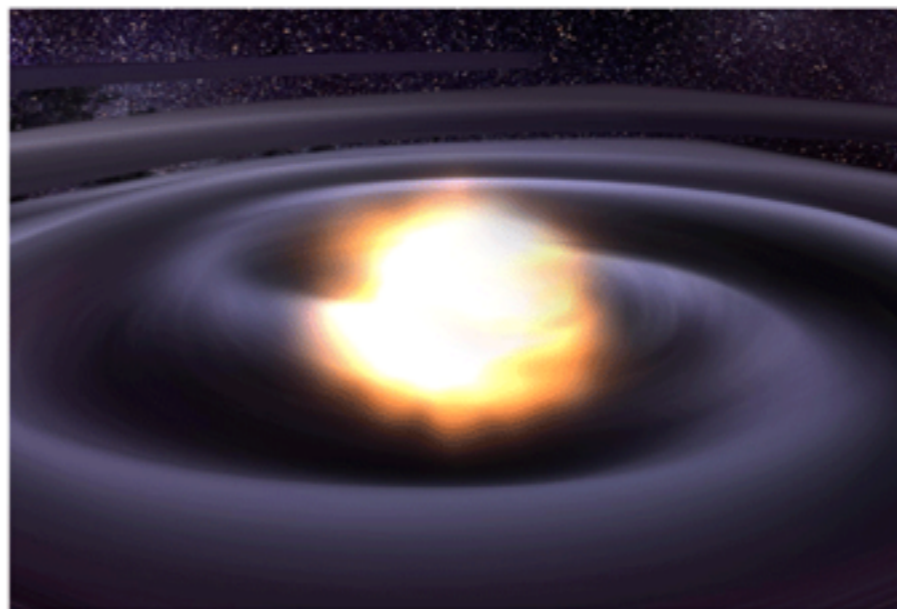
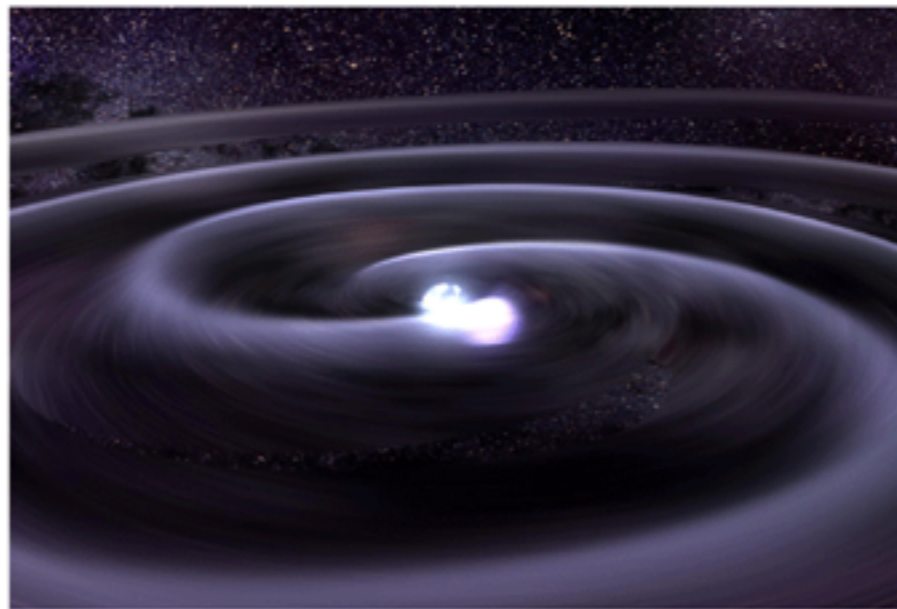
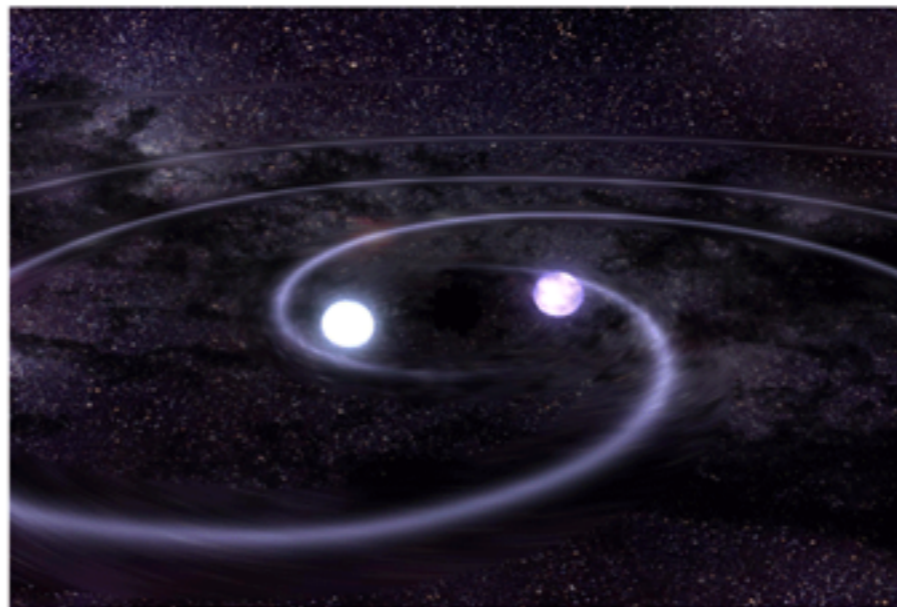






# gravitacijski valovi

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LIGO



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Hvala!

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## Nova študijska programa “Fizika in astrofizika”:

- univerzitetni program 1. stopnje
- magistrski program 2. stopnje

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Univerza v Novi Gorici  
Fakulteta za naravoslovje

