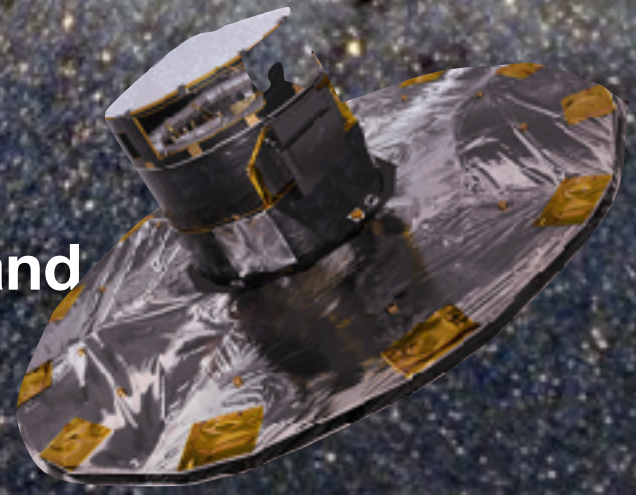
BLACK HOLES FROM MICROLENSING

Łukasz Wyrzykowski

(pron: Woo-cash Vi-zhi-kov-ski)

Warsaw University Astronomical Observatory, Poland



9th Gaia Science Alerts Workshop, Vipava 8.October 2018

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Simon Hodgkin (Cambridge)
Seppo Mattila (Turku)
Peter Jonker (Utrecht)
Iair Arcavi (LCOGT)
and many others

OGLE group
lead by
A. Udalski

Gaia group

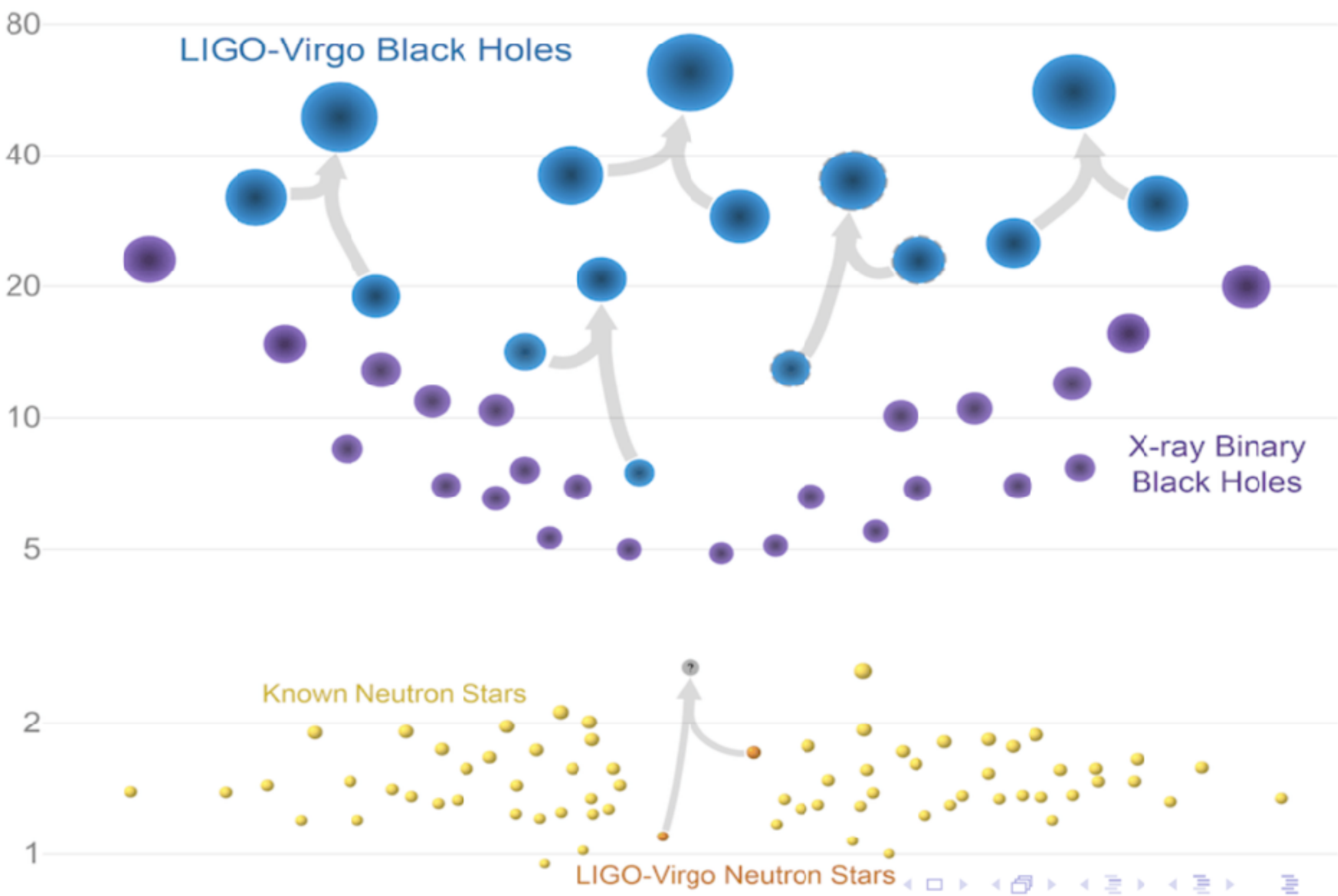
Gaia DPAC

gaia

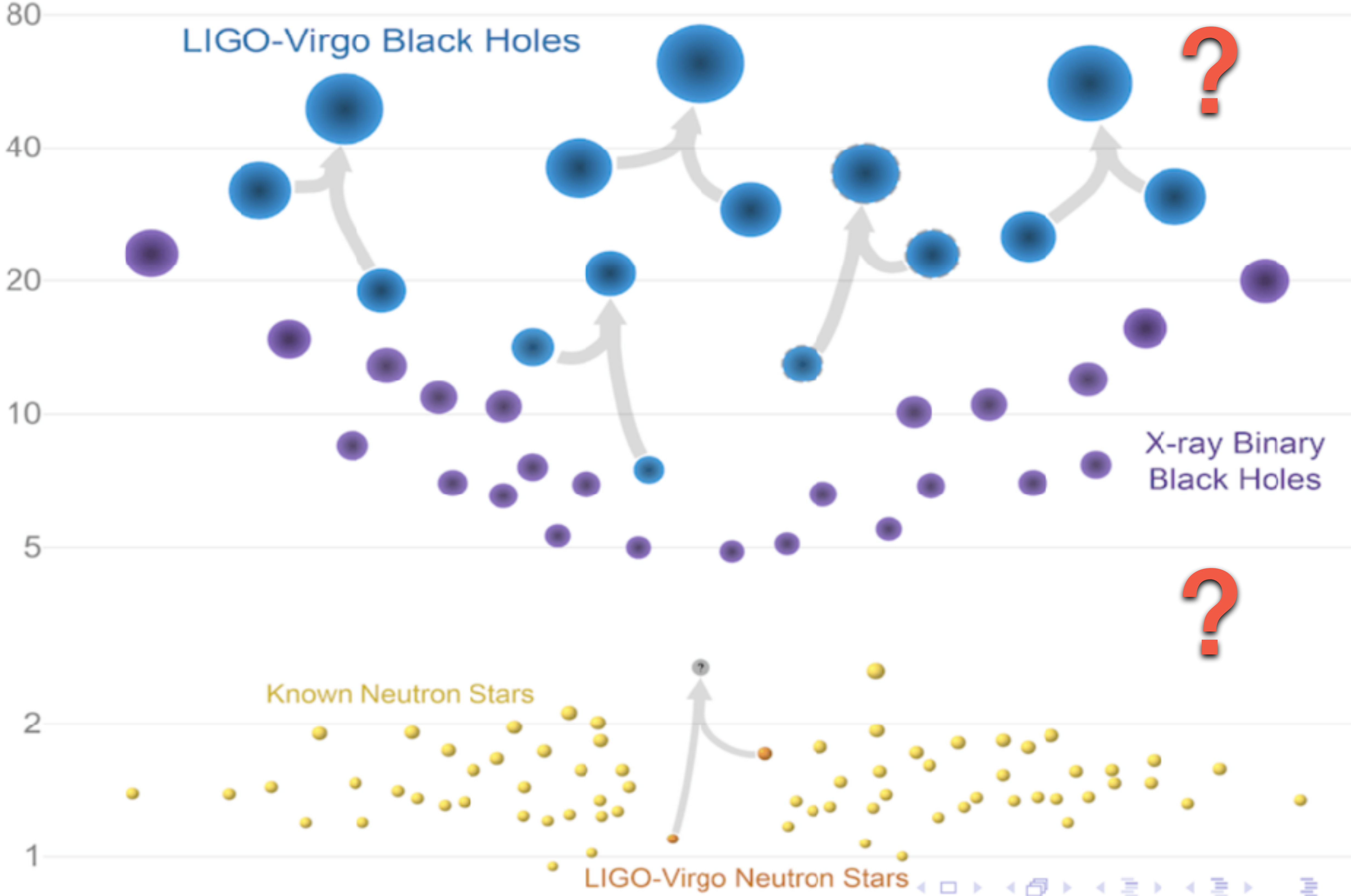
Institute of Astronomy

UNIVERSITY OF CAMBRIDGE

POPULATION OF KNOWN BLACK HOLES AND NEUTRON STARS



POPULATION OF KNOWN BLACK HOLES AND NEUTRON STARS



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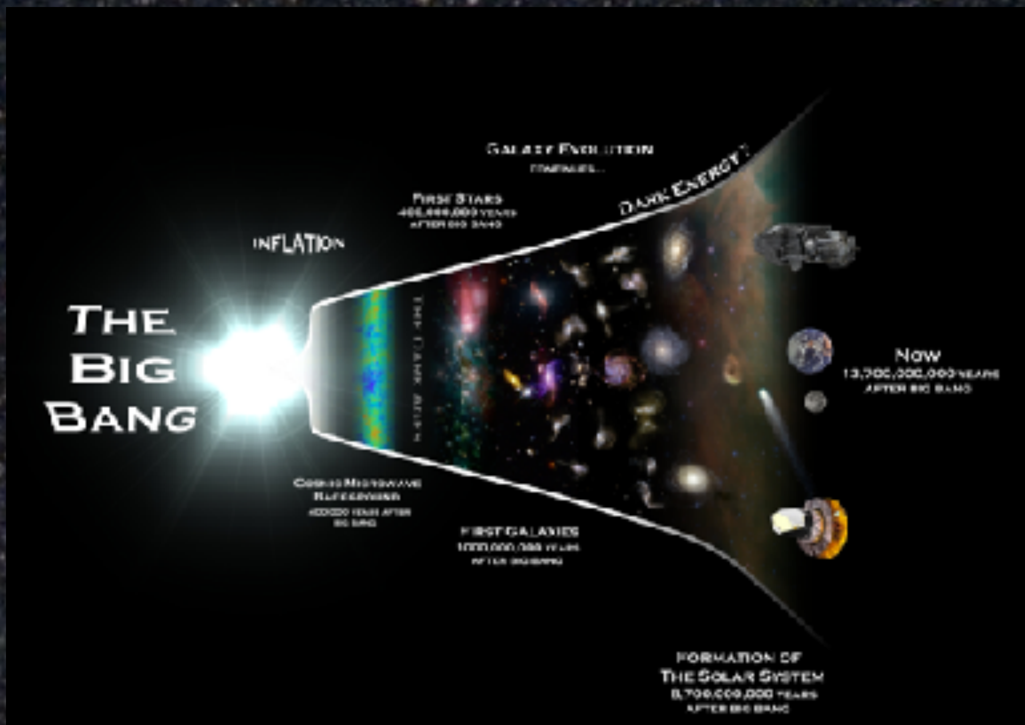
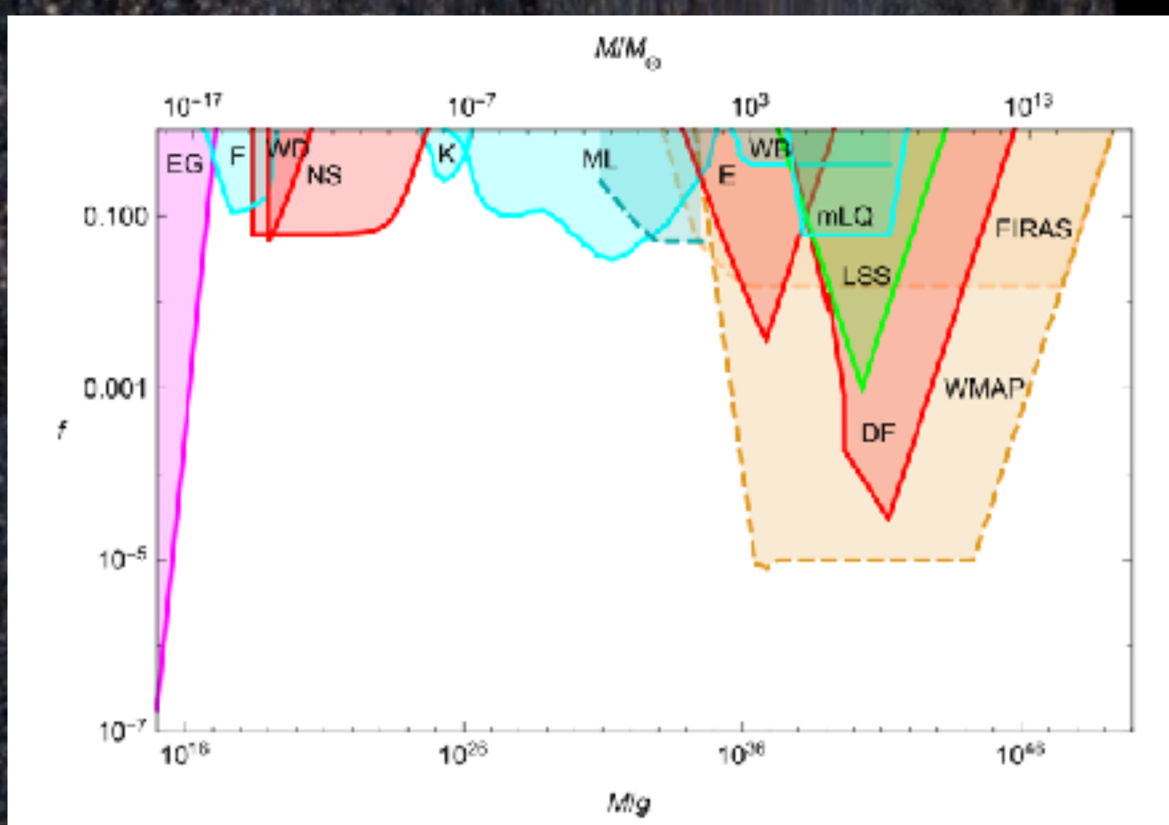
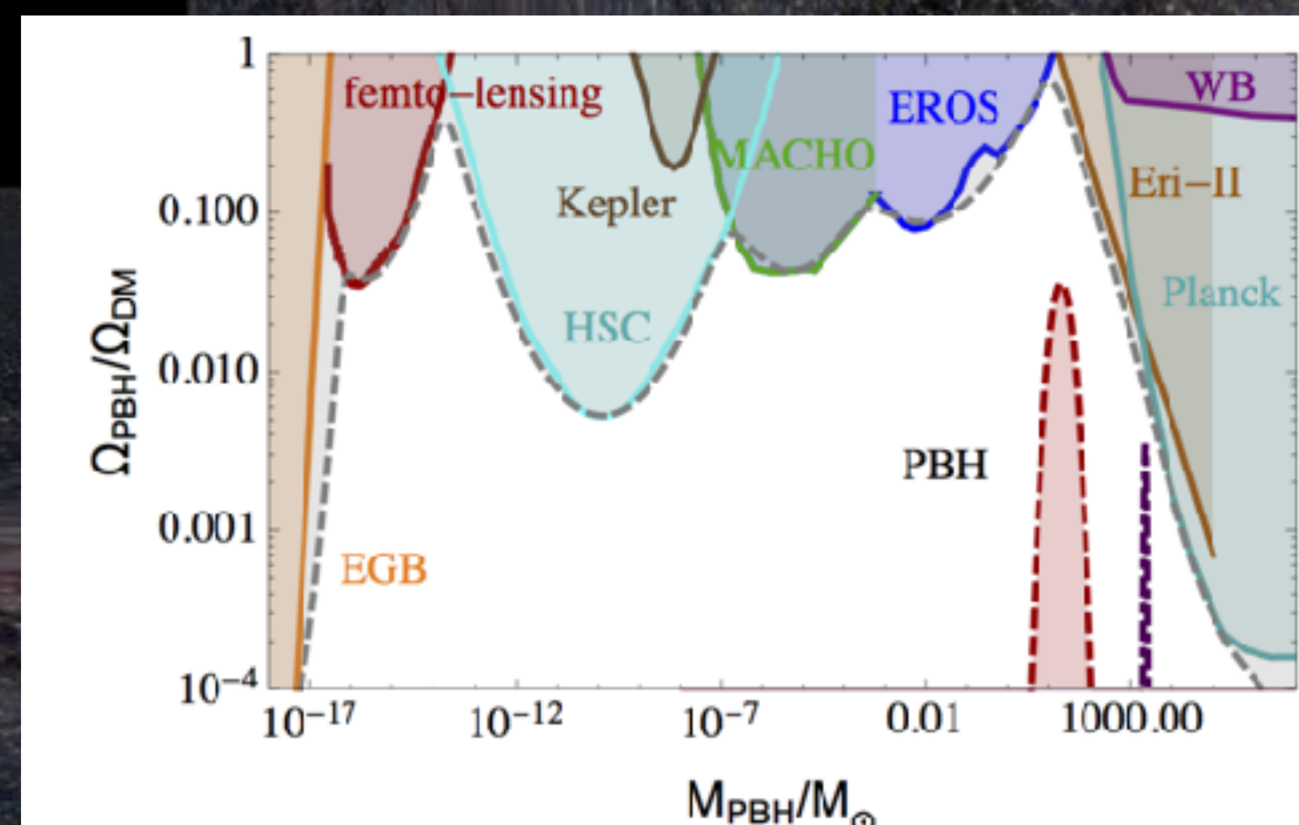
PRIMORDIAL BLACK HOLES AS DARK MATTER?



theoretical
non-barionic dark matter
collapsed at the dawn
of the Universe
and grown to tens of $M_\odot$



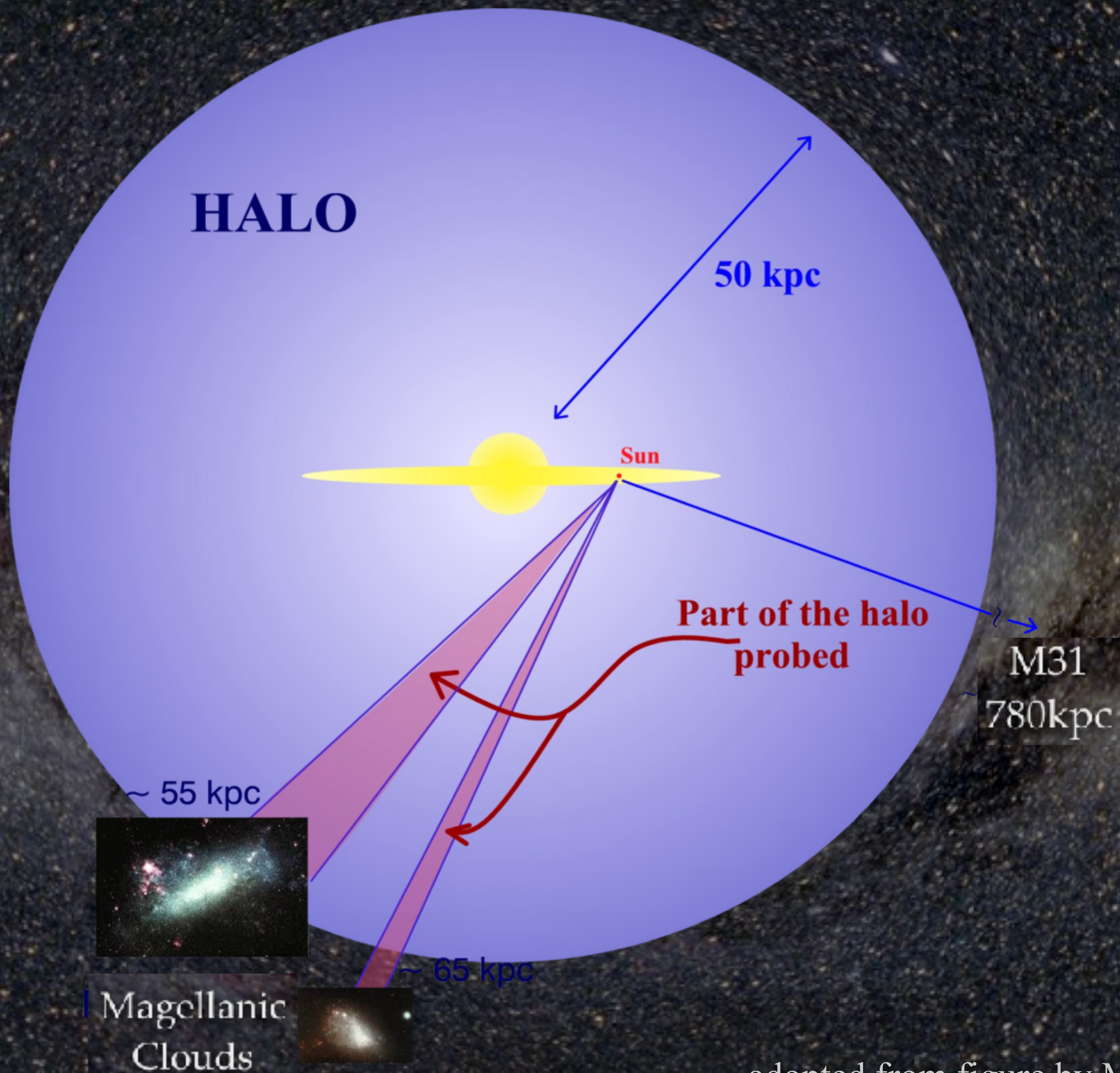


Carr et al. 2016

Garcia-Bellido & Clesse 2017

HOW TO FIND DARK MATTER?

Massive Astrophysical Compact Halo Objects



adopted from figure by M.Moniez

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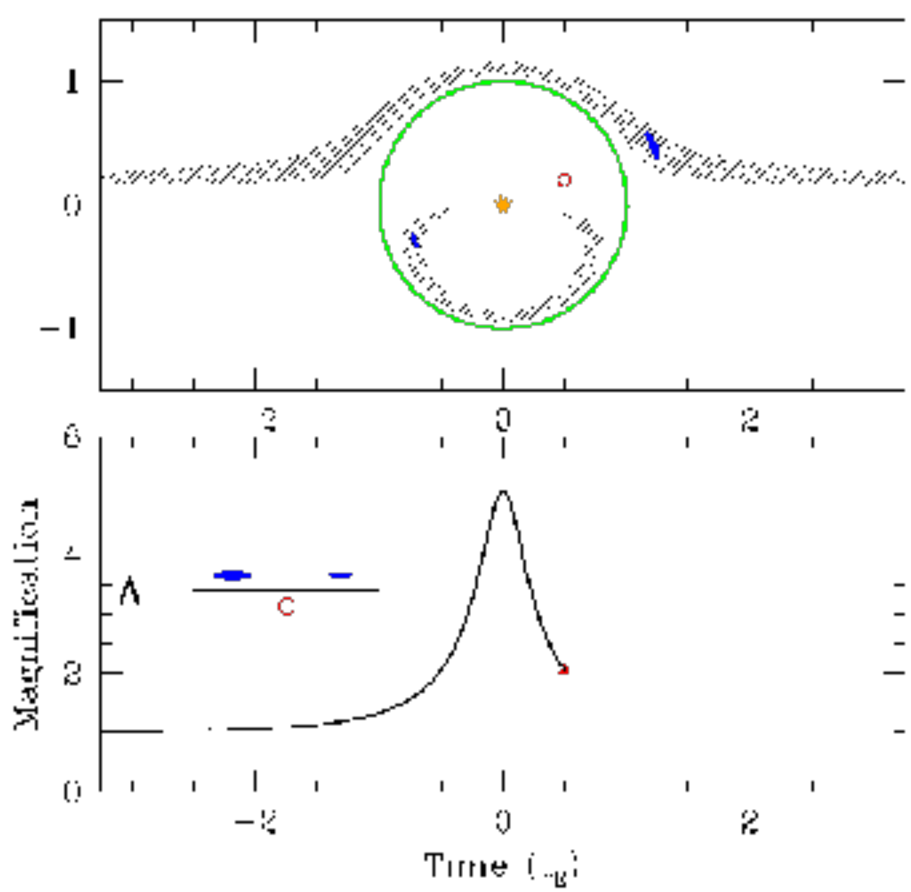
MICROLENSING

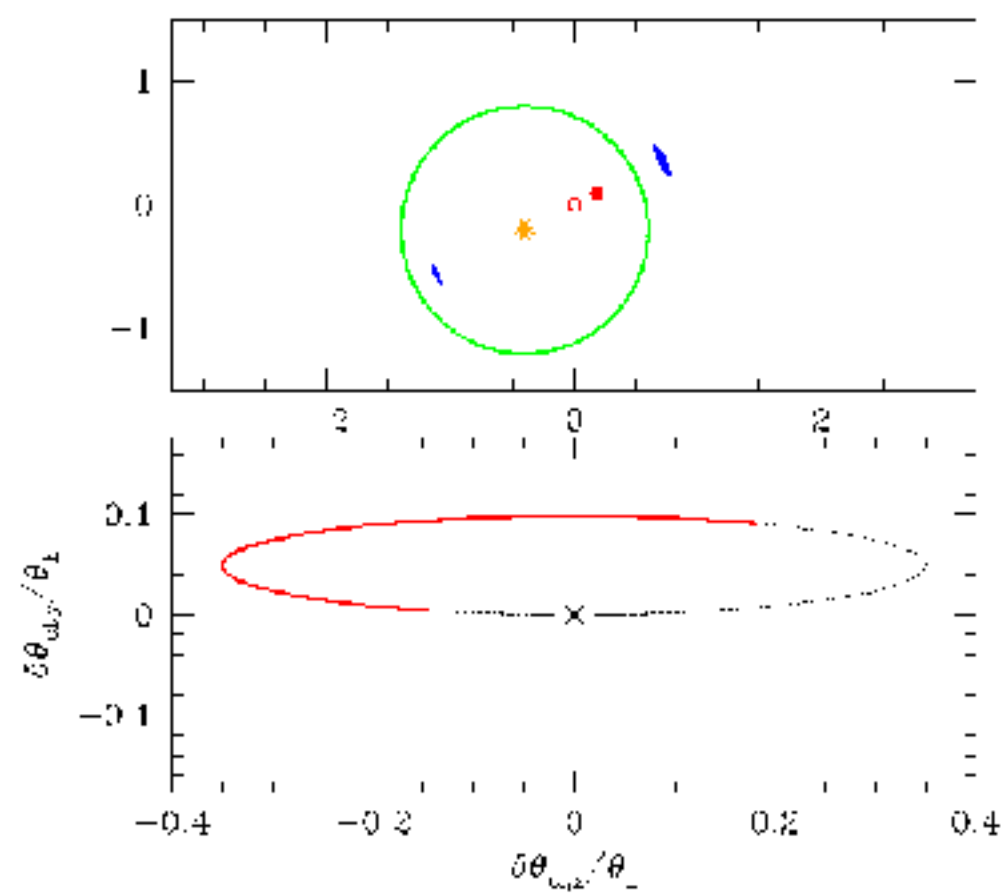
- Gravitational lensing by compact lenses (stellar or remnants)
- Mass range from Earth-like to ~100 MSun
- Sources: background stars (chance: 10^{-6} in the Bulge, 10^{-8} in the LMC)

photometry (sum of images)



~1 month

astrometry (centroid motion)



~1mas

animations by S.Gaudi

http://www.astronomy.ohio-state.edu/~gaudi/movies.html

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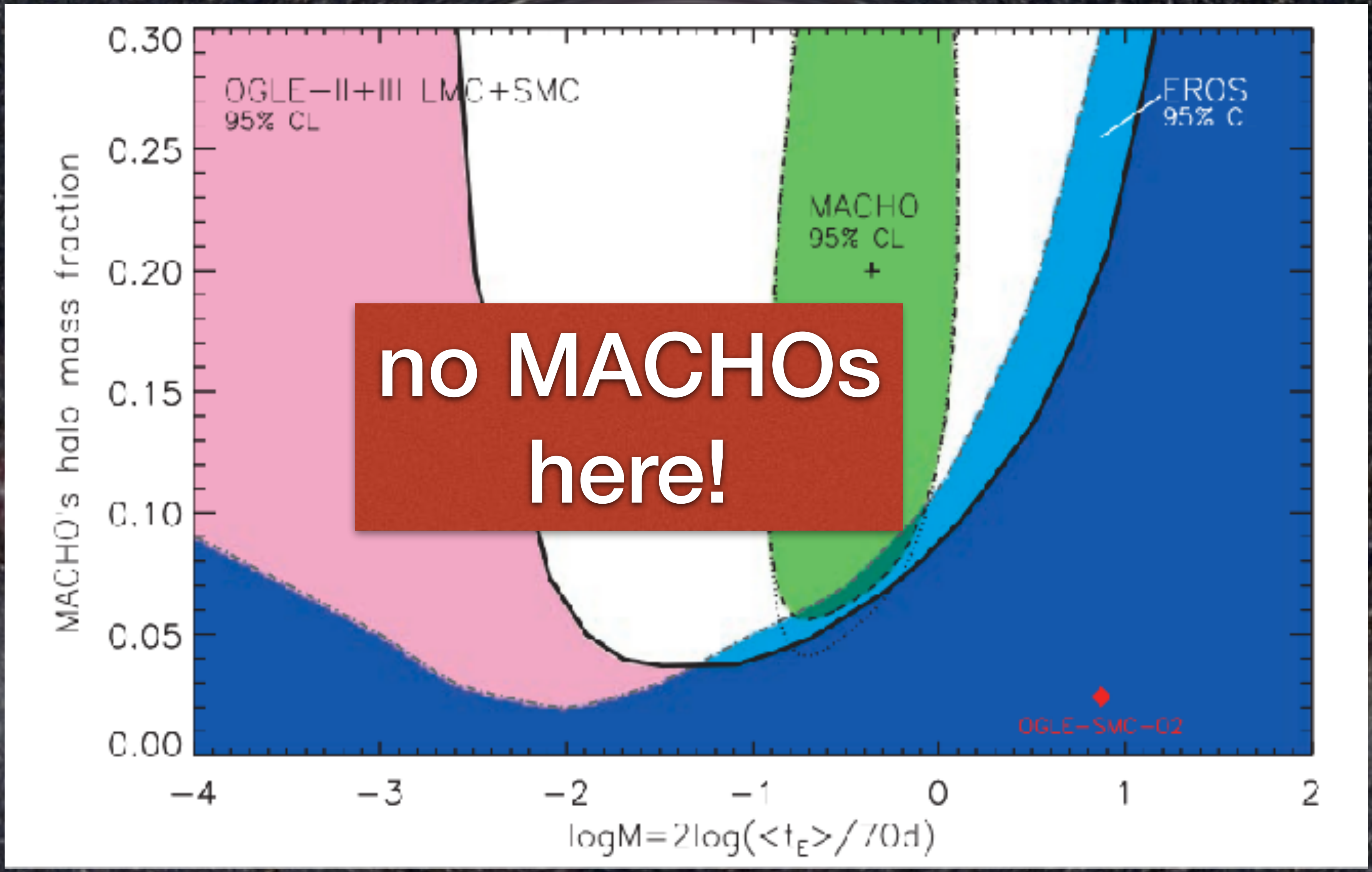
MICROLENSING CONSTRAINS ON HALO DARK MATTER

OGLE (1997-2009) monitoring of Magellanic Clouds - very few microlensing events
All can be explained by **self-lensing**: stars in the LMC lens stars from the LMC



Low mass compact objects **excluded** from MW halo up to **~ few MSun**.

Wyrzykowski+ 2009,2010,2011a,2011b

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MICROLENSING CONSTRAINS ON HALO DARK MATTER

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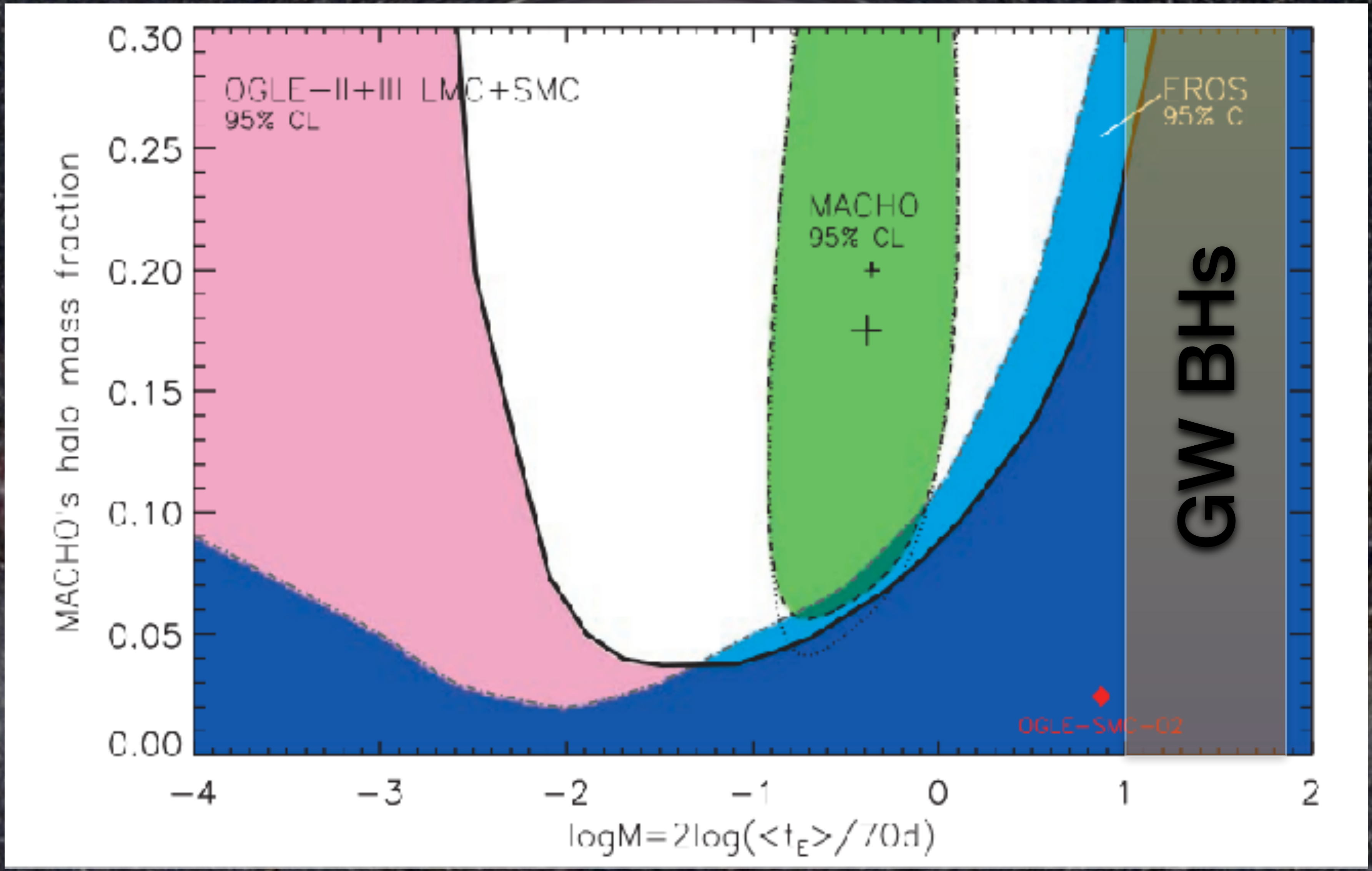

Low sensitivity in Gravitational Wave BH mass regime

Wyrzykowski+ 2009,2010,2011a,2011b

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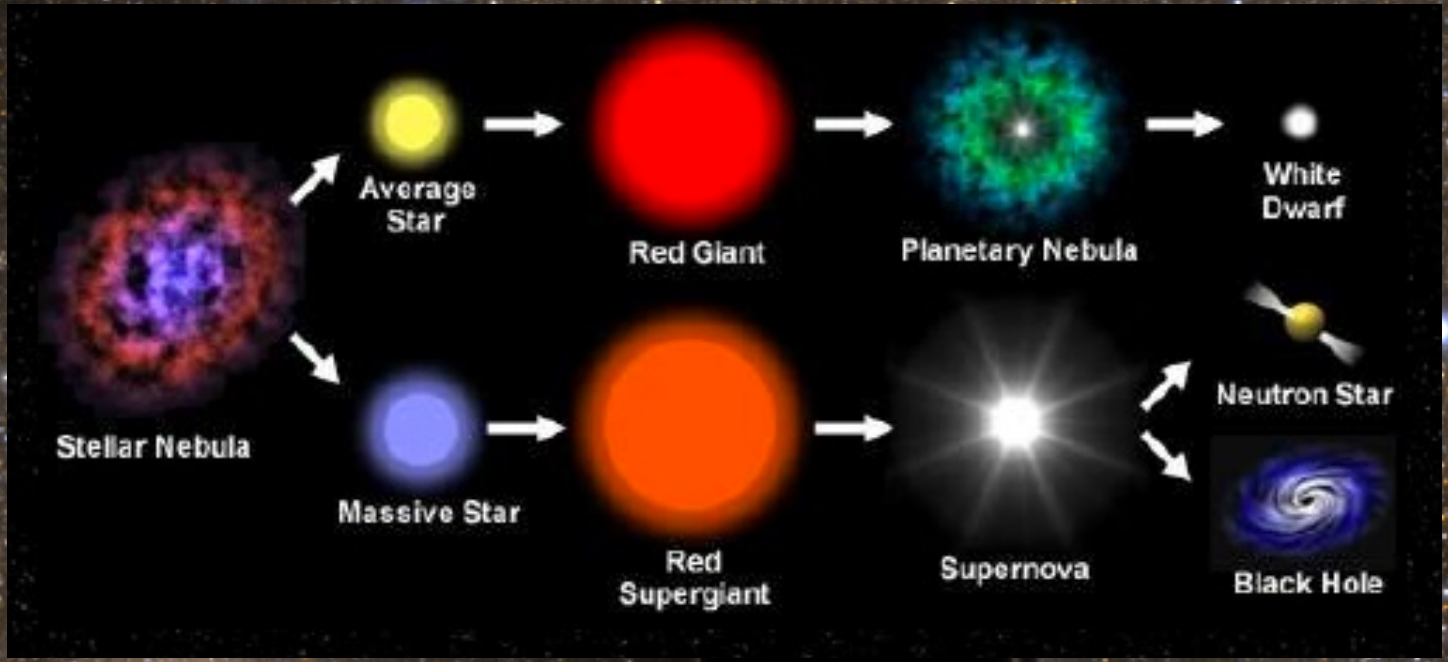
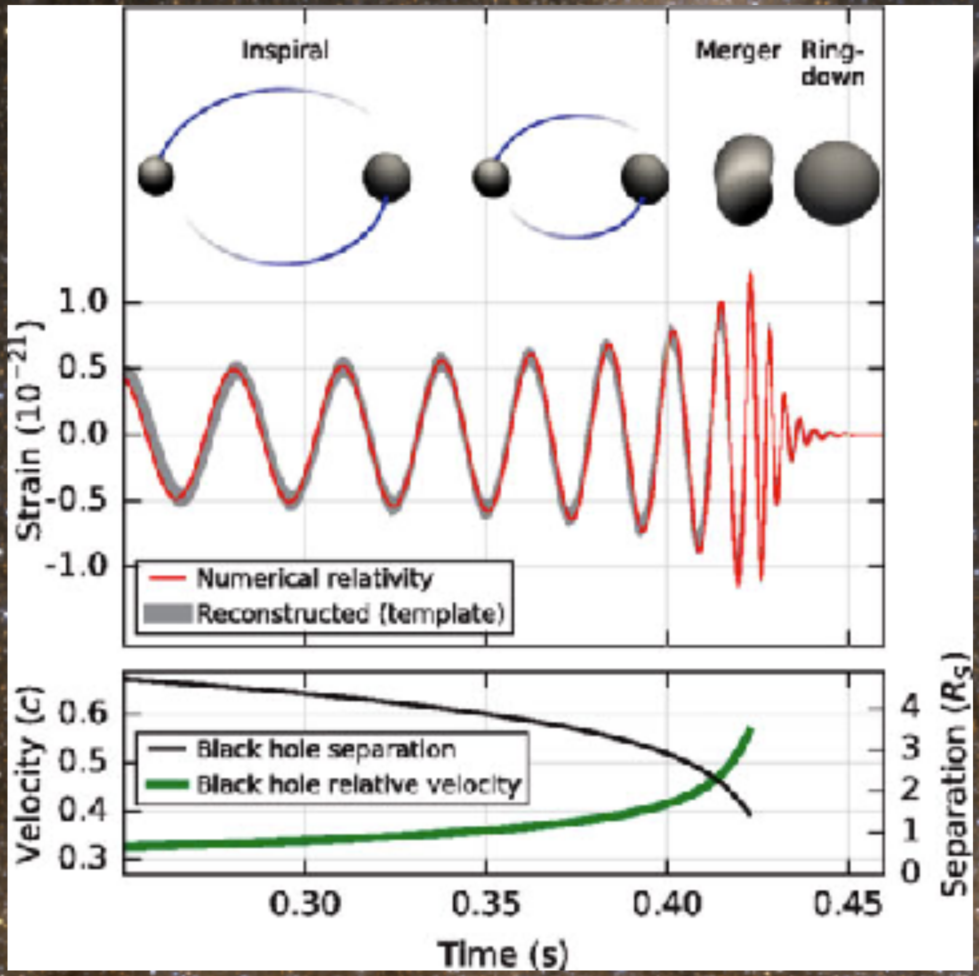
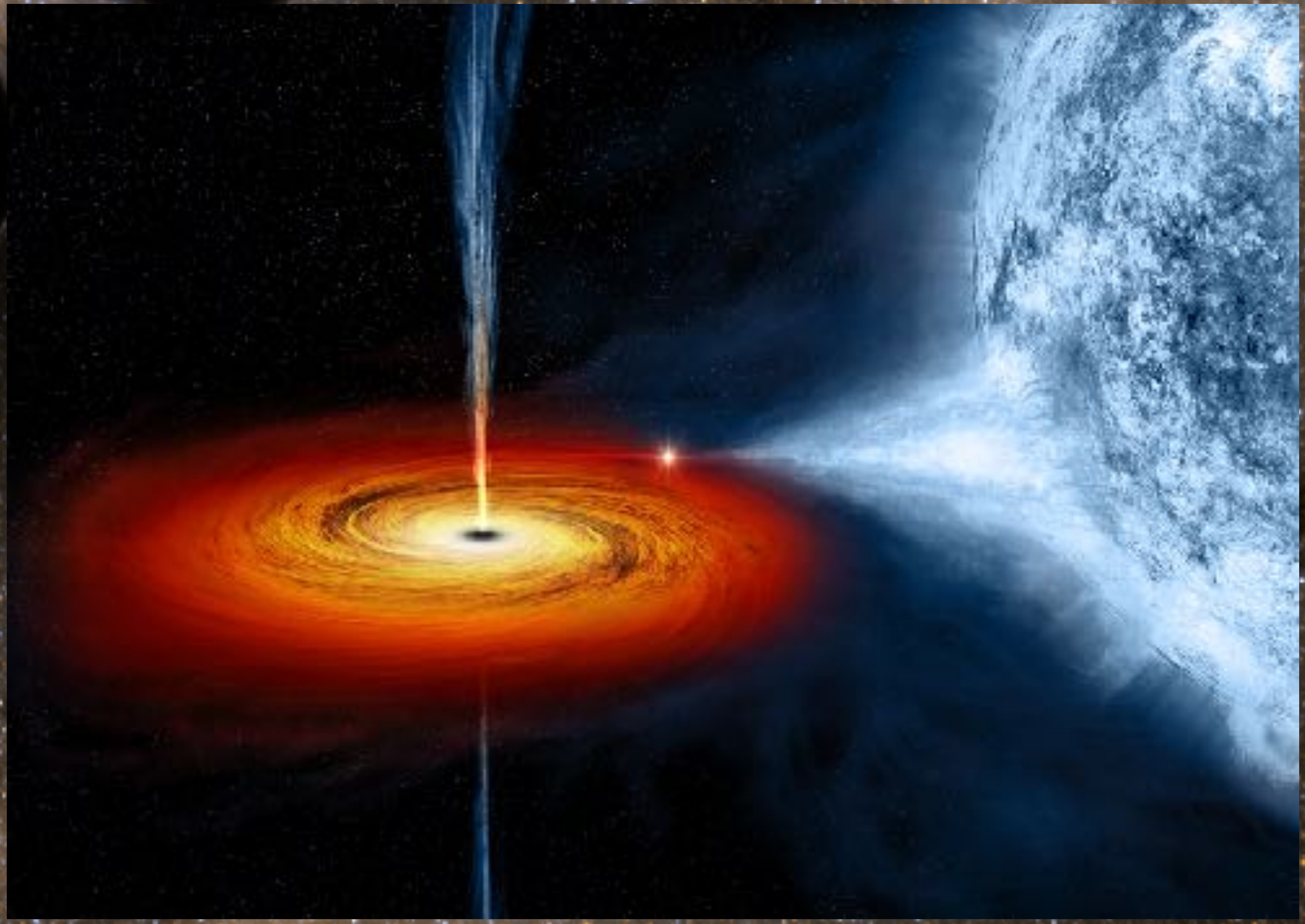
BLACK HOLES DO EXIST!



GW150914: 36 + 29 $M_\odot$ BHs

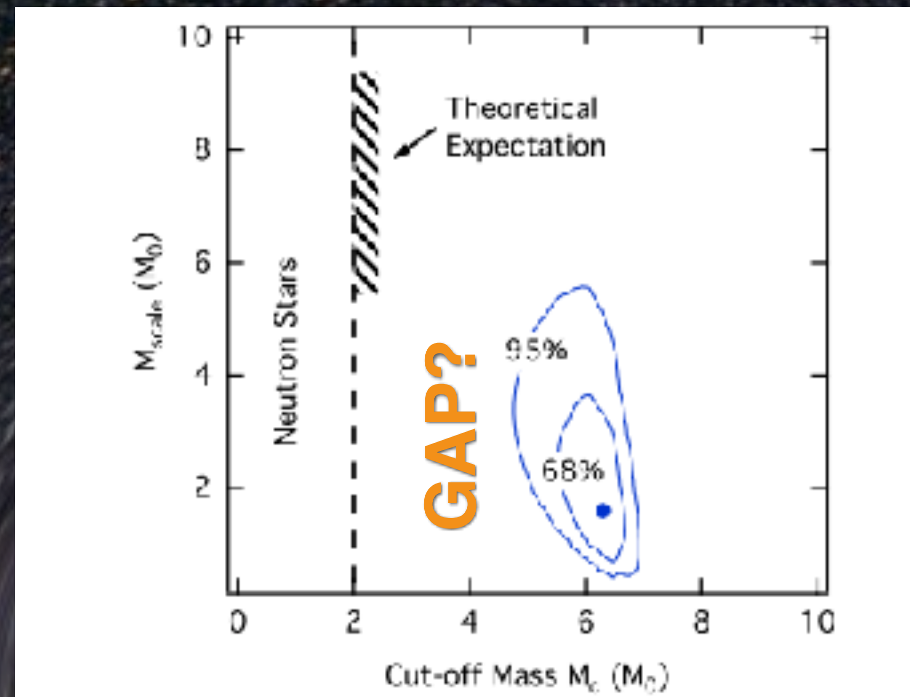


BH+Star binary systems

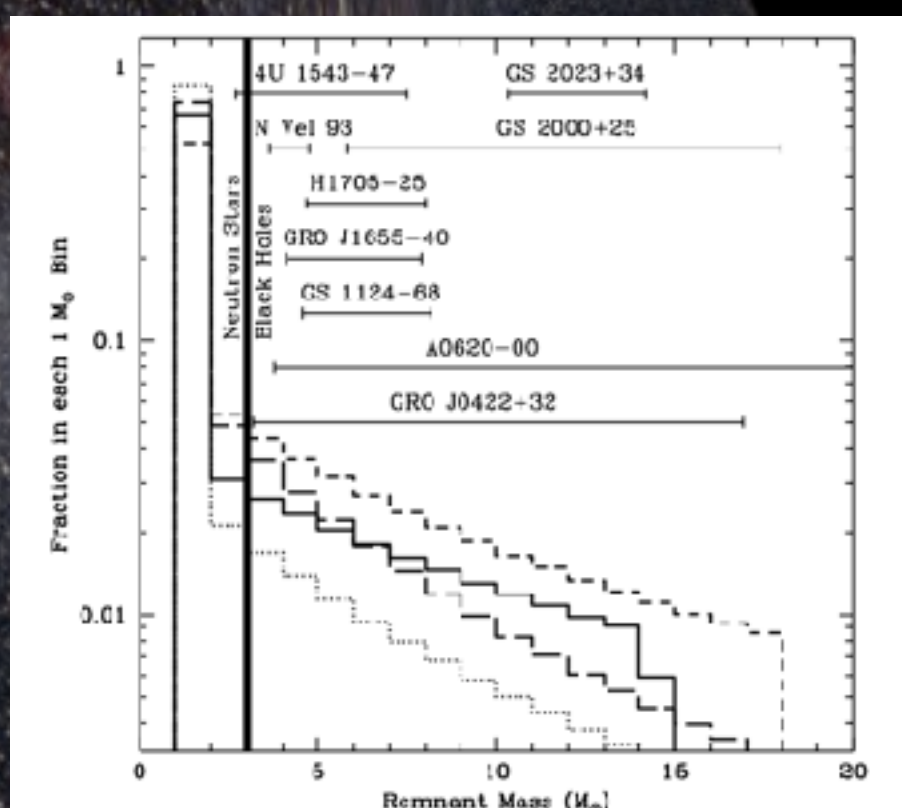


GAP OR NOT GAP?

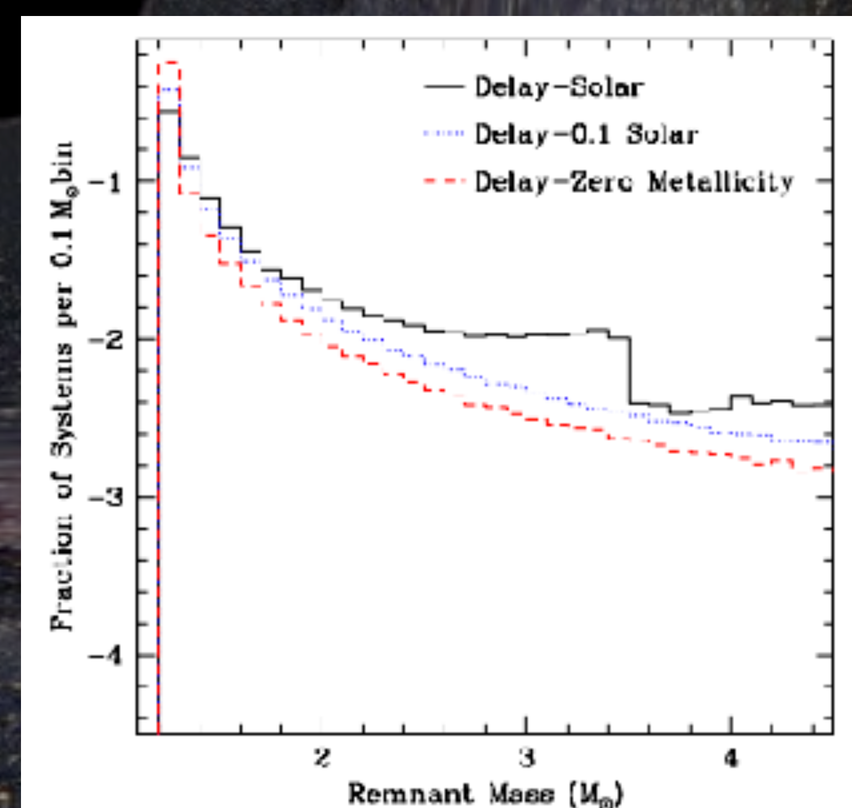
Observations:



Theory:



Fryer&Kalogera 2001



Fryer et al. 2012

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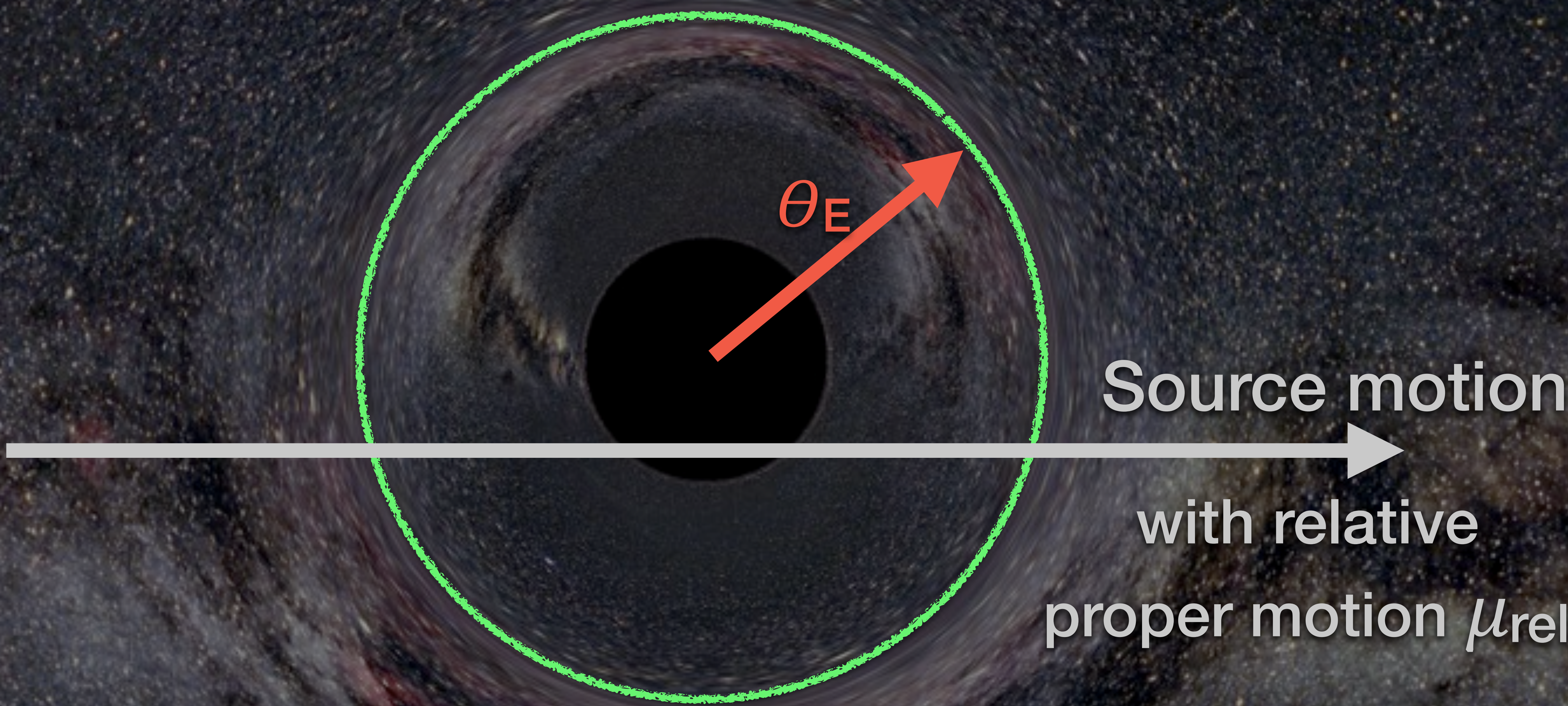
BLACK HOLES AS LENSES



for example:

$M_{BH} = 10\ M_{\odot}$ at D_L=1kpc

θ_E=10mas, μ_{rel} = 5mas/yr -> t_E = 2 yrs

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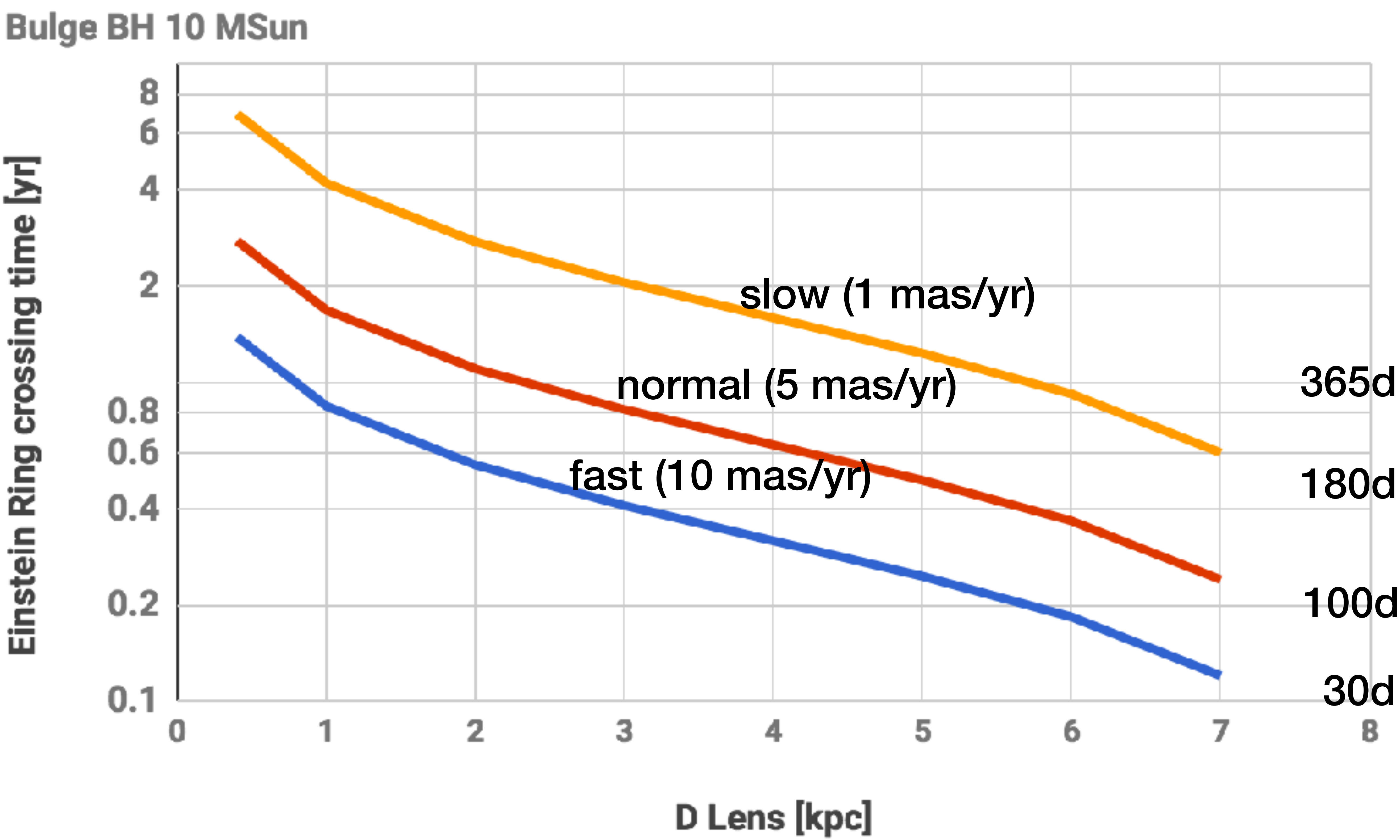
BLACK HOLES AS LENSES



HOW TO FIND BLACK HOLES?

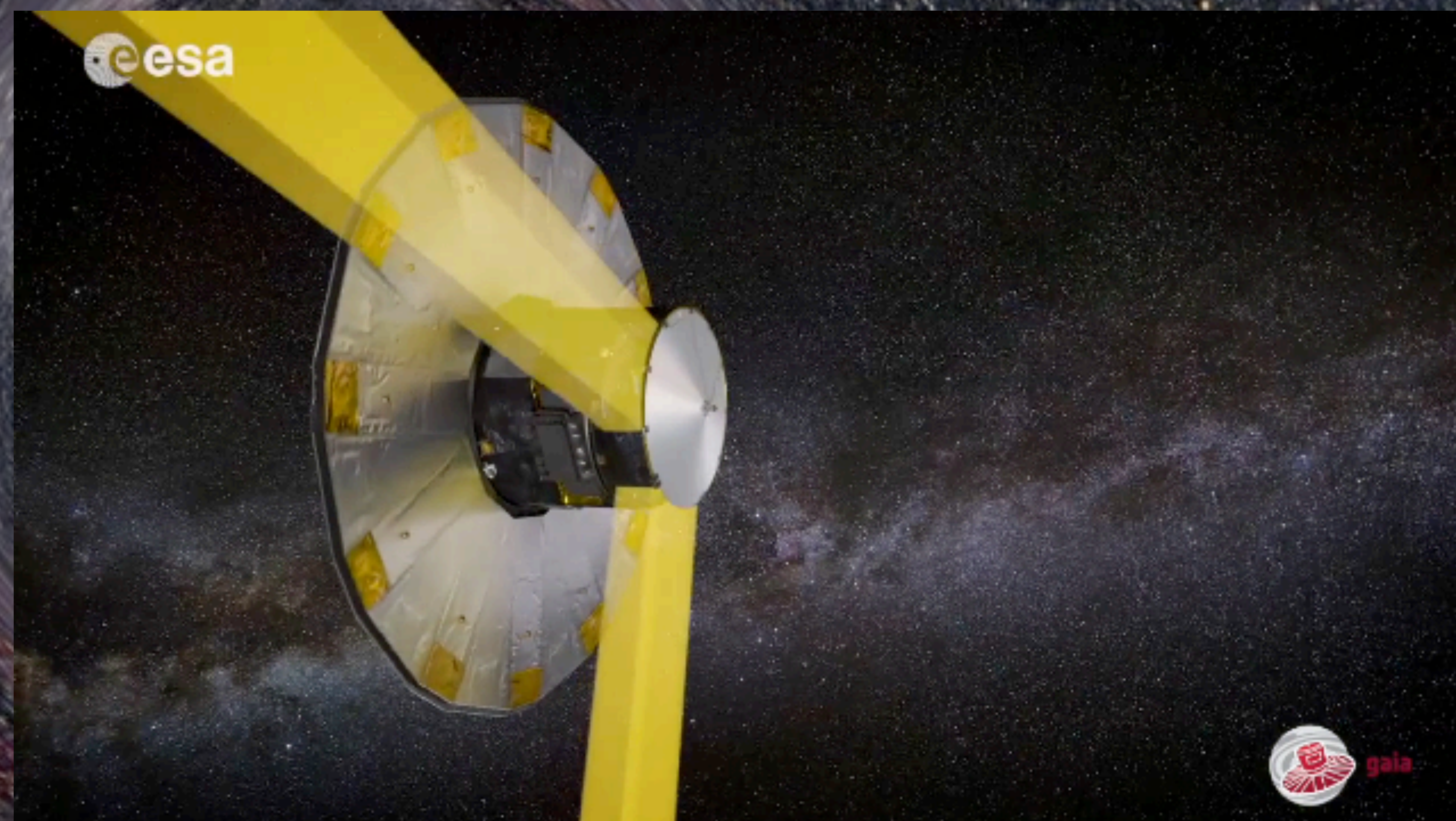
OGLE

http://ogle.astrouw.edu.pl

Polish 1.3m dedicated telescope
in Las Campanas, Chile
Surveying continuously since 1992.

Gaia Science Alerts

http://gsaweb.ast.cam.ac.uk/alerts

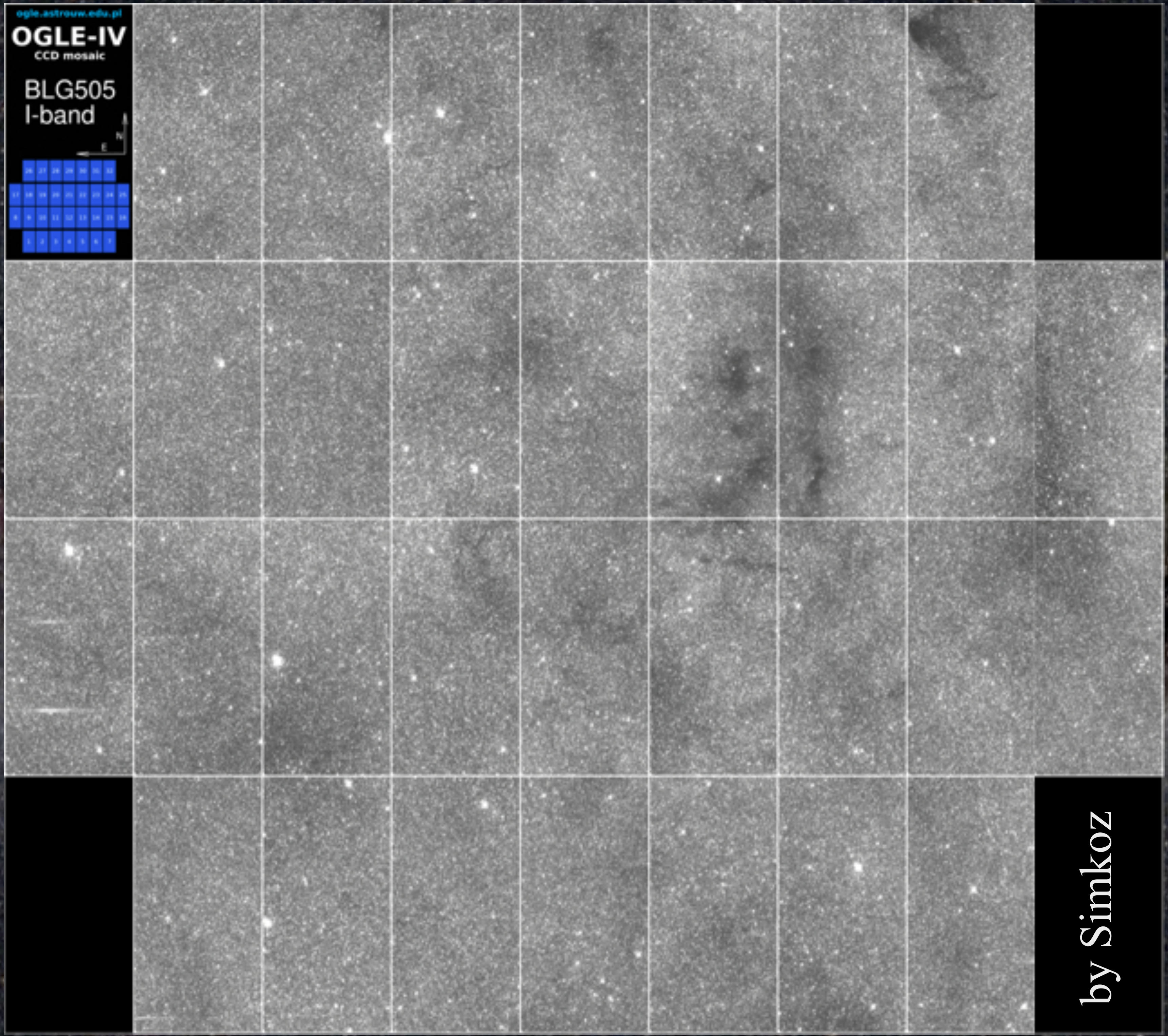


ESA space mission with 2x1.4m telescopes located in L2.
In operation since 2014.
DR1 in Sepember 2016,
DR2 in April 2018

5 MILLION STARS EVERY 3 MINUTES

OGLE bulge field

FoV 1.4 sq.deg., mag limit 21 mag in I-band



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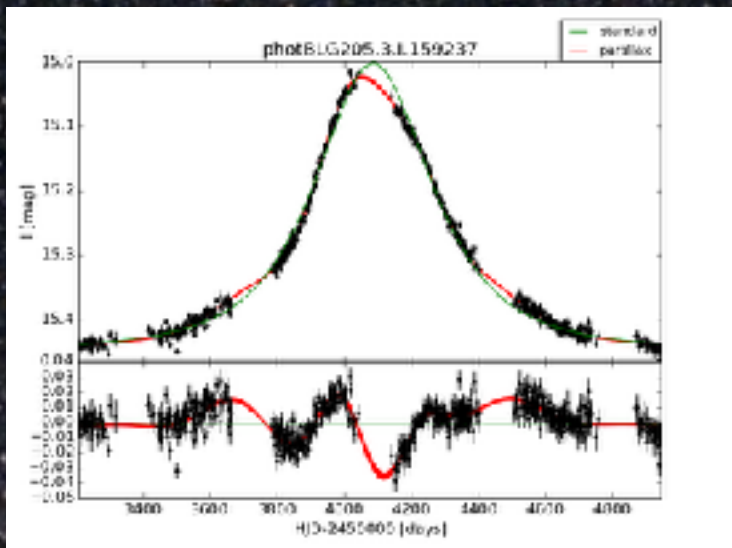
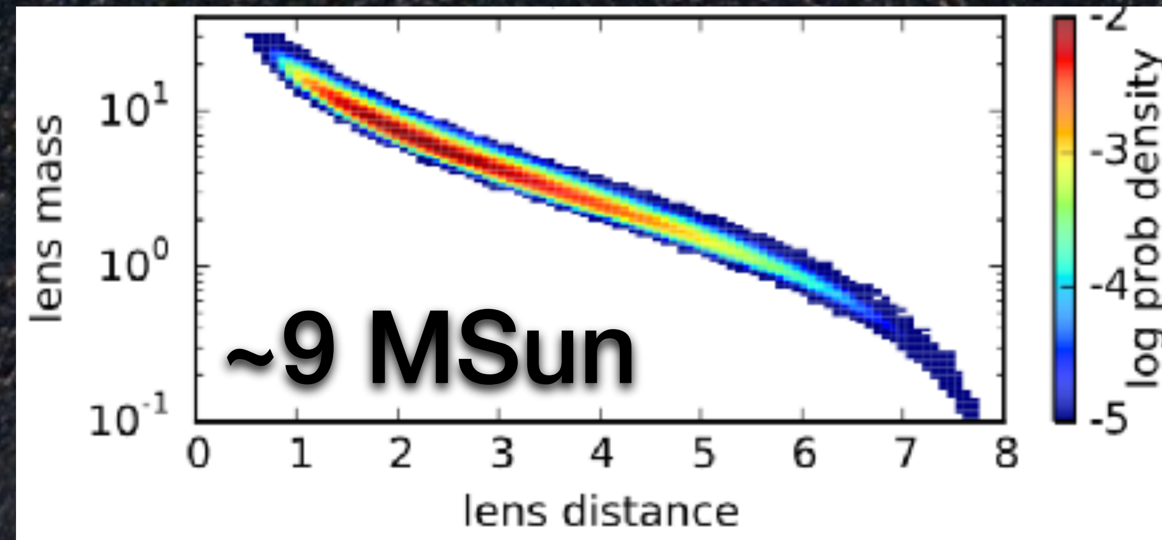
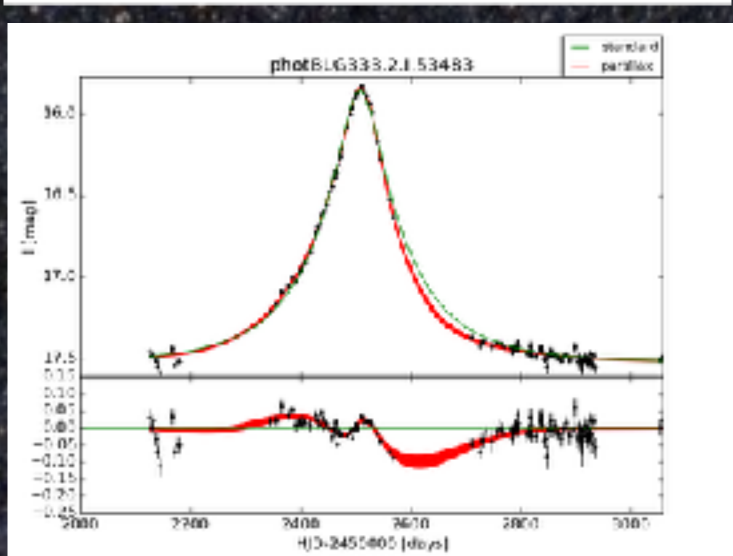
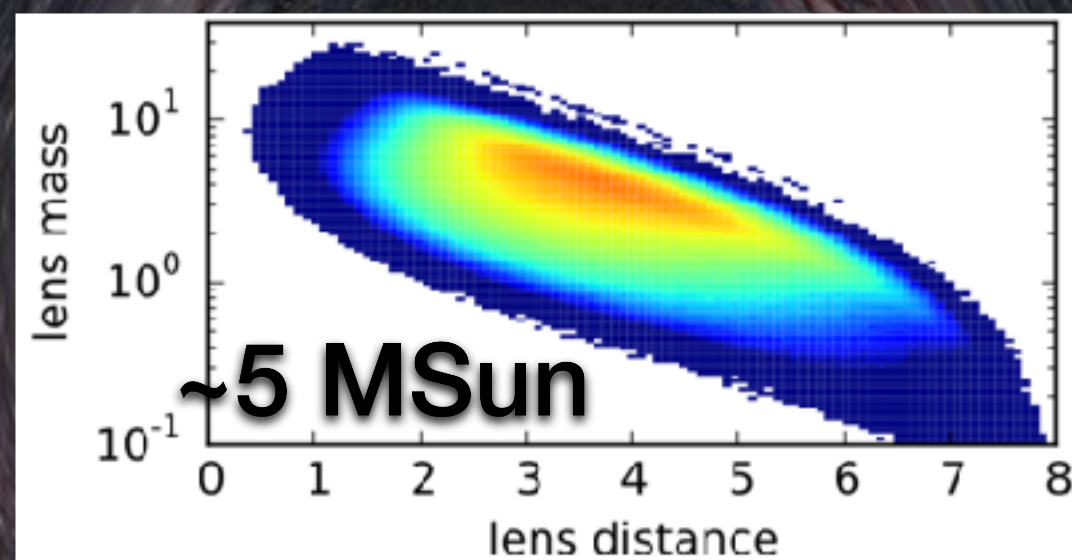
BH CANDIDATES FROM OGLE

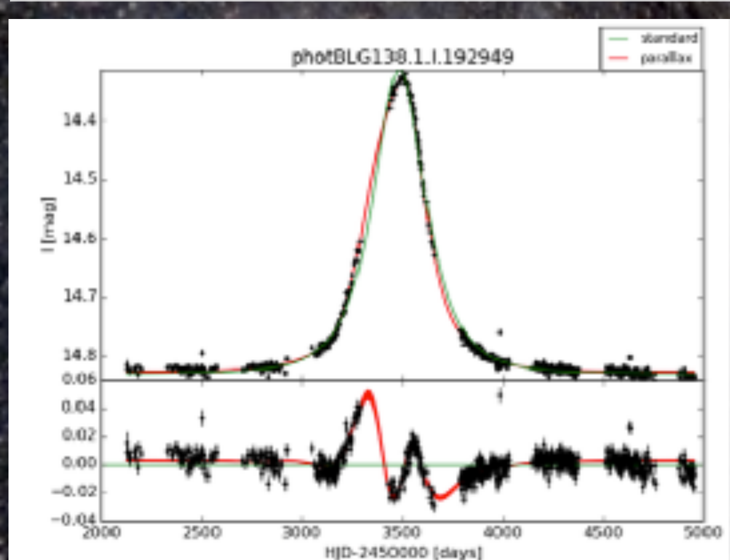


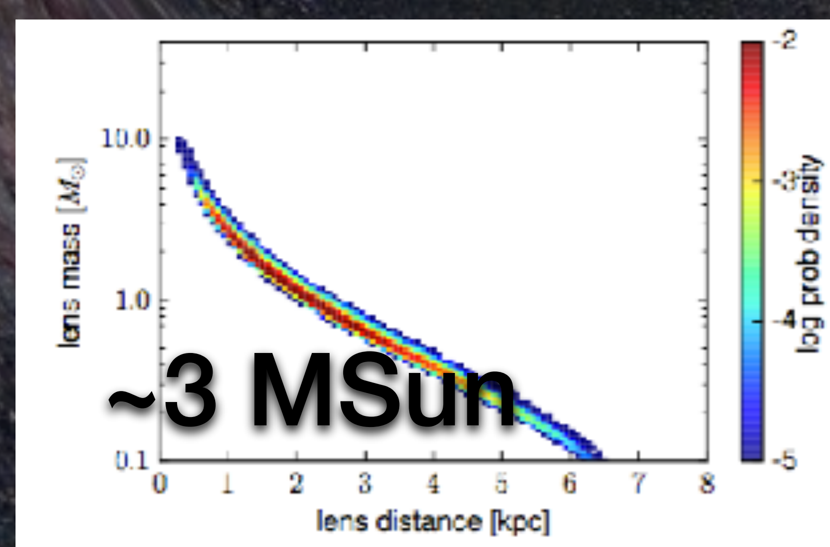


150 million Bulge stars monitored (2001-2009)









$$M = \frac{\theta_E}{\kappa \pi_E}$$

Annual Earth parallax

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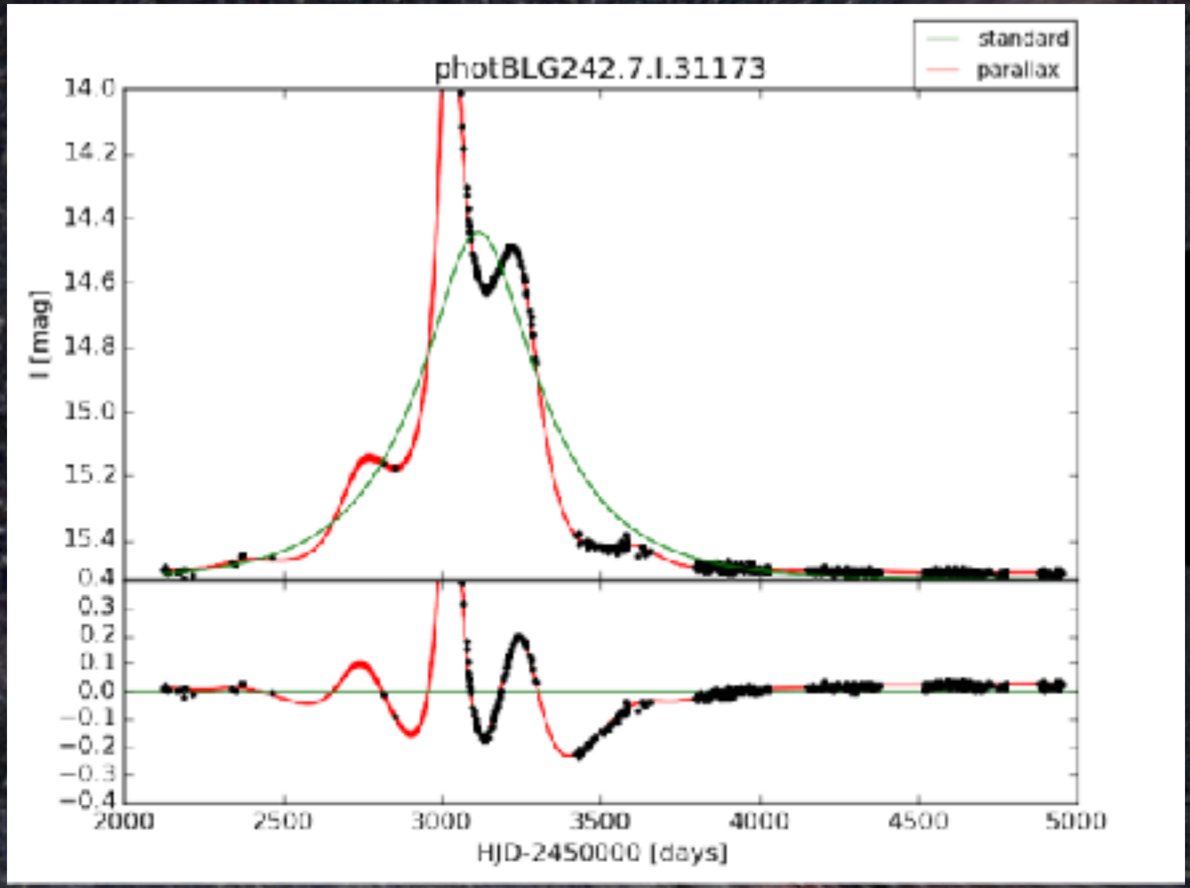
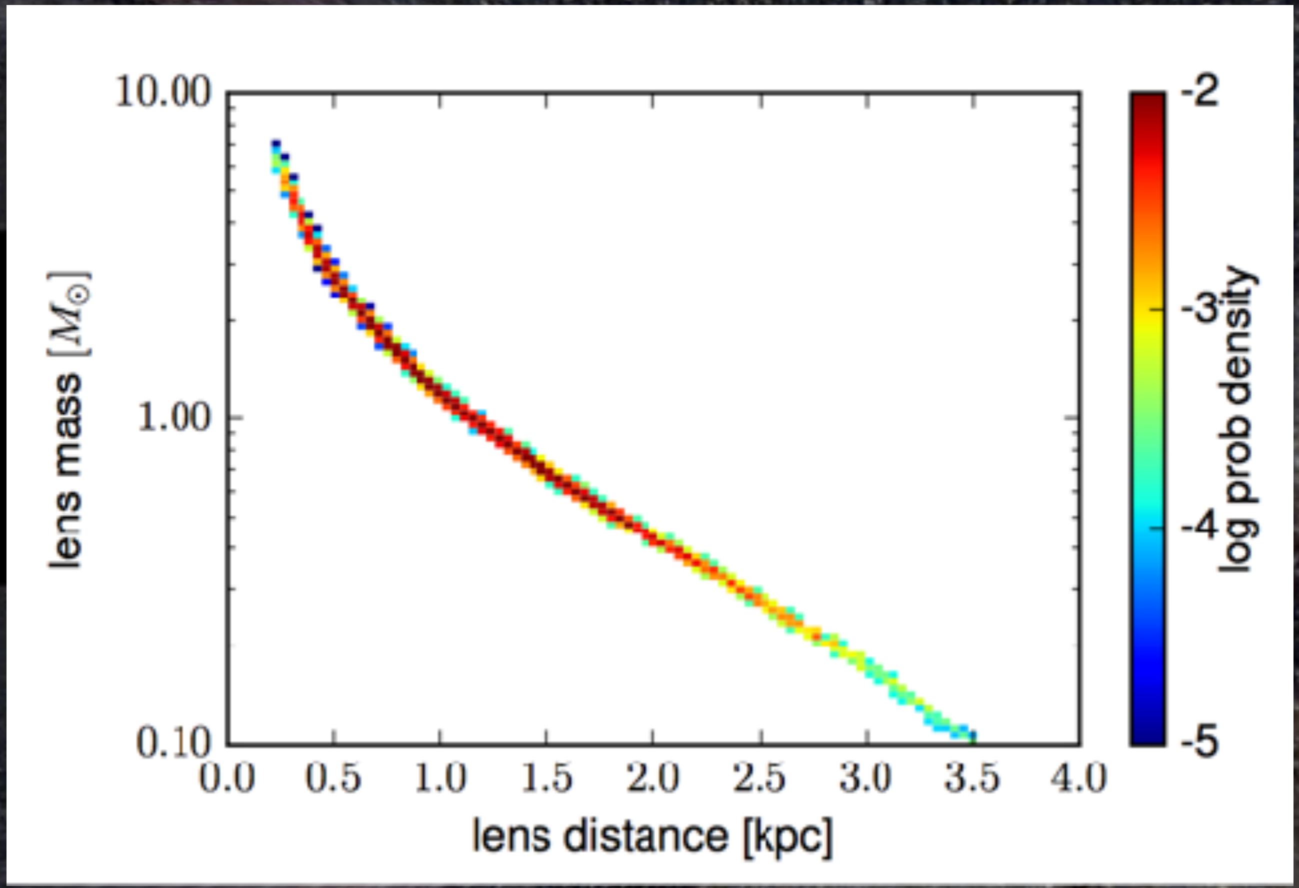
NEW NEUTRON STAR AT OUR DOORSTEPS?

or a primordial black hole?

OGLE3-ULENS-PAR-03





OGLE3-ULENS-	t_E [d]	Mass [$M_{\odot}$]	Distance [kpc]	blending	blend mag
PAR-03 (Warta) solution +	168	$1.7^{+1.9}_{-0.9}$	$0.7^{+0.5}_{-0.3}$	0.94	18.6
solution -	169	$1.7^{+1.9}_{-1.0}$	$0.7^{+0.6}_{-0.3}$	0.91	18.1 *

*if the lens is luminous, this one could be bright enough to distort Gaia astrometry

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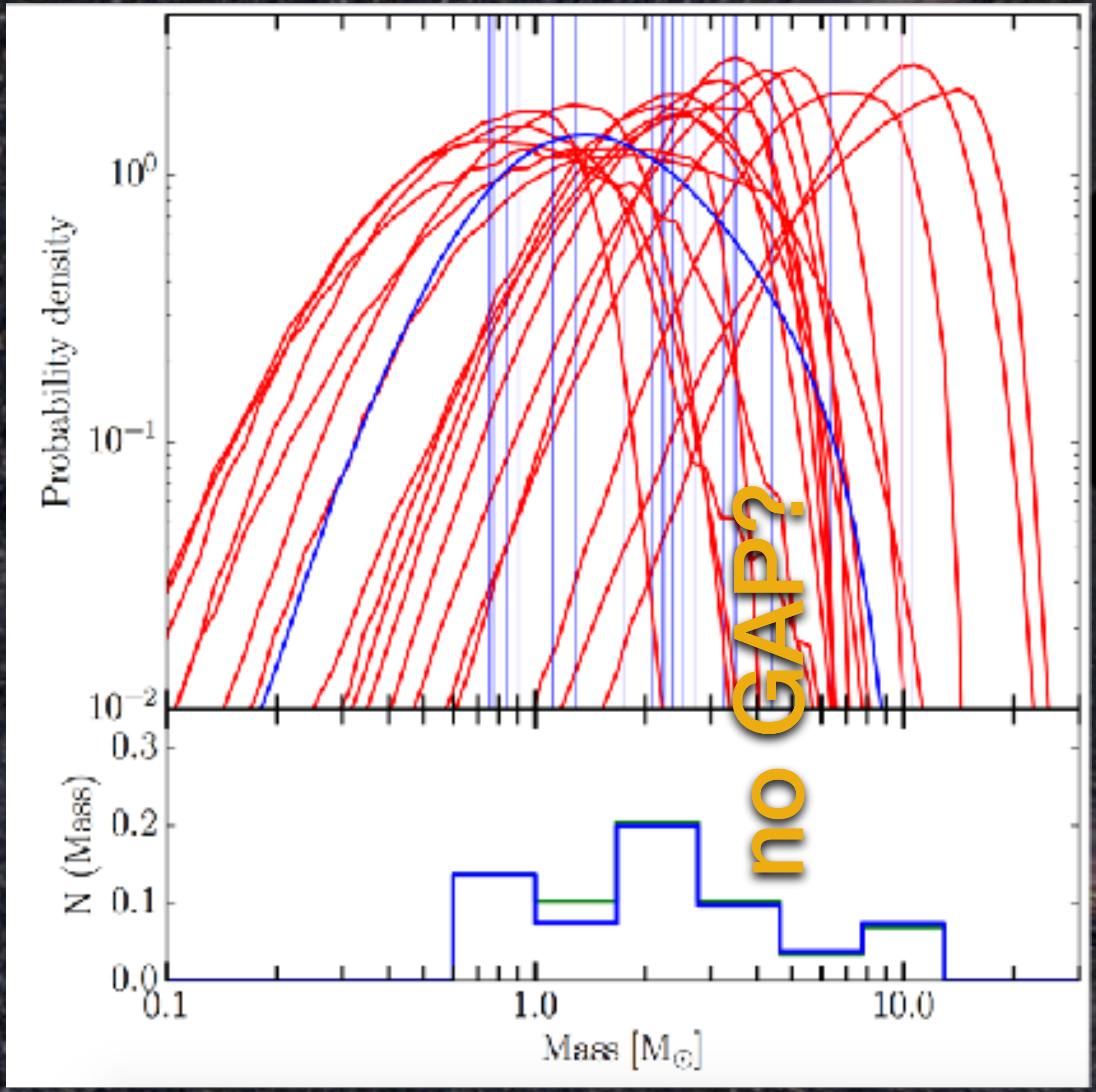
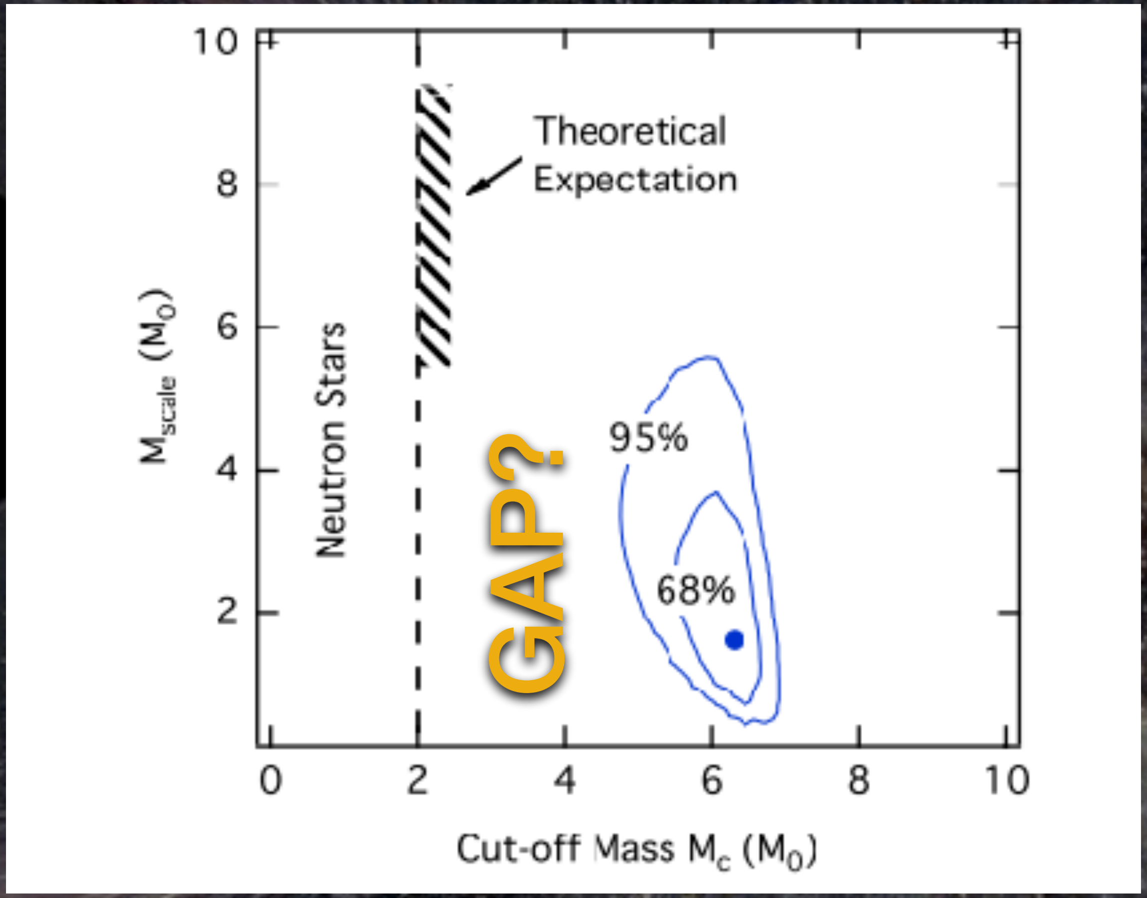
CLOSING THE MASS-GAP

- wide mass-gap with Mmin=5 MSun is excluded
- narrower mass-gap still possible (2-3 MSun)

single, with Gaia



X-ray binary systems



Ozel+2010

Wyrzykowski+2016,
Wyrzykowski&Mandel in prep.

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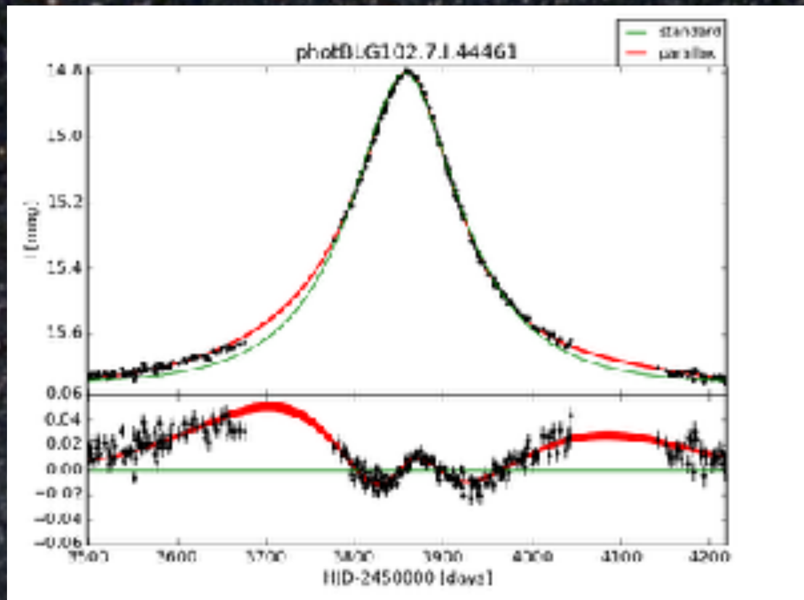
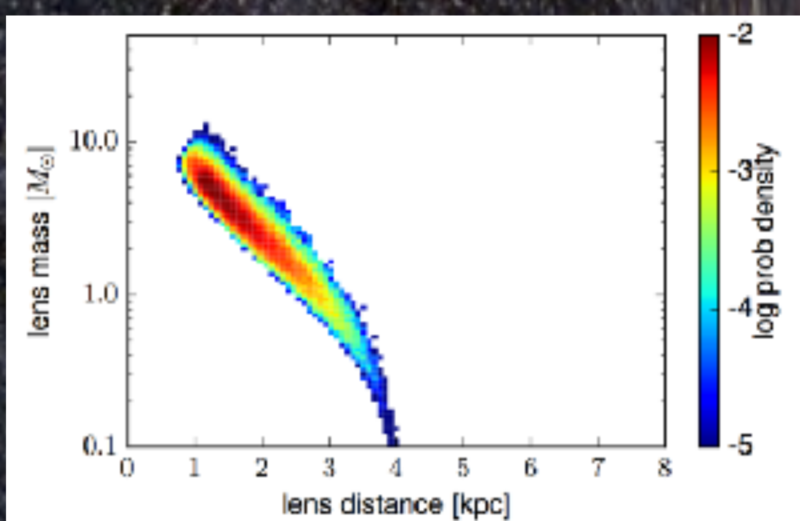
MASS-GAP DARK LENS CANDIDATES

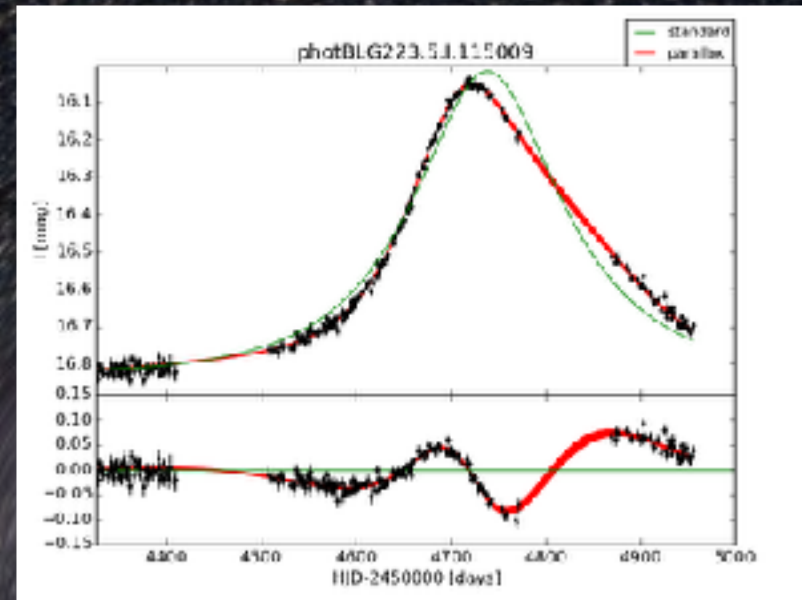
PAR-07 (Notec)



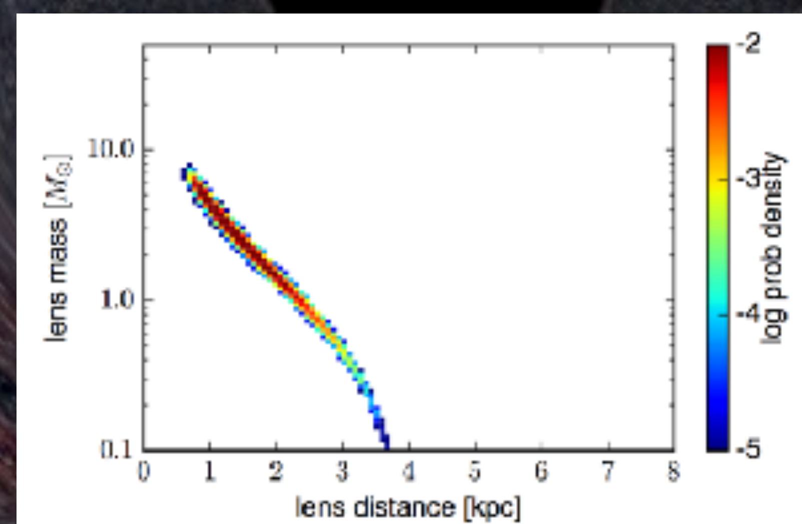
$4.4 \pm 1.8\ M_\odot$



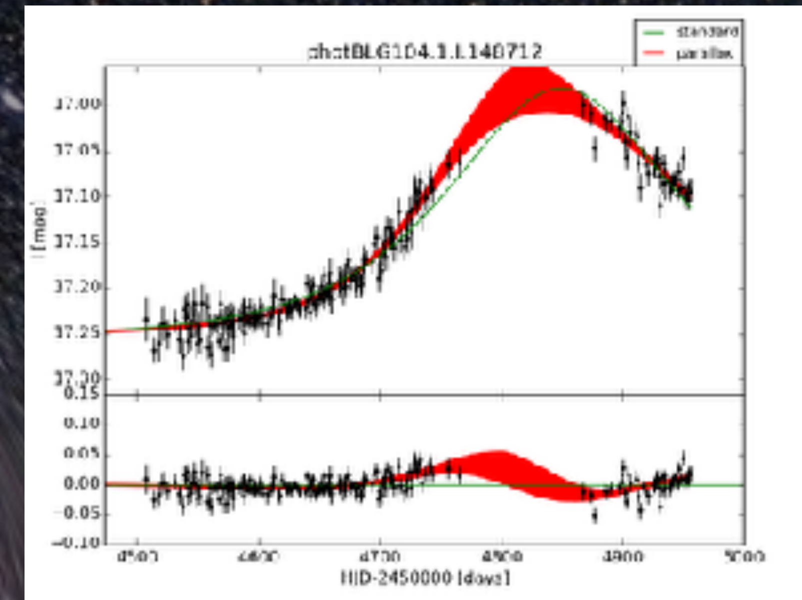
PAR-15 (Nysa)



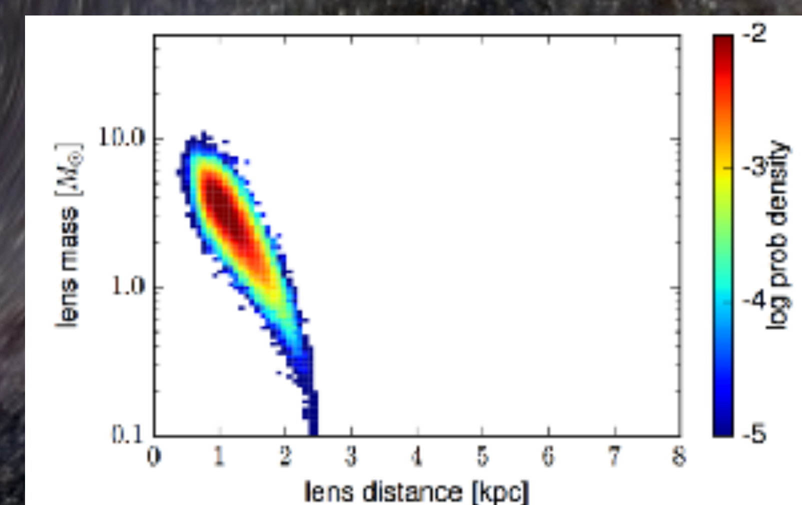
$3.5 \pm 1.4\ M_\odot$



PAR-30 (Slupia)



$3.3 \pm 1.2\ M_\odot$



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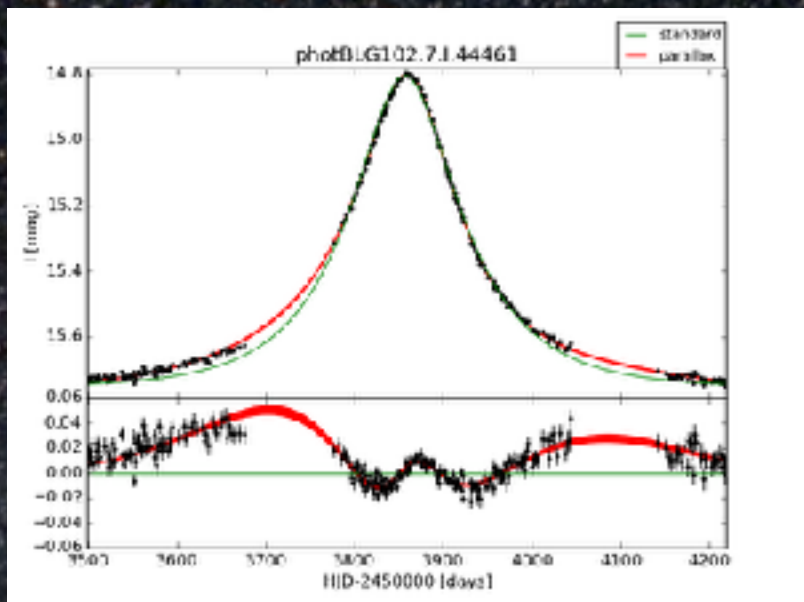
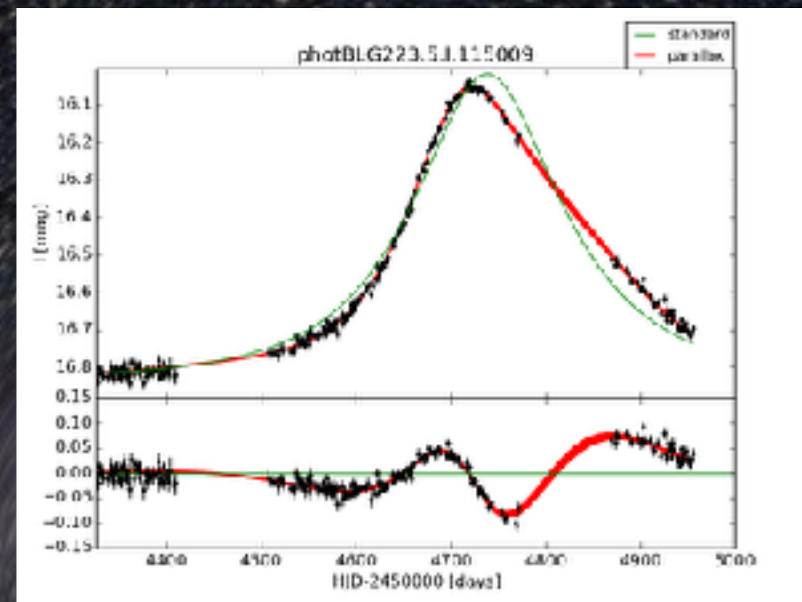
MASS-GAP DARK LENS CANDIDATES

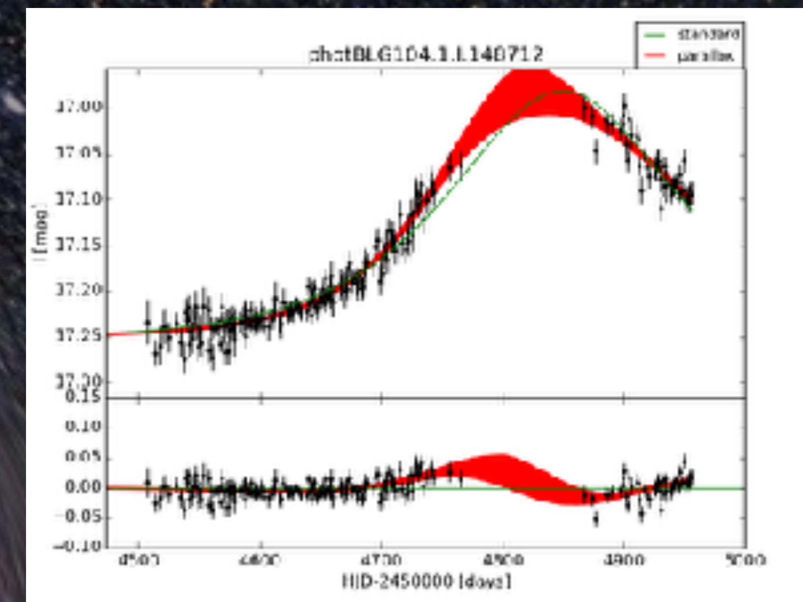
PAR-07 (Notec)



PAR-15 (Nysa)



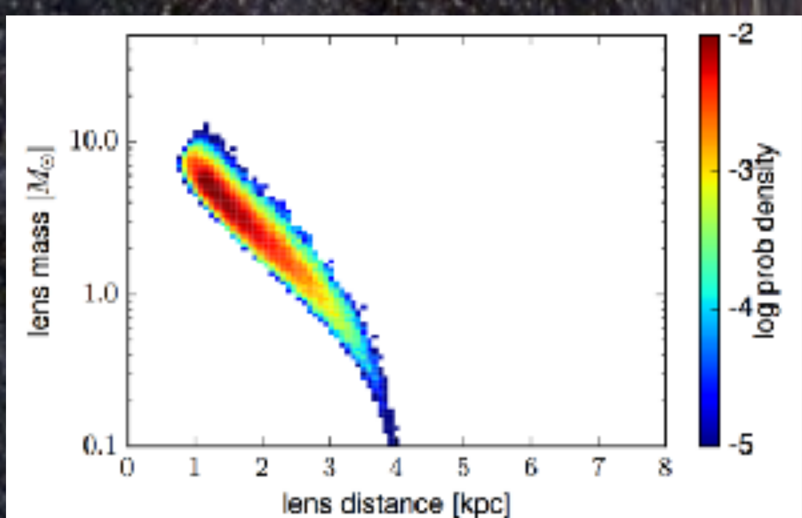
PAR-30 (Slupia)

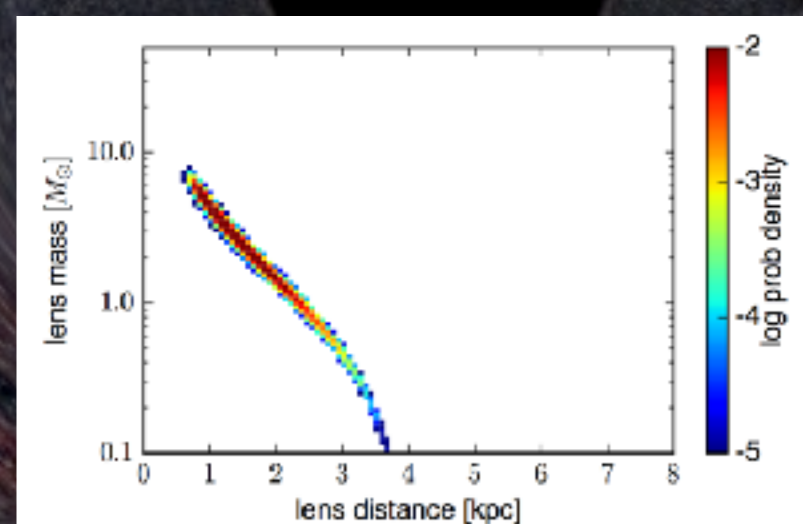


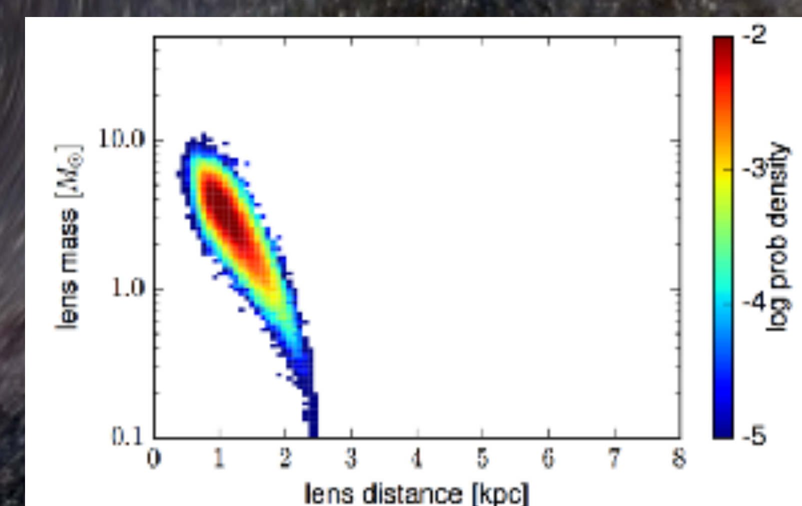
4.4±1.8 $M_\odot$

3.5±1.4 $M_\odot$

3.3±1.2 $M_\odot$



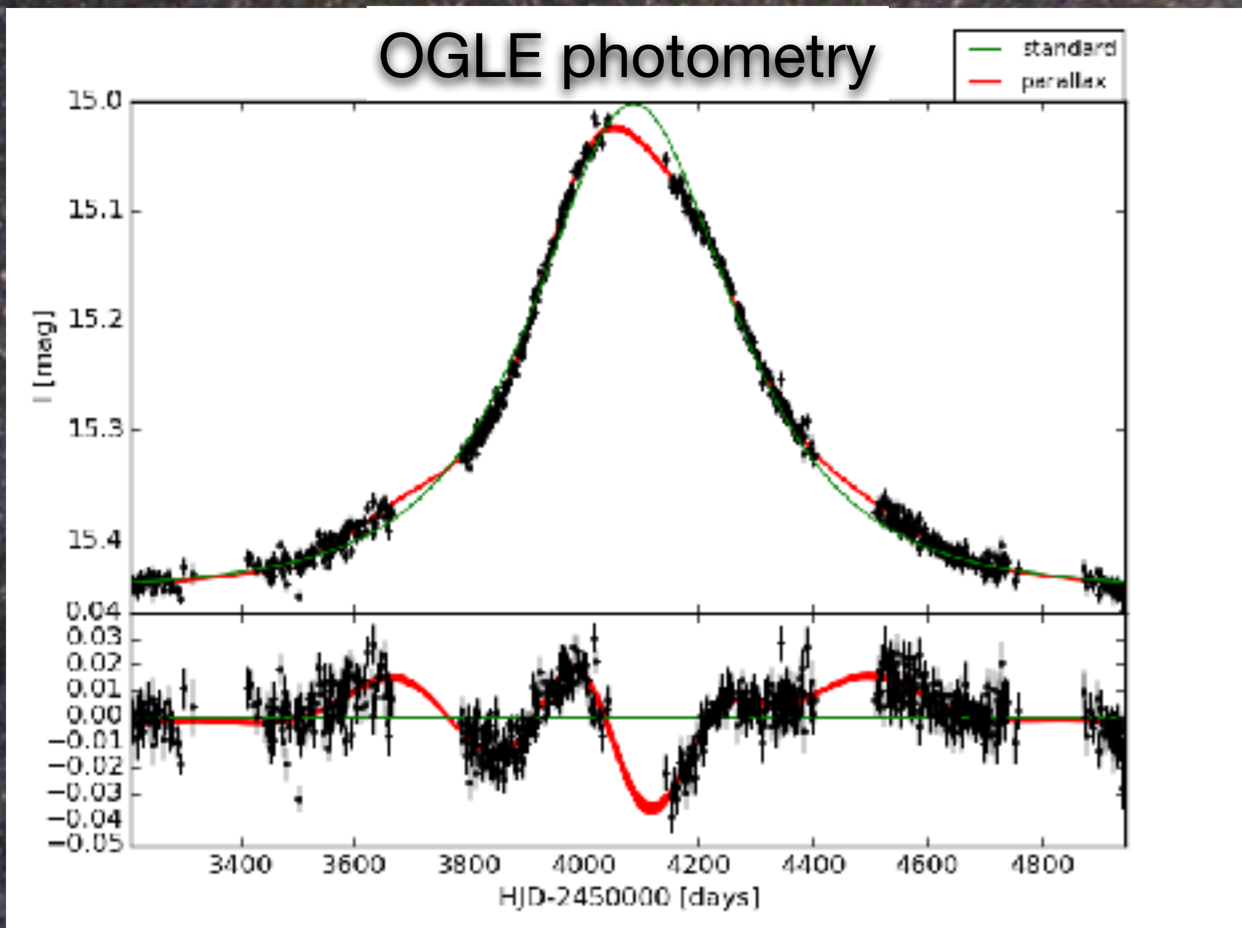


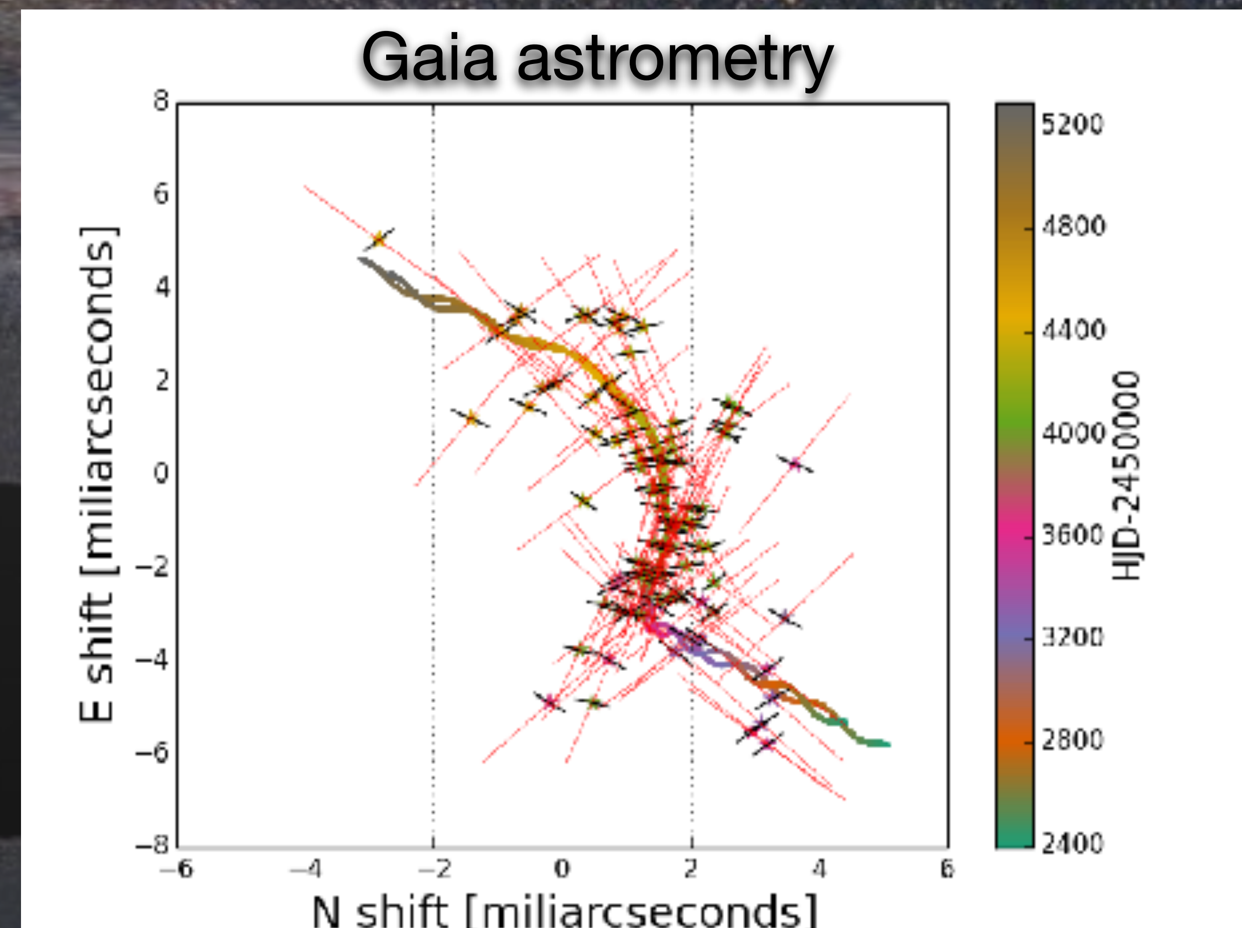


some degeneracy between M and D remains
-> theta_E needed !

ASTROMETRY FROM GAIA

OGLE3-ULENS-PAR-02 - candidate ~10MSun BH





OGLE photometry
from 2001-2008
and microlensing model

predicted
Gaia astrometry
for similar event
(real data in 2022)

Mass, Distance

Rybicki, Wyrzykowski+ 2018

See Kris's talk

HOW TO FIND BLACK HOLES?

on-going
microlensing events

OGLE

Gaia Science Alerts

ASAS-SN

follow-up

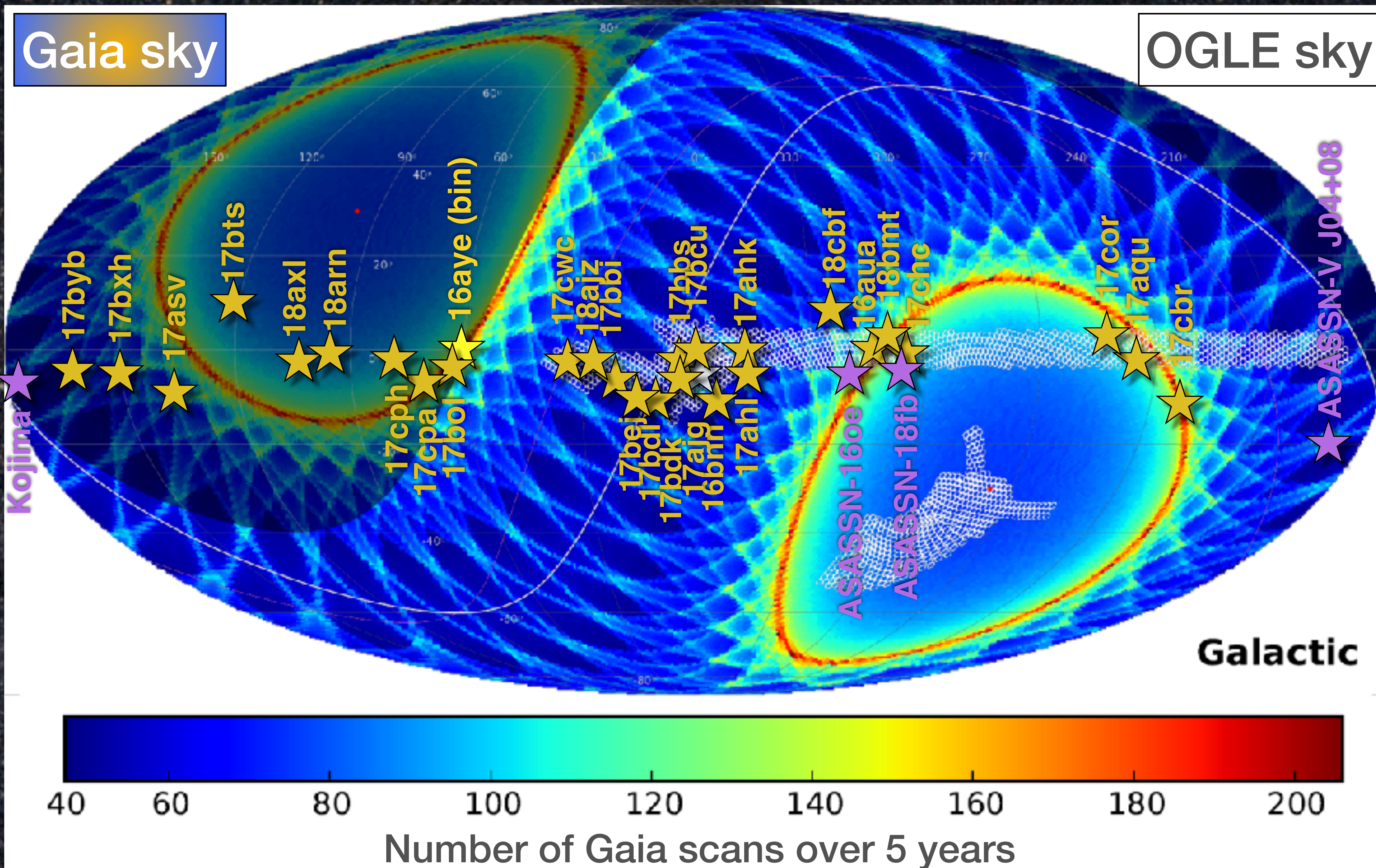
light curves (~20 telescopes)
spectra (VLT, Gemini, SALT)
space observations (Spitzer)

astrometric
time-series (DR4)

MICROLENSING EVENTS FROM GAIA

about 60 events since 2016

See Katarzyna's talk



Gaia figure by Nadia Blagorodnova, OGLE fields by Jan Skowron

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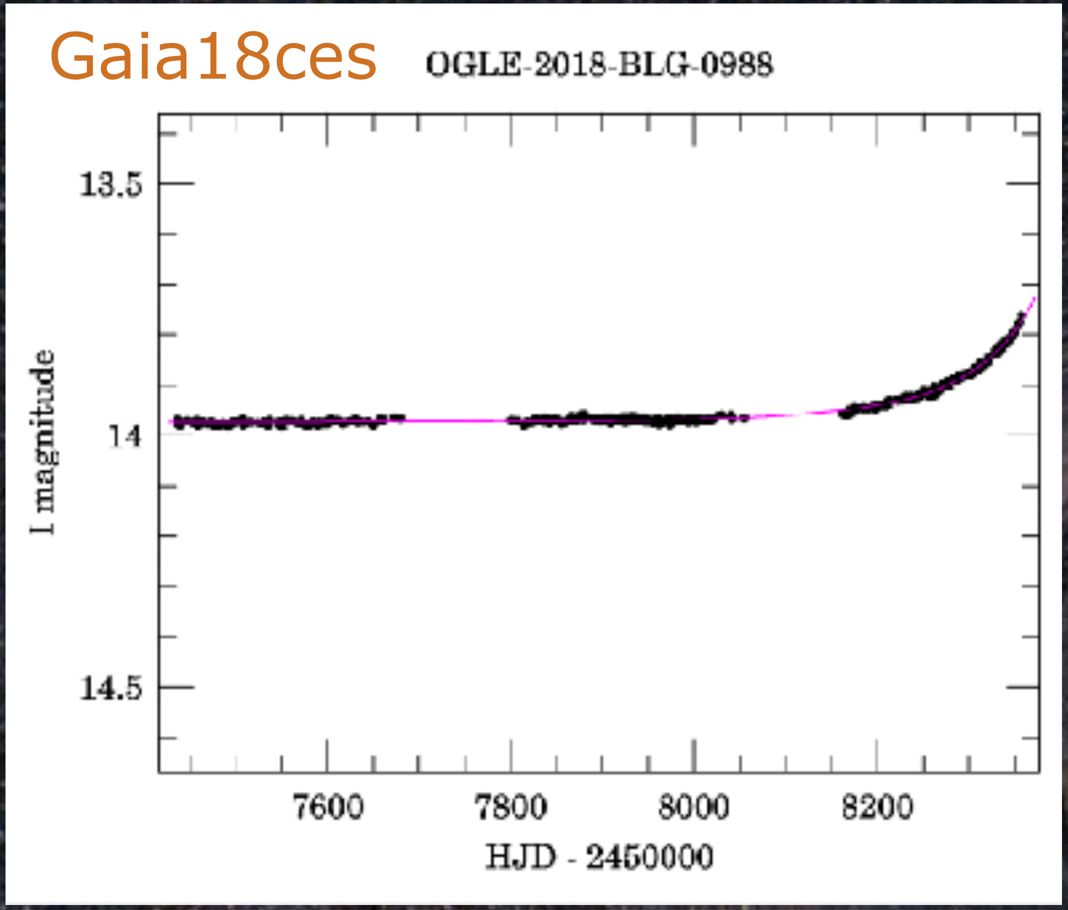
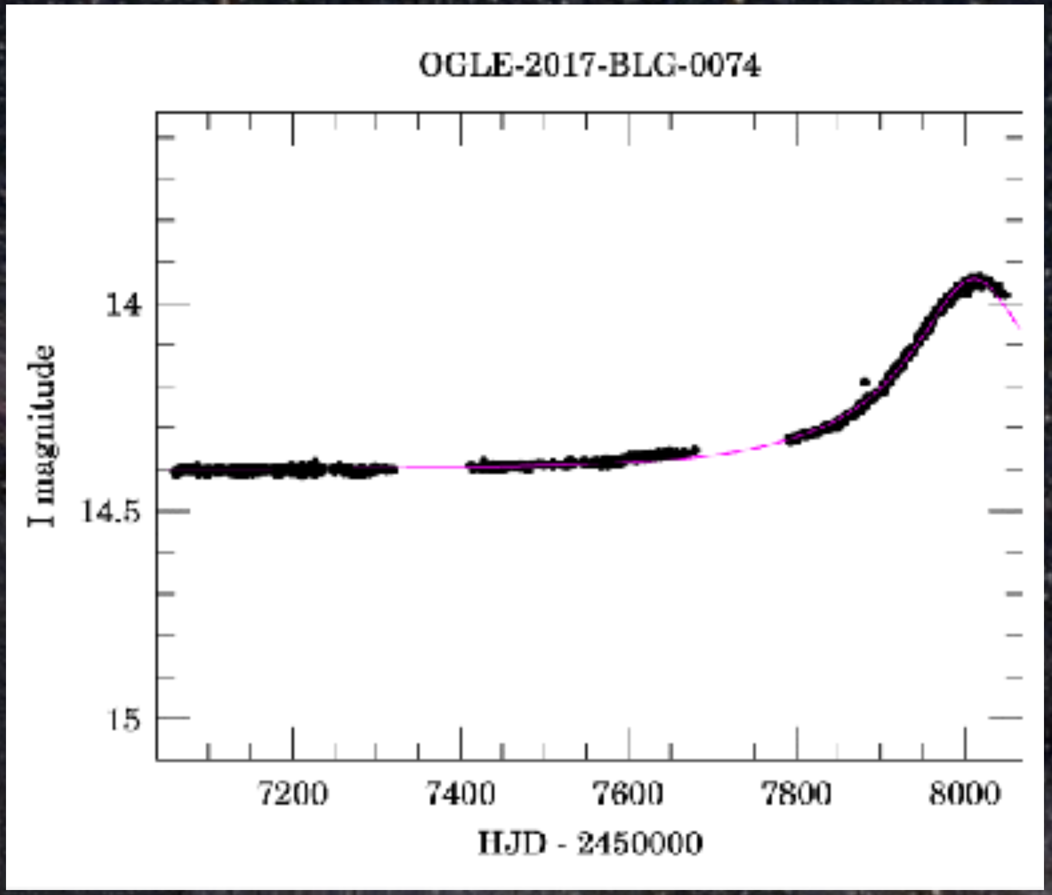
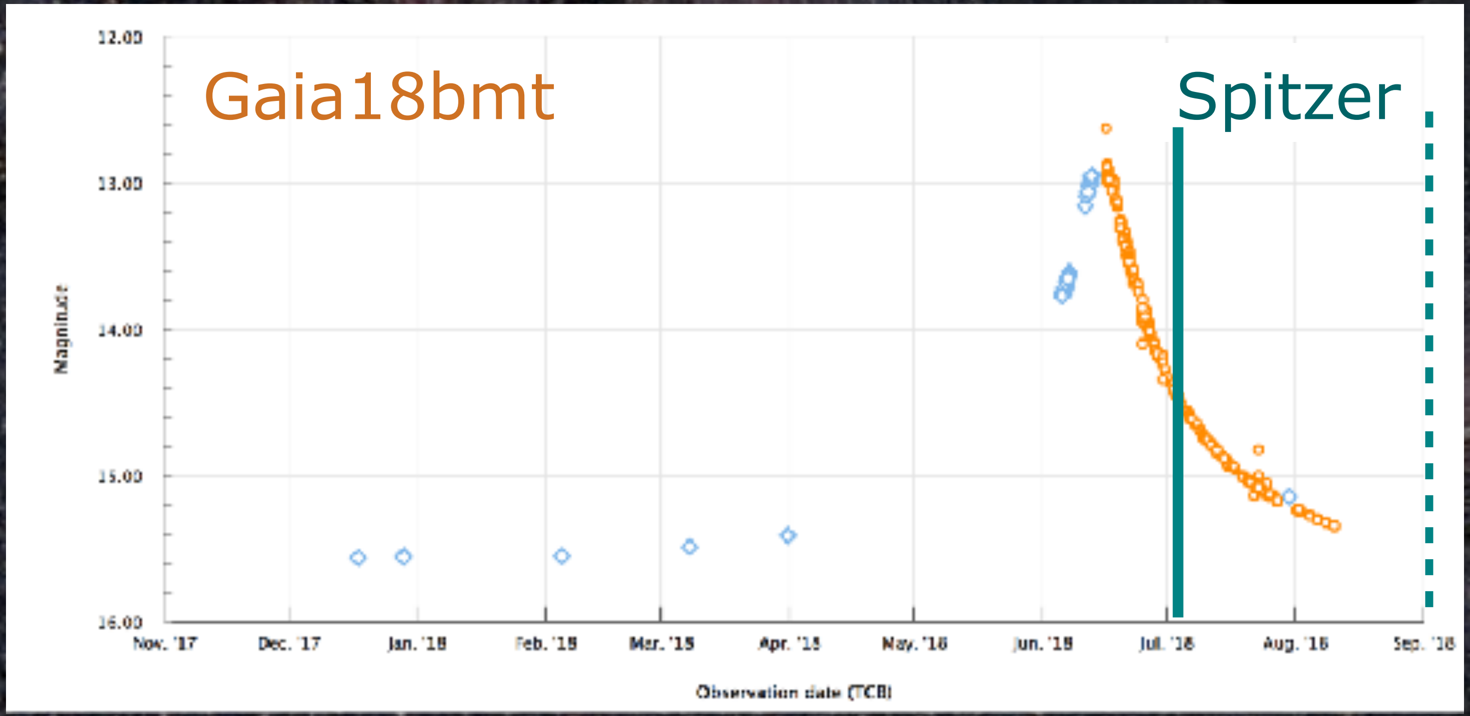
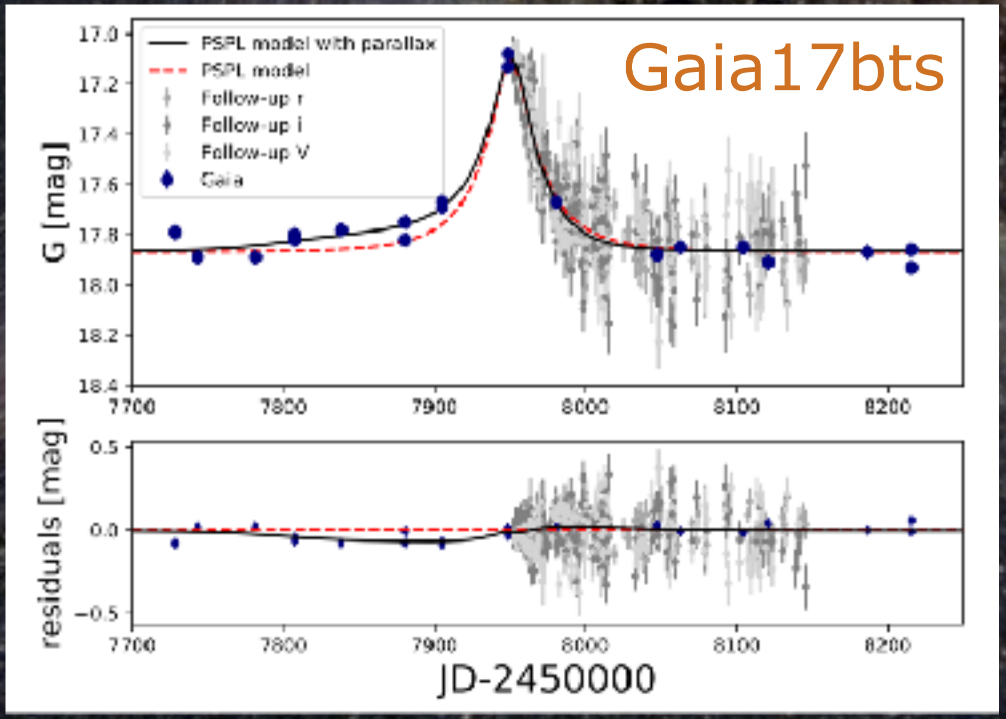
INTERESTING CANDIDATES









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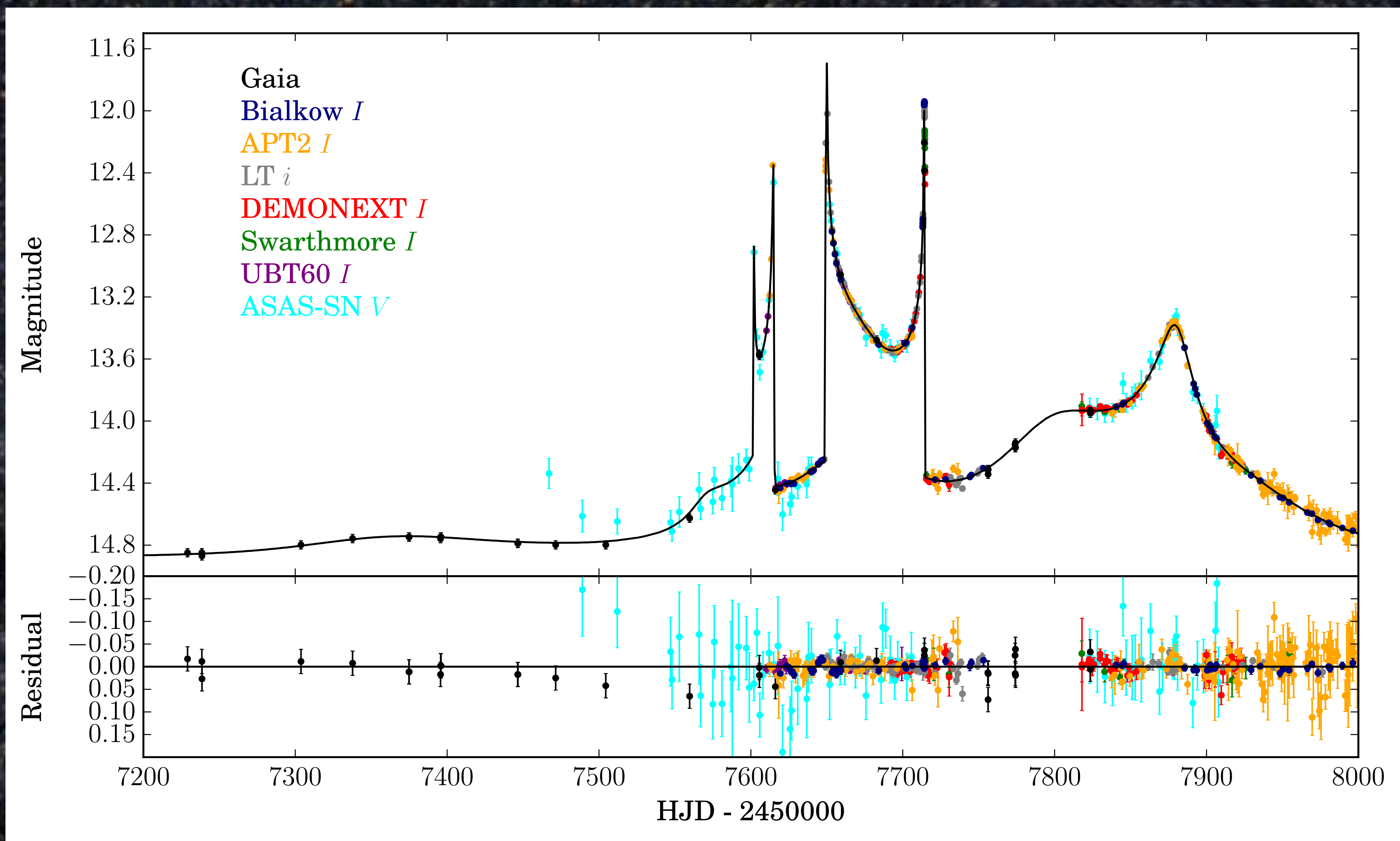
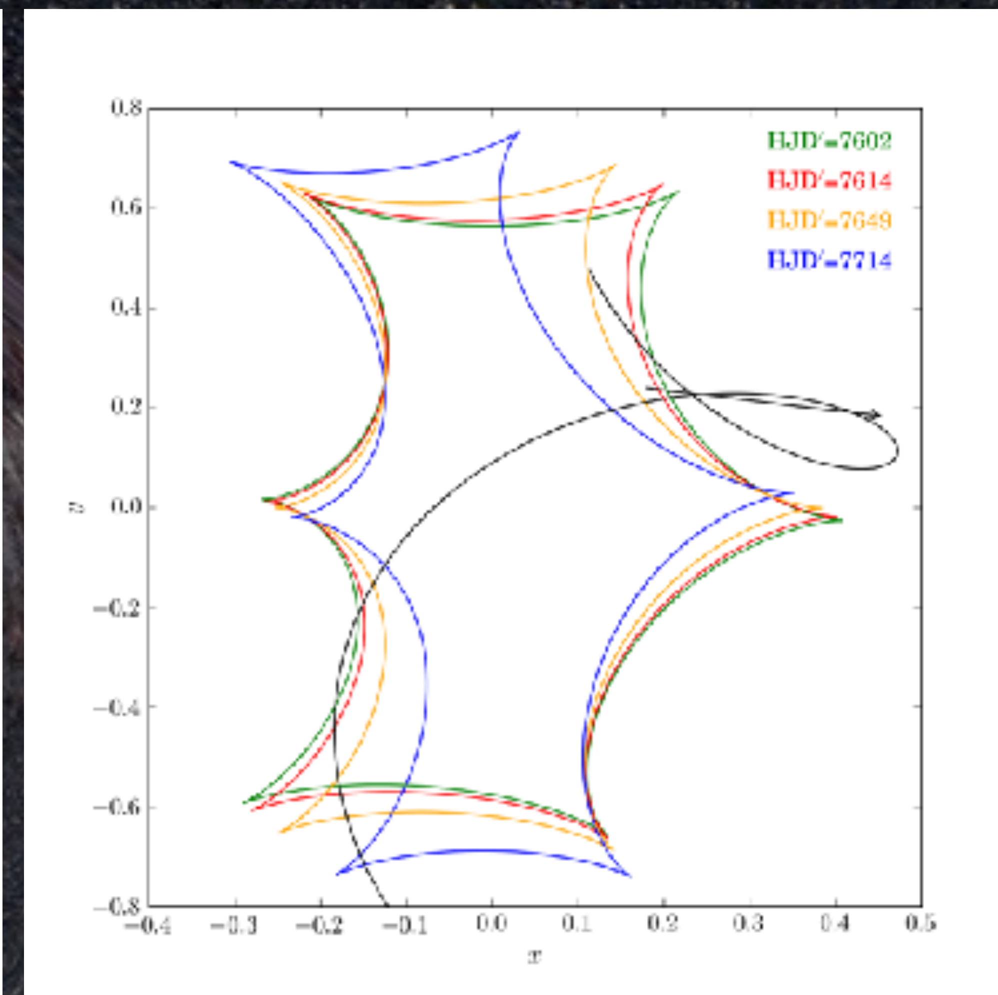
GAIA16AYE

probably the most complex binary microlensing event ever studied!





- multiple caustic crossings due to large microlensing parallax
- more than 2 years in duration
- more than 20,000 ground-based images taken (also by amateurs)
- impossible to solve without long-term ground-based follow-up

model by Przemek Mroz and Jan Skowron

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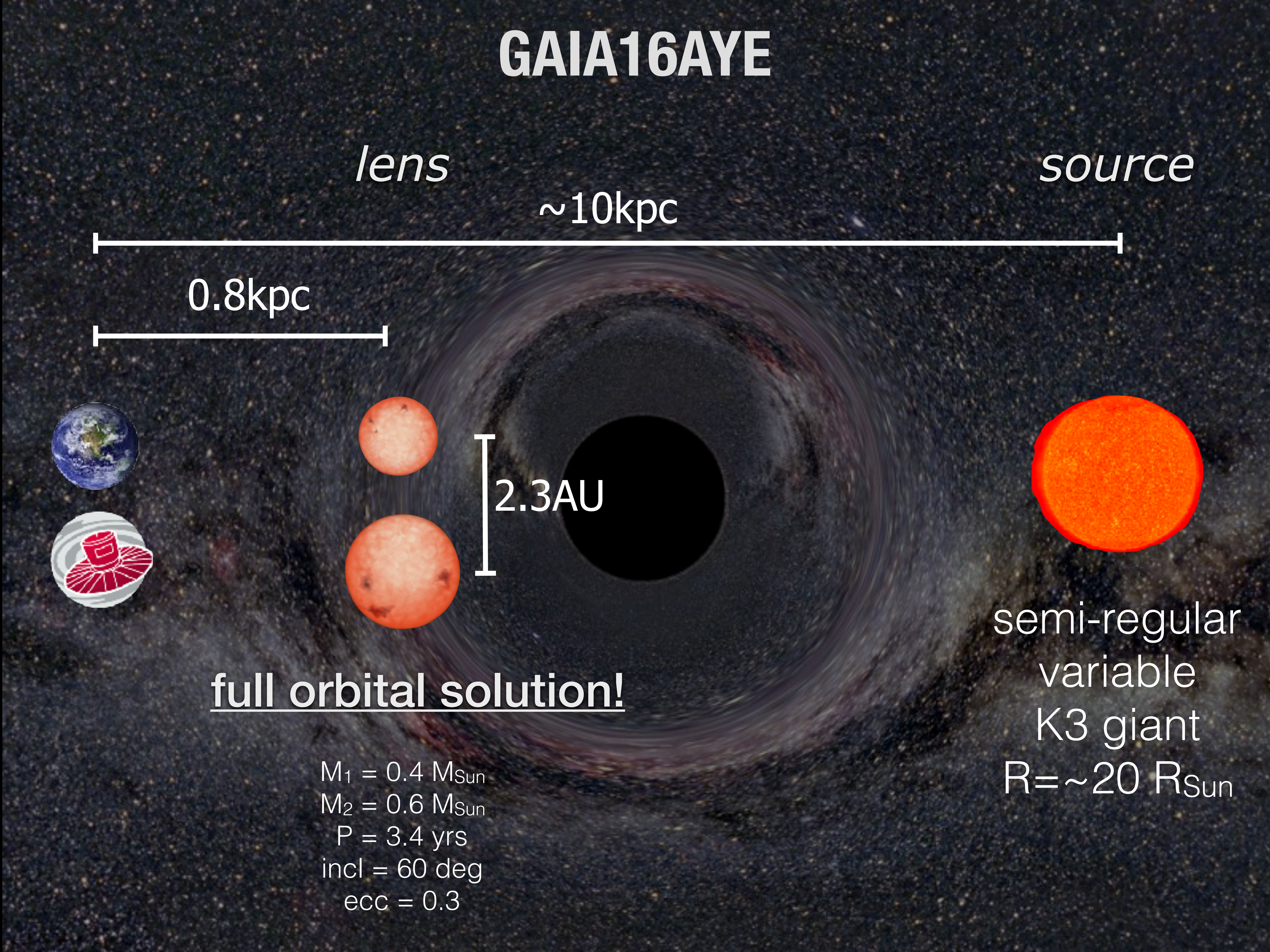
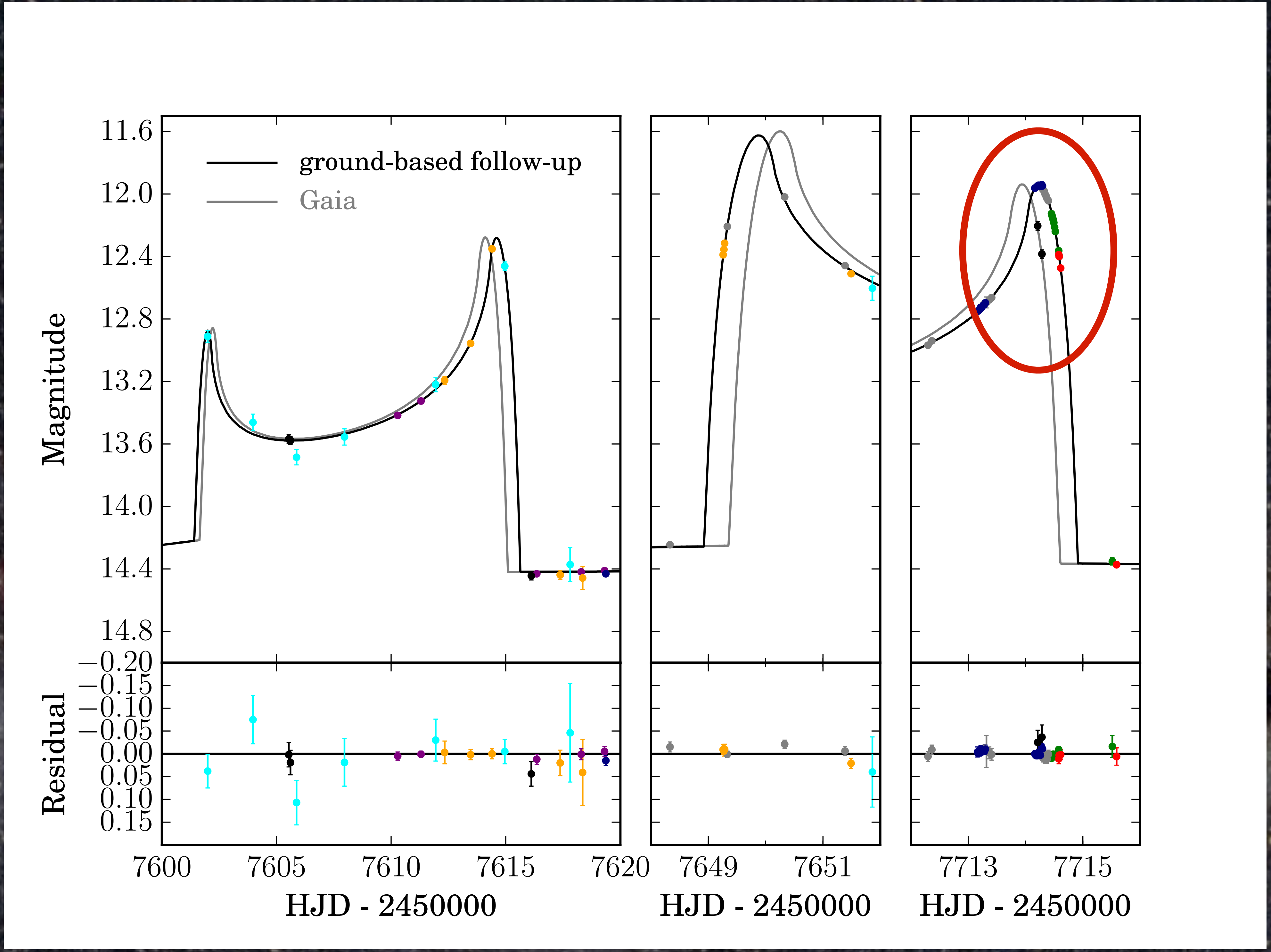

GAIA16AYE
lens
source
~10kpc
0.8kpc
2.3AU
full orbital solution!
M1 = 0.4 MSun
M2 = 0.6 MSun
P = 3.4 yrs
incl = 60 deg
ecc = 0.3
semi-regular
variable
K3 giant
R=~20 RSun

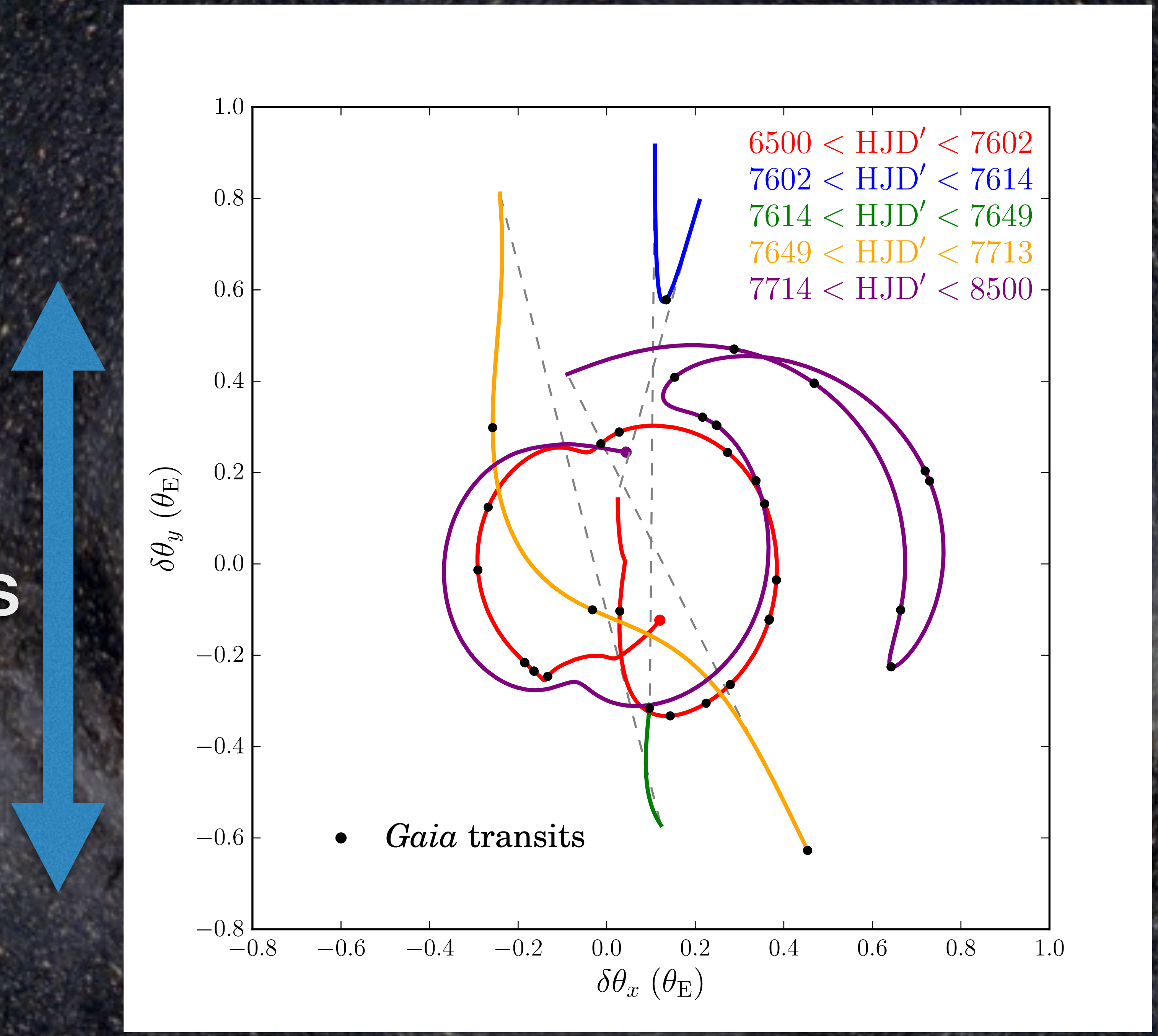
SPACE PARALLAX



At the casutic crossing the brightness changes within hours.
We were lucky that Gaia observed this event at the 4th caustic crossing!

GAIA16AYE ASTROMETRY

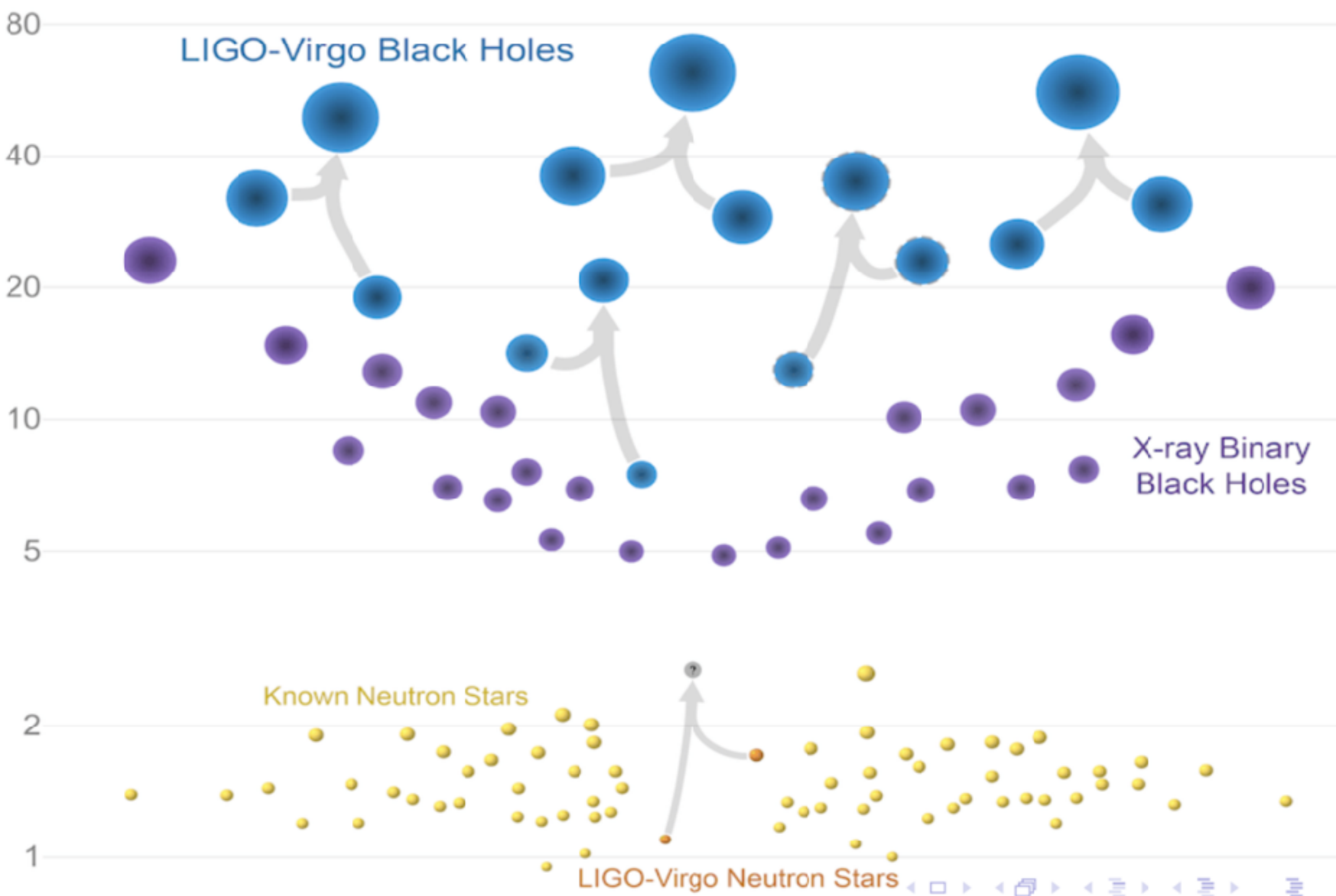
position of the centroid of the images (2, 3 or 5)



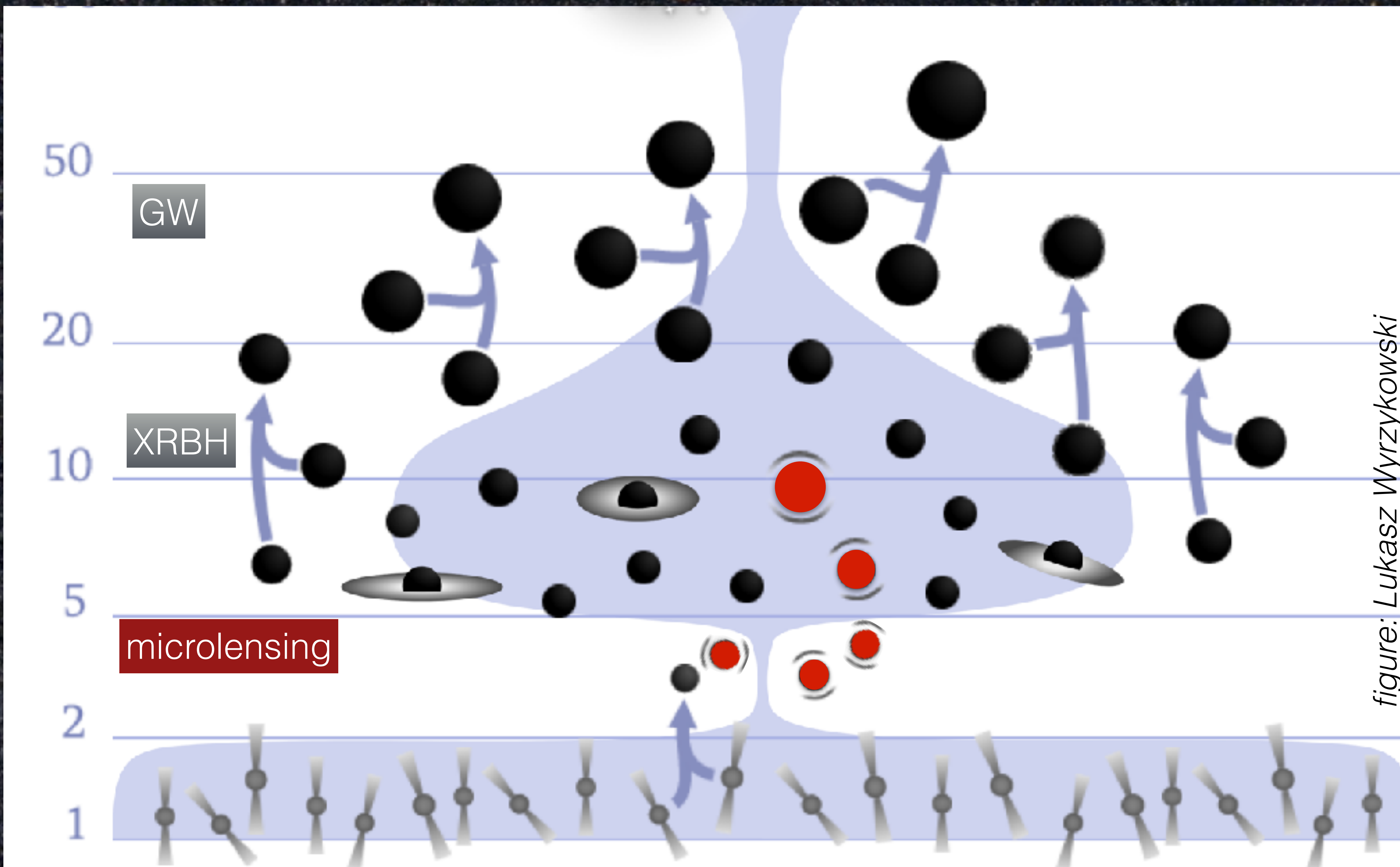
solely source centroid motion

real observations will smear this with proper motion and parallax of the source

POPULATION OF KNOWN BLACK HOLES AND NEUTRON STARS



POPULATION OF KNOWN BLACK HOLES AND NEUTRON STARS



Łukasz Wyrzykowski

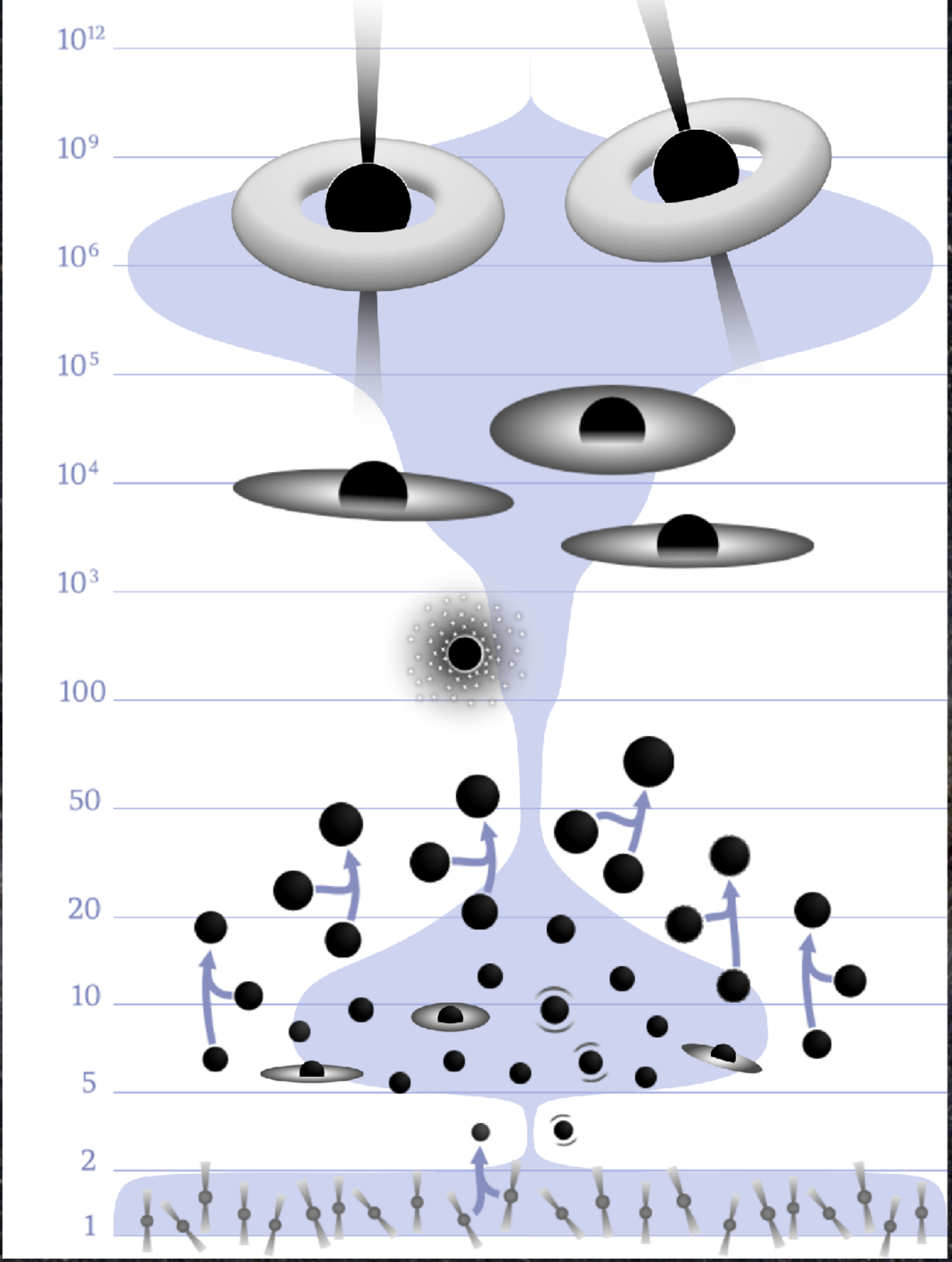


figure: Łukasz Wyrzykowski

Łukasz Wyrzykowski

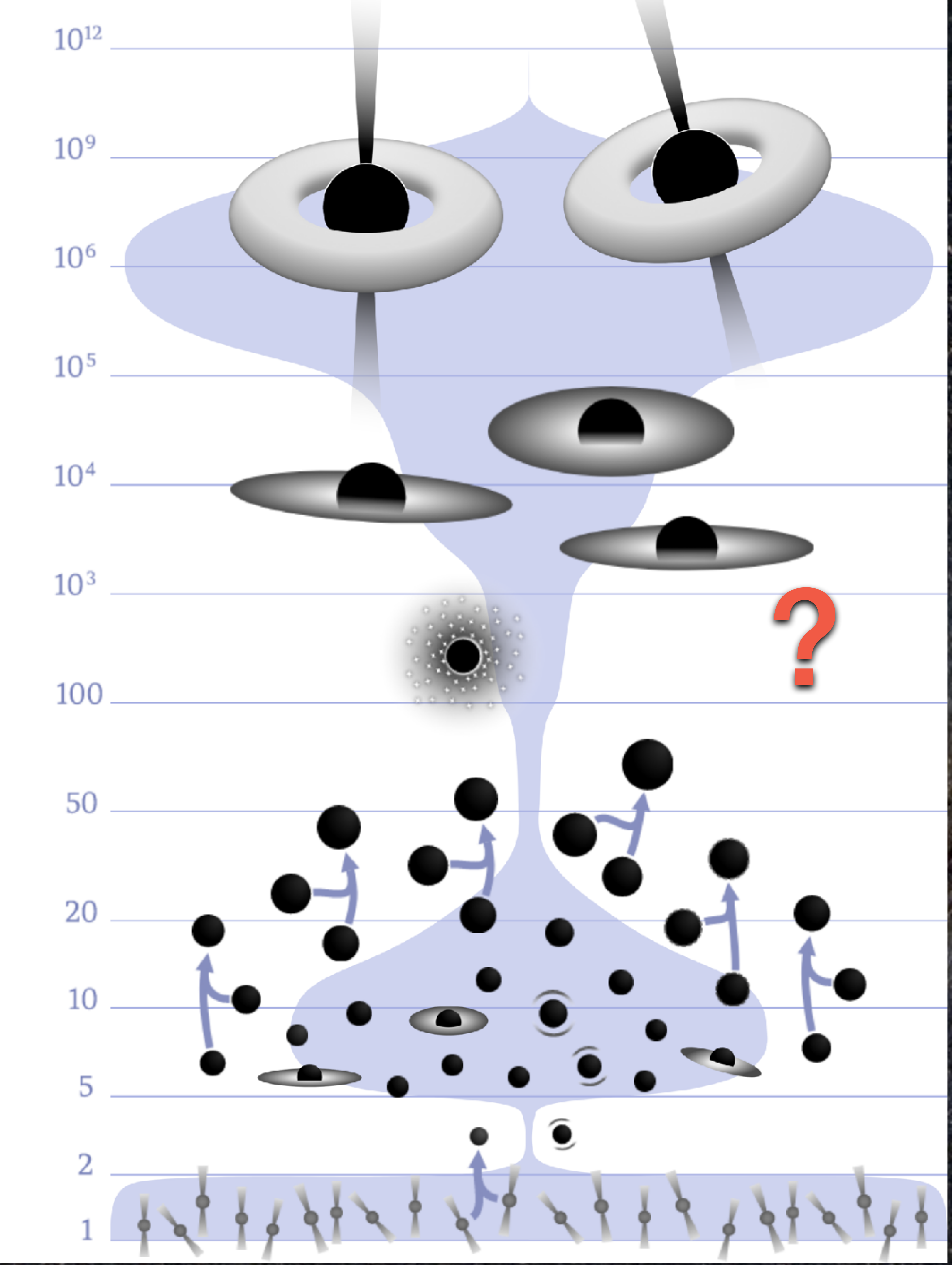
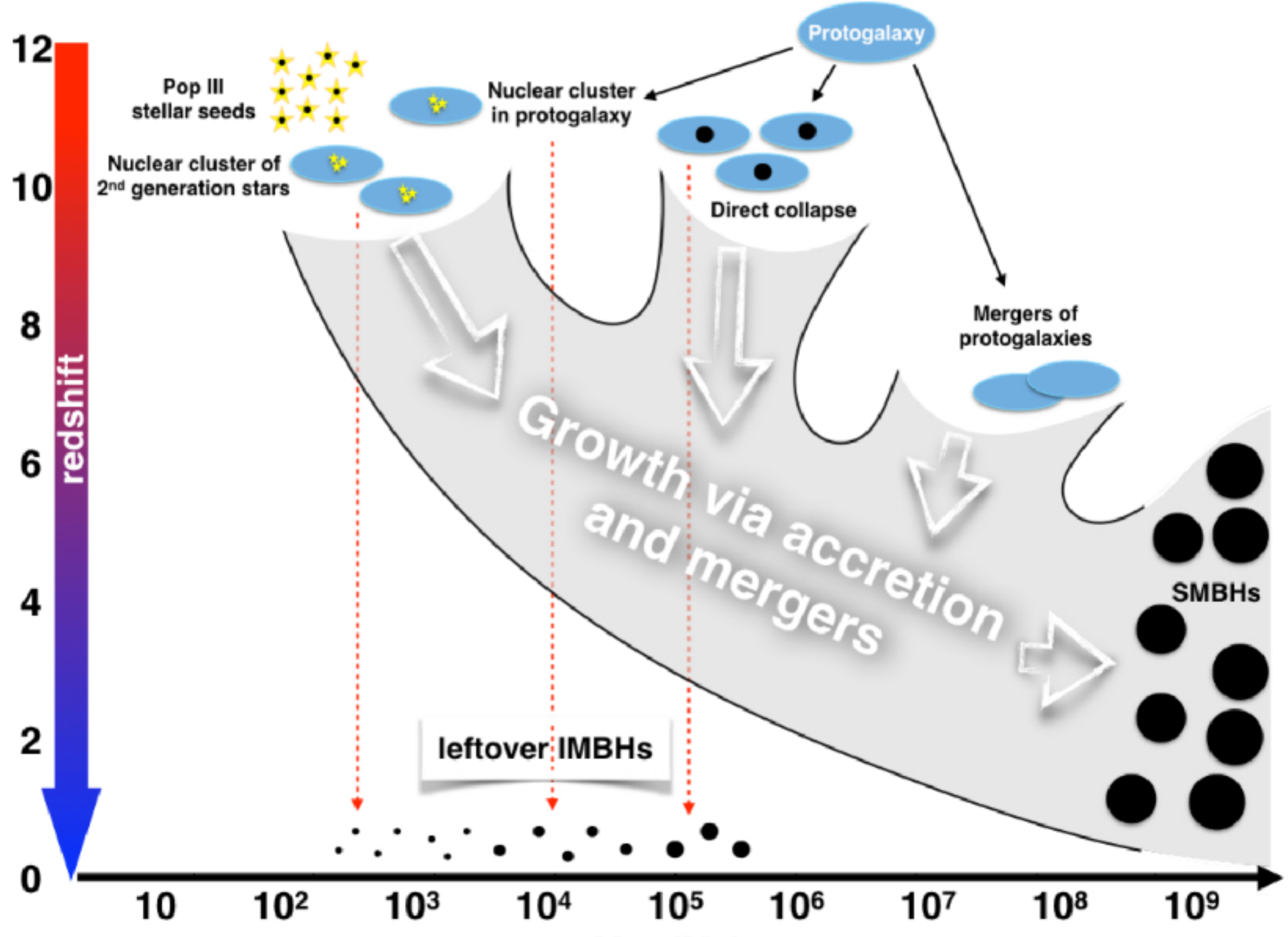


figure: Łukasz Wyrzykowski

Łukasz Wyrzykowski

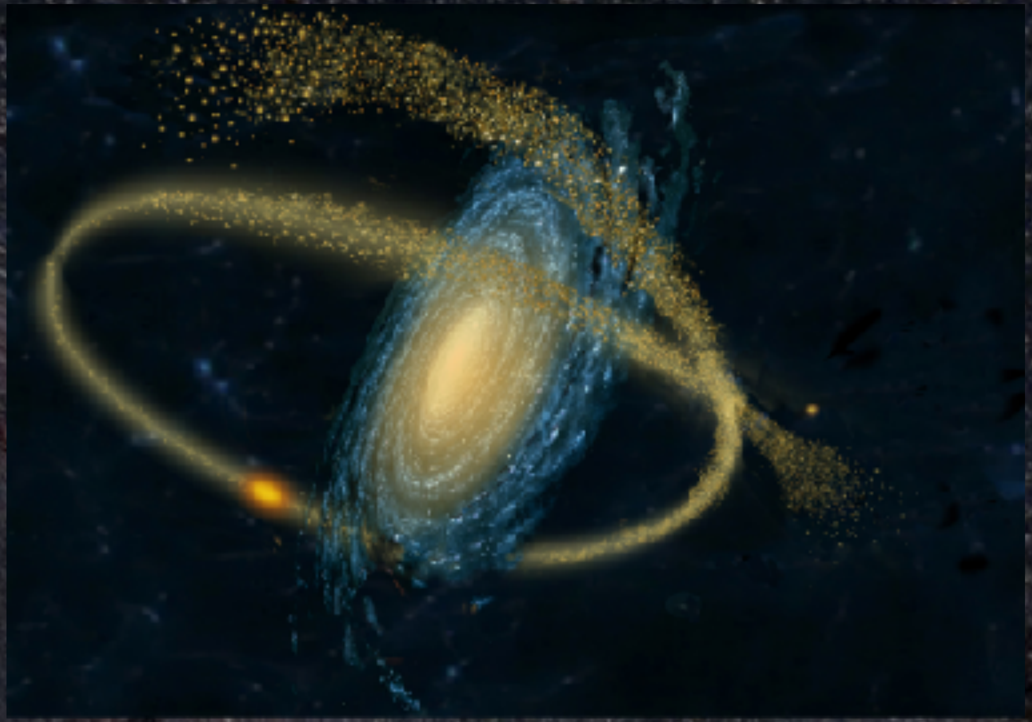
TRACKING BLACK HOLES EVOLUTION



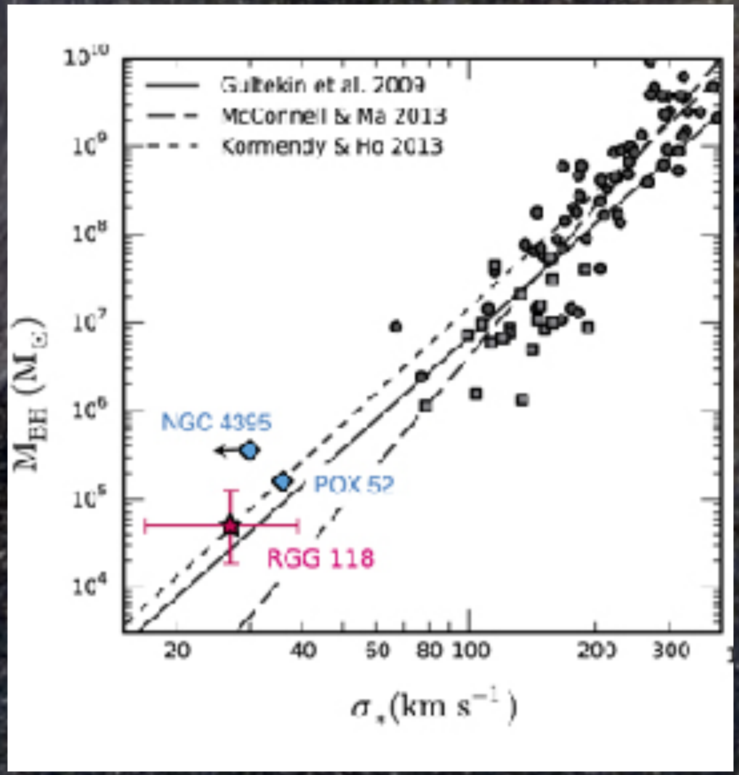
Mezcua (2017)

IMBH - WHERE ARE THEY?

MILKY WAY:
leftovers from disruption
of dwarf galaxies



DWARF GALAXIES:
in the centres of
old low-mass galaxies



Baldassare+15

Mezcua (2017)

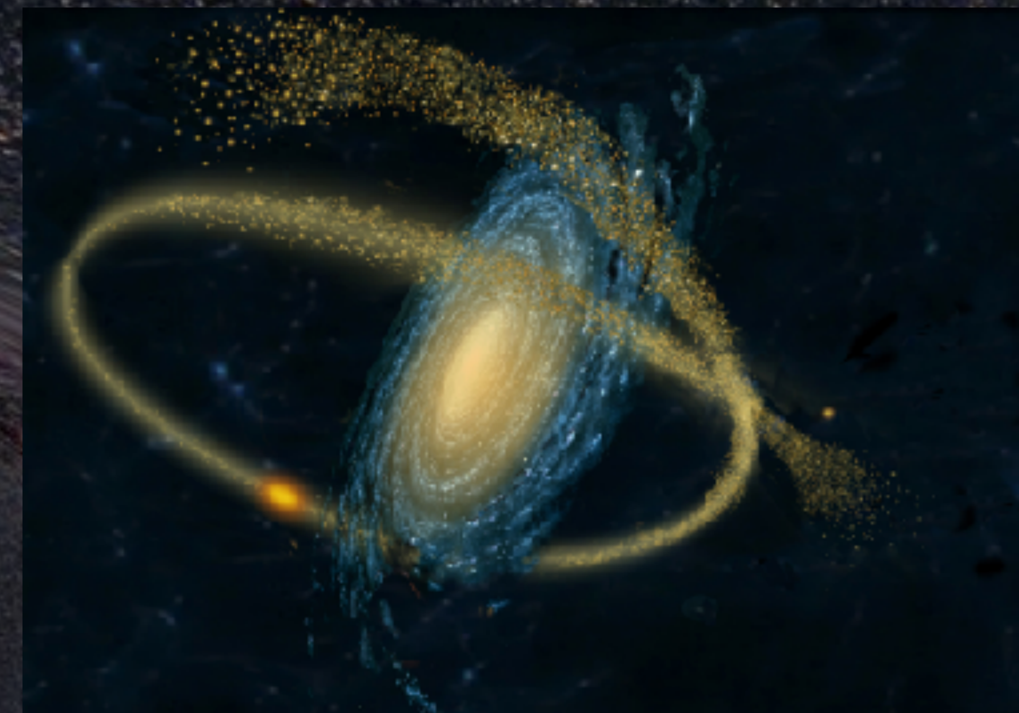
Greene 2012

Łukasz Wyrzykowski

IMBH - WHERE ARE THEY?

MILKY WAY:
leftovers from disruption
of dwarf galaxies

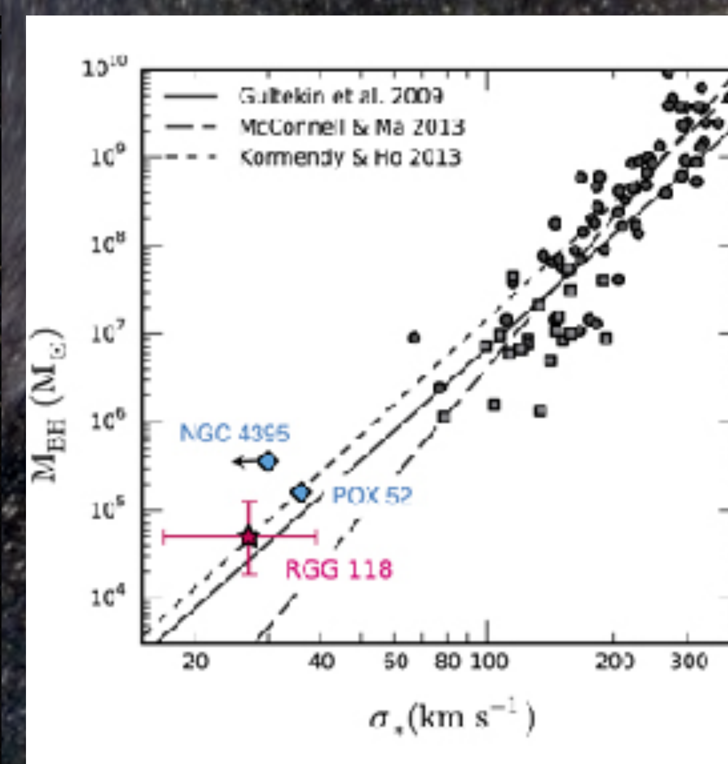
lensing



DWARF GALAXIES:
in the centres of
old low-mass galaxies

tidal disruption events

see Mariusz' and Nada's talks

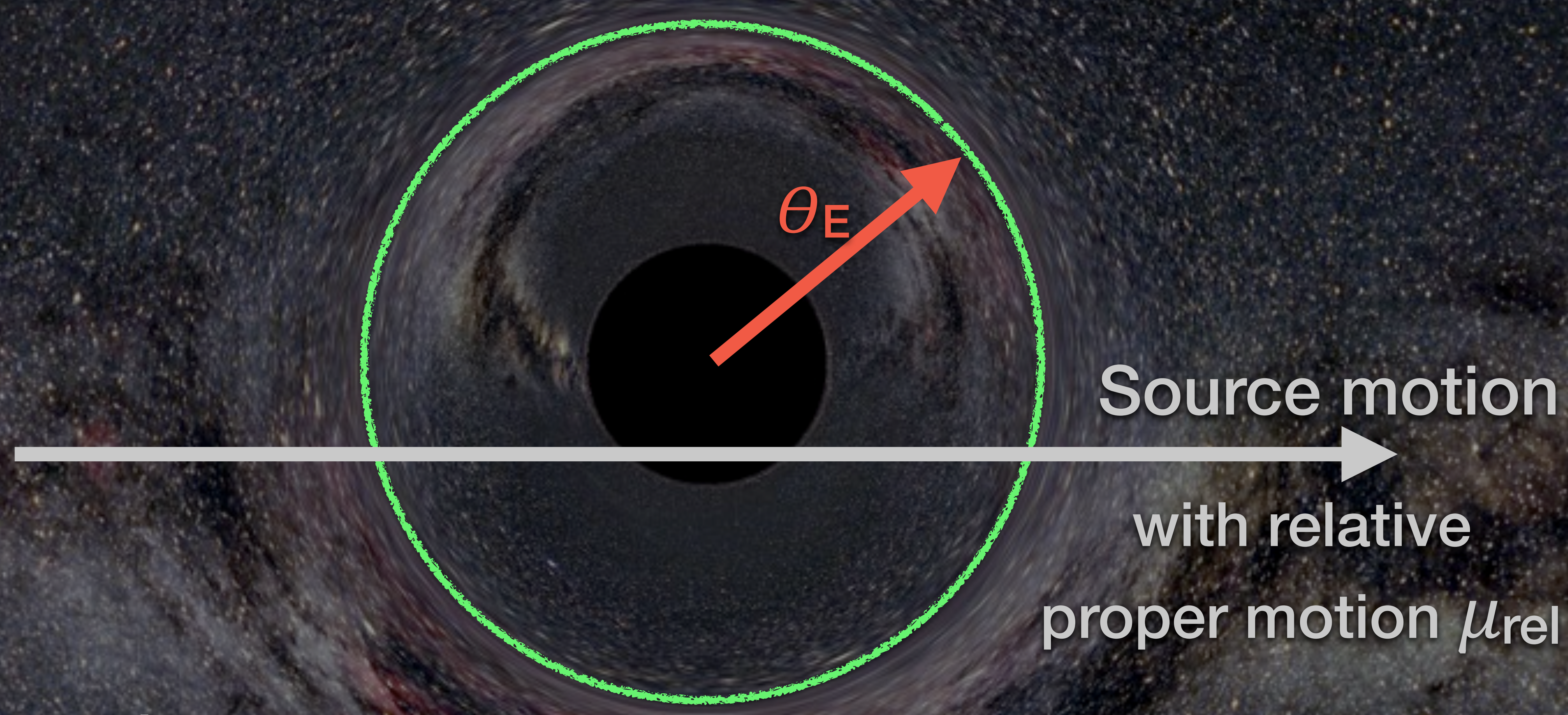


Baldassare+15

Greene 2012

Łukasz Wyrzykowski

BLACK HOLES AS LENSES



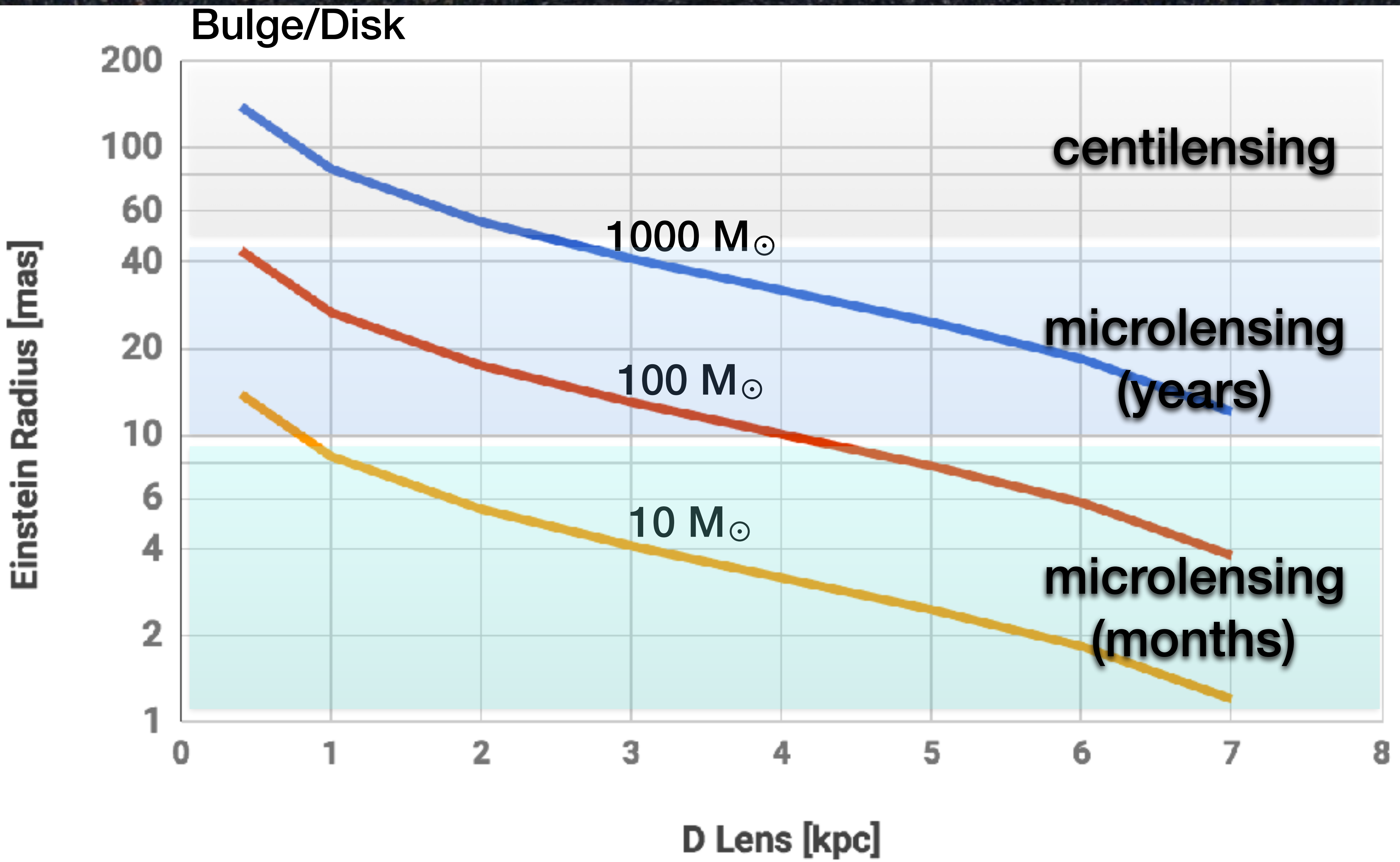
for example:

M_{BH} = 100 $M_\odot$ at D_L=1kpc -> t_E = 5 yrs

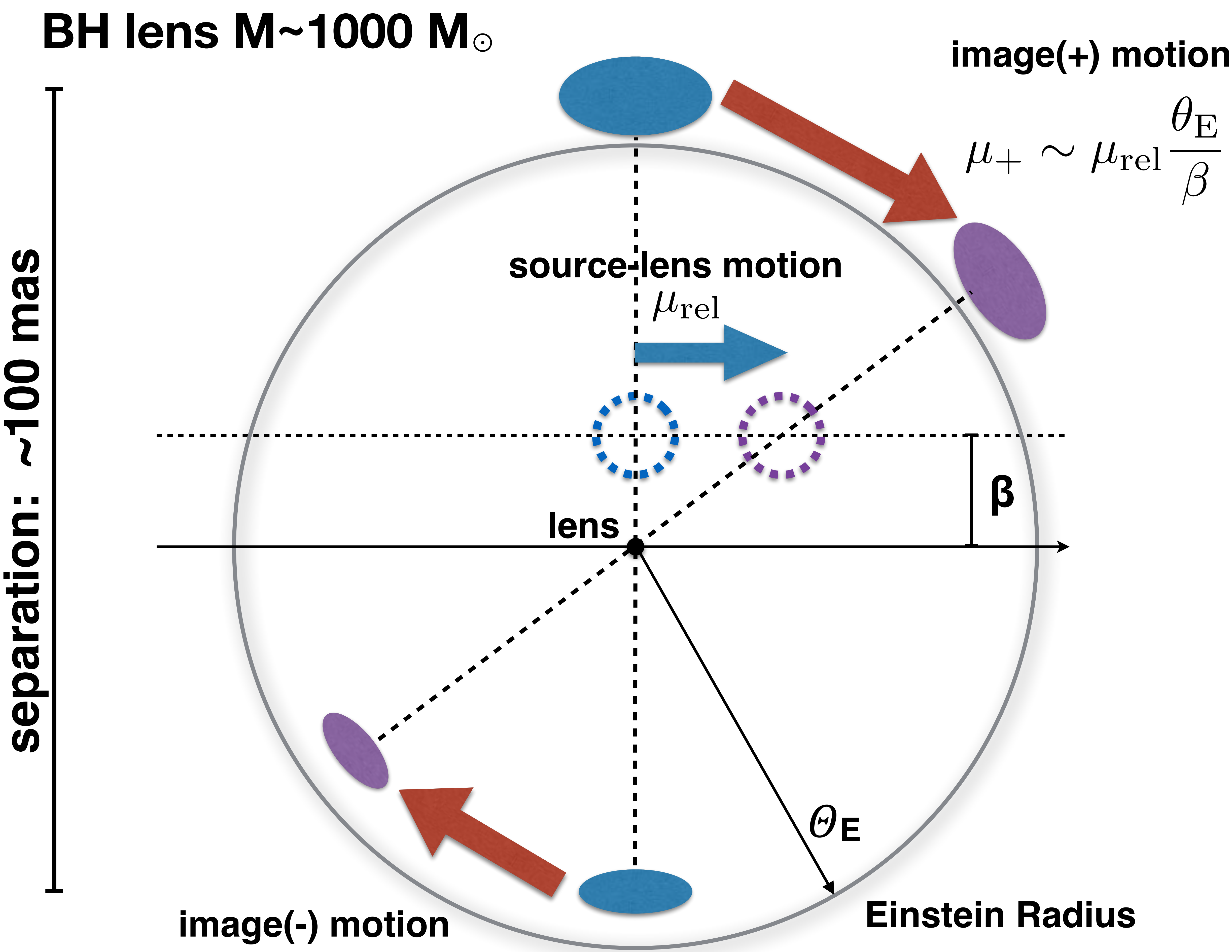
M_{BH} = 1000 $M_\odot$ at D_L=4kpc -> t_E = 6 yrs

Łukasz Wyrzykowski

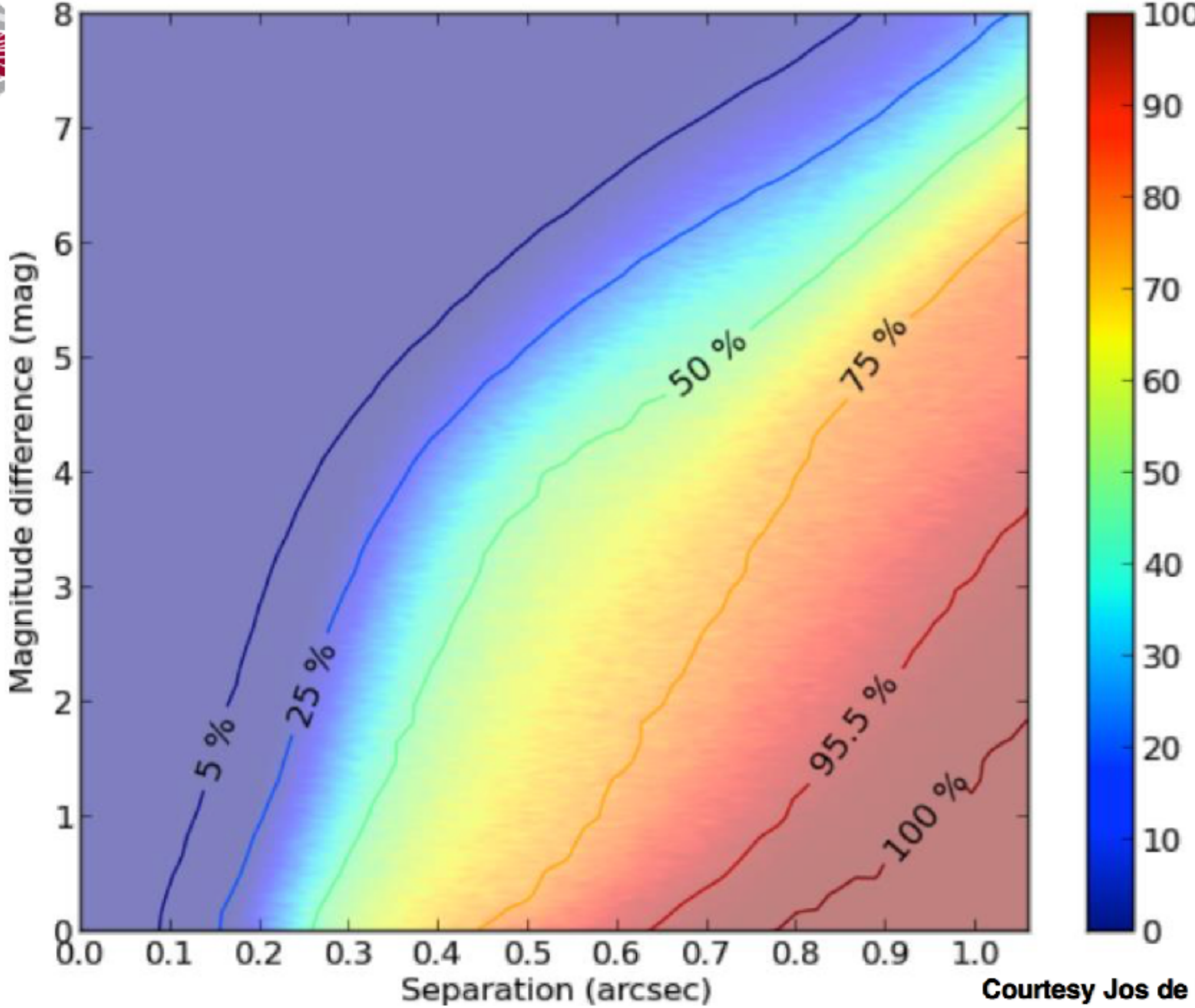
BLACK HOLES AS LENSES



Łukasz Wyrzykowski



BH lens M~1000 M$_\odot$
image(+) motion
$\mu_+ \sim \mu_{\rm rel} \frac{\theta_{\rm E}}{\beta}$
source-lens motion
$\mu_{\rm rel}$
β
lens
$\Theta_{\rm E}$
Einstein Radius
image(-) motion
separation: ~100 mas



Courtesy Jos de Bruijne

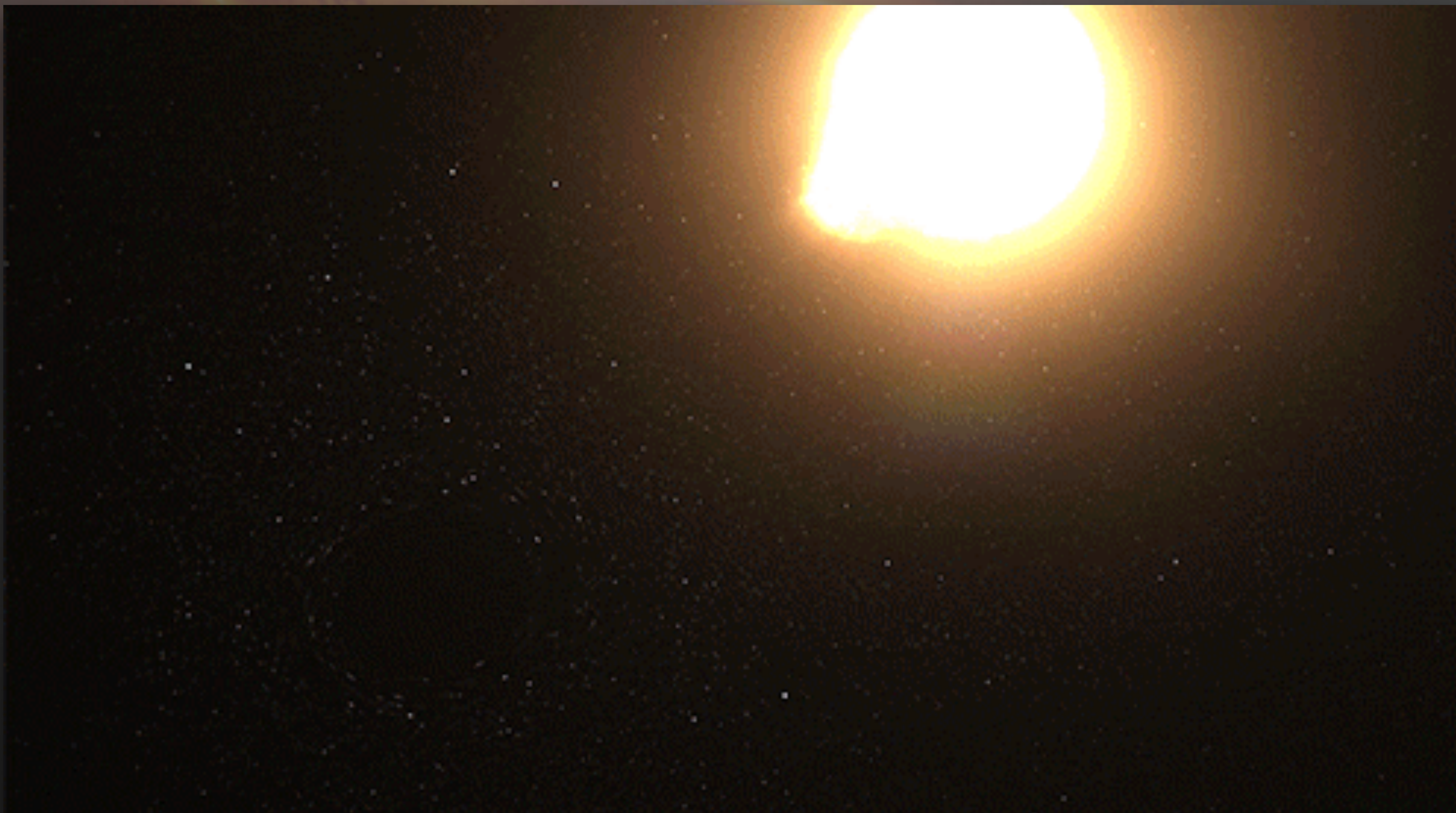
SUMMARY

- Microlensing can help discover low and high mass black holes, including the primordial ones
- remnant (dark lens) mass distribution -> no mass-gap?
- Gaia astrometry in 2023 (DR4) will yield accurate lens masses of currently on-going microlensing events
- Without ground-based photometry the Gaia data will be useless!
- IMBHs in Milky Way can be searched via lensing in Gaia data (but no alerts)

Łukasz Wyrzykowski

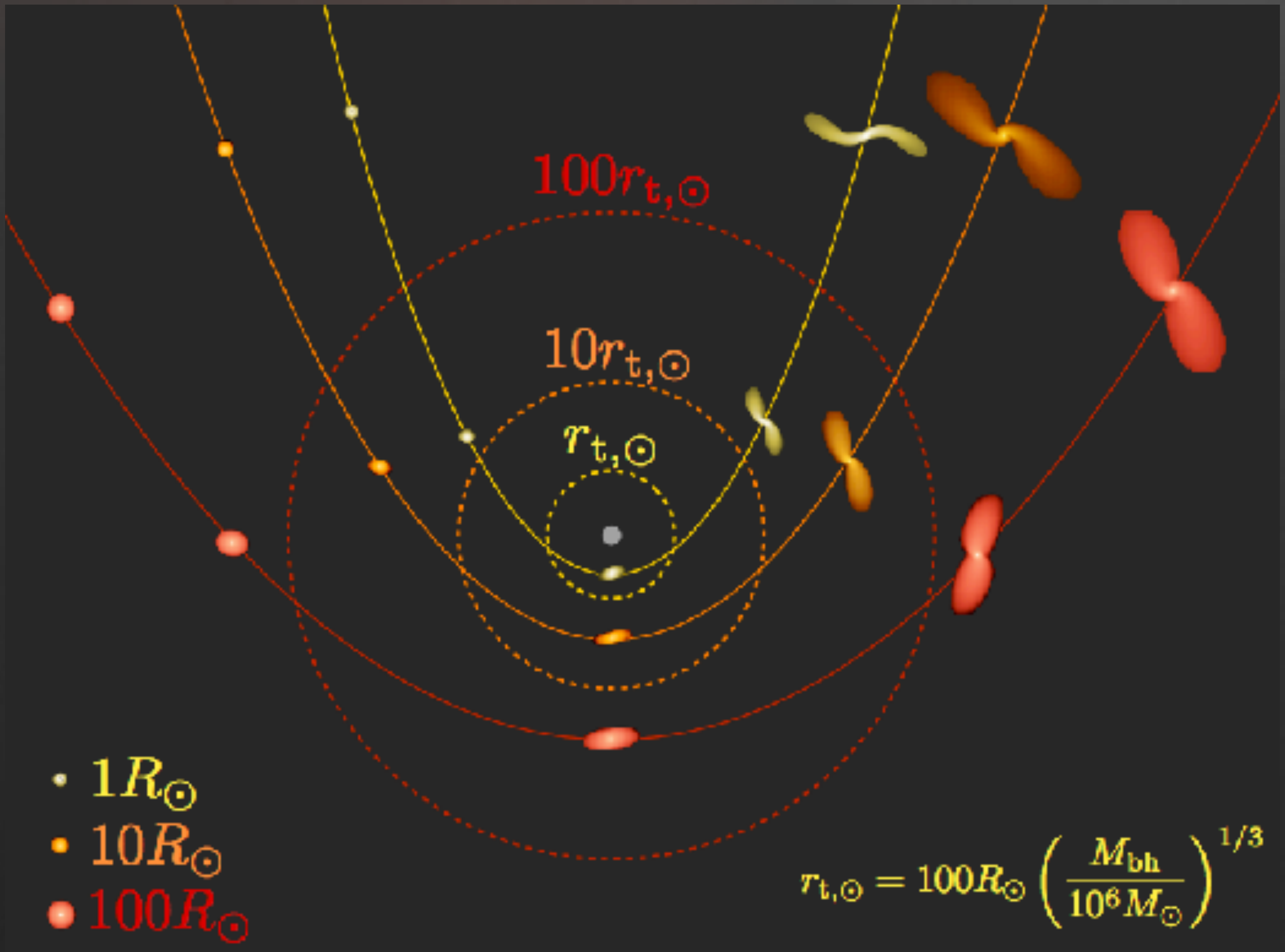
TIDAL DISRUPTION EVENTS

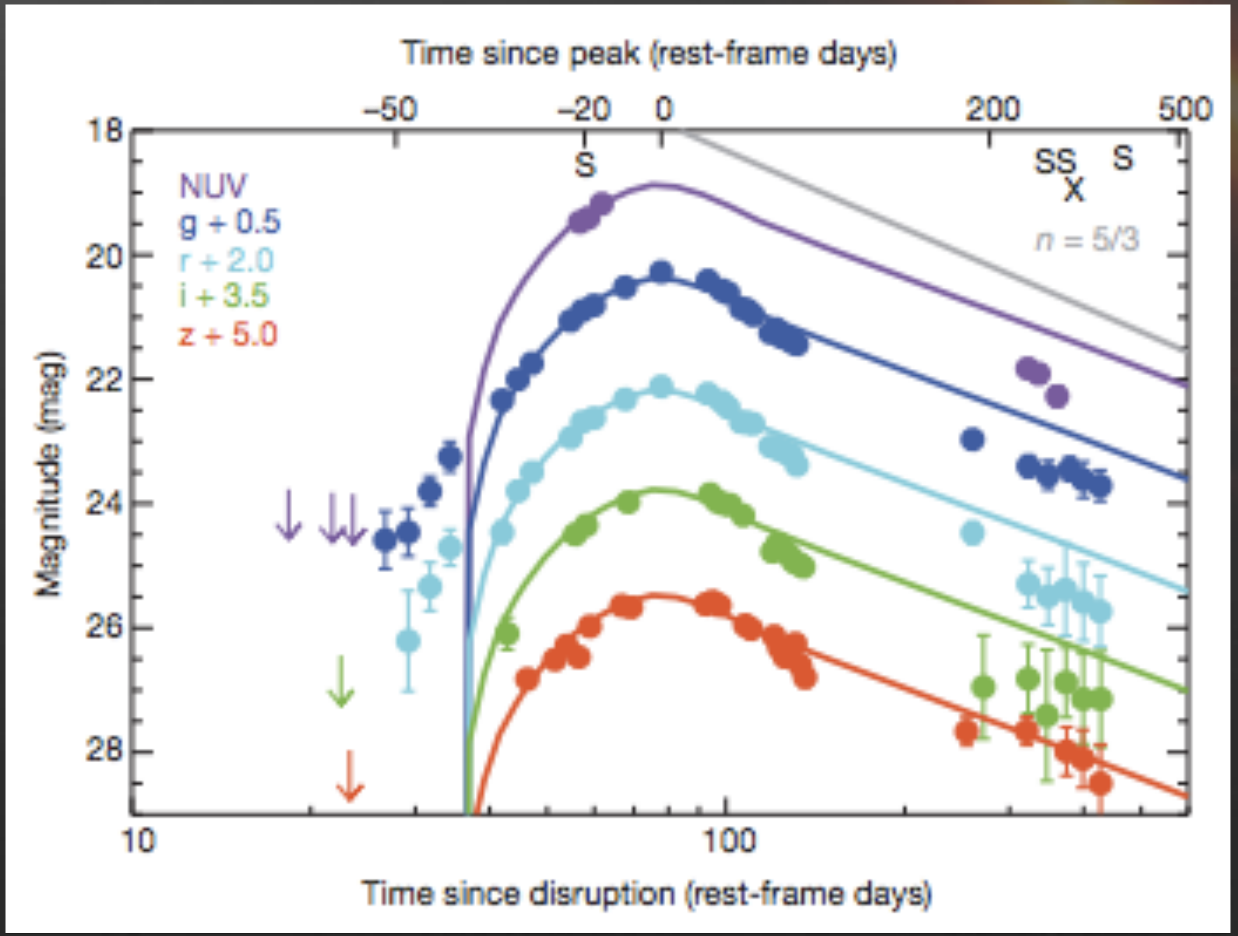
Quiet SMBH disrupting a star



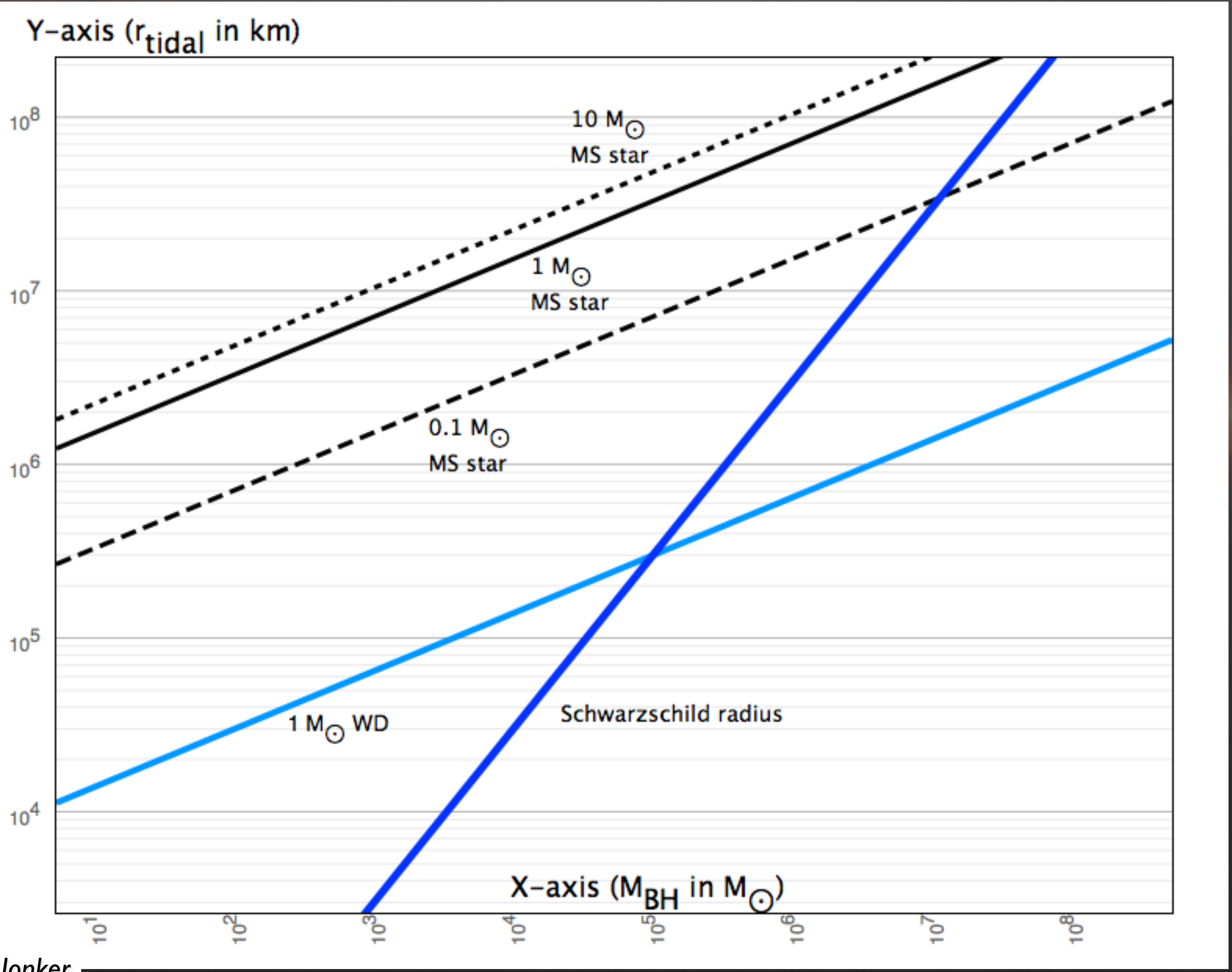
TIDAL DISRUPTION EVENTS

- disruption of a star by central Black Hole (up to 10^8 MSun)
- hot, UV-bright flares (>30,000K)
- 10^{-5} events per galaxy
- the shorter the flare, the less massive the BH
- channel for IMBH discovery (White Dwarf disruption)



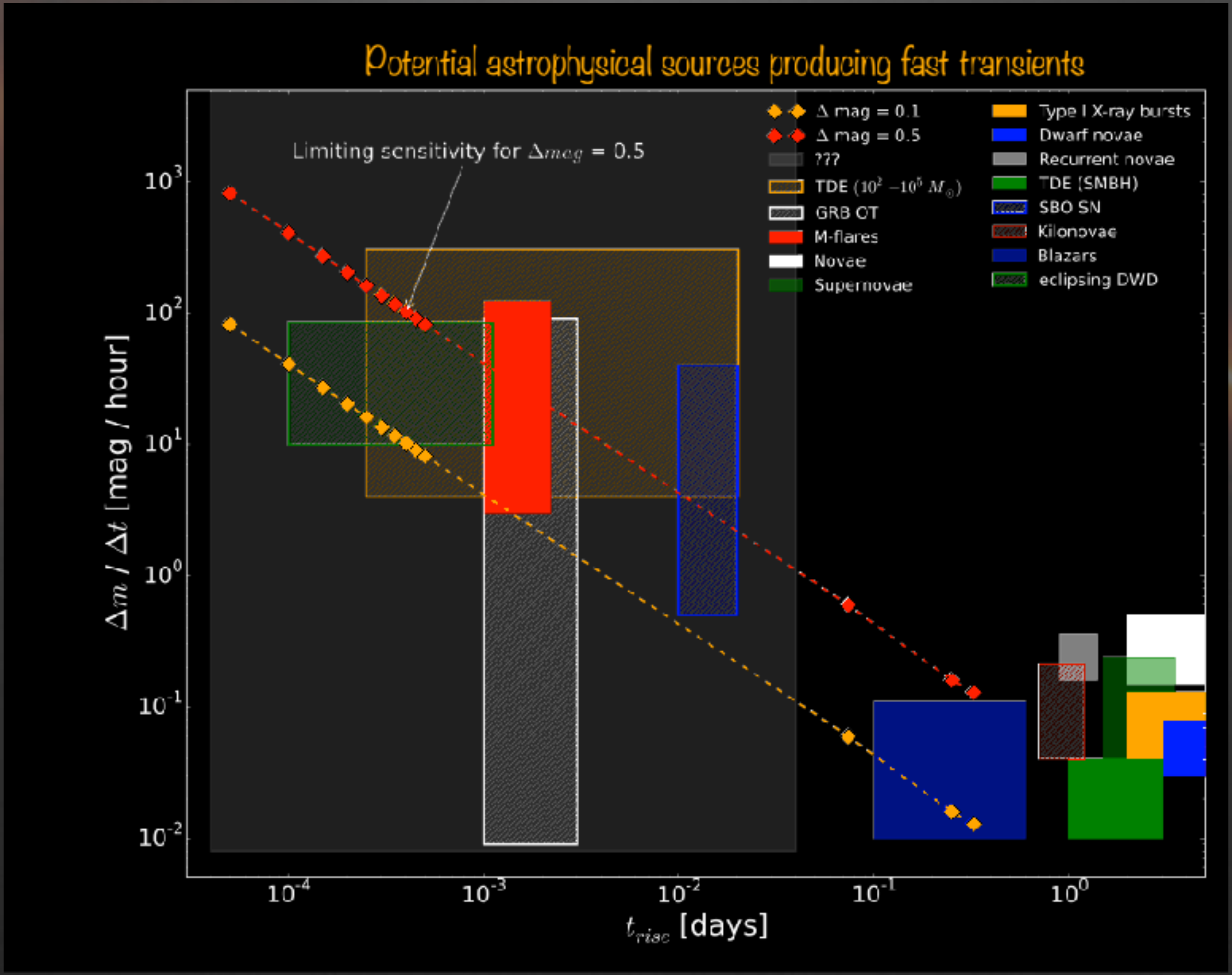


TIDAL DISRUPTION EVENTS & IMBHS



credit: Peter Jonker

TIDAL DISRUPTION EVENTS & IMBH

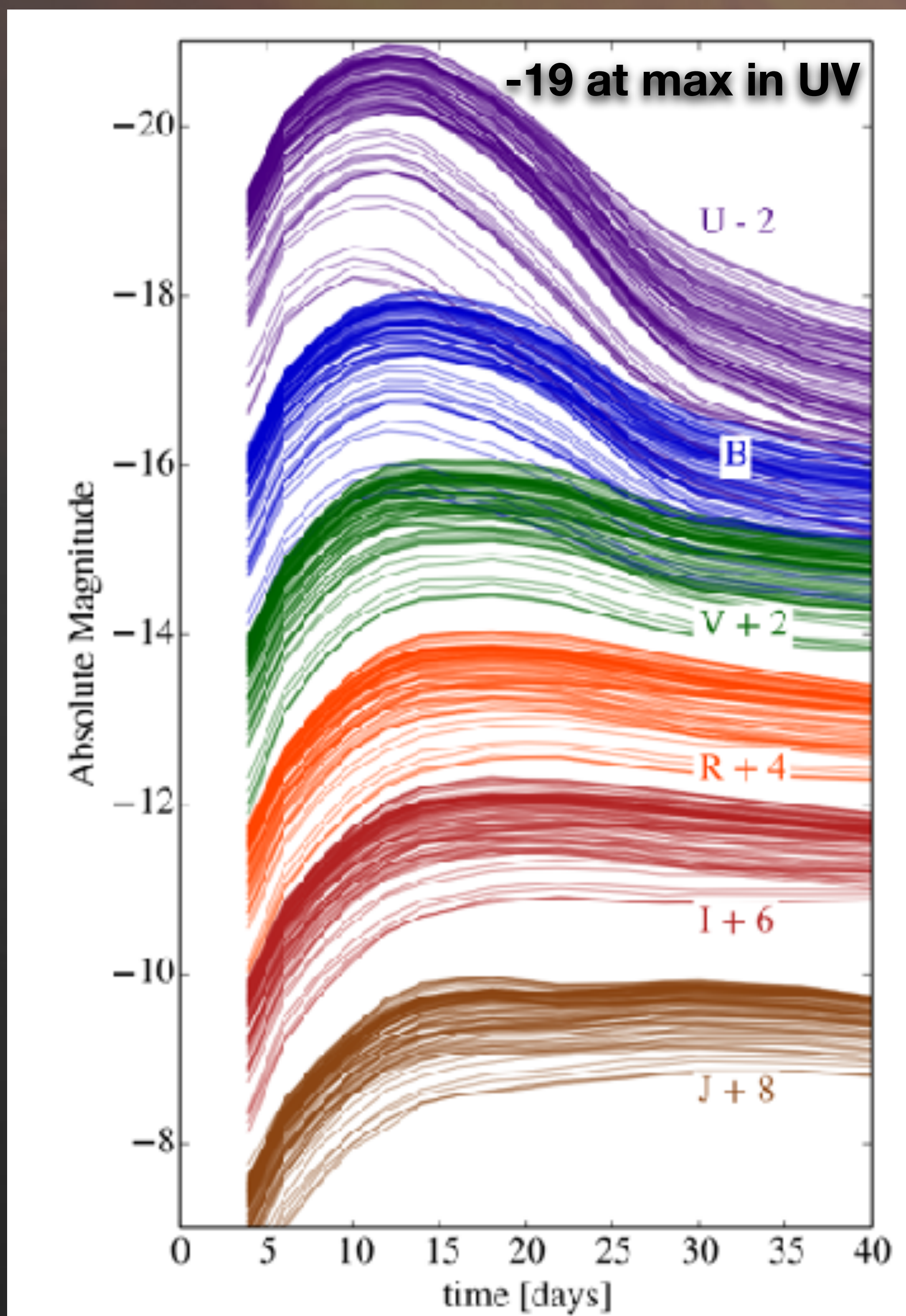


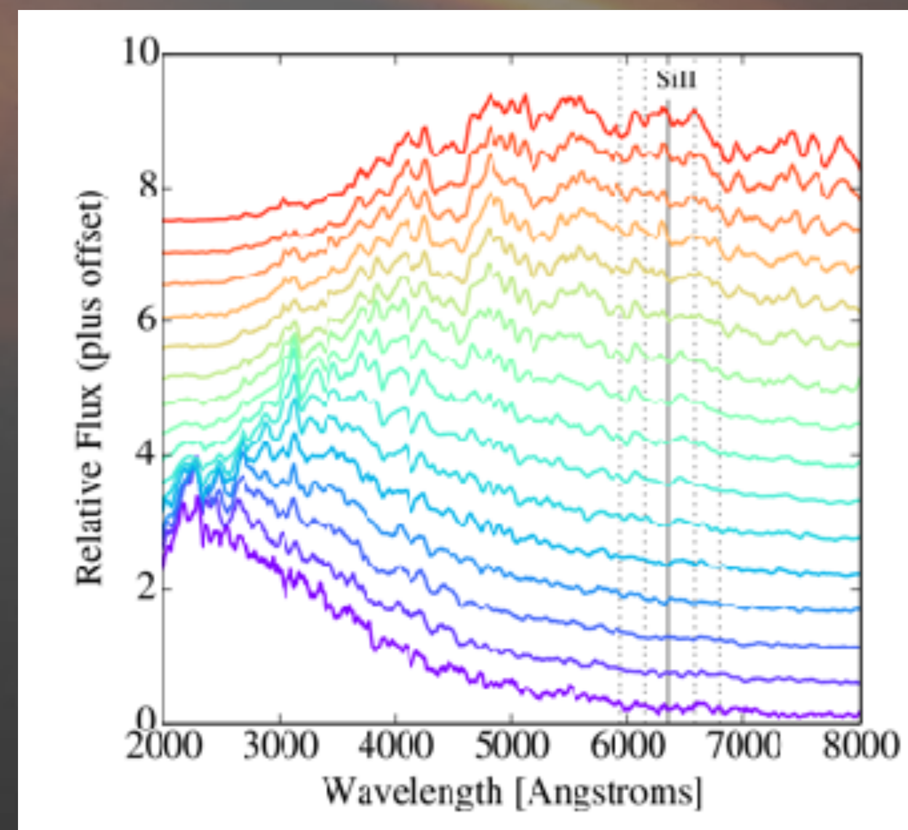
Wevers+2017

High-cadence all-sky observations needed to detect short TDE!

TIDAL DISRUPTION EVENTS & IMBH

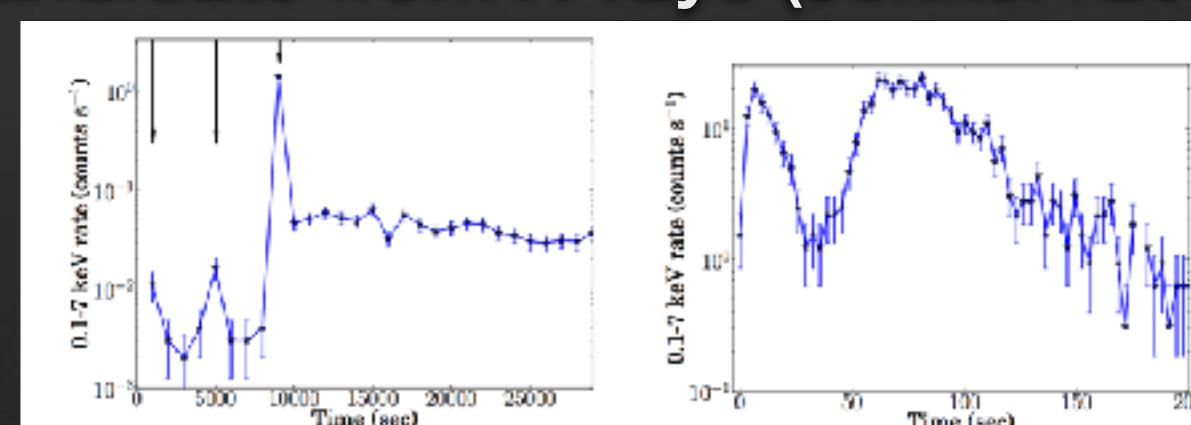
WD disruption by an IMBH model





Macleod+2015

Candidate from X-rays (Jonker+2013)



How to find an IMBH : surveys

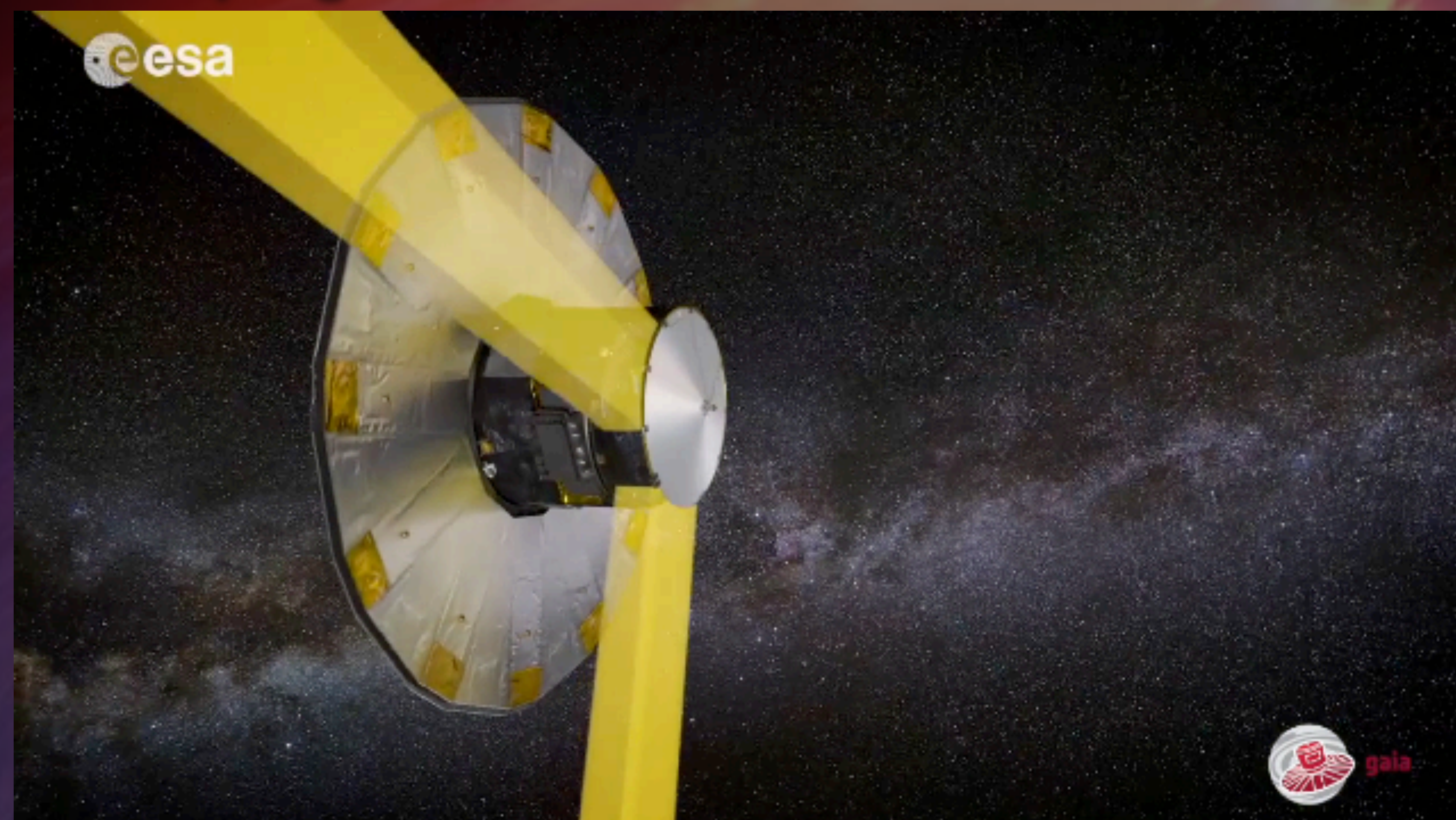
OGLE

http://ogle.astrouw.edu.pl

Polish 1.3m dedicated telescope
in Las Campanas, Chile
Surveying continuously since 1992.

Gaia Science Alerts

http://gsaweb.ast.cam.ac.uk/alerts



ESA space mission with 2x1.4m telescopes located in L2.
In operation since 2014.
DR1 in Sepember 2016,
DR2 in April 2018

How to find an IMBH : follow-up

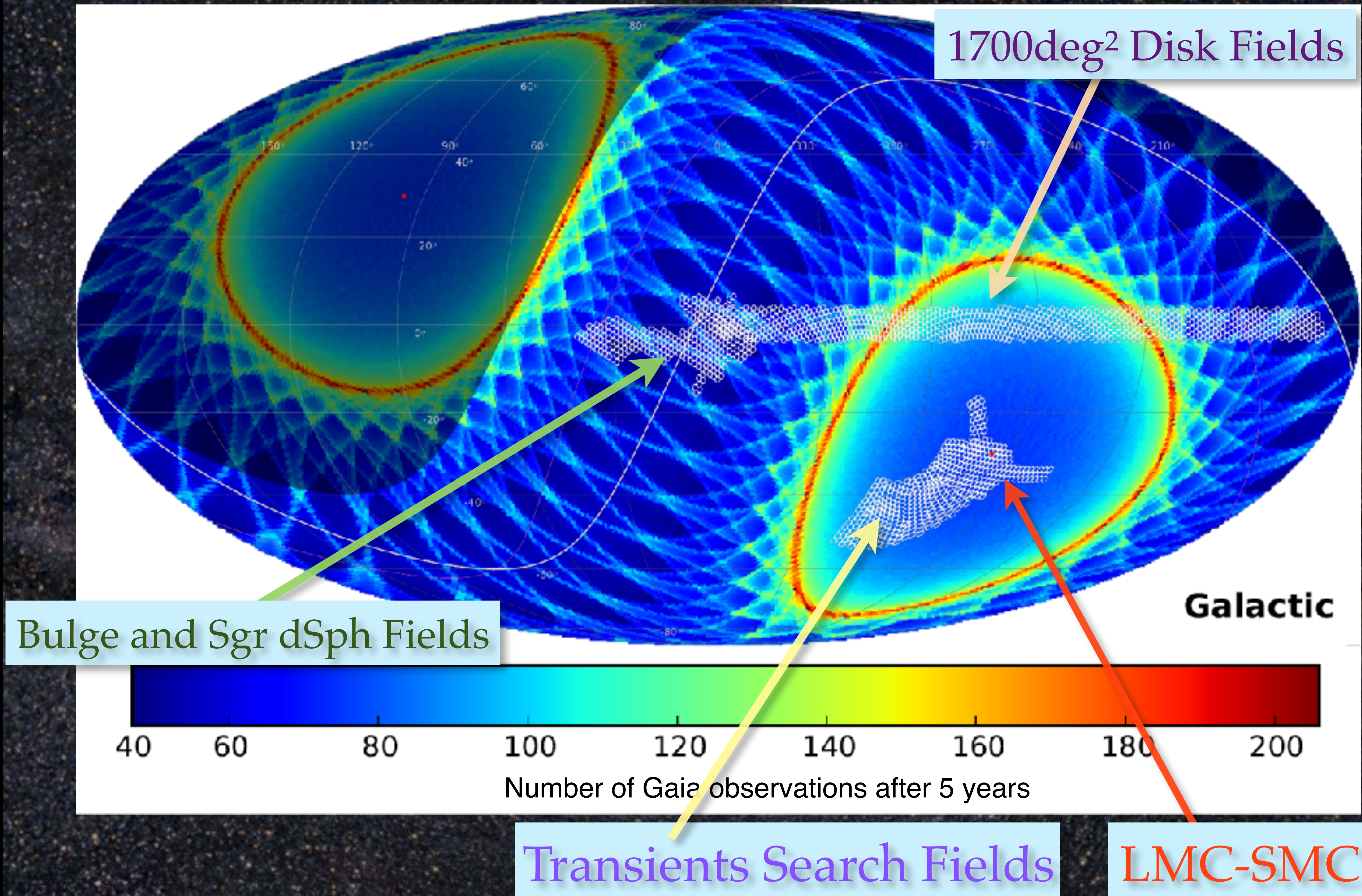
NOT/ALFOSC
NUTS PI: S. Mattila

SALT/RSS
Transient Universe
PI: D. Buckley

ESO/VLT/FORS2 (P<101)
PI: L. Wyrzykowski
PI: M. Gromadzki

ESO/NTT/EFOSC2
ePESSTO PI: S. Smartt

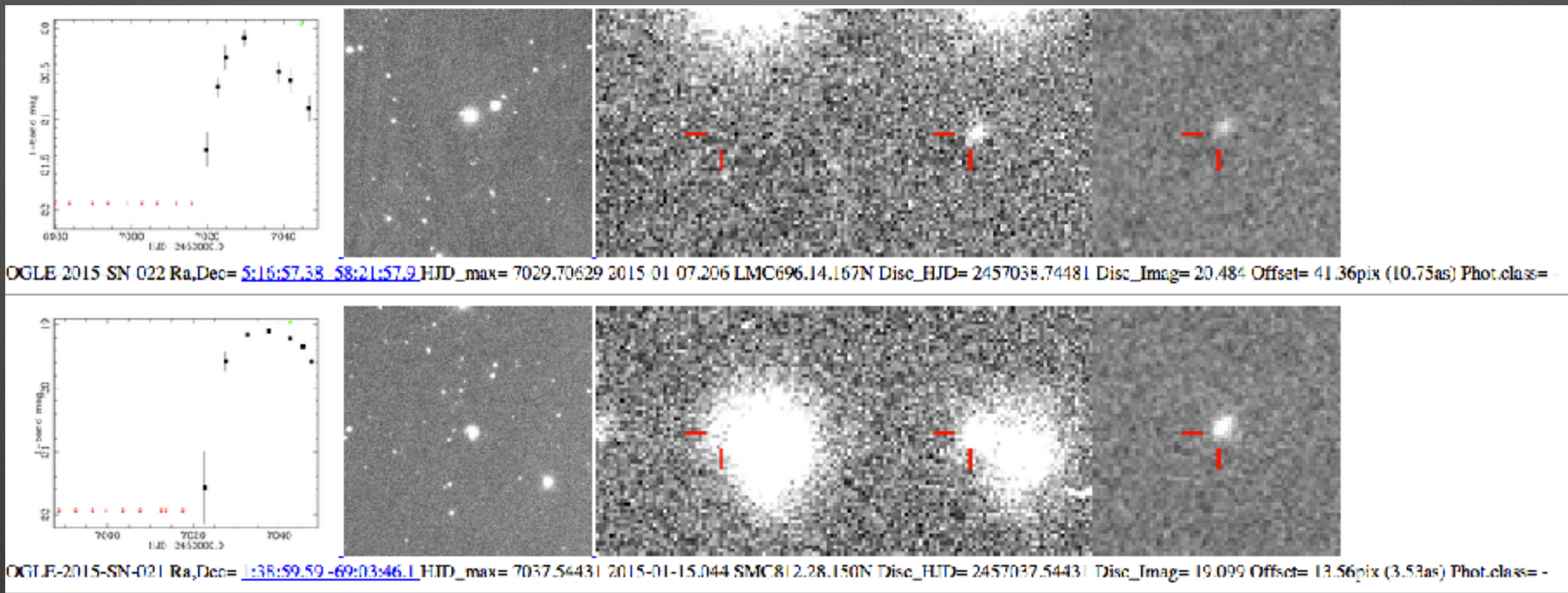
OGLE-GAIA SKY

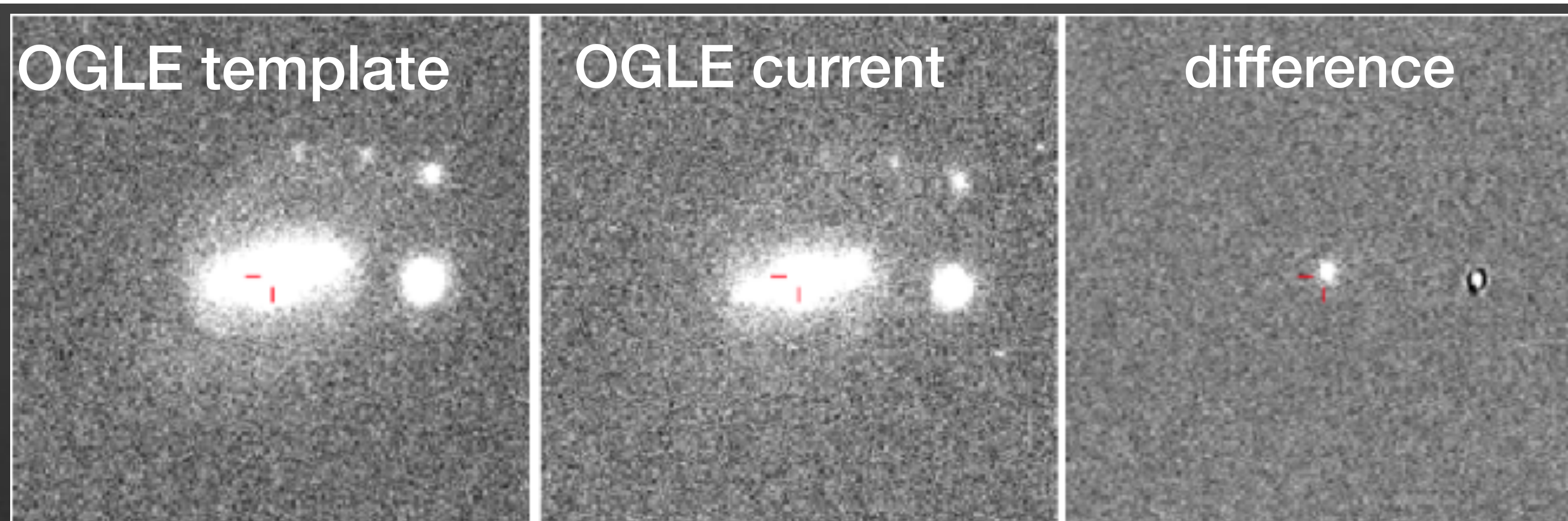


Gaia figure by Nadia Blagorodnova, OGLE fields by Jan Skowron

OGLE TRANSIENTS

700sq.deg monitored, 200 SN/year, 3rd world provider!

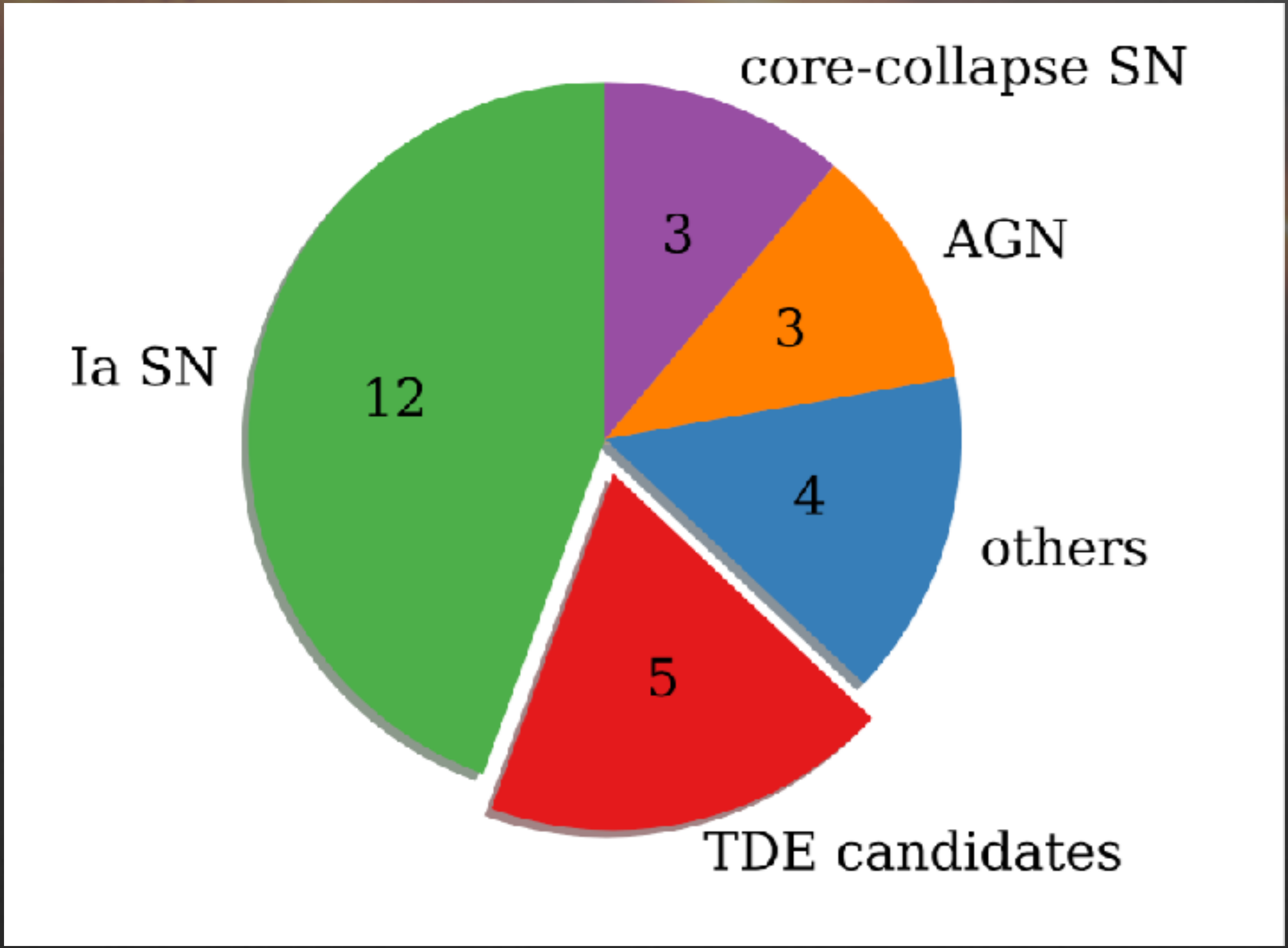




OGLE is good in finding nuclear transients
with difference imaging.

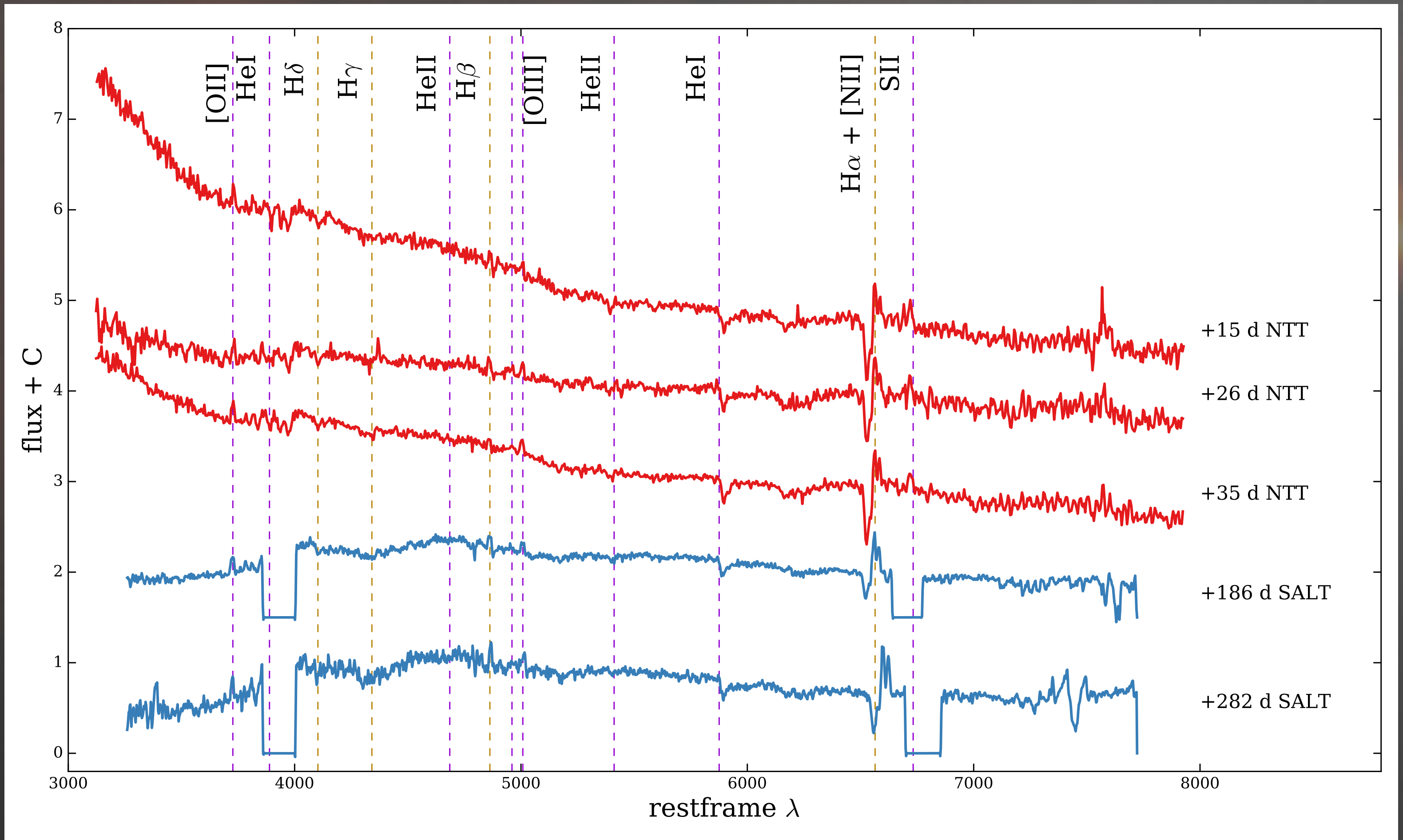
Wyrzykowski+2014

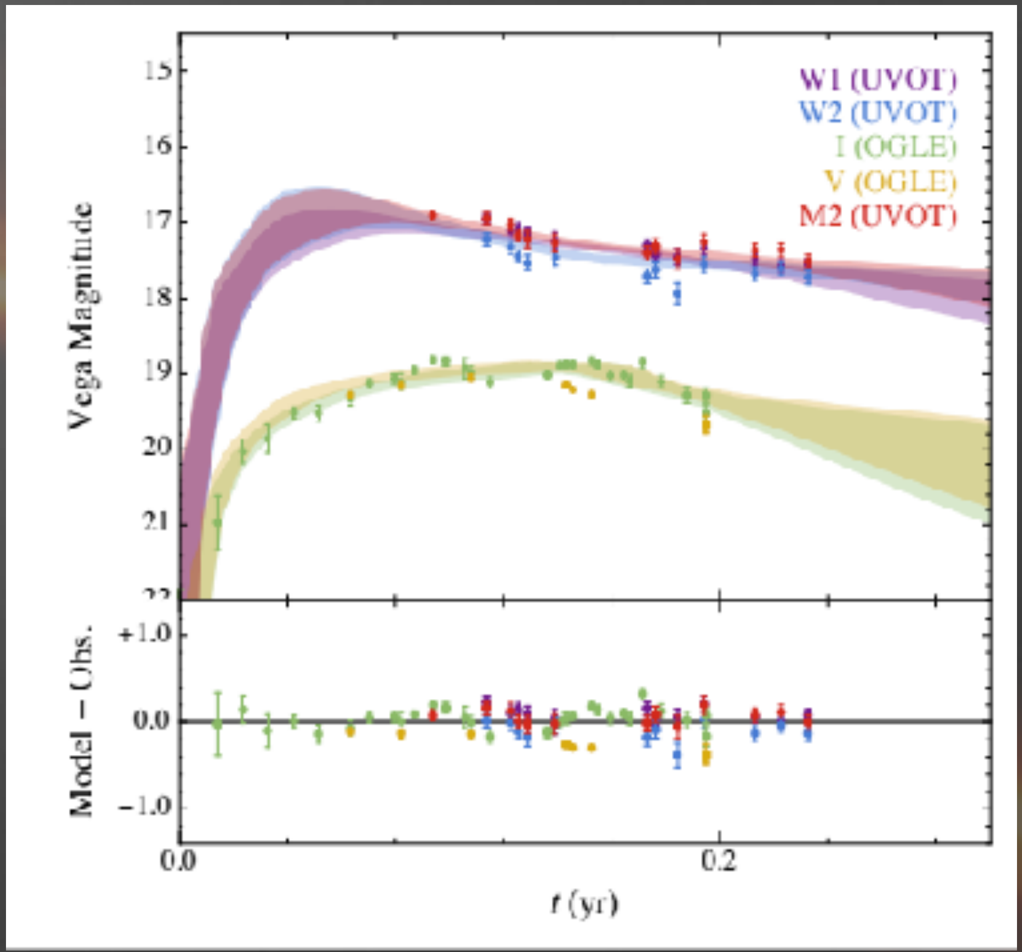
OGLE AND GAIA NUCLEARS 2016-2017

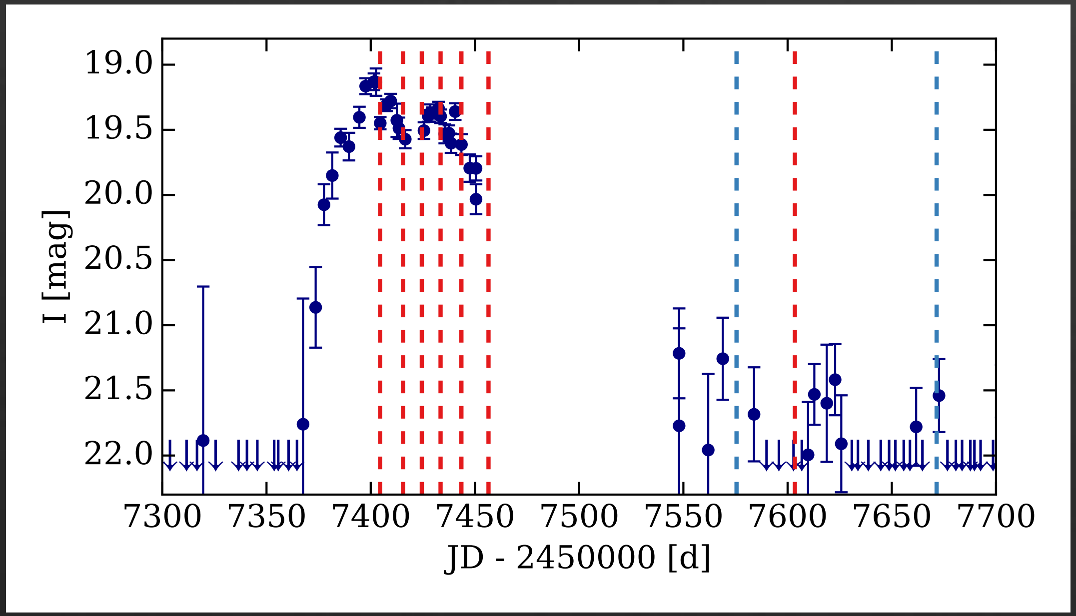


Alex Hamanowicz Master thesis 2017

OGLE16AAA - HUNGRY BLACK HOLE



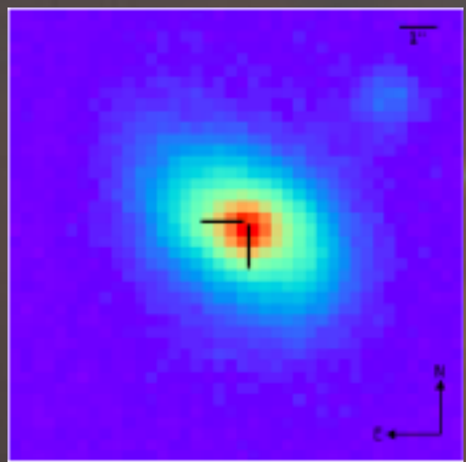


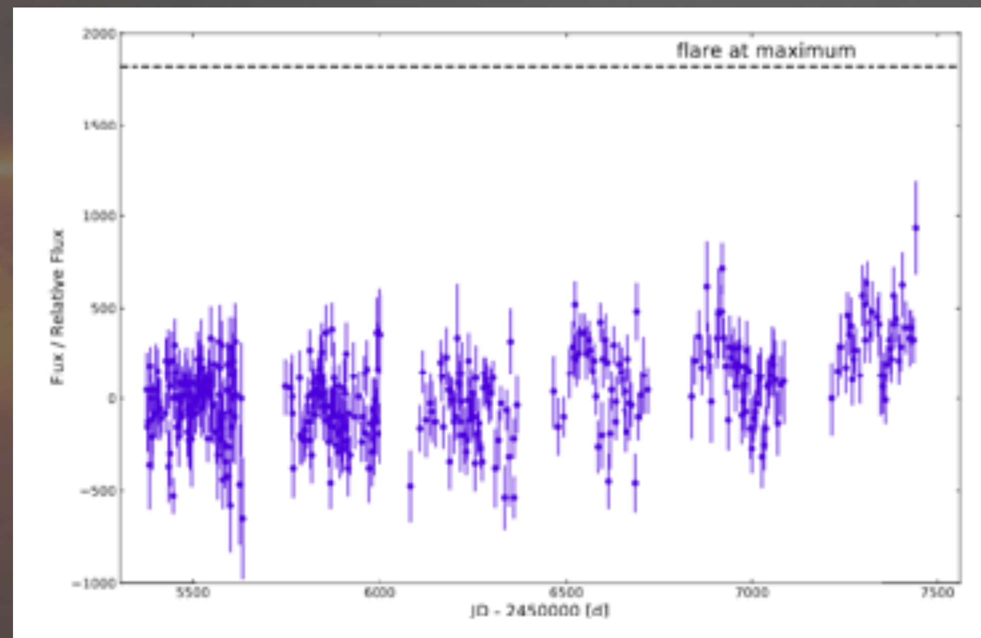


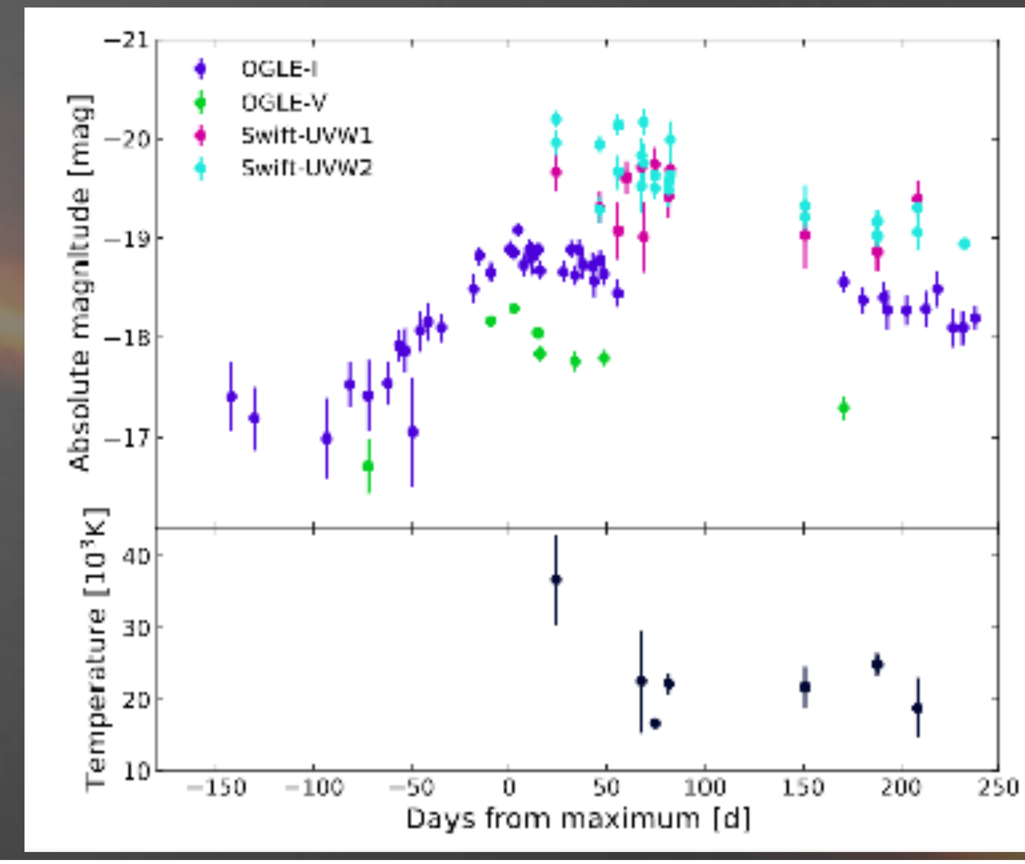
- z=0.167, peak absolute mag M=-20.5 mag
- slowly rising I-band light curve (~30d) - unlike in most SNe, UV-bright (Swift)
- very broad HeII and Hα emission
- hot black-body flare spectrum: 22,000K
- weak narrow AGN lines
- SMBH: $10^{6.5}$ MSun, star: 0.3 MSun

Wyrzykowski+2017

OGLE17AAJ







UV-bright (observed with Swift)

constant temperature >20000K

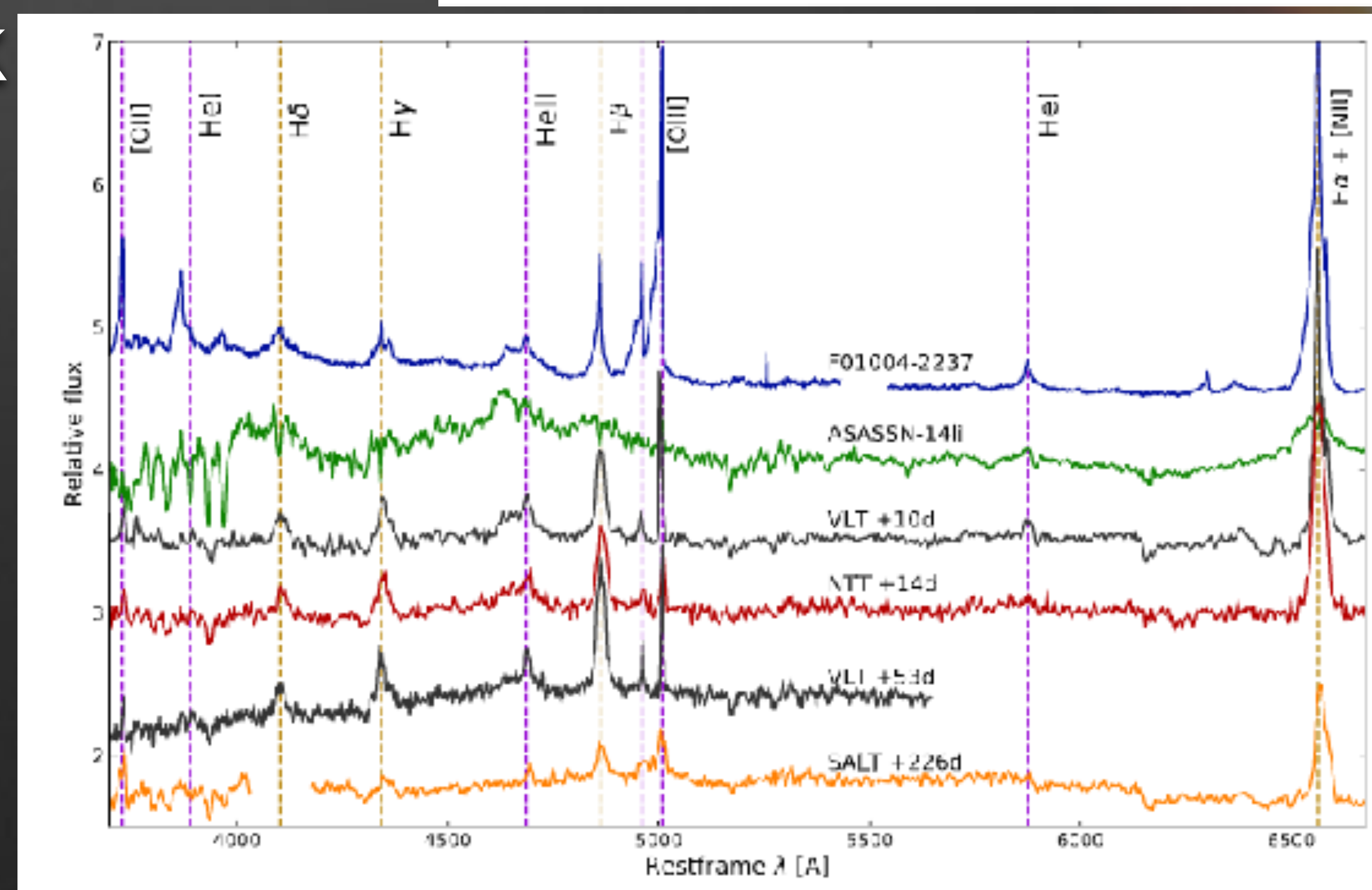
z=0.116

absolute magnitude
M_I = -18.8 mag
(host subtracted)

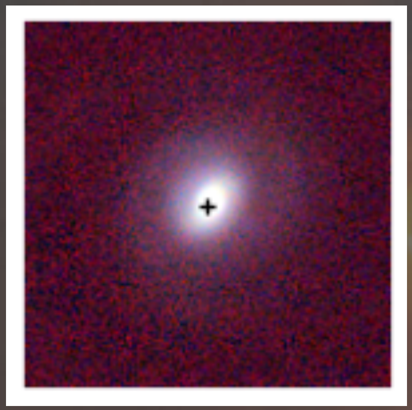
previous low-level variability

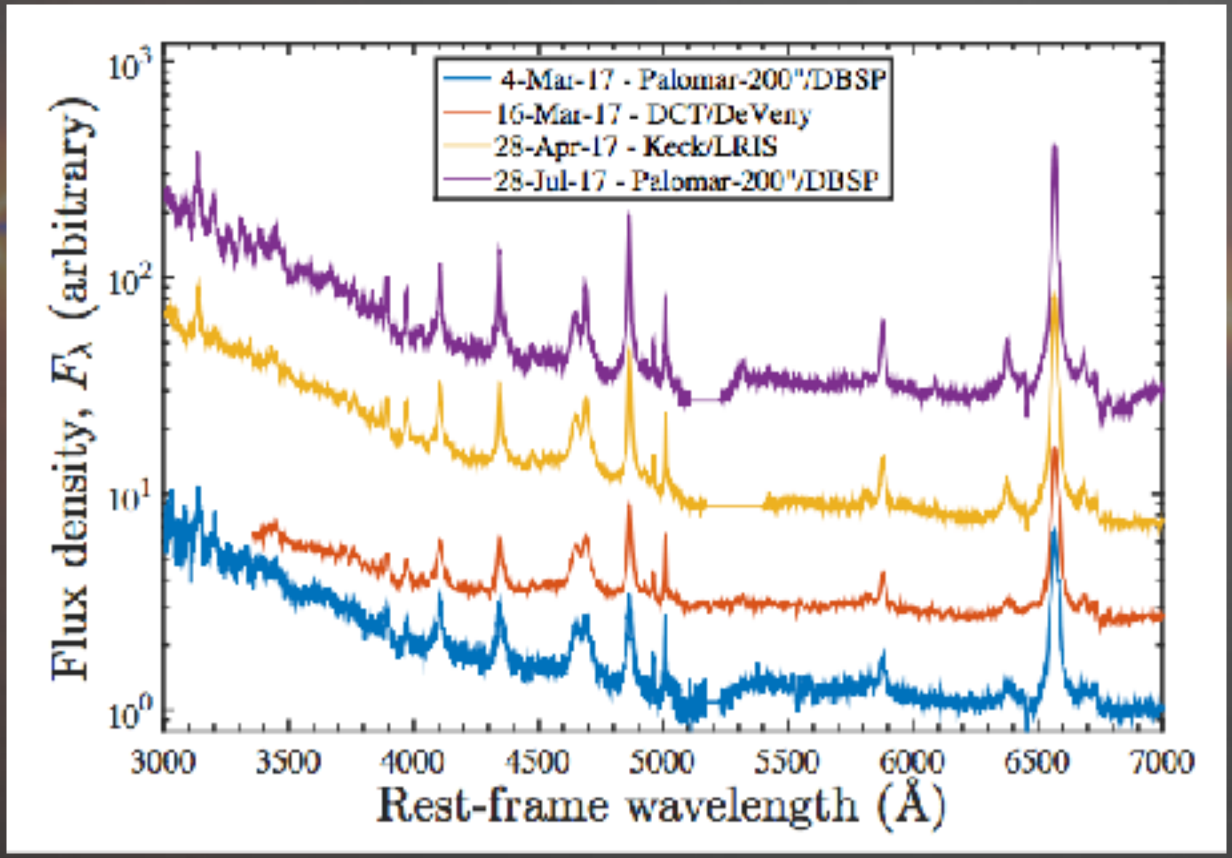
TDE? New kind of AGN flare?

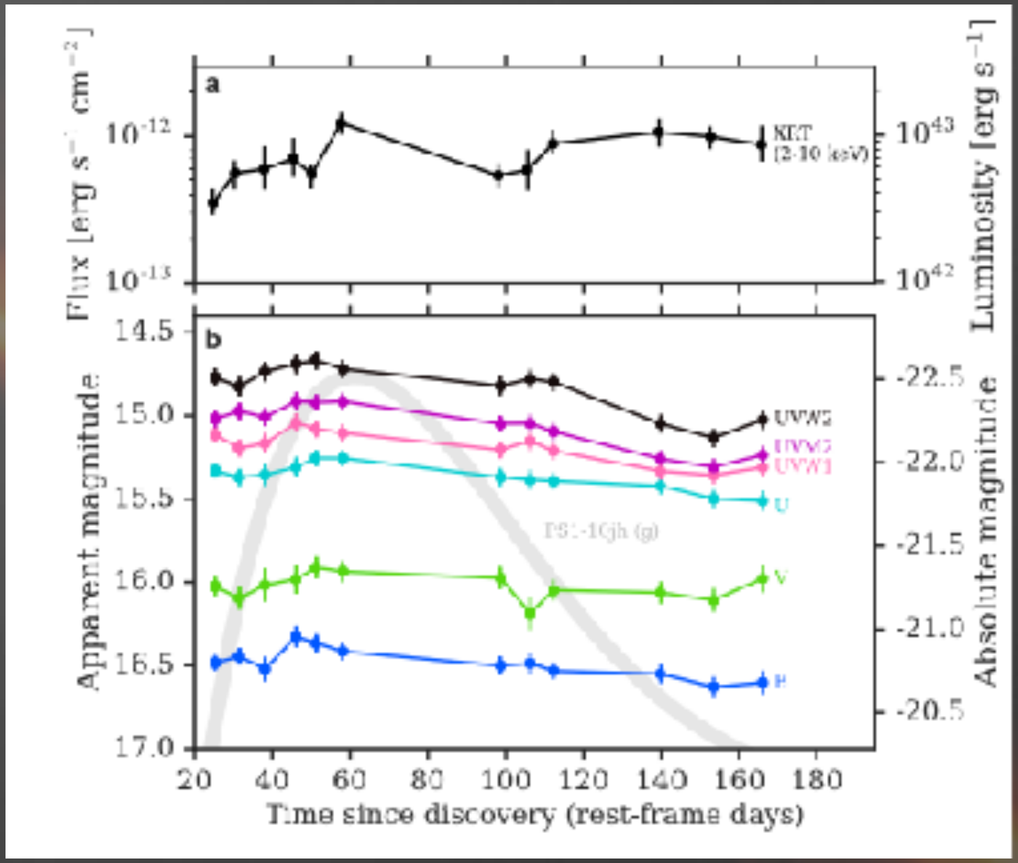
(Gromadzki submitted)

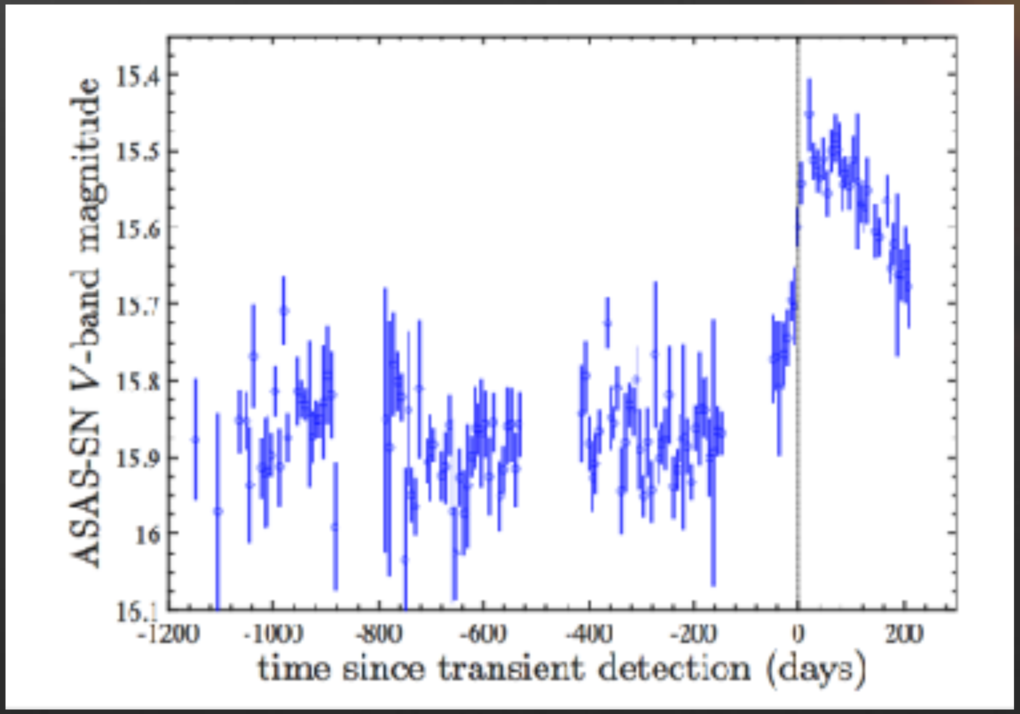


ASASSN-17BGT - NEW CLASS OF AGN FLASHES?









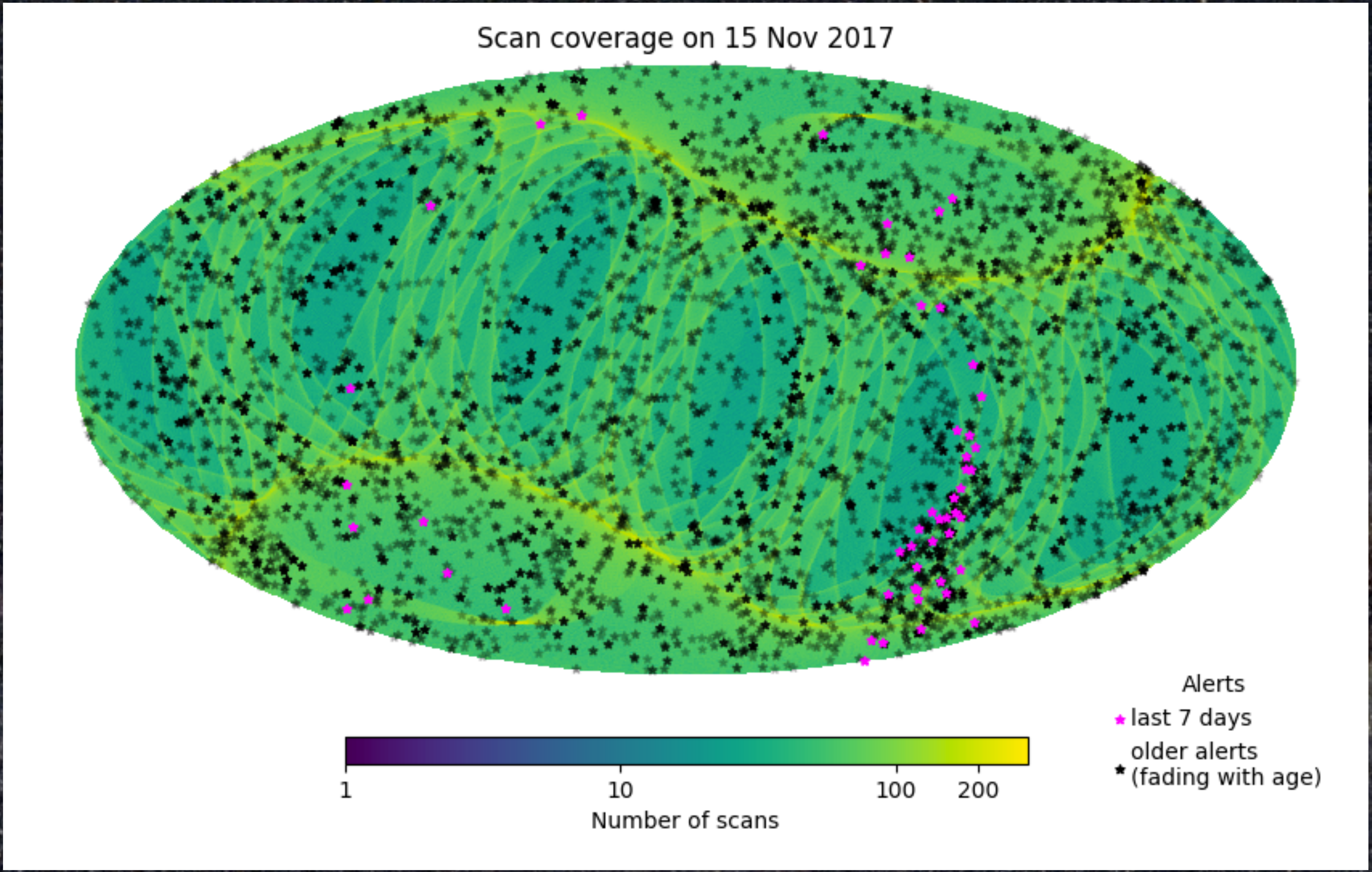
UV-bright (observed with Swift)

~20,000K emission

New class of AGN flares?
Re-ignition of an AGN?

(Trakhenbrot et al. incl. Wyrzykowski, Gromadzki, Hamanowicz, submitted)

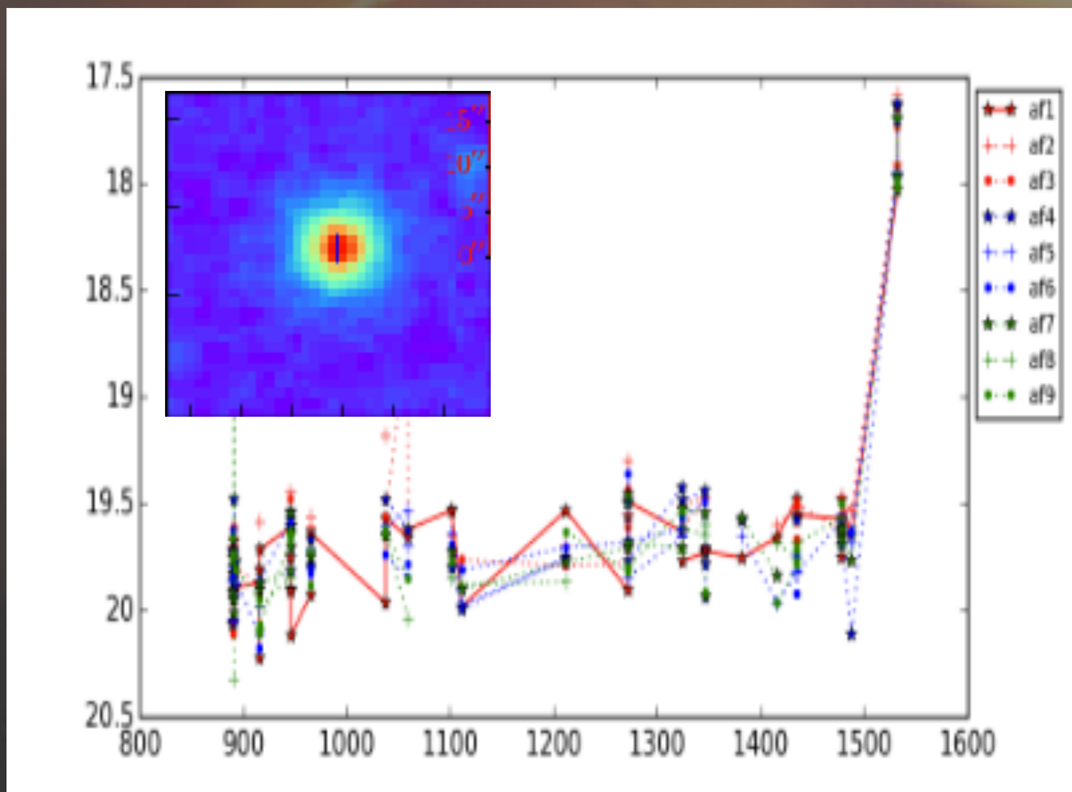
MAP OF GAIA ALERTS



http://gsaweb.ast.cam.ac.uk/alerts/maps/alerts-equatorial-coverage-map.png

Nuclear transients in Gaia

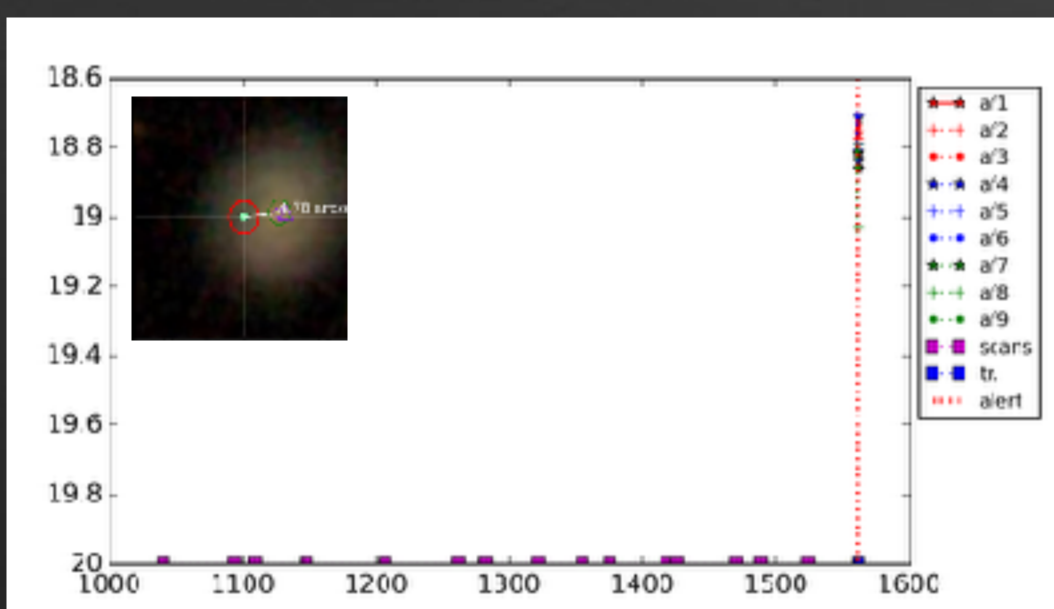
Gaia's adventages: astrometry and spectra

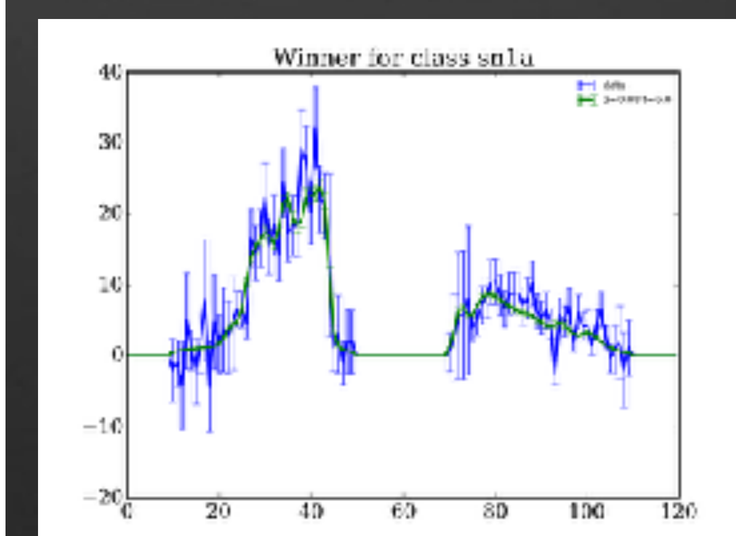


Currently the astrometric accuracy is about 0.1arcsec.

Sub-mas astrometry will help recognise genuine nuclear transients (in DR4/2022).

possible real-time astrometry for the alerts from 2019





single Gaia spectrum at <19mag can distinguish transient type (SN/TDE)

calibrated BPRP spectra soon to be available for alerts

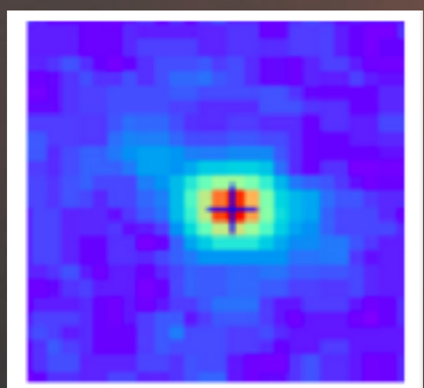
Blagorodnova+2015,2016

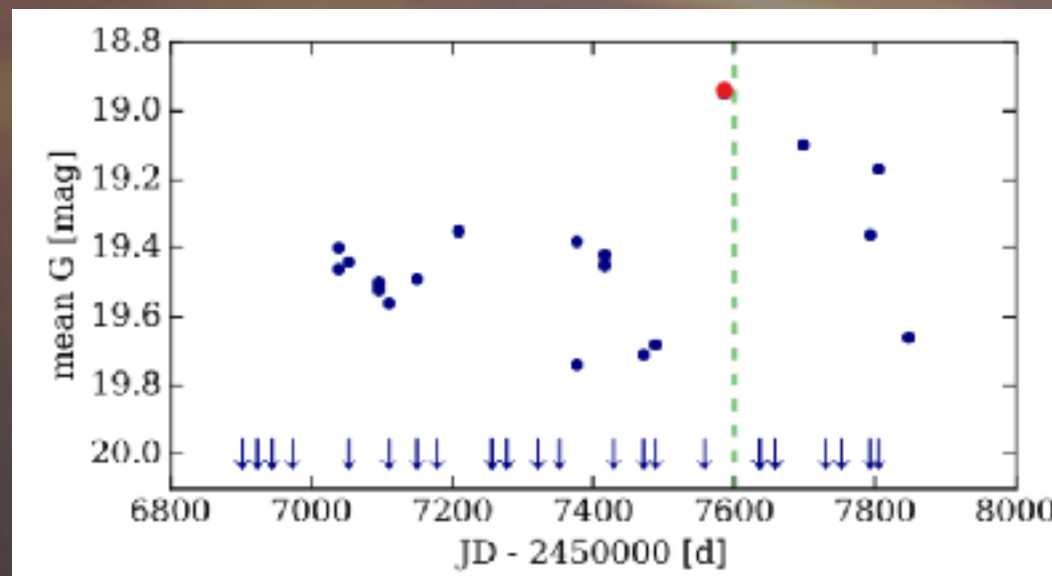
raw public Gaia data!

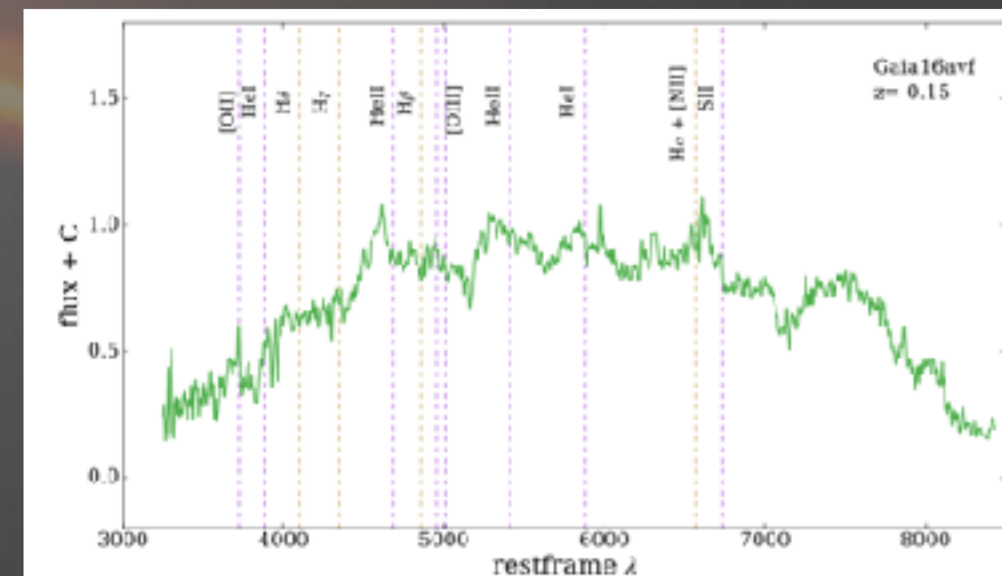
Nuclear transients in Gaia

examples

Gaia16avf

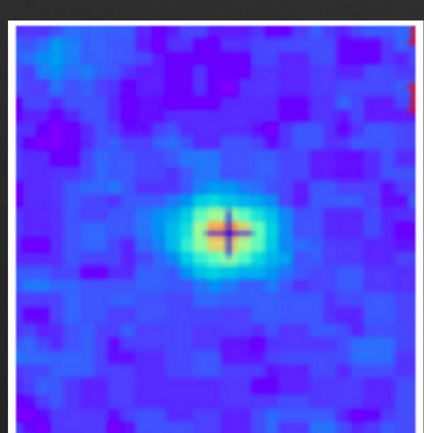


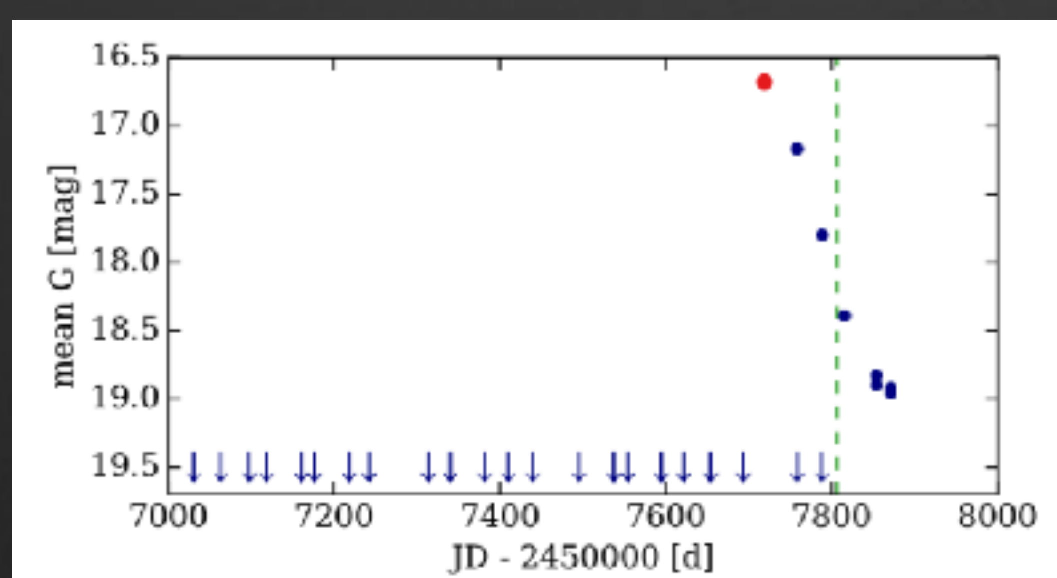


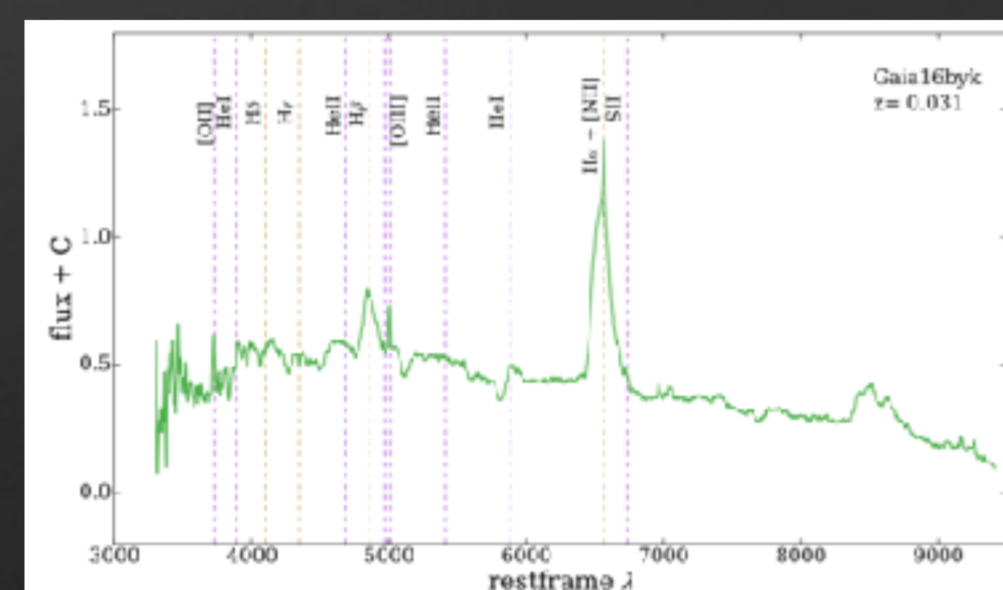


NOT follow-up (NUTS)

Gaia16byk



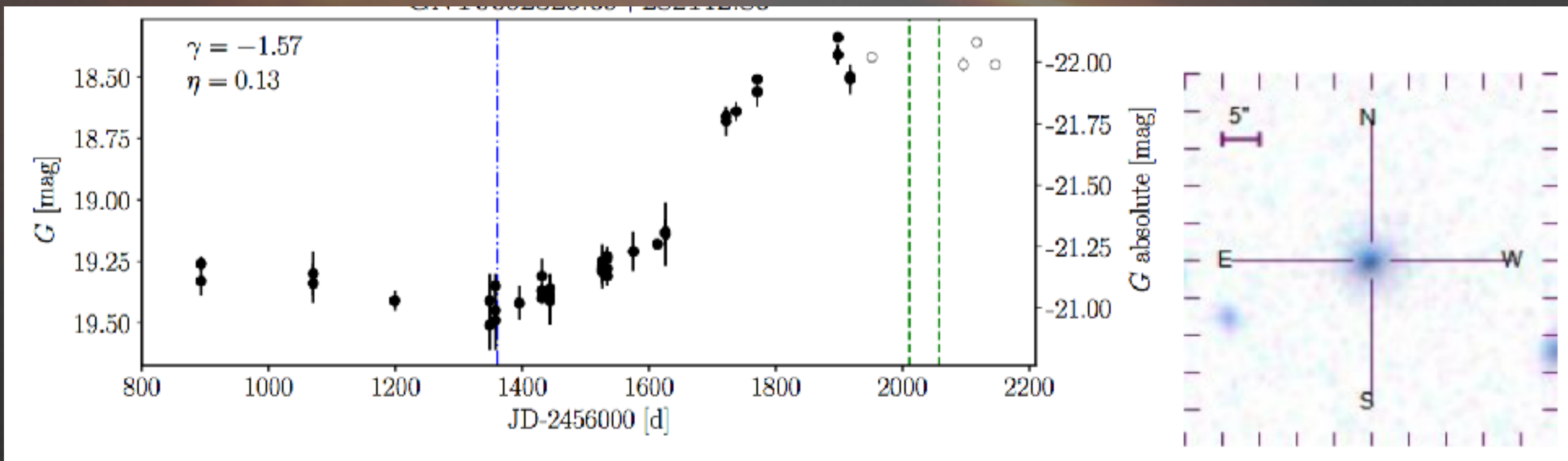




Nuclear transients in Gaia

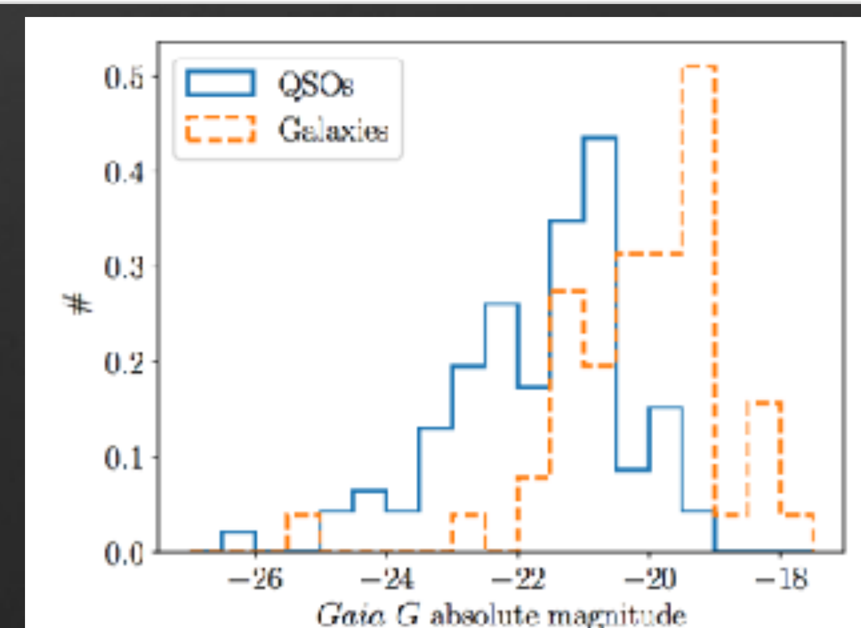
Current Alerts Pipeline not sensitive enough to nuclears!

Independent check in the Gaia light curves revealed hundreds of potential nuclear alerts.



Significant population of bright nuclear transients!

work in progress
to improve the alerting system
(Cambridge, Warsaw, Utrecht, Nova Gorica, Turku)

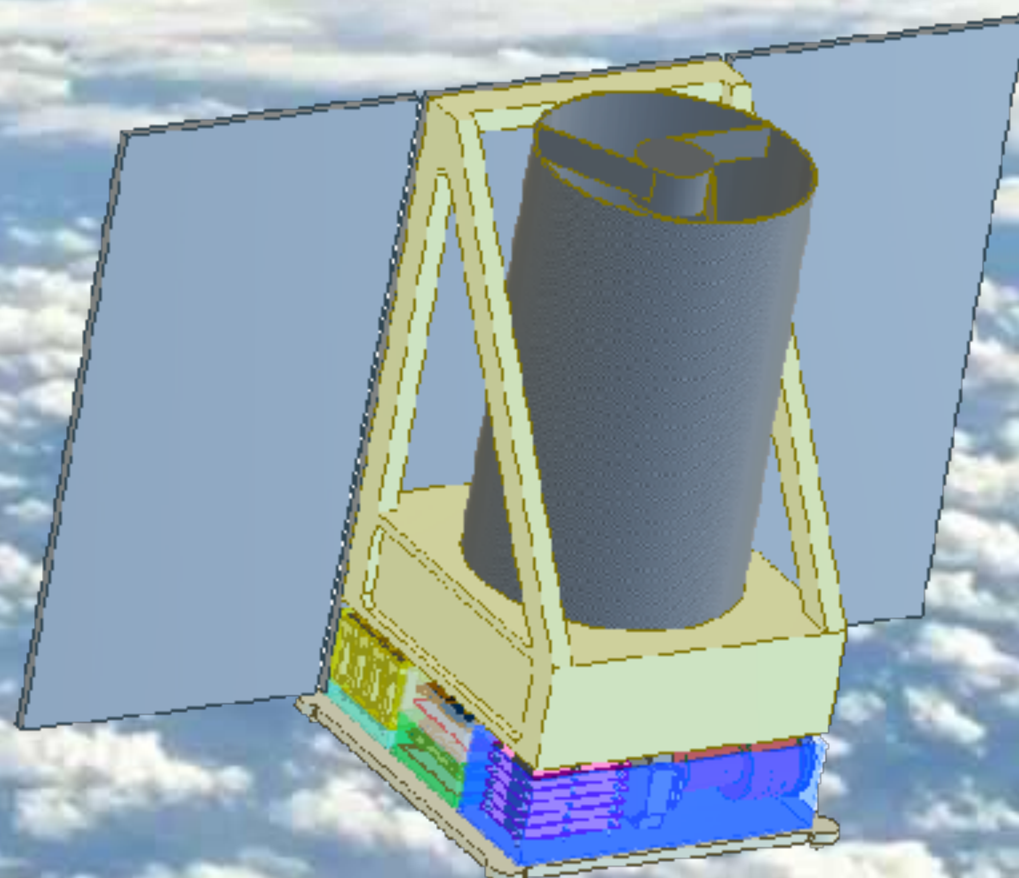


Kostrzewa-Rutkowska et al. submitted

Let’s go to space!

- UV survey for bright nuclear flares - probe IMBHs
- additional science:

  novae, kilonovae, supernovae, super-luminous supernovae
- Polish HyperSAT platform for small instruments (10-100kg of load)
- ASAS-SN - like telescopes, 30min cadence,100deg^2, to 19 mag
- tests: ground u-band survey + strato balloons



SUMMARY

- Microlensing can help discover low and high mass black holes, including the primordial ones

- remnant (dark lens) mass distribution -> no mass-gap?

- Gaia astrometry in 2022 (DR4) will yield accurate lens masses of currently on-going microlensing events

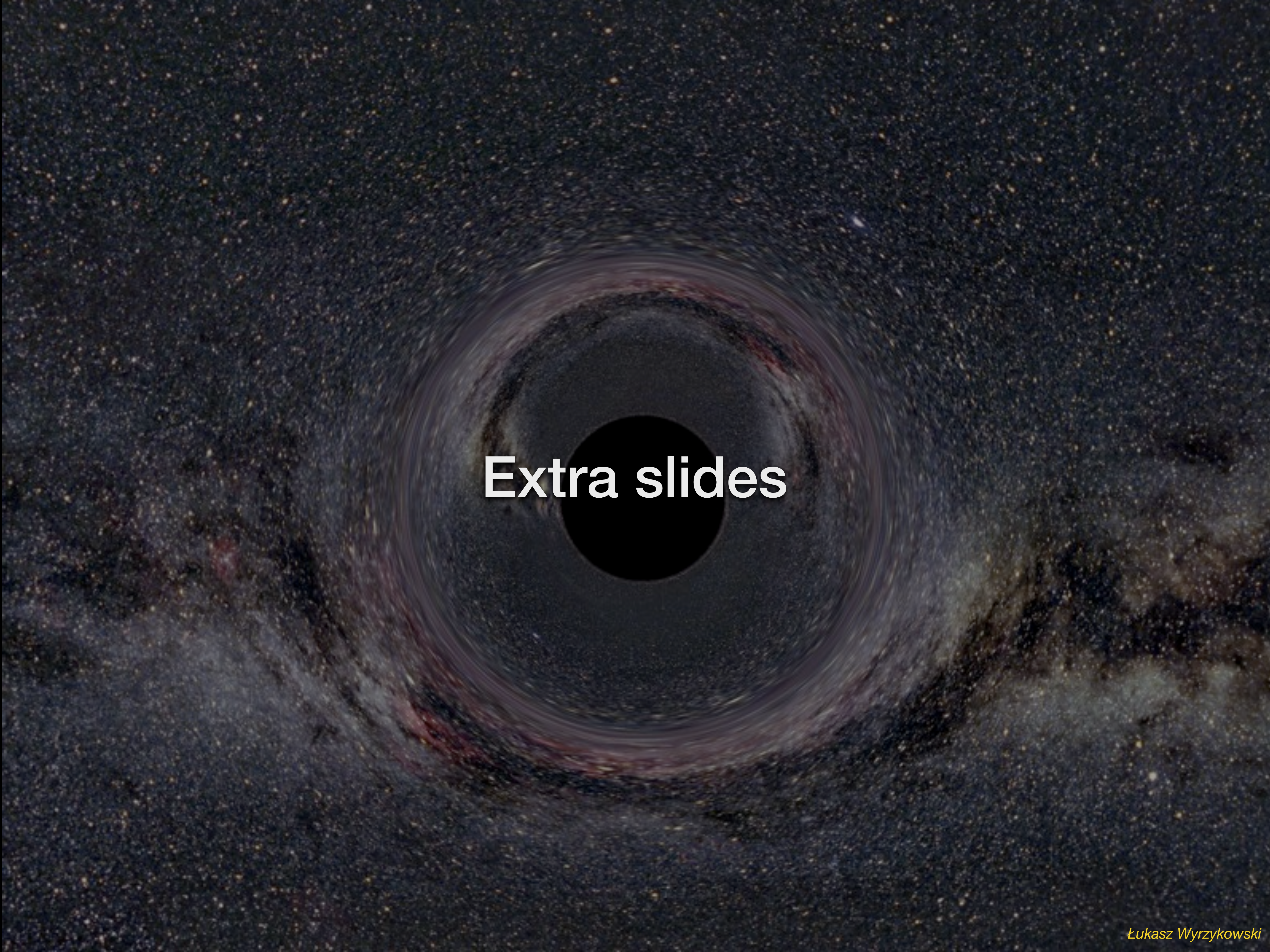
- IMBHs in other galaxies can be found with tidal disruption events

- Gaia Alerts will improve its sensitivity to nuclear transients over next years and will provide sub-mas astrometry and spectra!

- Short-lived UV flashes best observed from space (TDE on IMBH and kilonovae)

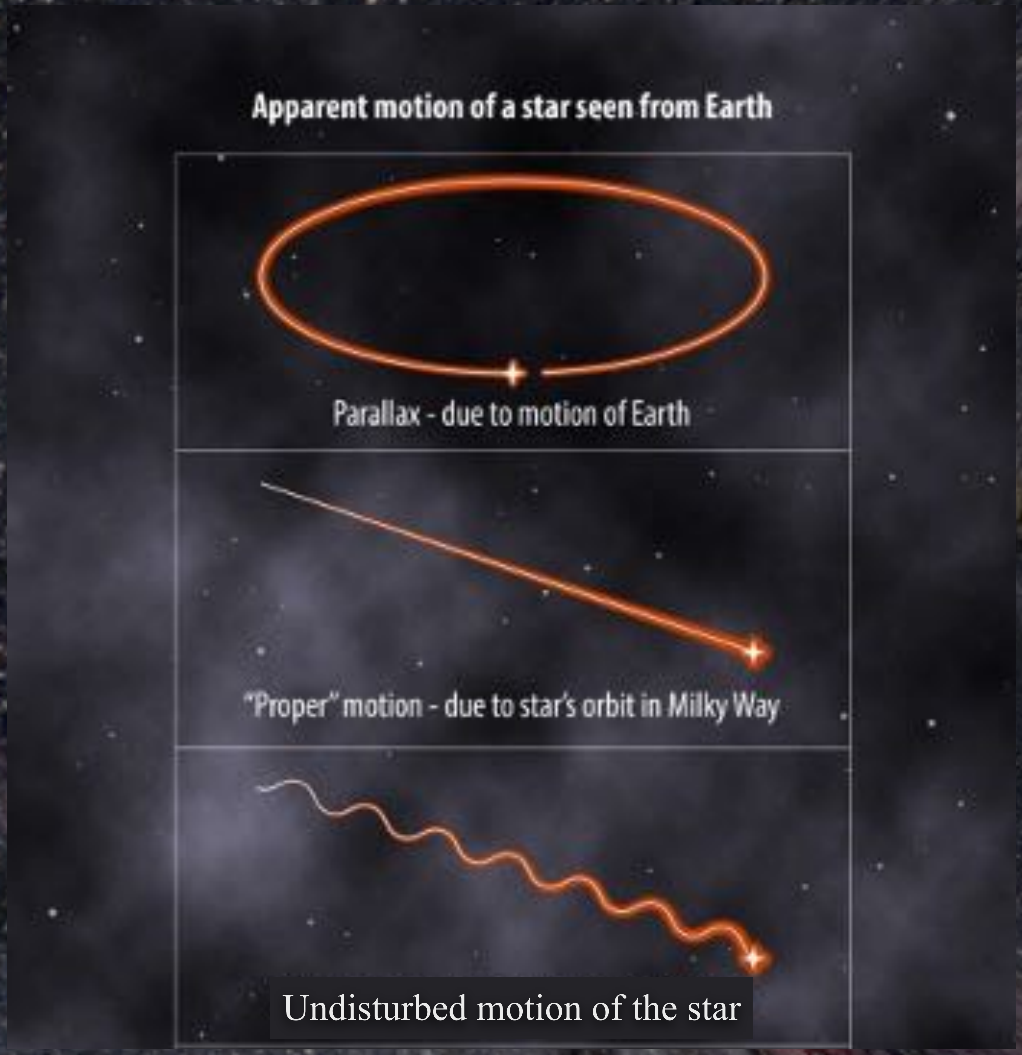
Łukasz Wyrzykowski

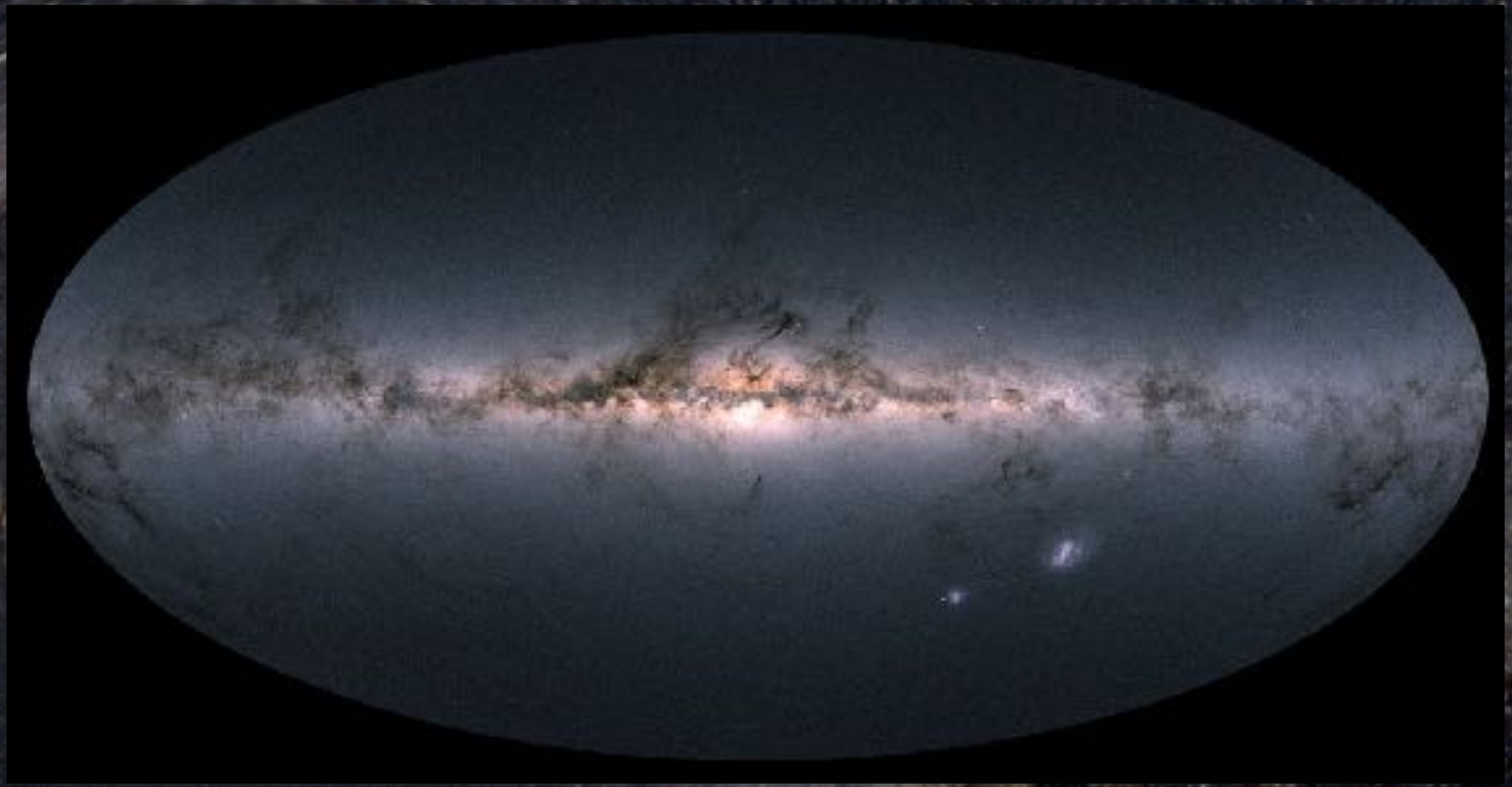
Extra slides



GAIA AND MICROLENSING

April 2018: 1.3 billion stars in the Milky Way have their parallaxes and proper motions measured based on 2014-2016 observations by Gaia.





Gaia+2018

Łukasz Wyrzykowski

GAIA AND MICROLENSING

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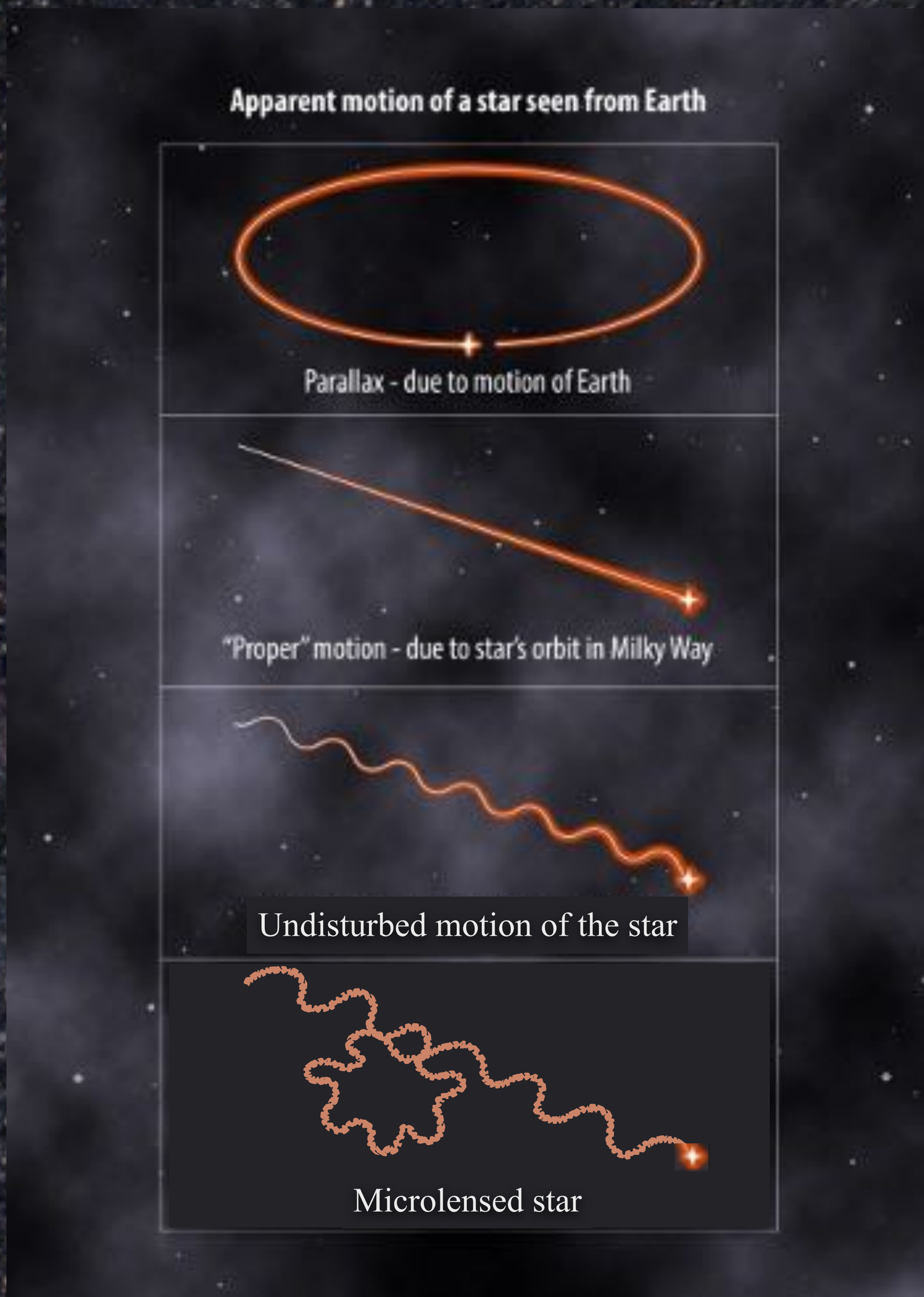
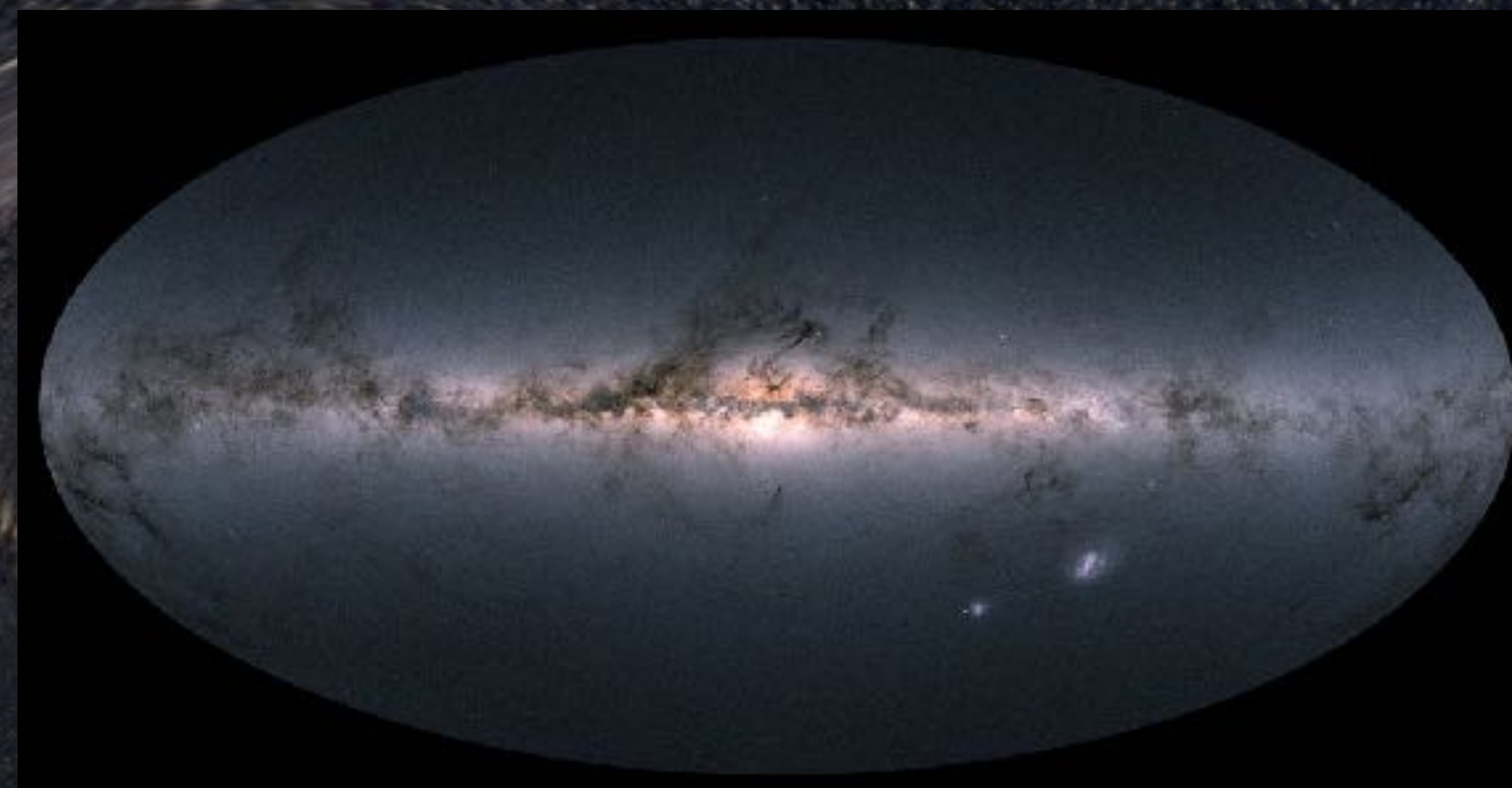


Gaia+2018



Microlensed images separated by ~mas are not resolvable by Gaia.

But the motion of their centroid can be detected!

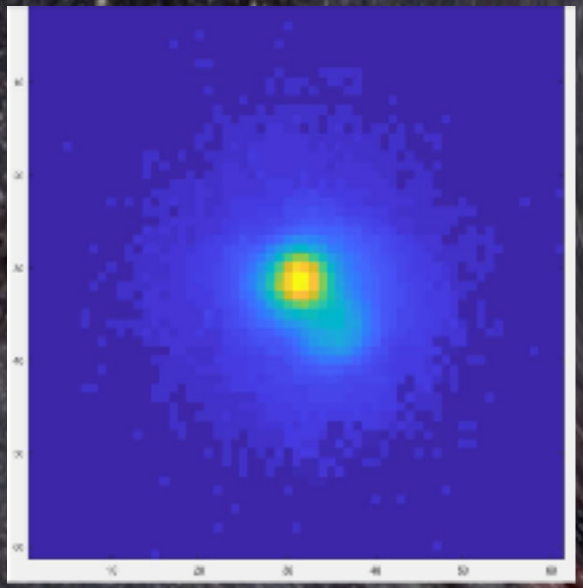
Size of the loop ~ Einstein Radius

HOW TO CONFIRM A BH LENS?

- high resolution imaging after 15 years
- if non-BH the star should appear next to the source
- separation about 50 mas
- brightness estimated from blending

simulated luminous lens

(Credit: Alek Kurek)



VLT/NACO image of PAR-02

Kurek, Wyrzykowski in prep.

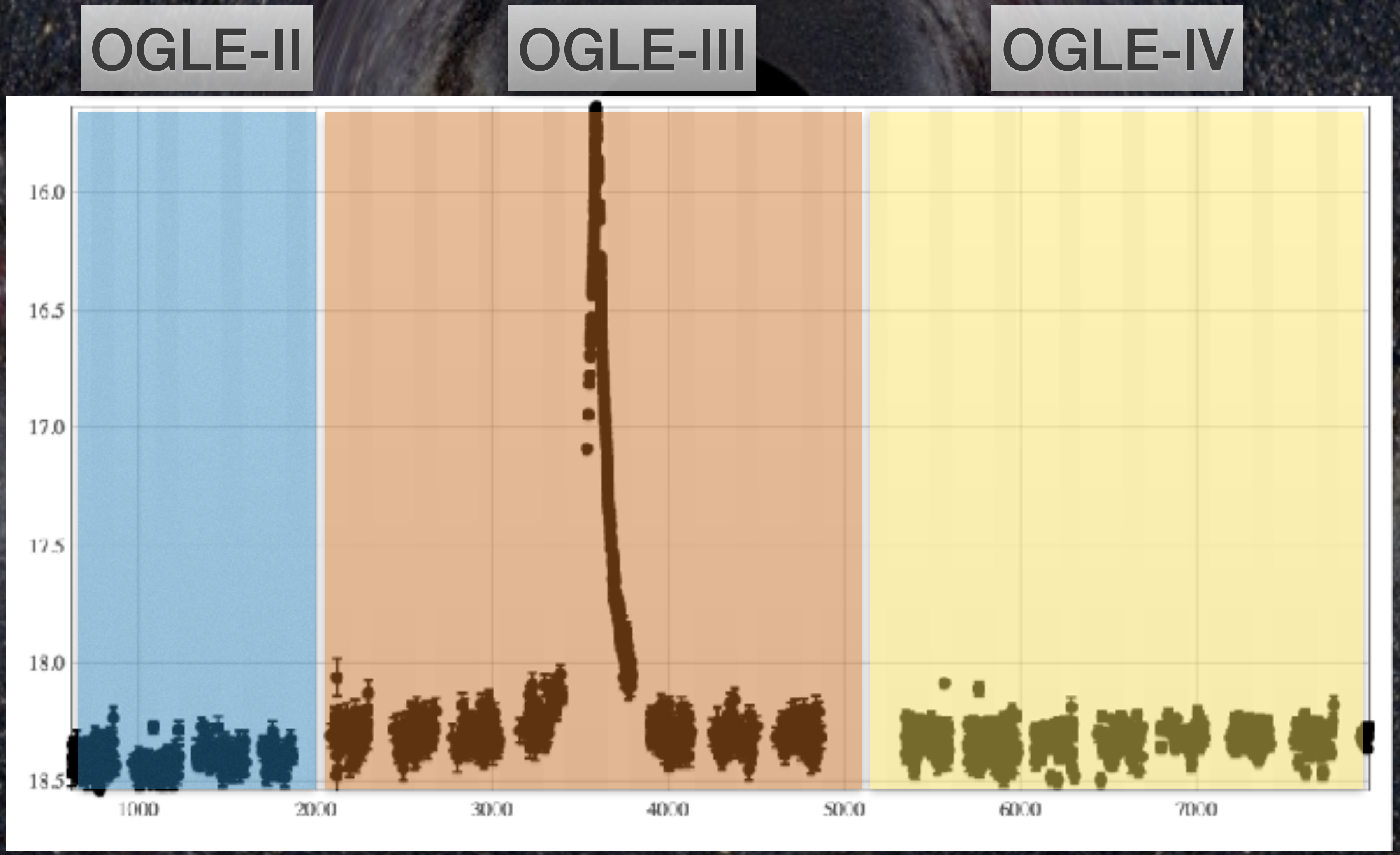
no obvious luminous lens seen!

FUTURE WORK

OGLEII + OGLEIII + OGLEIV = 20 years-long light curves

search for events with M_{BH} ~100 MSun (GW-like)

t_E > 4 years



1997 OGLE-2005-SMC-001 2017

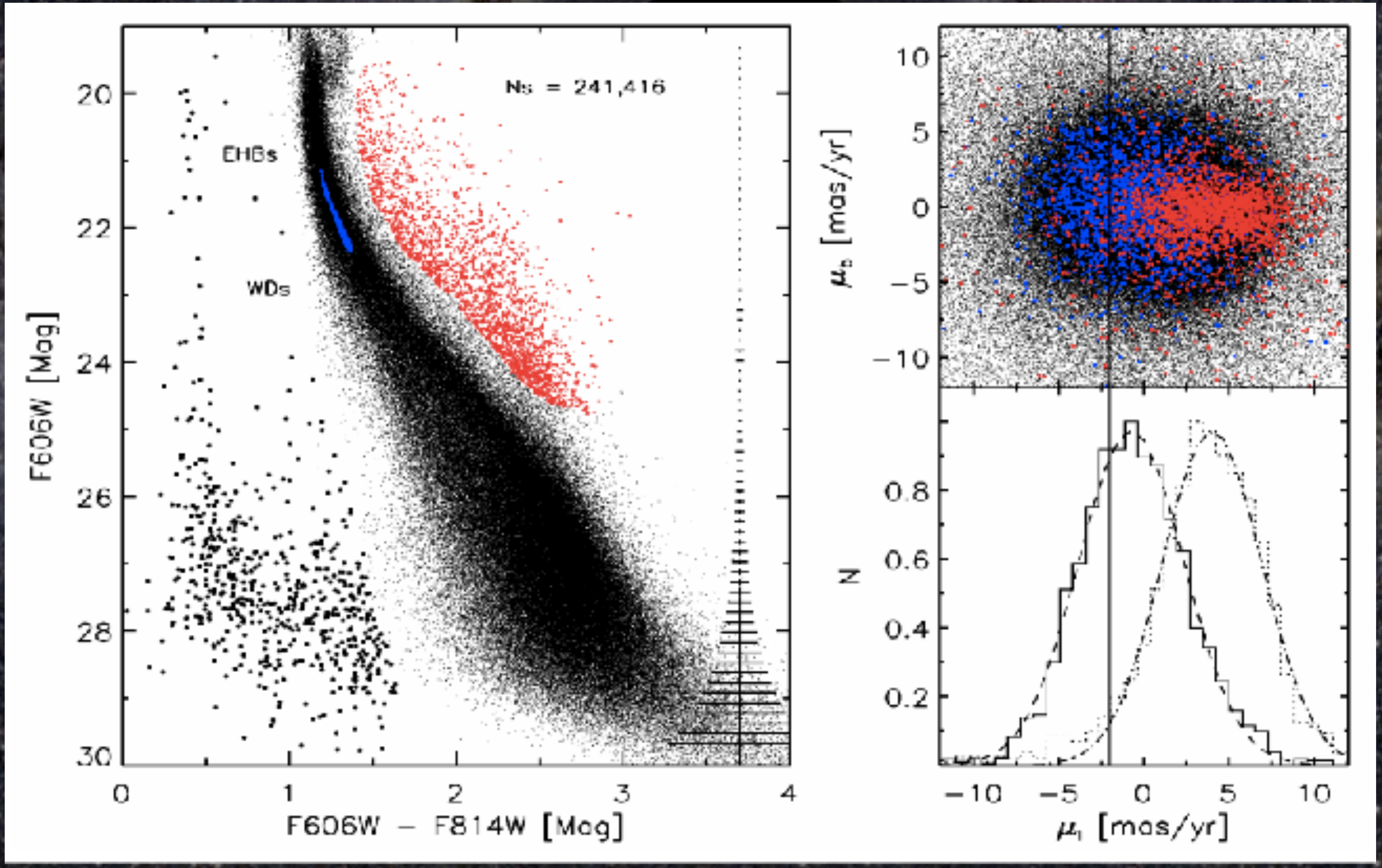
Łukasz Wyrzykowski

GUESSING THE MASS

Assume:

- know source distance (selected Red Clump sources)
- source moves randomly as all Bulge stars
- stellar remnants in the Galactic Disk move as all the stars

$$M = \frac{\theta_E}{\kappa \pi_E} = \frac{\mu_{rel} t_E}{\kappa \pi_E}$$



Calamida+2014

Łukasz Wyrzykowski

GUESSING THE MASS

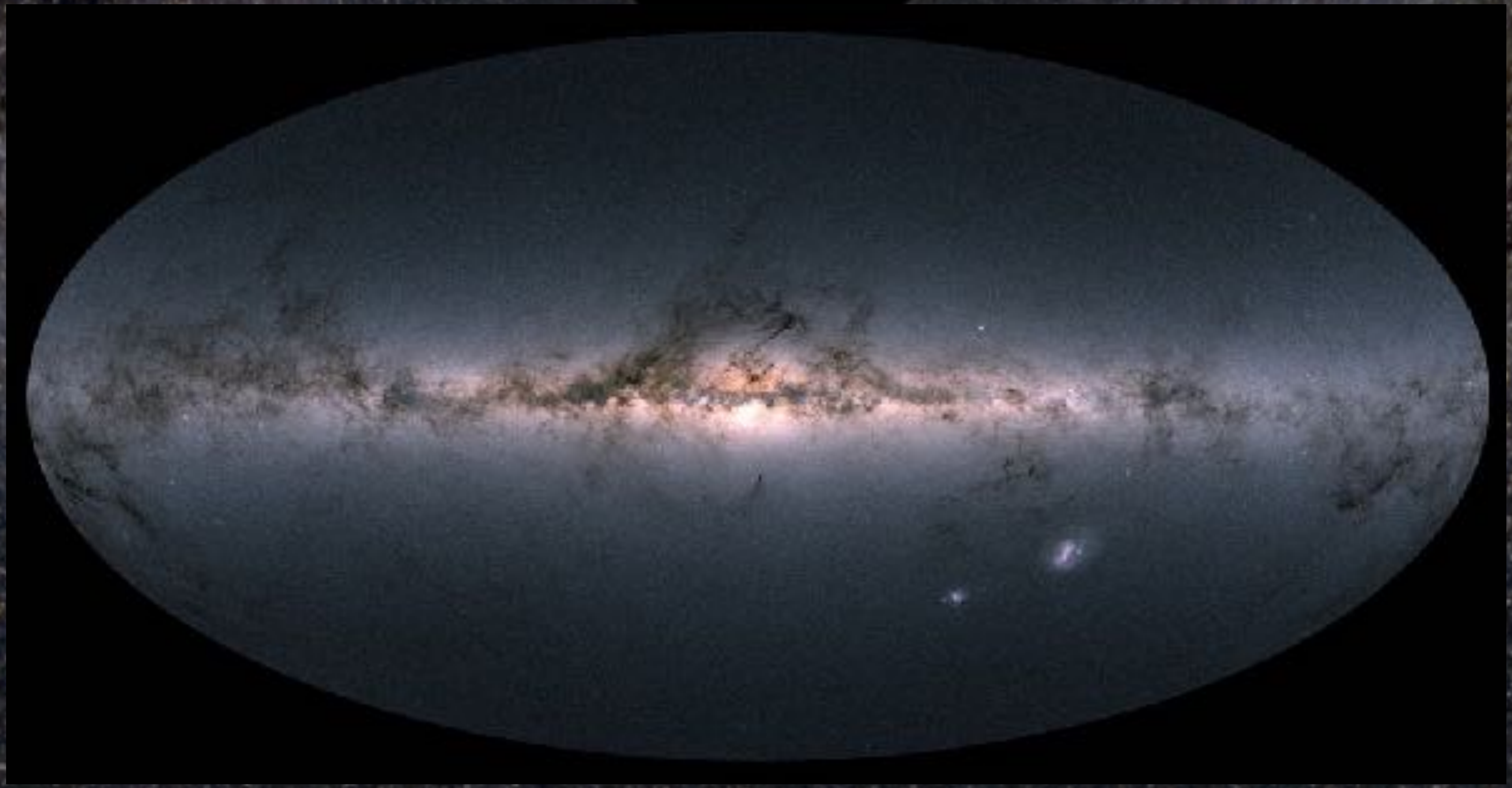
Assume:

- know source distance ~~(selected Red Clump sources)~~
- ~~source moves randomly as all Bulge stars~~
- stellar remnants in the Galactic Disk move as all the stars

$$M = \frac{\theta_E}{\kappa \pi_E} = \frac{\mu_{rel} t_E}{\kappa \pi_E} = \frac{(\mu_L - \mu_S) t_E}{\kappa \pi_E}$$

* direction of mu_L is known from the parallax vector

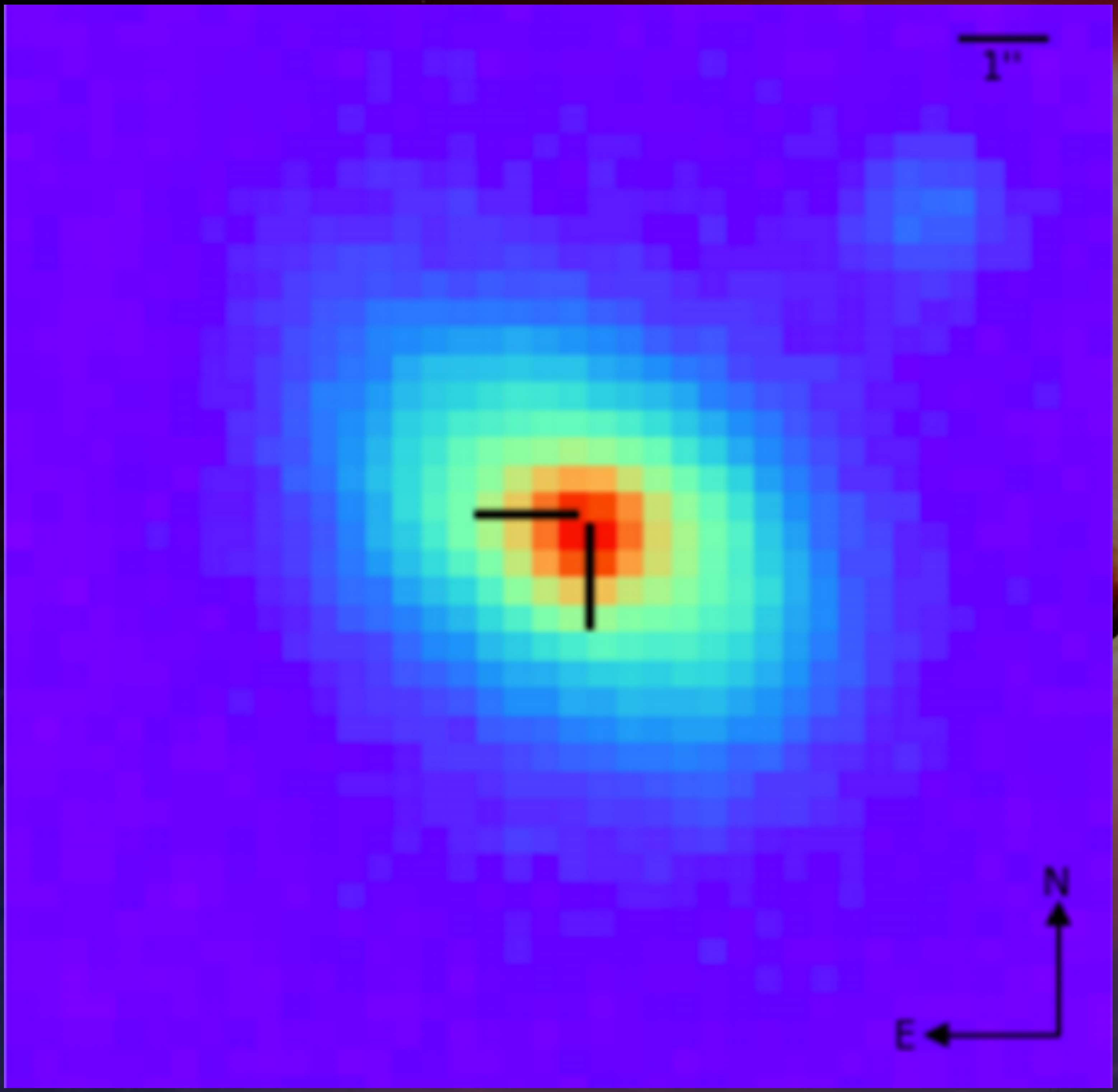
Gaia DR2 from April 2018 provided distances and PM for 1.3 billion stars!



Gaia+2018

Łukasz Wyrzykowski

OGLE17aaj



OGLE17aaj

RA= 01:56:24.92
DEC=-71:04:15.9

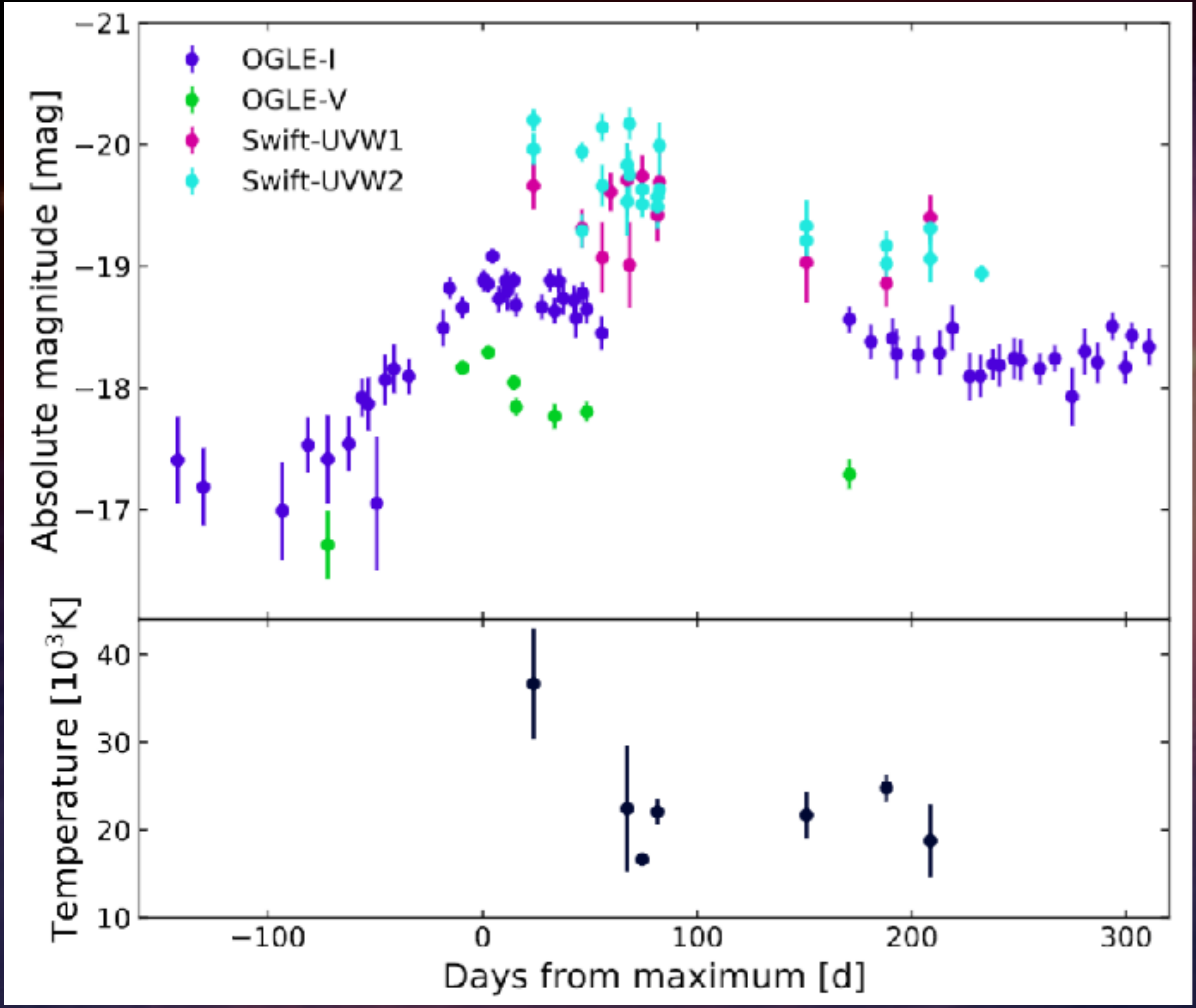
z=0.116

M(I)=-18.8

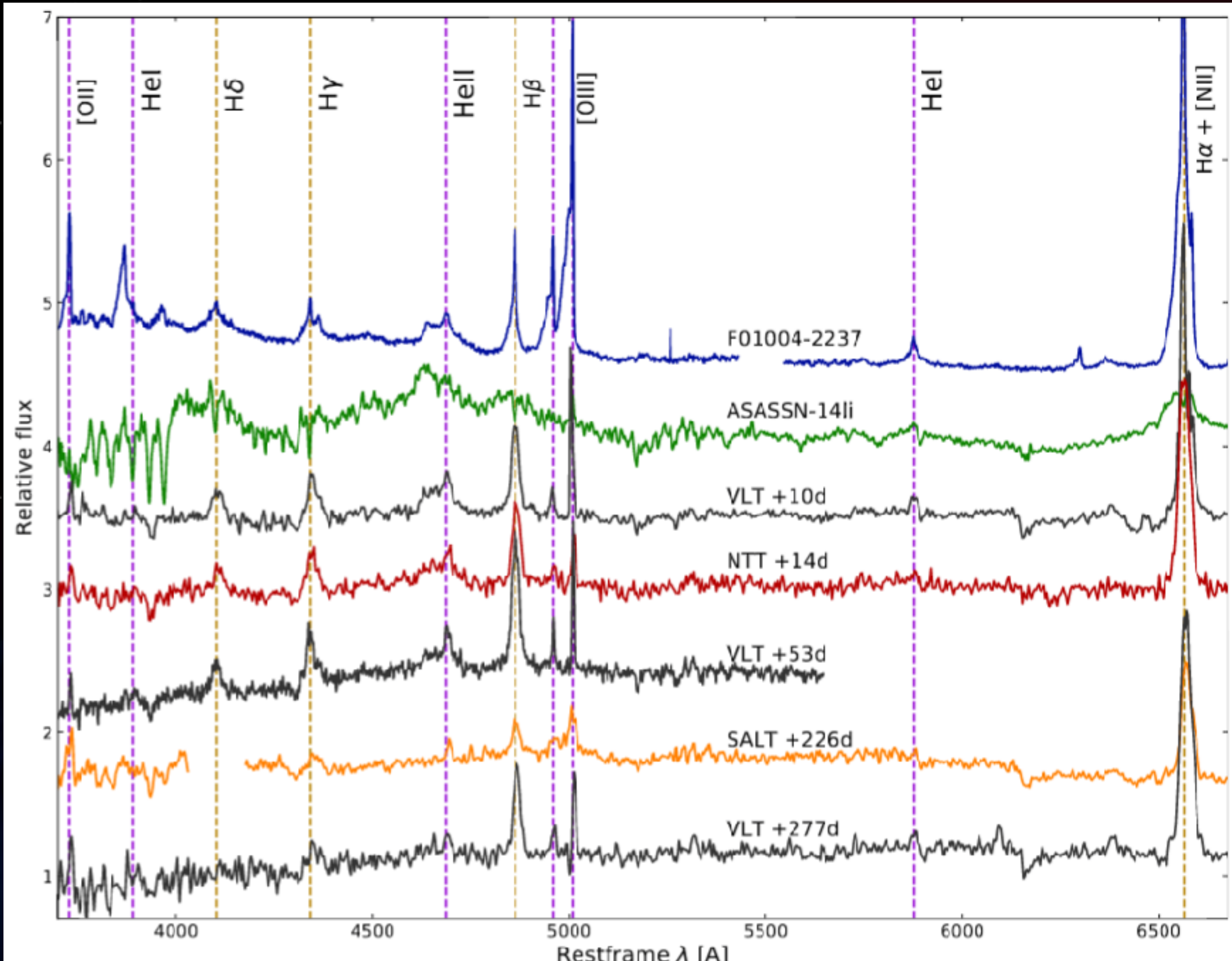
Slow rise ~60d

TDE?

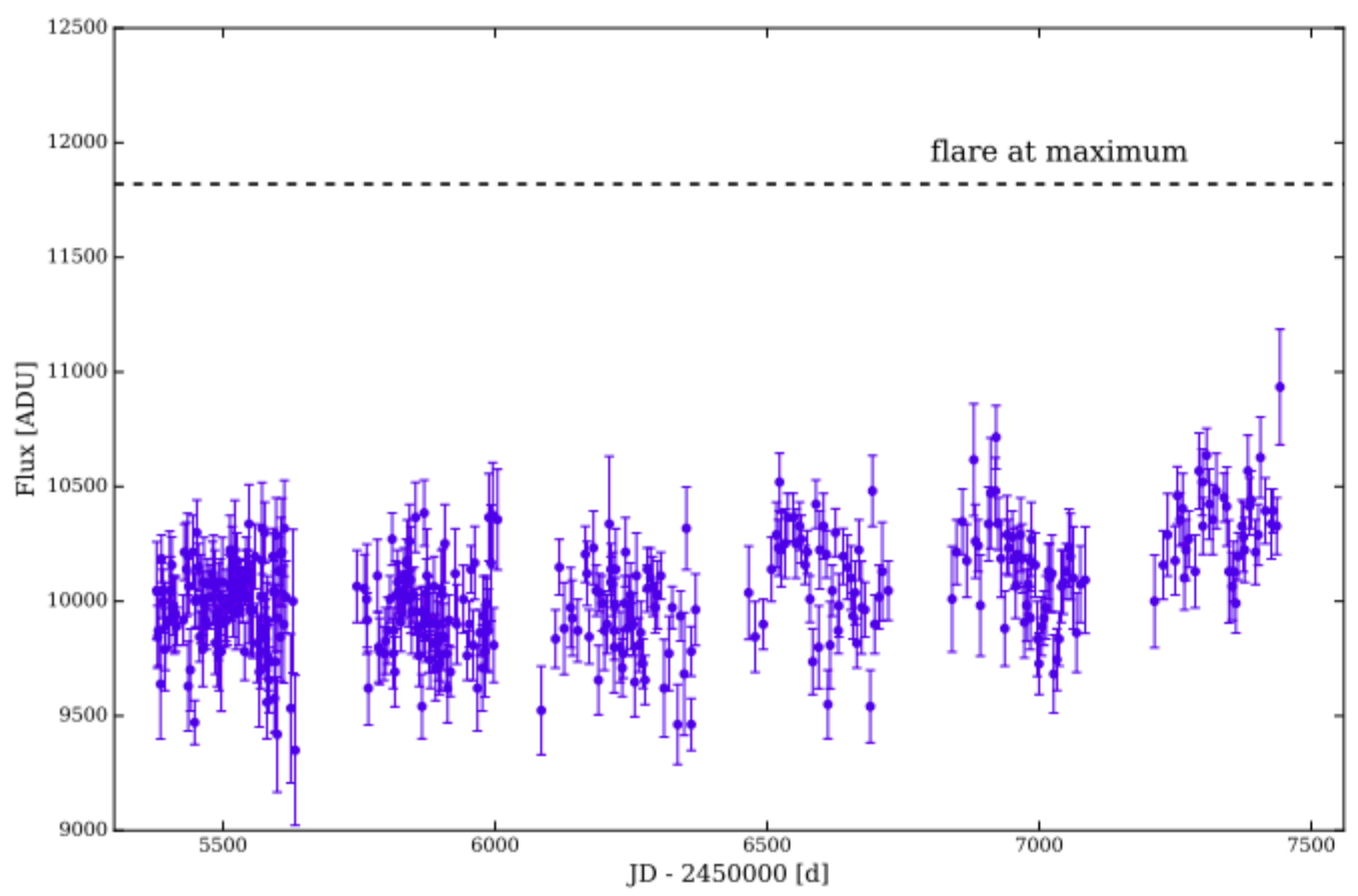
Similar to F01004-2237
URLIG TDE
(Tadhunter et al. 2017)



OGLE17aaj - spectral evolution

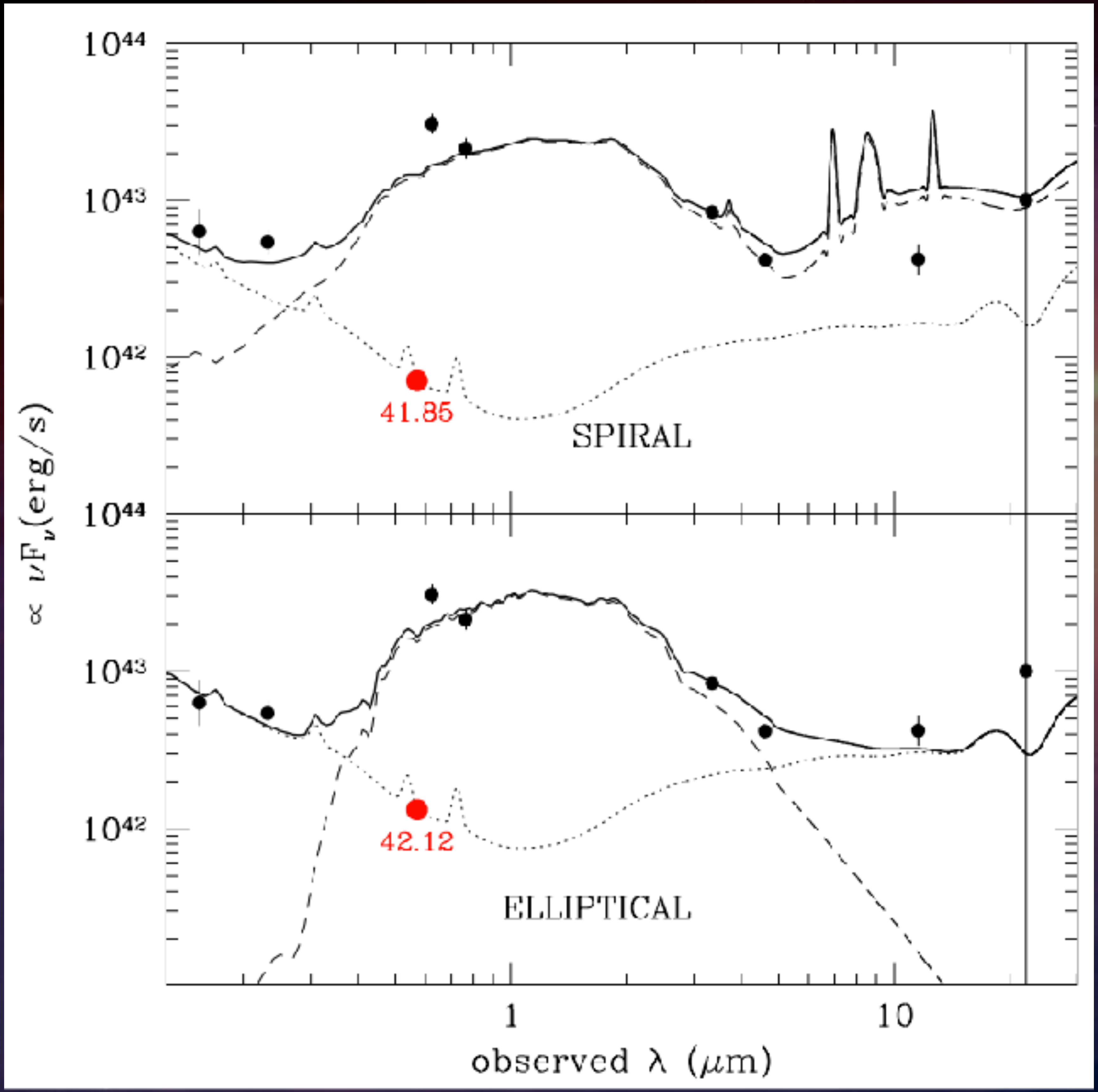


OGLE17aaj - host- pre-outburst variability

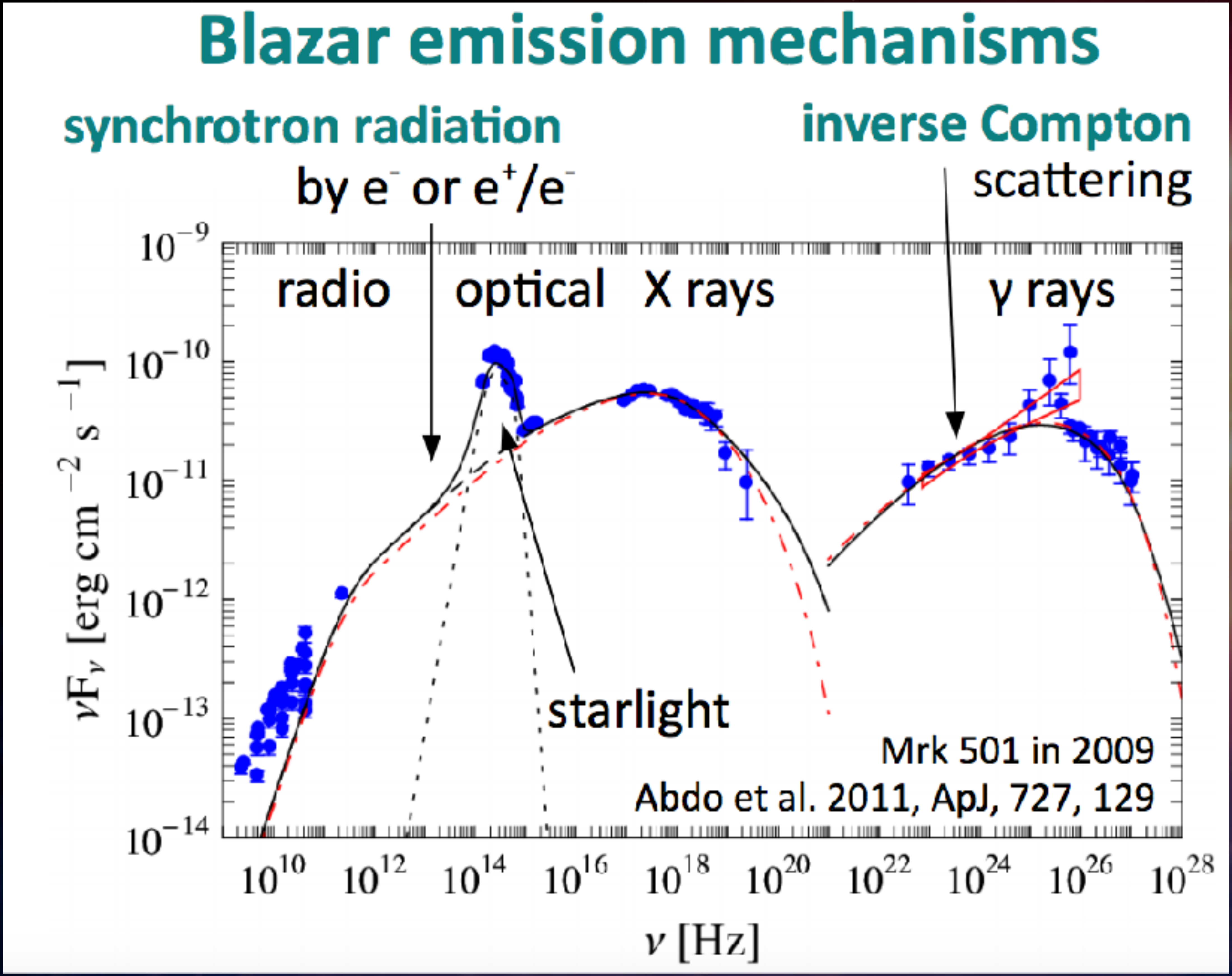


OGLE17aaj - host - black hole mass

FWHM(Hb)=1500 km/s
M(BH)=~10^6 Msun

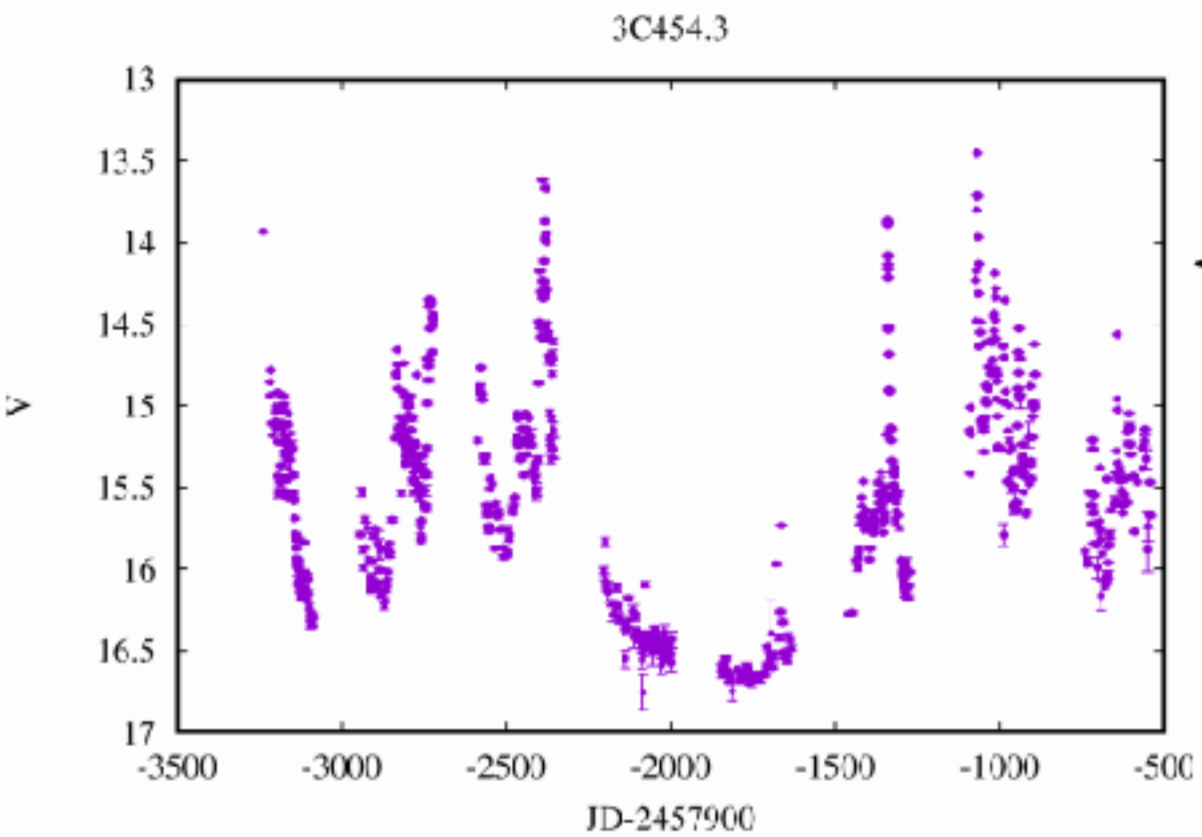


ASAS-SN17gs


Blazar emission mechanisms
synchrotron radiation
by e⁻ or e⁺/e⁻
inverse Compton
scattering
radio
optical
X rays
γ rays
starlight
Mrk 501 in 2009
Abdo et al. 2011, ApJ, 727, 129
νF_ν [erg cm^{-2} s^{-1}]
ν [Hz]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22} 10^{24} 10^{26} 10^{28}

ASAS-SN17gs

Example blazar lightcurves

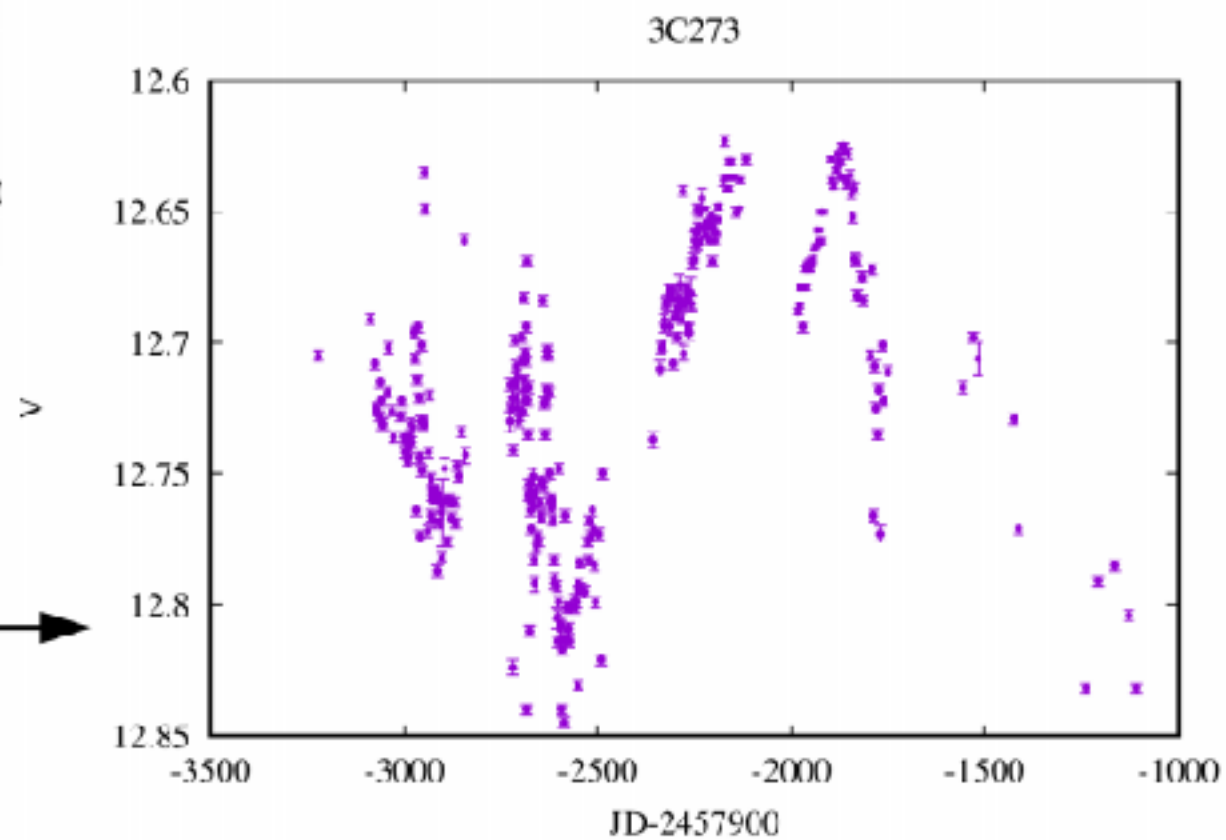


Jet dominates optical light

Flares

Jet contribution comparable to other AGN components

Slow irregular variations



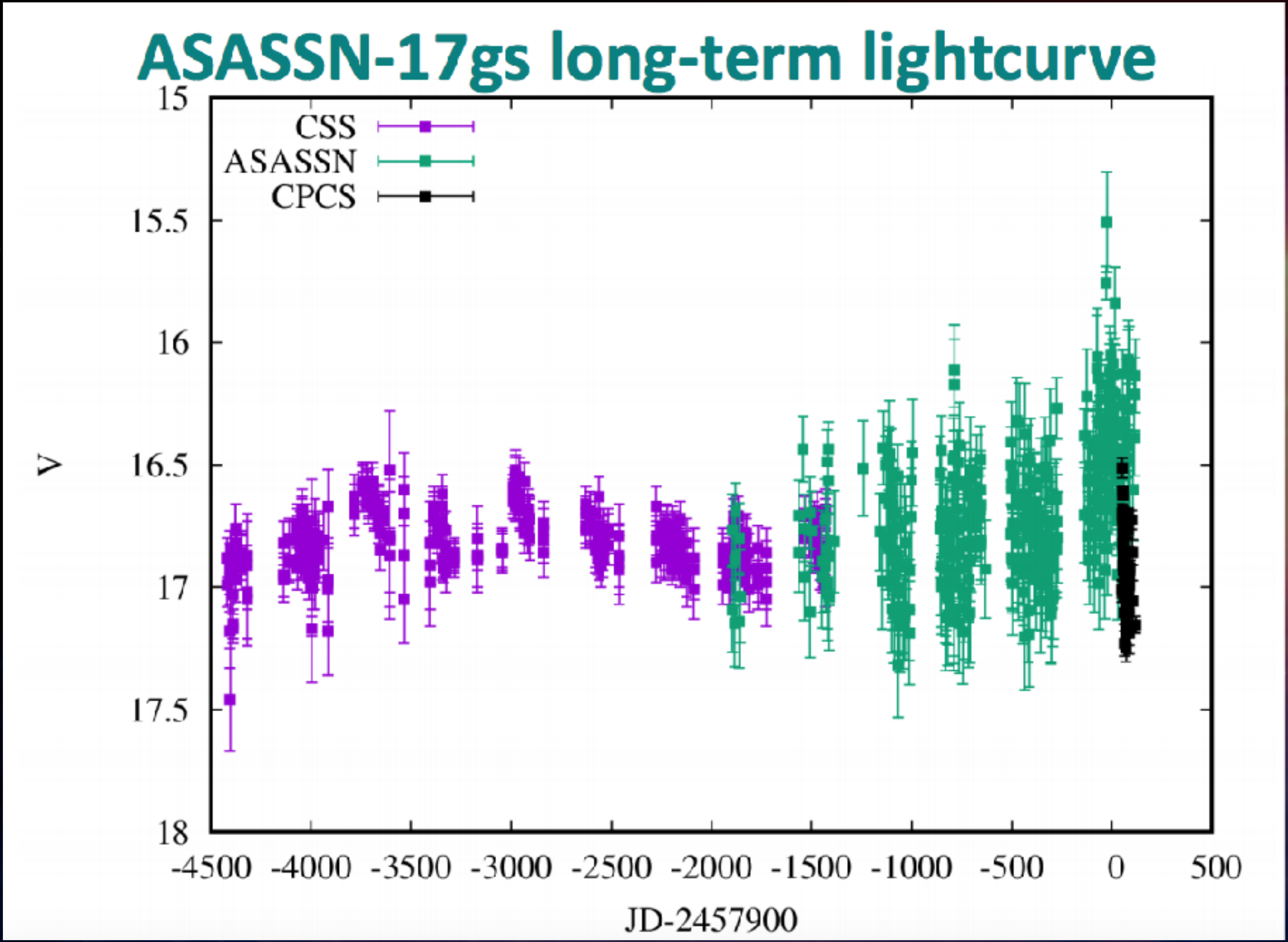
SMARTS monitoring data by Bonning et al. 2012, ApJ, 756, 13

ASAS-SN17gs

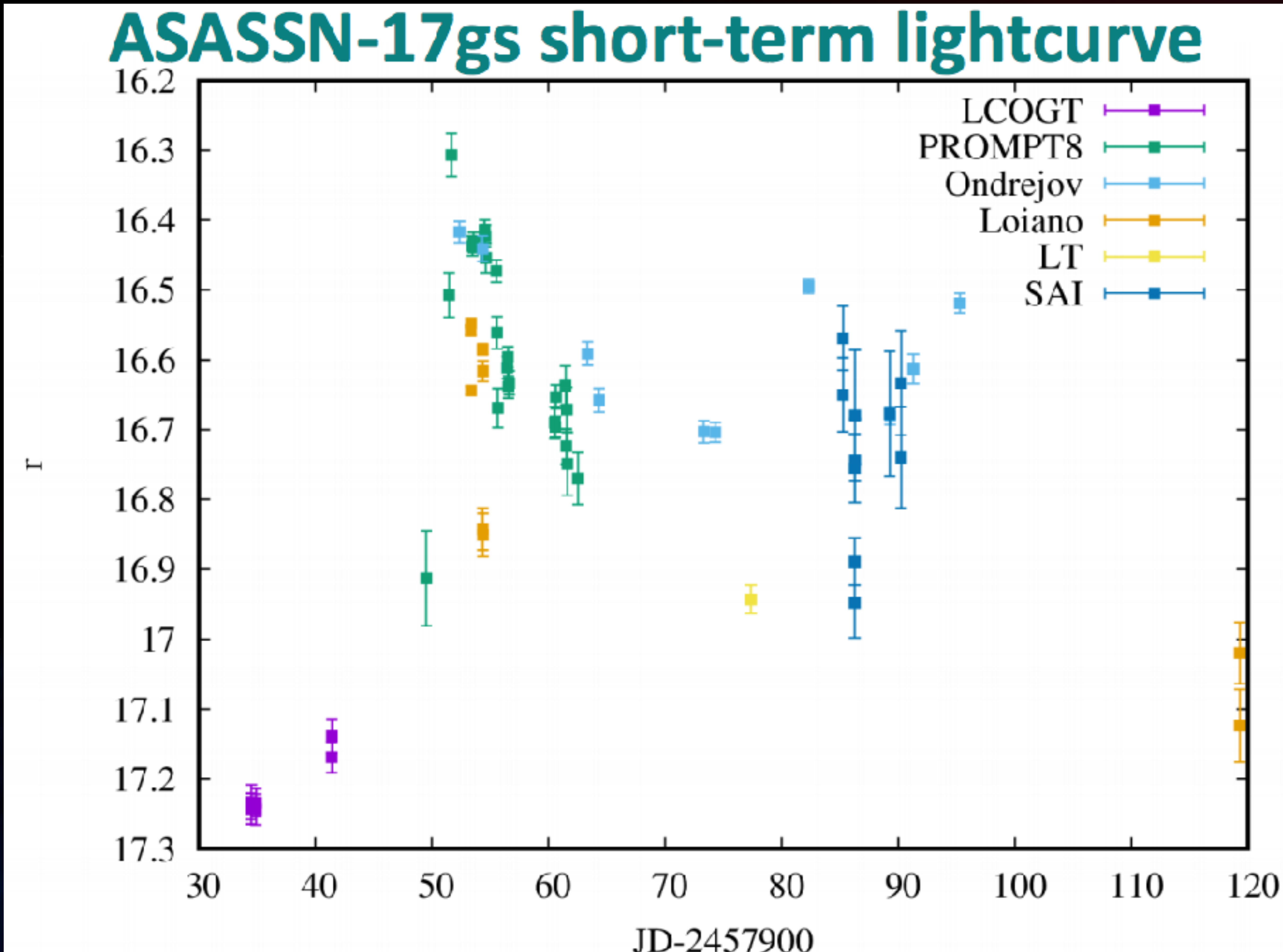
ASASSN-17gs = 2017egv

- Discovered on 2017-05-25 near the center of galaxy 2MASX J15441967-0649156
- Coincides with a **GeV transient** observed by Fermi/LAT (ATel #10482)
- **X-ray transient** by MAXI (ATel #10495) and Swift/XRT
- MDM 2.4m Hiltner telescope on 2017-06-14 measured host **z=0.171** (ATel #10491)
- **No** previous **X-ray** detection
- **Historical radio detection** (NVSS) 47 mJy at 1.4 GHz

ASAS-SN17gs

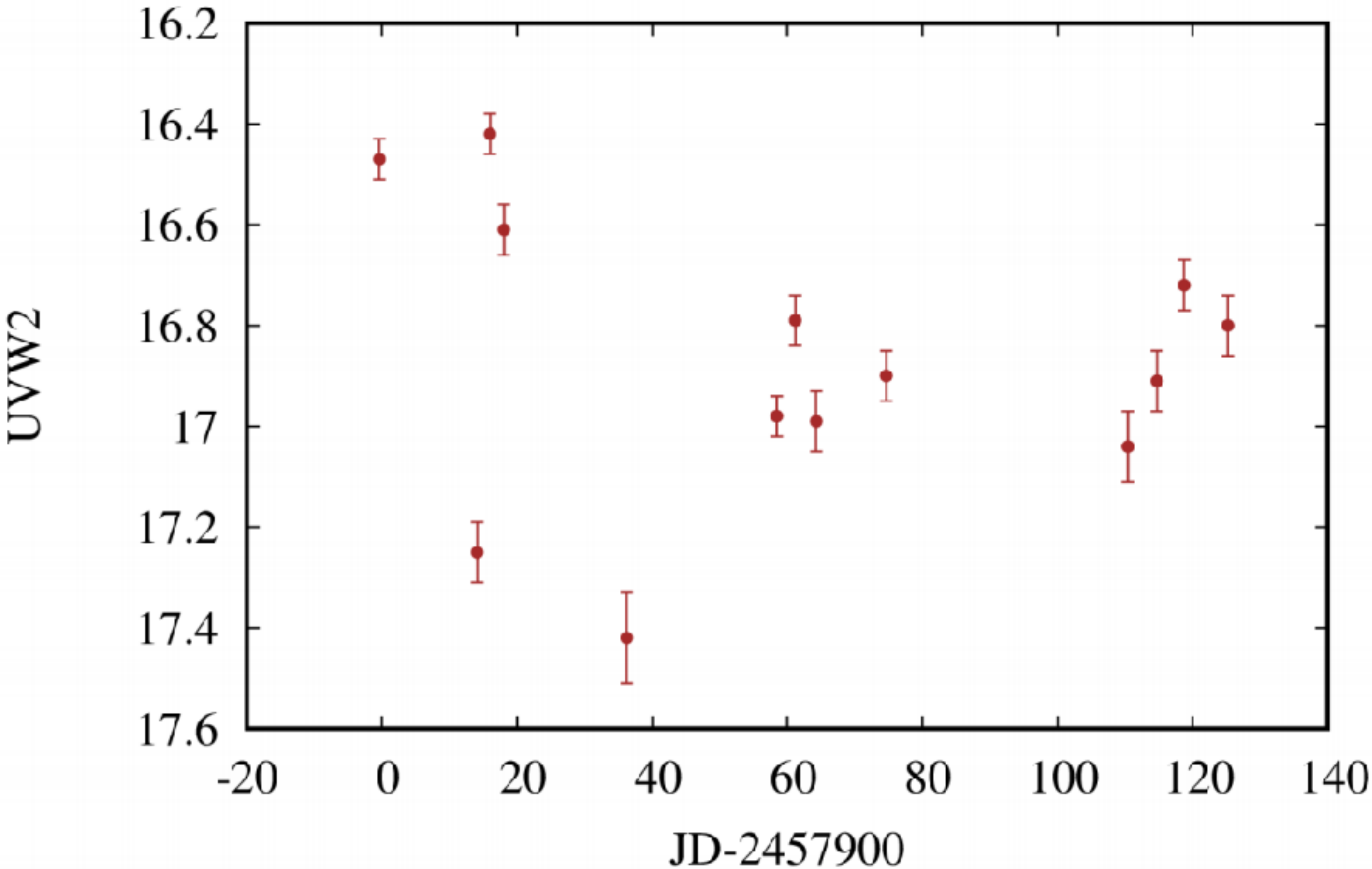

ASASSN-17gs long-term lightcurve
CSS
ASASSN
CPCS
V
15
15.5
16
16.5
17
17.5
18
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
500
JD-2457900

ASAS-SN17gs


ASASSN-17gs short-term lightcurve
LCOGT
PROMPT8
Ondrejov
Loiano
LT
SAI
I
16.2
16.3
16.4
16.5
16.6
16.7
16.8
16.9
17
17.1
17.2
17.3
30
40
50
60
70
80
90
100
110
120
JD-2457900

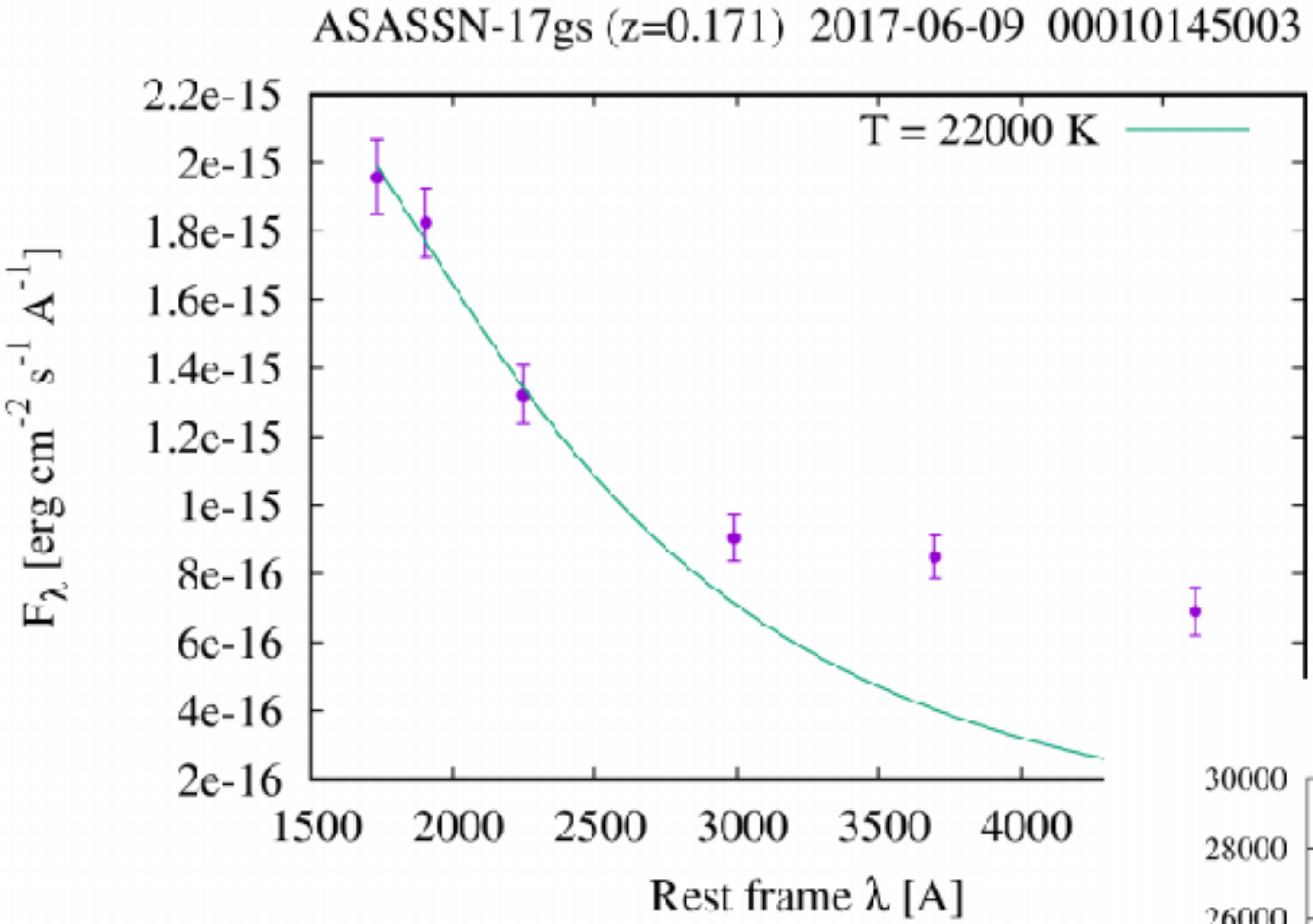
ASAS-SN17gs

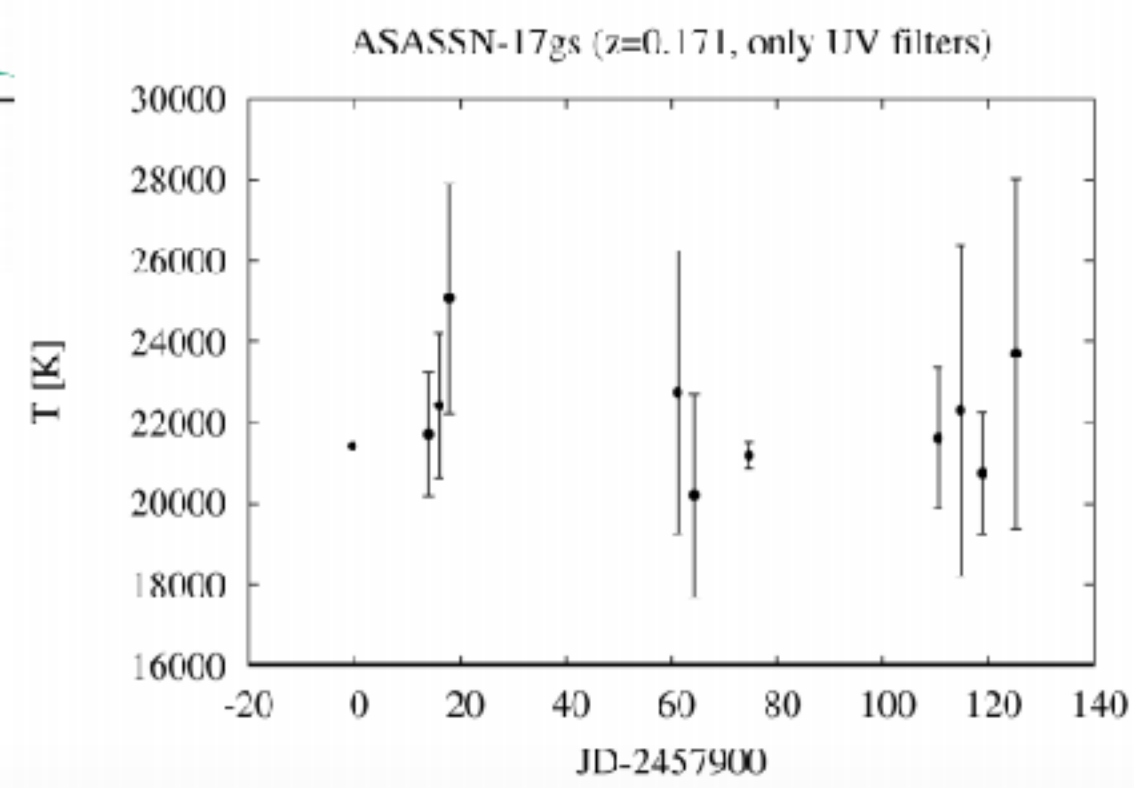
Short-term UV lightcurve from Swift



ASAS-SN17gs

UV color temperature



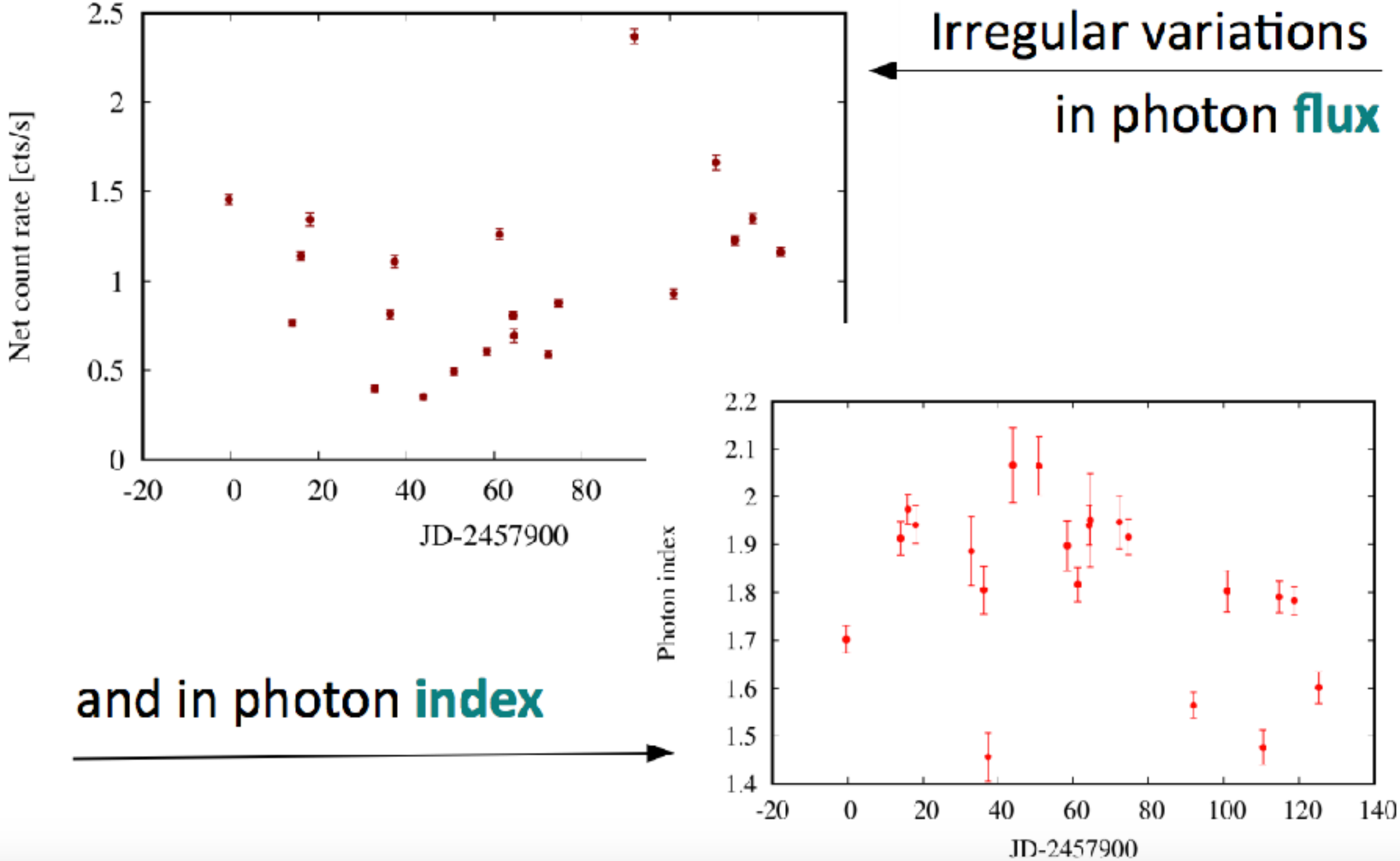


ASAS-SN17gs

Swift/XRT lightcurve

Irregular variations in photon **flux**

and in photon **index**

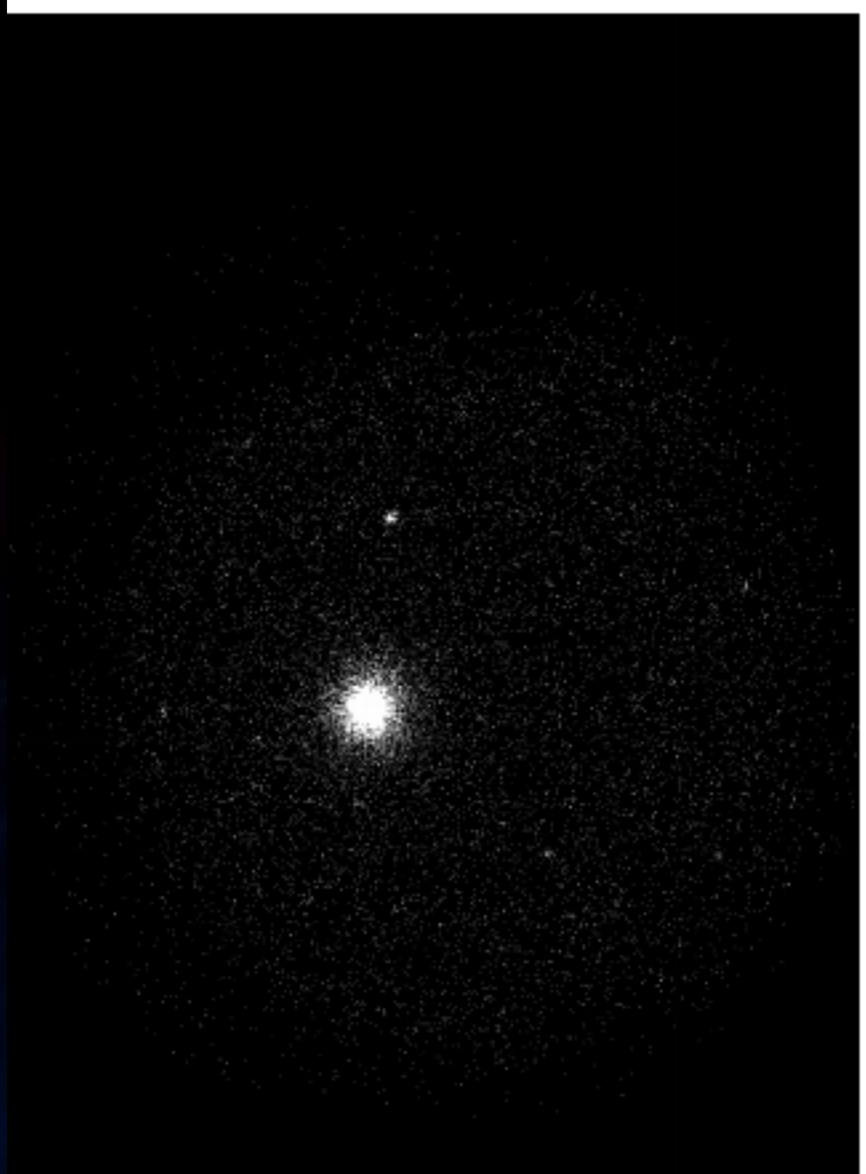


ASAS-SN17gs

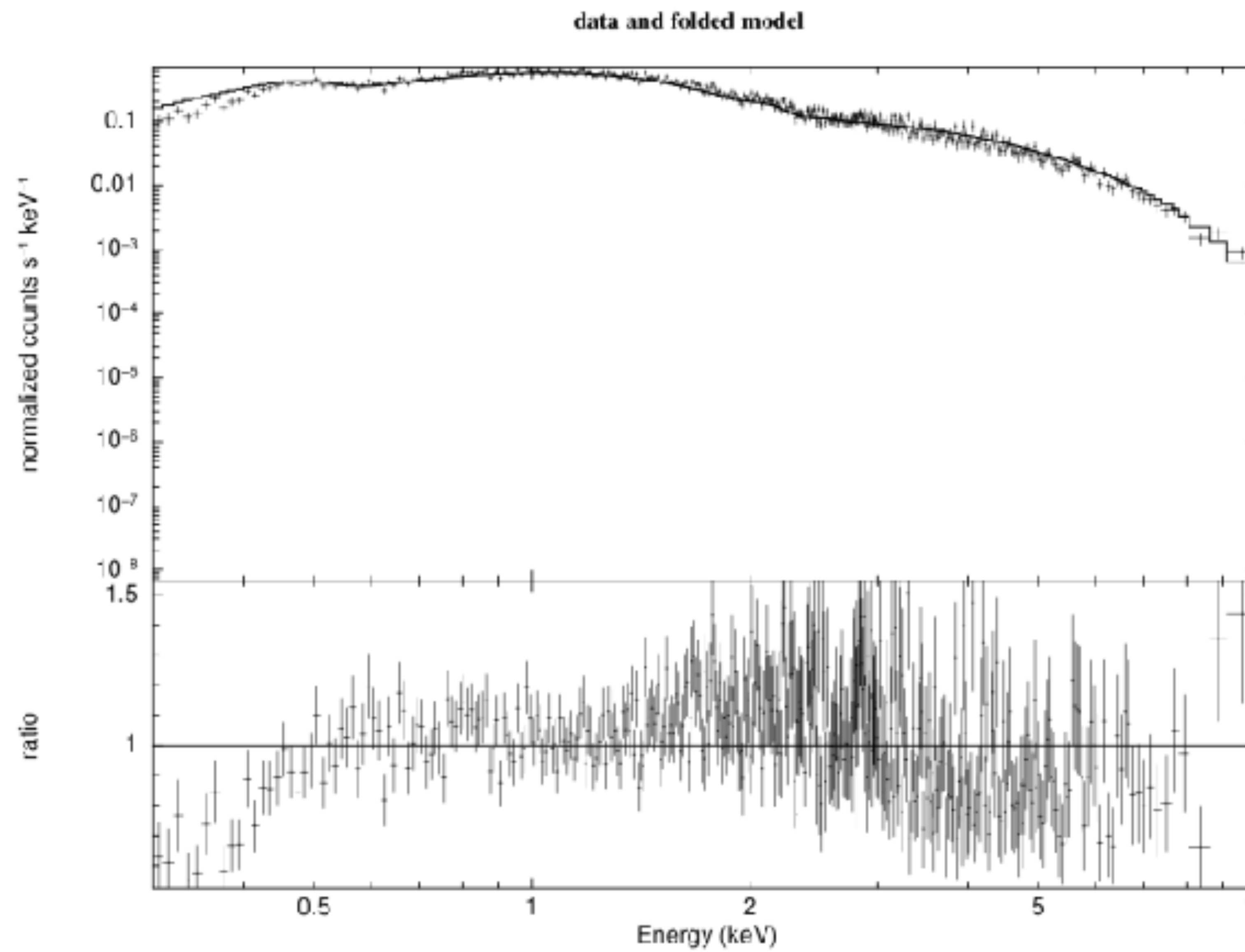
Stacked Swift/XRT data

Exposure: **30ks** between 2017-05-26 and 2017-09-28
Absorbed power law model with **Γ = 1.79** +/-0.01

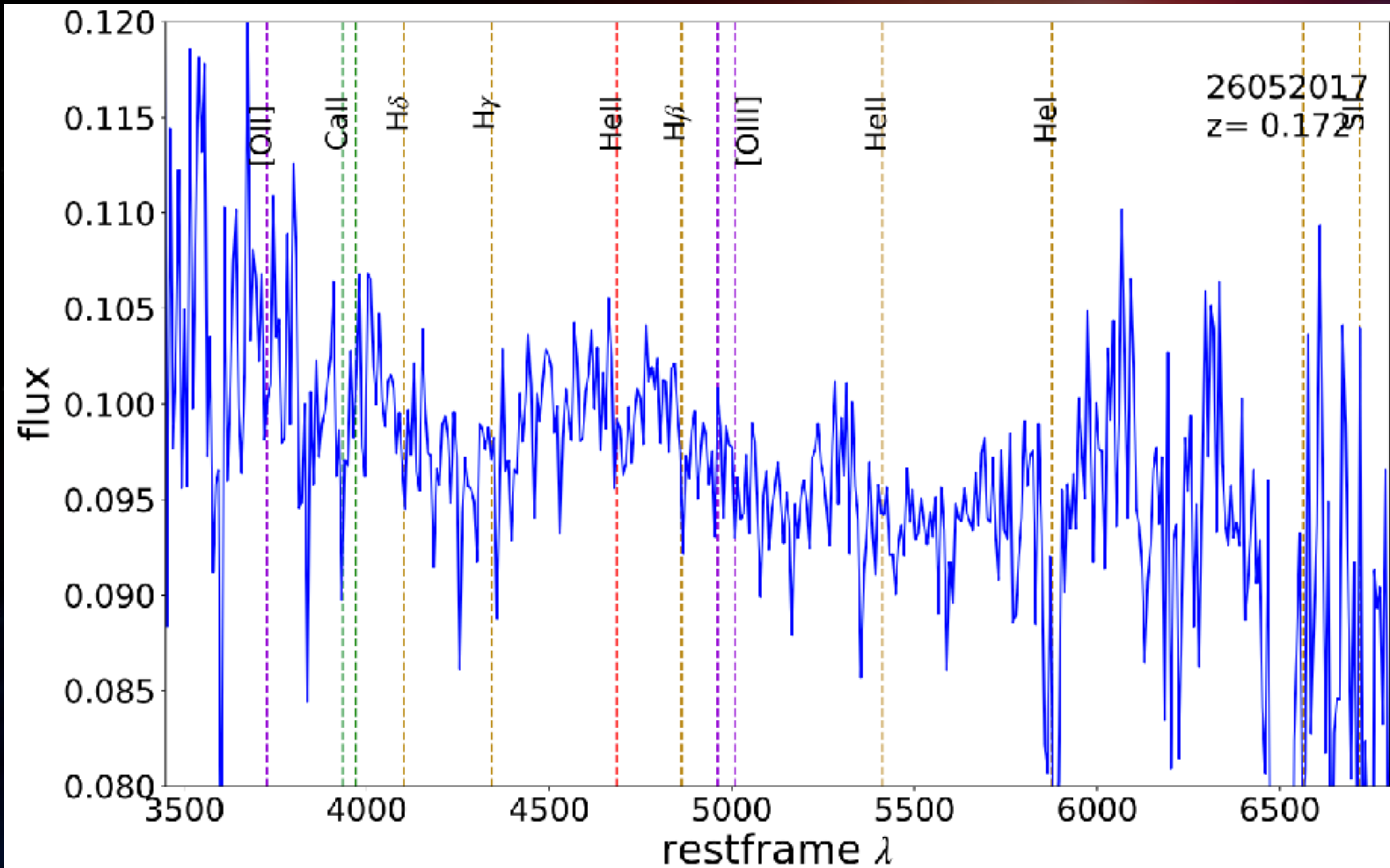
X-ray image



X-ray spectrum

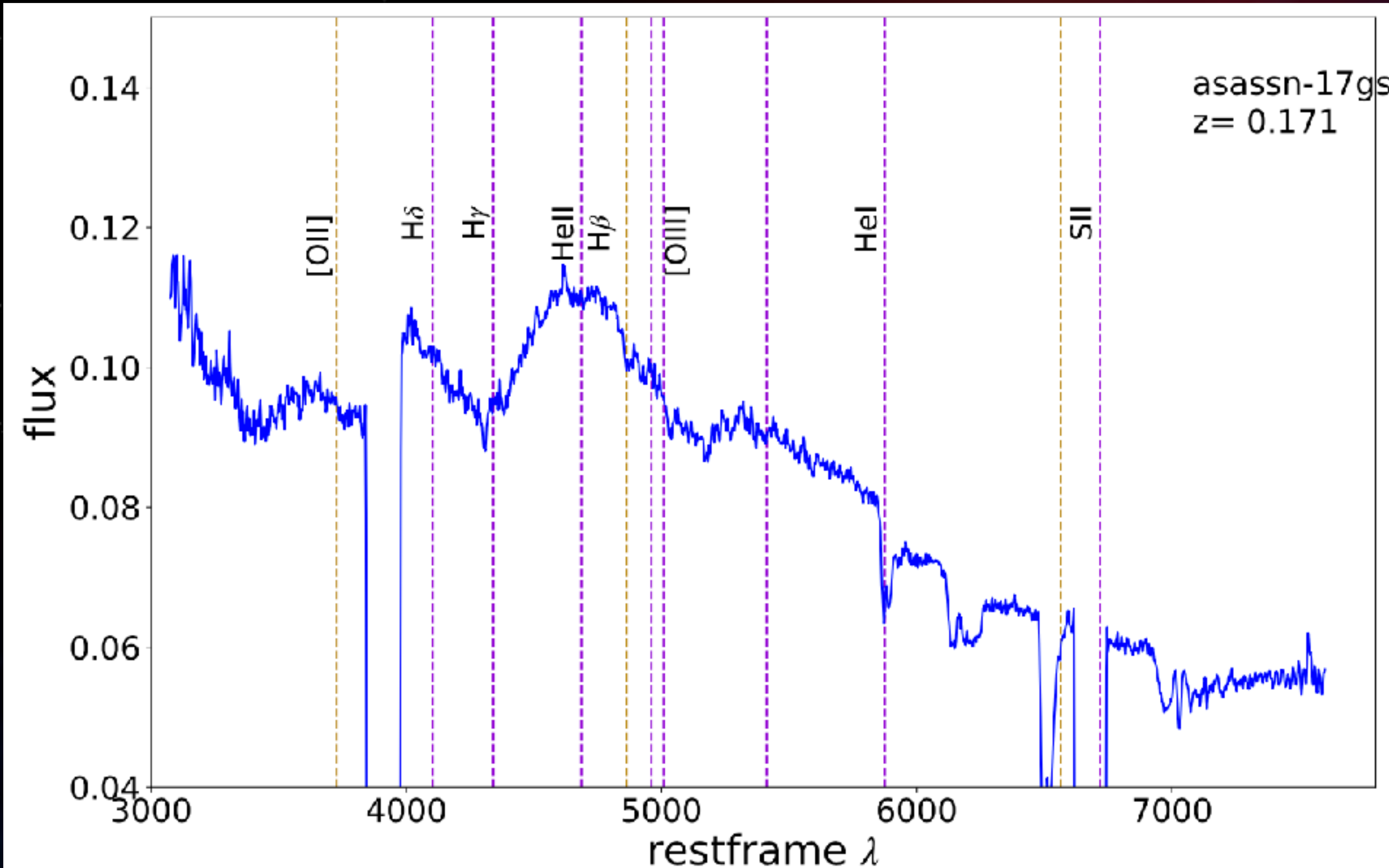


ASAS-SN17gs



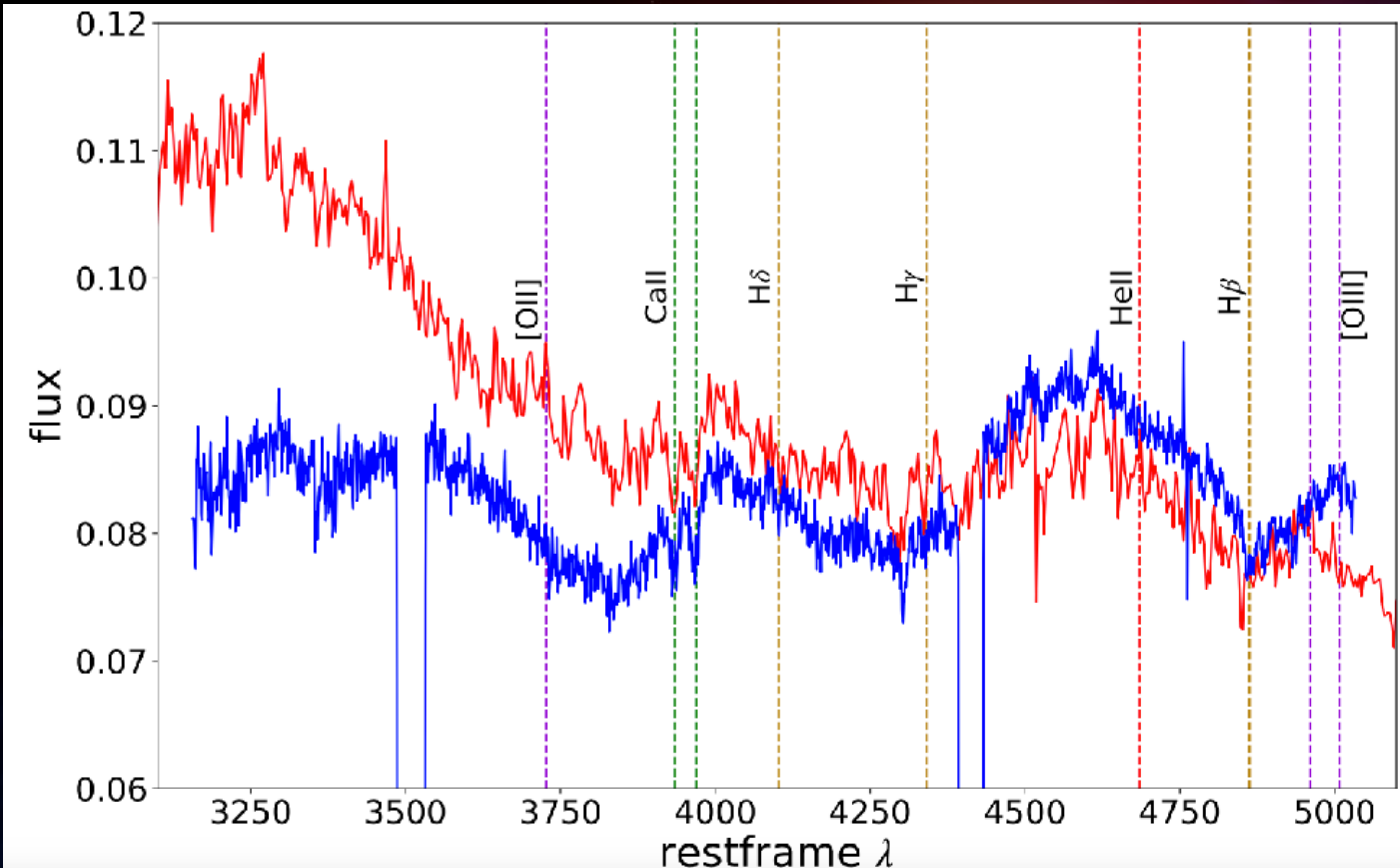
26052017
z= 0.172
[OII]
CaII
Hδ
Hγ
HeII
Hβ
[OIII]
HeII
HeI
flux
restframe λ
0.120
0.115
0.110
0.105
0.100
0.095
0.090
0.085
0.080
3500
4000
4500
5000
5500
6000
6500

ASAS-SN17gs



asassn-17gs
z= 0.171
[OII]
Hδ
Hγ
HeII
Hβ
[OIII]
HeI
SII
flux
0.14
0.12
0.10
0.08
0.06
0.04
3000
4000
5000
6000
7000
restframe λ

ASAS-SN17gs



0.12
0.11
0.10
0.09
0.08
0.07
0.06
flux
3250
3500
3750
4000
4250
4500
4750
5000
restframe λ
[OII]
CaII
Hδ
Hγ
HeII
Hβ
[OIII]