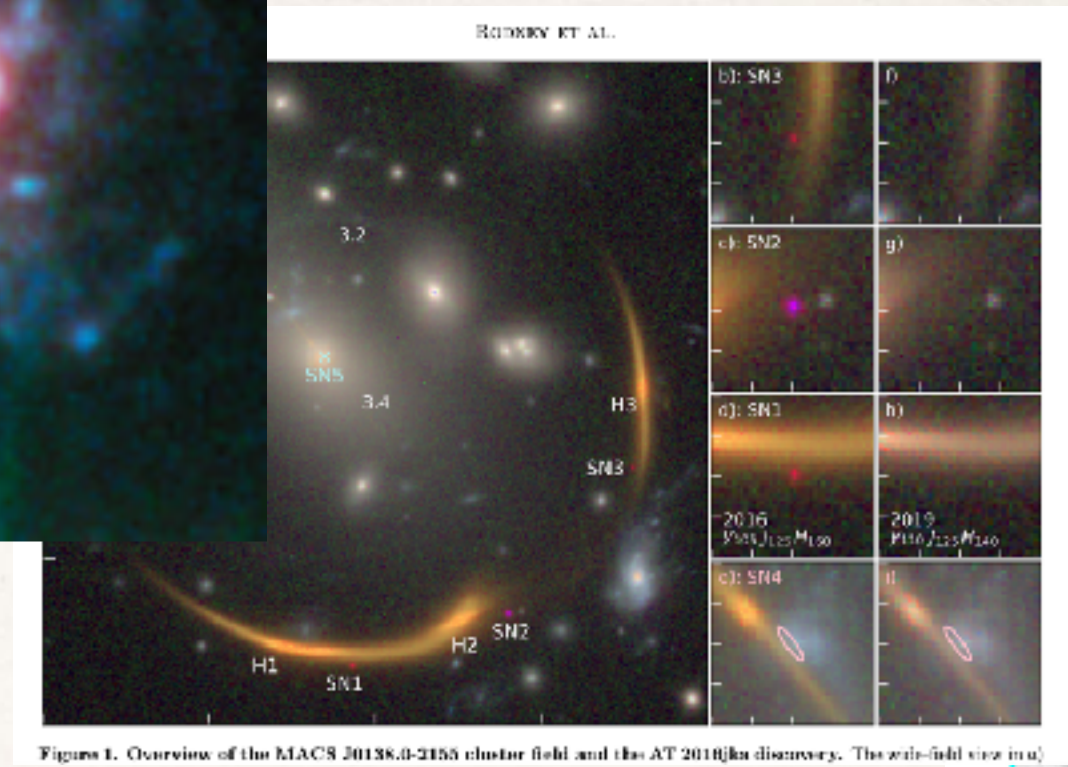
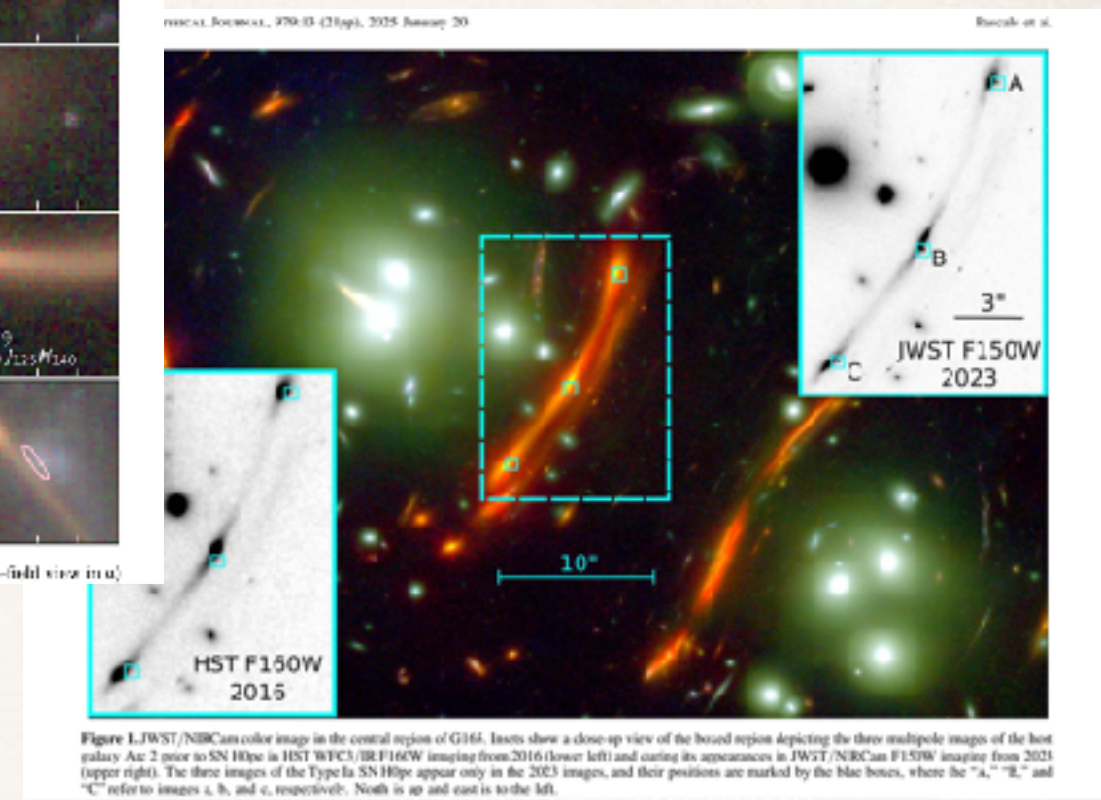




(Some) systematics in TD estimates in clusters and (some) other anecdotes

Israel Science Foundation — Israel Space Agency — Ministry of Science & Technology — BSF — NSF

Adi Zitrin (BGU)

Aug 5th, 2026, precisionTD@Tokyo

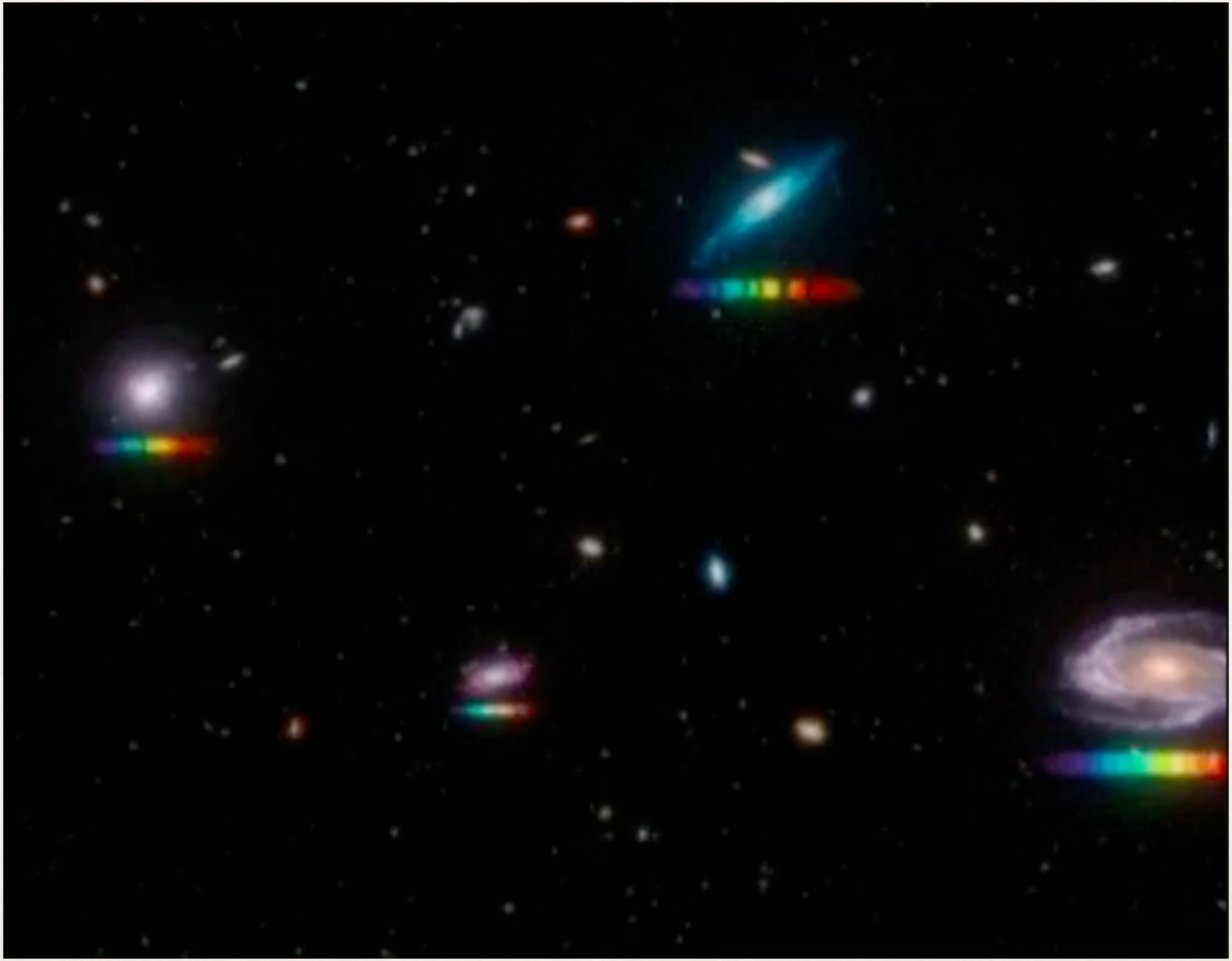
15 mins talk: 5 anecdotes x 3 mins each

1. TDs CHANGE WITH TIME, TOO

In Memory of
David Eichler

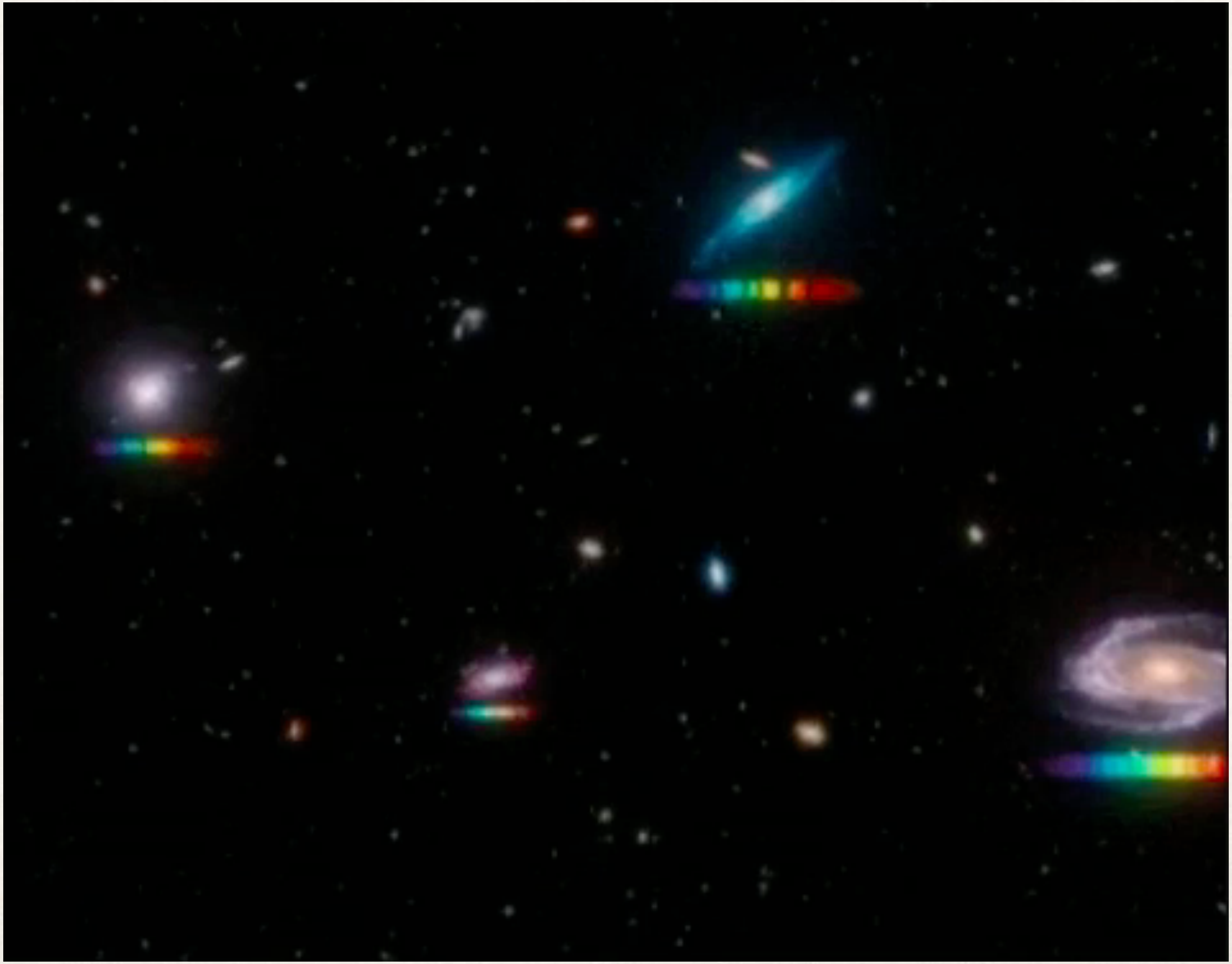
(1951, Brooklyn — 2021, Beer-Sheva)

What is Real-Time Cosmology?



GIPHY from COSMOS

What is Real-Time Cosmology?



GIPHY from COSMOS

What is Real-Time Cosmology?

- Measuring the temporal change of radial and transverse position of sources in the sky in real time (Quercellini+ 2010; Sandage 1962, Loeb 1998)
- Meaning, for example, delta_z in a certain delta_t, or, **dz/dt**.
- How much did the universe expand/change in that time period

Real-Time Cosmology: Why?

$$H(z) = \sqrt{H_0^2(\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0})},$$

$$\frac{dz}{dt_0} = (1+z)H_0 - H(z)$$

- As we know, the Hubble (Hubble -Lemaitre?) “constant” is a function of z, H(z)

- We can *characterize* the function H(z) from various probes. So we can *characterize* dz/dt. Real-Time cosmology refers to ***directly measuring*** by how much the universe changes in a certain (earthly) time period, and as a function of redshift.

- Realtime cosmology: measuring the temporal change of radial and transverse position of sources in the sky in real time (Quercellini+ 2010; Sandage 1962, Loeb 1998)

- In simple words: measure universe (ie redshift) today, measure it tomorrow, see how differs.

Challenge

- Age of universe: 13.8 Gyr, ~10^10 yr
- Human lifetime: close to ~ 10^2 yr
- In a human lifetime we thus witness only a 10^-8 change in universe.
- Since we can't measure nearly anything to that accuracy (redshift, distances, etc.), can’t do real-time cosmology directly.
- If we wanted to observe the universe changing (esp., expanding) in real time, to say, ~1% relative change, need to wait ~10^8 yr.

Challenge

- Example - in one earthly year:
- dz = 1.369110185744580E-11
- 1/R02 = 0.999999999928459
- H02 =69.999999997746471
- OmegaM2 =0.299999999954929
- OmegaL2 =0.700000000045071

Ideas to bypass challenge

- Loeb 1998

- Two observations, set a few decades apart, of large samples of quasars using sensitive high-resolution spectrographs where cross-correlating the (many) Lyman-alpha absorption lines. For example CODEX spectrograph (Espresso?).

- Multiple images: Comparison of the spectra of two multiple images should be offset by the amount corresponding to how much the universe expanded in the TD.

BUT: so far ideas not feasible

- Quasars so far not stood up to the challenge and haven't supplied the required measurements.
- Multiply imaged galaxies are not point sources - measure integrated spectra so cannot measure z as accurately as required.
- Transverse (random) motion will govern signal

Another idea:

- Time-delay between multiple images of a persistent/repeating source *will change with time* due to the radial and transverse motions of the lens (and source), and due to mass growth (Piattella & Giani 2017, Broadhurst & Oliver 1991). **Cool!**

- **BUT:** change in TD per year due to redshift drift is of order ~10^-2 - 10^-3 s. Can't measure TDs to that accuracy for any source so far.

However, FRBs can be useful

- Zitrin & Eichler 2018:

- Note that FRB time delays can be measured to superb accuracy - because FRBs only last about 10^-3 sec.

Some possible applications and highlights of lensed FRBs

- FRBs are strong ms bursts detected in increasing numbers over passed decade or two
- Extragalactic mostly according to dispersion measure, some repeat, few localised
- Engine unknown, likely stemming from magnetars
- No reported lensed FRB detection to date, but expected.
- Accurate H_0 from very accurate time delays (10^-3 s), esp. if localized and a proper model can be constructed. (e.g. Zheng-Xiang Li et al)
- Probe Dark Matter (e.g., Eichler 2017, Munoz+ 2016)
- Cosmological parameters / cosmology (e.g., Wucknitz, Spitler & Pen 2020, Abadi & Kovetz 2021)
- Real-Time Cosmology (e.g., Zitrin & Eichler 2018)
- Fundamental physics

*Estimated number of repeating FRBs lensed by clusters/galaxies

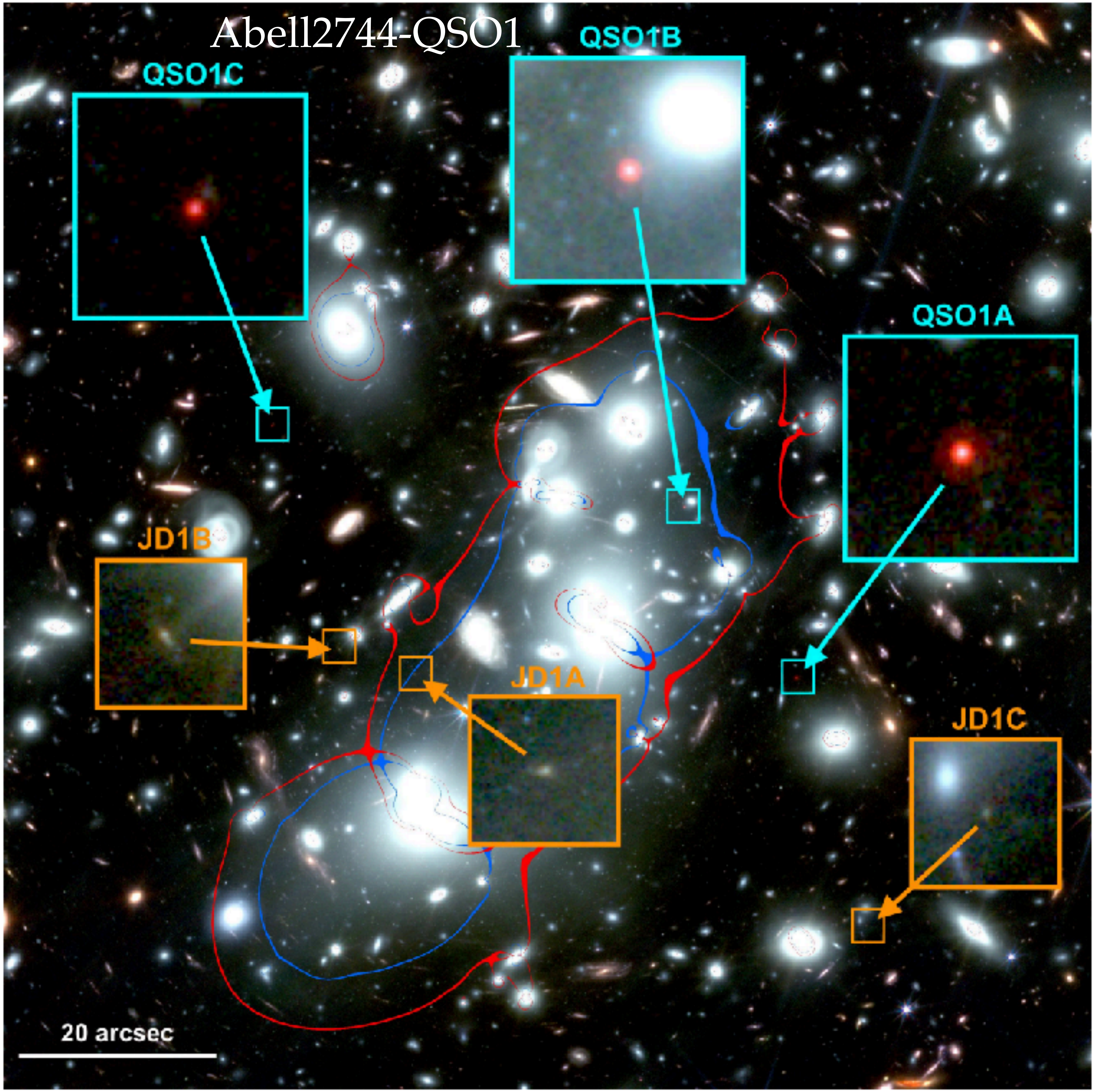
- 10^4 massive clusters in sky
- cross section for multiple images about 10 arcsec^2, or 10^-6 sq. deg.
- So in total 10^-2 sq. degrees across sky. With 4*10^4 sq. deg. of sky and ~10^7 repeating FRBs with SKA-like sensitivity, **a few to ~10 repeating FRBs lensed by some rich cluster** (not too many! see quasars).
- But **by galaxies many more, perhaps up to ~10^4**.

Conclusion @ realtime cosmology with lensed FRBs

- FRB time delays *can be measured to high enough accuracy to allow for real-time cosmology* (repeating FRBs!)
- Depending on rate/number of course (need enough lensed repeating ones).
- Transverse component governs effect (change in TD of 0.1-1 s per year), but might be averaged out with many sources. of course the transverse effect itself is very interesting.
- Radial effect and mass assembly effects are of same order, (10^-2-10^-3 s roughly), to be distinguished statistically or by new means.
- Later paper (May 2020) by Wucknitz, Spitler and Ue Li Pen, suggests using quad lenses and interference pattern to remove proper motion from drift. See also Covone & Sereno 2022.

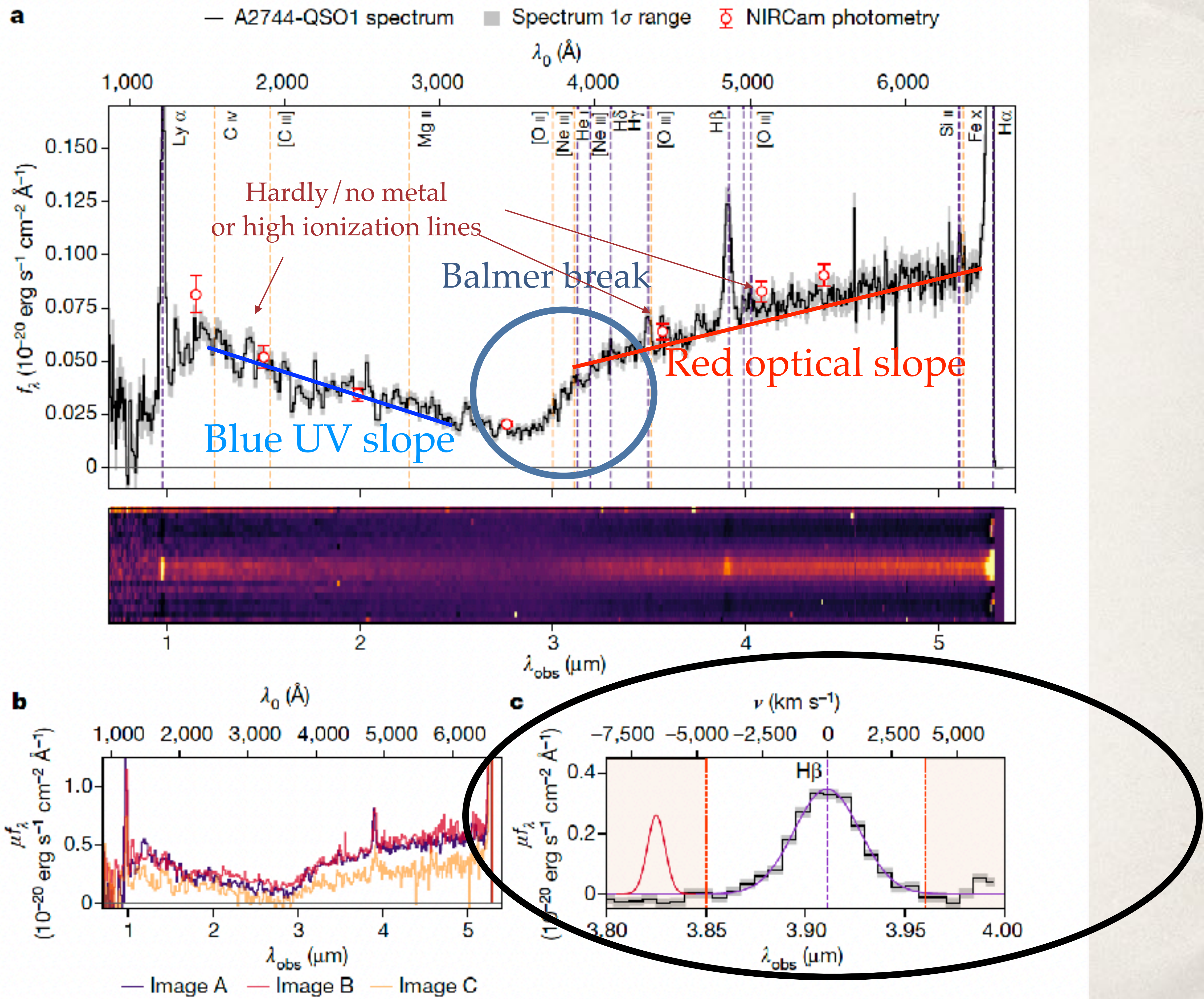
2. TDs and/of AGN lensed by clusters


JWST UNCOVER program
Bezanson, Labbe et al.



Furtak, AZ et al. 2023

<—See Guido's paper



a
A2744-QSO1 spectrum
Spectrum 1σ range
NIRCam photometry
λ0 (Å)
Ly α
C IV
[C III]
Mg II
[O II]
[Ne III]
He I
Hδ
Hγ
[O III]
Hβ
Si II
Fe X
Hα
fλ (10^-20 erg s^-1 cm^-2 Å^-1)
Hardly / no metal
or high ionization lines
Balmer break
Red optical slope
Blue UV slope
λobs (μm)
b
μfλ (10^-20 erg s^-1 cm^-2 Å^-1)
Image A
Image B
Image C
c
v (km s^-1)
Hβ

Article

A high black-hole-to-host mass ratio in a lensed AGN in the early Universe

https://doi.org/10.1038/s41586-024-07184-8

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Check for updates

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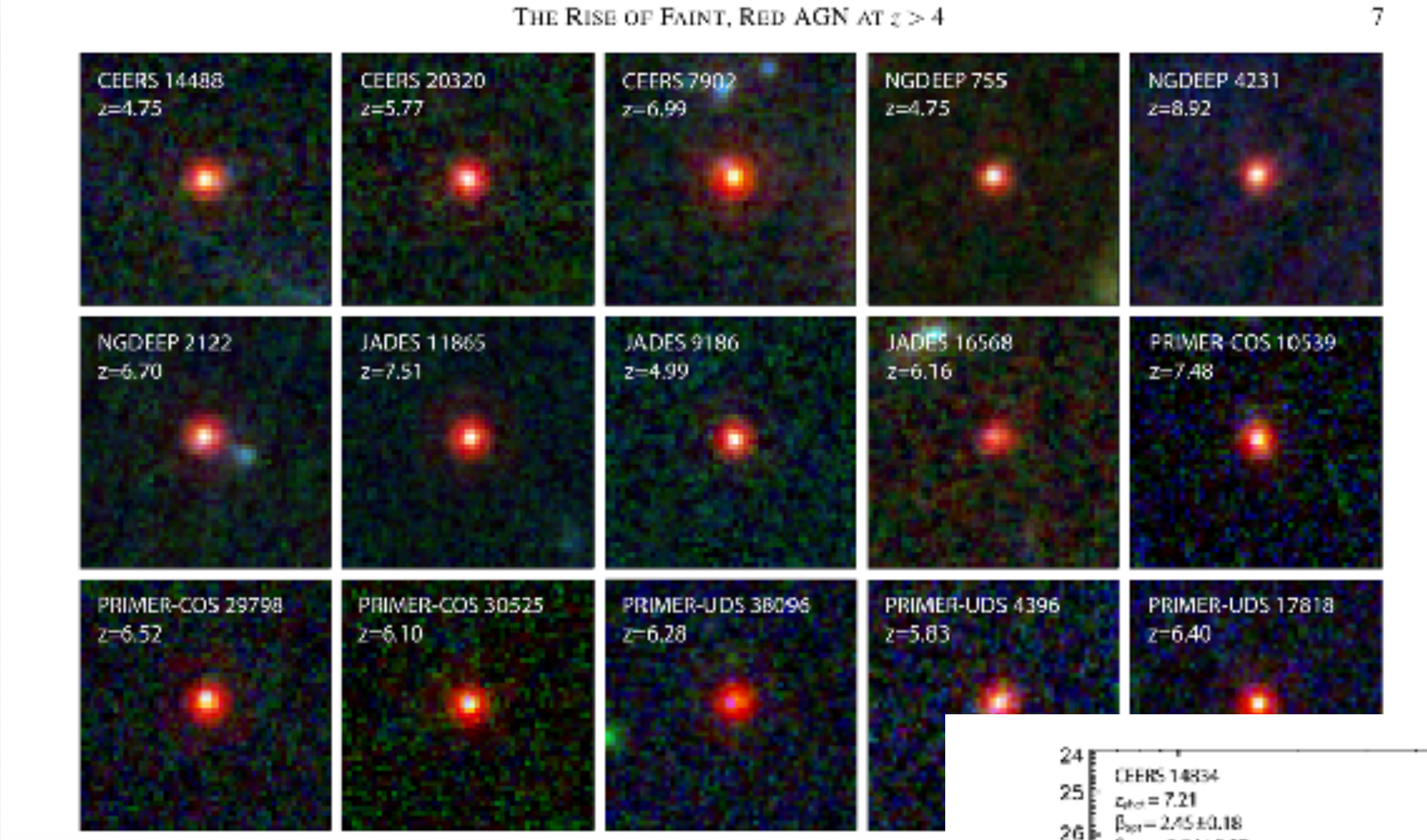
Early JWST observations have uncovered a population of red sources that might represent a previously overlooked phase of supermassive black hole growth[1–3]. One of the most intriguing examples is an extremely red, point-like object that was found to be triply imaged by the strong lensing cluster Abell 2744 (ref. 4). Here we present deep JWST/NIRSpec observations of this object, Abell2744-QSO1. The spectroscopy confirms that the three images are of the same object, and that it is a highly reddened ($A_V \simeq 3$) broad emission line active galactic nucleus at a redshift of $z_{\rm spec} = 7.0451 \pm 0.0005$. From the width of H$\beta$ (full width at half-maximum = 2,800 ± 250 km s^{-1}), we derive a black hole mass of $M_{\rm BH} = 4^{+2}_{-1} \times 10^7\, M_\odot$. We infer a very high ratio of black-hole-to-galaxy mass of at least 3%, an order of magnitude more than that seen in local



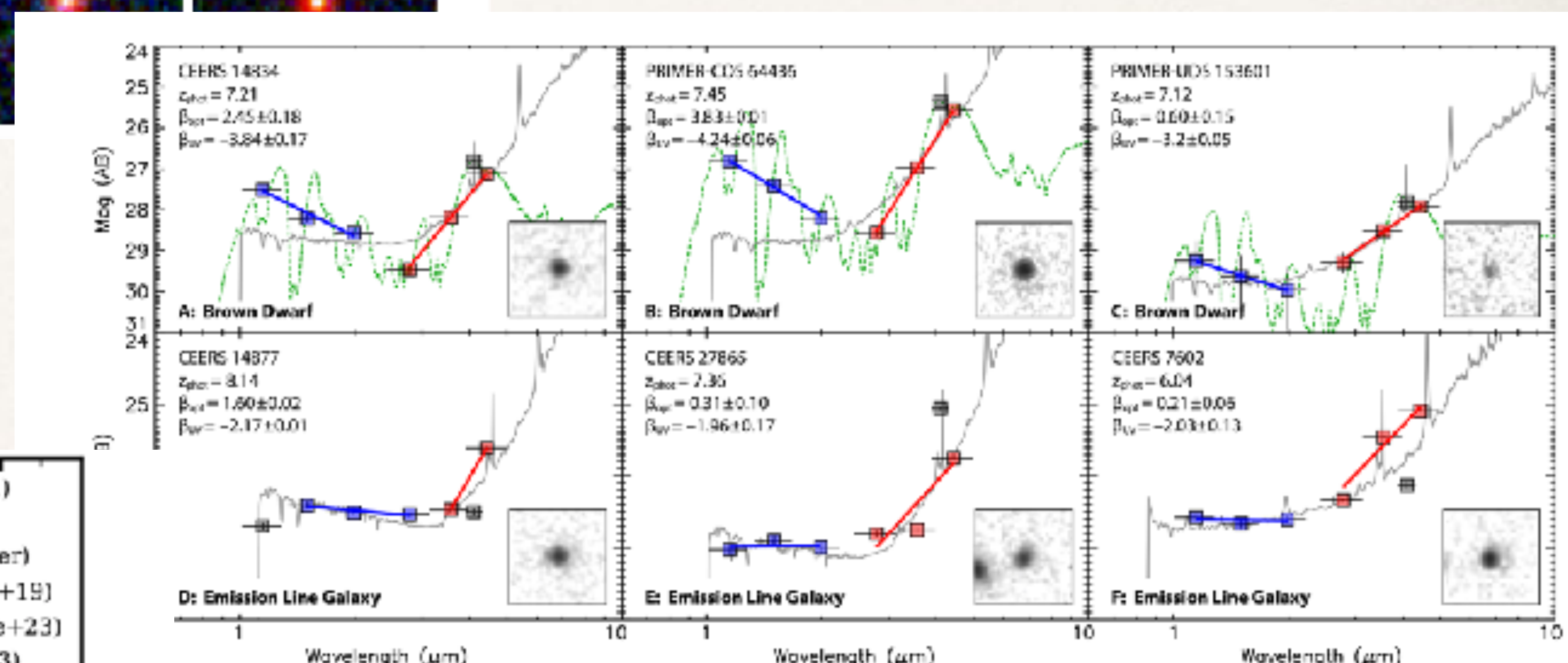
Little Red Dots

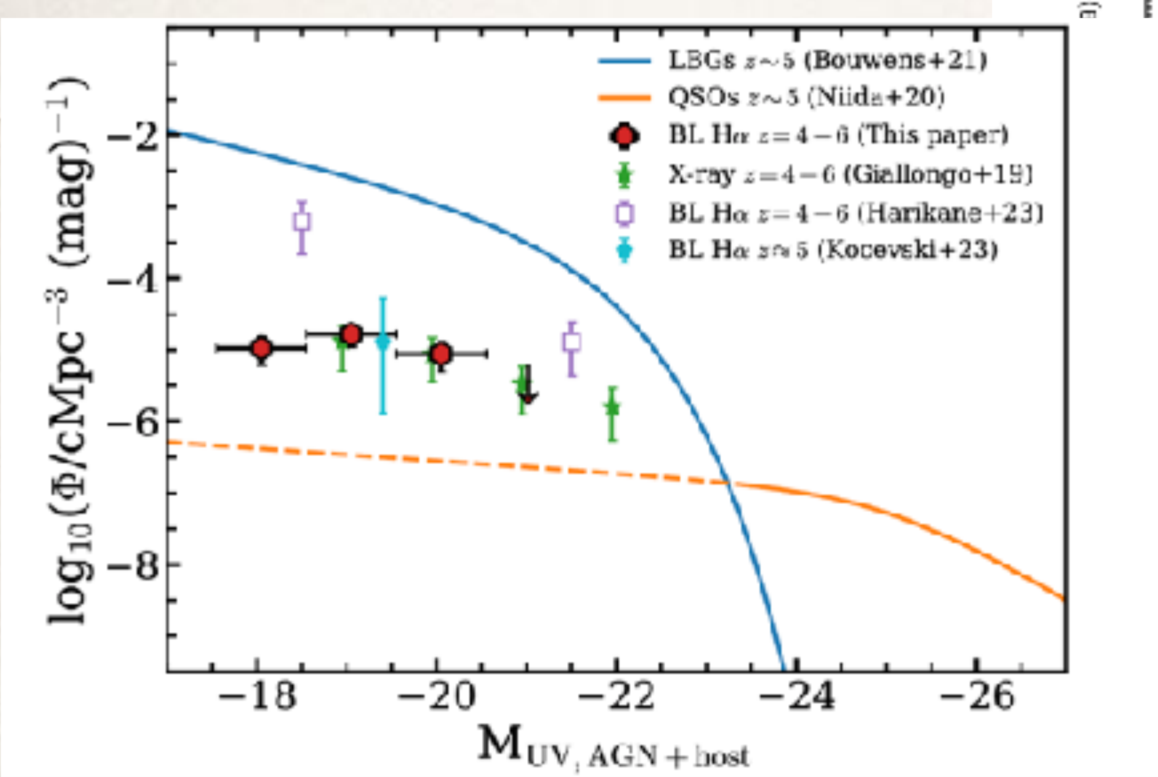
Matthee et al.

Kocevski et al.

and by now an endless list…

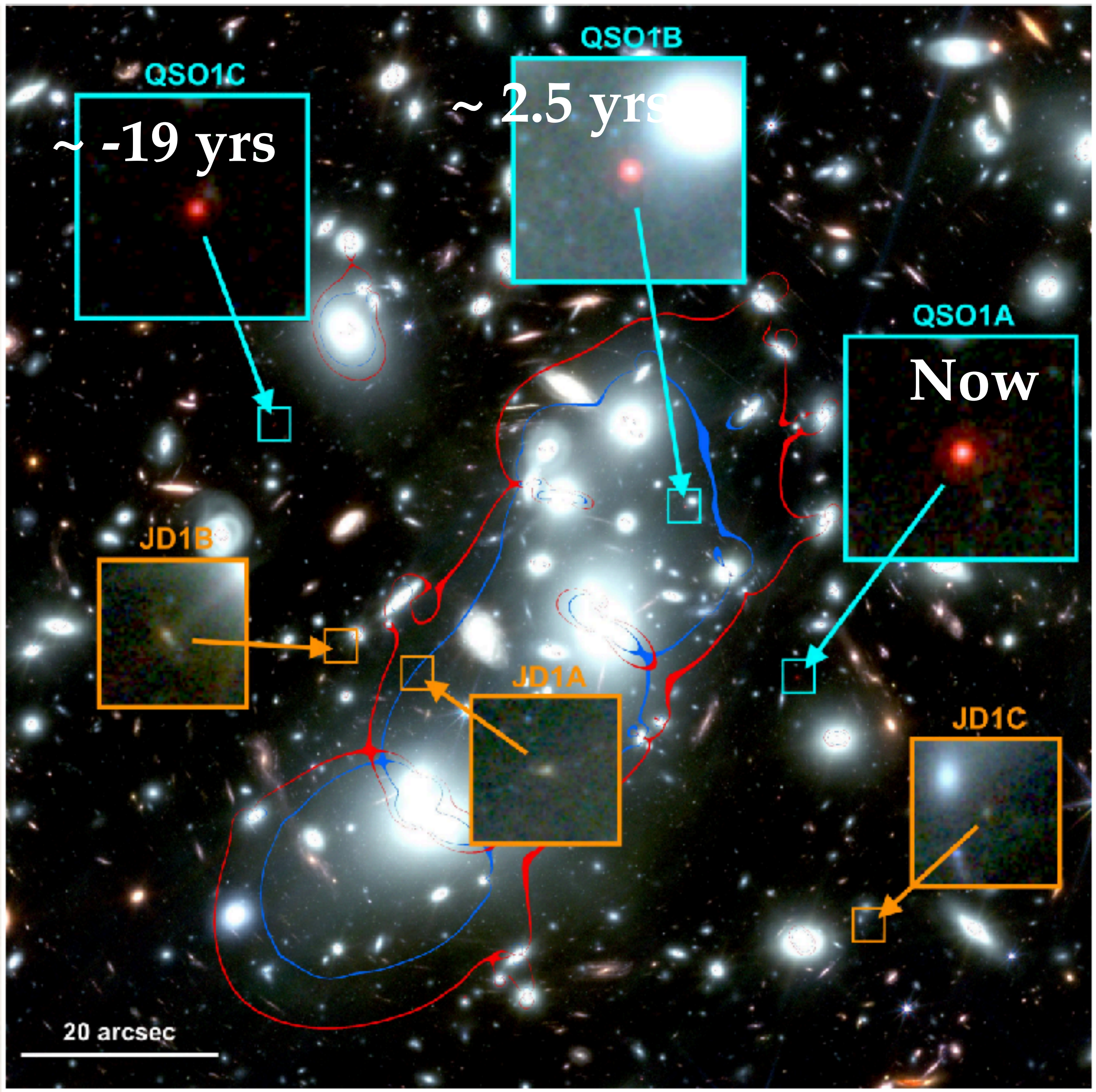
(Or, I should say no more)

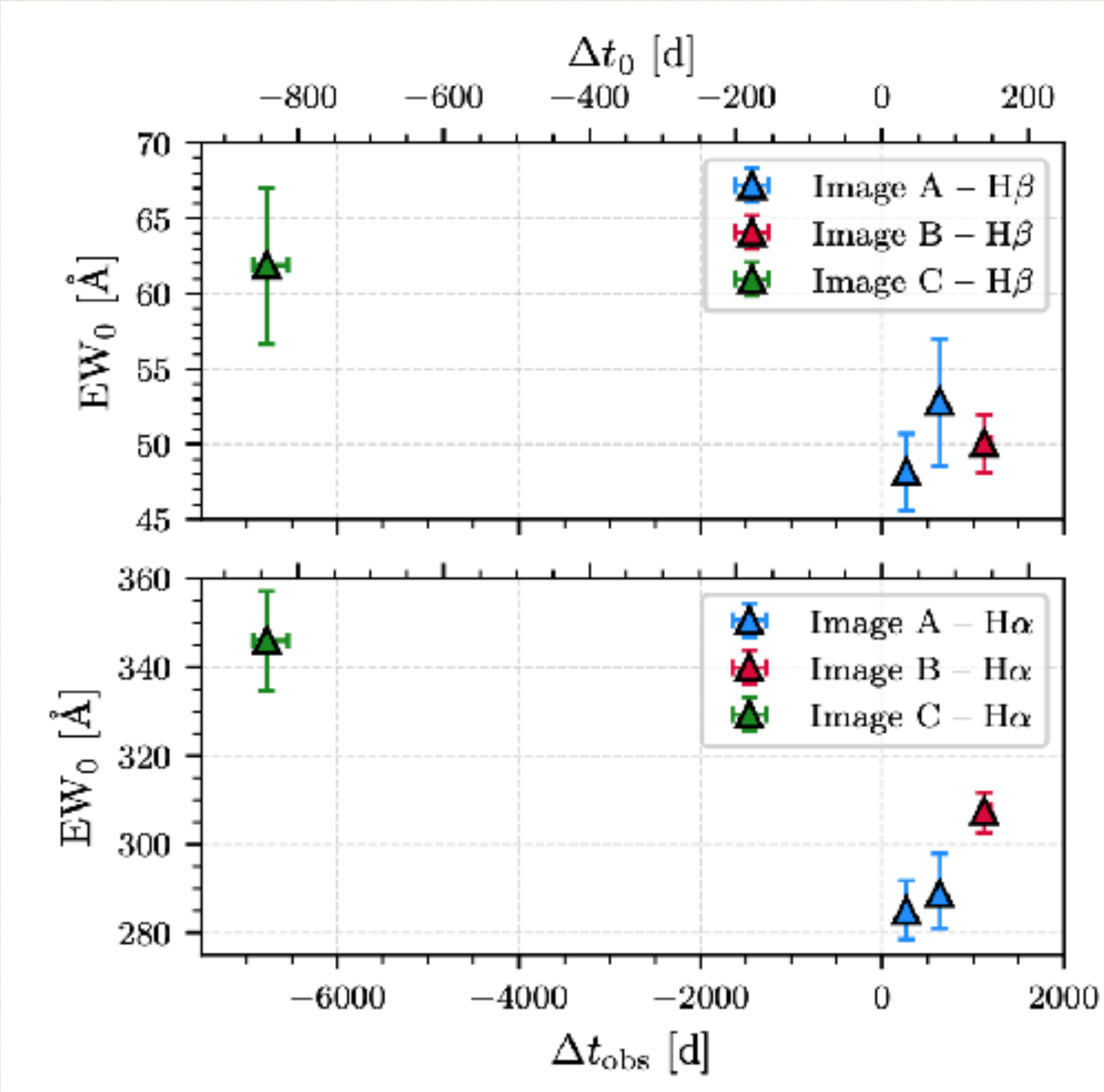




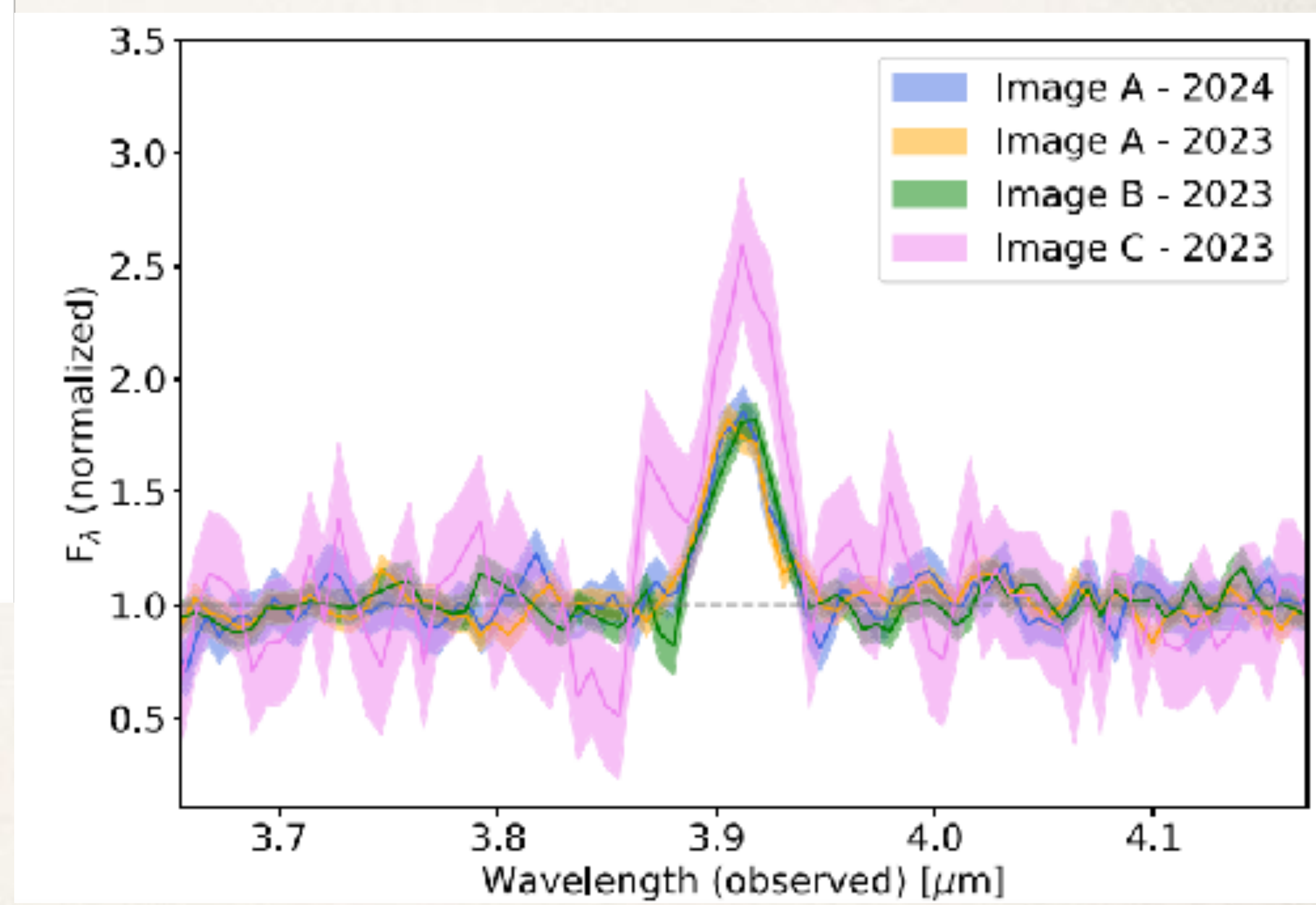
Investigating photometric and spectroscopic variability in the multiply-imaged 'Little Red Dot' A2744-QSO1

Lukas J. Furtak[1⋆], Amy R. Secunda[2], Jenny E. Greene[3], Adi Zitrin[1], Ivo Labbé[4], Miriam Golubchik[1], Rachel Bezanson[5], Vasily Kokorev[6], Hakim Atek[7], Gabriel B. Brammer[8,9], Iryna Chemerynska[7], Sam E. Cutler[10], Pratika Dayal[11], Robert Feldmann[12], Seiji Fujimoto[6], Joel Leja[13,14,15], Yilun Ma (马逸伦)[3], Jorryt Matthee[16], Rohan P. Naidu[17], Erica J. Nelson[18], Pascal A. Oesch[19,8], Richard Pan[20], Sedona H. Price[5], Katherine A. Suess[18], Bingjie Wang (王冰洁)[13,14,15], John R. Weaver[10] and Katherine E. Whitaker[10,8]

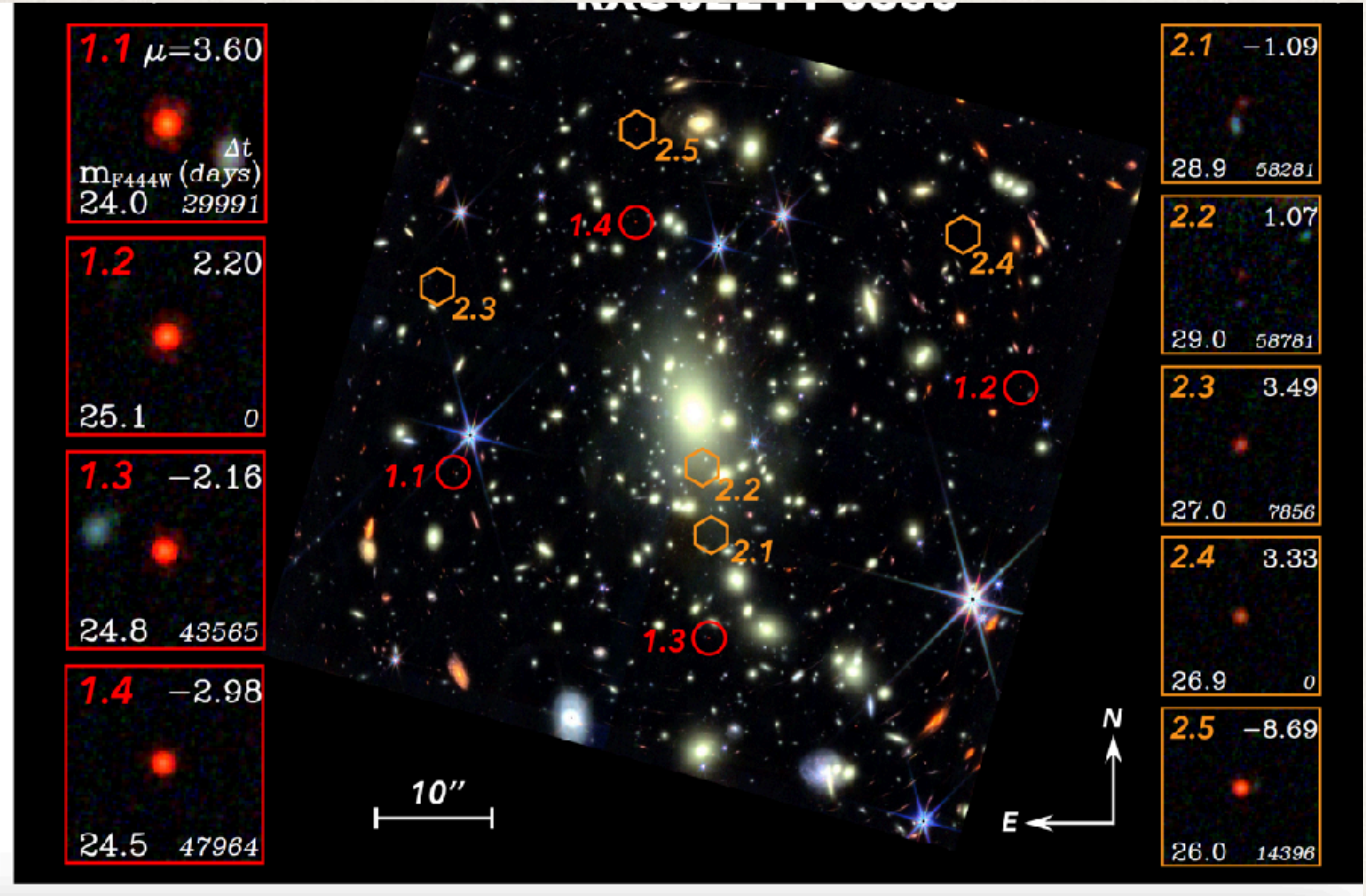




Furtak+ 2025



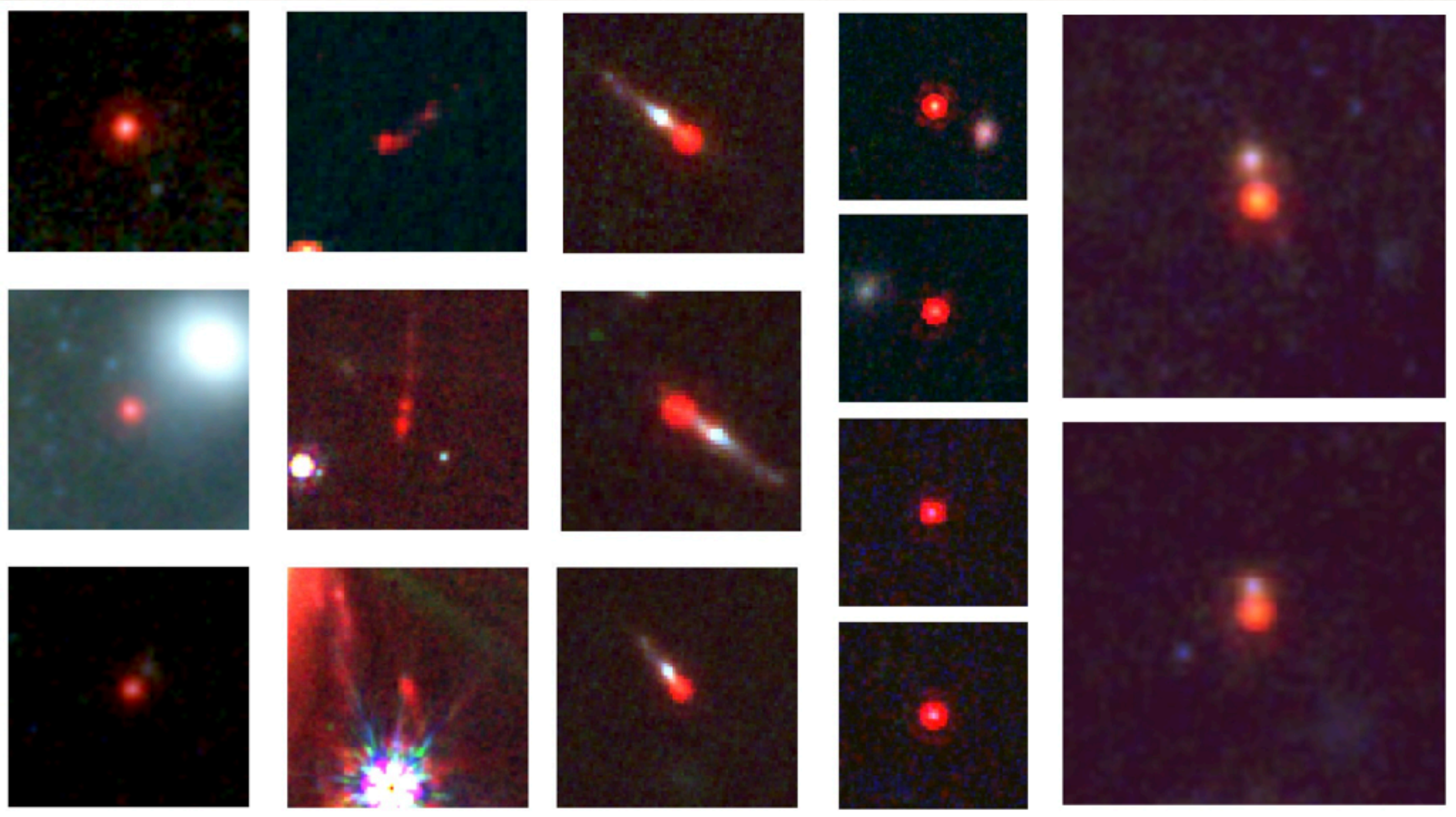
See also Ji+ 2025



Zhang, …+ Sun 2026

Variability!?

Ensemble of lensed LRDs



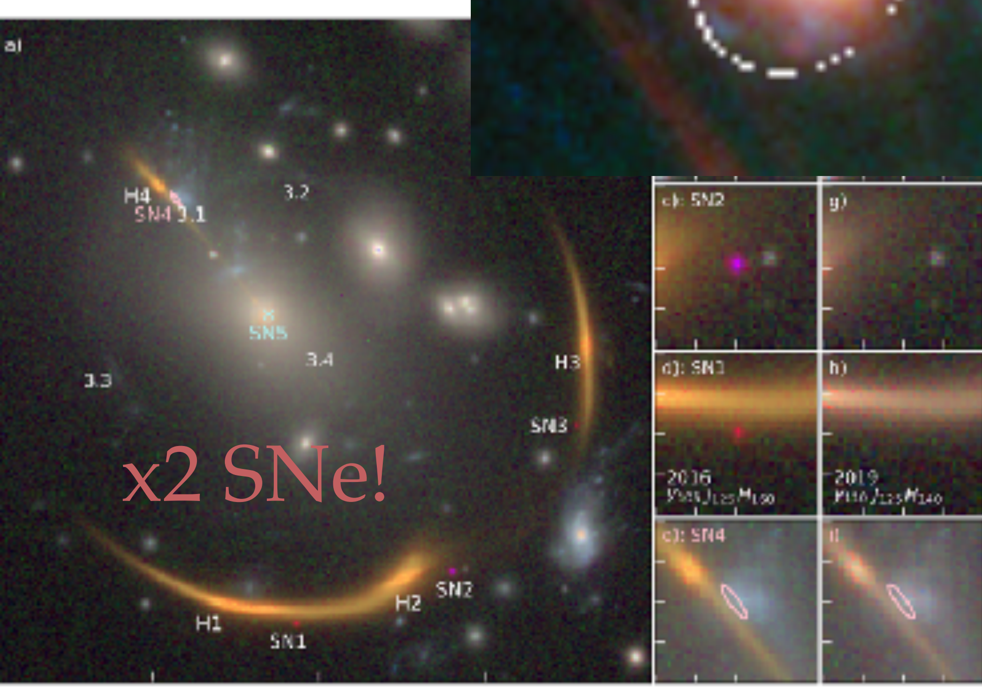
Zitrin 2026

3. Lensing of distant SNe

Examples of Multiply imaged SNe

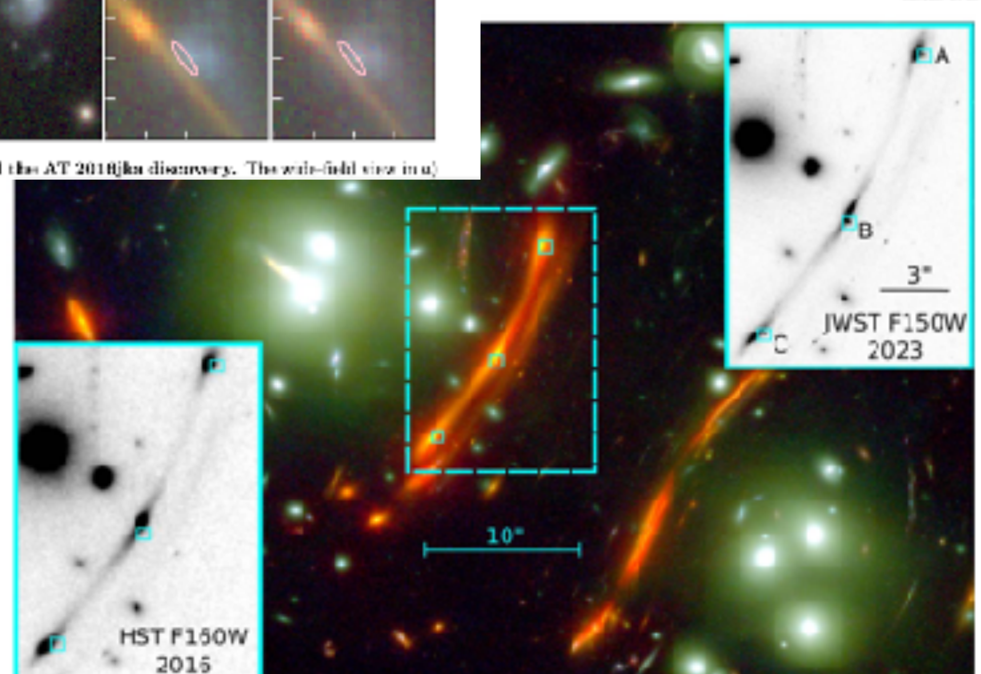
Kelly+

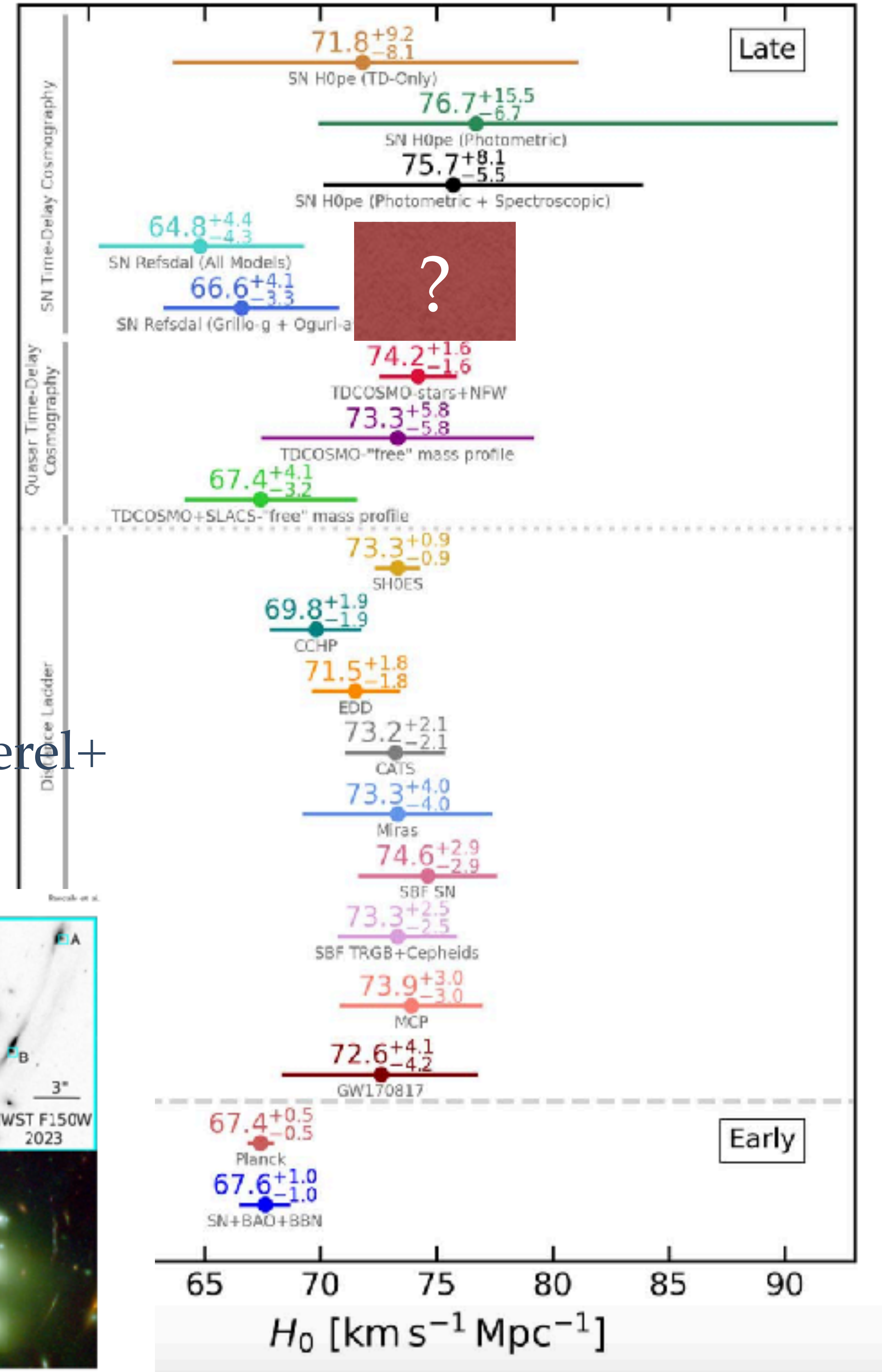
Rodney, Pierel+

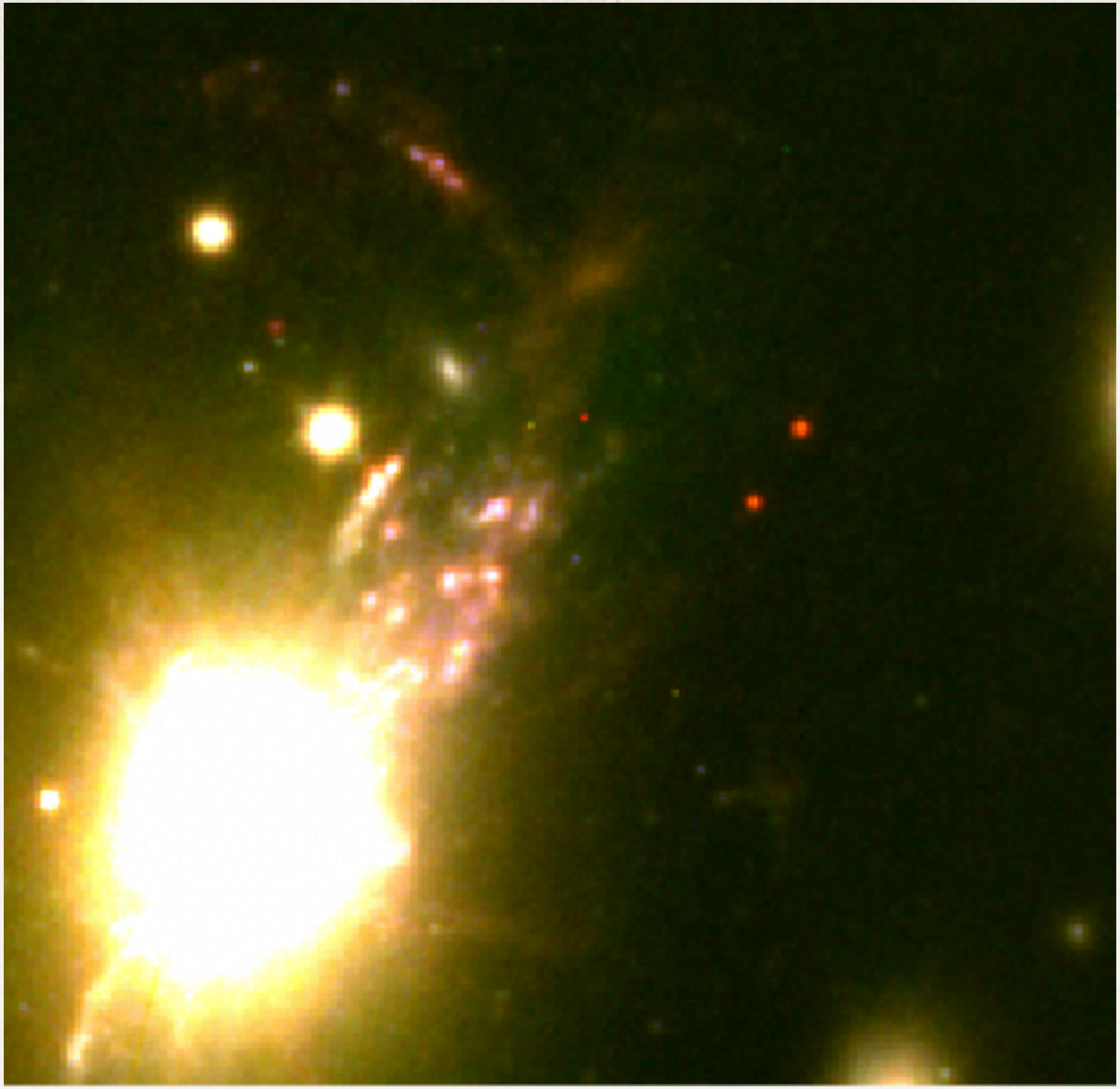


x2 SNe!

Pascale+



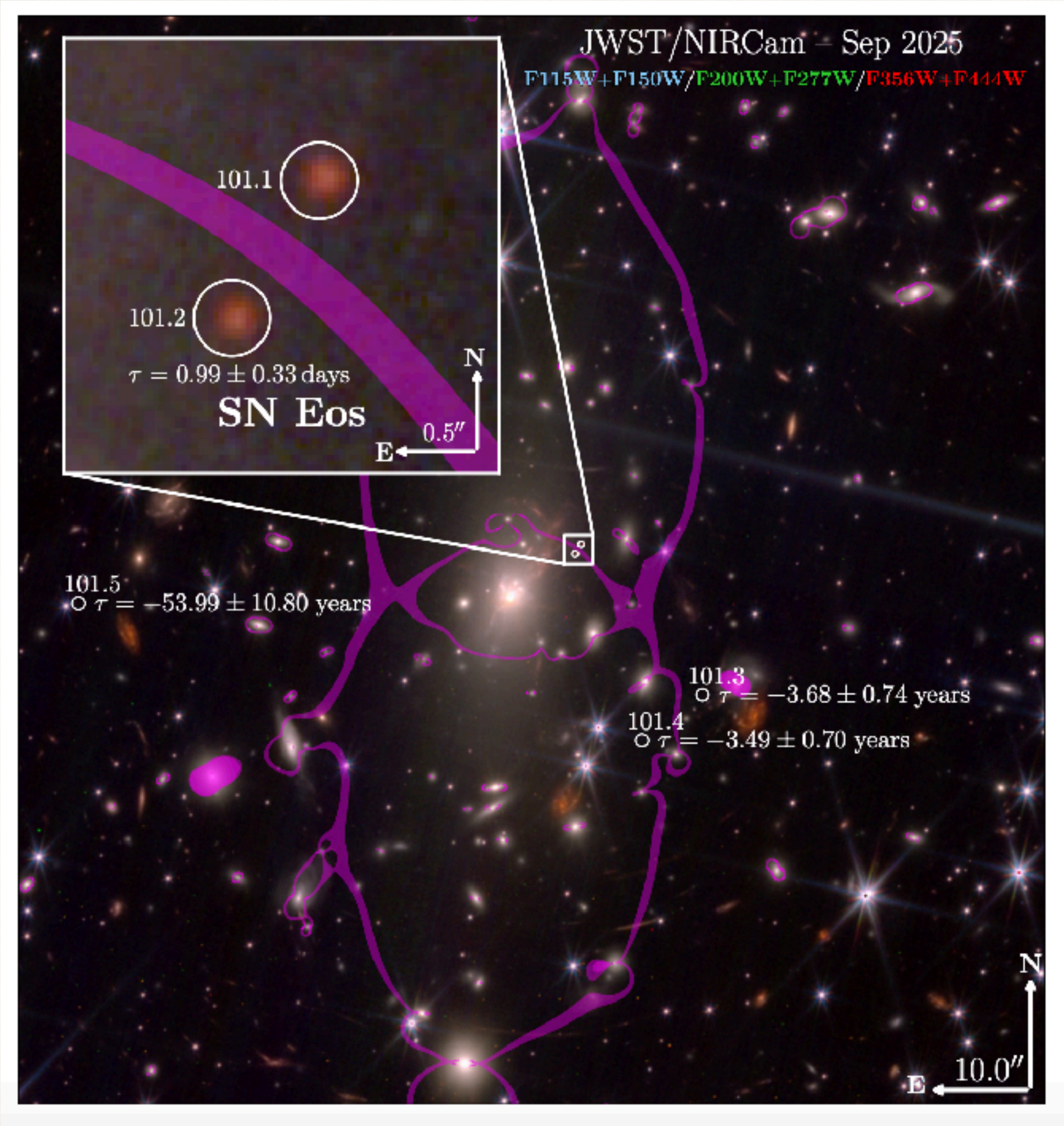




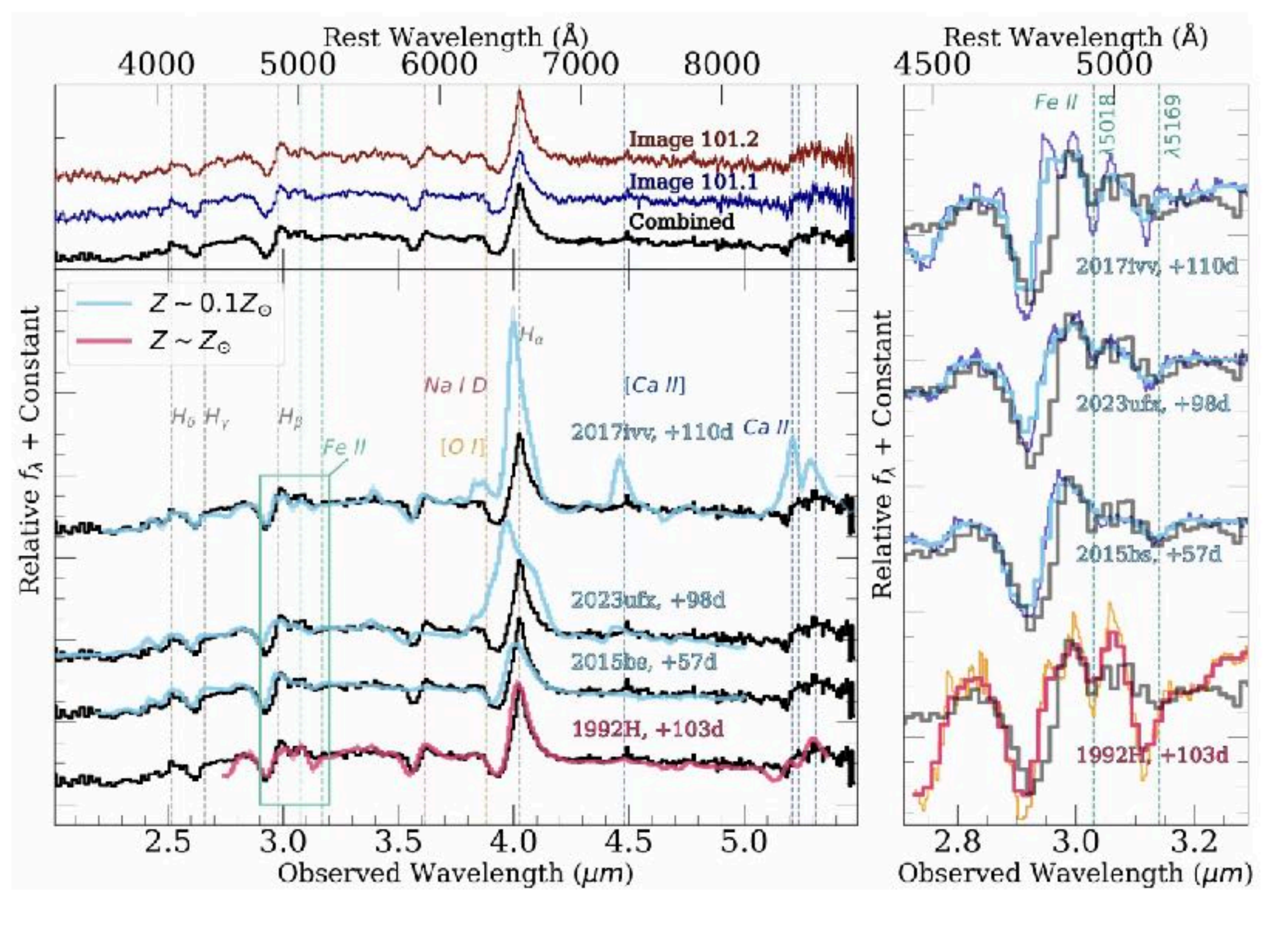
MACS1931 VENUS imaging

Coulter+

Allingham+

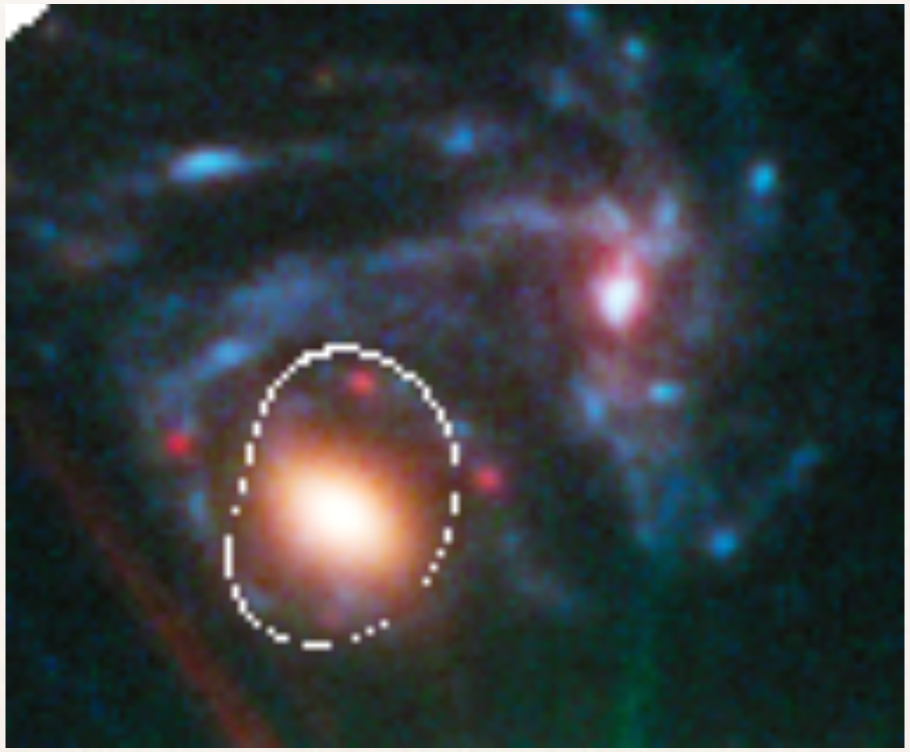


Coulter+



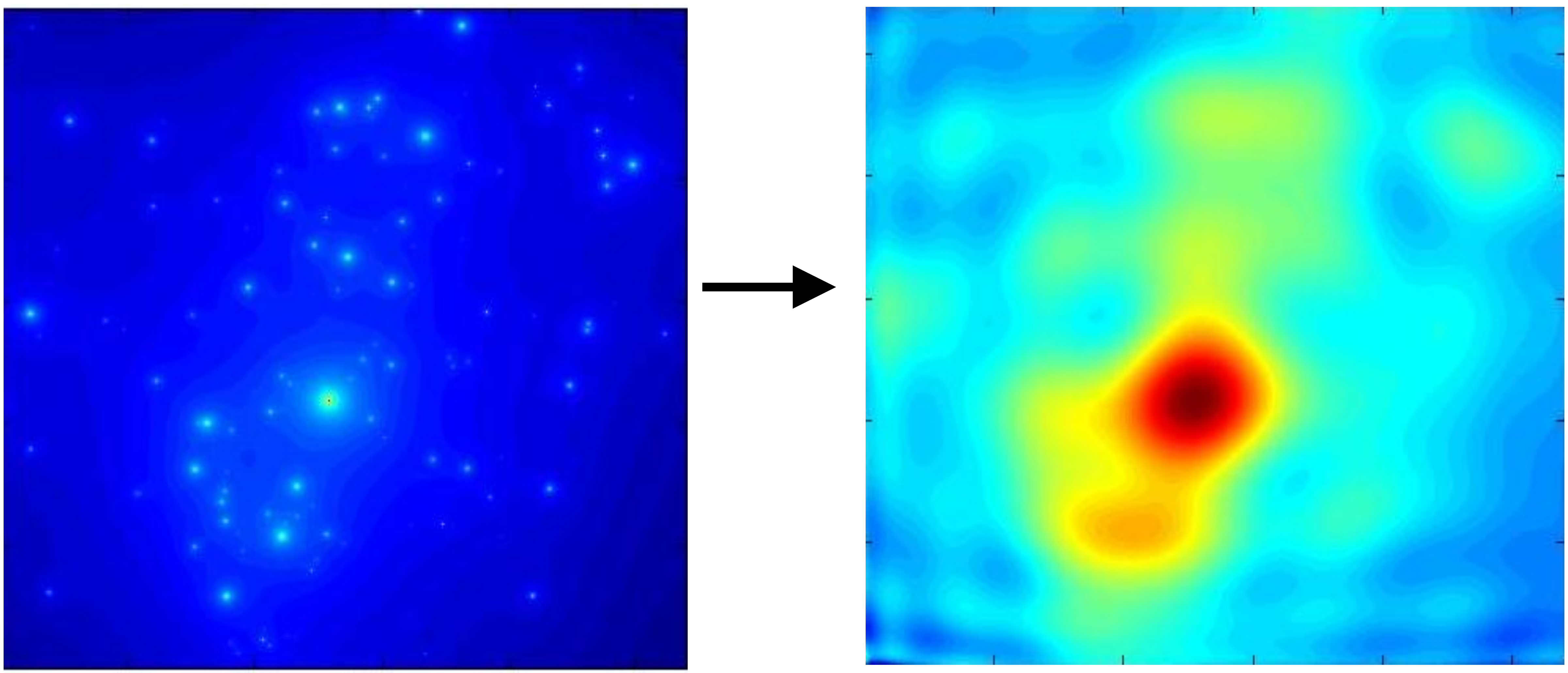
JWST detects more lensed SNe than HST

4. (ALWAYS?) START FROM THE POTENTIAL

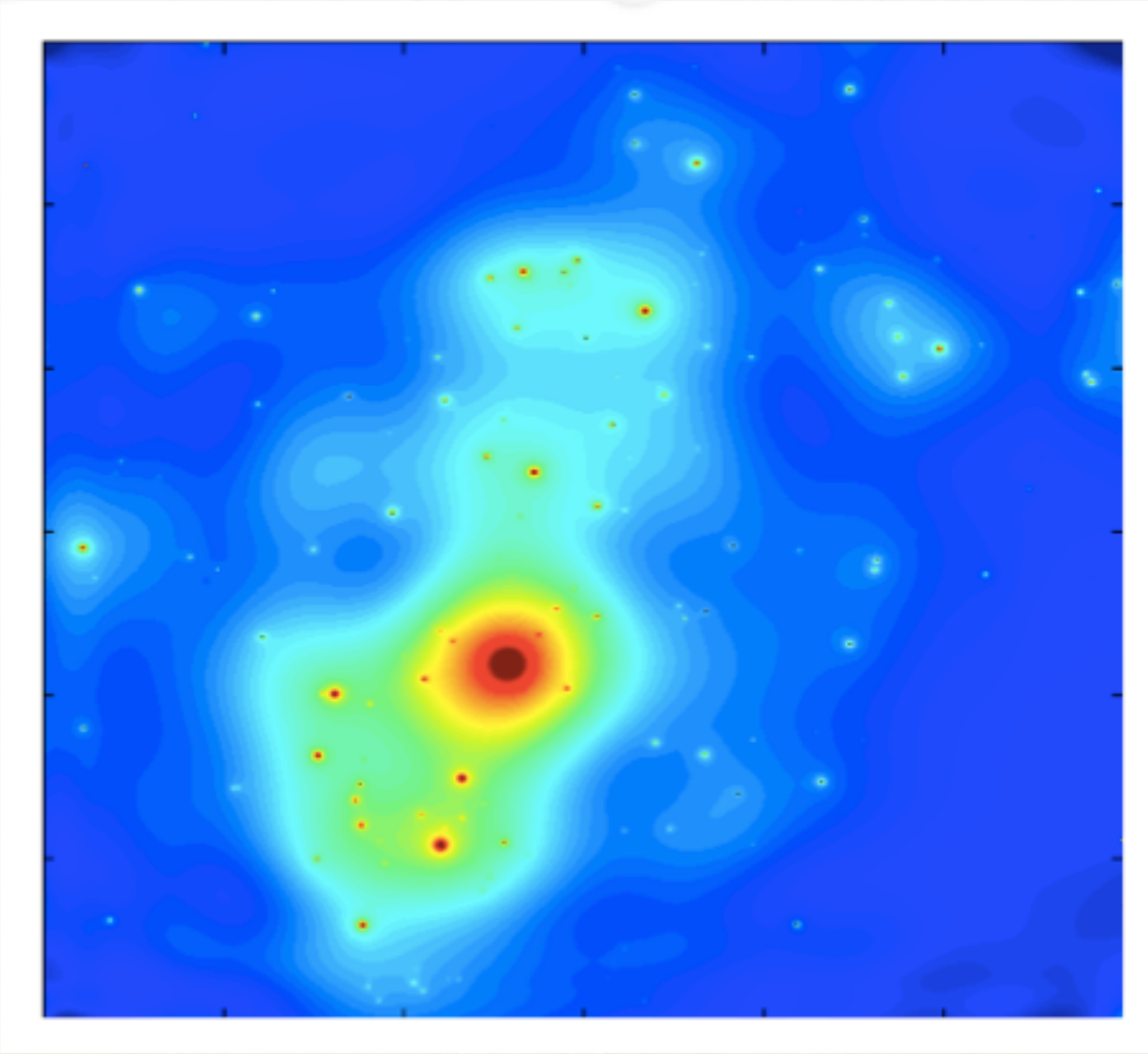


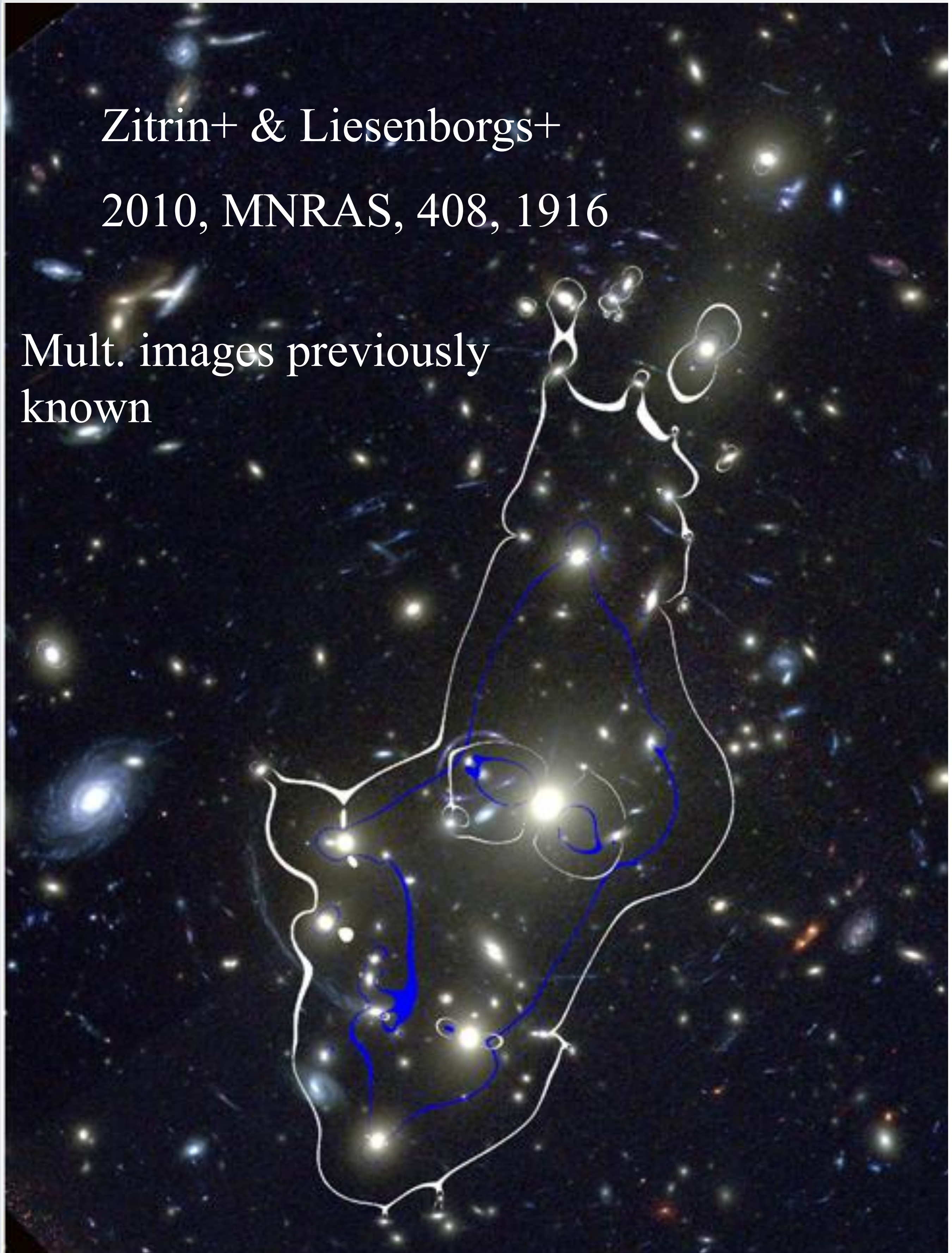
LTM: Hows

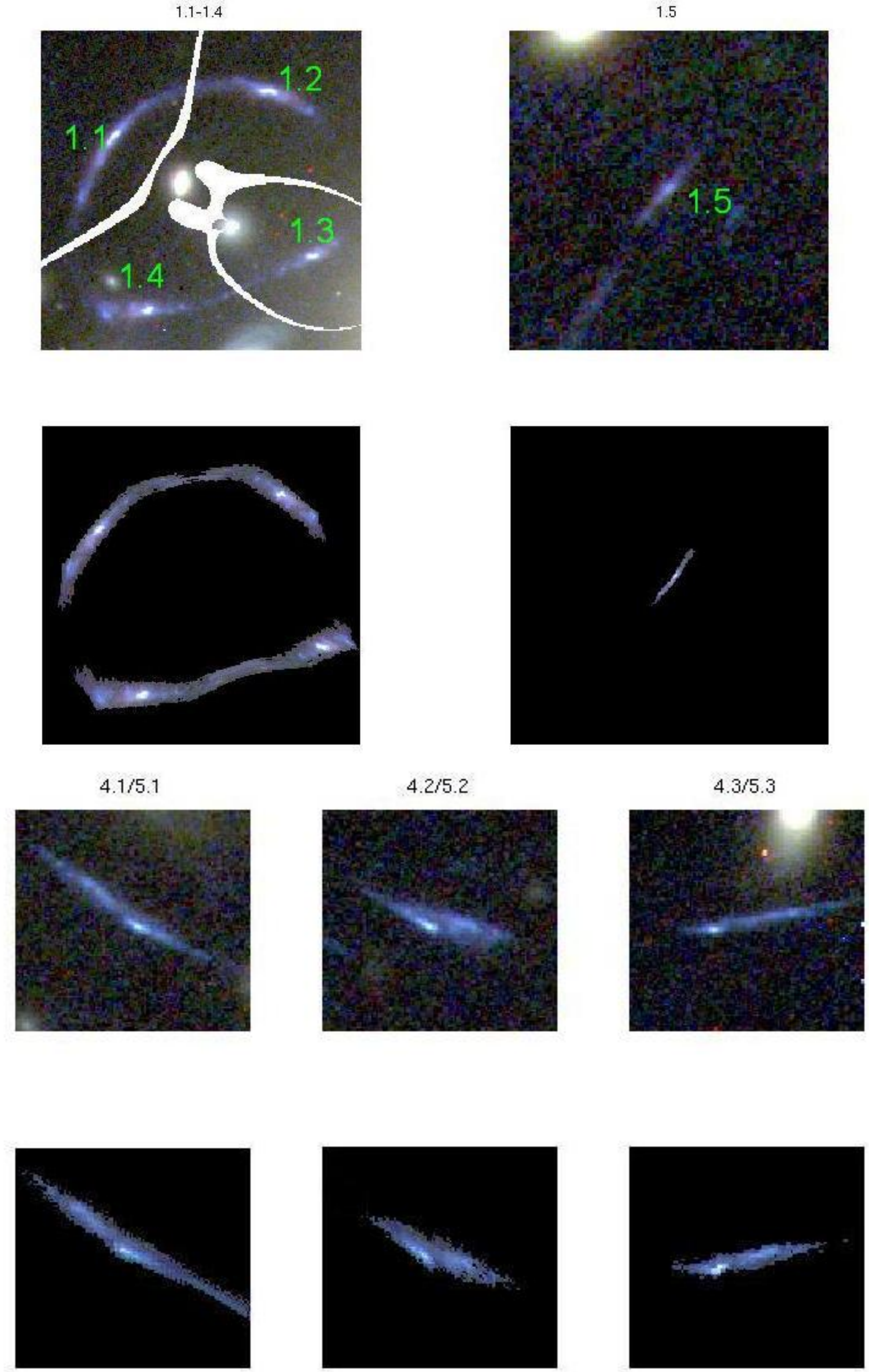
- Smooth the resulting mass dist. to obtain the (LTM) DM component:



Light Traces Mass (our method, Zitrin+)

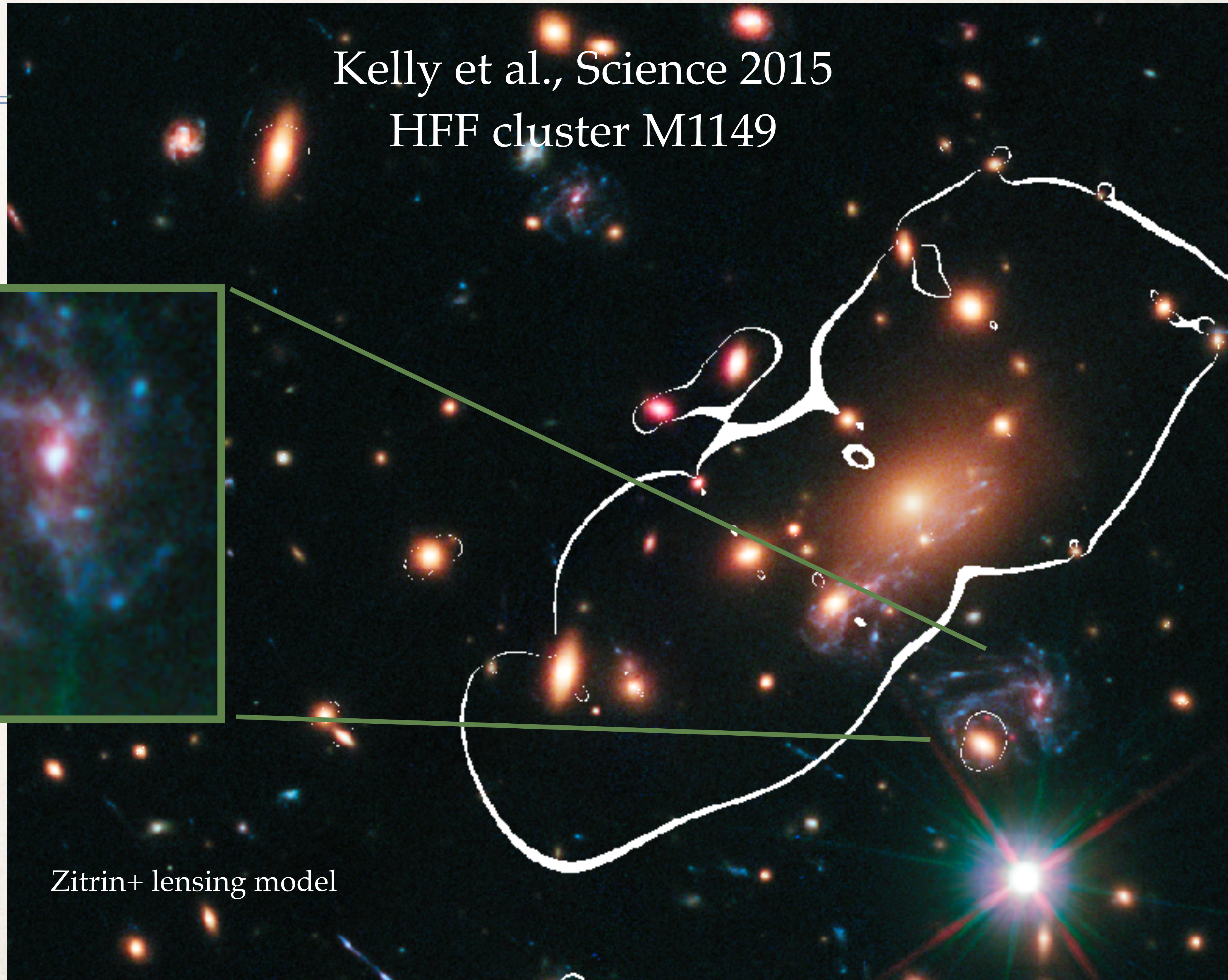



Zitrin+ & Liesenborgs+
2010, MNRAS, 408, 1916
Mult. images previously known


1.1-1.4
1.1
1.2
1.3
1.4
1.5
1.5
4.1/5.1
4.2/5.2
4.3/5.3

First Multiply-Imaged SN!

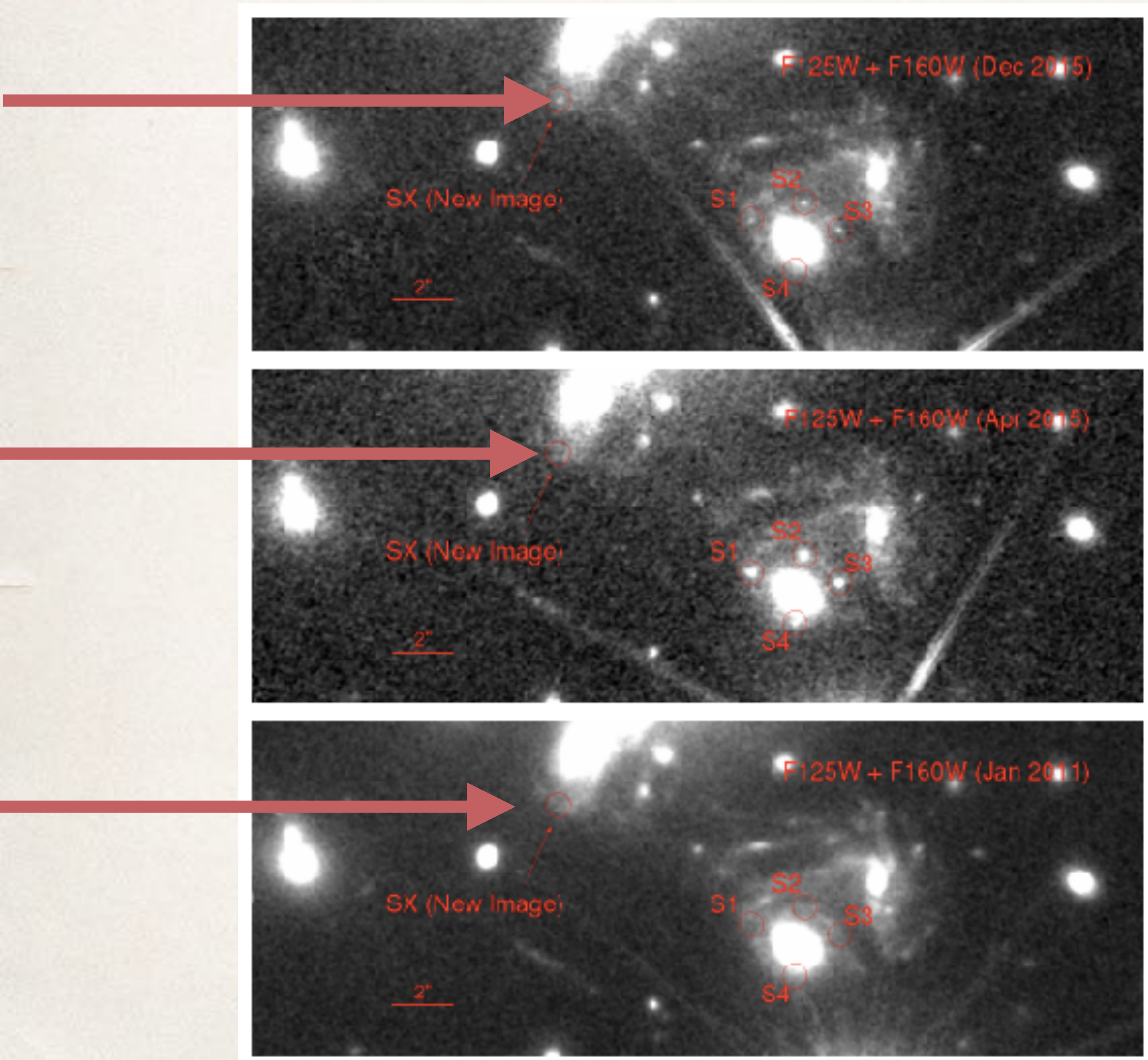
exactly 50 years after prediction

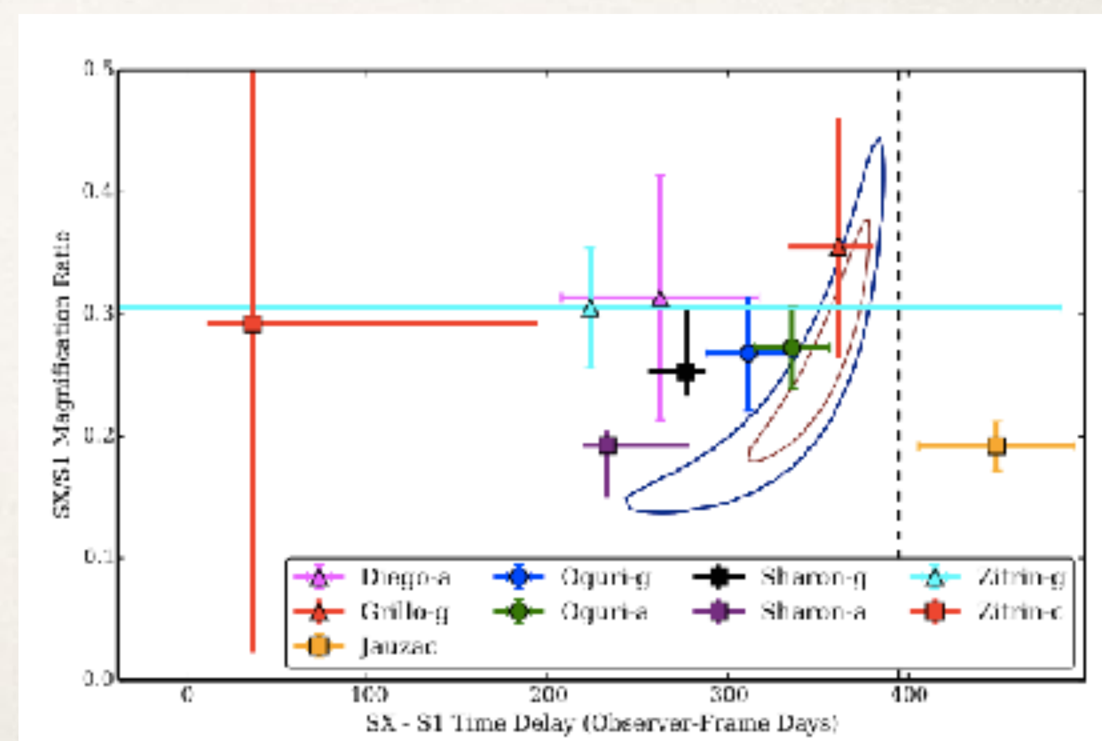


Can help break degeneracies in mass modeling

Reappearance (again!)

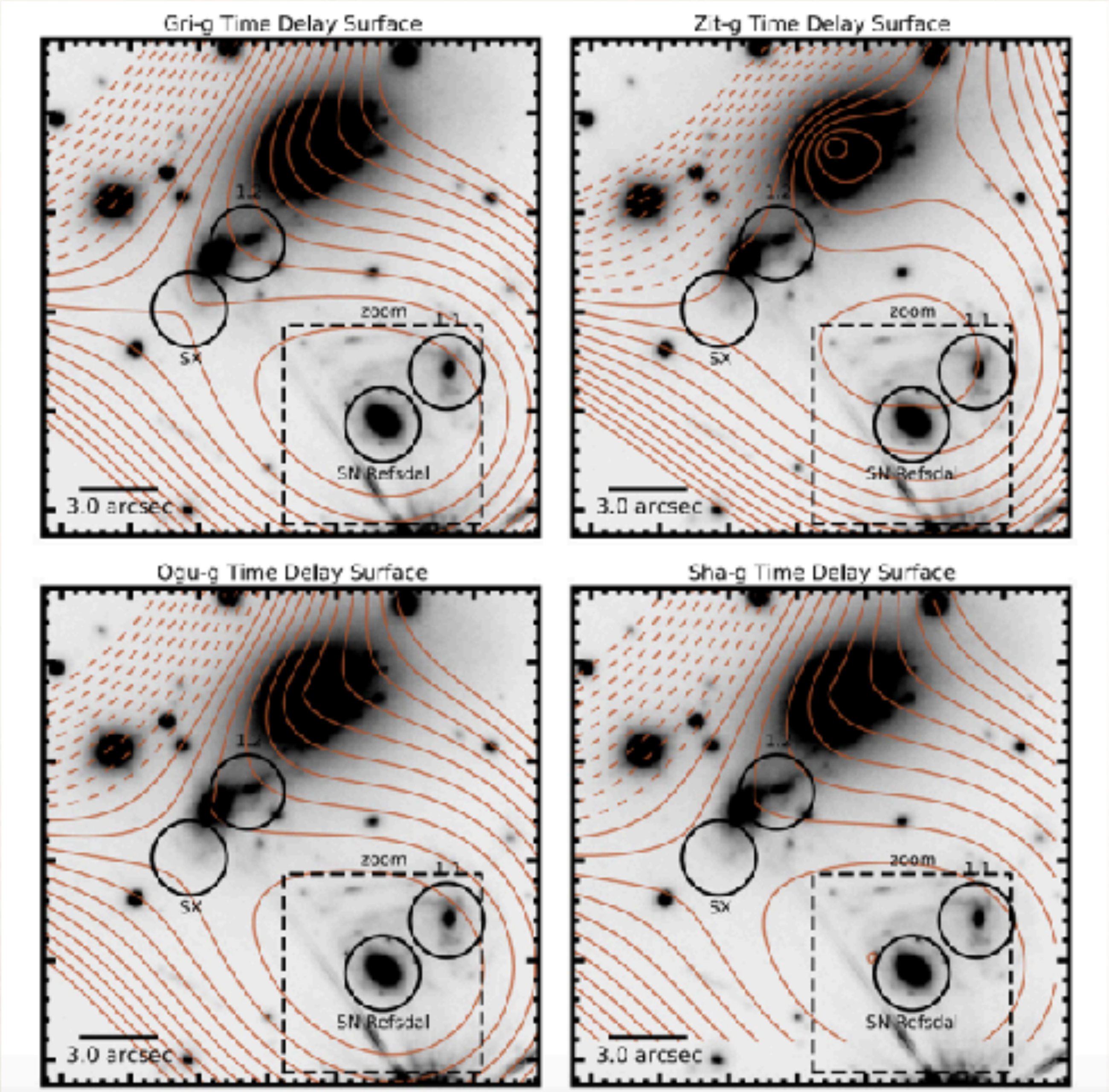
Kelly et al. 2016





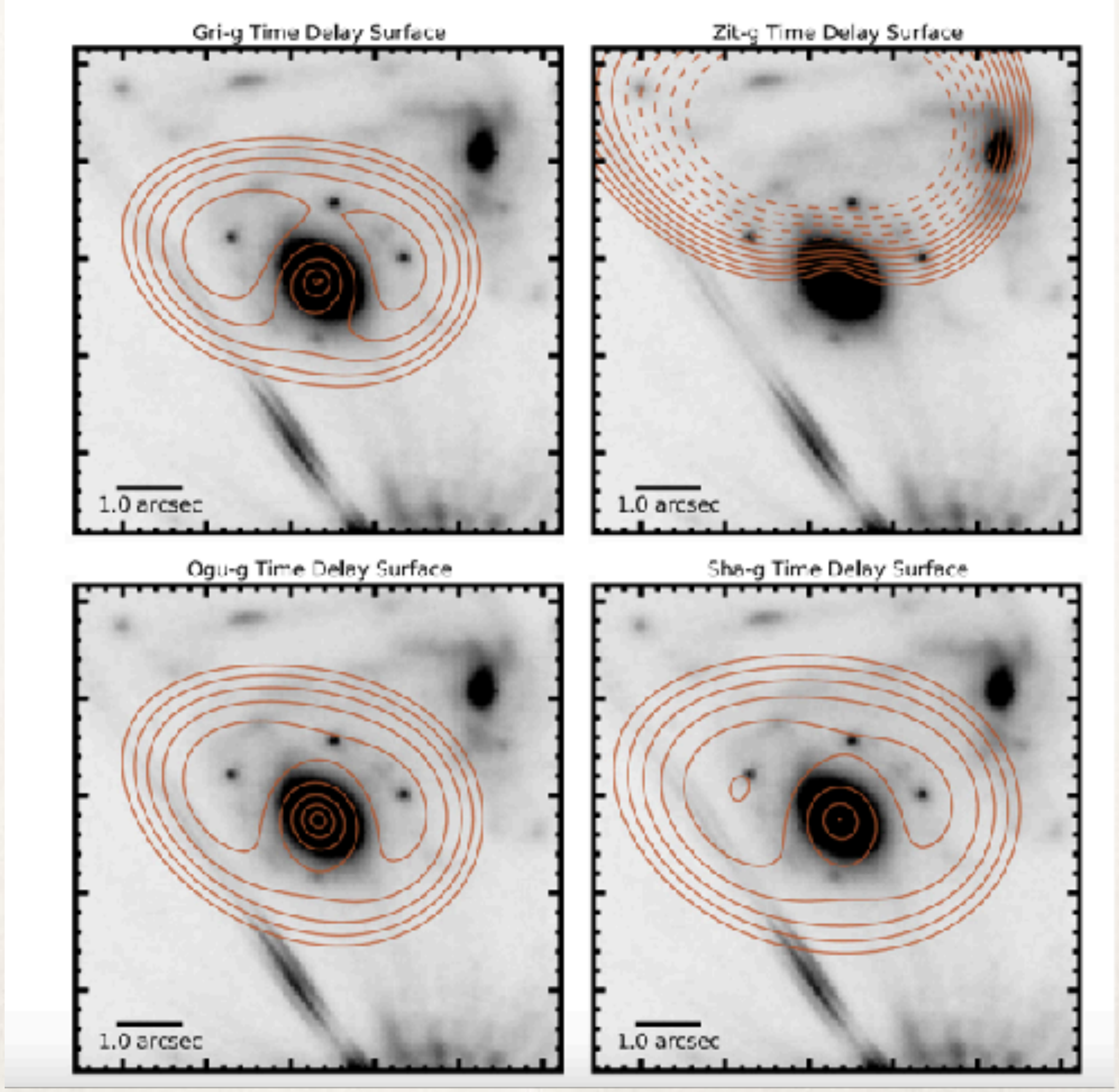
Reappearance (again!)

Treu et al 2016, see also Rodney et al. 2016



Reappearance (again!)

Treu et al 2016, see also Rodney et al. 2016



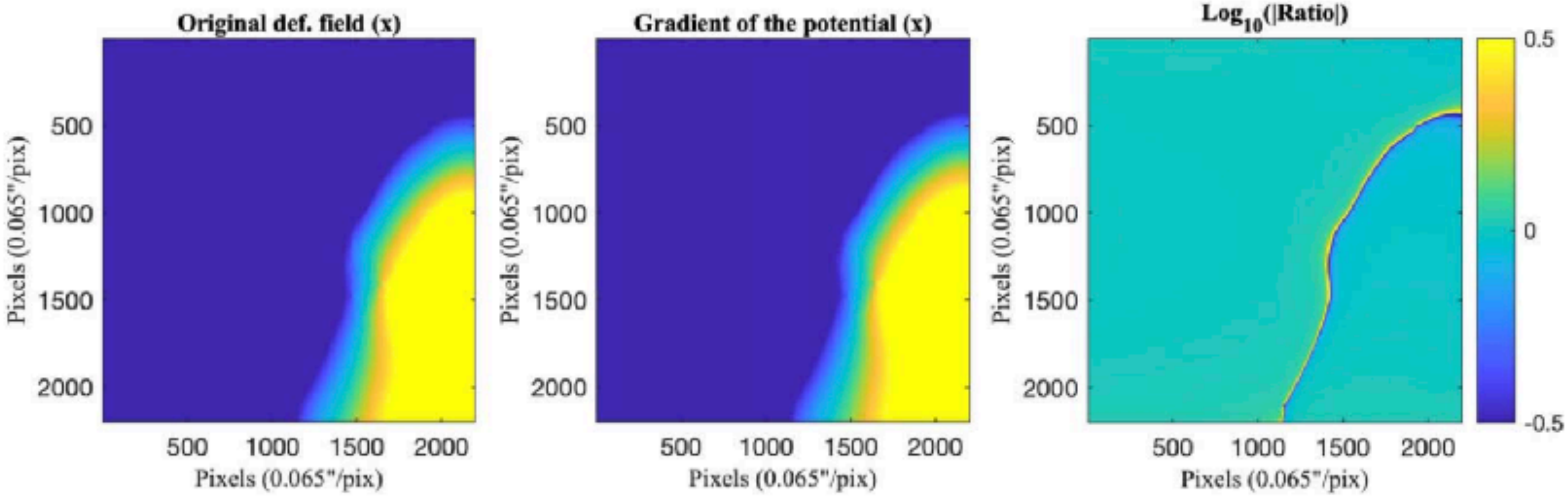


Figure 6. Residual from the calculation of the numerically integrated potential. Left: the original best-fit x-axis deflection field. Center: the derived x-axis deflection field obtained from the gradient of the (numerically integrated) potential. Right: $\log_{10}$ of the absolute value of the ratio of the two deflection fields. While the ratio equals unity in most of the field, a numerical residual is clearly seen. Values were limited to ± 0.5 to emphasize the artifact.

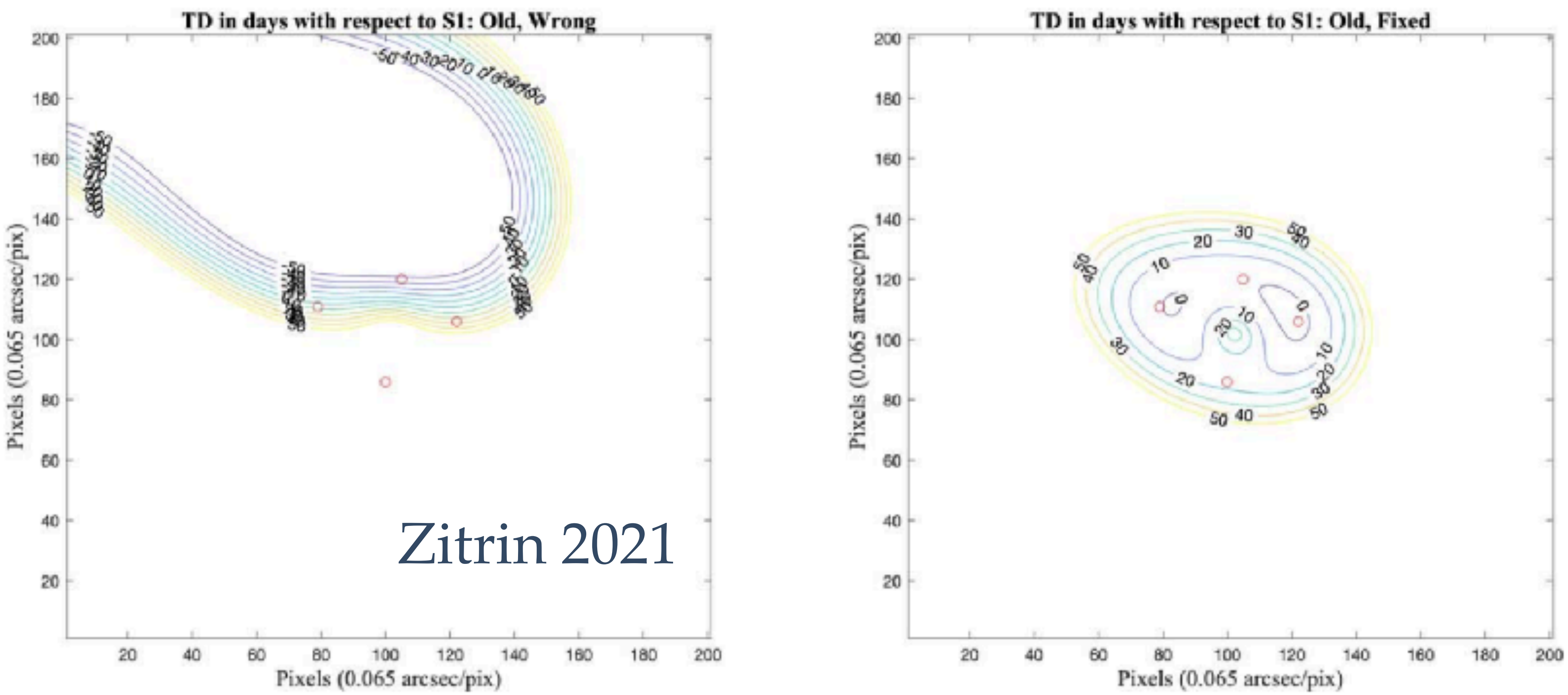
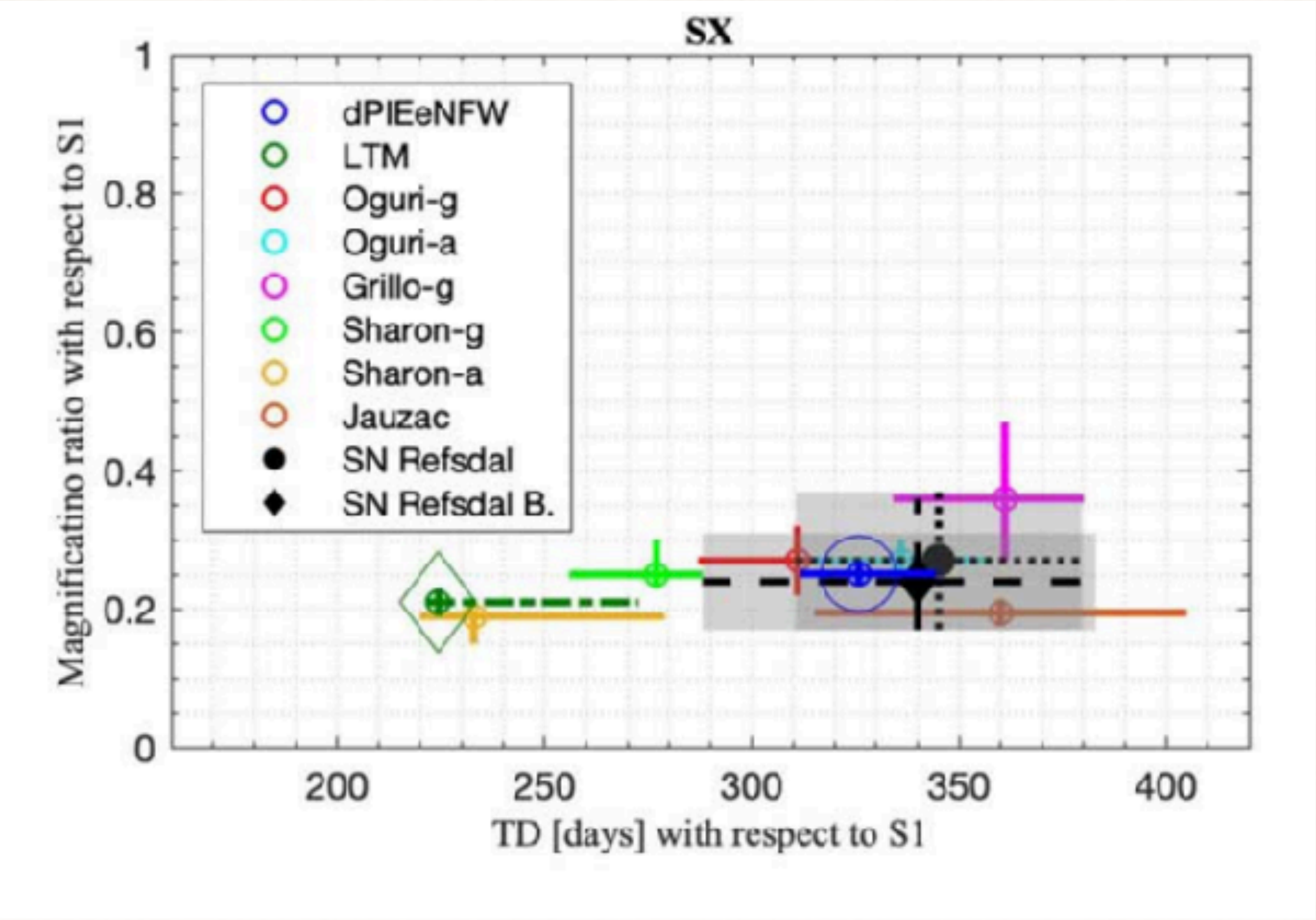


Figure 7. Contours for the TD surface from our old LTM model, in decrements of 10 days. Left: example of the deformed TD surface with the old code in which the potential and deflection fields were not perfectly self-consistent (potential obtained by numerical integration). Right: TD surface for the same old model, after correction to the code (the deflection field was taken directly to be the gradient of the (integrated) potential, see text). Red circles mark the positions of the four SN images of the Einstein cross. The TD surface from our new model presented in this work is shown in Figure 1 and the relevant values are listed in Table 1.


SX
dPIEeNFW
LTM
Oguri-g
Oguri-a
Grillo-g
Sharon-g
Sharon-a
Jauzac
SN Refsdal
SN Refsdal B.
Magnificatino ratio with respect to S1
TD [days] with respect to S1
0
0.2
0.4
0.6
0.8
1
200
250
300
350
400

Zitrin 2021

d. Constraining H_0 via time delays

Each image arrives at a different time

$$t(\vec{\theta}) = \frac{(1+z_d)}{c}\frac{D_d D_s}{D_{ds}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi(\vec{\theta})\right]$$
$$= t_{geom} + t_{grav} .$$

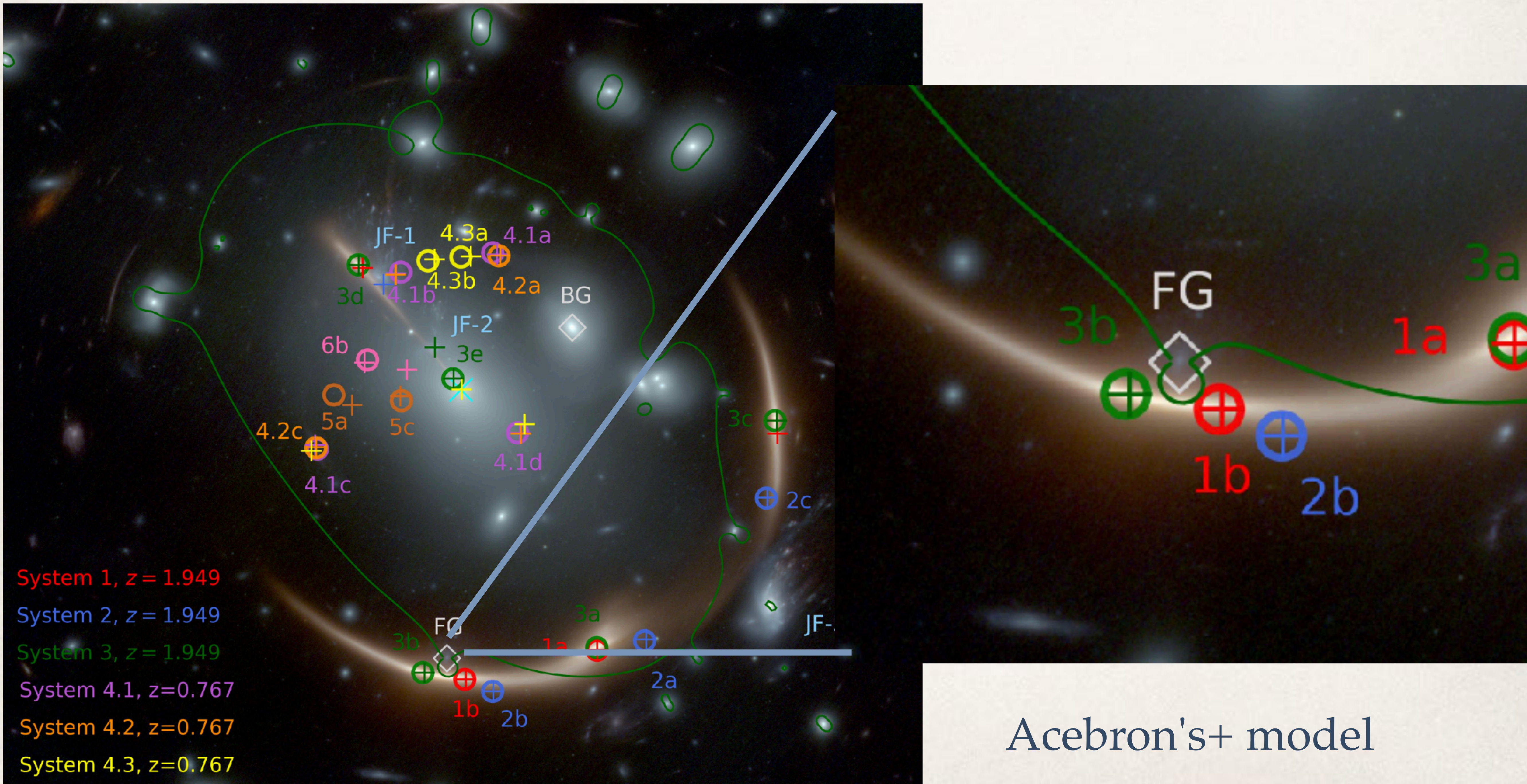
Refsdal 1964

where D (and thus)
Delta_t is proportional to 1/H_0
(Hubble parameter today)

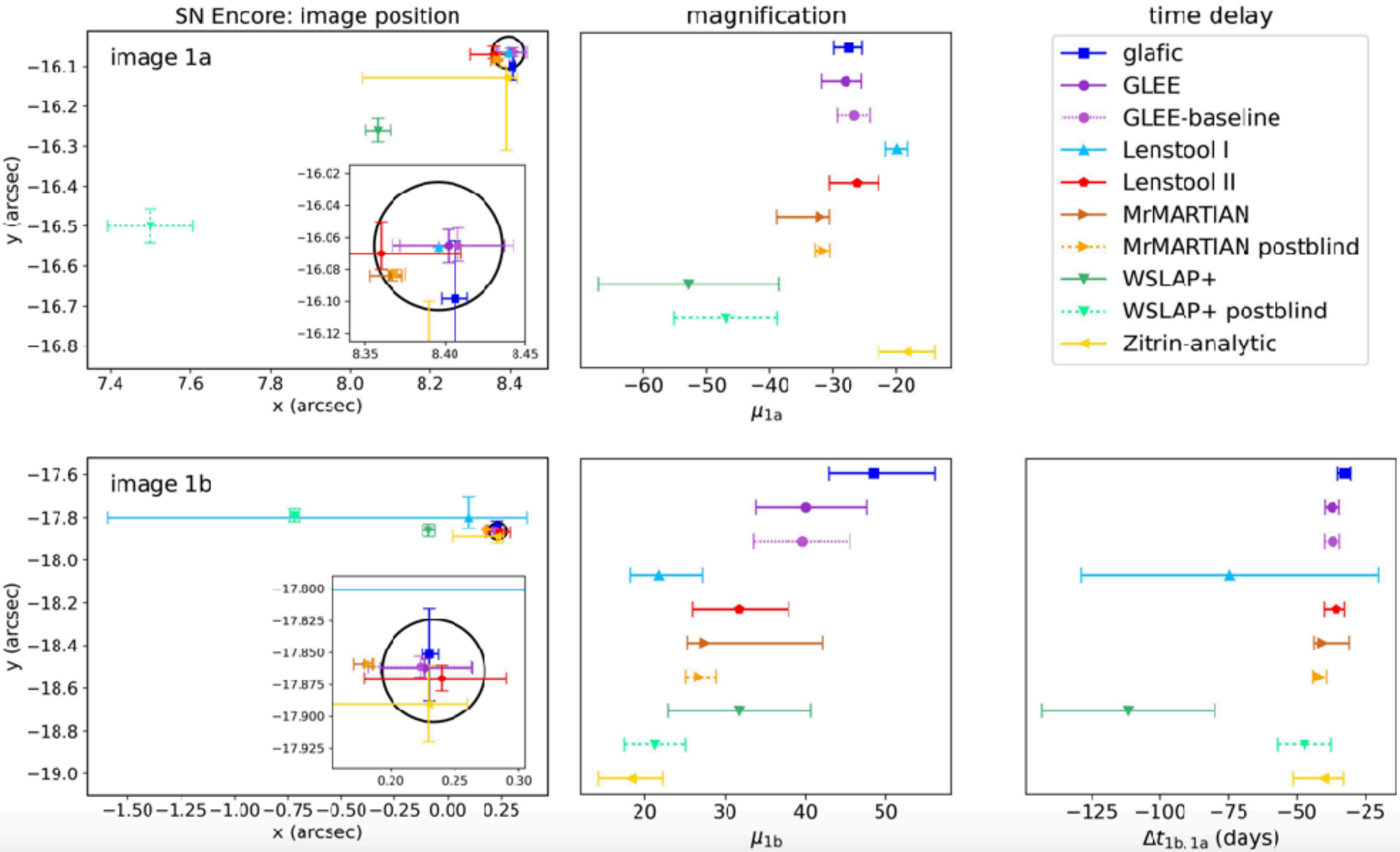
from this we know that
H_0 ~70 km/s/ Mpc

5. Mu-TD biases ?

5. SN Encore Mu-TD biases?



Acebron's+ model


SN Encore: image position
magnification
time delay
image 1a
image 1b
y (arcsec)
x (arcsec)
μ_{1a}
μ_{1b}
$\Delta t_{1b,1a}$ (days)
glafic
GLEE
GLEE-baseline
Lenstool I
Lenstool II
MrMARTIAN
MrMARTIAN postblind
WSLAP+
WSLAP+ postblind
Zitrin-analytic

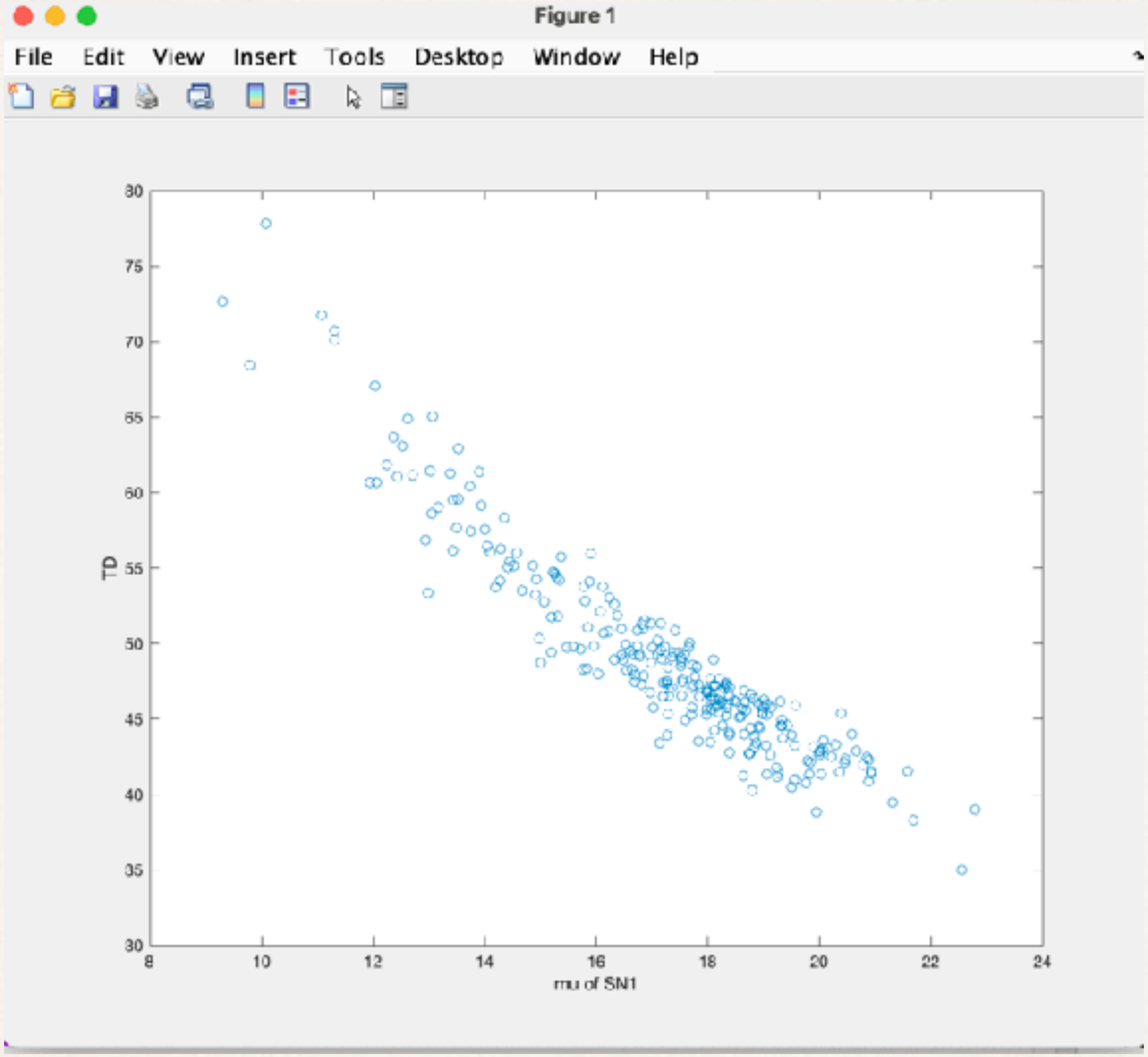


Figure 1
File Edit View Insert Tools Desktop Window Help
80
75
70
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60
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TD
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16
18
20
22
24
mu of SN1

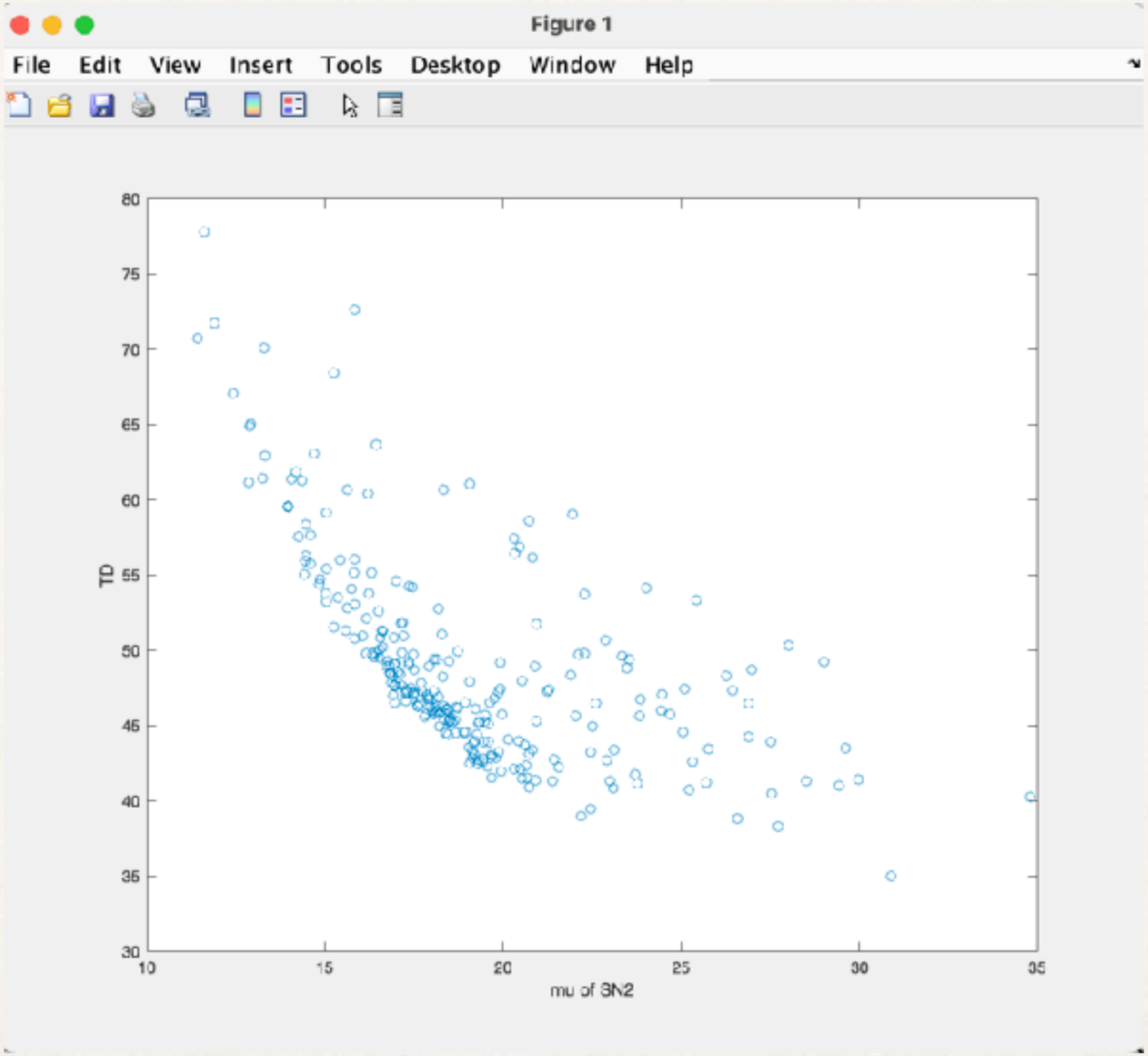
Figure 1
File Edit View Insert Tools Desktop Window Help
TD
mu of SN2
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35

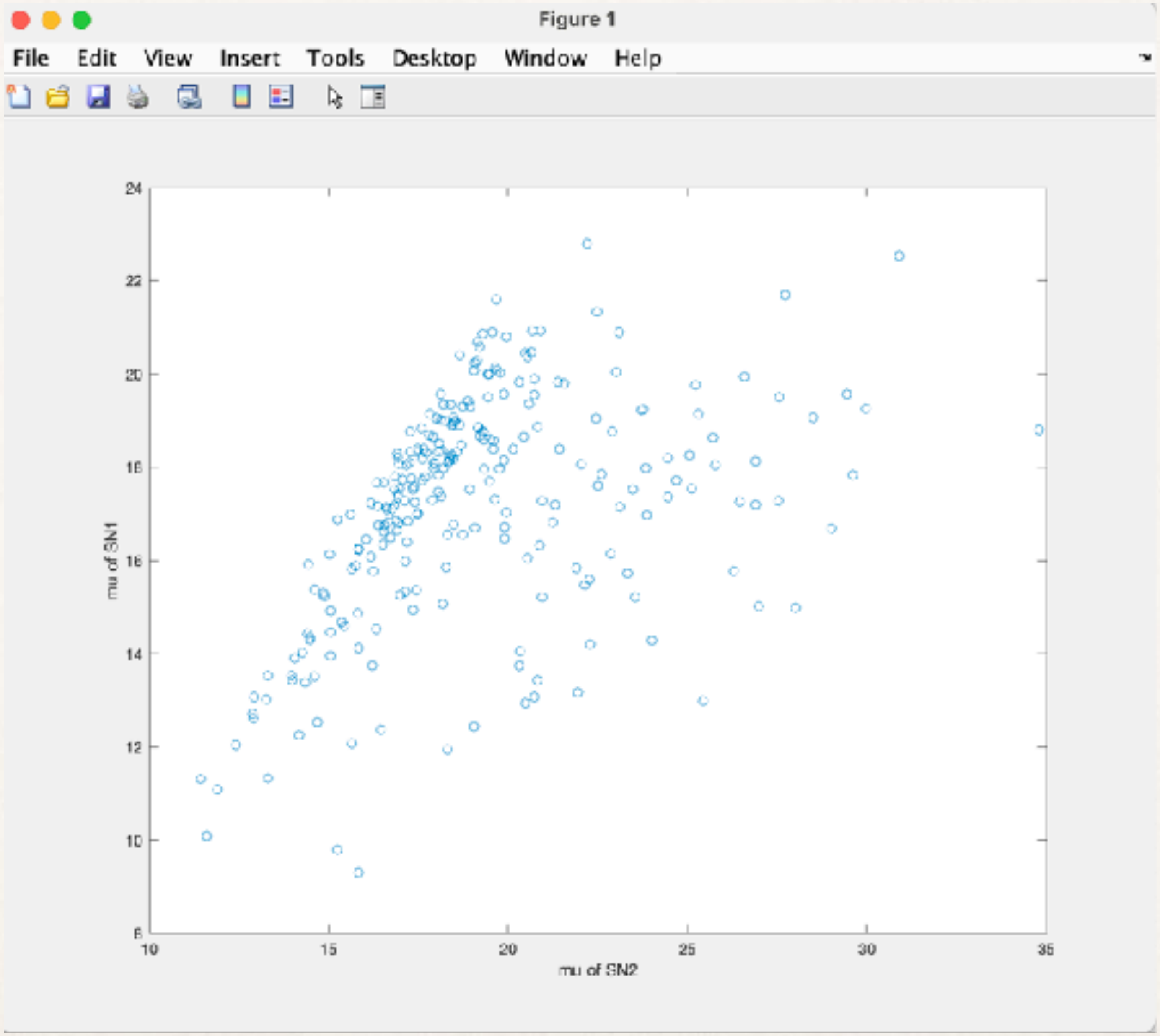
Figure 1
File Edit View Insert Tools Desktop Window Help
mu of SN1
mu of SN2
24
22
20
18
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12
10
8
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15
20
25
30
35

Summary

1. Time delays change with time, too —> real-time cosmology

2. TDs and LRDs (and other AGN, reverberation mapping)

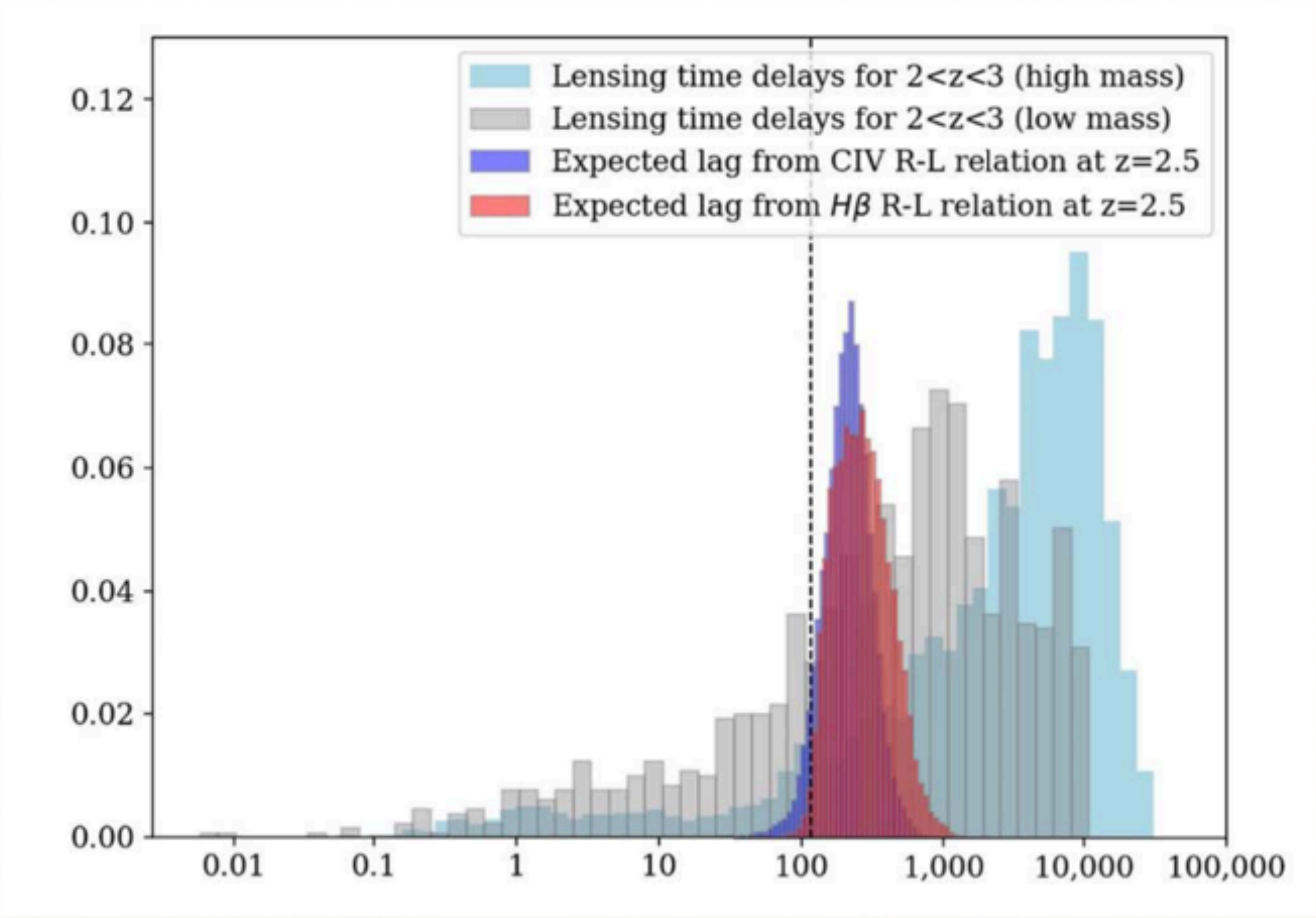
3. How TDs led to the detection the farthest known supernovae Eos

4. (Always?) start from the potential

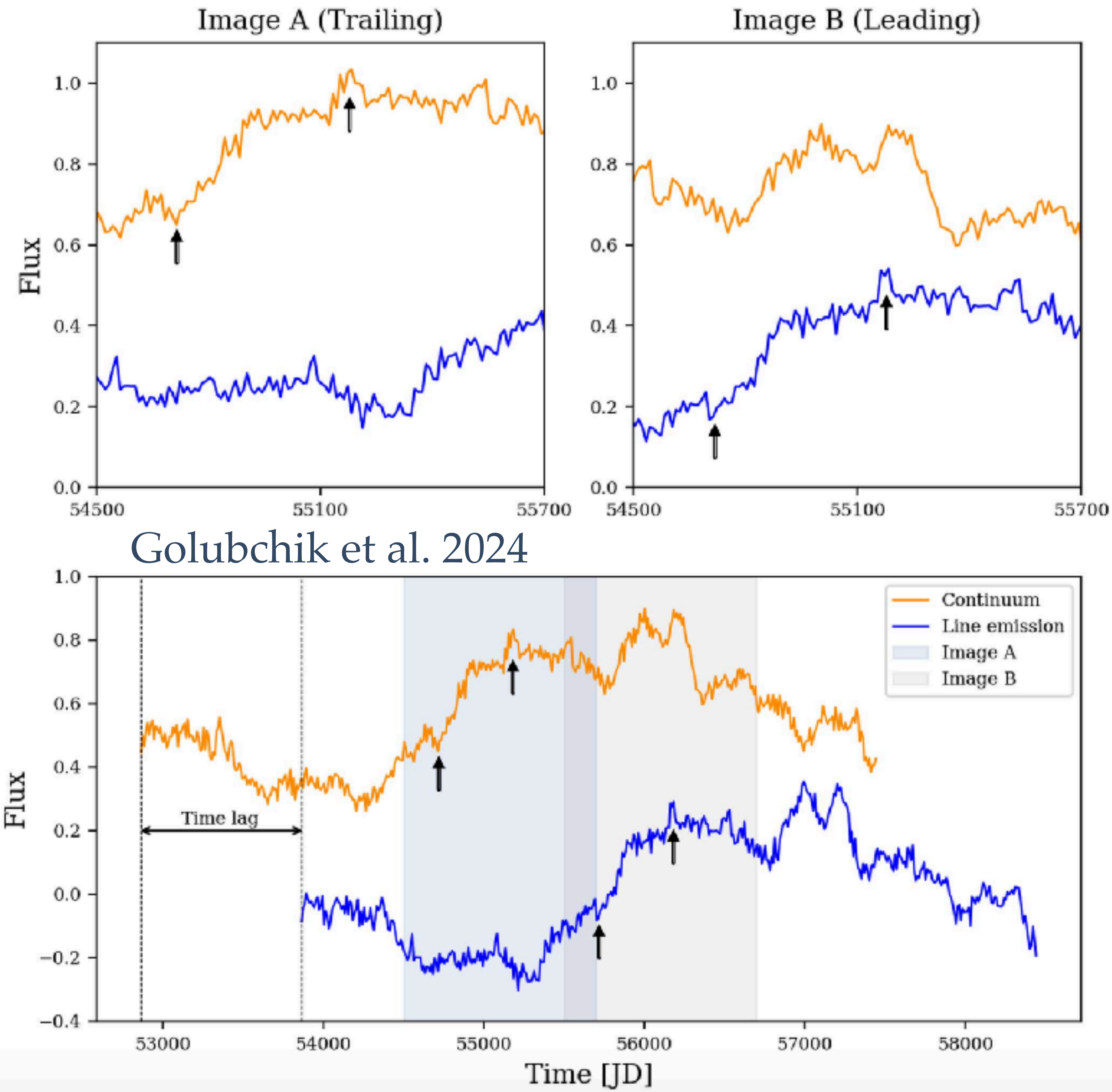
5. Mu-TD biases from inclusion of local cluster members/ other factors (investigation in progress…)

Thank you

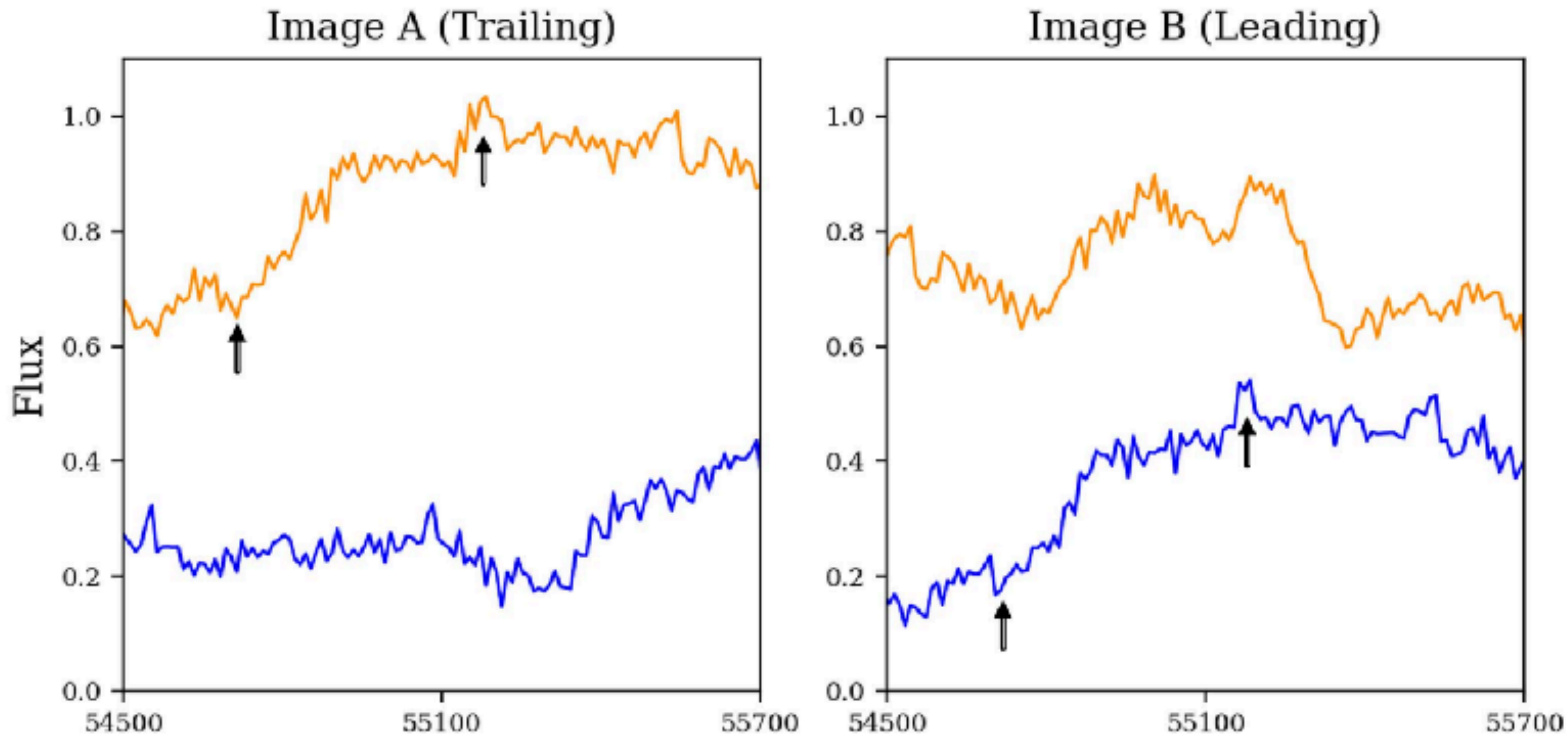
Golubchik et al. 2024



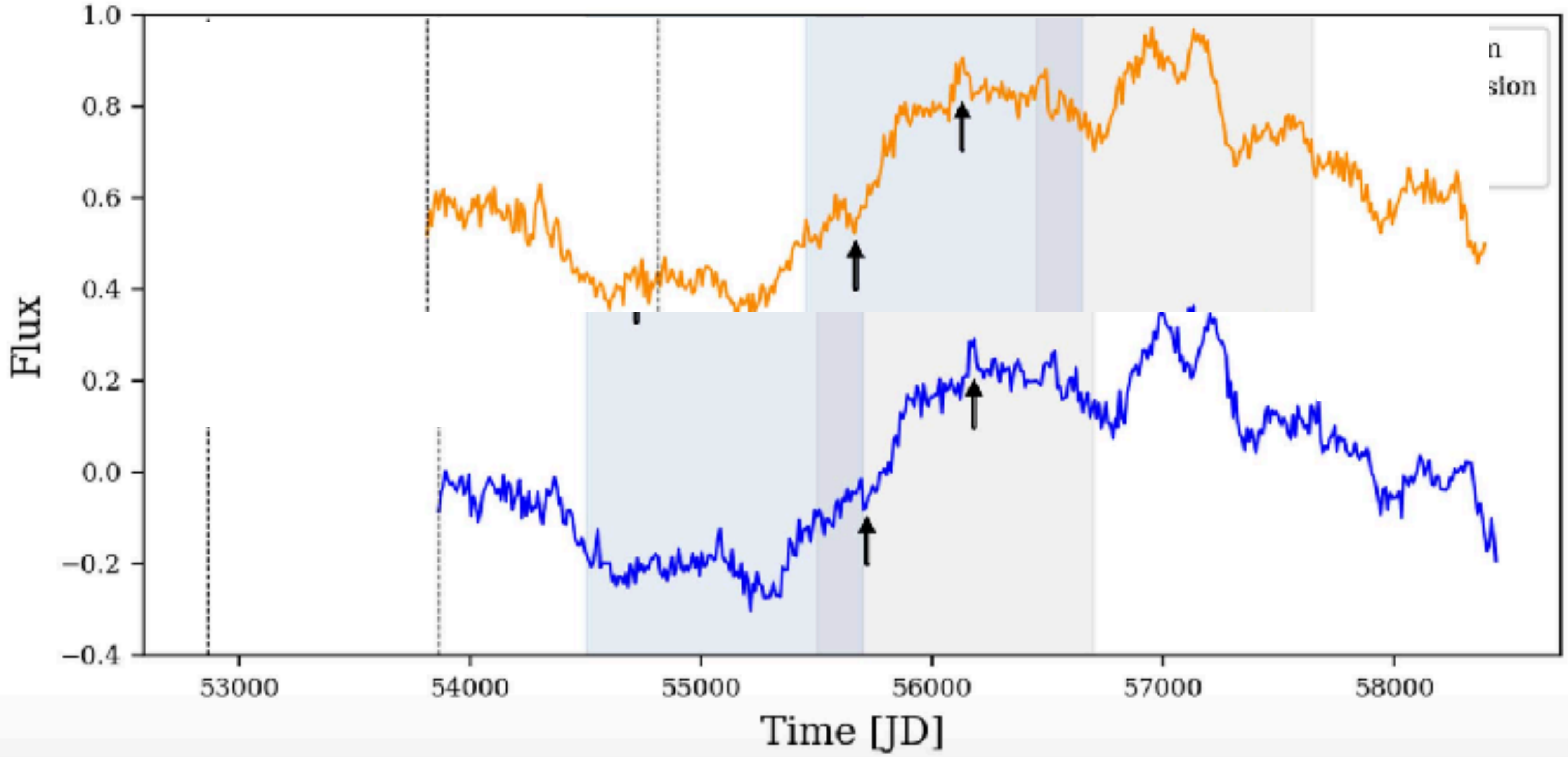
TD [days]



Golubchik et al. 2024



Golubchik et al. 2024



In fact, something similar was already done also in practice: Williams, Treu et al. 2021