Cosmological applications of strong lenses in LSST

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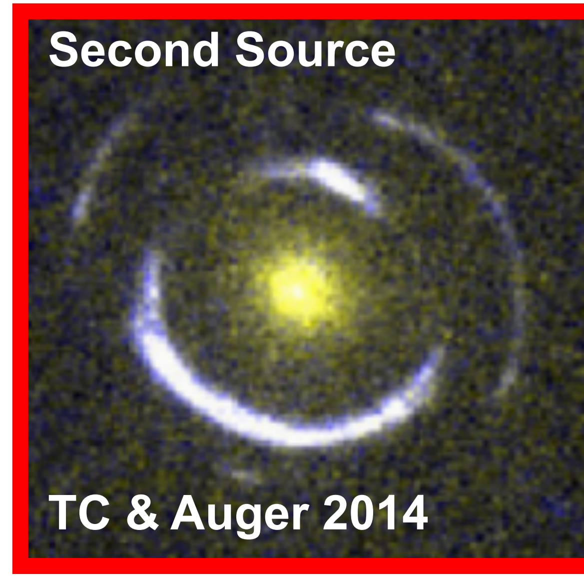
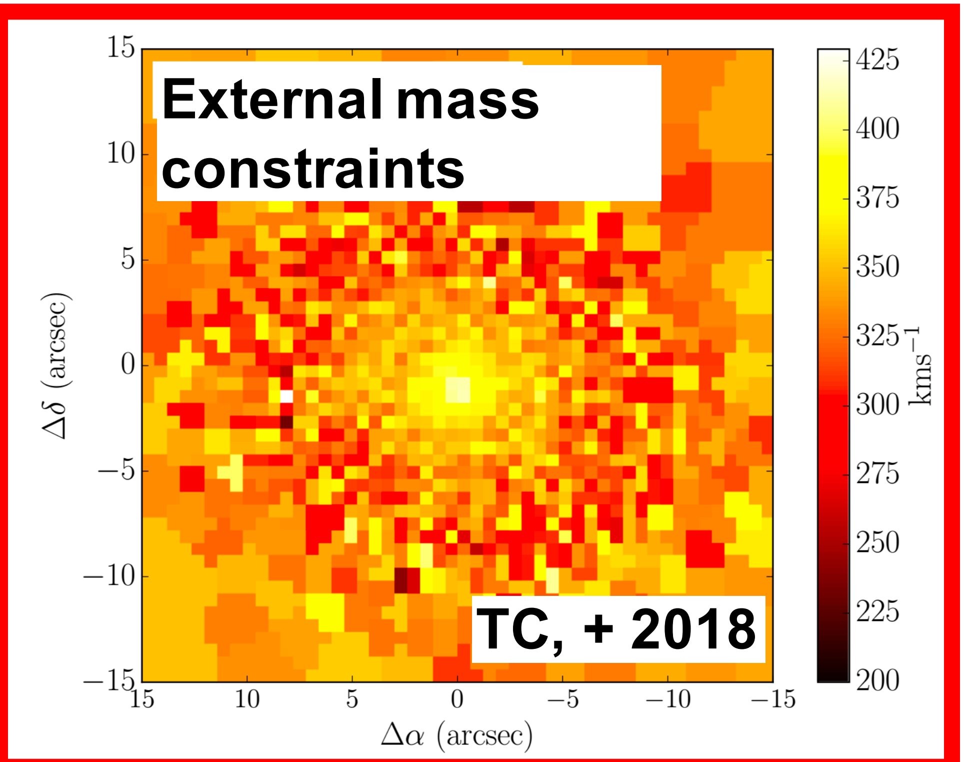
$$\theta_{\mathrm{E}} = \sqrt{\frac{GM(\theta_{\mathrm{E}})}{c^2} \frac{D_{\mathrm{ls}}}{D_{\mathrm{ol}} D_{\mathrm{os}}}}$$

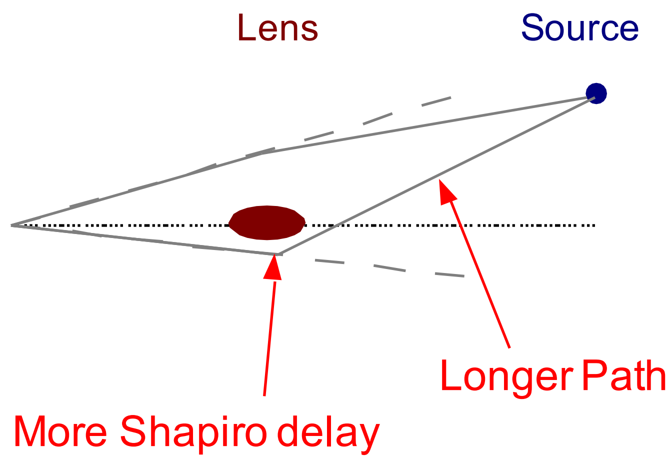
Three paths forward

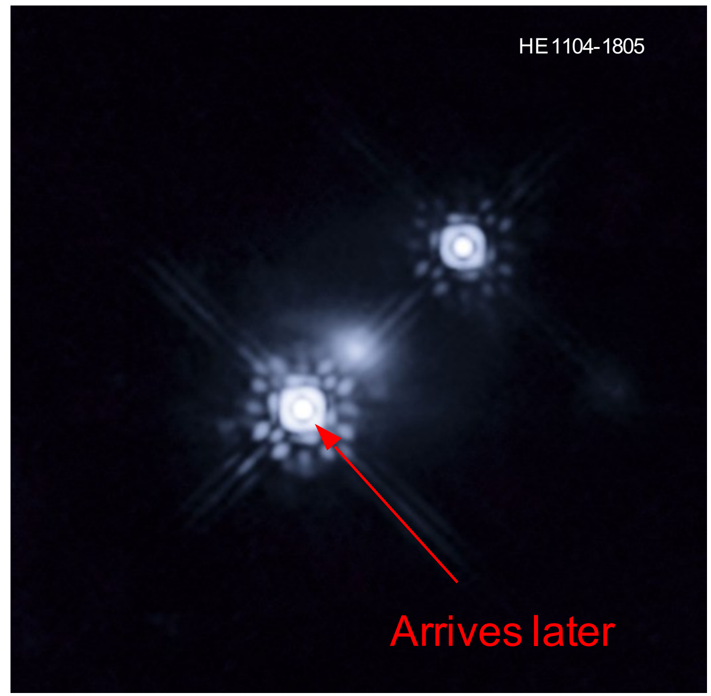
$$\theta_E = \sqrt{\frac{GM(\theta_E)}{c^2}\frac{D_{ls}}{D_{ol}D_{os}}}$$





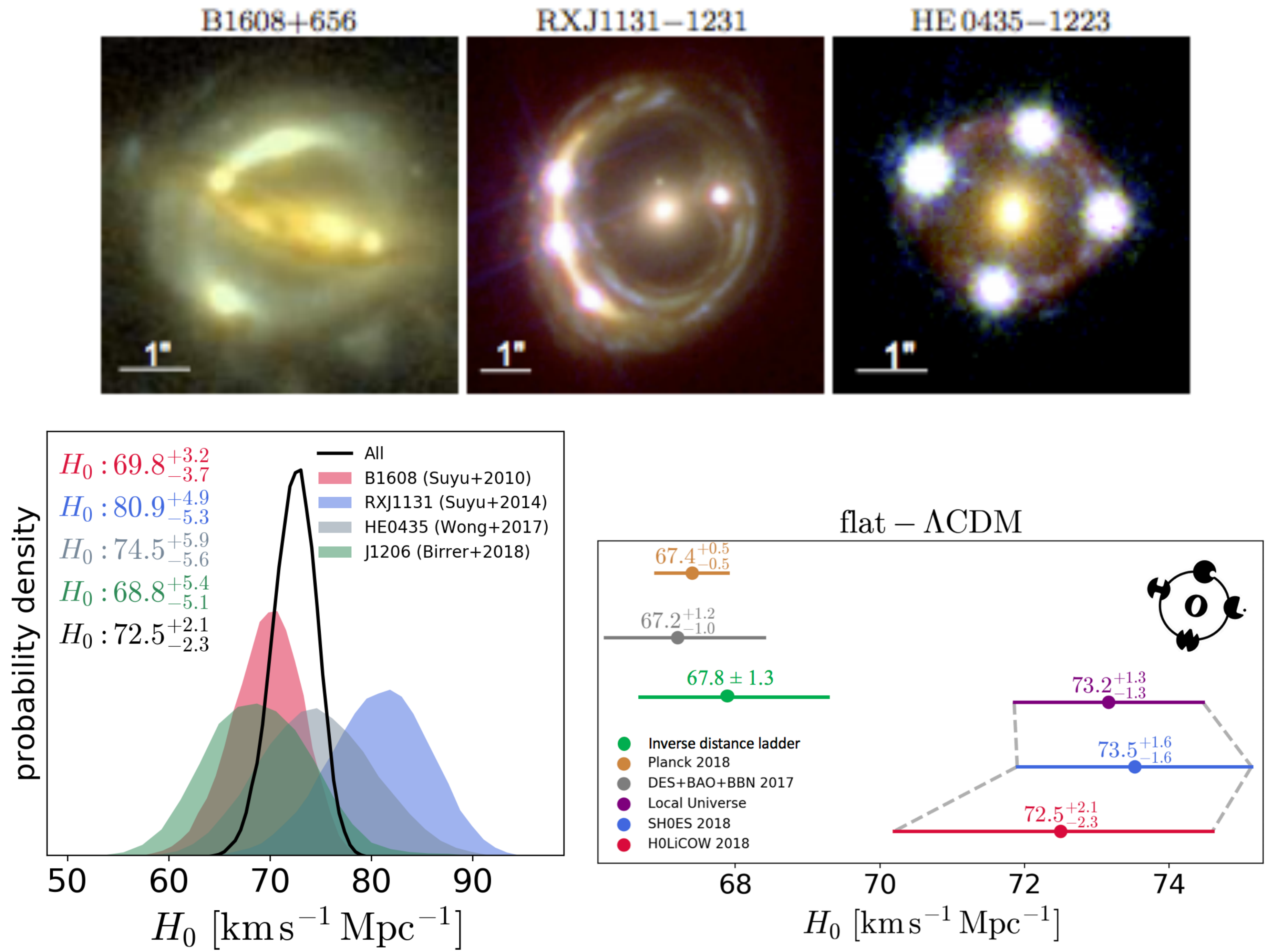
Strong lensing time delays



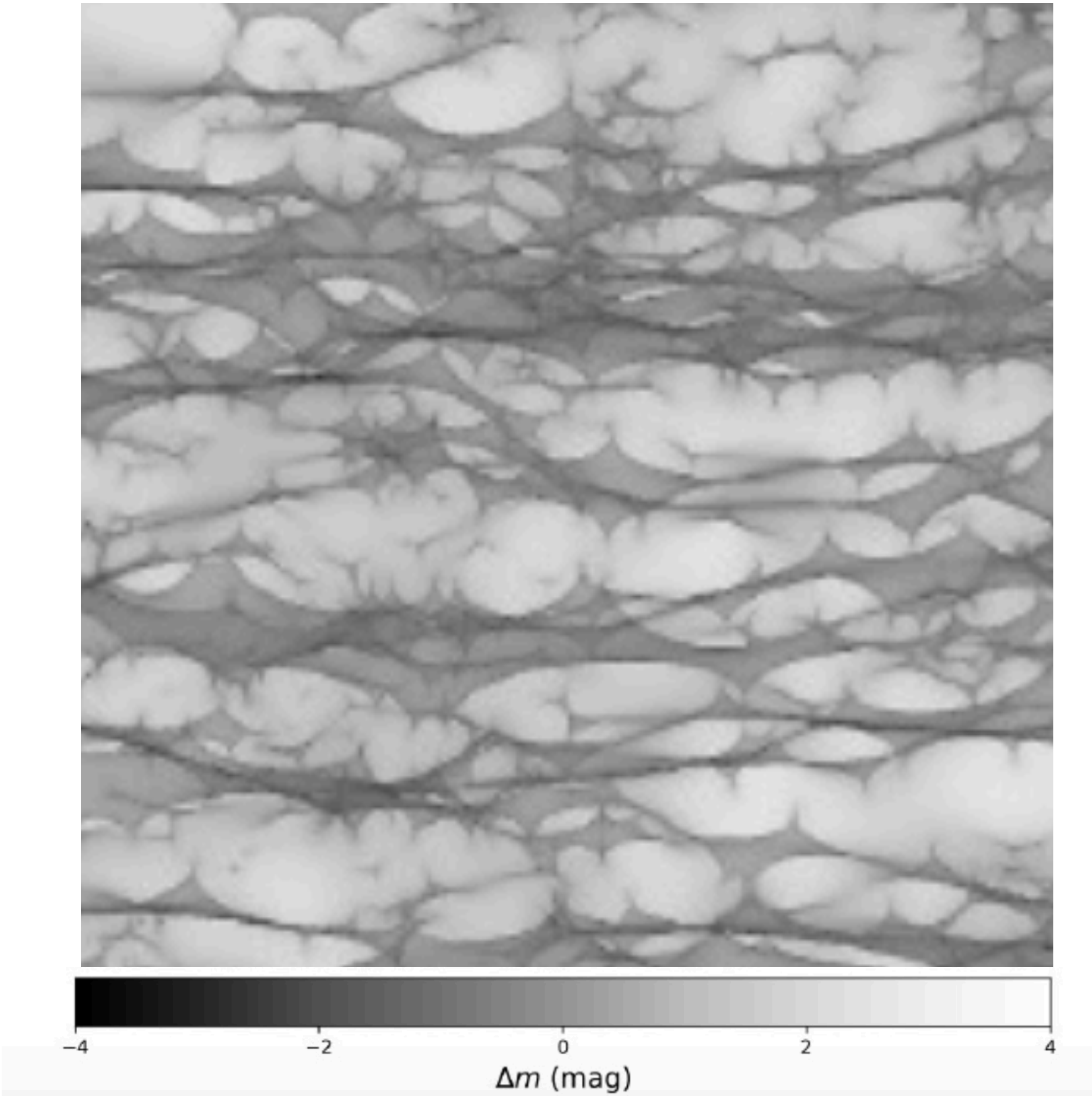


$$\Delta t \quad \propto \quad D_{\Delta t} = (1 + z_l)\ (D_l D_s)/D_{ls}$$

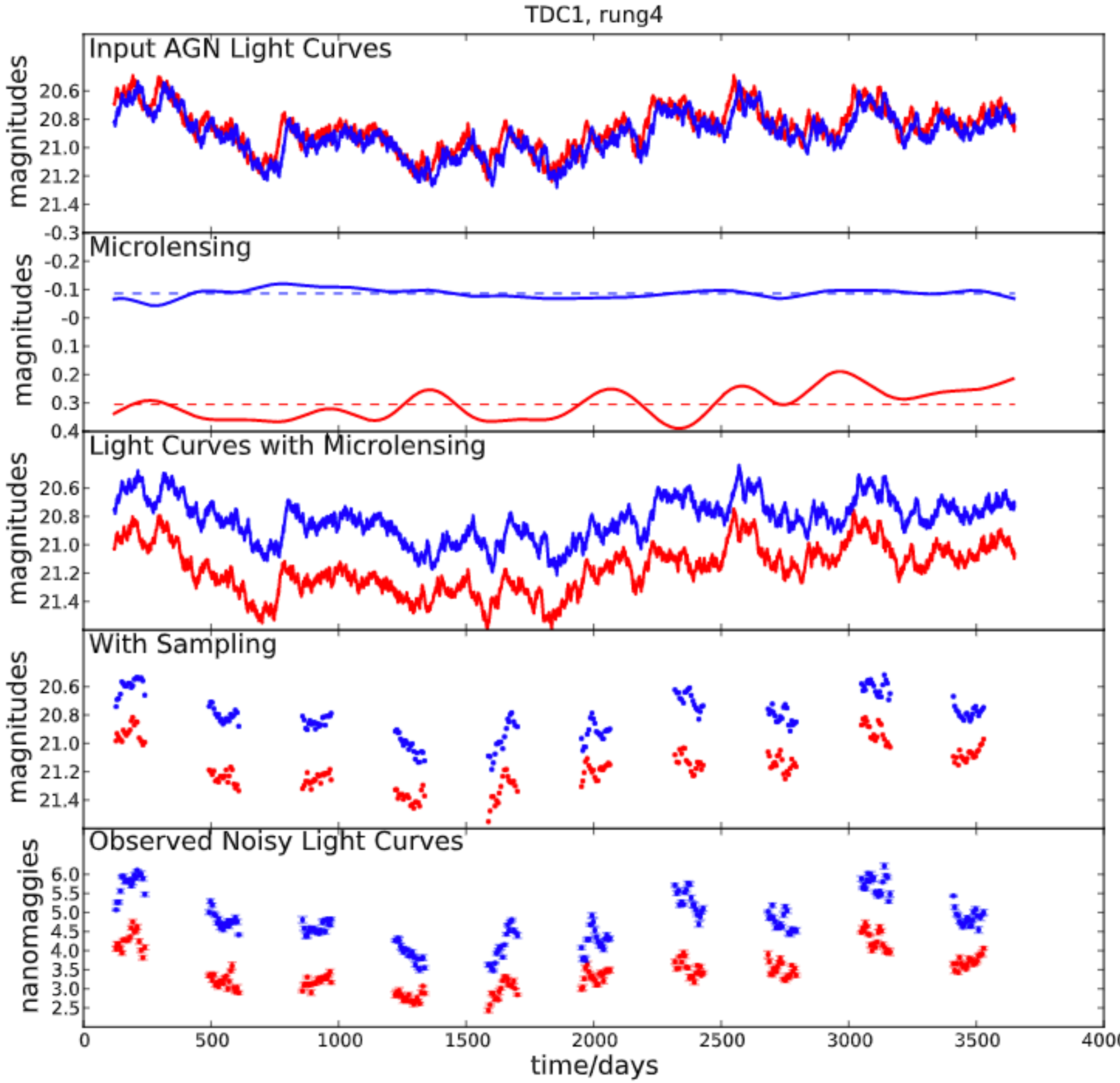
Most sensitive to the Hubble constant.

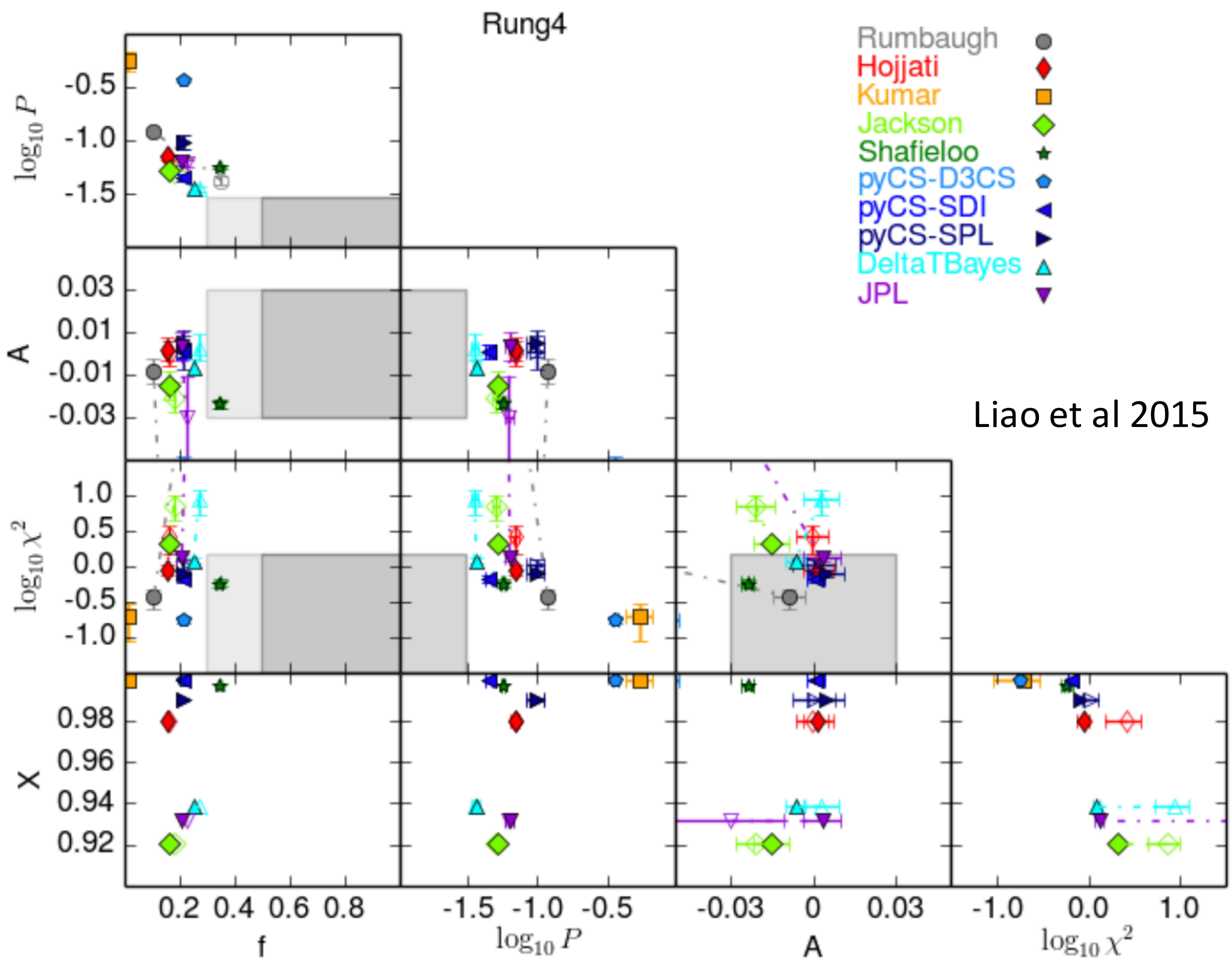


B1608+656
RXJ1131−1231
HE 0435−1223
1"
1"
1"
$H_0: 69.8^{+3.2}_{-3.7}$
$H_0: 80.9^{+4.9}_{-5.3}$
$H_0: 74.5^{+5.9}_{-5.6}$
$H_0: 68.8^{+5.4}_{-5.1}$
$H_0: 72.5^{+2.1}_{-2.3}$
All
B1608 (Suyu+2010)
RXJ1131 (Suyu+2014)
HE0435 (Wong+2017)
J1206 (Birrer+2018)
probability density
50
60
70
80
90
H_0 [km s^{-1} Mpc^{-1}]
flat − ΛCDM
$67.4^{+0.5}_{-0.5}$
$67.2^{+1.2}_{-1.0}$
67.8 ± 1.3
$73.2^{+1.3}_{-1.3}$
$73.5^{+1.6}_{-1.6}$
$72.5^{+2.1}_{-2.3}$
Inverse distance ladder
Planck 2018
DES+BAO+BBN 2017
Local Universe
SH0ES 2018
H0LiCOW 2018
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]

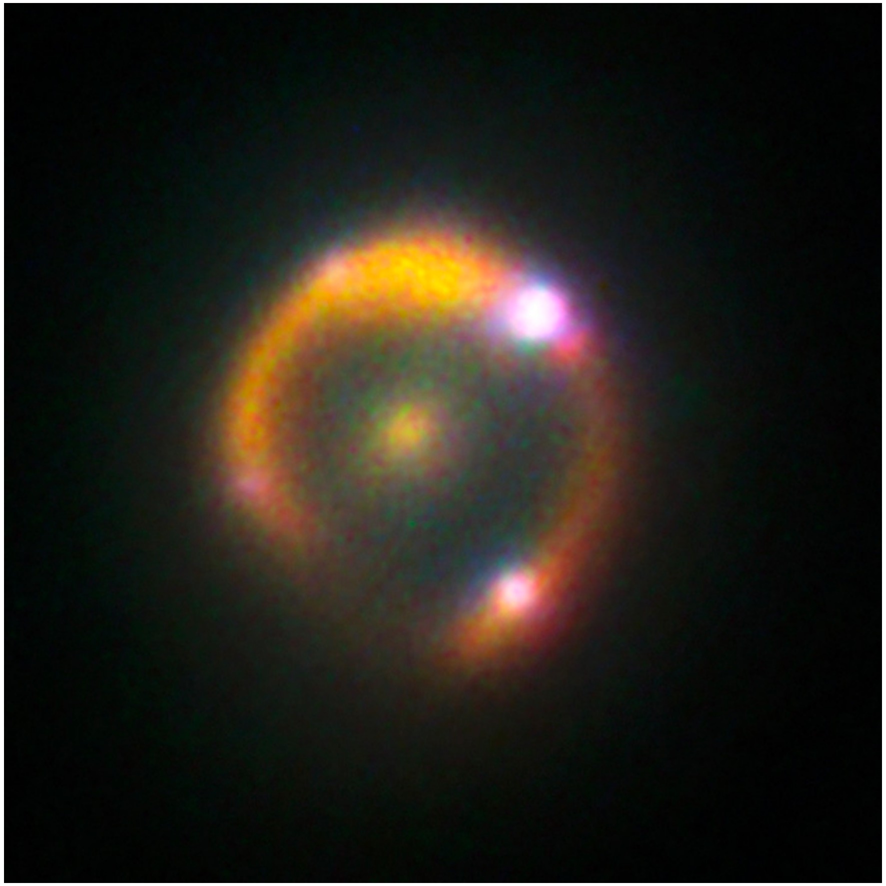


−4
−2
0
2
4
Δm (mag)


TDC1, rung4
Input AGN Light Curves
Microlensing
Light Curves with Microlensing
With Sampling
Observed Noisy Light Curves
magnitudes
nanomaggies
time/days
20.6
20.8
21.0
21.2
21.4
-0.3
-0.2
-0.1
-0
0.1
0.2
0.3
0.4
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
0
500
1000
1500
2000
2500
3000
3500
4000



yield significantly higher f than does sparser sampling. Taking the results of TDC1 at face value, we estimate that LSST should provide around 400 robust time-delay measurements, each with $P < 0.03$ and $|A| < 0.01$, comparable to current lens modeling uncertainties. In terms of observing strategies, we find that A and f depend mostly on season length, while P depends mostly on cadence and campaign duration.

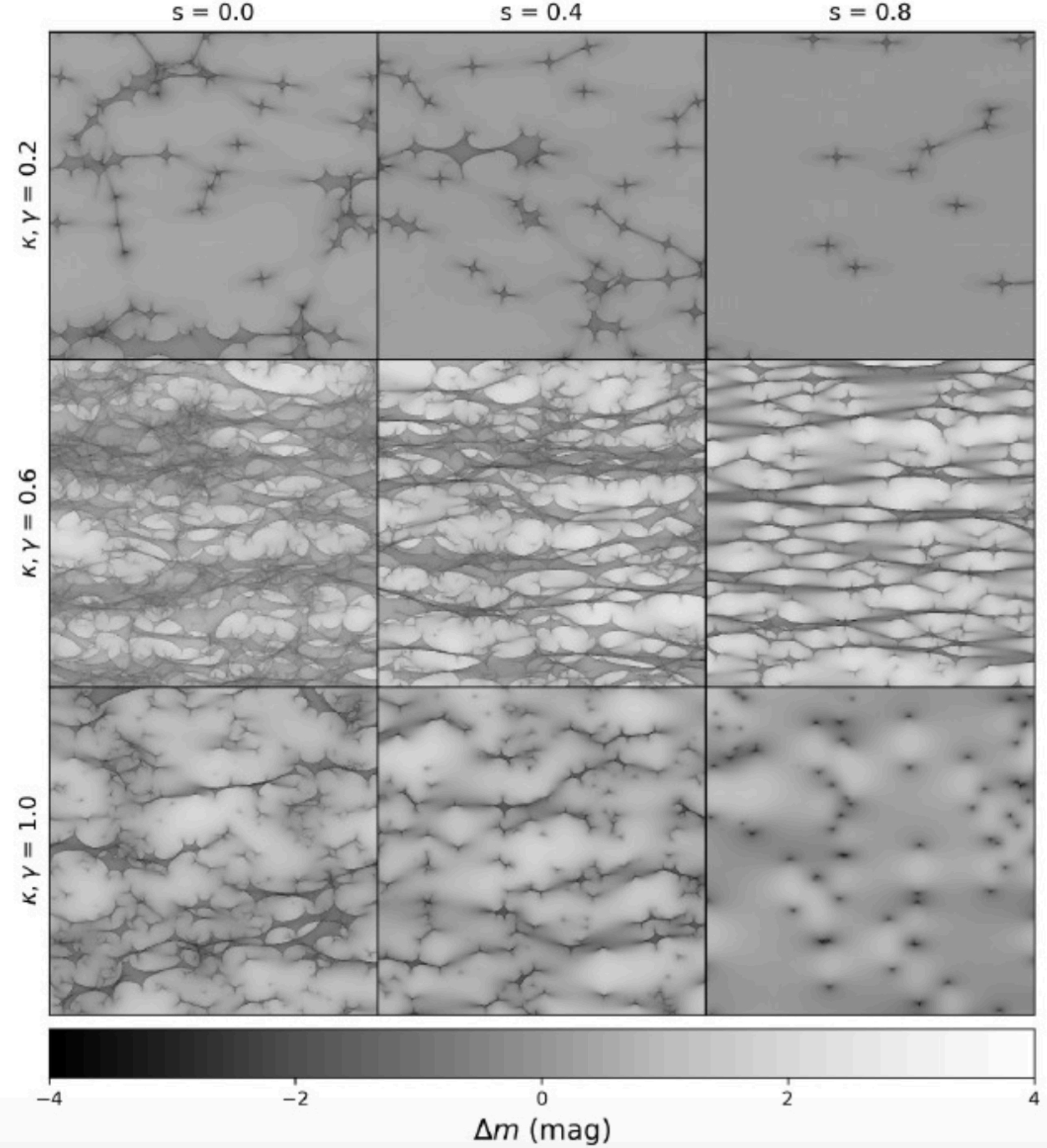


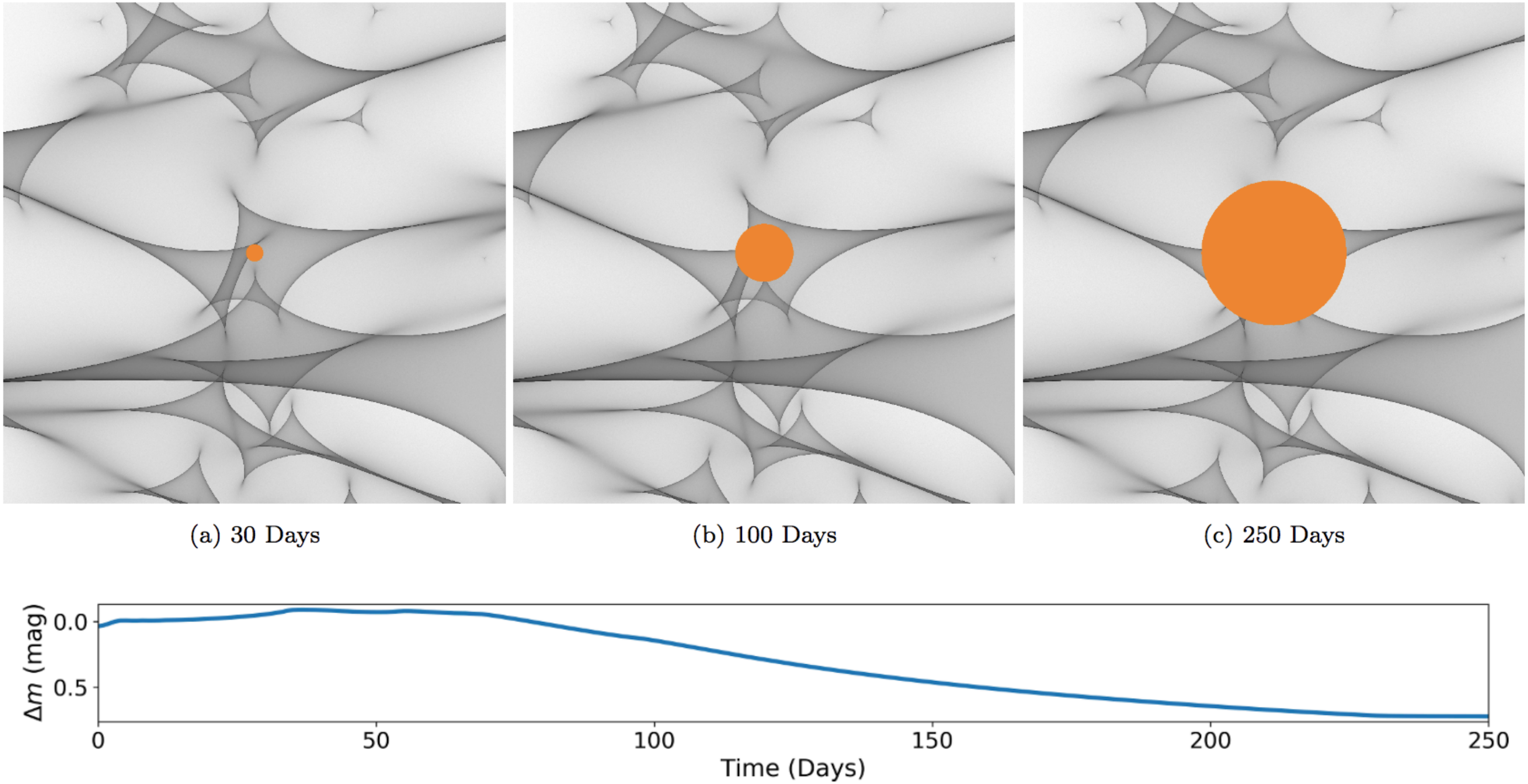
Lensed type Ia SNe

- LSST will **discover** 400 lensed SNe per year (Goldstein et al. 2019). 50 will be type Ia.
  - But LSST lightcurves alone aren't nearly good enough.

Look for transients in ellipticals that aren't Ia's at z_photo

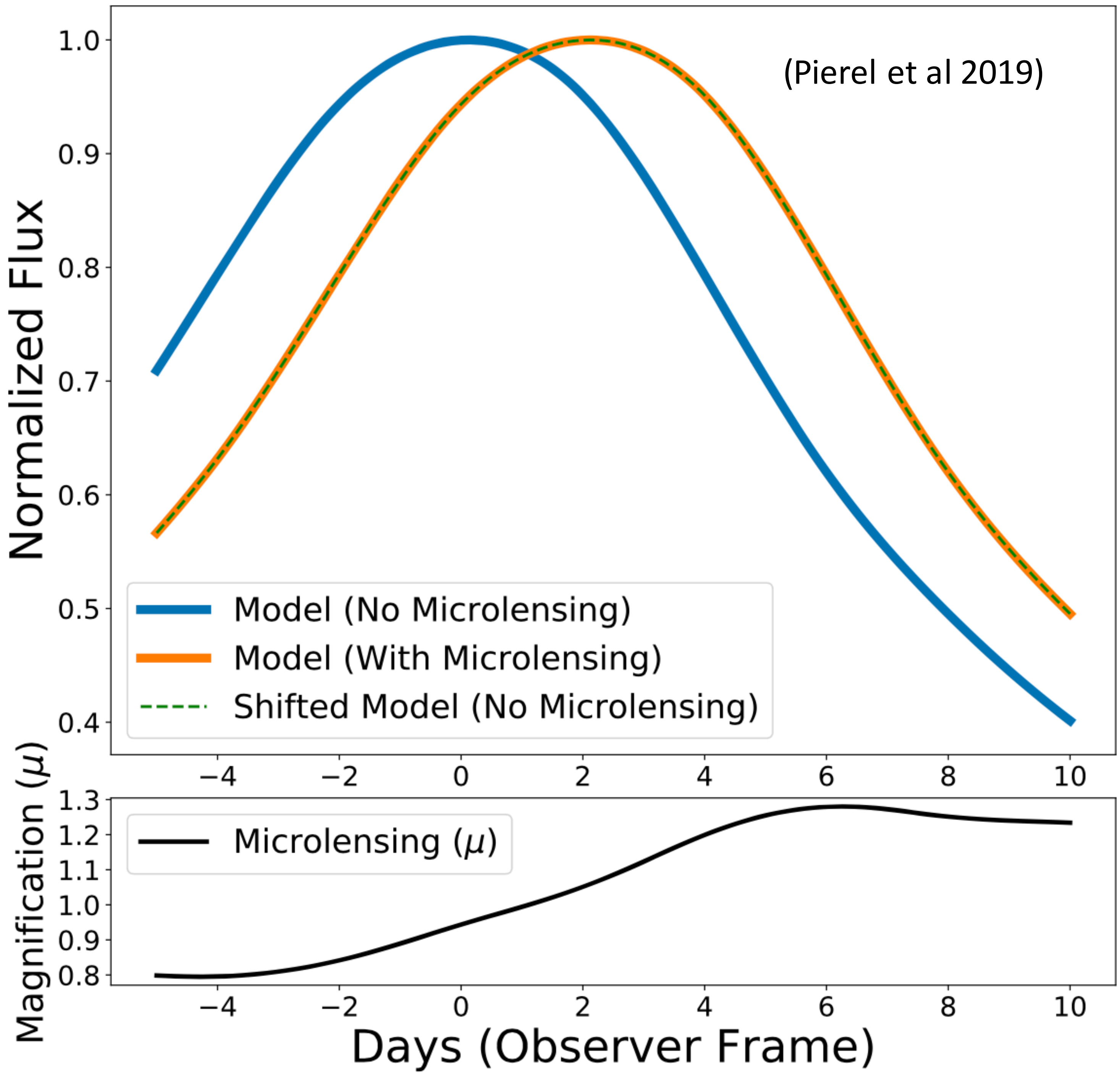
(Goldstein et al 2018)


s = 0.0
s = 0.4
s = 0.8
κ, γ = 0.2
κ, γ = 0.6
κ, γ = 1.0
−4
−2
0
2
4
Δm (mag)

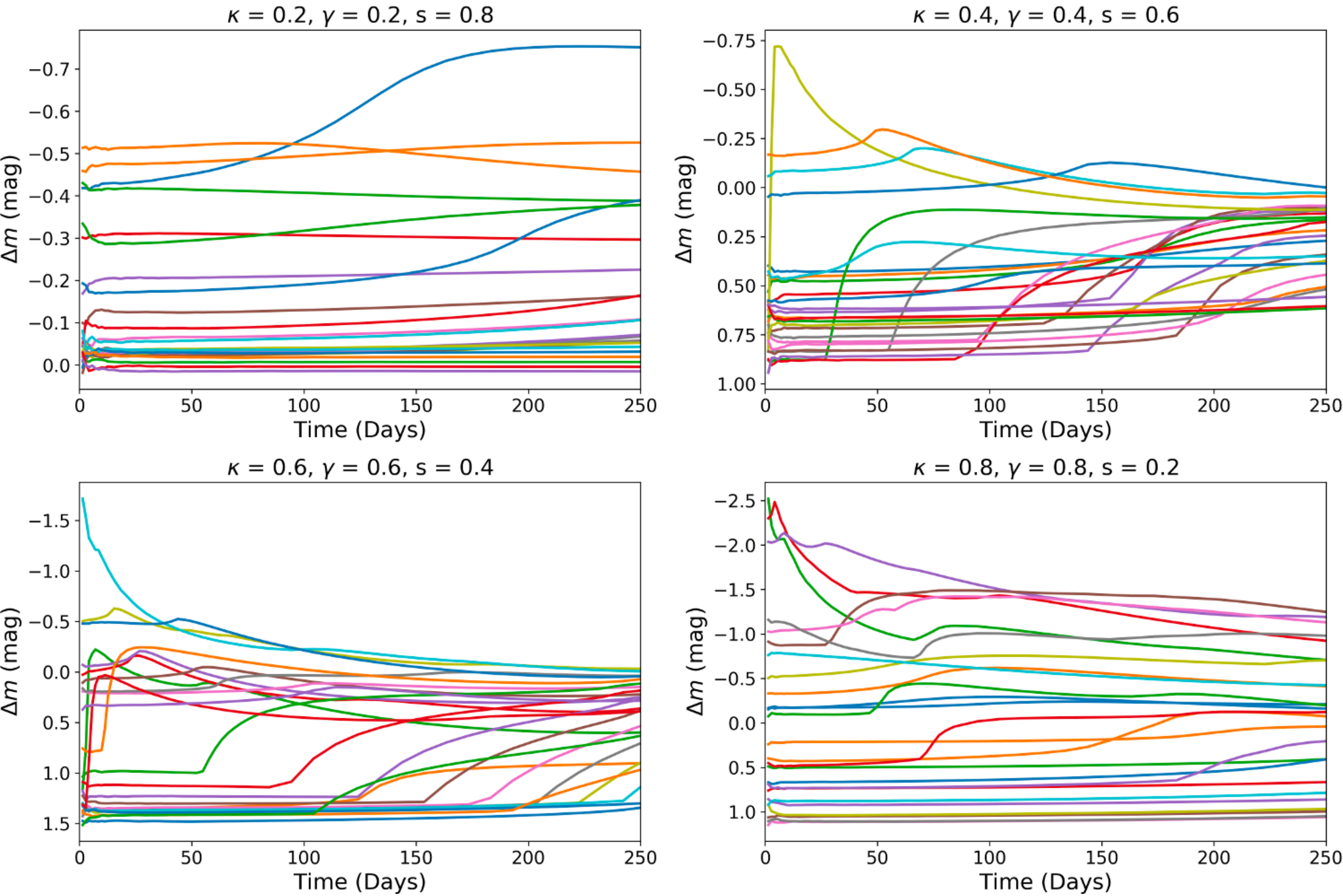


(a) 30 Days (b) 100 Days (c) 250 Days

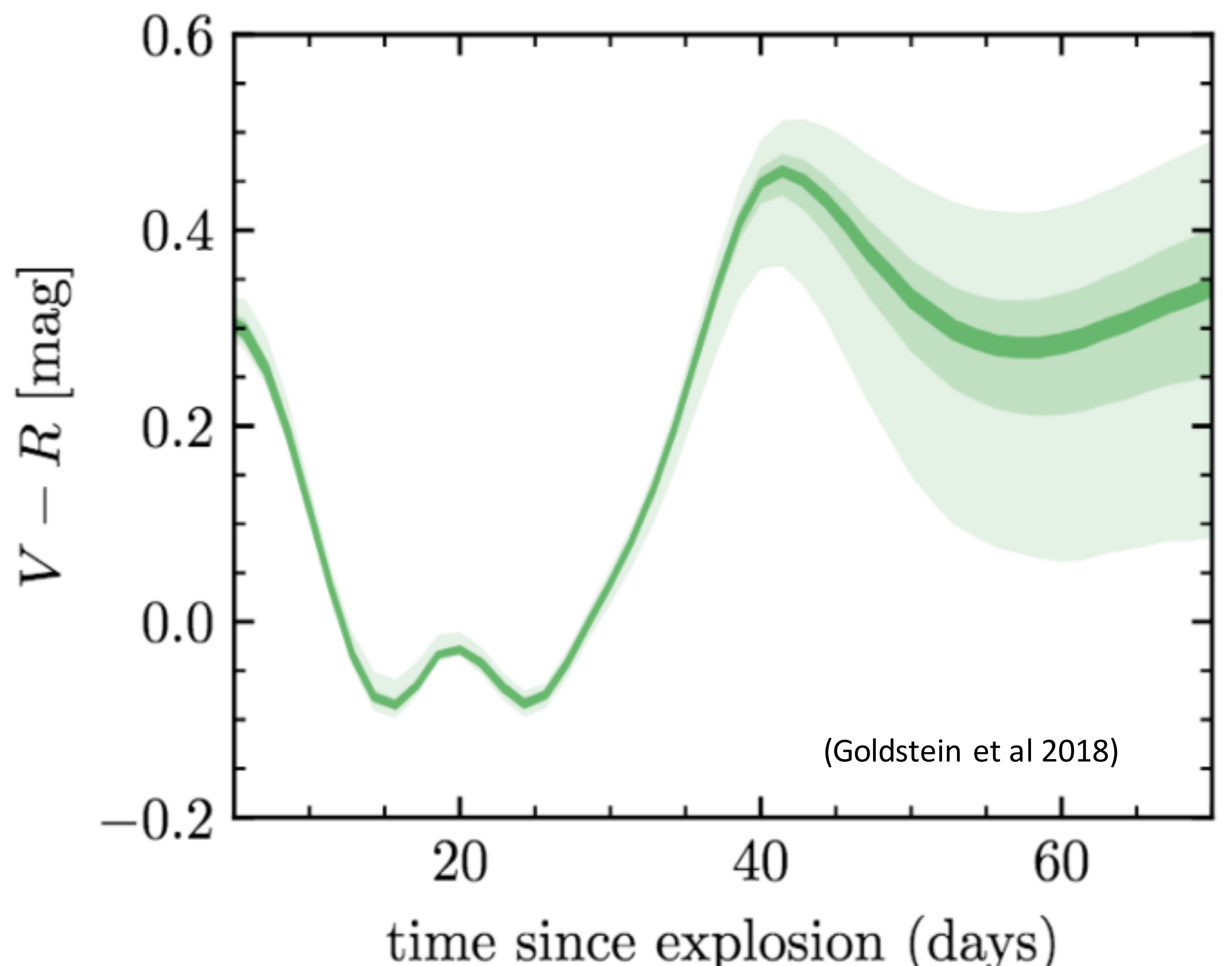
(Foxley-Marrable et al 2018)

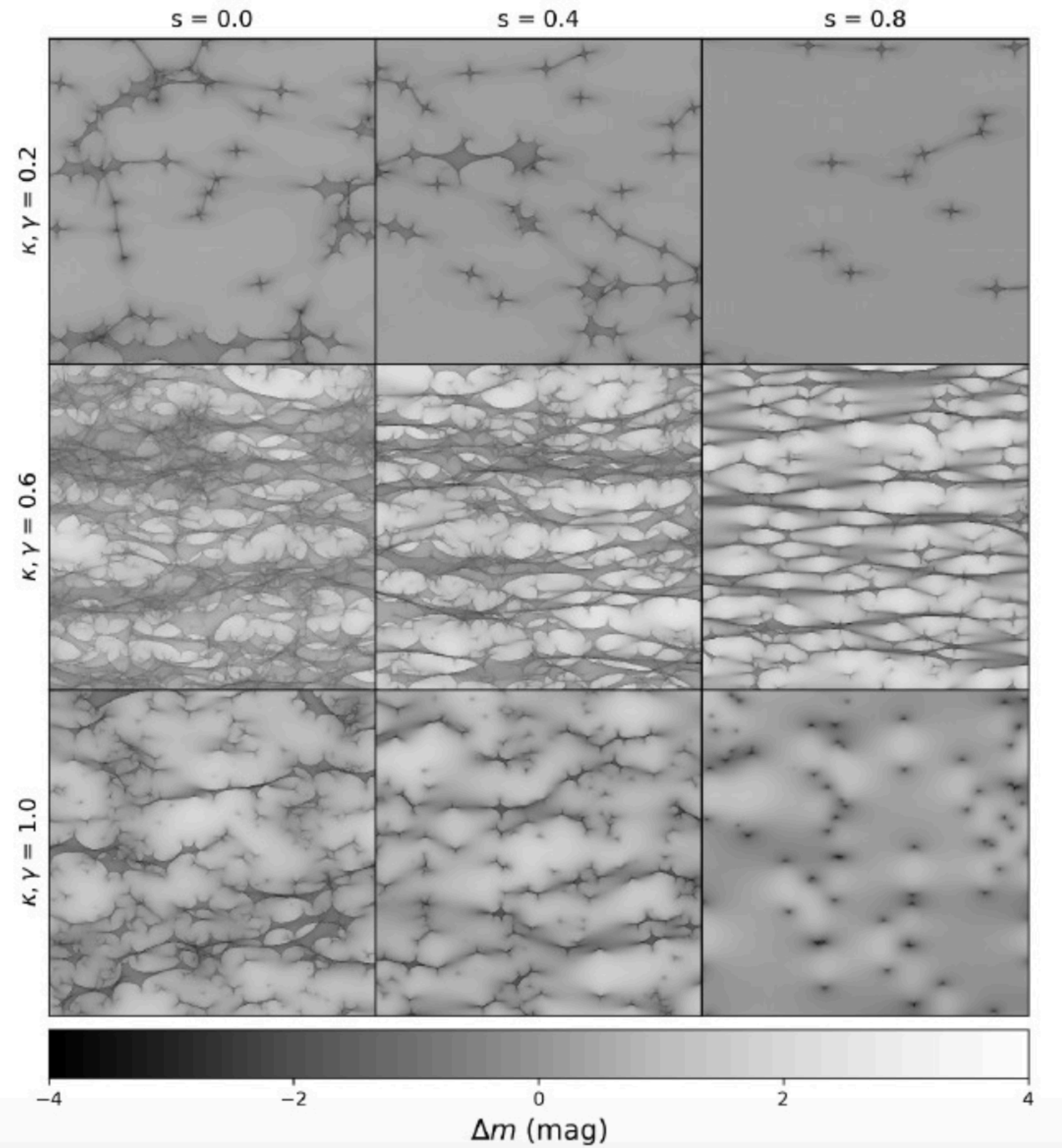


(Pierel et al 2019)
Normalized Flux
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Model (No Microlensing)
Model (With Microlensing)
Shifted Model (No Microlensing)
−4
−2
0
2
4
6
8
10
Magnification (μ)
1.3
1.2
1.1
1.0
0.9
0.8
Microlensing (μ)
−4
−2
0
2
4
6
8
10
Days (Observer Frame)

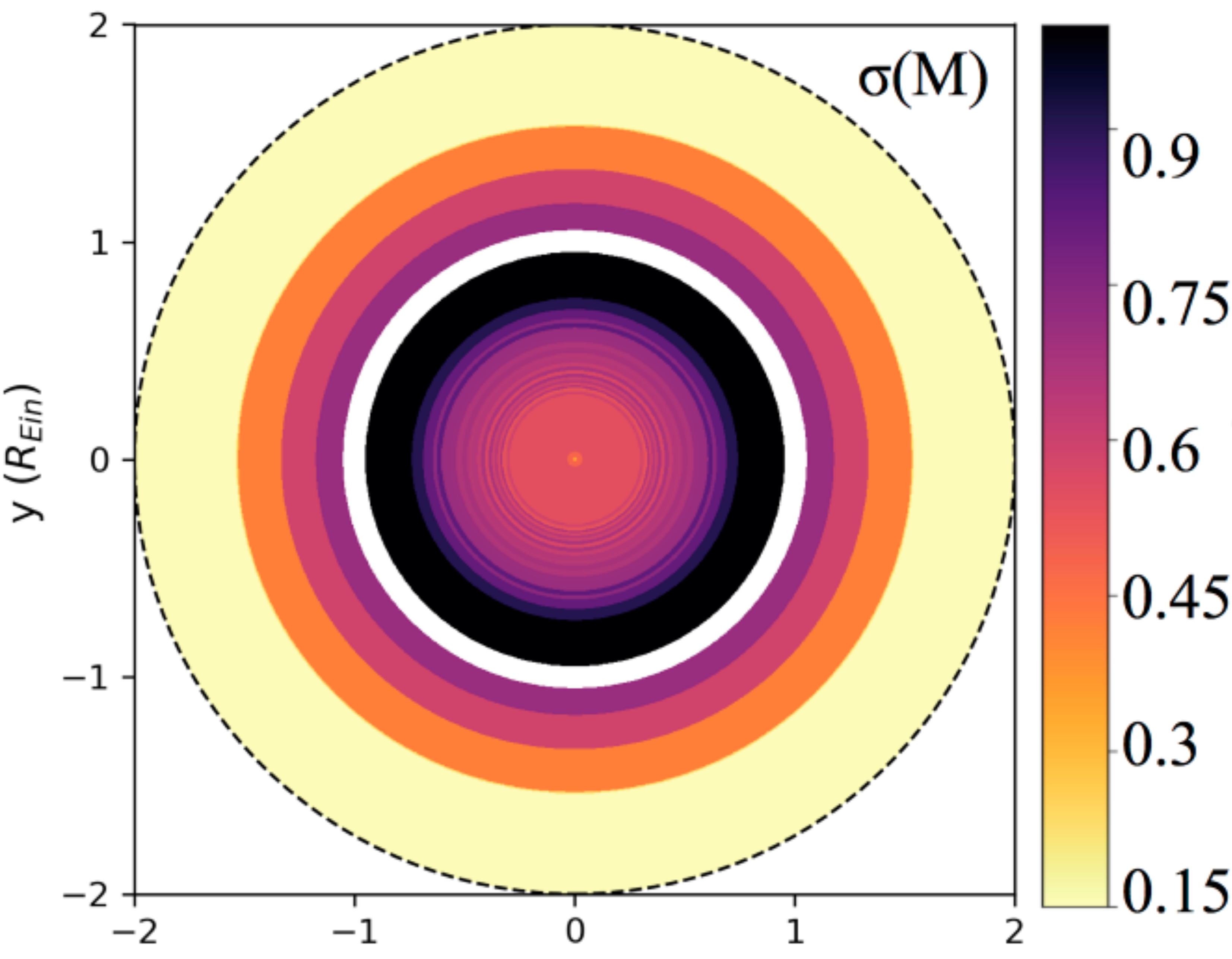


(Foxley-Marrable et al 2018)


0.6
0.4
0.2
0.0
−0.2
20
40
60
V − R [mag]
time since explosion (days)
(Goldstein et al 2018)



s = 0.0
s = 0.4
s = 0.8
κ, γ = 0.2
κ, γ = 0.6
κ, γ = 1.0
−4
−2
0
2
4
Δm (mag)



(Foxley-Marrable et al 2018)

PREDICTIONS FOR H_0

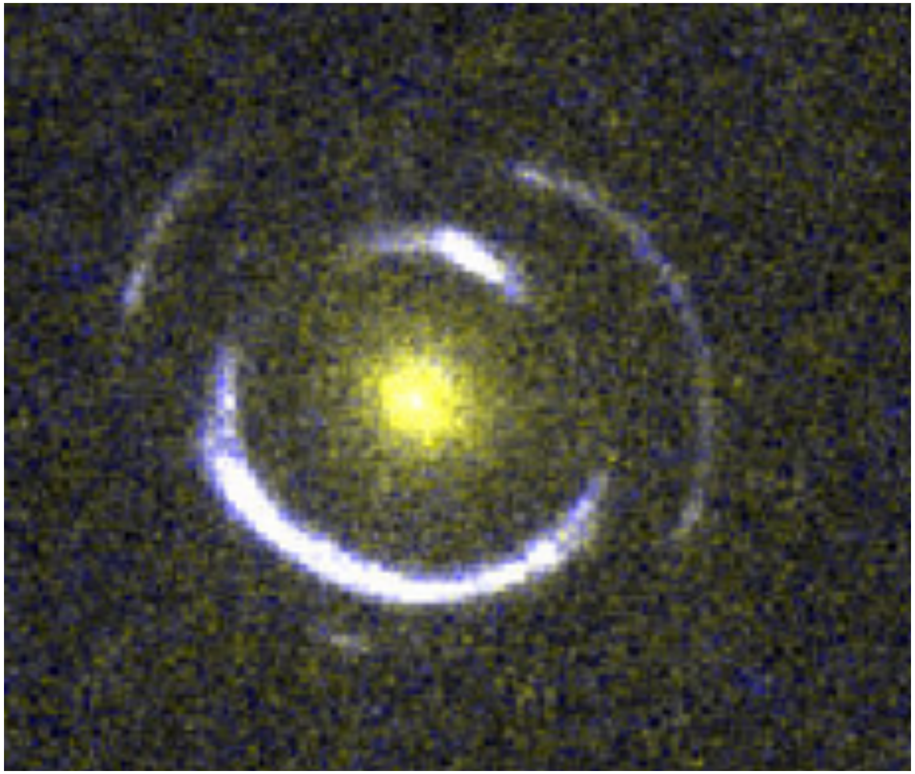
Suppression degrades to just 0.6% if we restrict the sample to ~140 standardisable systems.

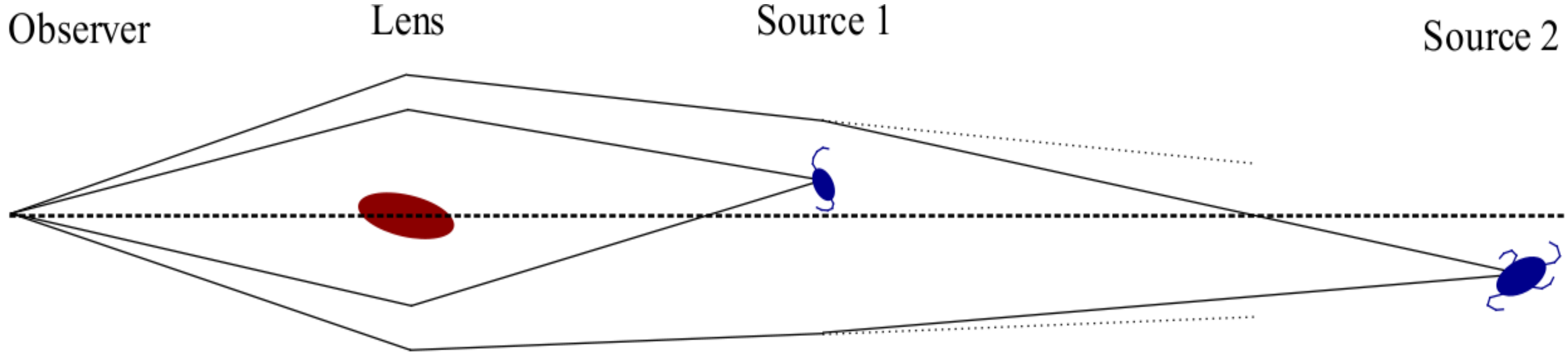
Further decays to 1.1% using only ~ 28 standardisable quads.

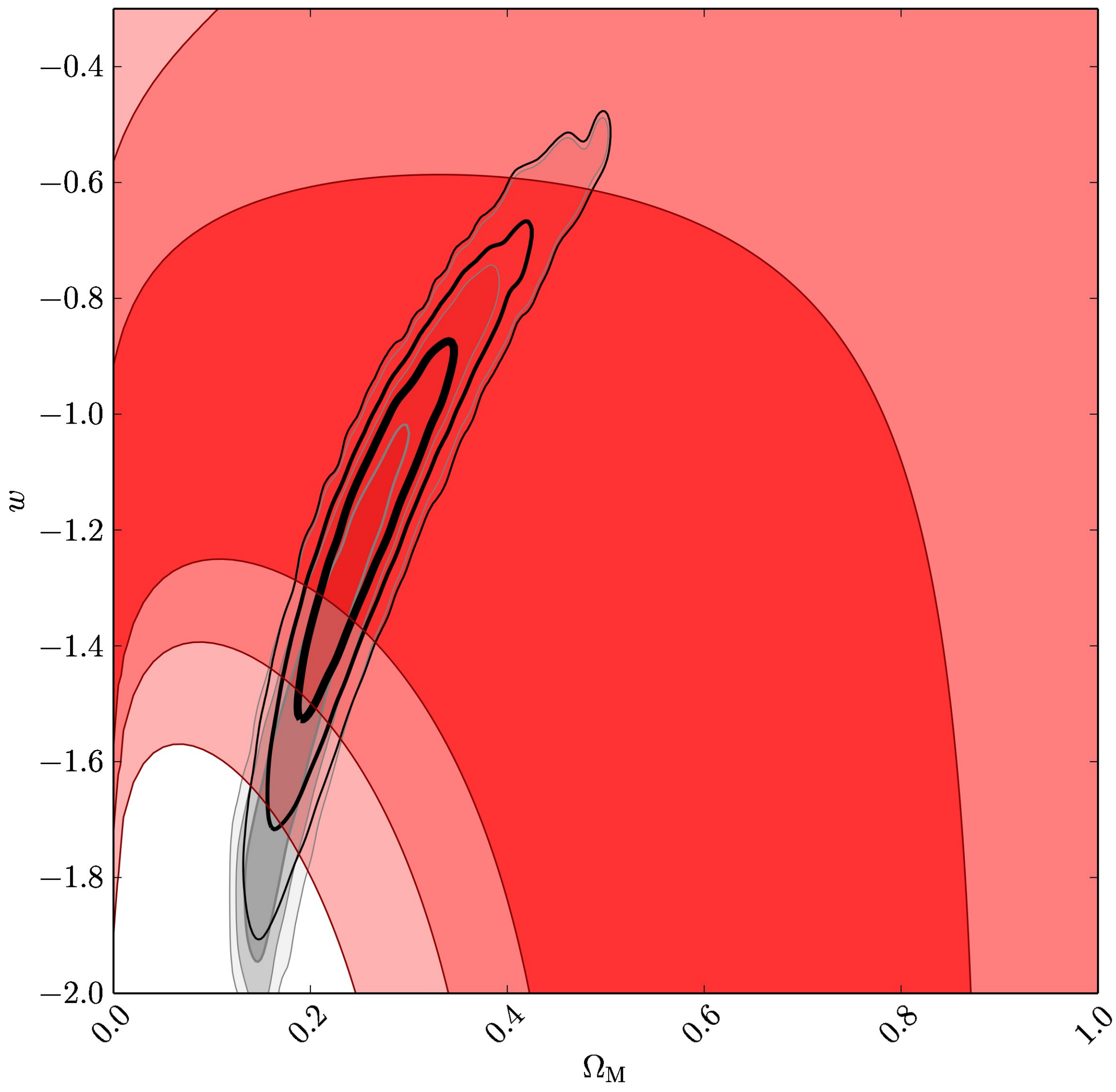
(Foxley-Marrable et al 2018)

Compound lenses

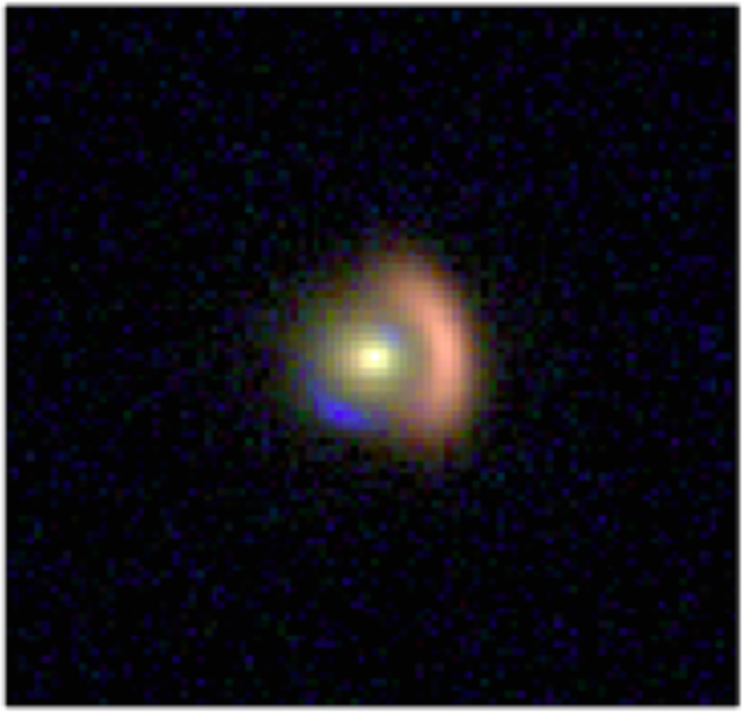
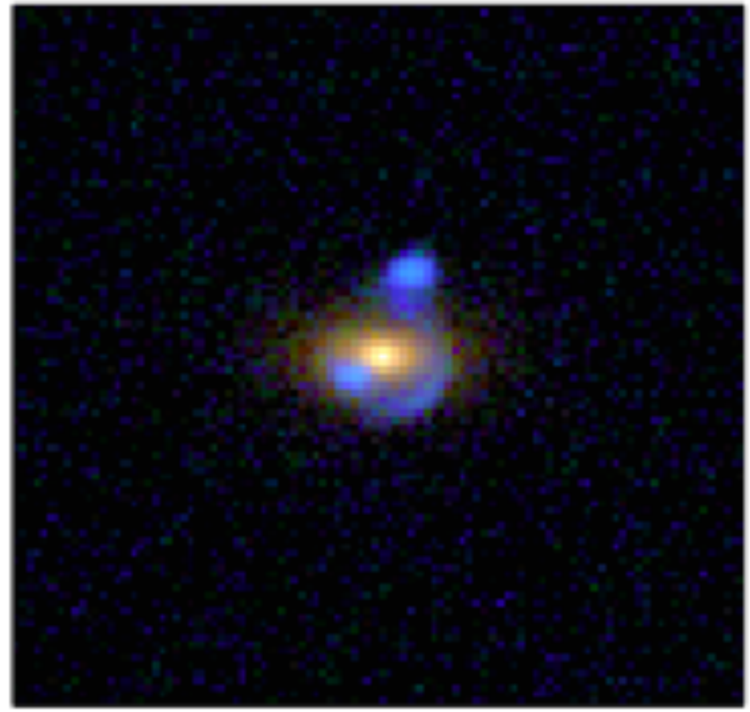
$$\theta_{\rm E} = \sqrt{\frac{GM(\theta_{\rm E})}{c^2}\frac{D_{\rm ls}}{D_{\rm ol}D_{\rm os}}}$$



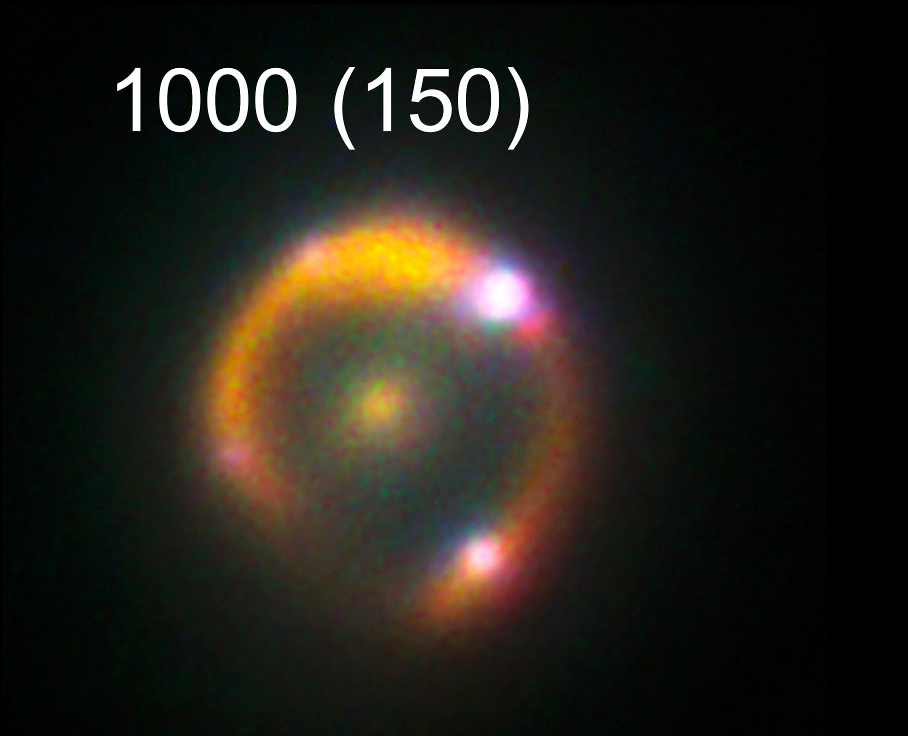


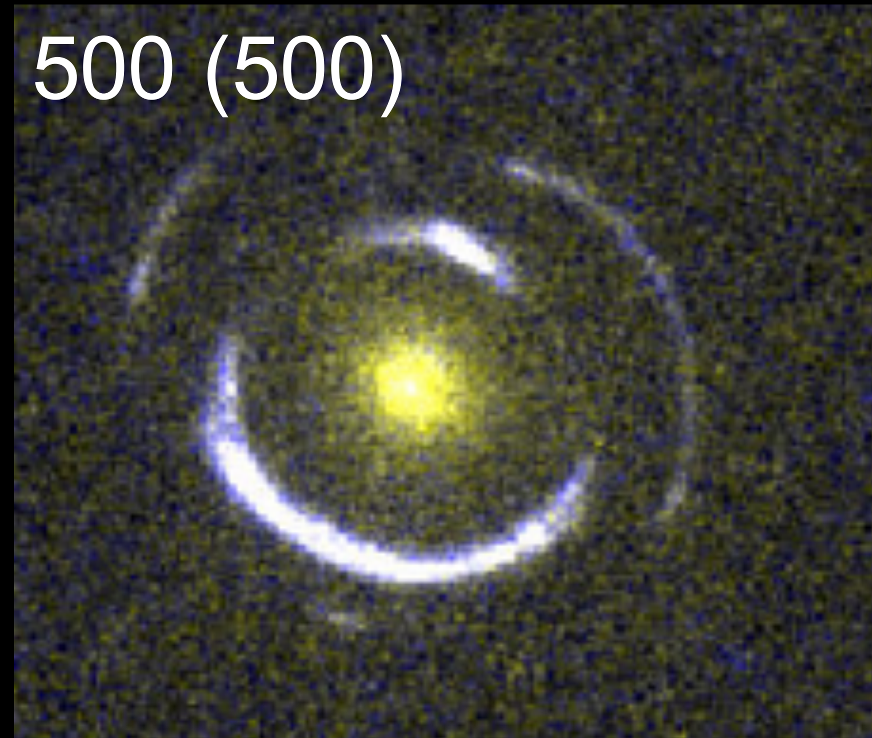


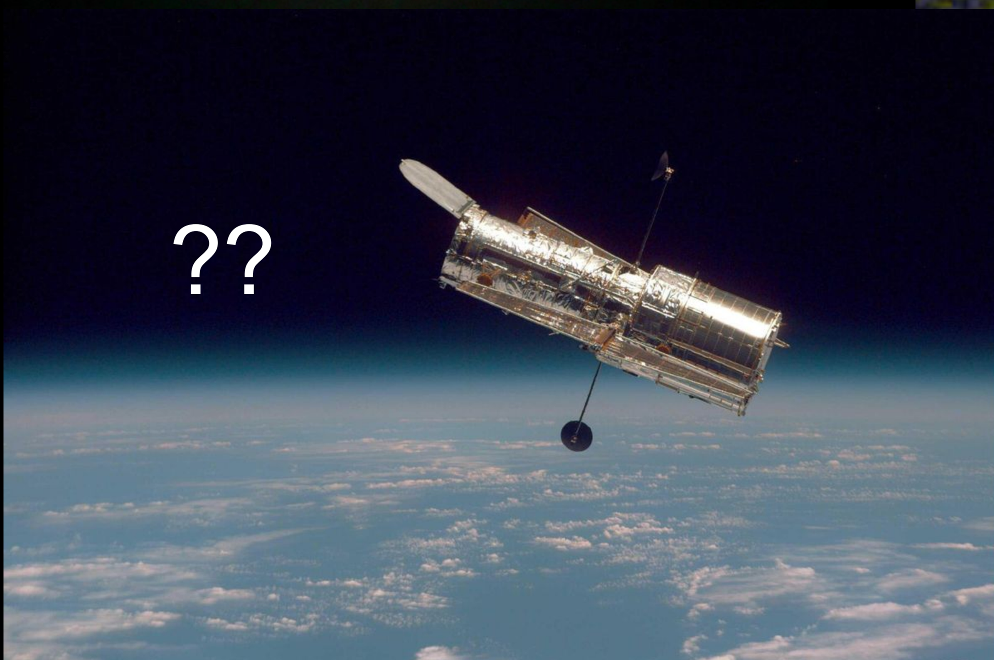
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
w
0.0
0.2
0.4
0.6
0.8
1.0
Ω_M

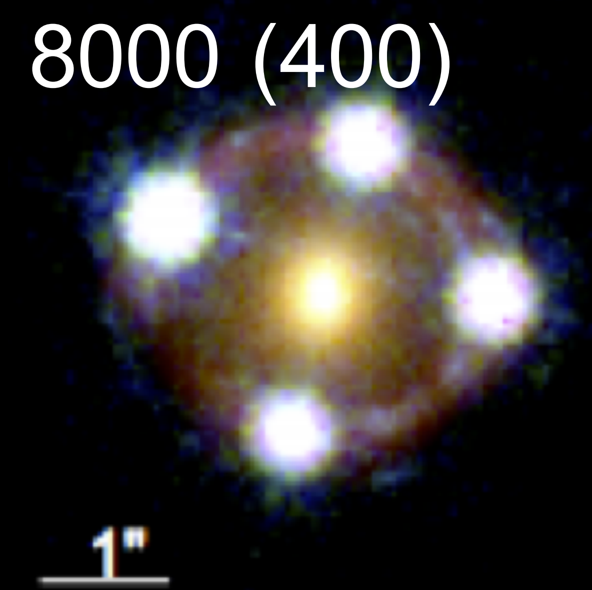
 

~100 in best single epoch seeing images
~200 in full 10 year stack
~500 total with seeing optimised Y10 stacks


1000 (150)


500 (500)


??


8000 (400)
1"