XXXIII Canary Islands Winter School of Astrophysics

Fundamental Physics with Galaxies (lecture IV)

Kfir Blum | Weizmann Institute of Science

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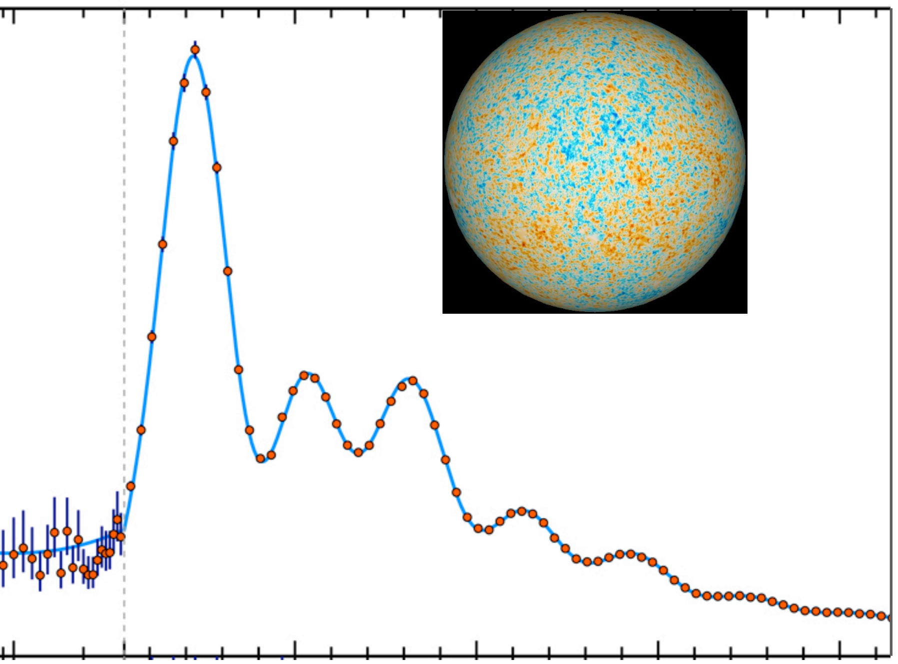
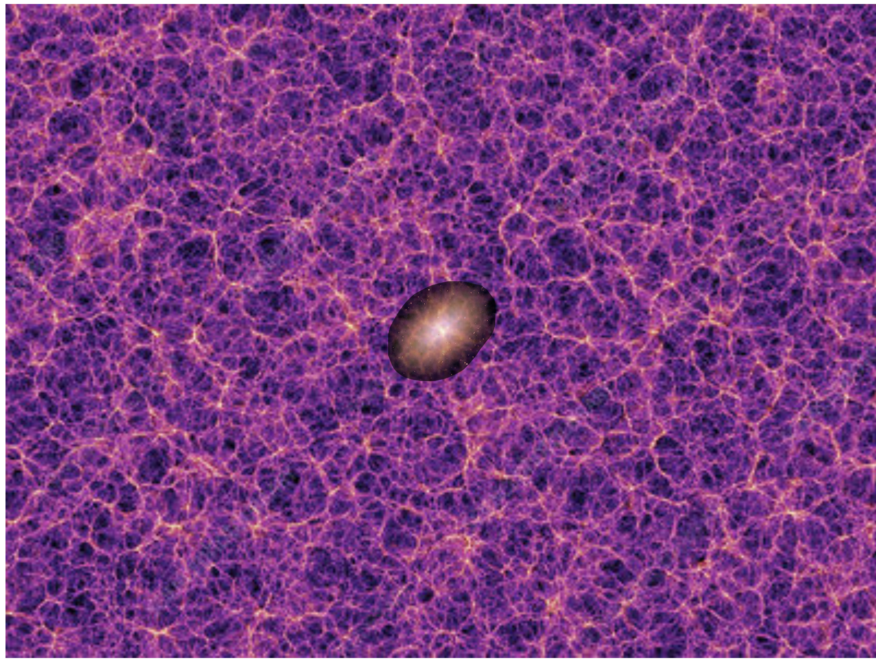
Galaxies vs. Cosmology





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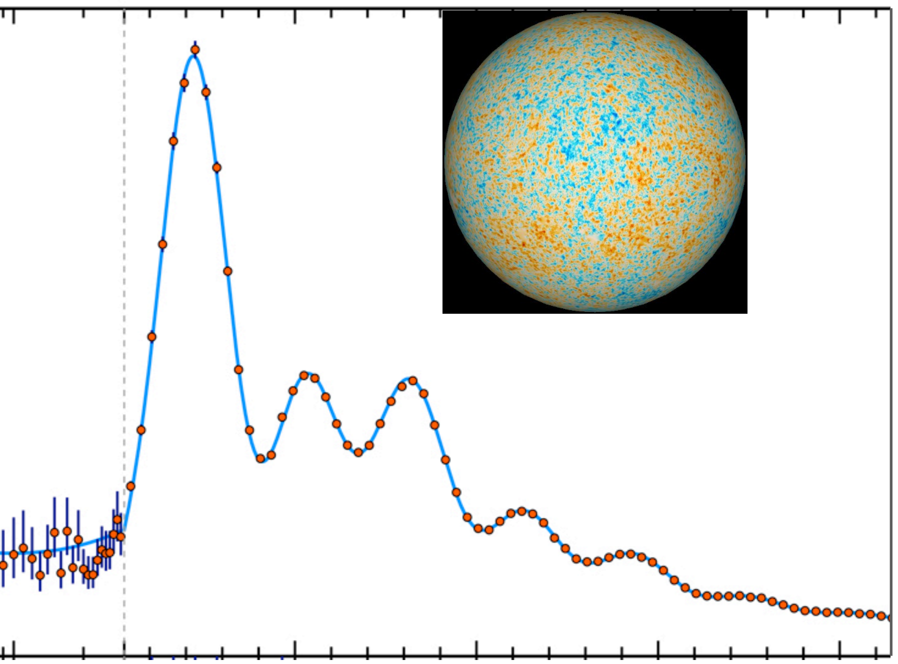
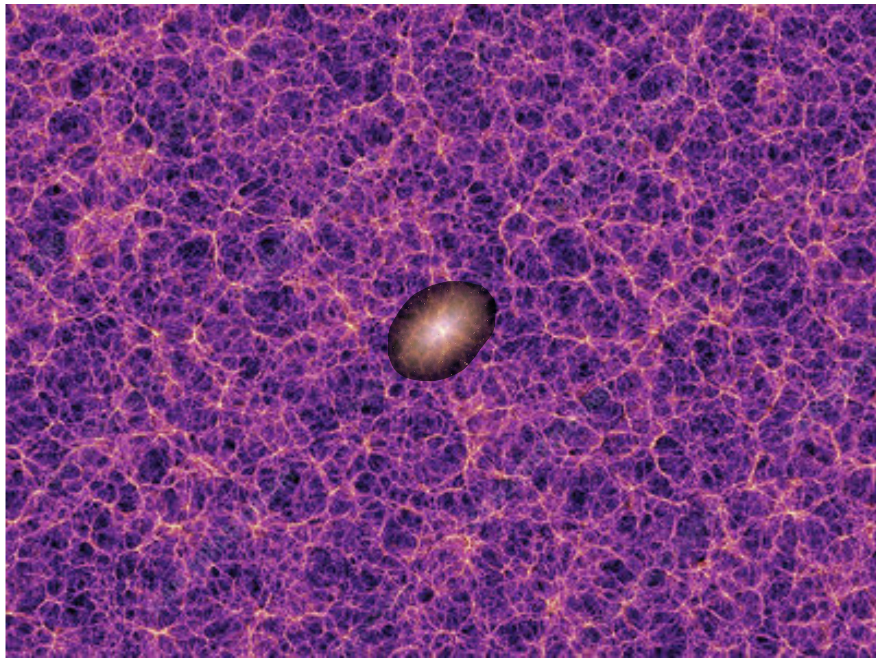
Galaxies vs. Cosmology





1. Dark matter is kind’a dark

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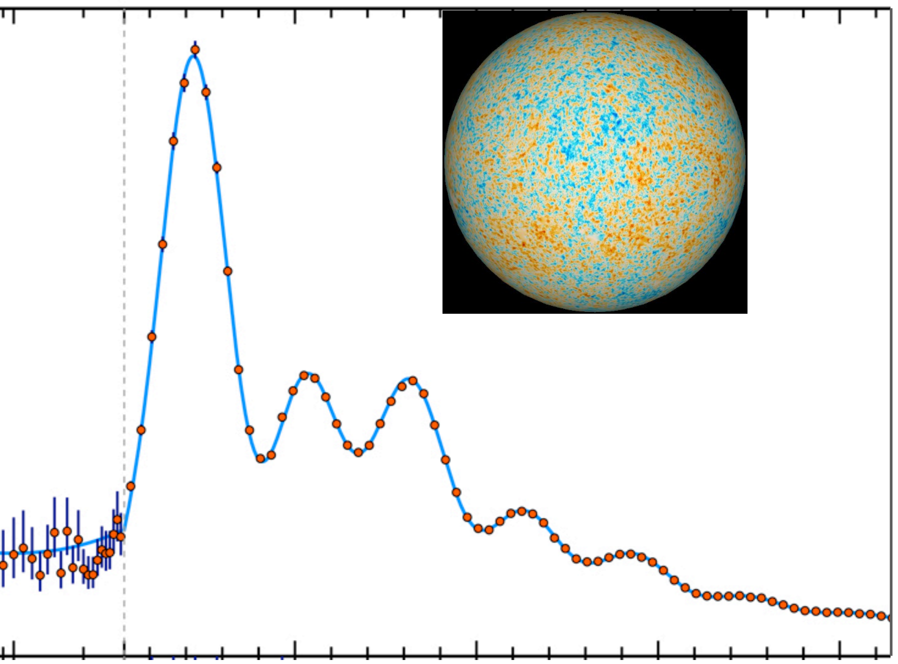

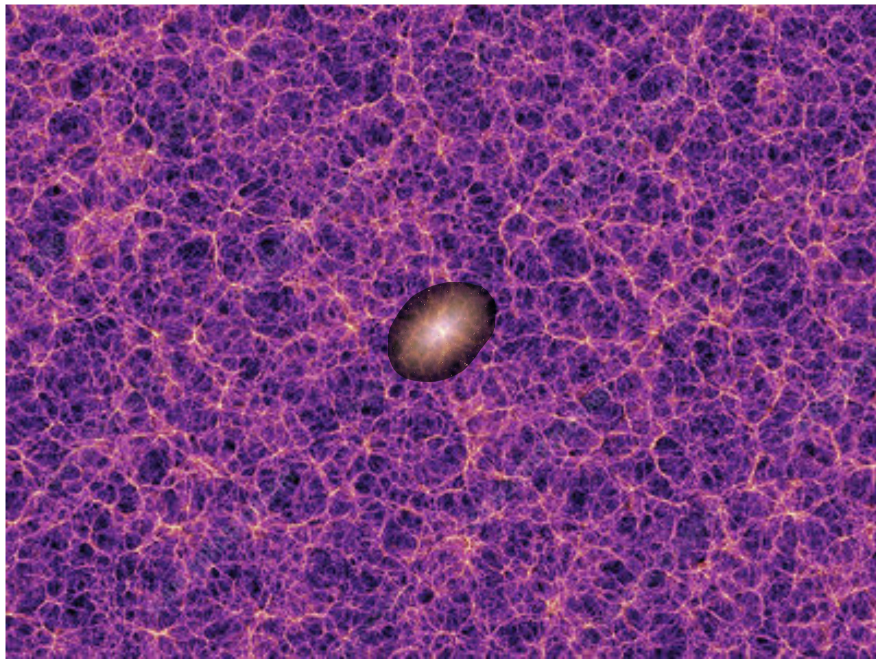

1. Dark matter is kind'a dark

2. Galaxies meet the Hubble tension

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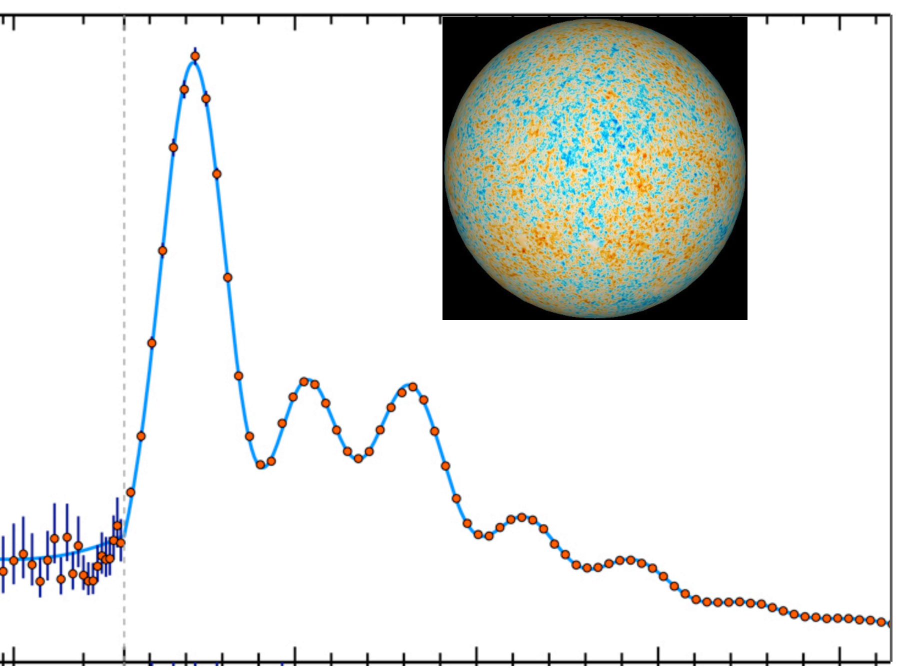
Galaxies vs. Cosmology



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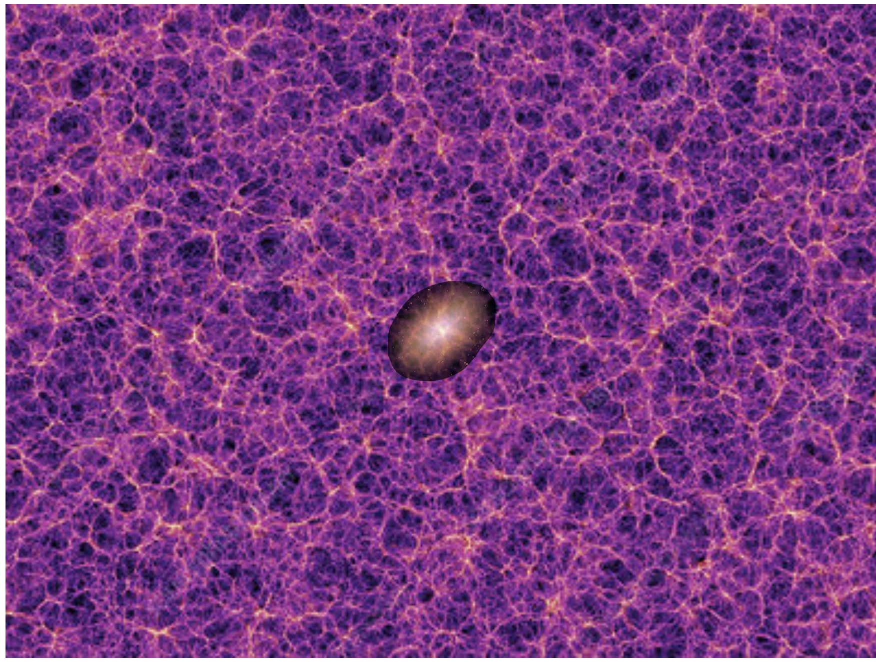


2. Galaxies meet the Hubble tension (*sheet happens*)

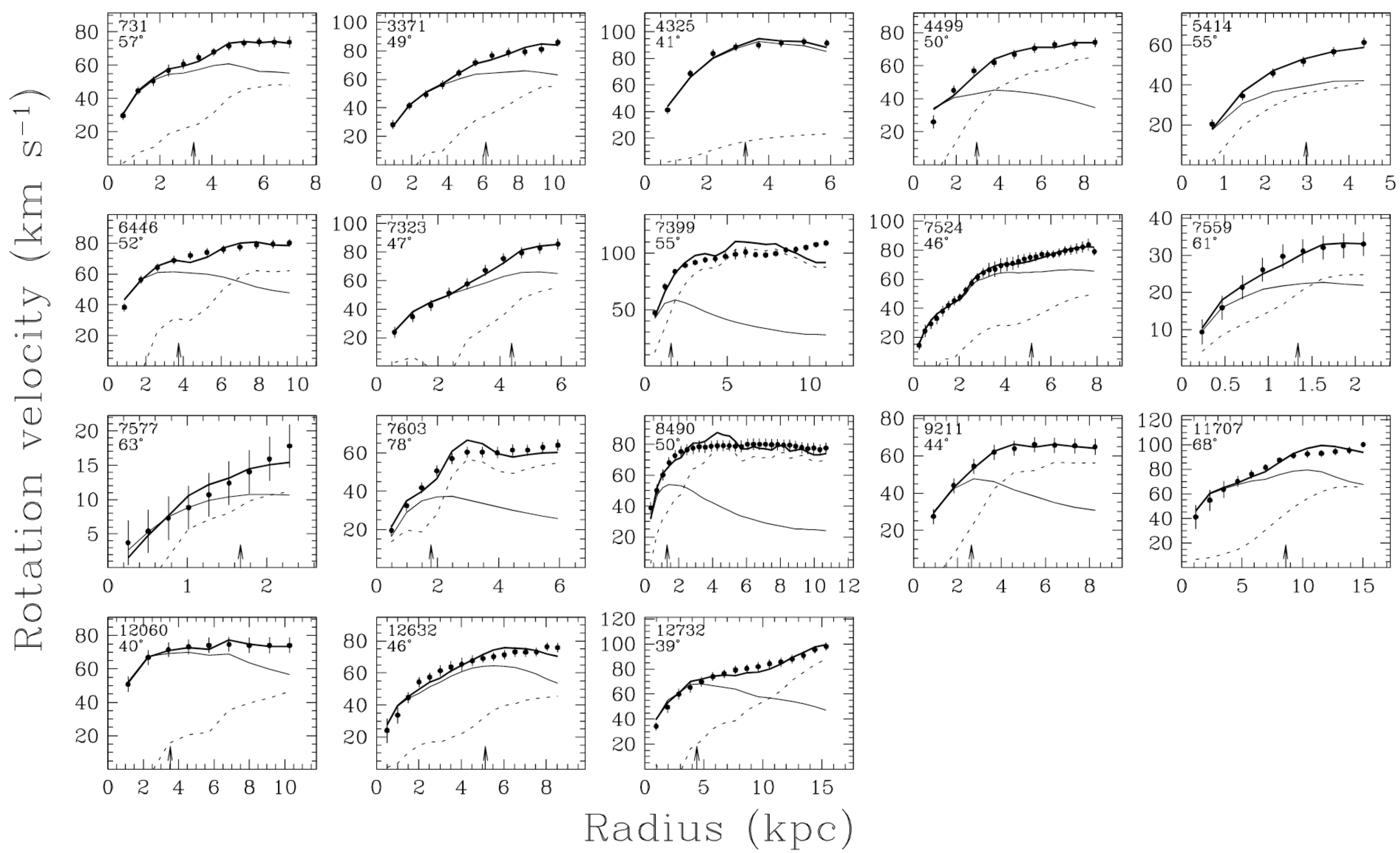
Dark matter is kind’a dark

Dark matter is kind'a dark

Suppose protons collide with dark matter particles, cross section $\sigma_{\chi p}$.

Sancisi astro-ph/0311348
(``*Renzo's rule*")
Swaters et al 1207.2729
McGaugh 1412.3767

Rotation curves trace light?
…light traces rotation curves?



Dark matter is kind'a dark

Suppose protons collide with dark matter particles, cross section $\sigma_{\chi p}$.
The dark matter mass density in M31, on ~10 kpc scales, is $\rho_\chi \approx 0.4\ \mathrm{GeV/cm^3}$ (burrowing from the Milky Way).
The number density is $n_\chi = \rho_\chi / m_\chi \approx 0.4\ \mathrm{cm^{-3}} \left(\mathrm{GeV/m_\chi}\right)$.
A proton has 1 collision with a dark matter particle per time t if

$$t \approx \frac{1}{n_\chi \sigma_{\chi p} v} = \frac{m_\chi}{\rho_\chi \sigma_{\chi p} v}$$

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A proton has 1 collision with a dark matter particle per 10 Gyr if $$\frac{\sigma_{\chi p}}{m_\chi} \approx \frac{1}{\rho_\chi v t} \approx \frac{0.4\ \mathrm{b}}{\mathrm{GeV}} \left(\frac{10\ \mathrm{Gyr}}{t}\right)\left(\frac{200\ \mathrm{km/s}}{v}\right)$$

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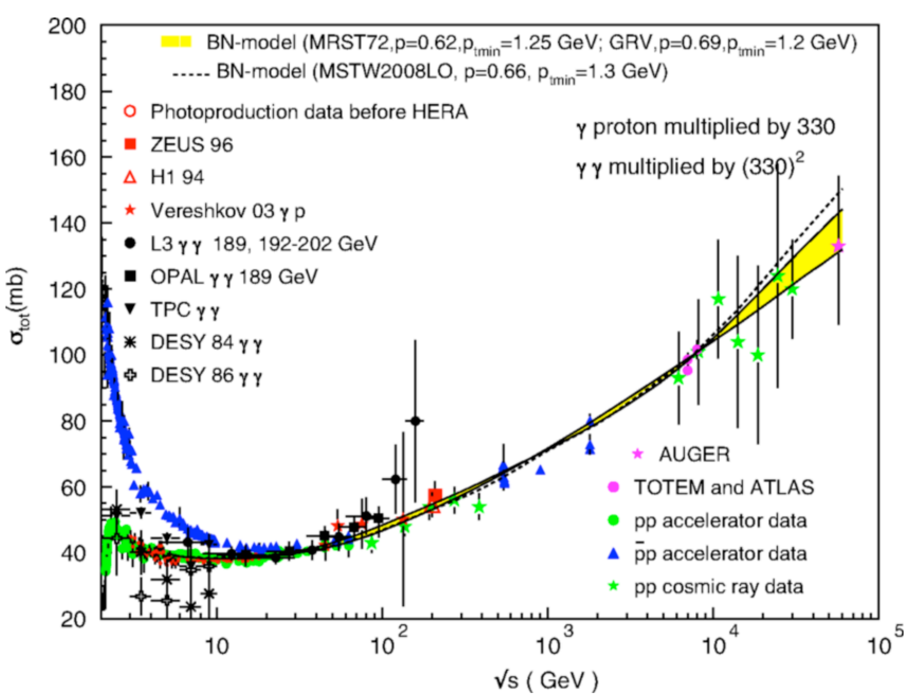
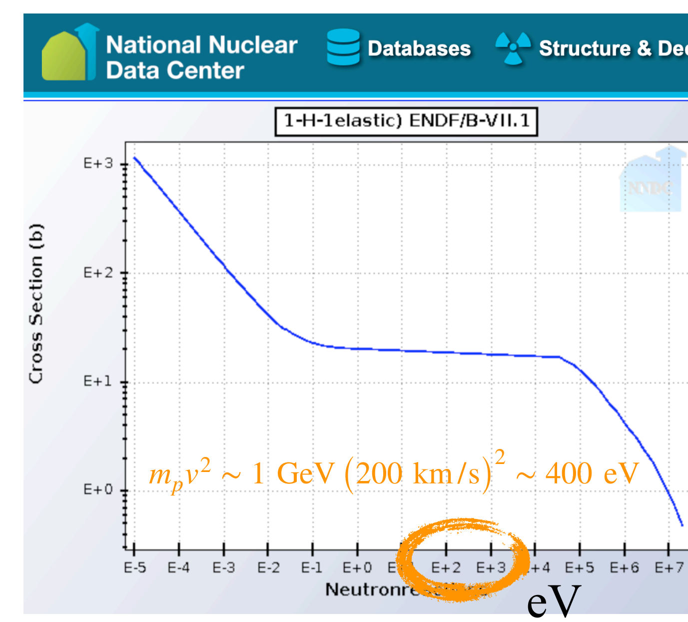


For comparison, low-energy proton-neutron elastic cross section:*

$$\frac{\sigma_{np}}{m_n} \approx \frac{20\ \mathrm{b}}{\mathrm{GeV}}$$

Proton-proton cross sec at ~10 GeV:

$$\frac{\sigma_{pp}}{m_p} \approx \frac{0.04\ \mathrm{b}}{\mathrm{GeV}}$$



*dominated by deuteron resonance

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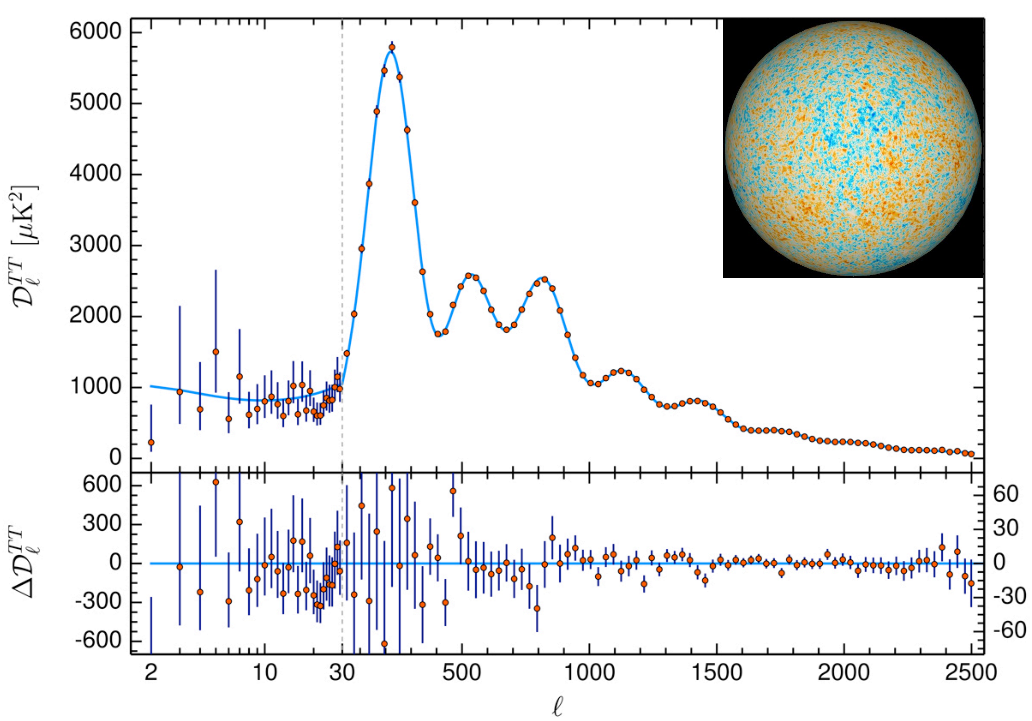

Cosmology doesn't like this.
In the early Universe, typical time between $p\chi$ collisions:

$$t_{\chi \mathrm{p}}(z) \approx \frac{1}{\rho_\chi(z) v(z)} \frac{m_\chi}{\sigma_{\chi p}} \approx \frac{1}{\rho_\chi(z)} \sqrt{\frac{m_p}{T(z)}} \frac{m_\chi}{\sigma_{\chi p}}$$

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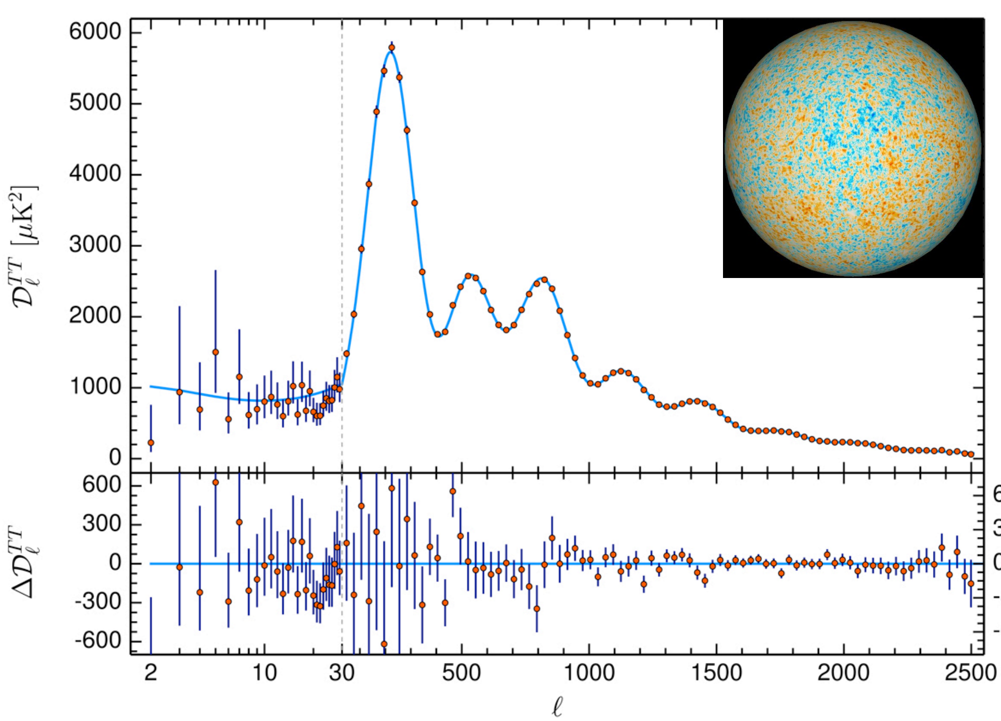

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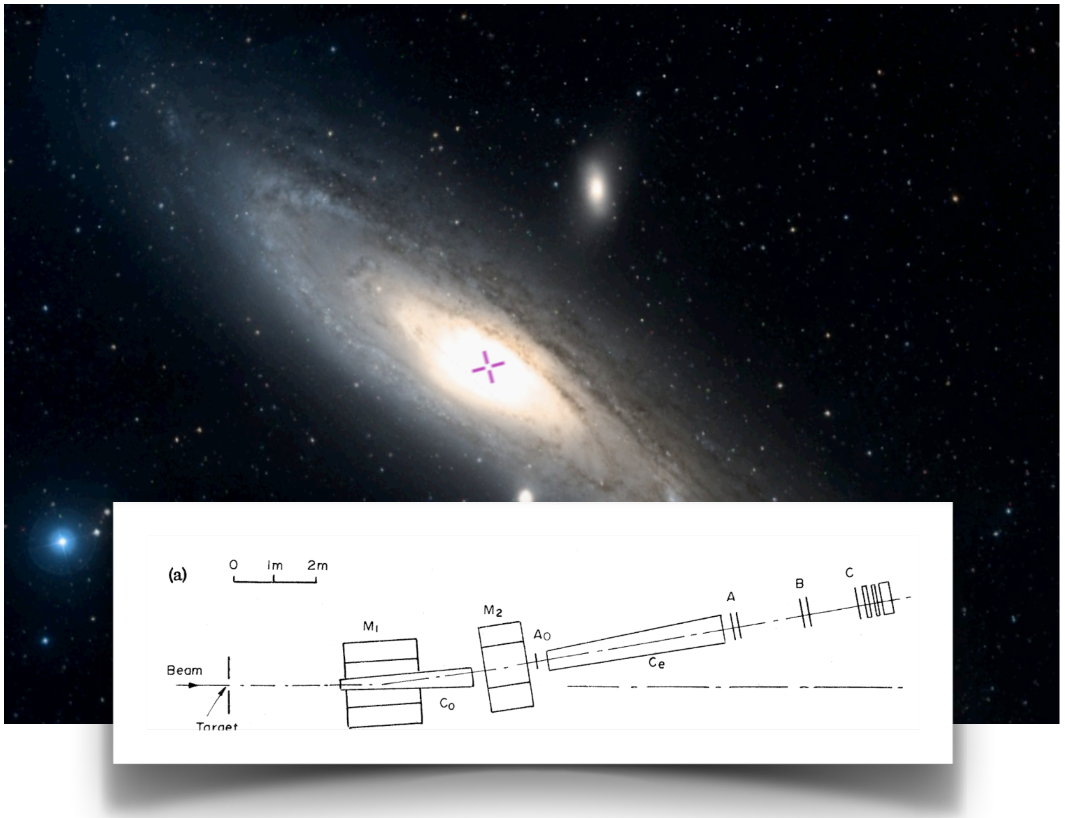

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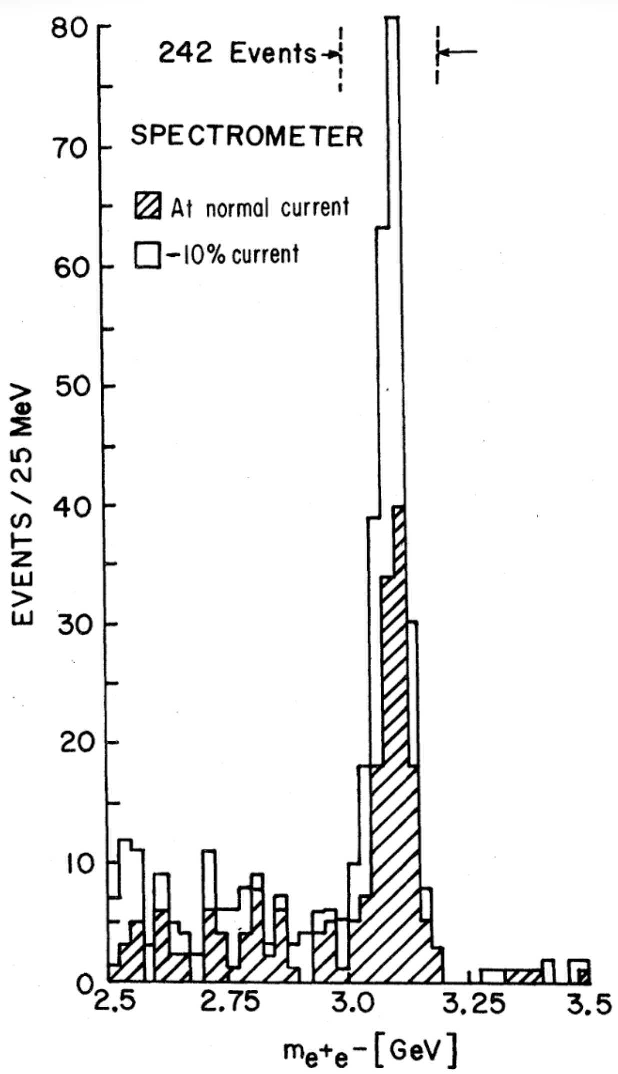

PhysRevLett.33.1404

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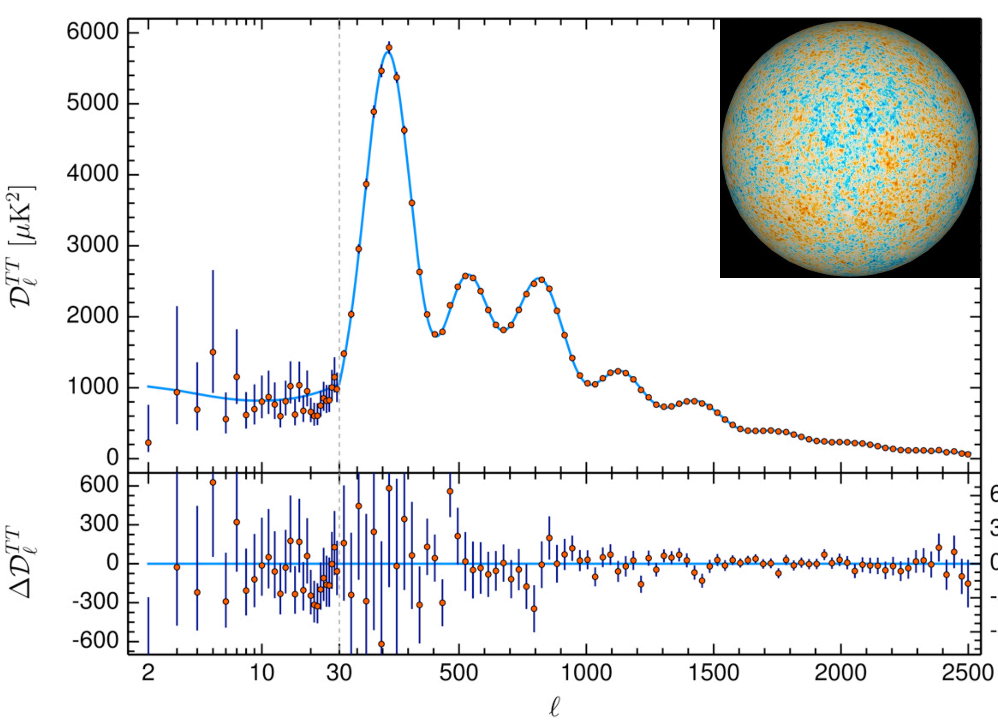

Cosmology doesn't like this.

In the early Universe, typical number of $p\chi$ collisions per Hubble time:

$$\frac{1}{t_{\chi \mathrm{p}} H} \approx \frac{\rho_\chi(z)\sqrt{\dfrac{T(z)}{m_p}}\dfrac{\sigma_{\chi p}}{m_\chi}}{\sqrt{\dfrac{8\pi^3 g_*}{90}\dfrac{T^2(z)}{M_{pl}}}} \approx 200\left(\frac{1+z}{10^6}\right)^{\frac{3}{2}}\left(\frac{\sigma_{\chi p}/m_\chi}{0.4\ \mathrm{b/GeV}}\right)$$

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-4	1.8×10^{-17}	1.7×10^{-17}	27 Gpc
-2	3.0×10^{-9}	6.2×10^{-10}	738 Mpc
-1	1.6×10^{-5}	1.4×10^{-6}	313 Mpc
$\boxed{0}$	$\boxed{0.12}$	$\boxed{3.3 \times 10^{-3}}$	$\boxed{\text{138 Mpc}}$
+2	1.3×10^{5}	9.5×10^{3}	46 Mpc

Dvorkin, KB, Kamionkowski 1311.2937,
Gluscevic et al 1903.05140,
Maamari et al 2010.02936,
Nguyen et al 2107.12380
…

Distance traveled by proton in M31 during ~10 Gyr is vt ~ 2 Mpc.
Cosmological data implies mean free path for colliding with dark matter particles is larger than λ.

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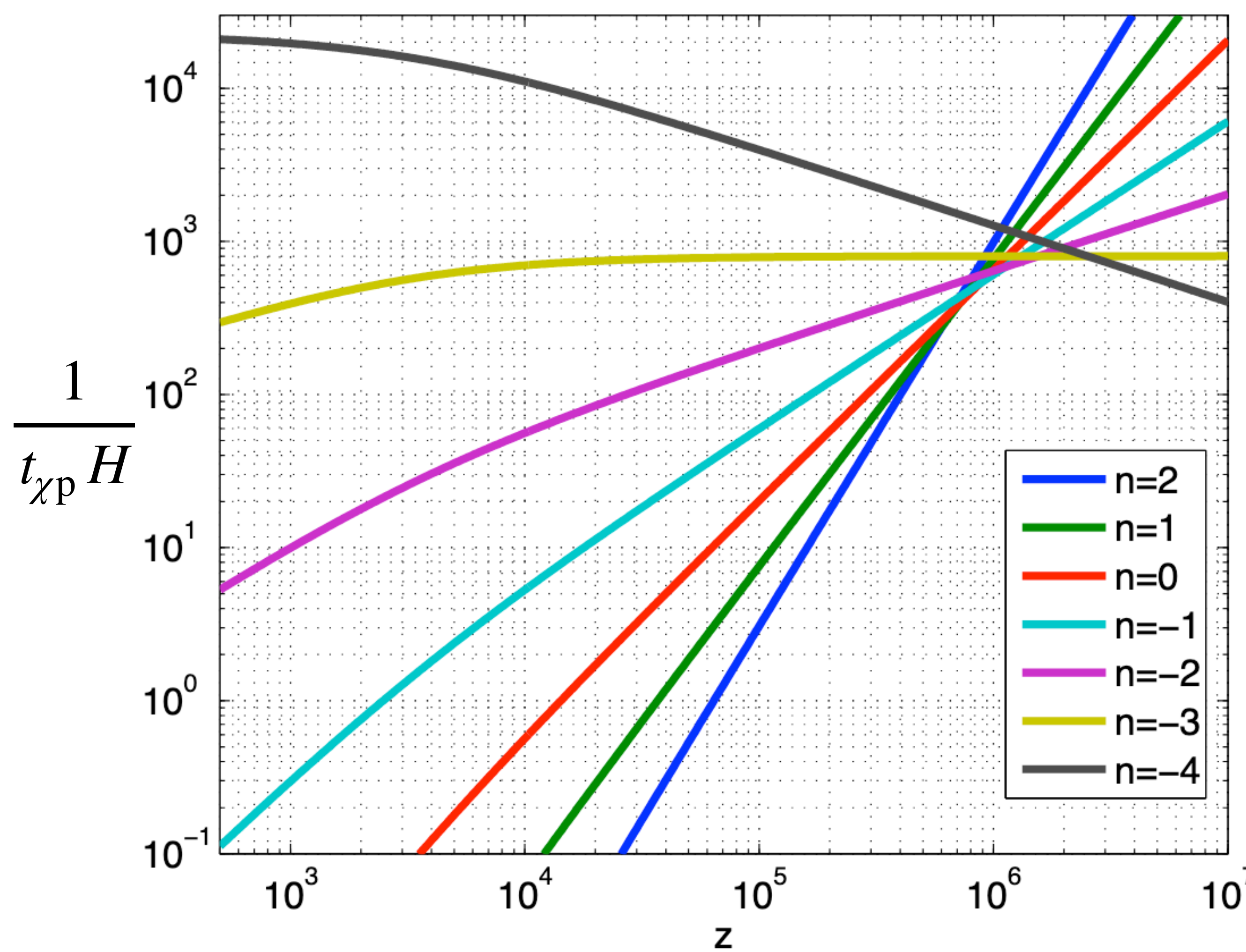

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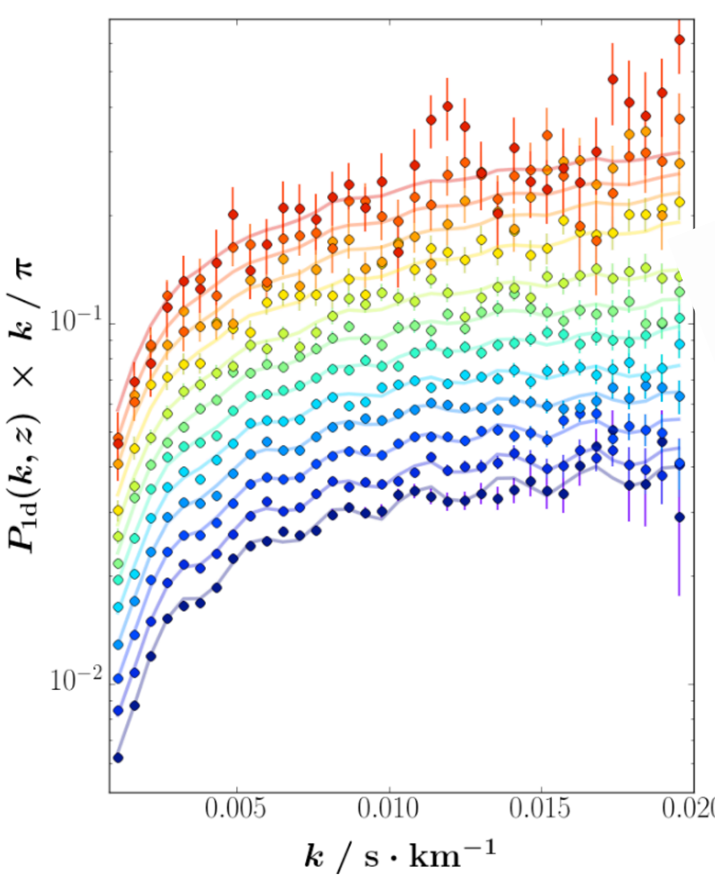
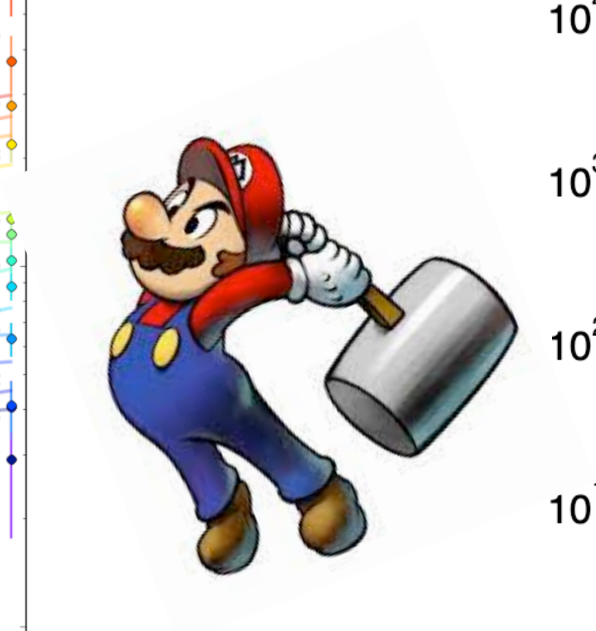
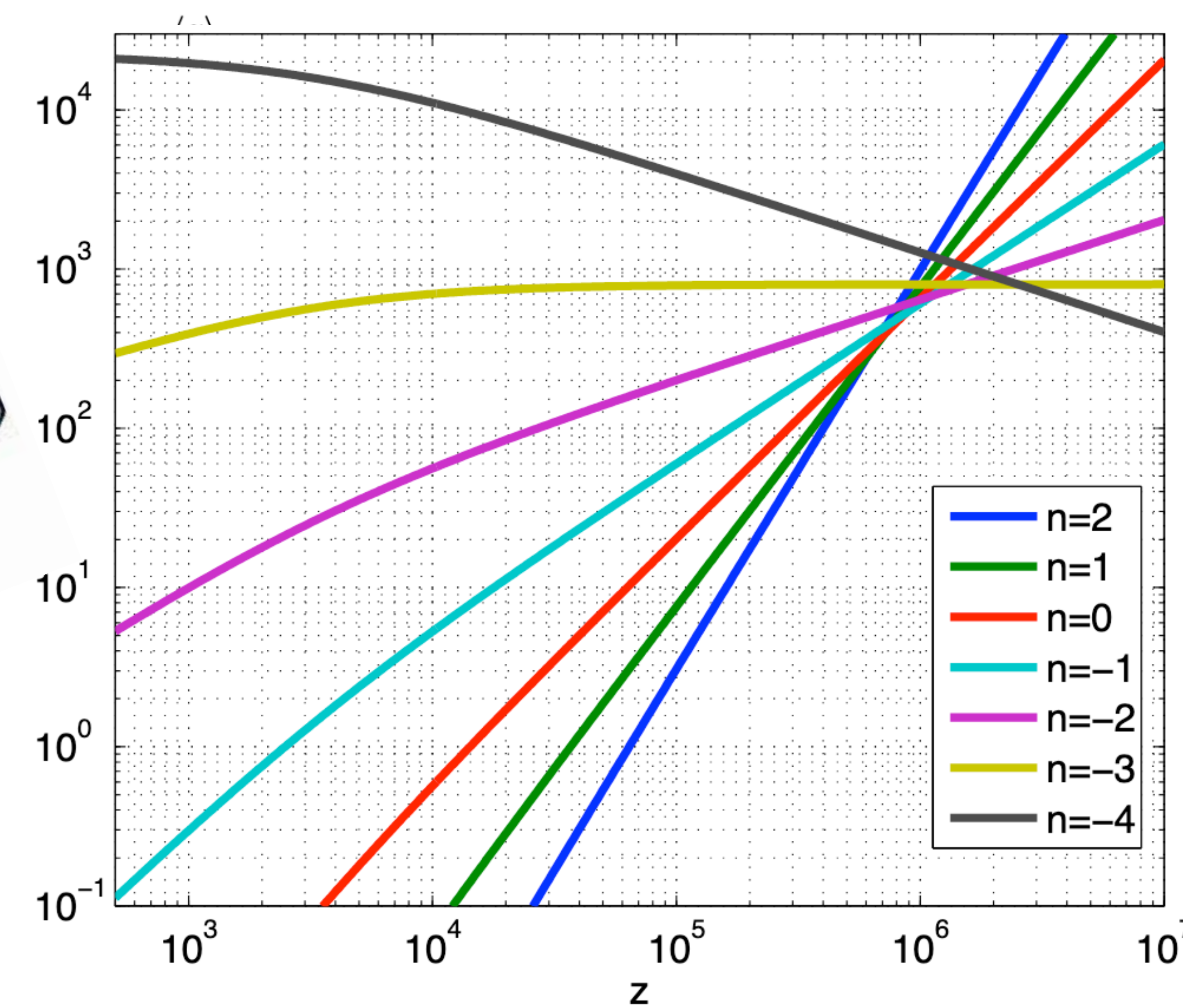


Baur et al 1706.03118





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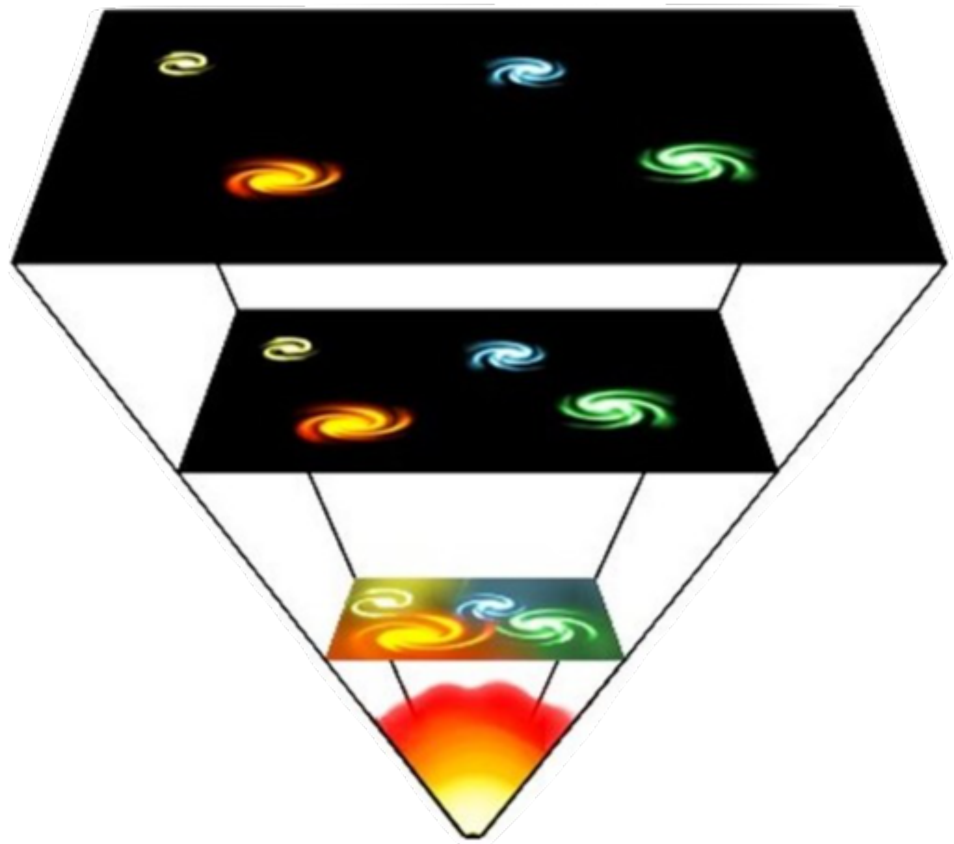
(e.g. Holdom 1986)

Dark matter electric charge? $q_\chi = \epsilon e$

$$\epsilon \lesssim 10^{-6} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)^{\frac{1}{2}}$$

Galaxies and the Hubble tension

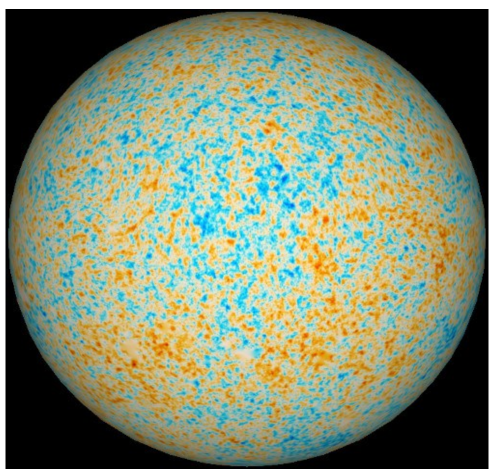


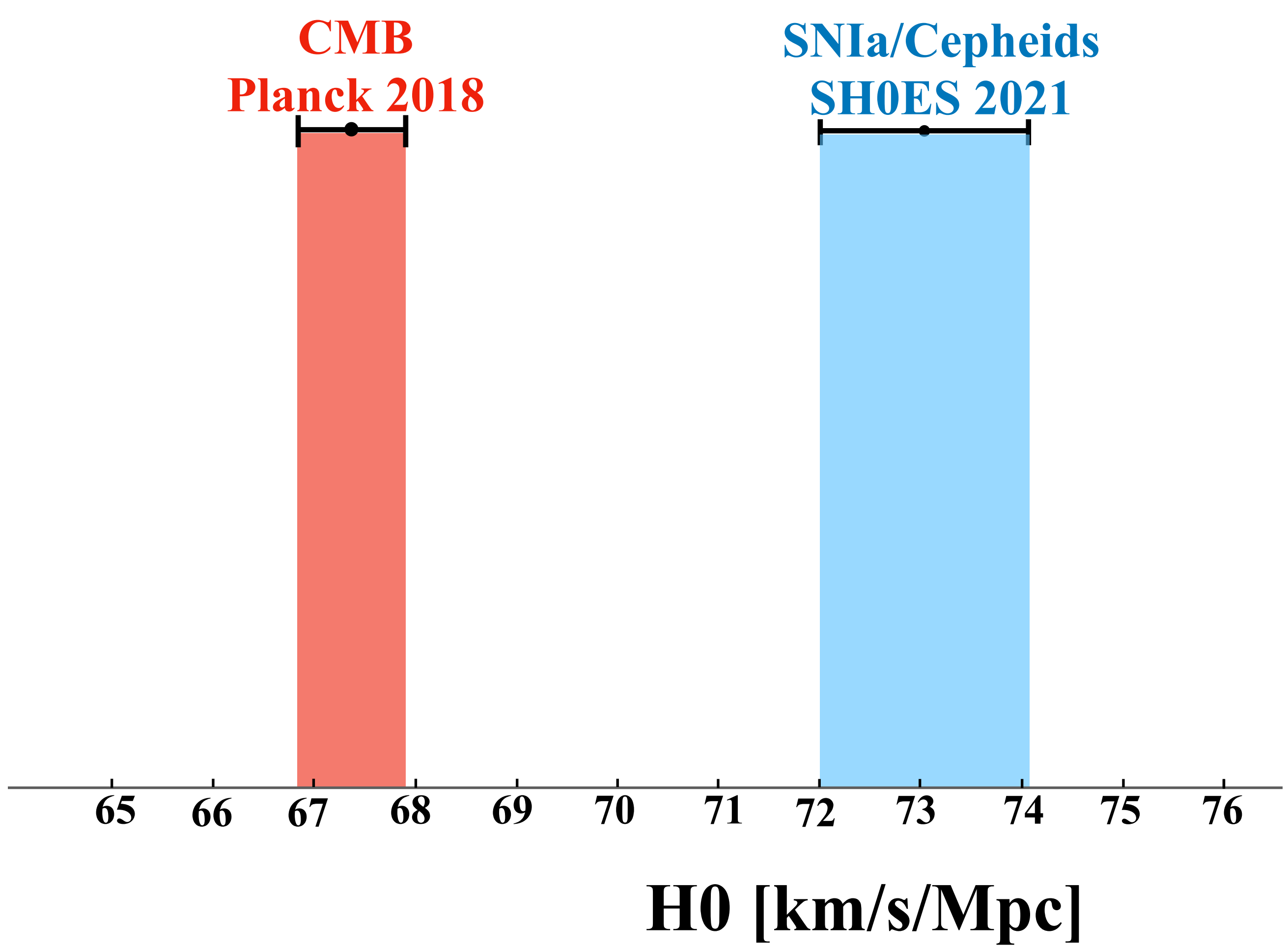
The expansion of the Universe is governed largely by dark matter and dark energy.

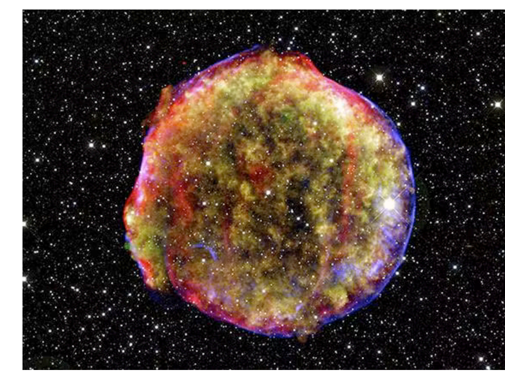
The simplest effective theory that captures the dynamics is Λ_{CDM}.
It presents extremely puzzling features.

It would not come as a surprise if Λ_{CDM} cracks open one of these days.

H_0 tension?



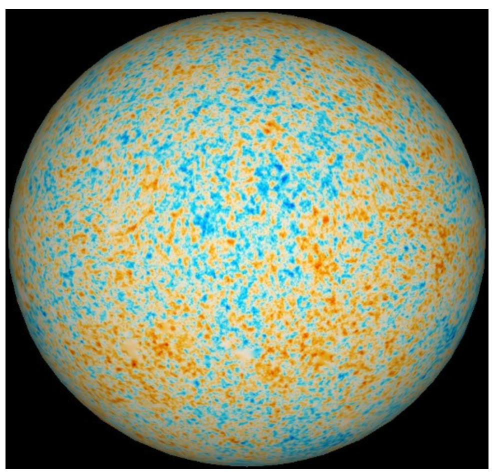

CMB
Planck 2018
SNIa/Cepheids
SH0ES 2021
65
66
67
68
69
70
71
72
73
74
75
76
H0 [km/s/Mpc]

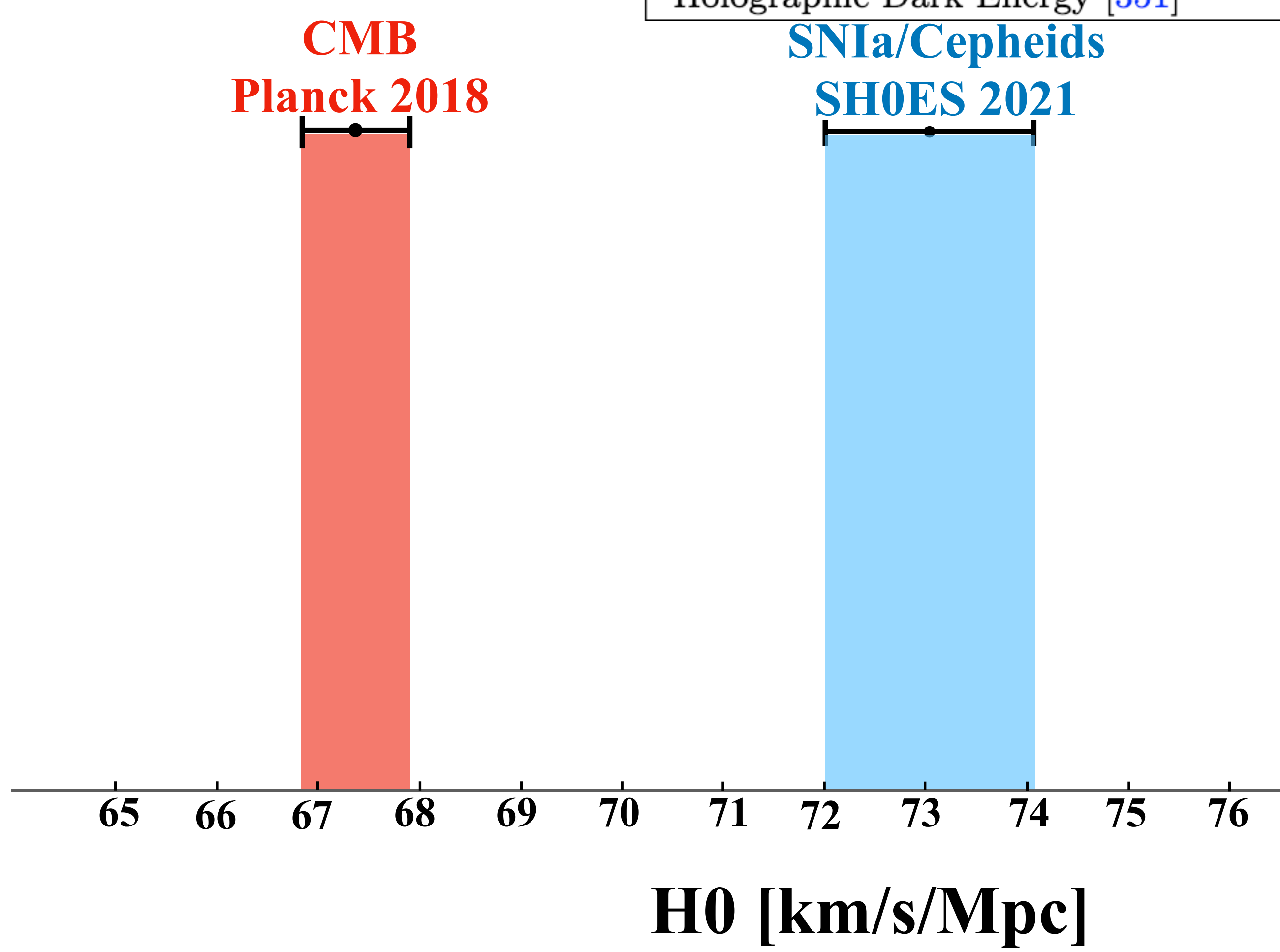


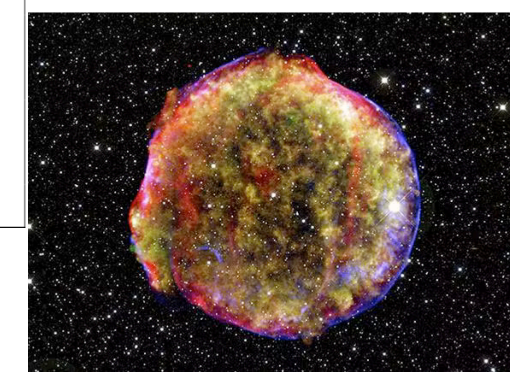
Perhaps a BΛCDM solution?
e.g. Di Valentino 2103.01183

tension $\leq 1\sigma$ *"Excellent models"*
Early Dark Energy [228, 235, 240, 250]
Exponential Acoustic Dark Energy [259]
Phantom Crossing [315]
Late Dark Energy Transition [317]
Metastable Dark Energy [314]
PEDE [394]
Vacuum Metamorphosis [402]
Elaborated Vacuum Metamorphosis [401, 402]
Sterile Neutrinos [433]
Decaying Dark Matter [481]
Neutrino-Majoron Interactions [509]
IDE [637, 639, 657, 661]
DM - Photon Coupling [685]
$f(\mathcal{T})$ gravity theory [812]
BD-ΛCDM [851]
Über-Gravity [59]
Galileon Gravity [875]
Unimodular Gravity [890]
Time Varying Electron Mass [990]
$\Lambda\!\!\!\Lambda$CDM [995]
Ginzburg-Landau theory [996]
Lorentzian Quintessential Inflation [979]
Holographic Dark Energy [351]

H0 tension?







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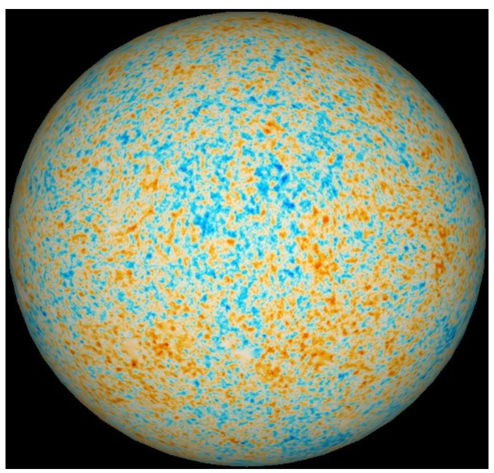
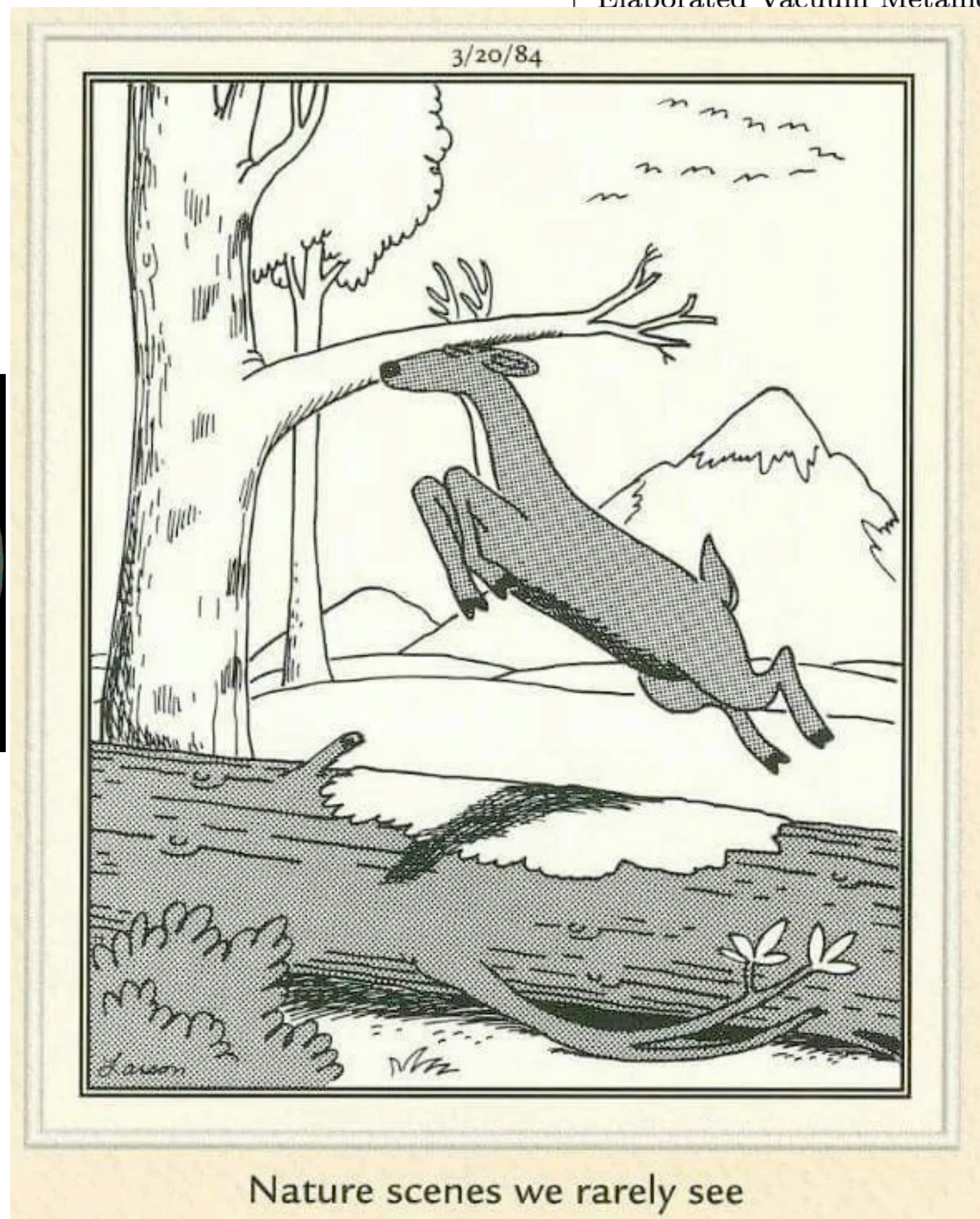
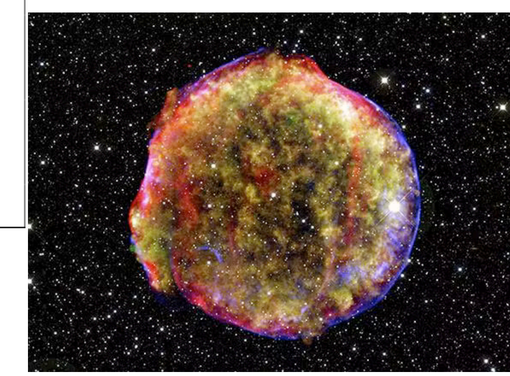
[990]
6]
flation [979]
51]



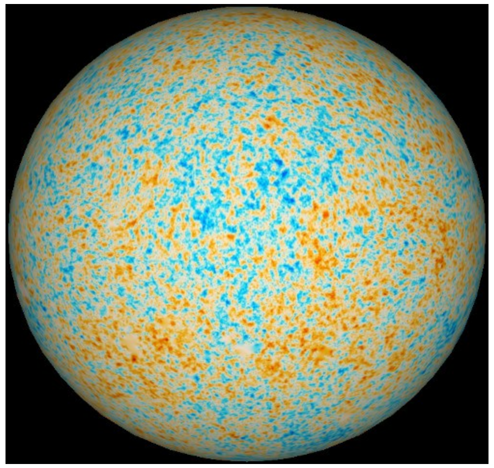


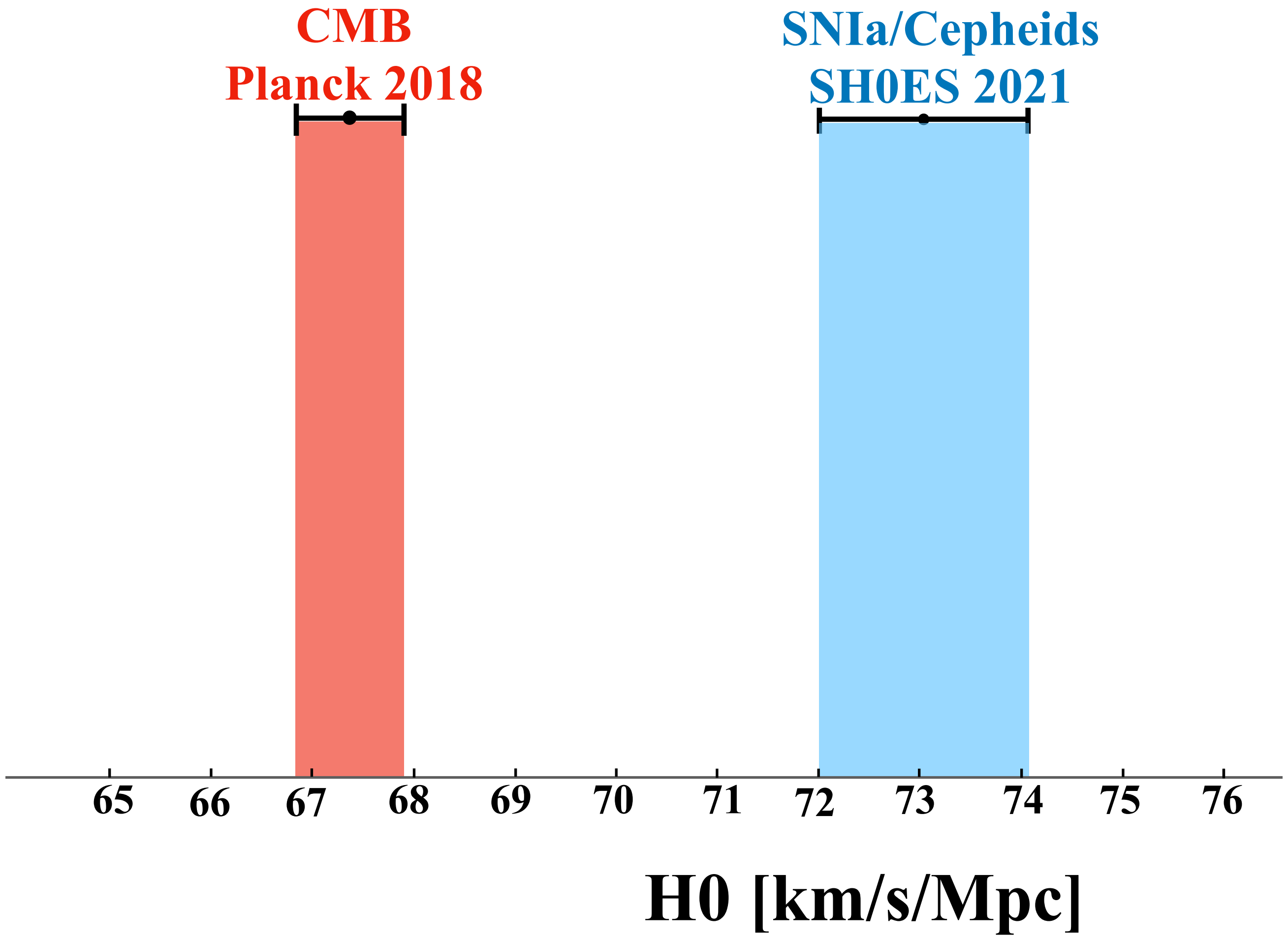


76

H0 [km/s/Mpc]

H0 tension?




CMB
Planck 2018
SNIa/Cepheids
SH0ES 2021
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67
68
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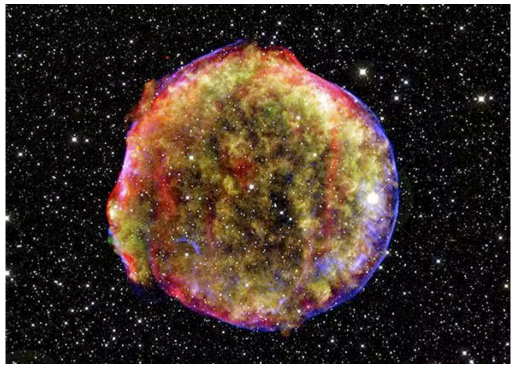
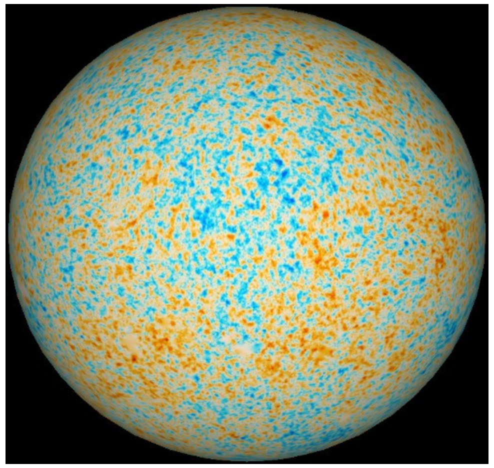
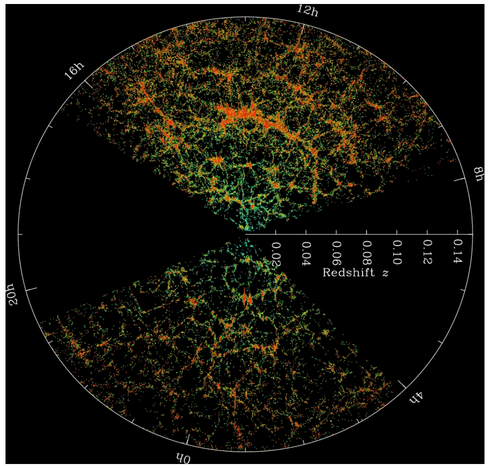
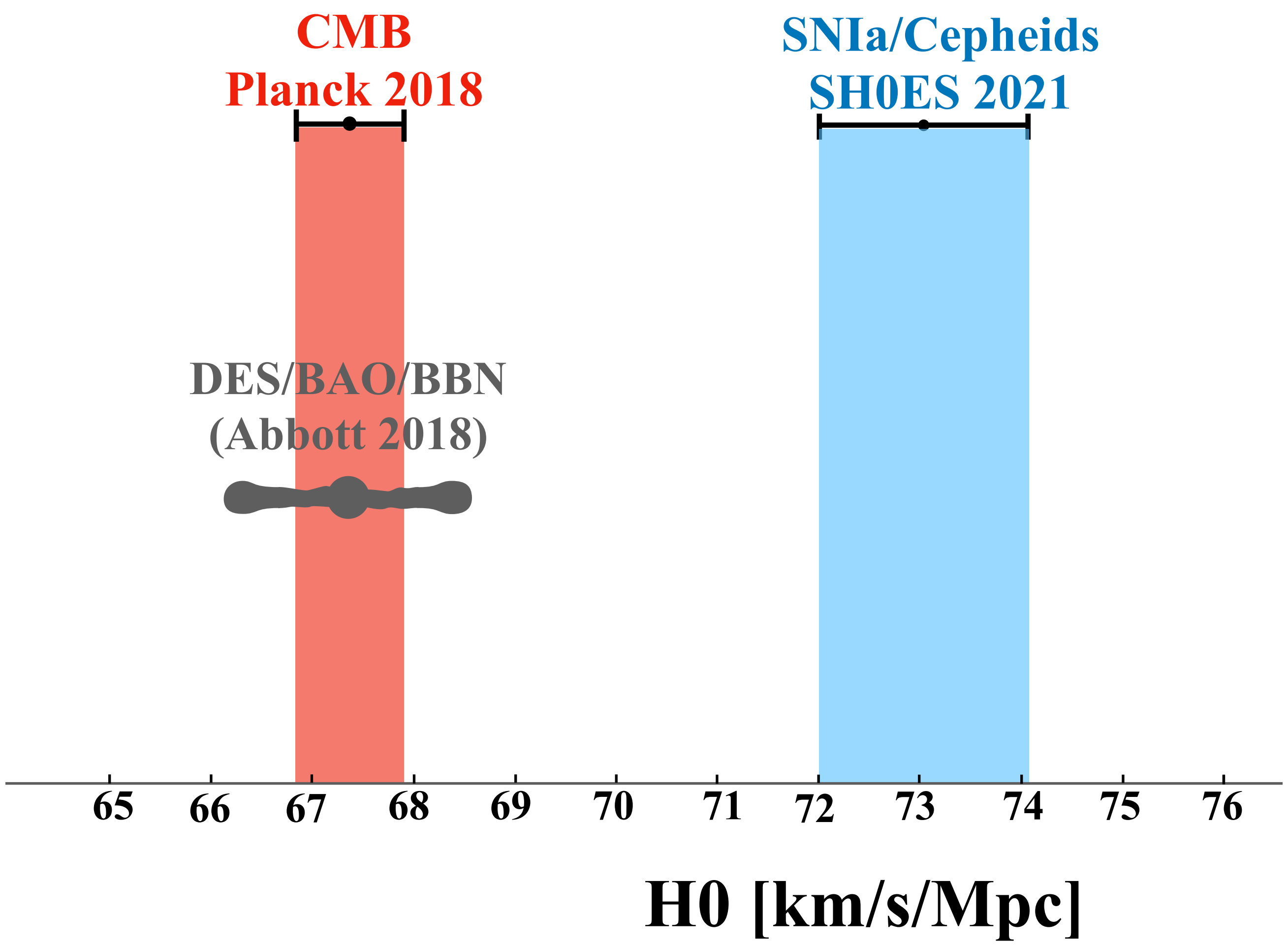
71
72
73
74
75
76
H0 [km/s/Mpc]



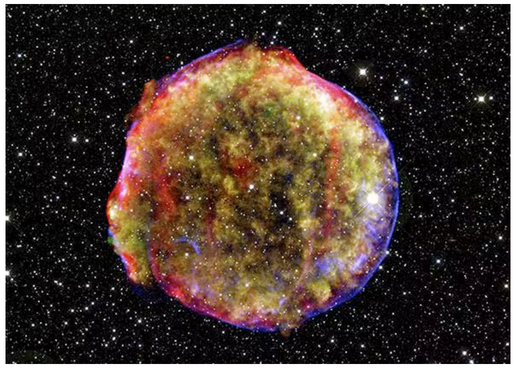
H0 tension?



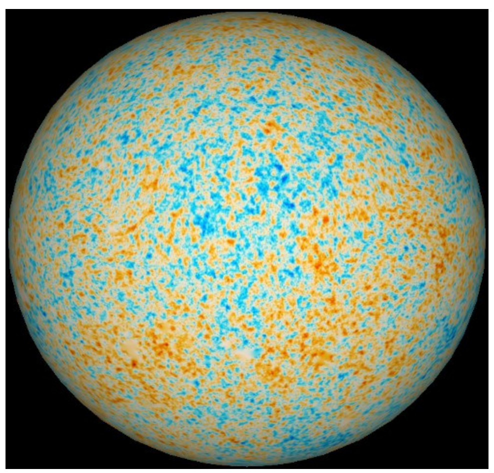


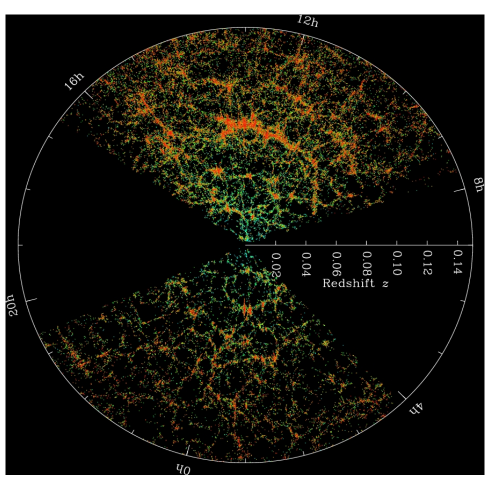


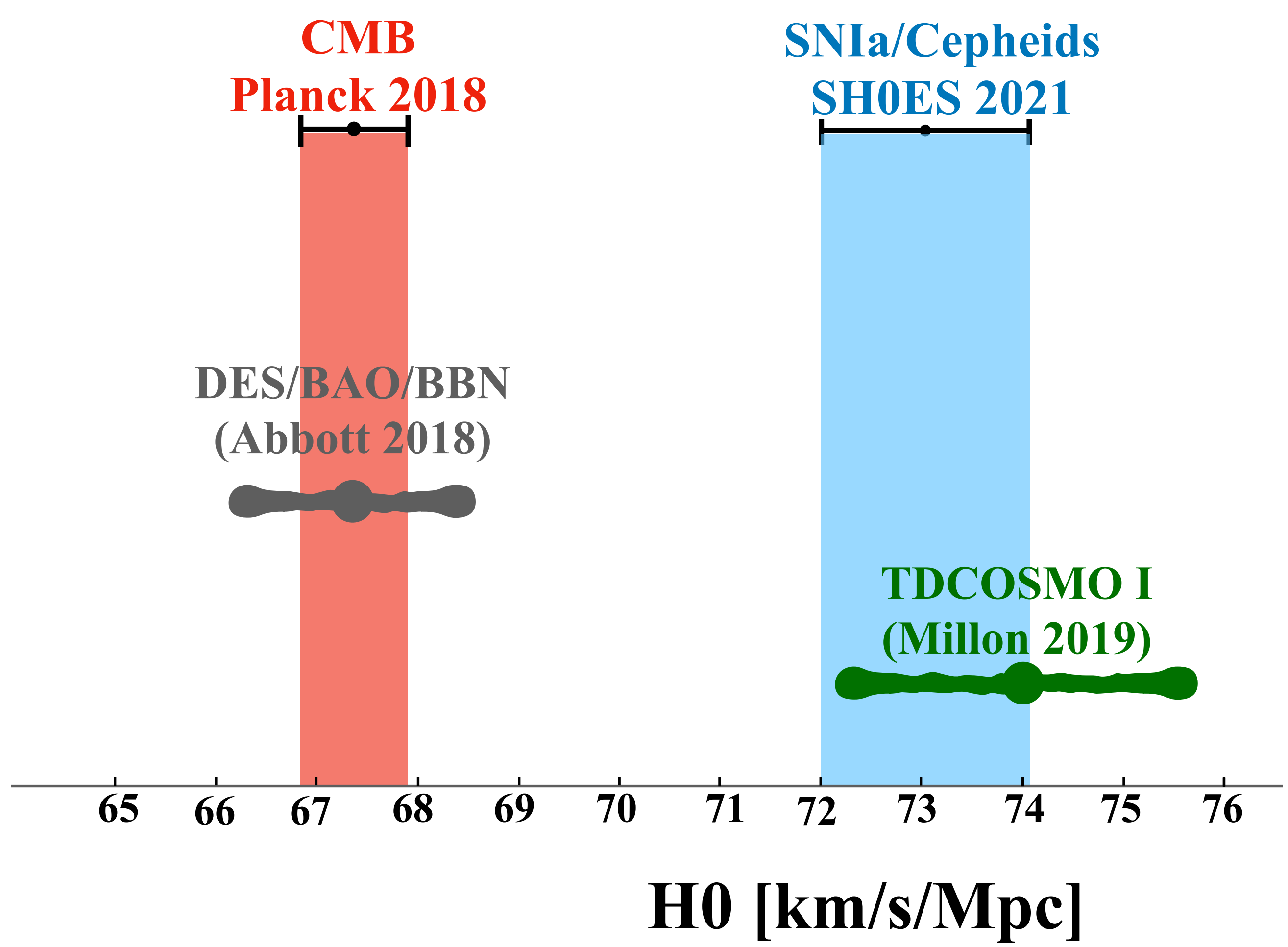
CMB
Planck 2018
SNIa/Cepheids
SH0ES 2021
DES/BAO/BBN
(Abbott 2018)
65 66 67 68 69 70 71 72 73 74 75 76
H0 [km/s/Mpc]

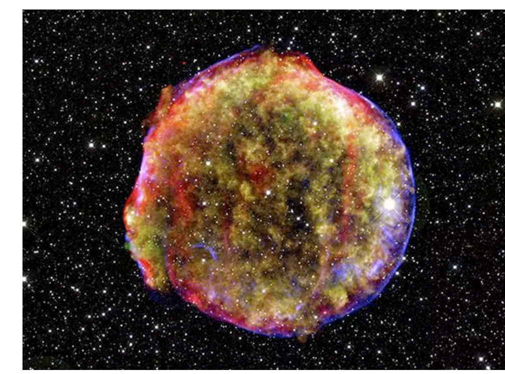


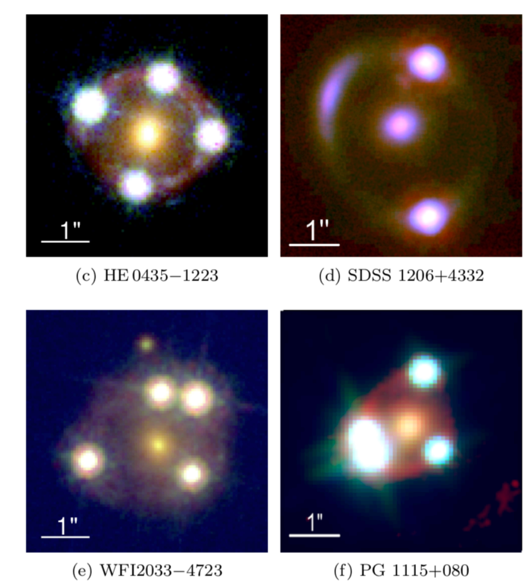
H_0 tension?





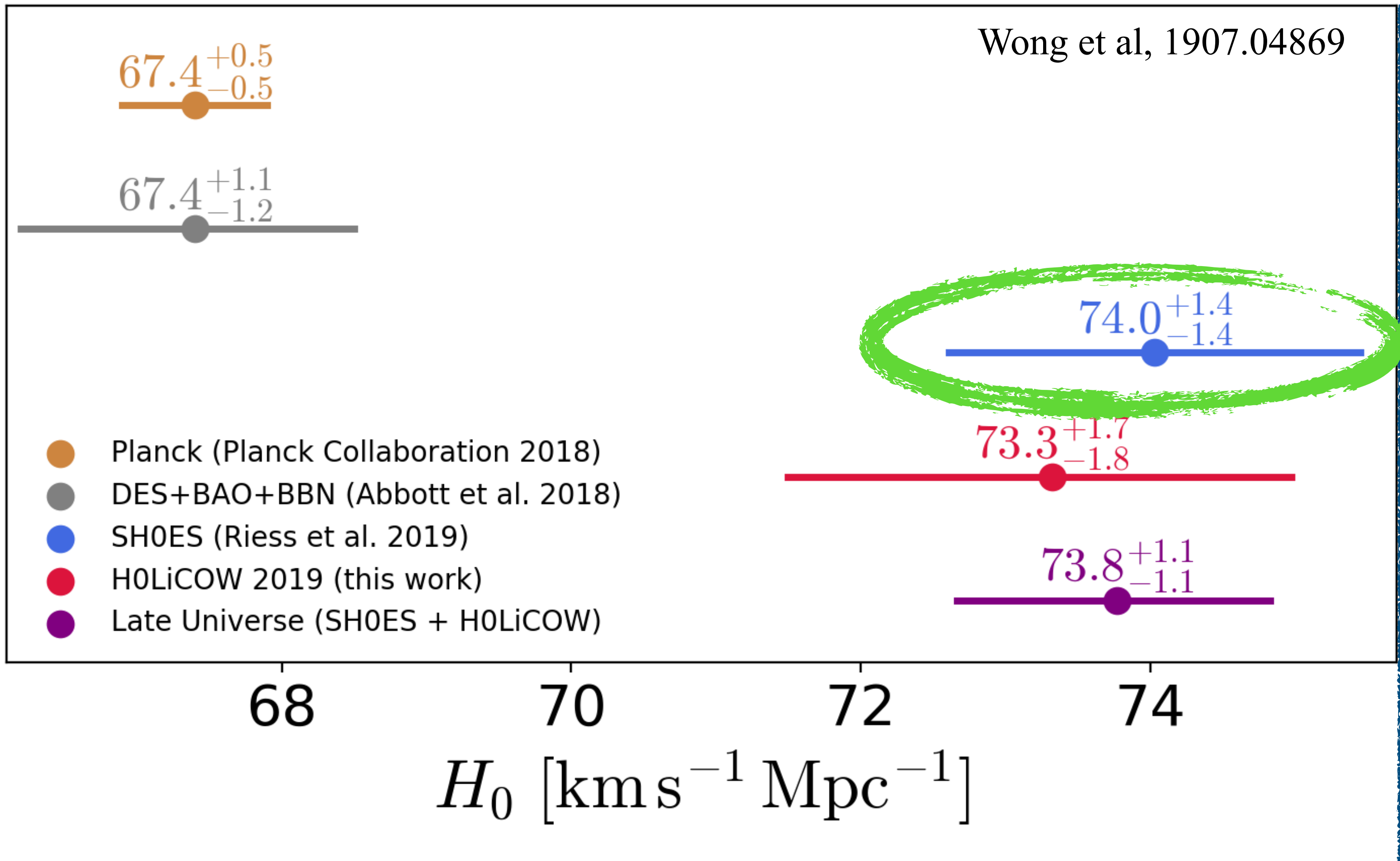


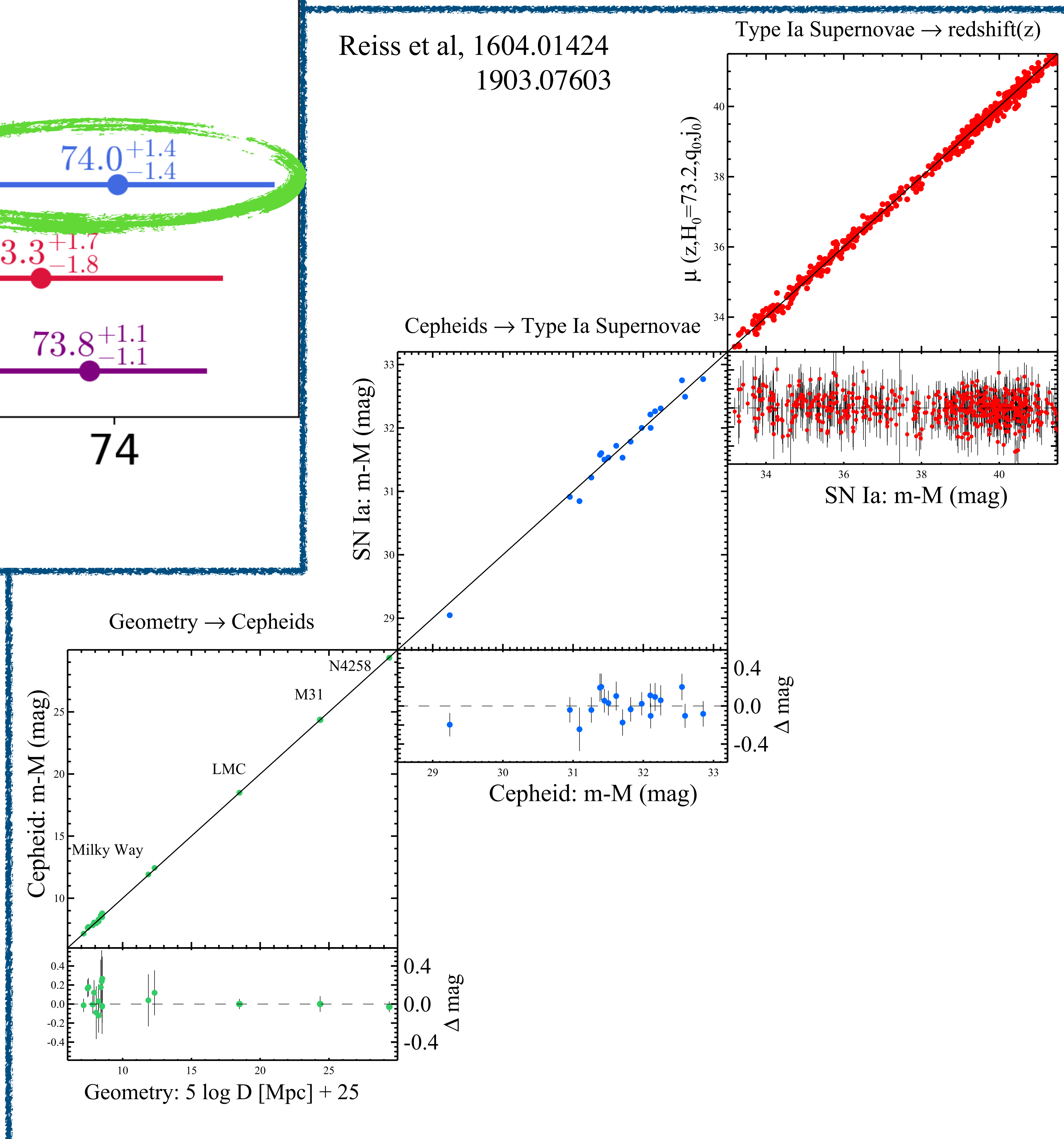




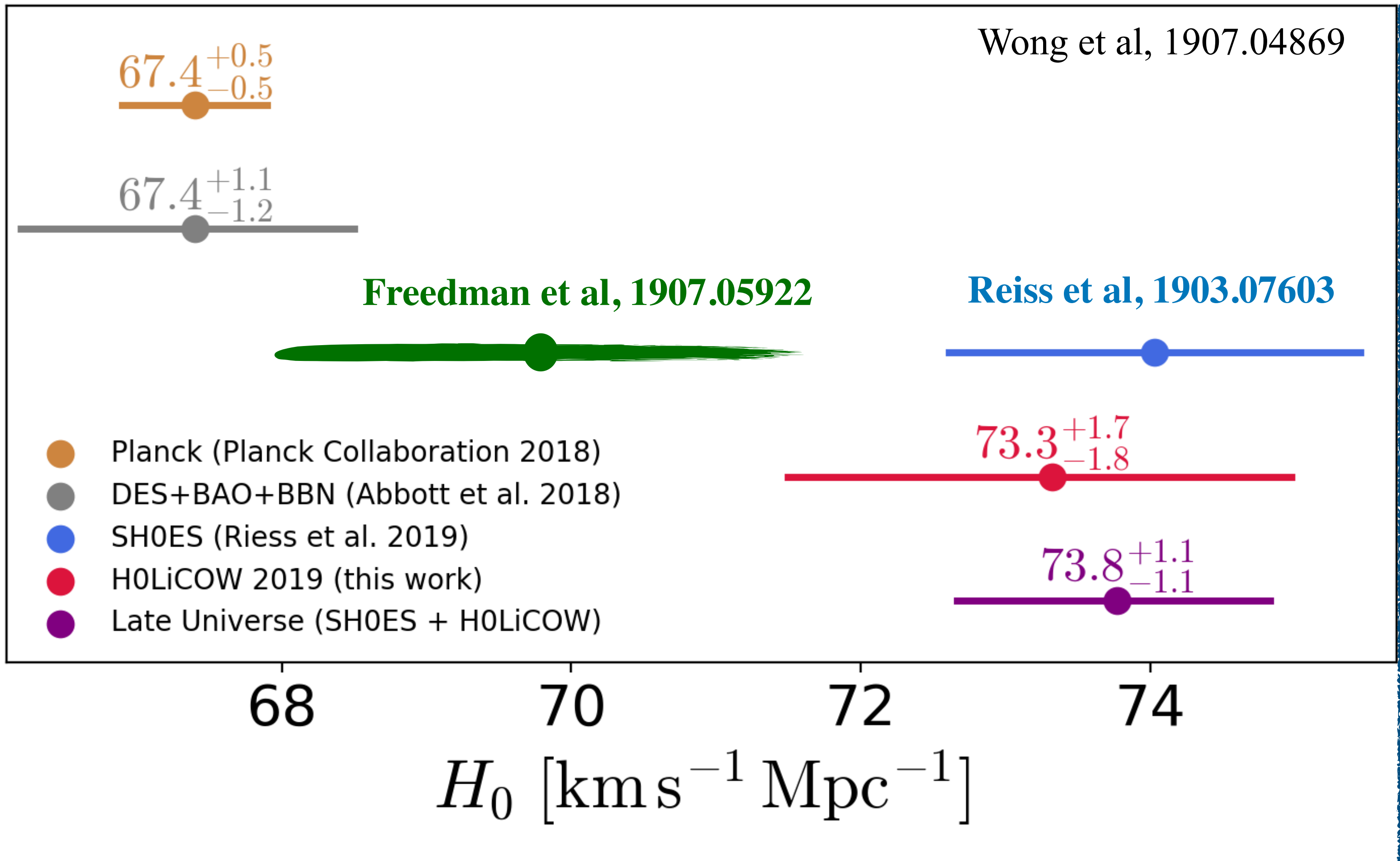
(c) HE 0435−1223 (d) SDSS 1206+4332

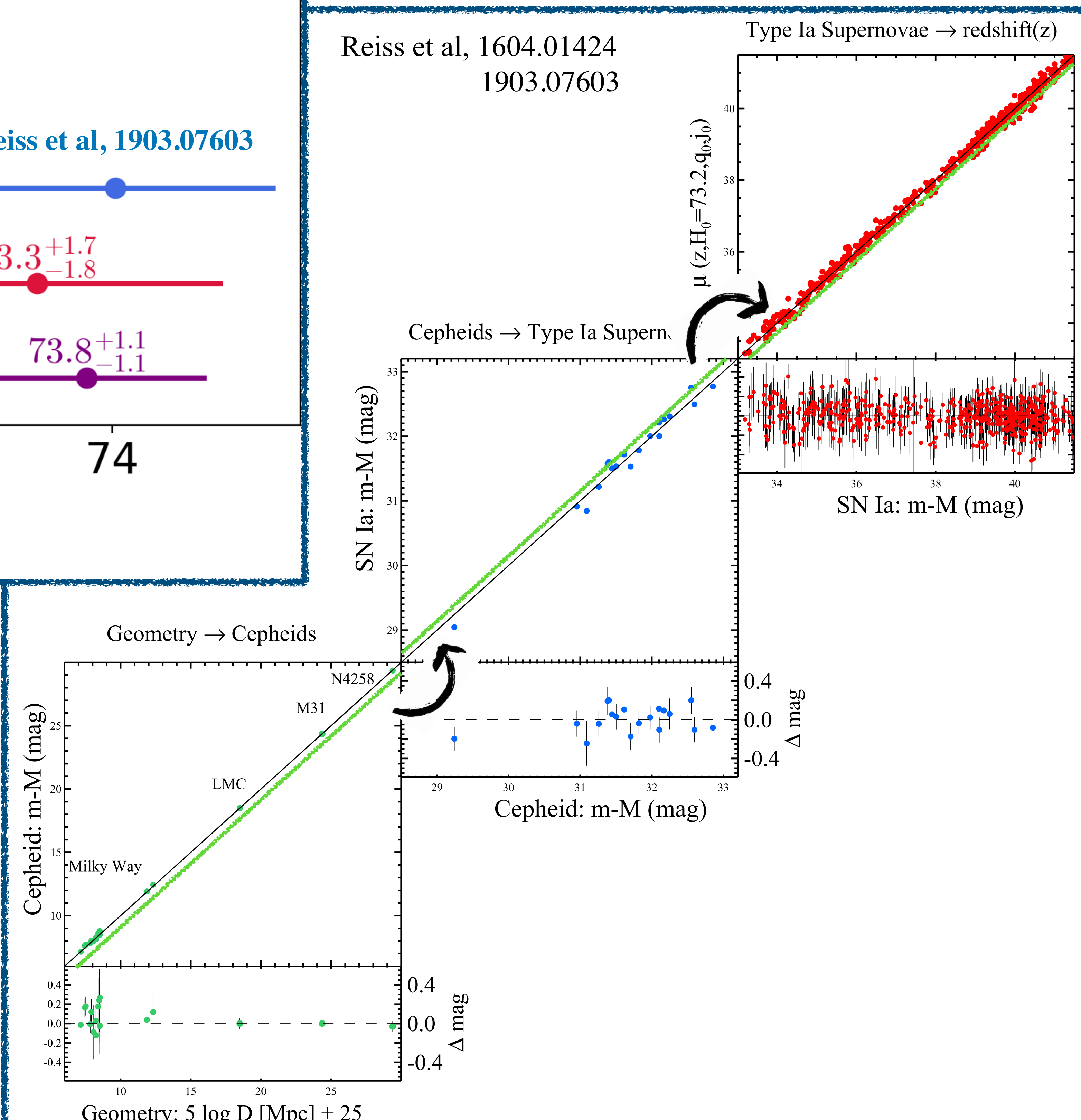
(e) WFI2033−4723 (f) PG 1115+080





Classic distance ladder.





Classic distance ladder.

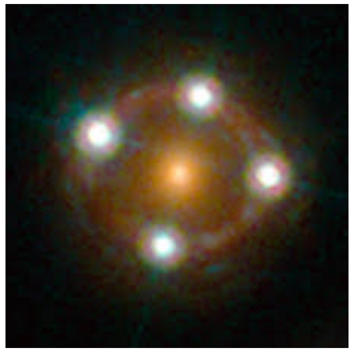
Two independent efforts to calibrate the ladder: cepheids vs. TRGB.

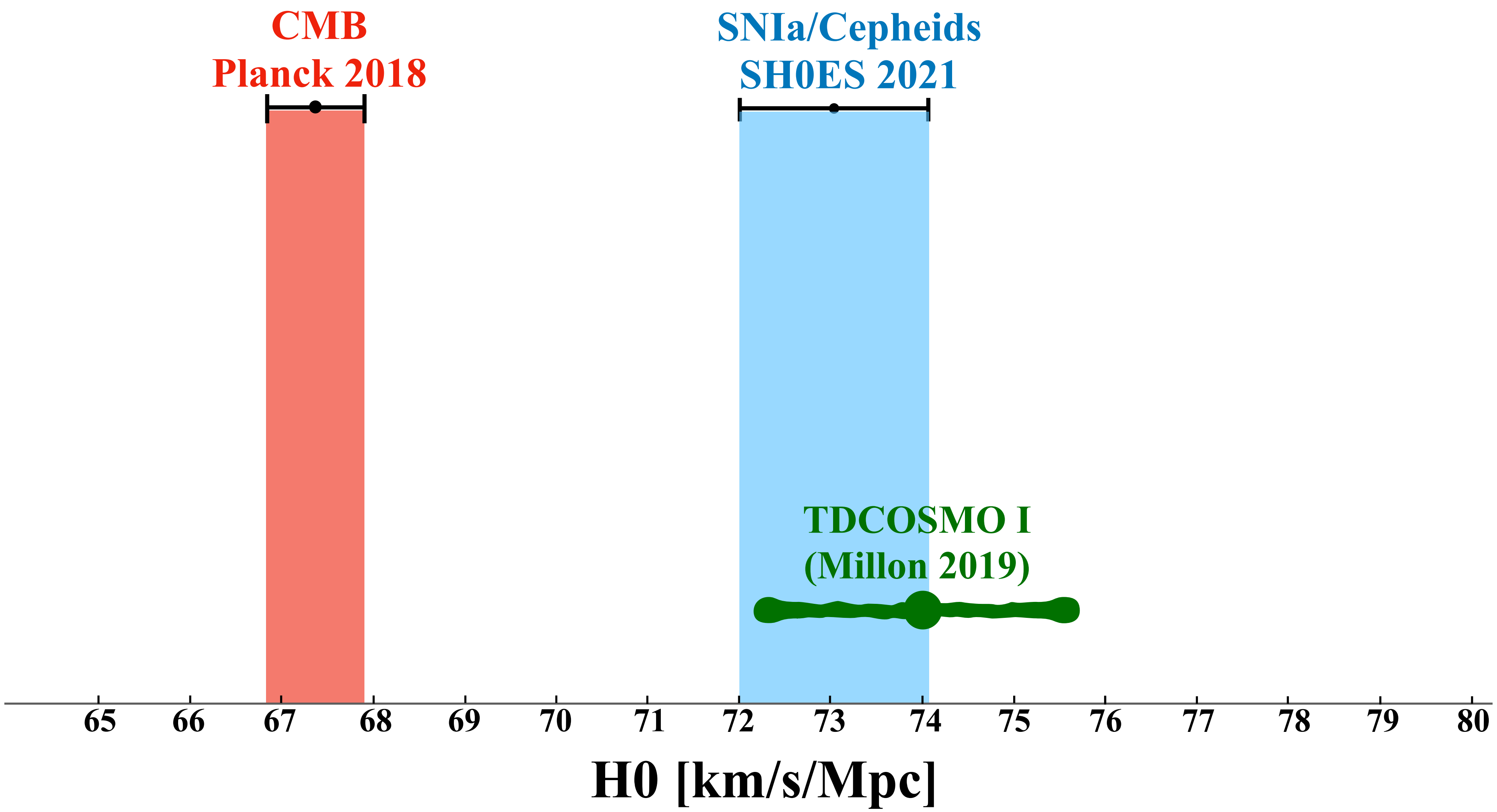
H0 tension

SNIa and **gravitational lensing agree?**

TDCOSMO
http://www.tdcosmo.org/projects.html

- H0LiCOW
- COSMOGRAIL
- STRIDES
- SHARP
- COSMICLENS





H0 tension

SNIa and **gravitational lensing *dis*agree?**

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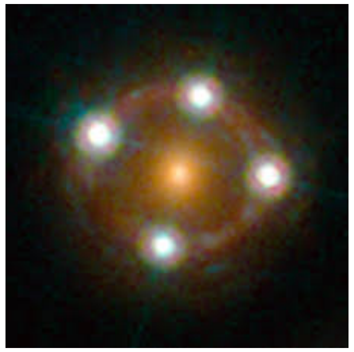
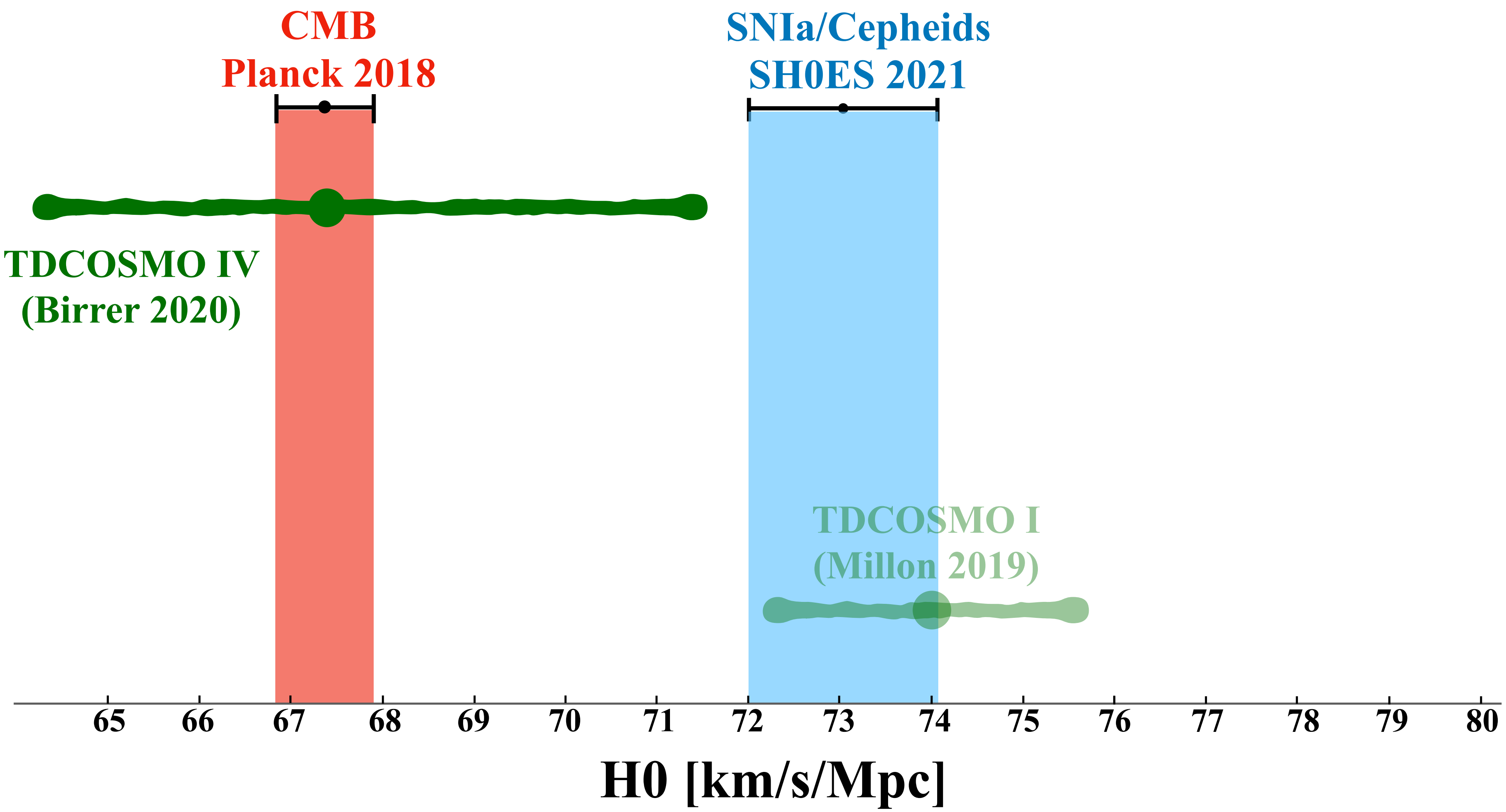
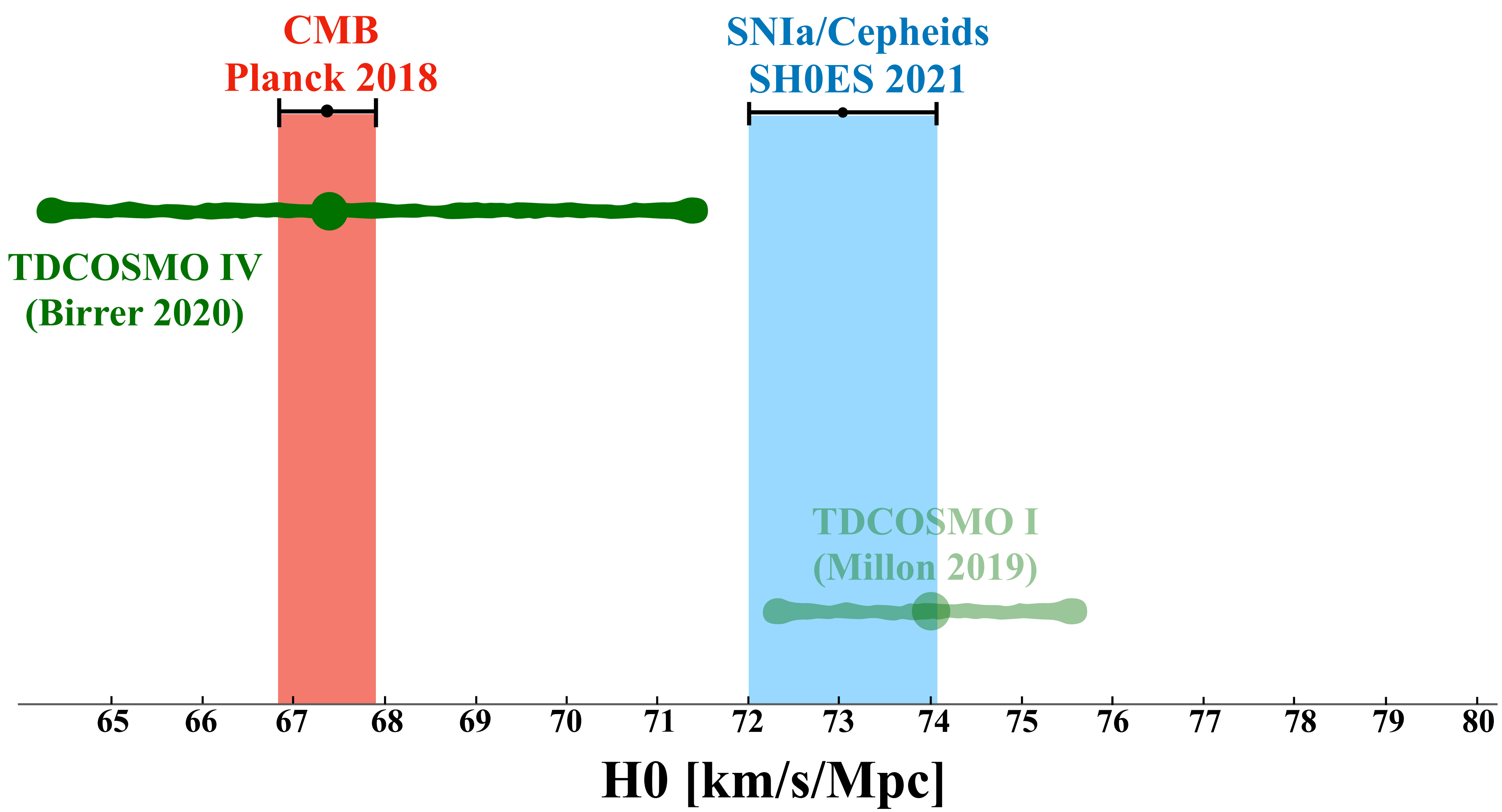


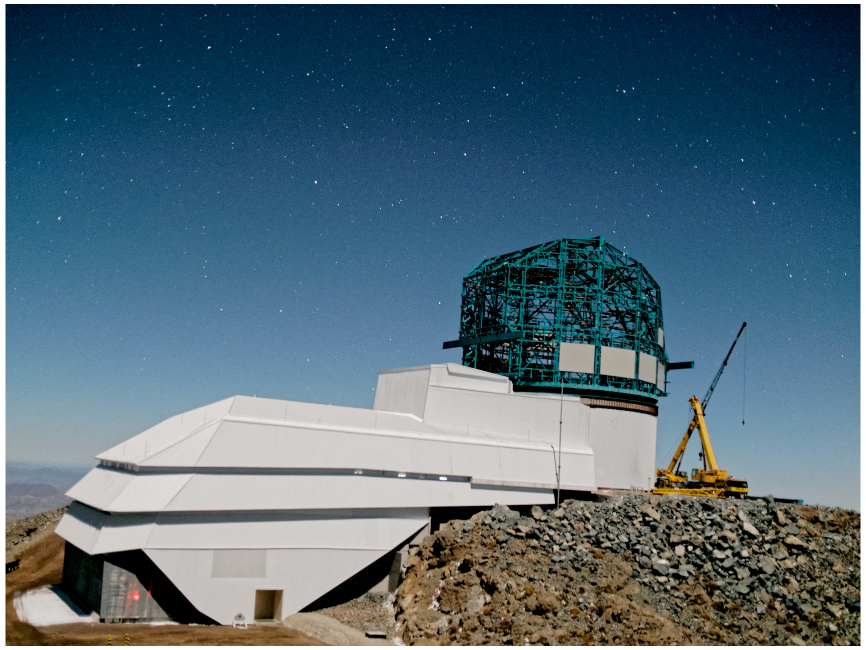


1. Recap: how lensing measures H0
2. Challenges: modeling degeneracy (TDCOSMO I —> IV)
3. Opportunities: galactic structure

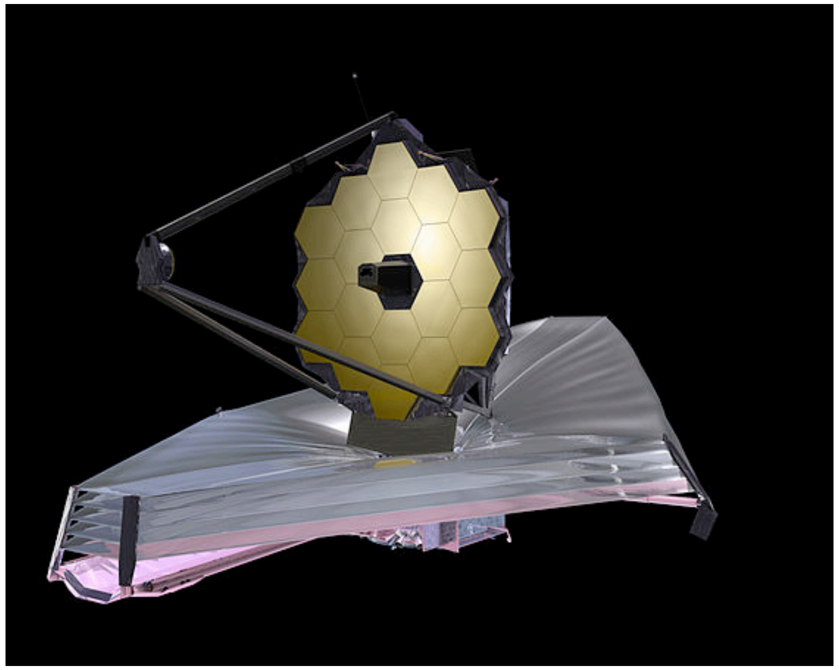


1. Recap: how lensing measures H_0
2. Challenges: modeling degeneracy (TDCOSMO I —> IV)
3. **Opportunities: galactic structure**

LSST: 100's of strongly lensed variable quasars
Oguri, Marshall, 1001.2037



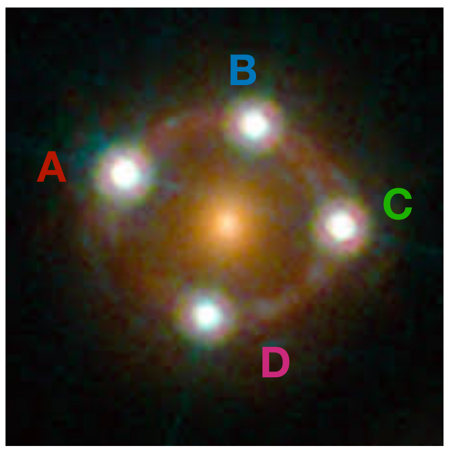
JWST: improved kinematics
Yıldırım, Suyu, Halkola, 1904.07237
Birrer, Treu, 2008.06157

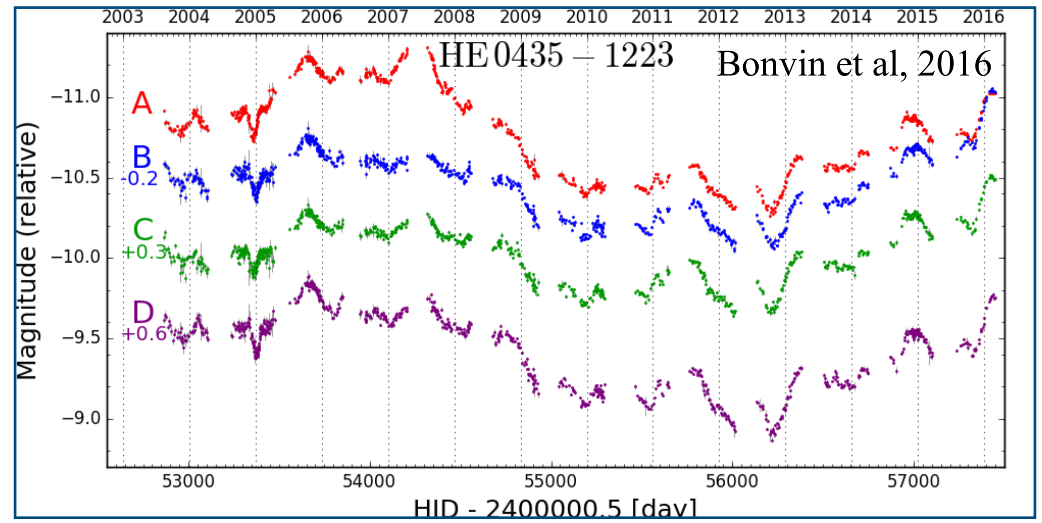


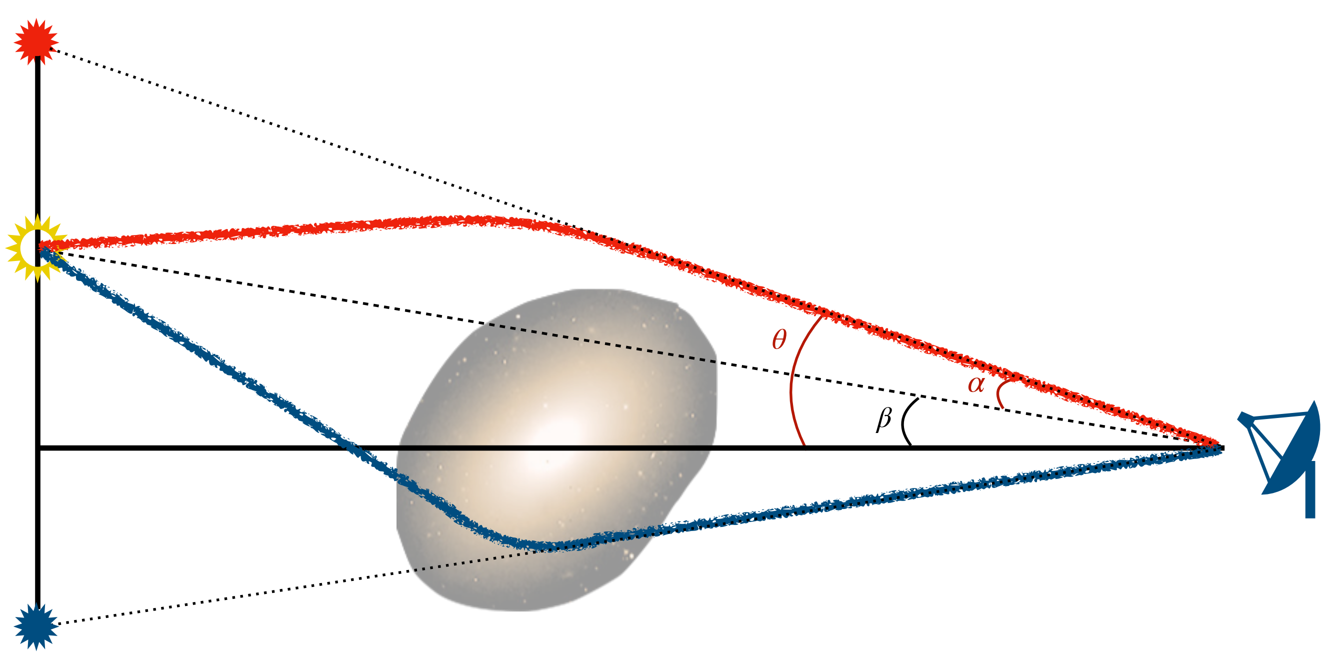
1. Recap: how lensing measures H0

Observables:

- Extended source image
- Time delay Δt





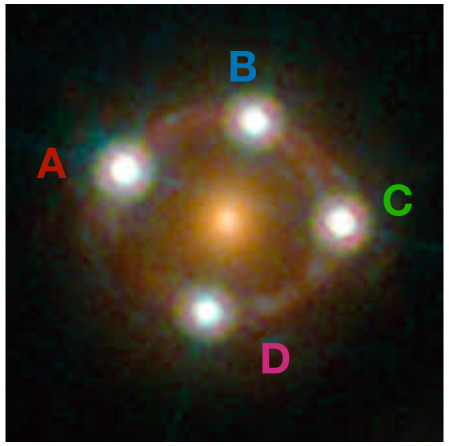


1. Recap: how lensing measures H0

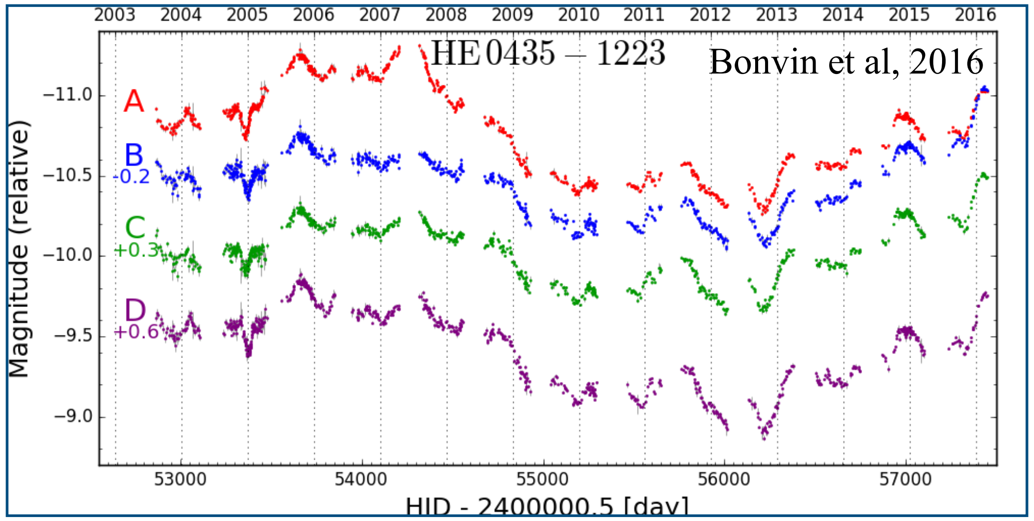
Observables:

- Extended source image

$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta})$$

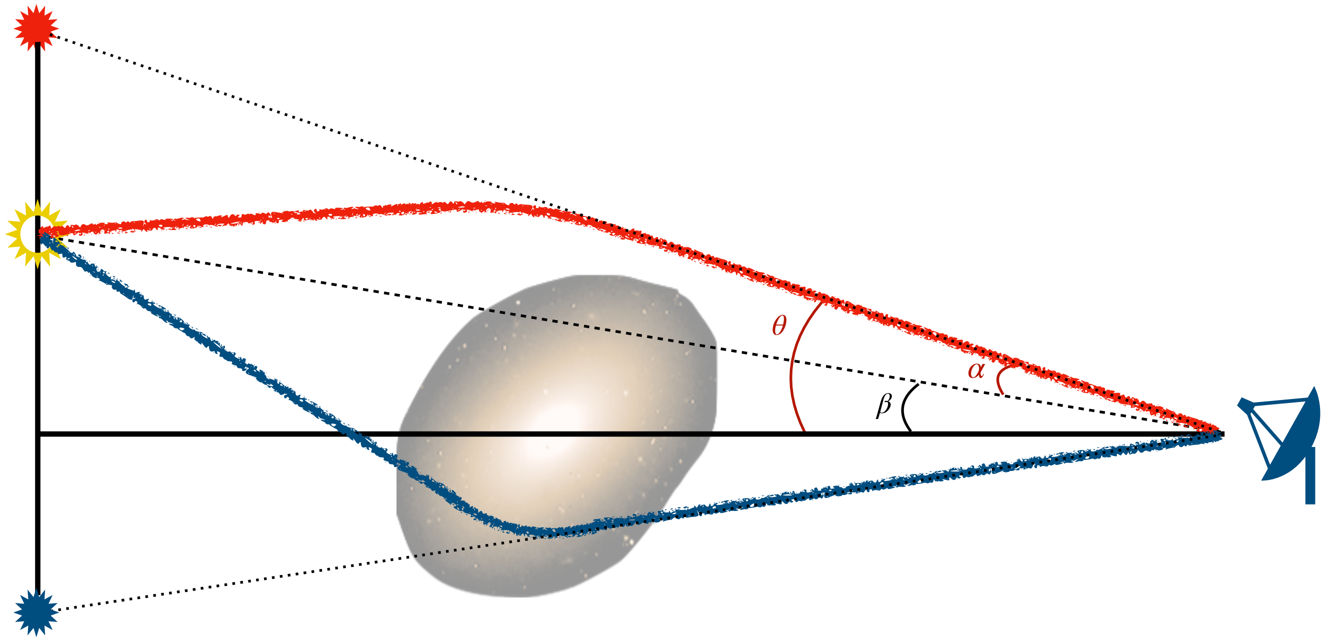


- Time delay Δt



$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\rm crit}} = \frac{1}{2}\vec{\nabla}_\theta \cdot \vec{\alpha} = \frac{1}{2}\vec{\nabla}^2_\theta \psi$$

$$\Sigma_{\rm crit} = \frac{d_A(z_s,0)}{4\pi G\, d_A(z_l,0) d_A(z_s,z_l)}$$



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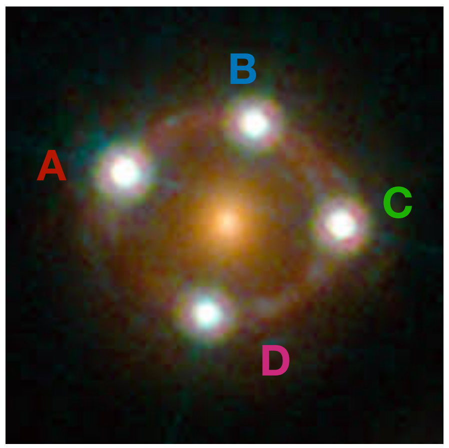
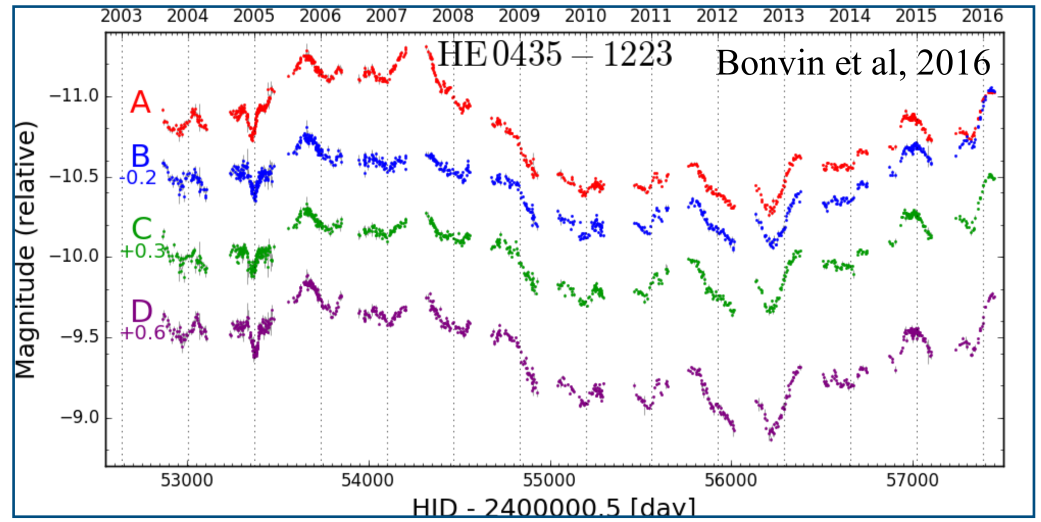
Observables:

- Extended source image

$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta})$$



- Time delay $\Delta t_{AB} = D_{\Delta t}\,\Delta\tau_{AB}$



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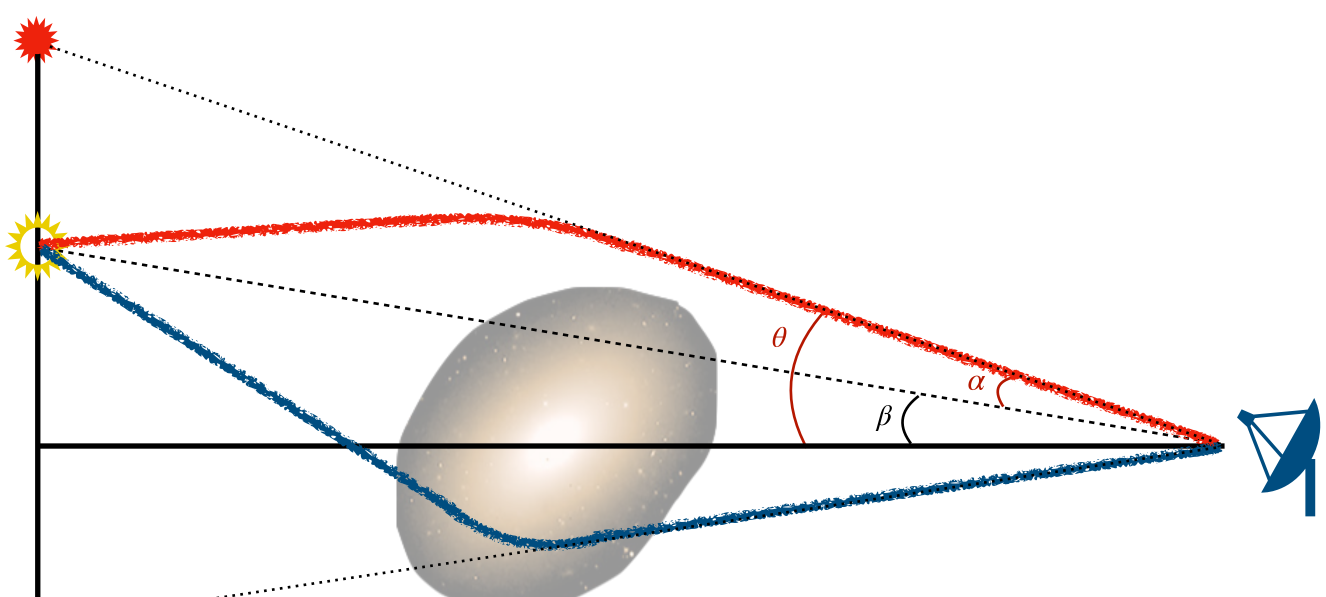
$$\tau(\vec{\theta}) = \frac{\vec{\theta}^2}{2} - \vec{\beta}\cdot\vec{\theta} - \psi(\vec{\theta})$$

$$\Sigma_{\rm crit} = \frac{d_A(z_s,0)}{4\pi G\, d_A(z_l,0)d_A(z_s,z_l)}$$

$$D_{\Delta t} = (1+z_l)\frac{d_A(z_l,0)d_A(z_s,0)}{d_A(z_s,z_l)}$$

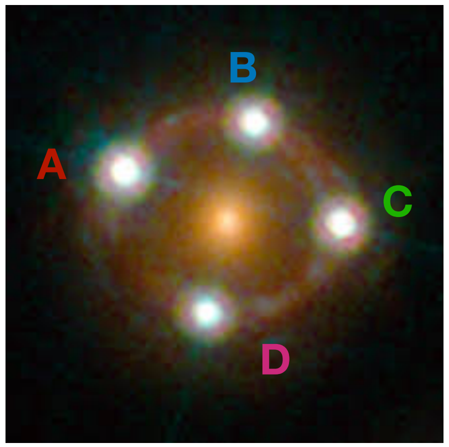


1. Recap: how lensing measures H0

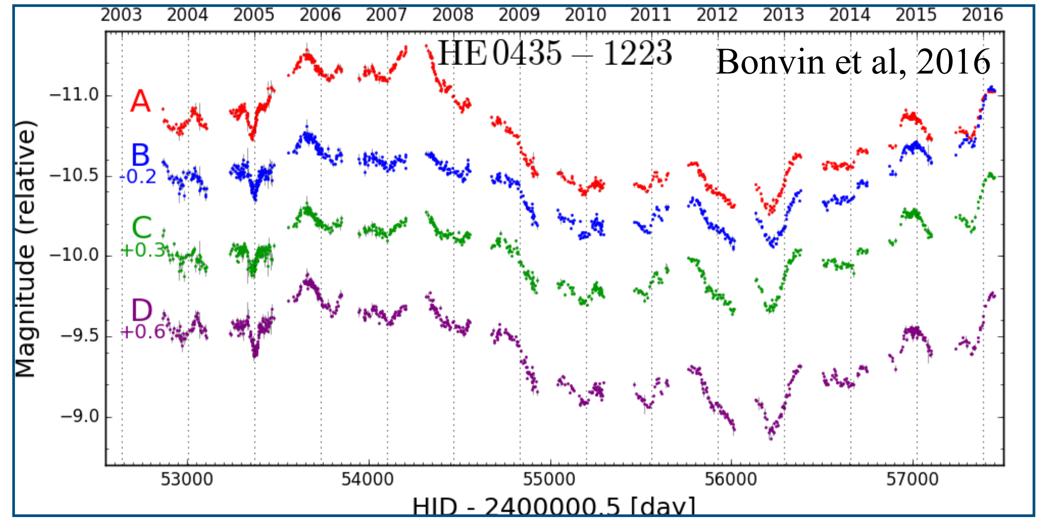
Observables:

- Extended source image

$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta})$$



- Time delay $\Delta t_{AB} = D_{\Delta t}\, \Delta\tau_{AB}$



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$$D_{\Delta t} = (1+z_l)\frac{d_A(z_l,0)d_A(z_s,0)}{d_A(z_s,z_l)}$$

1. From the image, reconstruct a model $\kappa(\vec{\theta}),\ \vec{\beta} \ \rightarrow\ \tau(\vec{\theta})$
2. Given the model and Δt, extract $D_{\Delta t} = \dfrac{\Delta t}{\Delta \tau} \propto \dfrac{1}{H_0}$

2. Challenges: modeling degeneracy

$$
\begin{aligned}
\vec{\theta} &= \vec{\beta} + \vec{\alpha} \\
&= \vec{\beta}_\lambda + \vec{\alpha}_\lambda \\
&= \lambda\vec{\beta} + \lambda\vec{\alpha} + (1-\lambda)\vec{\theta} \\
&= \lambda(\vec{\beta} + \vec{\alpha} - \vec{\theta}) + \vec{\theta} \\
&= \vec{\theta}
\end{aligned}
$$

$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\mathrm{crit}}} = \frac{1}{2}\vec{\nabla}_\theta \cdot \vec{\alpha} = \frac{1}{2}\vec{\nabla}_\theta^2 \psi$$

$$\tau(\vec{\theta}) = \frac{\vec{\theta}^2}{2} - \vec{\beta}\cdot\vec{\theta} - \psi(\vec{\theta})$$

$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta}) \longleftarrow \vec{\nabla}_\theta \tau(\vec{\theta}) = 0$$

Imaging + time delay **cannot** measure H0.
It cannot access the overall normalization of $\tau(\vec{\theta})$,
and the normalization of $\tau(\vec{\theta})$ is essentially H0.

$$D_{\Delta t} = \frac{\Delta t}{\Delta \tau} \propto \frac{1}{H_0}$$

2. Challenges: modeling degeneracy

$$\Gamma_i^{\mathrm{r}} = -\begin{pmatrix} \gamma_1^{\mathrm{r},i} & \gamma_2^{\mathrm{r},i} \\ \gamma_2^{\mathrm{r},i} & -\gamma_1^{\mathrm{r},i} \end{pmatrix}$$

$$(1-\kappa_i^{\mathrm{r}})(\mathbb{I}+\Gamma_i^{\mathrm{r}}) \simeq \mathbb{I} - (\mathbb{I}\kappa_i^{\mathrm{r}} - \Gamma_i^{\mathrm{r}}) =: \mathbb{I} - M_i^{\mathrm{r}}$$

$$\begin{aligned}
M_i^{\mathrm{s}} &\longmapsto M_i^{\mathrm{s},\lambda} = \lambda_{\mathrm{s}} M_i^{\mathrm{s}} + (1-\lambda_{\mathrm{s}})\mathbb{I}, \\
M_i^{\mathrm{ls}} &\longmapsto M_i^{\mathrm{ls},\lambda} = \lambda_{\mathrm{ls}} M_i^{\mathrm{ls}} + (1-\lambda_{\mathrm{ls}})\mathbb{I}, \\
M^{\mathrm{l}} &\longmapsto M^{\mathrm{l},\lambda} = \lambda_{\mathrm{l}} M^{\mathrm{l}} + (1-\lambda_{\mathrm{l}})\mathbb{I}, \\
\vec{\beta}_i &\longmapsto \vec{\beta}_i^{\lambda} = \lambda_{\mathrm{s}} \vec{\beta}_i, \\
\vec{\alpha}_1(\vec{\theta}) &\longmapsto \vec{\alpha}_1^{\lambda}(\vec{\theta}) = \lambda_{\mathrm{s}}\, \lambda_{\mathrm{ls}}^{-1}\, \vec{\alpha}_1(\lambda_{\mathrm{l}}^{-1}\, \vec{\theta}), \\
\psi_1(\vec{\theta}) &\longmapsto \psi_1^{\lambda}(\vec{\theta}) = \lambda_{\mathrm{s}}\, \lambda_{\mathrm{ls}}^{-1}\, \lambda_{\mathrm{l}} \psi_1(\lambda_{\mathrm{l}}^{-1}\, \vec{\theta}).
\end{aligned}$$

$$\kappa(\overrightarrow{\theta}) = \frac{\Sigma(\overrightarrow{\theta})}{\Sigma_{\mathrm{crit}}} = \frac{1}{2}\overrightarrow{\nabla}_\theta \cdot \overrightarrow{\alpha} = \frac{1}{2}\overrightarrow{\nabla}_\theta^2 \psi$$

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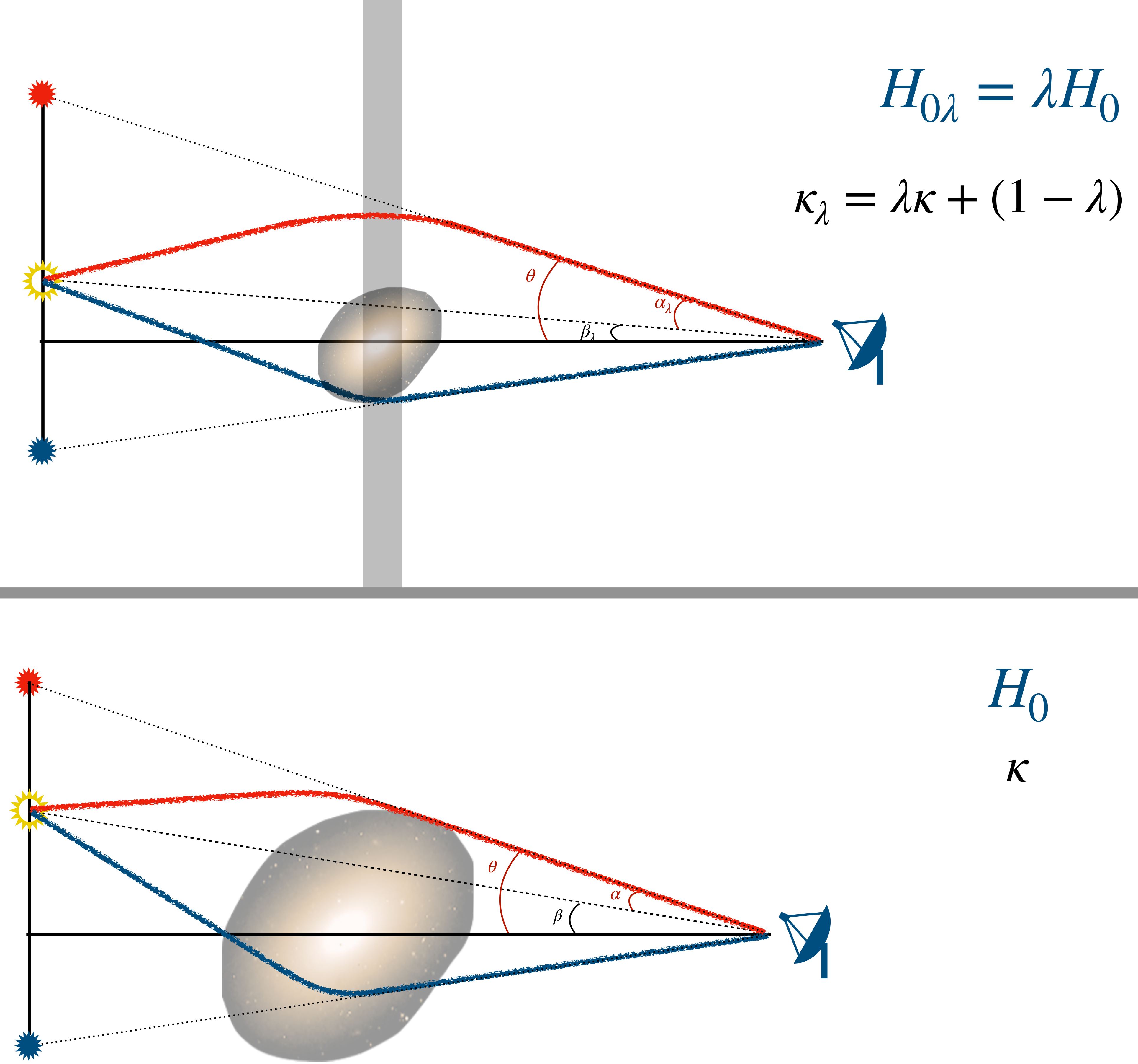
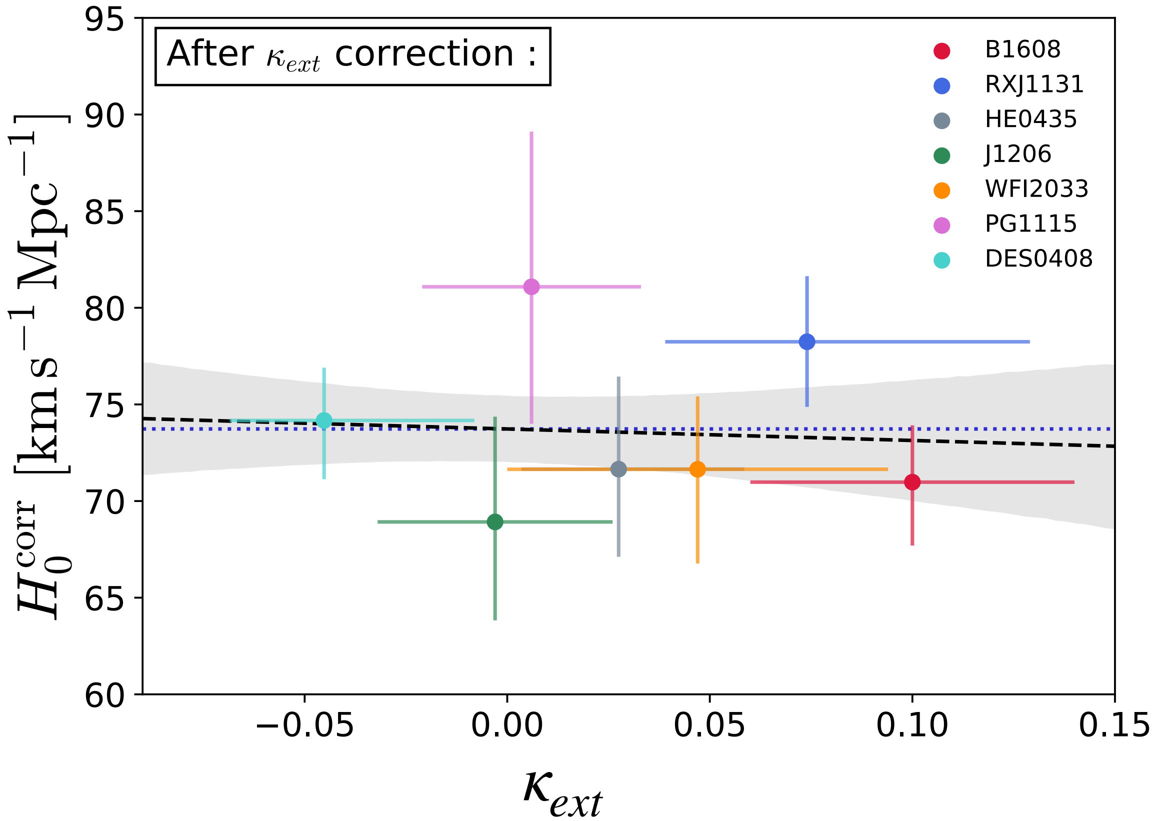
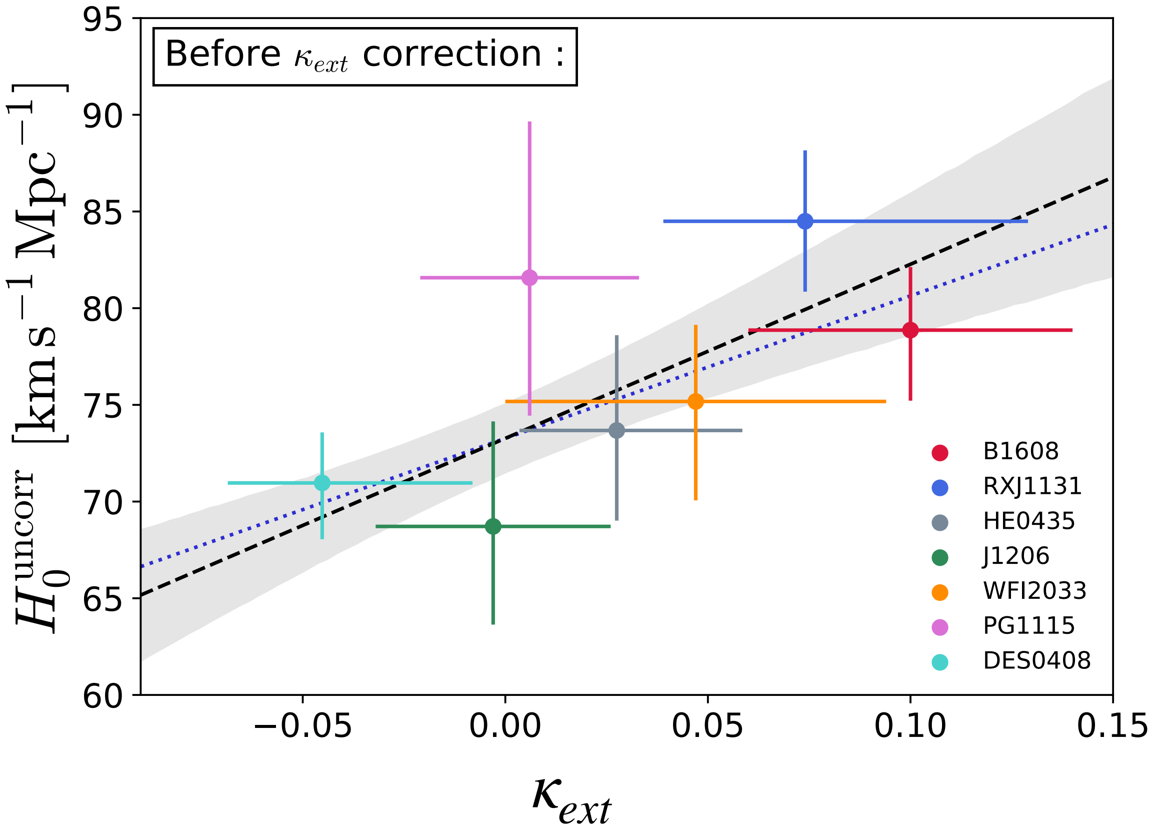
$$D_{\Delta t} = \frac{\Delta t}{\Delta \tau} \propto \frac{1}{H_0}$$



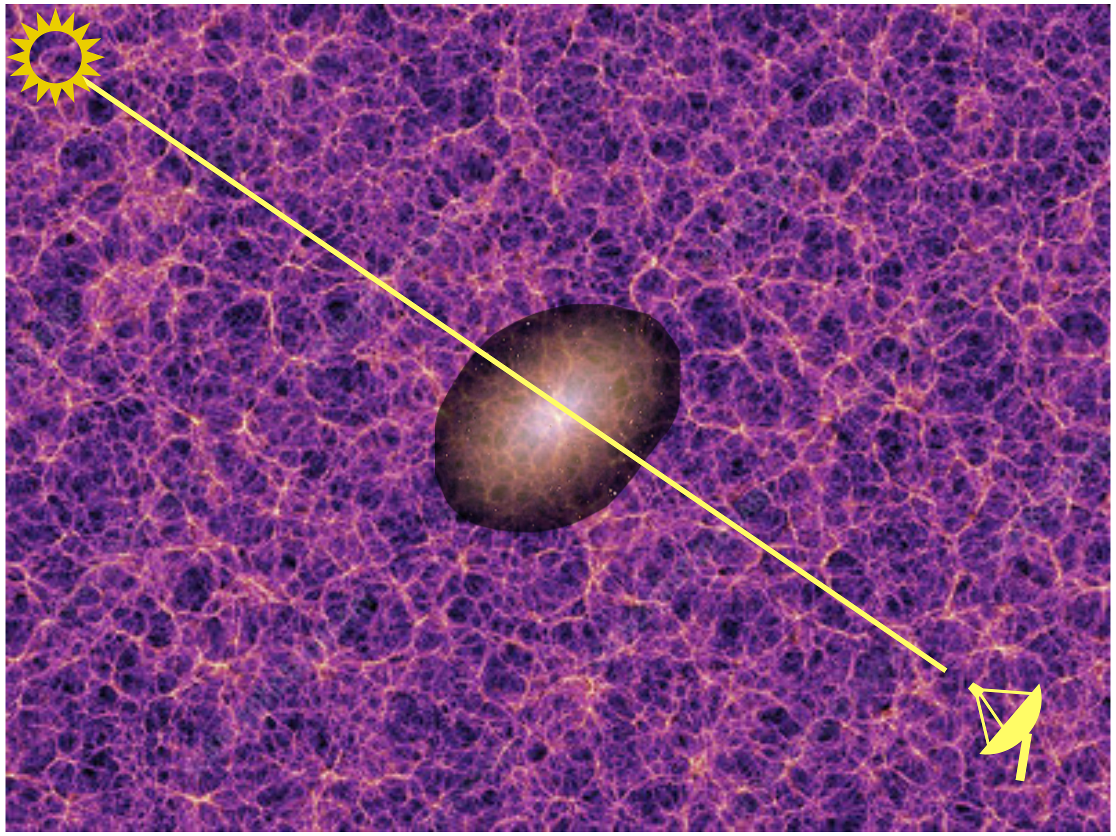
$H_{0\lambda} = \lambda H_0$
$\kappa_\lambda = \lambda\kappa + (1 - \lambda)$
θ
α_λ
β_λ
H_0
κ
θ
α
β

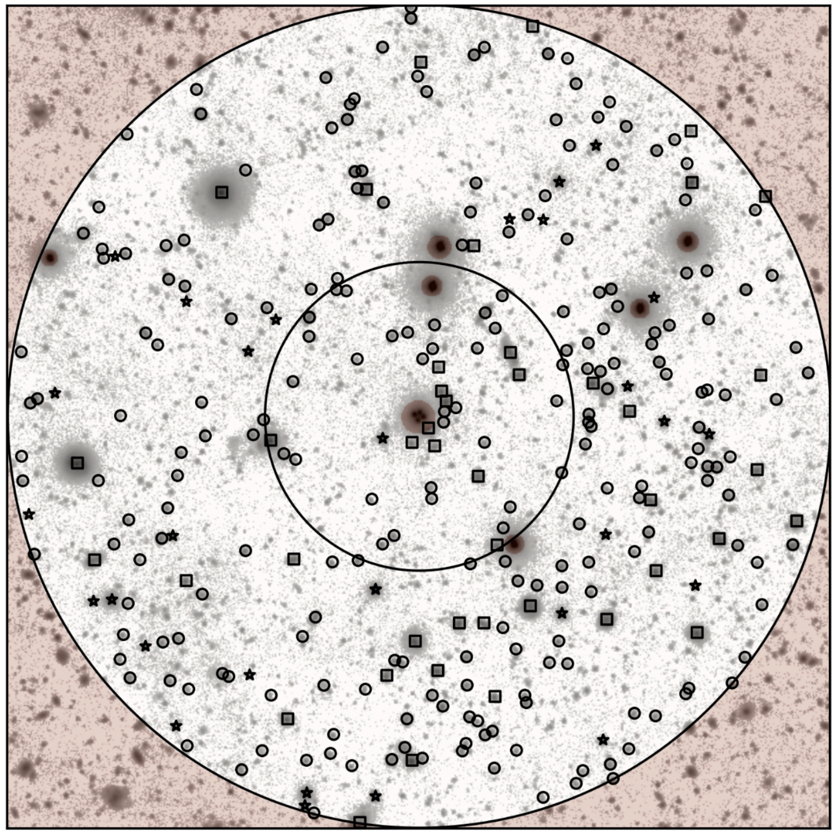
Millon et al, 1912.08027 **(TDCOSMO I)**



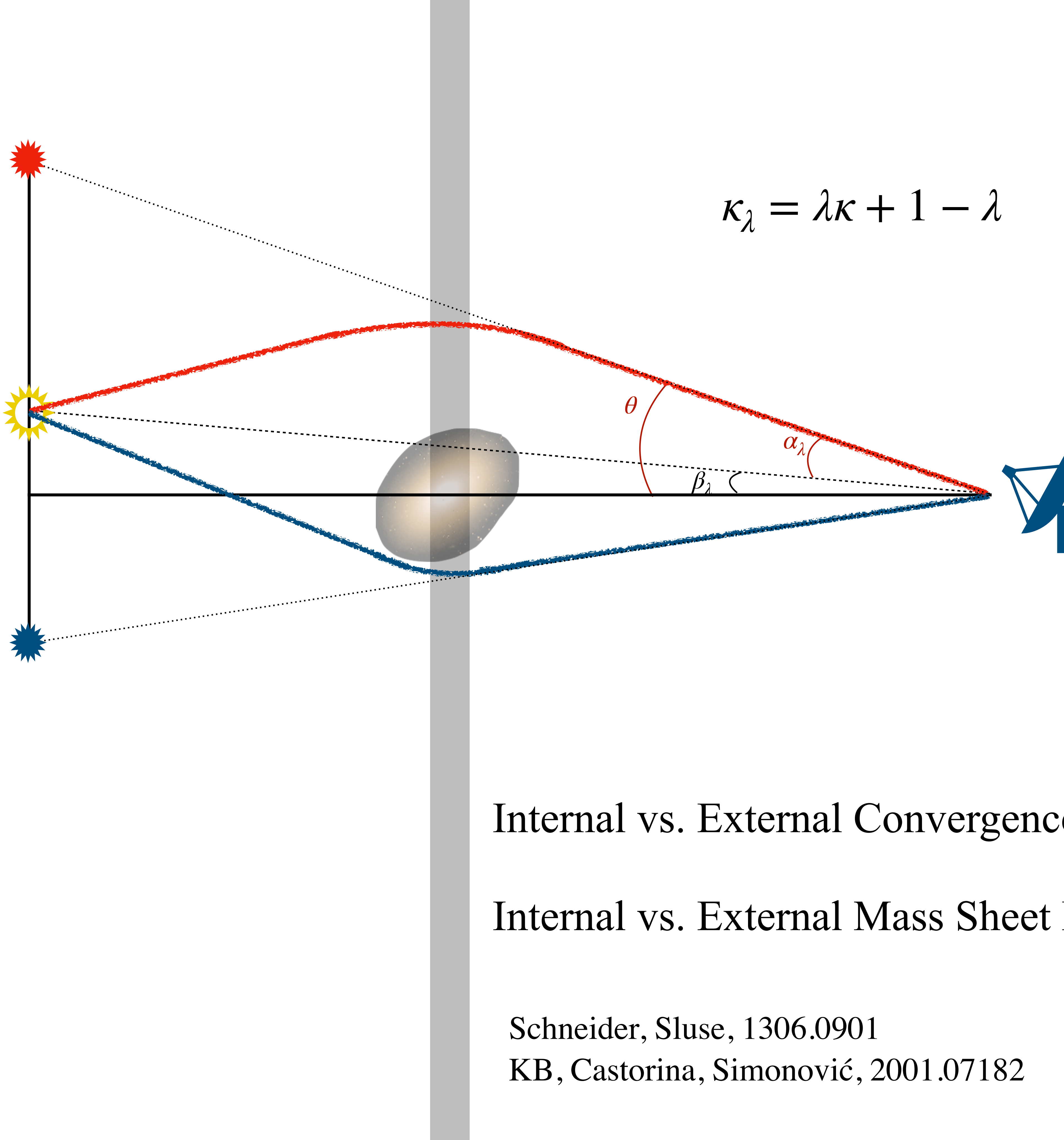


External convergence





Rusu et al, 1607.01047 (H0LiCOW III)



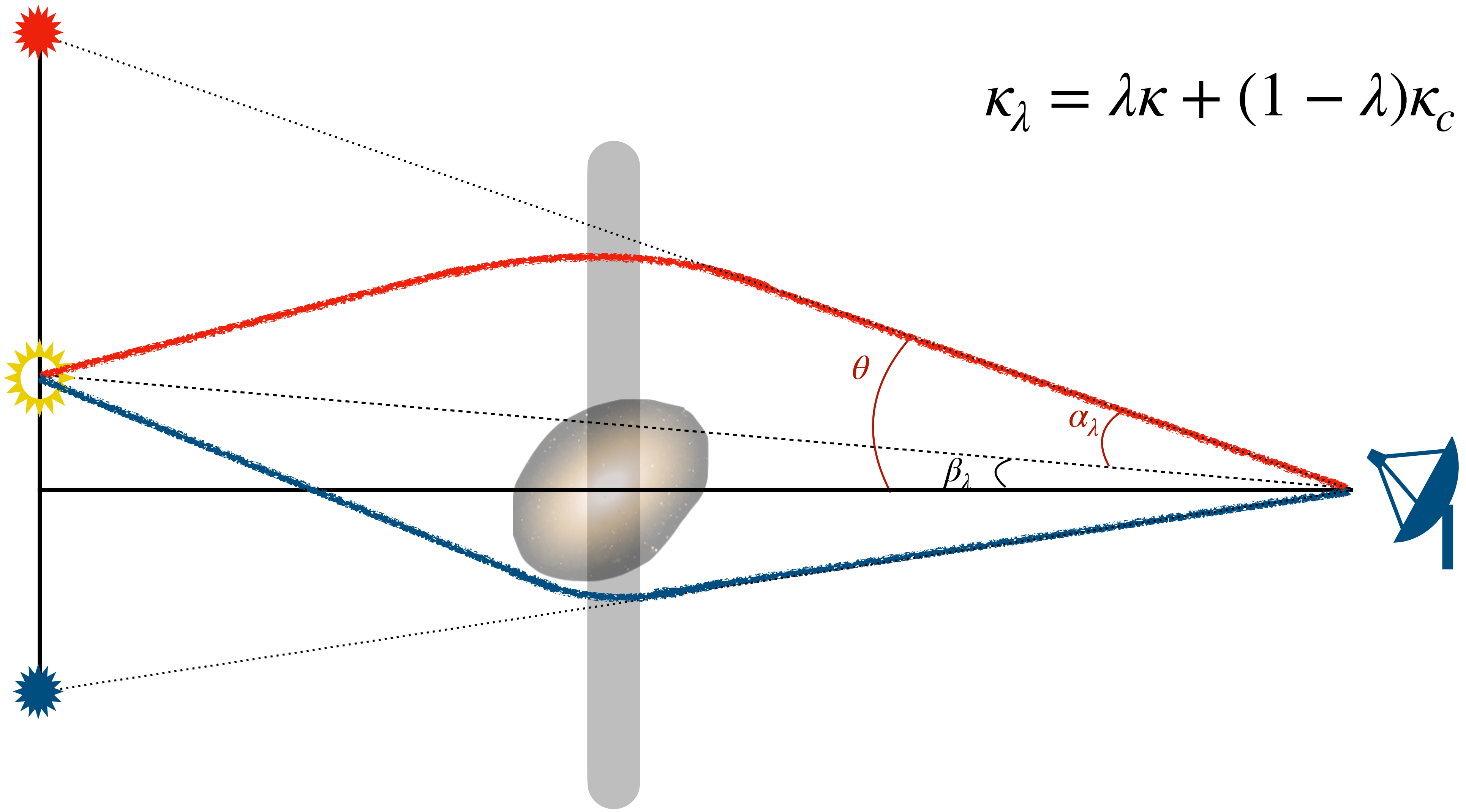
$$\kappa_\lambda = \lambda\kappa + 1 - \lambda$$

Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

Schneider, Sluse, 1306.0901
KB, Castorina, Simonović, 2001.07182

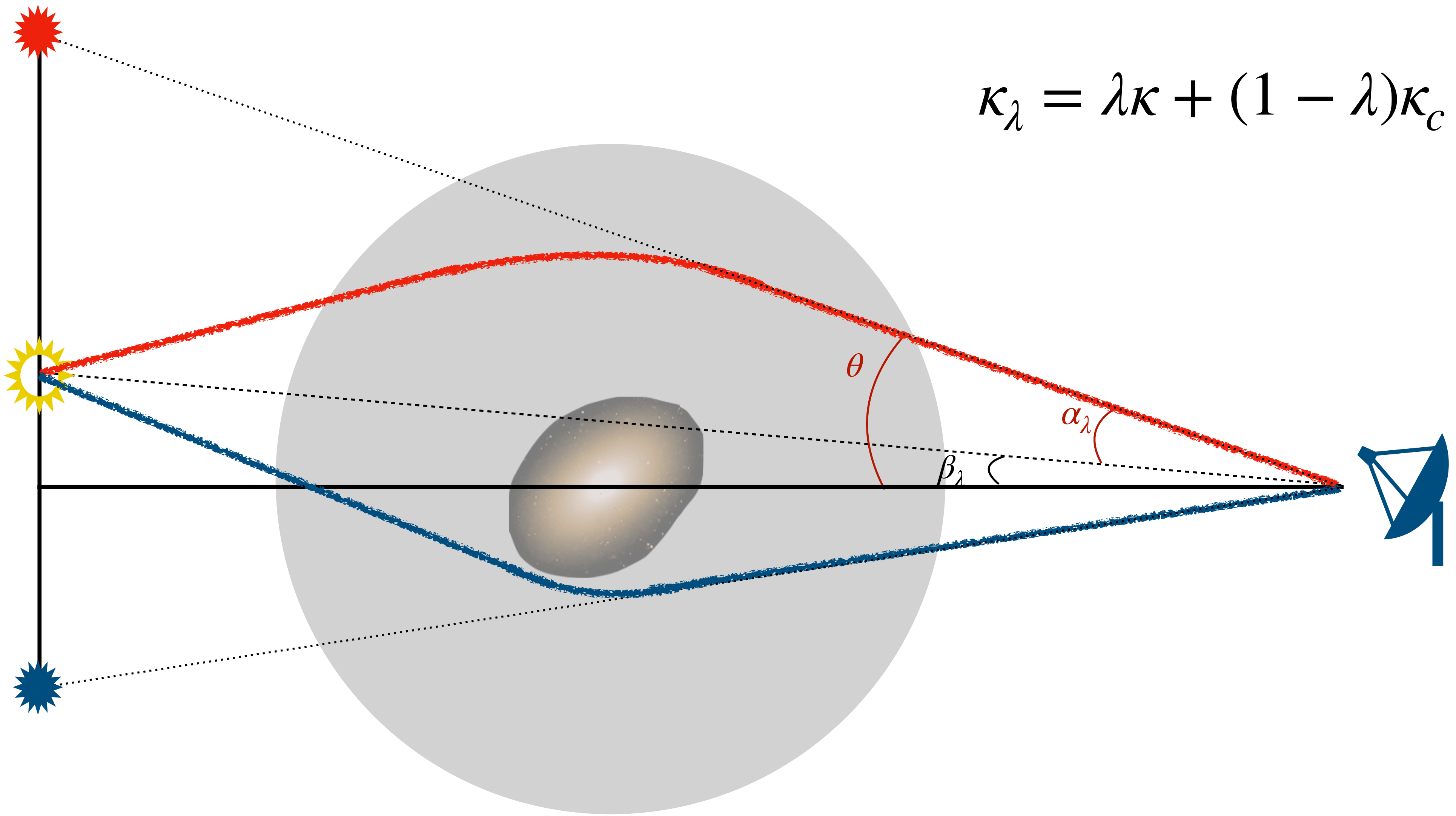
$$\kappa_\lambda = \lambda\kappa + (1-\lambda)\kappa_c$$



Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

Schneider, Sluse, 1306.0901
KB, Castorina, Simonović, 2001.07182



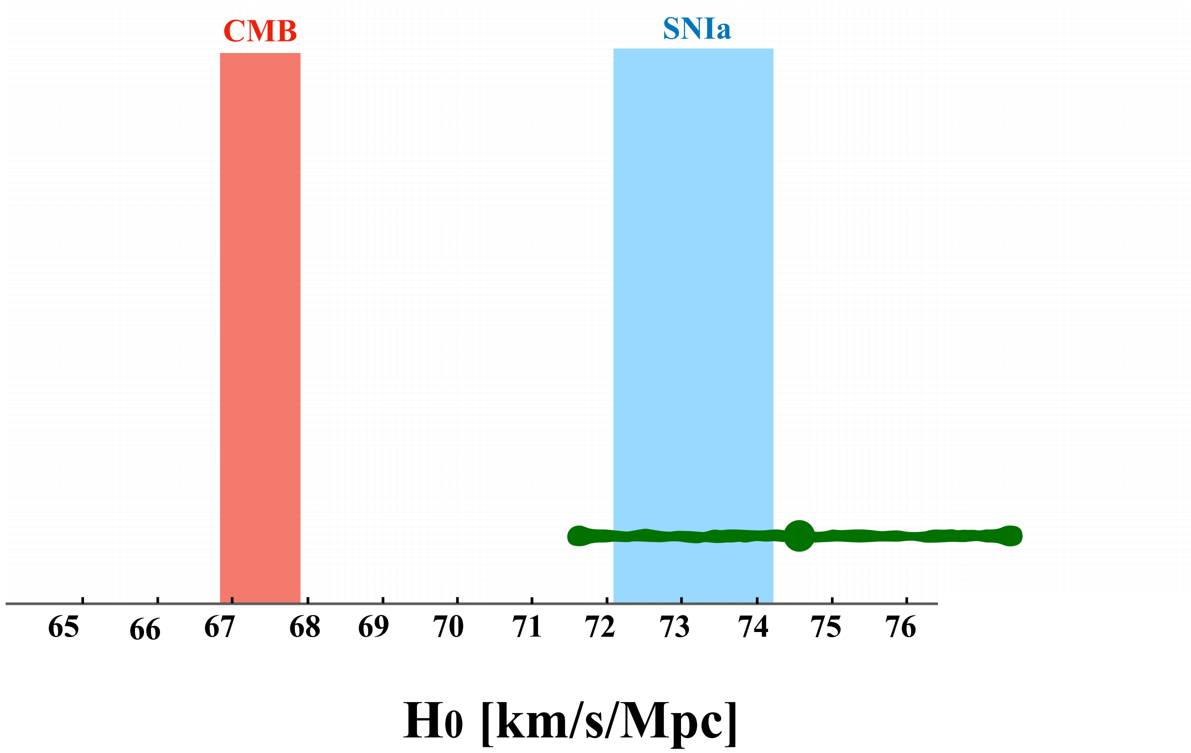
$$\kappa_\lambda = \lambda\kappa + (1-\lambda)\kappa_c$$

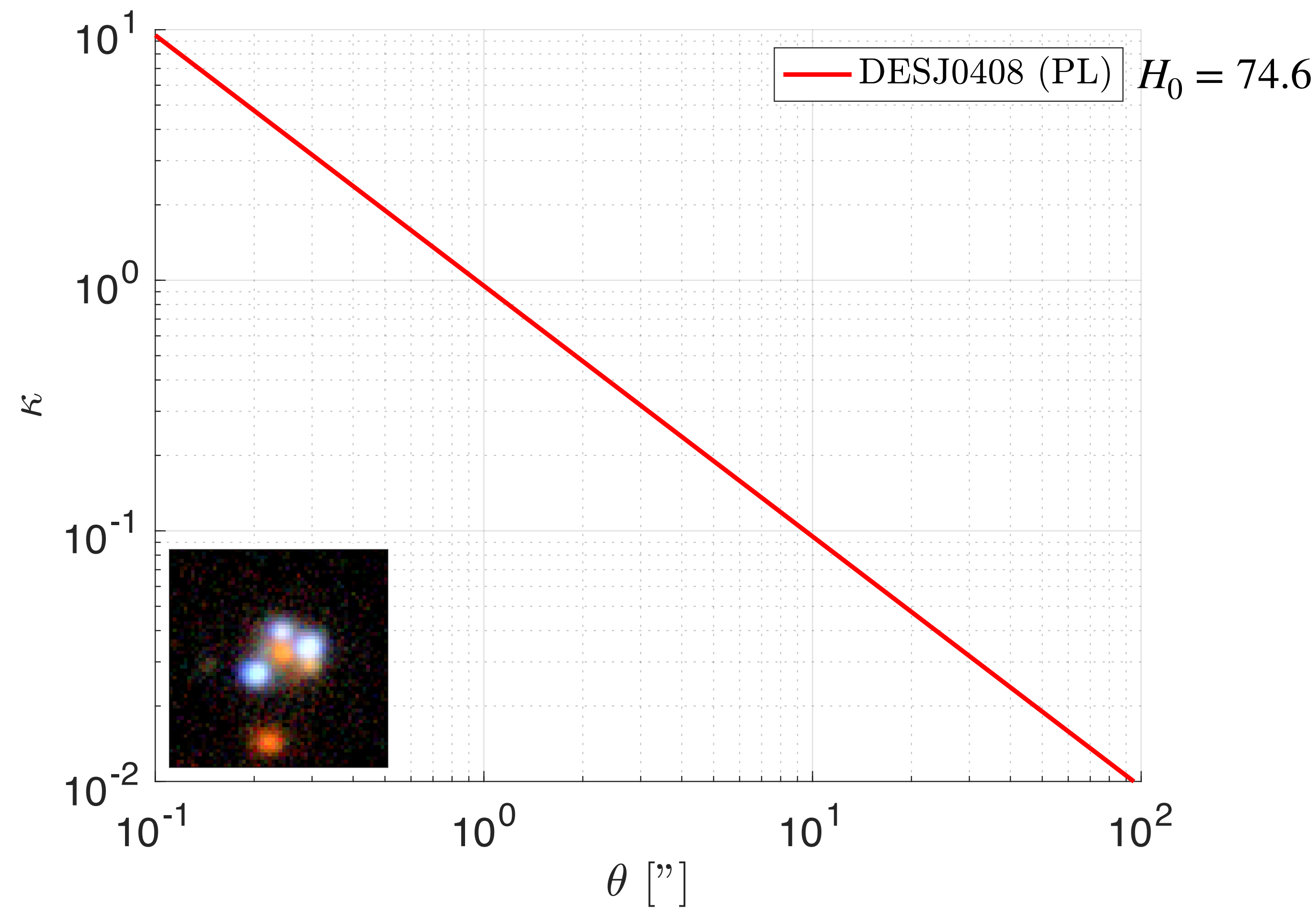
Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

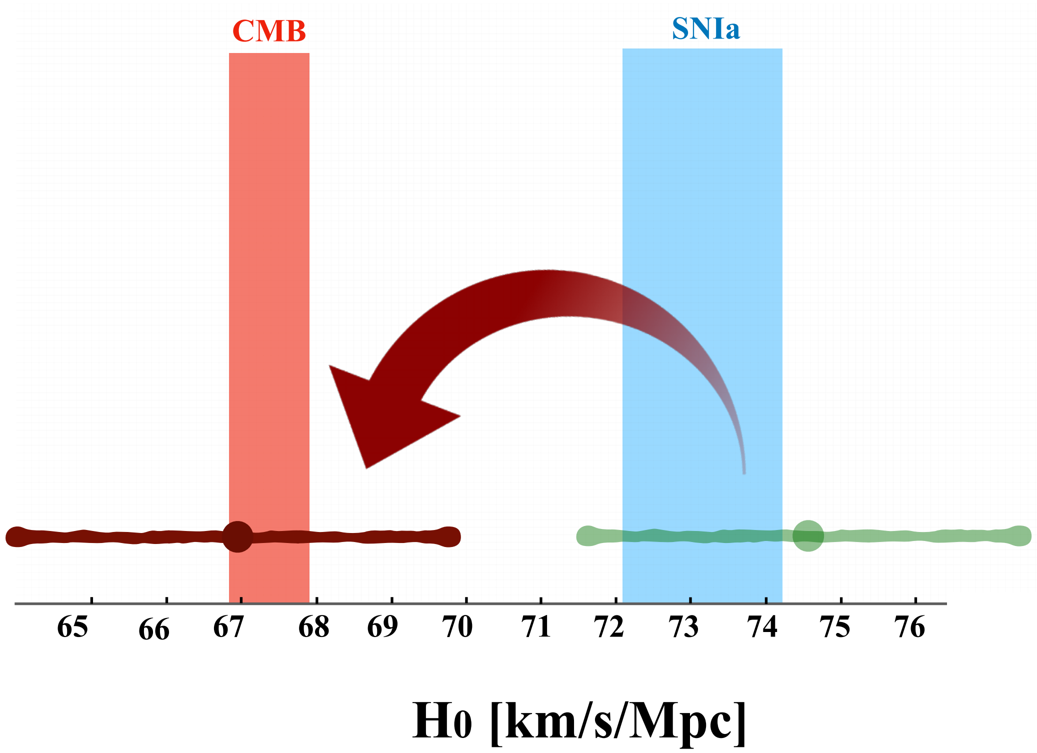
Schneider, Sluse, 1306.0901
KB, Castorina, Simonović, 2001.07182

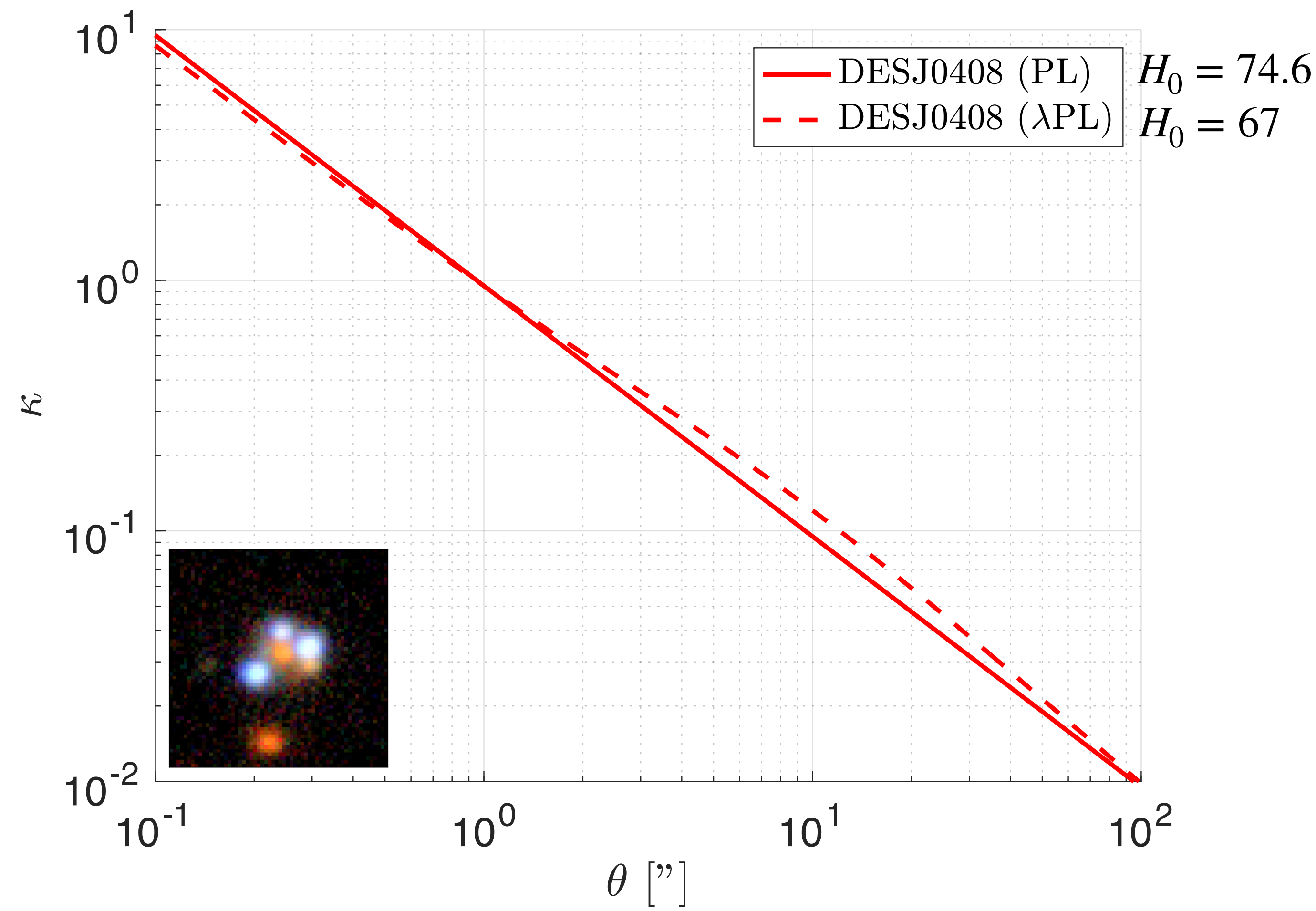
2. Challenges: modeling degeneracy



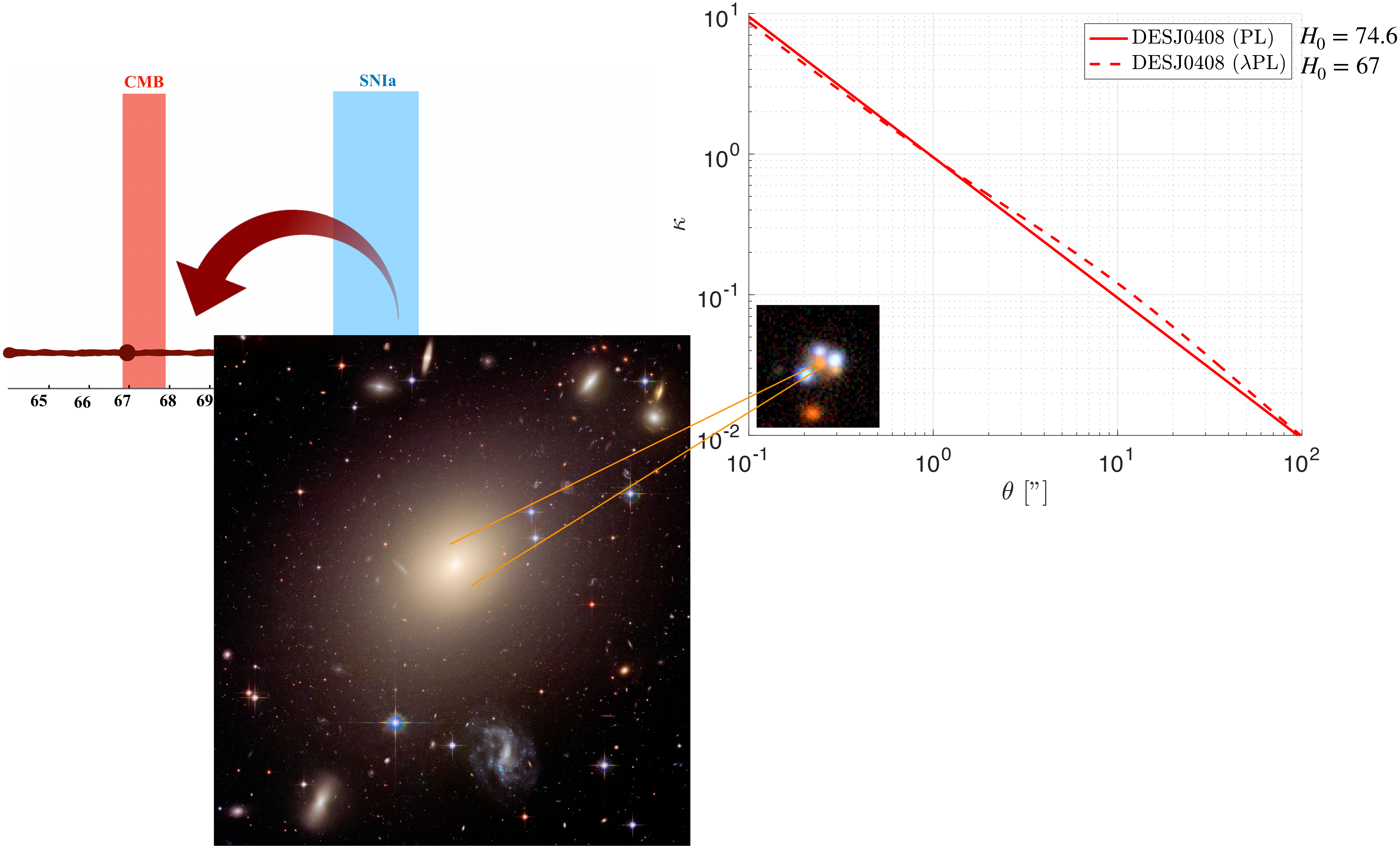


2. Challenges: modeling degeneracy





3. Opportunities: **galactic structure**



Birrer et al 2020 (**TDCOSMO IV**)

Data sets	H_0 [km s^{-1}Mpc^{-1}]	$\lambda_{\mathrm{int},0}$	α_λ	$\sigma(\lambda_{\mathrm{int}})$	a_{ani}	$\sigma(a_{\mathrm{ani}})$	$\sigma_{\sigma^{\mathrm{P}},\mathrm{sys}}$
TDCOSMO-only	$74.5^{+5.6}_{-6.1}$	$1.02^{+0.08}_{-0.09}$	$0.00^{+0.07}_{-0.07}$	$0.01^{+0.03}_{-0.01}$	$2.32^{+1.62}_{-1.17}$	$0.16^{+0.50}_{-0.14}$	-
TDCOSMO + $\mathrm{SLACS}_{\mathrm{IFU}}$	$73.3^{+5.8}_{-5.8}$	$1.00^{+0.08}_{-0.08}$	$-0.07^{+0.06}_{-0.06}$	$0.07^{+0.09}_{-0.05}$	$1.58^{+1.58}_{-0.54}$	$0.15^{+0.47}_{-0.13}$	-
TDCOSMO + $\mathrm{SLACS}_{\mathrm{SDSS}}$	$67.4^{+4.3}_{-4.7}$	$0.91^{+0.05}_{-0.06}$	$-0.04^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.01}$	$1.52^{+1.76}_{-0.70}$	$0.28^{+0.45}_{-0.25}$	$0.06^{+0.02}_{-0.02}$
TDCOSMO + $\mathrm{SLACS}_{\mathrm{SDSS+IFU}}$	$67.4^{+4.1}_{-3.2}$	$0.91^{+0.04}_{-0.04}$	$-0.07^{+0.03}_{-0.04}$	$0.06^{+0.08}_{-0.04}$	$1.20^{+0.70}_{-0.27}$	$0.18^{+0.50}_{-0.15}$	$0.06^{+0.02}_{-0.02}$

A&A 643, A165 (2020)
https://doi.org/10.1051/0004-6361/202038861

Astronomy & Astrophysics

TDCOSMO

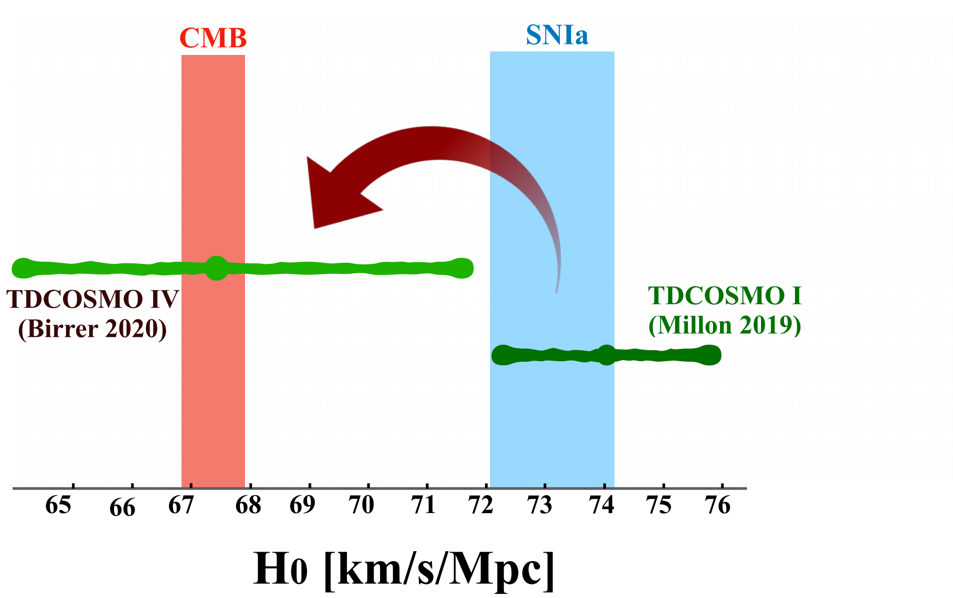
IV. Hierarchical time-delay cosmography – joint inference of the Hubble constant and galaxy density profiles★

S. Birrer[1], A. J. Shajib[2], A. Galan[3], M. Millon[3], T. Treu[2], A. Agnello[4], M. Auger[5,6], G. C.-F. Chen[7], L. Christensen[4], T. Collett[8], F. Courbin[3], C. D. Fassnacht[7,9], L. V. E. Koopmans[10], P. J. Marshall[1], J.-W. Park[1], C. E. Rusu[11], D. Sluse[12], C. Spiniello[13,14], S. H. Suyu[15,16,17], S. Wagner-Carena[1], K. C. Wong[18], M. Barnabè[23], A. S. Bolton[19], O. Czoske[20], X. Ding[2], J. A. Frieman[21,22], and L. Van de Vyvere[12]

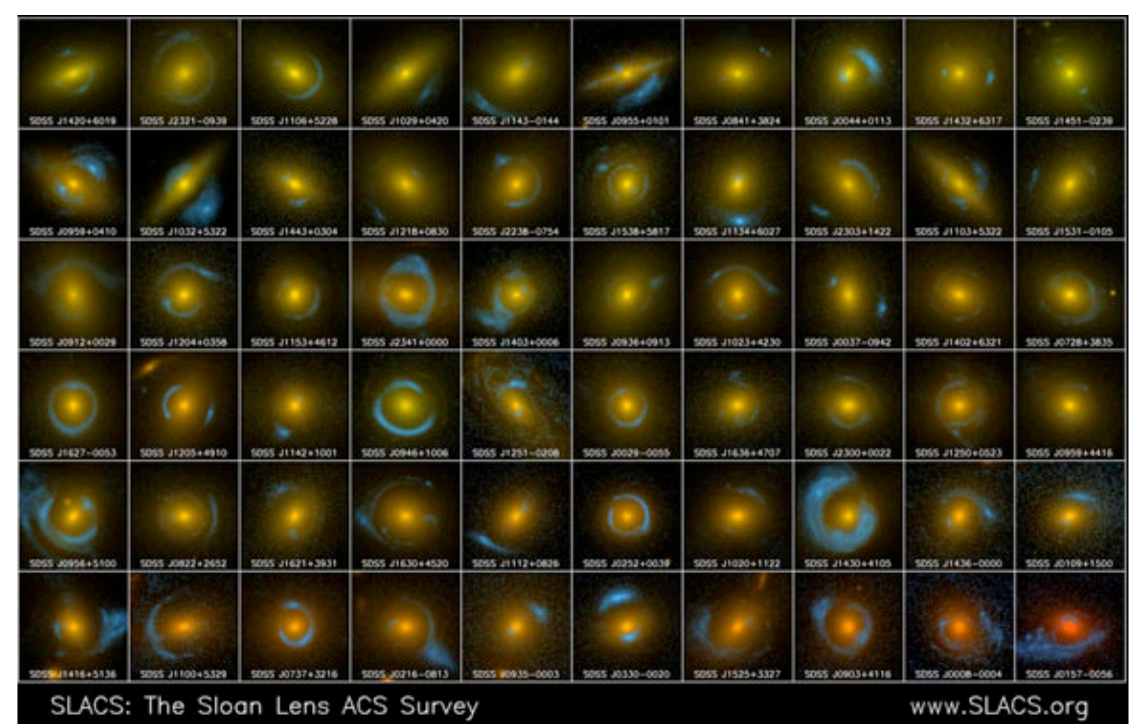
3. Opportunities: **galactic structure**

Birrer et al 2020 (**TDCOSMO IV**)

Data sets	H_0 [km s^{-1}Mpc^{-1}]	$\lambda_{\rm int,0}$	α_λ	$\sigma(\lambda_{\rm int})$	$a_{\rm ani}$	$\sigma(a_{\rm ani})$	$\sigma_{\sigma^{\rm P},{\rm sys}}$
TDCOSMO-only	$74.5^{+5.6}_{-6.1}$	$1.02^{+0.08}_{-0.09}$	$0.00^{+0.07}_{-0.07}$	$0.01^{+0.03}_{-0.01}$	$2.32^{+1.62}_{-1.17}$	$0.16^{+0.50}_{-0.14}$	-
TDCOSMO + $\rm SLACS_{IFU}$	$73.3^{+5.8}_{-5.8}$	$1.00^{+0.08}_{-0.08}$	$-0.07^{+0.06}_{-0.06}$	$0.07^{+0.09}_{-0.05}$	$1.58^{+1.58}_{-0.54}$	$0.15^{+0.47}_{-0.13}$	-
TDCOSMO + $\rm SLACS_{SDSS}$	$67.4^{+4.3}_{-4.7}$	$0.91^{+0.05}_{-0.06}$	$-0.04^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.01}$	$1.52^{+1.76}_{-0.70}$	$0.28^{+0.45}_{-0.25}$	$0.06^{+0.02}_{-0.02}$
TDCOSMO + $\rm SLACS_{SDSS+IFU}$	$67.4^{+4.1}_{-3.2}$	$0.91^{+0.04}_{-0.04}$	$-0.07^{+0.03}_{-0.04}$	$0.06^{+0.08}_{-0.04}$	$1.20^{+0.70}_{-0.27}$	$0.18^{+0.50}_{-0.15}$	$0.06^{+0.02}_{-0.02}$



Hint from SLACS *kinematics?*

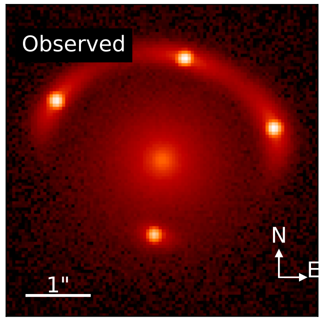


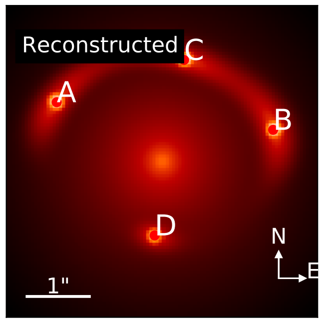
SLACS (Bolton et al 2006++)

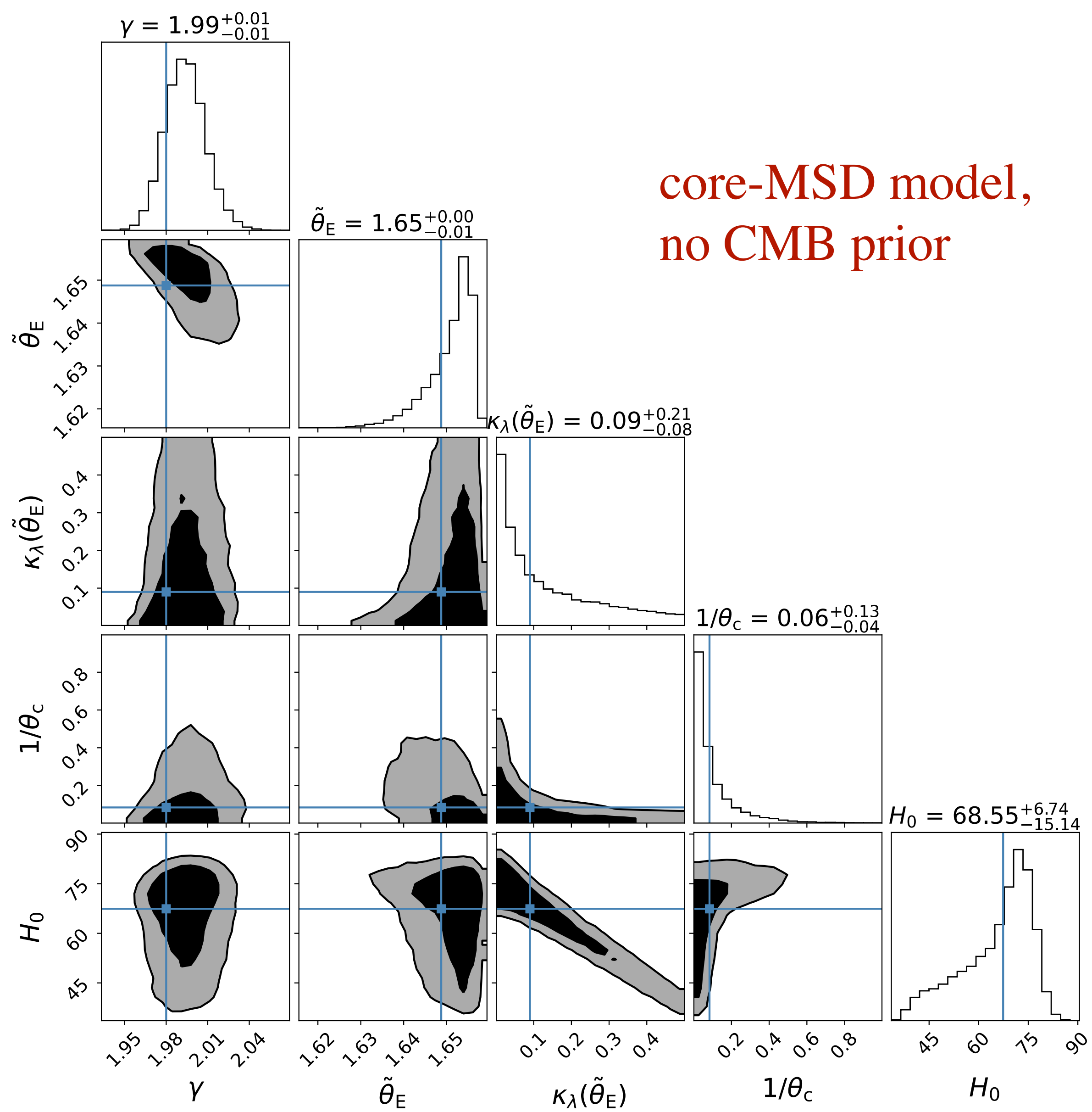
3. Opportunities: **galactic structure**

What do we learn about **galaxies** if we add CMB/LSS prior?

Expect evidence for core component, reflecting precision on H_0

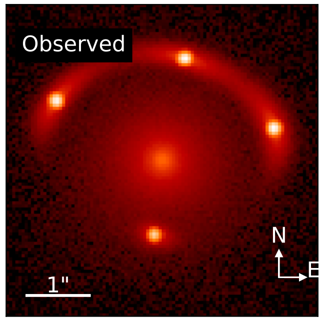






core-MSD model,
no CMB prior

3. Opportunities: **galactic structure**



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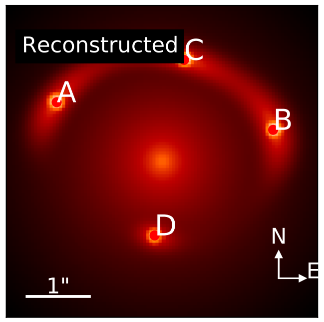
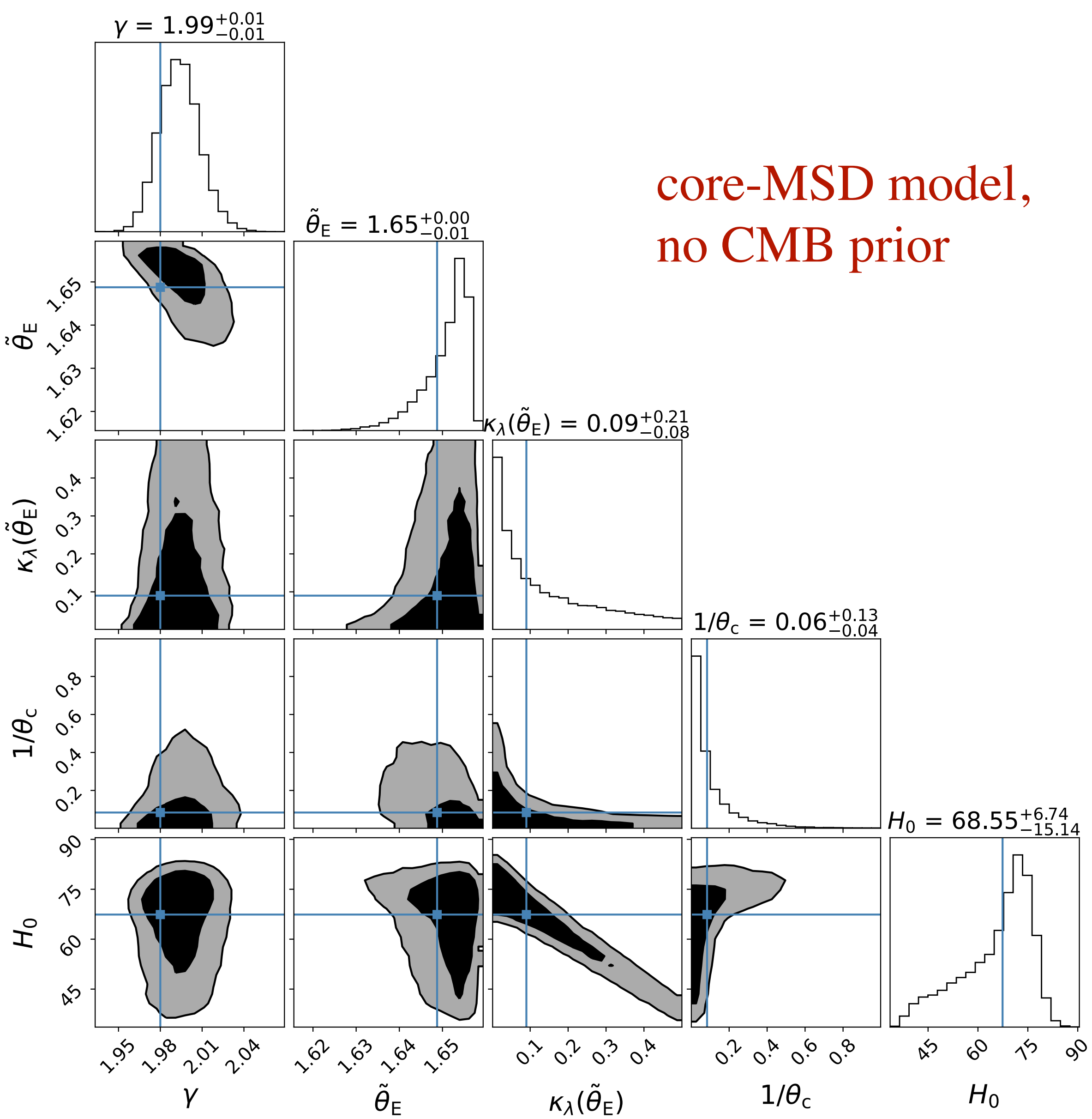


Could reach >2σ *per system*

KB, Teodori, 2105.10873



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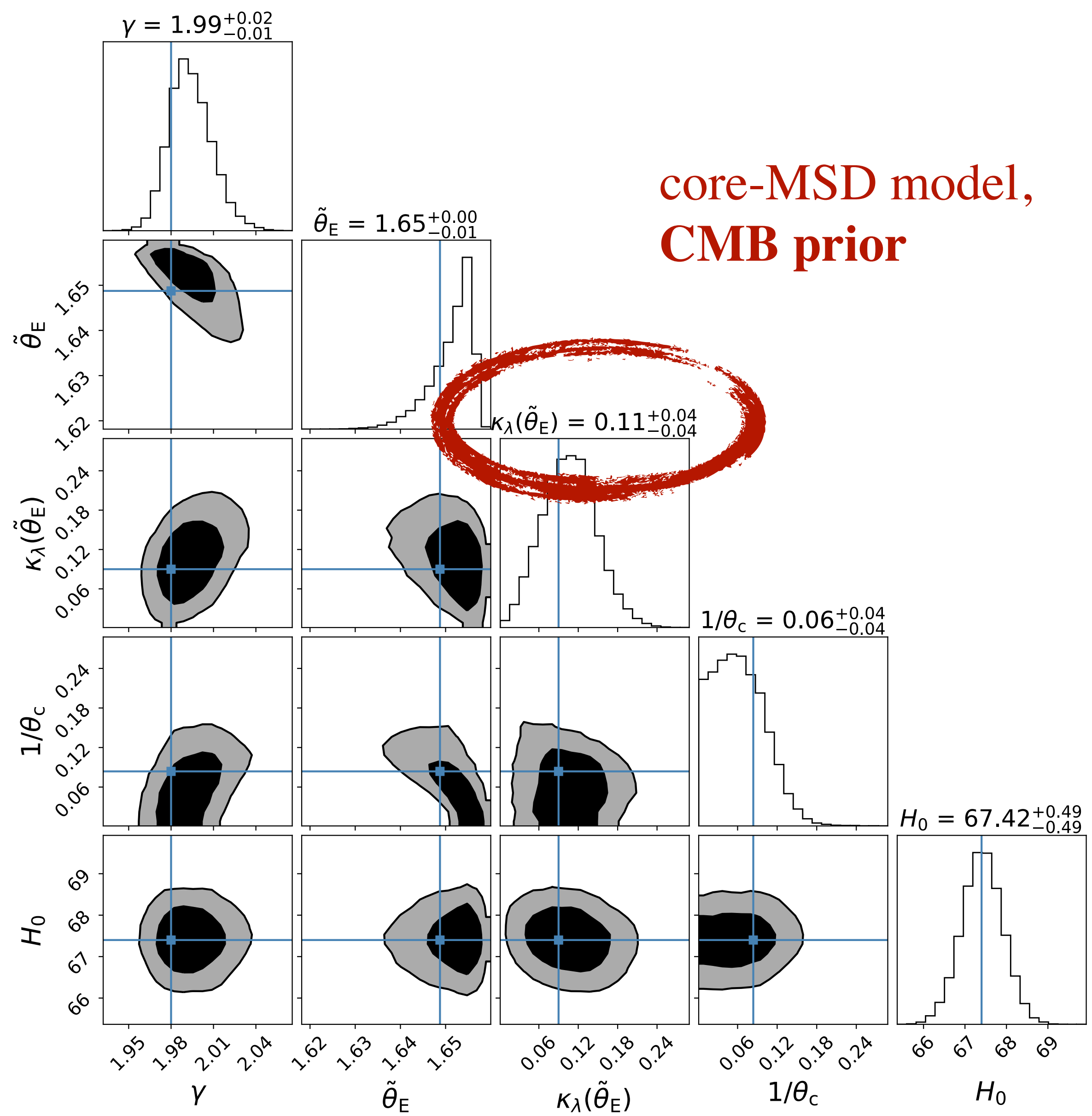
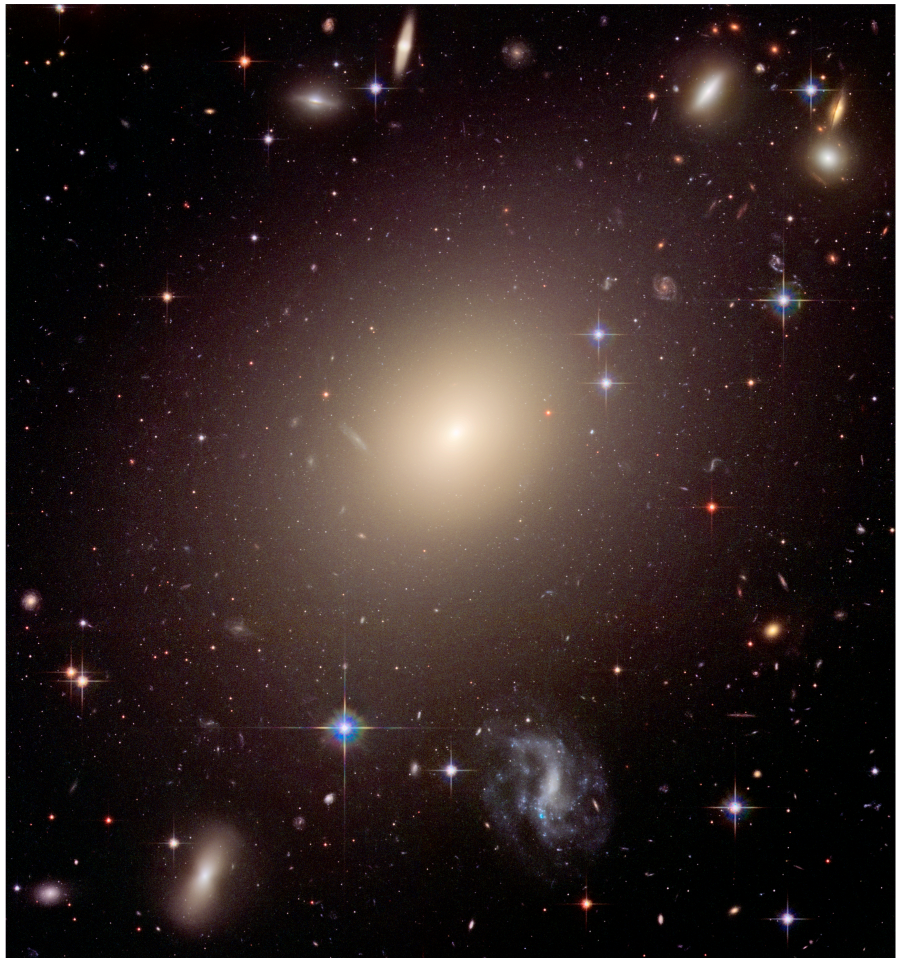


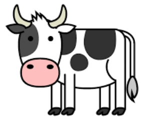
core-MSD model,
CMB prior

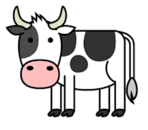
``Internal MSD" may require a non-minimal density profile.

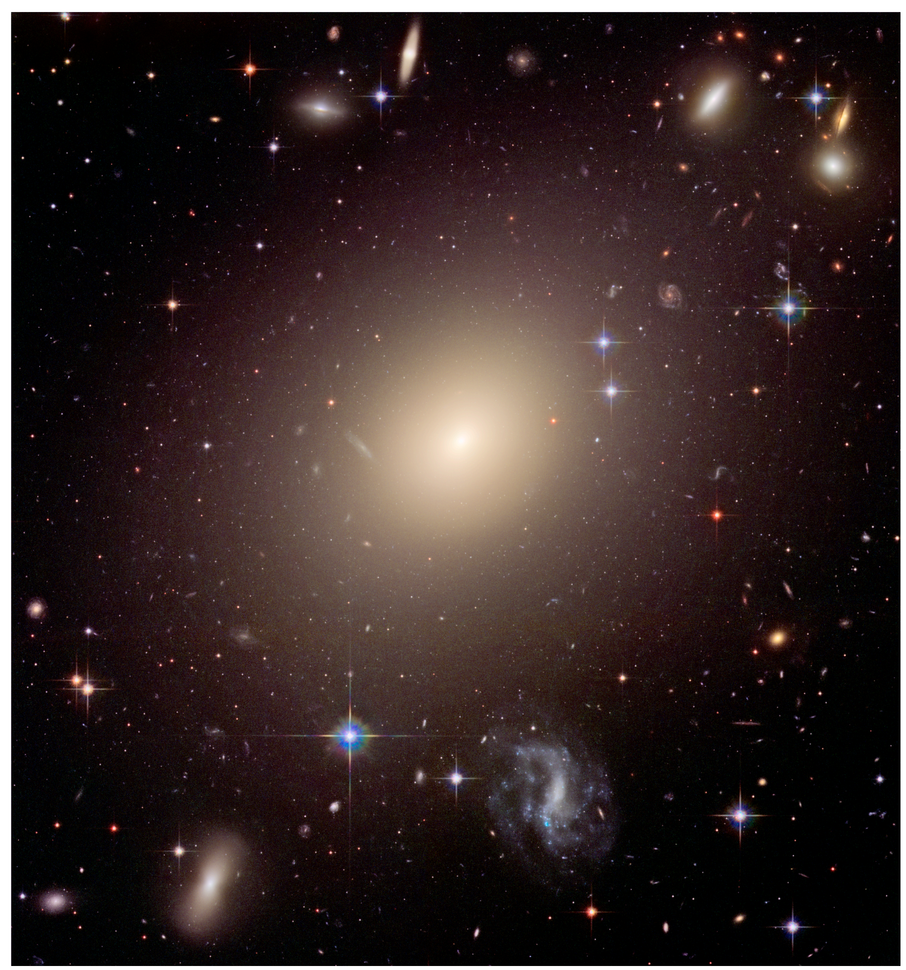
- Why would galaxies be non-minimal?
- Why should galaxies have a core component?



``Internal MSD" may require a non-minimal density profile.

 Why would galaxies be non-minimal? ***Why not? (What is dark matter?)***

 Why should galaxies have a core component? ***Can think of several reasons.***



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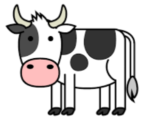
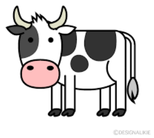


Why would galaxies be non-minimal?

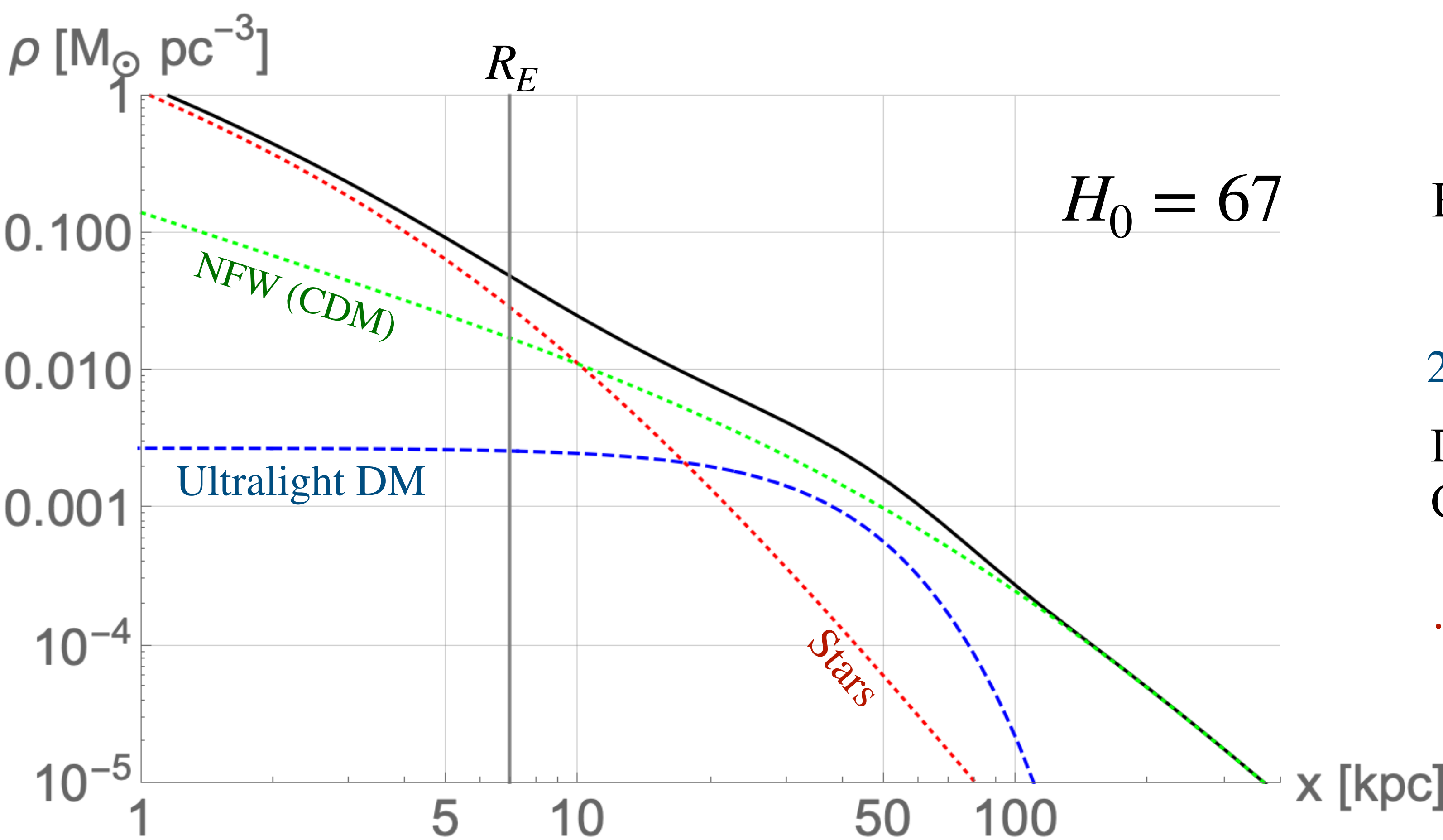
Why not? (What is dark matter?)



Why should galaxies have a core component?

Can think of several reasons.

Dark matter not boring NFW? …a little bit of **ultralight dark matter?**



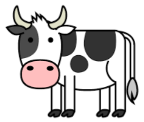
KB, Teodori, 2105.10873

20 % of total DM, $m = 2.5 \times 10^{-25}$ eV

Dynamical relaxation consistent at O(1).
Cosmology OK.

…need more simulations and study…

``Internal MSD" may require a non-minimal density profile.



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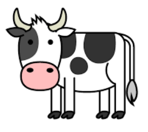
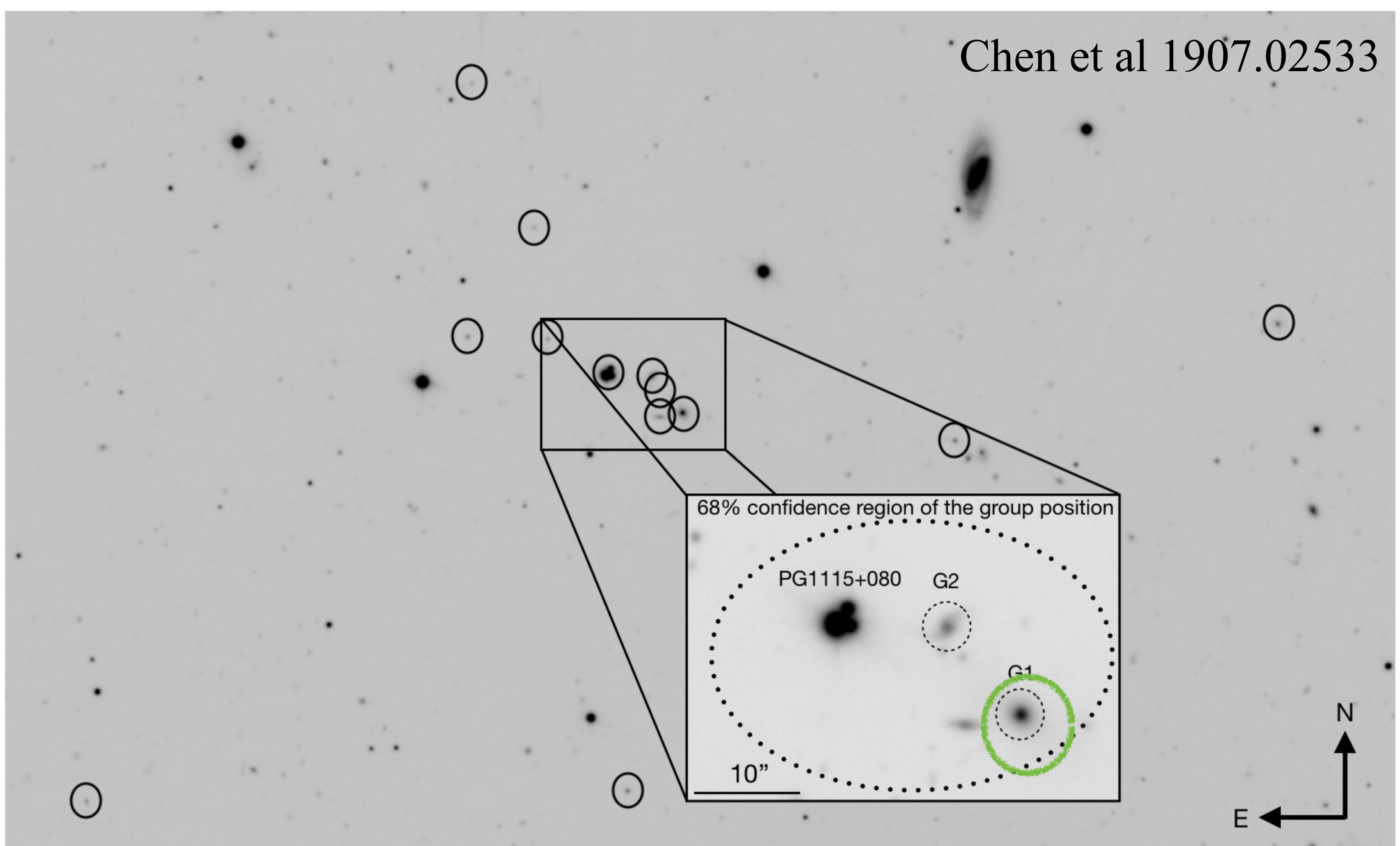


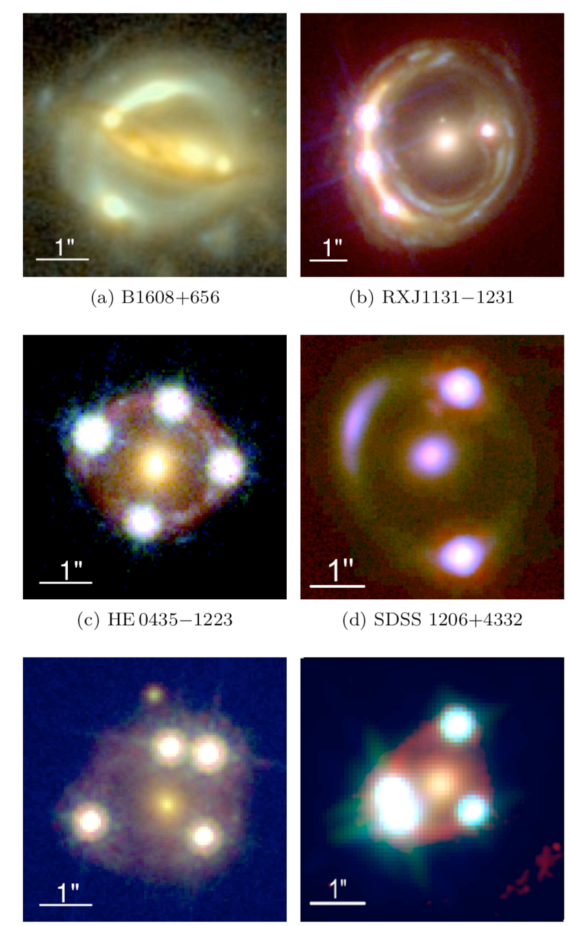
Why should galaxies have a core component?

Can think of several reasons.

What about host clusters/groups?



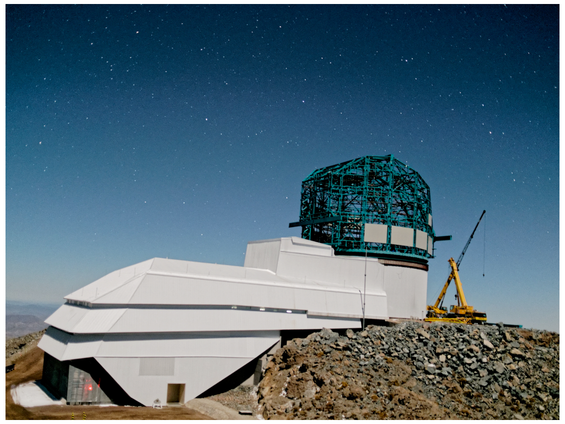
X ray blob (on BCG…): Grant et al astro-ph/0305137



(a) B1608+656
(b) RXJ1131−1231
(c) HE 0435−1223
(d) SDSS 1206+4332
(e) WFI2033−4723
(f) PG 1115+080

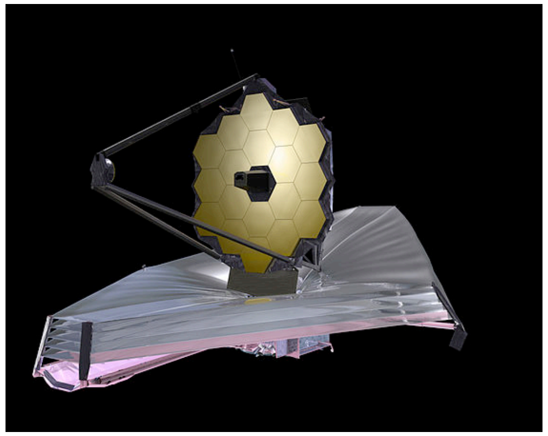
LSST: 100’s of lensed quasars

Oguri, Marshall 2010

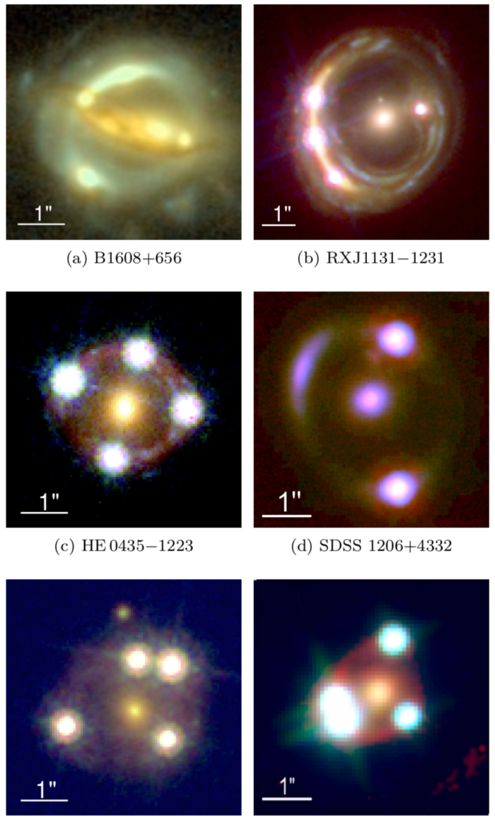


JWST: kinematics

Yıldırım, Suyu, Halkola 2019; Birrer, Treu 2021



Next few years: very interesting for lensing cosmography.



(a) B1608+656 (b) RXJ1131−1231

(c) HE 0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

The Standard Model of Particle Physics and Astrophysics

No gravity

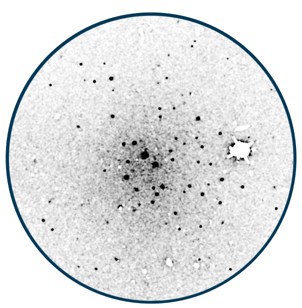
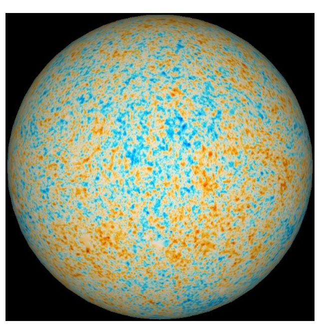
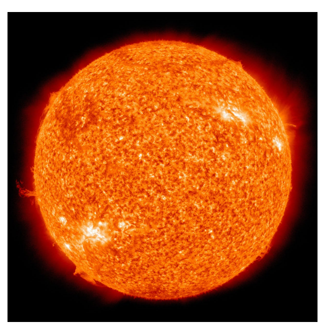
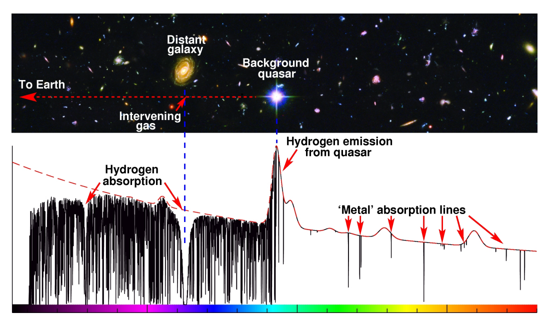
Does not include neutrino mass
Does not include dark matter

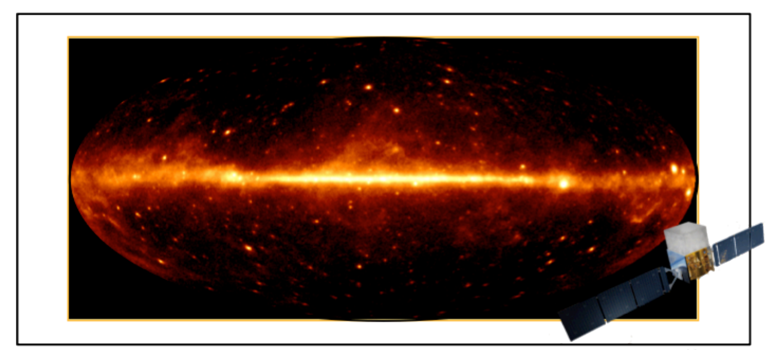
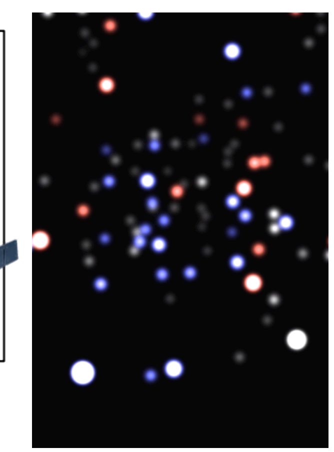
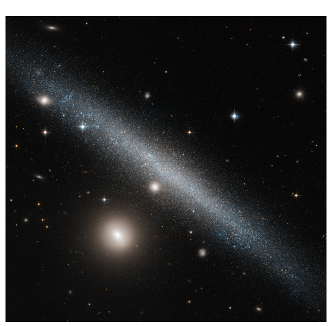
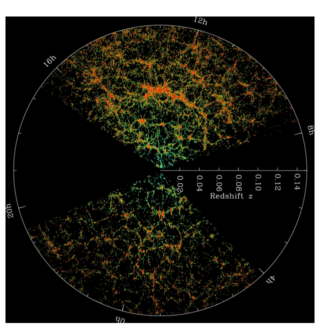
Cosmic inflation (origin of Universe)
Baryon asymmetry (origin of matter)

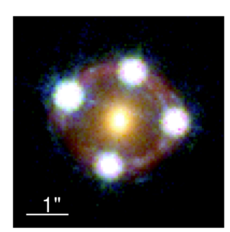
Why vacuum energy *just (not)* zero?
Why weak scale << Planck scale?
Why no strong CP violation?
Almost grand unification?
Why Higgs vacuum *just* metastable?

- Observed first in astrophysics
- Observed only in astrophysics
- Constrained by astrophysics

Thank you!



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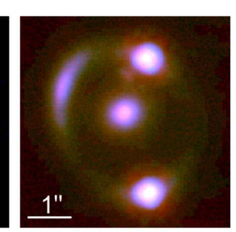

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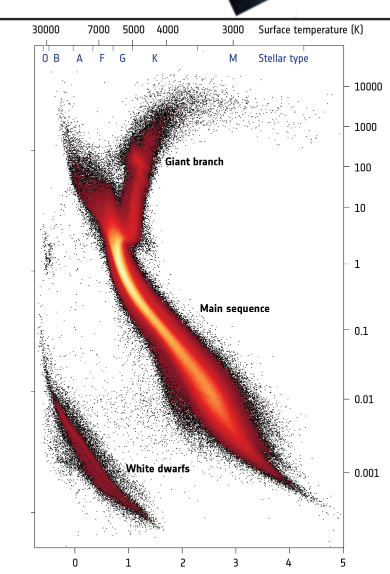
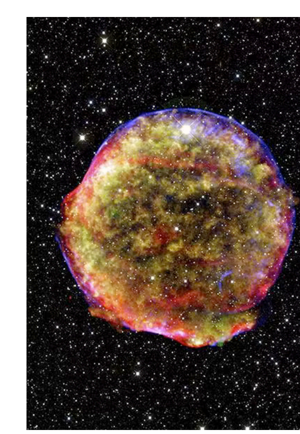
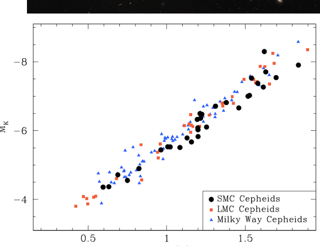
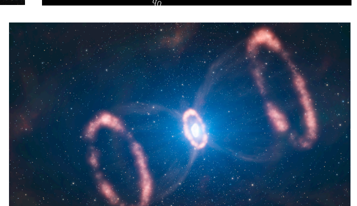
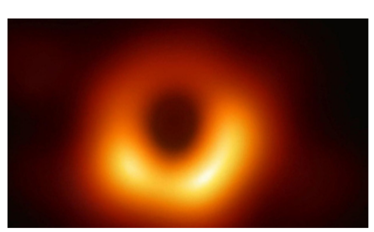
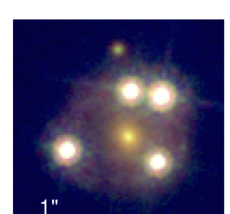
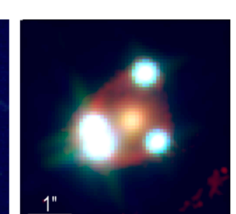
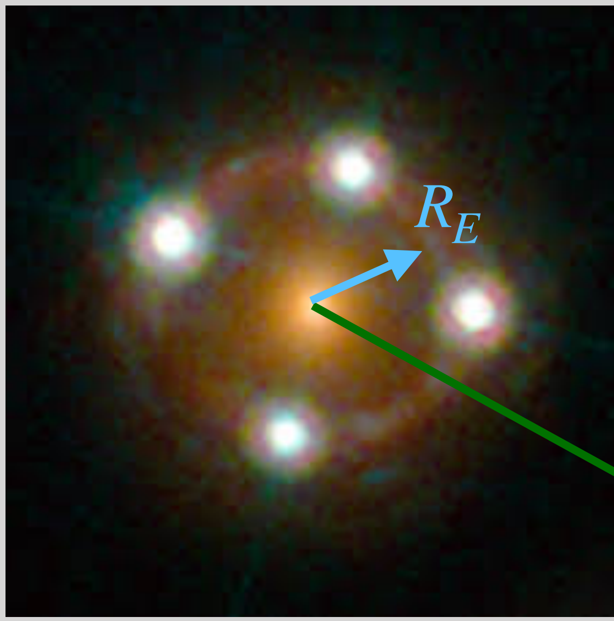


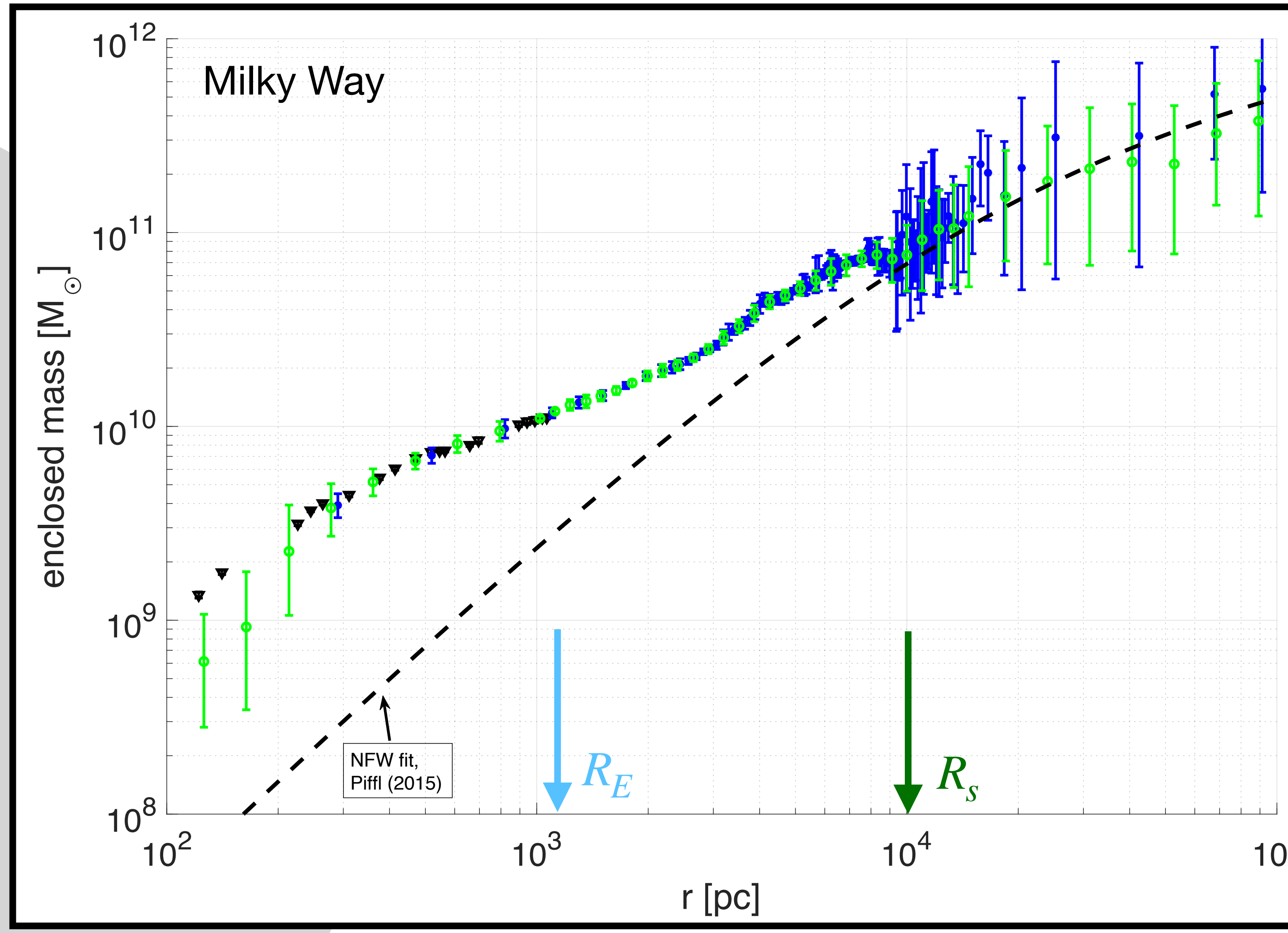



(e) WFI2033−4723


(f) PG 1115+080

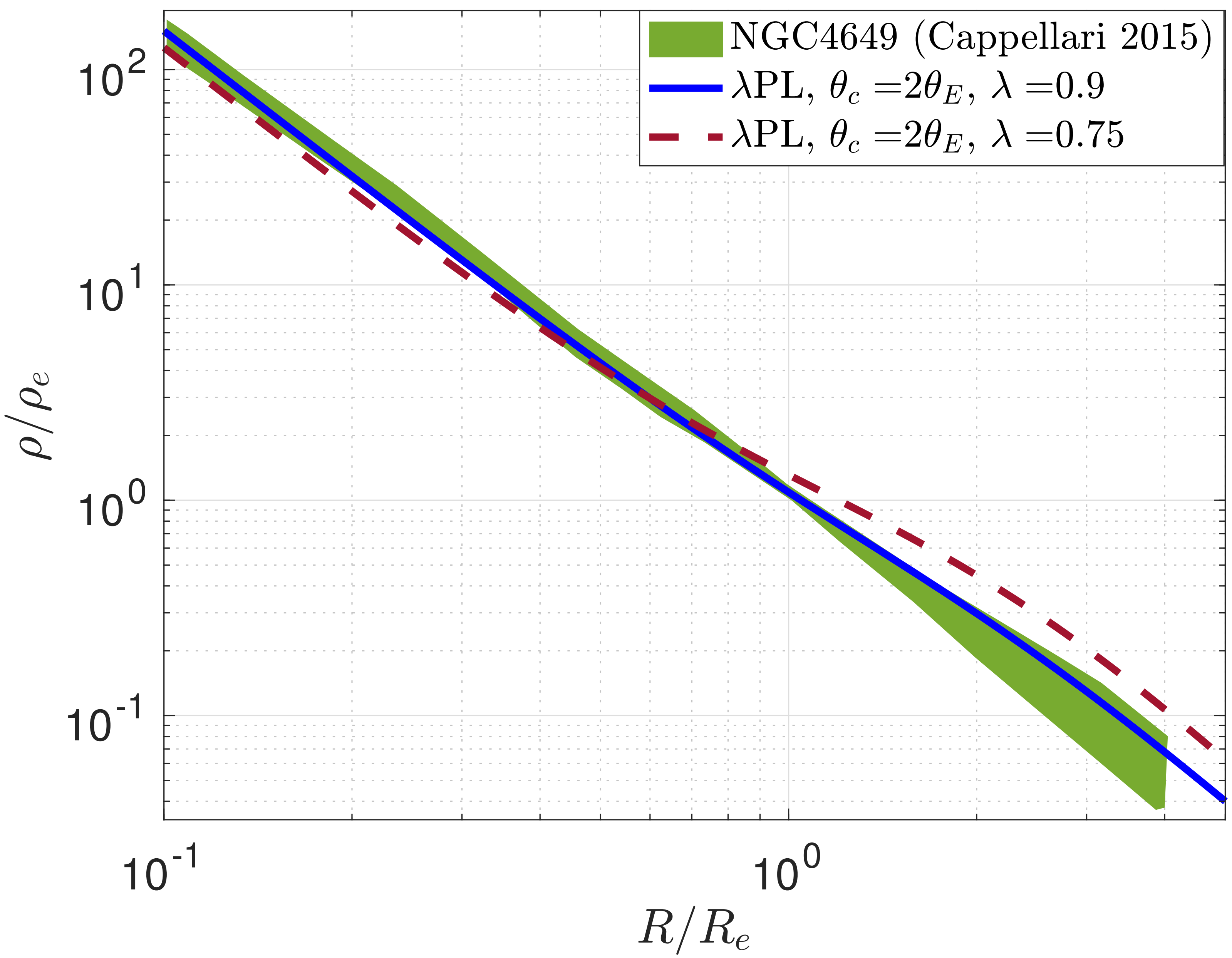





R_s

	H_0	$\lambda = 67/H_0$	γ	θ_E ["]	θ_s ["]	lens redshift z_l	ref
RXJ1131	$76.1^{+3.6}_{-4.3}$	$0.88^{+0.06}_{-0.04}$	1.98	1.6	19	0.295	Chen et al. (2016)
PG1115	$83.0^{+7.8}_{-7.0}$	$0.81^{+0.07}_{-0.07}$	2.18	1.1	17	0.311	Chen et al. (2019)
HE0435	$71.7^{+5.1}_{-4.6}$	$0.93^{+0.07}_{-0.06}$	1.87	1.2	10	0.4546	Chen et al. (2019)
DESJ0408	$74.6^{+2.5}_{-2.9}$	$0.9^{+0.03}_{-0.03}$	2	1.9	13	0.6	Shajib et al. (2019)
WFI2033	$72.6^{+3.3}_{-3.5}$	$0.92^{+0.05}_{-0.04}$	1.95	0.9	11	0.6575	Rusu et al. (2019)
J1206	$67.0^{+5.7}_{-4.8}$	$1^{+0.08}_{-0.08}$	1.95	1.2	4.7	0.745	Birrer et al. (2019)

Stellar kinematics (of *other* elliptical galaxies)

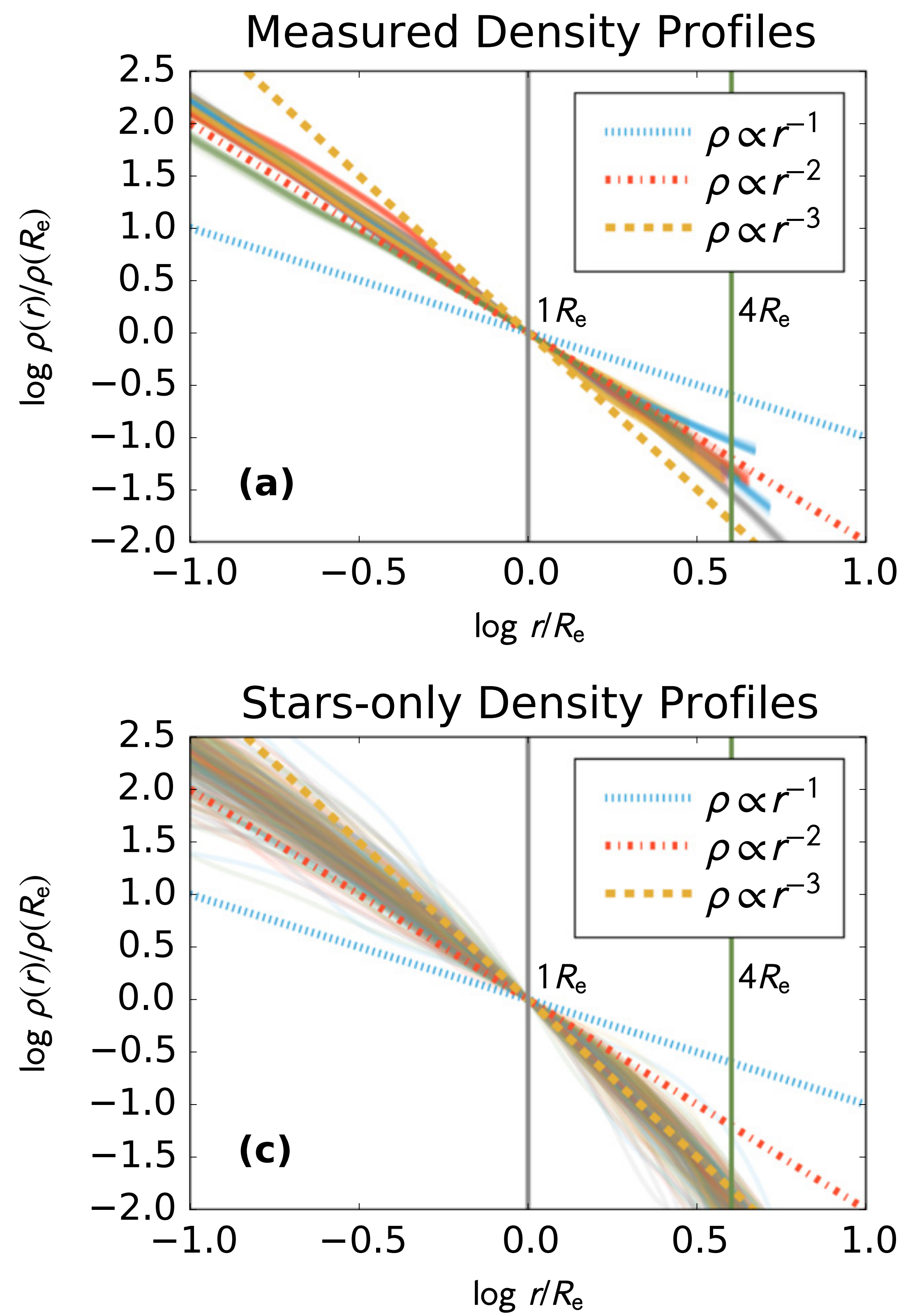


Stellar kinematics (of *other* elliptical galaxies)

Cappellari et al, 1504.00075

$$\rho_{\rm DM}(r) = \rho_s \left(\frac{r}{r_s}\right)^{\alpha} \left(\frac{1}{2} + \frac{1}{2}\frac{r}{r_s}\right)^{-\alpha-3}. \quad (3)$$

Our models have seven free parameters. Some are poorly constrained but are not of interest here. They are just "nuisance parameters," marginalized out to derive the total mass profiles studied here. The parameters are (i) the inclination i; (ii) the anisotropy $\beta_z \equiv 1 - \sigma_z^2/\sigma_R^2$, with σ_z and σ_R the stellar dispersion in cylindrical coordinates, for the MGE Gaussians with $\sigma_j < R_e$; (iii) the anisotropy for the remaining Gaussians at larger radii; (iv) the stellar $(M/L)_{\rm stars}$; (v) the break radius of the dark halo, constrained to be $10 < r_s < 50$ kpc; (vi) the halo density ρ_s at r_s; and (vii) the dark halo slope α for $r \ll r_s$.



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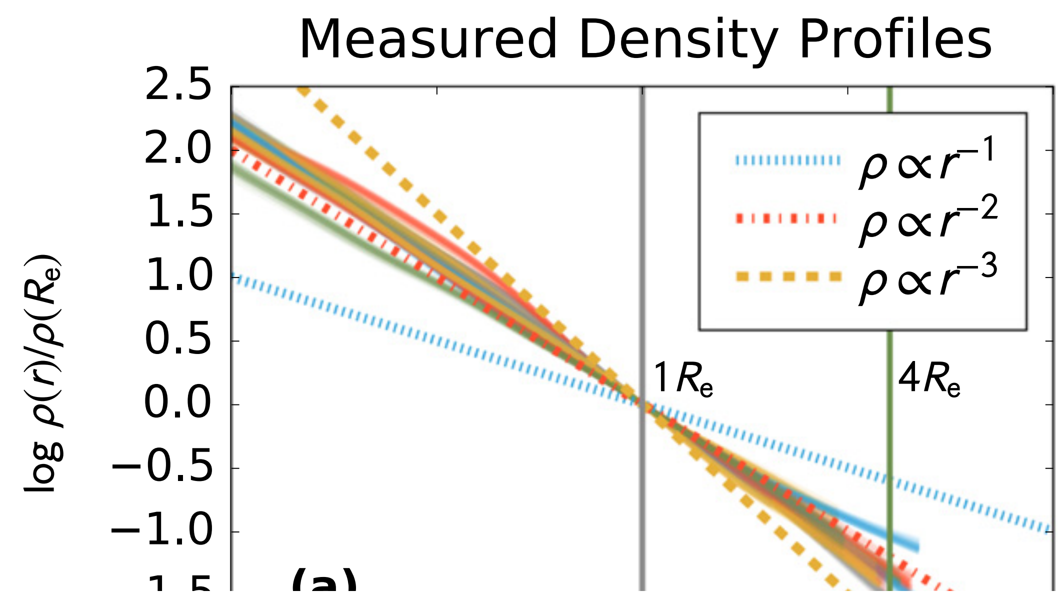

A friend:

...a cored structure of the kind you propose would be difficult to exclude from measurements of the stellar kinematics. Part of the reason is the mass profile-velocity anisotropy degeneracy. Another part is simply that no one has tried: most modelers fit the system to a small number of components (stars, gas, dark matter, central black hole) with constant mass-to-light ratio and none of these look like the core you propose. It would be straightforward for some of the modelers to try adding cores.

I suppose some critics will say that your **cores are ad hoc**, but I think they are **less ad hoc than most of the modifications to cosmology needed to explain the Hubble discrepancy!**

Stellar kinematics (of *other* galaxies, e.g., Milky Way)