Gravitational probes of ultralight dark matter

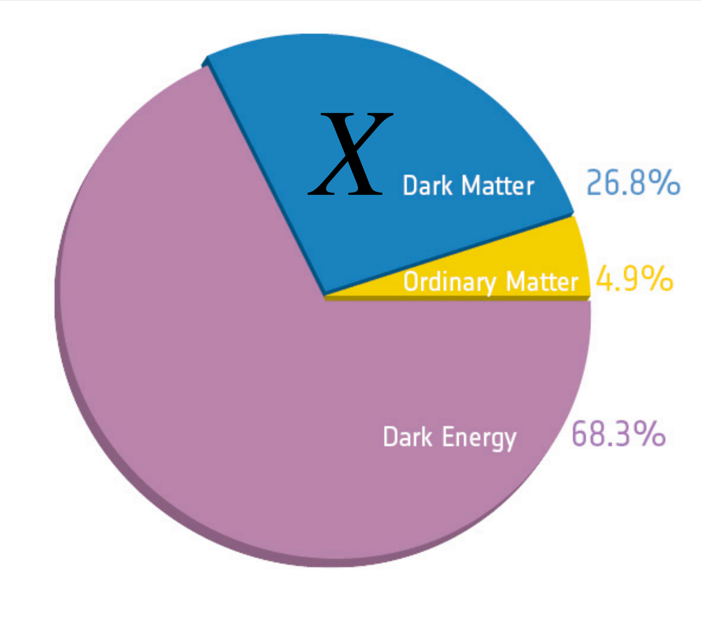
Sofia, COSMIC WISPers 11/09/2025

Kfir Blum / Weizmann Institute

m

10^{-21} eV

$10^{-10}\ M_\odot \sim 10^{56}$ eV



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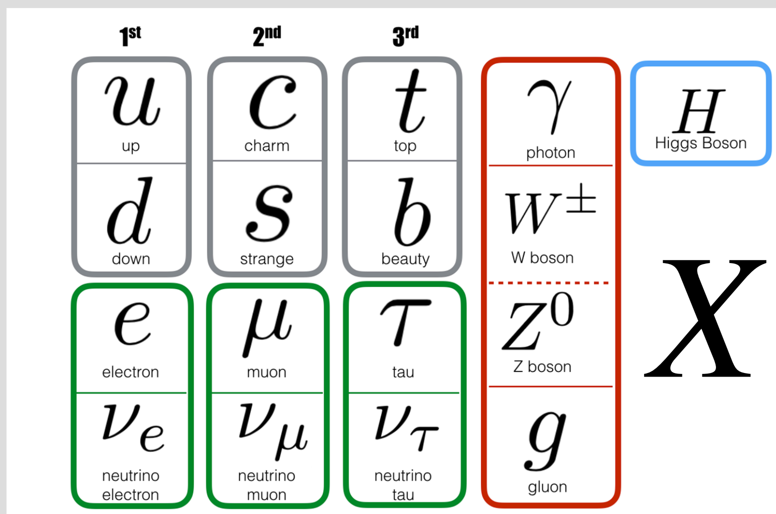
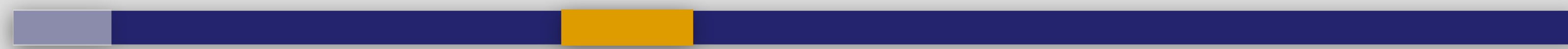
WIMPs



m



10^{-21} eV

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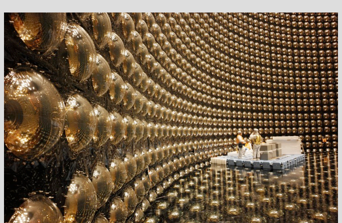
WIMPs

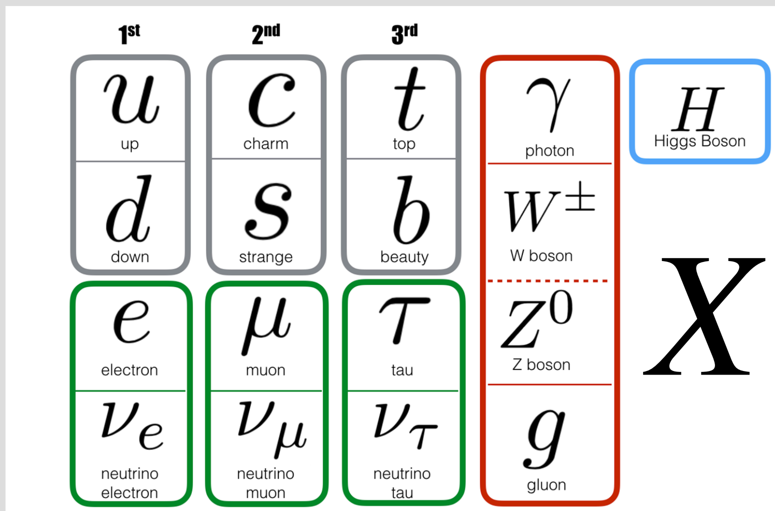
AMS

Fermi

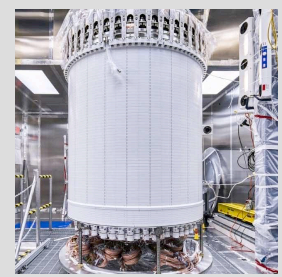


Super K

HESS



XENONnT



LZ

SENSEI

m

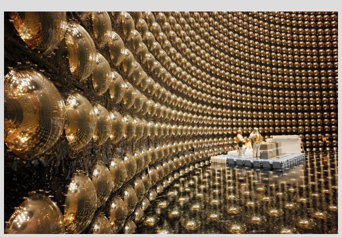
10^{-21} eV

$10^{-10}\ M_{\odot} \sim 10^{56}$ eV

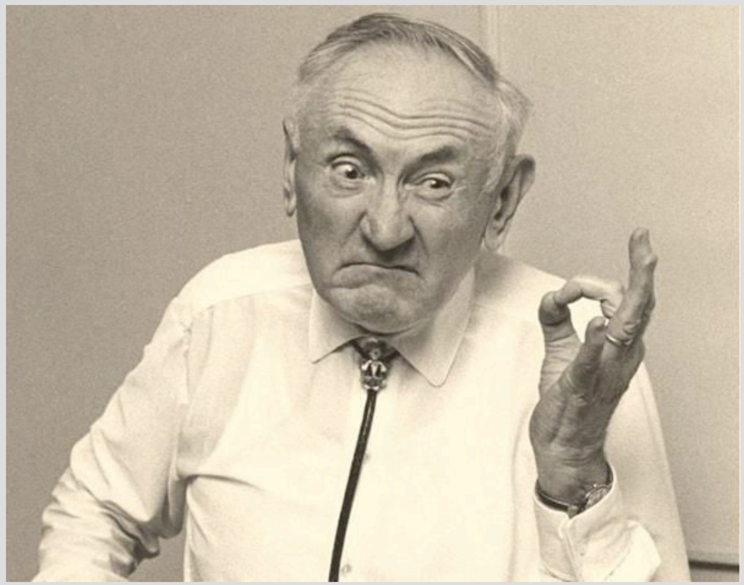
so far, nada


AMS

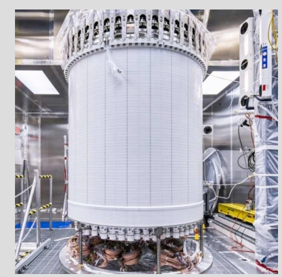

Fermi


Super K


HESS




XENONnT


LZ

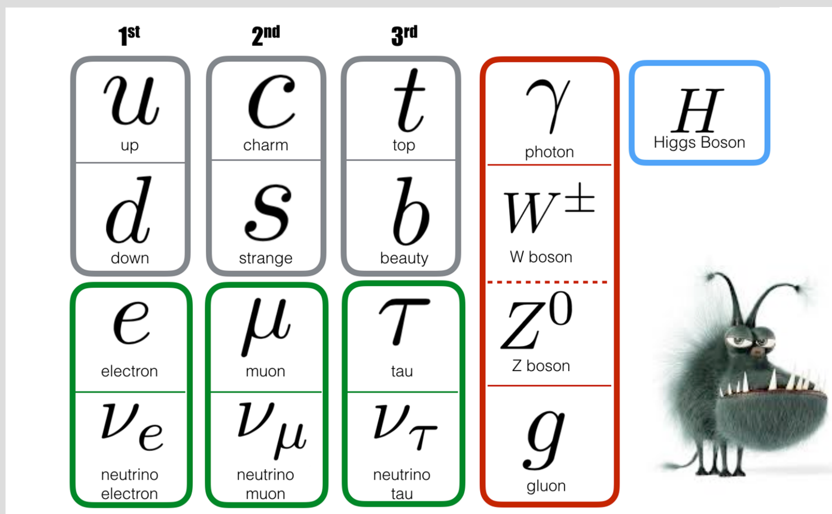

SENSEI

m

10^{-21} eV

$10^{-10}\ M_{\odot} \sim 10^{56}$ eV

WISPs



m

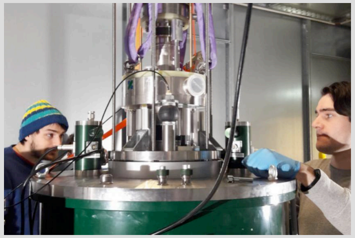
10^{-21} eV

$10^{-10}\ M_\odot \sim 10^{56}$ eV

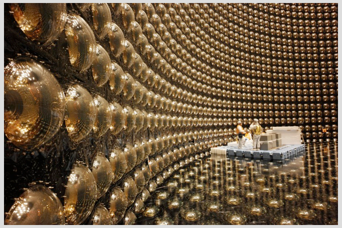
WISPs

MADMAX

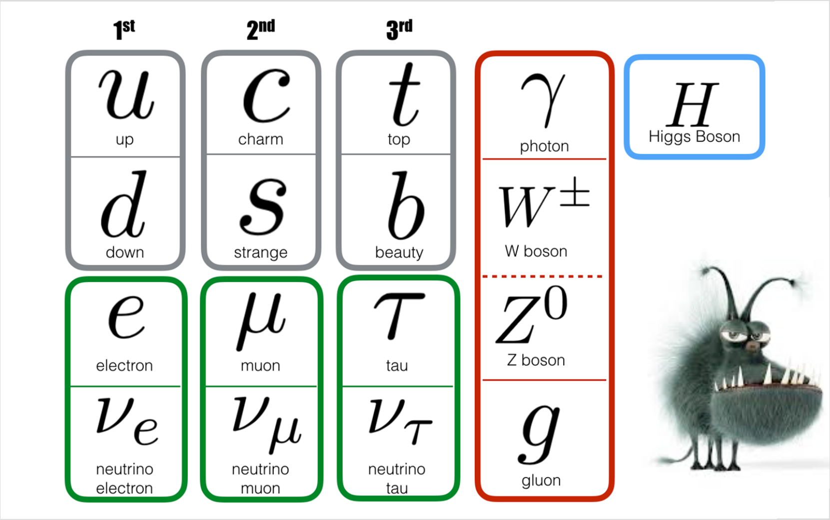
ABRACADABRA



CASPEr



Super K



CAST

DM radio

ADMX

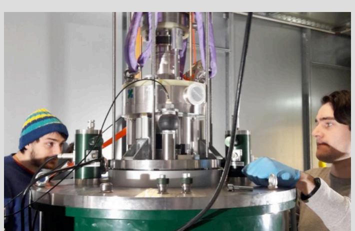
m

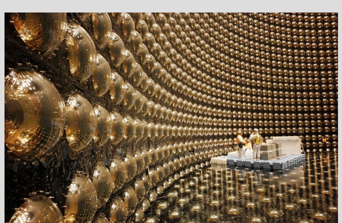
10^{-21} eV $10^{-10}\ M_{\odot} \sim 10^{56}$ eV

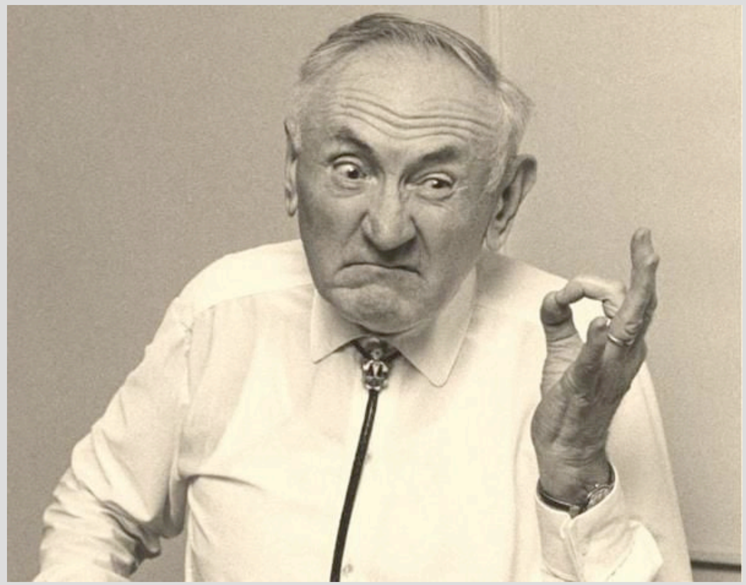
so far, nada


MADMAX

ABRACADABRA


CASPEr


Super K




CAST


DM radio


ADMX

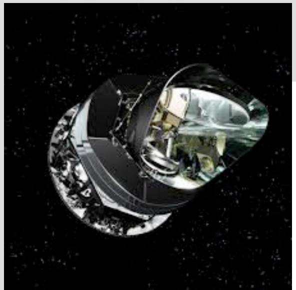
m

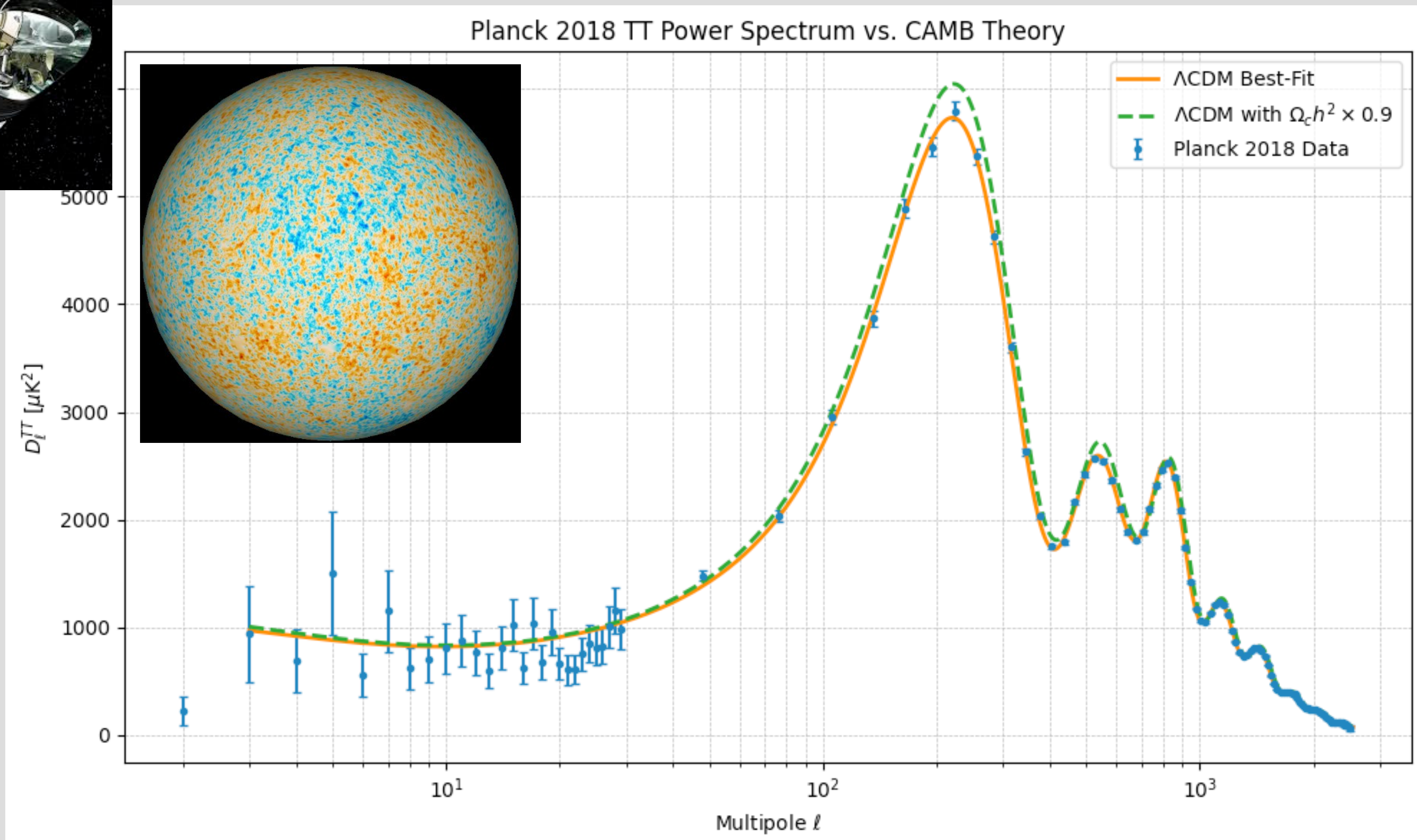
10^{-21} eV

$10^{-10}\ M_{\odot} \sim 10^{56}$ eV


Gravitation alone
m
10^{-21} eV
$10^{-10}\ M_\odot \sim 10^{56}$ eV

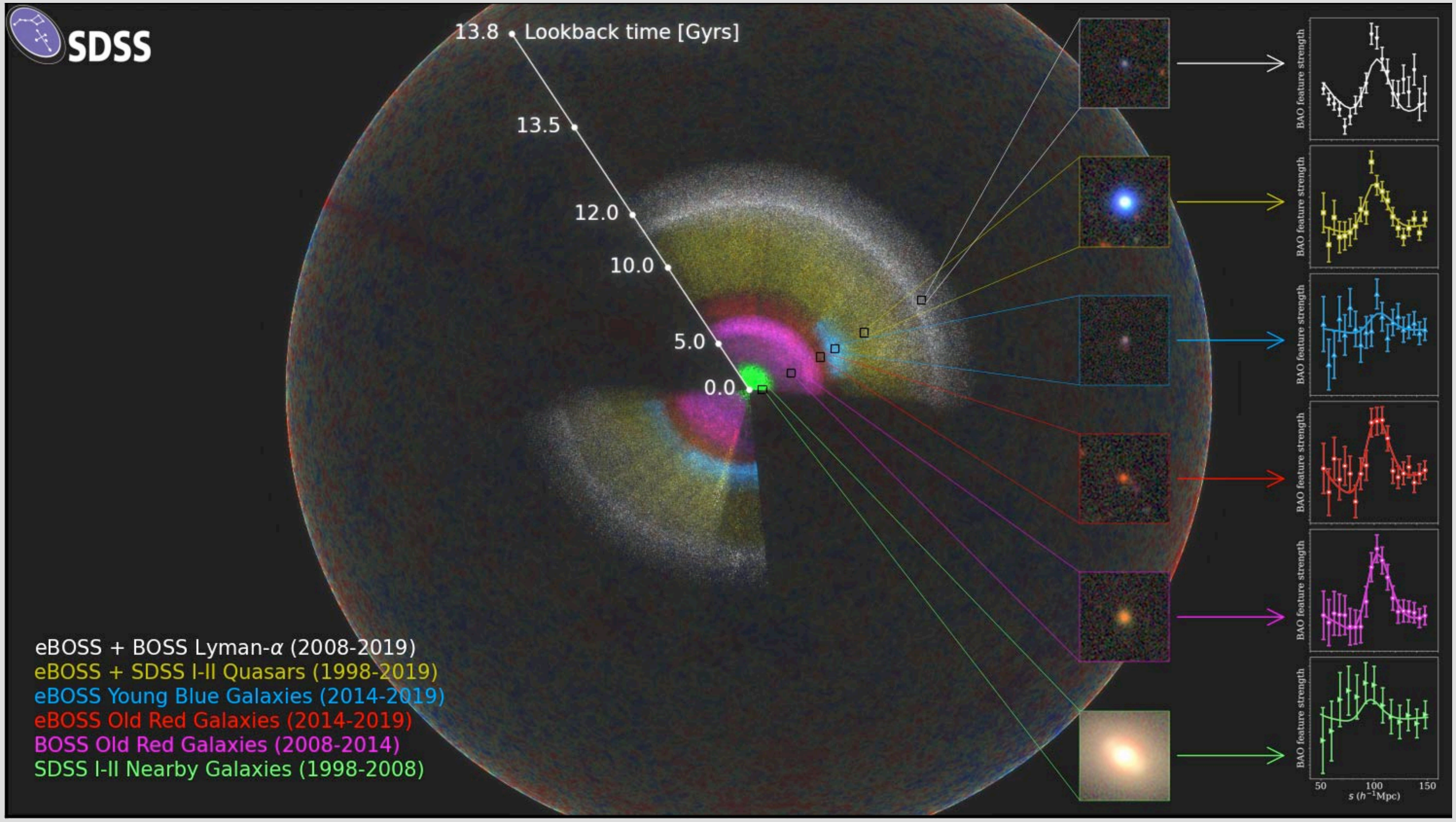
Dark matter: cosmic microwave background (CMB)





* Python code in backup slide

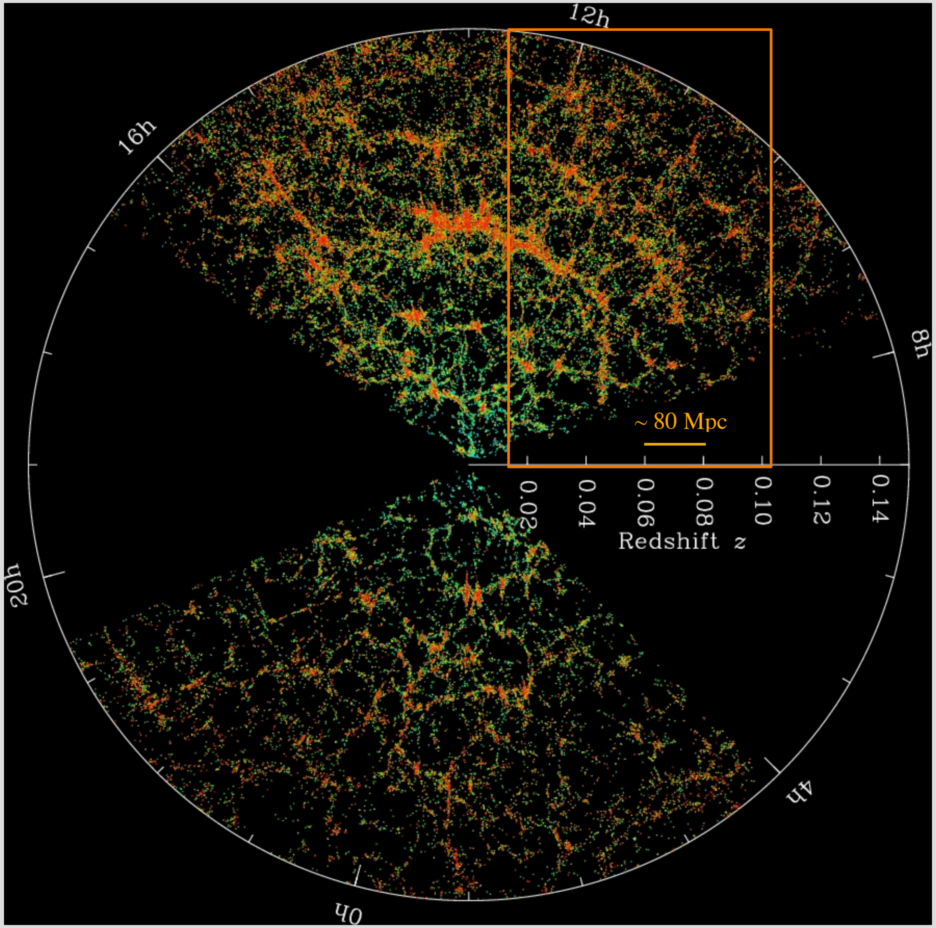
Dark matter: galaxy clustering



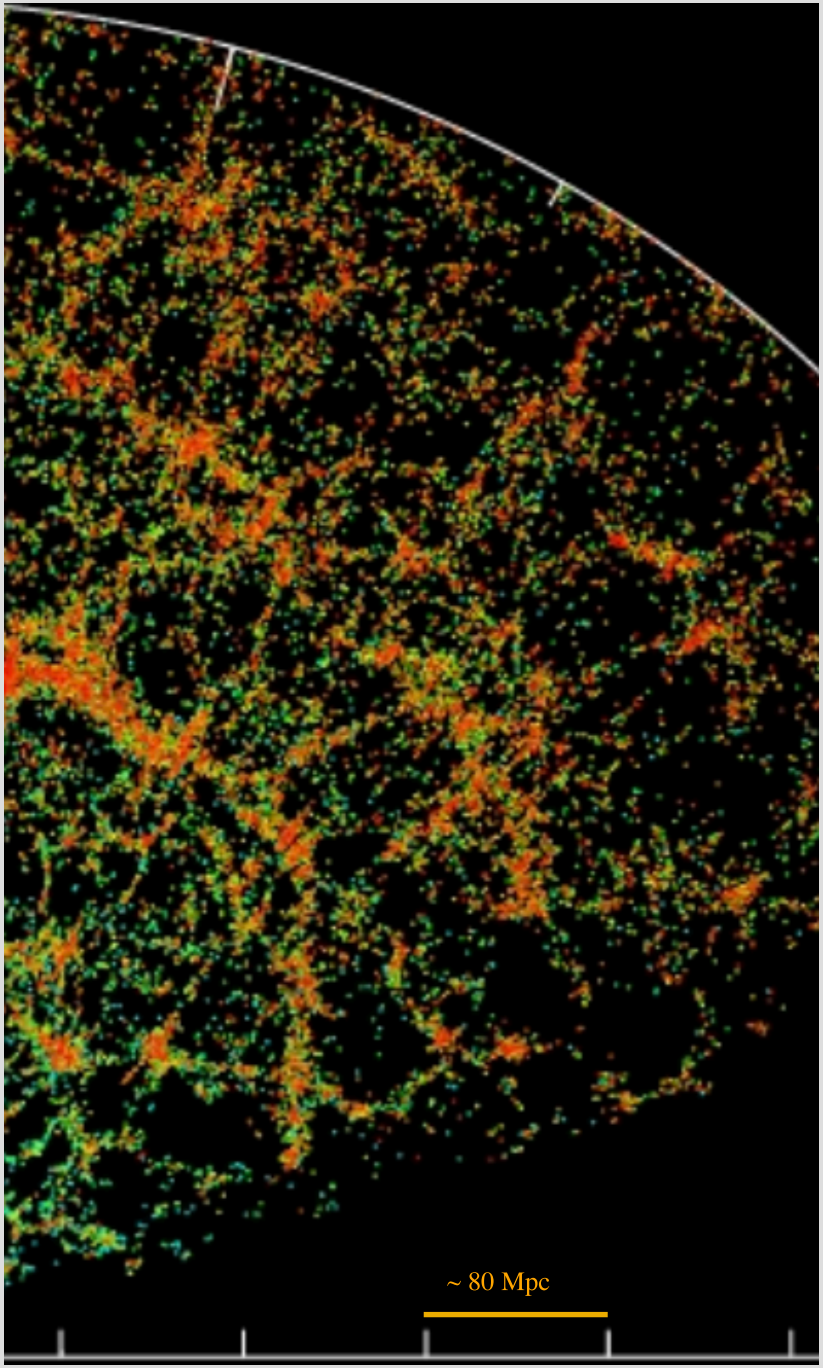
Credit: Anand Raichoor (EPFL), Ashley Ross (Ohio State University) and the SDSS Collaboration

Dark matter: galaxy clustering

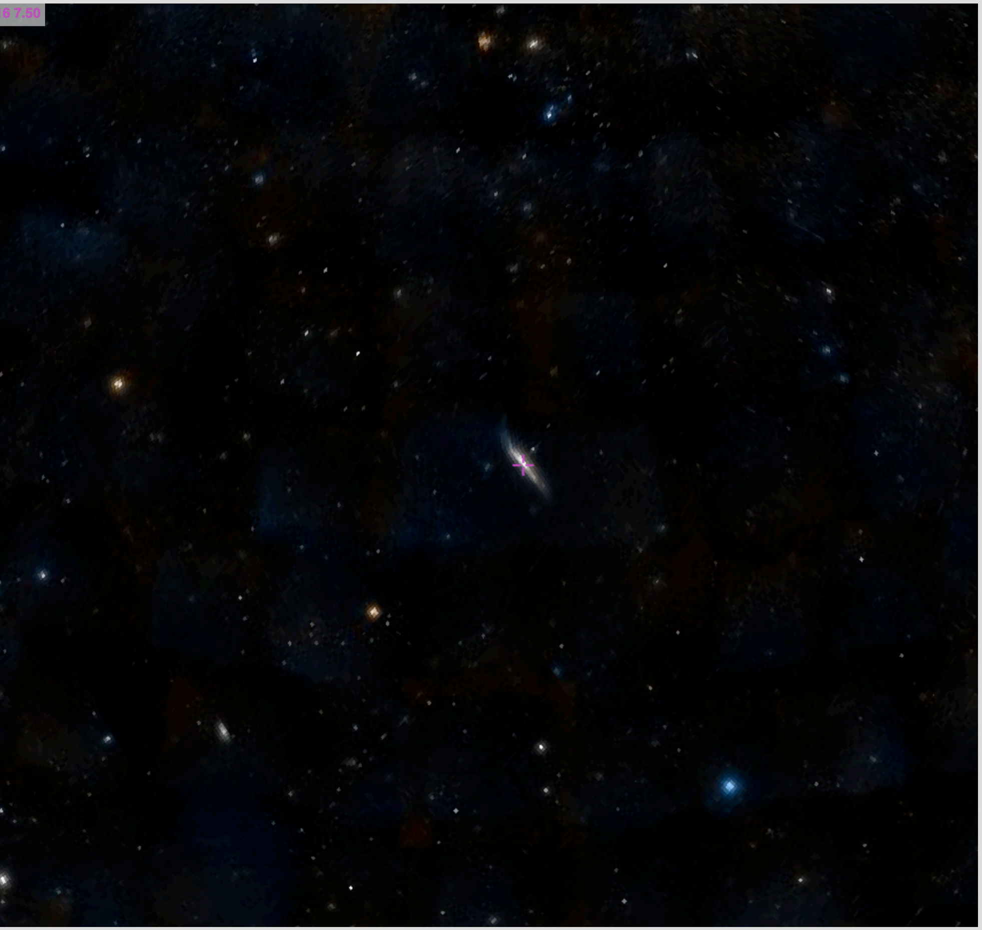
https://classic.sdss.org/legacy/



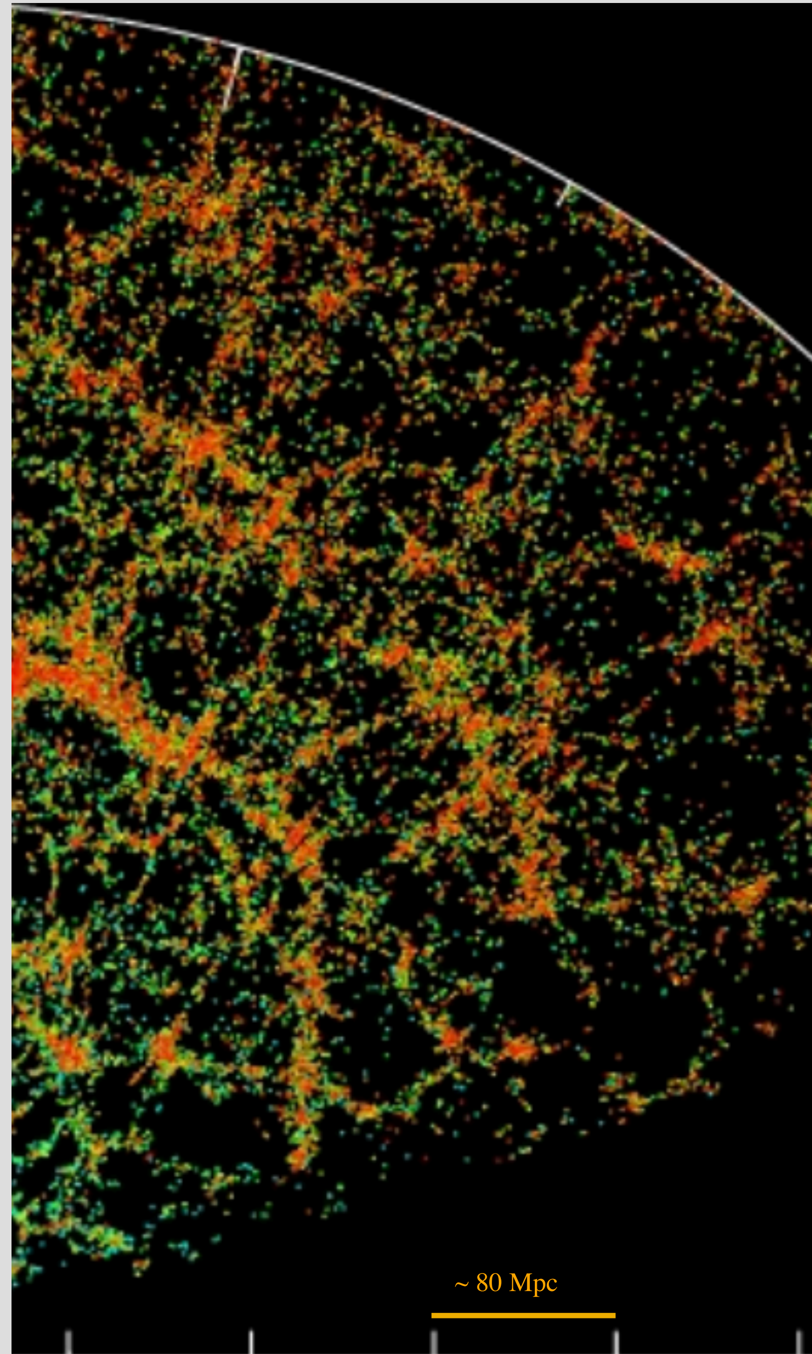
Dark matter: galaxies



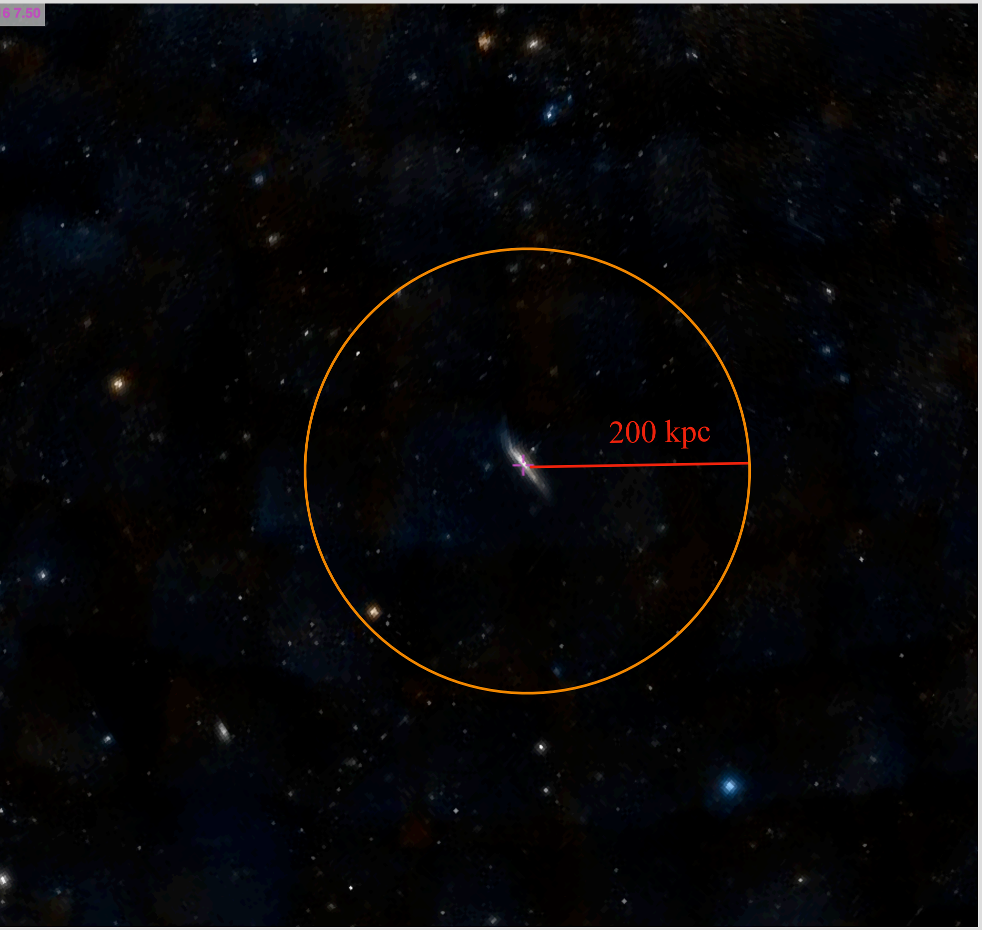
Dark matter: galaxies



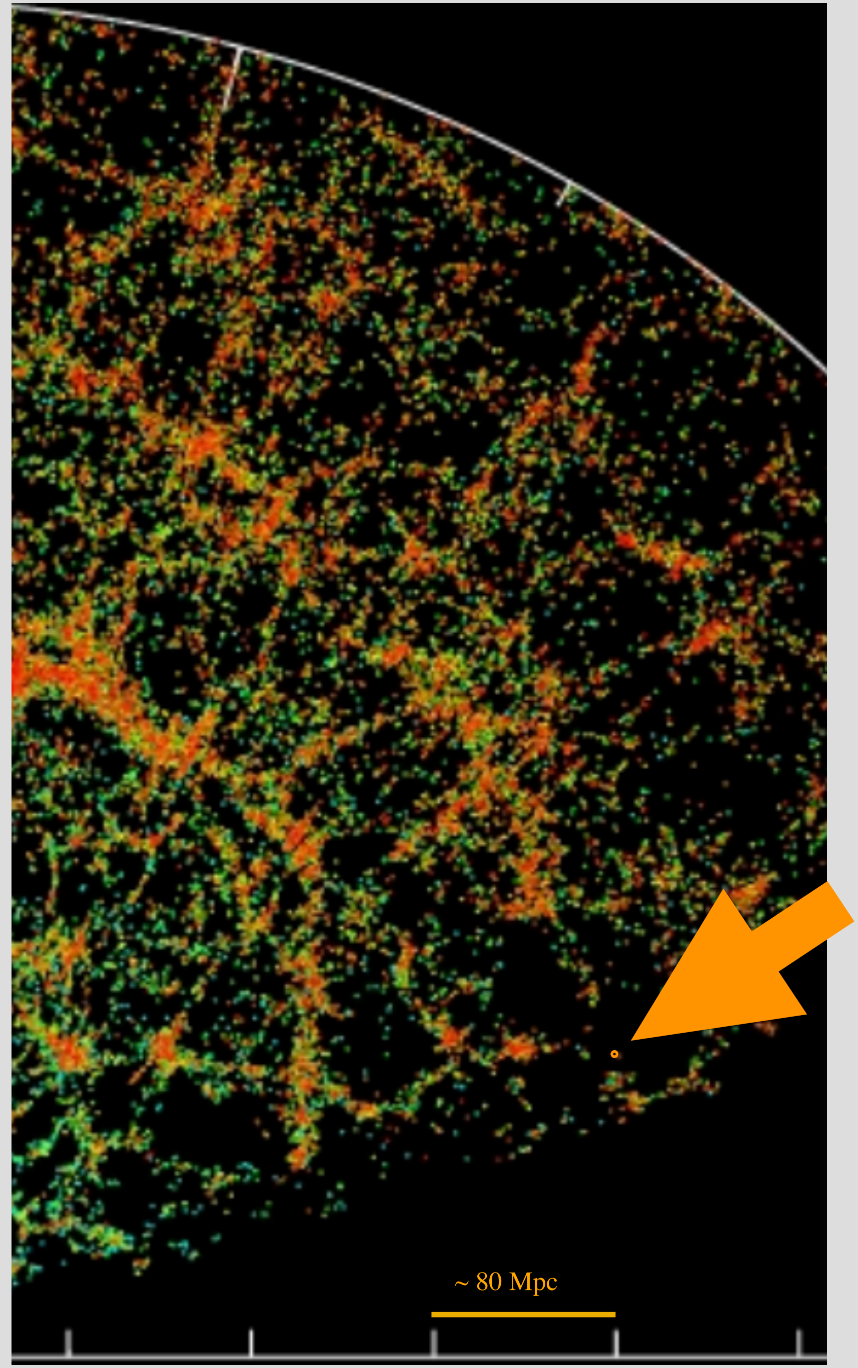
https://simbad.cds.unistra.fr/simbad/sim-basic?Ident=M31



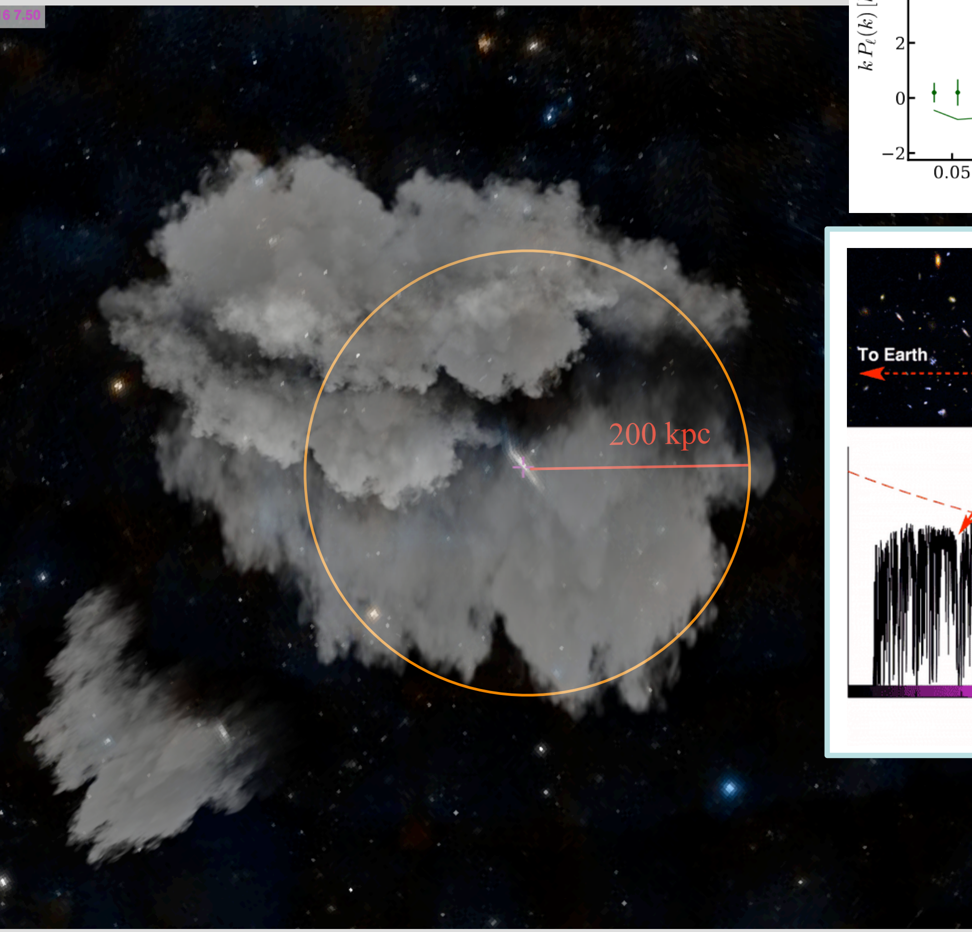
Dark matter: galaxies

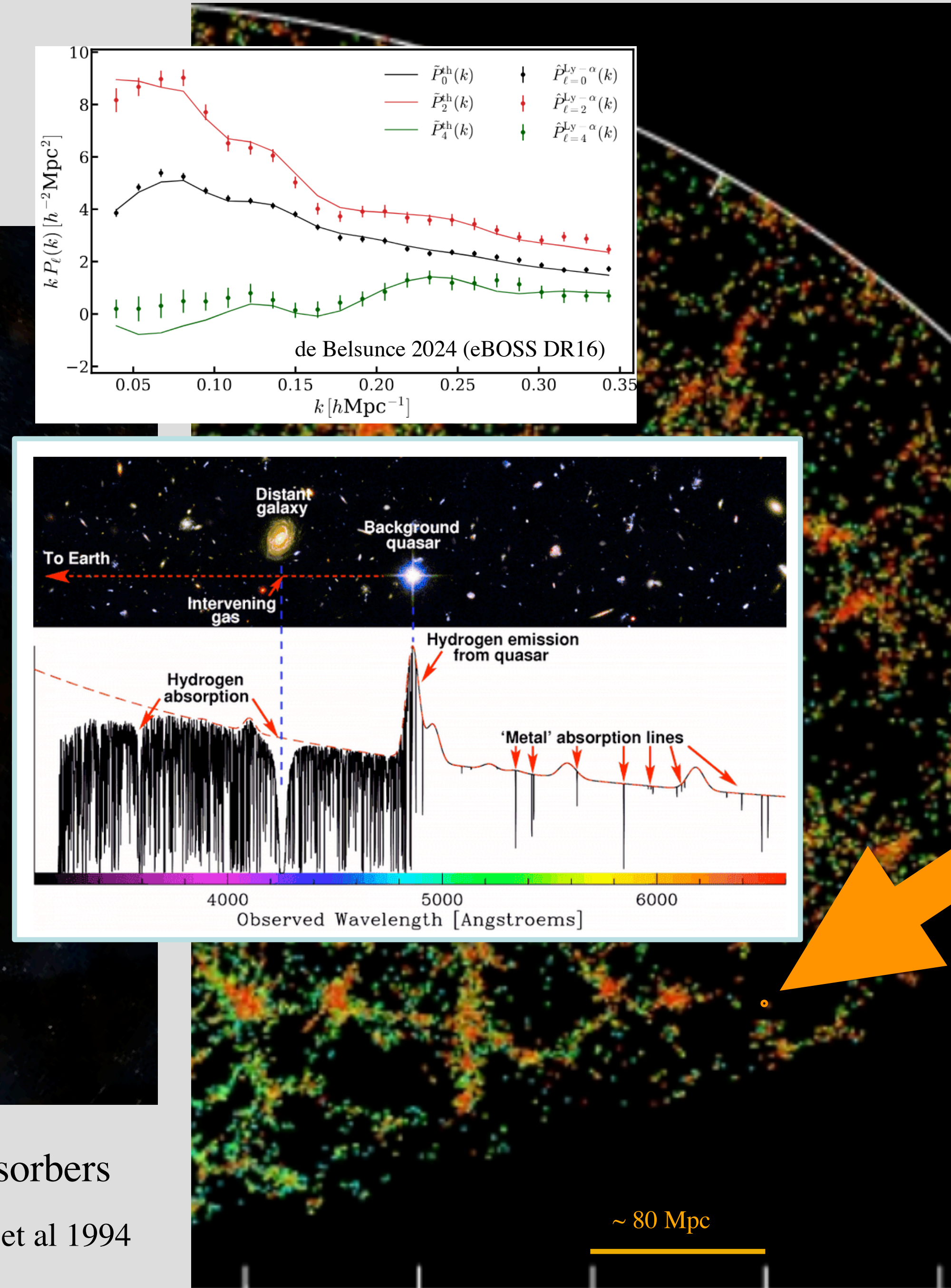


https://simbad.cds.unistra.fr/simbad/sim-basic?Ident=M31



Dark matter: galaxies

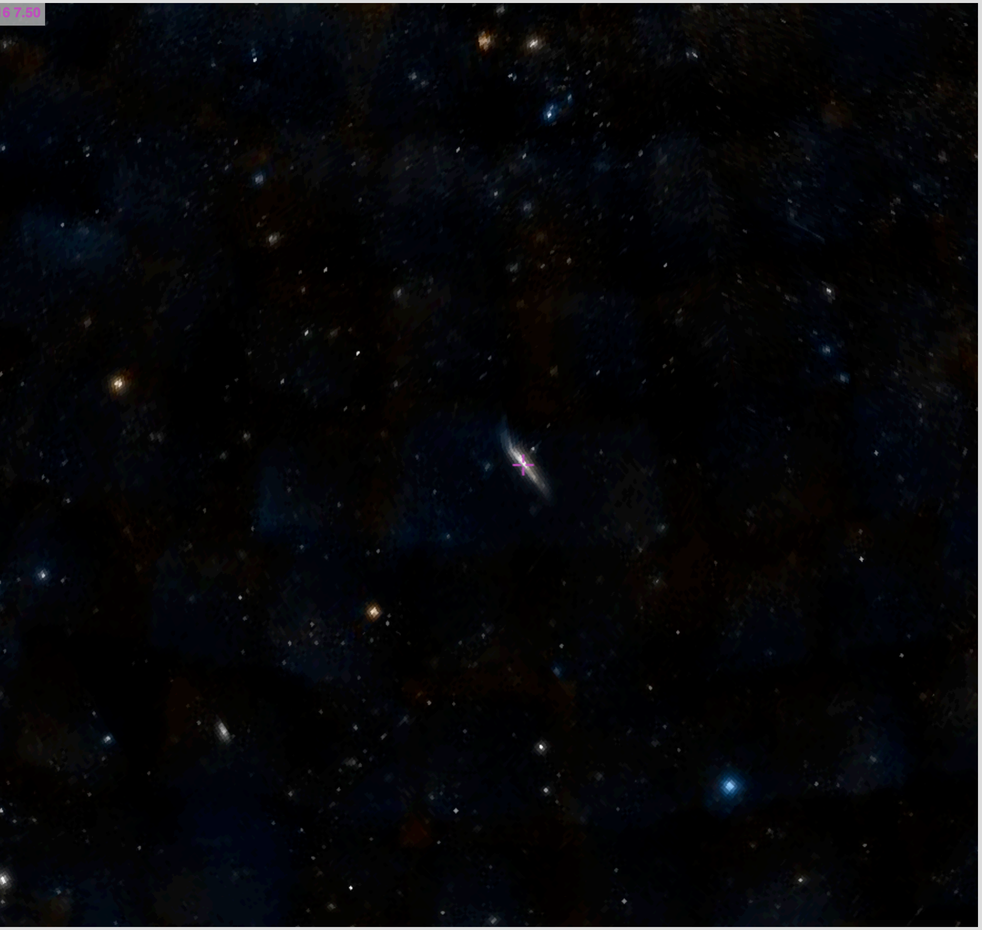




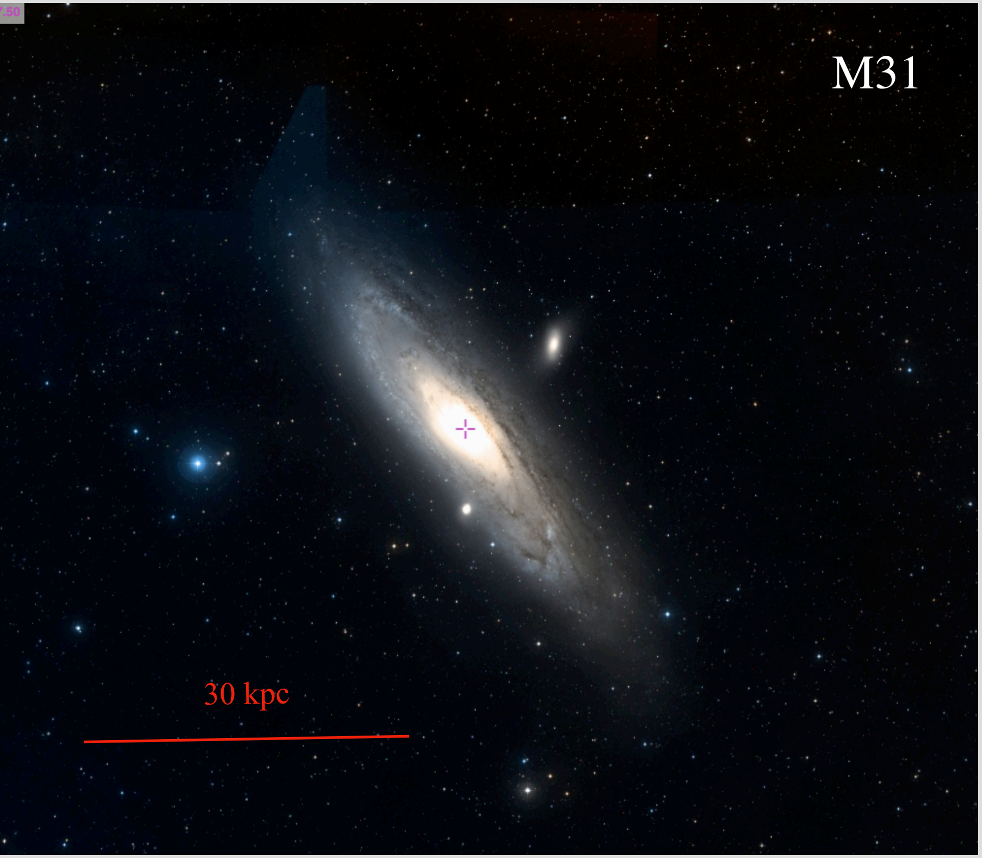
This is also the scale size of Lyman-alpha absorbers

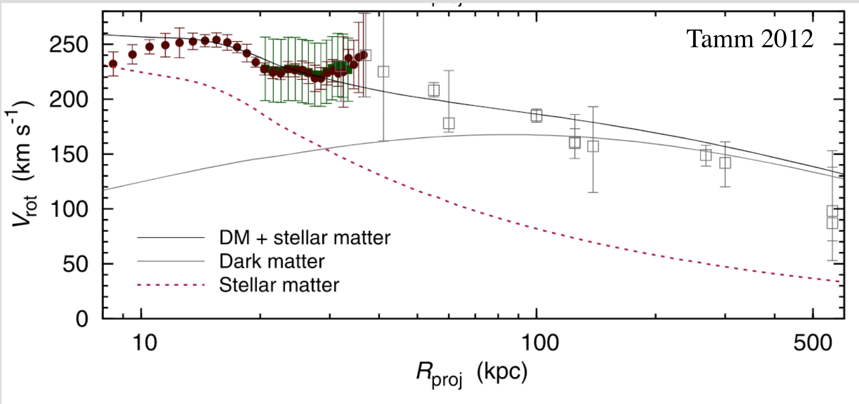
e.g. Bechtold et al 1994

Dark matter: galaxies

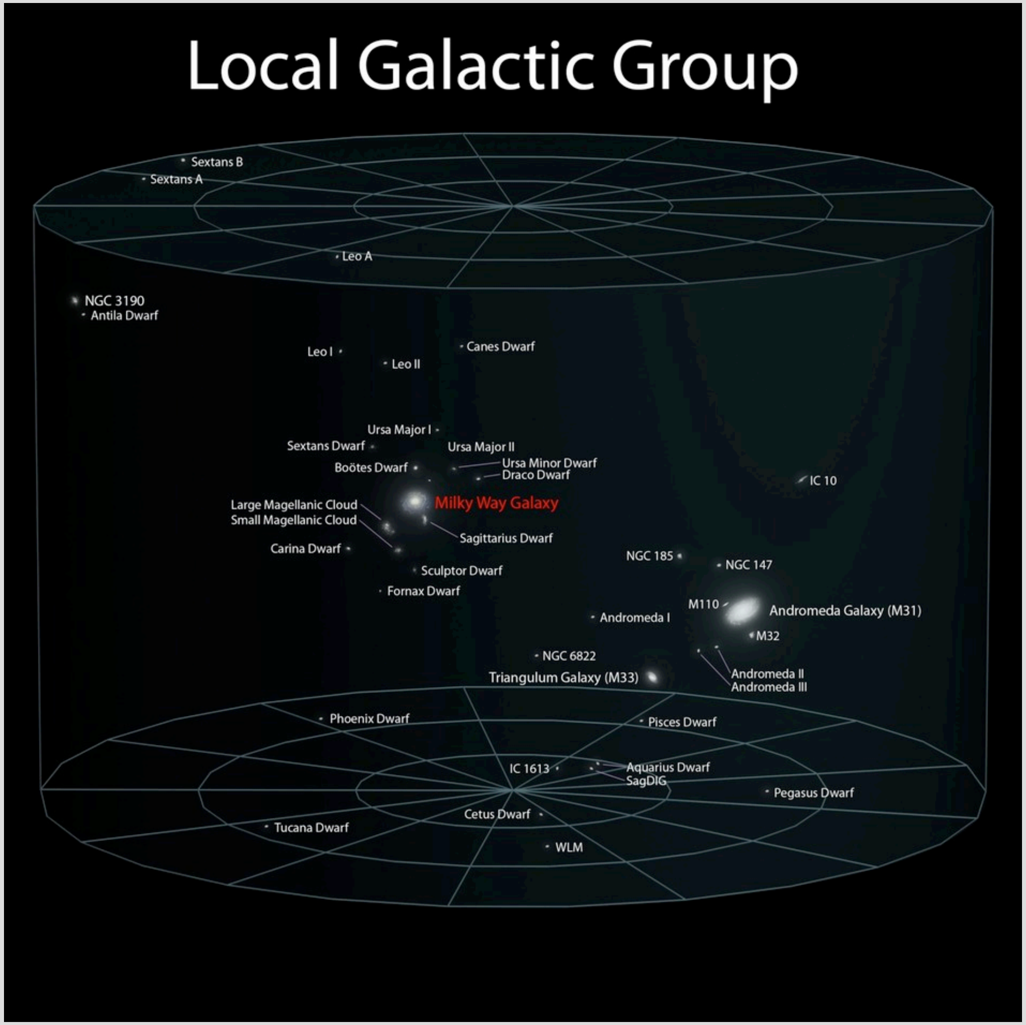


Dark matter: galaxies

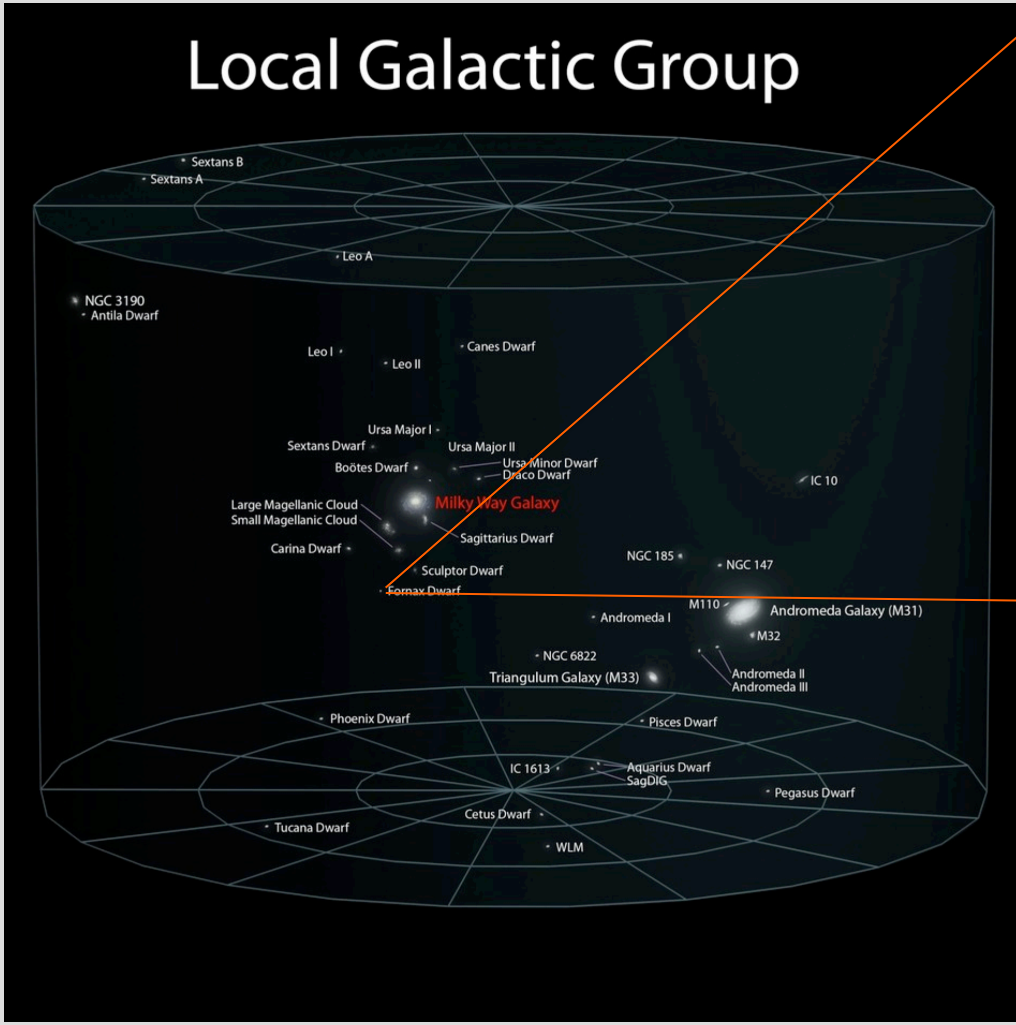




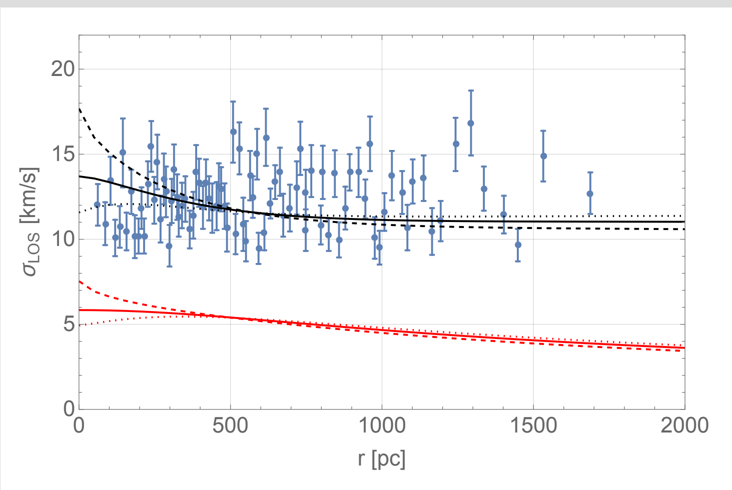
Dark matter: galaxies



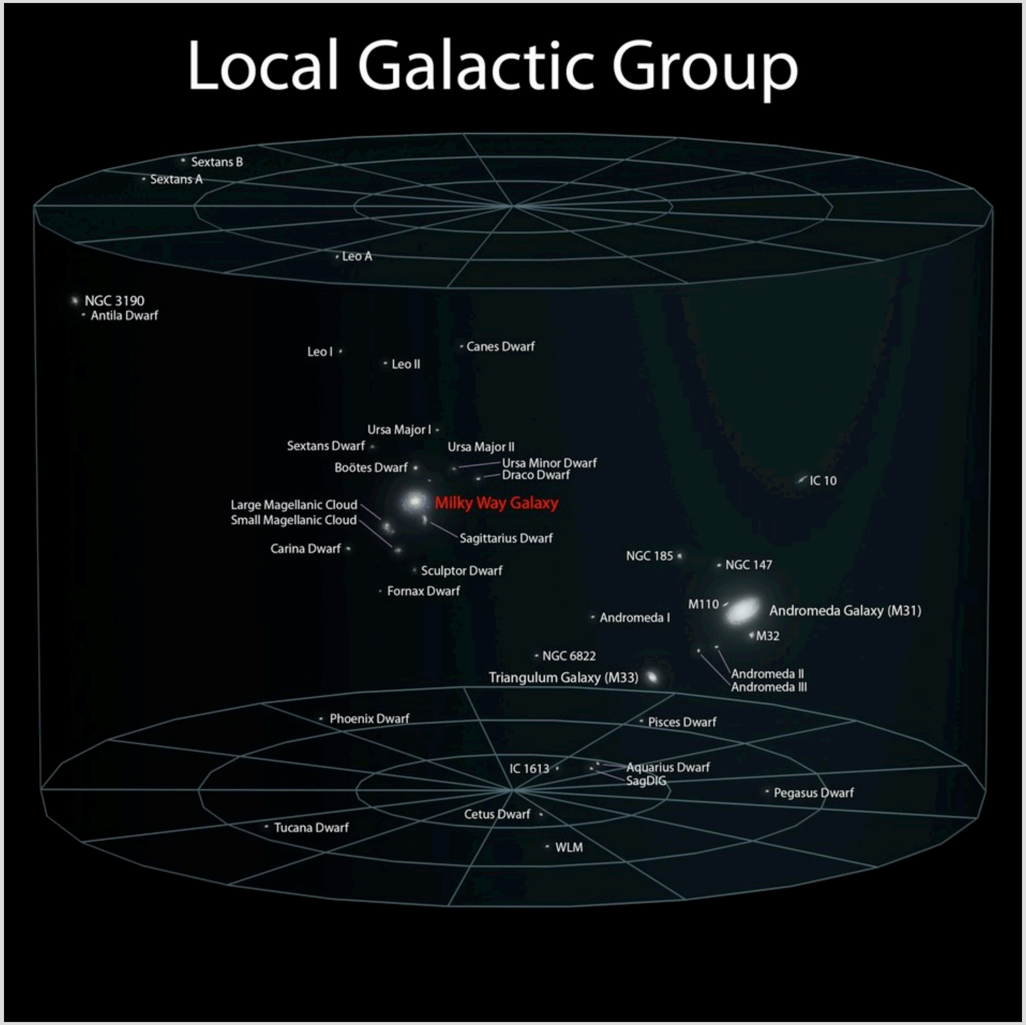
Dark matter: galaxies



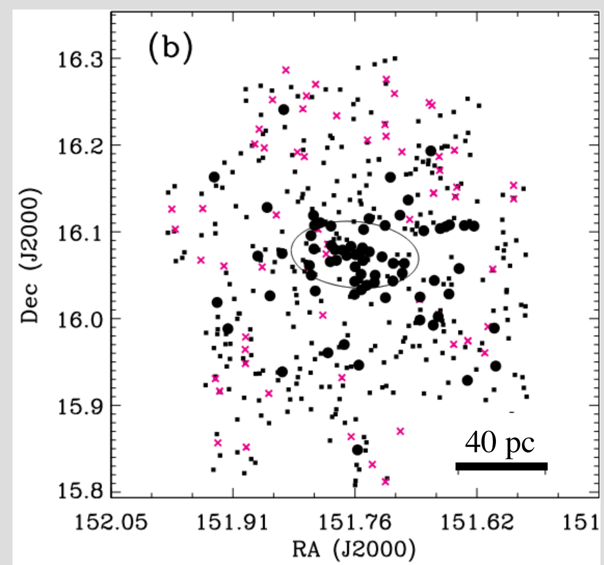
Fornax dwarf galaxy



Dark matter: galaxies



Fornax dwarf galaxy



Simon et al 1007.4198

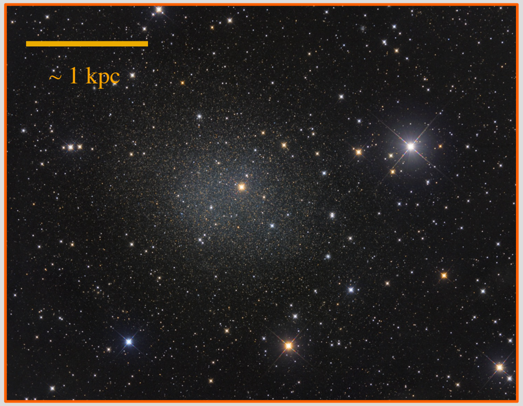
Segue II

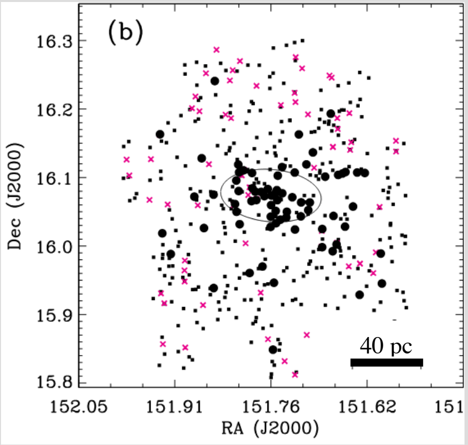
As of today, many gravity-only probes of light WISPs.

I will talk about two examples:

1. Lower limit on mass of DM: dwarf galaxies

Teodori et al 2501.07631, 2504.16202





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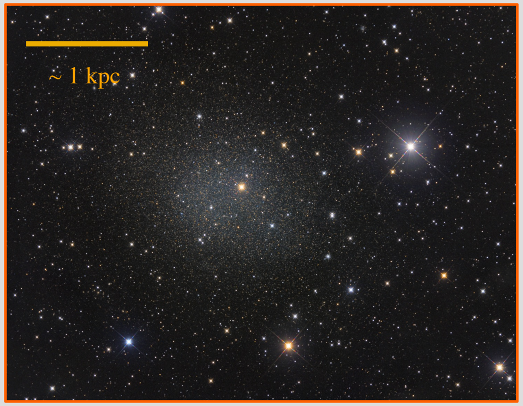
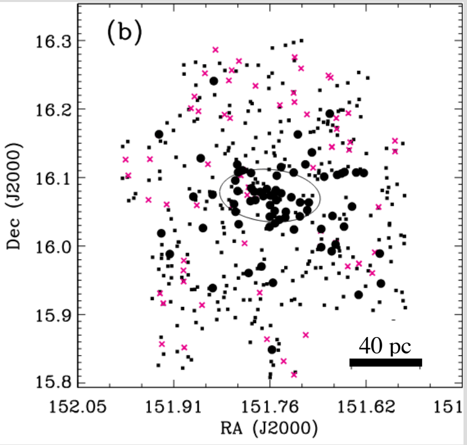
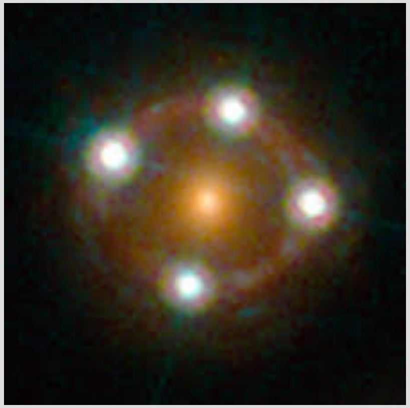
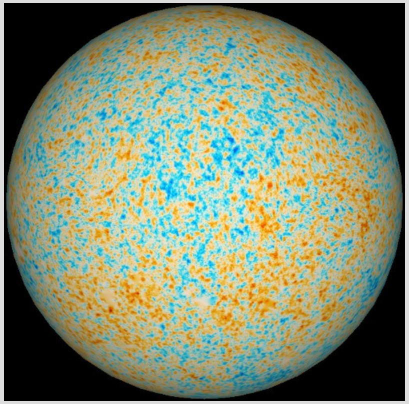




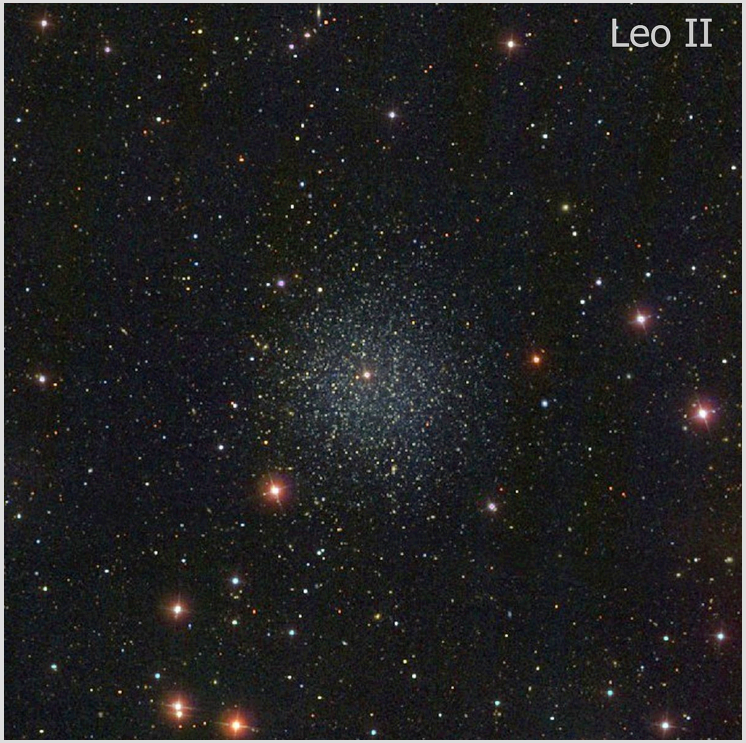
2. Room for discovery: ***AxionH0graphy !***

Teodori et al 2105.10873, 2409.04134





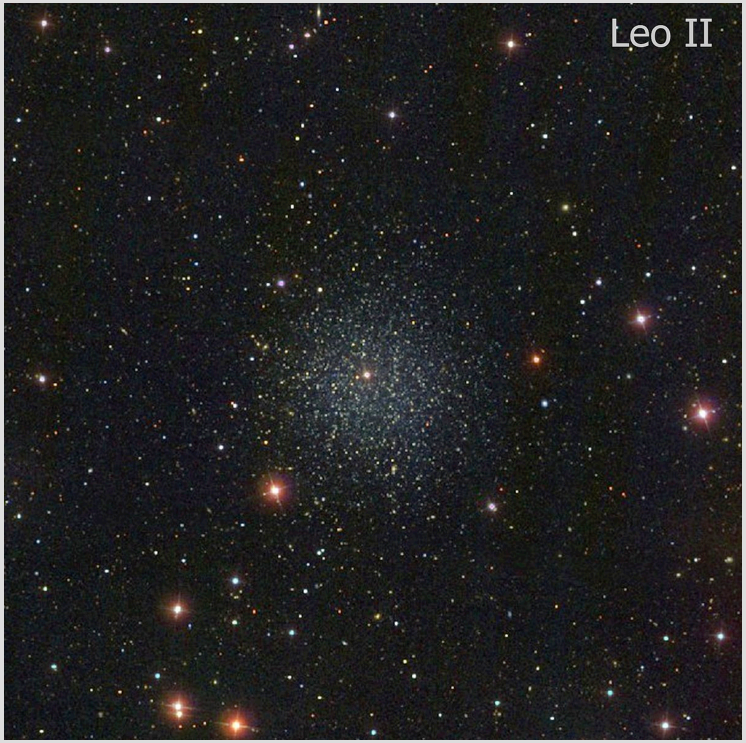
Lower bound on m from galaxies

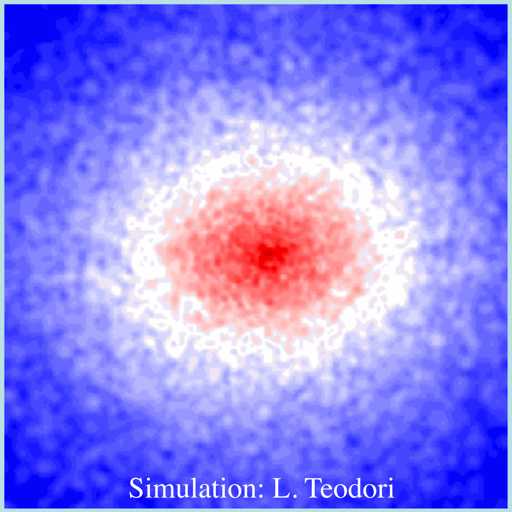


m

5×10^{-21} eV

Lower bound on m from galaxies





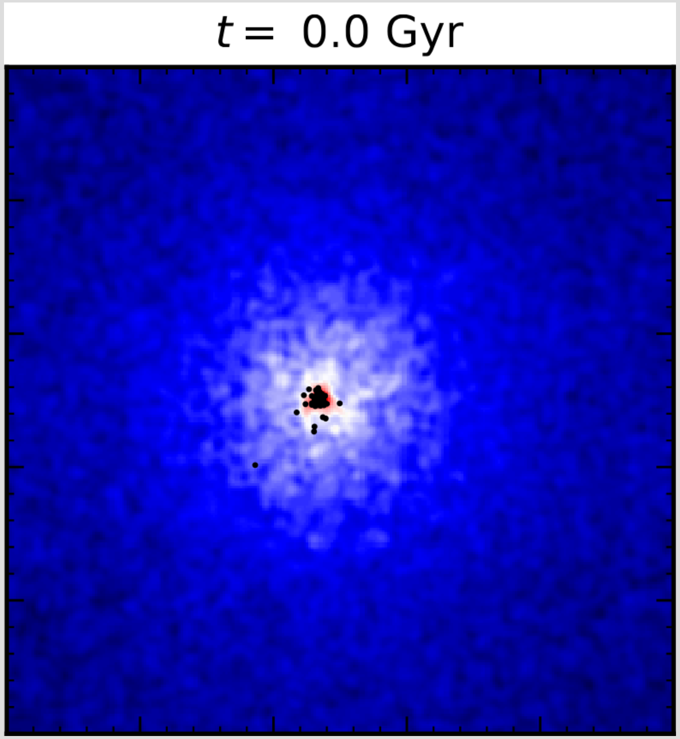
Bar-Or 1809.07673, 2010.10212,
Church 1809.04744,
Schive 1912.09483,
Dutta Chowdhury 2303.08846,
Yang 2403.09845,
Dalal 2203.05750, May 2509.02781
Teodori 2501.07631

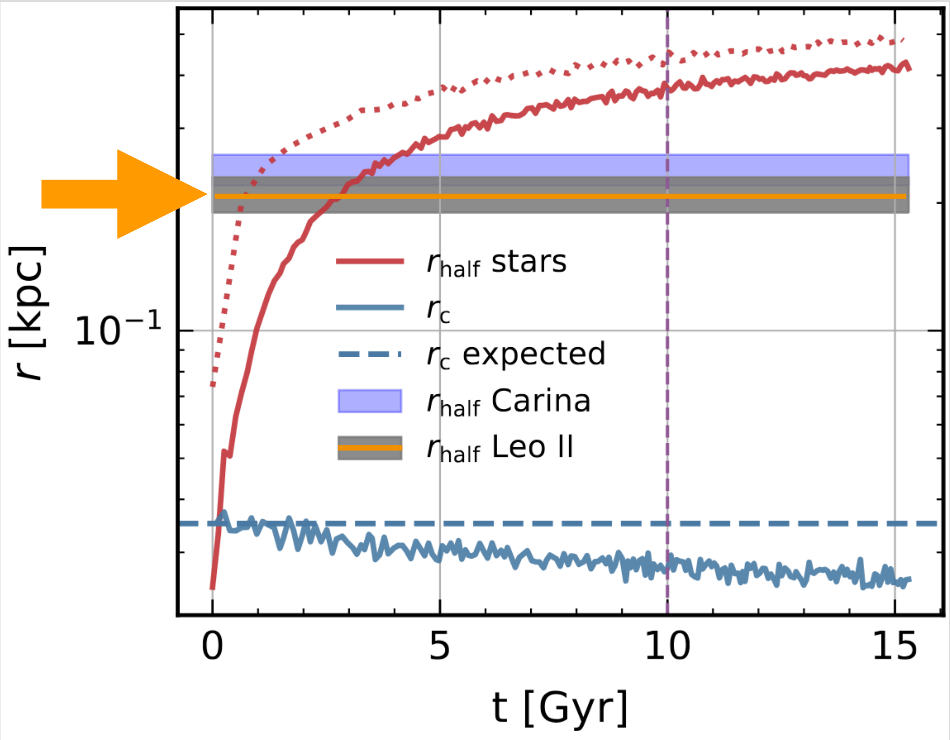
m

5×10^{-21} eV

Lower bound on m from galaxies

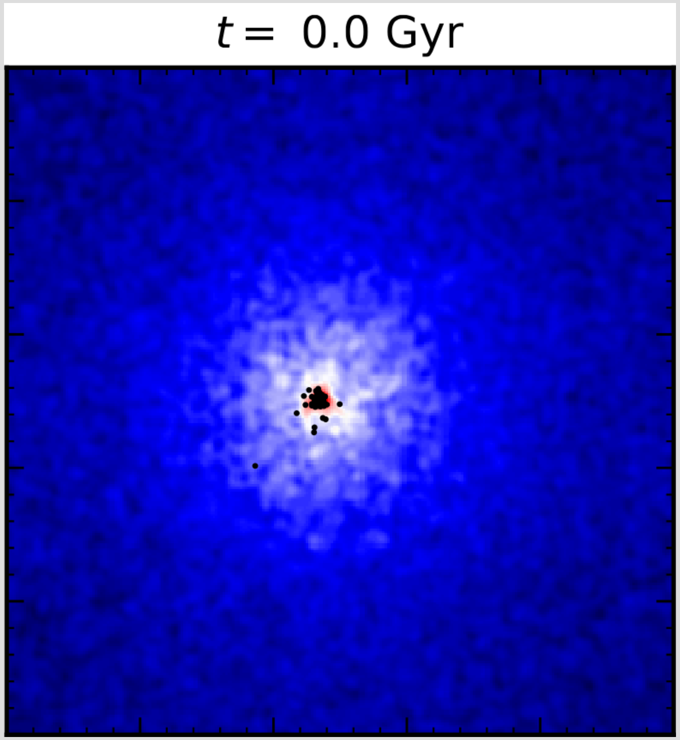
Teodori
2501.07631

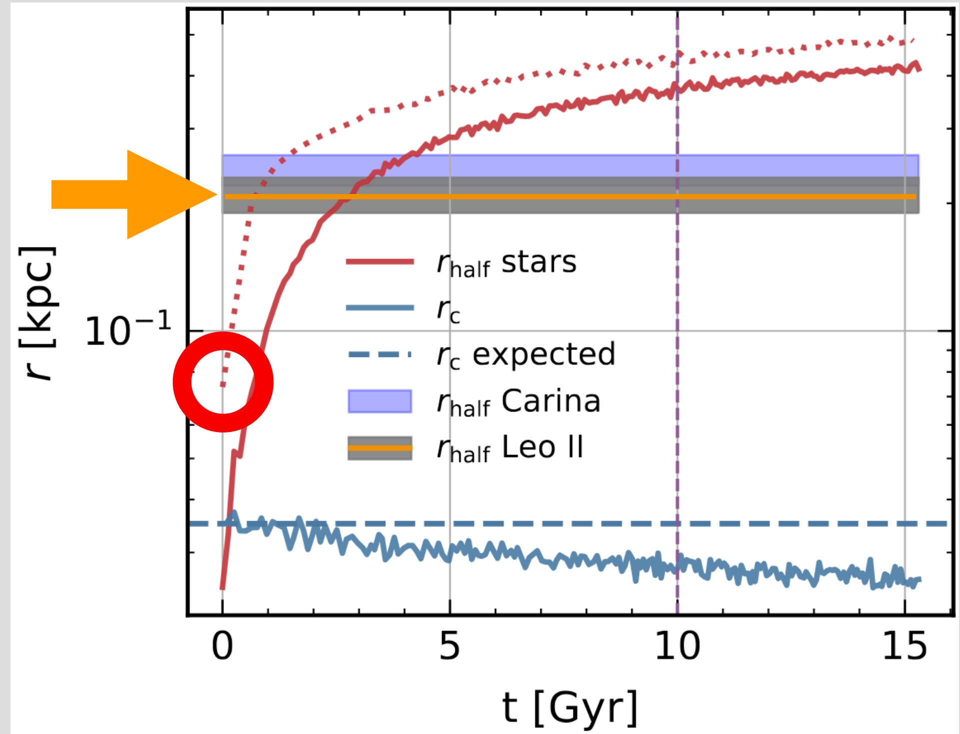




Lower bound on m from galaxies

Teodori
2501.07631



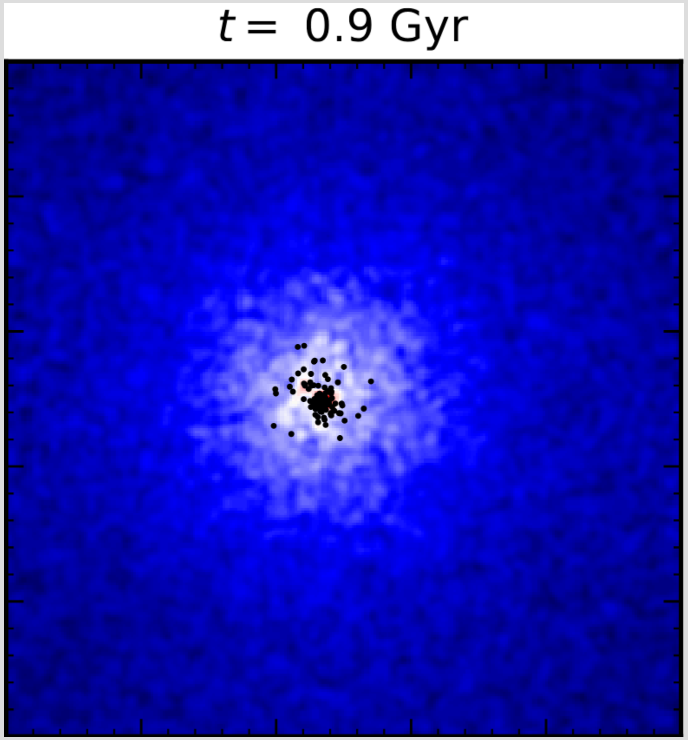


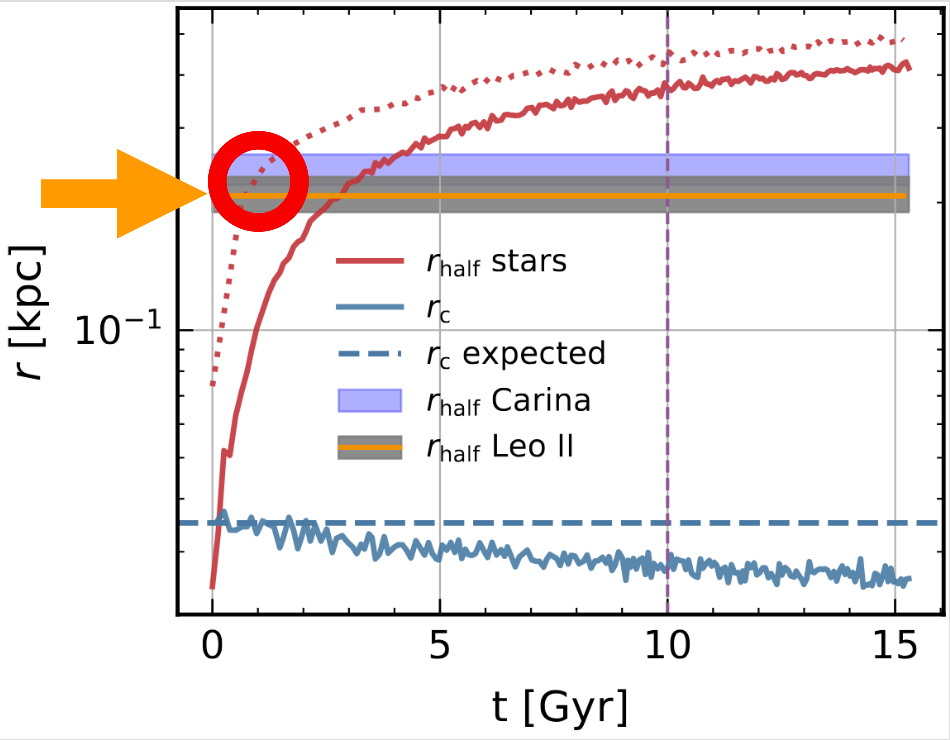
m

5×10^{-21} eV

Lower bound on m from galaxies

Teodori
2501.07631



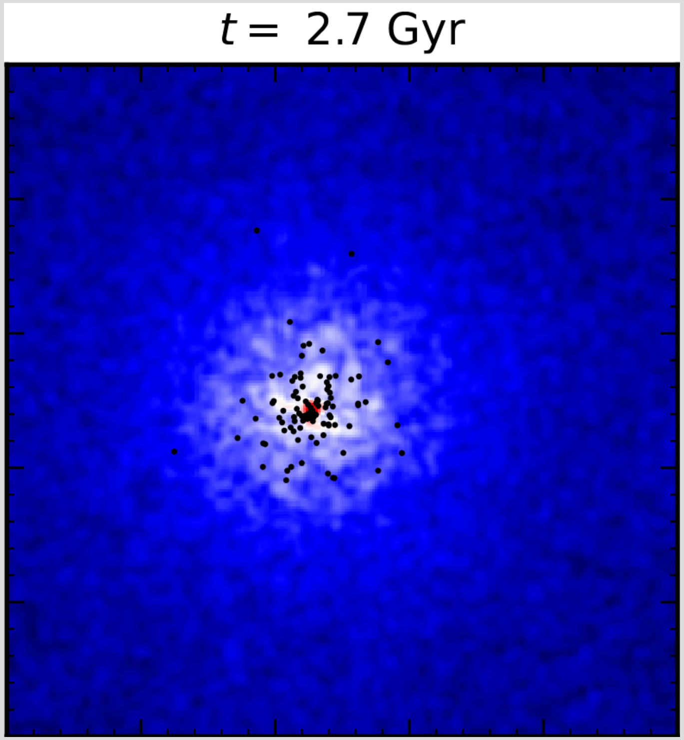


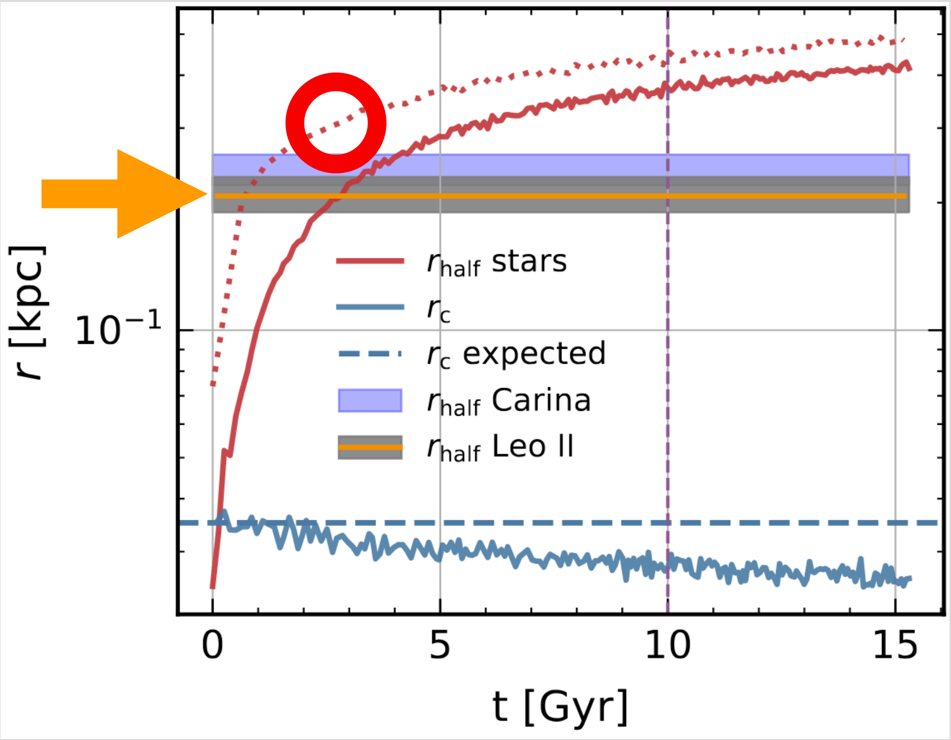
m

5×10^{-21} eV

Lower bound on m from galaxies

Teodori
2501.07631



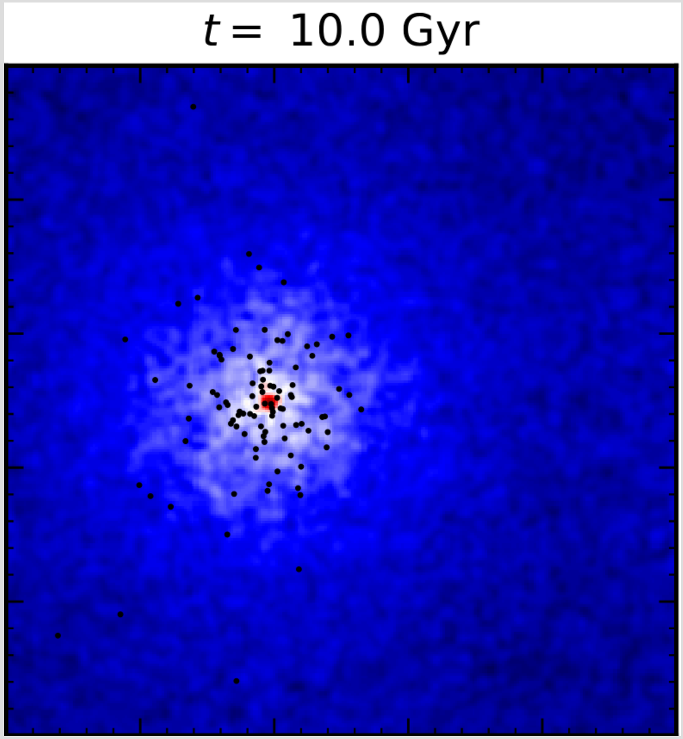


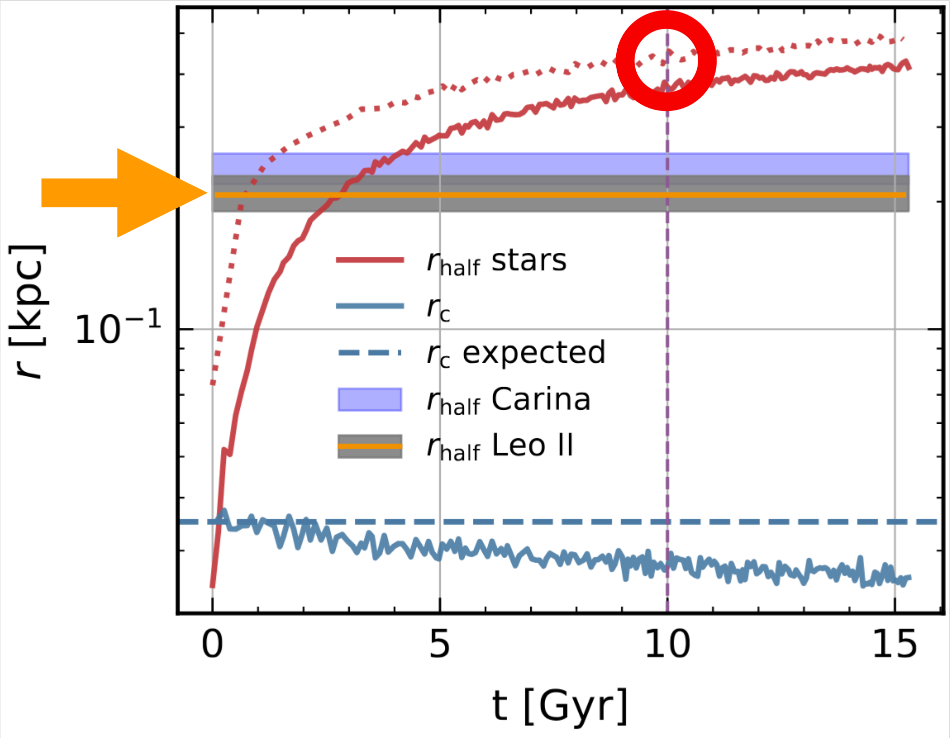
m

5×10^{-21} eV

Lower bound on m from galaxies

Teodori
2501.07631





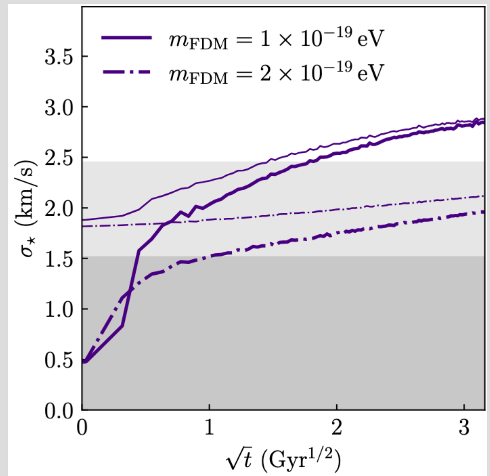
m

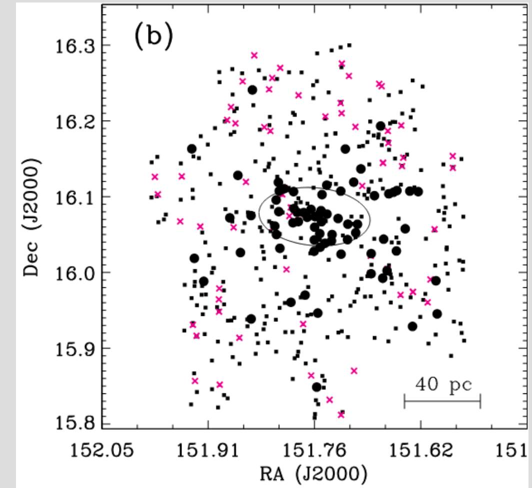
5×10^{-21} eV

Lower bound on m from galaxies

Dalal & Kravstov 2203.05750
$m > 3 \times 10^{-19}$ eV

Based on UFDs Segue 1 & Segue 2.
(Make the point that other UFDs exist.)





Simon et al 1007.4198

May et al 2509.02781
$m > 8 \times 10^{-18}$ eV

…but in fact simulated 10^{-22} eV.
Soliton formation time, for instance, *much* faster than at 8×10^{-18}eV.
…and is Ursa Major 3/UNIONS 1 an UFD, or a self-gravitating star cluster? (Devlin et al 2504.21301)

Another question. Dynamical heating by ULDM can be understood by means of quasiparticles (Bar-Or 1809.07673, 2010.10212).
Heating occurs by approach to equipartition **when MQP >>** $M_\odot$. For m of 5×10^{-21} eV, QP mass in Leo II is MQP ~ $10^5 M_\odot$.
But for 8×10^{-18}eV in UM3/U1 it is MQP < $1 M_\odot$. **…Why would there be heating?…**

m

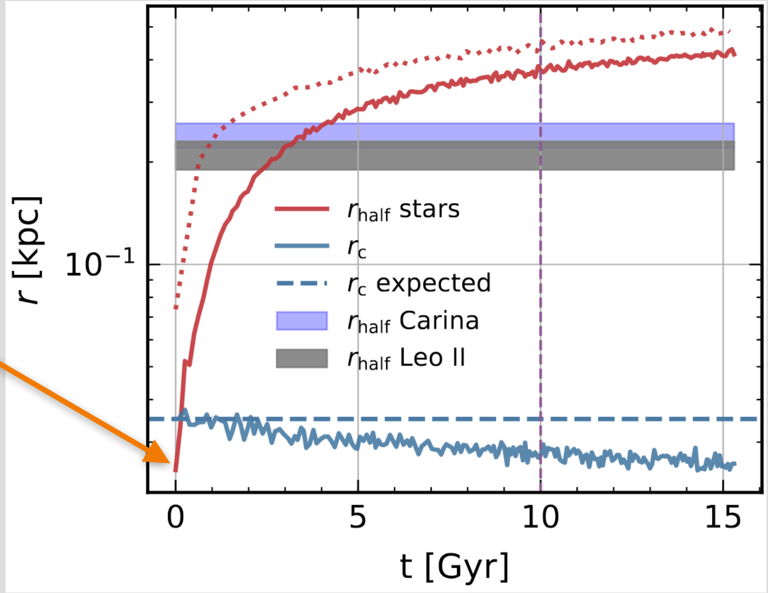
$5 \times 10^{-21} \rightarrow 3 \times 10^{-19}$ eV ?
8×10^{-18} eV ?

Lower bound on m from galaxies

Caveat in Teodori 2501.07631,
and in Dalal & Kravstov 2203.05750, May et al 2509.02781:
Stellar self-gravity was neglected.
— Should revisit with N-body stars,
rather than test particles.

For Leo II, for example, this stage is not clearly under control without star self gravity.

What is the situation for UFDs?
(For claimed bound in 2509.02781, also QP mass vs. star mass question)



$5 \times 10^{-21} \;\rightarrow\; 3 \times 10^{-19}$ eV ?

8×10^{-18} eV ?

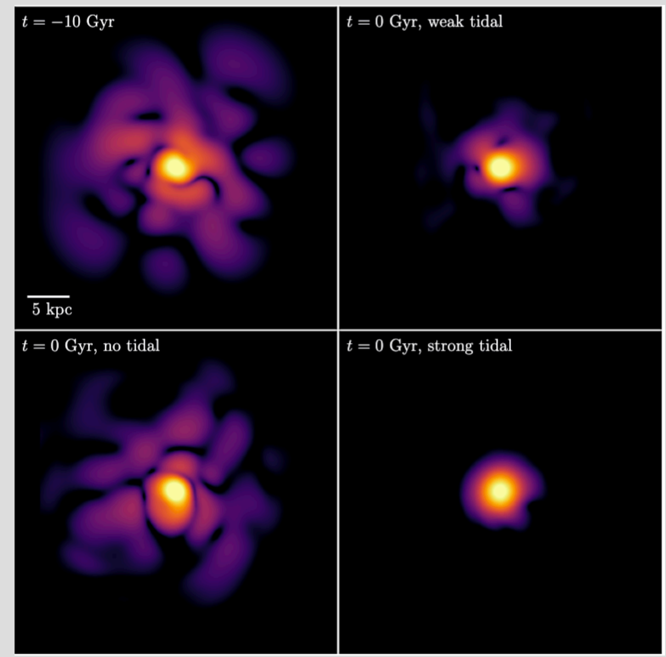
Lower bound on m from galaxies

Another possible caveat in Teodori 2501.07631
(probably not in May et al 2509.02781)

Milky-Way tidal field may strip dwarf satellite halo, leaving ``bare soliton" with less heating.

— Demonstrated possible caveat for m of 10^{-22}eV in Fornax
— Does not look like a caveat for m $\gtrsim 10^{-21}$eV, but more simulations required to be safe.

Yang et al 2507.01686



$5 \times 10^{-21} \rightarrow 3 \times 10^{-19}$ eV ?
8×10^{-18} eV ?

Lower bound on m from galaxies

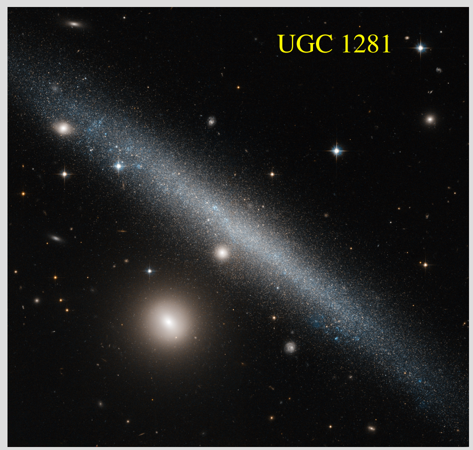
Dynamical heating may give the strongest bound. But there are many more observational tests.

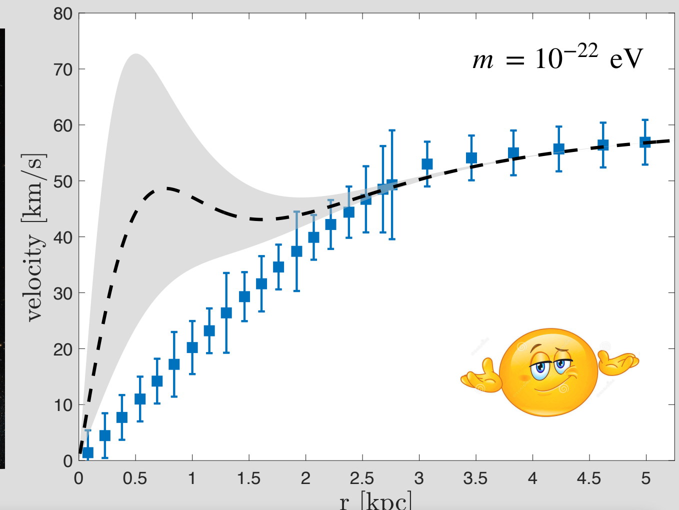
Bounds from stationary <u>Jeans modeling</u> complimentary & consistent.
(Live sims show that Jeans model is reasonable approximation *adiabatically* (e.g. Teodori 2501.07631))

E.g. Zimmerman et al 2405.20374 (Leo II dwarf) $m > 2.2 \times 10^{-21}$ eV

Blum et al 1805.00122 (low-surface-brightness disc galaxies) $m \gtrsim 10^{-21}$ eV

…





m

$5 \times 10^{-21} \rightarrow 3 \times 10^{-19}$ eV ?

8×10^{-18} eV ?

Lower bound on m from galaxies

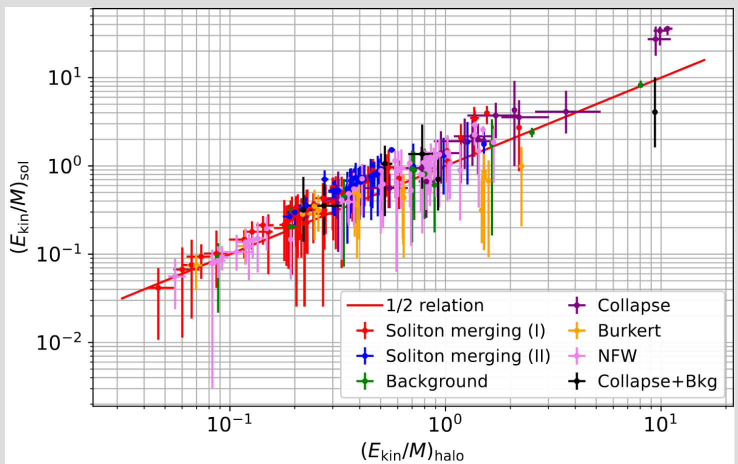
Dynamical heating may give the strongest bound. But there are many more observational tests.

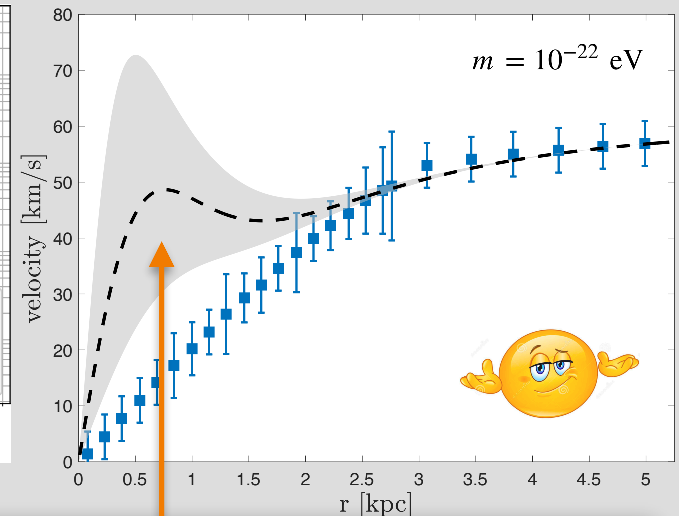
Bounds from stationary <u>Jeans modeling</u> complimentary & consistent.
(Live sims show that Jeans model is reasonable approximation *adiabatically* (e.g. Teodori 2501.07631))

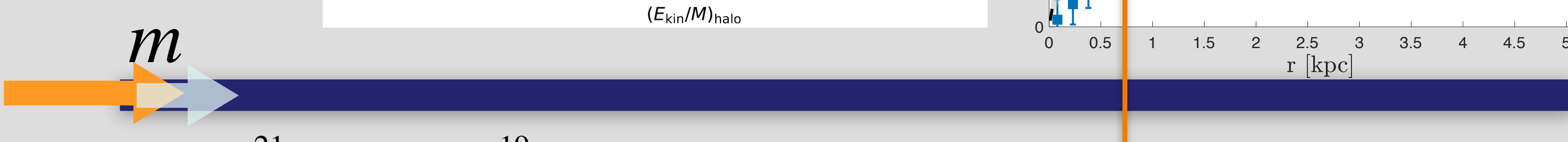
E.g. Zimmerman et al 2405.20374 (Leo II dwarf) $m > 2.2 \times 10^{-21}$ eV

Blum et al 1805.00122 (low-surface-brightness disc galaxies) $m \gtrsim 10^{-21}$ eV

…







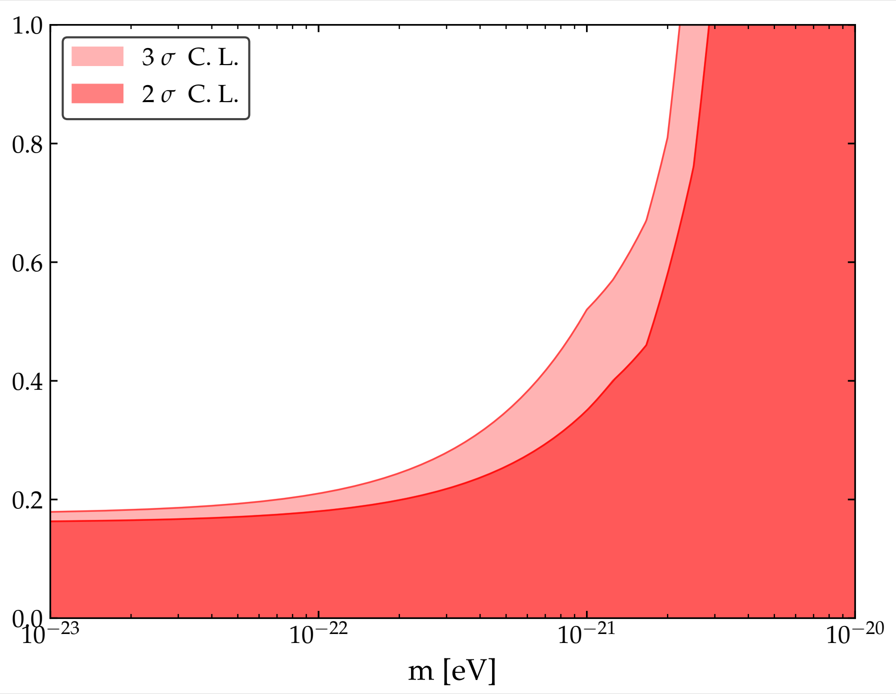
$5 \times 10^{-21} \rightarrow 3 \times 10^{-19}$ eV ?
8×10^{-18} eV ?

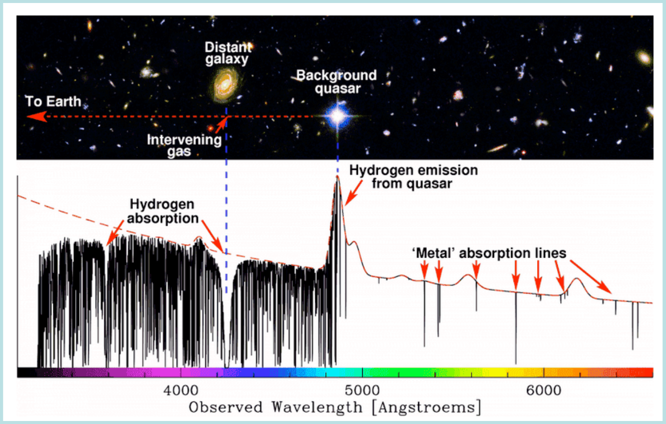
Soliton robust phenomenon (e.g. Blum et al 2504.16202)

Lower bound on m from cosmology

$\frac{\Omega_m}{\Omega_{m,obs}}$

Kobayashi et al 1708.00015 (Ly-alpha)





Also:
Hlozek et al 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)
…

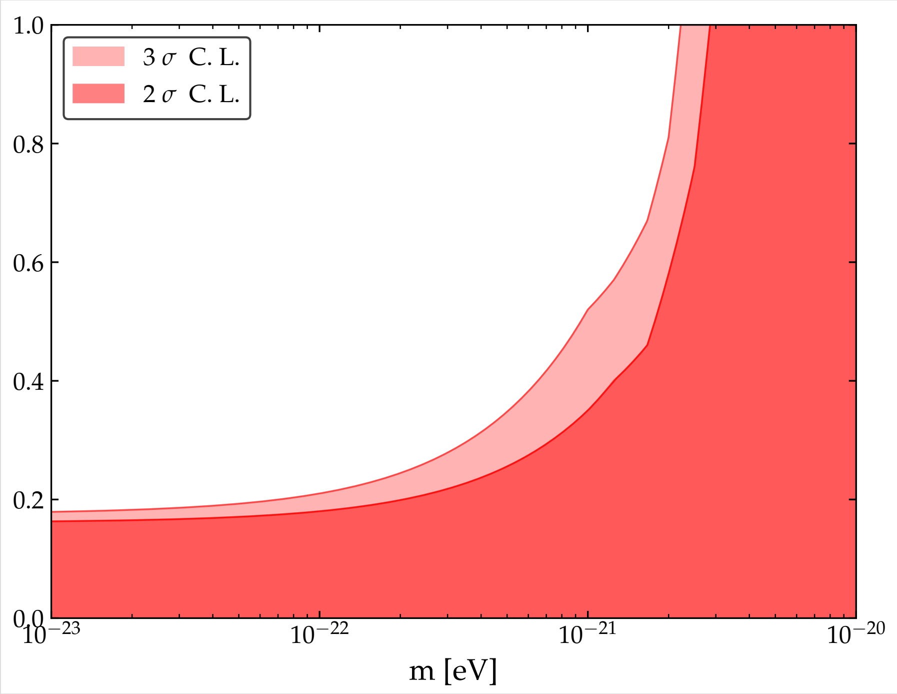
m

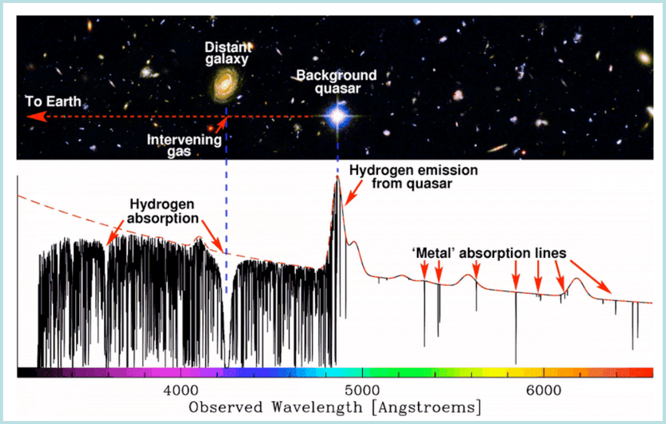
3×10^{-21} eV

Lower bound on m from cosmology

Kobayashi et al 1708.00015 (Ly-alpha)

$\frac{\Omega_m}{\Omega_{m,obs}}$





Also:
Hlozek et al 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)
…

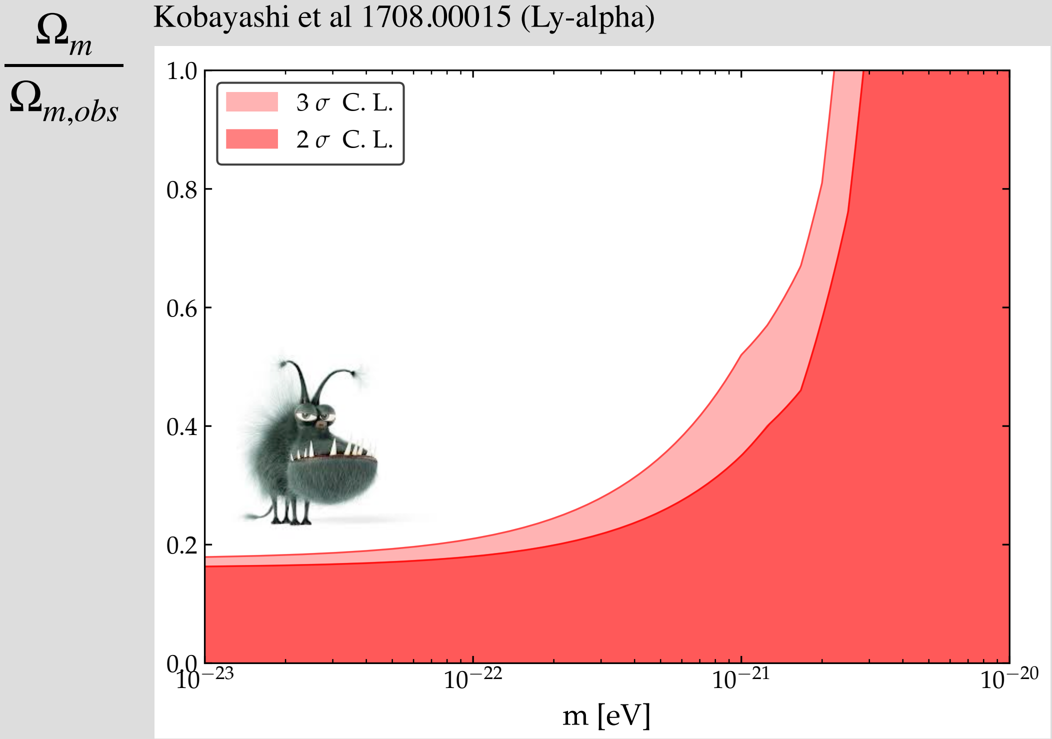
m

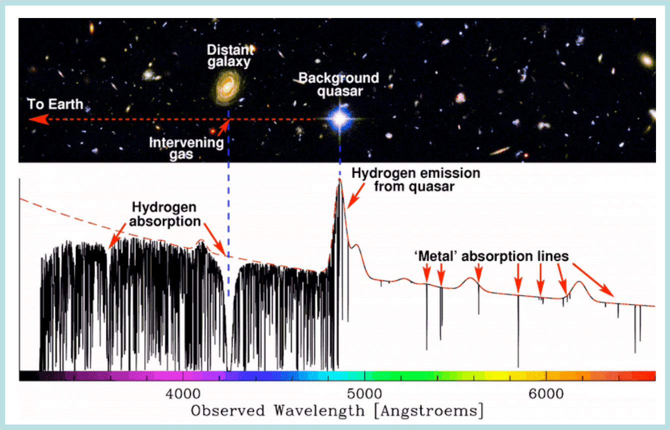
3×10^{-21} eV

Rogers & Peiris 2007.12705: $m > 2 \times 10^{-20}$ eV

A bit of WISPful thinking

Kobayashi et al 1708.00015 (Ly-alpha)





Also:
Hlozek et al 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)
…

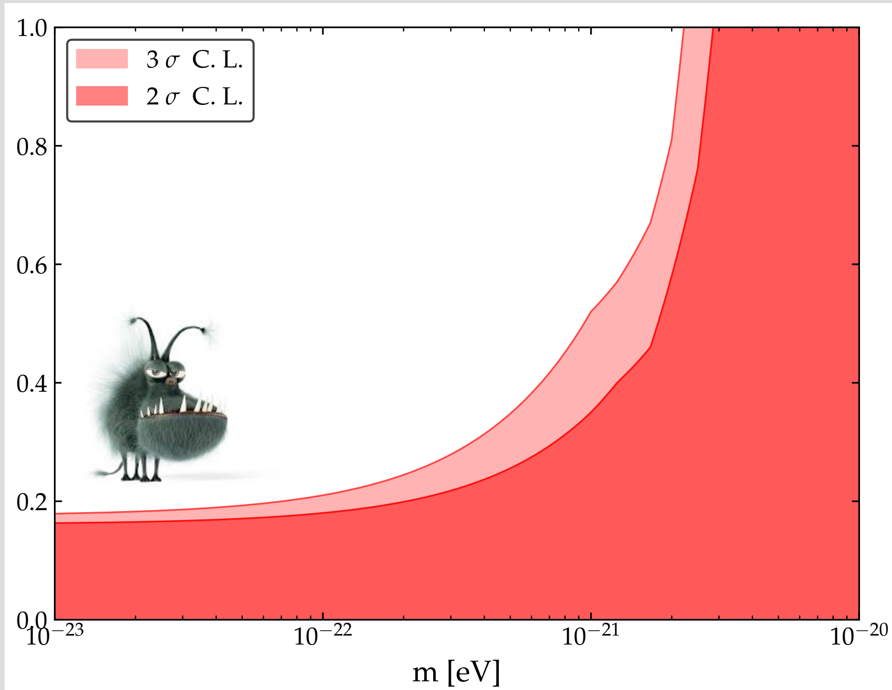
We have strong bounds on ULDM being all of DM.

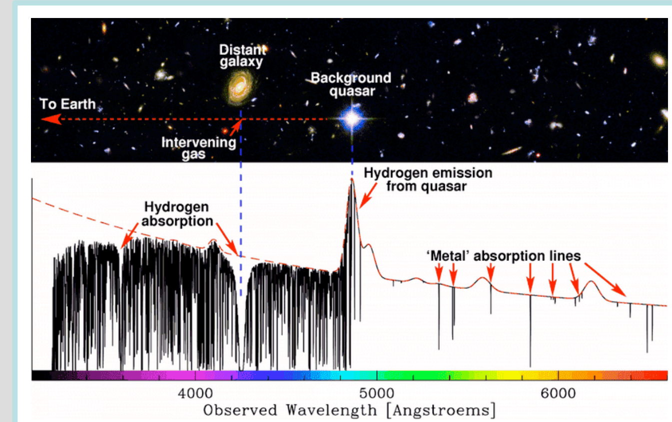
But what about just a fraction? Aka **Axiverse** (Arvanitaki et al 0905.4720)
Here there is plenty of room for a *discovery*.

A bit of WISPful thinking

Kobayashi et al 1708.00015 (Ly-alpha)

$$\frac{\Omega_m}{\Omega_{m,obs}}$$



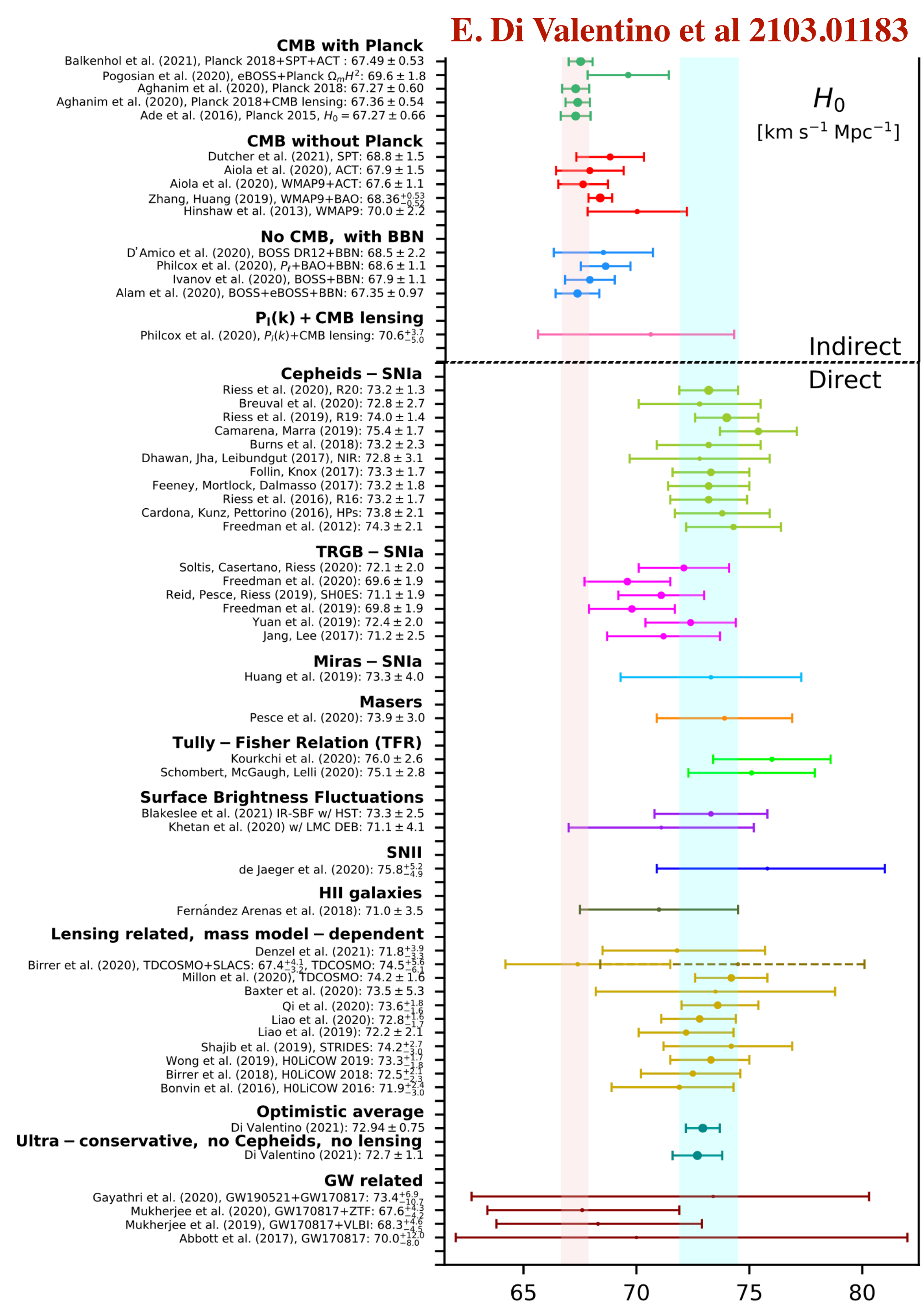


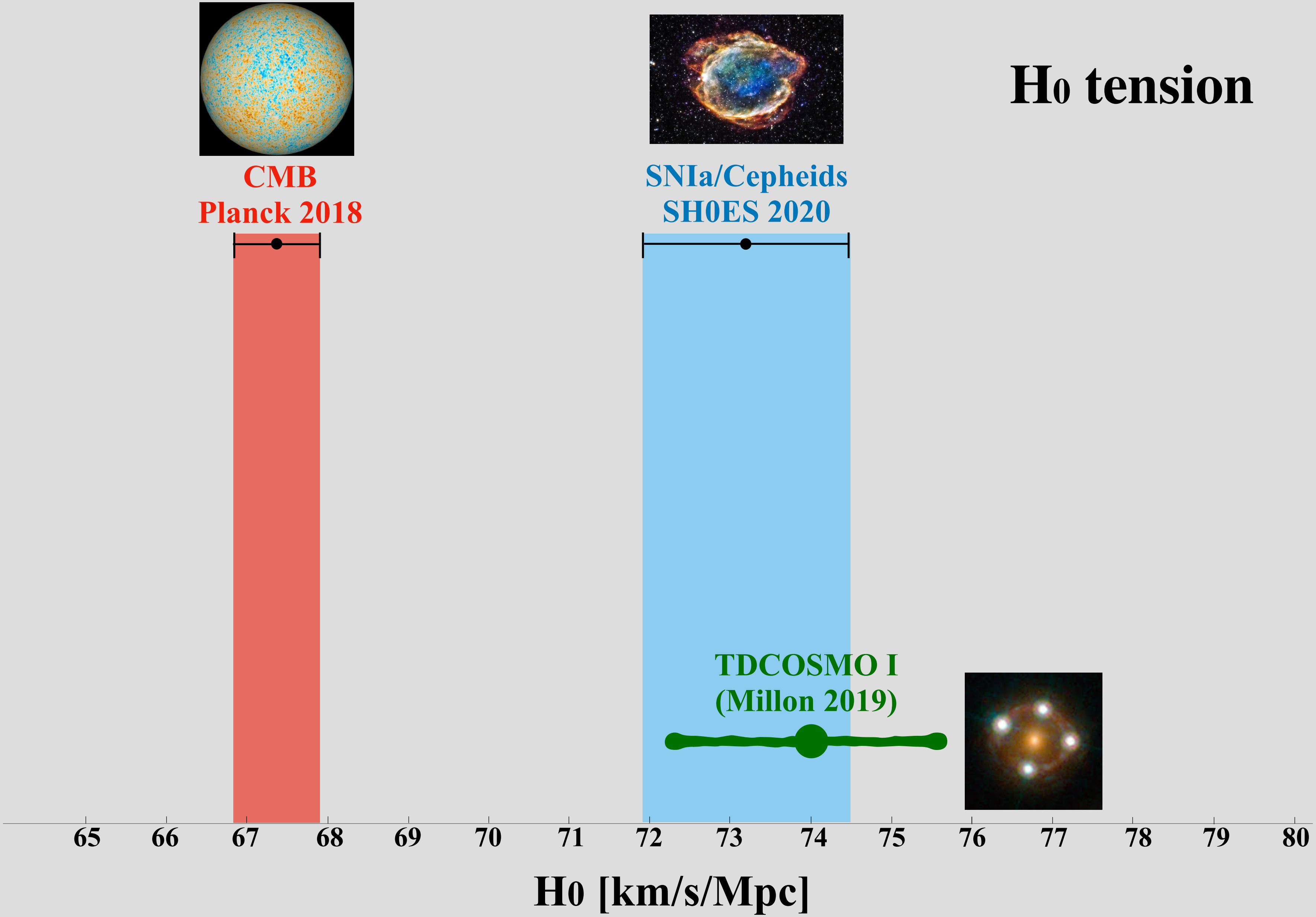
Also:
Hlozek et al 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)
…

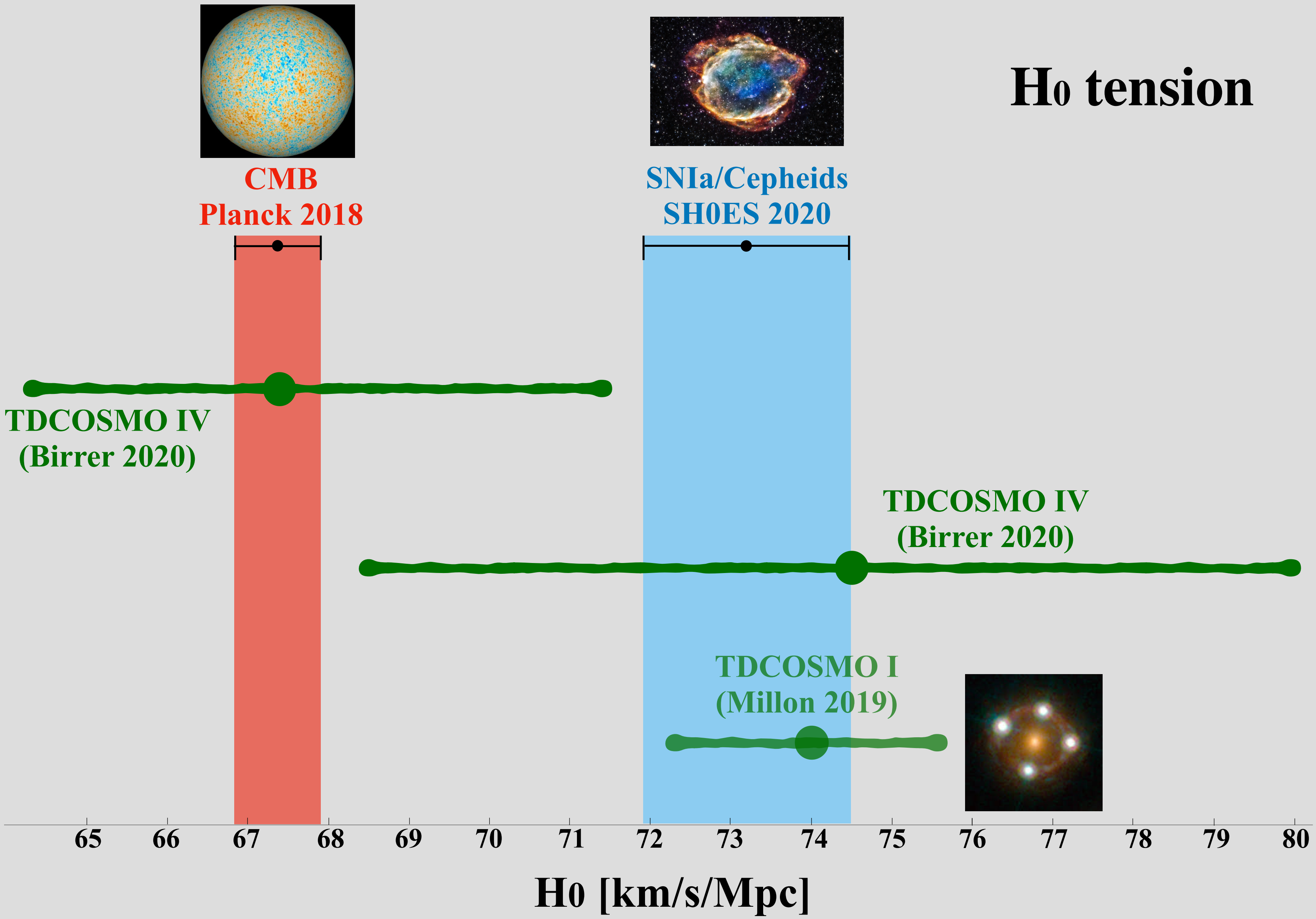
Vacuum misalignment (pre-inflationary)

$$\frac{\Omega_m}{\Omega_{m,obs}} \approx \left(\frac{m}{10^{-21}\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{10^{17}\ \mathrm{GeV}}\right)^{2} \approx 0.1 \left(\frac{m}{10^{-25}\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{3\times 10^{17}\ \mathrm{GeV}}\right)^{2}$$

H_0 tension


E. Di Valentino et al 2103.01183
H_0
[km s^{-1} Mpc^{-1}]
CMB with Planck
Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.53
Pogosian et al. (2020), eBOSS+Planck $\Omega_m H^2$: 69.6 ± 1.8
Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60
Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54
Ade et al. (2016), Planck 2015, H_0 = 67.27 ± 0.66
CMB without Planck
Dutcher et al. (2021), SPT: 68.8 ± 1.5
Aiola et al. (2020), ACT: 67.9 ± 1.5
Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1
Zhang, Huang (2019), WMAP9+BAO: $68.36^{+0.53}_{-0.52}$
Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2
No CMB, with BBN
D'Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2
Philcox et al. (2020), P_l+BAO+BBN: 68.6 ± 1.1
Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1
Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97
$P_l(k)$ + CMB lensing
Philcox et al. (2020), $P_l(k)$+CMB lensing: $70.6^{+3.7}_{-5.0}$
Indirect
Direct
Cepheids – SNIa
Riess et al. (2020), R20: 73.2 ± 1.3
Breuval et al. (2020): 72.8 ± 2.7
Riess et al. (2019), R19: 74.0 ± 1.4
Camarena, Marra (2019): 75.4 ± 1.7
Burns et al. (2018): 73.2 ± 2.3
Dhawan, Jha, Leibundgut (2017), NIR: 72.8 ± 3.1
Follin, Knox (2017): 73.3 ± 1.7
Feeney, Mortlock, Dalmasso (2017): 73.2 ± 1.8
Riess et al. (2016), R16: 73.2 ± 1.7
Cardona, Kunz, Pettorino (2016), HPs: 73.8 ± 2.1
Freedman et al. (2012): 74.3 ± 2.1
TRGB – SNIa
Soltis, Casertano, Riess (2020): 72.1 ± 2.0
Freedman et al. (2020): 69.6 ± 1.9
Reid, Pesce, Riess (2019), SH0ES: 71.1 ± 1.9
Freedman et al. (2019): 69.8 ± 1.9
Yuan et al. (2019): 72.4 ± 2.0
Jang, Lee (2017): 71.2 ± 2.5
Miras – SNIa
Huang et al. (2019): 73.3 ± 4.0
Masers
Pesce et al. (2020): 73.9 ± 3.0
Tully – Fisher Relation (TFR)
Kourkchi et al. (2020): 76.0 ± 2.6
Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8
Surface Brightness Fluctuations
Blakeslee et al. (2021) IR-SBF w/ HST: 73.3 ± 2.5
Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1
SNII
de Jaeger et al. (2020): $75.8^{+5.2}_{-4.9}$
HII galaxies
Fernández Arenas et al. (2018): 71.0 ± 3.5
Lensing related, mass model – dependent
Denzel et al. (2021): $71.8^{+3.9}_{-3.3}$
Birrer et al. (2020), TDCOSMO+SLACS: $67.4^{+4.1}_{-3.2}$, TDCOSMO: $74.5^{+5.6}_{-6.1}$
Millon et al. (2020), TDCOSMO: 74.2 ± 1.6
Baxter et al. (2020): 73.5 ± 5.3
Qi et al. (2020): $73.6^{+1.8}_{-1.6}$
Liao et al. (2020): $72.8^{+1.6}_{-1.7}$
Liao et al. (2019): 72.2 ± 2.1
Shajib et al. (2019), STRIDES: $74.2^{+2.7}_{-3.0}$
Wong et al. (2019), H0LiCOW 2019: $73.3^{+1.7}_{-1.8}$
Birrer et al. (2018), H0LiCOW 2018: $72.5^{+2.1}_{-2.3}$
Bonvin et al. (2016), H0LiCOW 2016: $71.9^{+2.4}_{-3.0}$
Optimistic average
Di Valentino (2021): 72.94 ± 0.75
Ultra – conservative, no Cepheids, no lensing
Di Valentino (2021): 72.7 ± 1.1
GW related
Gayathri et al. (2020), GW190521+GW170817: $73.4^{+6.9}_{-10.7}$
Mukherjee et al. (2020), GW170817+ZTF: $67.6^{+4.3}_{-4.2}$
Mukherjee et al. (2019), GW170817+VLBI: $68.3^{+4.6}_{-4.5}$
Abbott et al. (2017), GW170817: $70.0^{+12.0}_{-8.0}$
65
70
75
80


H0 tension
CMB
Planck 2018
SNIa/Cepheids
SH0ES 2020
TDCOSMO I
(Millon 2019)
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
H0 [km/s/Mpc]

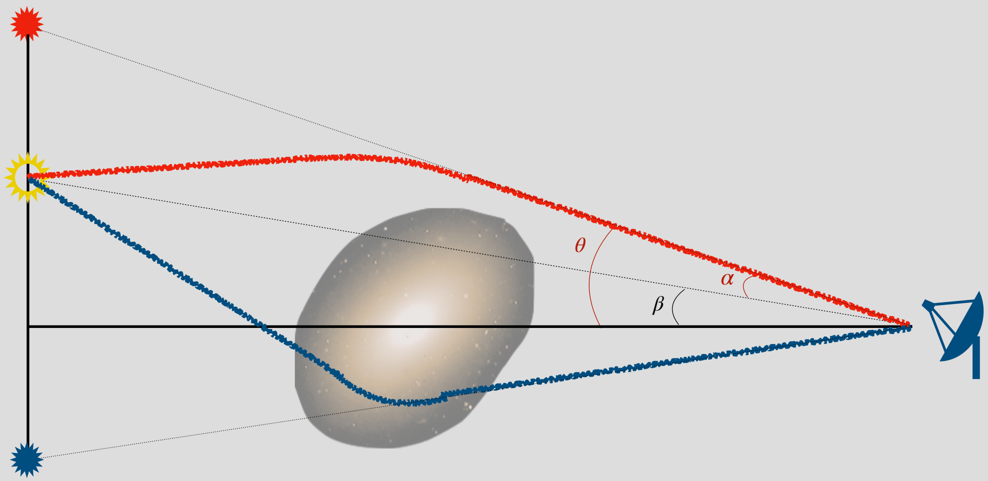


H0 tension
CMB
Planck 2018
SNIa/Cepheids
SH0ES 2020
TDCOSMO IV
(Birrer 2020)
TDCOSMO IV
(Birrer 2020)
TDCOSMO I
(Millon 2019)
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
H0 [km/s/Mpc]

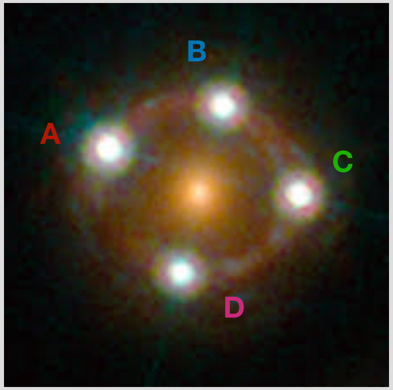
Time delay cosmography:

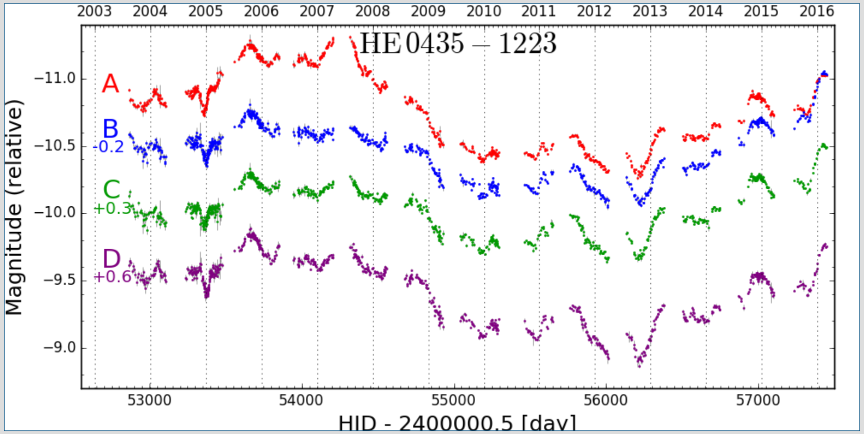
TDCOSMO
http://www.tdcosmo.org/projects.html

- H0LiCOW
- COSMOGRAIL
- STRIDES
- SHARP
- COSMICLENS



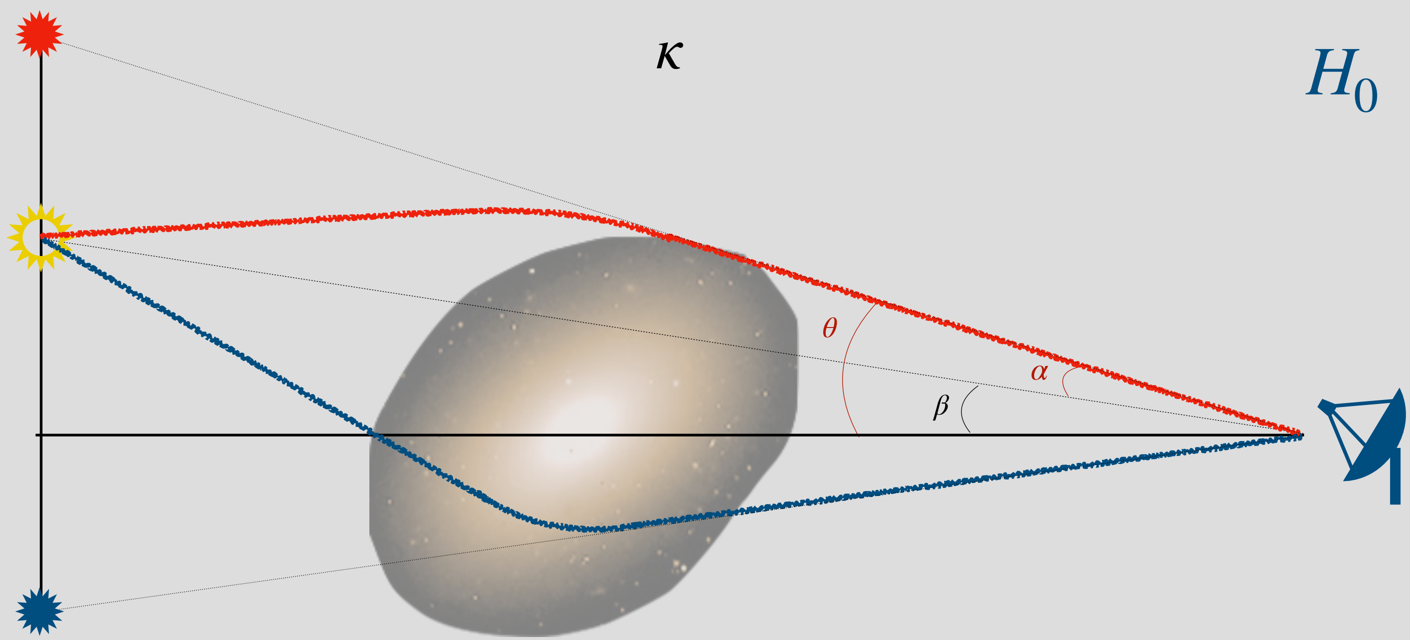
Bonvin et al, 2016

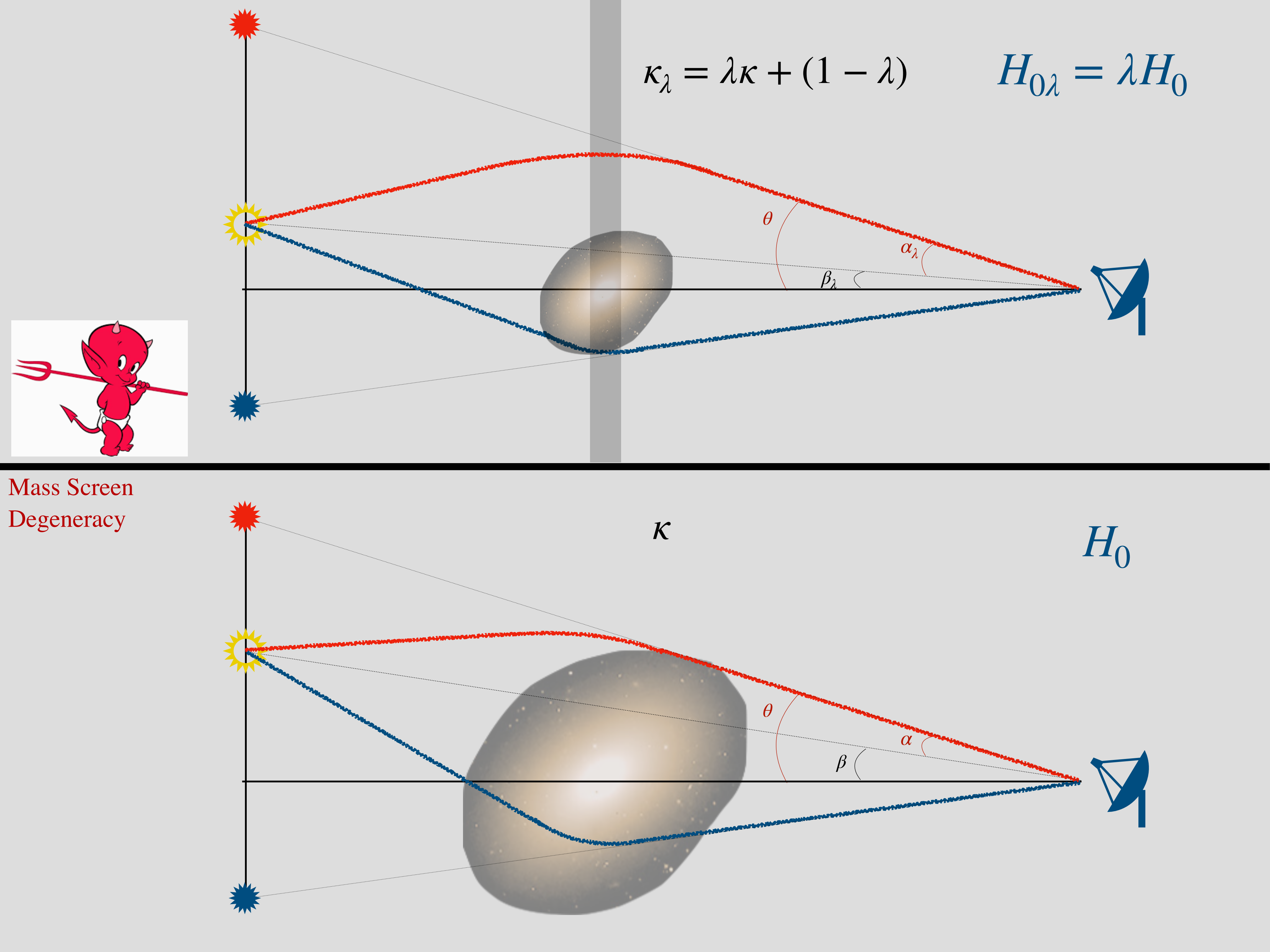




$$\vec{\theta} = \vec{\beta} + \vec{\alpha}$$
$$= \vec{\beta}_\lambda + \vec{\alpha}_\lambda$$
$$= \lambda\vec{\beta} + \lambda\vec{\alpha} + (1-\lambda)\vec{\theta}$$
$$= \lambda(\vec{\beta} + \vec{\alpha} - \vec{\theta}) + \vec{\theta}$$
$$= \vec{\theta}$$

Mass Screen Degeneracy

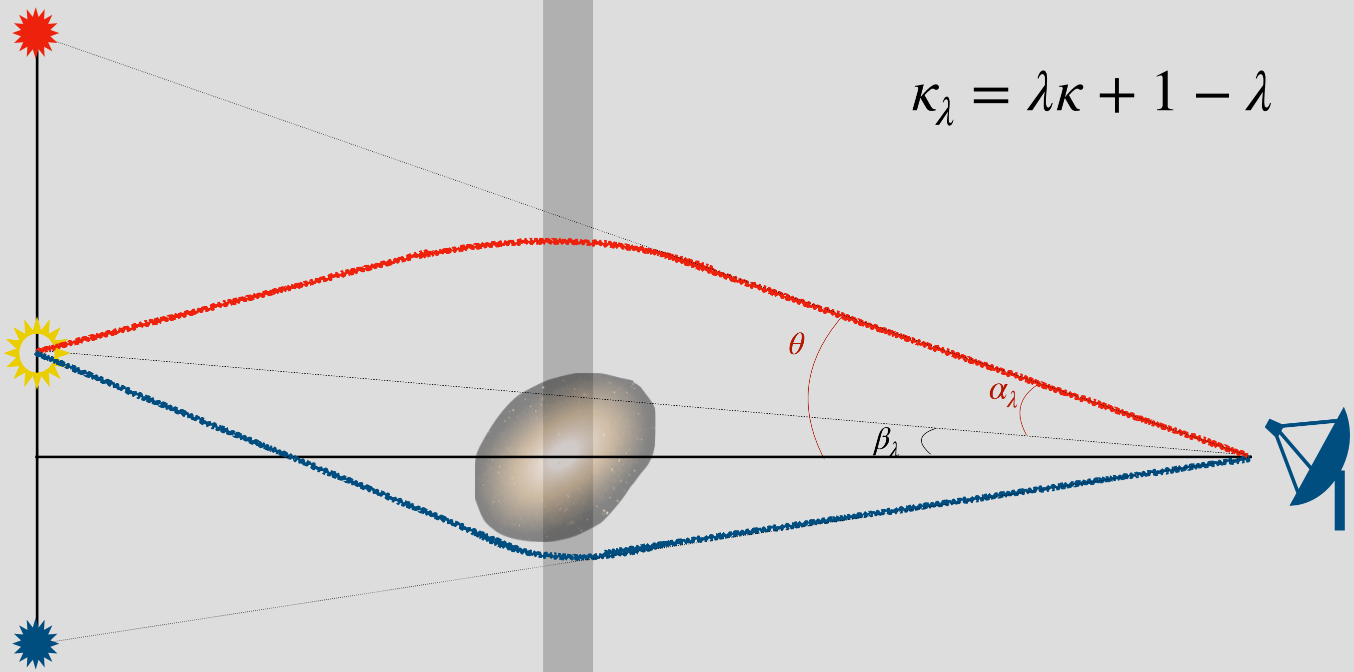




$\kappa_\lambda = \lambda\kappa + (1 - \lambda)$
$H_{0\lambda} = \lambda H_0$
θ
α_λ
β_λ
Mass Screen
Degeneracy
κ
H_0
θ
α
β

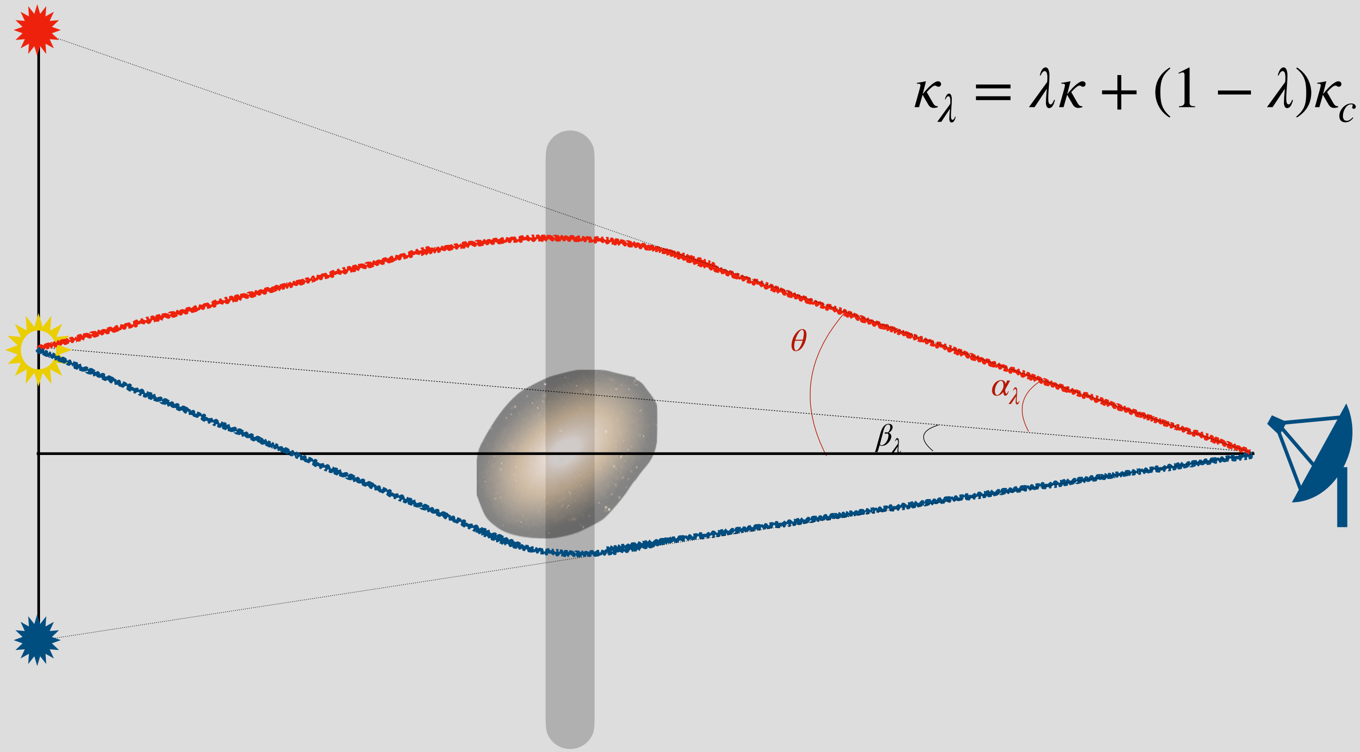
Schneider & Sluse 2013
Blum, Castorina, Simonovic 2020

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



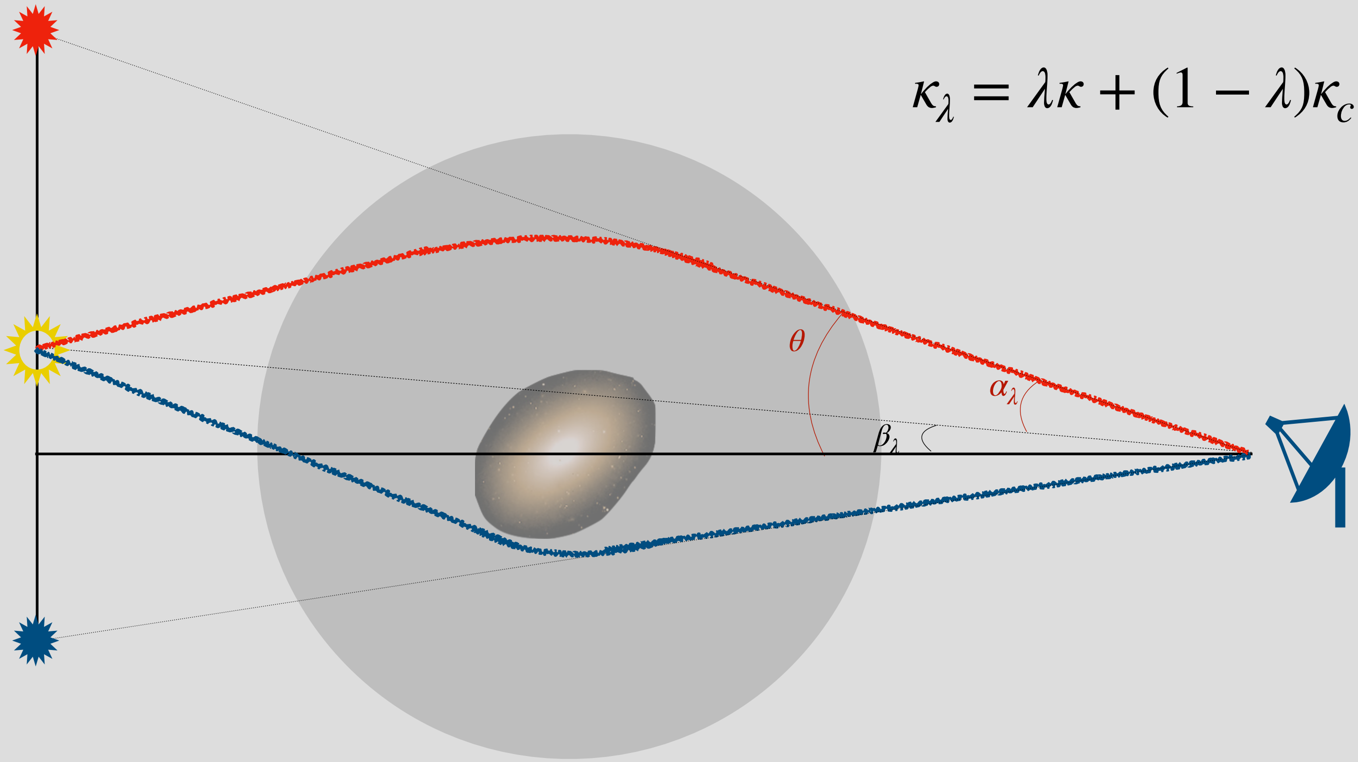
Schneider & Sluse 2013
Blum, Castorina, Simonovic 2020

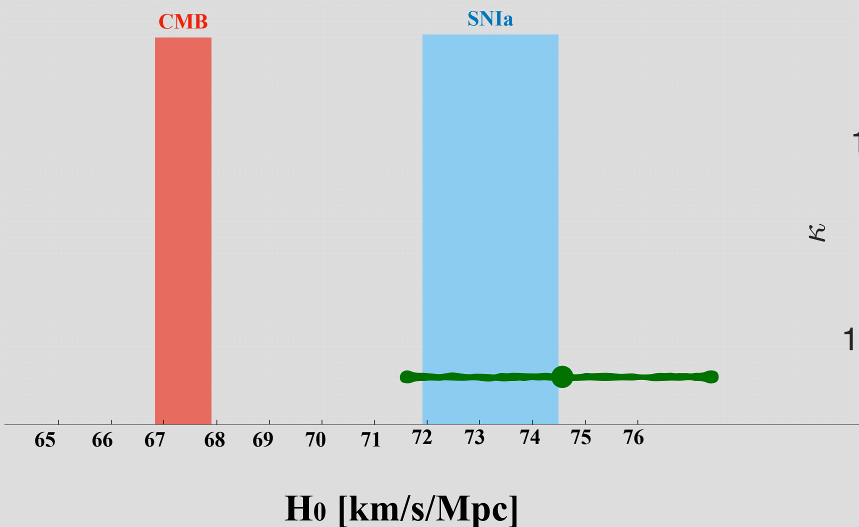
$$\kappa_\lambda = \lambda\kappa + (1-\lambda)\kappa_c$$

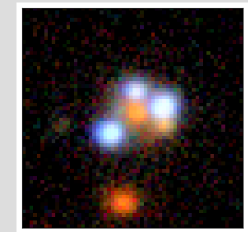


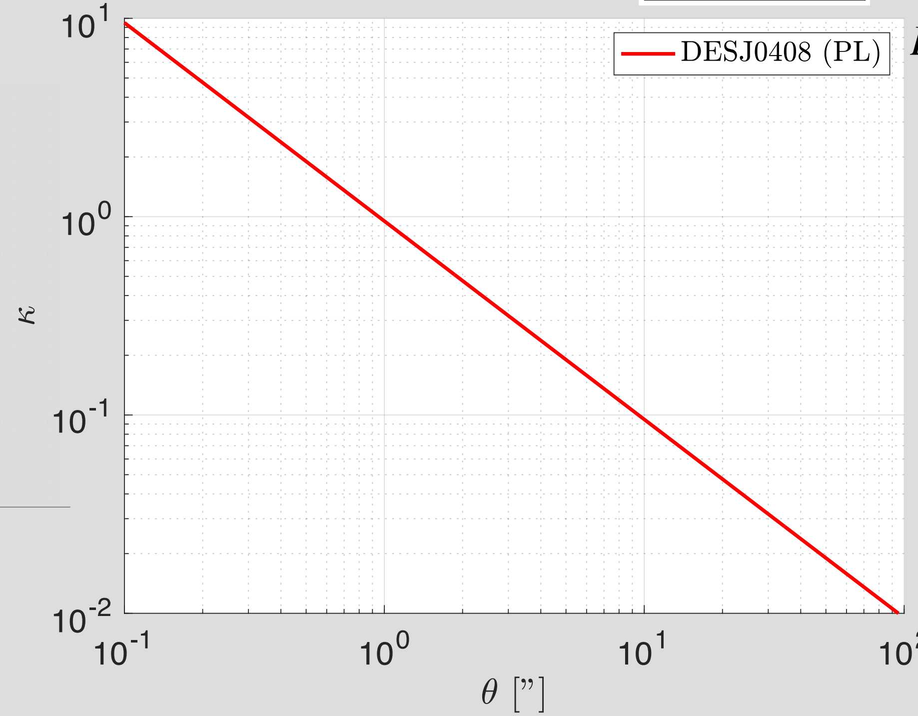
Schneider & Sluse 2013
Blum, Castorina, Simonovic 2020

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

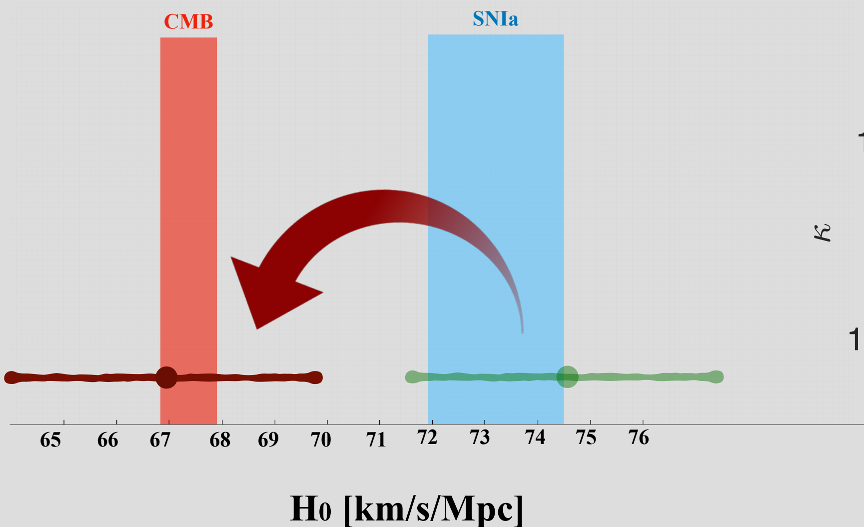


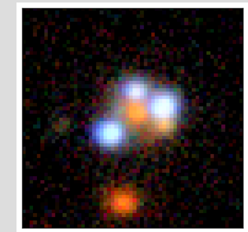

CMB
SNIa
65
66
67
68
69
70
71
72
73
74
75
76
H0 [km/s/Mpc]

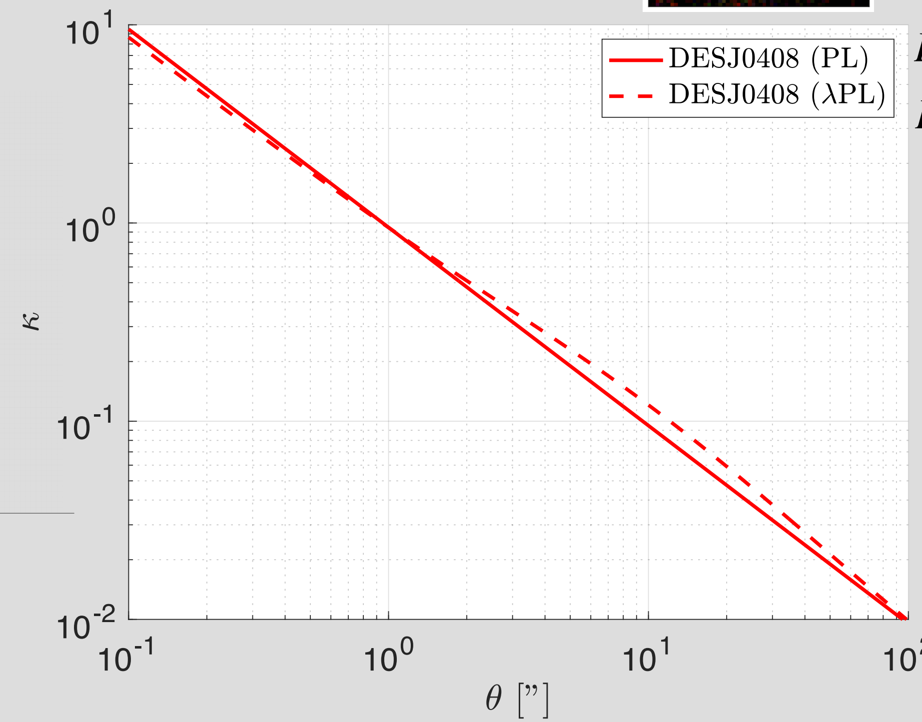



DESJ0408 (PL)
10^{1}
10^{0}
10^{-1}
10^{-2}
κ
10^{-1}
10^{0}
10^{1}
10^{2}
θ ["]

$H_0 = 74.6$

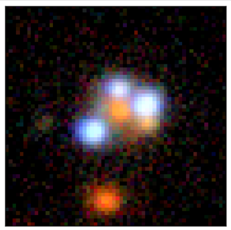

CMB
SNIa
65
66
67
68
69
70
71
72
73
74
75
76
H0 [km/s/Mpc]

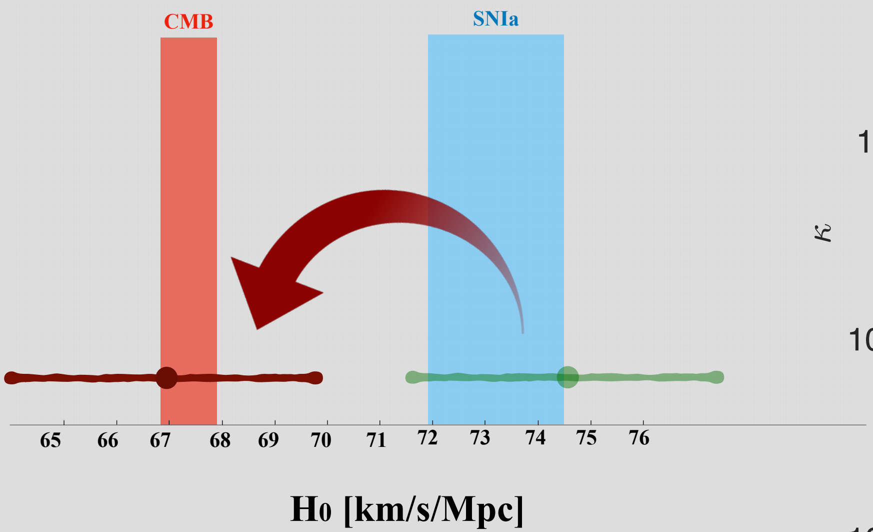


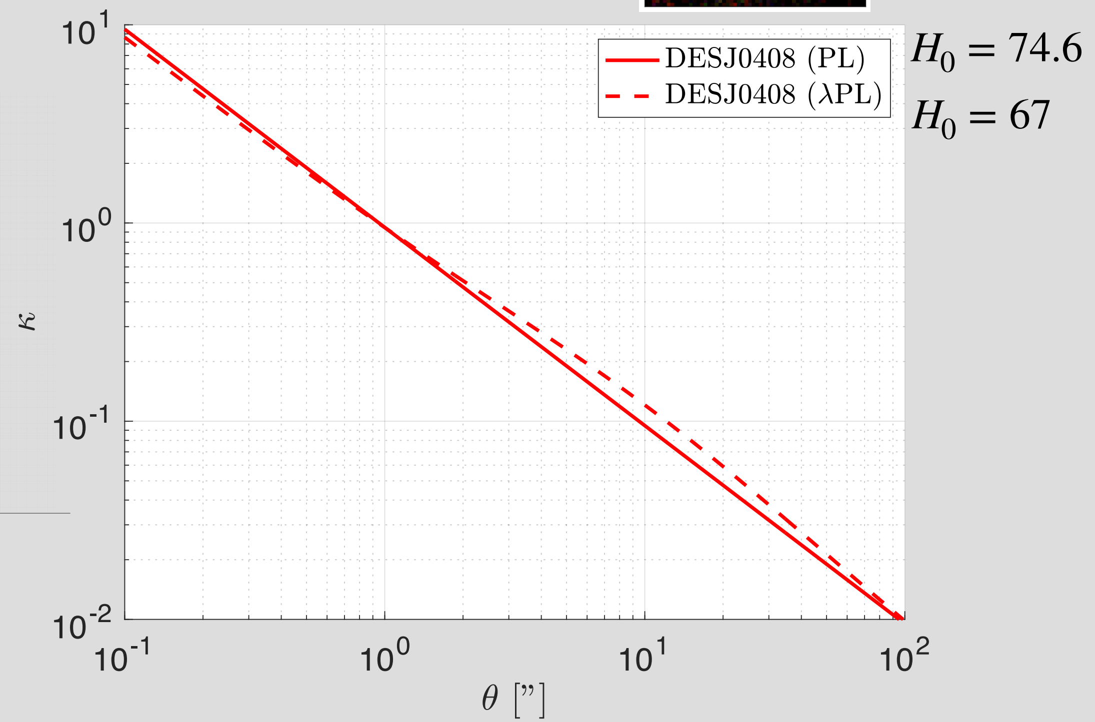

DESJ0408 (PL)
DESJ0408 (λPL)
10^{1}
10^{0}
10^{-1}
10^{-2}
κ
10^{-1}
10^{0}
10^{1}
10^{2}
θ ["]

$H_0 = 74.6$

$H_0 = 67$



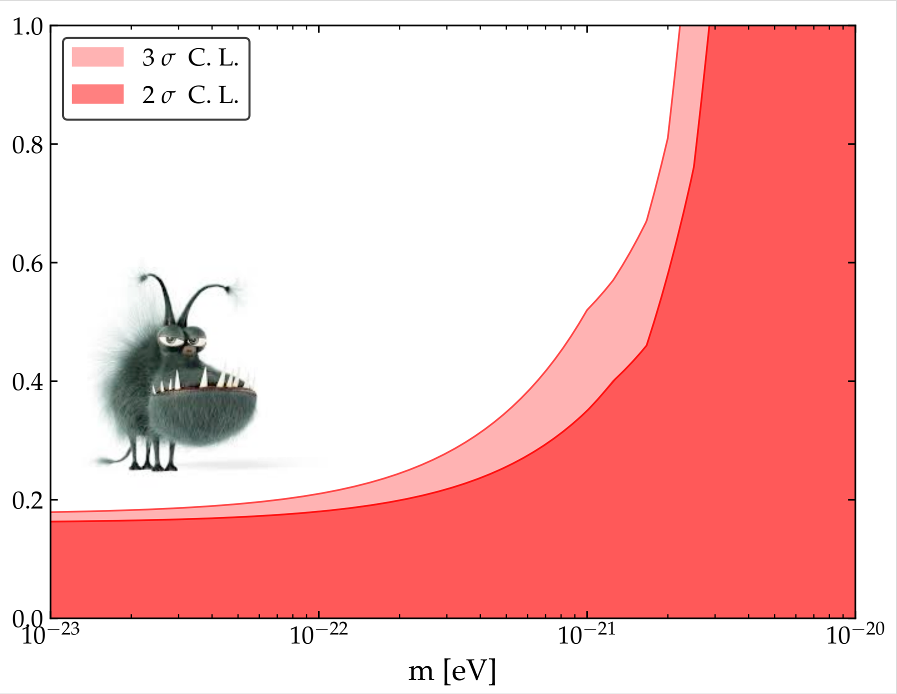




A sub-dominant, extended, core *component* in massive galaxies — can explain the lensing H0 tension.

What can produce such a core?…

$$\frac{\Omega_m}{\Omega_{m,obs}}$$



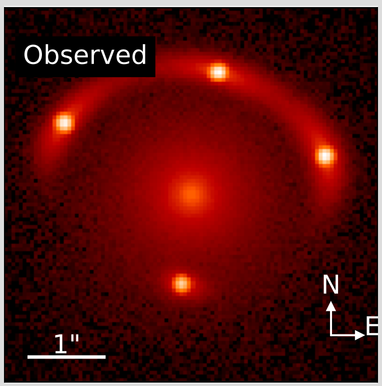
Vacuum misalignment (pre-inflationary)

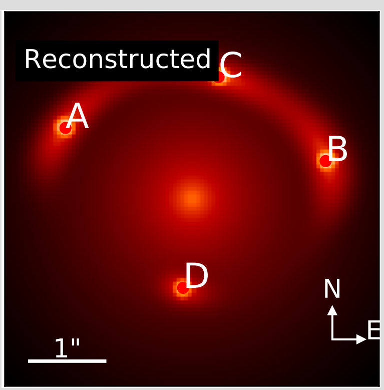
$$\frac{\Omega_m}{\Omega_{m,obs}} \approx \left(\frac{m}{10^{-21}\ \text{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{10^{17}\ \text{GeV}}\right)^{2} \approx 0.1 \left(\frac{m}{10^{-25}\ \text{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{3\times 10^{17}\ \text{GeV}}\right)^{2}$$

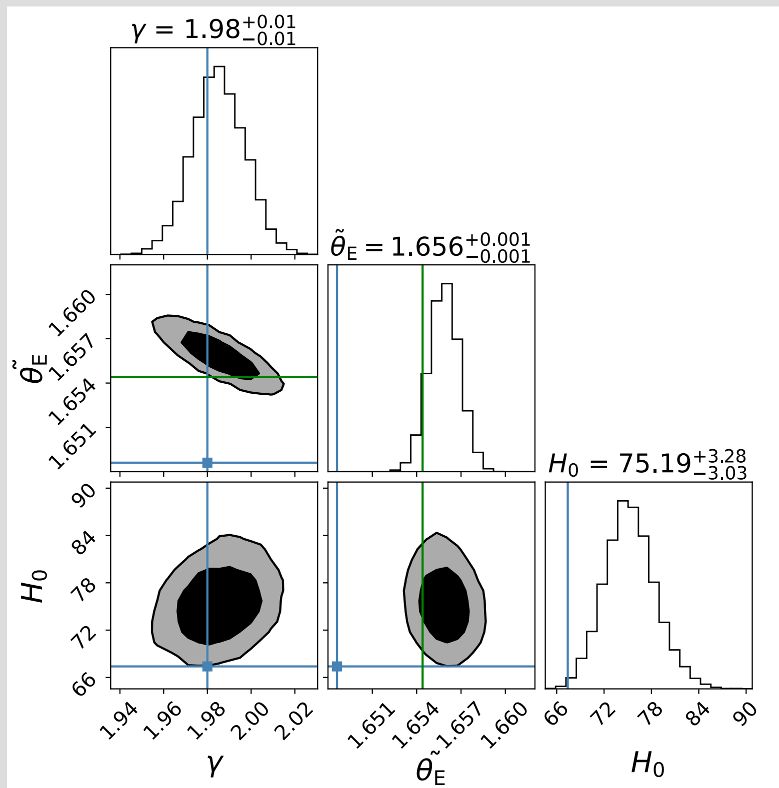
AxionH0graphy !

Teodori & Blum, 2105.10873, 2409.04134

A sub-dominant component of ULDM would dynamically condense around massive galaxies.







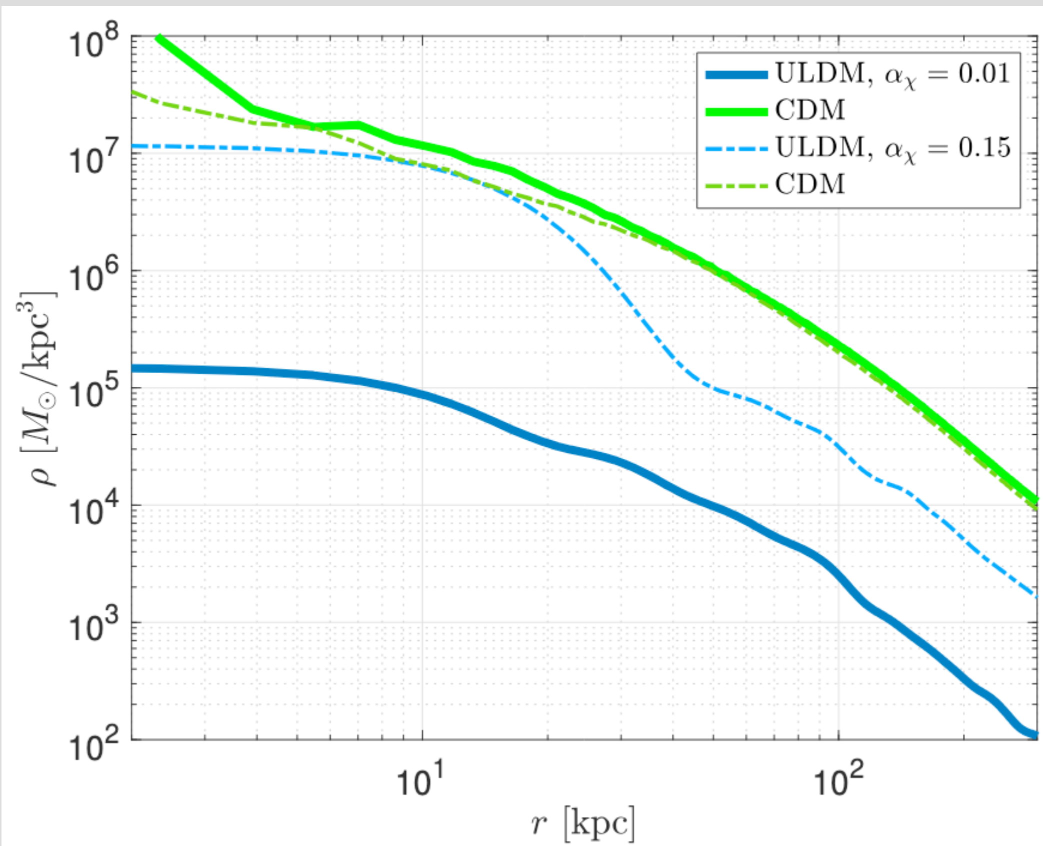
Mock inference using pure power-low model.

Truth: H0=67.4 km/s/Mpc, and a 10% core!

m

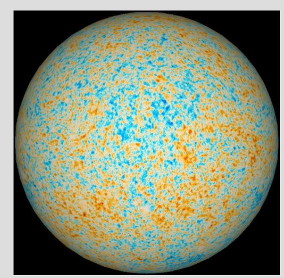
Simulations

Teodori, Blum, 2409.04134 AxionH0graphy



If a small fraction (~10%) of DM is ULDM, this may first be seen as a small, but potentially significant bias in quasar time-delay measurements of H0.

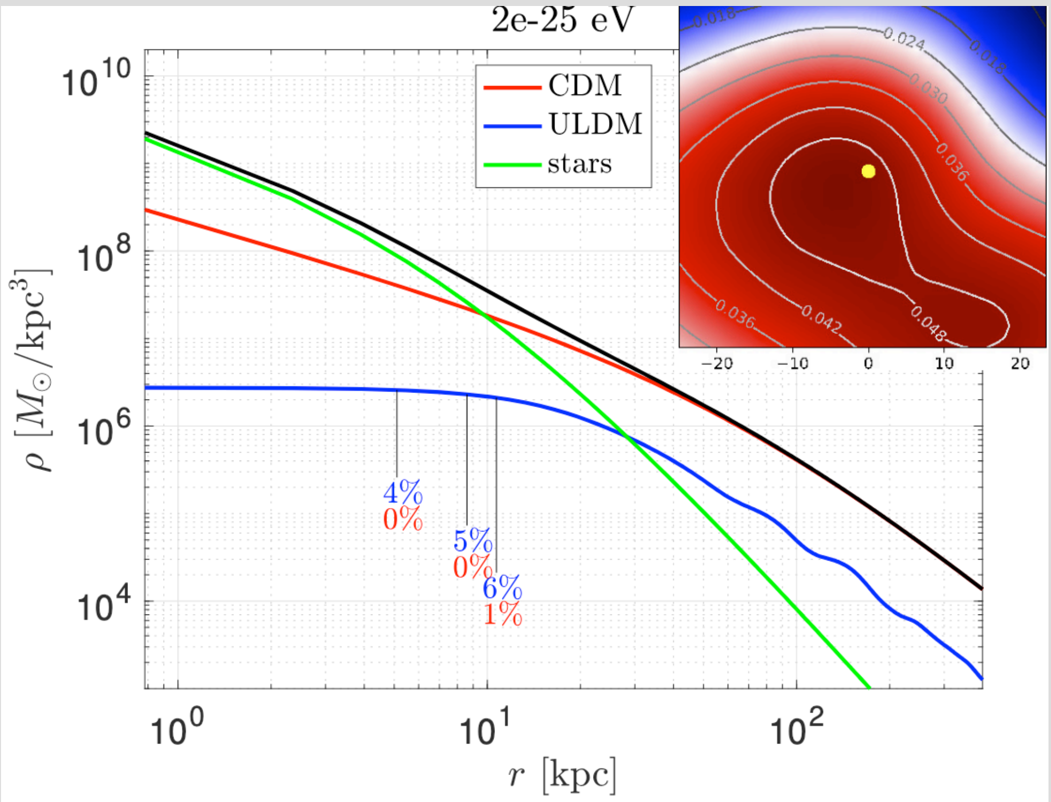
Needs H0 prior!
e.g. SNIa, or CMB.


+


m

Simulations

Teodori, Blum, 2409.04134 AxionH0graphy



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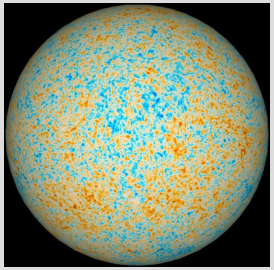
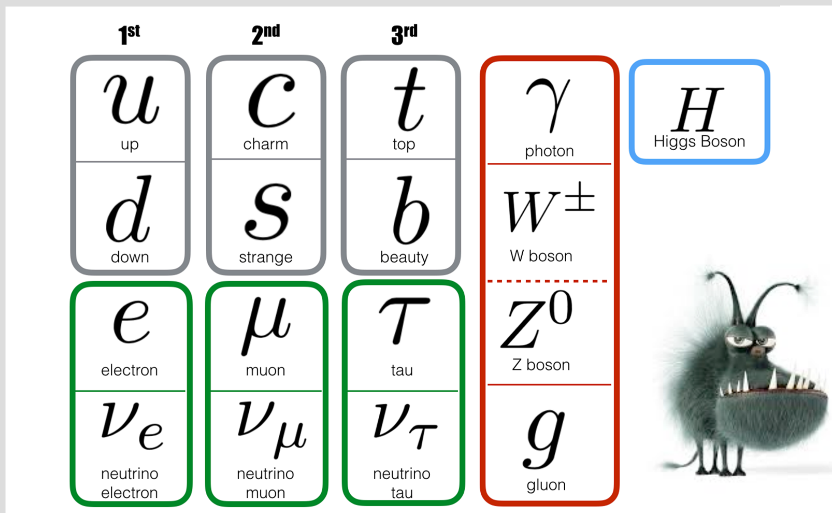


+

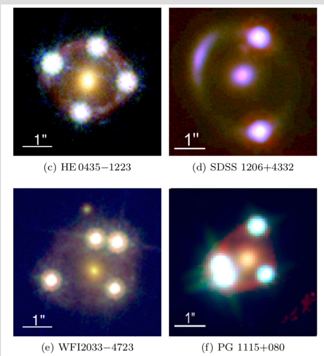
Summary

Summary

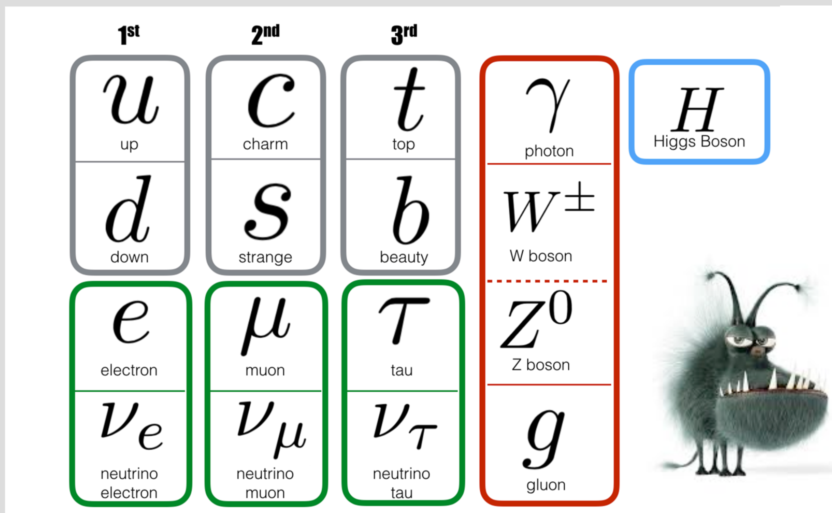
WISPs

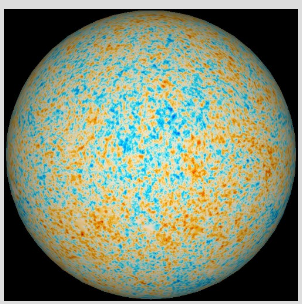


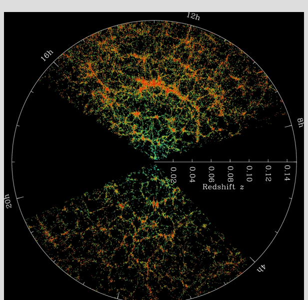

Gravitation alone
m
$\sim 10^{-20}$ eV
$\sim 10^{-17}$ eV ?

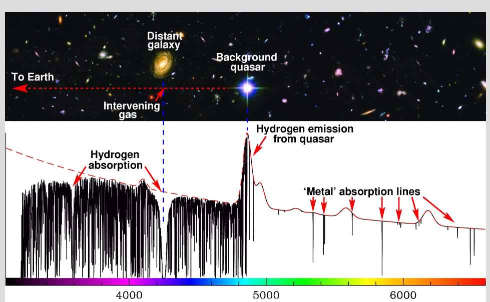

(c) HE 0435−1223
(d) SDSS 1206+4332
(e) WFI2033−4723
(f) PG 1115+080

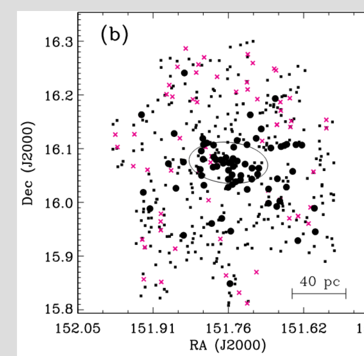
WISPs

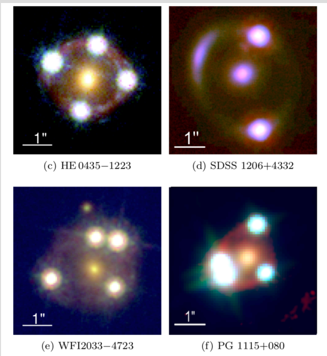

1st
2nd
3rd
u up
c charm
t top
d down
s strange
b beauty
e electron
μ muon
τ tau
νe neutrino electron
νμ neutrino muon
ντ neutrino tau
γ photon
W± W boson
Z0 Z boson
g gluon
H Higgs Boson



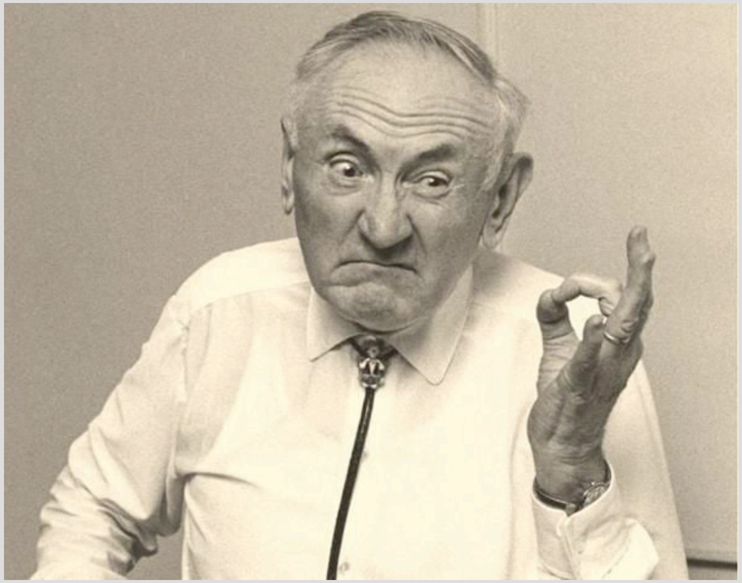

Redshift z

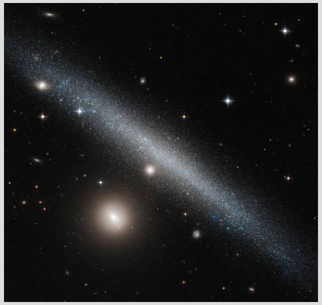

Distant galaxy
Background quasar
To Earth
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
'Metal' absorption lines
4000
5000
6000

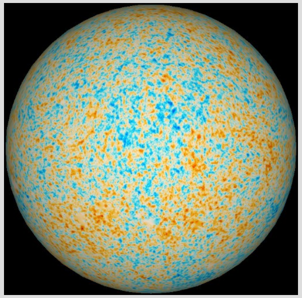

(b)
Dec (J2000)
RA (J2000)
40 pc
16.3
16.2
16.1
16.0
15.9
15.8
152.05
151.91
151.76
151.62

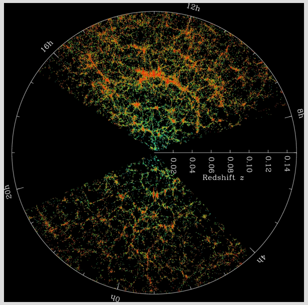


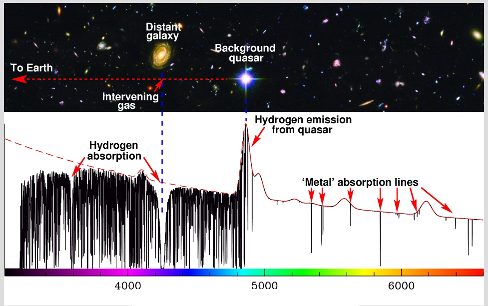
so far, nada?



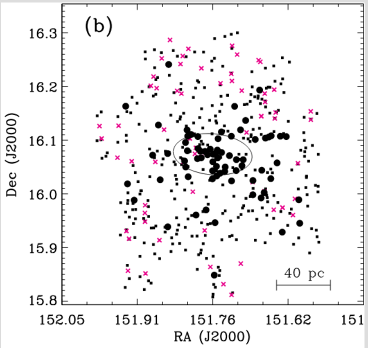








Thank You!



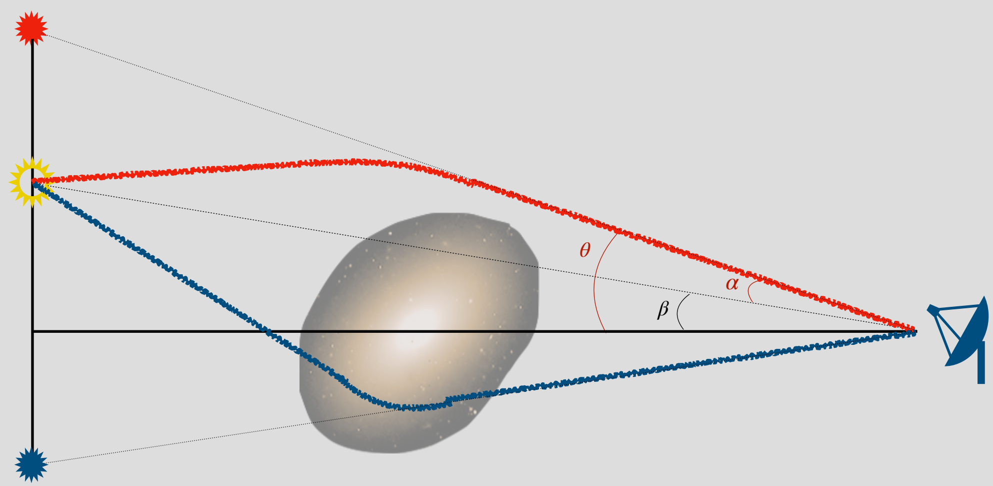
Xtra

Time delay cosmography:

1. From the image, reconstruct a model $\kappa(\theta),\ \beta$
2. Given the model and Δt_{ij}, extract $\mathscr{D} \propto 1/H_0$

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

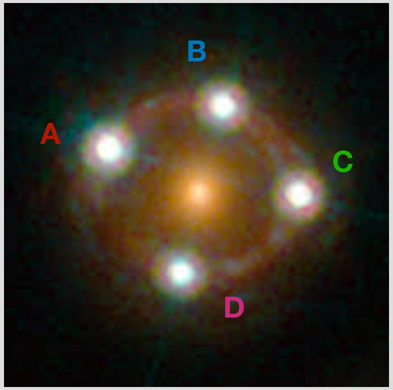
- H0LiCOW
- COSMOGRAIL
- STRIDES
- SHARP
- COSMICLENS

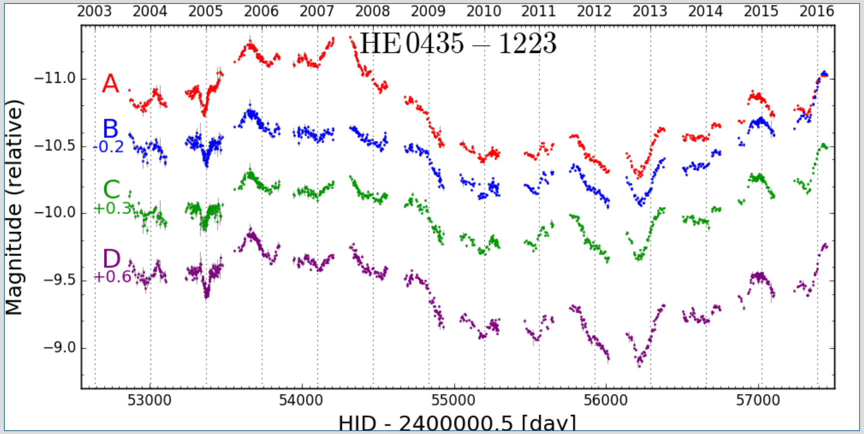


Bonvin et al, 2016

Observables:

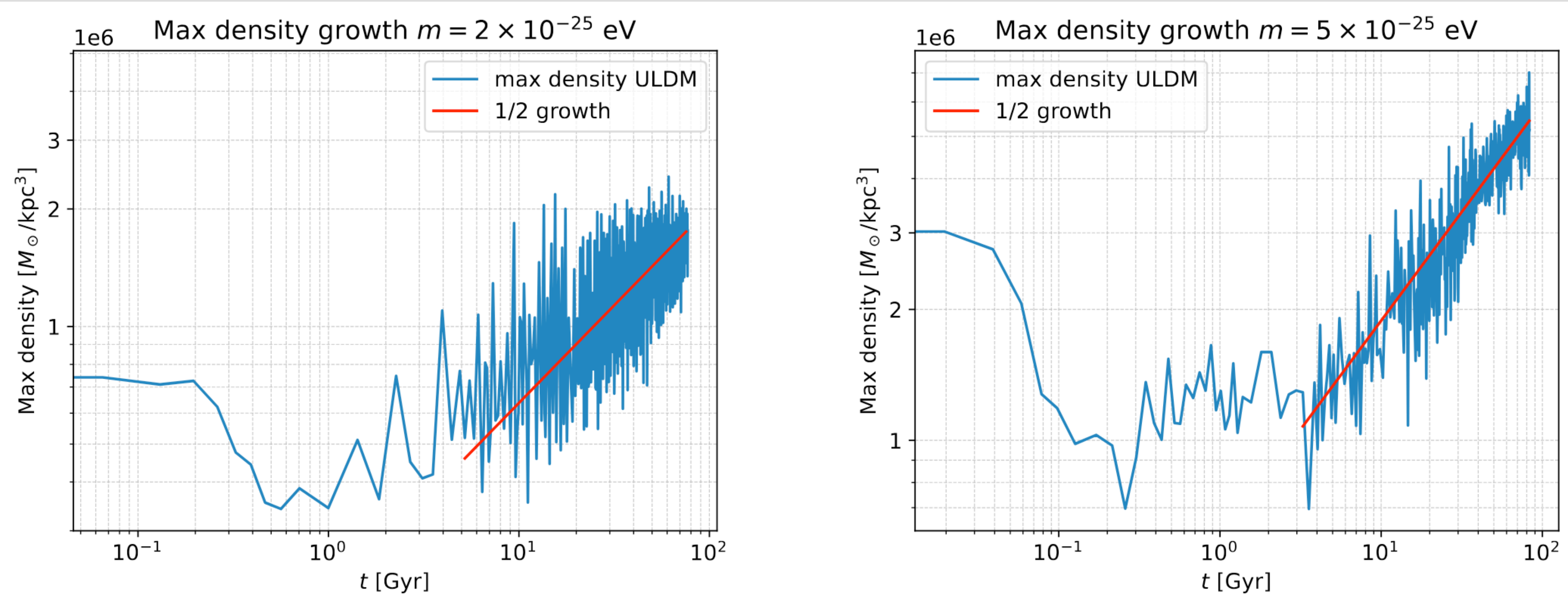
- Extended source image
- Time delay Δt_{ij}

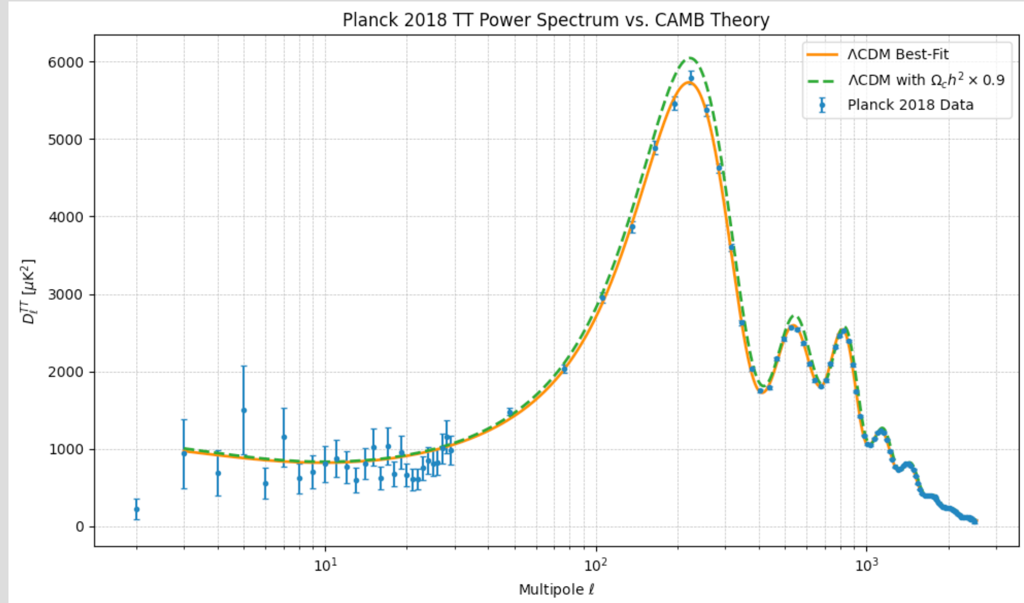




Simulations

Teodori, Blum, 2409.04134 AxionH0graphy





Copy-paste to Jupyter nb with access to internet:

```
# Optional: Install CAMB if not already installed
!pip install camb

import numpy as np
import matplotlib.pyplot as plt
import requests
from io import StringIO
import camb
from camb import model, initialpower

# URLs for full and binned TT spectrum
urls = {
    "full": "https://irsa.ipac.caltech.edu/data/Planck/release_3/ancillary-data/cosmoparams/COM_PowerSpect_CMB-TT-full_R3.01.txt",
    "binned": "https://irsa.ipac.caltech.edu/data/Planck/release_3/ancillary-data/cosmoparams/COM_PowerSpect_CMB-TT-binned_R3.01.txt"
}

# Function to download and parse Planck data
def fetch_planck_tt_data(url):
    r = requests.get(url)
    r.raise_for_status()
    data = np.genfromtxt(StringIO(r.text))
    ell, Dl, err = data[:, 0], data[:, 1], data[:, 2]
    return ell, Dl, err

# Fetch Planck data
ell_full, Dl_full, err_full = fetch_planck_tt_data(urls["full"])
ell_binned, Dl_binned, err_binned = fetch_planck_tt_data(urls["binned"])

# Combine: use unbinned for ell <= 29, binned for ell >= 30
mask_low = ell_full <= 29
mask_high = ell_binned >= 30

ell_data = np.concatenate([ell_full[mask_low], ell_binned[mask_high]])
Dl_data = np.concatenate([Dl_full[mask_low], Dl_binned[mask_high]])
err_data = np.concatenate([err_full[mask_low], err_binned[mask_high]])

# Function to compute Dl_theory for a given omch2
def compute_theory_curve(omch2):
    pars = camb.CAMBparams()
    pars.set_cosmology(H0=67.36, ombh2=0.02237, omch2=omch2, tau=0.0544)
    pars.InitPower.set_params(As=np.exp(3.0448)/1e10, ns=0.9649)
    pars.set_for_lmax(2500, lens_potential_accuracy=1)
    pars.WantCls = True
    pars.Want_CMB_lensing = True
    results = camb.get_results(pars)
    powers = results.get_cmb_power_spectra(pars, CMB_unit='muK')
    totCL = powers['total']
    ell = np.arange(totCL.shape[0])
    Dl = totCL[:, 0]
    return ell[ell > 2], Dl[ell > 2]

# Theory curves
ell_theory, Dl_best = compute_theory_curve(0.1200)
_, Dl_reduced = compute_theory_curve(0.1200 * 0.9)

# Plot
plt.figure(figsize=(10, 6))
plt.errorbar(ell_data, Dl_data, yerr=err_data, fmt='o', capsize=2, markersize=3, label='Planck 2018 Data')
plt.plot(ell_theory, Dl_best, lw=2, label='ΛCDM Best-Fit')
plt.plot(ell_theory, Dl_reduced, lw=2, ls='--', label=r'ΛCDM with $\Omega_c h^2 \times 0.9$')
plt.xlabel(r'Multipole $\ell$')
plt.ylabel(r'$D_\ell^{TT}$ [$\mu$K$^2$]')
plt.title("Planck 2018 TT Power Spectrum vs. CAMB Theory")
plt.xscale("log")
plt.grid(True, which='both', ls='--', lw=0.5)
plt.legend()
plt.tight_layout()
plt.show()
```

The government in my country does NOT represent me.

I do NOT represent the government in my country.

(Not any more than Iranian exiles represent theirs.)

We are fighting in the streets in all means of non-violent protest
to bring down this government.
Any even remotely sensible democratic government would have been down by now.

There are no real zero-sum game solutions to the tragedy in Israel and Palestine.
There is no fuc%#ng reason for this to be painted as a zero-sum game.

End this fuc%#ng war. Release Oct 7 hostages.
Kick out the extremists on both sides.

اليهود والعرب يرفضون أن يكونوا أعداء

יהודים וערבים מסרבים להיות אויבים