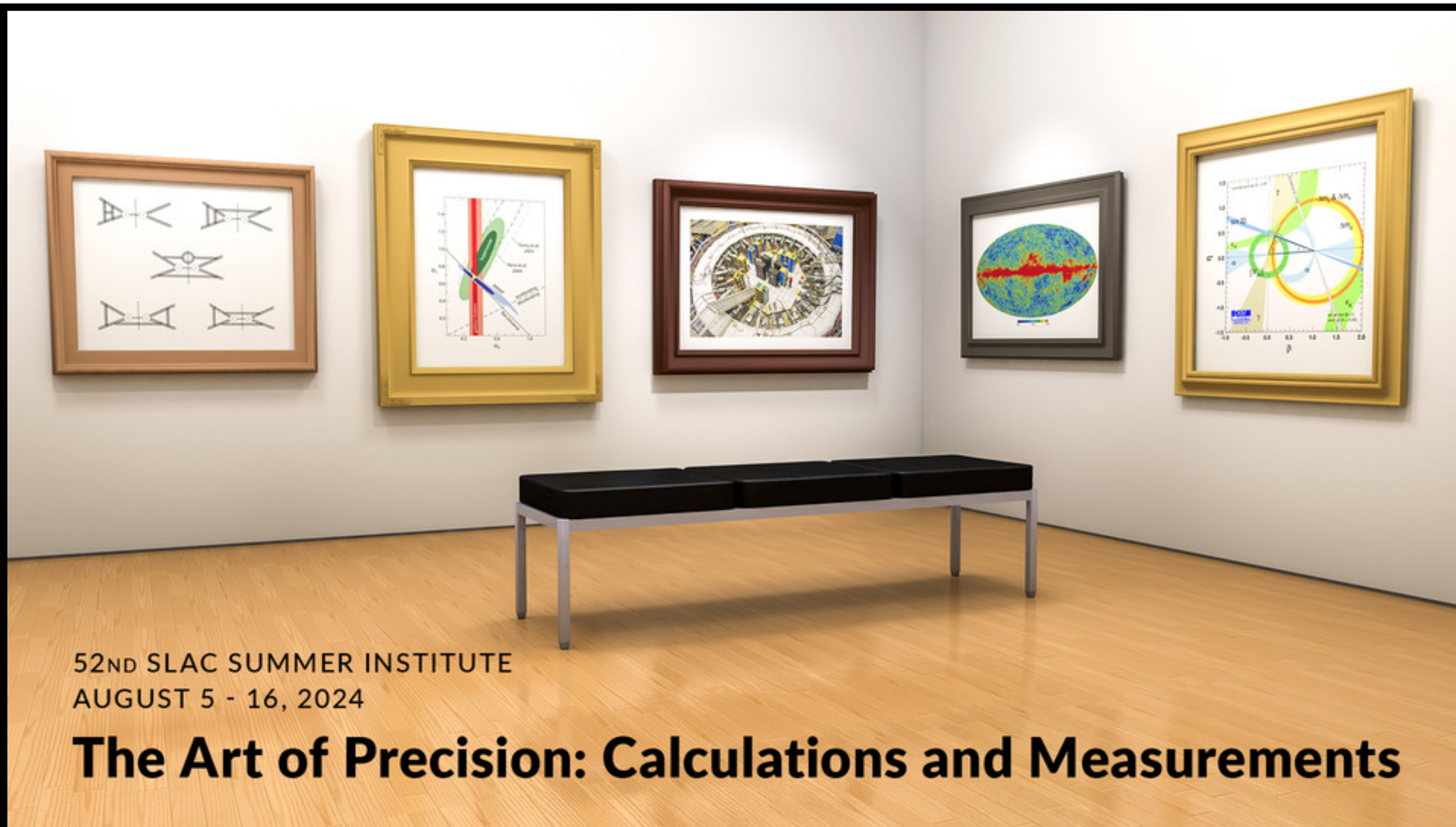


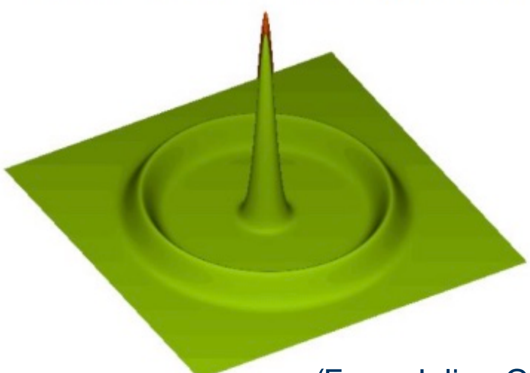
CMB Theory @ 52nd SSI

Lloyd Knox **UC Davis** **15 August 2024**

Determining H_0 from CMB Data in 3 steps
Step 1: Calibrating a Standard Ruler

$$a dr = c_{\rm s} dt$$

Sound waves in the baryon density



Eisenstein, Seo, White et al. 2007

(From Julien Guy's lecture)

Determining H_0 from CMB Data in 3 steps
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Decoupling of baryons and photons

$$r_s = \int_0^{t_{\rm d}} c_{\rm s} dt/a = \int_0^{a_{\rm d}} c_{\rm s} \frac{da}{a^2 H(a)}$$

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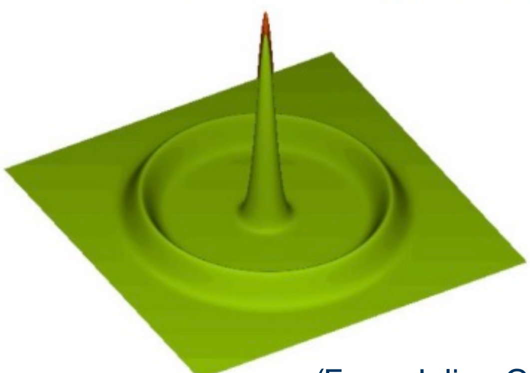

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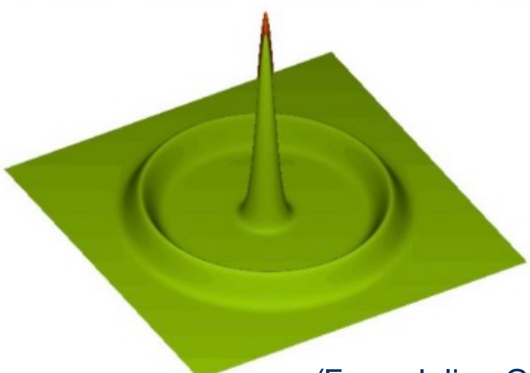

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Need to know $c_s(a)$ and $H(a)$ to calibrate the ruler.

Determining H_0 from CMB Data
Step 1: Calibrating a Standard Ruler

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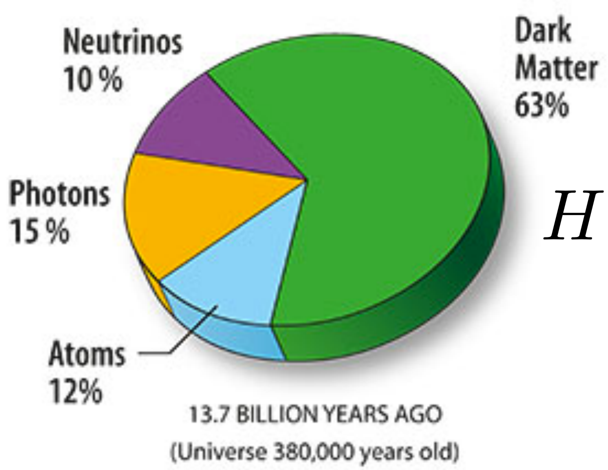
Need to know $c_s(a)$ and $H(a)$ to calibrate the ruler.

$$c_s^2 = \partial P/\partial \rho \longleftarrow \rho_b / \rho_\gamma$$



$$H^2(a) = 8\pi G/3(\rho_\gamma + \rho_\nu + \rho_\mathrm{m})$$

Determining H_0 from CMB Data
Step 1: Calibrating a Standard Ruler

$$r_s = \int_0^{t_\mathrm{d}} c_\mathrm{s} dt/a = \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$$

Need to know c_s(a) and H(a) to calibrate the ruler.

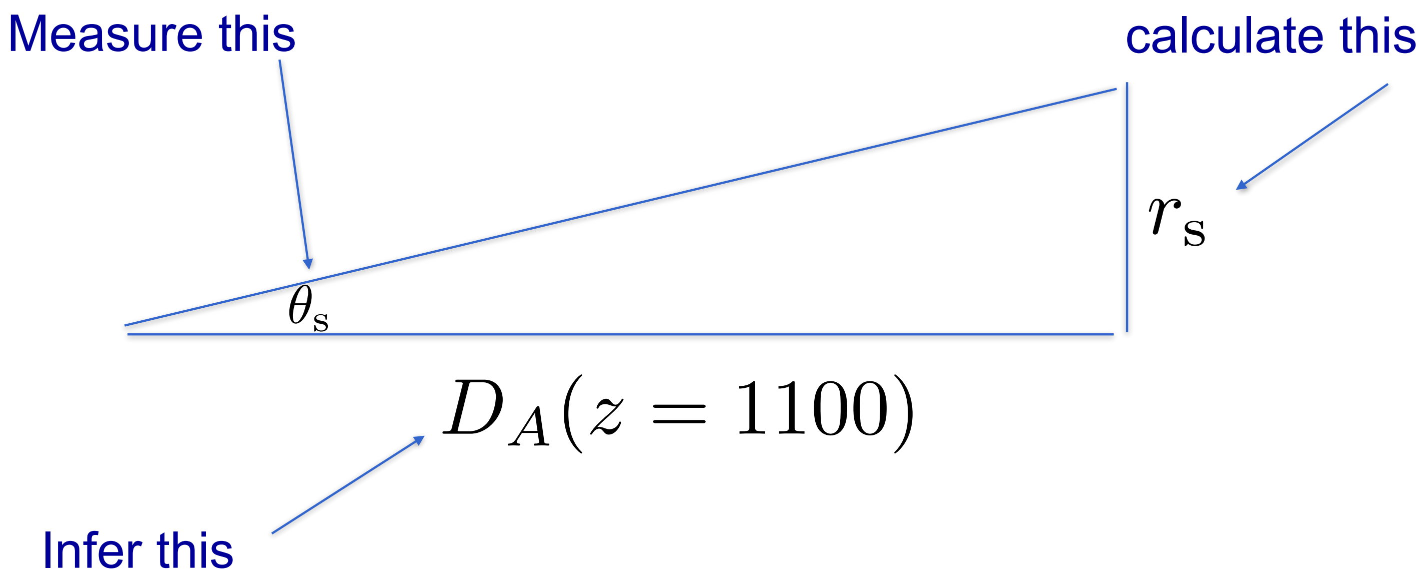
$$c_s^2 = \partial P/\partial\rho$$

Pressure of plasma impacts peak morphology (odd/even height modulation)

$$H^2(a) = 8\pi G/3(\rho_\gamma + \rho_\nu + \rho_\mathrm{m})$$

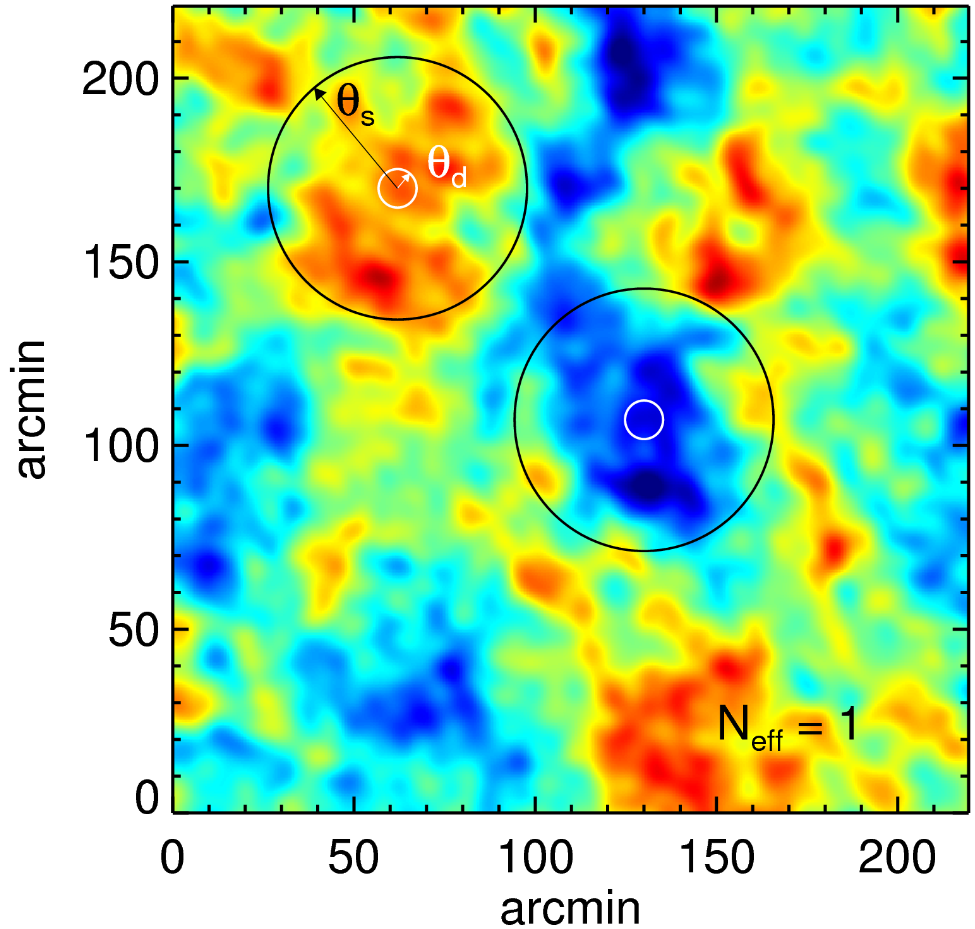
"Radiation Driving" effect (Hu & White 1997)

Determining H_0 from CMB Data
Step 2: Use the Ruler to Infer Distance

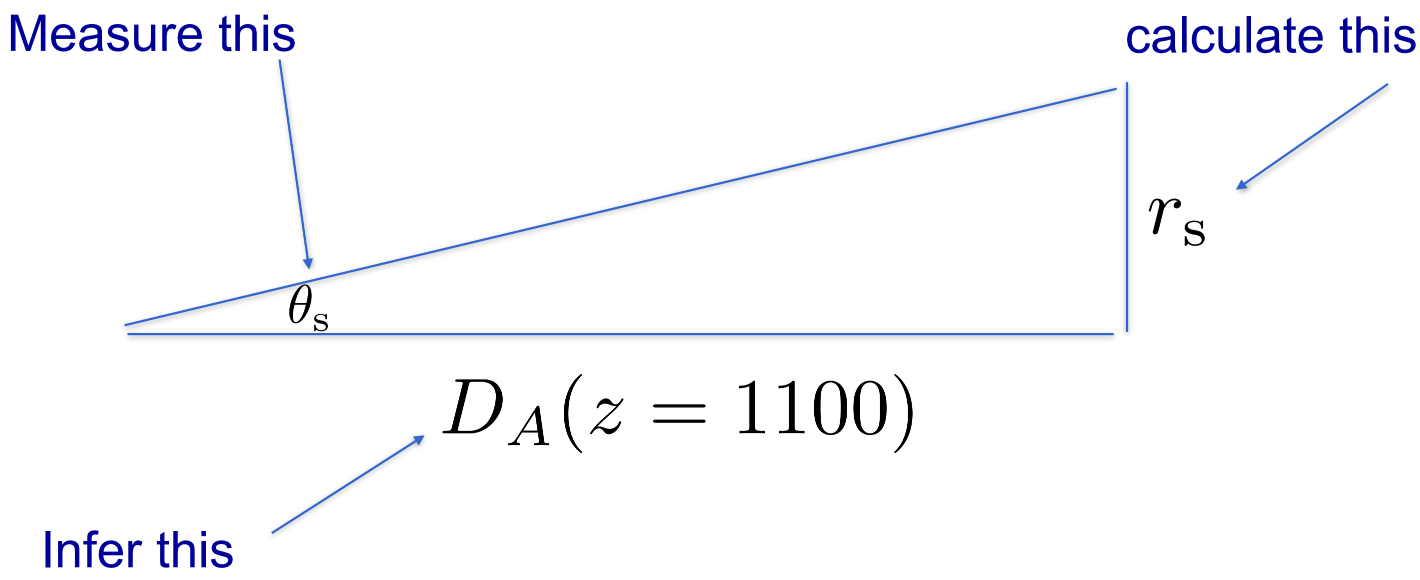


$\theta_{\rm s} = r_{\rm s}/D_A$ is typical size of hot or cold spot

$\theta_{\rm d} = r_{\rm d}/D_A$ map is smoothed below this scale



Determining H_0 from CMB Data
Step 2: Use the Ruler to Infer Distance



Step 3: $$D_A(z) = \int_0^z dz'/H(z')$$

To get the right D_A, only thing left in the model to adjust is the cosmological constant. With that done, we have H(z).

Questions?

Outline

- Hubble constant from the CMB (and LCDM)
- Acoustic dynamics are very sensitive to gravitational potential evolution ==> strong constraints to the introduction of new components and new interactions (and very strong evidence for CDM)
- Implications for models with light relics
- FFAT scaling transformation symmetry and a rate ratio perspective
- Recombination?

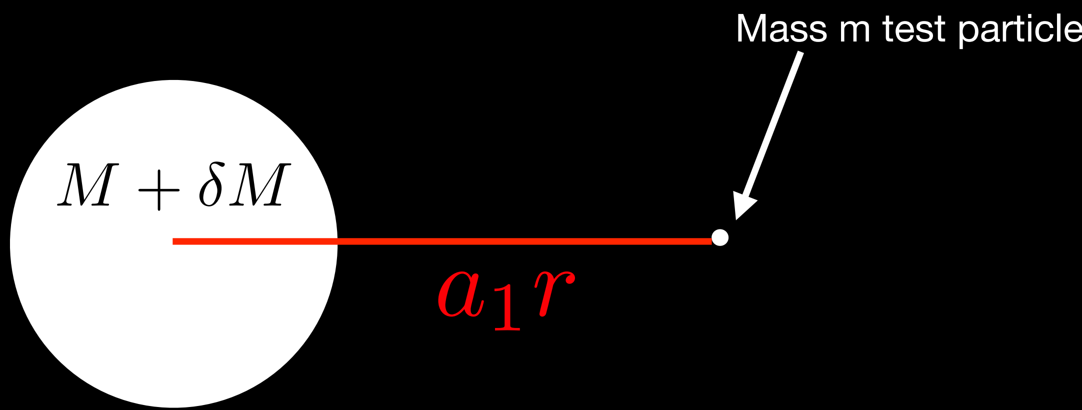
Five years ago…

[Submitted on 10 Aug 2019 (v1), last revised 16 Sep 2019 (this version, v2)]

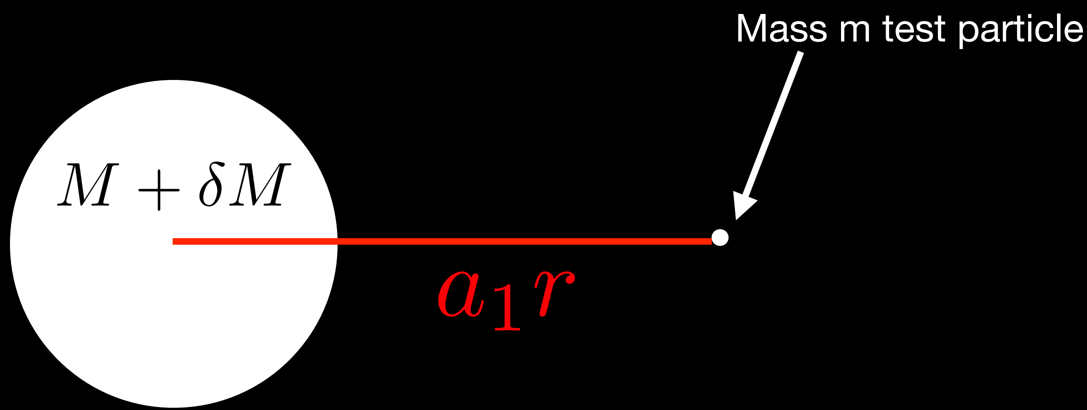
The Hubble Hunter's Guide

Lloyd Knox, Marius Millea

Measurements of the Hubble constant, and more generally measurements of the expansion rate and distances over the interval $0 < z < 1$, appear to be inconsistent with the predictions of the standard cosmological model (ΛCDM) given observations of cosmic microwave background temperature and polarization anisotropies. Here we consider a variety of types of departures from ΛCDM that could, in principle, restore concordance among these datasets, and we explain why we find almost all of them unlikely to be successful. We single out the set of solutions that increase the expansion rate in the decade of scale factor expansion just prior to recombination as the least unlikely. These solutions are themselves tightly constrained by their impact on photon diffusion and on the gravitational driving of acoustic oscillations of the modes that begin oscillating during this epoch -- modes that project on to angular scales that are very well measured. We point out that a general feature of such solutions is a residual to fits to ΛCDM, like the one observed in Planck power spectra. This residual drives the modestly significant inferences of angular-scale dependence to the matter density and anomalously high lensing power, puzzling aspects of a data set that is otherwise extremely well fit by ΛCDM.

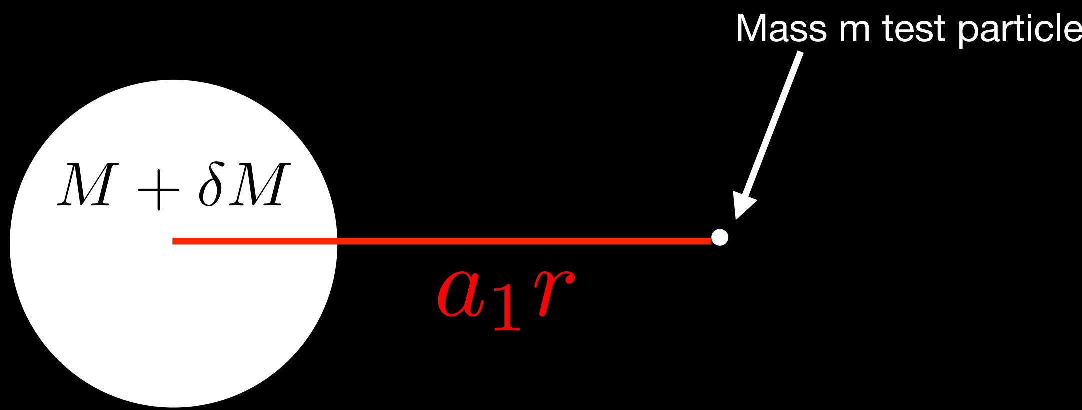


$$\phi / m = -G \frac{\delta M}{a_1 r}$$



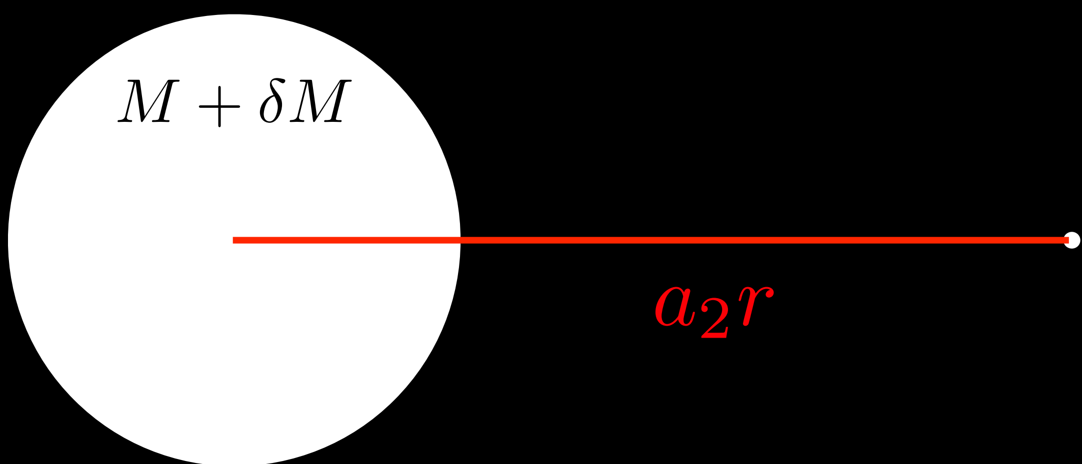
$$\phi/m = -G\frac{\delta M}{a_1 r}$$

Let’s evolve forward, first assuming uniform expansion and no transport of matter

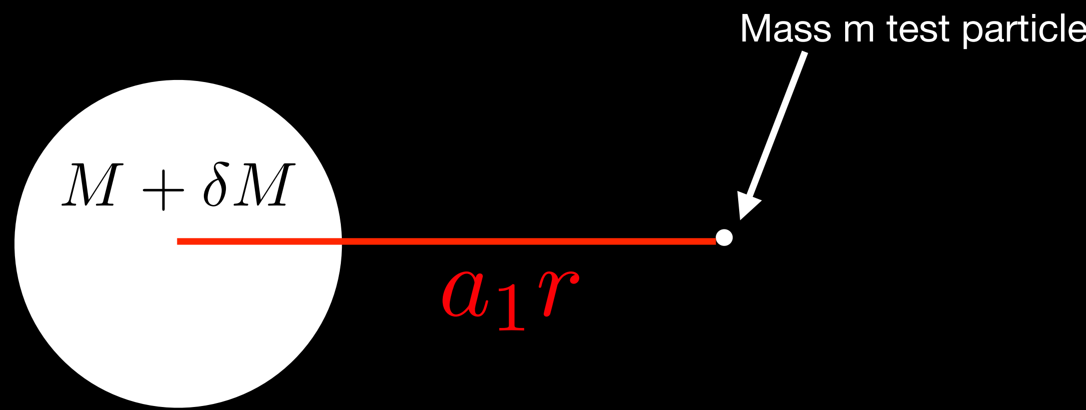


$$\phi_1/m = -G\frac{\delta M}{a_1 r}$$

Let’s evolve forward, first assuming uniform expansion and no transport of matter



$$\phi_2/m = -G\frac{\delta M}{a_2 r}$$



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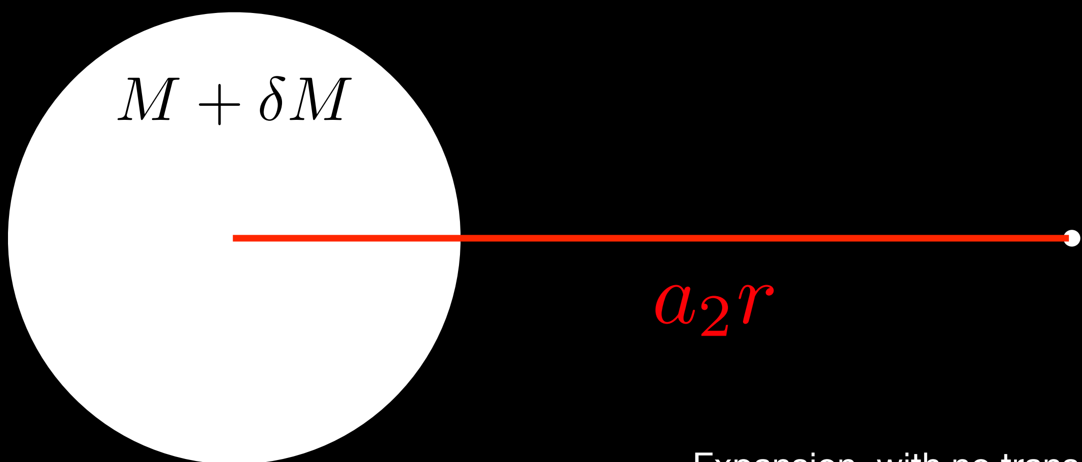
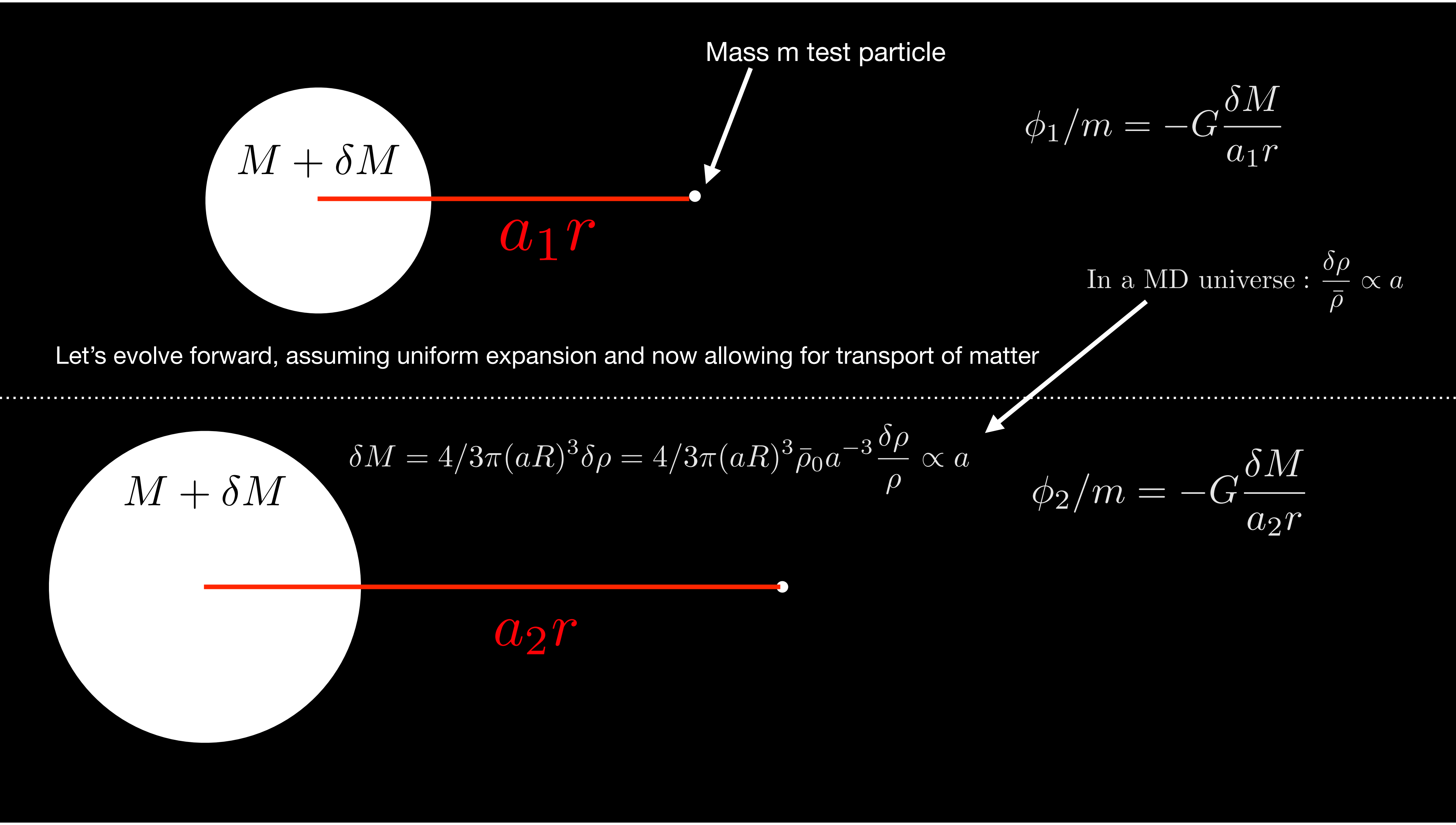
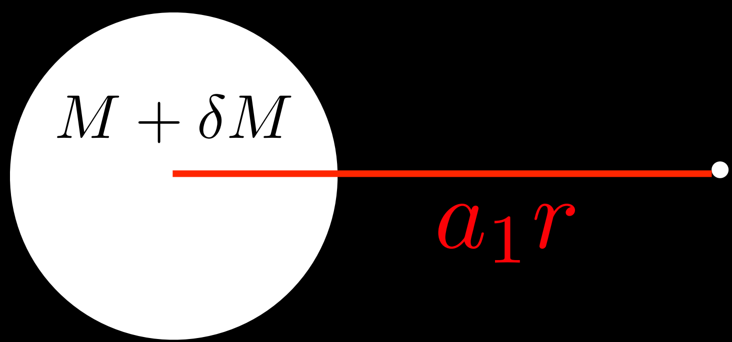


$$\phi_2/m = -G\frac{\delta M}{a_2 r}$$

Expansion, with no transport, causes the gravitational potential to decay.


Mass m test particle
$M + \delta M$
$a_1 r$
$\phi_1/m = -G\frac{\delta M}{a_1 r}$
In a MD universe : $\frac{\delta\rho}{\bar{\rho}} \propto a$
Let’s evolve forward, assuming uniform expansion and now allowing for transport of matter
$\delta M = 4/3\pi(aR)^3\delta\rho = 4/3\pi(aR)^3\bar{\rho}_0 a^{-3}\frac{\delta\rho}{\rho} \propto a$
$M + \delta M$
$\phi_2/m = -G\frac{\delta M}{a_2 r}$
$a_2 r$

Mass m test particle



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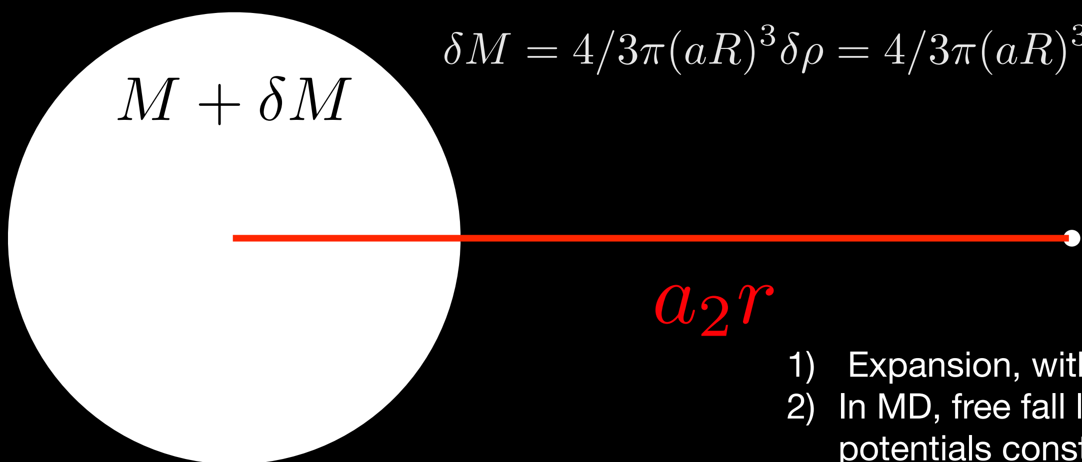
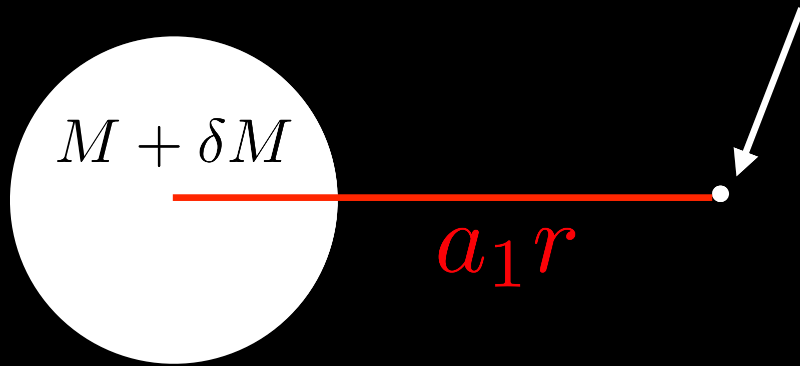


$$\phi_2/m = -G\frac{\delta M}{a_2 r}$$

1) Expansion, with no transport, causes the gravitational potential to decay.
2) In MD, free fall leads to transport that exactly balances expansion to keep potentials constant.

Mass m test particle



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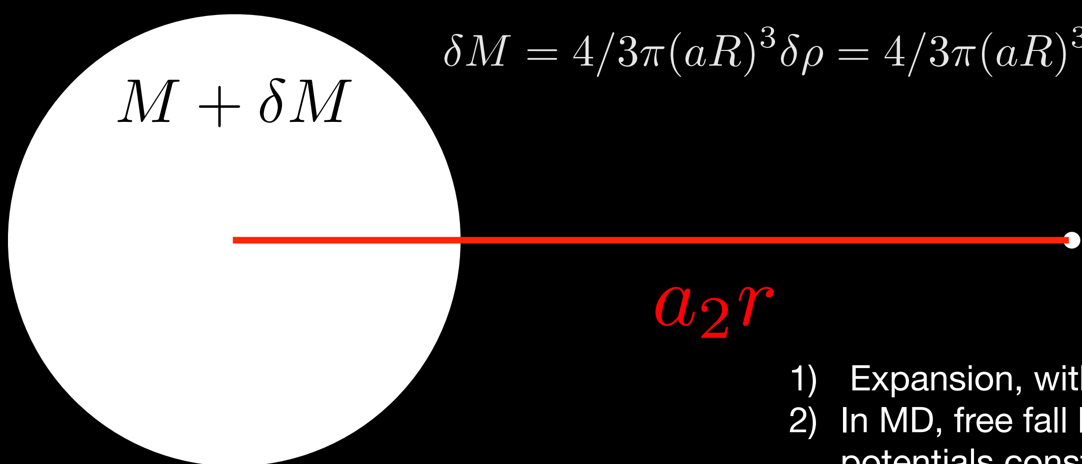
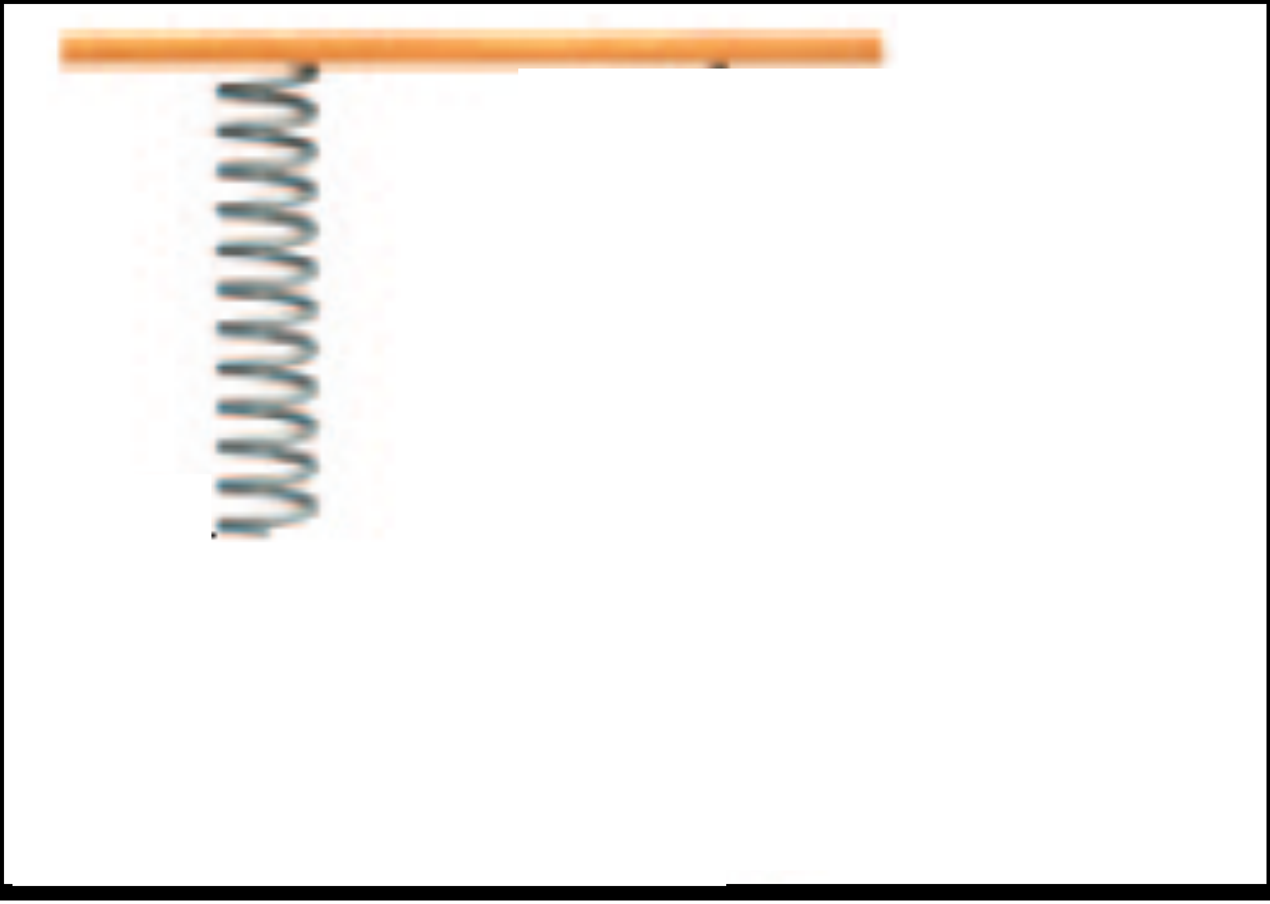
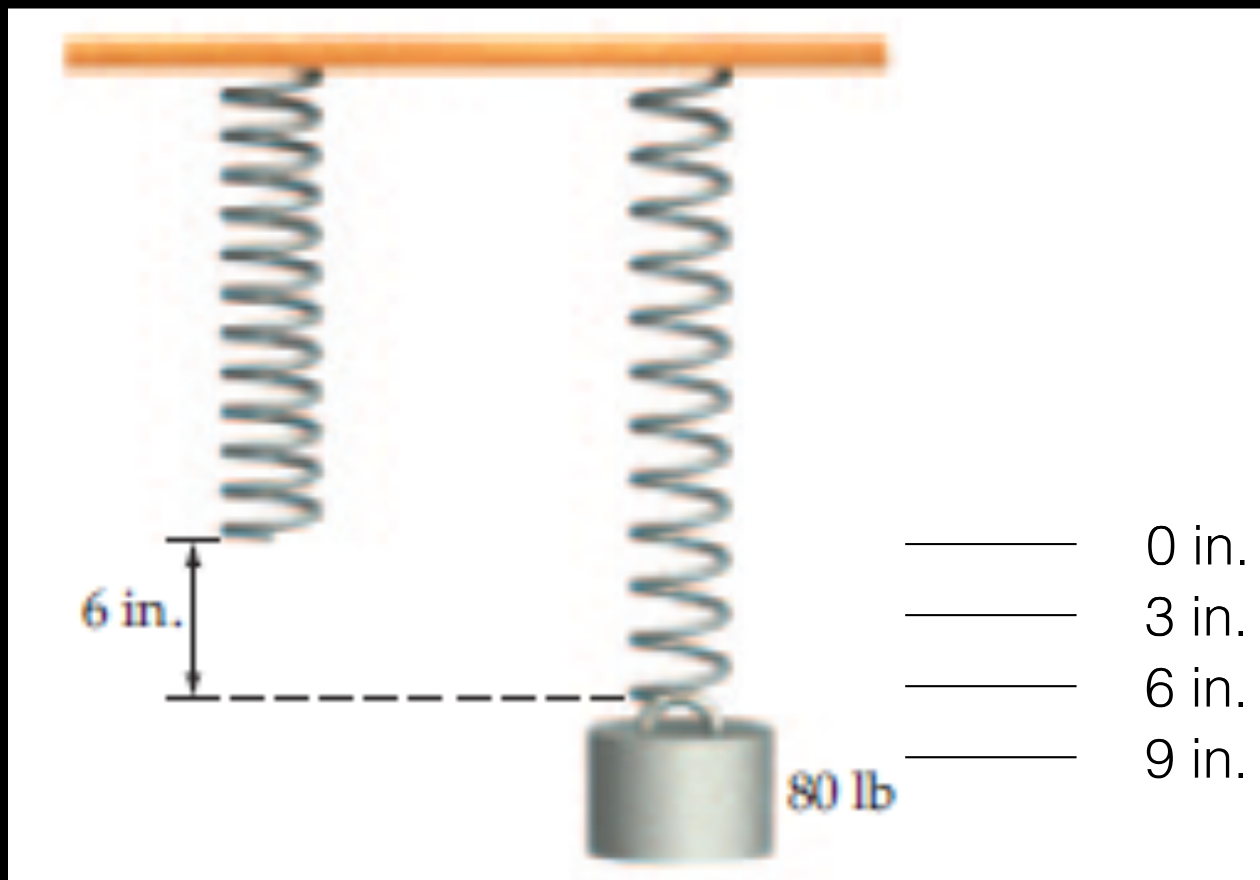


$$\phi_2/m = -G\frac{\delta M}{a_2 r}$$

1) Expansion, with no transport, causes the gravitational potential to decay.
2) In MD, free fall leads to transport that exactly balances expansion to keep potentials constant.
3) In RD, pressure support slows transport so gravitational potentials decay

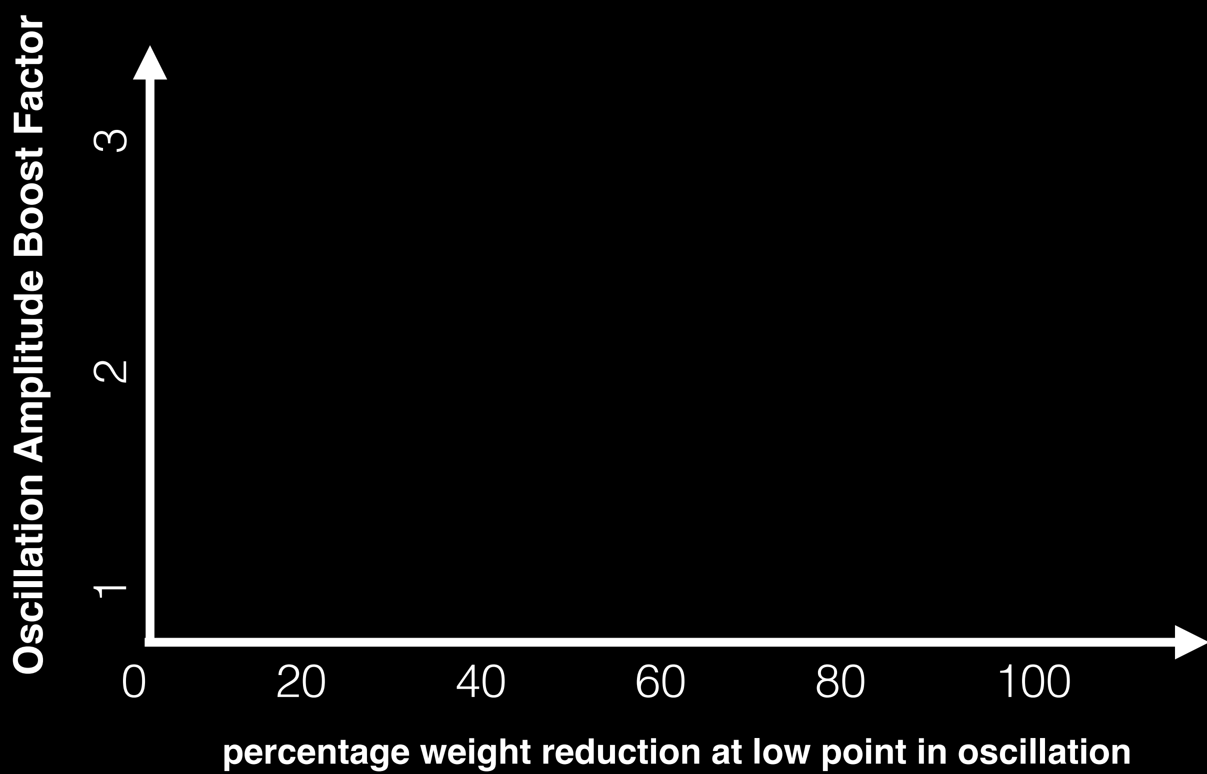
HO





6 in.
80 lb
0 in.
3 in.
6 in.
9 in.

Amplitude Boost vs. Weight Reduction



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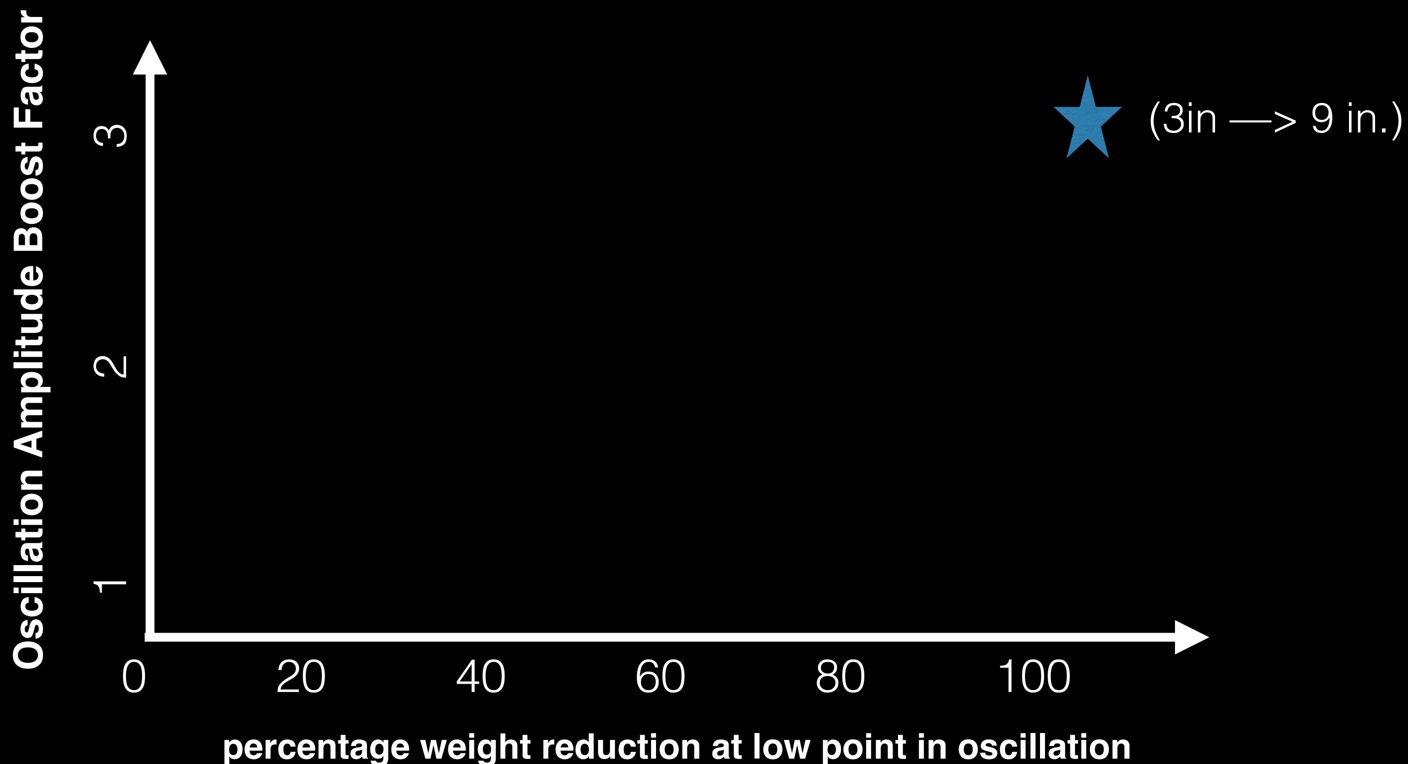

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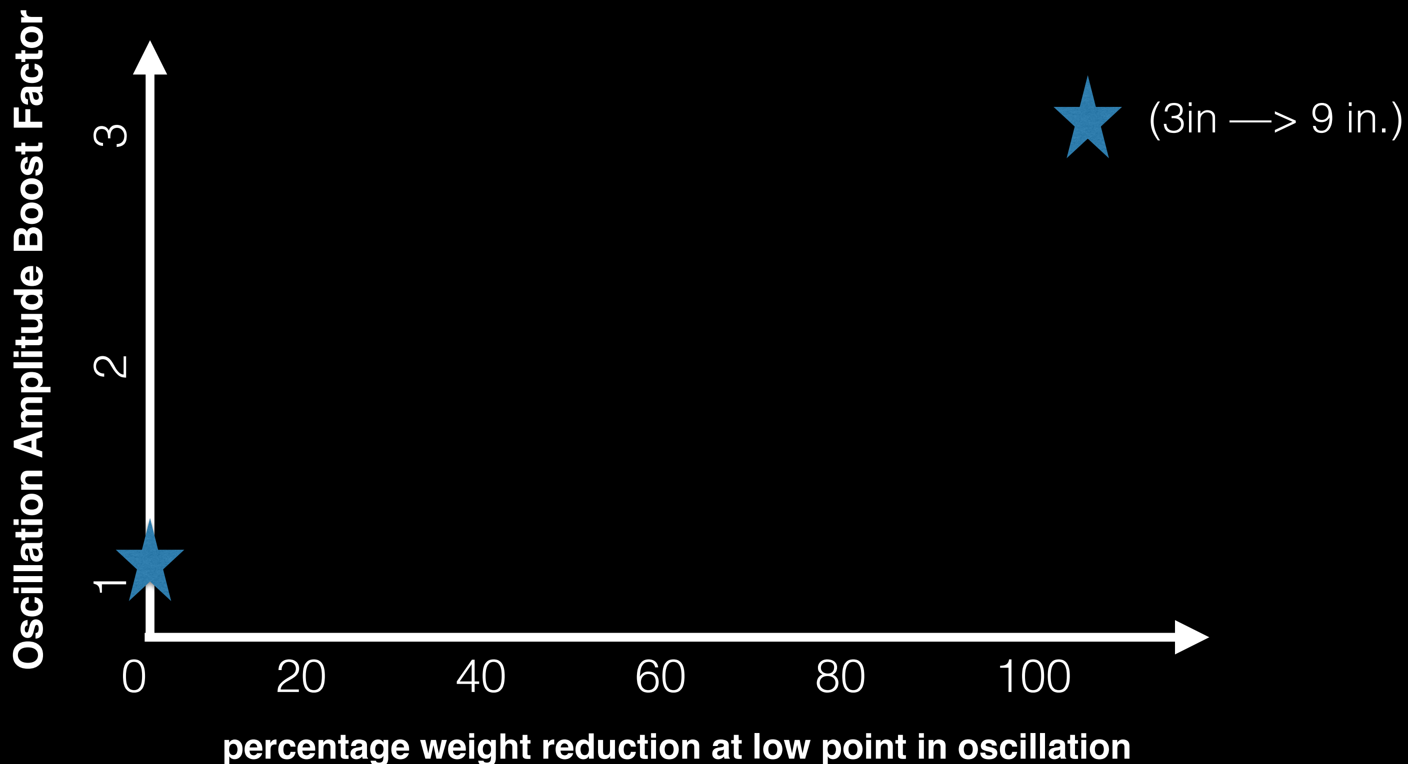

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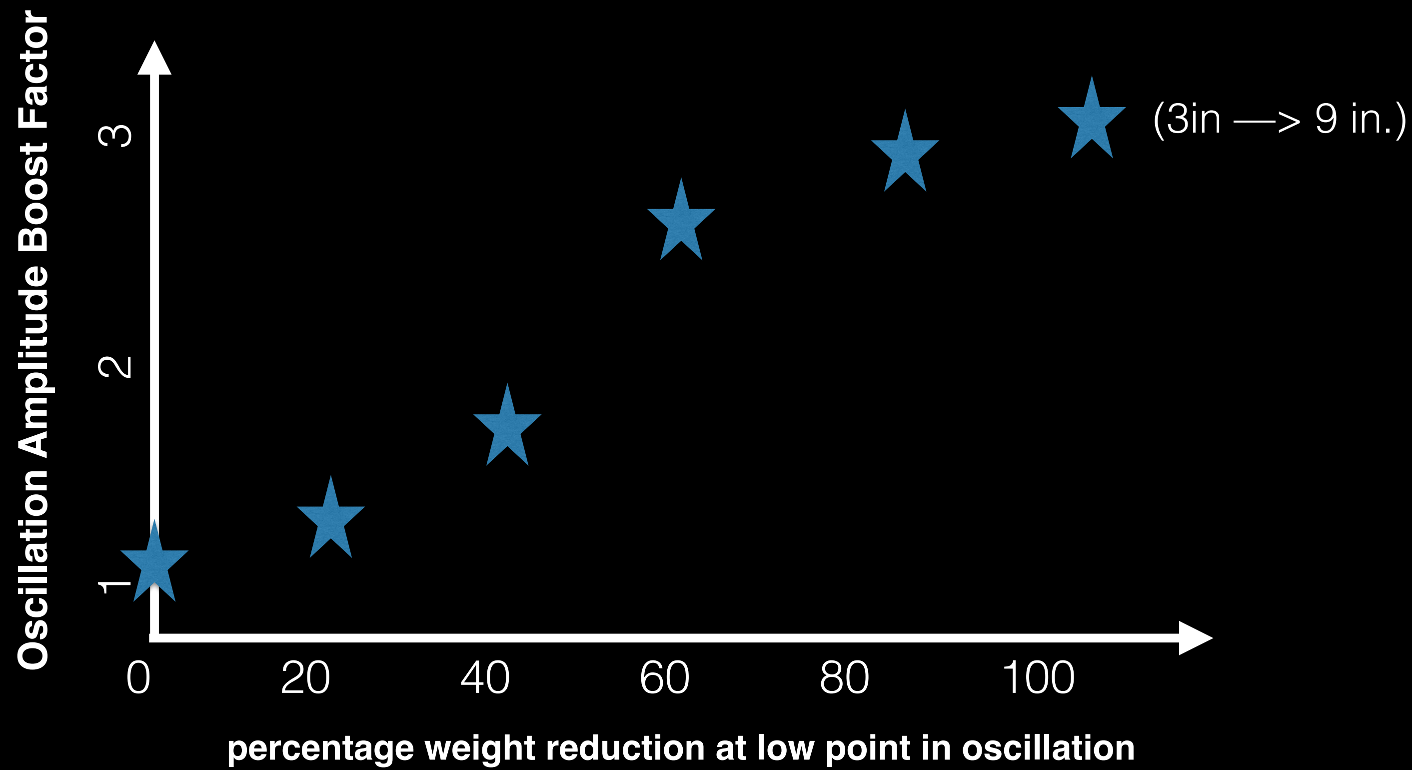
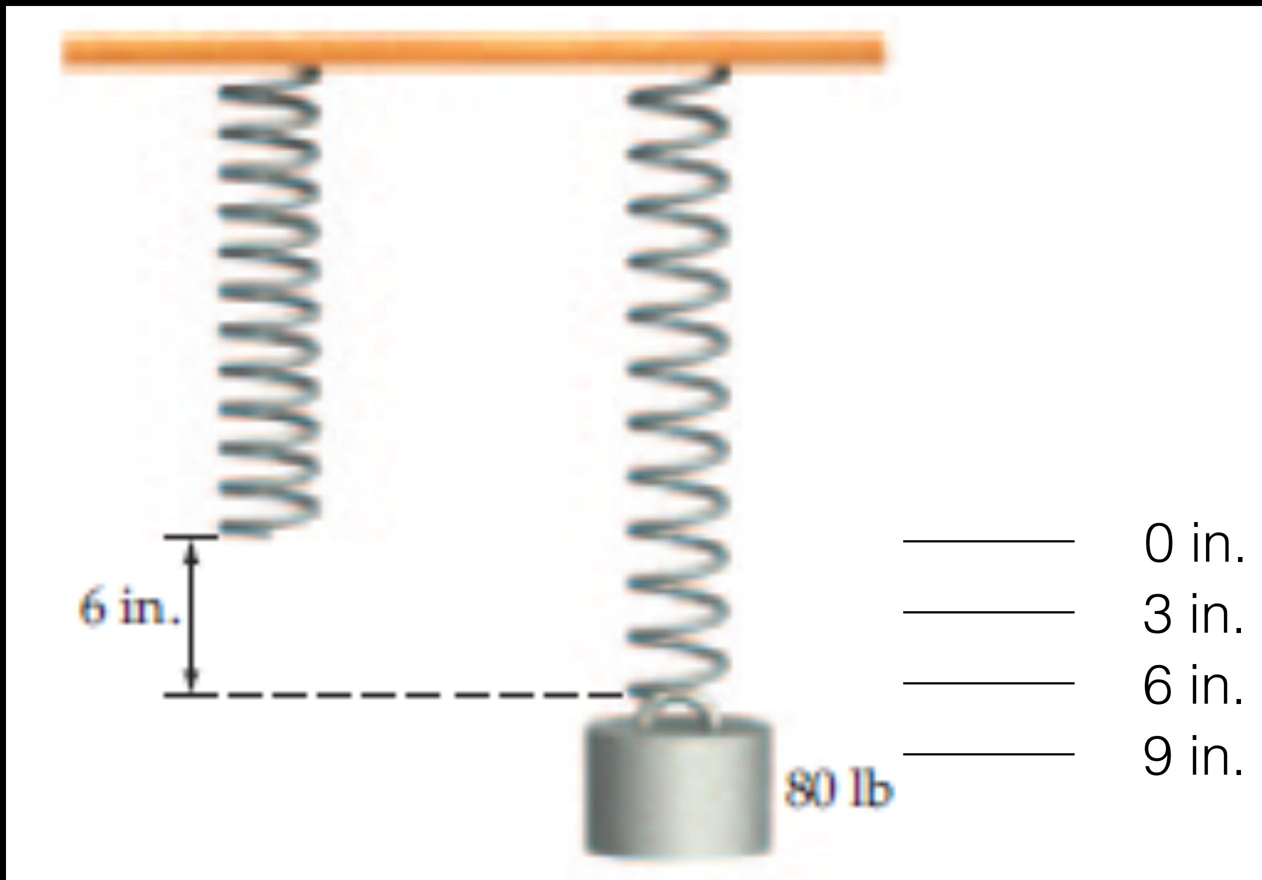


HO under tension



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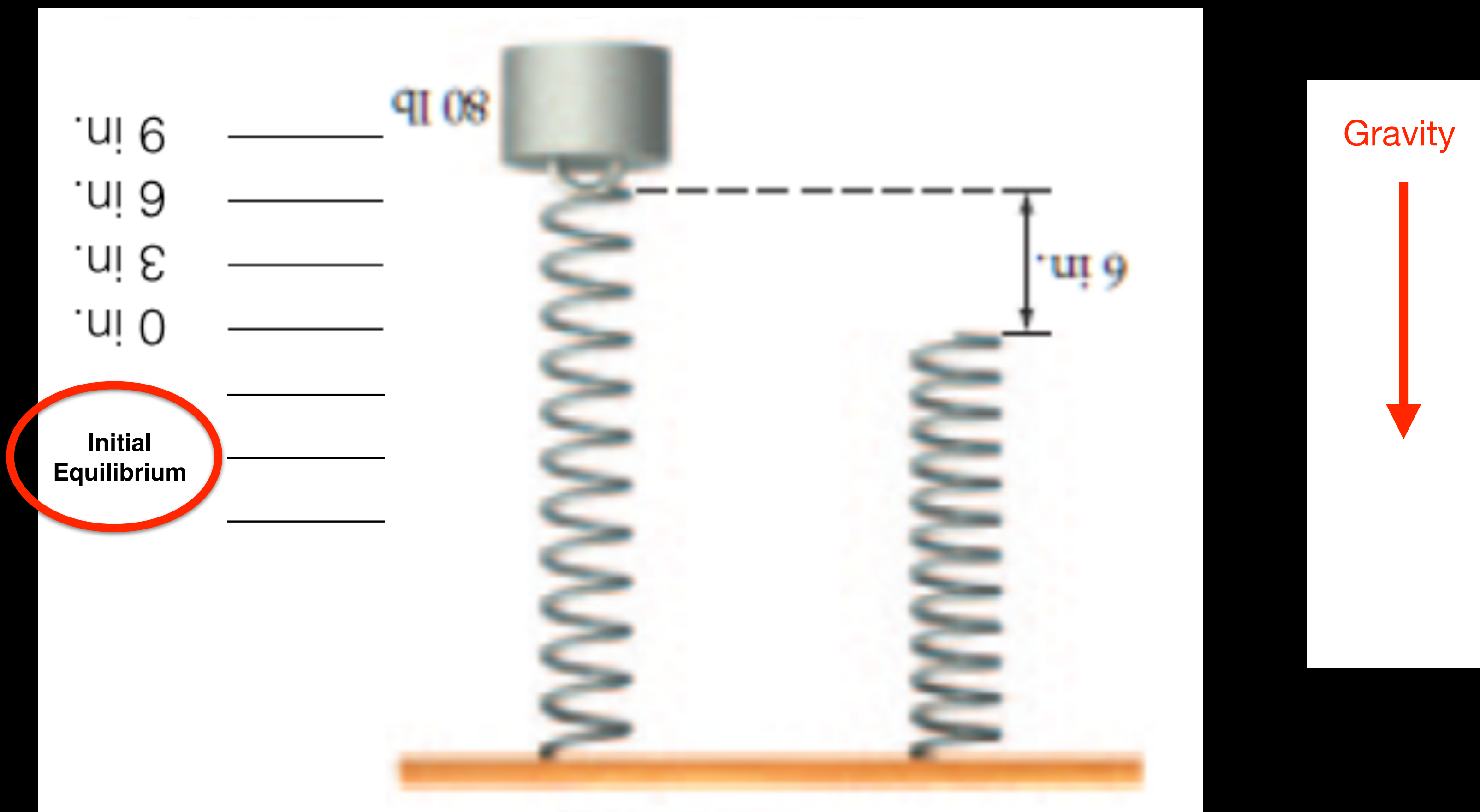

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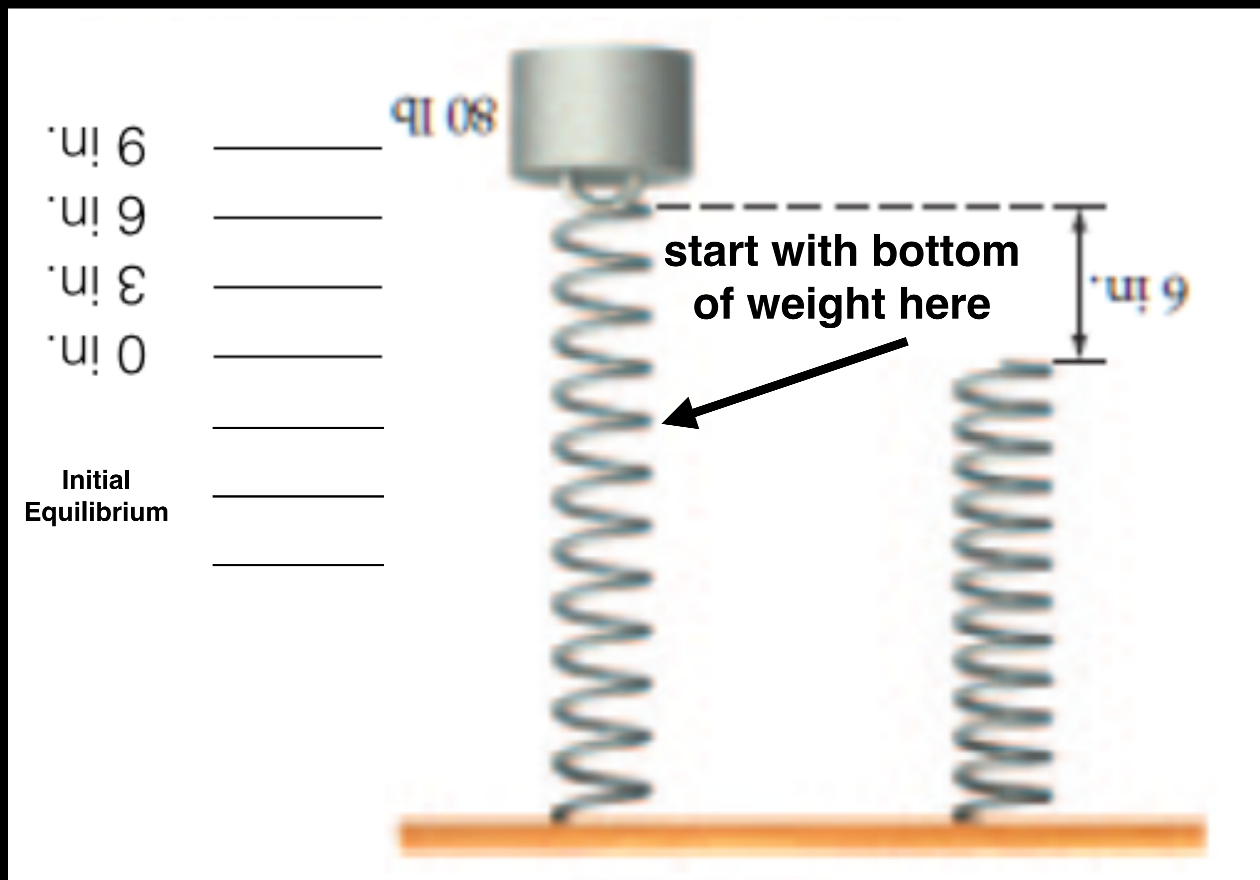
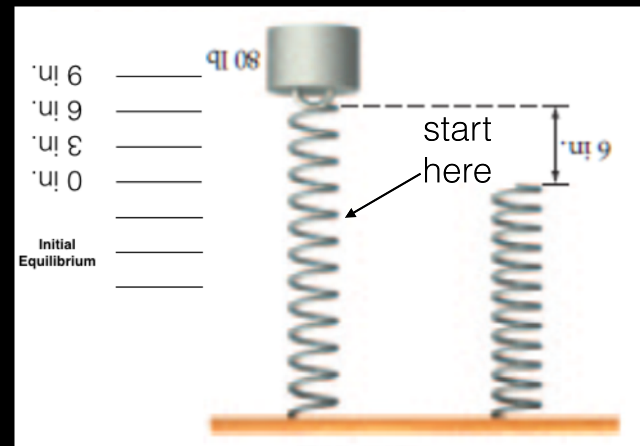


matter domination

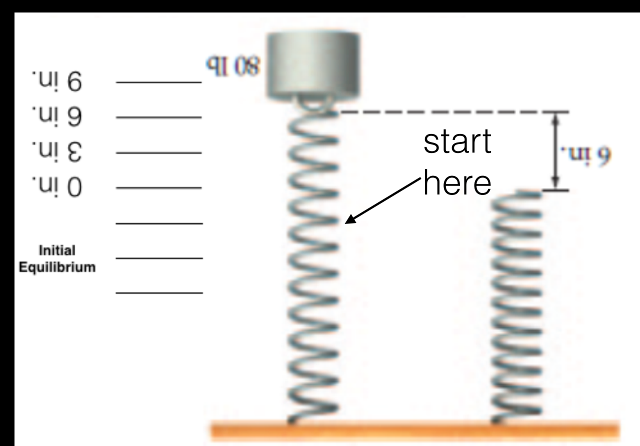
range of oscillation —>



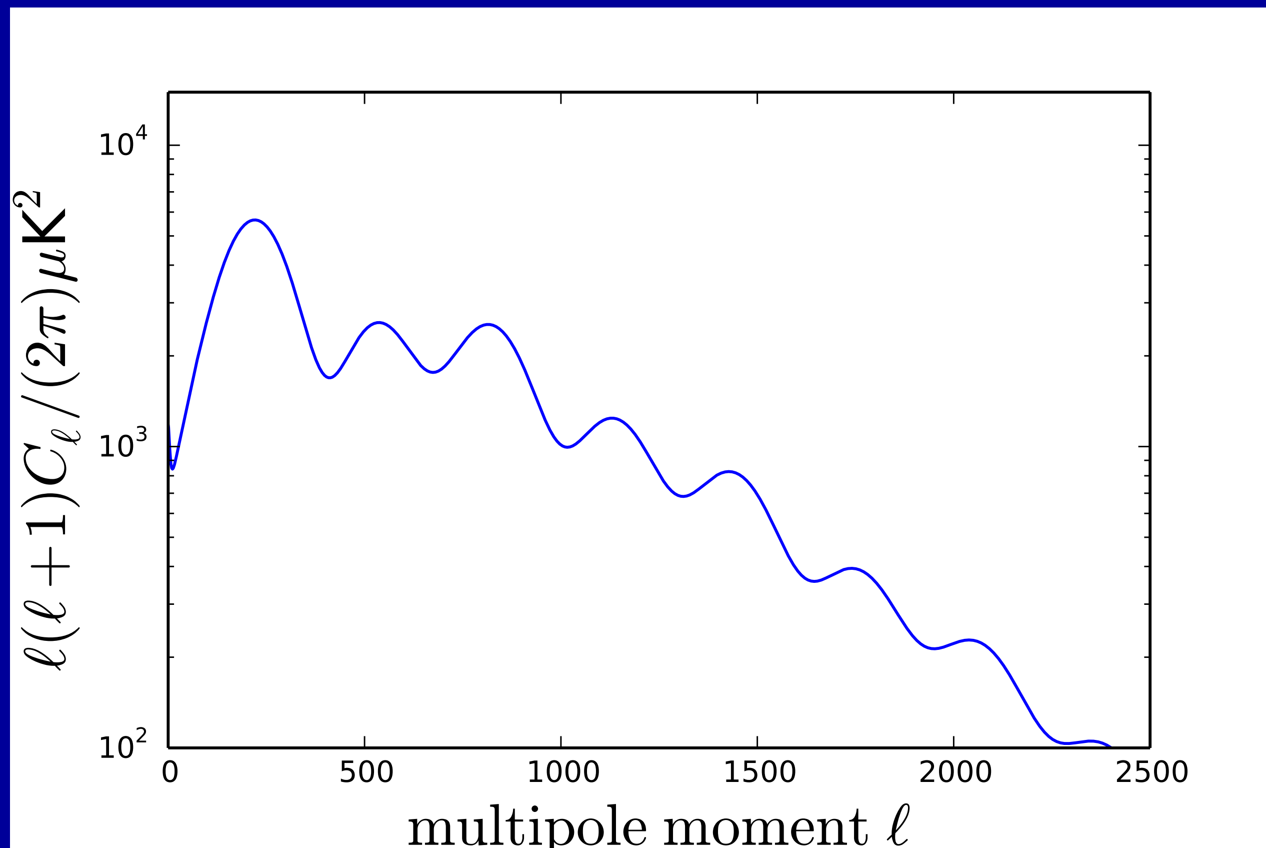
(because grav potential is constant
during matter domination)

radiation domination

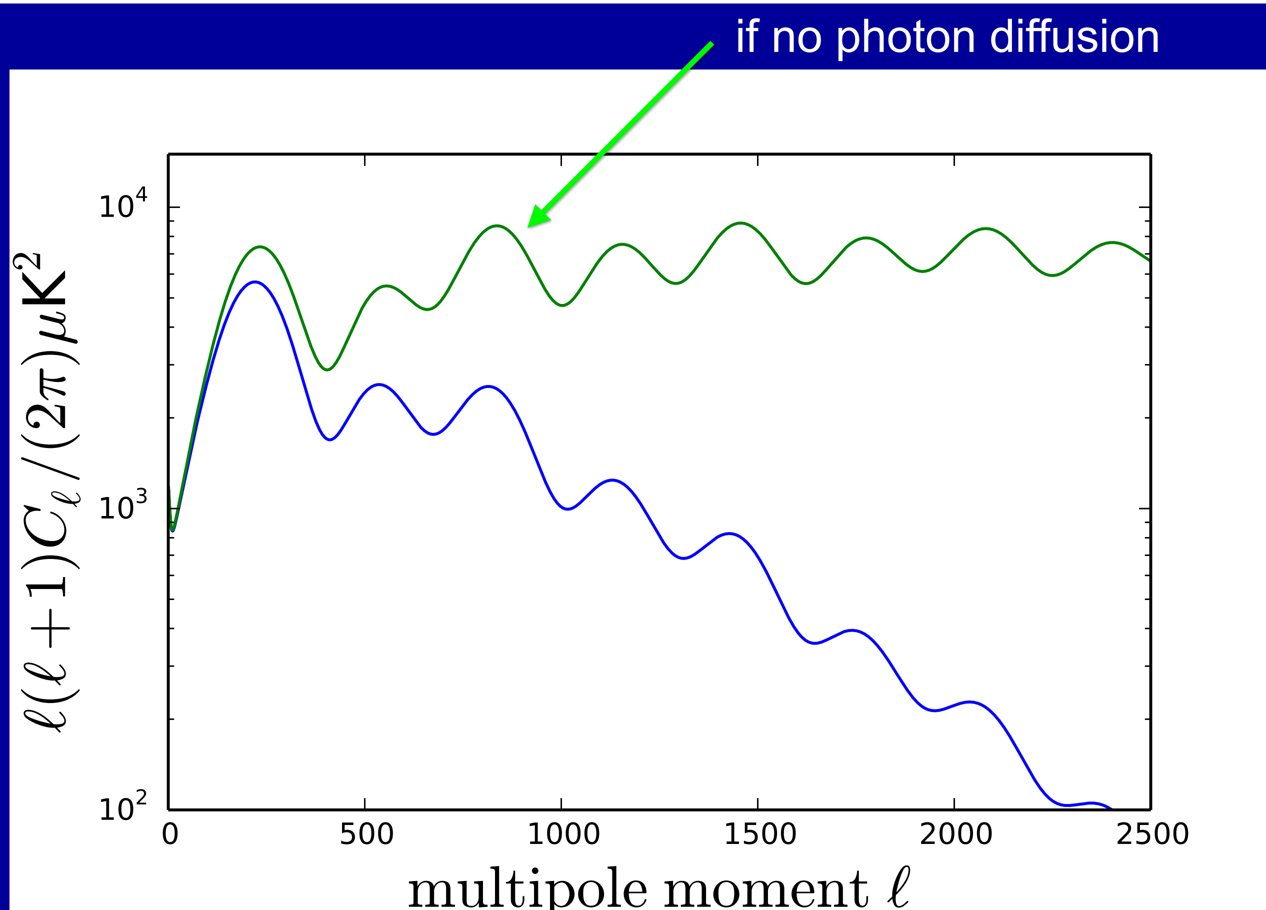
range of oscillation —>



(because grav potential nearly all
gone after 1st compression)



10^4
10^3
10^2
0
500
1000
1500
2000
2500
$\ell(\ell+1)C_\ell/(2\pi)\mu\mathrm{K}^2$
multipole moment ℓ

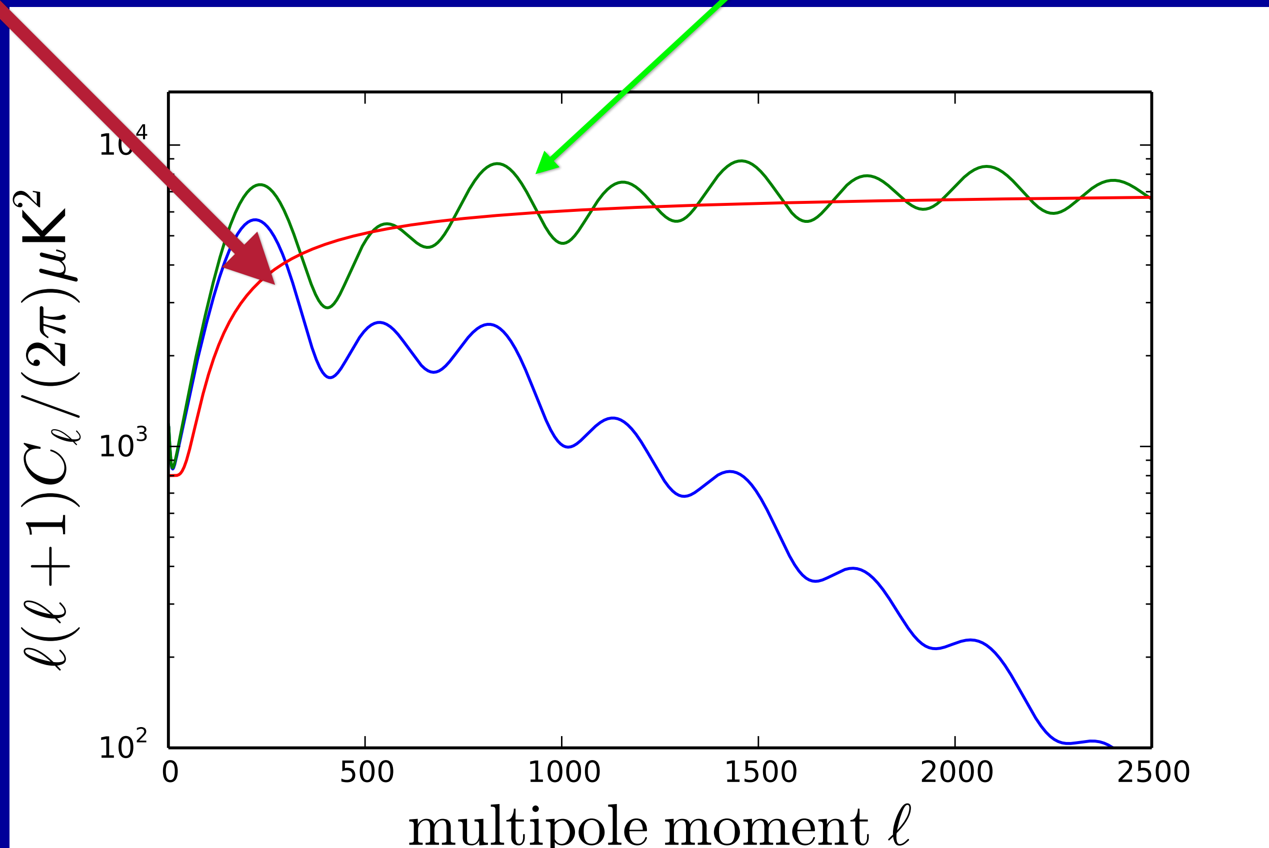


Modes that project into ell enter the horizon (begin oscillating) during:

<=== Matter Domination | ==> Radiation Domination

The "potential envelope" of Hu & White (1997)

if no photon diffusion



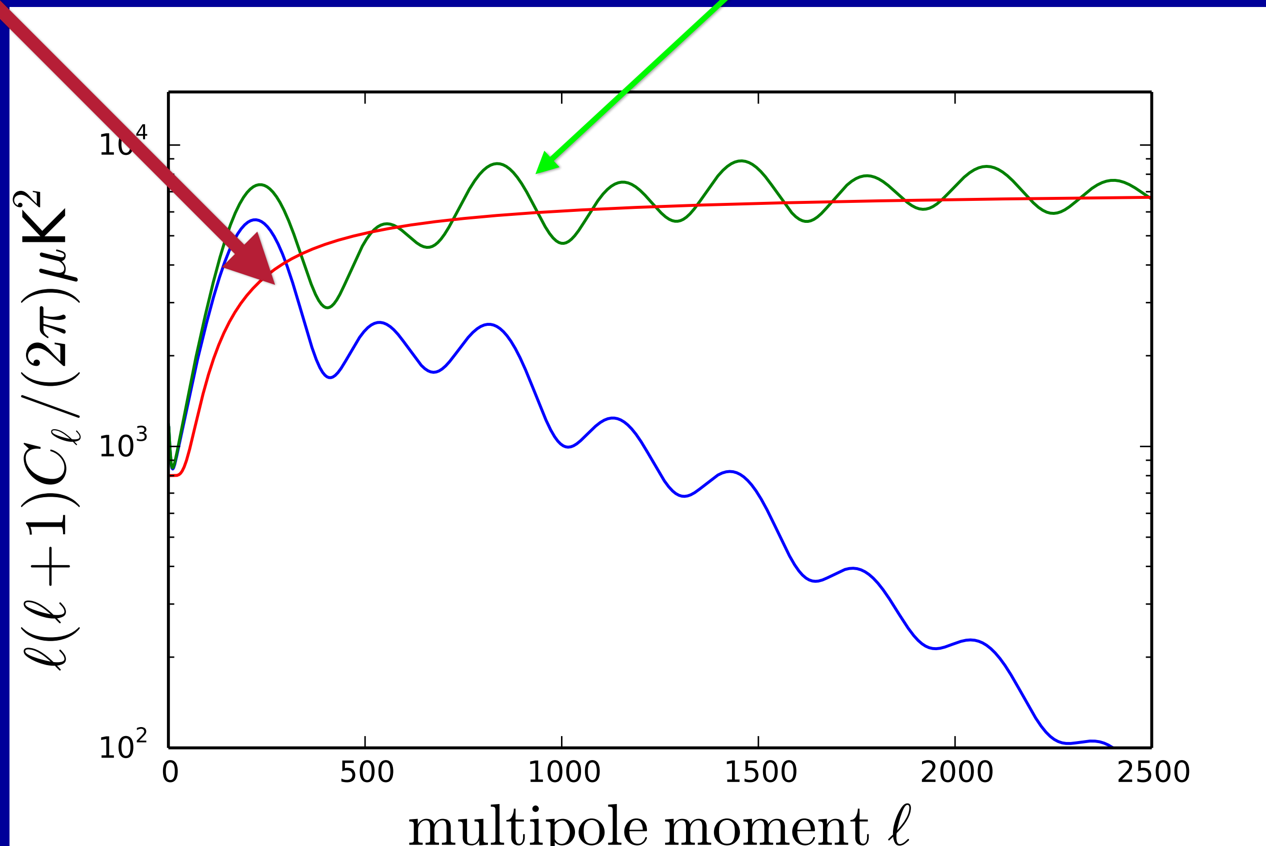
0 78 87 91 93 95

percentage of energy density in relativistic matter when oscillations begin (horizon crossing)

The “potential envelope” of Hu & White (1997)

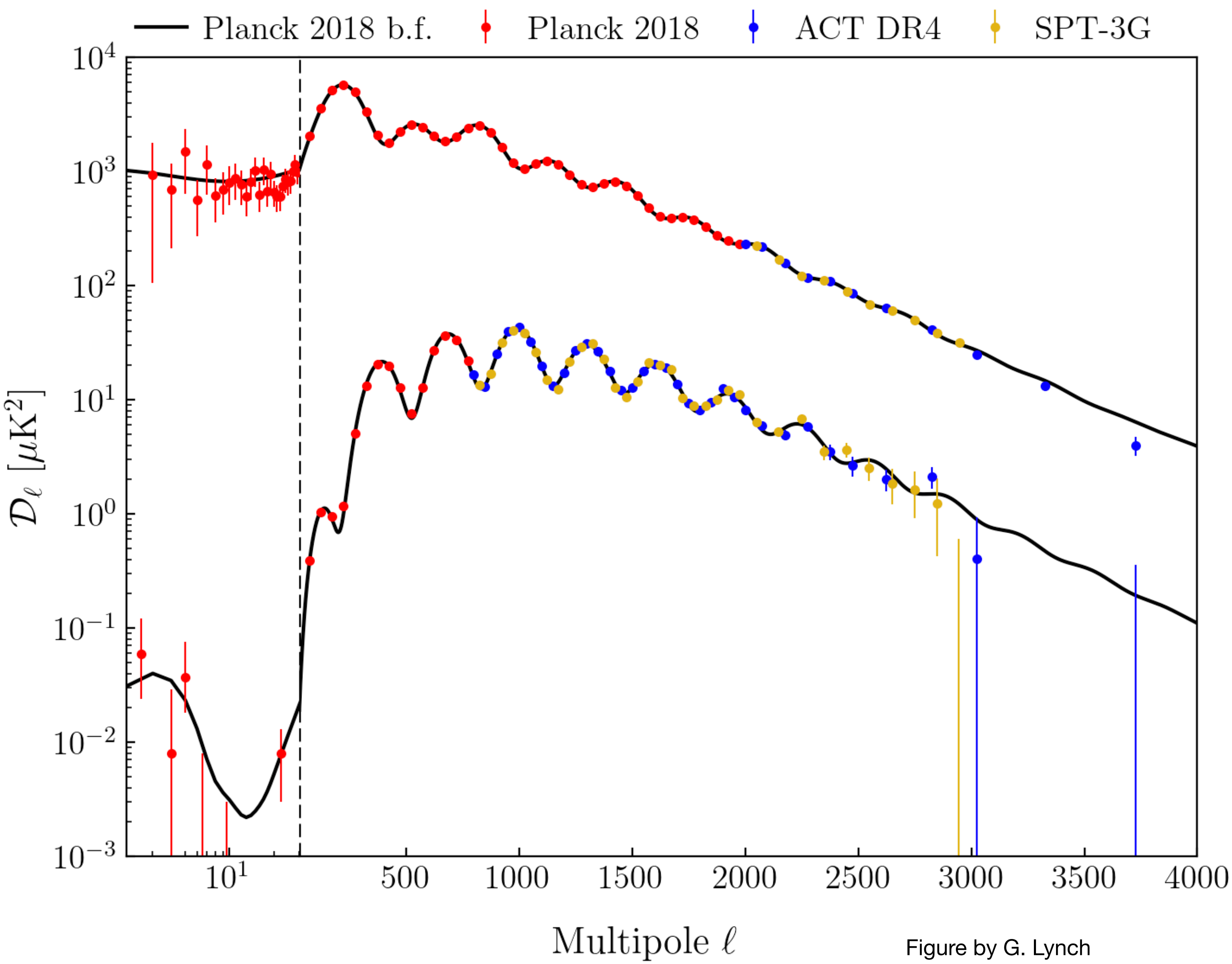
if no photon diffusion

“Radiation driving"



0 10 21 31 42 51

scale factor at recombination divided by scale factor at horizon crossing


Planck 2018 b.f.
Planck 2018
ACT DR4
SPT-3G
$\mathcal{D}_\ell$ [μK^2]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
500
1000
1500
2000
2500
3000
3500
4000
Multipole ℓ
Figure by G. Lynch

Outline

- Hubble constant from the CMB (and LCDM)
- Acoustic dynamics are very sensitive to gravitational potential evolution ==> strong constraints to the introduction of new components and new interactions (and very strong evidence for CDM)
- Implications for models with light relics
- FFAT scaling transformation symmetry and a rate ratio perspective
- Recombination?

Implications for light relics

If you want to increase light relic density, keep matter to radiation ratio fixed

$$\rho_{\mathrm{rad}} \to \lambda \rho_{\mathrm{rad}}$$

Increasing light relic energy density increases radiation density by definition

$$\rho_{\mathrm{m}} \to \lambda \rho_{\mathrm{m}}$$

Can increase density of non-relativistic matter (by adding more CDM)

Implications for light relics

If you want to increase light relic density, keep matter to radiation ratio fixed

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What is this going to do to $\theta_s = r_s/D_A$?

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$$\rho_{\rm m} \to \lambda \rho_{\rm m}$$

Can increase density of non-relativistic matter (by adding more CDM)

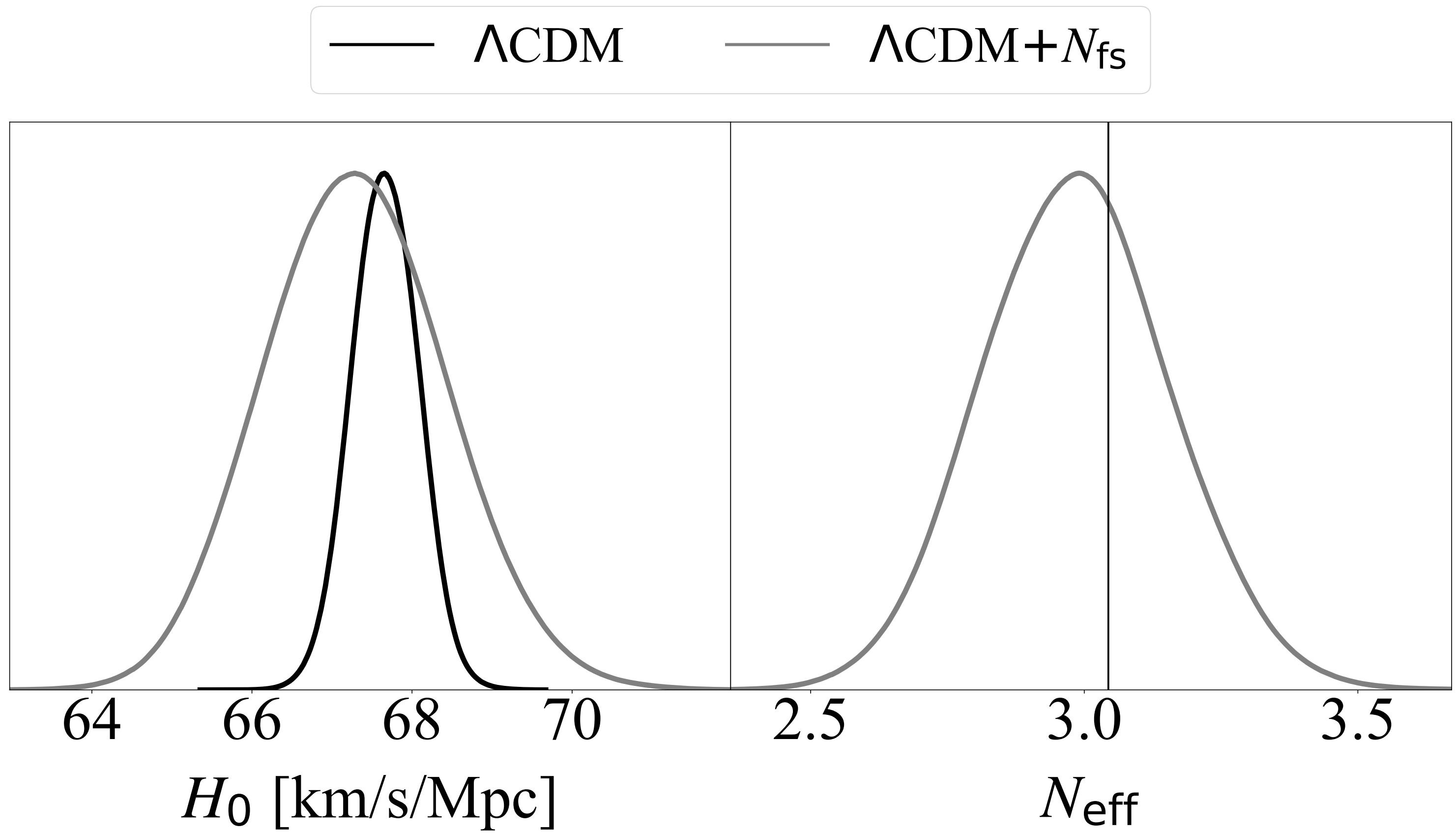
What is this going to do to $\theta_s = r_s/D_A$?

Adding this scaling: $\rho_\Lambda \to \lambda \rho_\Lambda$ will keep θ_s fixed

$$H \to \sqrt{\lambda} H \quad r_s \to r_s/\sqrt{\lambda} \quad D_A \to D_A/\sqrt{\lambda}$$

1D marginal posterior probability densities given Planck + BAO

The “fs” is for “free-streaming” (light relics)



Sensitivity to increased Neff via increased H(z)

The sound horizon $r_s \sim 1/H$

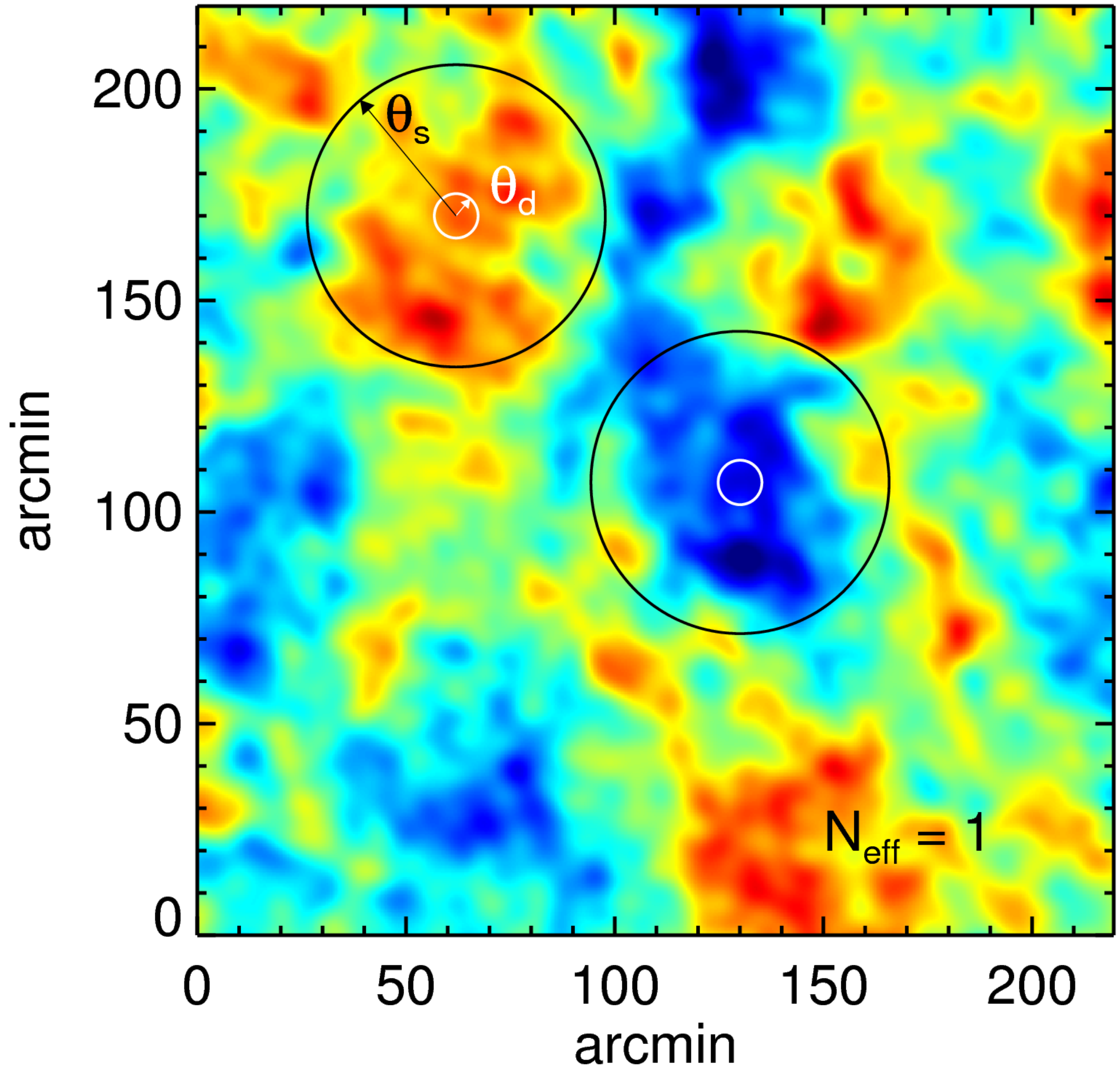
$$\theta_{\rm s} = r_{\rm s}/D_A$$

Photon diffusion is a random walk so $r_d \sim 1/H^{0.5}$

$$\theta_{\rm d} = r_{\rm d}/D_A$$

$$\theta_{\rm d}/\theta_{\rm s} = r_{\rm d}/r_{\rm s} \propto H^{1/2}$$

Neff affects the ratio of sound horizon to diffusion scale



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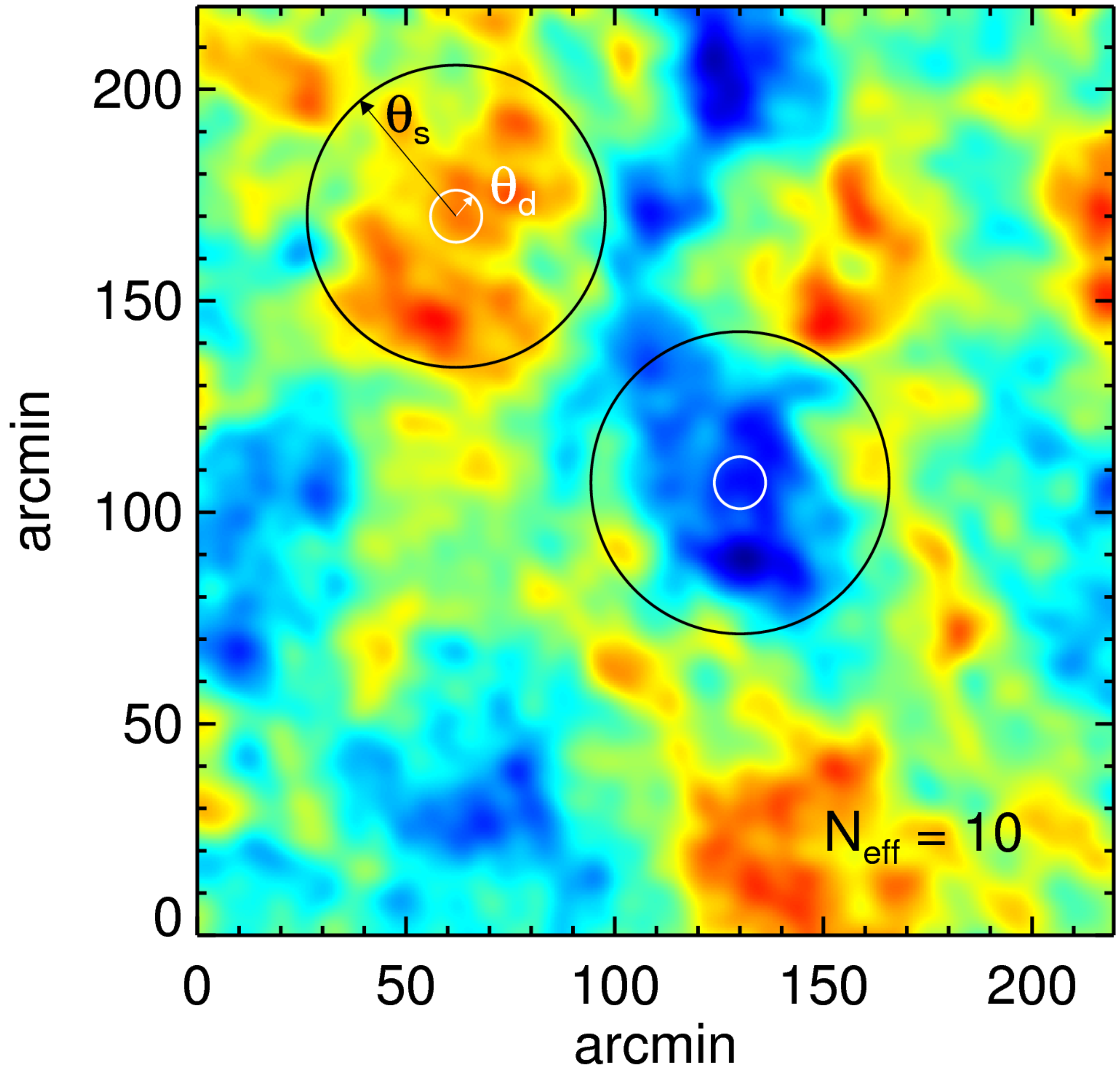

1D marginal posterior probability densities given Planck + BAO

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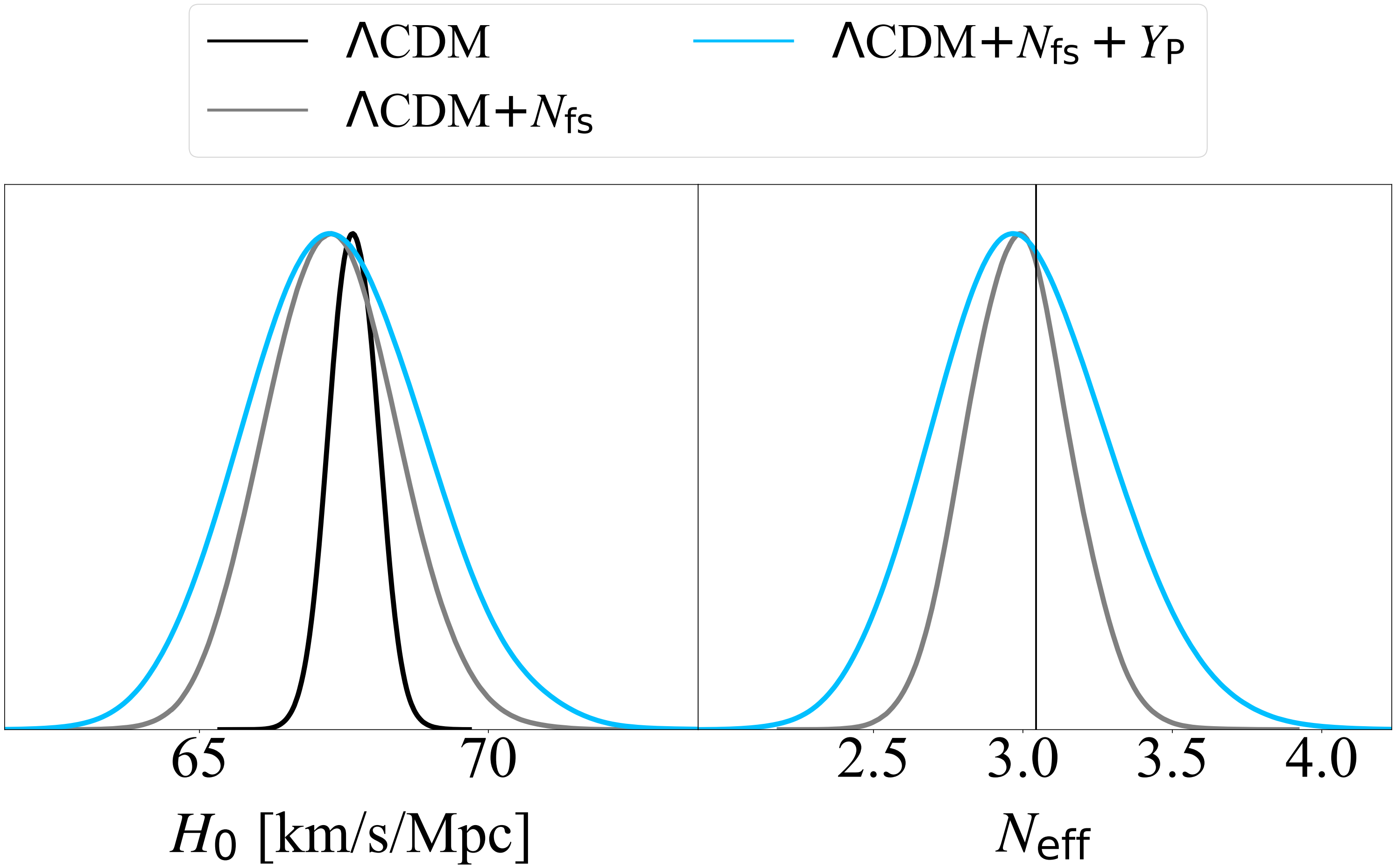

Implications for light relics

Why still constrained after taking care of diffusion problem?

$$\rho_{\rm rad} \to \lambda \rho_{\rm rad}$$

Increasing light relic energy density increases radiation density by definition

$$\rho_{\rm m} \to \lambda \rho_{\rm m}$$

Can increase density of non-relativistic matter (by adding more CDM)

$$\rho_{\Lambda} \to \lambda \rho_{\Lambda}$$

This scaling transformation still leads to some changes to gravitational potential evolution.
Q: What about this might lead to gravitational potential evolution?

Implications for light relics

Why still constrained after taking care of diffusion problem?

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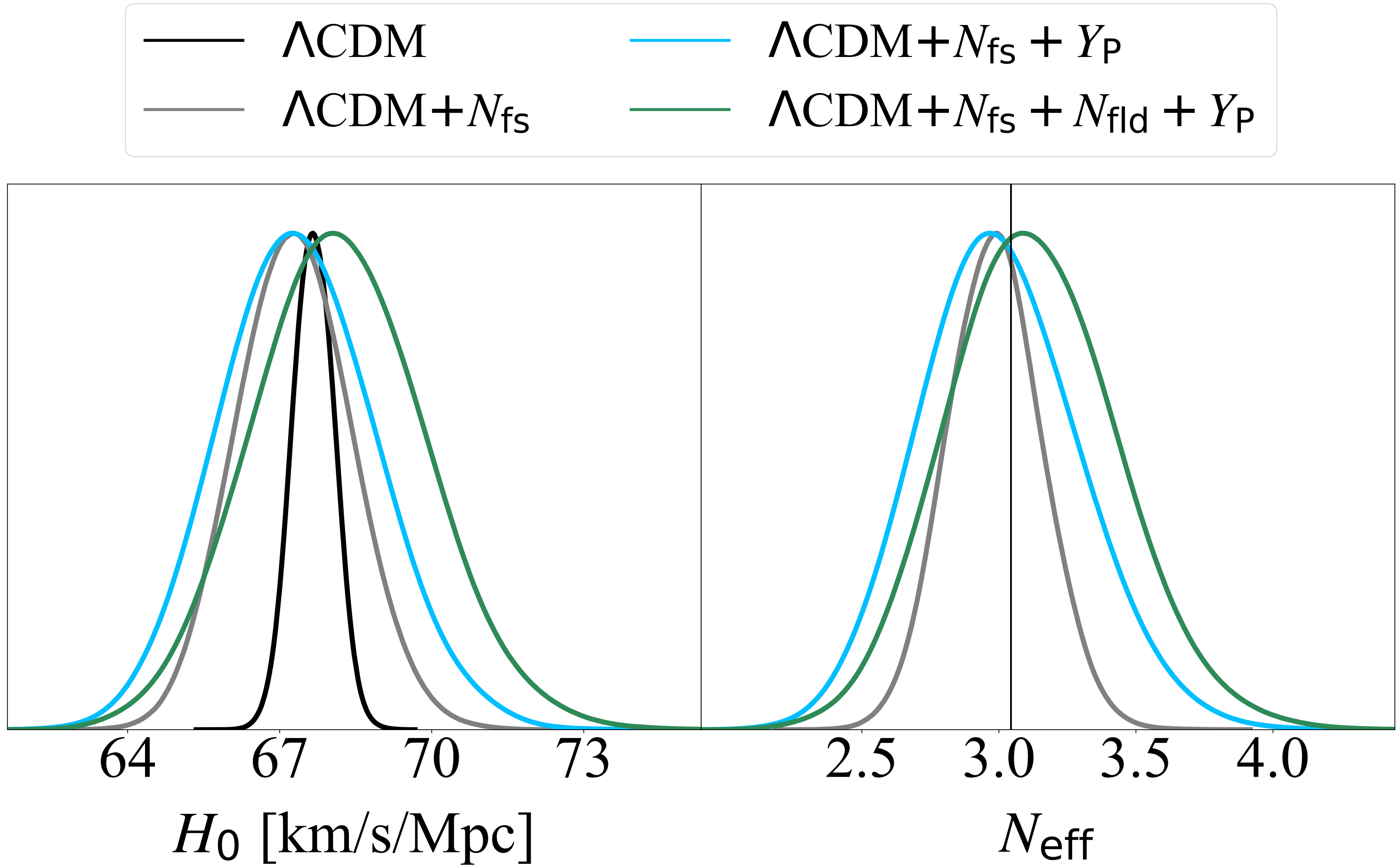
$$\rho_{\Lambda} \to \lambda\rho_{\Lambda}$$

This scaling transformation still leads to some changes to gravitational potential evolution.
Q: What about this might lead to gravitational potential evolution?

1) free-streaming light relics stream out of over densities at the speed of light as opposed to photons that do so at the plasma sound speed ==> grav potential decay is even faster (Bashinsky & Seljak 2004)
2) Baryons are pressure supported (prior to recombination) so are not falling freely like the CDM. Increasing the CDM to baryon ratio helps to preserve potential wells (Ge, Cyr-Racine & Knox 2023)

1D marginal posterior probability densities given Planck + BAO



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$$\Delta T/T(\theta,\phi), Q_{\rm CMB}(\theta,\phi), U_{\rm CMB}(\theta,\phi), \frac{\delta\rho_{\rm m}}{\rho_{\rm m}}(\theta,\phi,z)$$

are all invariant under

$$\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i}$$

$$\sigma_{\rm T} n_e \to \lambda \sigma_{\rm T} n_e$$

$$A_{\rm S} \to \lambda^{1-n_{\rm S}} A_{\rm S}$$

CGK [Cyr-Racine, Ge, and LK (2022)]

See also Zahn & Zaldarriaga (2003) who got partway there

The Free Fall, Amplitude, and Thomson (FFAT) scaling transformation

All the dimensional coefficients in the relevant Einstein and Boltzmann equations can be derived from:

$$\sqrt{G\rho_i}$$

$(\text{for each } i = \gamma, \nu, \text{CDM}, \text{baryons}, \Lambda)$

Free Fall Rate

$$k$$

Fourier wave number

$$\sigma_{\mathrm{T}} n_e$$

Thomson Scattering Rate

Cyr-Racine, Ge, and LK (2022)

Zahn and Zaldarriaga (2003)

All the dimensional coefficients in the relevant Einstein and Boltzmann equations can be derived from:

$$\sqrt{G\rho_i}$$

$(\text{for each } i = \gamma, \nu, \text{CDM}, \text{baryons}, \Lambda)$

Free Fall Rate

$$\sigma_{\rm T} n_e$$

Thomson Scattering Rate

$$k$$

Fourier wave number

Note that this includes $H = \sqrt{\frac{8\pi}{3} \sum_i G\rho_i}$

Cyr-Racine, Ge, and LK (2022)

Zahn and Zaldarriaga (2003)

$$\Delta T/T(\theta,\phi), Q_{\mathrm{CMB}}(\theta,\phi), U_{\mathrm{CMB}}(\theta,\phi), \frac{\delta\rho_{\mathrm{m}}}{\rho_{\mathrm{m}}}(\theta,\phi,z)$$

are all invariant under

$$\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i}$$

$$\sigma_{\mathrm{T}} n_e \to \lambda \sigma_{\mathrm{T}} n_e$$

$$A_{\mathrm{S}} \to \lambda^{1-n_{\mathrm{S}}} A_{\mathrm{S}}$$

Compensates for the k scaling

CGK [Cyr-Racine, Ge, and LK (2022)]

See also Zahn & Zaldarriaga (2003) who got partway there

The Free Fall, Amplitude, and Thomson (FFAT) scaling transformation

Ge, Cyr-Racine, and Knox
Phys. Rev. D (2023)

Cyr-Racine, Ge, and Knox
Phys. Rev. Lett. (2022)

Fei Ge (UC Davis)

Francis-Yan Cyr-Racine
(U. of New Mexico)

Barriers to implementing FFAT Scaling

$$\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i} \qquad \sigma_{\rm T} n_e \to \lambda \sigma_{\rm T} n_e \qquad A_{\rm S} \to \lambda^{1-n_{\rm S}} A_{\rm S}$$

Barriers to implementing FFAT Scaling

$\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i}$ $\sigma_{\mathrm{T}} n_e \to \lambda \sigma_{\mathrm{T}} n_e$ $A_{\mathrm{S}} \to \lambda^{1-n_{\mathrm{S}}} A_{\mathrm{S}}$

We've measured G and FIRAS has determined $\rho_{\gamma,0}$

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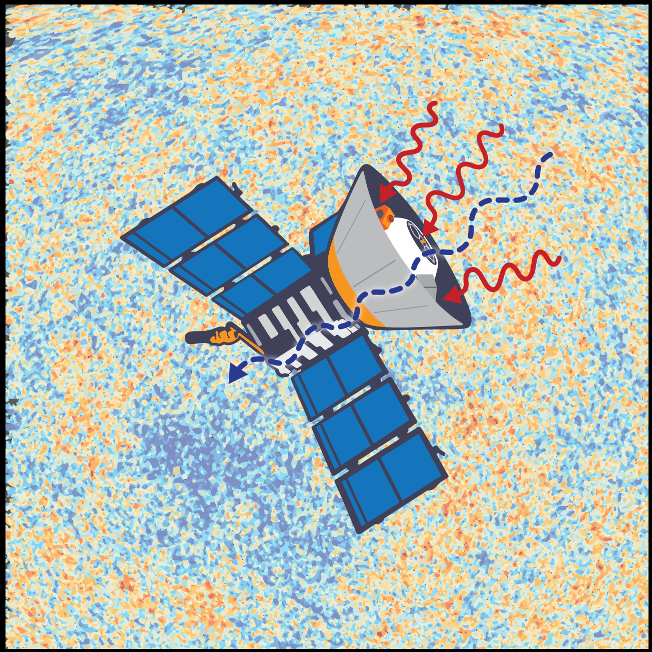
We've measured G and FIRAS has determined $\rho_{\gamma,0}$

Solution: Introduce a dark photon that allows for

$$\sqrt{G(\rho_\gamma + \rho_{D\gamma})} = \lambda\sqrt{G\rho_\gamma}$$

w/o violating FIRAS constraints



- To satisfy FIRAS we need **dark photons**
- They have to source metric perturbations like light photons do ==> transition from fluid to free streaming ==> we need **dark baryons** to enable dark recombination
- To preserve all the important rate ratios we also need a free-streaming additional light relic that we might call ‘**dark neutrinos**.’

Cosmological whackamole on steroids?

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Maybe not: we get all this from one copy of the standard model of particle physics.
a `mirror world' dark sector (MWDS)

e.g. Chacko et al. (2006)

Barriers to implementing FFAT Scaling

$\sqrt{G\rho_i} \rightarrow \lambda\sqrt{G\rho_i}$

$\sigma_{\mathrm{T}} n_e \rightarrow \lambda \sigma_{\mathrm{T}} n_e$

$A_{\mathrm{S}} \rightarrow \lambda^{1-n_{\mathrm{S}}} A_{\mathrm{S}}$

No barrier to this

Barriers to implementing FFAT Scaling

$$\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i} \qquad \sigma_{\mathrm{T}} n_e \to \lambda \sigma_{\mathrm{T}} n_e \qquad A_{\mathrm{S}} \to \lambda^{1-n_{\mathrm{S}}} A_{\mathrm{S}}$$

$$n_e(z) = X_e(z) n_B (1 - Y_{\mathrm{P}})$$

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Approximately achieve scaling by $1 - Y_{\rm P} \to \lambda(1 - Y_{\rm P})$

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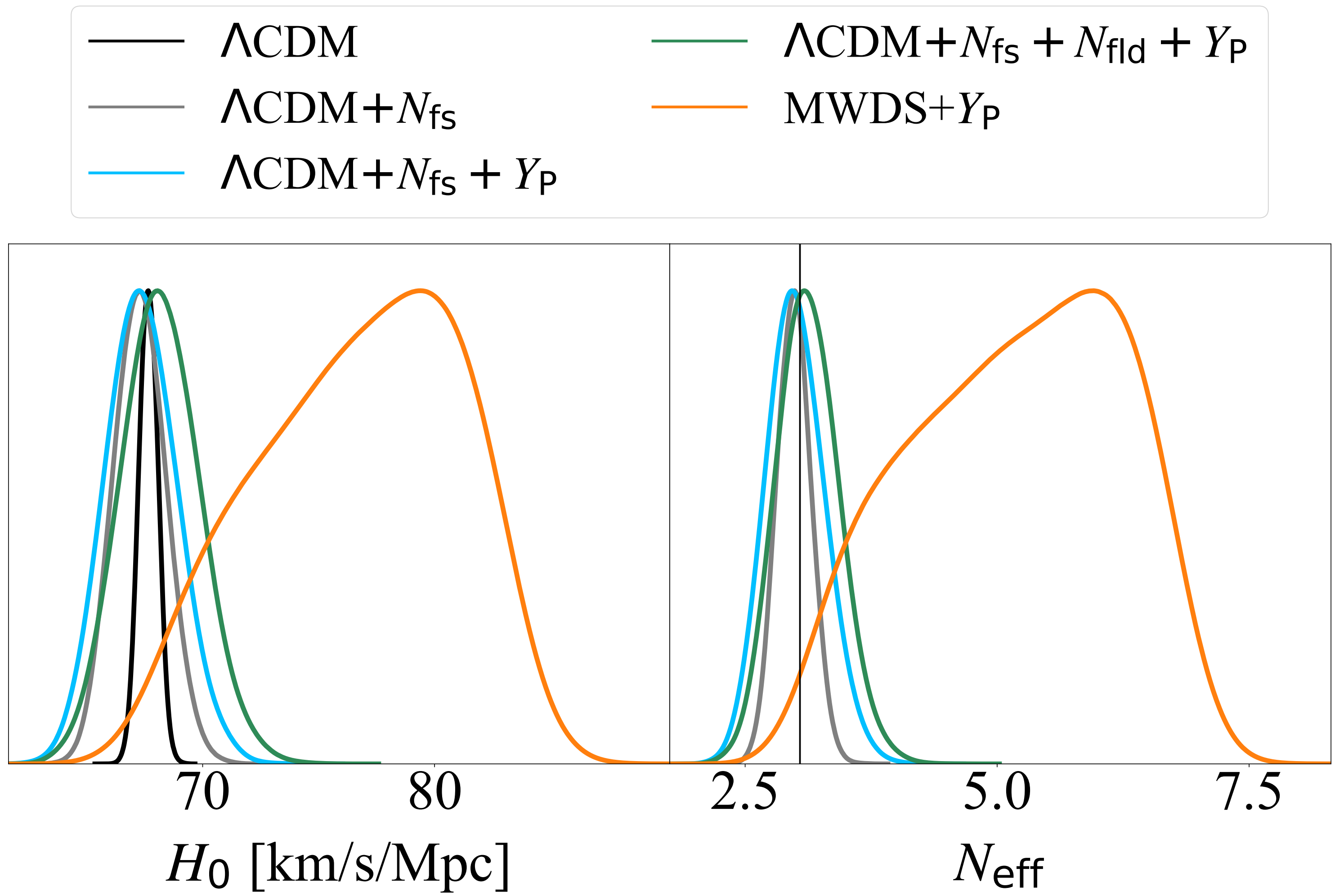
$$n_e(z) = X_e(z) n_B (1 - Y_{\rm P})$$

Sensitive to atomic reaction rates

Approximately achieve scaling by $1 - Y_{\rm P} \to \lambda(1 - Y_{\rm P})$

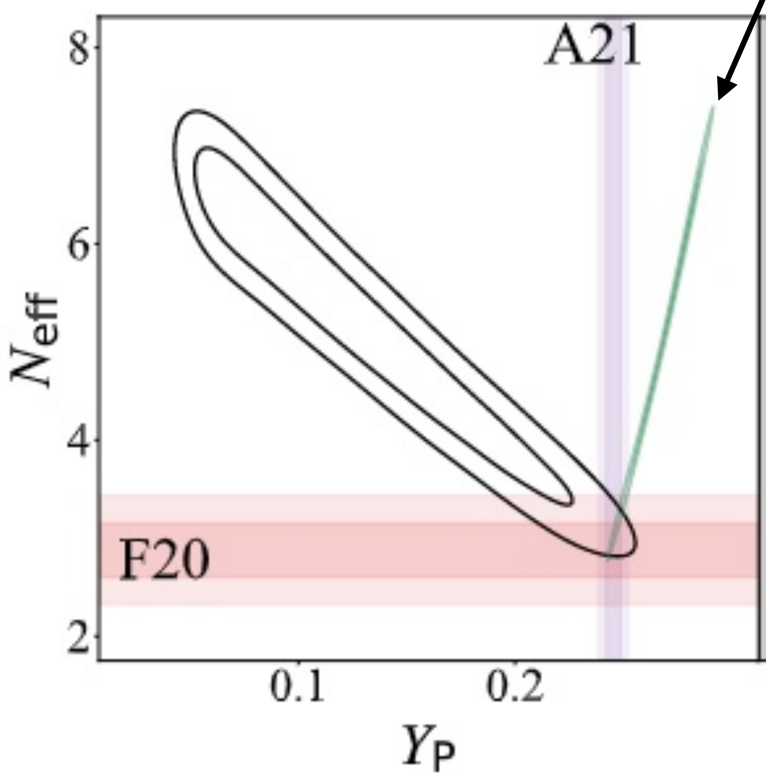
1D marginal posterior probability densities given Planck + BAO



BBN Consistent Yp

A21 = measurement of Yp (Aver et al. 2021)

Contours assume MWDS + free Yp



F20 = constraints on Neff from BBN + D/H and Yp measurements (Fields et al. 2020)

Ge, Cyr-Racine & LK (2023)

Rate Ratio Changes and Related Observational Impact

Rate ratio change	Observational Impact	Quantitative Impact on CMB Power Spectra from 10% change	Prior literature
1. $\sigma_\mathrm{T} n_\mathrm{e}(z)/H(z)$	Silk damping Polarization generation	10 to 15%	Hu & White (1996), Zahn & Zaldarriaga (2004), Martins et al. (2010), Hou et al. (2013)
2. $\frac{\sqrt{\rho_\mathrm{rad,fs}}}{\sqrt{\rho_\mathrm{rad,fluid}}}$	Early boost to delta rho/rho Temporal phase shift in acoustic oscillations	5 to 6%	Bashinksy & Seljak (2004), Follin et al. (2015), Baumann et al. (2016)
3. $\frac{\sqrt{\rho_\mathrm{m,pressure}}}{\sqrt{\rho_\mathrm{m,pressureless}}}$	Baryon-like effect on acoustic peak heights Changes to matter power spectrum	2 to 3%	Ge, Cyr-Racine & Knox (2023)
4. $\text{recombination rates}/H(z)$	All changes flow through 1.	1 to 2%	Zahn & Zaldarriaga (2003) Ge, Cyr-Racine & LK (2023)

Outline

- Hubble constant from the CMB (and LCDM)
- Acoustic dynamics are very sensitive to gravitational potential evolution ==> strong constraints to the introduction of new components and new interactions
- Implications for models with light relics
- FFAT scaling transformation symmetry and a rate ratio perspective
- Recombination?

From the Hubble Hunter's Guide:

The failure of α variation as a way to get to small $r_s^\star$ is a specific example of what we expect to be true in general: changes to the physics of recombination sufficient to change the sound horizon by 7% will wreak havoc on the shape of the damping tail. Admittedly, we have no proof that such a solution is not possible. But it seems highly unlikely that new physics alters $r_s^\star$ by changing recombination, while having an acceptably small impact on the shape of the CMB damping tail.

The unlikeliness is underscored by the fact that recombination occurs out of chemical equilibrium – the relevant atomic per-particle reaction rates are not much faster than the Hubble rate. The particular details of the ionization history resulting from this out-of-equilibrium recombination are marvelously consistent with the shape of the damping tail. Thus the task is more challenging than simply reproducing a generic equilibrium ionization history at a higher temperature.

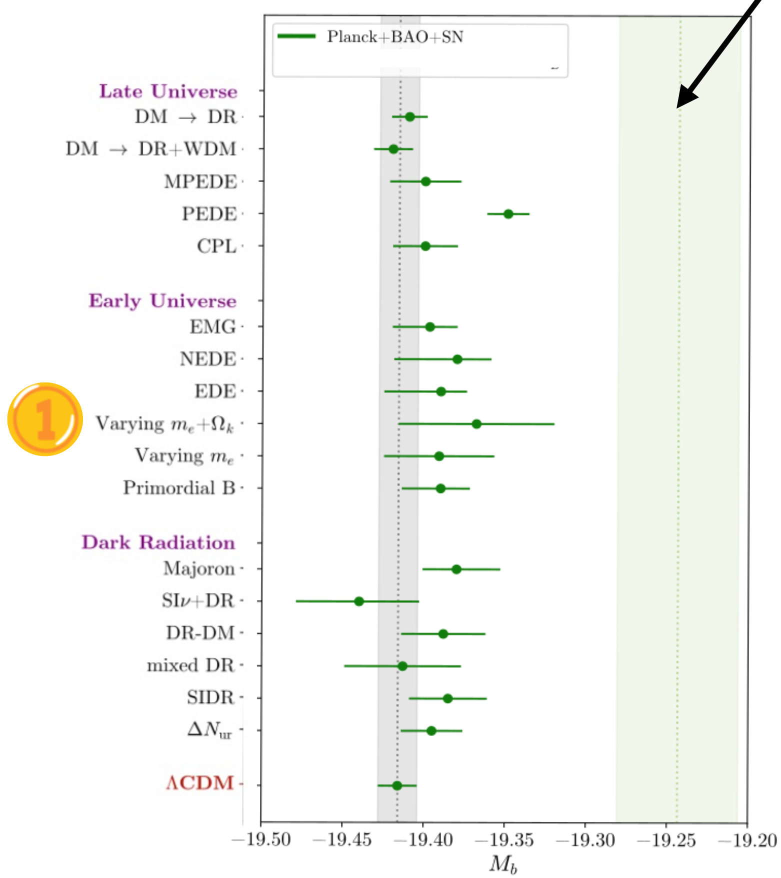
State of Theory

Hubble Constant Problem

Cepheid-calibrated supernovae

SHoES (Riess et al. 2021)

Figure adapted from "The H_0 Olympics: a Fair Comparison of Models" by Schöneberg et al. (2022)



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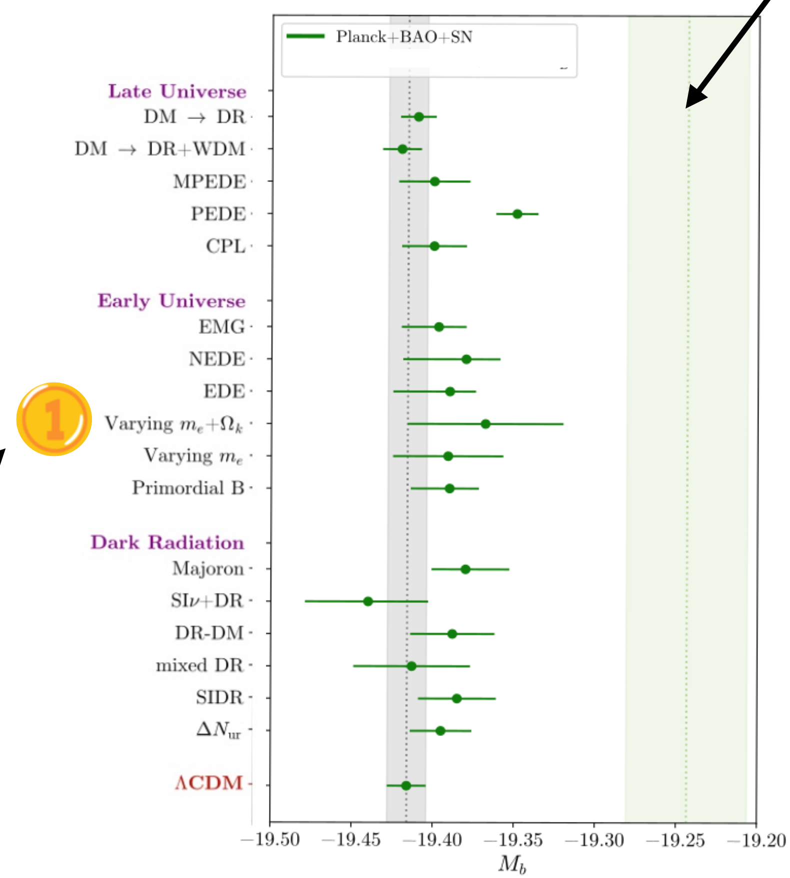
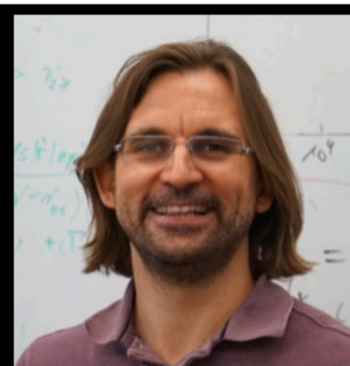


Changing recombination!

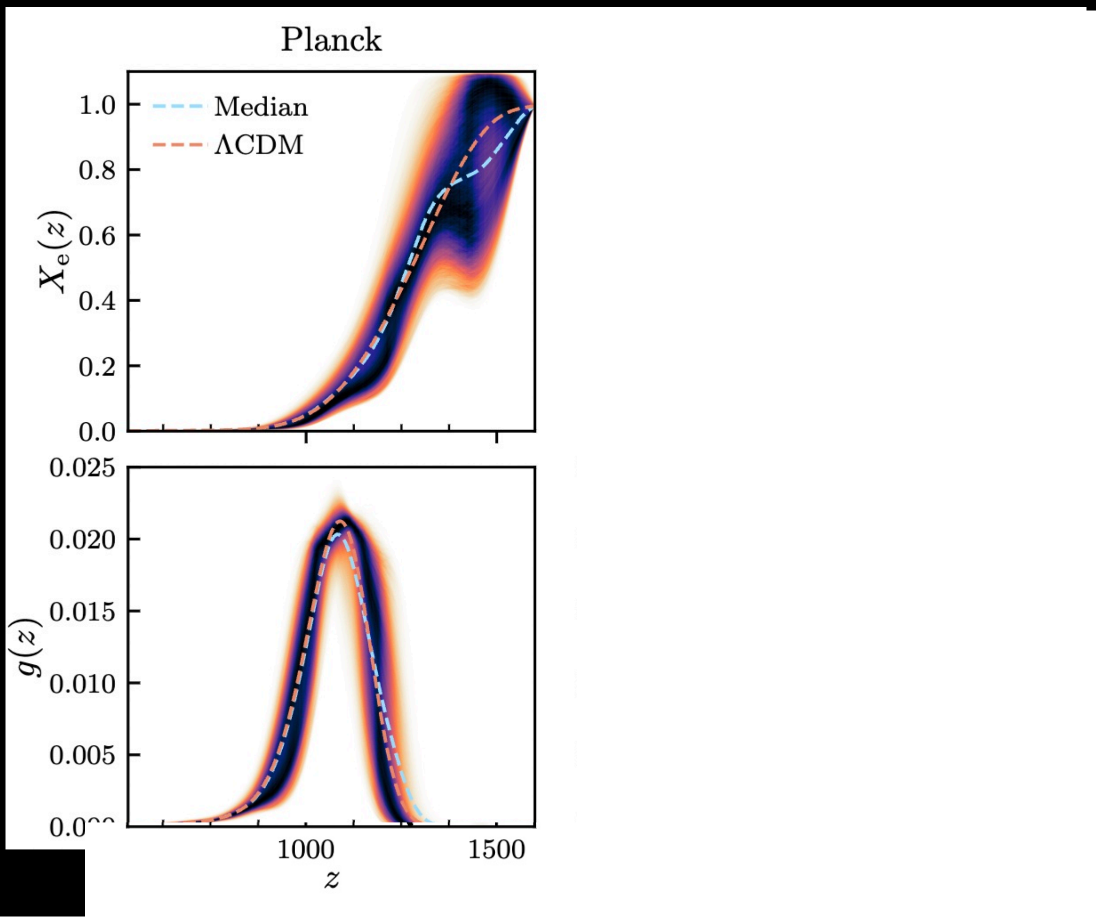
Reconstructing the recombination history by combining early and late cosmological probes, arXiv:2404.05715

Gabe Lynch (UC Davis)



Jens Chluba (Manchester)

- “ModRec” = Let $X_e(z)$ be determined by 7 control points and interpolation between them, and otherwise assume LCDM



- Huge departures are allowed!

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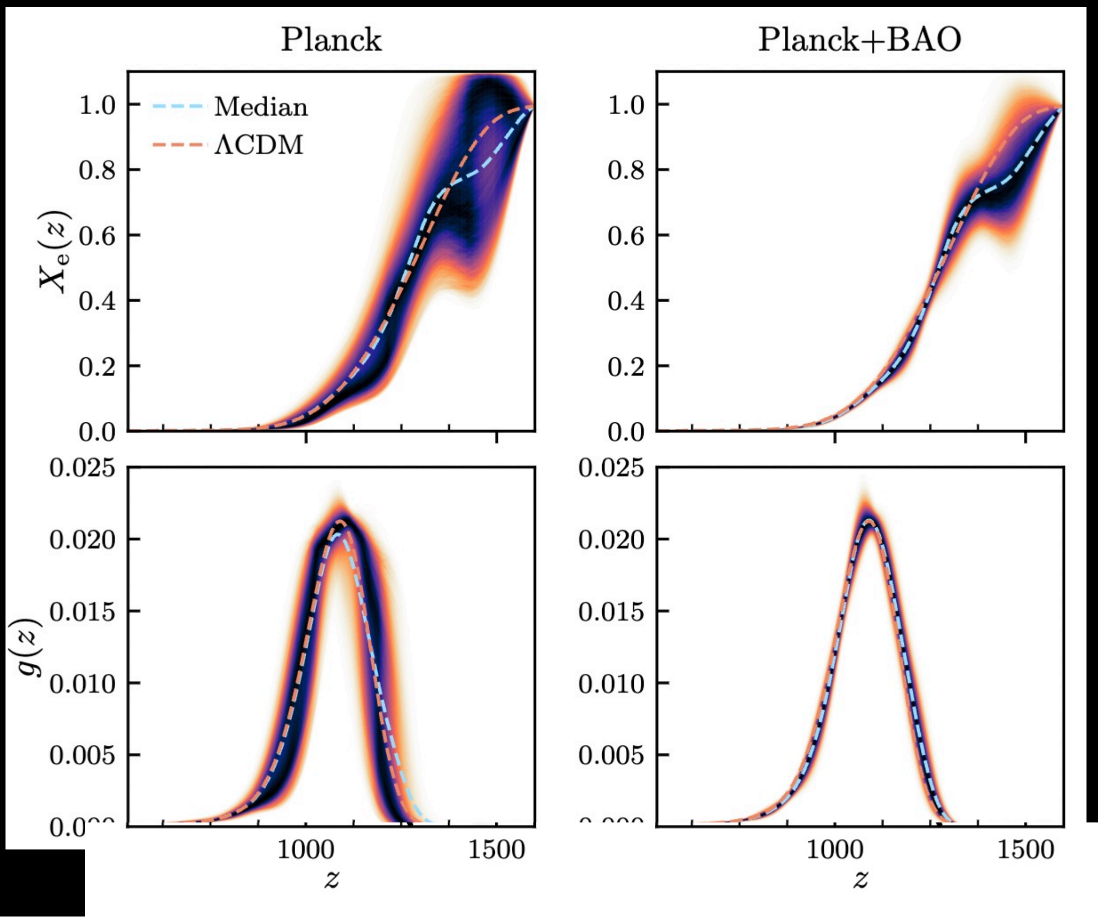


- Huge departures are allowed!
- BAO makes big difference via constraints on Ω_m and $r_d H_0$

[Submitted on 14 Jun 2024]

DESI and the Hubble tension in light of modified recombination

Gabriel P. Lynch, Lloyd Knox, Jens Chluba

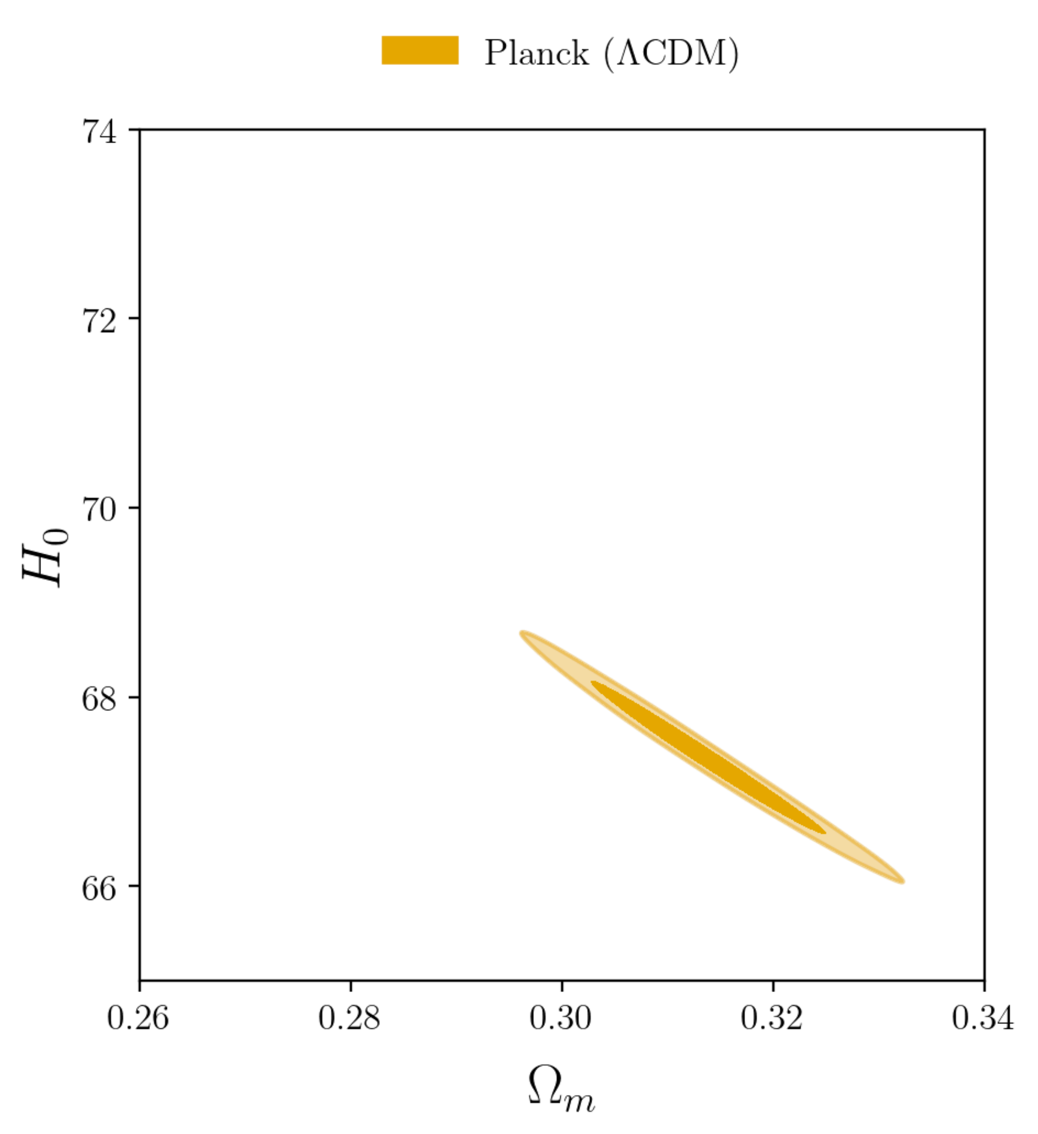
Recent measurements and analyses from the Dark Energy Spectroscopic Instrument (DESI) Collaboration and supernova surveys combined with cosmic microwave background (CMB) observations, indicate that the dark energy density changes over time. Here we explore the possibility that the dark energy density is constant, but that the cosmological recombination history differs substantially from that in ΛCDM. When we free up the ionization history, but otherwise assume the standard cosmological model, we find the combination of CMB and DESI data prefer i) early recombination qualitatively similar to models with small-scale clumping, ii) a value of H_0 consistent with the estimate from the SH0ES Collaboration at the 2σ level, and iii) a higher CMB lensing power, which takes pressure off of otherwise tight constraints on the sum of neutrino masses. Our work provides additional motivation for finding physical models that lead to the small-scale clumping that can theoretically explain the ionization history preferred by DESI and CMB data.

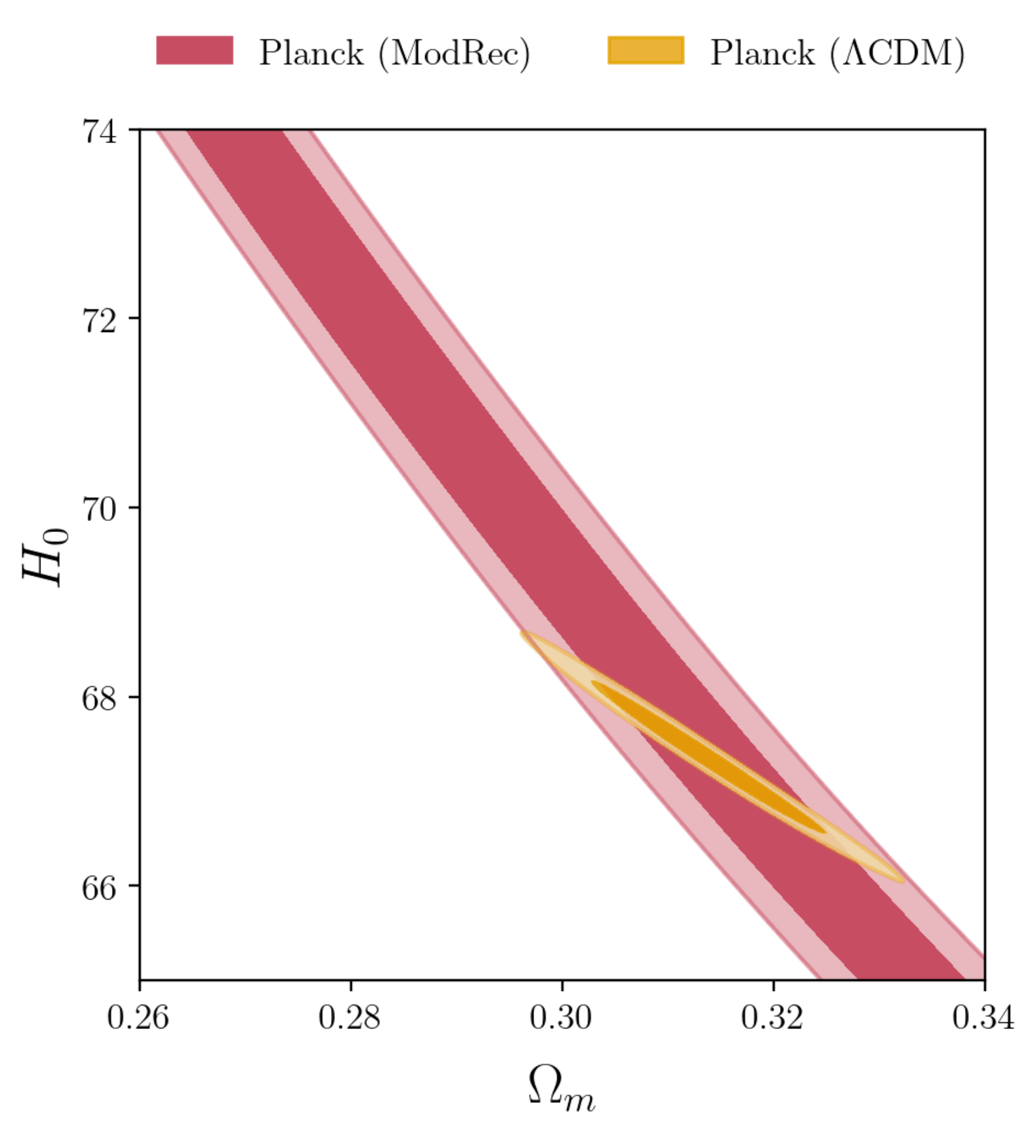
From intersection of

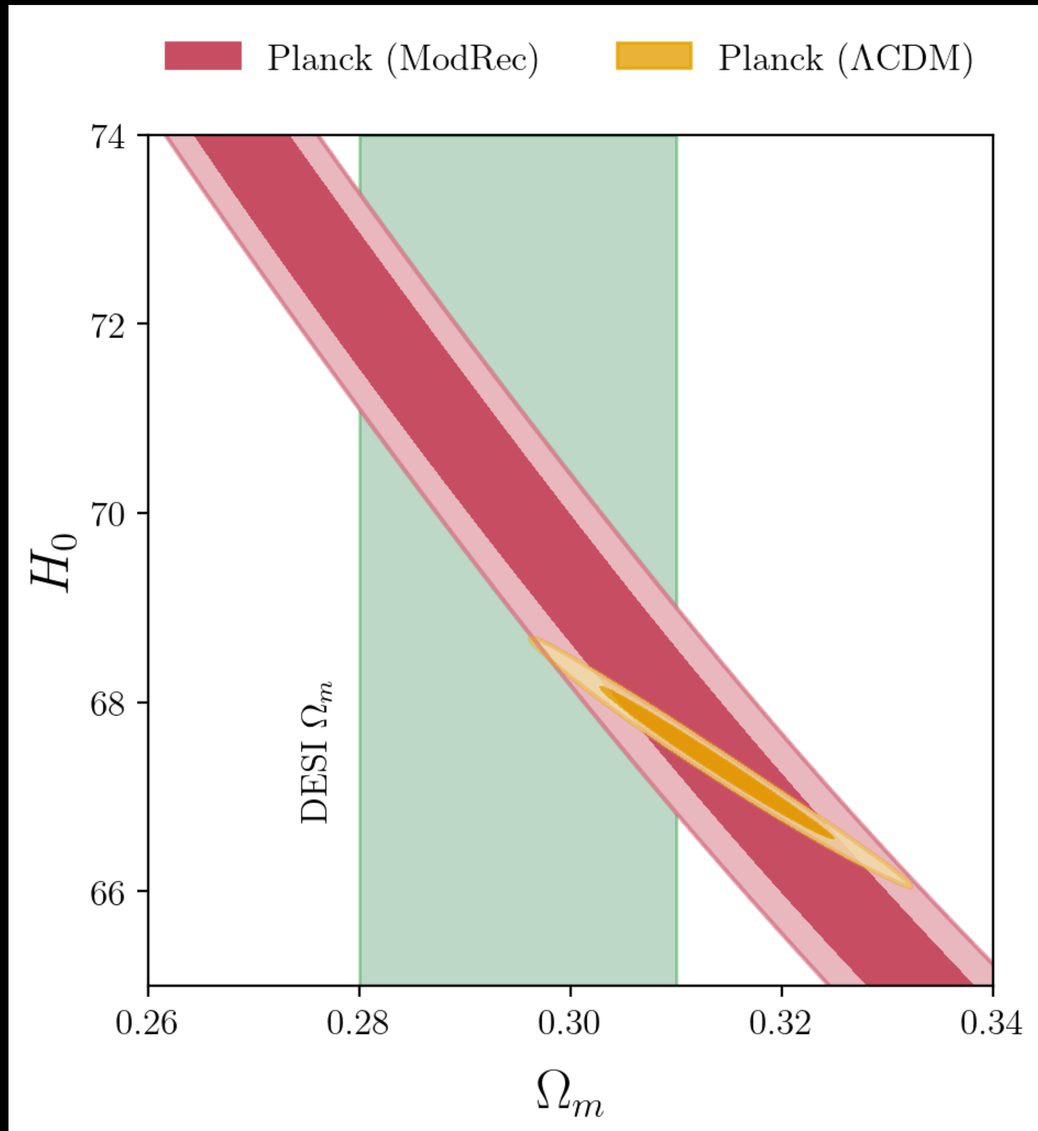
constraint on $\Omega_m h^2$
from radiation-driving effect

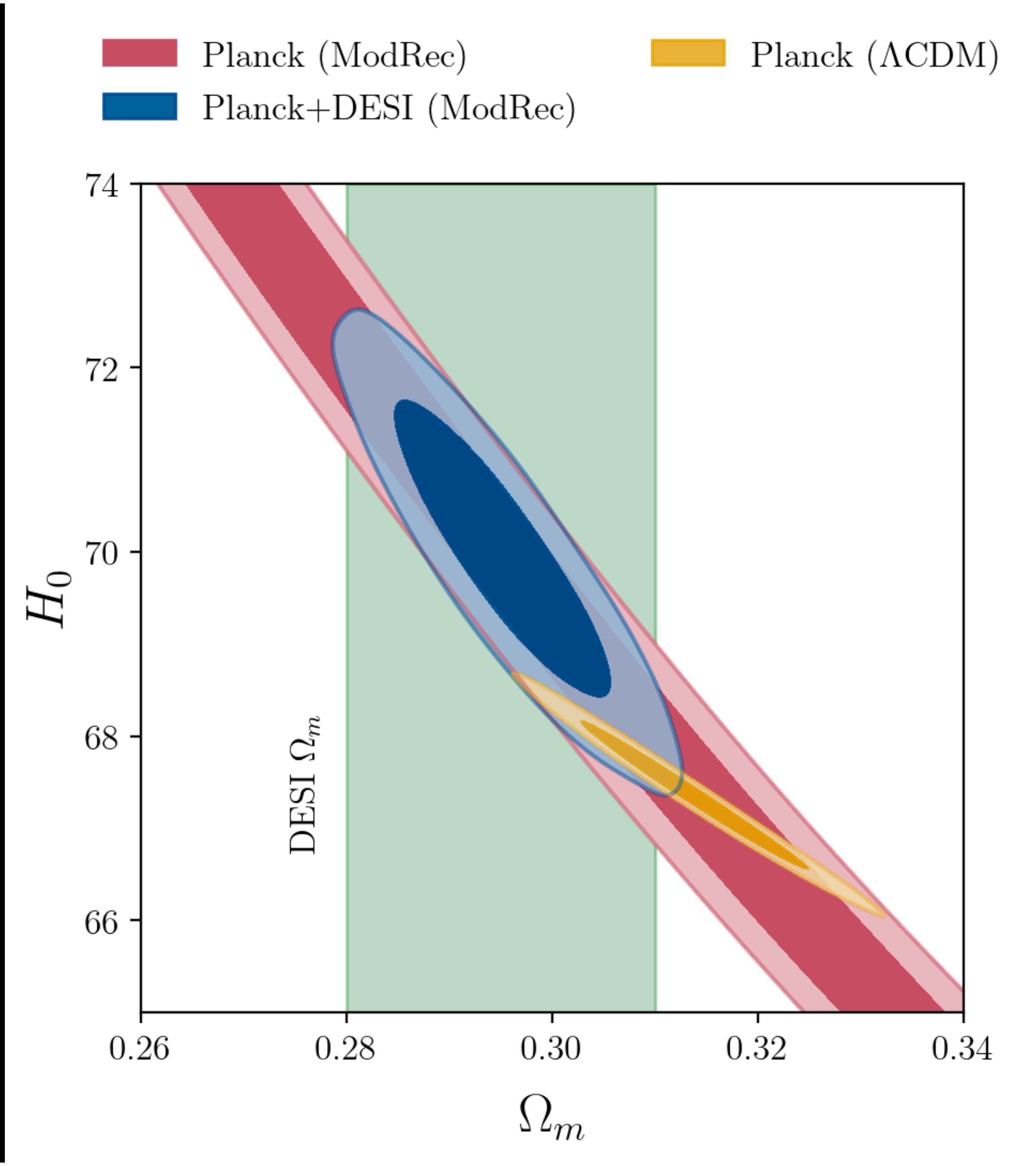
and

constraint on $\Omega_m h^3$
which correlates strongly in LCDM with the angular size of the sound horizon

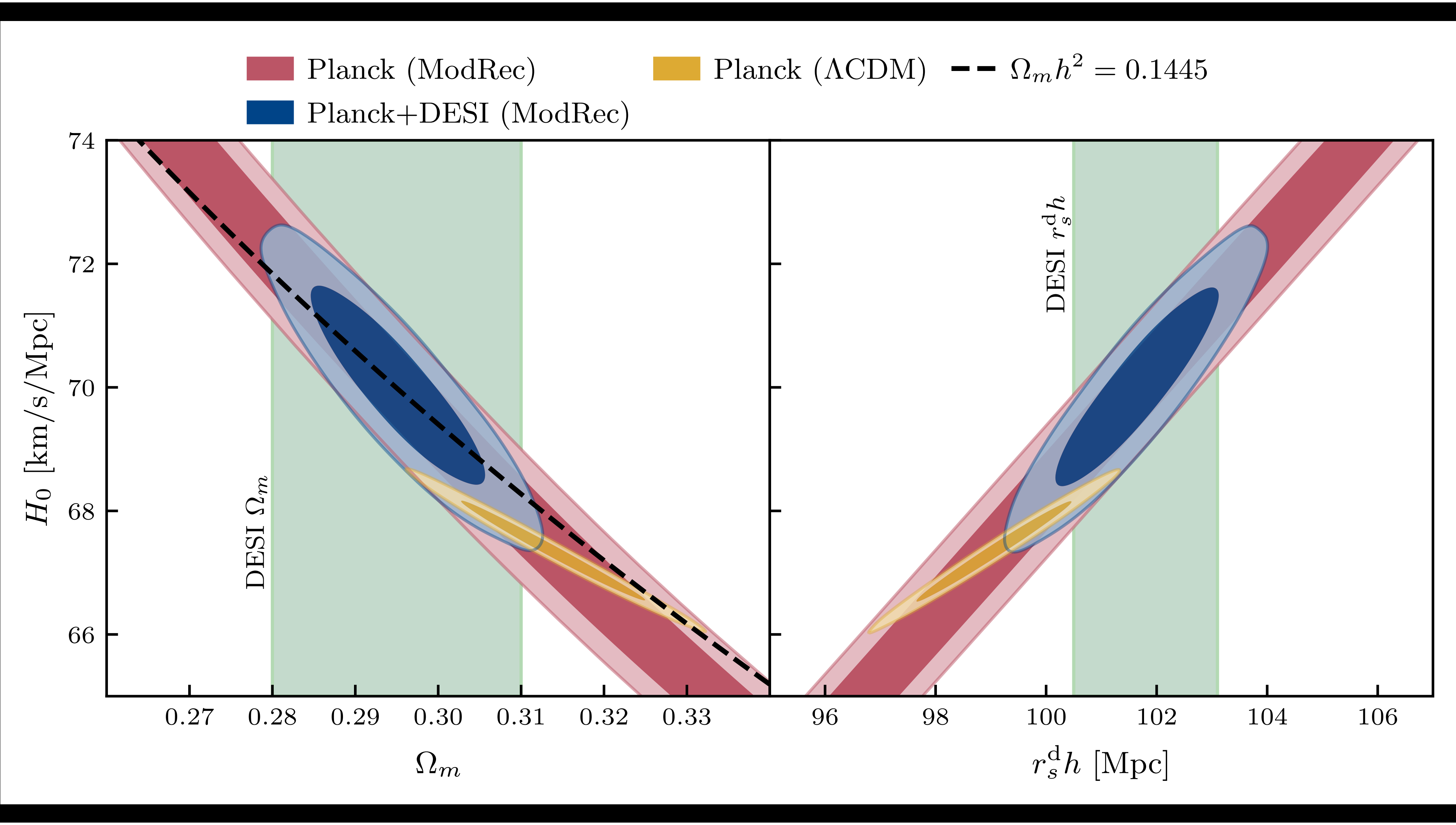



Planck (ModRec)
Planck (ΛCDM)
74
72
70
68
66
H_0
0.26
0.28
0.30
0.32
0.34
Ω_m


Planck (ModRec)
Planck (ΛCDM)
74
72
70
68
66
H_0
DESI Ω_m
0.26
0.28
0.30
0.32
0.34
Ω_m

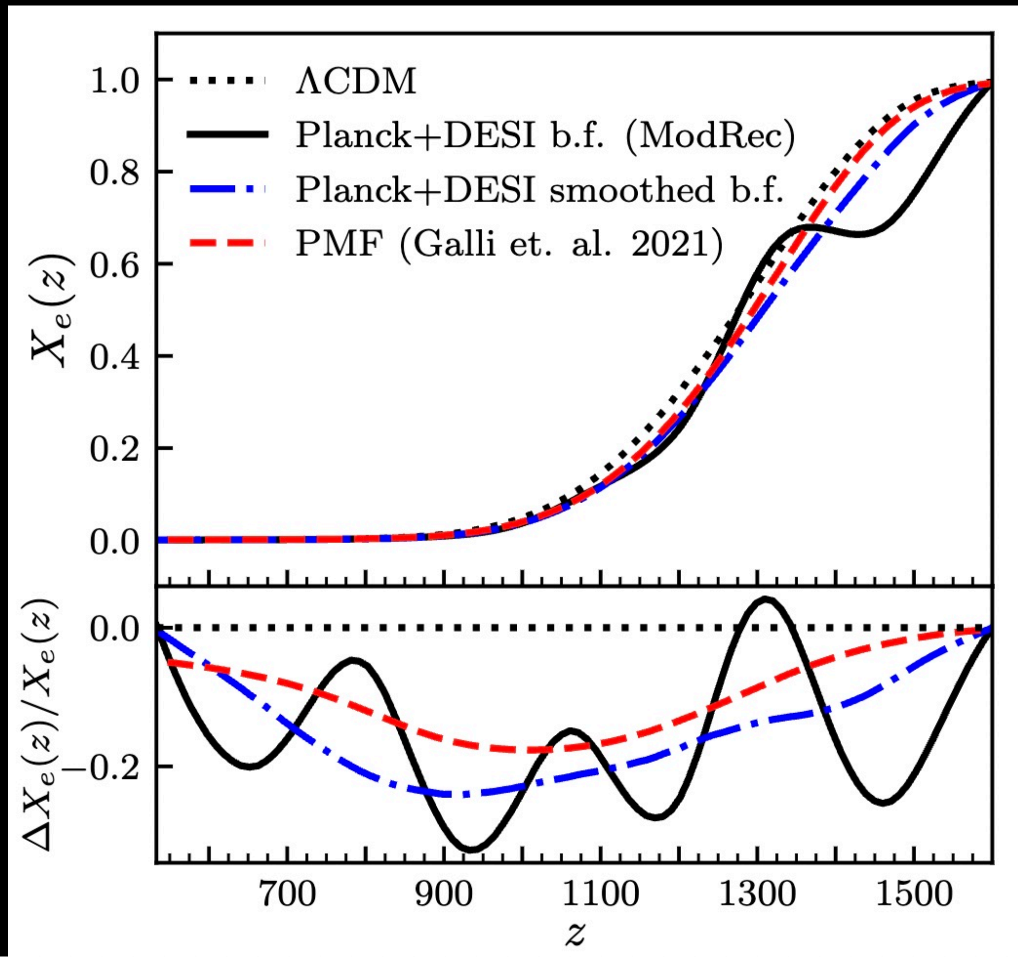


Planck (ModRec)
Planck+DESI (ModRec)
Planck (ΛCDM)
74
72
70
68
66
H_0
DESI Ω_m
0.26
0.28
0.30
0.32
0.34
Ω_m



Planck (ModRec)
Planck (ΛCDM)
$\Omega_m h^2 = 0.1445$
Planck+DESI (ModRec)
H_0 [km/s/Mpc]
74
72
70
68
66
DESI Ω_m
0.27
0.28
0.29
0.30
0.31
0.32
0.33
Ω_m
DESI $r_s^{\mathrm{d}} h$
96
98
100
102
104
106
$r_s^{\mathrm{d}} h$ [Mpc]

What physics could cause this?



CMB Theory

See talks tomorrow by Staggs and Schaan who will talk about experiments and the future

Summary

- Angular scales of CMB power spectra that are very precisely measured are sensitive to gravitational potential evolution in the decade of scale factor evolution prior to matter-radiation equality.
- We explored this in some detail, together with constraints from photon diffusion, in the case of light relics. But the physics applies much more broadly to provide sensitivity to additional components and their interactions during that epoch.
- A "mirror world dark sector" together with something to scale up the Thomson scattering rate can allow for very high values of H_0, but it then raises questions about light element abundances.
- FFAT scaling is a useful tool for analytic understanding of parameter constraints.
- If we really have to accommodate a high H_0, it might have to do with the physics of recombination. I still see this as unlikely since the standard model works so well, an impressive success. The kind of recombination modifications that boost H_0 are testable in the near future with forthcoming SPT-3G and ACT data!

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Michael and Ester Vaida