Title: The cosmology of electron scalars

Speakers: Zach Weiner

Series: Particle Physics

Date: November 28, 2023 - 11:00 AM

URL: https://pirsa.org/23110081

Abstract: The cosmic microwave background is a sensitive probe of early-Universe physics, and yet fundamental constants at recombination can differ from their present-day values due to degeneracies in the standard cosmological model. Such scenarios have been invoked to reconcile discrepant measurements of the present-day expansion rate, but even absent such motivation they raise the intriguing possibility of yet-undiscovered physics coupled directly to Standard Model particles. I will discuss theories in which a new scalar field shifts the electron's mass at early times; viable models are already stringently constrained by measurements of quasar absorption lines, the abundances of light elements, and the universality of free fall. I will show that the remaining parameter space is exactly that which allows not only the primary cosmic microwave background but also low-redshift distances to be consistent with observations. After presenting the results of parameter inference I will discuss additional cosmological and laboratory signatures of the model.

Zoom link https://pitp.zoom.us/j/99705853481?pwd=MTZRWC9hREkvOXpiZkxCM3UvdnRNQT09

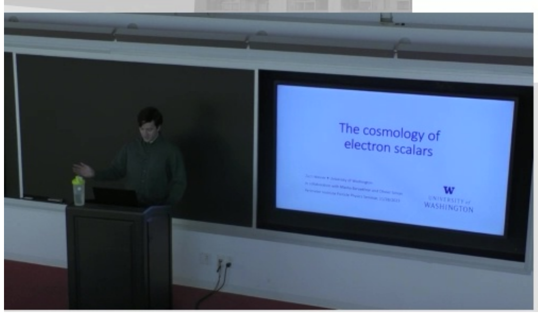
The cosmology of electron scalars

Zach Weiner • University of Washington

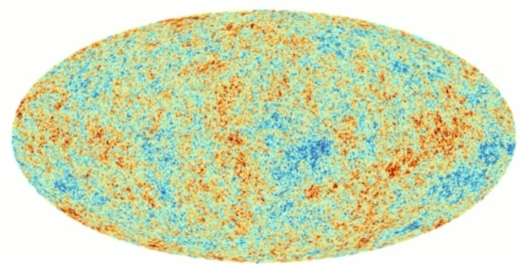
in collaboration with Masha Baryakhtar and Olivier Simon

Perimeter Institute Particle Physics Seminar, 11/28/2023

UNIVERSITY of WASHINGTON



questions and answers from cosmology

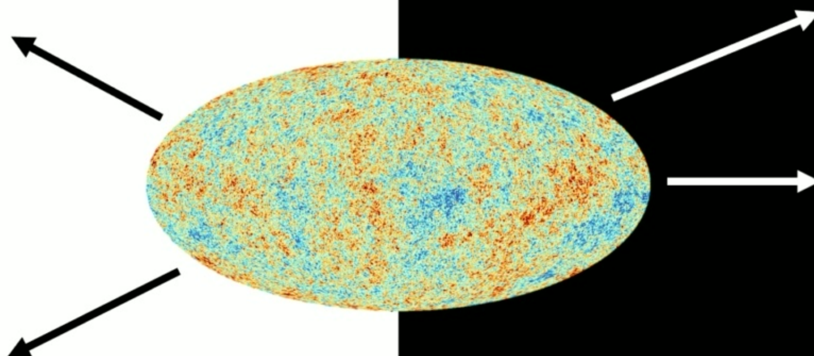


questions and answers from cosmology

Big Bang

$\gamma \longleftrightarrow e^+, e^-, p$

SM particles: initial hot, thermal state



neutrinos

$\sum m_\nu \lesssim 0.12\,\mathrm{eV}$

abundance consistent with weak decoupling

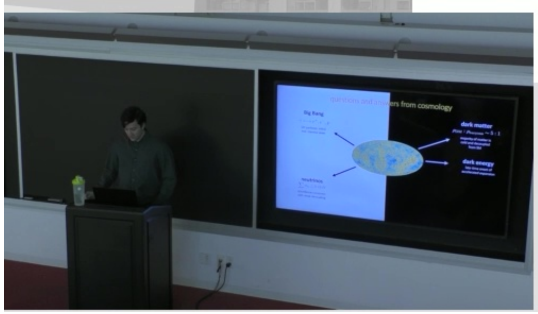
dark matter

$\rho_{\mathrm{DM}} : \rho_{\mathrm{baryons}} \sim 5:1$

majority of matter is cold and decoupled from SM

dark energy

late-time onset of accelerated expansion

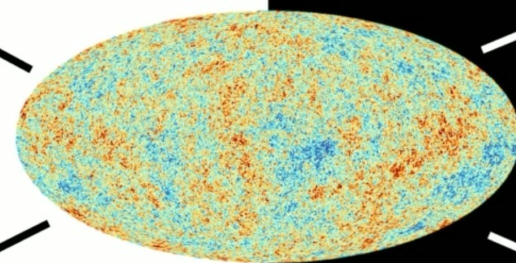


questions and answers from cosmology

Big Bang

$$X \overset{???}{\longleftrightarrow} \gamma \longleftrightarrow e^+, e^-, p \overset{???}{\longleftrightarrow} Y$$

what else can we learn
about (beyond) Standard
Model particle physics?

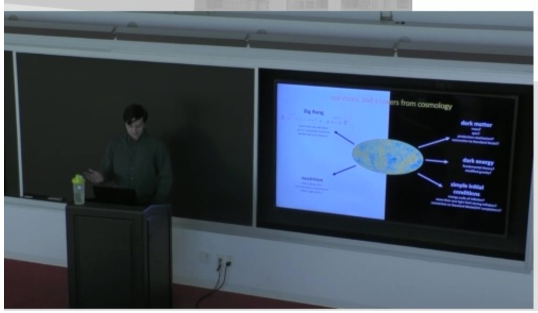


dark matter
mass?
spin?
production mechanism?
connection to Standard Model?

dark energy
fundamental theory?
modified gravity?

simple initial conditions
energy scale of inflation?
more than one light field during inflation?
connection to Standard Model/UV completions?

neutrinos
mass hierarchy?
nonstandard interactions?
other light relics?

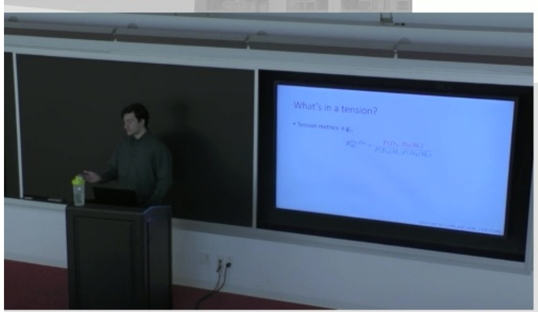


What's in a tension?

- Tension metrics: e.g.,

$$R_{M_1}^{D_A,D_B} = \frac{P(D_A, D_B|M_1)}{P(D_A|M_1)P(D_B|M_1)}$$

stated well by Cortês and Liddle, 2309.03286



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**marginalized over parameter space*

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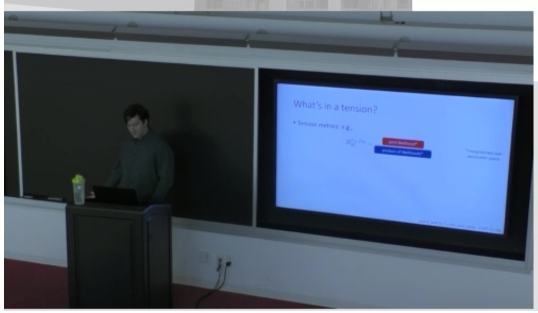

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**marginalized over parameter space*

- But I don’t care what H_0 is
- Model selection quantified via Bayes factor:

$$B^{D_A,D_B}_{M_1,M_2} = \text{ratio of joint likelihoods*}$$

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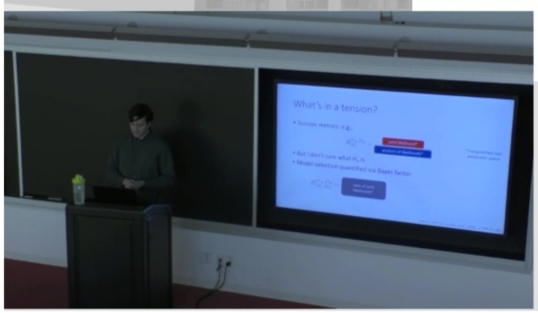

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*marginalized over parameter space

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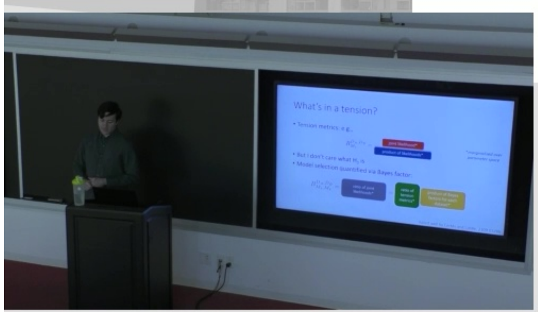
$$B_{M_1,M_2}^{D_A,D_B} = \text{ratio of joint likelihoods*} = \text{ratio of tension metrics*} \quad \text{product of Bayes factors for each dataset*}$$

stated well by Cortês and Liddle, 2309.03286



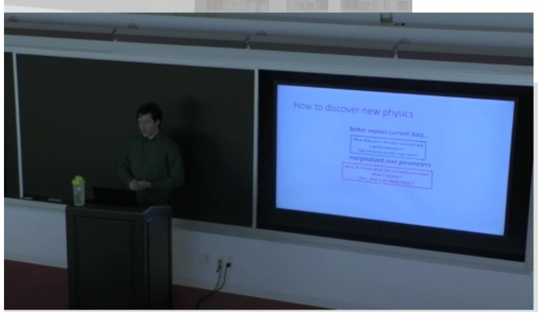
How to discover new physics

Better explain current data…

What features in the data currently lack
a good explanation?
How seriously should I take them?

…marginalized over parameters

What do I know about the microphysical model?
What's my prior?
(Also: what is the Bayes factor?)



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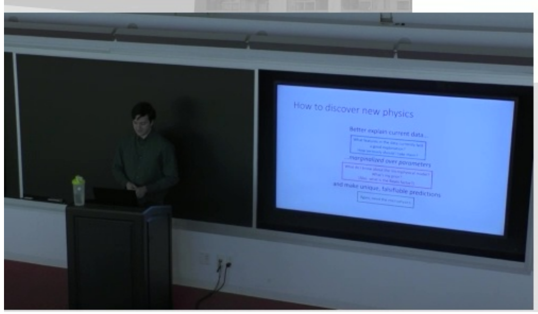
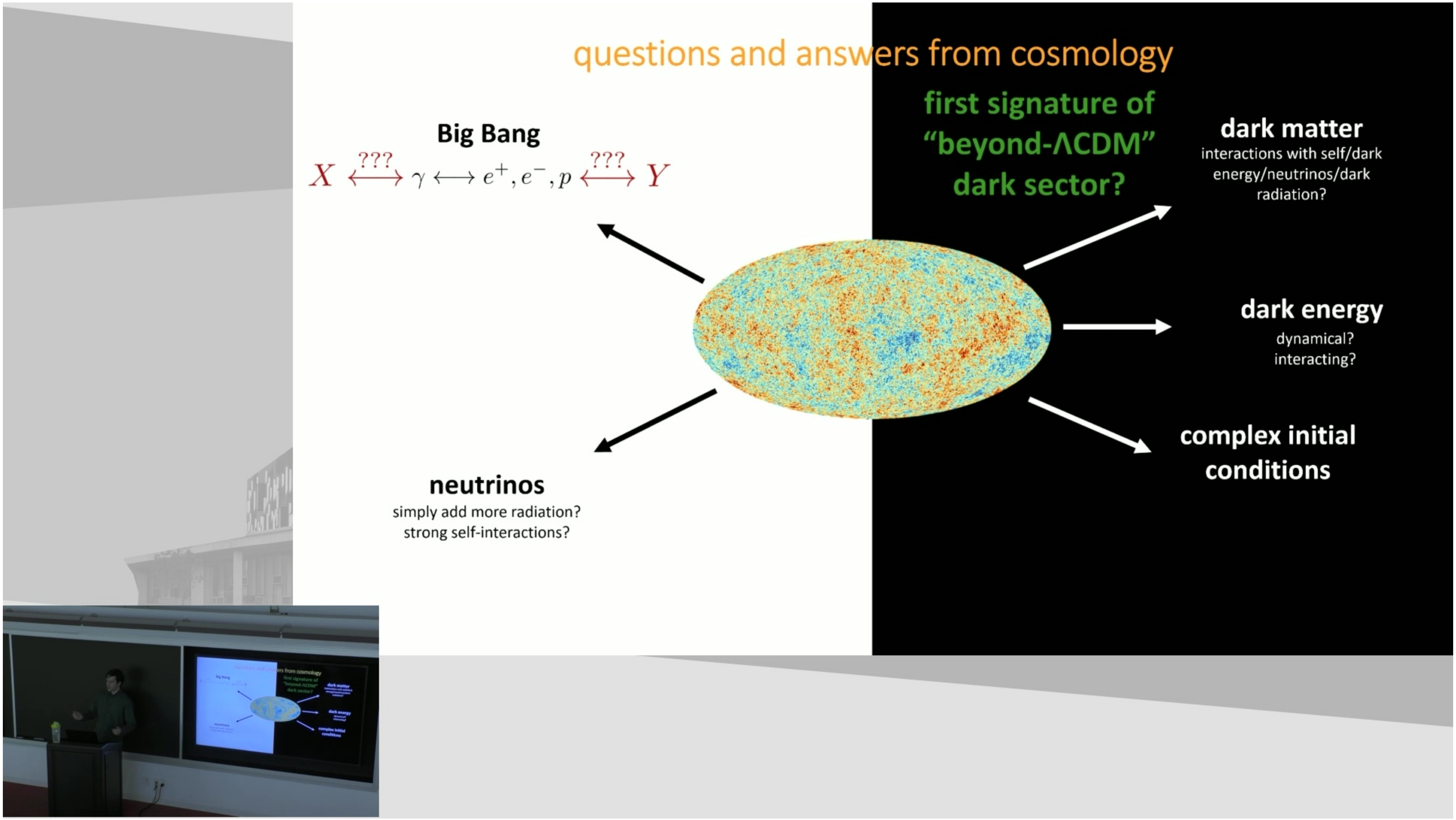
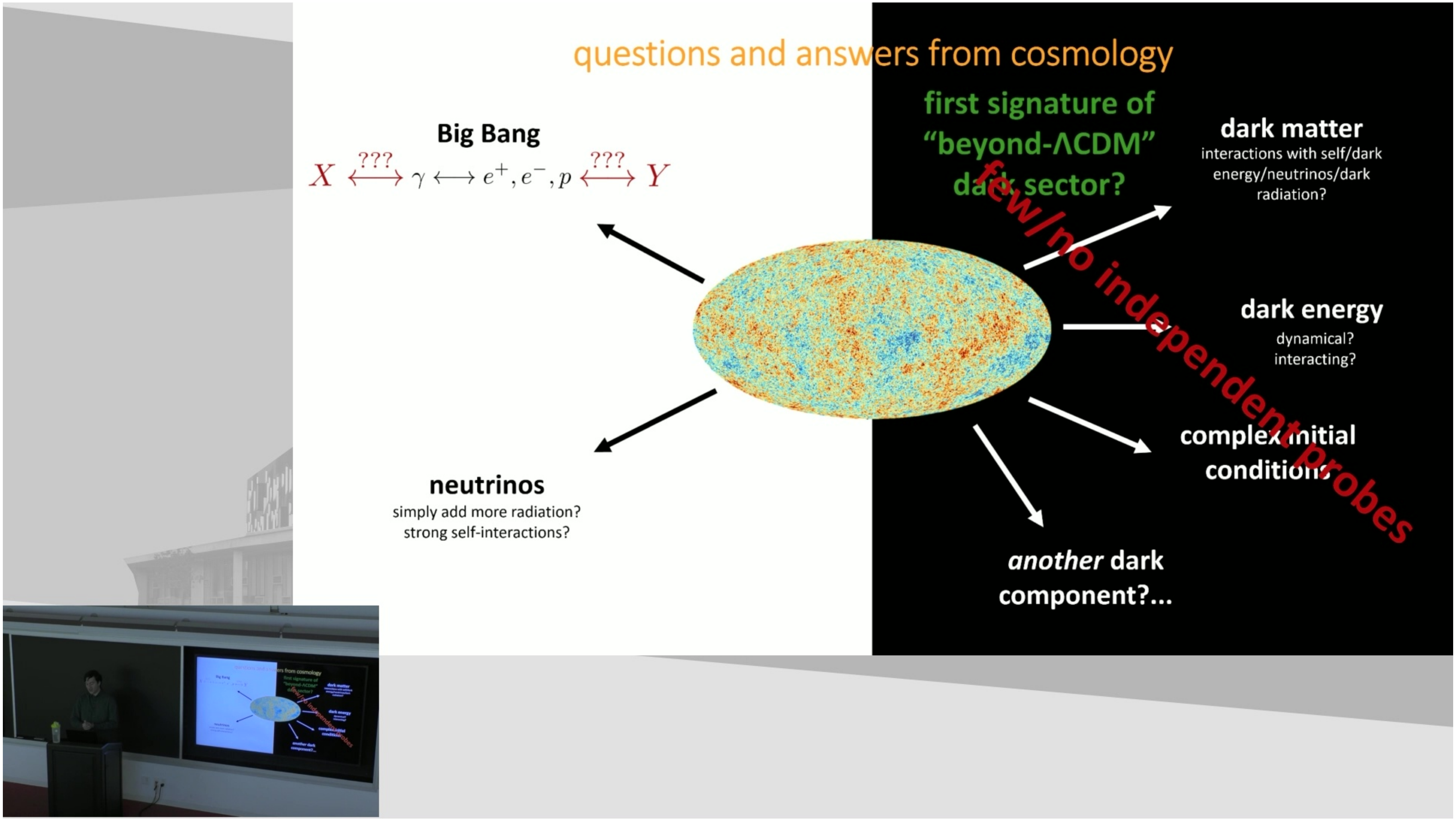
and make unique, falsifiable predictions

Again, need the microphysics




questions and answers from cosmology
Big Bang
$X \overset{???}{\longleftrightarrow} \gamma \longleftrightarrow e^+, e^-, p \overset{???}{\longleftrightarrow} Y$
neutrinos
simply add more radiation?
strong self-interactions?
first signature of
"beyond-ΛCDM"
dark sector?
dark matter
interactions with self/dark energy/neutrinos/dark radiation?
dark energy
dynamical?
interacting?
complex initial conditions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complex initial conditions
another dark component?...
neutrinos
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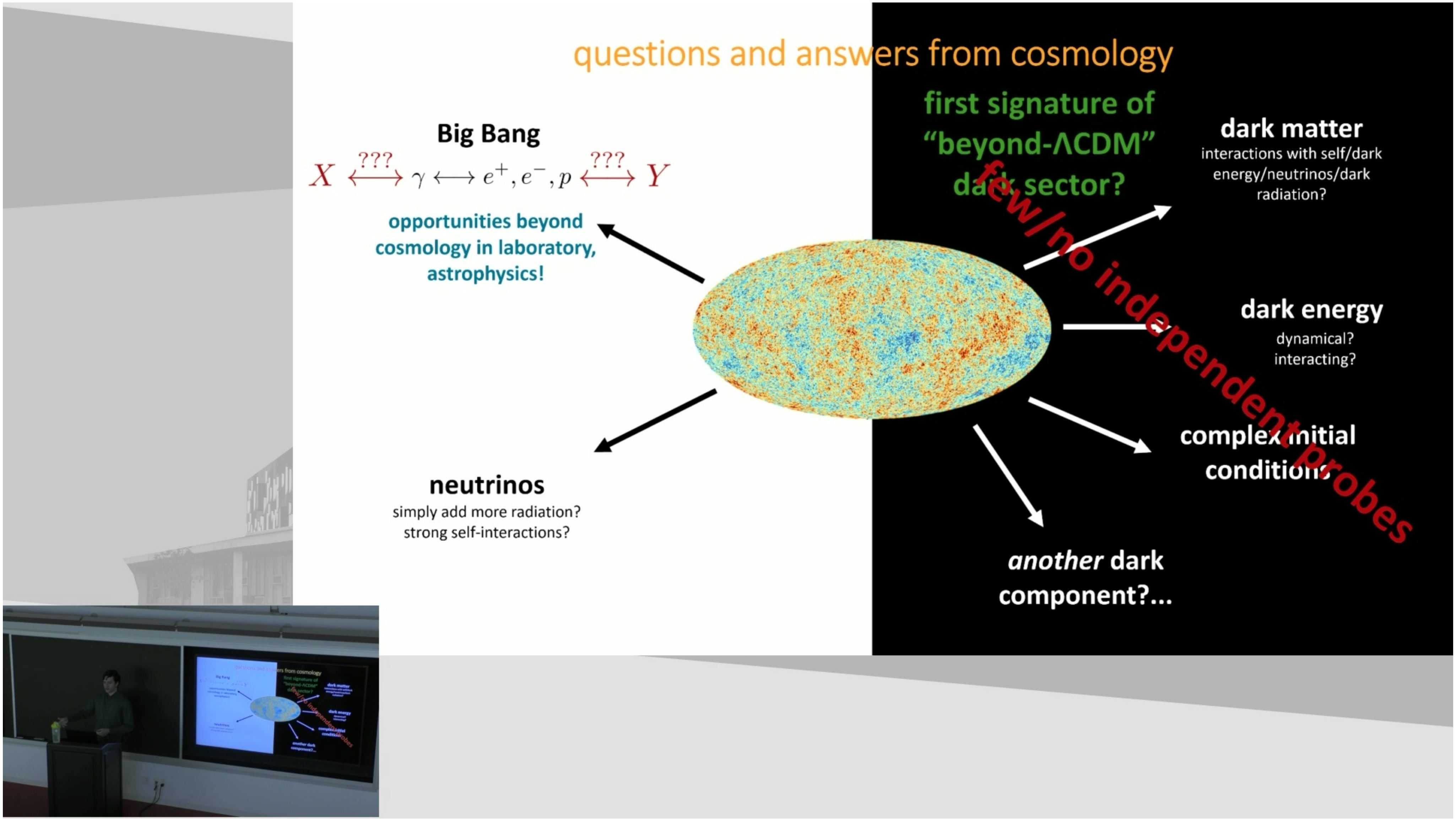
strong self-interactions?


questions and answers from cosmology
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$X \overset{???}{\longleftrightarrow} \gamma \longleftrightarrow e^+, e^-, p \overset{???}{\longleftrightarrow} Y$
opportunities beyond cosmology in laboratory, astrophysics!
neutrinos
simply add more radiation?
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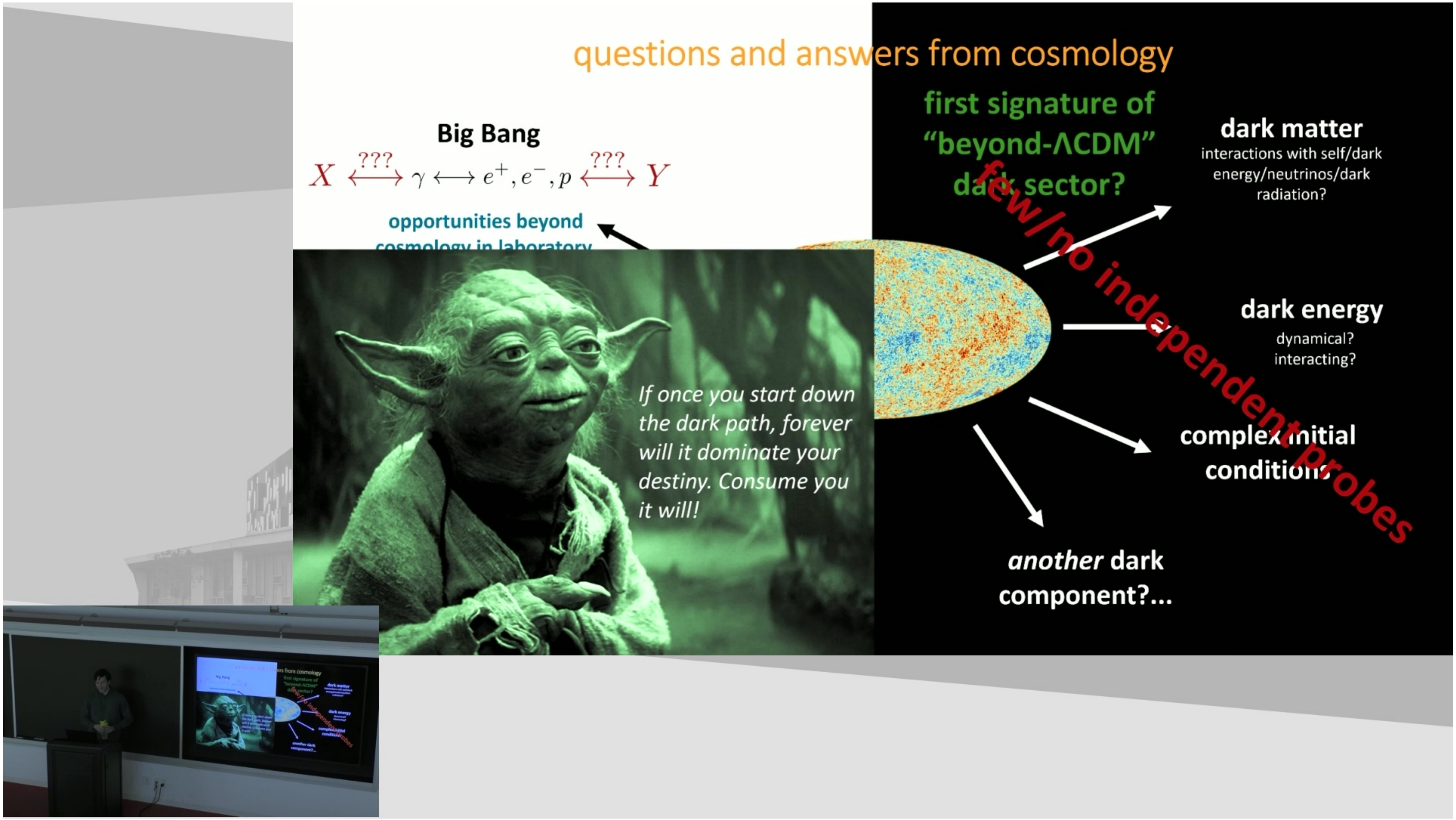
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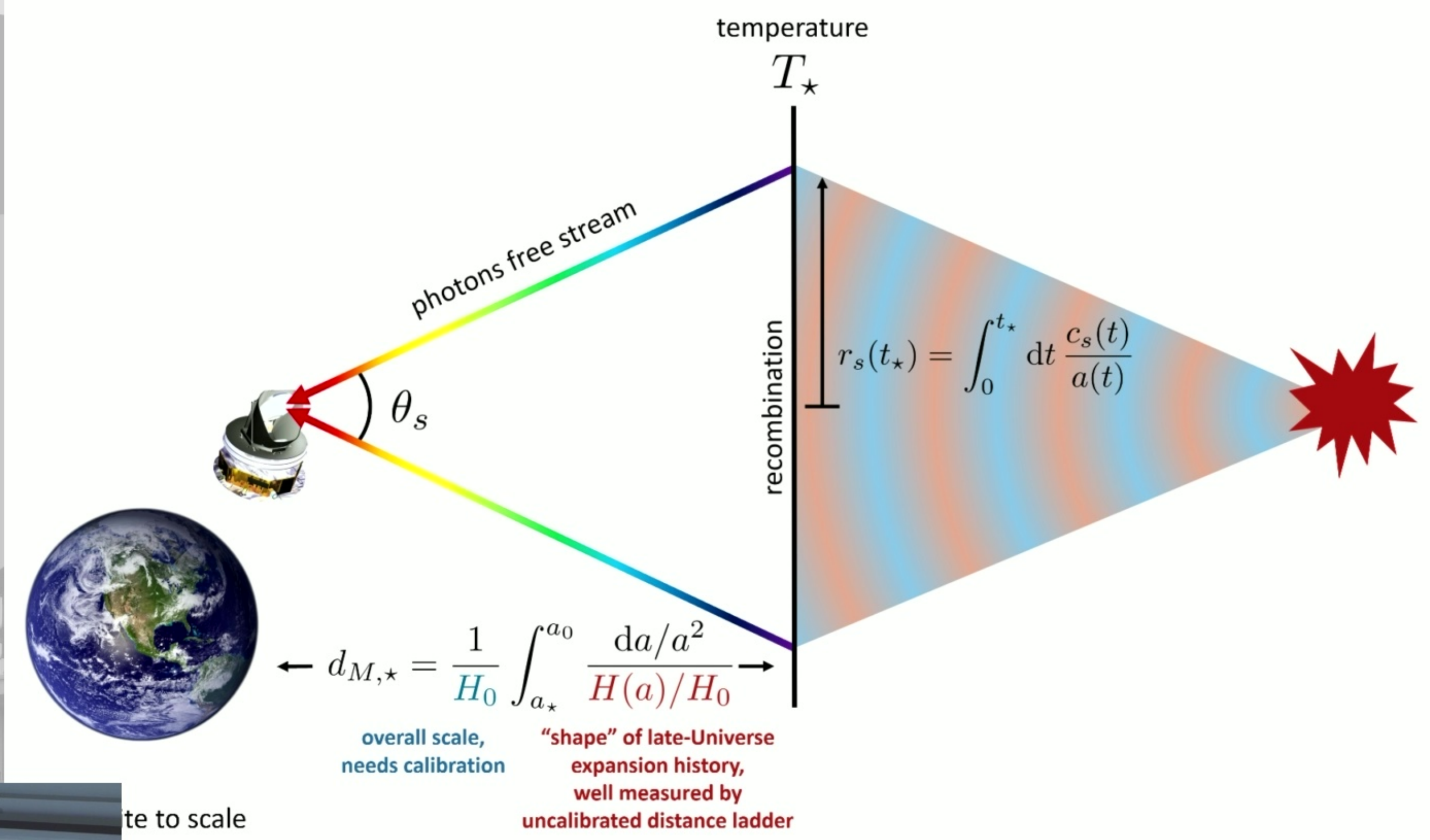
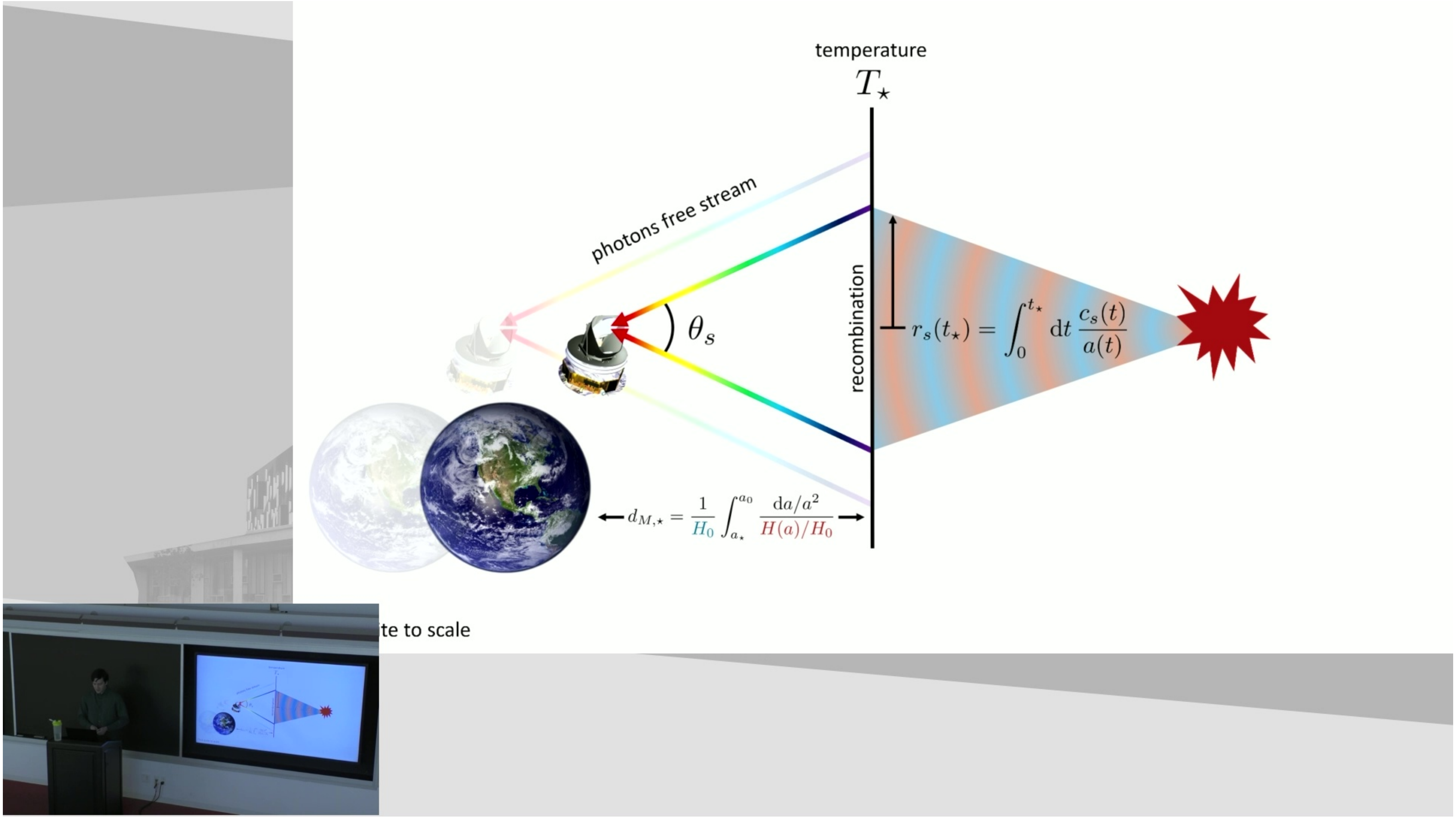
another dark component?...
If once you start down the dark path, forever will it dominate your destiny. Consume you it will!


temperature
$T_\star$
photons free stream
θ_s
recombination
$r_s(t_\star) = \int_0^{t_\star} \mathrm{d}t \, \frac{c_s(t)}{a(t)}$
$d_{M,\star} = \frac{1}{H_0} \int_{a_\star}^{a_0} \frac{\mathrm{d}a/a^2}{H(a)/H_0}$
overall scale,
needs calibration
"shape" of late-Universe
expansion history,
well measured by
uncalibrated distance ladder
te to scale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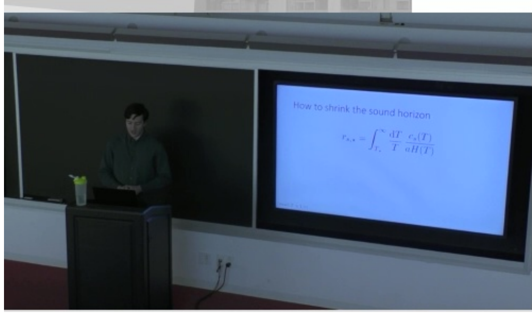
te to scale

How to shrink the sound horizon

$$r_{s,\star} = \int_{T_\star}^{\infty} \frac{\mathrm{d}T}{T} \, \frac{c_s(T)}{aH(T)}$$



$T \propto 1/a)$

How to shrink the sound horizon

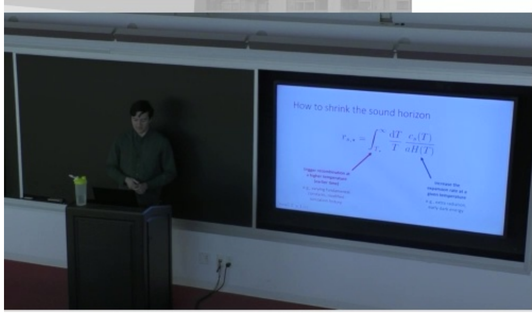
$$r_{s,\star} = \int_{T_\star}^{\infty} \frac{\mathrm{d}T}{T} \frac{c_s(T)}{aH(T)}$$

trigger recombination at a higher temperature (earlier time)

e.g., varying fundamental constants, modified ionization history

increase the expansion rate at a given temperature

e.g., extra radiation, early dark energy



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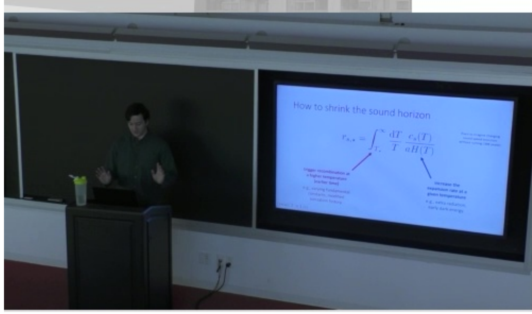

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Proposal: varying fundamental constants

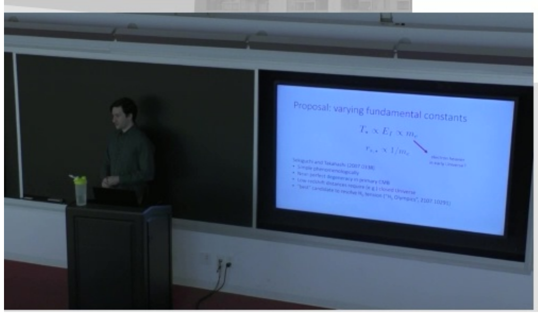
$$T_\star \propto E_I \propto m_e$$

$$r_{s,\star} \propto 1/m_e$$

electron heavier
in early Universe?

Sekiguchi and Takahashi (2007.0338)

- Simple phenomenologically
- Near-perfect degeneracy in primary CMB
- Low-redshift distances require (e.g.) closed Universe
- "best" candidate to resolve H_0 tension ("H_0 Olympics", 2107.10291)



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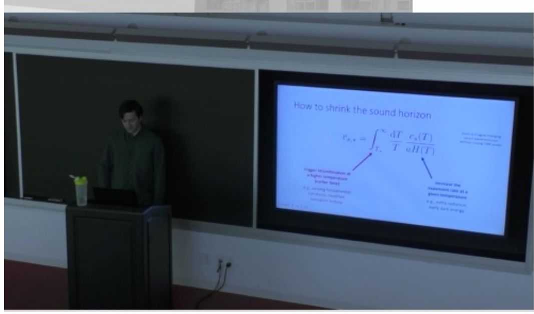

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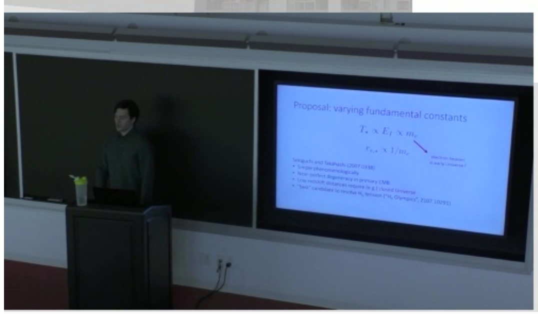


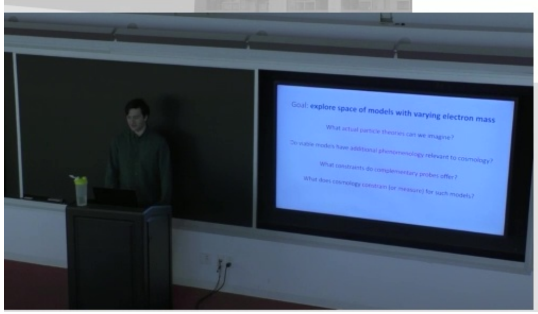
Goal: **explore space of models with varying electron mass**

What actual particle theories can we imagine?

Do viable models have additional phenomenology relevant to cosmology?

What constraints do complementary probes offer?

What does cosmology constrain (or measure) for such models?



Varying electron mass: probes

big bang nucleosynthesis

Altered rates of

- neutron -> proton reaction during weak decoupling

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$

- neutron decay after

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Heavier electron increases neutron abundance at ^{4}He formation

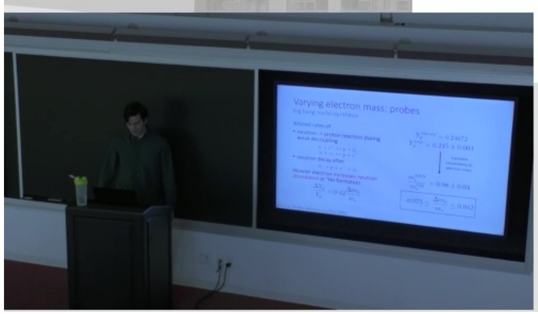
$$\frac{\Delta Y_p}{Y_p} = 0.42 \frac{\Delta m_e}{m_e}$$

$$Y_p^{\text{theory}} = 0.24672$$
$$Y_p^{\text{exp}} = 0.245 \pm 0.003$$

translate uncertainty to electron mass

$$\frac{m_e^{\text{BBN}}}{m_e^{\text{SM}}} = 0.98 \pm 0.03$$

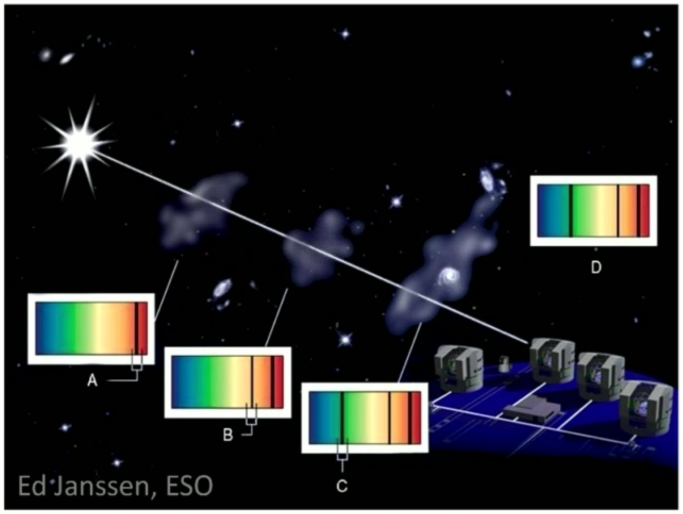
$$-0.075 \leq \frac{\Delta m_e}{m_e} \leq 0.042$$



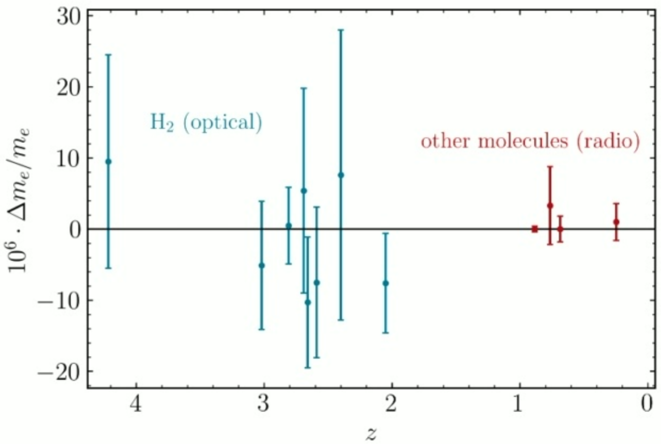
Bouley, Sørensen, Yu (2211.0982)

Varying electron mass: probes

quasar absorption lines



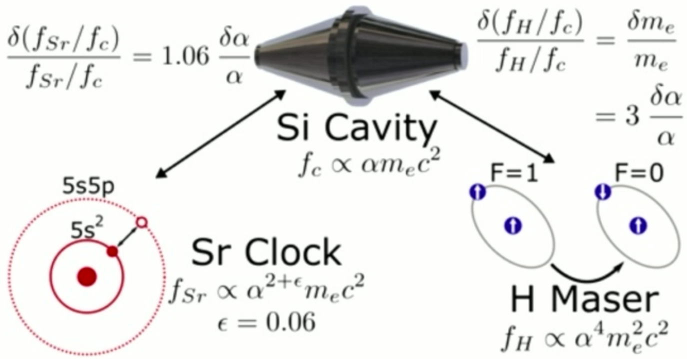
Measure molecular absorption lines along quasar sight lines



PPM measurements of fundamental constants

Varying electron mass: probes

atomic clocks and pulsar timing

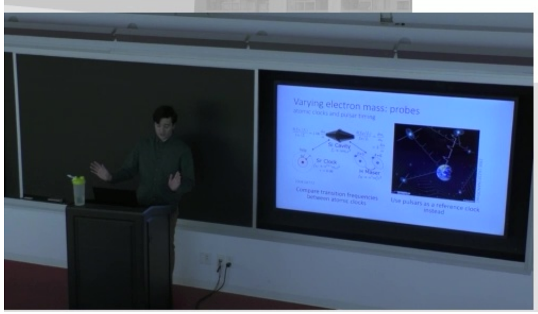


2008.08773

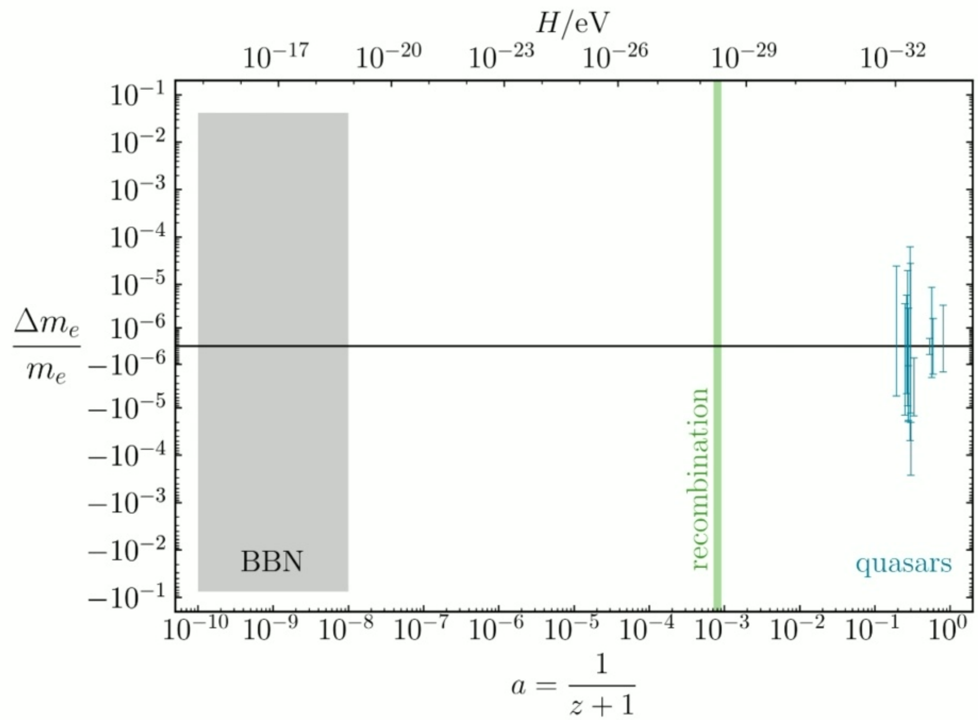
2306.16219 (NANOGrav)

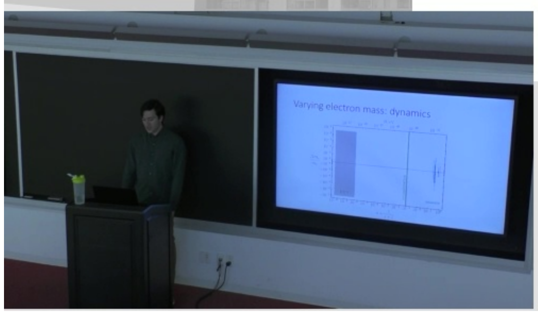
Compare transition frequencies between atomic clocks

Use pulsars as a reference clock instead



Varying electron mass: dynamics





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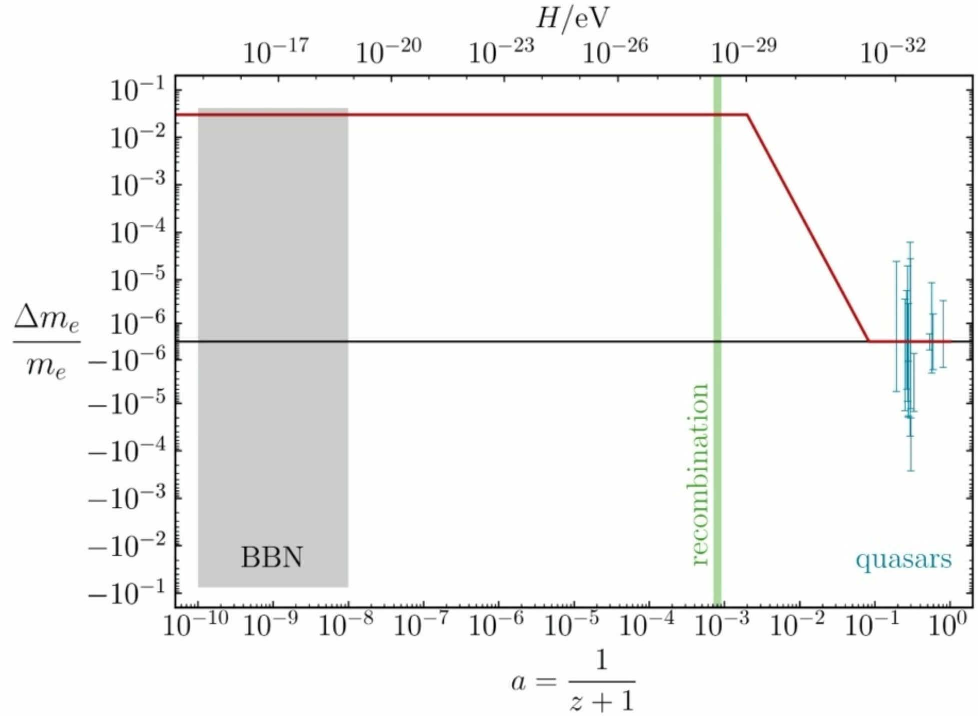


Varying electron mass: scalar models

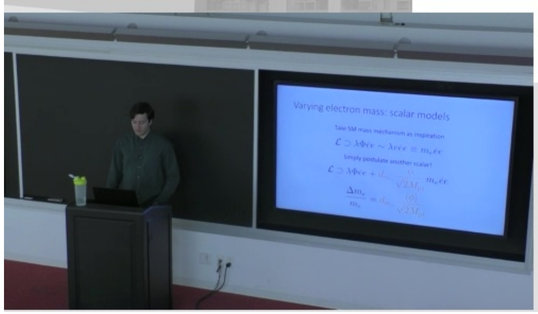
Take SM mass mechanism as inspiration

$$\mathcal{L} \supset \lambda \Phi \bar{e} e \sim \lambda v \bar{e} e \equiv m_e \bar{e} e$$

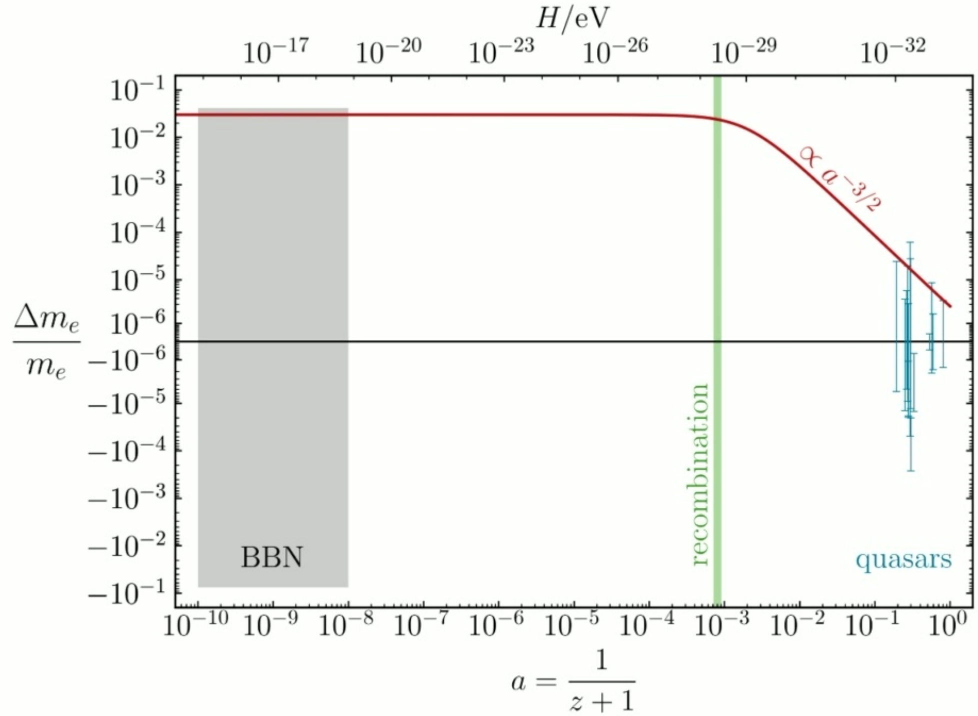
Simply postulate another scalar!

$$\mathcal{L} \supset \lambda \Phi \bar{e} e + d_{m_e} \frac{\phi}{\sqrt{2} M_{\rm pl}} m_e \bar{e} e$$

$$\frac{\Delta m_e}{m_e} = d_{m_e} \frac{\langle \phi \rangle}{\sqrt{2} M_{\rm pl}}$$



Varying electron mass: scalar models

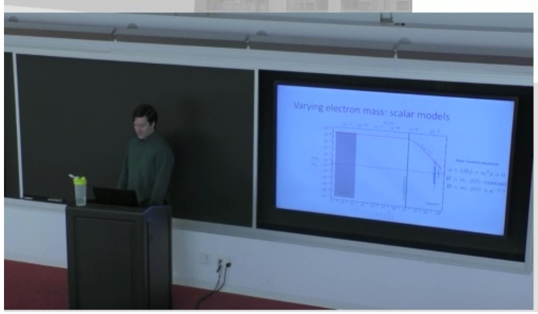


Klein-Gordon equation

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

$H > m$: $\phi(t)$ constant

$H < m$: $\phi(t) \propto a^{-3/2}$

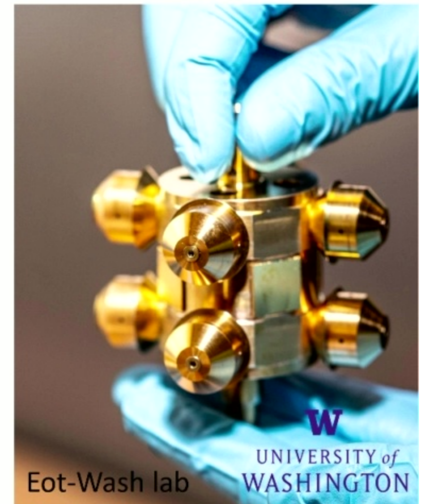


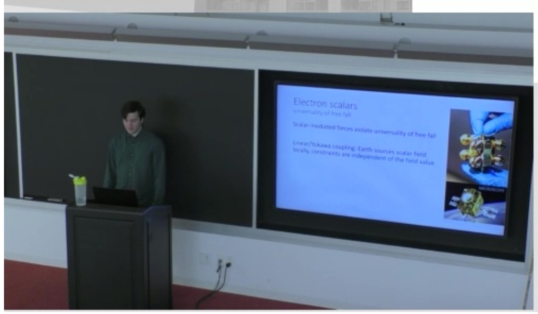
Electron scalars

universality of free fall

Scalar-mediated forces violate universality of free fall

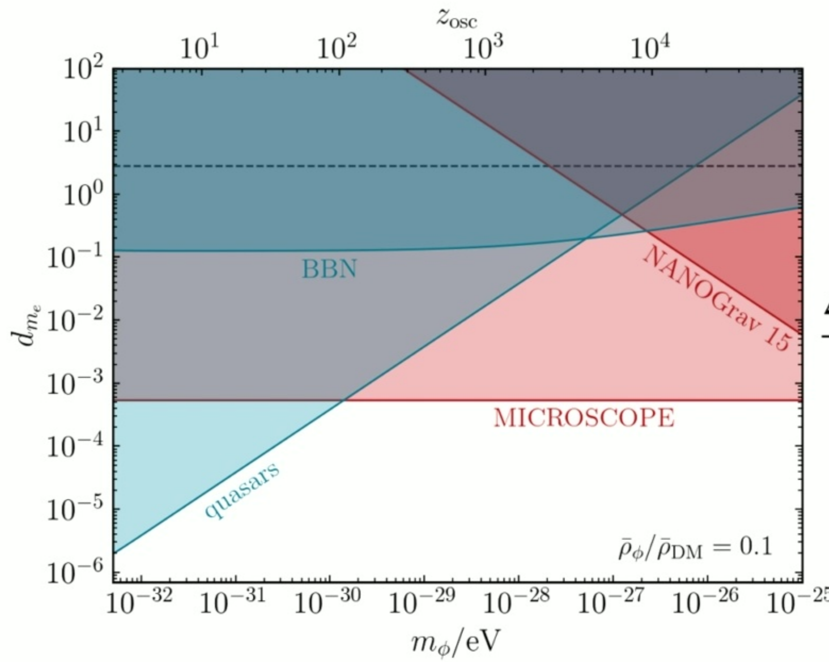
Linear/Yukawa coupling: Earth sources scalar field locally, constraints are independent of the field value





Electron scalars

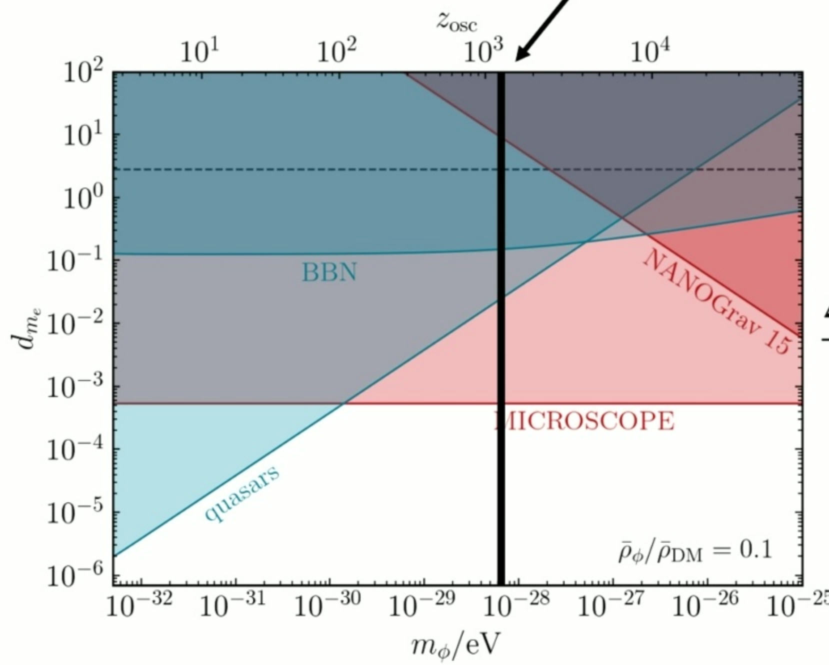
linear coupling



$$\frac{\Delta m_e}{m_e} = d_{m_e}\frac{\langle\phi\rangle}{M_{\rm pl}}$$

Electron scalars

linear coupling



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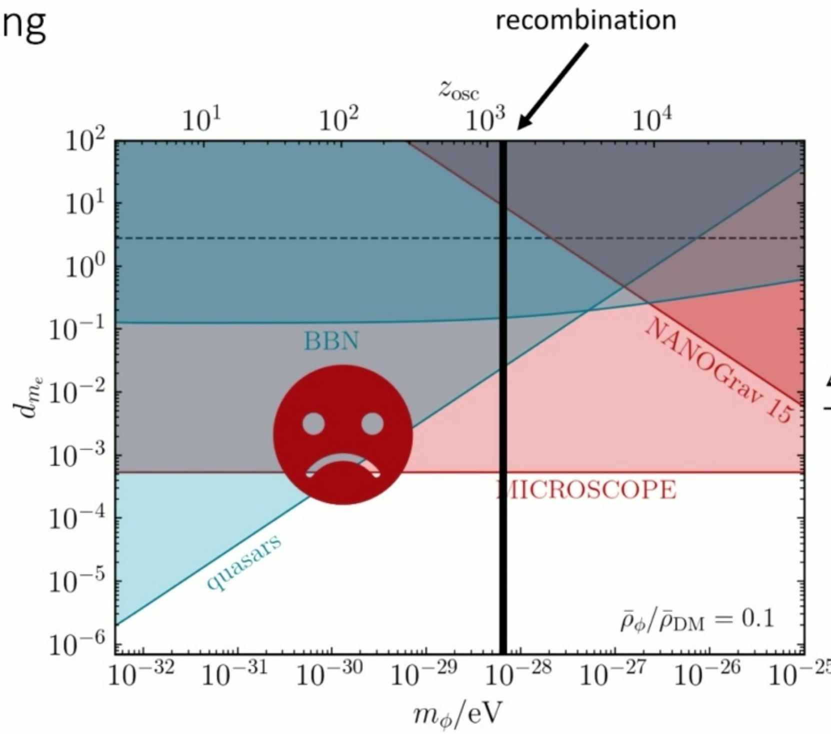
Electron scalars

linear coupling



$$\frac{\Delta m_e}{m_e} = d_{m_e}\frac{\langle\phi\rangle}{M_{\rm pl}}$$

What about an axion(like particle)?

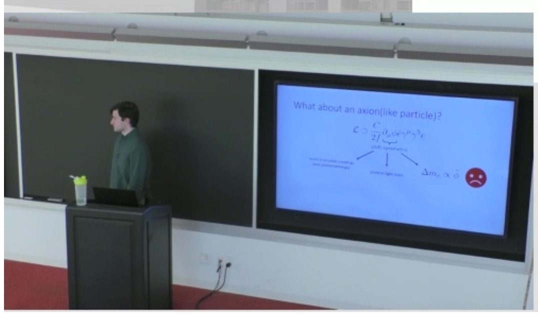
$$\mathcal{L} \supset \frac{C}{2f} \partial_\mu \phi \bar{e} \gamma^\mu \gamma^5 e$$

shift-symmetric

restricts possible couplings
(and phenomenology)

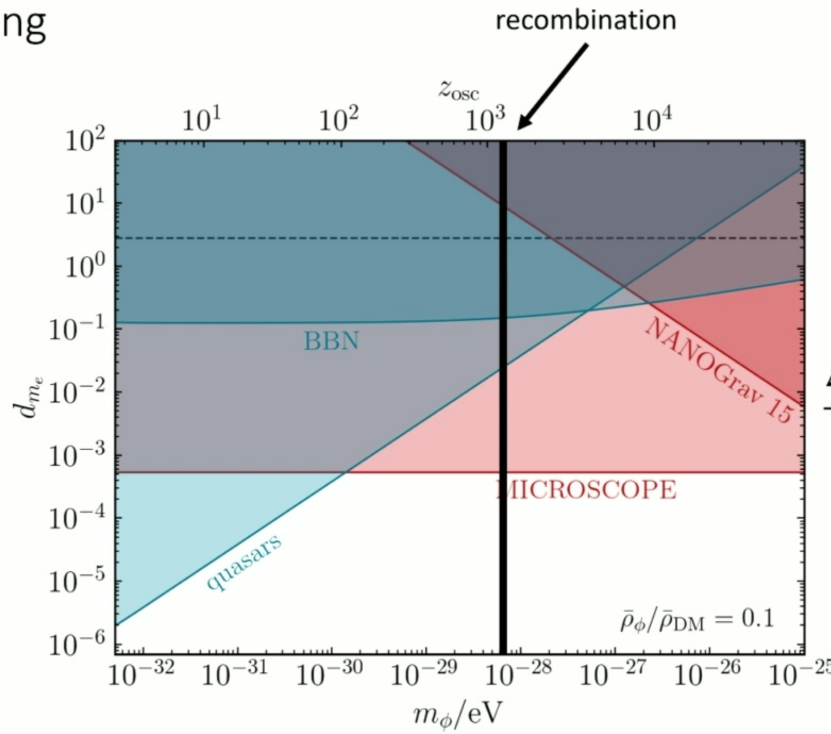
protects light mass

$\Delta m_e \propto \dot{\phi}$



Electron scalars

linear coupling



$$\frac{\Delta m_e}{m_e} = d_{m_e} \frac{\langle \phi \rangle}{M_{\rm pl}}$$

What about an axion(like particle)?

$$\mathcal{L} \supset \frac{C}{2f} \partial_\mu \phi \bar{e} \gamma^\mu \gamma^5 e$$

shift-symmetric

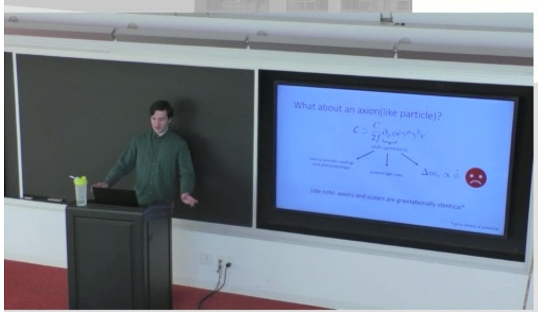
restricts possible couplings (and phenomenology)

protects light mass

$$\Delta m_e \propto \dot{\phi}$$

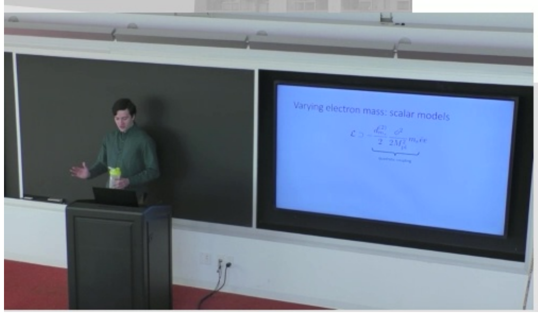
side note: axions and scalars are gravitationally identical*

*up to choice of potential

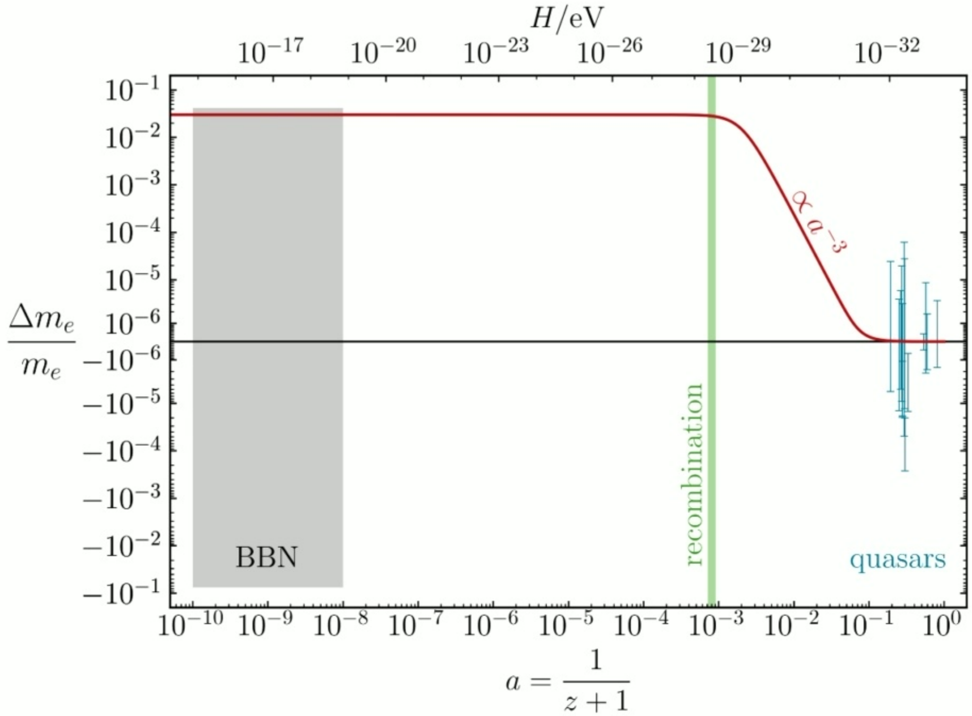


Varying electron mass: scalar models

$$\mathcal{L} \supset -\underbrace{\frac{d_{m_e}^{(2)}}{2}\frac{\phi^2}{2M_{\rm pl}^2}}_{\text{quadratic coupling}} m_e \bar{e} e$$



Varying electron mass: scalar models

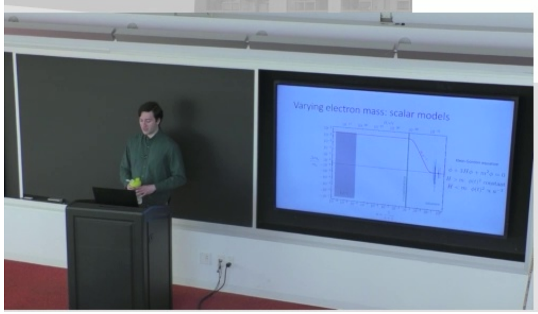


Klein-Gordon equation

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

$H > m$: $\phi(t)^2$ constant

$H < m$: $\phi(t)^2 \propto a^{-3}$



Electron scalars

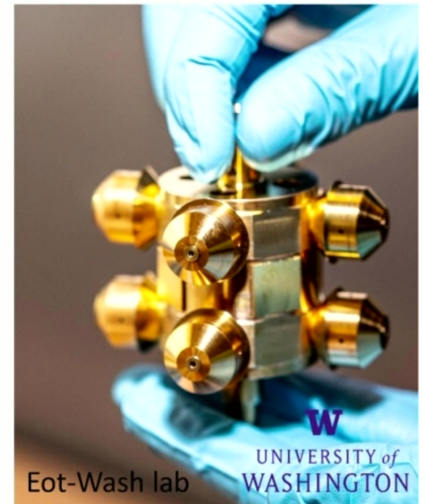
universality of free fall

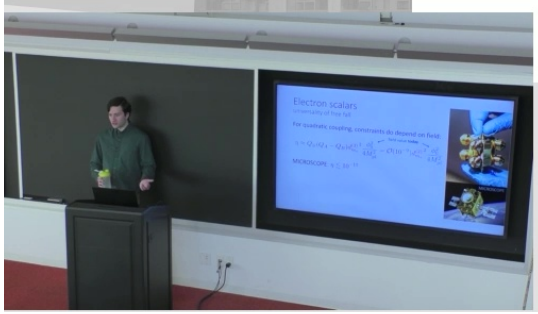
For quadratic coupling, constraints do depend on field:

field value **today**

$$\eta \approx Q_{\oplus}(Q_A - Q_B){d_{m_e}^{(2)}}^2 \frac{\phi_0^2}{4M_{\rm pl}^2} = \mathcal{O}(10^{-9}){d_{m_e}^{(2)}}^2 \frac{\phi_0^2}{4M_{\rm pl}^2}$$

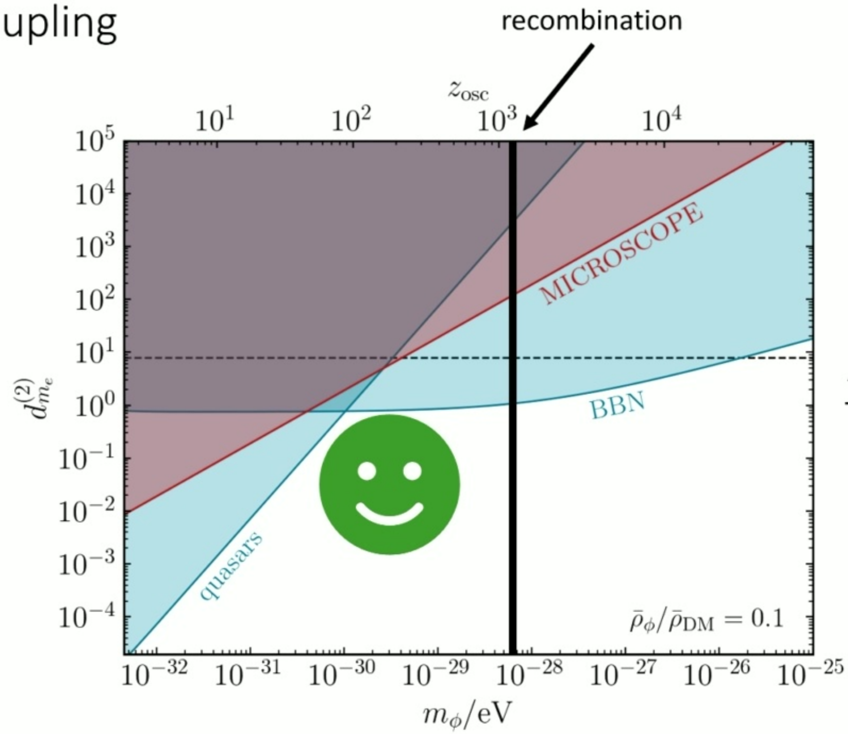
MICROSCOPE: $\eta \lesssim 10^{-15}$



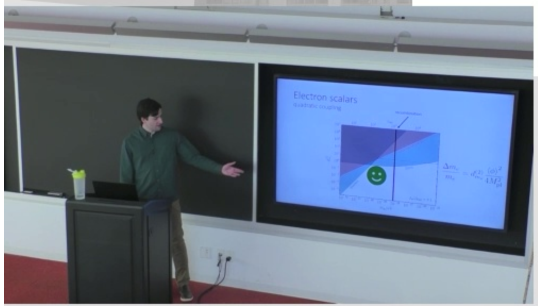


Electron scalars

quadratic coupling



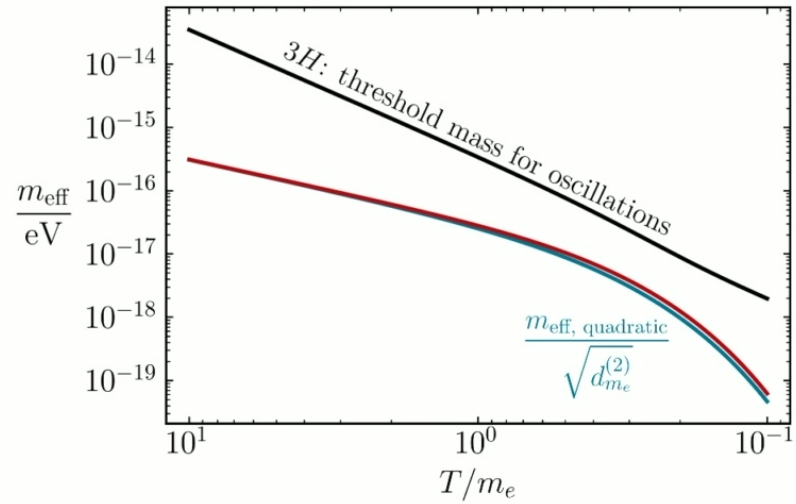
$$\frac{\Delta m_e}{m_e} = d^{(2)}_{m_e} \frac{\langle \phi \rangle^2}{4M_{\rm pl}^2}$$

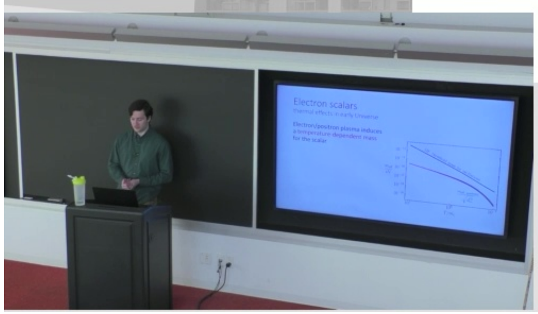


Electron scalars

thermal effects in early Universe

Electron/positron plasma induces a temperature-dependent mass for the scalar



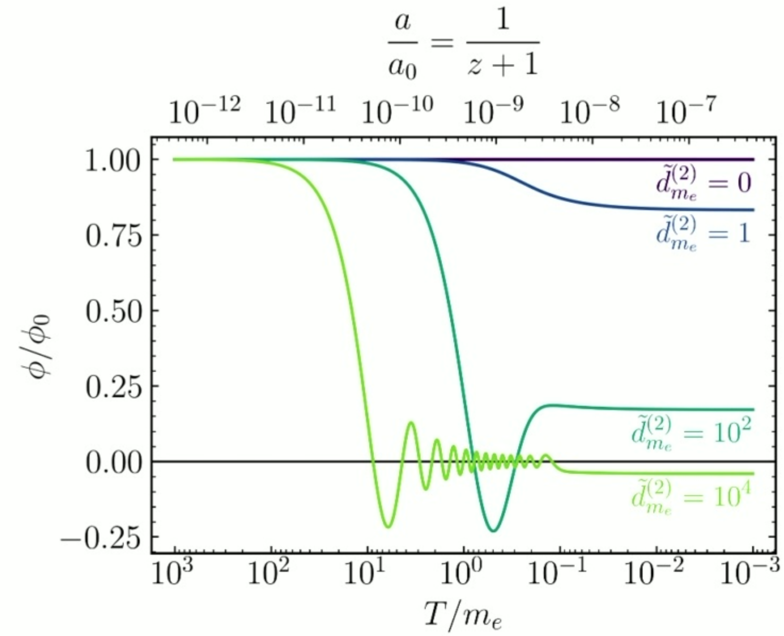


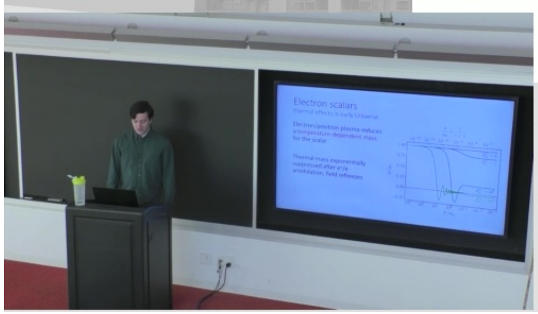
Electron scalars

thermal effects in early Universe

Electron/positron plasma induces a temperature-dependent mass for the scalar

Thermal mass exponentially suppressed after e^+/e^- annihilation, field refreezes





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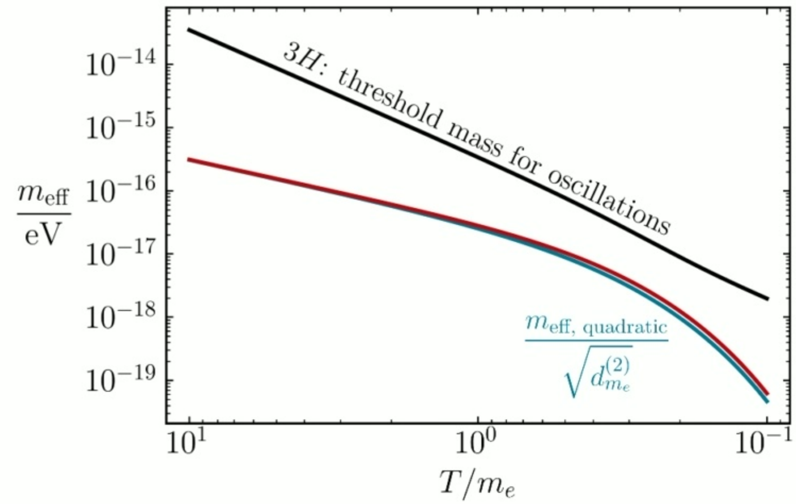

Electron scalars

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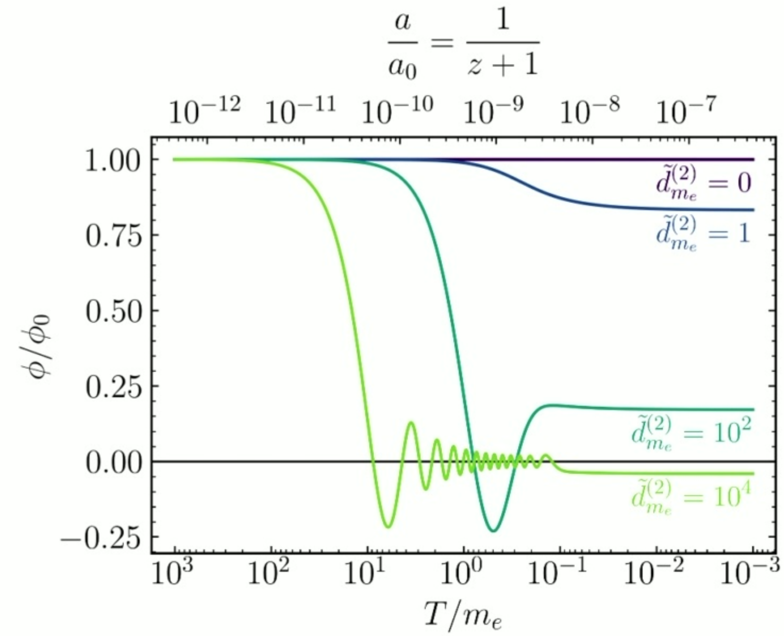
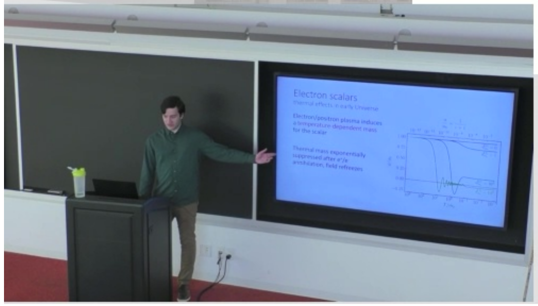




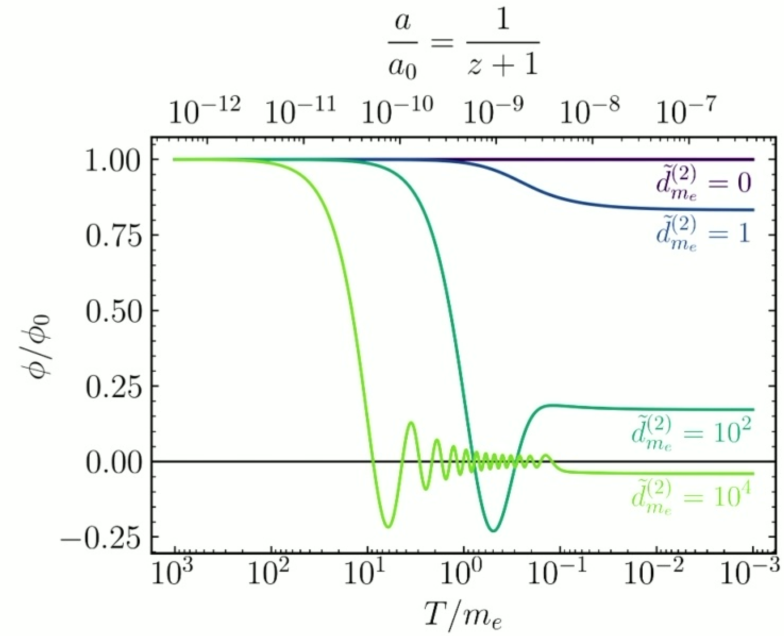
Electron scalars

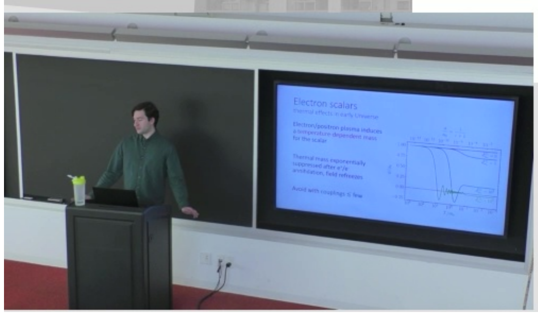
thermal effects in early Universe

Electron/positron plasma induces a temperature-dependent mass for the scalar

Thermal mass exponentially suppressed after e^+/e^- annihilation, field refreezes

Avoid with couplings $\lesssim$ few

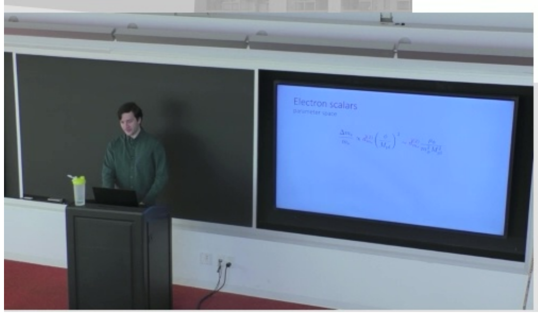




Electron scalars

parameter space

$$\frac{\Delta m_e}{m_e} \propto \tilde{d}^{(2)}_{m_e} \left(\frac{\phi}{M_{\rm pl}} \right)^2 \sim \tilde{d}^{(2)}_{m_e} \frac{\rho_\phi}{m_\phi^2 M_{\rm pl}^2}$$



Electron scalars

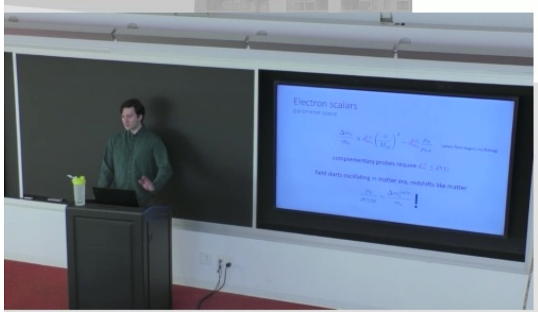
parameter space

$$\frac{\Delta m_e}{m_e} \propto \tilde{d}^{(2)}_{m_e} \left(\frac{\phi}{M_{\rm pl}}\right)^2 \sim \tilde{d}^{(2)}_{m_e} \frac{\rho_\phi}{\rho_{\rm tot}}$$ (when field begins oscillating)

complementary probes require $\tilde{d}^{(2)}_{m_e} \lesssim \mathcal{O}(1)$

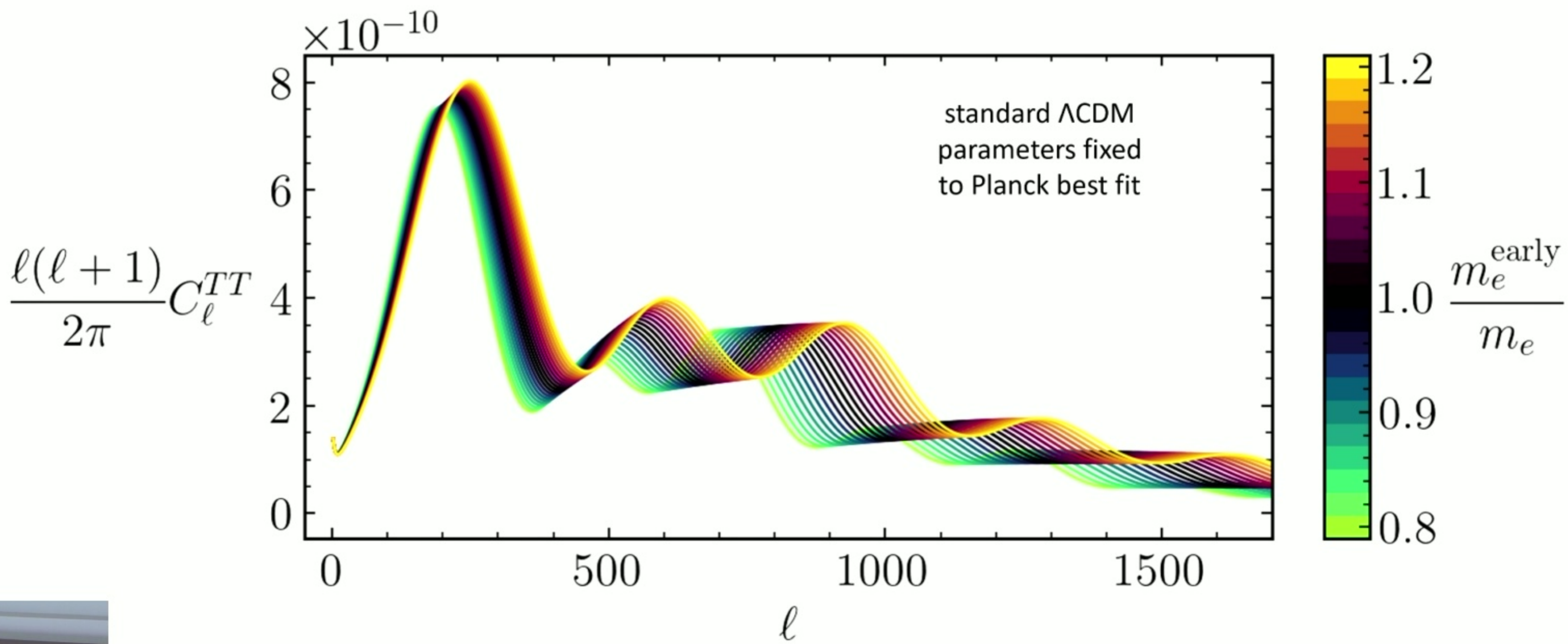
field starts oscillating in matter era, redshifts like matter

$$\frac{\rho_\phi}{\rho_{\rm CDM}} \sim \frac{\Delta m_e^{\rm early}}{m_e} \;!$$



Vanilla early recombination

cosmic microwave background



Vanilla early recombination

sound horizon

"sound horizon"
comoving distance propagating sound waves traveled by recombination

overall scale

"shape" of early-Universe expansion history

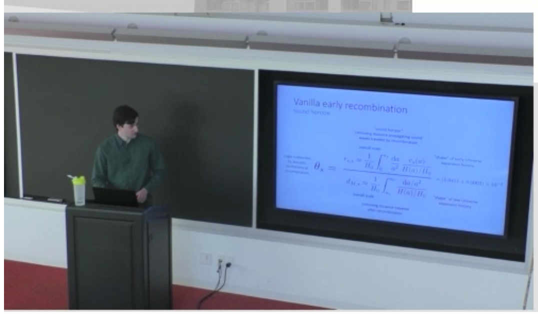
angle subtended by acoustic oscillations at recombination

$$\theta_s = \frac{r_{s,\star} \approx \frac{1}{H_0}\int_0^{a_\star} \frac{\mathrm{d}a}{a^2}\,\frac{c_s(a)}{H(a)/H_0}}{d_{M,\star} \approx \frac{1}{H_0}\int_{a_\star}^{a_0} \frac{\mathrm{d}a/a^2}{H(a)/H_0}} = (1.0411 \pm 0.0003) \times 10^{-2}$$

"shape" of late-Universe expansion history

overall scale

comoving distance traveled after recombination



Vanilla early recombination

sound horizon

$$c_s^2 = \frac{1}{3(1+R)}$$

$$R = \frac{3\omega_b}{4\omega_\gamma}\frac{a}{a_0}$$

what is the (comoving) horizon size at equality?

how soon after matter-radiation equality did recombination occur?

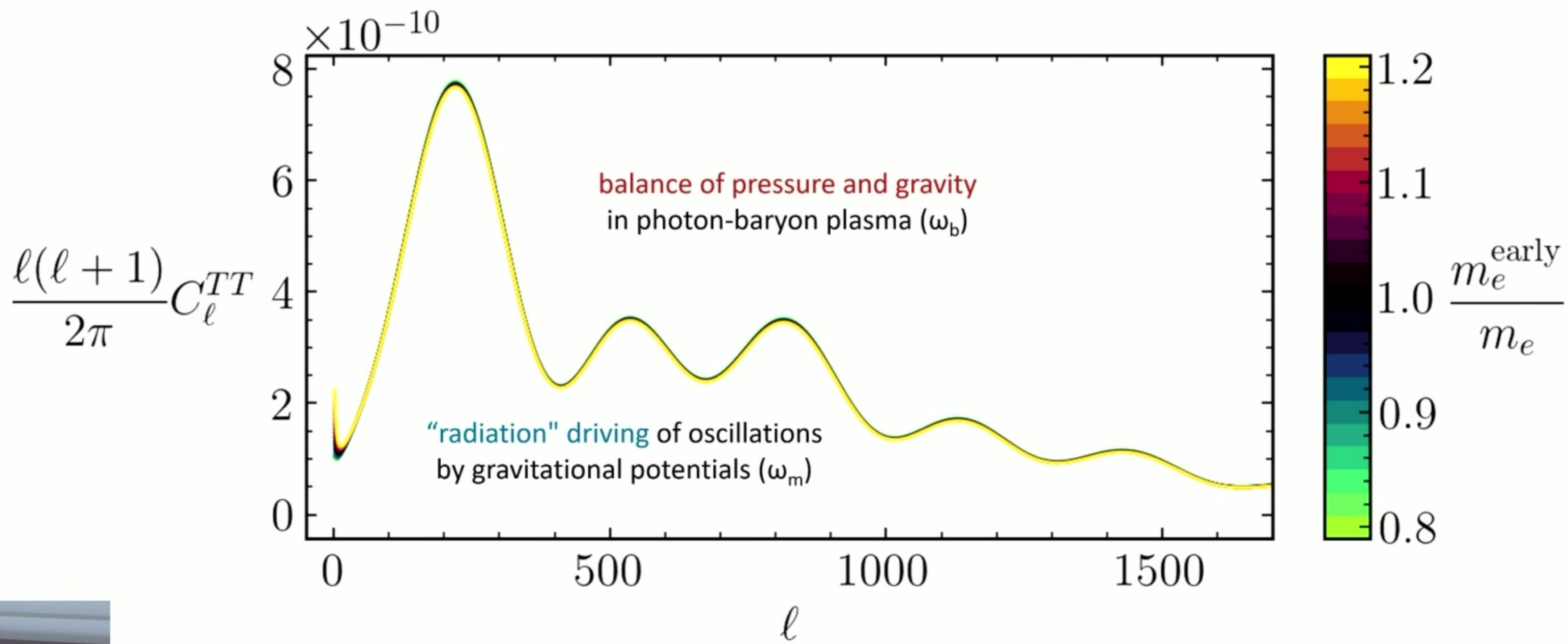
$$\theta_s = \frac{r_{s,\star} \propto \dfrac{a_\star}{\sqrt{\omega_r}}\left(\dfrac{a_{\rm eq}}{a_\star}\right)^{0.247} R_\star^{-0.0965}}{d_{M,\star} \propto \dfrac{1}{H_0}\Omega_m^{-0.4}} = (1.0411 \pm 0.0003) \times 10^{-2}$$

what is the critical (total) energy density?

how much did Universe expand while matter dominated vs. dark-energy dominated?

Vanilla early recombination

net result



Vanilla early recombination

diffusion damping

$$r_{D,\star}^2 = \frac{1}{6}\int_0^{a_\star} \frac{R^2 + \frac{16}{15}(1+R)}{(1+R)^2}\,\frac{1}{n_e\sigma_T}\,\frac{\mathrm{d}a/a}{a^2 H}$$

length scale below which photons diffuse

already fixed function of a/a* when increasing baryon density $\propto m_e$

$\propto 1/m_e^2$

$\propto a_\star^{-3}\omega_b \propto a_\star^{-4}R_\star$

already fixed function of a/a* when increasing net matter density $\propto m_e$

Vanilla early recombination

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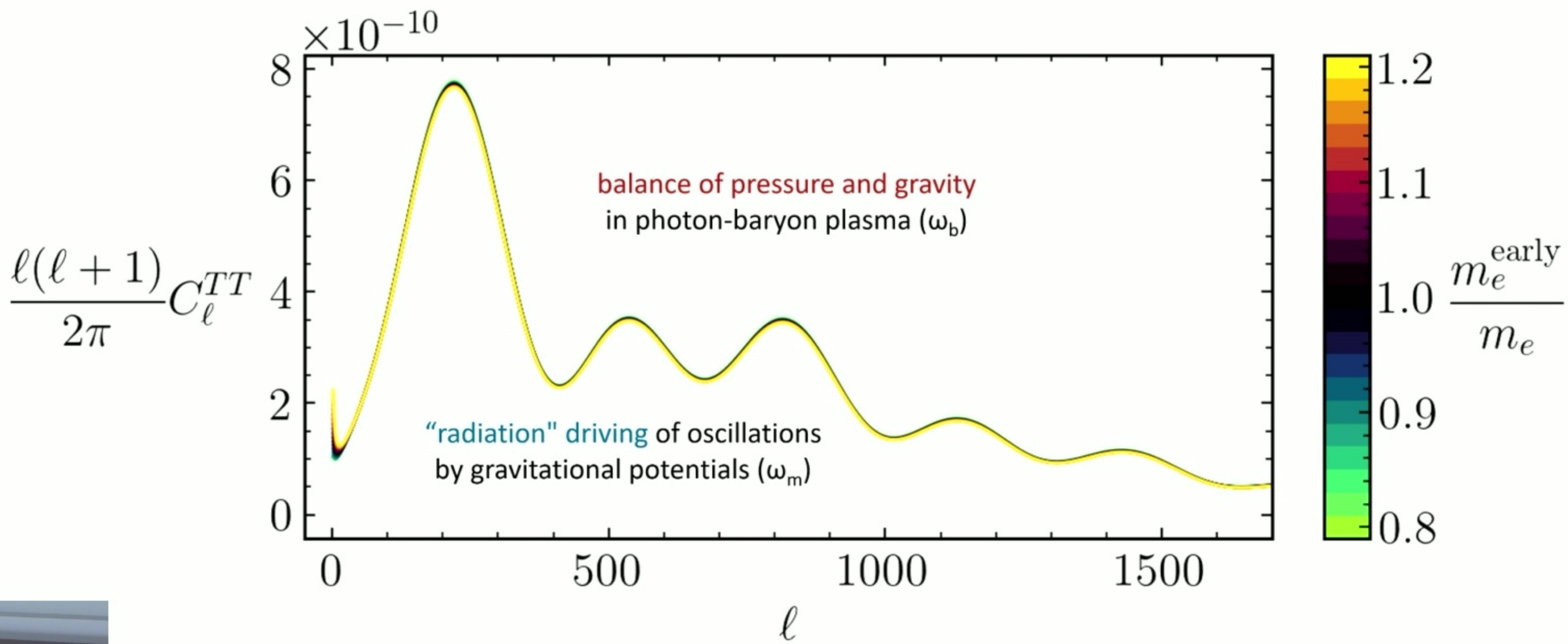
$r_{D,\star} \propto a_\star$

$r_{D,\star} \propto r_{s,\star}$

for free!

Vanilla early recombination

net result



Vanilla early recombination

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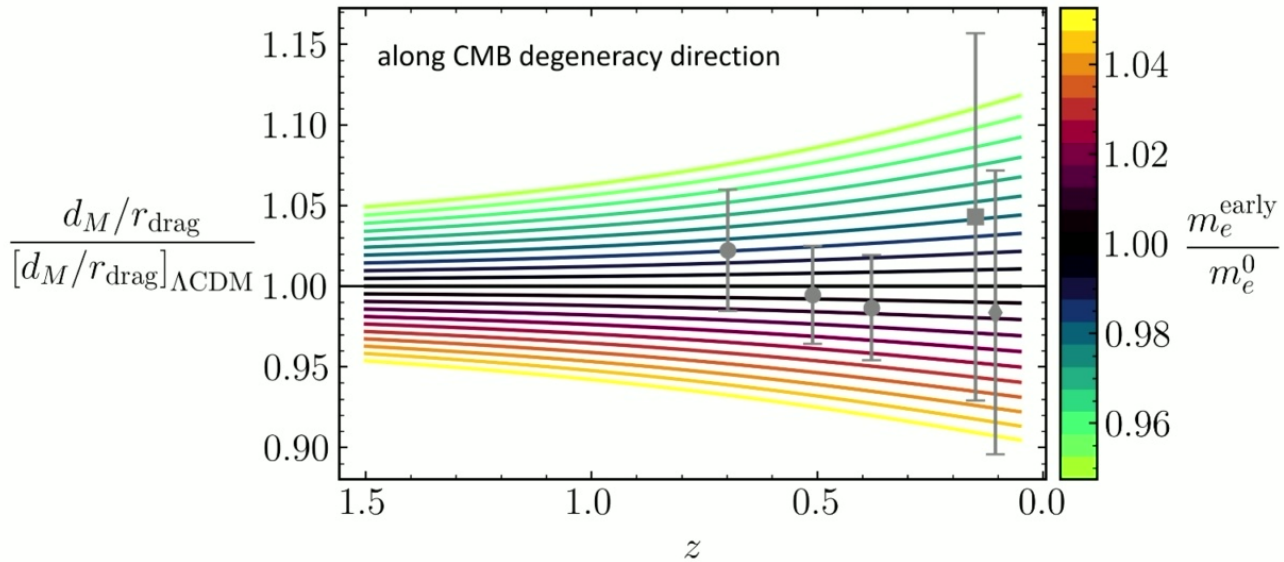
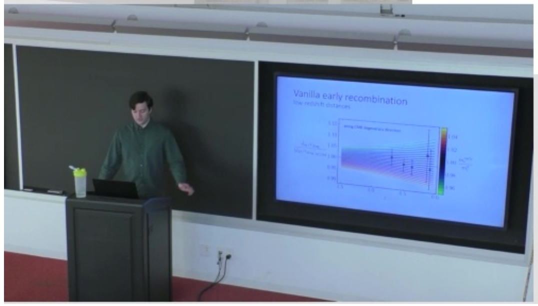
Vanilla early recombination

low-redshift distances





Vanilla early recombination

low-redshift distances

$$d_M^{\rm flat}(a) = \frac{1}{H_0}\int_a^{a_0} \frac{{\rm d}a'/{a'}^2}{H(a')/H_0}$$

overall scale, needs calibration — **"shape" of late-Universe expansion history**

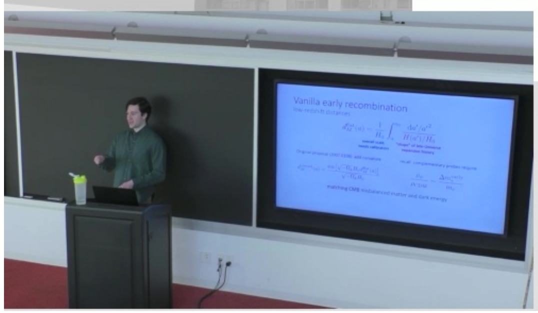
Original proposal (2007.0338): add curvature

$$d_M^{\rm curved}(a) = \frac{\sin\left[\sqrt{-\Omega_k} H_0 d_M^{\rm flat}(a)\right]}{\sqrt{-\Omega_k} H_0}$$

recall: complementary probes require

$$\frac{\rho_\phi}{\rho_{\rm CDM}} \sim \frac{\Delta m_e^{\rm early}}{m_e}$$

matching CMB misbalanced matter and dark energy



Vanilla early recombination

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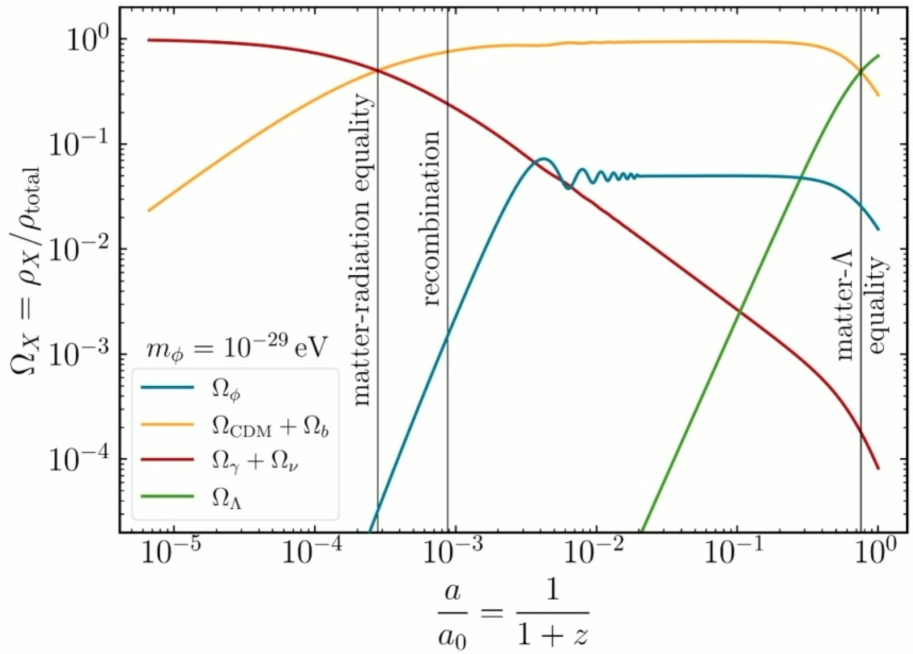
$$\frac{\rho_\phi}{\rho_{\text{CDM}}} \sim \frac{\Delta m_e^{\text{early}}}{m_e}$$

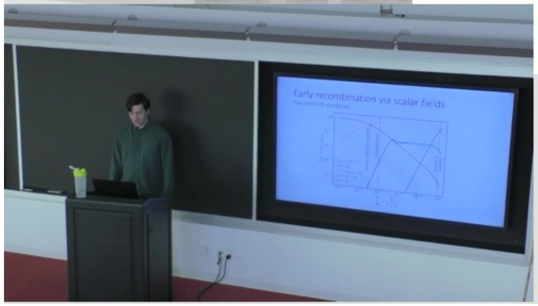
matching CMB misbalanced matter and dark energy

but scalar field *becomes matterlike when it starts oscillating*

Early recombination via scalar fields

low-redshift distances





Early recombination via scalar fields

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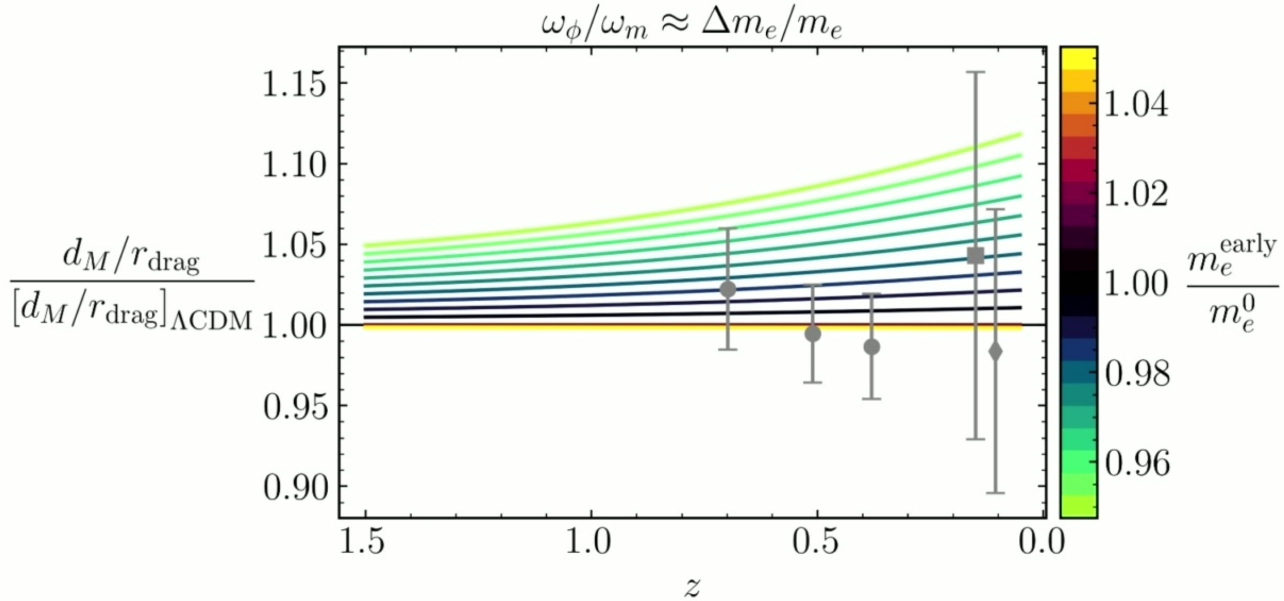
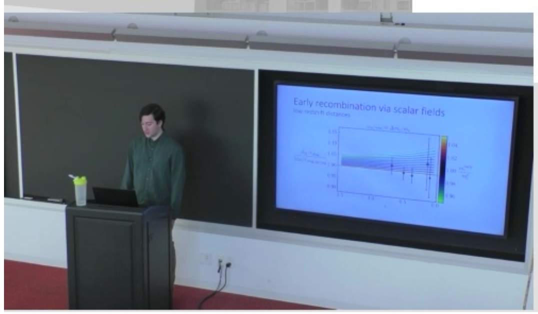
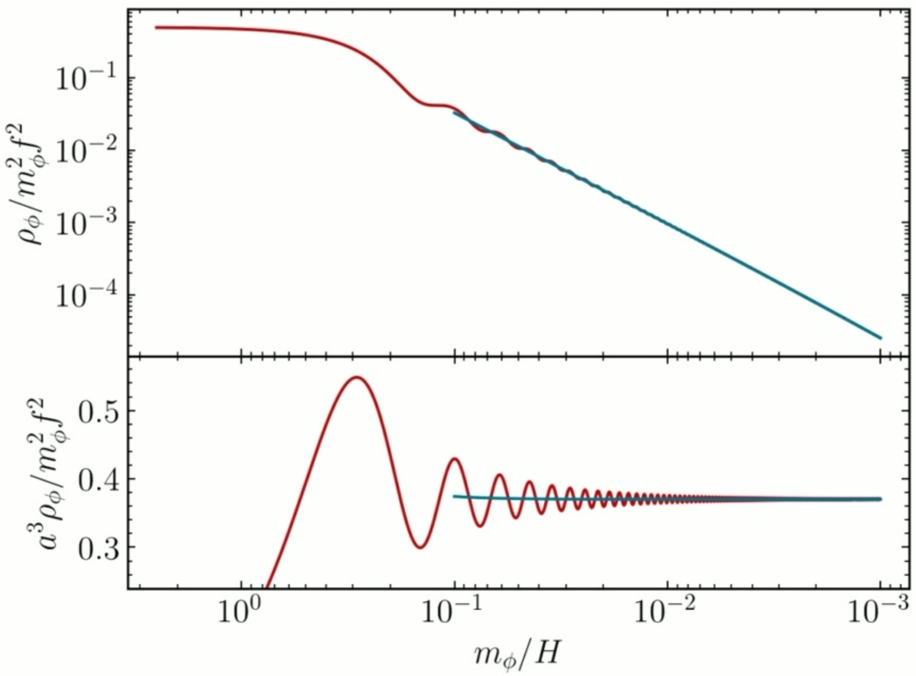
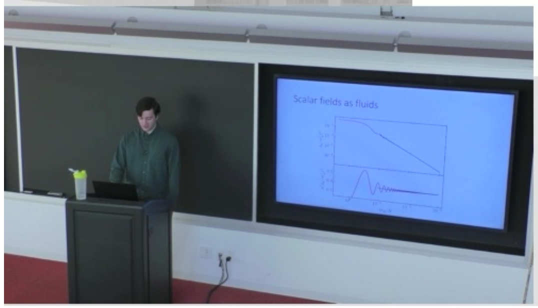




Scalar fields as fluids



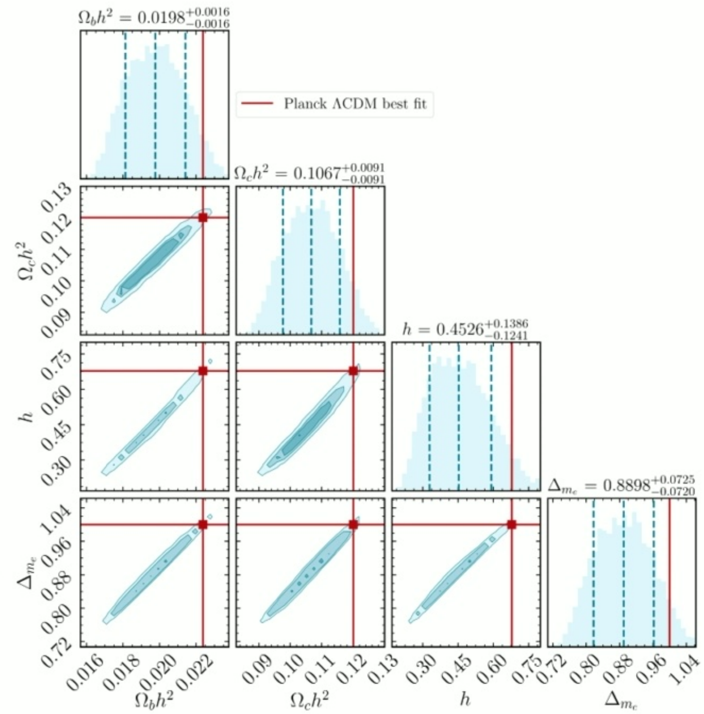


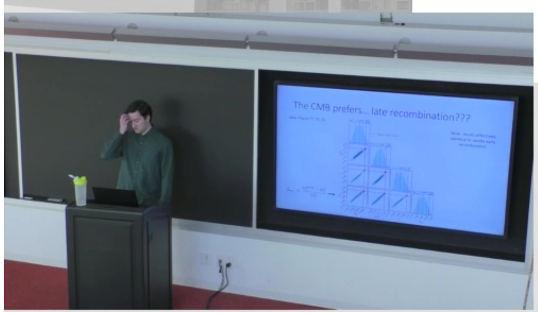
The CMB prefers… late recombination???

data: Planck TT, TE, EE

Note: results effectively identical in vanilla early recombination

$$\Delta_{m_e} \equiv \frac{m_e^{\text{early}} - m_e^0}{m_e^0} \longrightarrow$$





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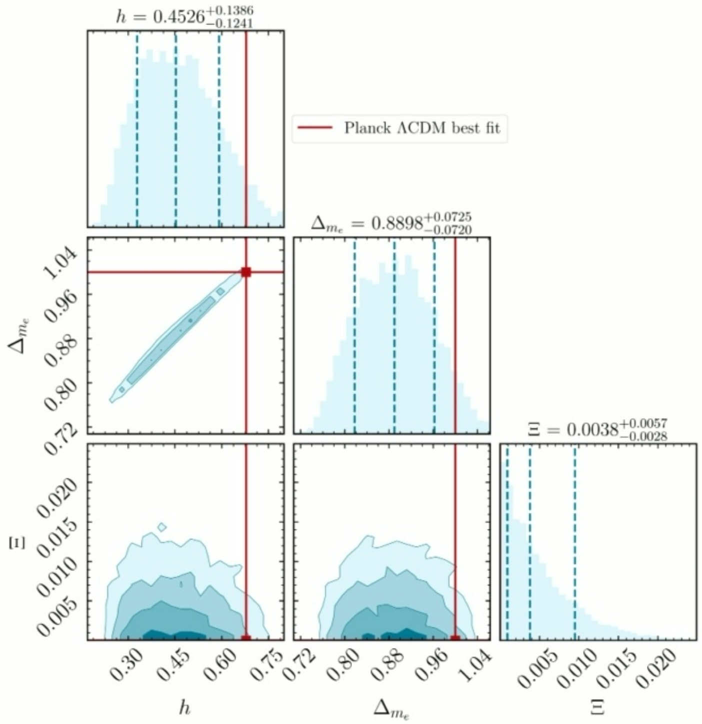
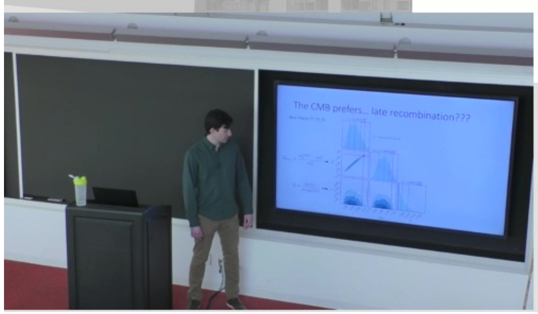
$$\Delta_{m_e} \equiv \frac{m_e^{\text{early}} - m_e^0}{m_e^0} \rightarrow$$

$$\Xi \equiv \frac{\rho_\phi(t_0)}{\rho_{\text{CDM}}(t_0)} \rightarrow$$





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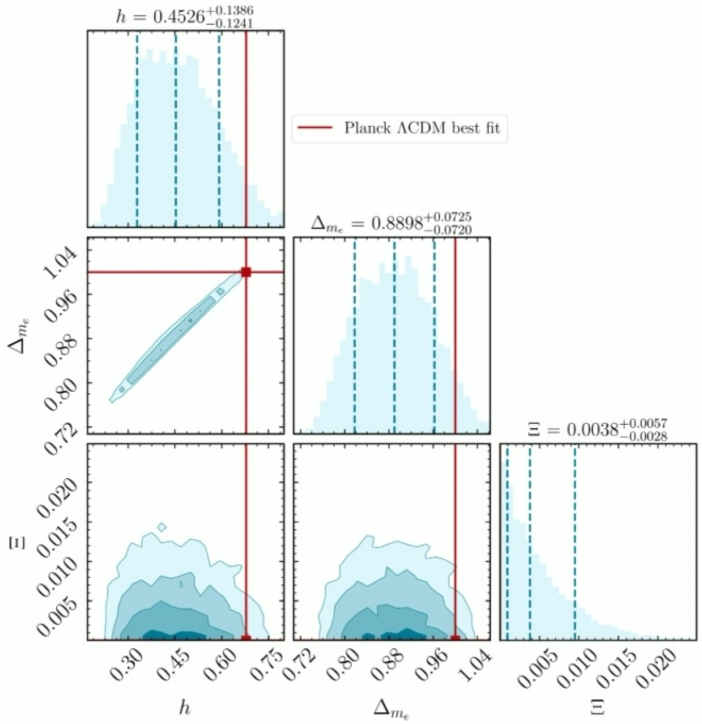
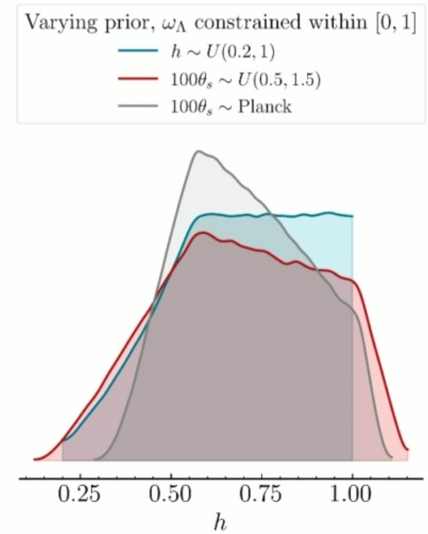
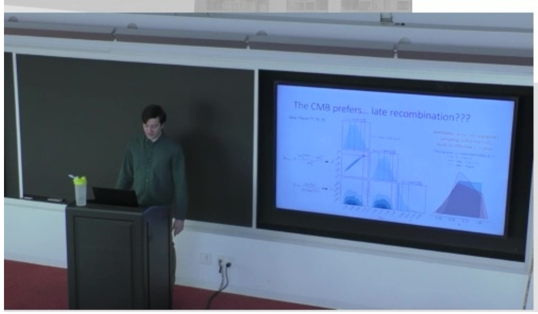
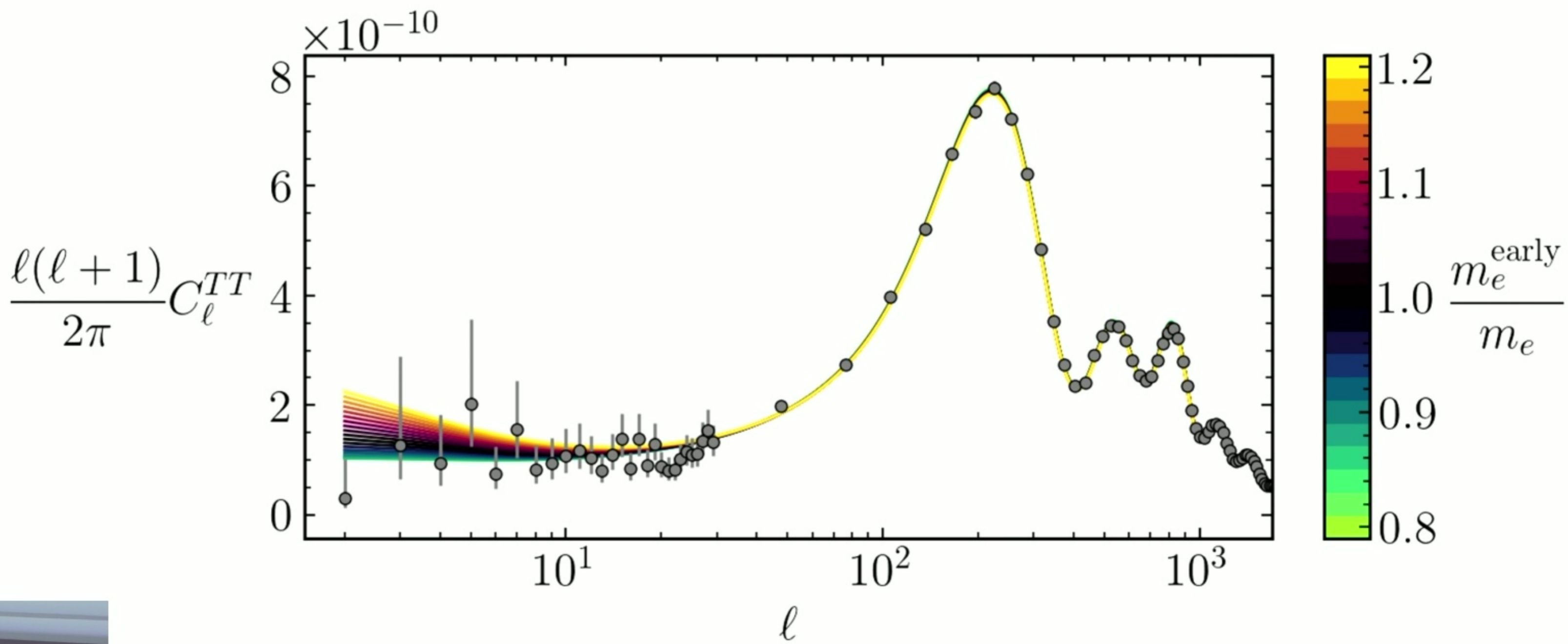


WARNING: prior not negligible!
sampling uniformly in θ_s
leads to effective $1/h$ prior





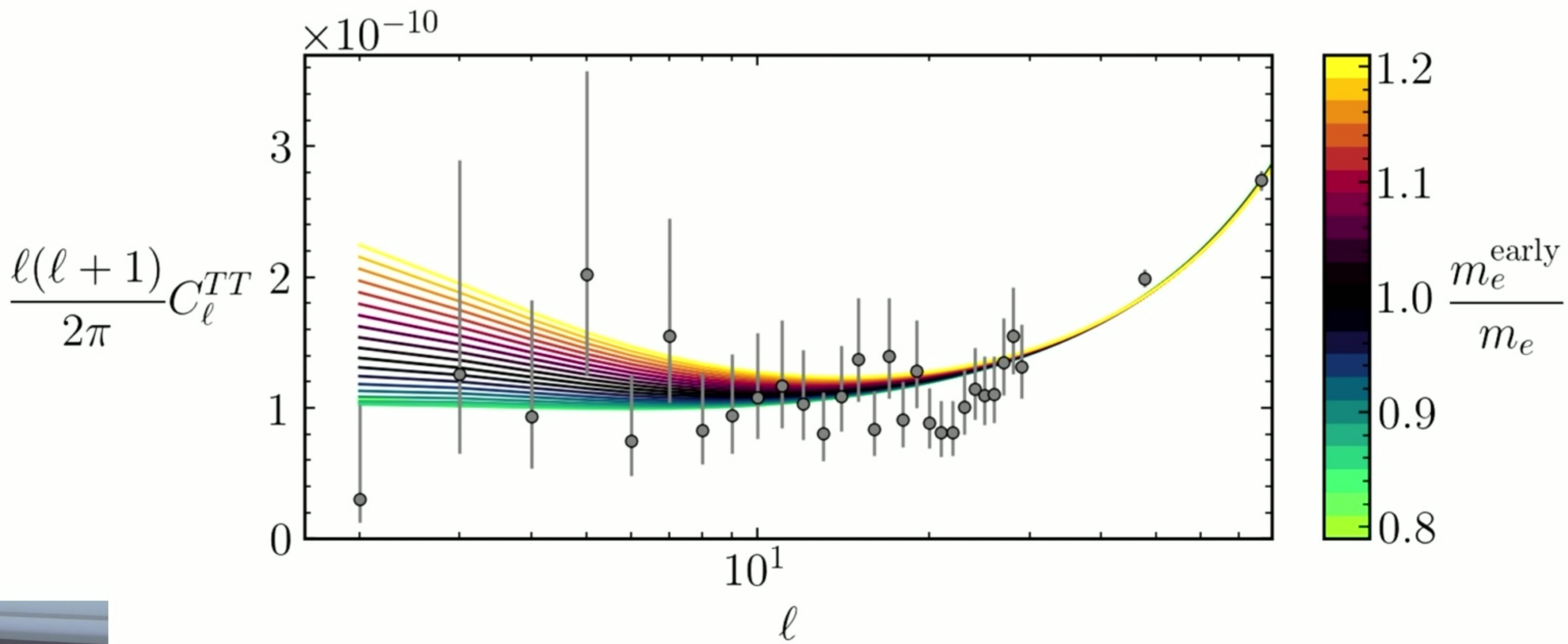
ISW effect



$\times 10^{-10}$
8
6
4
2
0
$\frac{\ell(\ell+1)}{2\pi} C_\ell^{TT}$
10^1
10^2
10^3
ℓ
1.2
1.1
1.0
0.9
0.8
$\frac{m_e^{\rm early}}{m_e}$

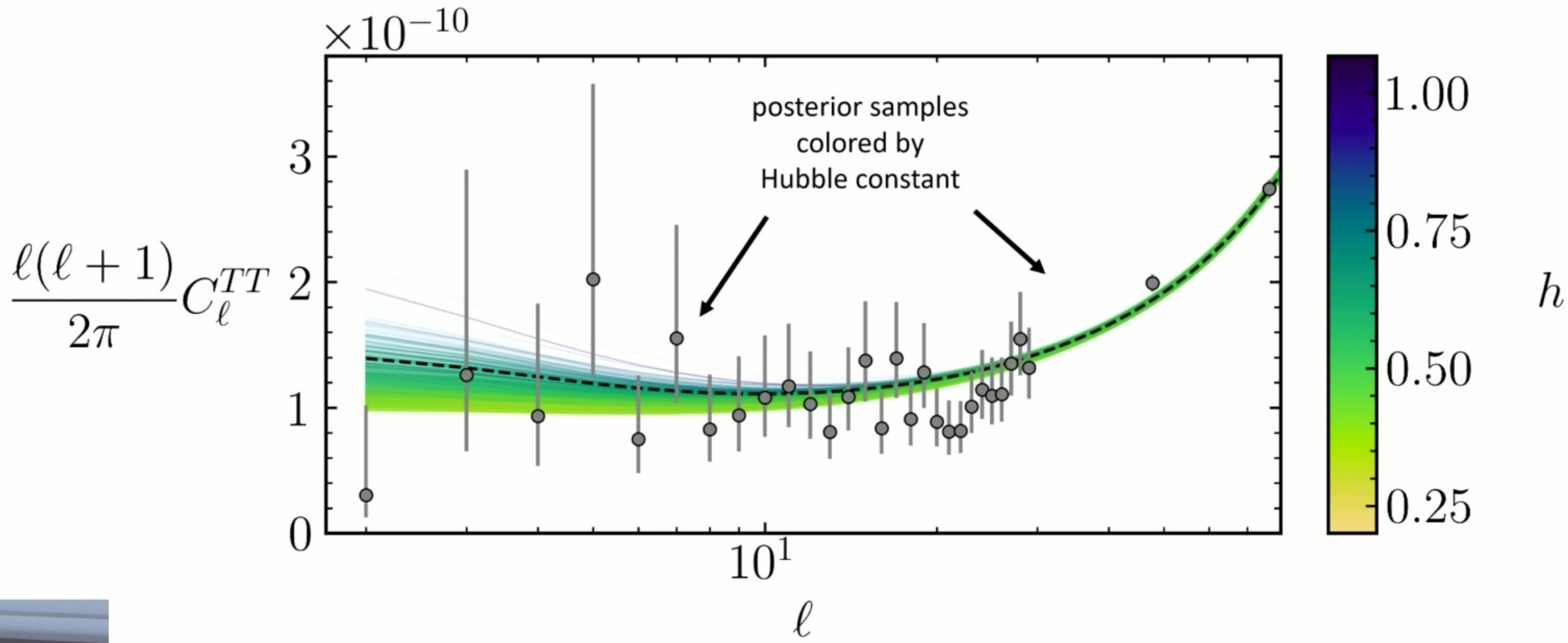
ISW effect

ISW effect



$\times 10^{-10}$
$\frac{\ell(\ell+1)}{2\pi} C_\ell^{TT}$
3
2
1
0
10^1
ℓ
1.2
1.1
1.0
0.9
0.8
$\frac{m_e^{\text{early}}}{m_e}$

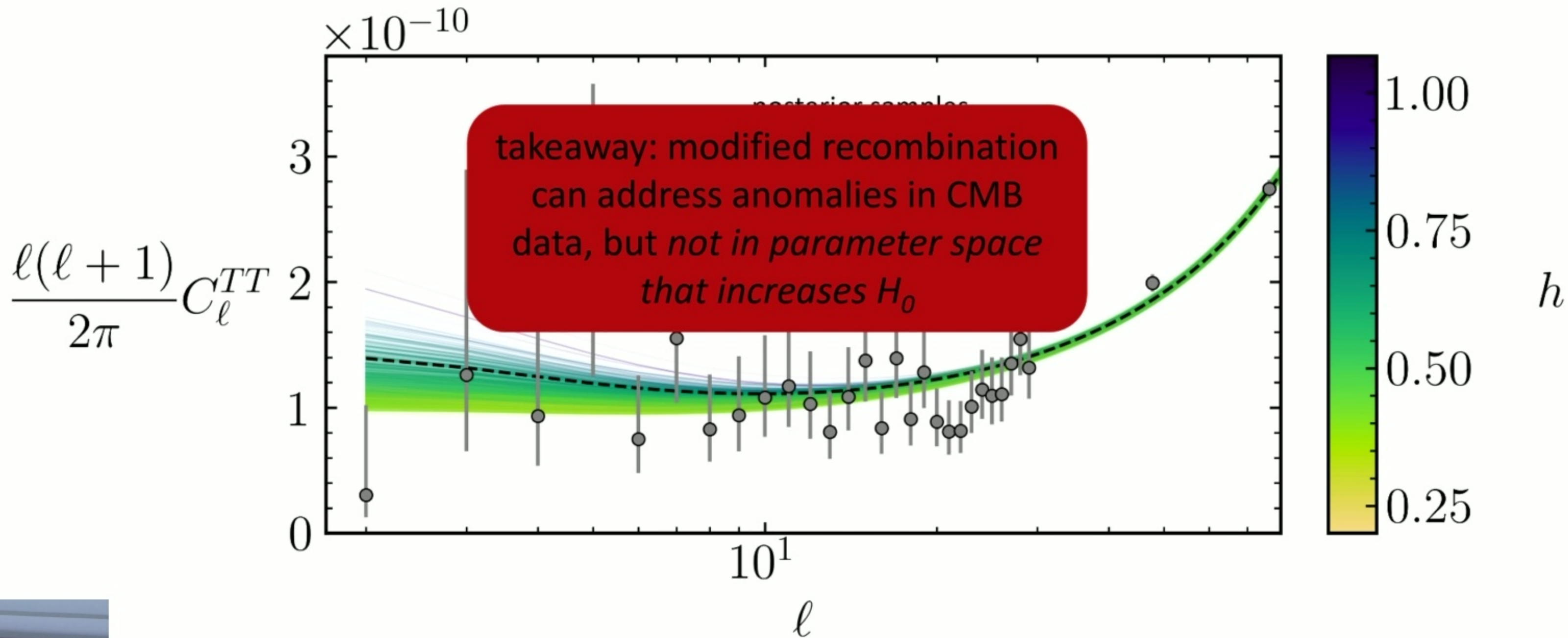
ISW effect



$\times 10^{-10}$
posterior samples colored by Hubble constant
$\frac{\ell(\ell+1)}{2\pi} C_\ell^{TT}$
0
1
2
3
10^1
ℓ
1.00
0.75
0.50
0.25
h

ISW effect

Bayes factor = ratio of tension metrics x product of Bayes factors for each dataset



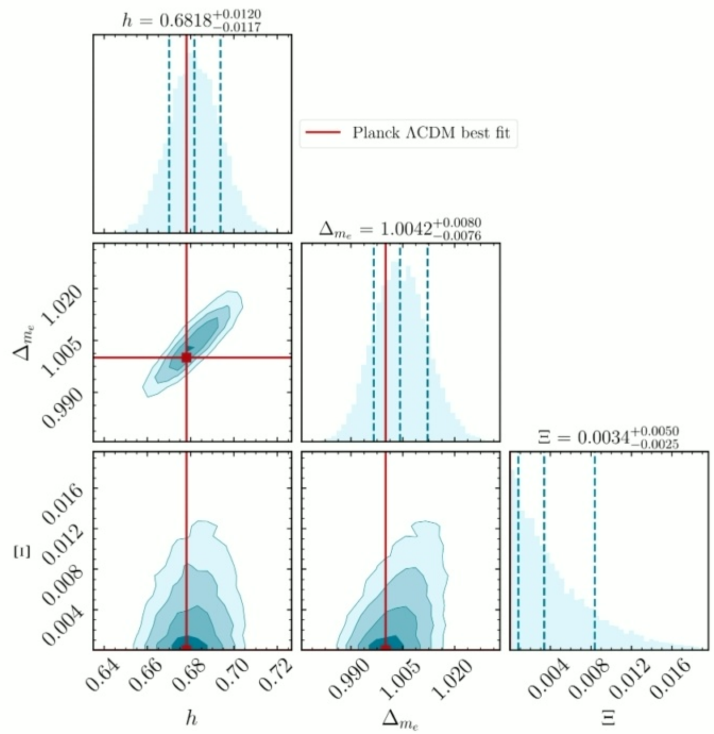
takeaway: modified recombination can address anomalies in CMB data, but *not in parameter space that increases H_0*

Adding BAO distances

data: Planck TT, TE, EE
+ BAO scale from
- eBOSS LRG DR16
- SDSS DR7 MGS
- 6dFGS

$$\Delta_{m_e} \equiv \frac{m_e^{\text{early}} - m_e^0}{m_e^0} \rightarrow$$

$$\Xi \equiv \frac{\rho_\phi(t_0)}{\rho_{\text{CDM}}(t_0)} \rightarrow$$



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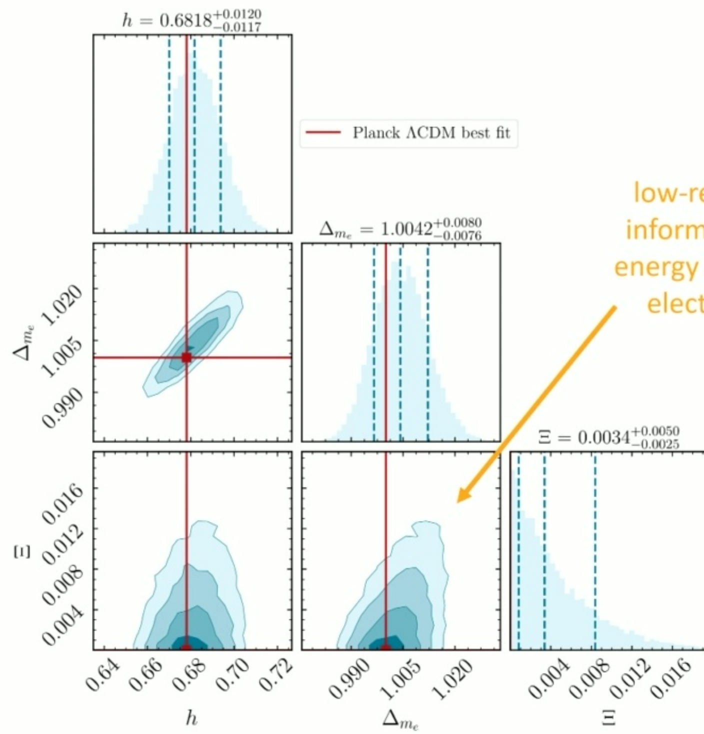
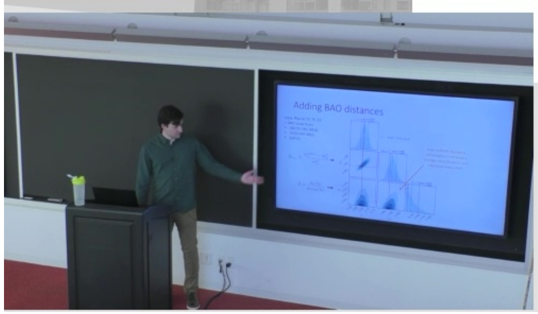
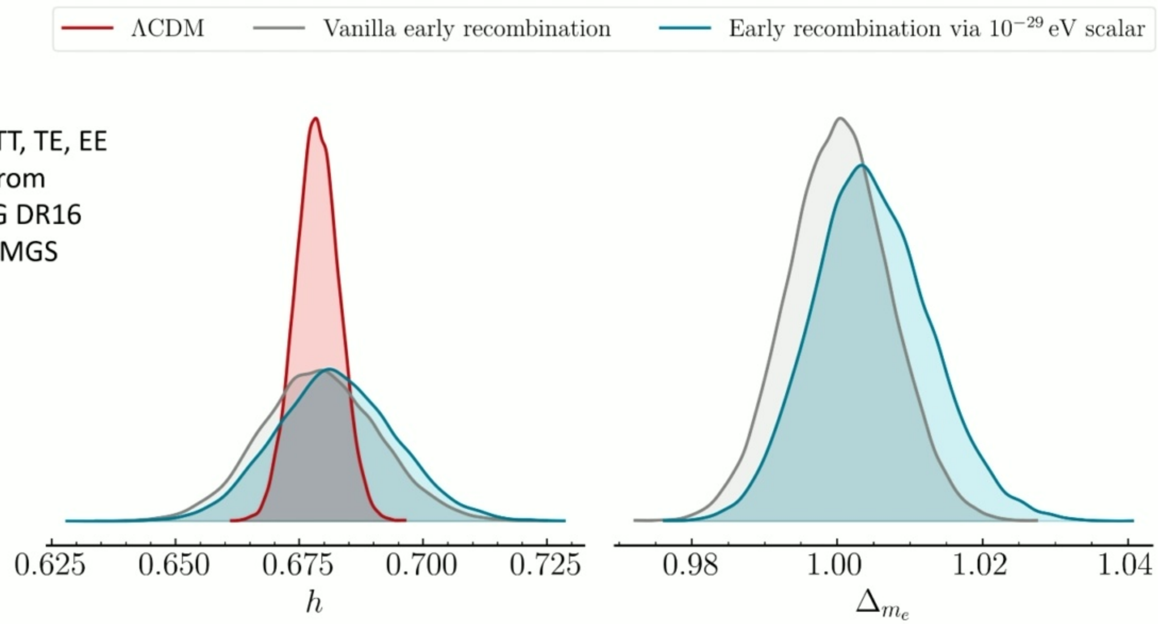


low-redshift distance information correlates energy contribution and electron mass shift



Showdown

data: Planck TT, TE, EE
+ BAO scale from
- eBOSS LRG DR16
- SDSS DR7 MGS
- 6dFGS



Additional phenomenology

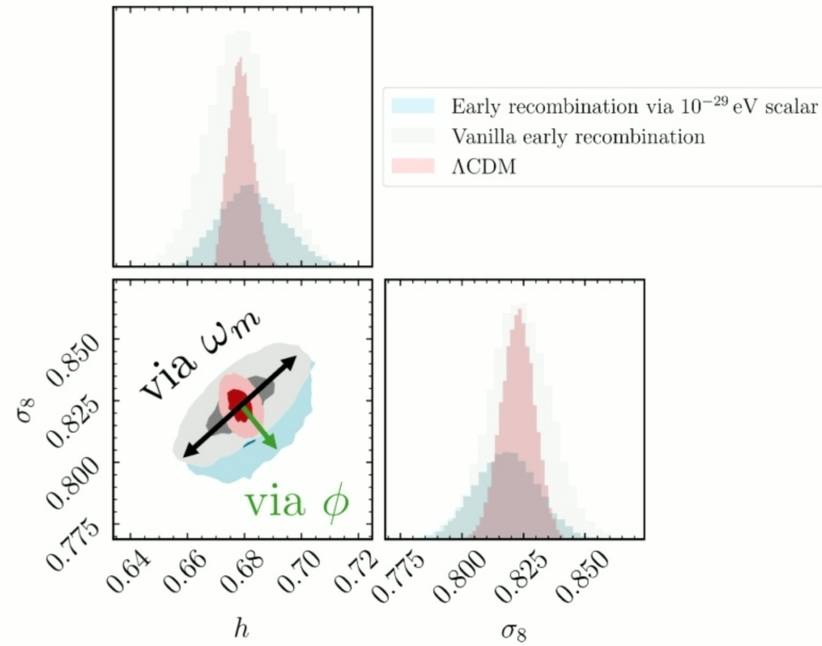
structure growth

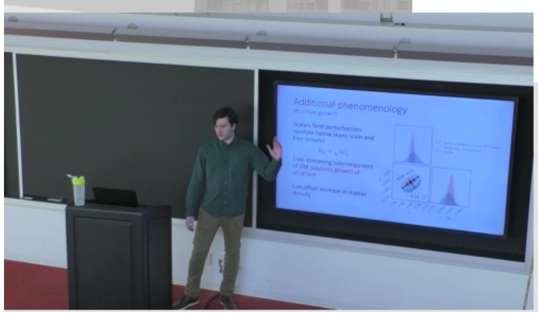
Scalars field perturbations oscillate below Jeans scale and free stream!

$$k_{\rm fs} \propto \sqrt{m_\phi}$$

Free-streaming subcomponent of DM suppress growth of structure

Can offset increase in matter density





Conclusion

Theory learns much from cosmology, but cosmology also stands to learn much from theory!