The Early Universe as a Laboratory for Particle Physics

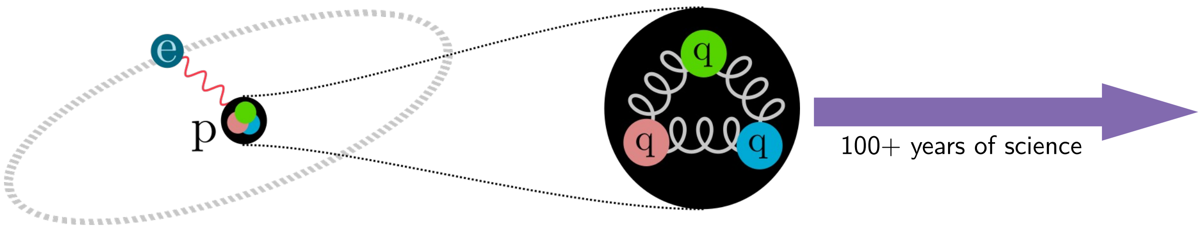
Nikita Blinov

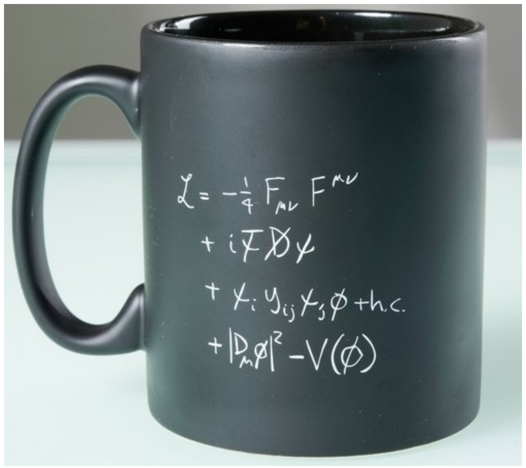
April 6, 2021

York University

Triumph of the Standard Model

Standard Model describes properties and interactions of leptons, quarks and force carriers





CERN Gift Shop

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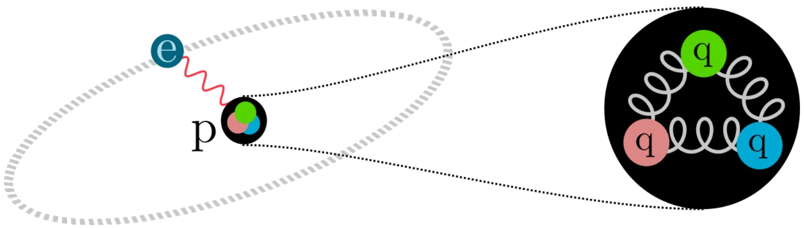
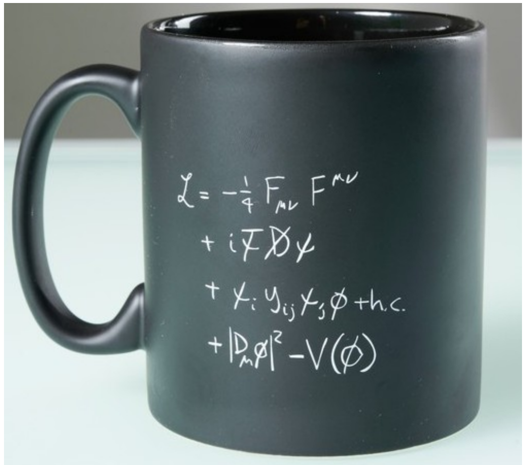


100+ years of science



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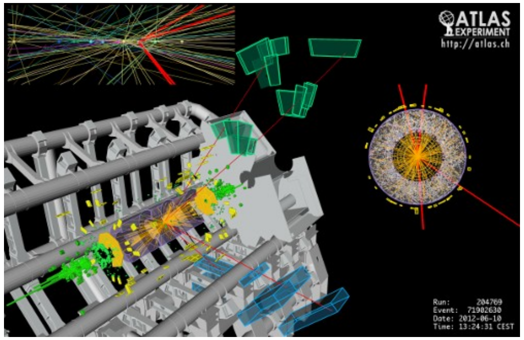
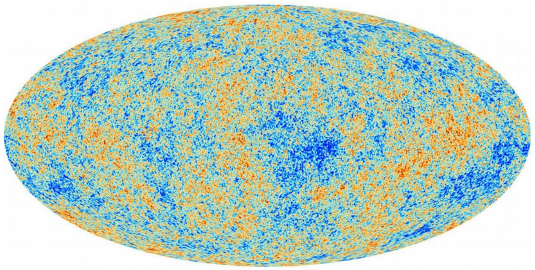
Enormous dynamic range when combined with gravity

Large Hadron Collider probes ~$\mathbf{10^{-20}}$ **m**

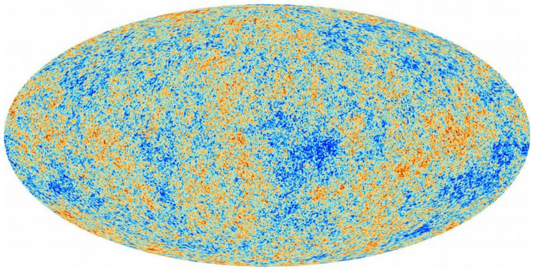


Cosmic Microwave Background: ~$\mathbf{10^{+24}}$ **m**



The Cosmological Fine Print

On **largest** scales, the universe is well-described by a handful of parameters



Planck '18

Universe Facts

Standard Model	
Photons	**0.005%**
Neutrinos	**0.004%**
Baryons	**5%**
Non-Standard Model	
Dark Energy	**68.5%**
Dark Matter	**26.5%**

*Abundances are based on the Standard Cosmological model. They may be different in other models.

Only measured indirectly

Why not 0?

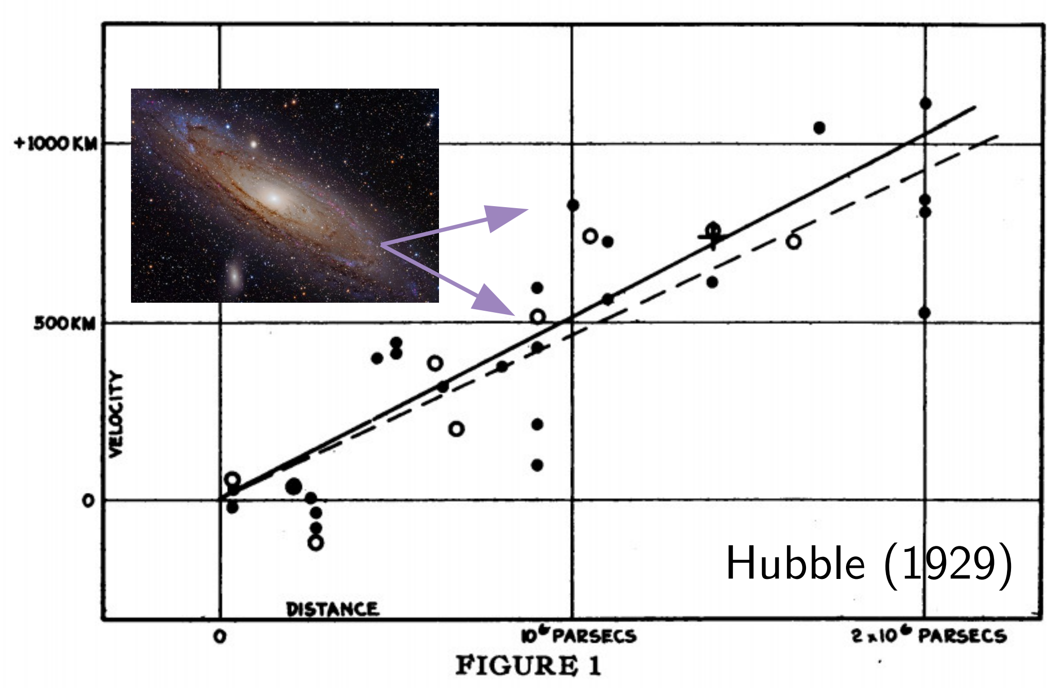
Inconsistent with quantum estimates

No candidate in Standard Model

The Expanding Universe

Far-away objects (like galaxies) are receding from us

$$v \approx H_0 d$$



$$H_0^{(1929)} \sim 500 \text{ km/s/Mpc}$$

Earlier estimates by Lemaitre (1927) and Robertson (1928)

The Expanding Universe

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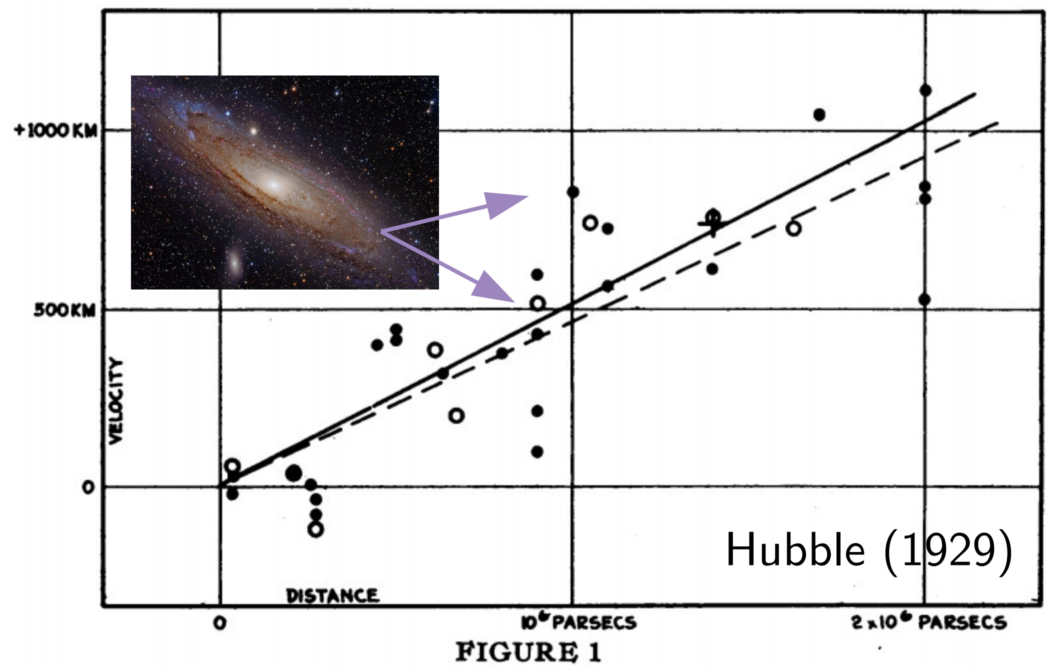
$$v \approx H_0 d$$



$$H_0^{(2019)} \approx 74.03 \pm 1.42 \text{ km/s/Mpc}$$

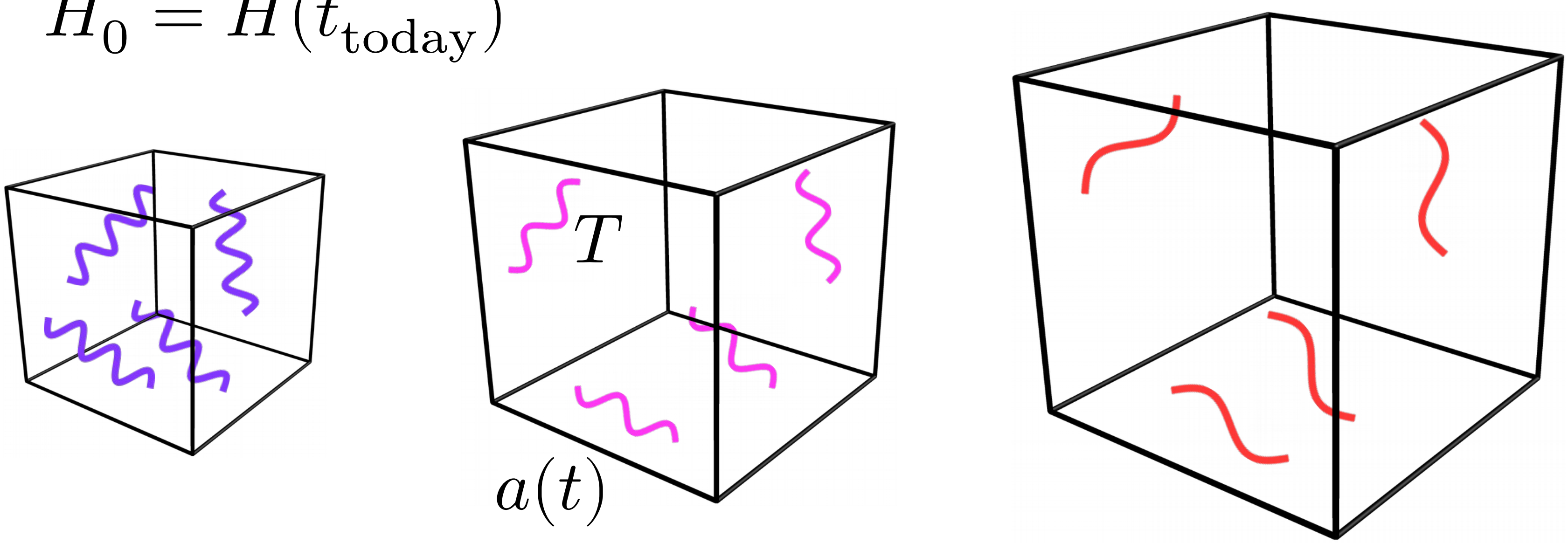
Riess *et al* 2019

Expansion in General Relativity

General Relativity relates expansion rate to the contents of the universe

$$H(t) \propto \sqrt{\rho_{\rm rad}(t) + \rho_{\rm bar}(t) + \rho_{\rm dm}(t) + \rho_{\rm de} + \ldots}$$

$$H_0 = H(t_{\rm today})$$



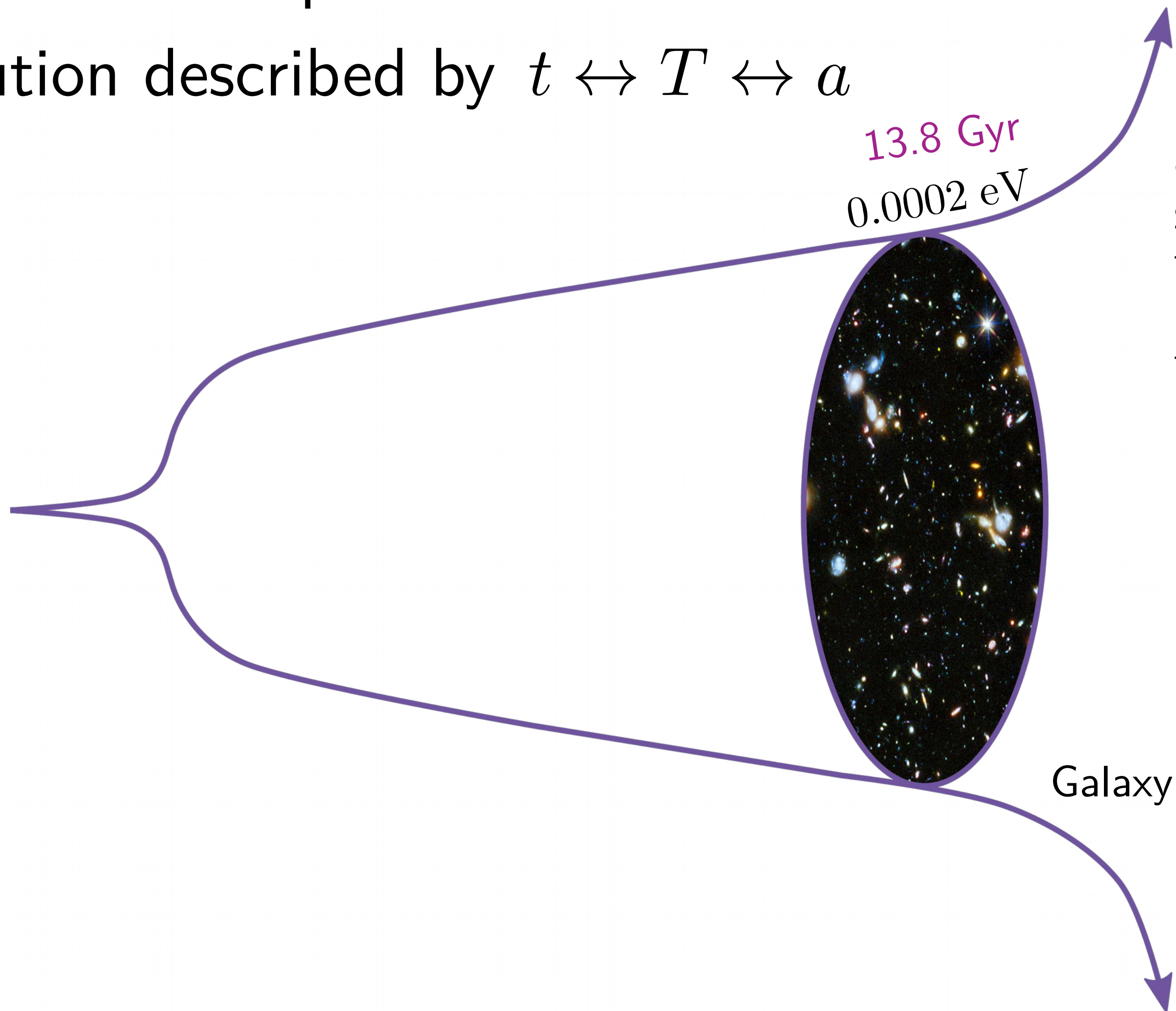
t_1 t_2 t_3

Hotter and denser in the past!

Early Universe Primer

The universe expanded from a hot dense state

Evolution described by $t \leftrightarrow T \leftrightarrow a$



Compare with:

Solar surface:

T $\sim$ 0.5 eV

Room temp:

T $\sim$ 1/40 eV

Galaxy formation, life etc

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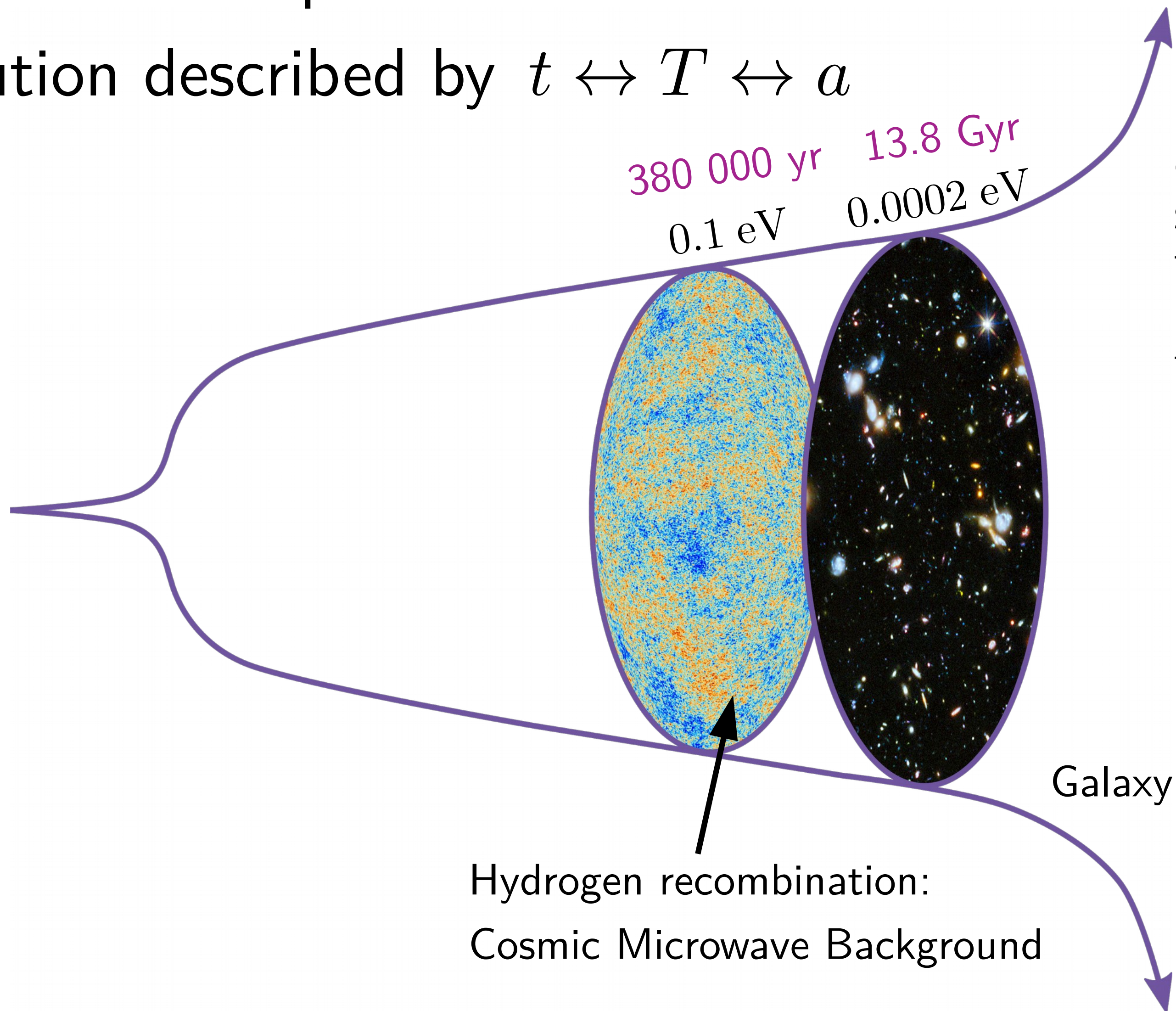

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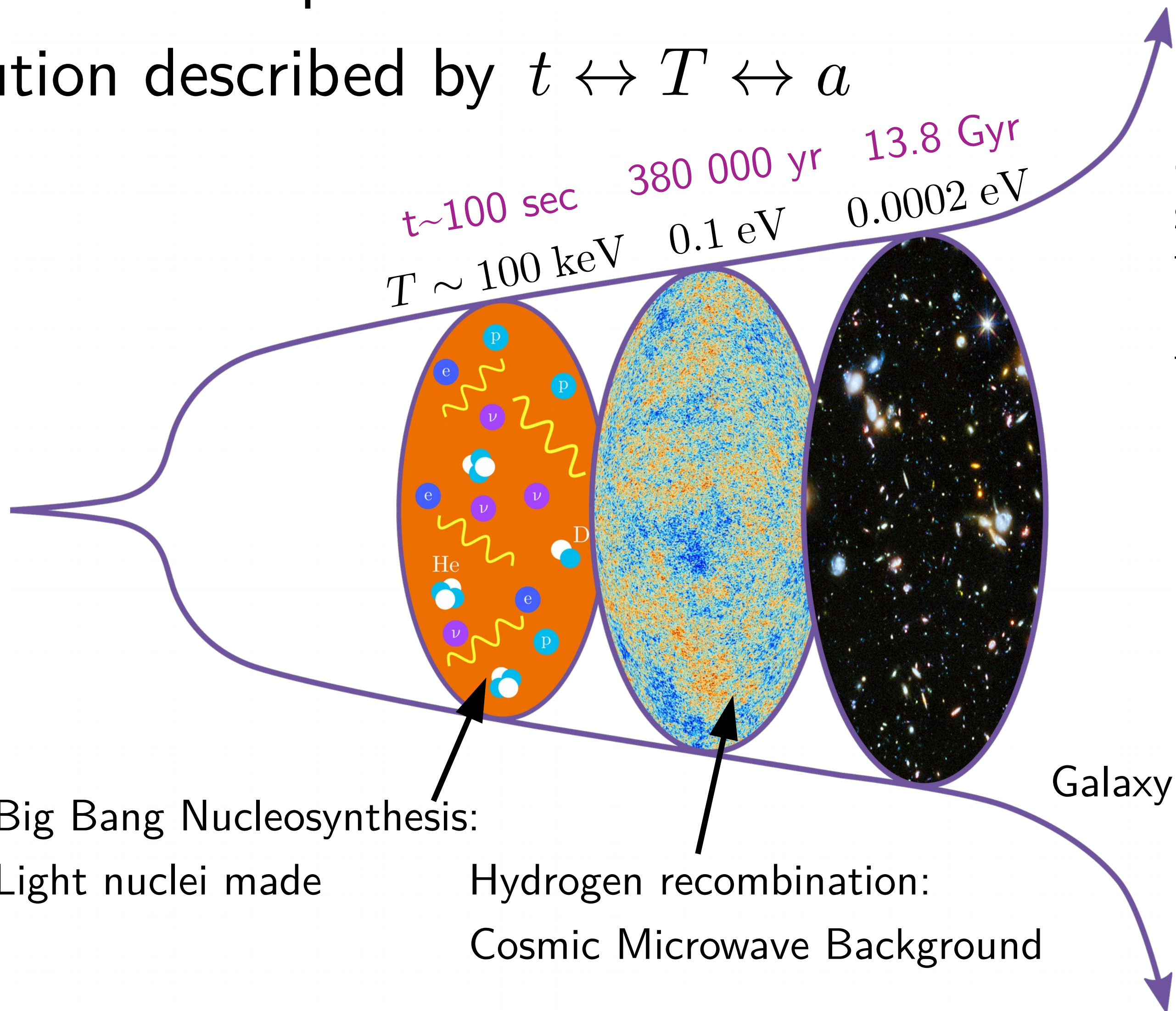

Compare with:

Solar surface:

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Galaxy formation, life etc

Big Bang Nucleosynthesis:

Light nuclei made

Hydrogen recombination:

Cosmic Microwave Background

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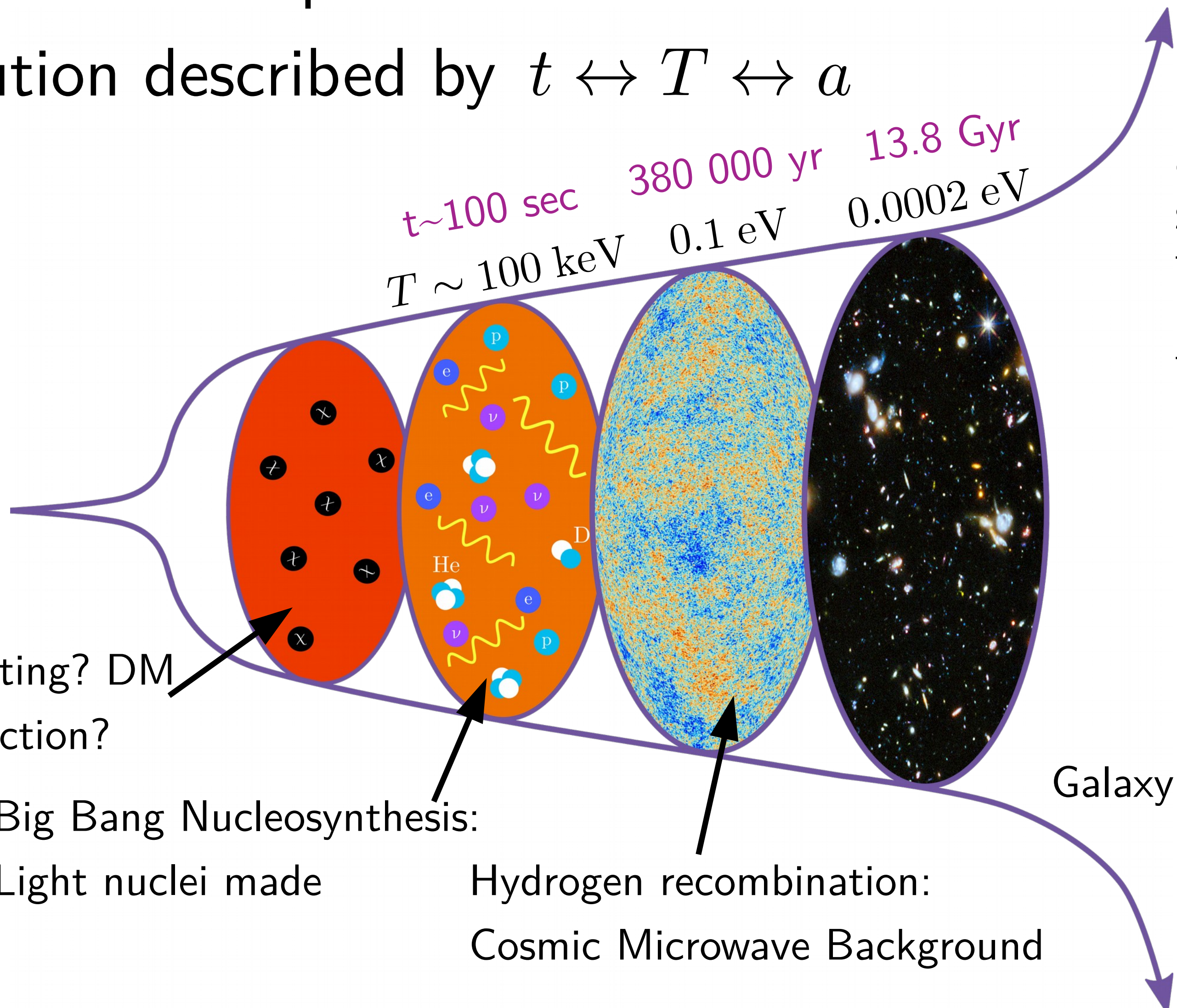

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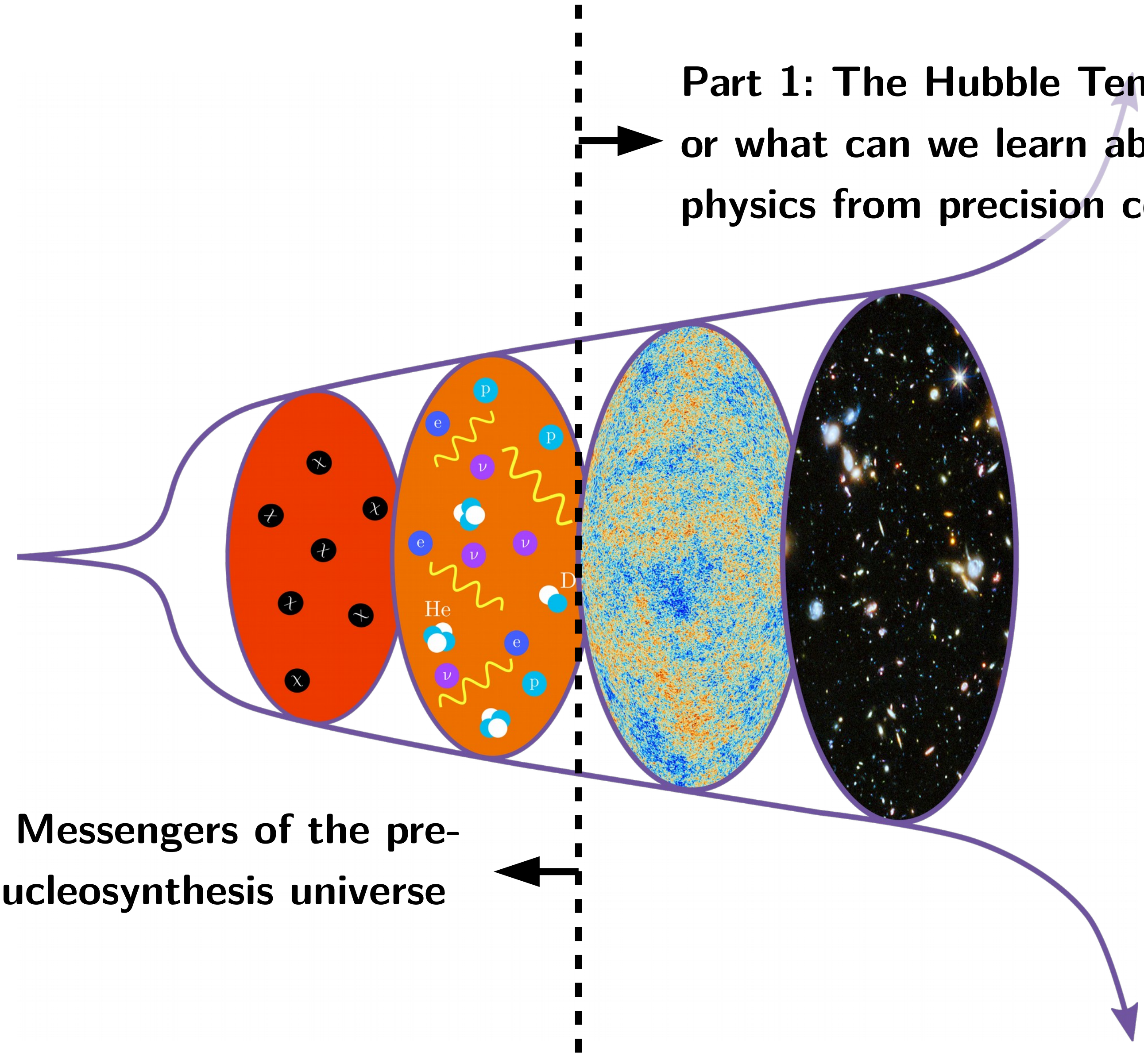
Plan For This Talk

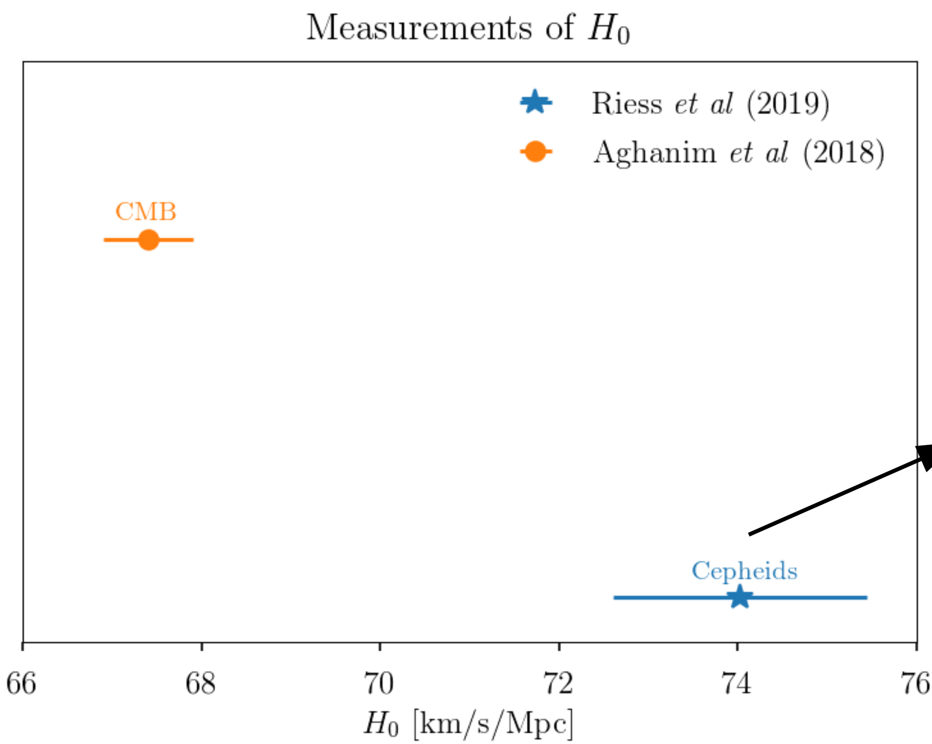
Part 1: The Hubble Tension, or what can we learn about new physics from precision cosmology



Part 2: Messengers of the pre-nucleosynthesis universe

Part 1: The Hubble Tension

Long standing disagreement between direct ("local") measurements of H_0 and early-time inferences

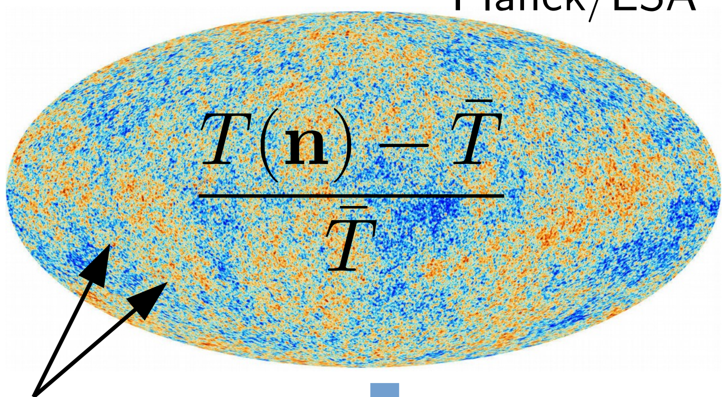


Like Hubble's original measurement

Highly significant tension between two of the most precise values!

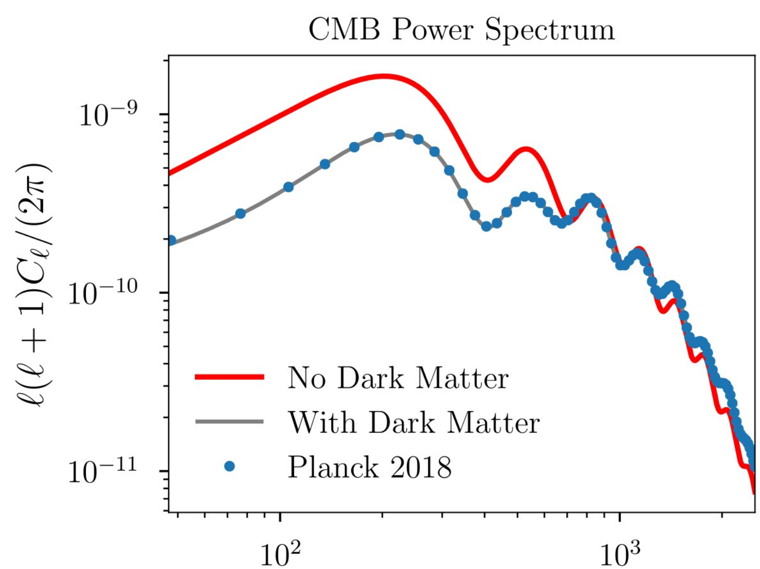
Quantitative Cosmology from The CMB

Planck/ESA



$\theta \sim \frac{\pi}{\ell}$

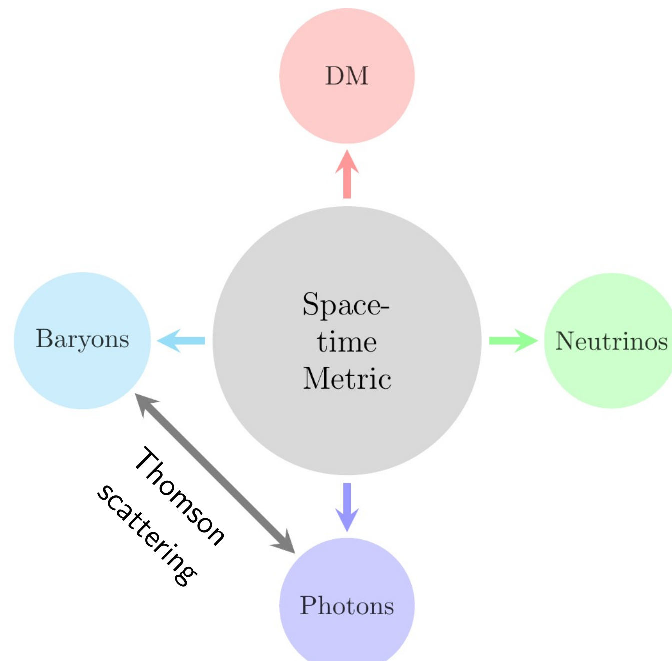
Power Spectrum



larger angular scales ← Multipole ℓ → Smaller angular scales

$\sim \frac{\pi}{\theta}$

Cosmological models track evolution of different fluids under influence of interactions, gravity



Peaks in the Power Spectrum

Peak **position** depends on contents of the universe and evolution of density perturbations

$$\ell_{peak} \approx n(\pi - \delta\varphi)/\theta_s$$

b/g evolution

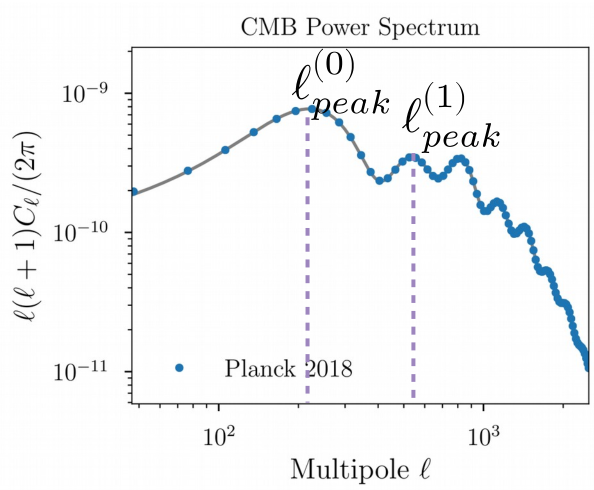
Particle densities

Measured precisely

Evolution of perturbations

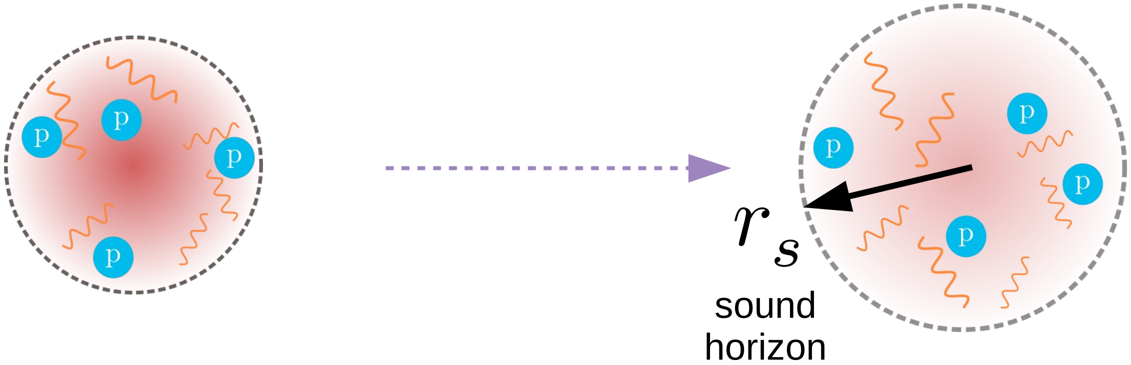
Particle Interactions

See, e.g., Pan, Knox, Mulroe & Narimani (2016)



The Sound Horizon

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s / D_A$ where



$$r_s = \int_0^{t_{rec}} \frac{dt}{a(t)} c_s(a) = \int_0^{a_{rec}} da \frac{c_s(a)}{a^2 H(a)}$$

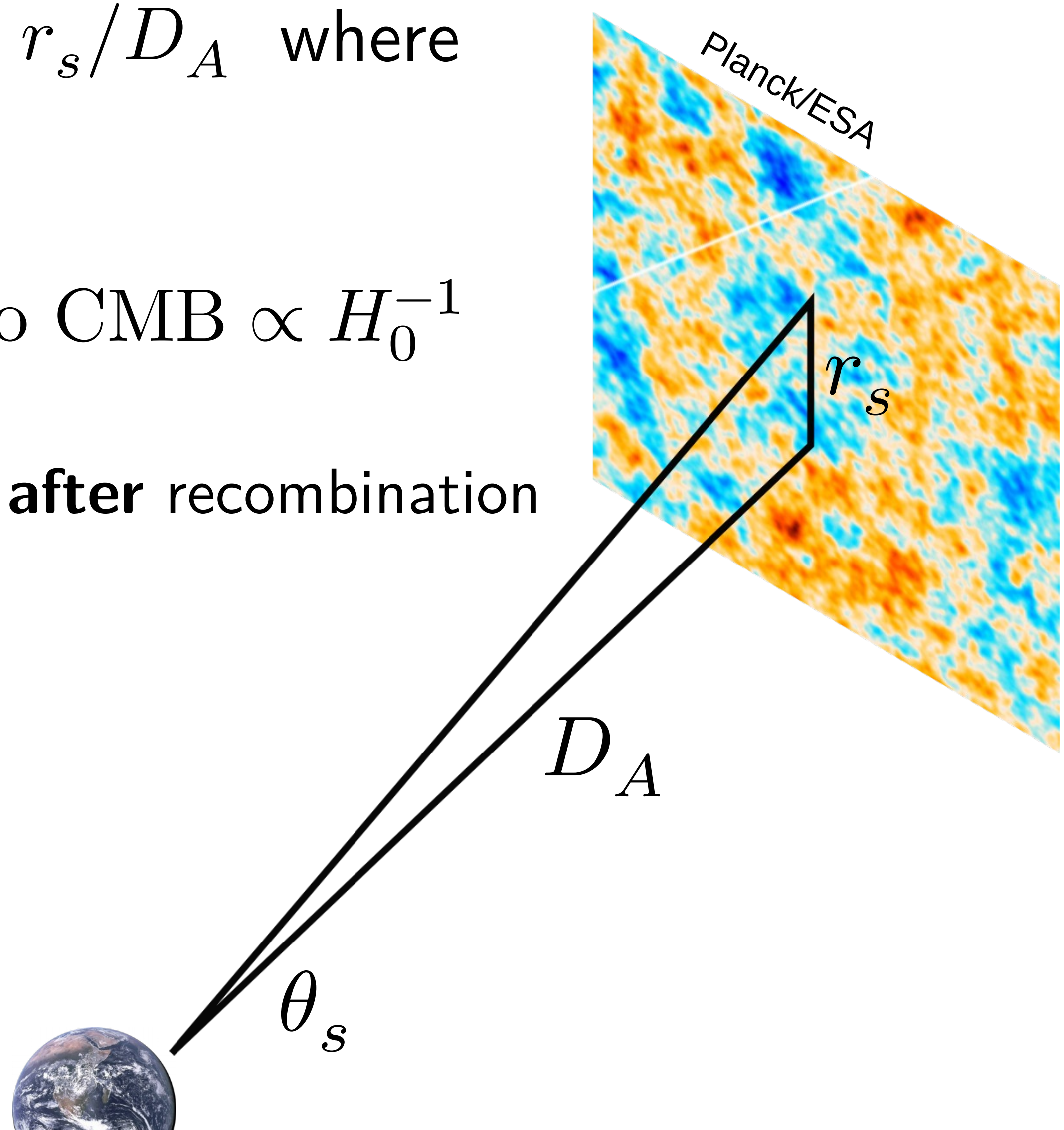
Depends on evolution **before** recombination

Distance to the CMB

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s / D_A$ where

$$D_A = \text{distance to CMB} \propto H_0^{-1}$$

Depends on expansion **after** recombination



Hubble from the CMB

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s/D_A$ where

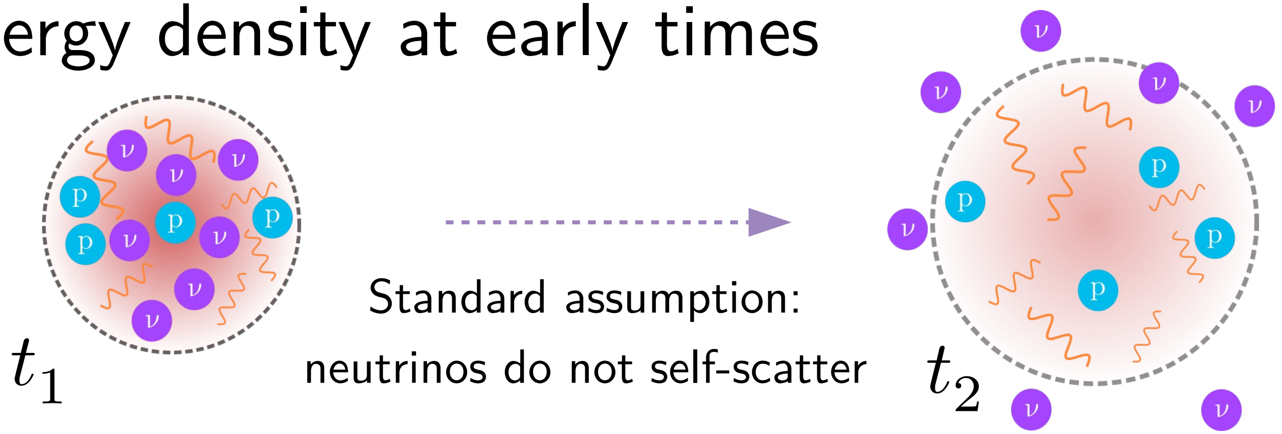
$$H_0 \propto \theta_s / r_s$$

Inference of $\mathbf{H_0}$ is modified if $\mathbf{r_s}$ is changed!

Origin of Phase Shift: Free-streaming Nus

$$\ell_{peak} \approx n(\pi - \delta\varphi)/\theta_s$$

- Neutrinos free-stream and make up about 41% of the energy density at early times



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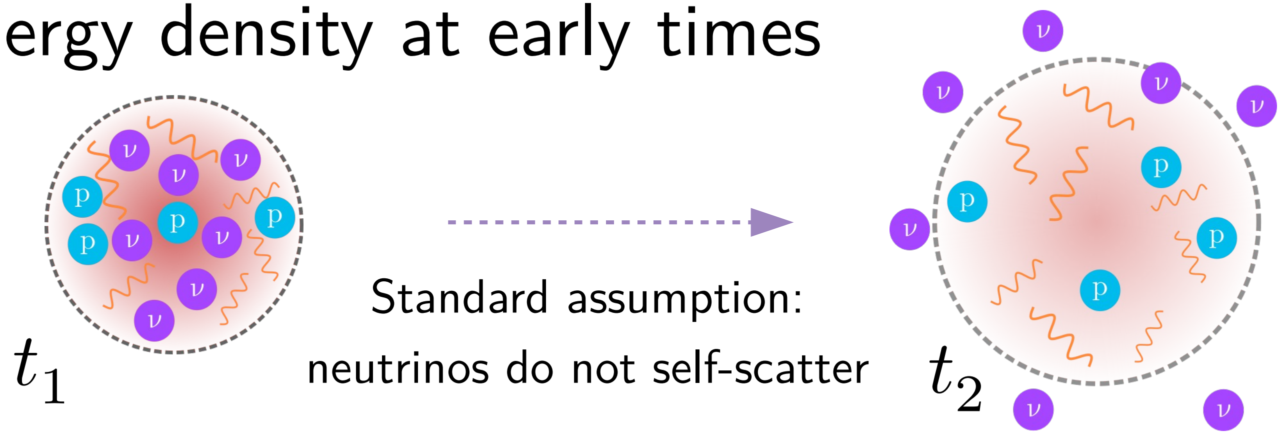
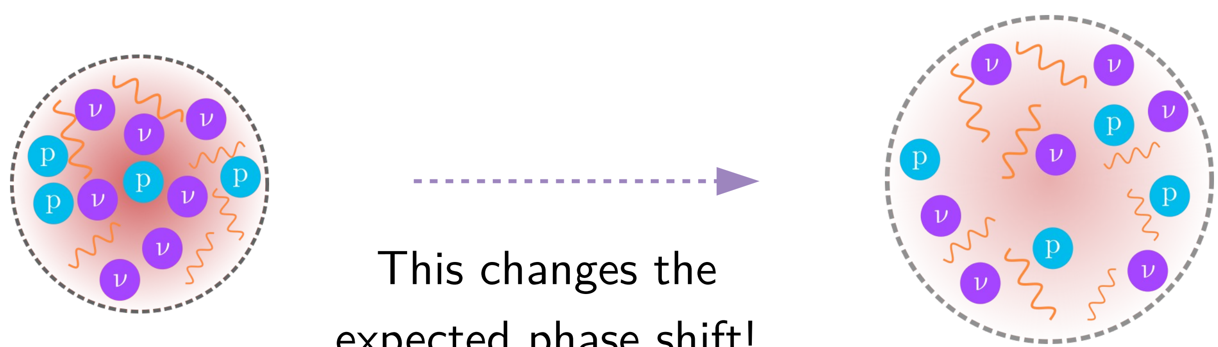


- No free-streaming if neutrinos self-interact



Solving the Hubble Tension

- Modifying amount of neutrinos changes the sound horizon
- Neutrino self-interactions can prevent free-streaming

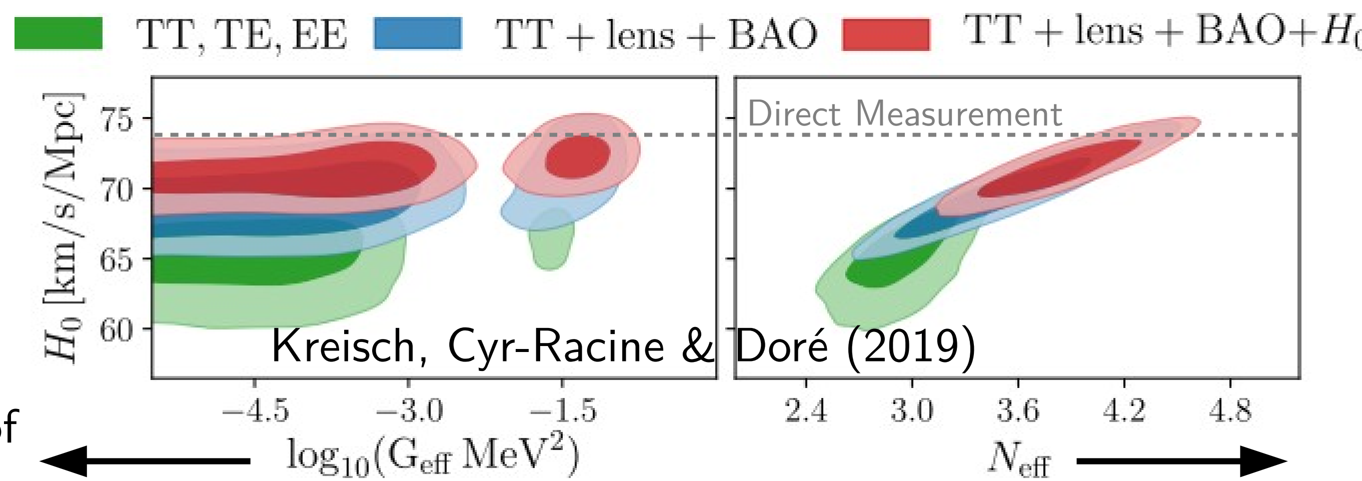
$$\ell_{peak} \approx n(\pi - \delta\varphi)\frac{D_A}{r_s}$$

Changing neutrino properties modifies inference of H_0 !

Self-Interacting Neutrinos

Consistent fit to early cosmology and Riess *et al* (2019) H_0 obtained in models with strong neutrino self-interactions

$$\mathcal{L} \supset G_{\rm eff}\nu\nu\nu\nu$$



Kreisch, Cyr-Racine & Doré (2019)

Interaction of neutrinos: Phase shift

Amount of neutrinos: Modifies r_s

$$G_{\rm eff} = (4.7^{+0.4}_{-0.6}\ \ {\rm MeV})^{-2}$$

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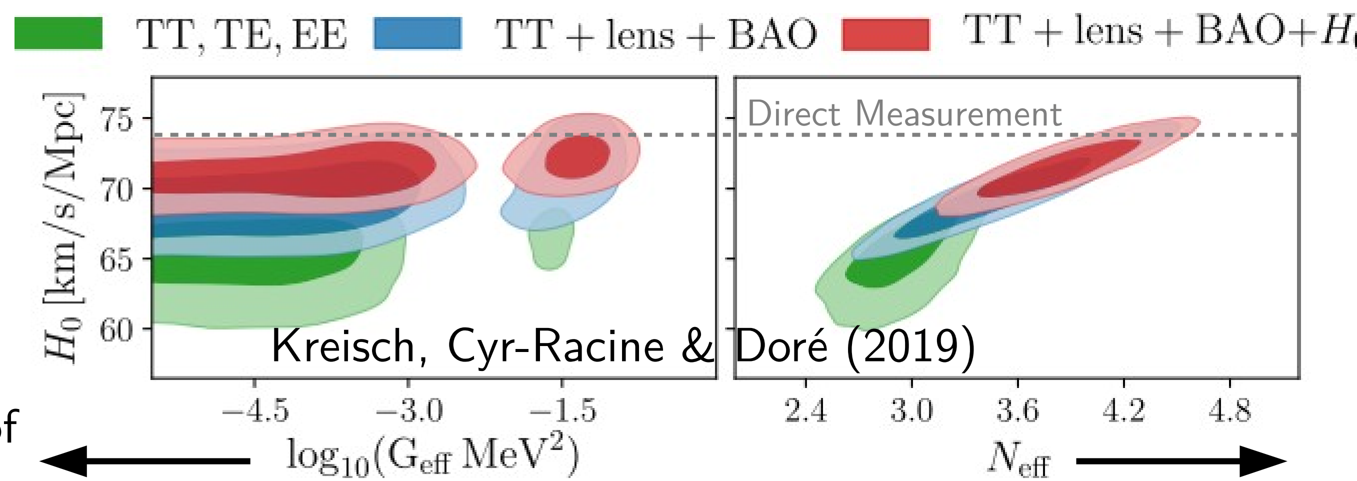

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Interaction of neutrinos: Phase shift

Amount of neutrinos: Modifies r_s

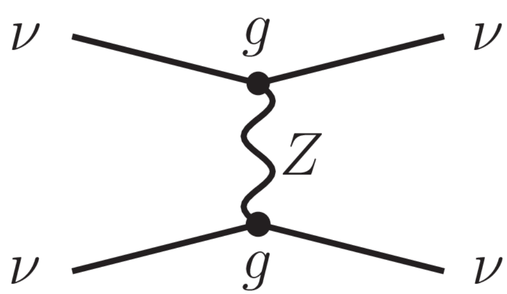
$$G_{\rm eff} = (4.7^{+0.4}_{-0.6}\ \ {\rm MeV})^{-2}$$

Can one have such a neutrino self-interaction in realistic models?

NB, Kelly, Krnjaic, McDermott (2019)

Neutrino Self-Interactions in the SM

Neutrinos self-interact in the SM, not often enough!



$$\mathcal{L} \supset G_F \nu\nu\nu\nu$$

$$G_F \sim \frac{g^2}{m_Z^2} = \left(3 \times 10^5 \text{ MeV}\right)^{-2}$$

Probability for a typical neutrino to scatter via G_F is less than 10^{-15} during the CMB era

Solution to H0 demands

$$G_{\text{eff}} \sim 10^9 G_F$$

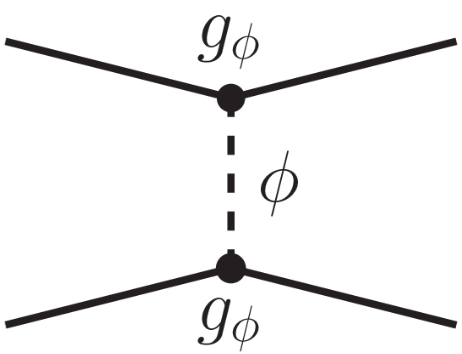
How do you get such a large self-interaction?

NB, Kelly, Krnjaic, McDermott (2019)

Towards the "Ultra-Violet"

New light particle can mediate strong-self interactions among neutrinos

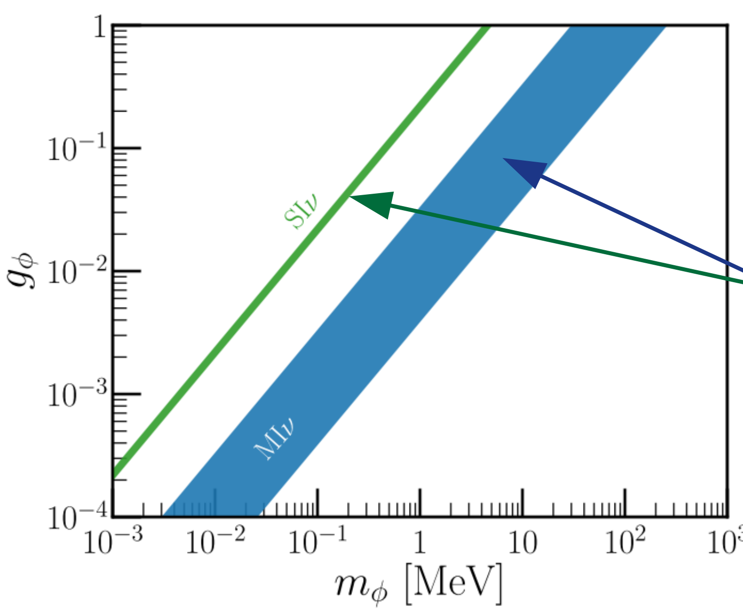
$$G_{\rm eff} \sim 10^9 G_F$$



$$G_{\rm eff} \approx \frac{g_\phi^2}{m_\phi^2} = (10\ {\rm MeV})^{-2} \left(\frac{g_\phi}{10^{-1}}\right)^2 \left(\frac{\rm MeV}{m_\phi}\right)^2$$

10^5 times lighter than Z

Mediator Coupling constant

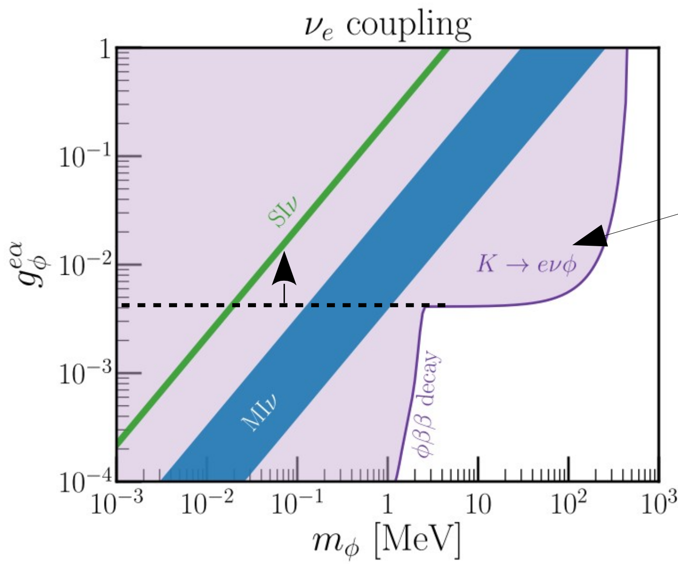


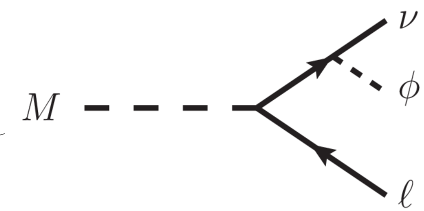
Mediator mass

Solve/alleviate H_0 tension in these regions

NB, Kelly, Krnjaic, McDermott (2019)

Rare Meson Decays

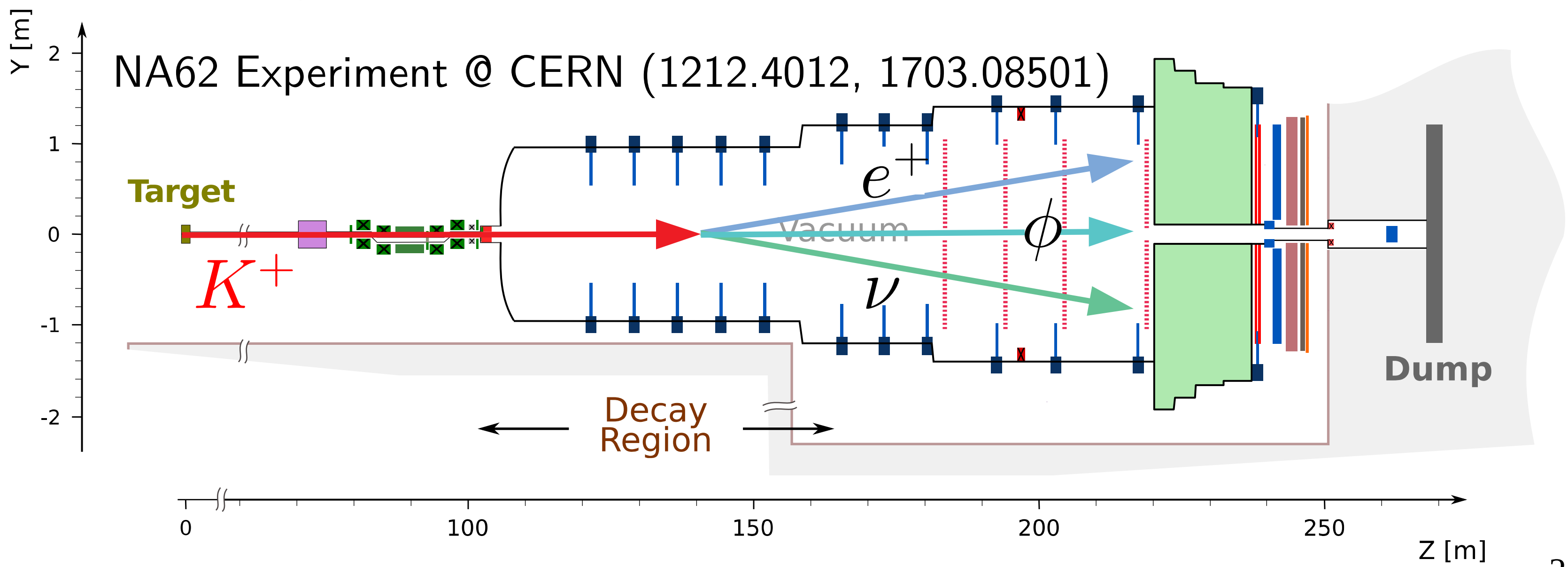




SM Prediction

$$\frac{\mathrm{Br}(K^+ \to e^+\nu)}{\mathrm{Br}(K^+ \to \mu^+\nu)} \approx \left(\frac{m_e}{m_\mu}\right)^2$$

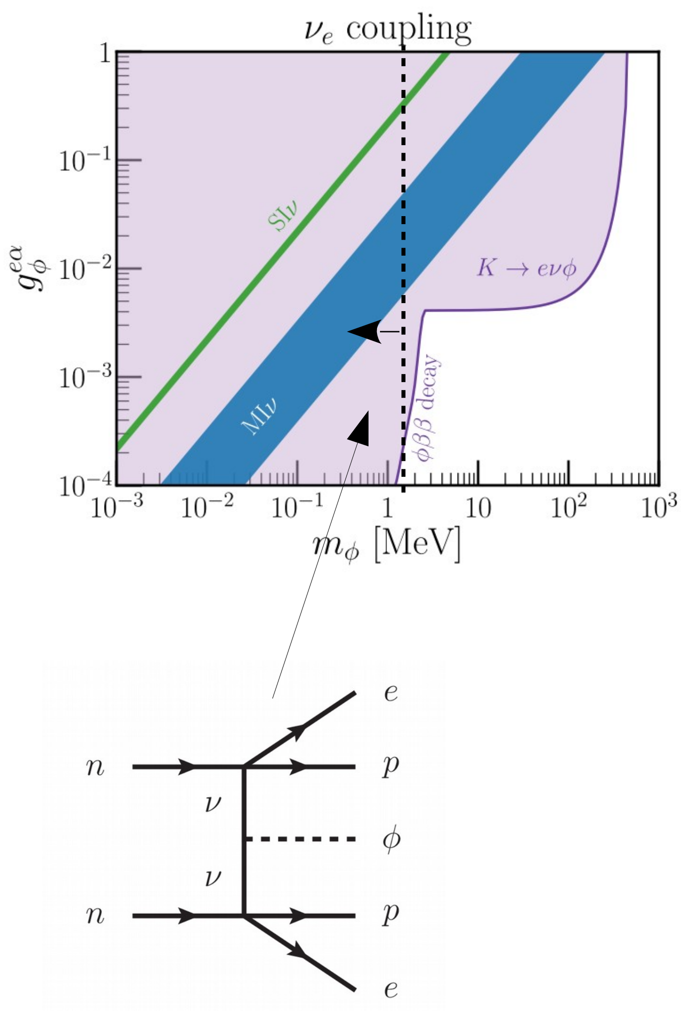
NA62 Experiment @ CERN (1212.4012, 1703.08501)



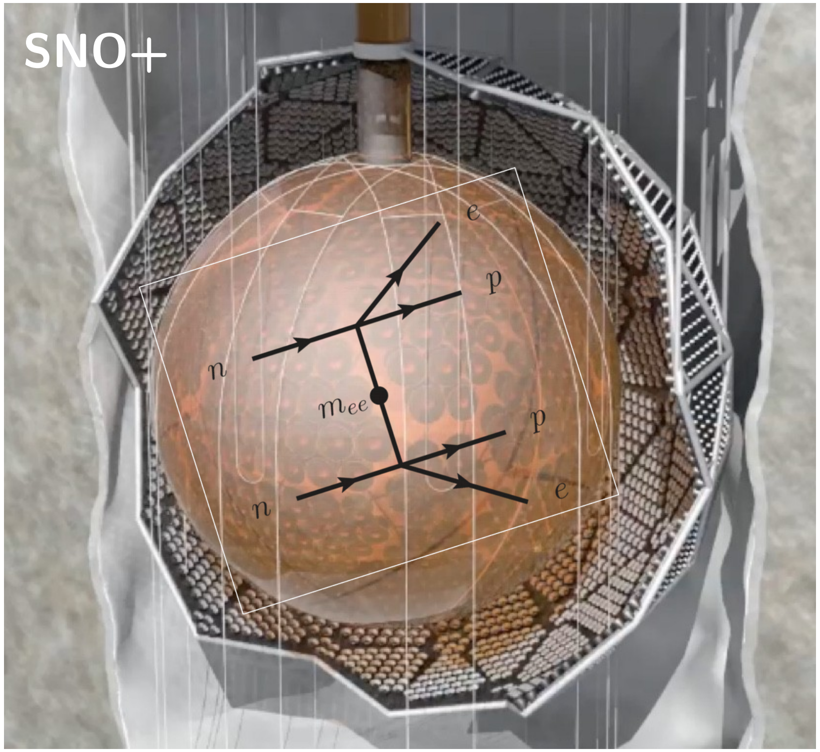
Can also use precision pion measurements from PIENU @ TRIUMF

Searches for 0nu Double Beta Decays

Neutrinoless double beta decay searches can used to search for nu self-interactions



$$(A, Z) \to (A, Z+2) + 2e^-$$

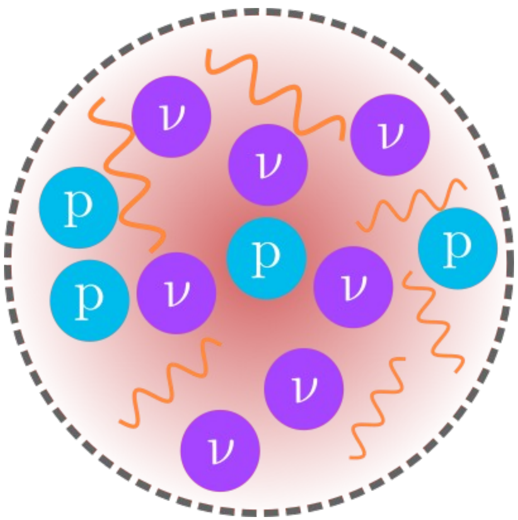


NB, Kelly, Krnjaic, McDermott (2019)

Non-Free-streaming Radiation in General

Experimental constraints on new physics interacting with neutrinos rule out this possibility.

But CMB only sensitive to gravitational influence of neutrinos. Could they really be something else?



NB, Marques-Tavares (2020)

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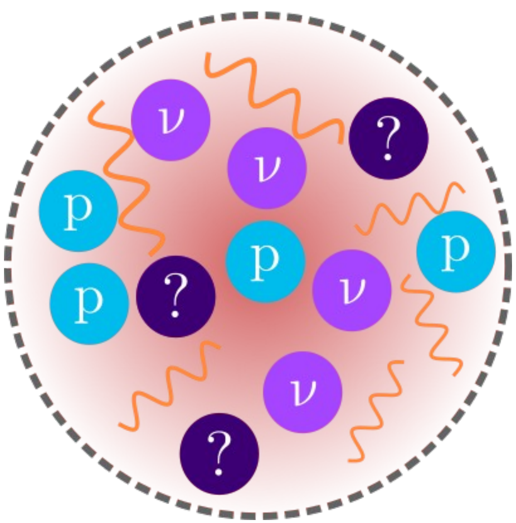
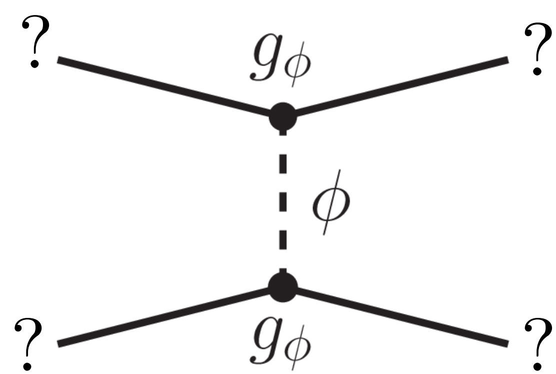
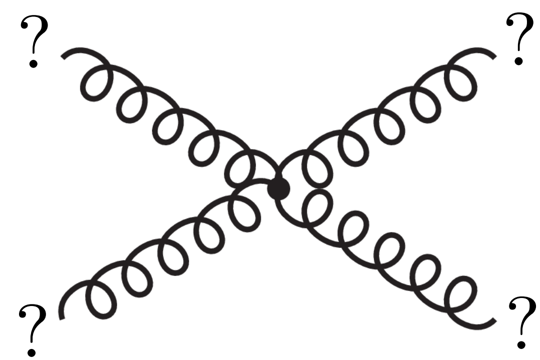




neutrino-like



gluon-like

NB, Marques-Tavares (2020)

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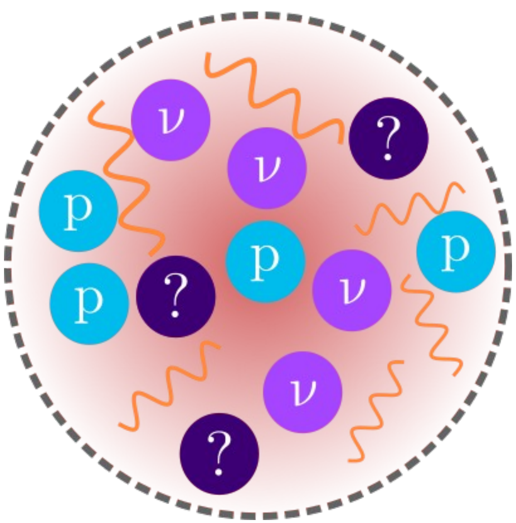

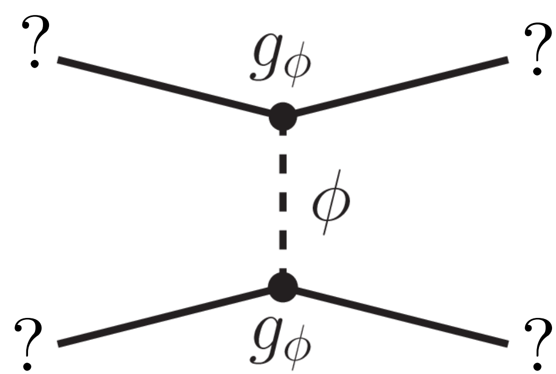

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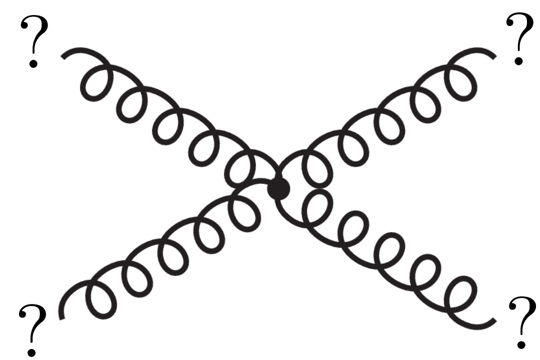


gluon-like

The CMB can test this idea in a *model-independent* way

NB, Marques-Tavares (2020)

Non-Freestreaming/Interacting Radiation

- Consider extended cosmology with free-streaming and non-free-streaming (fluid-like) radiation

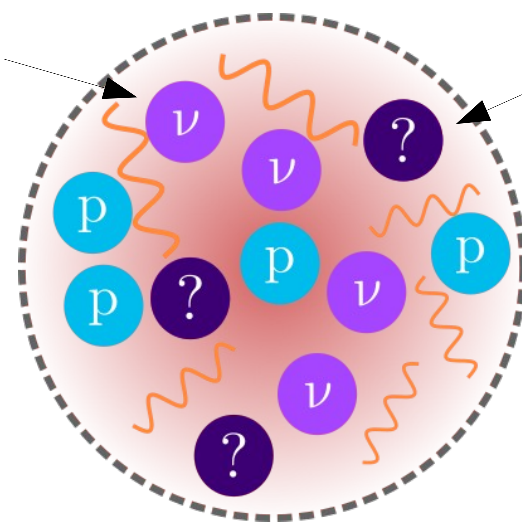
$$\rho_{\rm rad} = \rho_\gamma \left[1 + 0.23(N_{\rm eff} + N_{\rm fld})\right]$$

=3 in SM =0 in SM

$N_{\rm eff}$

Free-streaming

(SM neutrino-like)



$N_{\rm fld}$

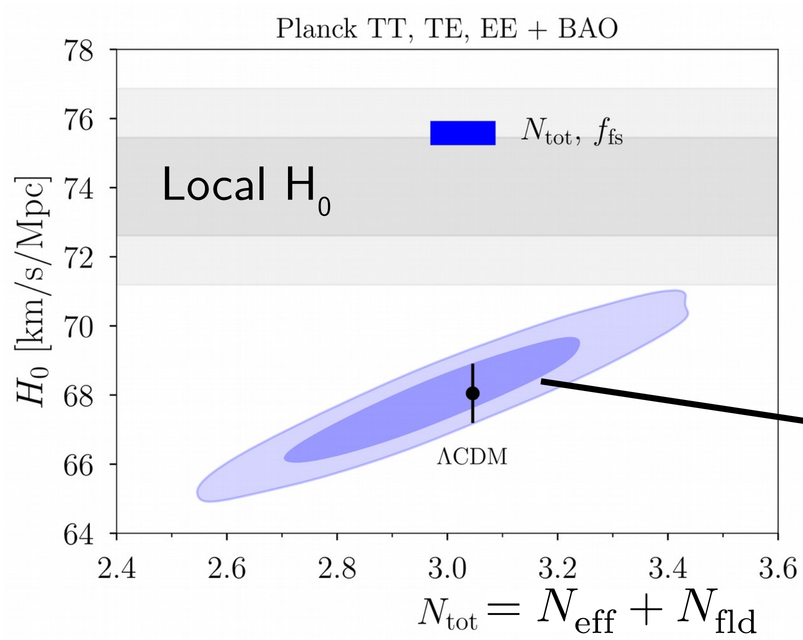
Non-free-streaming

(Fluid-like)

NB, Marques-Tavares (2020); Brust, Cui & Sigurdson (2017); Baumann, Green, Meyers & Wallisch (2016)

Constraints on Dark Radiation

Allow radiation density and free-streaming fraction to vary



Fit to cosmological data

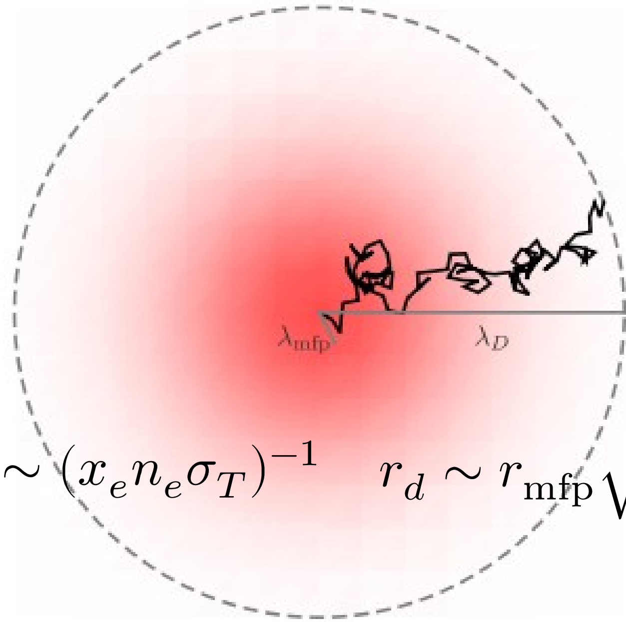
NB, Marques-Tavares (2020)

No preference for beyond-SM from early cosmology alone!

Still no consistent fit to both direct H_0 and CMB

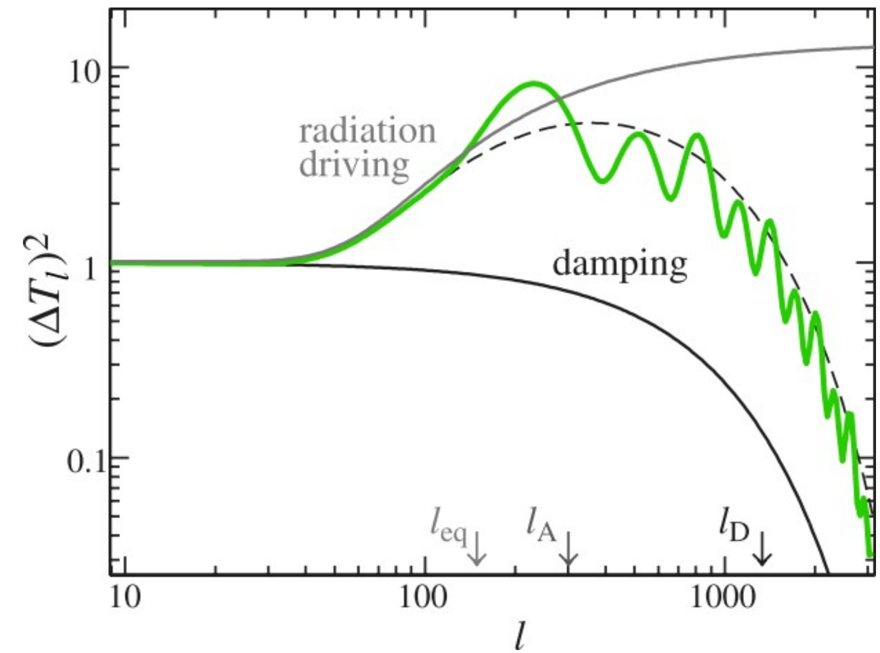
see also Brinckmann *et al* (2012.11830)

Photon Diffusion Damping



$$r_{\rm mfp} \sim (x_e n_e \sigma_T)^{-1} \qquad r_d \sim r_{\rm mfp}\sqrt{t/r_{\rm mfp}}$$

Hu, Fukugita, Zaldarriaga & Tegmark (2000)



Diffusion scale also depends on early expansion history!

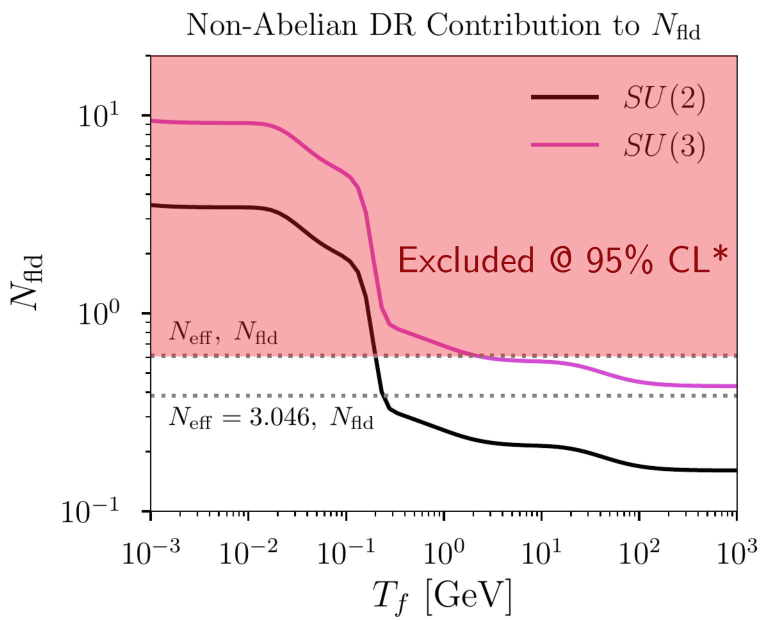
Precise measurements at large ℓ preclude large modifications to r_d relative to r_s

Constraints on Gluon-like Radiation

- Assuming the non-Abelian sector was in thermal equilibrium until temperature T_f, can predict abundance at CMB

$$N_{\text{fld}} = c\left[\frac{g_{*S}(T_\gamma)}{g_{*S}(T_f)}\right]^{4/3}(N^2-1)$$

Number of "colours"

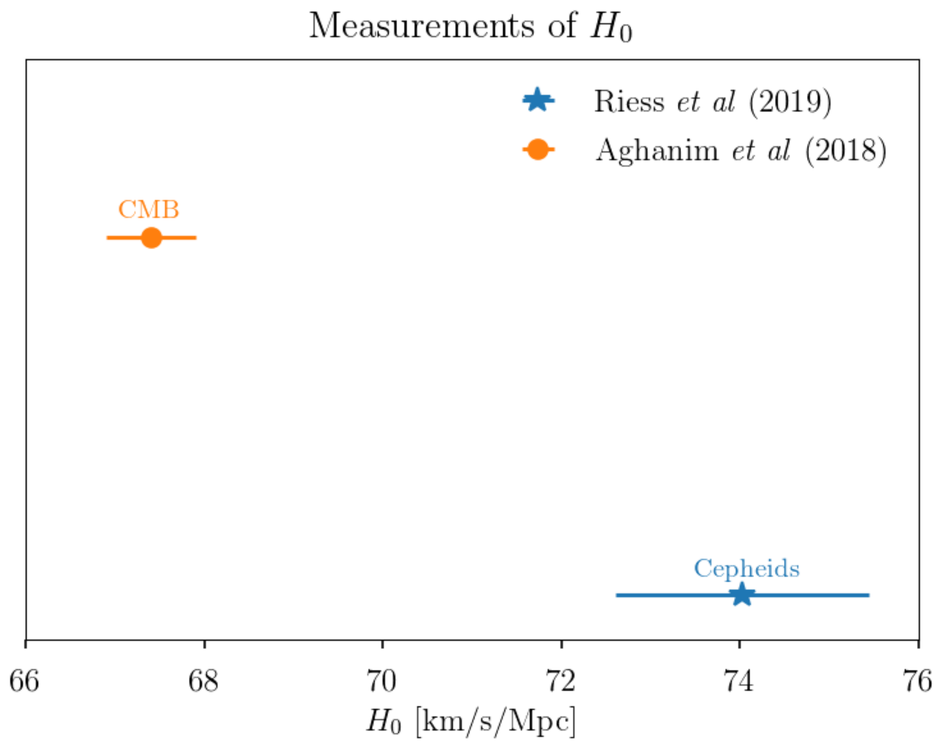


*Assuming no non-SM entropy injections

NB, Marques-Tavares (2020)

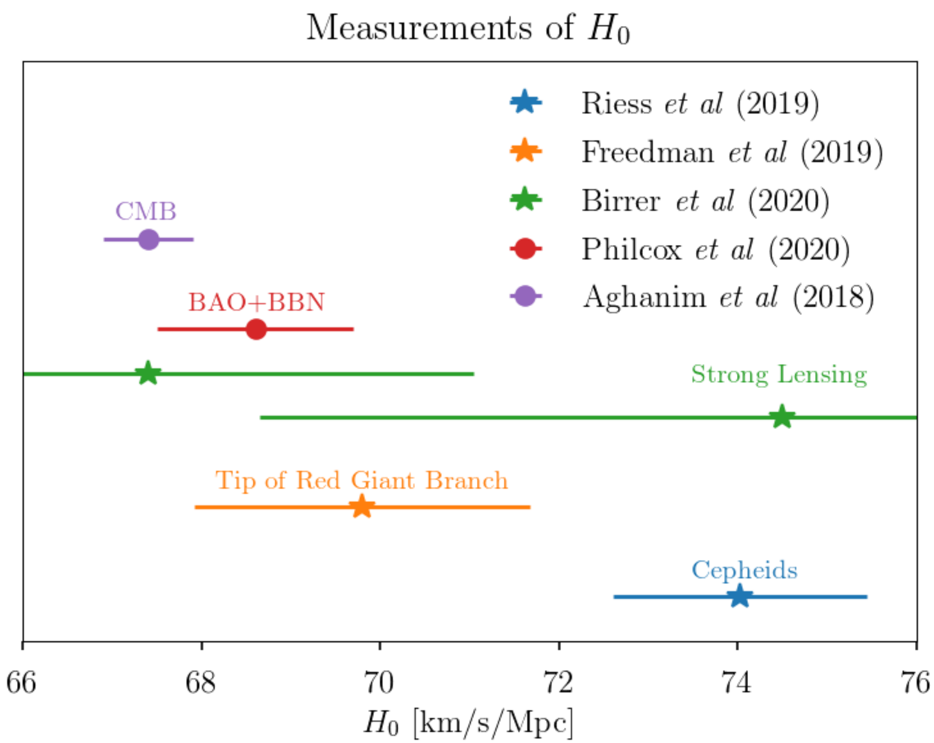
Status of the Hubble Tension

Simple models fail to solve the Hubble tension without running into laboratory/cosmology constraints

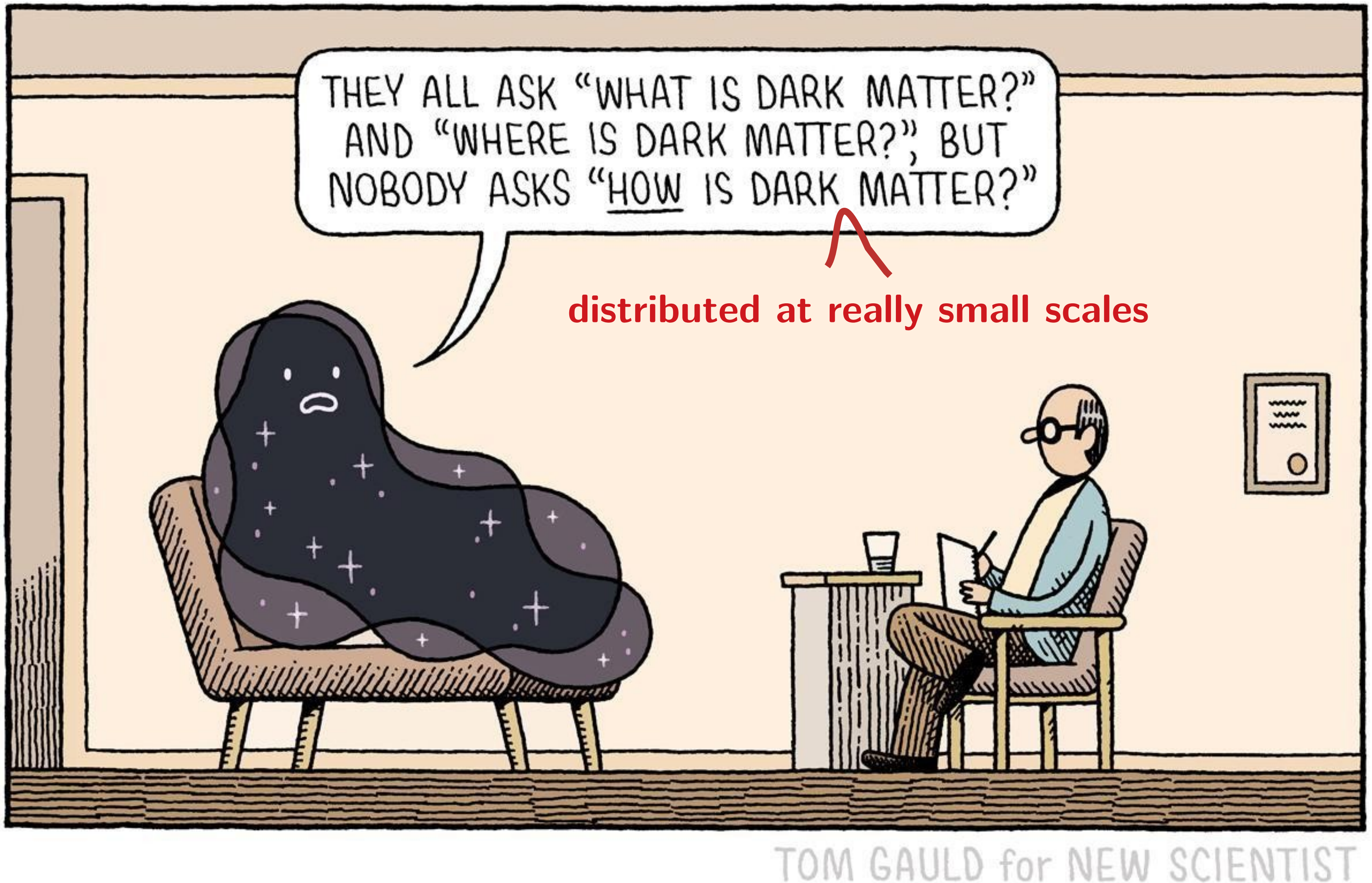


Status of the Hubble Tension

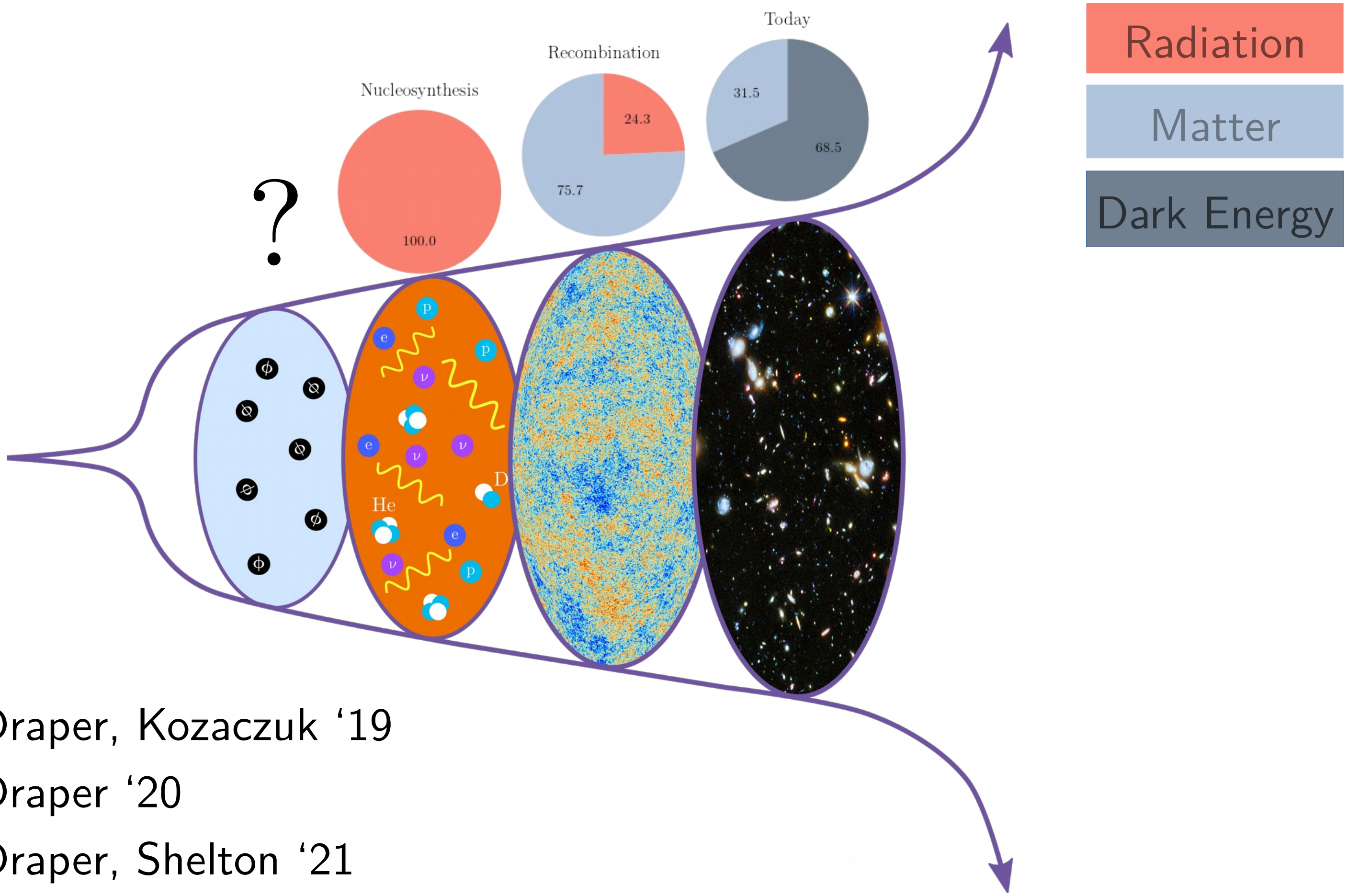
Simple models fail to solve the Hubble tension without running into laboratory/cosmology constraints



Part 2: Messengers of the Pre-Nucleosynthesis Universe



The Pre-Nucleosynthesis Universe



NB, Dolan, Draper, Kozaczuk ‘19

NB, Dolan, Draper ‘20

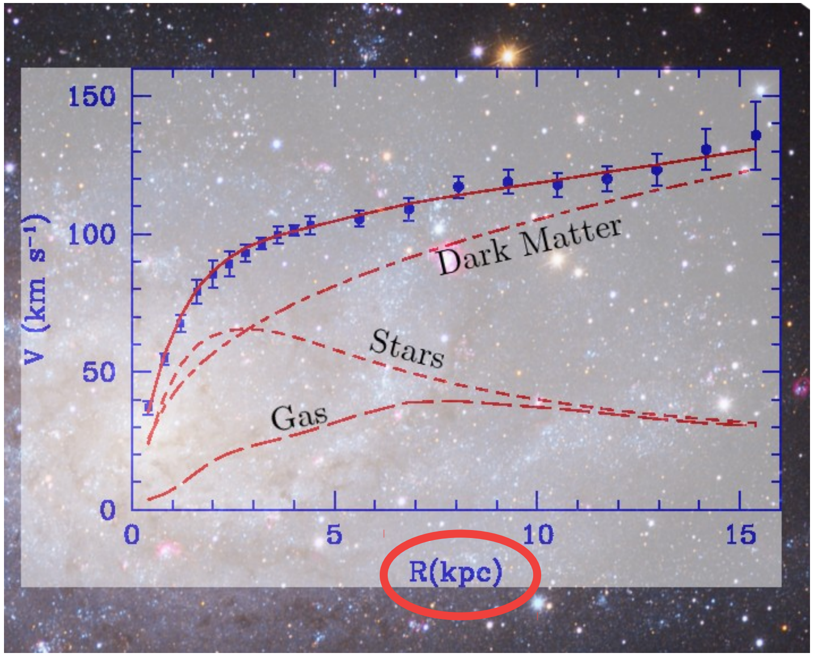
NB, Dolan, Draper, Shelton ‘21

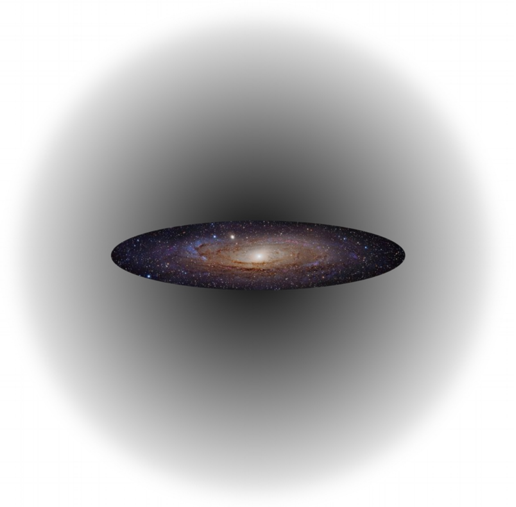
Is the evolution radiation-dominated (RD) all the way up?

Are there any remnants of the pre-BBN universe?

Small Scale Distribution of Dark Matter

DM distribution *measured* down to scales of $\sim$ kpc





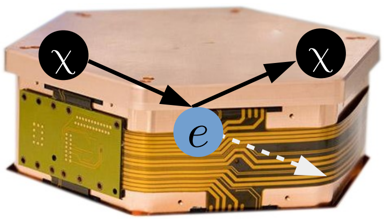
Particle nature of DM and its early universe dynamics can leave an imprint on much smaller length scales!

What's the Big Deal Anyway?

Small scale distribution of DM determines potential observables; e.g.

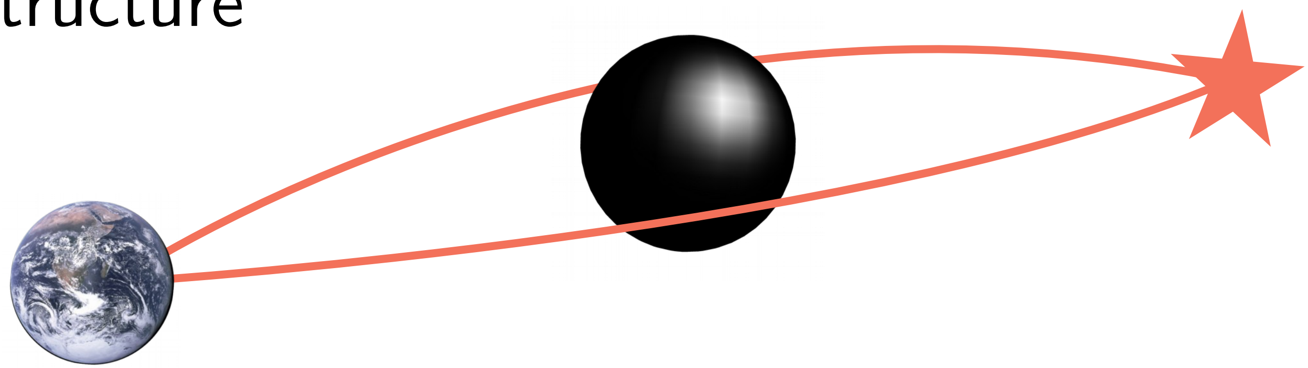
- Direct detection experiments search for energy deposition in terrestrial detectors

  Sensitive to DM density on scales of $\sim$ 10 AU



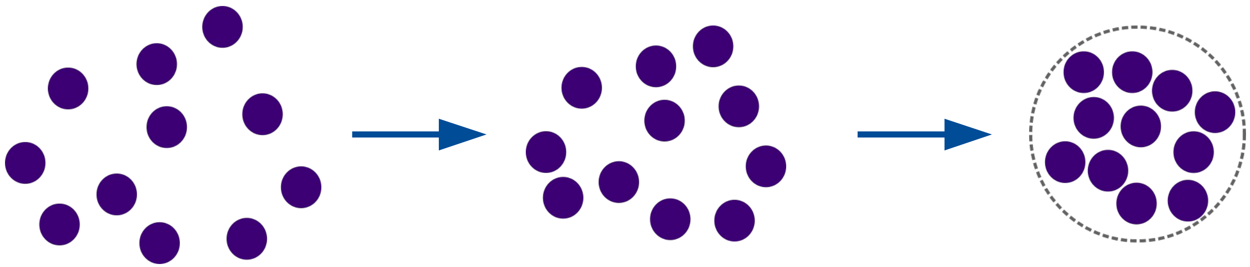
SuperCDMS SNOLAB

- Light from distant objects can be lensed by DM substructure



How Do Dark Matter Halos Form?

Primordial density fluctuations grow until they begin to self-gravitate



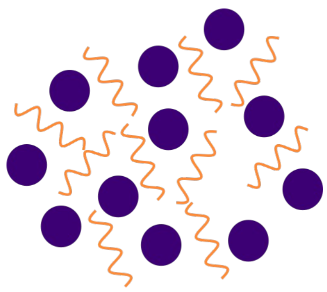
1) Initial conditions 2) Evolution 3) Gravitational collapse

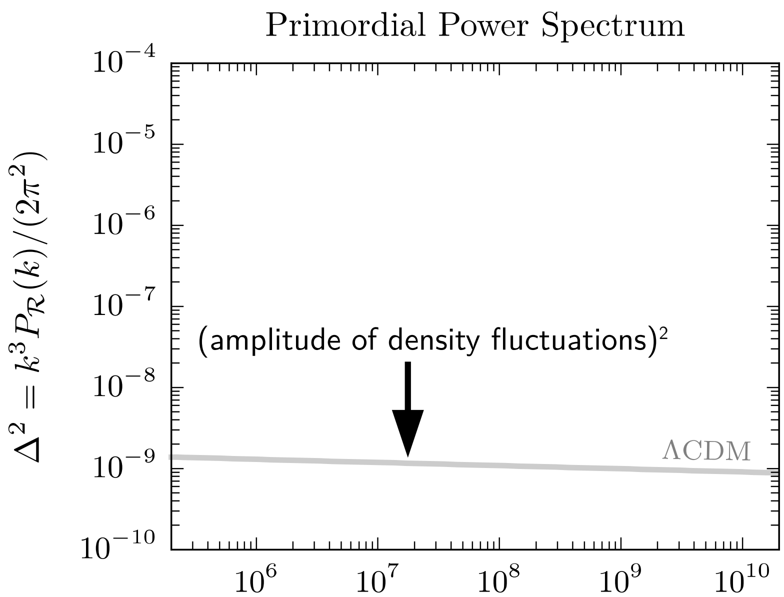
Enhanced structure can arise due to novel dynamics at any of these steps

Initial Conditions: Standard Assumption

Density perturbations small on all scales

$$\frac{\delta\rho_{\rm dm}}{\bar{\rho}_{\rm dm}} \sim \frac{\delta\rho_\gamma}{\bar{\rho}_\gamma} \sim 10^{-5}$$





larger length scales ← $k/k_{\rm eq}$ → Smaller length scales

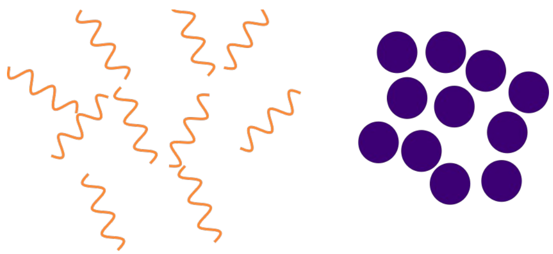
Can we test these assumptions? What are the alternatives?

Length scales probed by CMB have $k/k_{\rm eq} \sim 1$

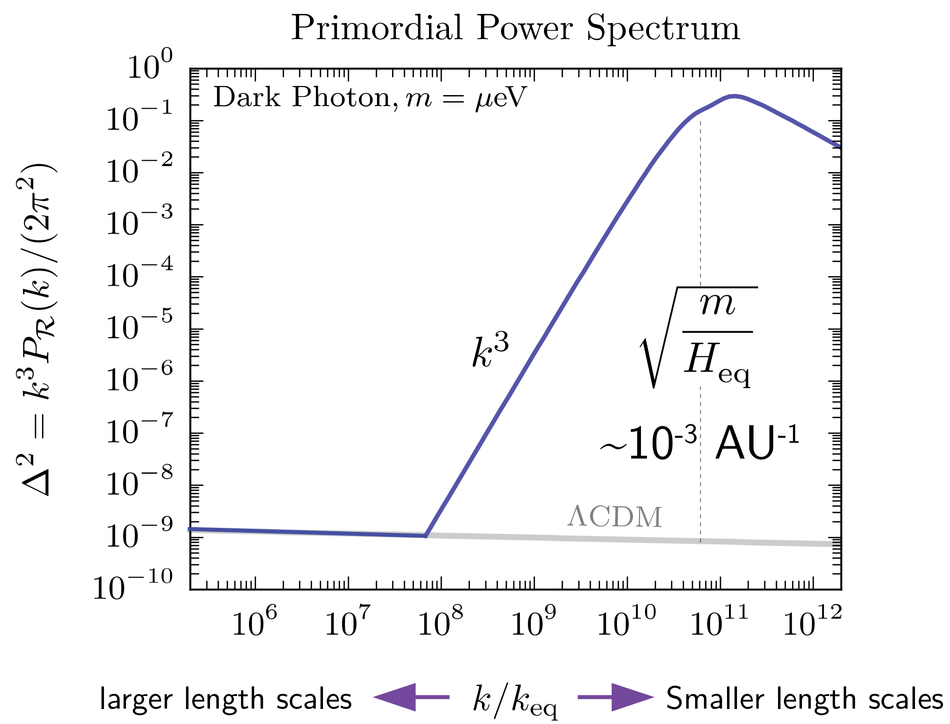
Initial Conditions: Vector Dark Matter

- DM can be “born” clumpy

Vector Dark Matter produced during inflation



$$\frac{\delta\rho_{\rm dm}}{\bar{\rho}_{\rm dm}} \gg \frac{\delta\rho_{\gamma}}{\bar{\rho}_{\gamma}}$$



Graham, Mardon & Rajendran (2015)

Properties of the power spectrum (peak and slopes) tied to DM mass and spin

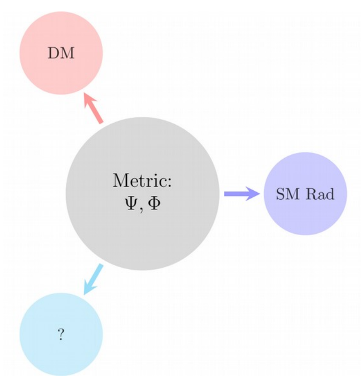
Evolution of Density Perturbations

Initial density fluctuations need to be evolved to late times

Evolution of DM density perturbation governed by energy/momentum conservation + gravity $\delta = [\rho_{dm}(x) - \bar{\rho}_{dm}]/\bar{\rho}_{dm}$

$$\ddot{\delta} + \mathcal{H}\dot{\delta} + \cdots = -k^2\Psi - 3\ddot{\Phi}$$

Background cosmology



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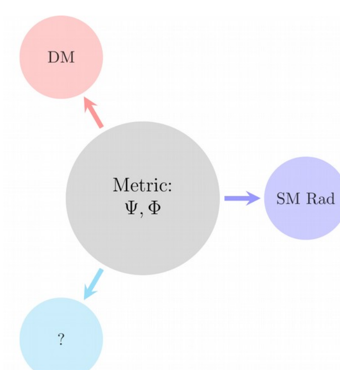
Gravitational driving



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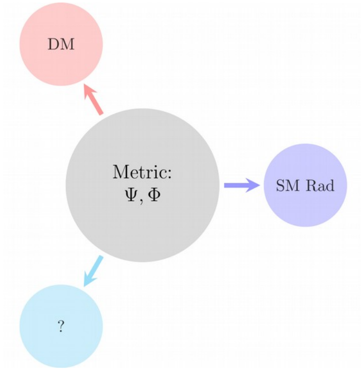
Background cosmology

Scale-dependent effects:

Radiation pressure, wave effects

Gravitational driving



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Background cosmology

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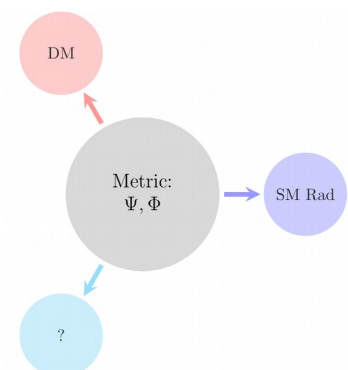
Radiation pressure, wave effects

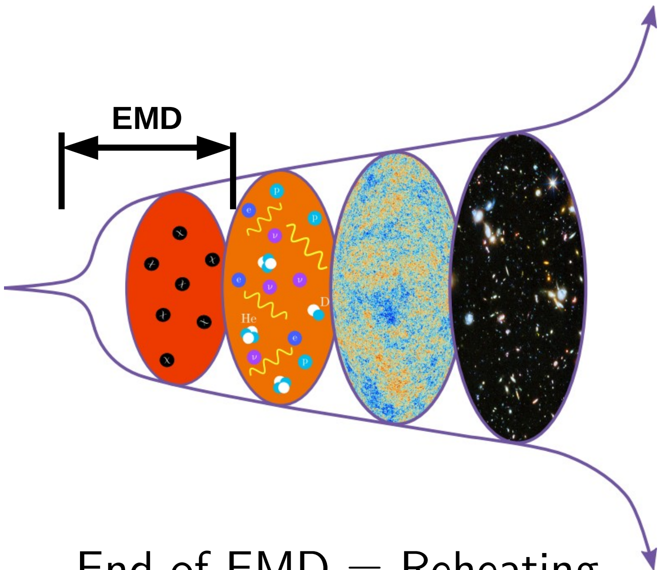
Gravitational driving

$$\delta \propto \begin{cases} a & \text{matter dom.} \\ \ln a & \text{radiation dom.} \end{cases}$$

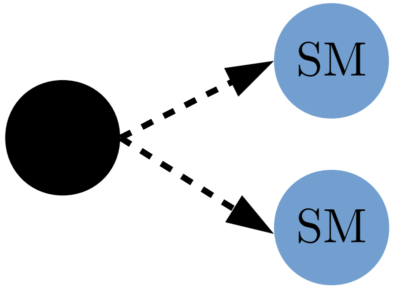


Early Matter Domination (EMD)

Pre-BBN (T > 5 MeV) universe dominated by **matter** instead of radiation



End of EMD = Reheating



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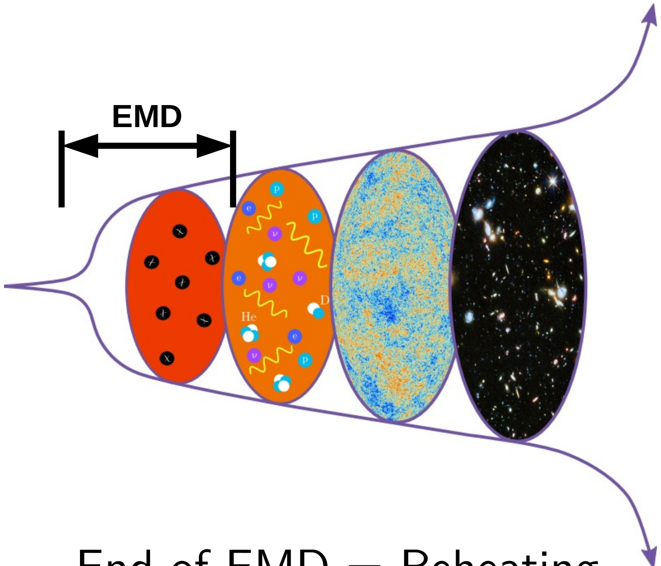

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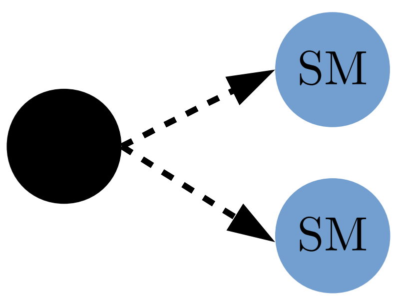
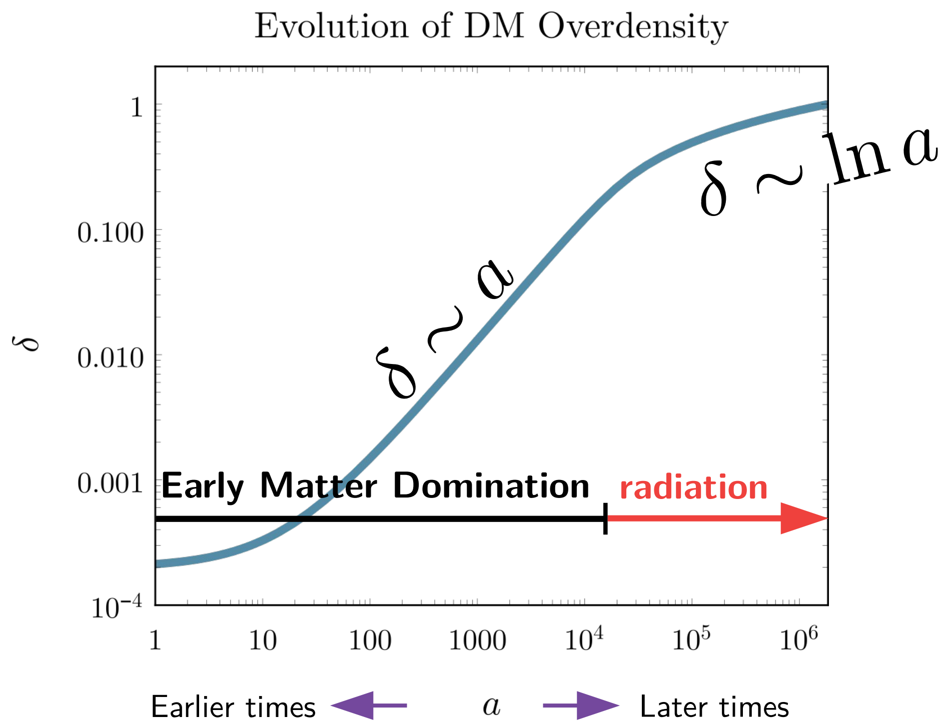


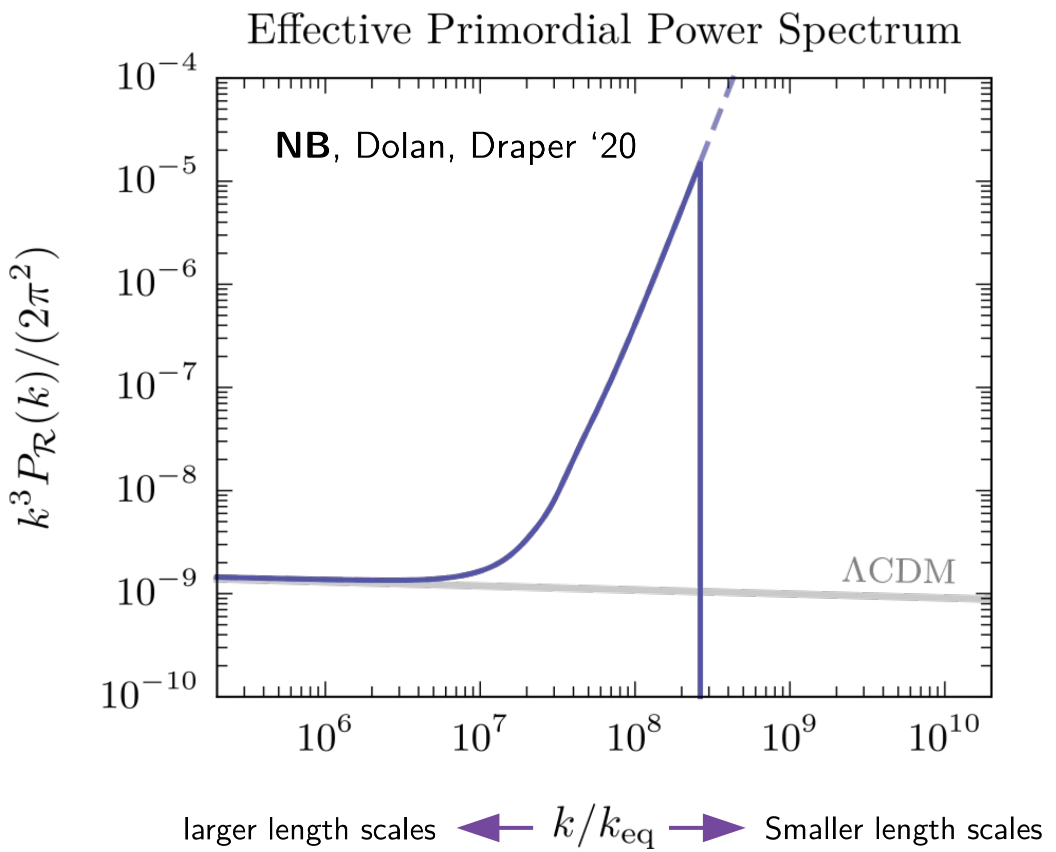


CDM & WIMPs: Erickcek, Sigurdson '11

ALPS: **NB**, Dolan, Draper '20

EMD enhances growth of small-scale density perturbations

Impact of EMD

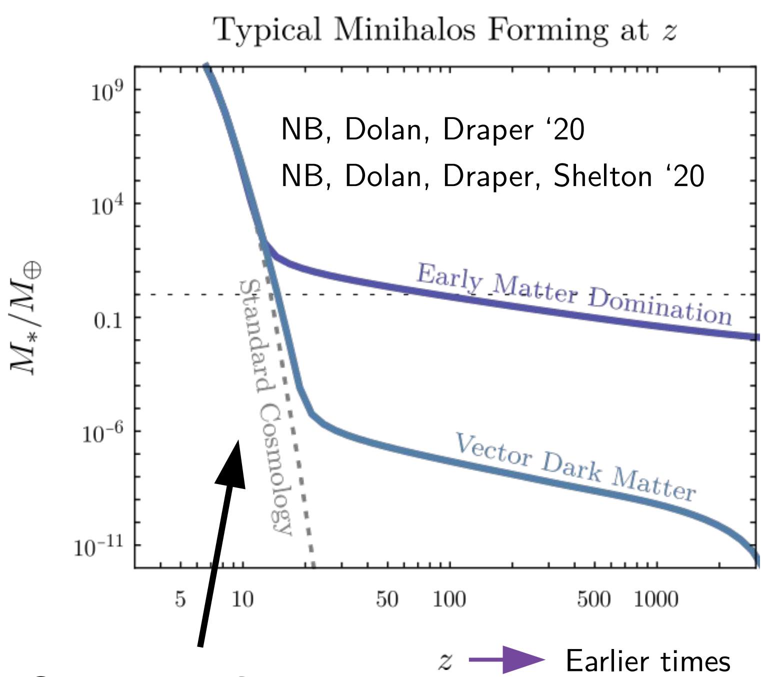


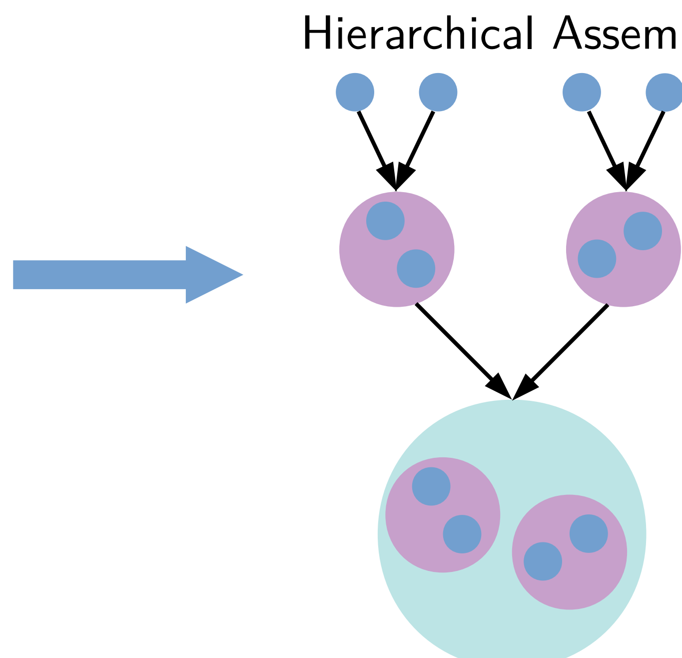
DM becomes clumpy in course of pre-BBN cosmology

Formation of Minihalos

Enhanced overdensities at small scales natural in different particle/cosmology models

Gravitational collapse begins much earlier. Minihalos – first gravitationally bound objects to form.





Standard Cosmology:

First halos form at z< 30

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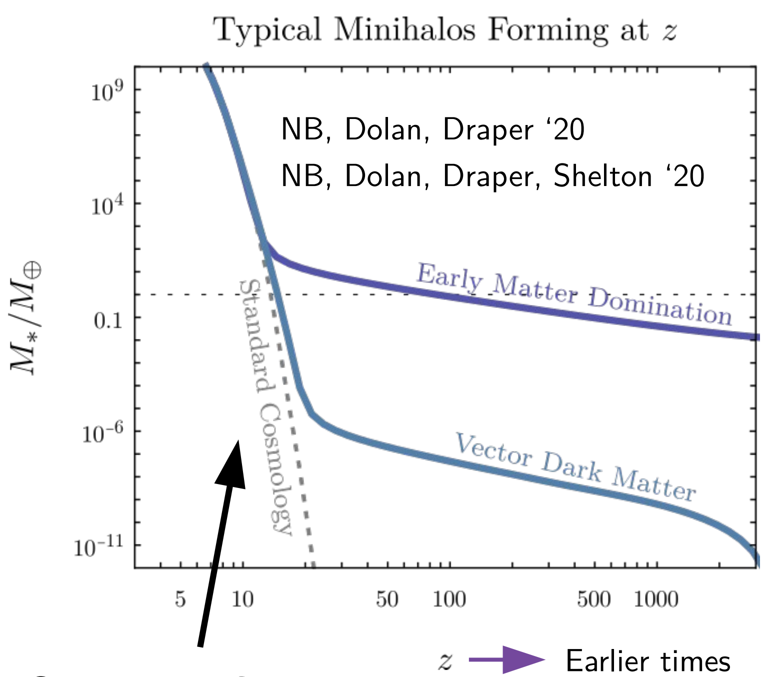
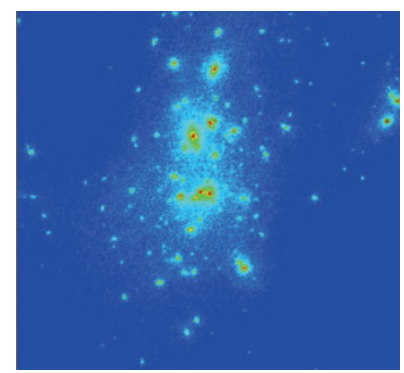


Minihalo at z=30



Erickcek & Waldstein '17

Standard Cosmology:

First halos form at z< 30

Properties of Minihalos (EMD)

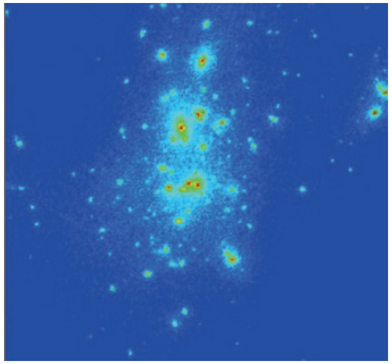
Density:

$$\rho(z_c) \approx 230\ \mathrm{GeV/cm^3}\ \left(\frac{1+z_c}{100}\right)^3$$

Compare with:

Average "local" DM density ~ 0.3 GeV/cm^3

Average Earth density ~ 3x10^{24} GeV/cm^3



Erickcek & Waldstein '17

Size:

$$R(z_c) \sim 10^3\ \mathrm{AU} \times \left(\frac{5\ \mathrm{MeV}}{T_{\mathrm{RH}}}\right)\left(\frac{100}{1+z_c}\right)^{3/2}$$

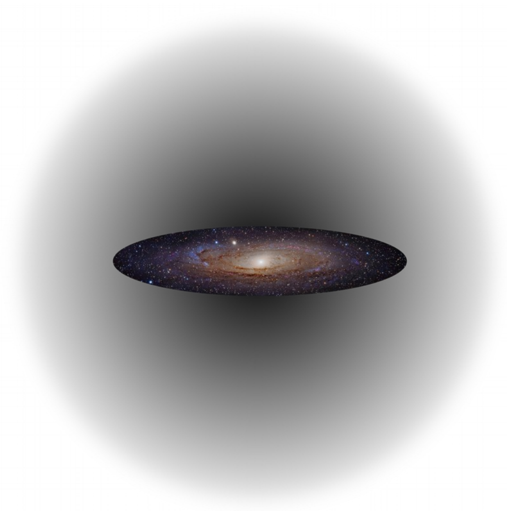
Compare with: Solar system ~ 10^2 AU

NB, Dolan, Draper '20

Earlier collapse⇒denser, more compact minihalos

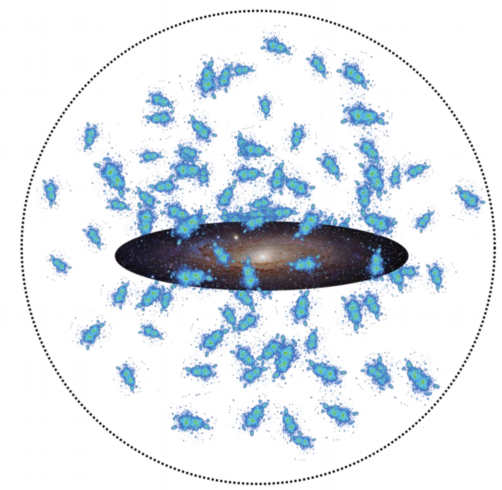
Galactic Dark Matter Halo

Standard Cosmology



vs

EMD or Vector Dark Matter



Clumps not to scale

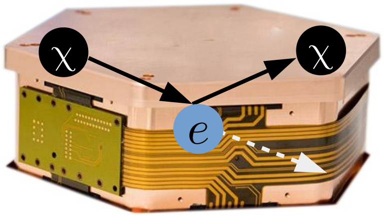
Minihalo mass, size distribution sensitive to power spectrum – potential to distinguish different models. Simulations required!

Running into a Minihalo

- Direct detection experiments search for energy deposition in terrestrial detectors

- Earth-minihalo encounter rate

$$\sim 10^4 \ \mathrm{yr} \left(\frac{M_\oplus}{M} \right)$$



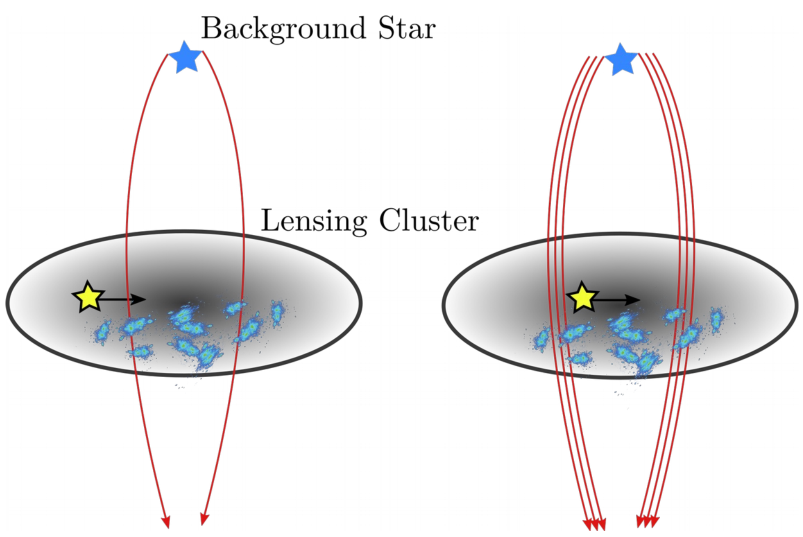
SuperCDMS SNOLAB

*Only a rough estimate! Depends on precise distribution of minihalos at late times

Standard direct detection probes can come up empty!

A Gravitational Search: Photometric Lensing

- Highly magnified, extragalactic star is microlensed by a intra-lens star/black hole
- Tiny density fluctuations due to minihalos amplified
- This “noise” is imprinted on microlensing lightcurve



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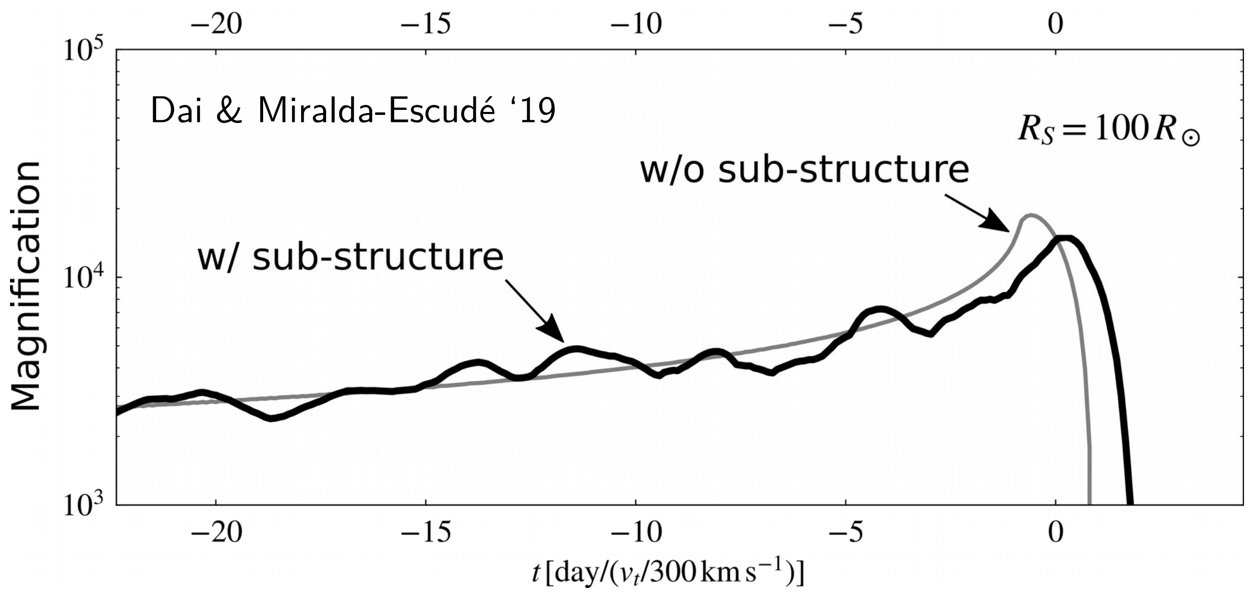
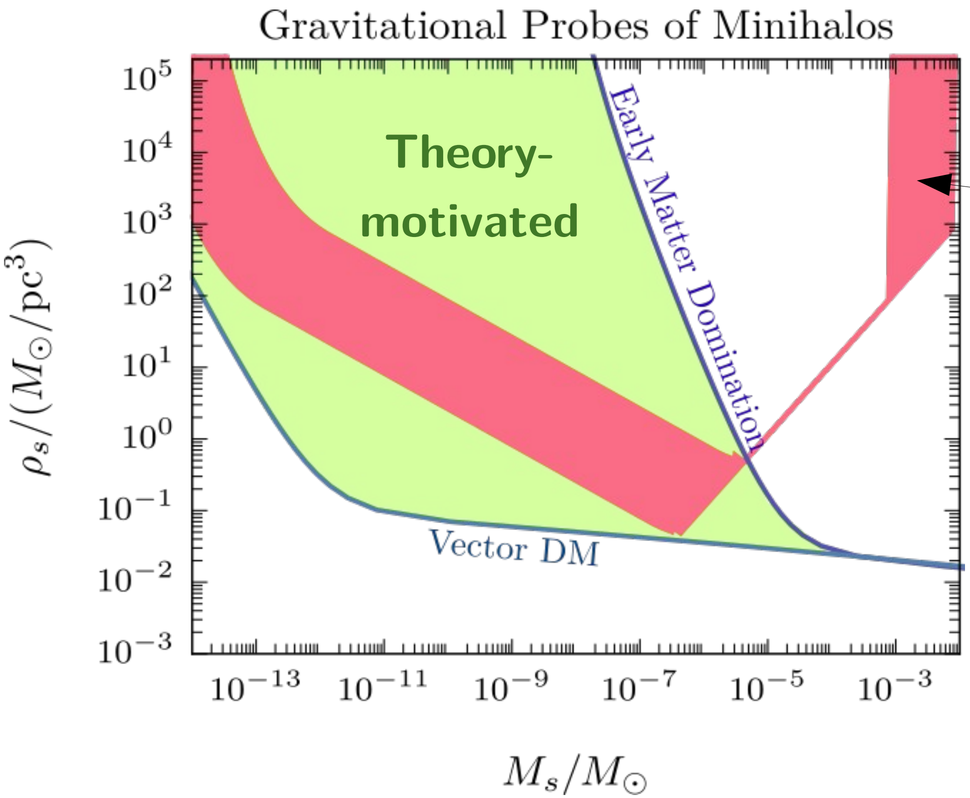


Future Sensitivity of Gravitational Probes

Clump Density



Microlensing sensitivity

Clump Mass

NB, Dolan, Draper ‘20

NB, Dolan, Draper, Shelton ‘21

Future observations can probe first moments after the Big Bang!

Conclusion

Experimental and observational tools give unprecedented window into the early universe:

- Cosmological data probes contents of the universe and their interactions

We can learn about physics beyond the Standard Model!

- We must be careful to interpret this data with terrestrial experiments in mind

- Early evolution of the universe is unknown

Dark matter substructure can offer vital clues!

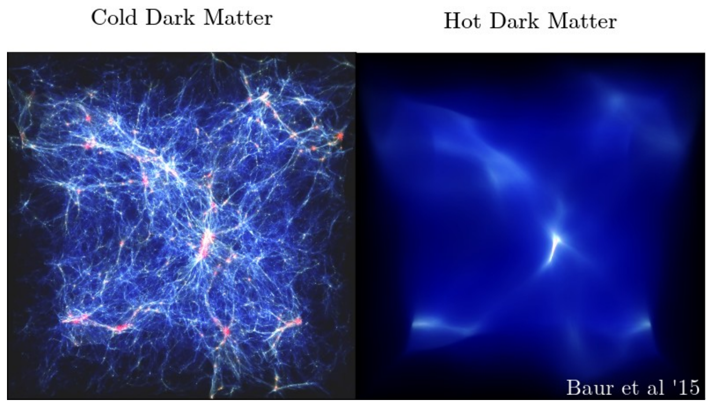
Thank you/Merci!

Appendix

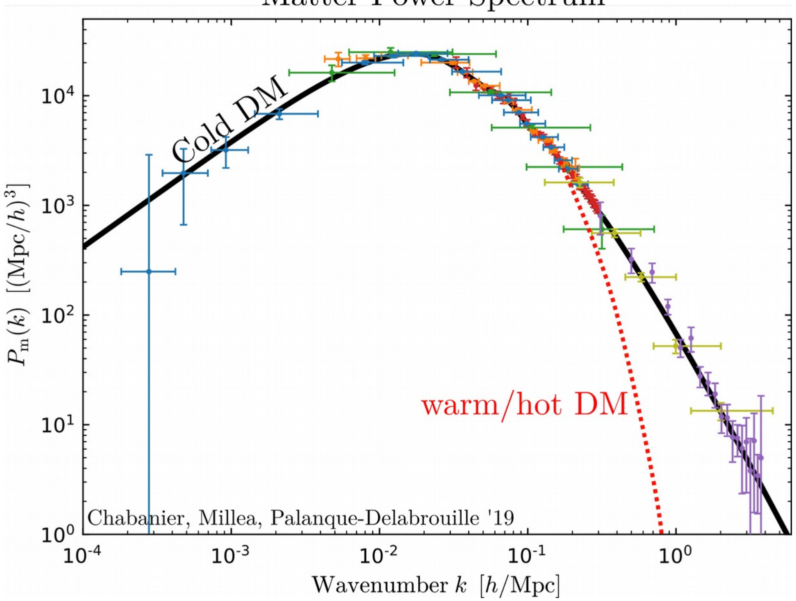
Dark Matter in the Universe

- $\sim$5 times more DM than normal stuff
- Non-relativistic ("cold")
- Present in galaxies
- Weakly (if at all) interacting with us

Simulations of Large-Scale Structure



Matter Power Spectrum



The Expanding Universe

Far-away objects (like galaxies) are receding from us

$$v \approx H_0 d$$

$$H_0^{(1929)} \sim 500\mathrm{km/s/Mpc}$$

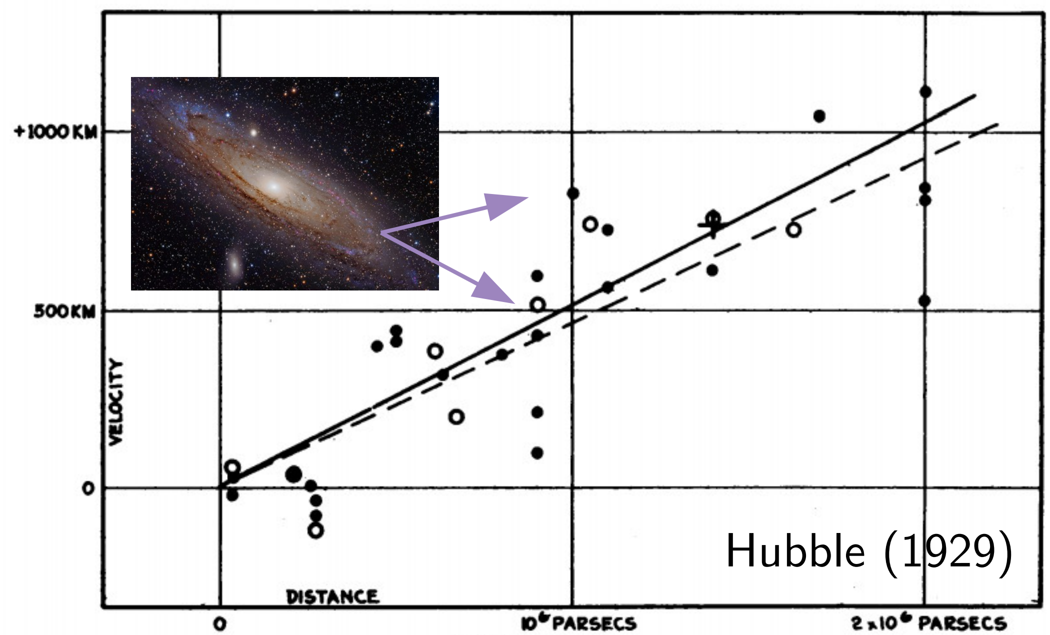


FIGURE 1

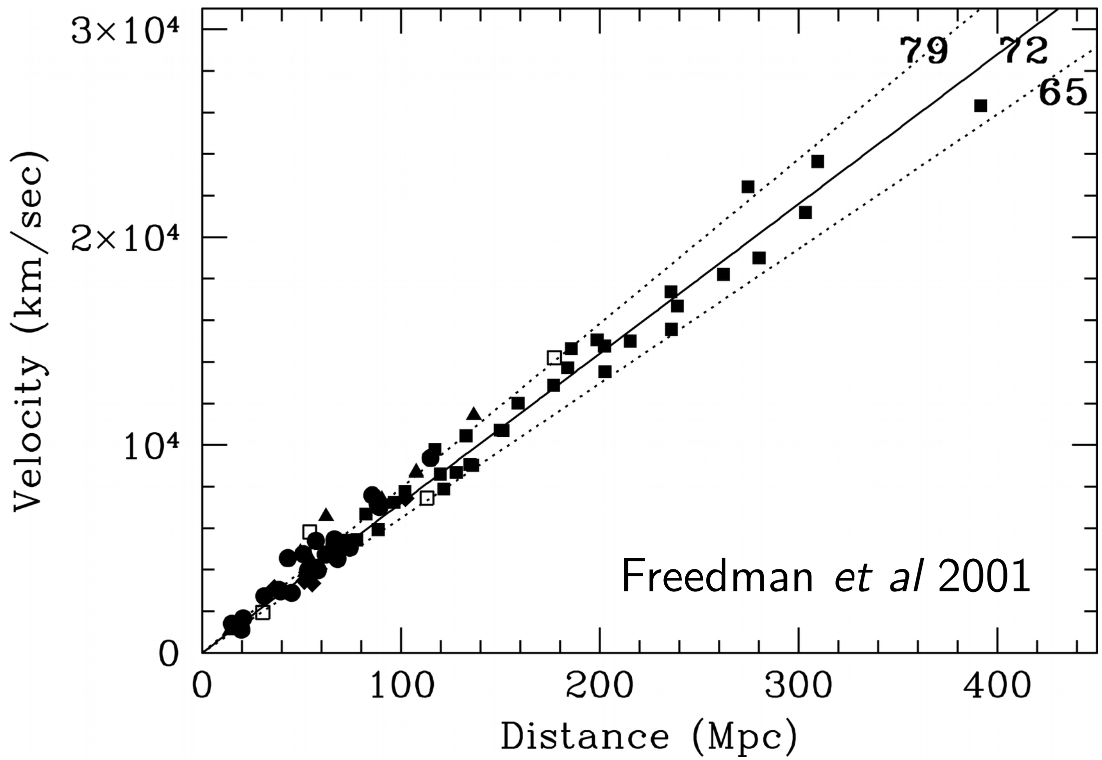
Earlier estimates by Lemaitre (1927) and Robertson (1928)

The Expanding Universe

Far-away objects (like galaxies) are receding from us

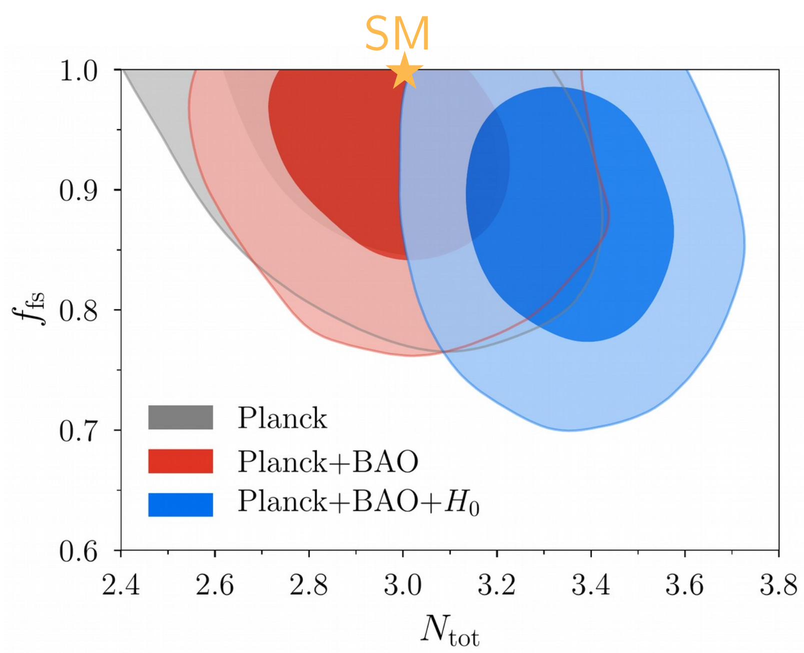
$$v \approx H_0 d$$

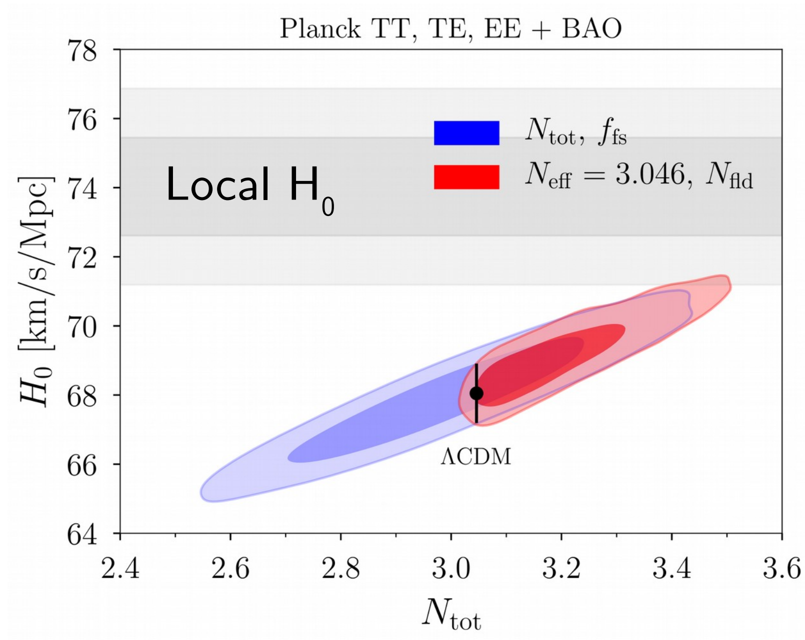
$$H_0^{(2019)} \approx 74.03 \pm 1.42 \text{ km/s/Mpc}$$ Riess *et al* 2019



Constraints on Dark Radiation

Allow radiation density and free-streaming fraction to vary





No preference for beyond-SM from early cosmology alone!

Still no consistent fit to both direct H_0 and CMB

NB, Marques-Tavares (2020); see also Brinckmann *et al* (2012.11830)

Connection to Particle Physics

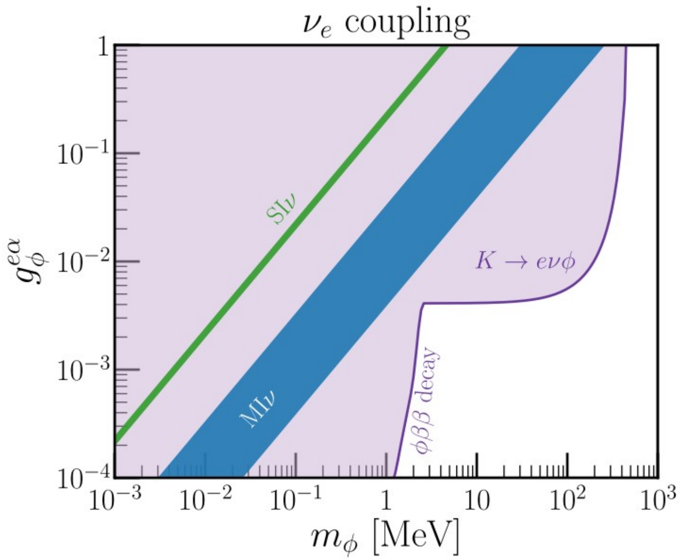
- Expansion rate (and derived quantities) probes the contents of the universe at early times

sensitivity to Beyond-SM contributions

- Observables depend on evolution of perturbations in cosmological fluids

sensitivity to new interactions of SM particles or within "dark" sector

Constraints From Particle Physics



NB, Kelly, Krnjaic, McDermott (2019)

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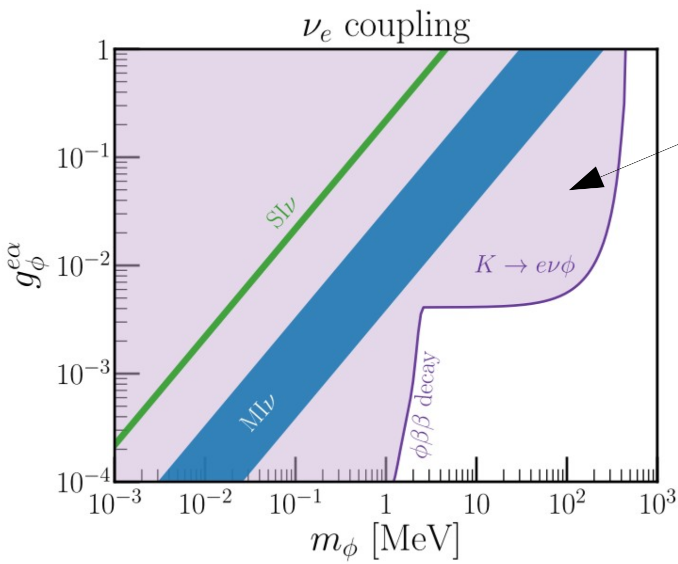

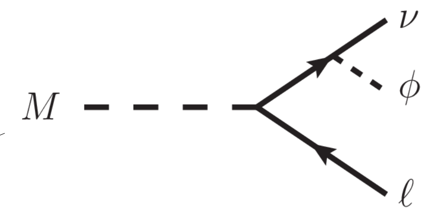

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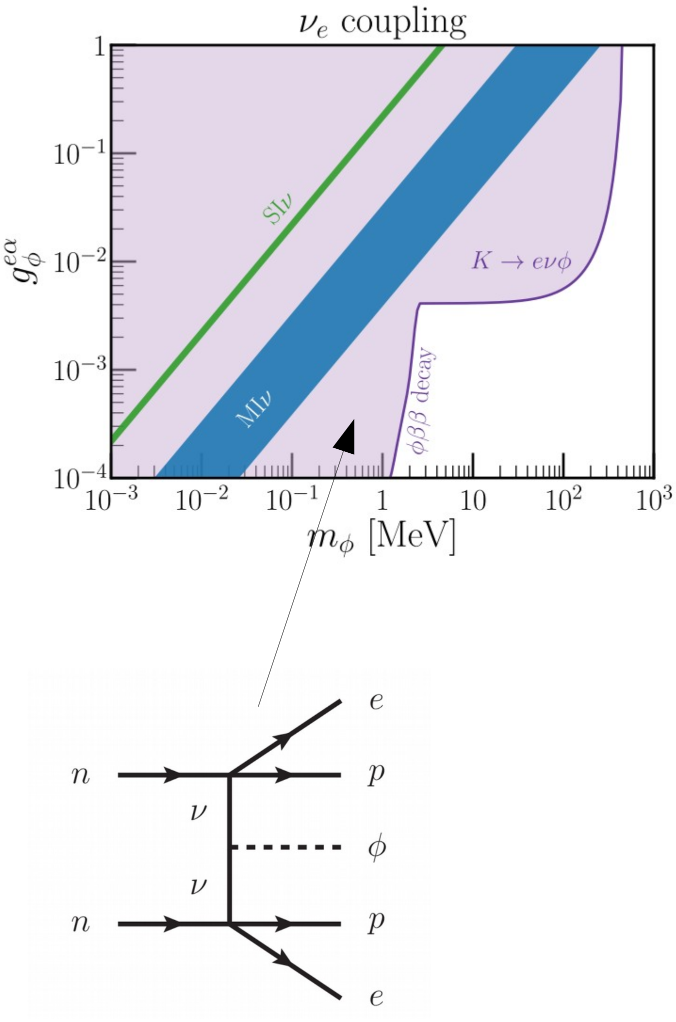

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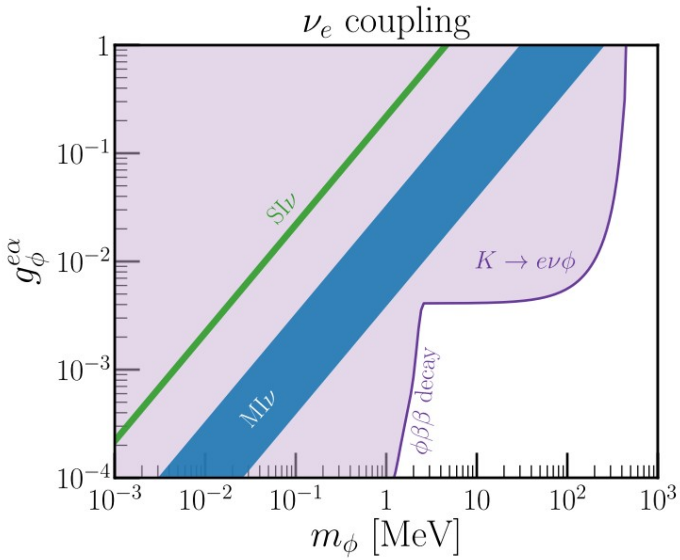

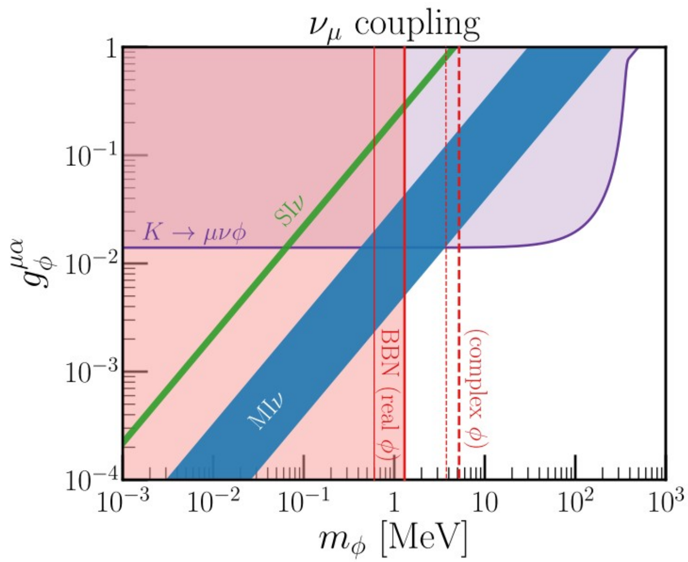

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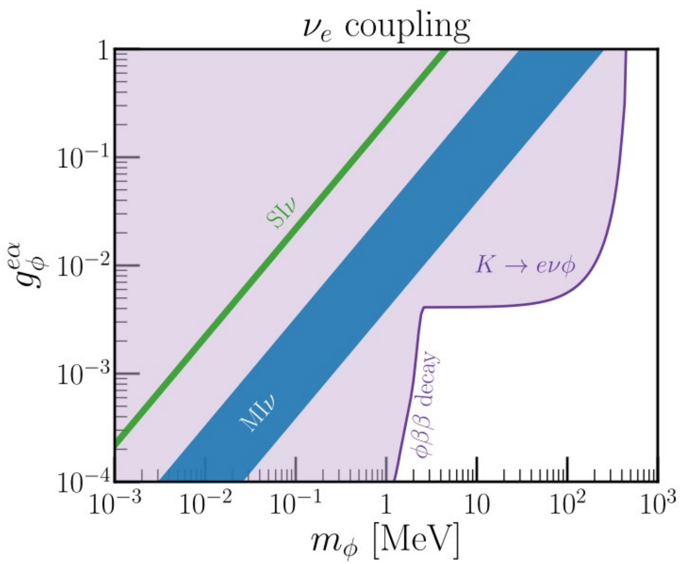
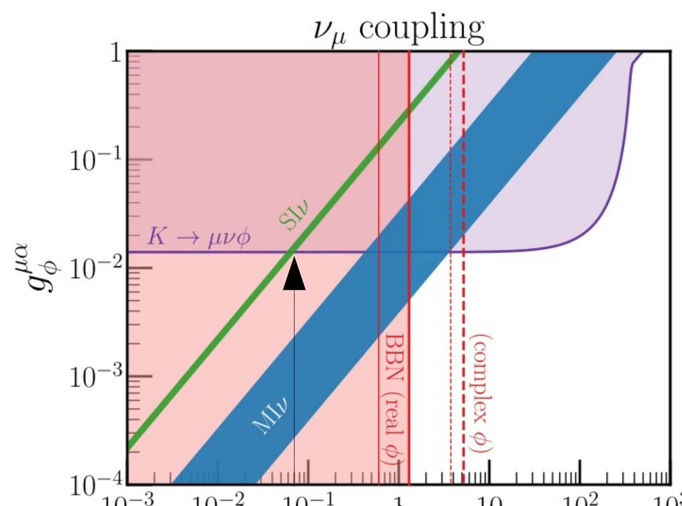
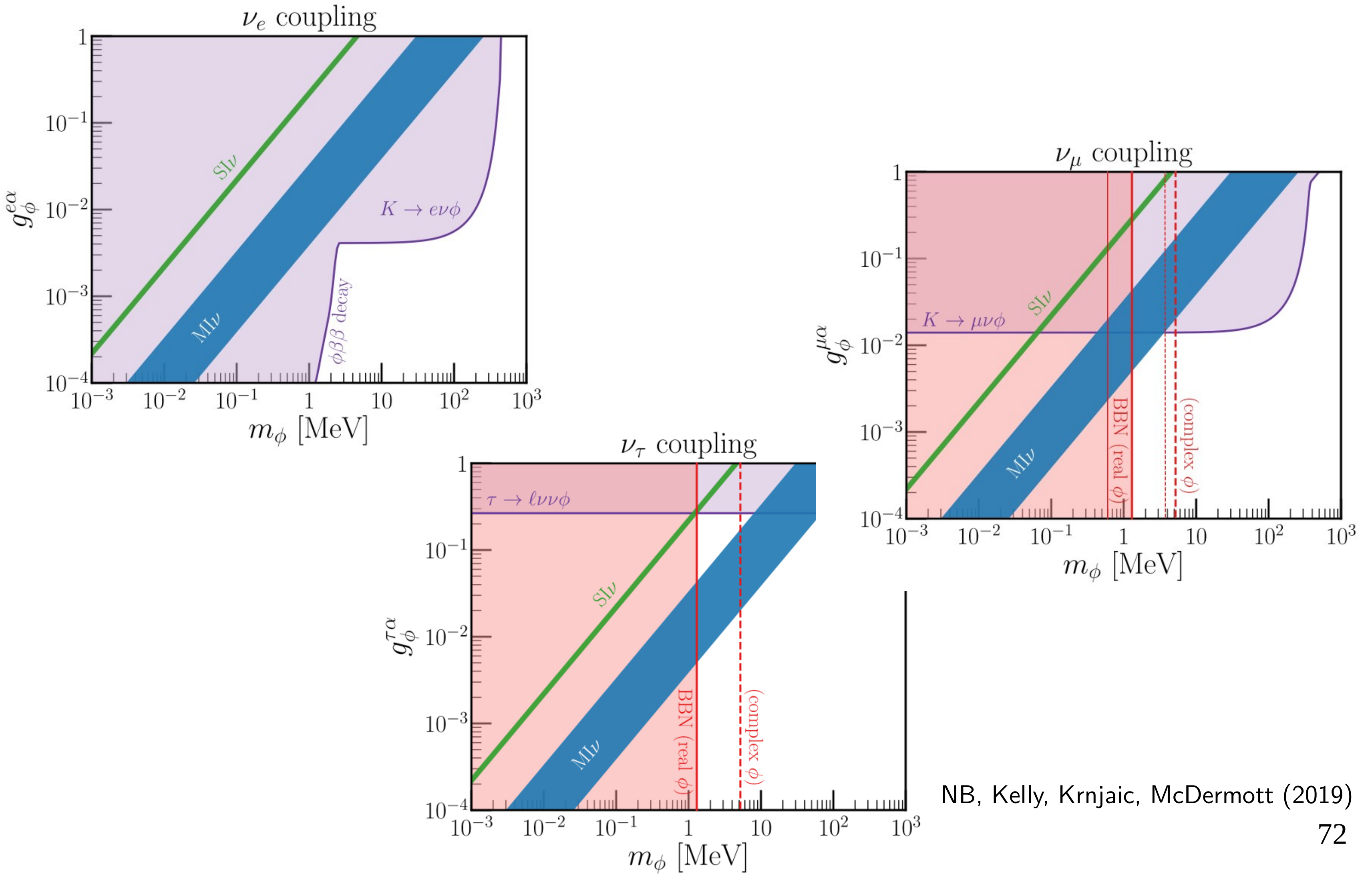




$$|g_{\alpha\beta}| \gtrsim 10^{-10}\left(\frac{\text{MeV}}{m_\phi}\right) \Rightarrow \rho_\phi \sim T^4$$

NB, Kelly, Krnjaic, McDermott (2019)

Constraints From Particle Physics



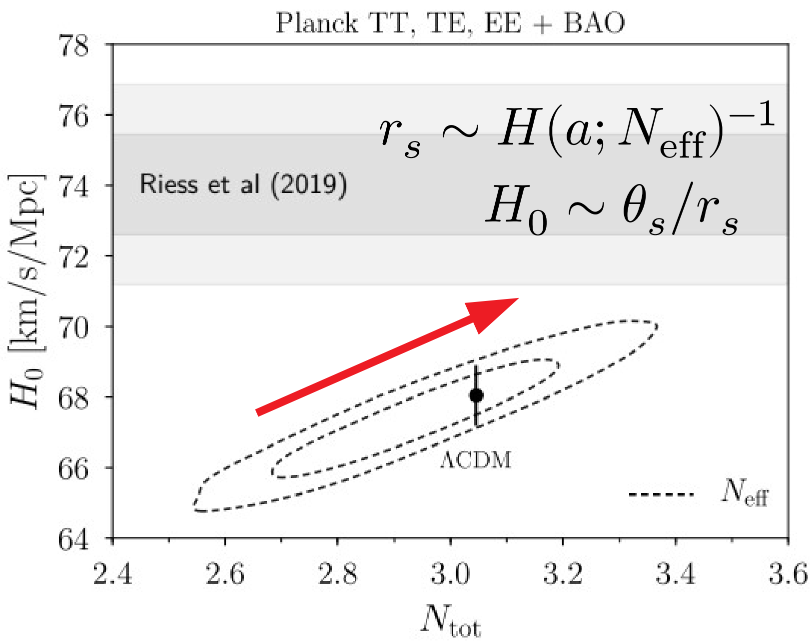
NB, Kelly, Krnjaic, McDermott (2019)

Extra Radiation

- Simplest BSM way to reduce sound horizon: non-interacting radiation/relativistic species

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8} N_{\rm eff} \left(\frac{4}{11} \right)^{4/3} \right]$$

- $N_{\rm eff} = 3$ in SM, $N_{\rm eff} > 3$ with dark radiation



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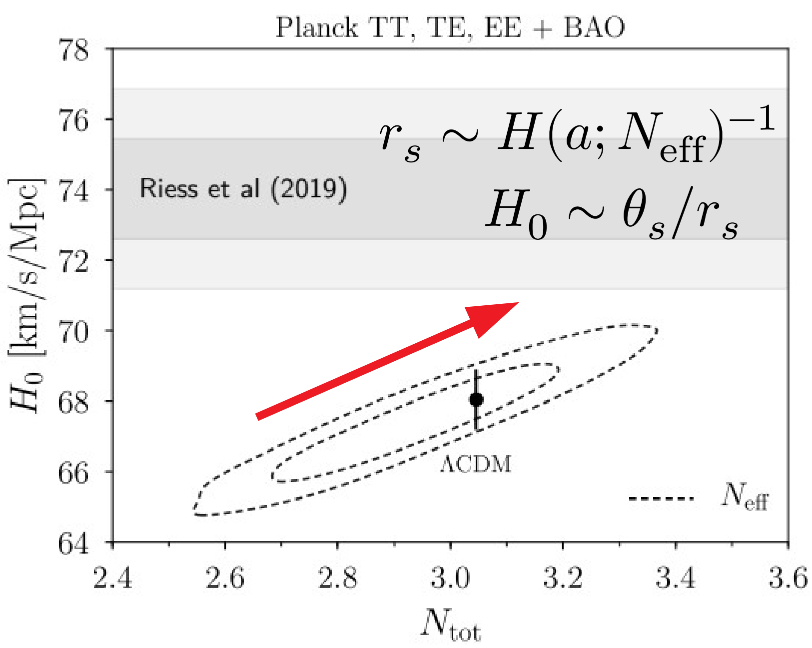


$$\Delta\chi^2 = (\chi^2_{N_{\rm eff}} - \chi^2_{\Lambda{\rm CDM}})_{\rm min}$$

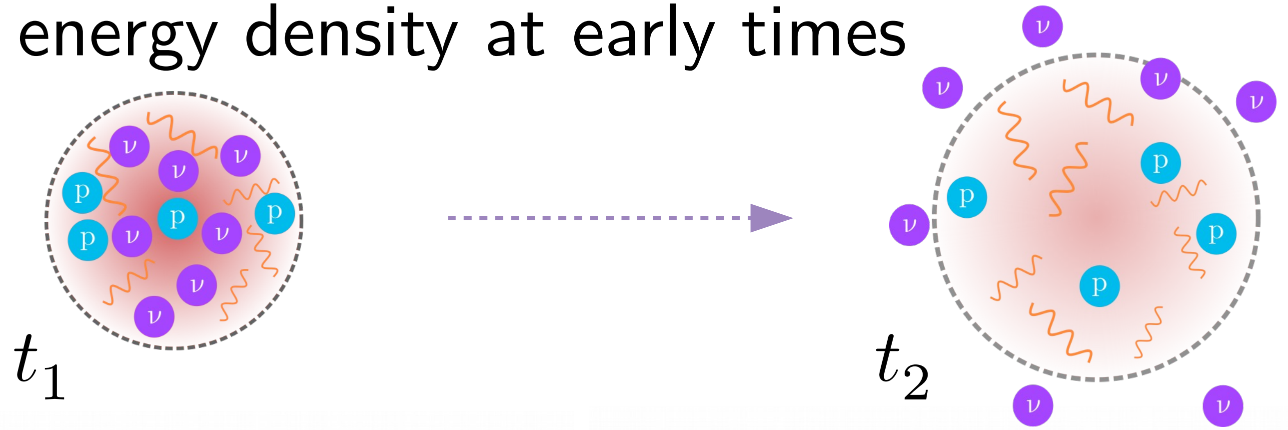
Data Set	$N_{\rm eff}$
TTTEEE	$+2.68$
low-ℓ TT	-0.63
low-ℓ EE	$+0.09$
lensing	$+0.17$
BAO	$+0.39$
H_0	-4.99
total	-2.3

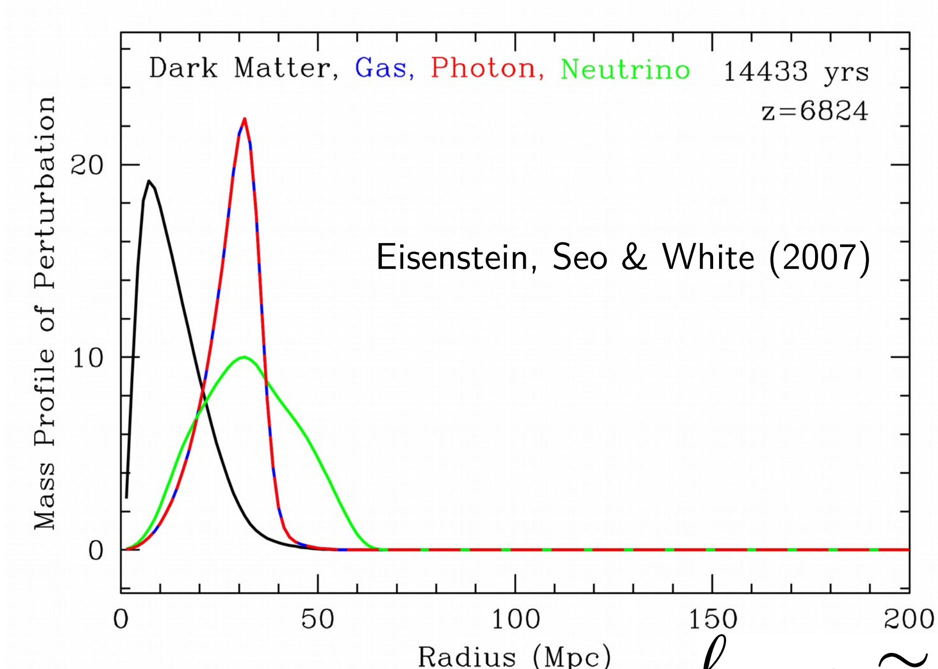
Worse fit to CMB tail

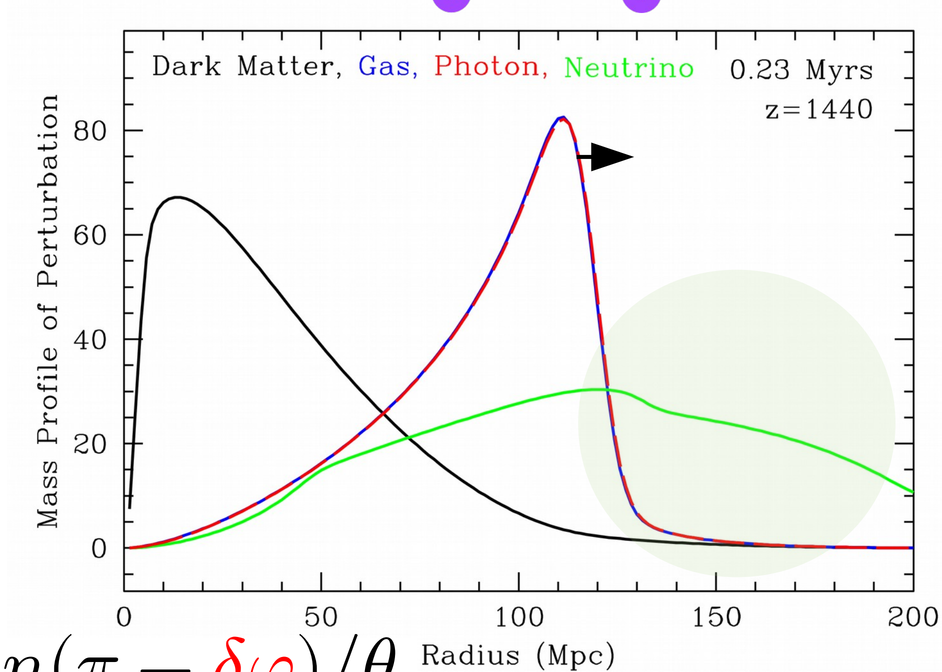
Better fit to local H_0

Origin of Phase Shift: Free-streaming Nus

- Neutrinos are super-sonic and make up about 41% of the energy density at early times







$$\ell_{peak} \approx n(\pi - \delta\varphi)/\theta_s$$

Self-Interacting Neutrinos II

$$G_{\text{eff}} = (4.7^{+0.4}_{-0.6}\ \text{MeV})^{-2}$$

Best fit points have large departures from CDM in other cosmological parameters

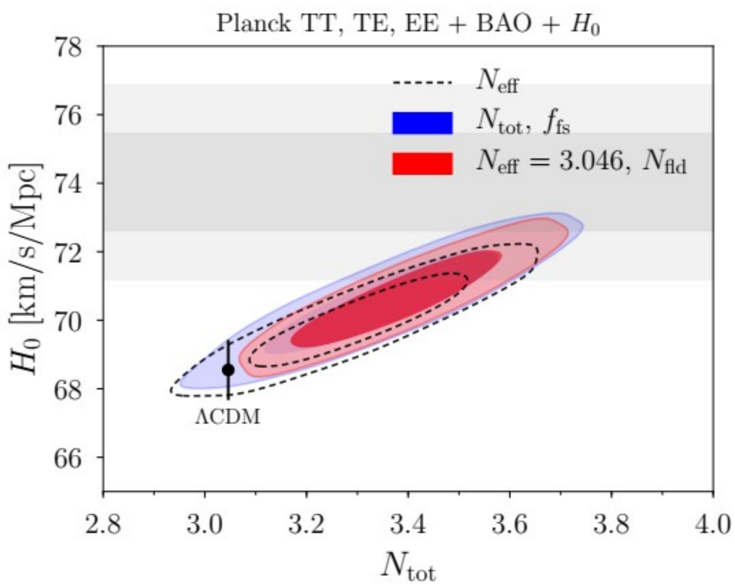
$$N_{\text{eff}} \approx 4, \ \sum m_\nu = 0.4\,\text{eV}, \ldots$$

Can one have such a neutrino self-interaction in realistic models?

NB, Kelly, Krnjaic, McDermott (2019)

Consistency With Local Measurements

Data is consistent with a larger contribution of interacting radiation than free-streaming allowing for a better fit to $_0$



NB, Marques-Tavares (2020)

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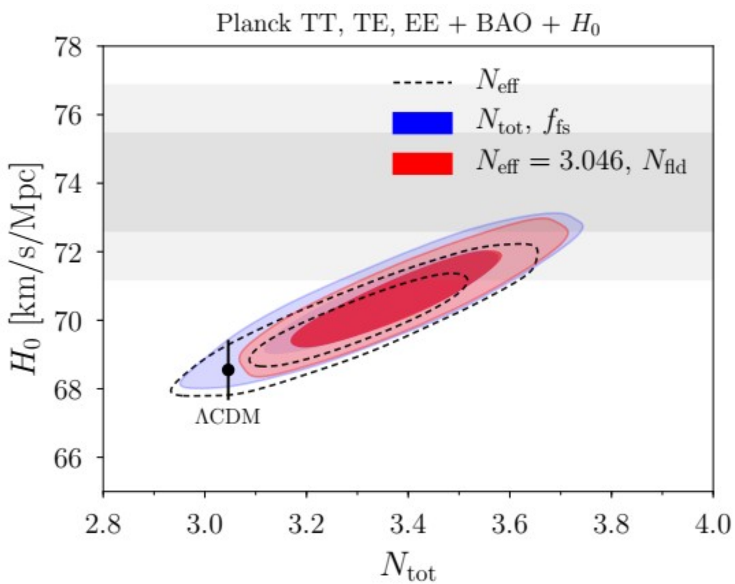


$$\Delta\chi^2 = (\chi^2 - \chi^2_{\Lambda\mathrm{CDM}})_{\min}$$

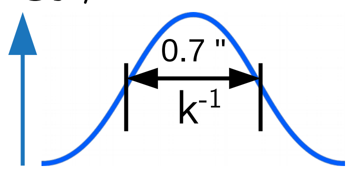
Data Set	$N_{\rm eff}$	$N_{\rm eff} = 3.046,\ N_{\rm fld}$	$N_{\rm tot},\ f_{\rm fs}$
TTTEEE	$+2.68$	$+6.24$	$+6.24$
low-ℓ TT	-0.63	-0.56	-0.56
low-ℓ EE	$+0.09$	-1.06	-0.29
lensing	$+0.17$	$+0.8$	$+0.39$
BAO	$+0.39$	$+0.73$	$+1.04$
H_0	-4.99	-9.93	-10.81
total	-2.3	-3.81	-4.02

High ℓ temperature and polarization data key in constraining extra radiation (free-streaming or not)

NB, Marques-Tavares (2020)

Structure Growth During EMD

Evolution of DM density perturbation governed by energy/momentum conservation + gravity $\delta = [\rho_\chi(x) - \bar{\rho}_\chi]/\bar{\rho}_\chi$

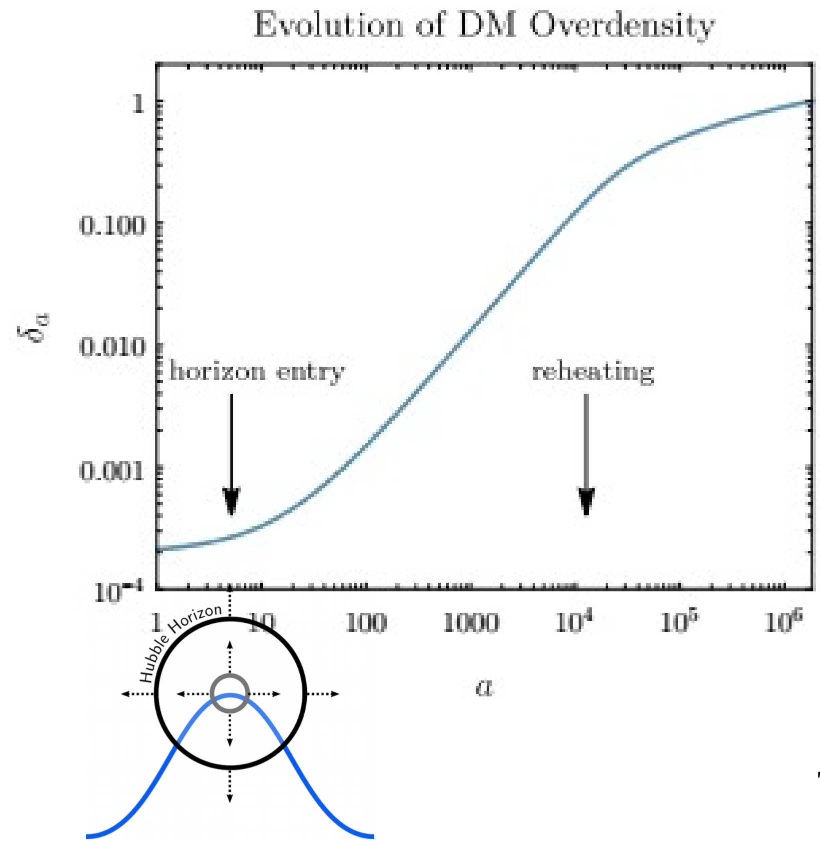


$$\ddot{\delta} + \mathcal{H}\dot{\delta} \approx -k^2\Psi$$

Growth depends on b/g expansion through $\mathcal{H}$

$$\delta \propto \begin{cases} a & \mathrm{MD} \\ \ln a & \mathrm{RD} \end{cases}$$

EMD enhances growth by a factor $\sim a_{\mathrm{RH}}/a_{\mathrm{hor}}$

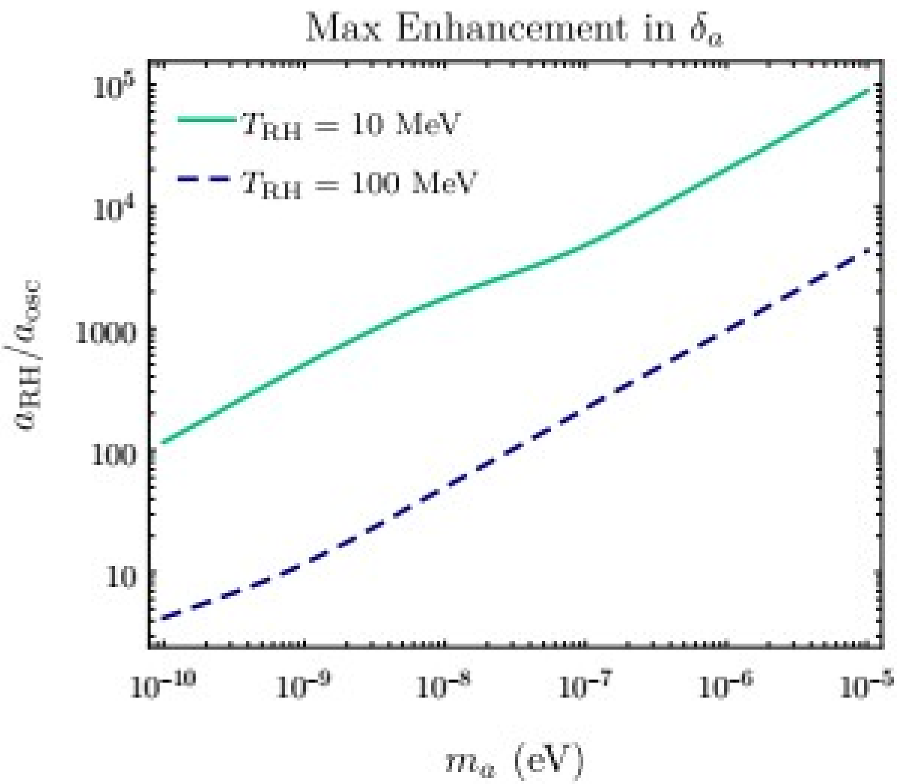


Enhanced Growth of Perturbations

Density perturbations starting at ~ 10^{-4} can grow by several orders of magnitude during EMD

Amplitude of primordial density fluctuations set by inflation

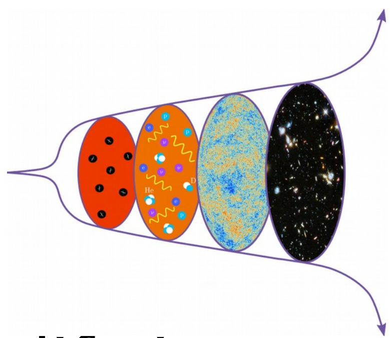
Maximum Enhacement from EMD



Non-Standard Cosmology from the UV

Universe can be matter-dominated (MD) early on, instead of radiation-dominated (RD) early on because

- Heavy particles ϕ abundant in string theory, supersymmetry, extra dimensions



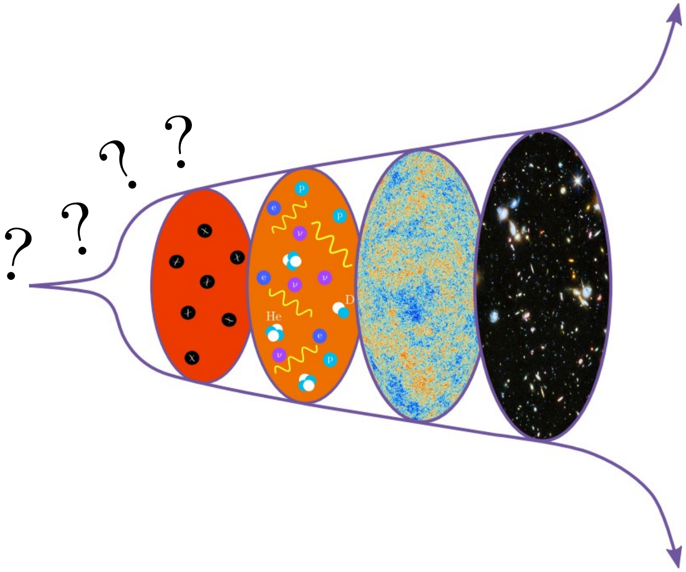
- Generically produced during inflation
- If weakly coupled, they can have a long lifetime

$$\tau_\phi = 0.1\ \mathrm{s} \left(\frac{100\ \mathrm{TeV}}{m_\phi}\right)^3 \left(\frac{\Lambda}{M_{\mathrm{Pl}}}\right)^2$$

Imprints of the Early Universe

DM substructure is one of only two ways to access pre-nucleosynthesis physics

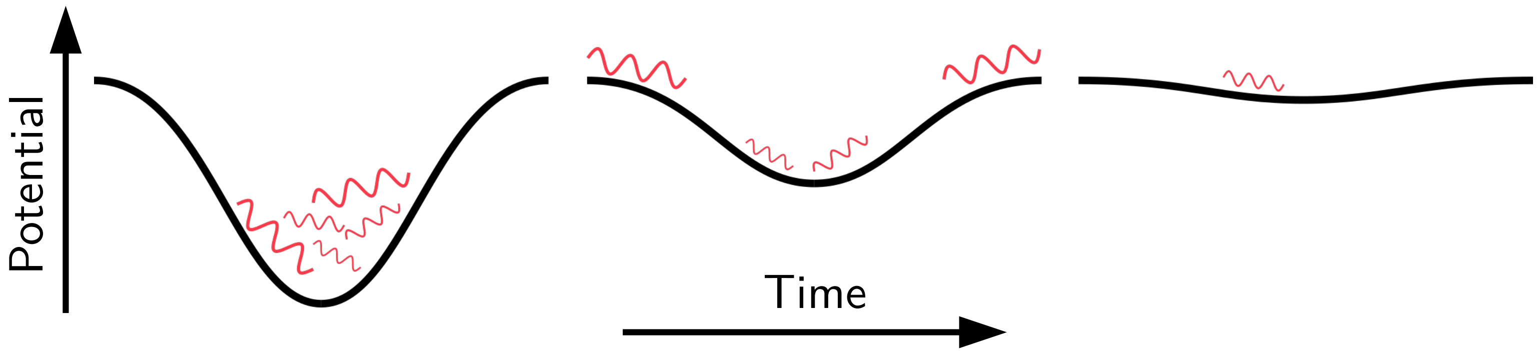
- Non-standard cosmological histories
- Inflationary particle production and other dynamics
- Phase transitions



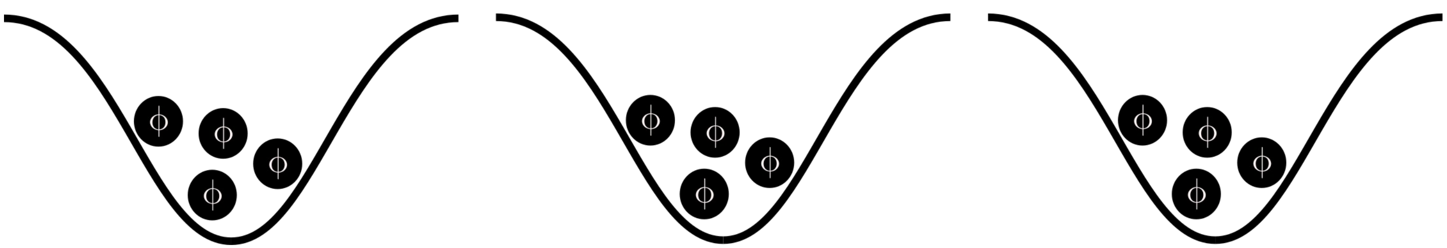
Impact on Small-Scale Structure

Modified cosmology also changes the growth of density perturbations

- *Radiation domination*: gravitational potentials decay

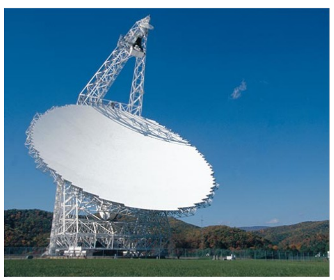


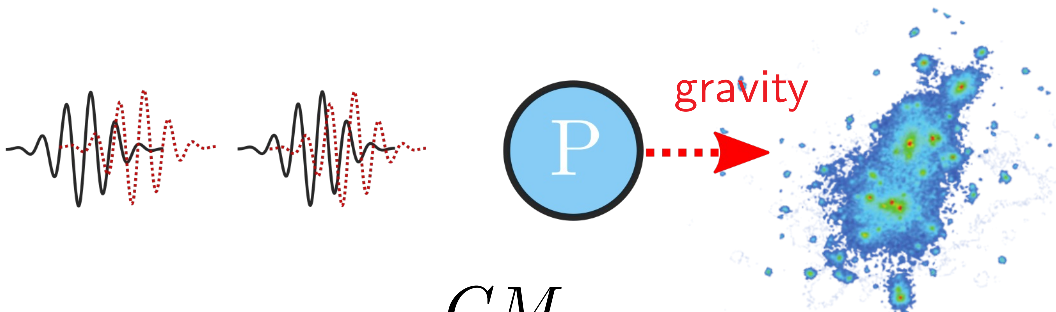
- *(Early) Matter domination*: gravitational potentials stay constant



Pulsar Timing Arrays

- Pulsars – stability comparable to atomic clocks!
- Minihalo can pass close to a pulsar
- Gravitational interaction shifts pulse arrival time





$$\text{frequency shift} \sim \frac{GM}{v r_{\text{min}}}$$

Dror et al ‘19