The Early Universe as a Laboratory for Particle Physics

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Triumph of the Standard Model

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

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

Enormous dynamic range when combined with gravity

Large Hadron Collider probes $\sim 10^{-20} \text{ m}$

Cosmic Microwave Background: $\sim 10^{+24} \text{ m}$
On **largest** scales, the universe is well-described by a handful of parameters.

**Universe Facts**

<table>
<thead>
<tr>
<th><strong>Standard Model</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>0.005%</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>0.004%</td>
</tr>
<tr>
<td>Baryons</td>
<td>5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Non-Standard Model</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Energy</td>
<td>68.5%</td>
</tr>
<tr>
<td>Dark Matter</td>
<td>26.5%</td>
</tr>
</tbody>
</table>

*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

\[ v \approx H_0 d \]

Hubble (1929)

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

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
Expansion in General Relativity

General Relativity relates expansion rate to the contents of the universe

\[ H(t) \propto \sqrt{\rho_{\text{rad}}(t) + \rho_{\text{bar}}(t) + \rho_{\text{dm}}(t) + \rho_{\text{de}} + \ldots} \]

\[ H_0 = H(t_{\text{today}}) \]

Hotter and denser in the past!
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
The universe expanded from a hot dense state
Evolution described by \( t \leftrightarrow T \leftrightarrow a \)

Compare with:
- Solar surface: \( T \sim 0.5 \text{ eV} \)
- Room temp: \( T \sim 1/40 \text{ eV} \)

Hydrogen recombination: Cosmic Microwave Background

Galaxy formation, life etc
Early Universe Primer

The universe expanded from a hot dense state
Evolution described by \( t \leftrightarrow T \leftrightarrow a \)

Big Bang Nucleosynthesis:
Light nuclei made

Hydrogen recombination:
Cosmic Microwave Background

Galaxy formation, life etc

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Solar surface:
\( T \sim 0.5 \, \text{eV} \)
Room temp:
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- Room temp: \( T \sim 1/40 \) eV

Reheating? DM Production?

Big Bang Nucleosynthesis:
- Light nuclei made

Hydrogen recombination:
- Cosmic Microwave Background

Galaxy formation, life etc
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

Highly significant tension between two of the most precise values!
Cosmological models track evolution of different fluids under influence of interactions, gravity.

\[ \theta \sim \frac{\pi}{\ell} \]

**CMB Power Spectrum**

- Larger angular scales: \( \ell \) smaller
- Smaller angular scales: \( \ell \) larger

**Planck/ESA**

\[ T(n) - \bar{T} \]

\[ \frac{\ell(\ell + 1)C_\ell}{2\pi} \]
Peaks in the Power Spectrum

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

\[ \ell_{\text{peak}} \approx n(\pi - \delta \varphi)/\theta_s \]

Measured precisely

Evolution of perturbations

**Particle Interactions**

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

$H_0$ is \textit{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 \textbf{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

$$H_0 \propto \frac{\theta_s}{r_s}$$

Inference of $H_0$ is modified if $r_s$ is changed!
Origin of Phase Shift: Free-streaming Nus

\[ \ell_{\text{peak}} \approx n(\pi - \delta \varphi)/\theta_s \]

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

Standard assumption: neutrinos do not self-scatter
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

- Standard assumption: neutrinos do not self-scatter

- No free-streaming if neutrinos self-interact

This changes the expected phase shift!
Solving the Hubble Tension

• Modifying amount of neutrinos changes the sound horizon

• Neutrino self-interactions can prevent free-streaming

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

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

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

Interaction of neutrinos:
- Phase shift

Amount of neutrinos:
- Modifies $r_s$

$$G_{\text{eff}} = \left(4.7^{+0.4}_{-0.6} \text{ MeV}\right)^{-2}$$
Can one have such a neutrino self-interaction in realistic models?

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

NB, Kelly, Krnjaic, McDermott (2019)
Neutrino Self-Interactions in the SM

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

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

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

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

\[ G_{\text{eff}} \sim 10^9 G_F \]

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

10^5 times lighter than Z

Solve/alleviate H_0 tension in these regions

NB, Kelly, Krnjaic, McDermott (2019)
Rare Meson Decays

SM Prediction

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

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

\[(A, Z) \rightarrow (A, Z + 2) + 2e^-\]

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)
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?

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

\[ \rho_{\text{rad}} = \rho_\gamma [1 + 0.23(N_{\text{eff}} + N_{\text{fld}})] \]

\[ \begin{align*}
N_{\text{eff}} & = 3 \text{ in SM} \\
N_{\text{fld}} & = 0 \text{ in SM}
\end{align*} \]

\( \text{NB, Marques-Tavares (2020); Brust, Cui & Sigurdson (2017); Baumann, Green, Meyers & Wallisch (2016)} \)
Constraints on Dark Radiation

Allow radiation density and free-streaming fraction to vary

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

\[ r_{\text{mfp}} \sim (x_e n_e \sigma_T)^{-1} \quad r_d \sim r_{\text{mfp}} \sqrt{t/r_{\text{mfp}}} \]

Diffusion scale also depends on early expansion history!

Precise measurements at large \( l \) preclude large modifications to \( r_d \) relative to \( r_s \)

Hu, Fukugita, Zaldarriaga & Tegmark (2000)
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

![Graph showing measurements of $H_0$]

- **Aghanim et al (2018)**
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

They all ask "What is dark matter?" and "Where is dark matter?", but nobody asks "How is dark matter?"

distributed at really small scales
The Pre-Nucleosynthesis Universe

Is the evolution radiation-dominated (RD) all the way up?
Are there any remnants of the pre-BBN universe?

NB, Dolan, Draper, Kozaczuk ‘19
NB, Dolan, Draper ‘20
NB, Dolan, Draper, Shelton ‘21
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

• 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.

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

1) Initial conditions
2) Evolution
3) Gravitational collapse
Initial Conditions: Standard Assumption

Density perturbations small on all scales

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

Can we test these assumptions? What are the alternatives?

Length scales probed by CMB have \( k/k_{eq} \sim 1 \)
Initial Conditions: Vector Dark Matter

- DM can be “born” clumpy

Vector Dark Matter produced during inflation

\[ \frac{\delta \rho_{\text{dm}}}{\bar{\rho}_{\text{dm}}} \gg \frac{\delta \rho_\gamma}{\bar{\rho}_\gamma} \]

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

Graham, Mardon & Rajendran (2015)
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

\[ \delta = \frac{\rho_{dm}(x) - \bar{\rho}_{dm}}{\bar{\rho}_{dm}} \]

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

Background cosmology
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 $\delta = \left[ \rho_{dm}(x) - \bar{\rho}_{dm} \right] / \bar{\rho}_{dm}$

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

Background cosmology

Gravitational driving

[Diagram showing DM, SM Rad, and Metric: $\Psi, \Phi$]
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- **Background cosmology**
- **Scale-dependent effects:** Radiation pressure, wave effects
- **Gravitational driving**

Diagram:
- DM
- Metric: $\Psi, \Phi$
- SM Rad
Evolution of Density Perturbations

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- **Background cosmology**
- **Scale-dependent effects:** 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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Pre-BBN ($T > 5$ MeV) universe dominated by matter instead of radiation

End of EMD = Reheating

CDM & WIMPs: Erickcek, Sigurdson ‘11
ALPS: NB, Dolan, Draper ‘20

EMD enhances growth of small-scale density perturbations
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.

Typical Minihalos Forming at $z$

- $M_*/M_\odot$
  - $10^9$
  - $10^4$
  - $10^0$
  - $10^{-4}$
  - $10^{-9}$

- $z$
  - 5
  - 10
  - 50
  - 100
  - 500
  - 1000

- Standard Cosmology
- Vector Dark Matter
- Early Matter Domination

- NB, Dolan, Draper ‘20
- NB, Dolan, Draper, Shelton ‘20

Hierarchical Assembly

Standard Cosmology:
First halos form at $z < 30$
Formation of Minihalos

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Typical Minihalos Forming at $z$

- NB, Dolan, Draper ‘20
- NB, Dolan, Draper, Shelton ‘20

Minihalo at $z=30$

Erickcek & Waldstein ‘17

Standard Cosmology:
First halos form at $z < 30$
Properties of Minihalos (EMD)

Density:

\[ \rho(z_c) \approx 230 \, \text{GeV/cm}^3 \left( \frac{1 + z_c}{100} \right)^3 \]

Compare with:
Average “local” DM density \( \sim 0.3 \, \text{GeV/cm}^3 \)
Average Earth density \( \sim 3 \times 10^{24} \, \text{GeV/cm}^3 \)

Size:

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

Compare with: Solar system \( \sim 10^2 \, \text{AU} \)

NB, Dolan, Draper ‘20

Earlier collapse \( \Rightarrow \) denser, more compact minihalos
Galactic Dark Matter Halo

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

\[ \sim 10^4 \text{ yr} \left( \frac{M_{\oplus}}{M} \right) \]

*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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![Diagram showing magnification over time with sub-structure and no sub-structure comparisons]

Dai & Miralda-Escudé ‘19

\( R_S = 100R_\odot \)
Future Sensitivity of Gravitational Probes

Future observations can probe first moments after the Big Bang!

NB, Dolan, Draper ‘20
NB, Dolan, Draper, Shelton ‘21
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

- ~5 times more DM than normal stuff
- Non-relativistic ("cold")
- Present in galaxies
- Weakly (if at all) interacting with us
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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Riess et al 2019

Freedman et al 2001
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

\[ \nu_e \text{ coupling} \]

\[ g_{\phi}^{\text{ex}} \rightarrow 10^{-2} \]

\[ m_\phi \text{ [MeV]} \]

NB, Kelly, Krnjaic, McDermott (2019)
Constraints From Particle Physics

NB, Kelly, Krnjaic, McDermott (2019)
Constraints From Particle Physics
Constraints From Particle Physics
Constraints From Particle Physics

\[ |g_{\alpha \beta}| \gtrsim 10^{-10} \left( \frac{\text{MeV}}{m_\phi} \right) \Rightarrow \rho_\phi \sim T^4 \]
Constraints From Particle Physics

\[ \nu_e \text{ coupling} \]

\[ \nu_\mu \text{ coupling} \]

\[ \nu_\tau \text{ coupling} \]

NB, Kelly, Krnjaic, McDermott (2019)
Extra Radiation

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

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

- \( N_{\text{eff}} = 3 \) in SM, \( N_{\text{eff}} > 3 \) with dark radiation
Extra Radiation

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- \( N_{\text{eff}} = 3 \) in SM, \( N_{\text{eff}} > 3 \) with dark radiation

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.

\[ \ell_{peak} \approx \frac{n(\pi - \delta \varphi)}{\theta_s} \]
$G_{\text{eff}} = (4.7^{+0.4}_{-0.6}\text{ MeV})^{-2}$

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

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

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 $H_0$. 

\[
H_0 \text{ [km/s/Mpc]}
\]

\[
N_{\text{tot}}
\]

Planck TT, TE, EE + BAO + $H_0$

\[
\begin{align*}
N_{\text{eff}} & \\
N_{\text{tot}}, f_\text{ls} & \\
N_{\text{eff}} = 3.046, N_{\text{flb}} &
\end{align*}
\]

ACDM

NB, Marques-Tavares (2020)
Data is consistent with a larger contribution of interacting radiation than free-streaming allowing for a better fit to $0$

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

<table>
<thead>
<tr>
<th>Data Set</th>
<th>$N_{\text{eff}}$</th>
<th>$N_{\text{eff}} = 3.046, \ N_{\text{fld}}$</th>
<th>$N_{\text{tot}}, \ f_{\text{fs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTTEEE</td>
<td>$+2.68$</td>
<td>$+6.24$</td>
<td>$+6.24$</td>
</tr>
<tr>
<td>low-\ell TT</td>
<td>$-0.63$</td>
<td>$-0.56$</td>
<td>$-0.56$</td>
</tr>
<tr>
<td>low-\ell EE</td>
<td>$+0.09$</td>
<td>$-1.06$</td>
<td>$-0.29$</td>
</tr>
<tr>
<td>lensing</td>
<td>$+0.17$</td>
<td>$+0.8$</td>
<td>$+0.39$</td>
</tr>
<tr>
<td>BAO</td>
<td>$+0.39$</td>
<td>$+0.73$</td>
<td>$+1.04$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$-4.99$</td>
<td>$-9.93$</td>
<td>$-10.81$</td>
</tr>
<tr>
<td>total</td>
<td>$-2.3$</td>
<td>$-3.81$</td>
<td>$-4.02$</td>
</tr>
</tbody>
</table>

High $\ell$ 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

\[ \delta = \left[ \rho_\chi(x) - \bar{\rho}_\chi \right] / \bar{\rho}_\chi \]

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

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

\[ \delta \propto \begin{cases} 
    a & \text{MD} \\
    \ln a & \text{RD} 
\end{cases} \]

EMD enhances growth by a factor \( \sim a_{RH}/a_{hor} \)
Enhanced Growth of Perturbations

Density perturbations starting at $\sim 10^{-4}$ can grow by several orders of magnitude during EMD.

Amplitude of primordial density fluctuations set by inflation.

![Graph showing the maximum enhancement in $\delta_a$ vs. $m_a$ for different RH temperatures.](image)
Non-Standard Cosmology from the UV

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

- Heavy particles $\phi$ abundant in string theory, supersymmetry, extra dimensions
- Generically produced during inflation
- If weakly coupled, they can have a long lifetime

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

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

Dror et al. ‘19