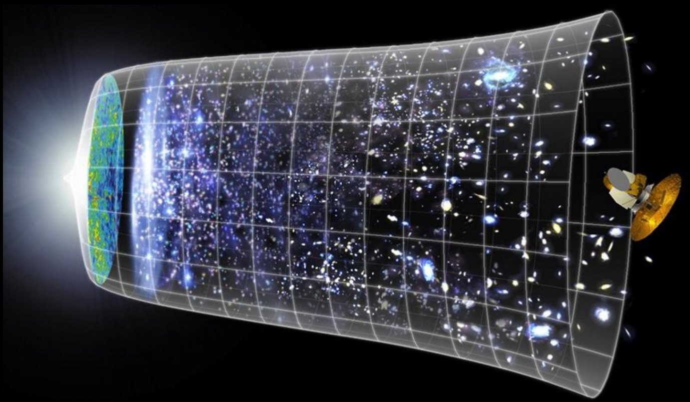
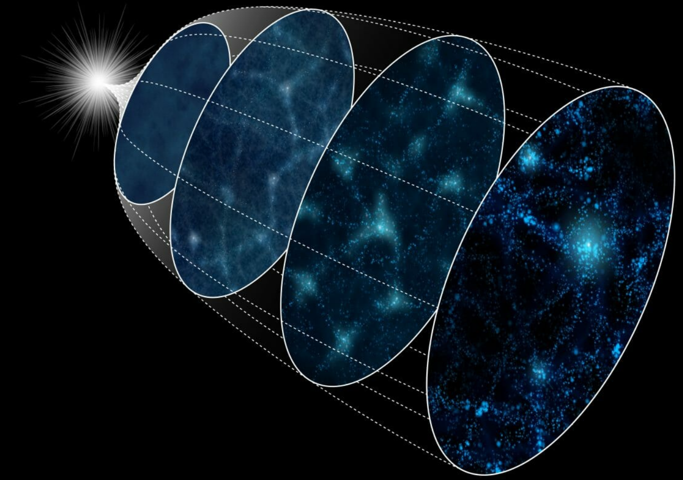
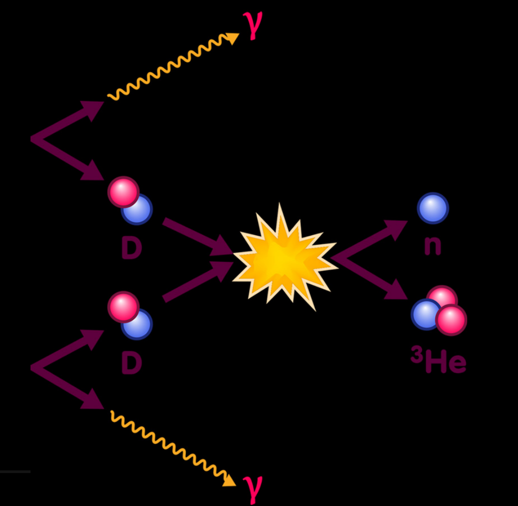







Fermilab Ying-Ying Li

# Cosmologically Degenerate Fermions

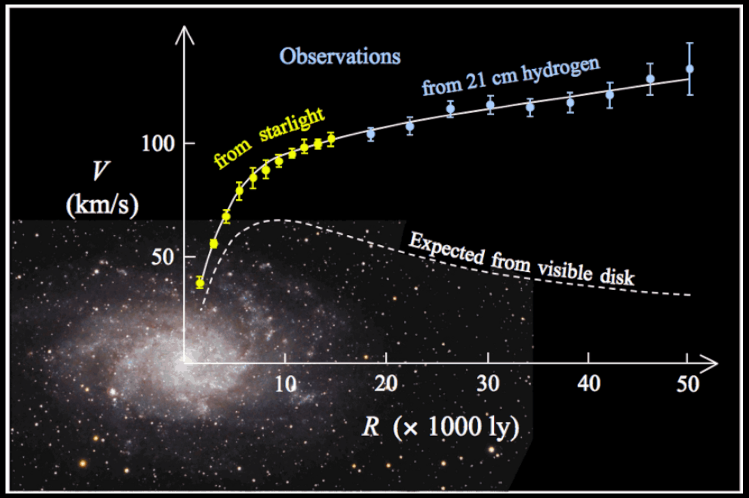
arXiv: 2108.02785

In collaboration with
Marcela Carena,
Nina M. Coyle,
Samuel D. McDermott,
Yuhsin Tsai

May 9, 2022 @Pheno 2022, U. Pittsburgh

# Evidences of dark matter: gravitational effects

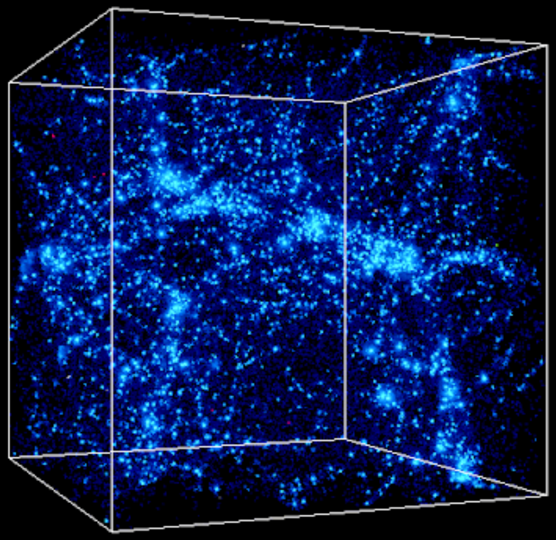
$z \sim 0$



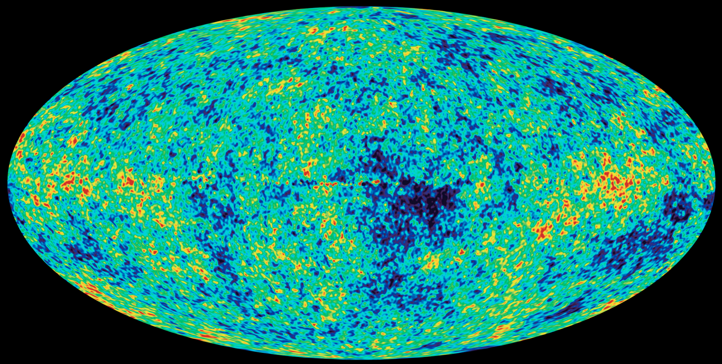

rotation curves

bullet cluster

$z > 0$



structure formation



cosmic microwave background (CMB)

Based on arXiv: 2108.02785

• mass? thermal history?

Cold dark matter: cold at all redshift,

$$P(z) \sim 0, \rho(z) \propto \rho(z=0)(1+z)^3$$

+ baryonic feedback (?) for small-scale structures

Based on arXiv: 2108.02785

- mass? thermal history?

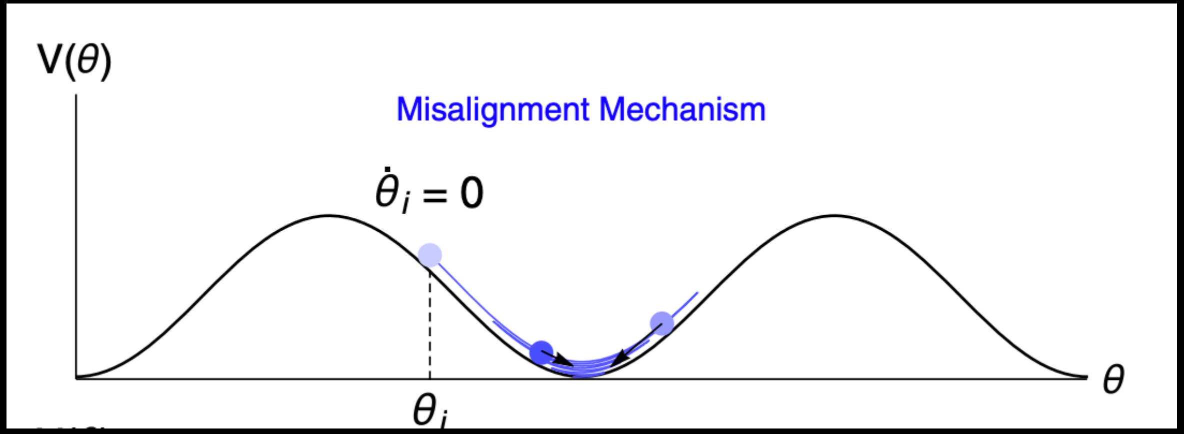
Warm dark matter: produced in the early universe with a temperature, motivated by the small-scale crisis

$$P(z < z_t) \sim 0, P(z > z_t) \propto \frac{1}{3}\rho(z)$$

had to be cold enough for structures to form $m_{\rm DM} \geq 5.3{\rm keV}$

[V. Iršič et al, arXiv: 1702.01764]

- Mixed dark matter
- dark energy -> dark matter




[T. Kobayashi et al, arXiv: 1708.00015]
[R. T. Co et al, arXiv:1910.14152]

**Based on arXiv: 2108.02785**

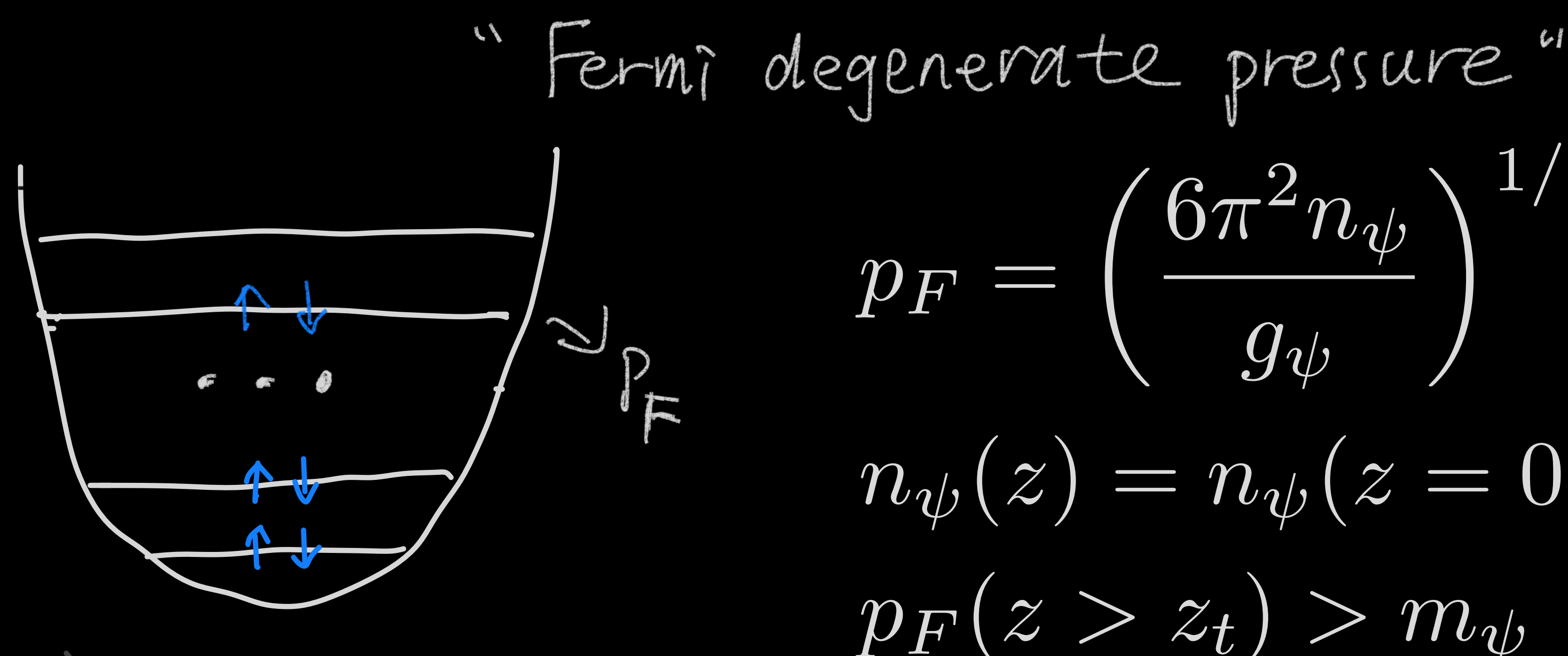
Consider the particle nature of DM:

For ***fermionic dark matter***, it simply cannot be as cold as being non-relativistic at arbitrary early time!

**Based on arXiv: 2108.02785**

Consider the particle nature of DM:

For ***fermionic dark matter***, it simply cannot be as cold as being non-relativistic at arbitrary early time!




$$p_F = \left(\frac{6\pi^2 n_\psi}{g_\psi}\right)^{1/3}$$

$$n_\psi(z) = n_\psi(z=0)(1+z)^3$$

$$p_F(z > z_t) > m_\psi$$

$z_t$ ***:non-relativistic to relativistic transition redshift***

Based on arXiv: 2108.02785

# Degenerate Fermionic Dark Matter in the Early Universe

non-relativistic
at present time

$$f(q) = \frac{1}{1 + e^{(q-\mu)/T}}$$

| $\text{WDM} : \mu \ll T,$ | $\text{DF} : \mu = p_F \gg T$ <br> $f(q) = \theta(p_F - q)$ |
|---|---|
| $\rho = \frac{3\zeta(3) g_\psi m_\psi T^3}{4\pi^2}$ | $\rho = \frac{g_\psi m_\psi p_F^3}{6\pi^2}$ |

$$1.75 z_t^{\text{WDM}}(T \sim m_\psi) \sim z_t^{\text{DF}}(p_F \sim m_\psi)$$

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$$1.75 z_t^{\mathrm{WDM}}(T \sim m_\psi) \sim z_t^{\mathrm{DF}}(p_F \sim m_\psi)$$

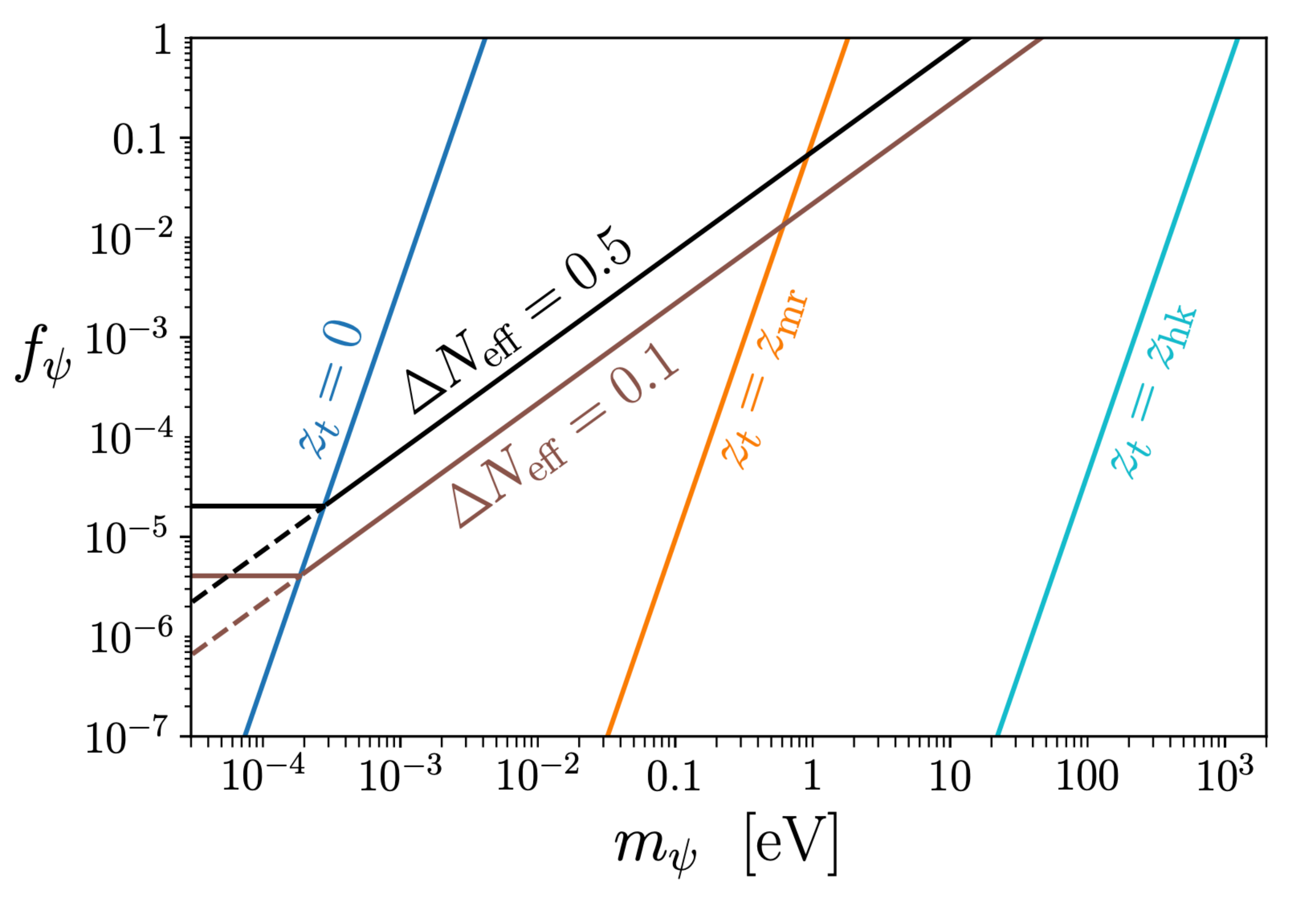
contribution to $\Delta N_{\mathrm{eff}}$ would be smaller by the factor $\frac{1 + z_t^{\mathrm{WDM}}}{1 + z_t^{\mathrm{DF}}}$

**the minimal mass allowed for fermionic dark matter!**

**Based on arXiv: 2108.02785**

# Degenerate Fermionic Dark Matter in the Early Universe

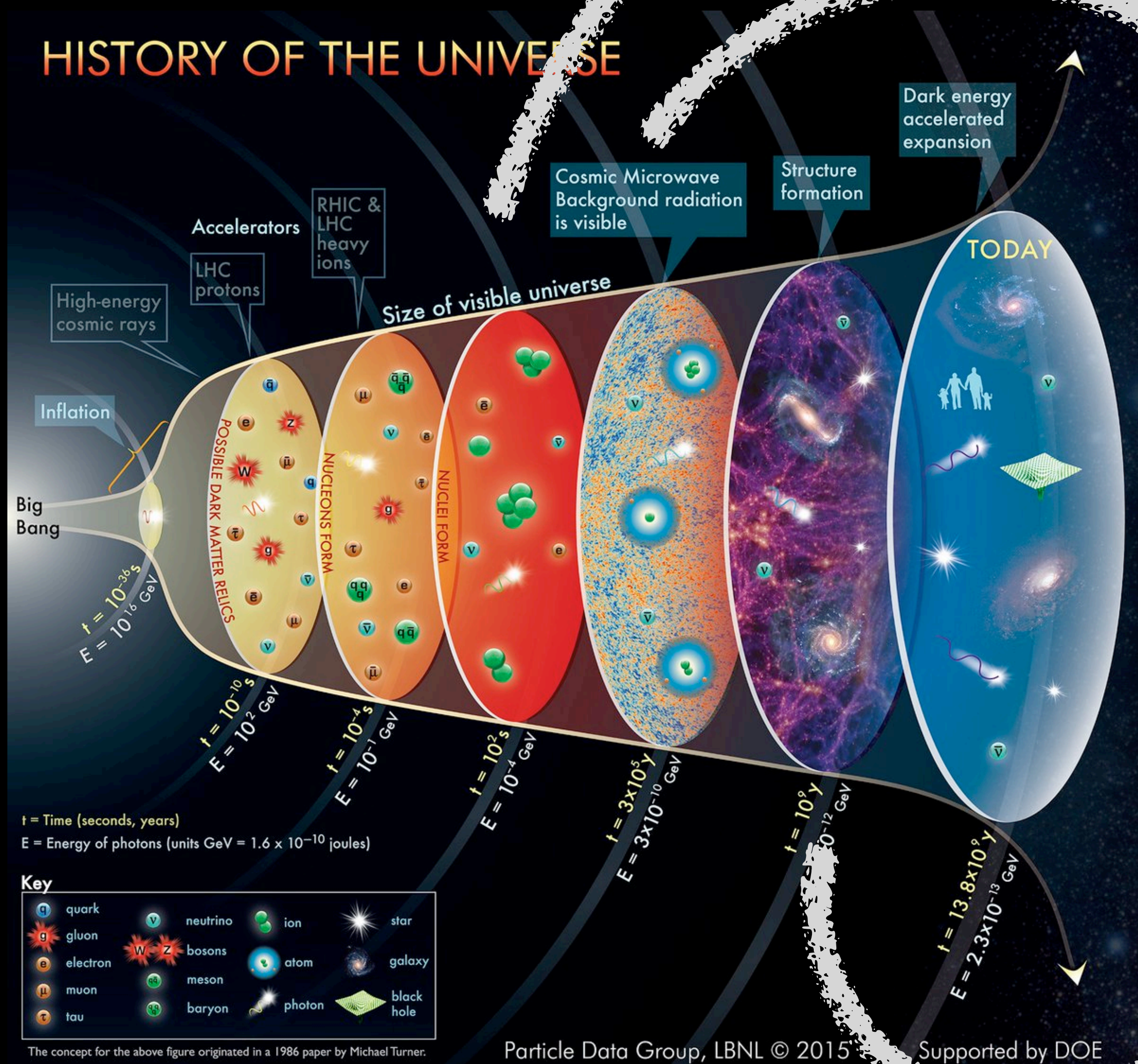
- thermally cold: kinetic energy from purely degenerate pressure
- 2 internal degrees of freedom, 1 flavor $g_\psi = 2, N_f = 1$
- fixed co-moving number, after the beginning of BBN




$z_{\rm mr} = 3300$

$z_{\rm hk} = 2 \times 10^7$

Based on arXiv: 2108.02785




## Big Bang Nucleosynthesis (BBN)

$\Delta N_{\rm eff}$

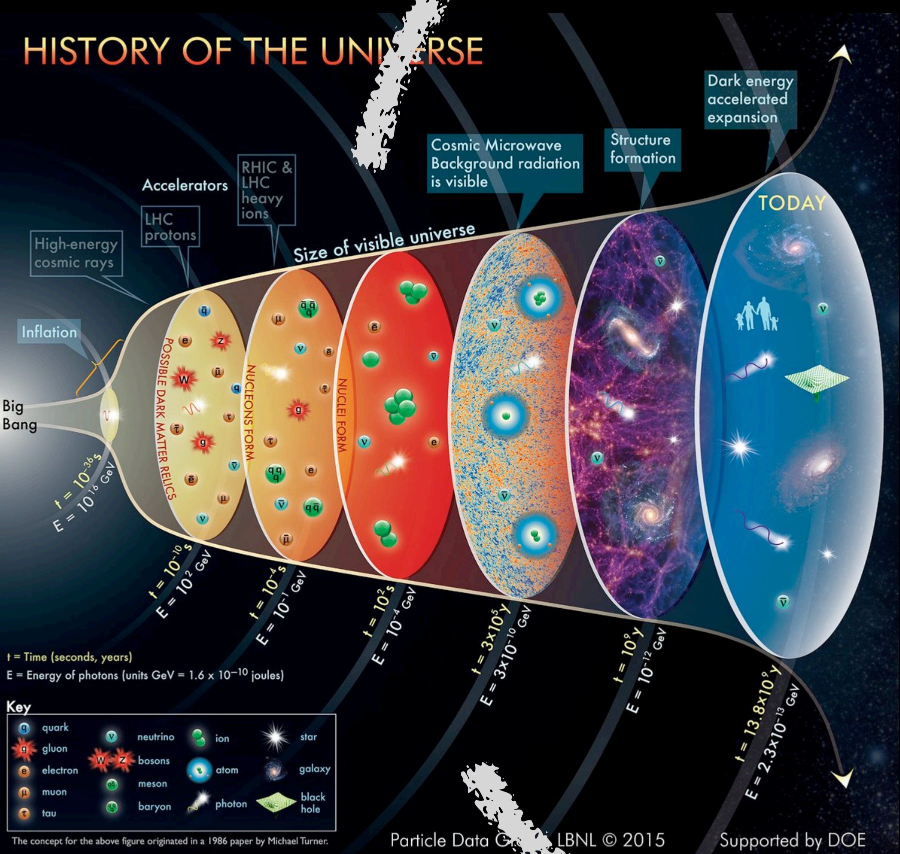
## Cosmic Microwave Background (CMB)

$\Delta N_{\rm eff}$

## Structure Formation

disappearance of matter

**Based on arXiv: 2108.02785**




## Big Bang Nucleosynthesis (BBN)

$T_f \sim \mathrm{MeV}, z \sim 10^9$

current bound:

$\Delta N_{\mathrm{eff}} < 0.12$, one parameter fit

[T. -H. Yeh, et al, arXiv:2011.13874]

$\Delta N_{\mathrm{eff}} < 0.37$, joint parameter fit

[V. Mossa, et al, Nature 587, 210 (2020)]

## Cosmic Microwave Background (CMB)

$T \sim 0.1\mathrm{eV}, z \sim 10^3$

current bound:

$\Delta N_{\mathrm{eff}} < 0.28$, one parameter fit

[N. Aghanim, et al, arXiv:1807.06209]

Multi-parameter extensions of LCDM, $\Delta N_{\mathrm{eff}} < 0.5$

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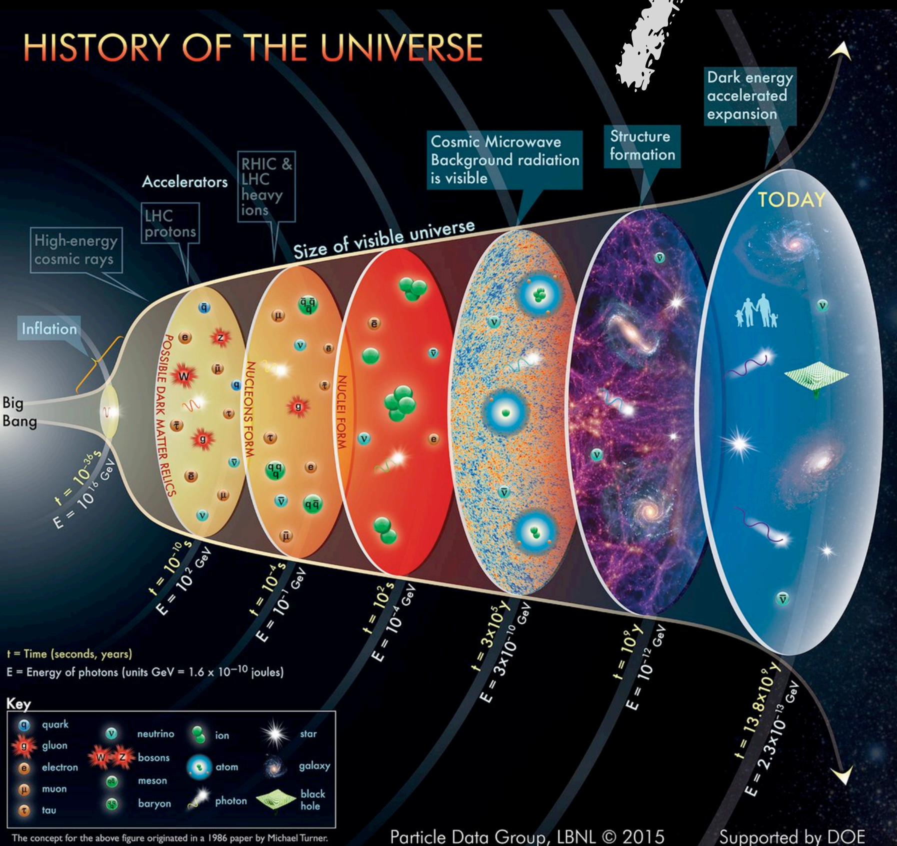
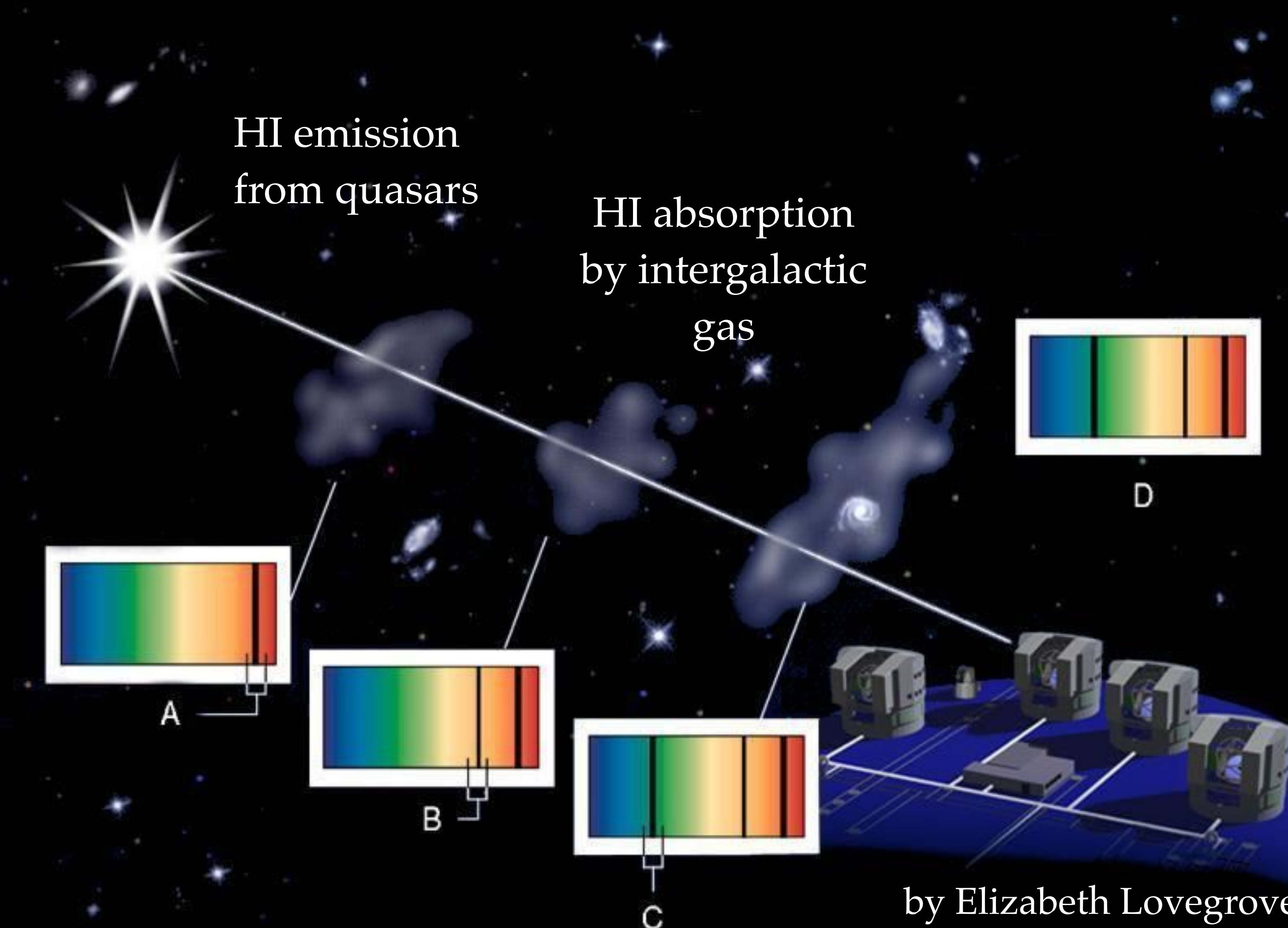
**Based on arXiv: 2108.02785**

Structure Formation: Ly $-\ \alpha$ forest, MW satellite
suppression of gravitational clustering

# Ly $-\ \alpha$ forest



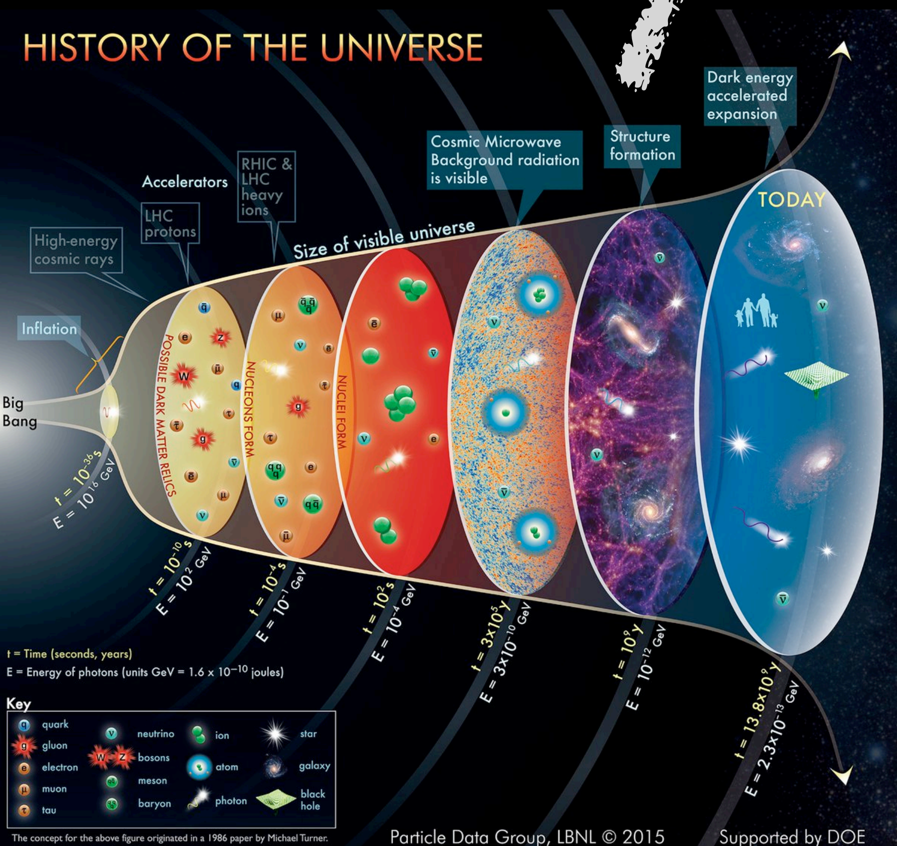




Measurement of matter distributions at intergalactic scales

**Based on arXiv: 2108.02785**

## Structure Formation: Ly $-\ \alpha$ forest, MW satellite

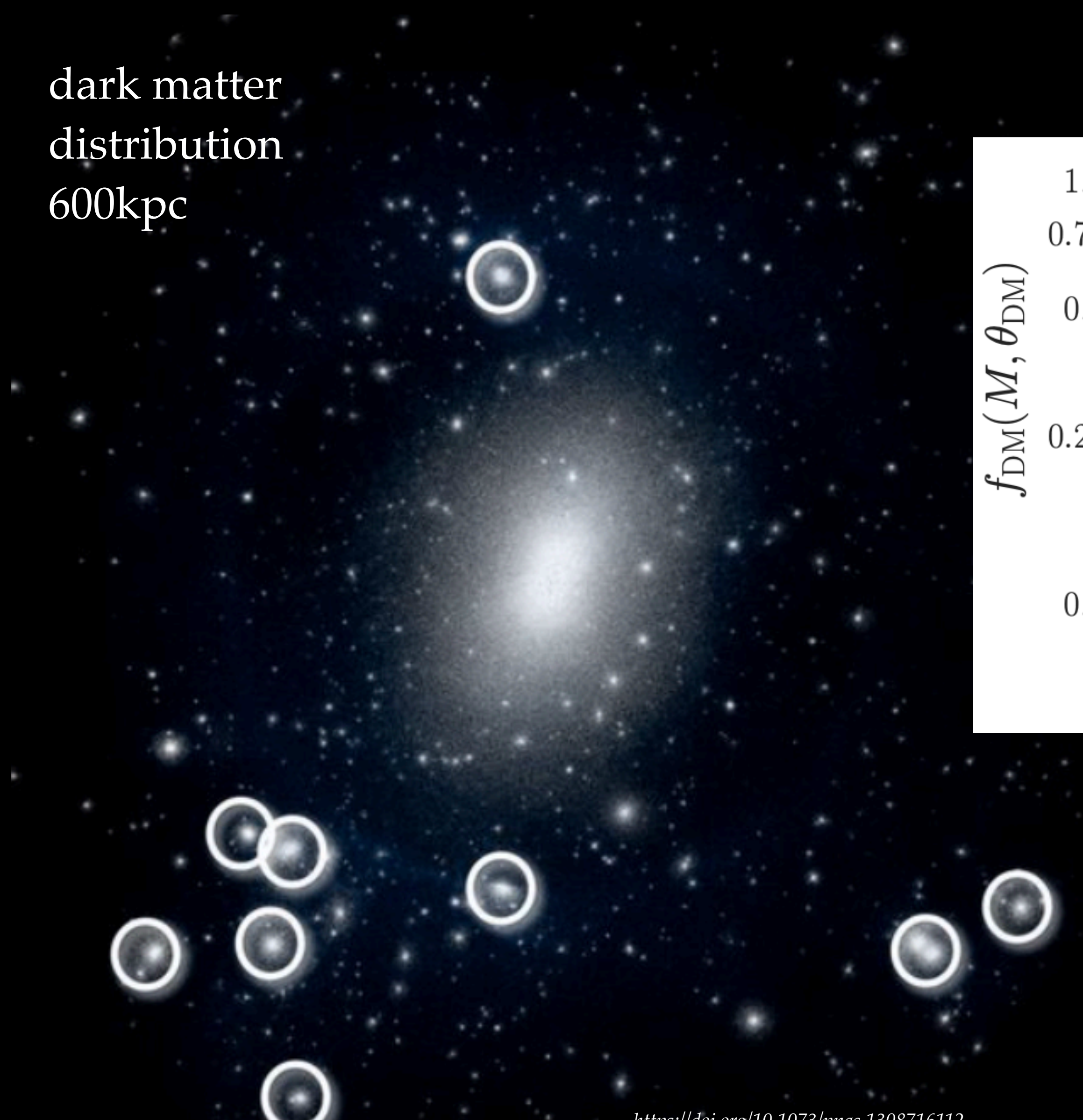
suppression of gravitational clustering



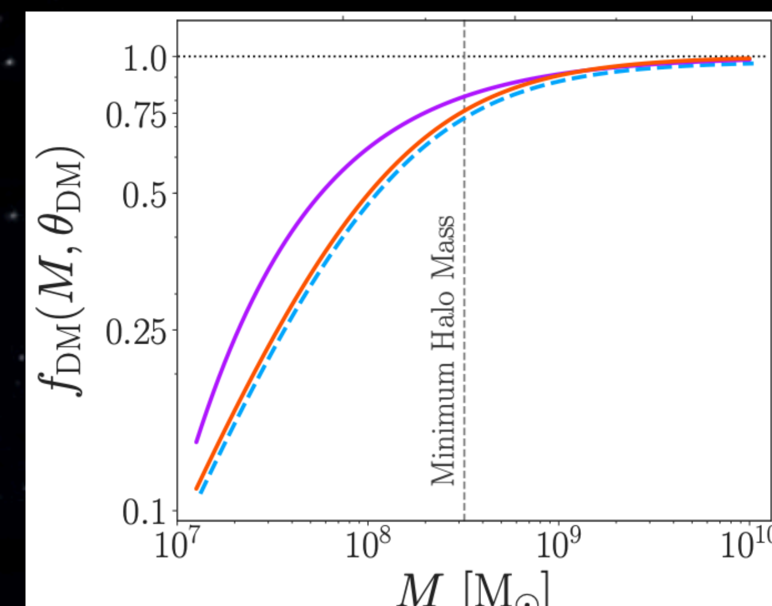

## MW satellite subhalo mass function (SHMF)

the abundance of subhalos within the viral radius of the Milky Way

dark matter distribution 600kpc



https://doi.org/10.1073/pnas.1308716112

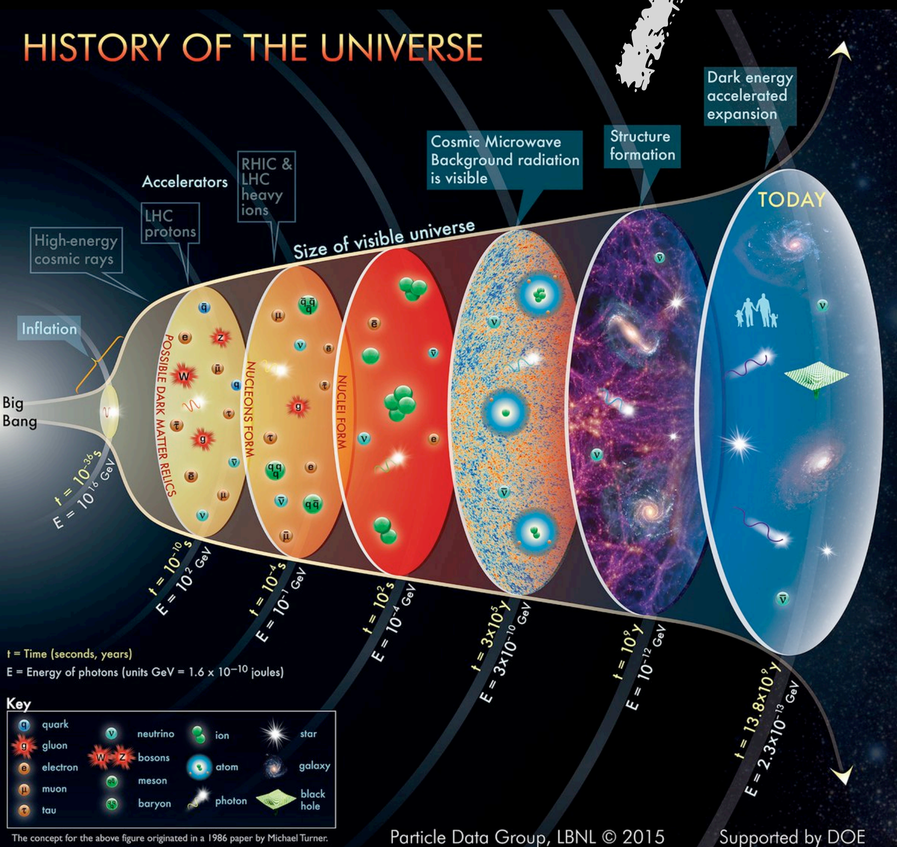



[E. O. Nadler, et al, arXiv:2008.00022]

**Based on arXiv: 2108.02785**

## Structure Formation: $\mathrm{Ly}-\alpha$ forest, MW satellite

suppression of gravitational clustering




the transfer function $$T^2(k) = \frac{P_{\mathrm{nCDM}}(k)}{P_{\mathrm{CDM}}(k)}$$

$$\mathrm{Ly}-\alpha : T^2(k < 20\mathrm{h/Mpc}) \geq 0.7$$

$$\mathrm{SHMF} : T^2(k < 50\mathrm{h/Mpc}) \geq 0.5$$

[R. Murgia, et al, arXiv:1704.07838]

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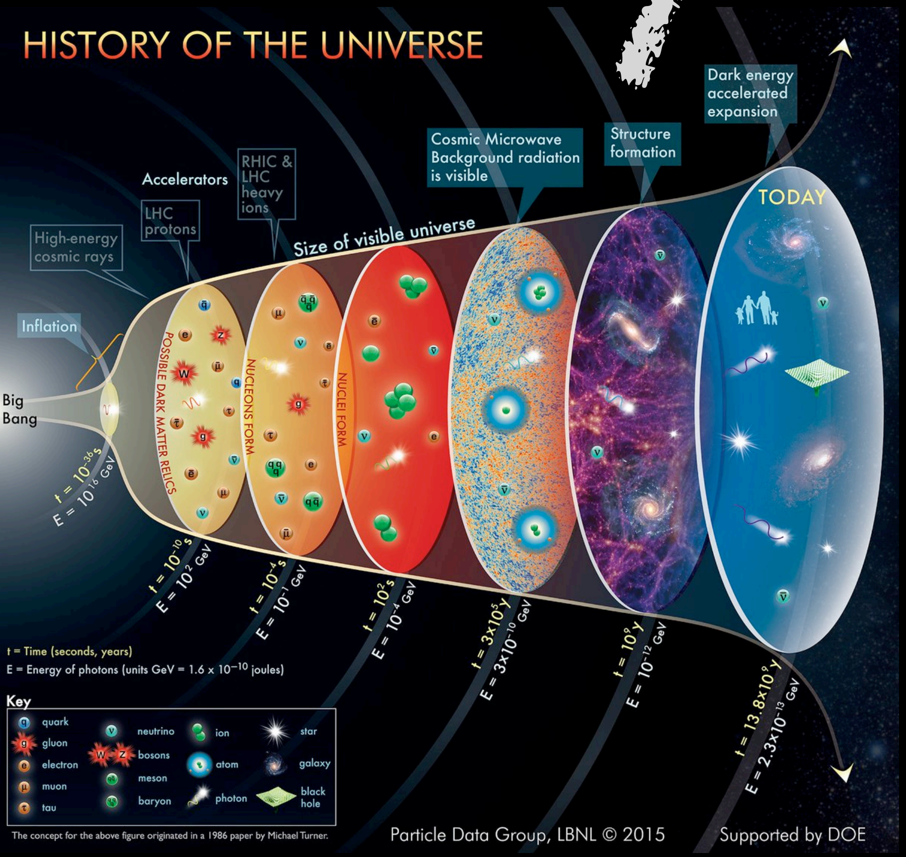
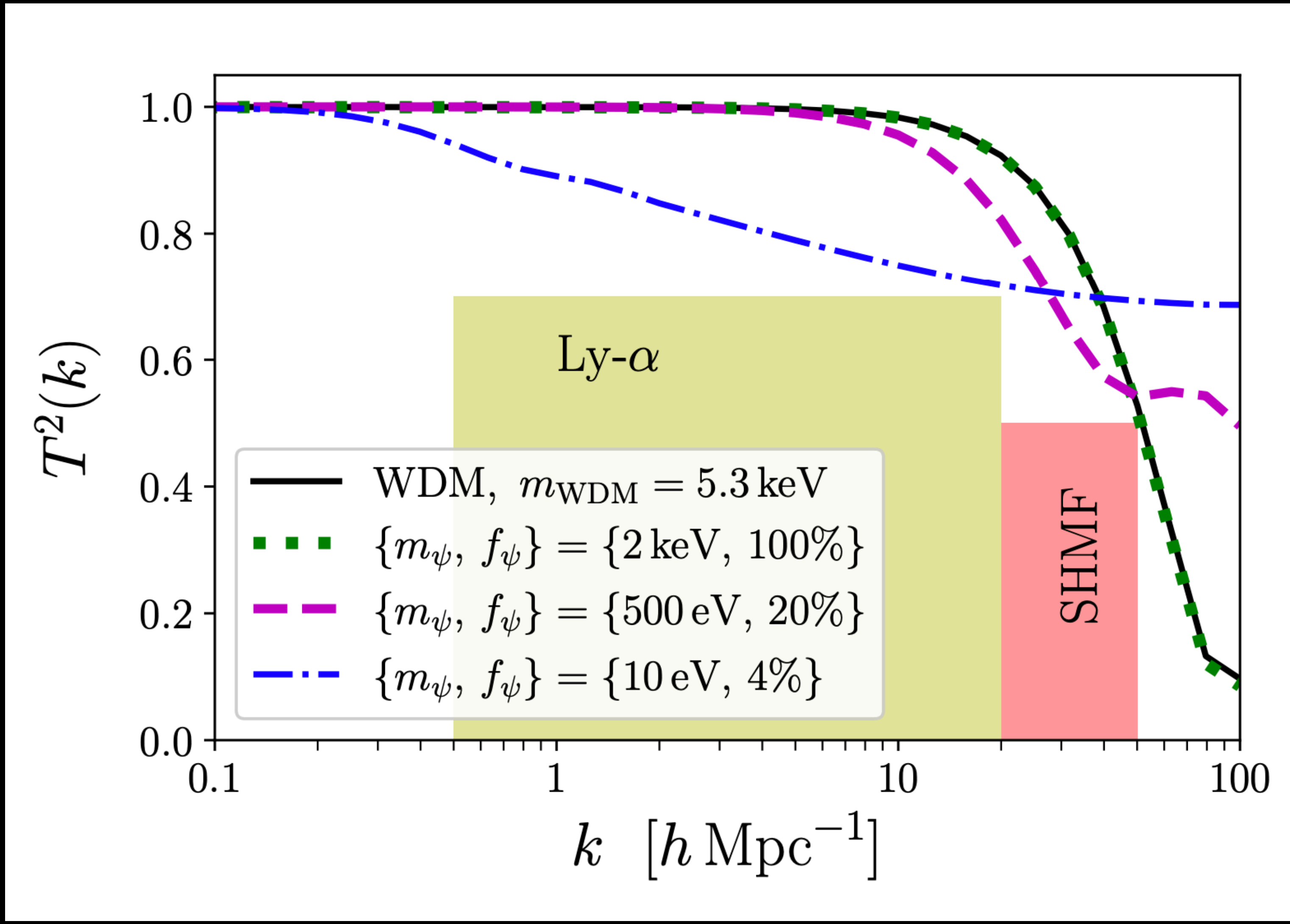
## Structure Formation: Ly $-\,\alpha$ forest, MW satellite suppression of gravitational clustering




the transfer function $T^2(k) = \dfrac{P_{\rm nCDM}(k)}{P_{\rm CDM}(k)}$

$$f_\psi\ \mathrm{DF} + (1 - f_\psi)\mathrm{CDM}$$




$\mathrm{Ly}-\alpha: T^2(k < 20\mathrm{h/Mpc}) \geq 0.7$

$\mathrm{SHMF}: T^2(k < 50\mathrm{h/Mpc}) \geq 0.5$

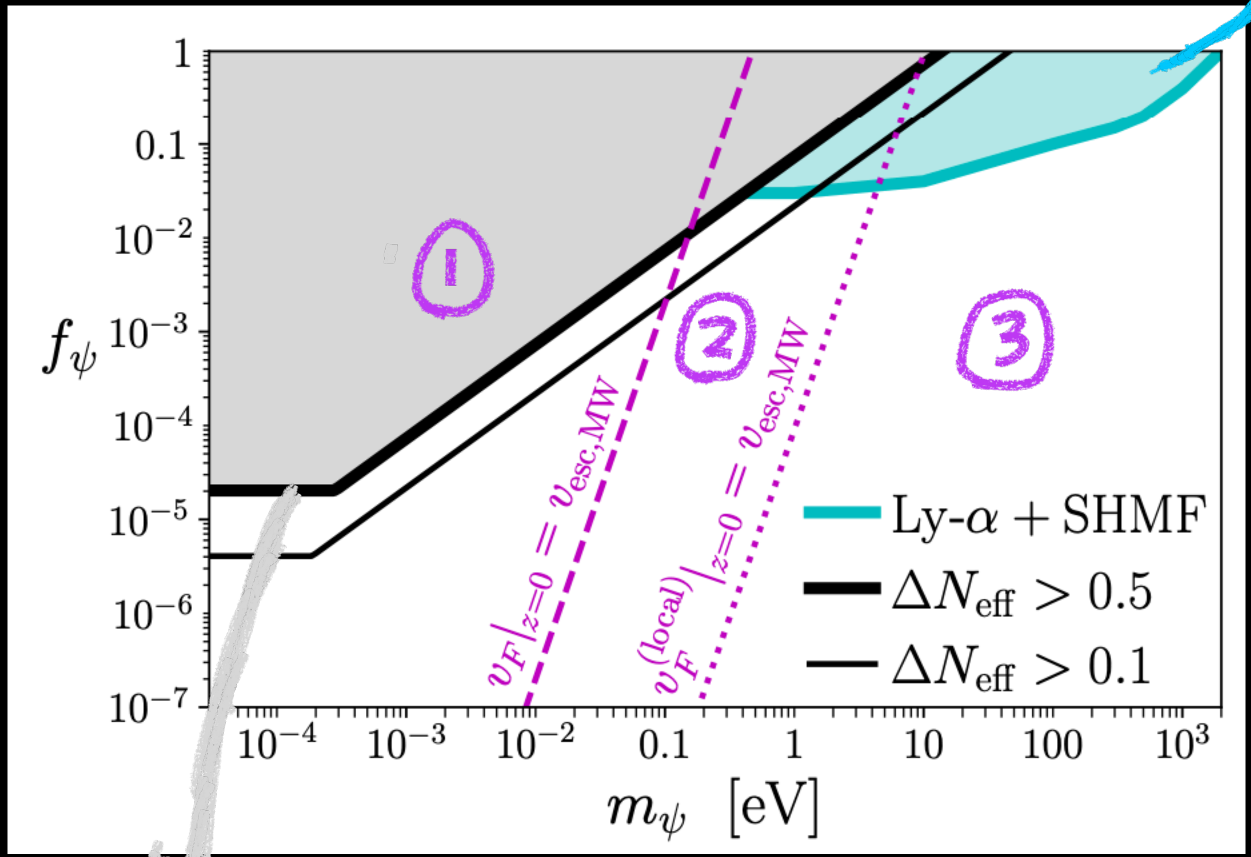
**Based on arXiv: 2108.02785**

Based on a modified CLASS package

extended to $f_\psi \sim 3\%, m_\psi \leq 1\mathrm{eV}$

$m_\psi \geq 2\mathrm{keV}, f_\psi = 1$

in comparison with $m_\psi \geq 5.3\mathrm{keV}$ for WDM




constrain $f_\psi$ as small as $2 \times 10^{-5}$!

**opens up parameter space for model Building!**

**Based on arXiv: 2108.02785**

extended to $f_\psi \sim 3\%, m_\psi \leq 1\text{eV}$

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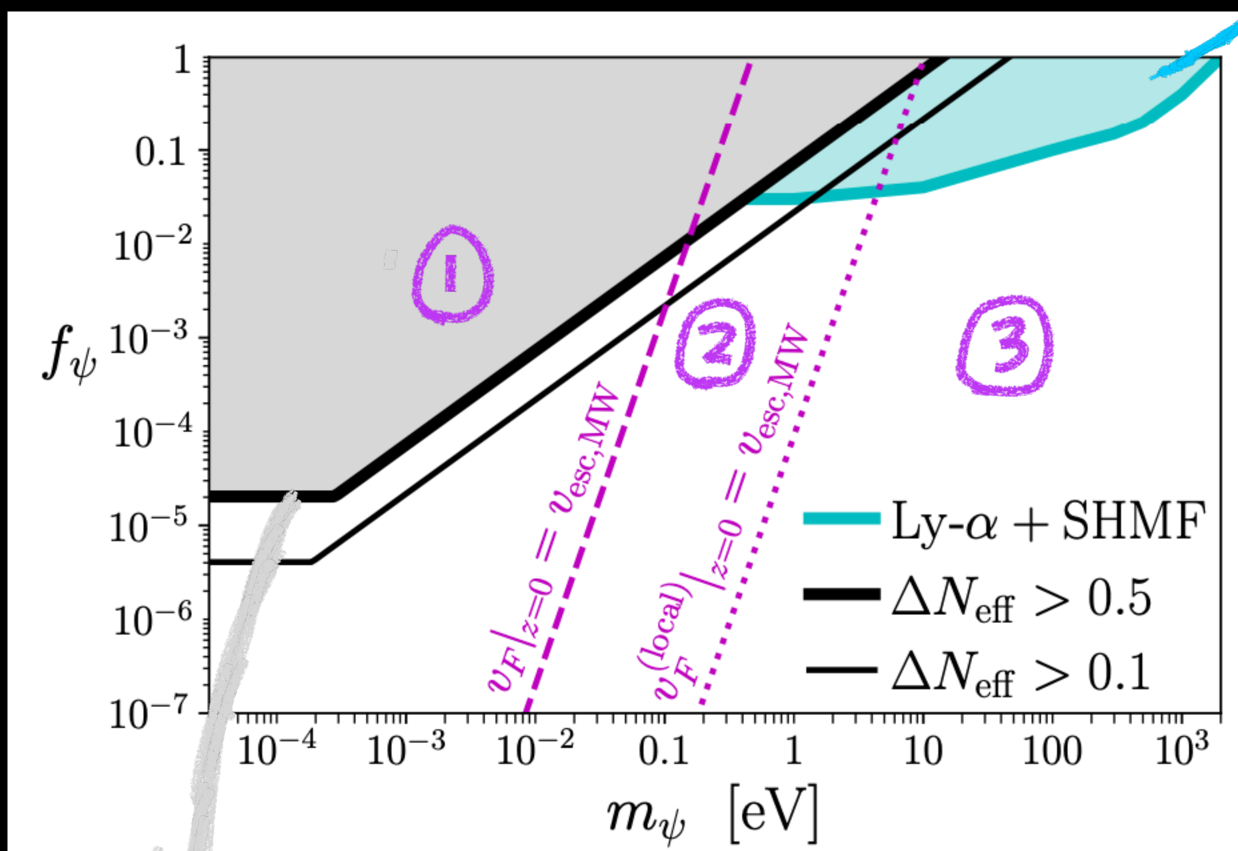


constrain $f_\psi$ as small as $2 \times 10^{-5}$!

## Local Implications

- Profile of Dwarf galaxies ( $70\text{eV} \sim 400\text{eV}$):

[L. Randall, et al, arXiv:1611.4590]

incompatible with the matter power spectrum measurement with $f_\psi = 1$

Based on arXiv: 2108.02785

extended to $f_\psi \sim 3\%, m_\psi \leq 1\text{eV}$

$m_\psi \geq 2\text{keV}, f_\psi = 1$

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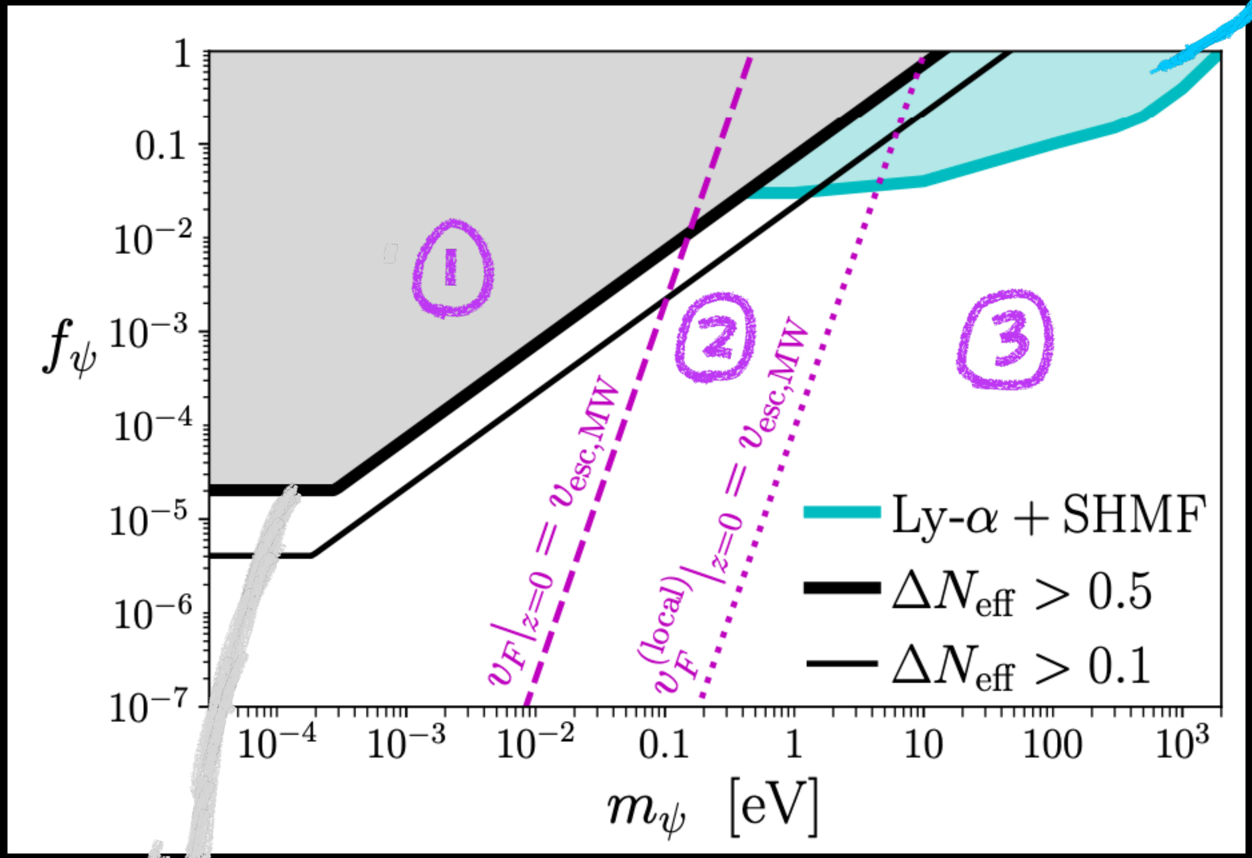


constrain $f_\psi$ as small as $2 \times 10^{-5}$!

- Modifying MW DM phase space density
  1. Not accumulating
  2. Smaller over density than CDM, or higher velocity, e.g. probed by novel material
  3. Similar phase space distribution to that of CDM

Based on arXiv: 2108.02785

extended to $f_\psi \sim 3\%, m_\psi \leq 1\text{eV}$

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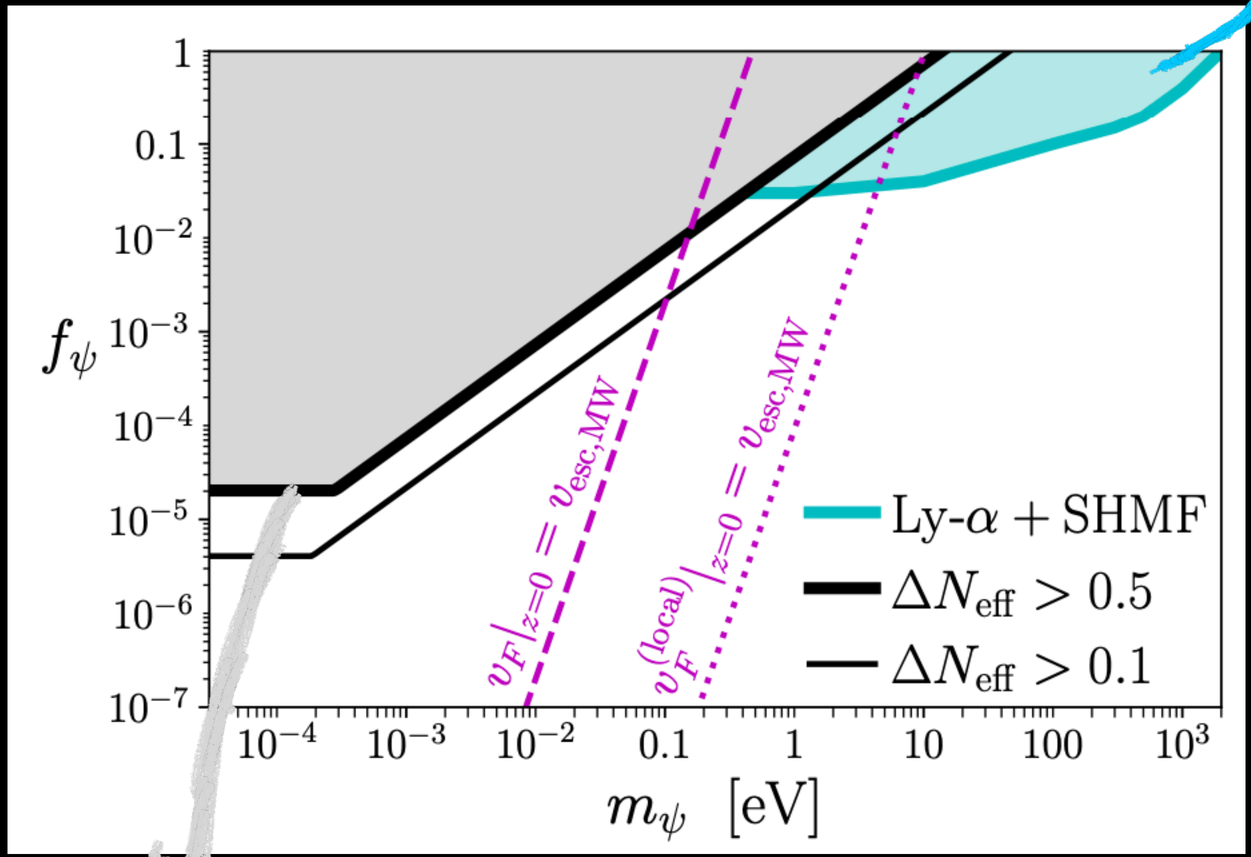



constrain $f_\psi$ as small as $2 \times 10^{-5}$!

Bound rescaling, as changing $N_f$

fixing $\left(\frac{p_F}{m_\psi}, f_\psi\right)$

$f_\psi \propto \rho_\psi \propto N_f m_\psi^4$

bound on $m_\psi \propto N_f^{-1/4}$

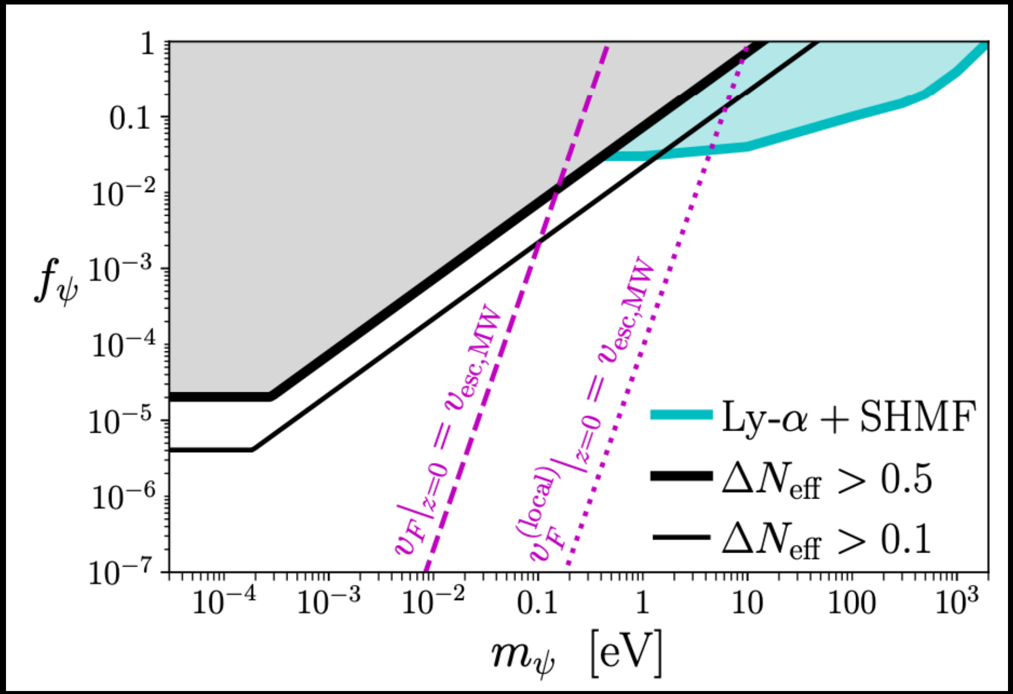
Same scaling for the profile of Dwarf galaxies: multi-flavor wouldn't help

Based on arXiv: 2108.02785

# Conclusions and Outlook

minimal kinetic energy in the early universe
—Degenerate Fermion State:

**minimal mass allowed for fermionic dark matter ~ 2keV**




**constrained fermionic dark matter with a portion as small as $10^{-5}$**

**degenerate pressure could lead to quite different MW dark matter phase space distributions**

**Outlook**

- **Our bound is nevertheless conservative: consider LSS data at smaller k?**
  [W. L. Xu, et al, arXiv:2107.09664]
- **Effects of scalar dark matter condensation on LSS**

**Based on arXiv: 2108.02785**

Thank you

Based on arXiv: 2108.02785

# Big Bang Nucleosynthesis (BBN)

$N_{\rm eff}$ ↗, $H$ ↗

$T_f(\text{neutron freeze} - \text{out})$ ↗, $\frac{n_n(T_f)}{n_{p^+}(T_f)}$ ↗

constraining the number of relativistic degree of freedom at $T_f \sim \text{MeV}, z \sim 10^9$

current bound:

$\Delta N_{\rm eff} < 0.12$, one parameter fit

[T. -H. Yeh, et al, arXiv:2011.13874]

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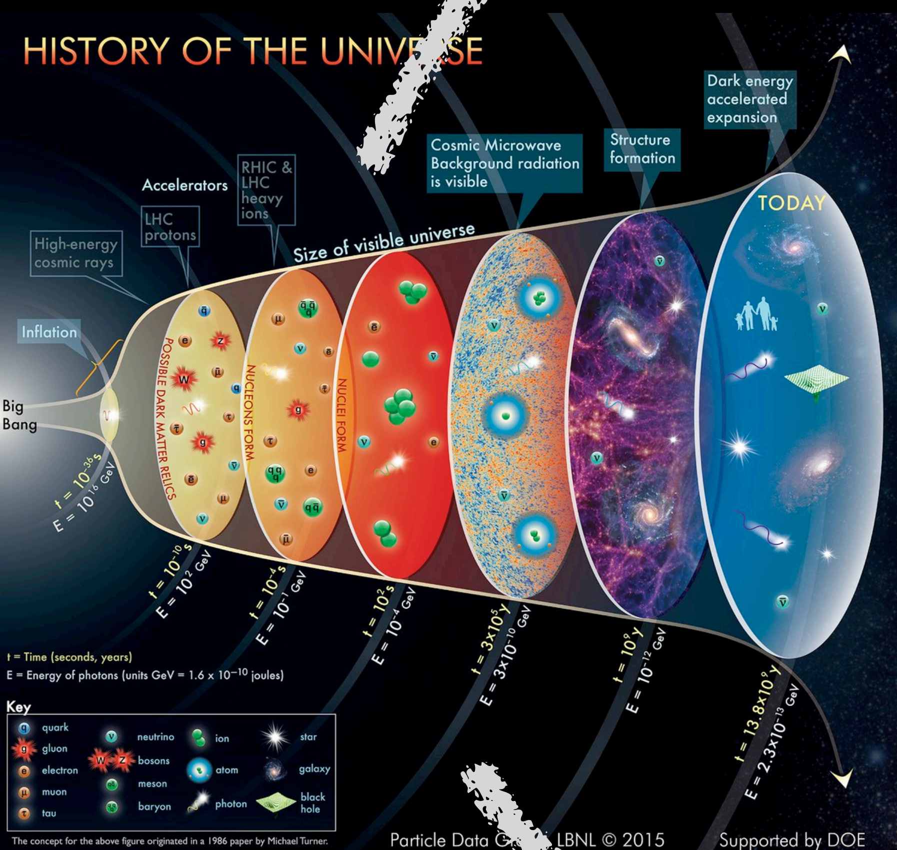
[V. Mossa, et al, Nature 587, 210 (2020)]




# Cosmic Microwave Background (CMB)

constraining the number of relativistic degree of freedom at $T \sim 0.1\text{eV}, z \sim 10^3$

current bound:

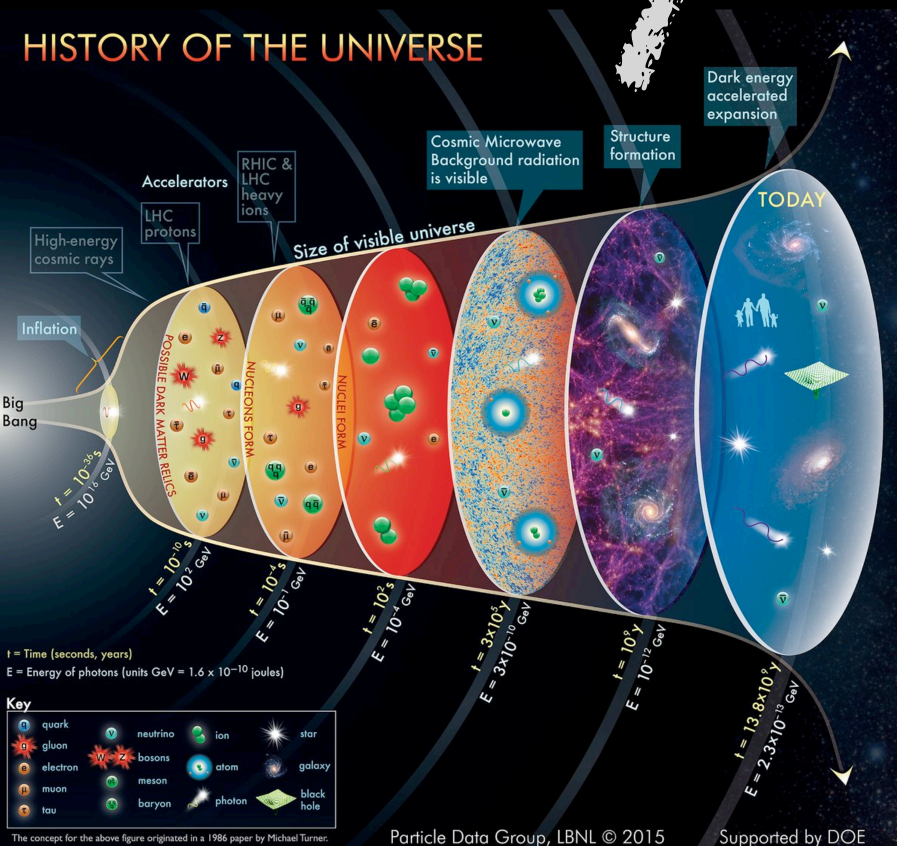
[N. Aghanim, et al, arXiv:1807.06209]

$\Delta N_{\rm eff} < 0.28$, one parameter fit

**Based on arXiv: 2108.02785**

## Structure Formation: Ly $-\ \alpha$ forest, MW satellite

suppression of gravitational clustering




linear matter power, normalized to that of CDM

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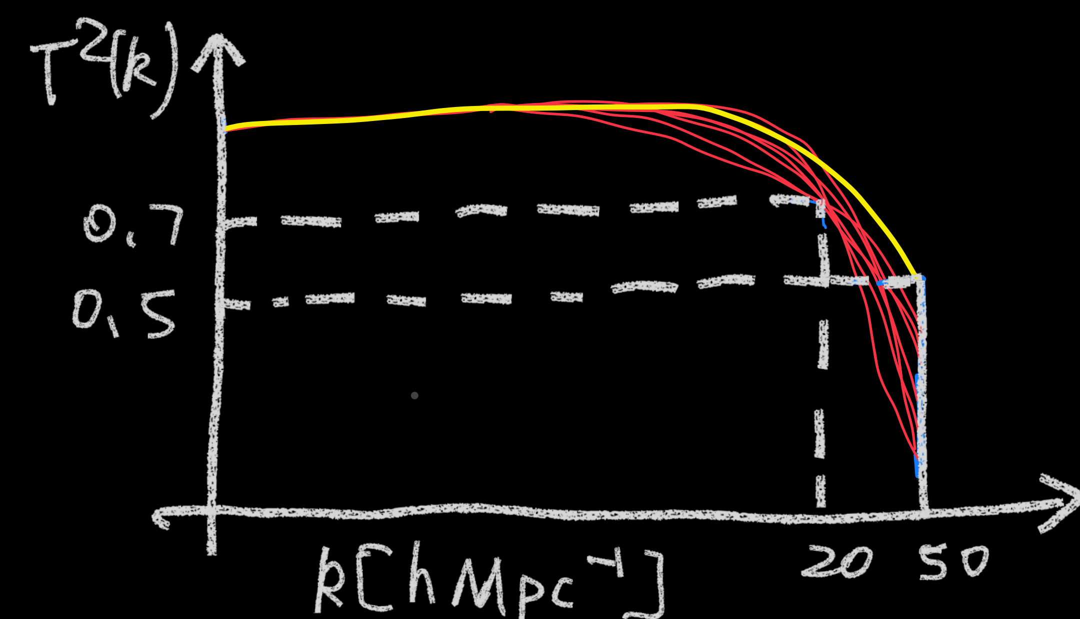
the abundance of sub halos within the viral radius of the Milky Way

subhalo mass function (SHMF)

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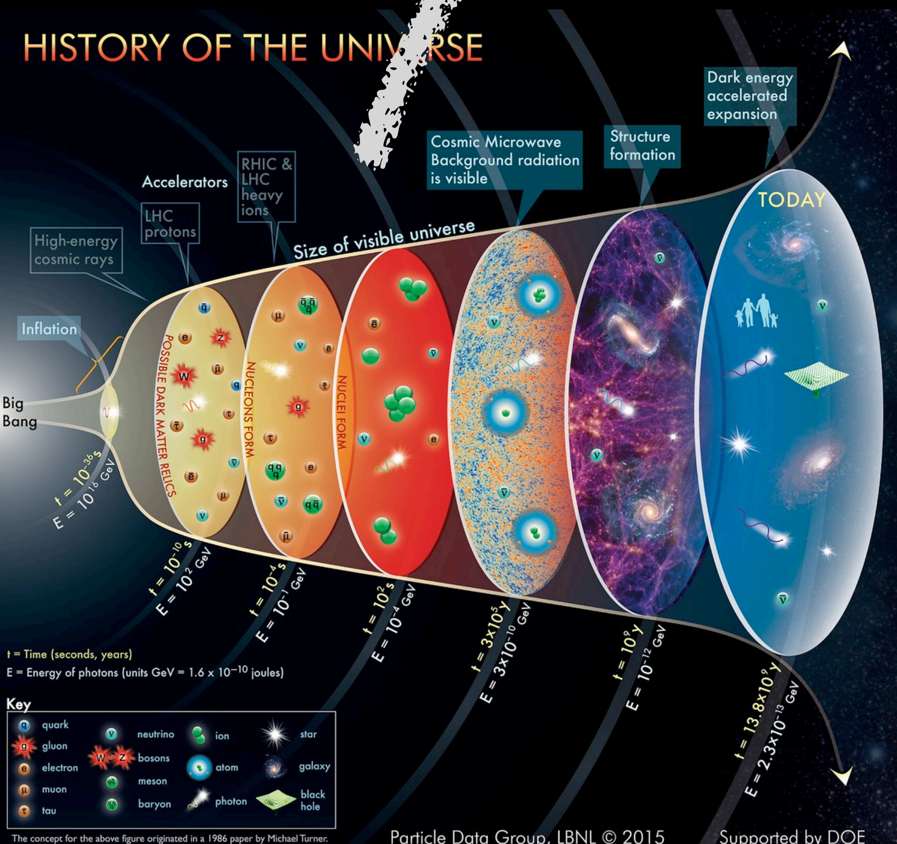
**Based on arXiv: 2108.02785**




# Big Bang Nucleosynthesis (BBN)

$$n + p^+ \to D \xrightarrow{\;n\;} H^3 \xrightarrow{\;p^+\;} He^4$$

$$n_{He^4} = \frac{1}{2} n_n(t_{nuc})$$

$$n_n(t_{nuc}) = n_n(T_f)\, e^{-t_{nuc}/\tau_n}$$

$$\frac{n_n(T_f)}{n_{p^+}(T_f)} = e^{-Q/T_f}, \quad T_f \sim \text{MeV}$$

$$N_{eff} \uparrow, \quad H \uparrow, \quad T_f \uparrow, \quad n_{He^4} \uparrow$$

constraining the number of relativistic degree of freedom at $T_f \sim \text{MeV}$, $z \sim 10^9$

current bound: DNeff < 0.12, one parameter fit [T. -H. Yeh, et al, arXiv:2011.13874]

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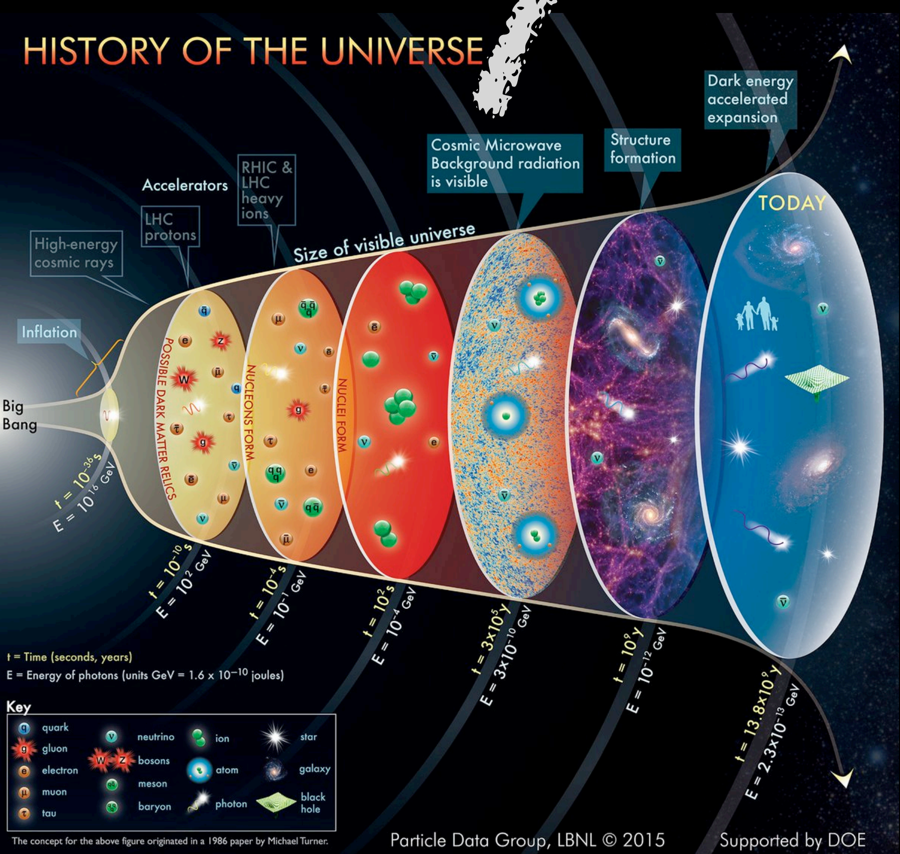


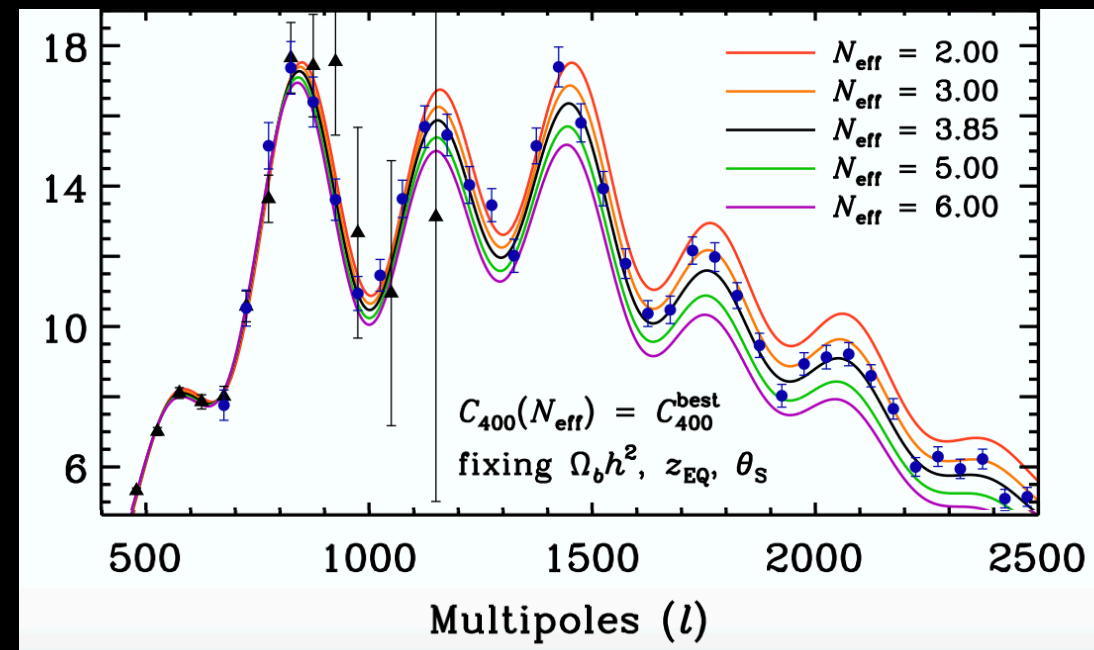


[Z. Hou. et al. arXiv:1104.2333]

damping factor : $f \propto e^{-2r_d/\lambda}$

$r_d \propto \theta_d, \theta_d/\theta_s \propto H^{1/2}$

fixing other parameters

$N_{eff}$ ↗ , $H$ ↗ , $f$ ↘

constraining the number of relativistic degree of freedom at $T \sim 0.1\text{eV}, z \sim 10^3$

current bound: DNeff < 0.28, one parameter fit [N. Aghanim, et al, arXiv:1807.06209]

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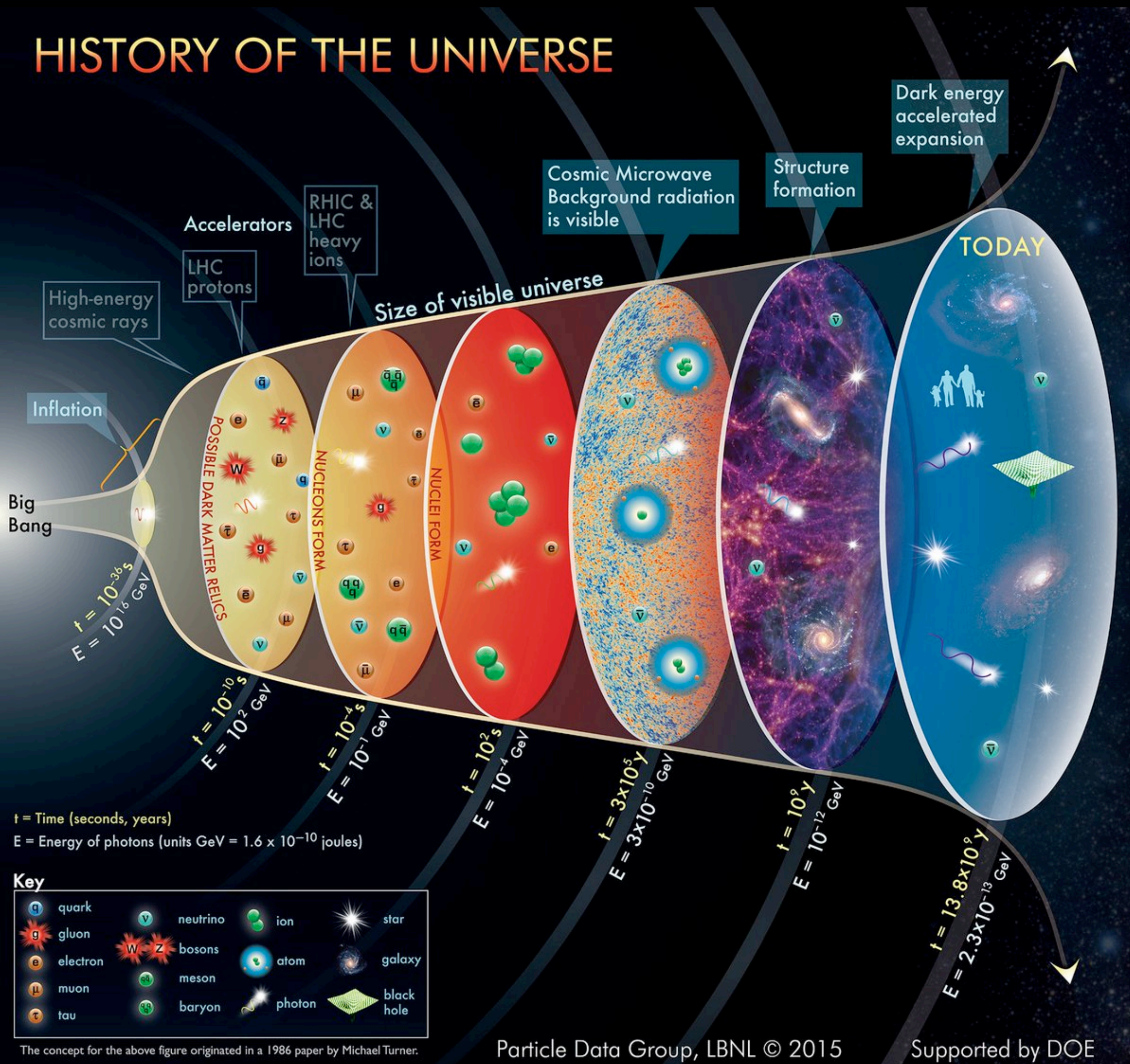


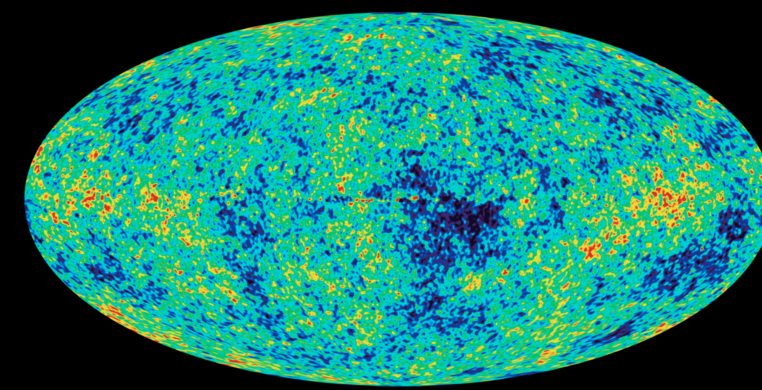

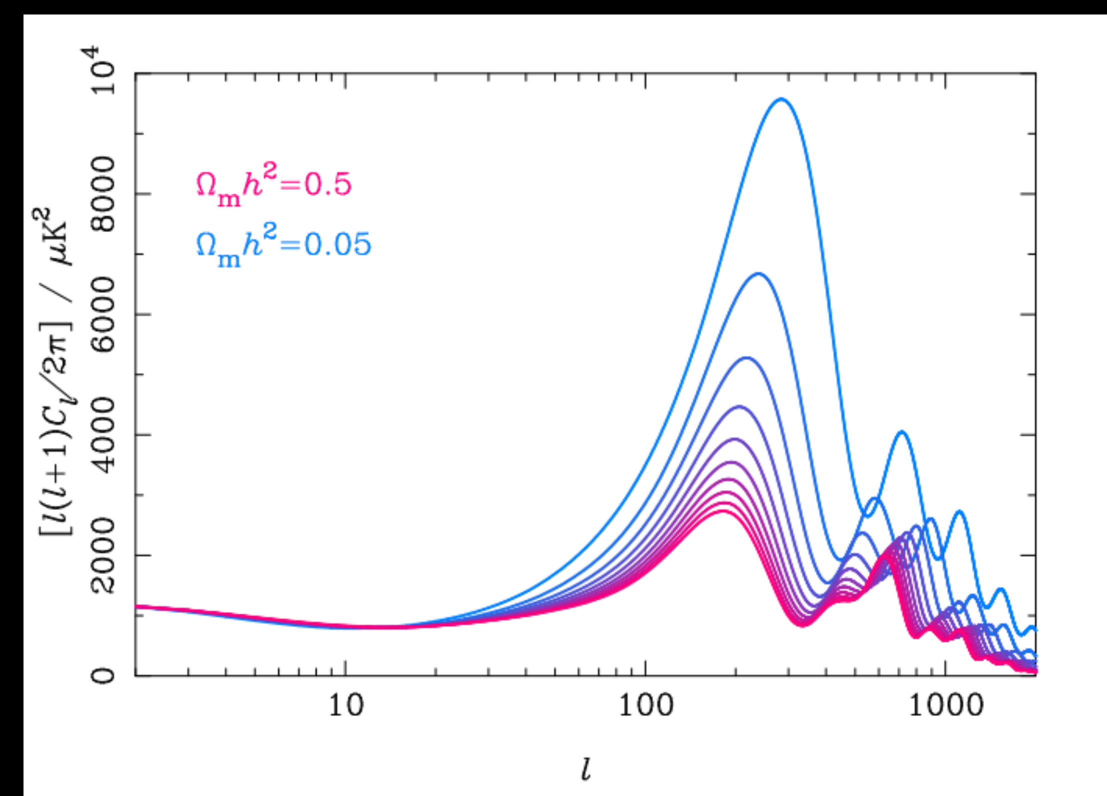


[A. Challinor, astro-ph.0403344]

Based on arXiv: 2108.02785