

 Fermilab

Ying-Ying Li

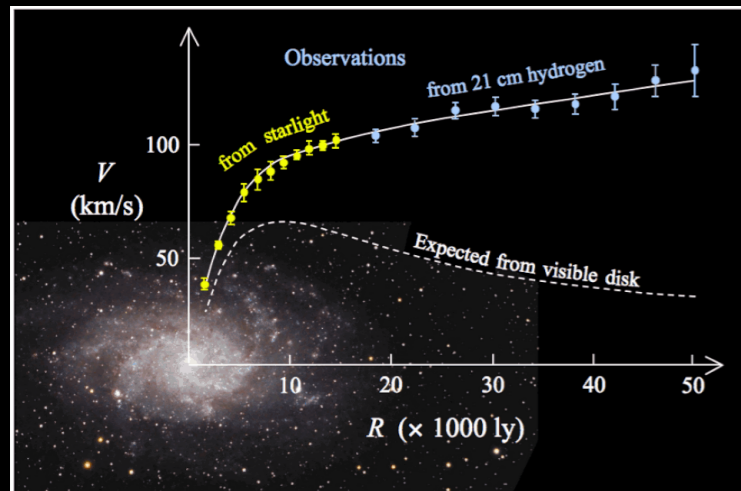
Cosmologically Degenerate Fermions

arXiv: 2108.02785
In collaboration with
Marcela Carena,
Nina M. Coyle,
Samuel D. McDermott,
Yuhsin Tsai

April 30, 2022 @PIKIMO 2022, Notre Dame

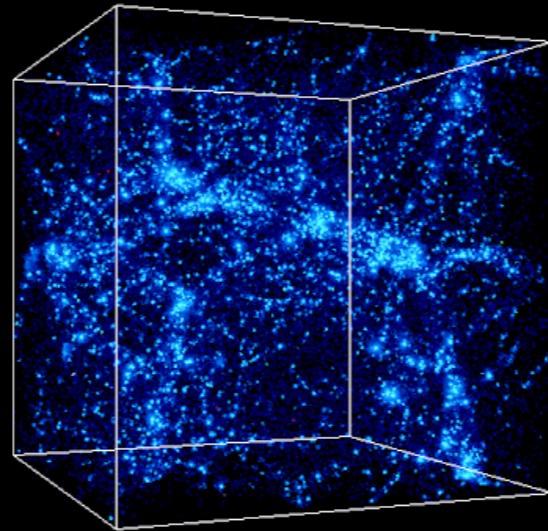
Evidences of dark matter: gravitational effects

$z \sim 0$

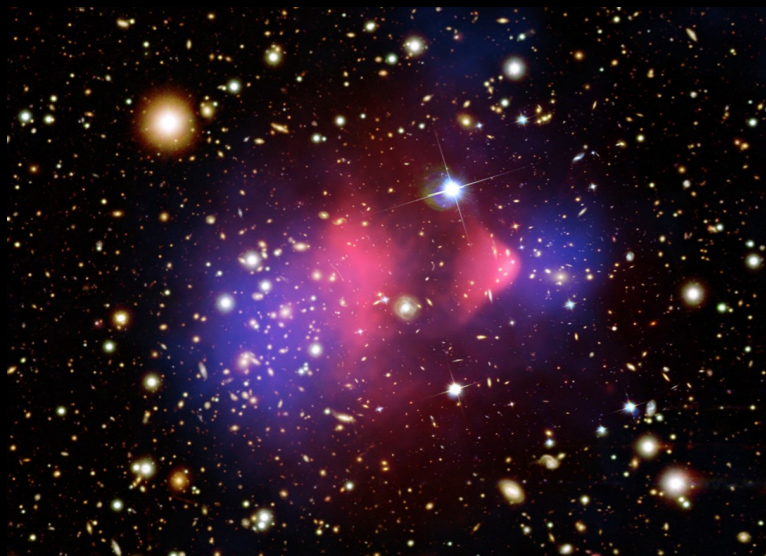


rotation curves

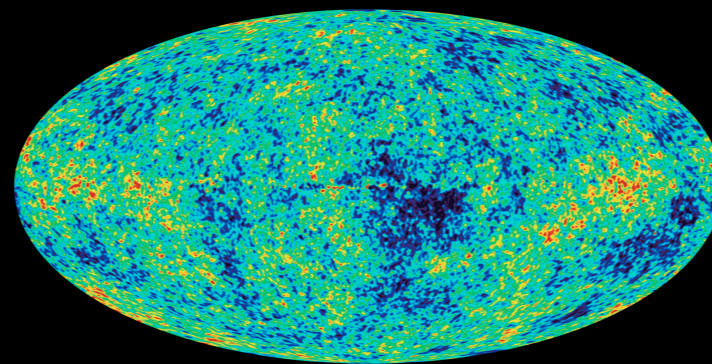
$z > 0$



structure formation



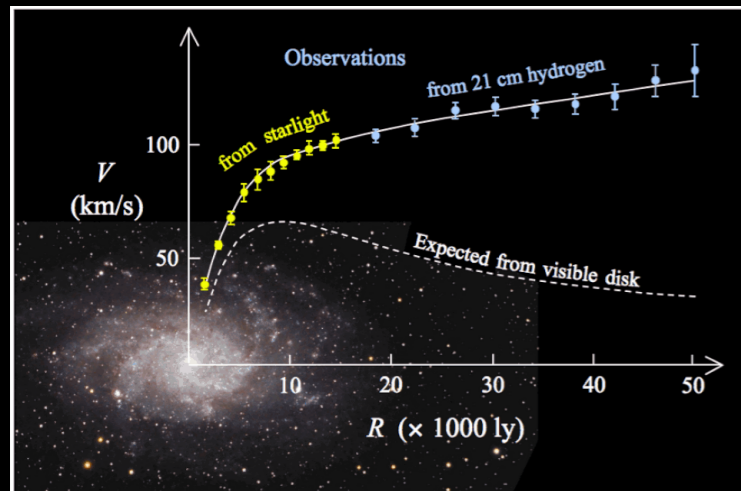
bullet cluster



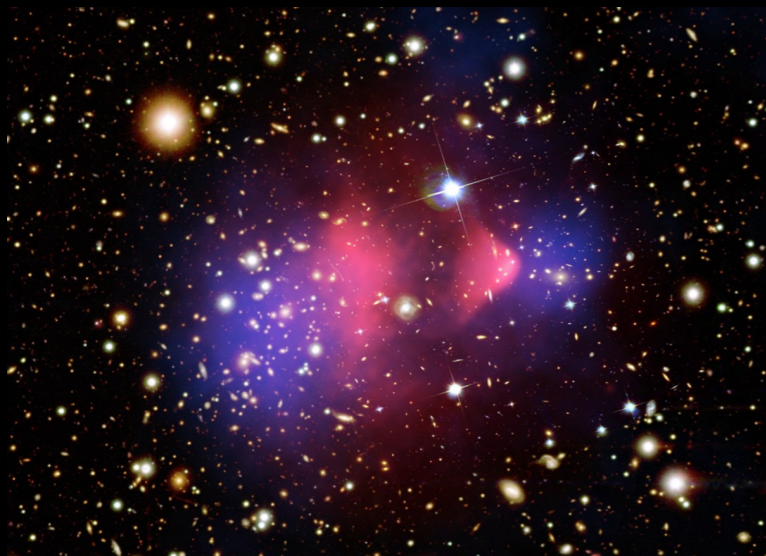
cosmic microwave background (CMB)

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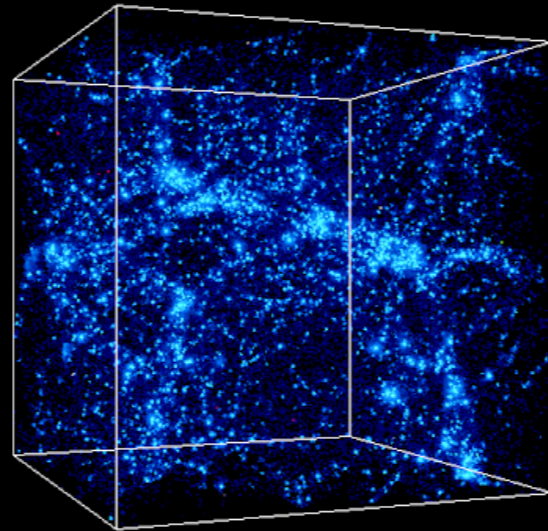


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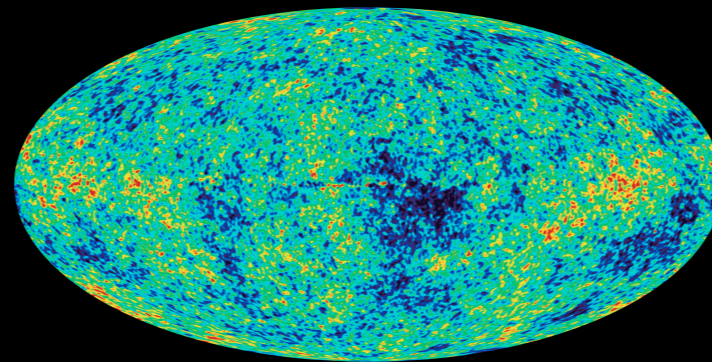
bullet cluster

$z > 0$



structure formation

additional interactions?
mass?
thermal history?



cosmic microwave background (CMB)

- 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

- 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 $m_{\text{DM}} \geq 5.3\text{keV}$

[V. Iršič et al, arXiv: 1702.01764]

- mass? thermal history?

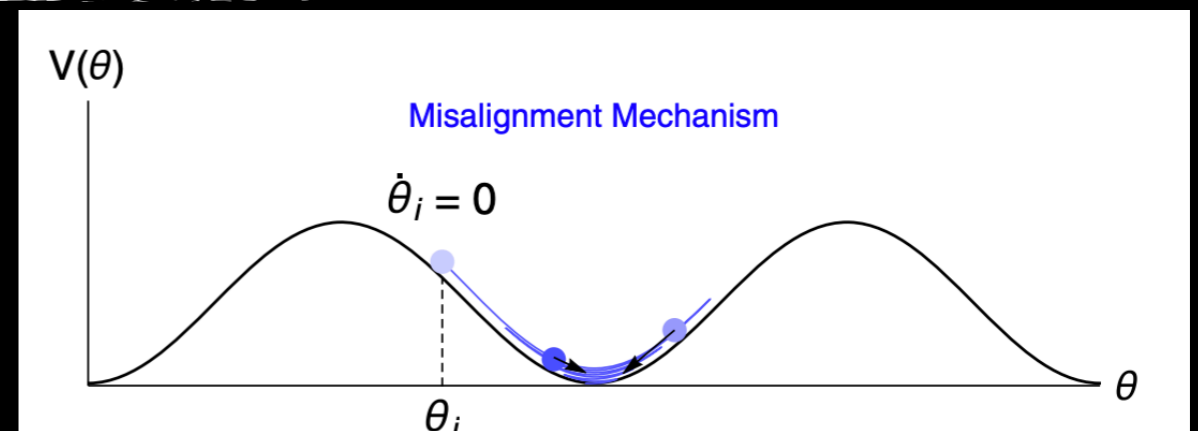
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[V. Iršič et al, arXiv: 1702.01764]

Mixed dark matter



[T. Kobayashi et al, arXiv: 1708.00015]

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

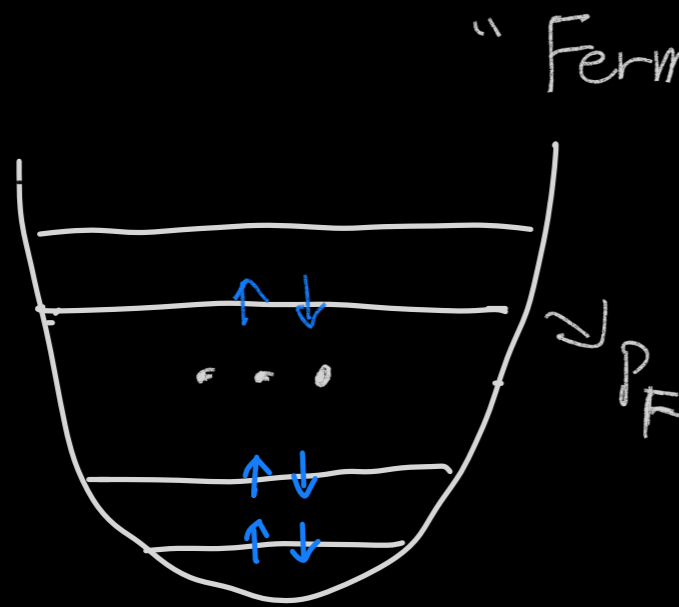
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Consider the particle nature of DM:

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

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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

Degenerate Fermionic Dark Matter in the Early Universe

- thermally cold: kinetic energy from purely degenerate pressure
- fixed co-moving number, after the beginning of BBN

Degenerate Fermionic Dark Matter in the Early Universe

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- fixed co-moving number, after the beginning of BBN

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

$$\text{WDM} : \mu \ll T,$$

$$\text{DF} : \mu = p_F \gg T$$

$$f(q) = \theta(p_F - q)$$

non-relativistic
at present time

$$\rho = \frac{3\zeta(3)g_\psi m_\psi T^3}{4\pi^2}$$

$$\rho = \frac{g_\psi m_\psi p_F^3}{6\pi^2}$$

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

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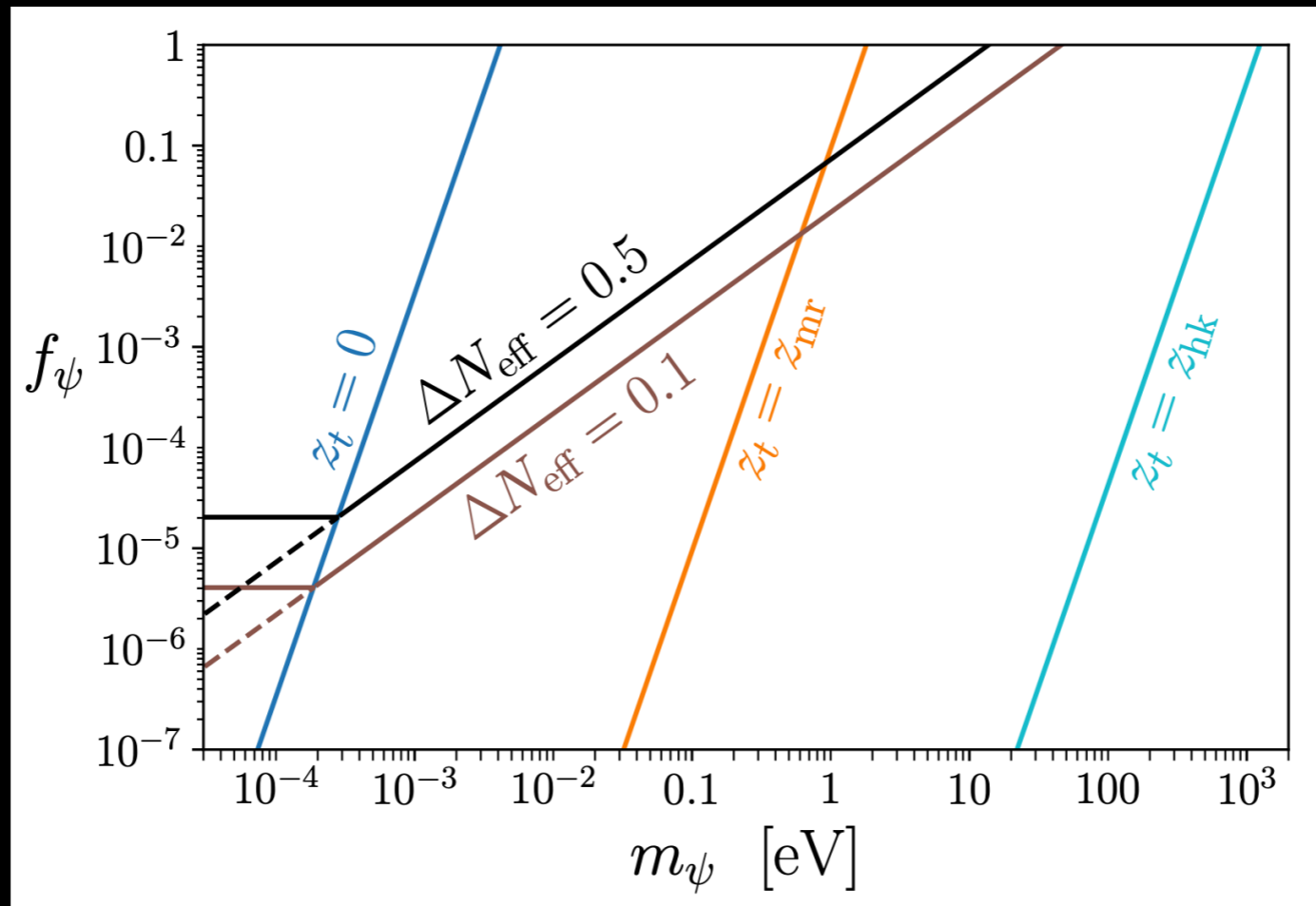
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the minimal mass allowed for fermionic dark matter!

Degenerate Fermionic Dark Matter in the Early Universe

- 2 internal degrees of freedom, 1 flavor $g_\psi = 2, N_f = 1$

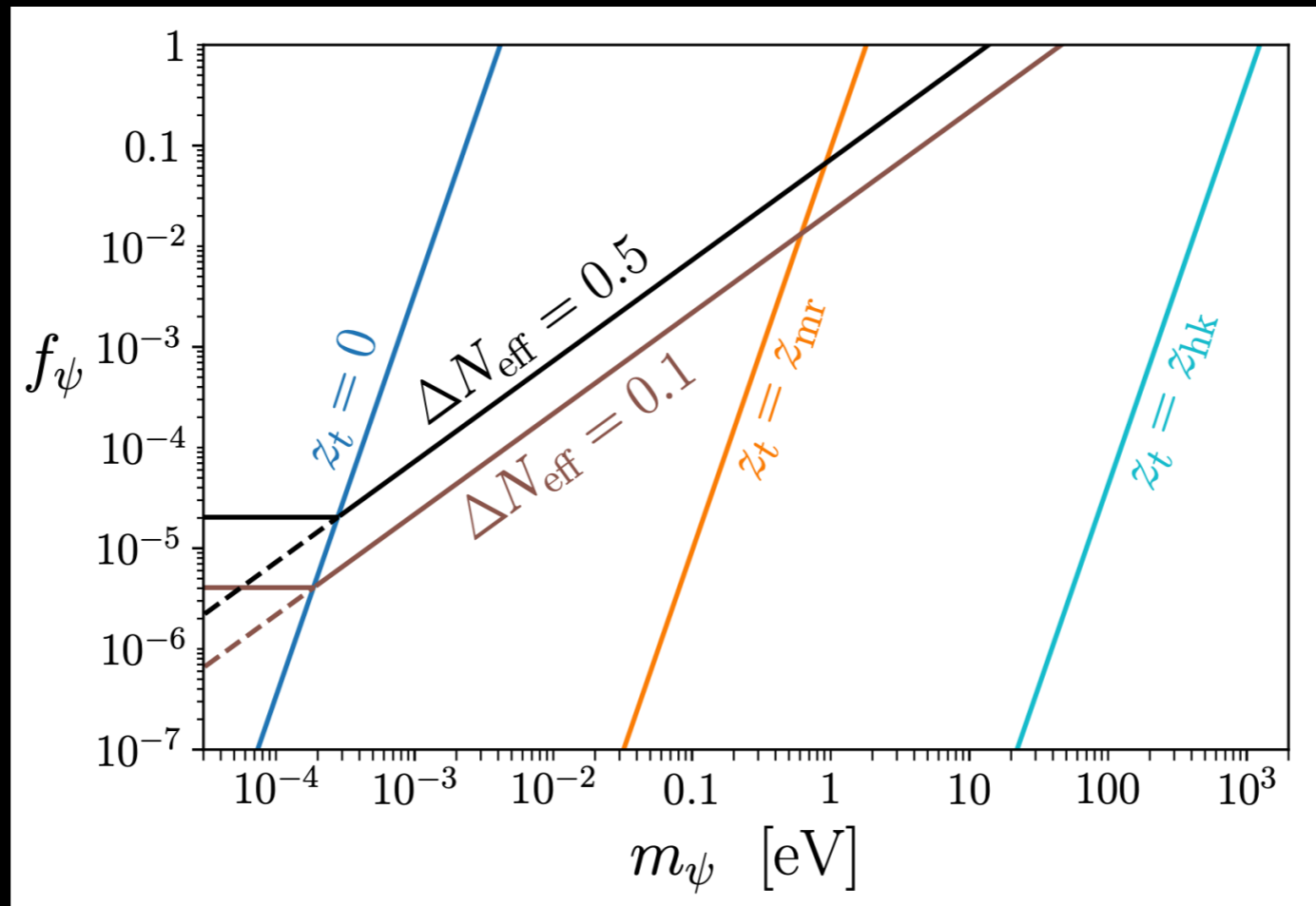


$$z_{\text{mr}} = 3300$$

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

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$$z_{\text{mr}} = 3300$$

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DF contribution to ΔN_{eff} would be smaller by the factor

$$\frac{1 + z_t^{\text{WDM}}}{1 + z_t^{\text{DF}}}$$

Big Bang Nucleosynthesis (BBN)

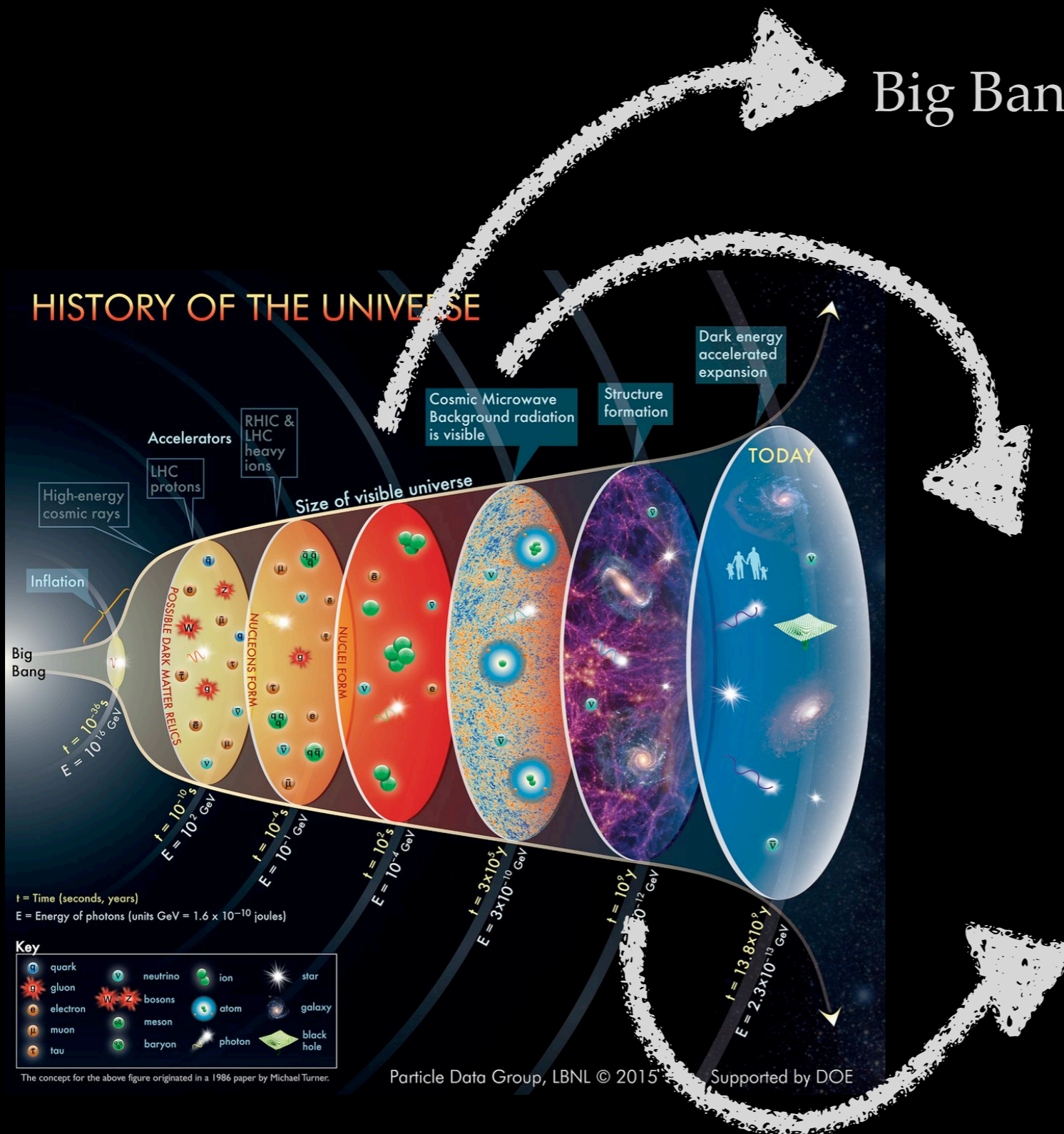
ΔN_{eff}

Cosmic Microwave Background (CMB)

ΔN_{eff}

Structure Formation
disappearance of matter

HISTORY OF THE UNIVERSE



Big Bang Nucleosynthesis (BBN)

$$N_{\text{eff}} \quad , \quad H$$

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

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

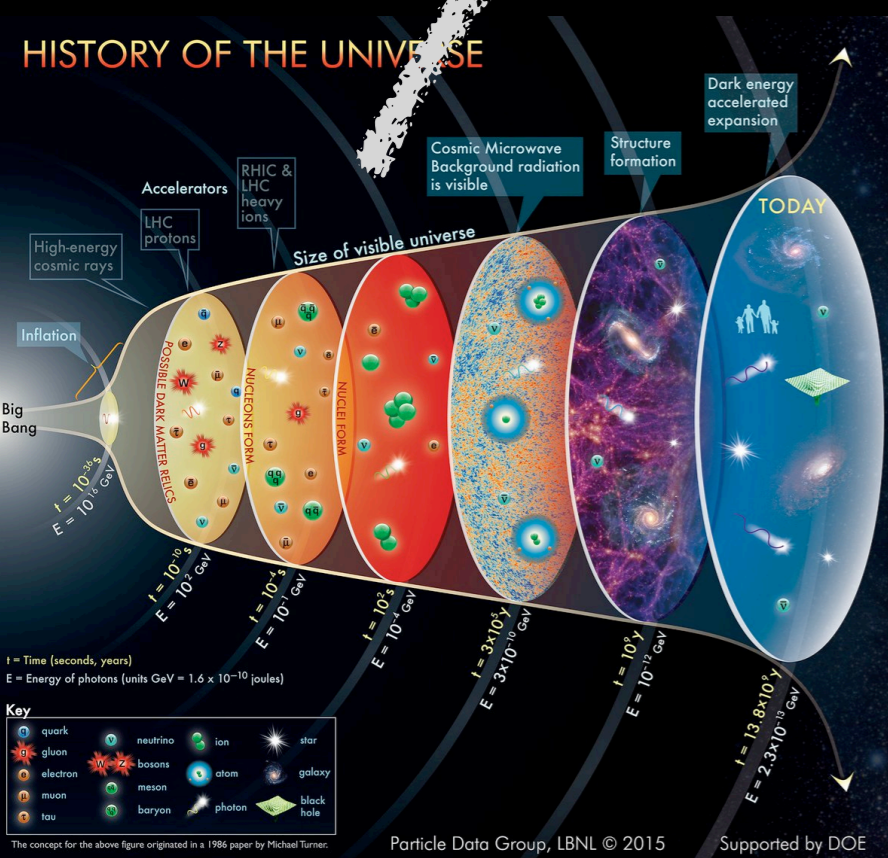
current bound:

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

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

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



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



Based on arXiv: 2108.02785

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N_{eff} , H 

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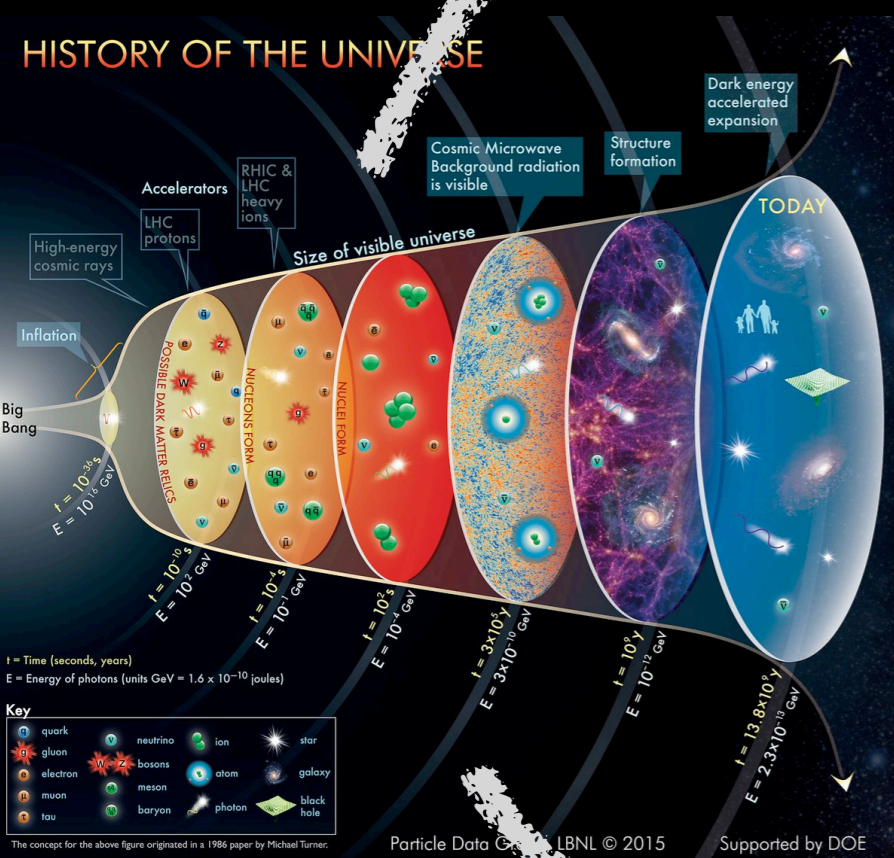
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Cosmic Microwave Background (CMB)

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

current bound:



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

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

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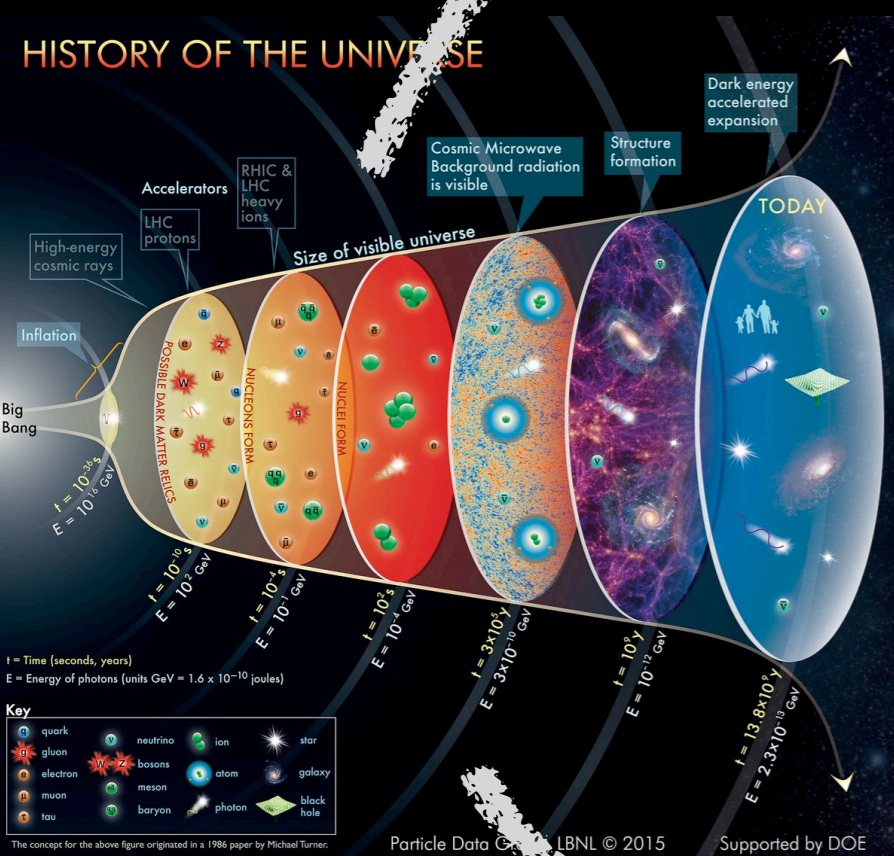
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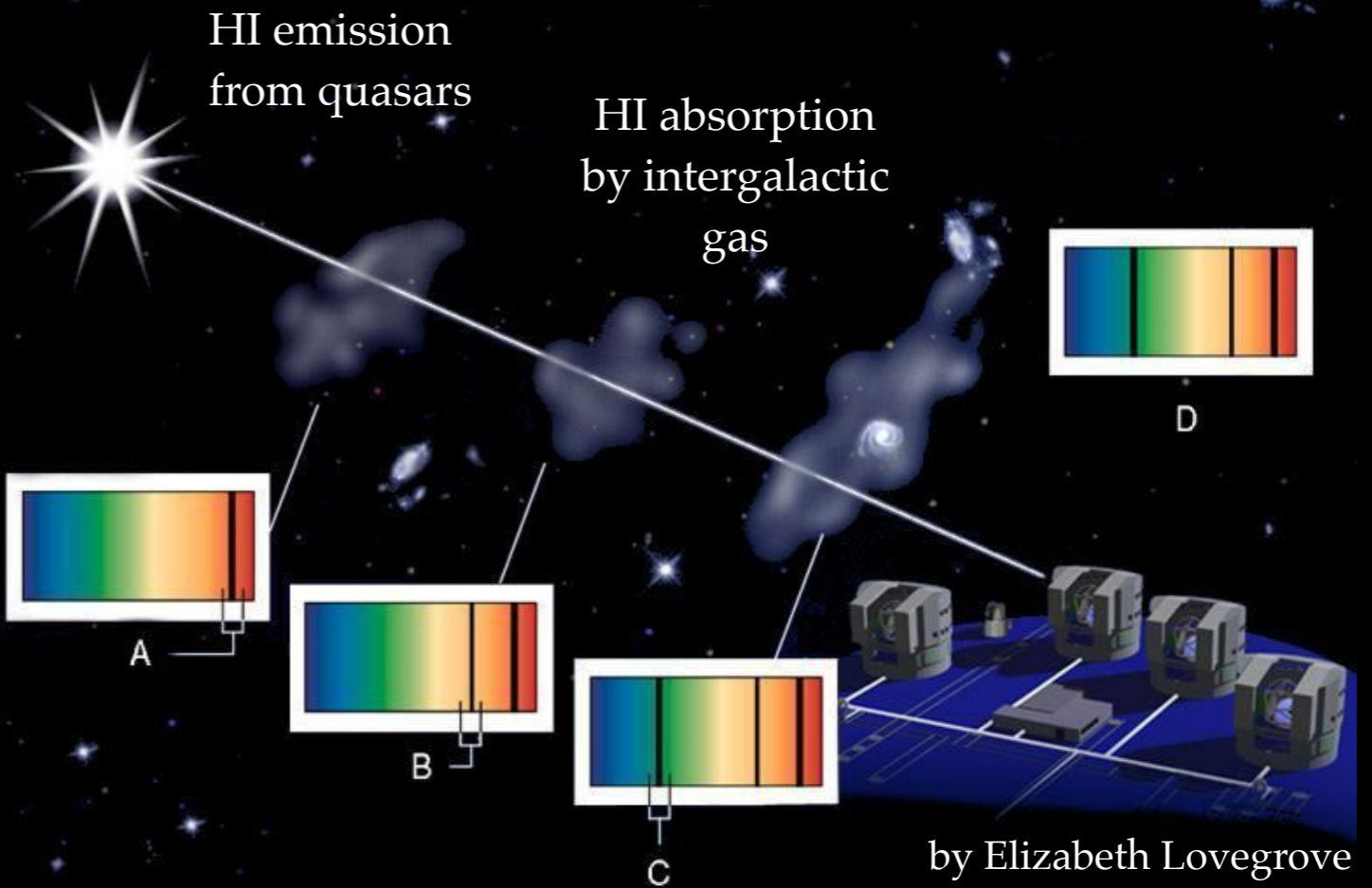
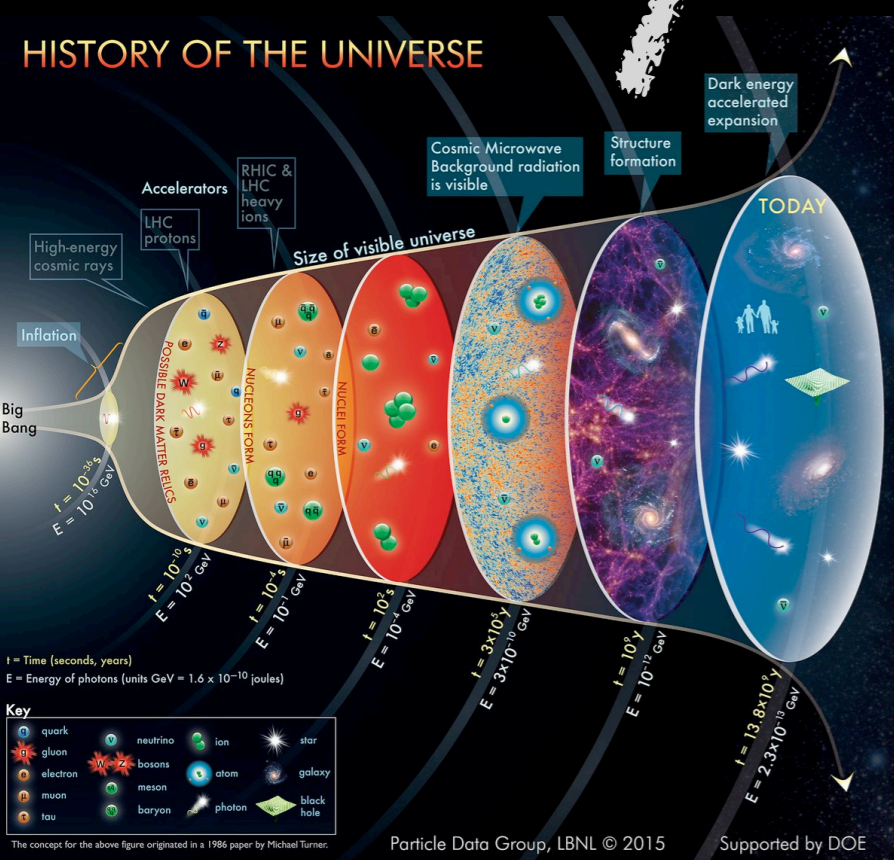
Multi-parameter extensions of LCDM, $\Delta N_{\text{eff}} < 0.5$

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

Based on arXiv: 2108.02785

Structure Formation: Ly - α forest, MW satellite suppression of gravitational clustering

Ly - α forest



Measurement of matter distributions at intergalactic scales

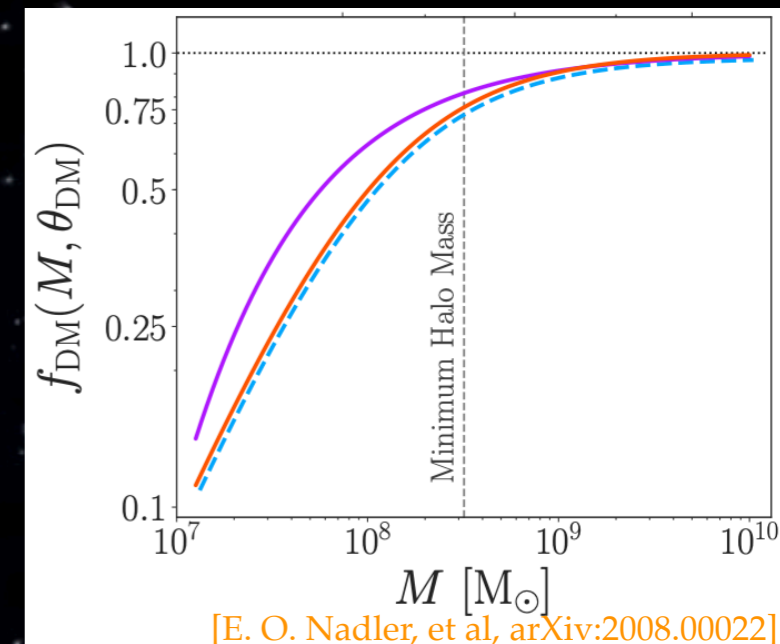
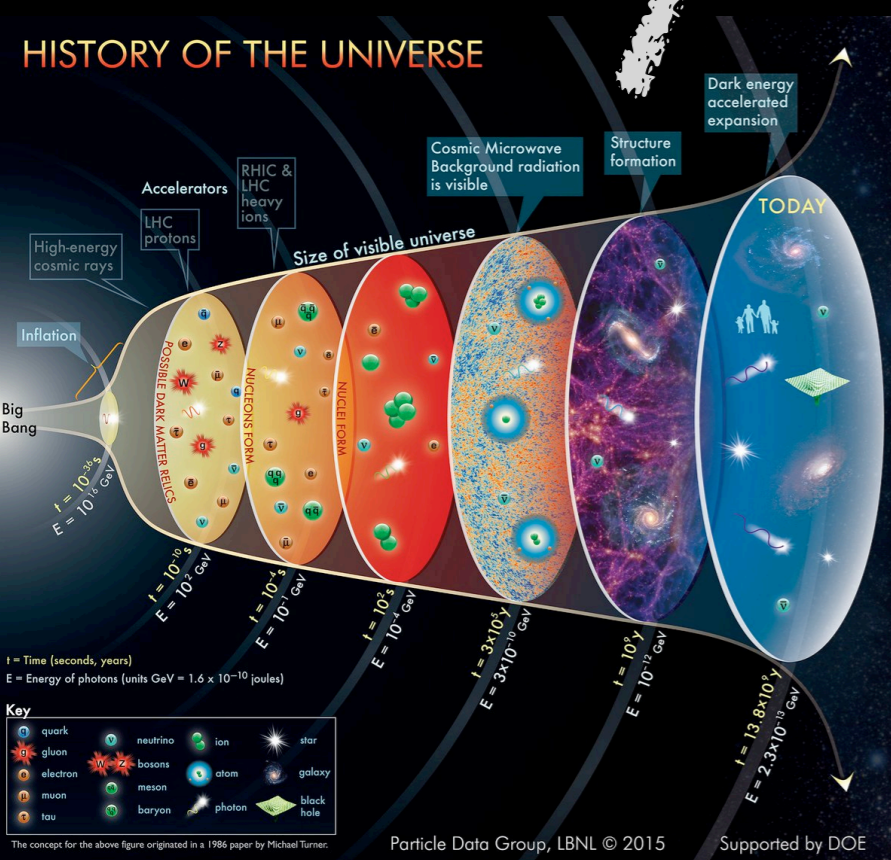
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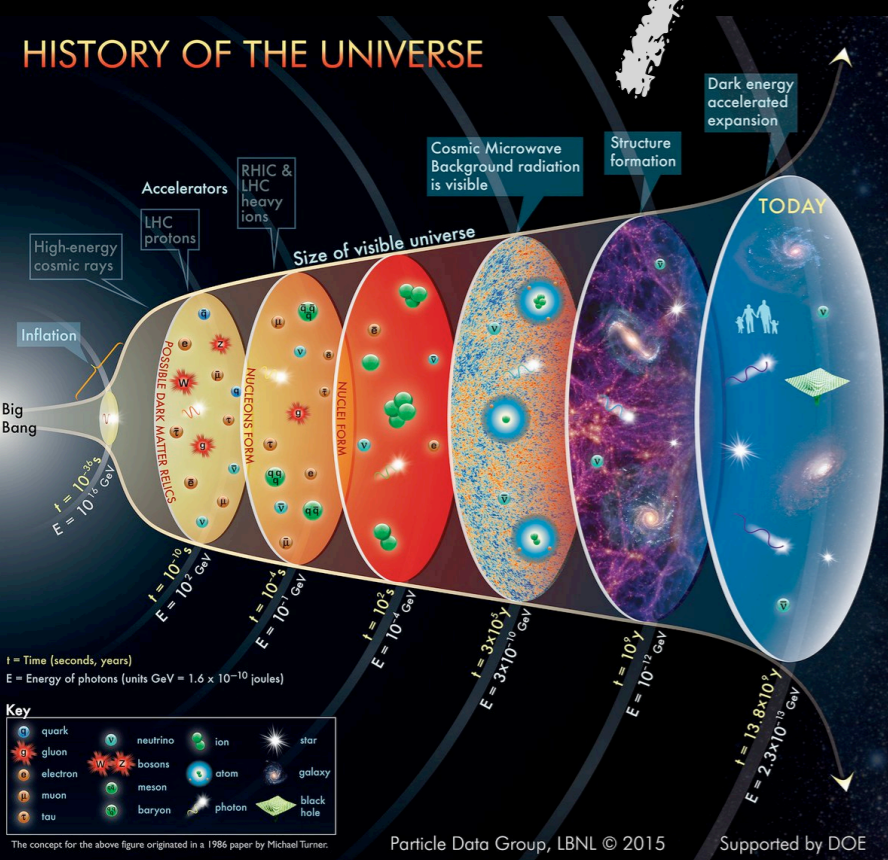
MW satellite subhalo mass function (SHMF)

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

Dark matter distribution
600kpc



Structure Formation: Ly – α forest, MW satellite suppression of gravitational clustering



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

Ly – α : $T^2(k < 20h/\text{Mpc}) \geq 0.7$

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

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

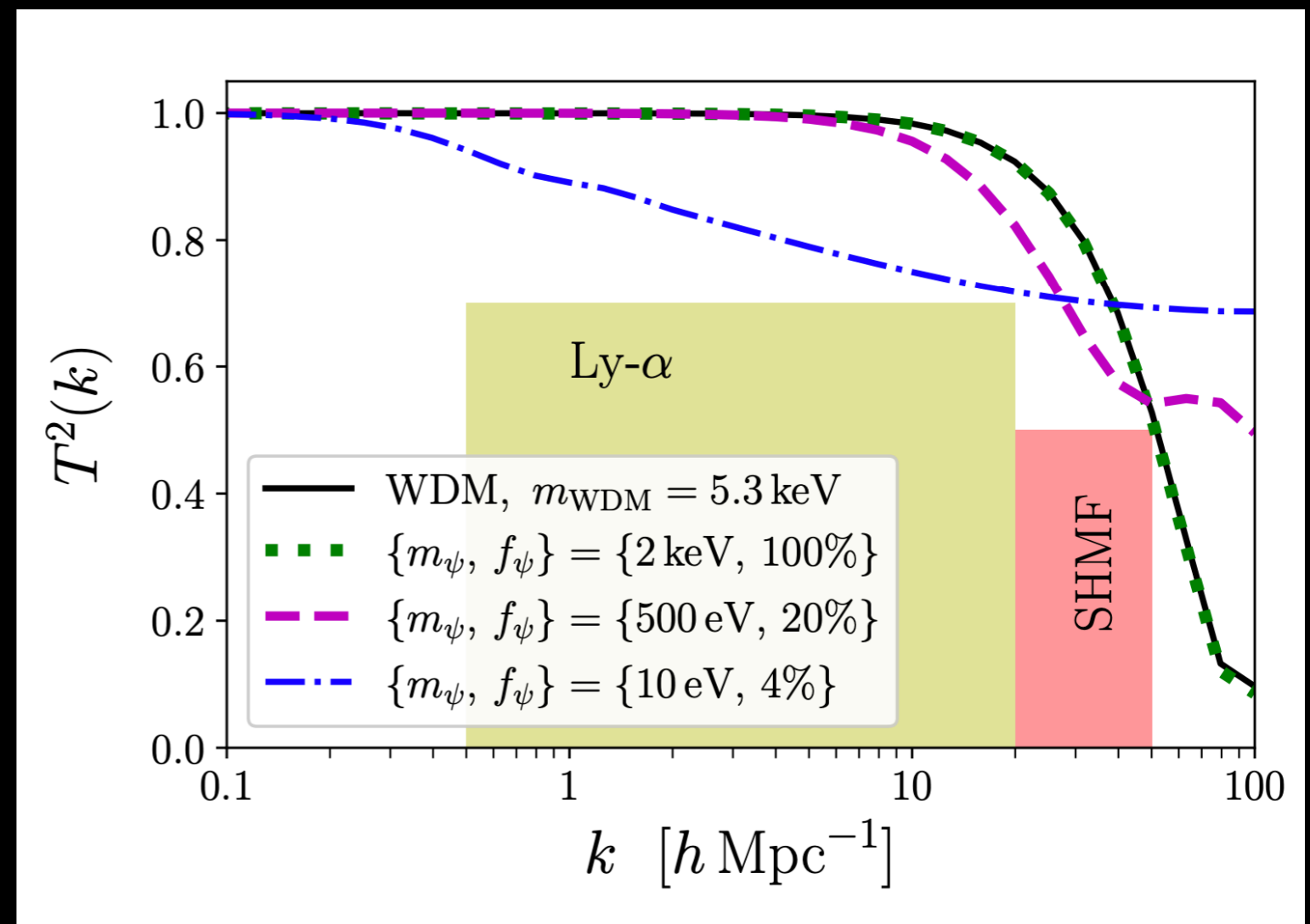
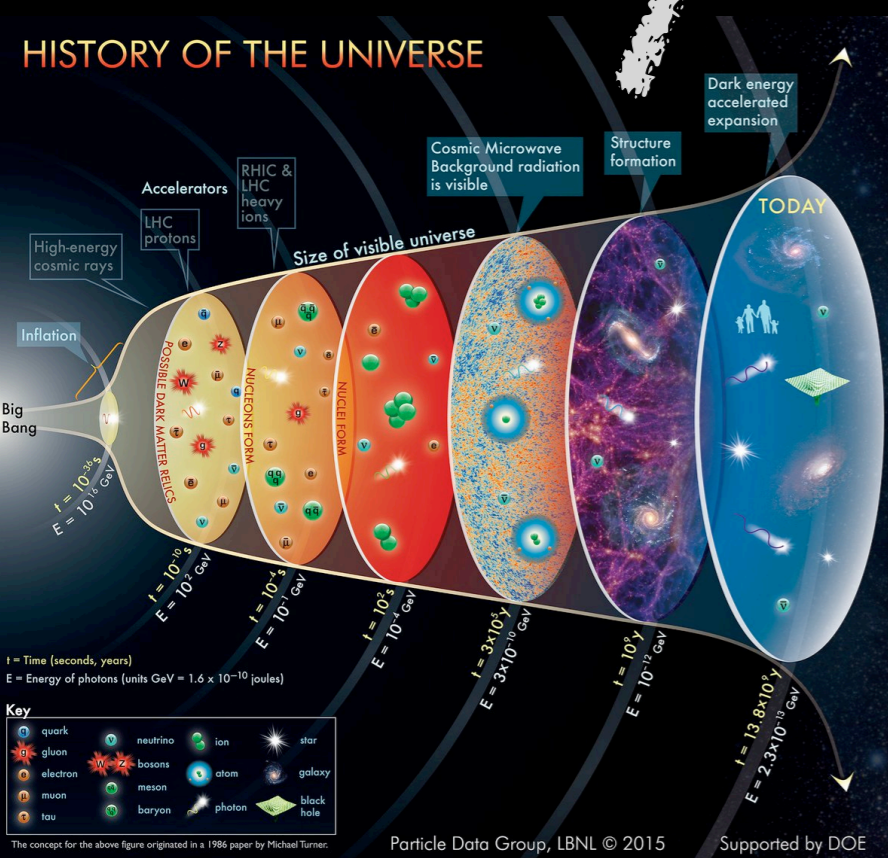
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Structure Formation: Ly - α forest, MW satellite suppression of gravitational clustering

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



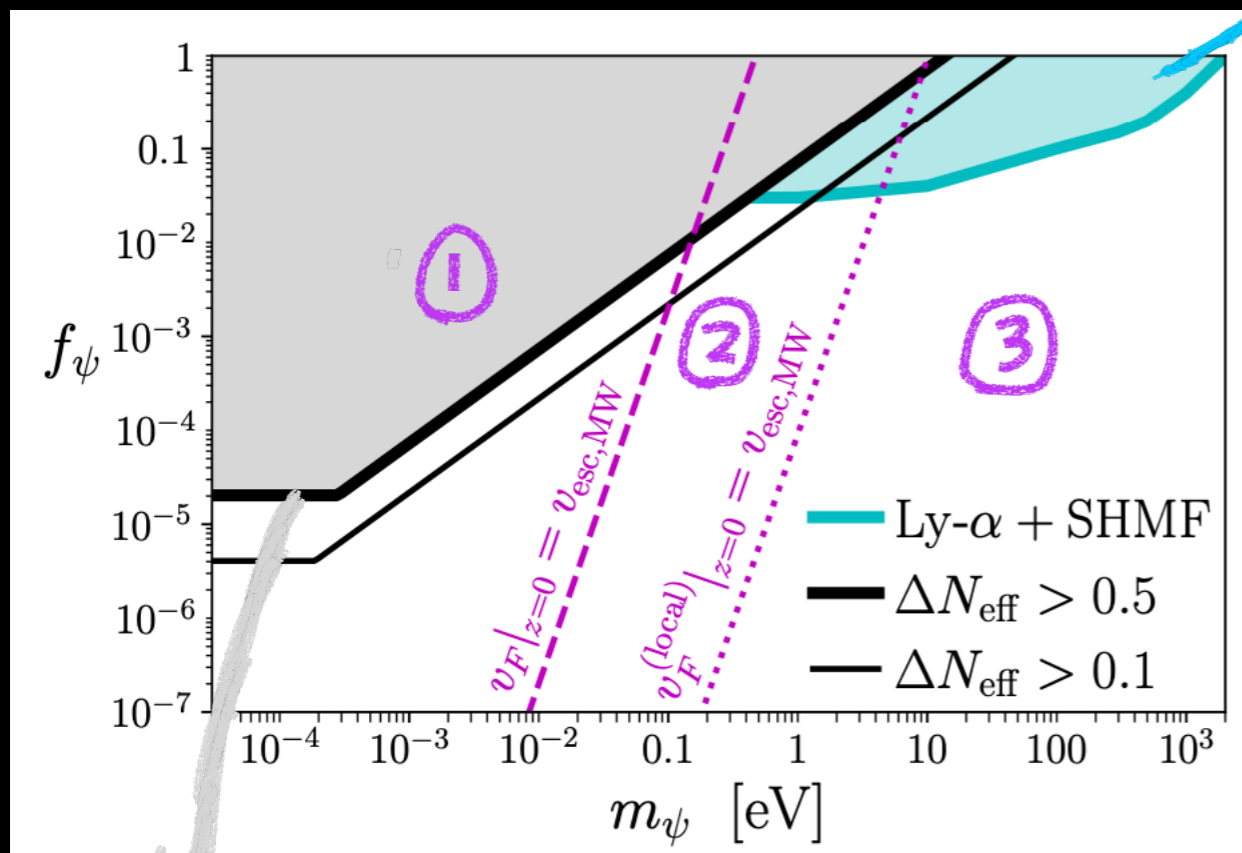
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extended to $f_\psi \sim 3\%$, $m_\psi \leq 1\text{eV}$

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

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



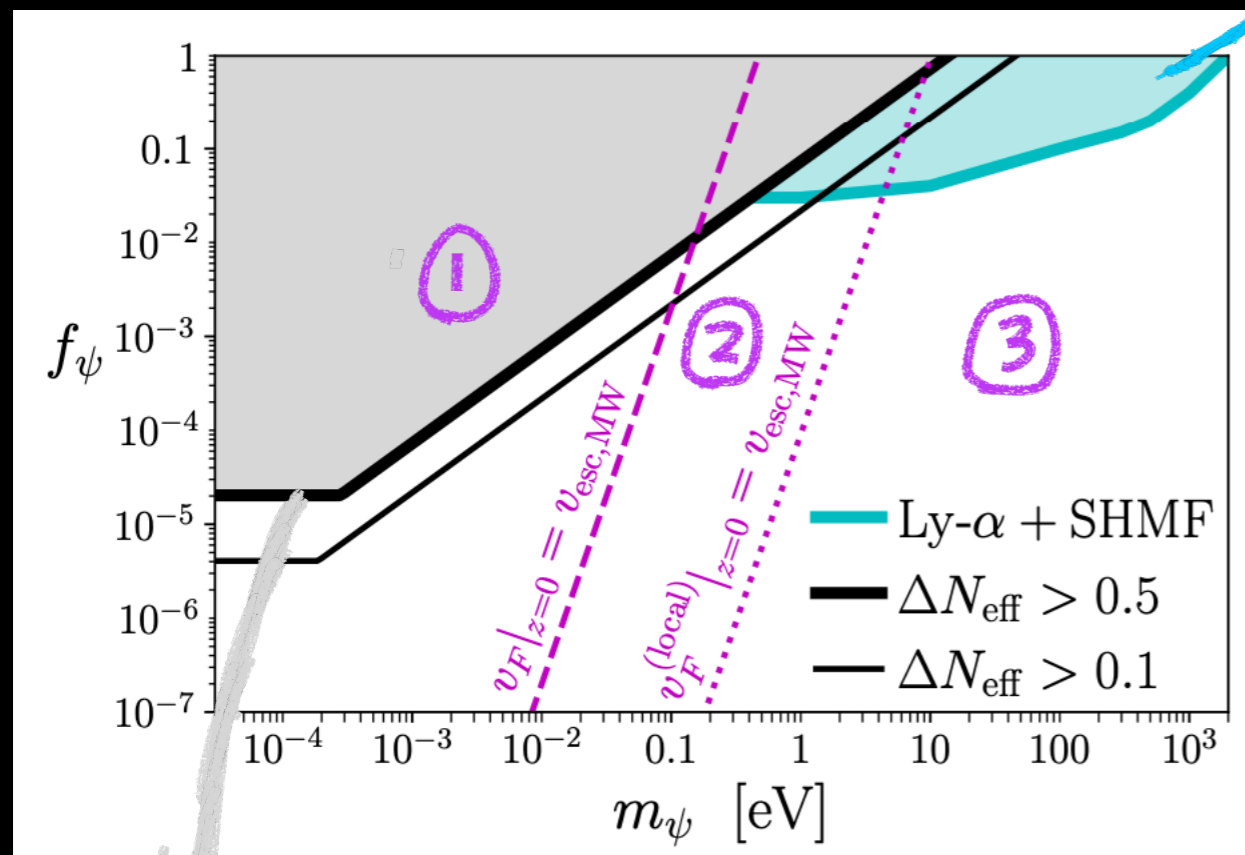
opens up parameter space for
model Building!

constrain f_ψ as small as 2×10^{-5} !

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Local Implications

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

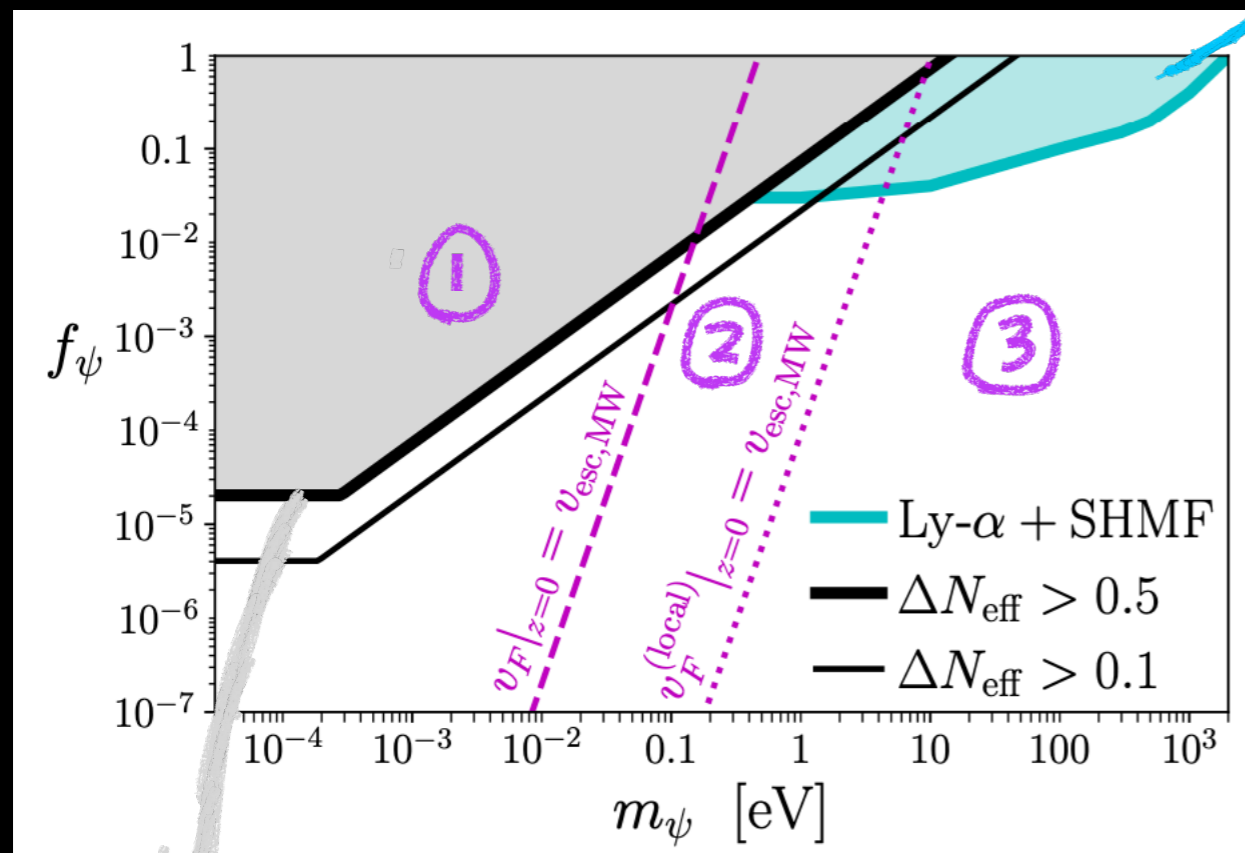
[L. Randall, et al, arXiv:1611.4590]

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

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

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

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



- Modifying MW DM phase space density

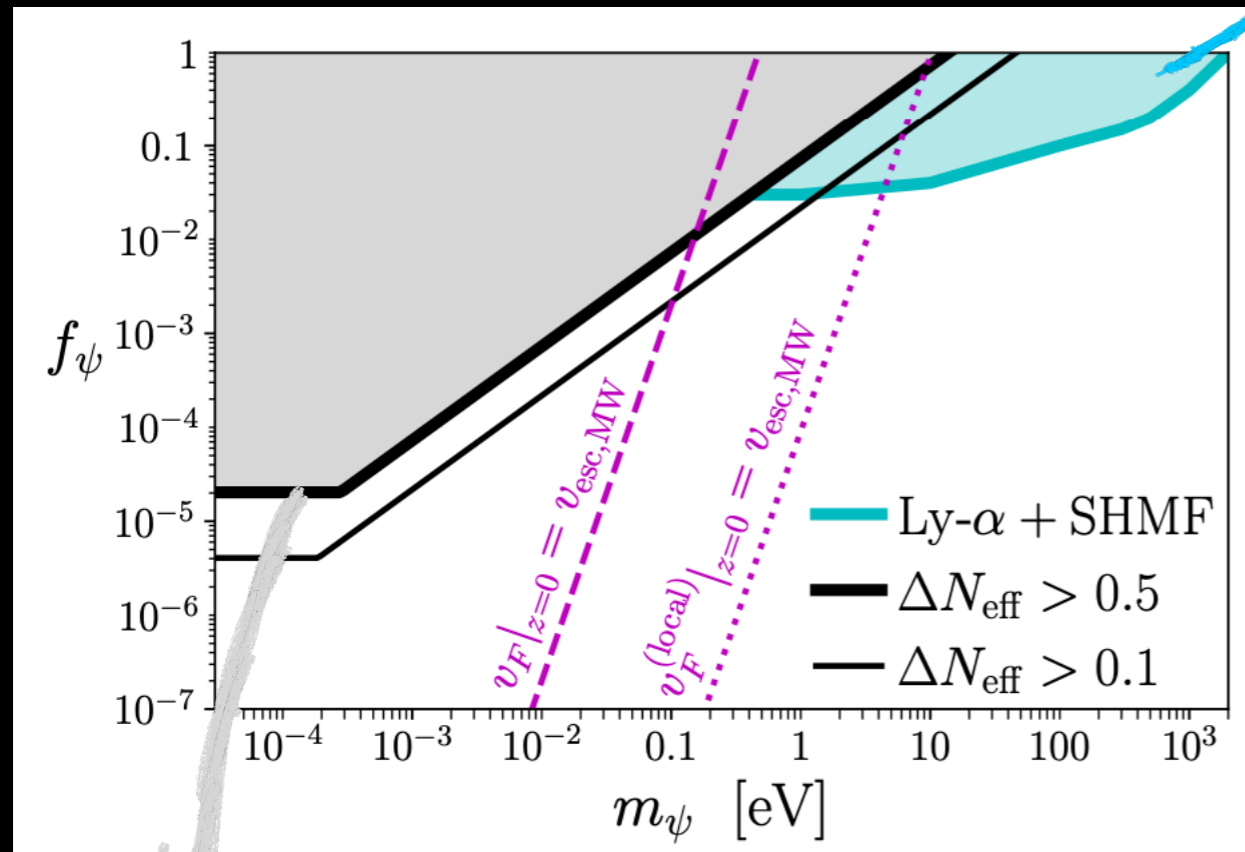
- ① Not accumulating
- ② Smaller over density than CDM, or higher velocity, e.g. probed by novel material
- ③ Similar phase space distribution to that of CDM

constrain f_ψ as small as 2×10^{-5} !

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constrain f_ψ as small as 2×10^{-5} !

Bound rescaling, as changing N_f

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

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

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

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

Conclusions and Outlook

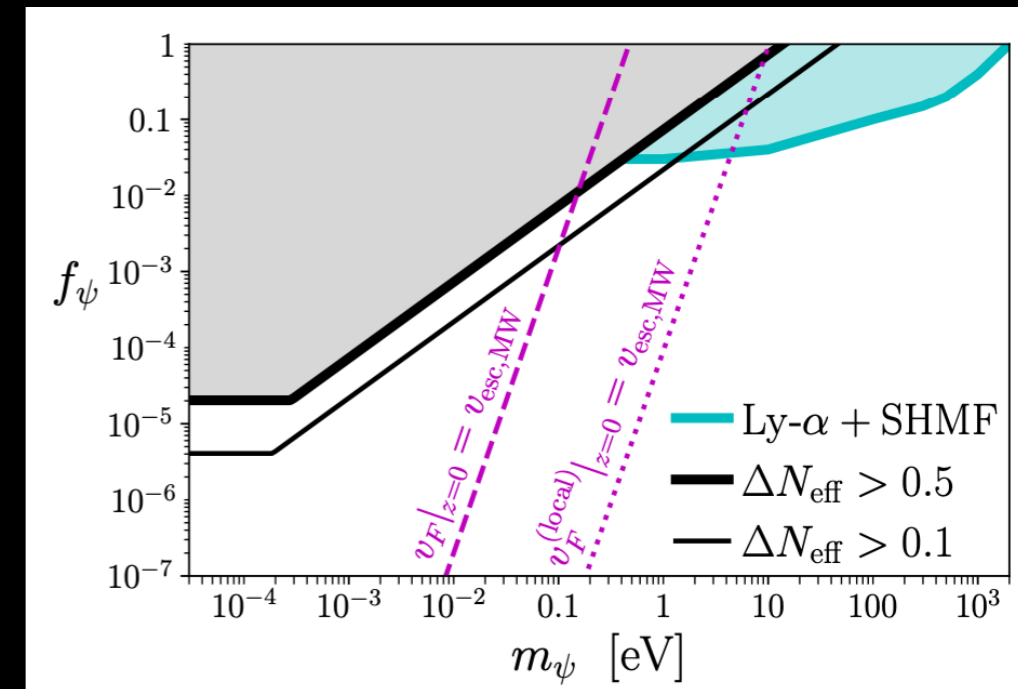
minimal kinetic energy in the early universe

—Degenerate Fermion State:

minimal mass allowed for
fermionic dark matter $\sim 2\text{keV}$

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

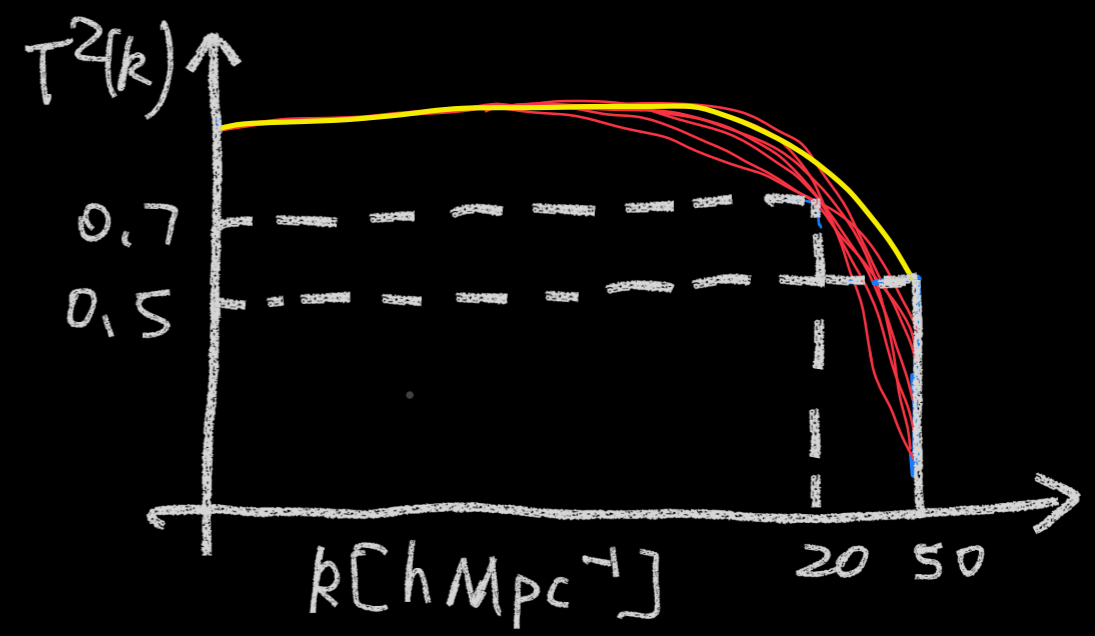
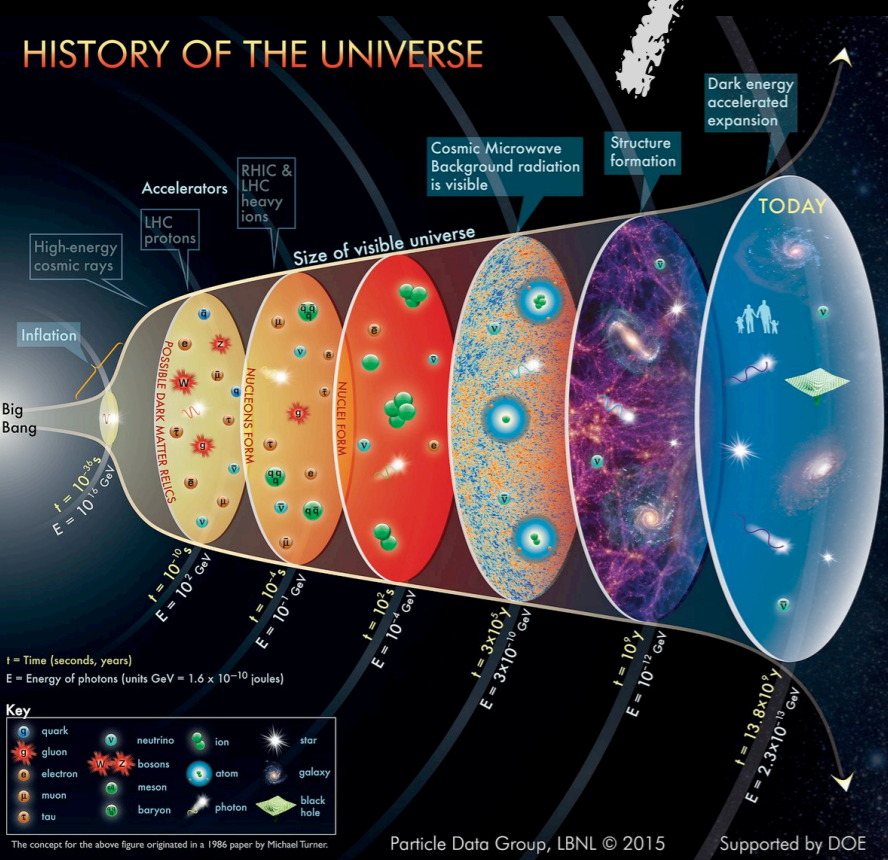
Thank you

Structure Formation: Ly - α forest, MW satellite suppression of gravitational clustering

linear matter power, normalized to that of CDM
the transfer function

$$T^2(k) = \frac{P_{\text{nCDM}}(k)}{P_{\text{CDM}}(k)}$$

the abundance of sub halos within the
viral radius of the Milky Way
subhalo mass function (SHMF)



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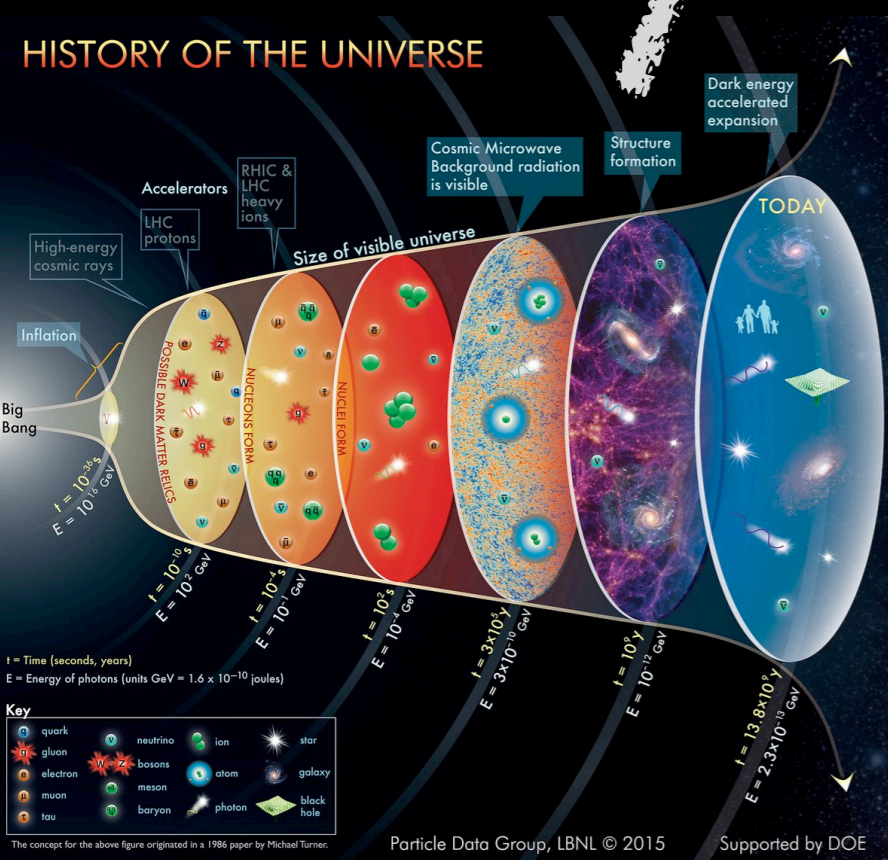
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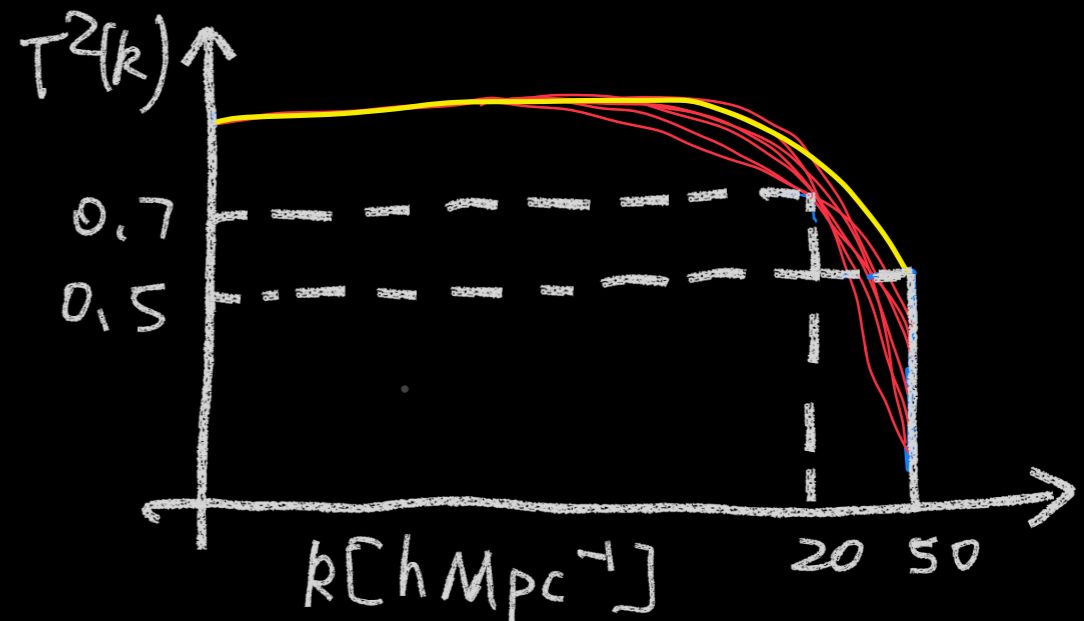
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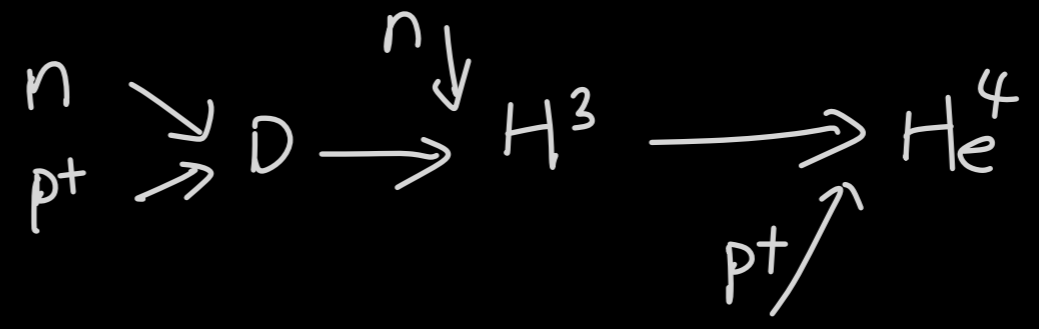
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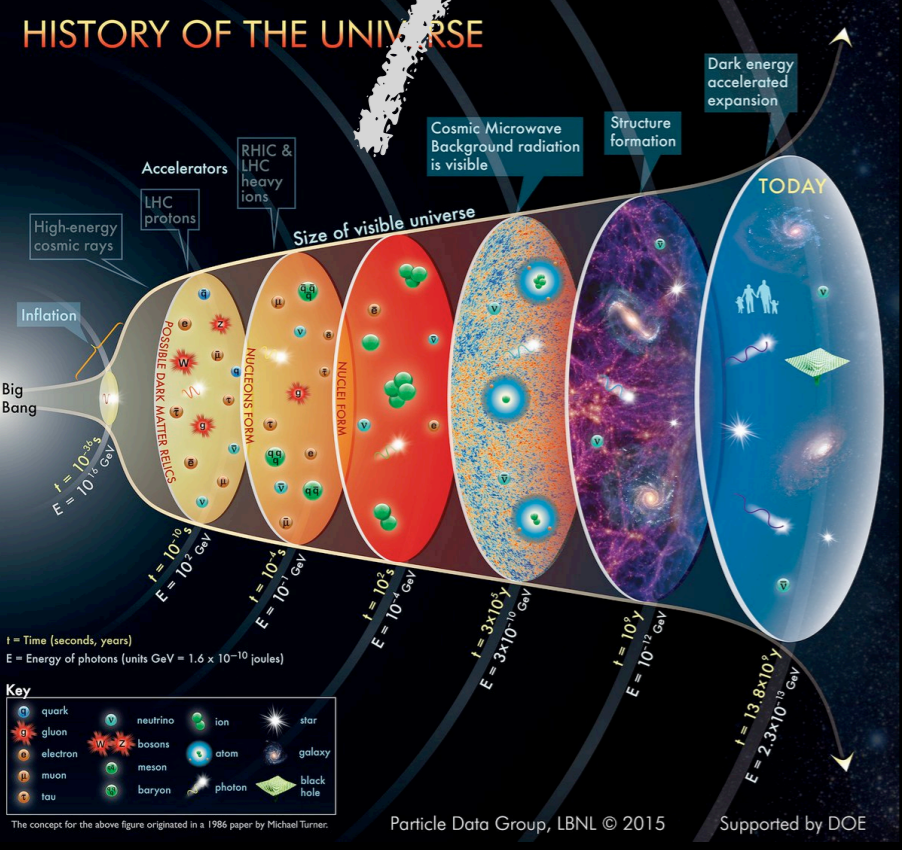


$$n_{He^4} = \frac{1}{2} n_n(t_{nuc})$$

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

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

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



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

current bound: $DN_{eff} < 0.12$, one parameter fit

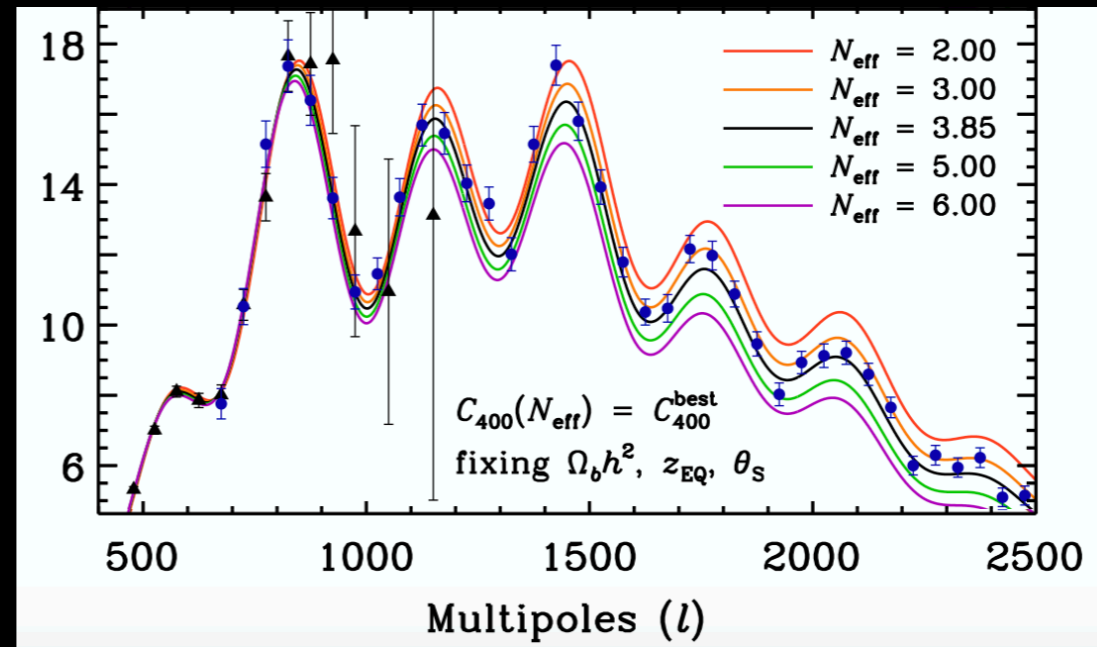
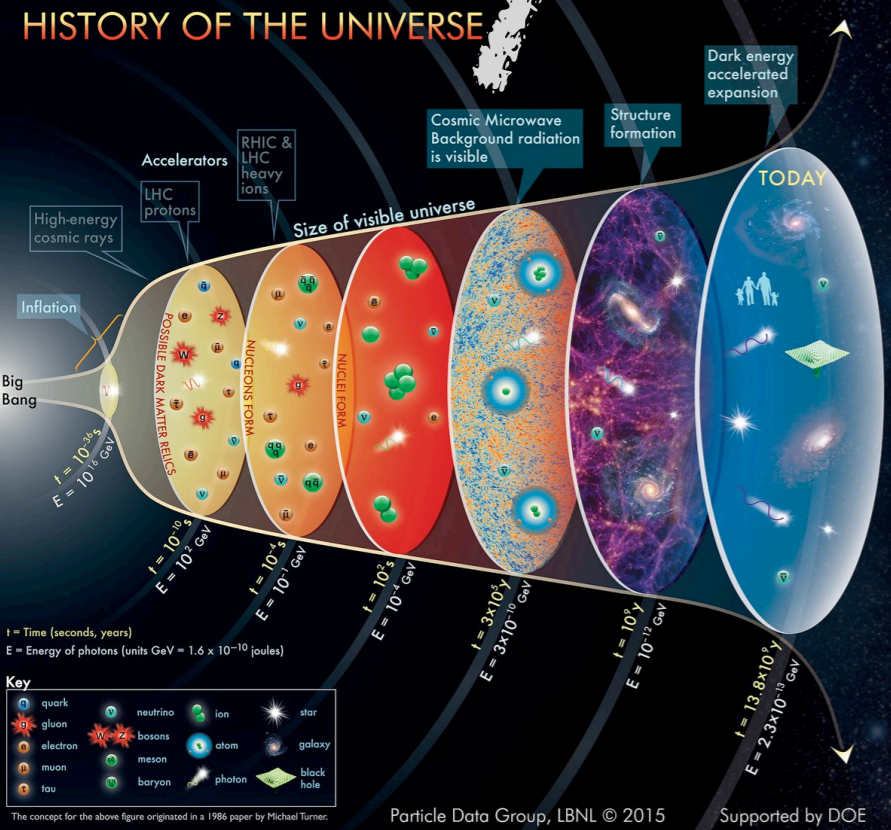
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[V. Mossa, et al, Nature 587, 210 (2020)]

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Cosmic Microwave Background (CMB)



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

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

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

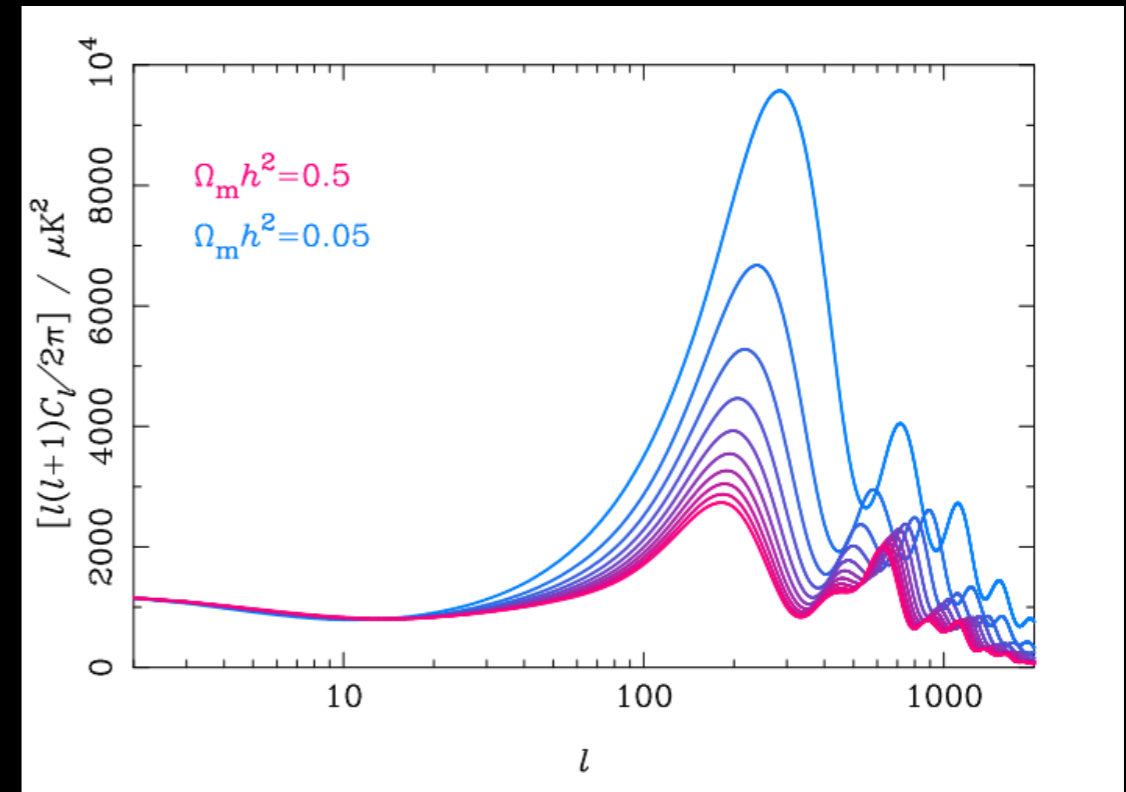
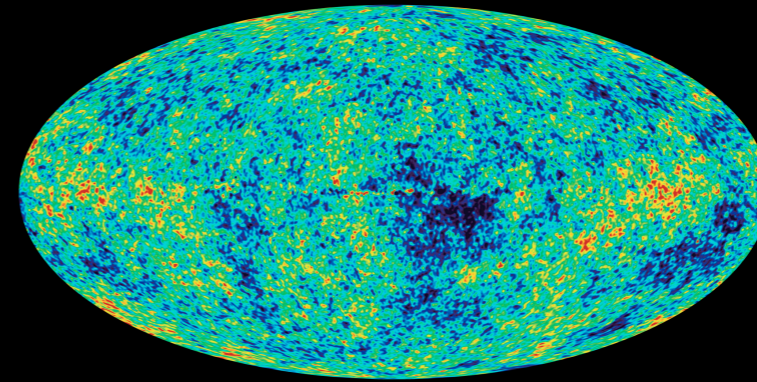
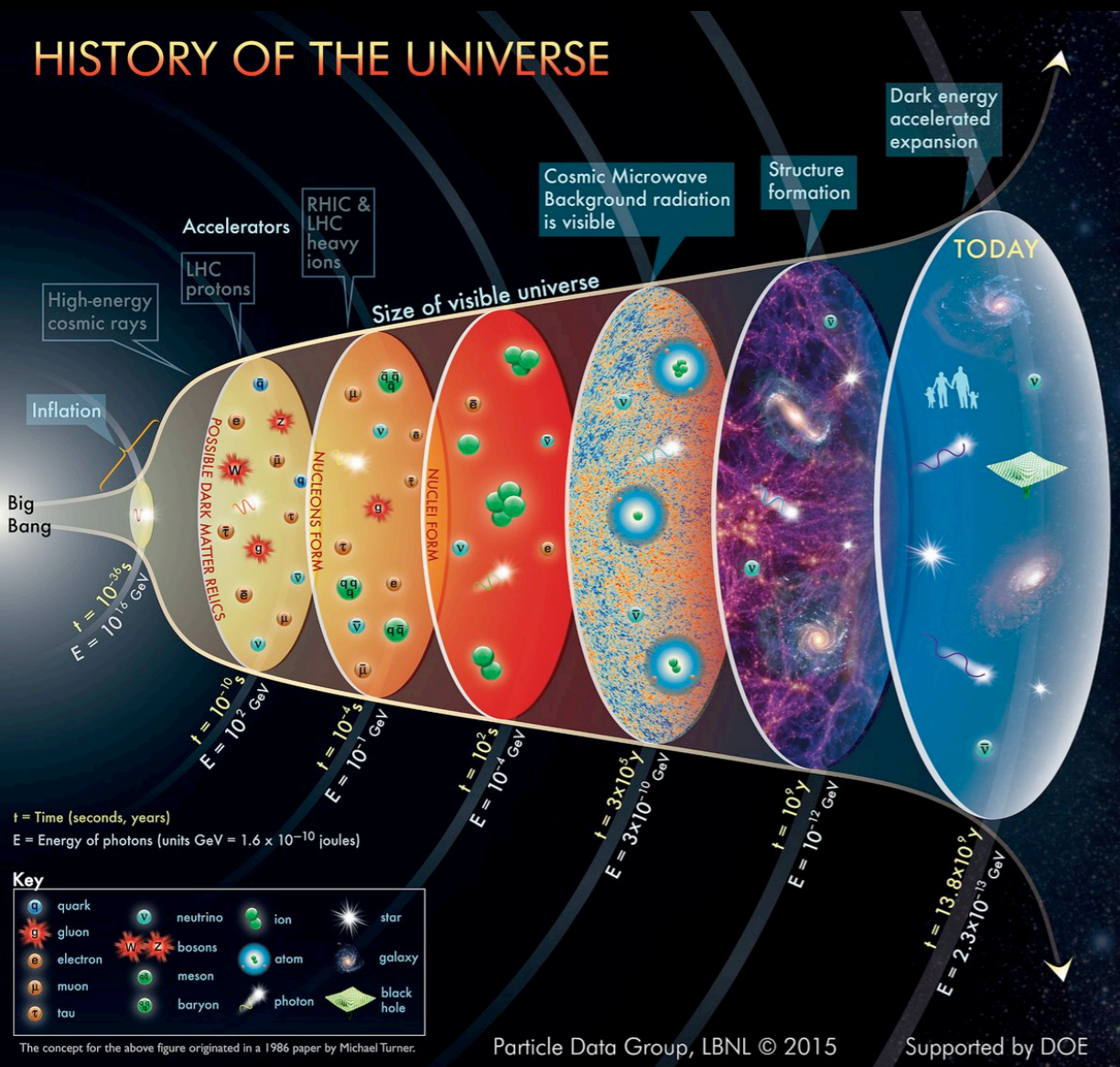
fixing other parameters

$N_{\text{eff}} \uparrow, H \uparrow, f \downarrow$

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Cosmic Microwave Background (CMB)



[A. Challinor, astro-ph.0403344]

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!

Assumptions

- Has a fixed comoving number, in particular after the beginning of the Big-Bang Nucleosynthesis;
- Doesn't form bound states in high density environments