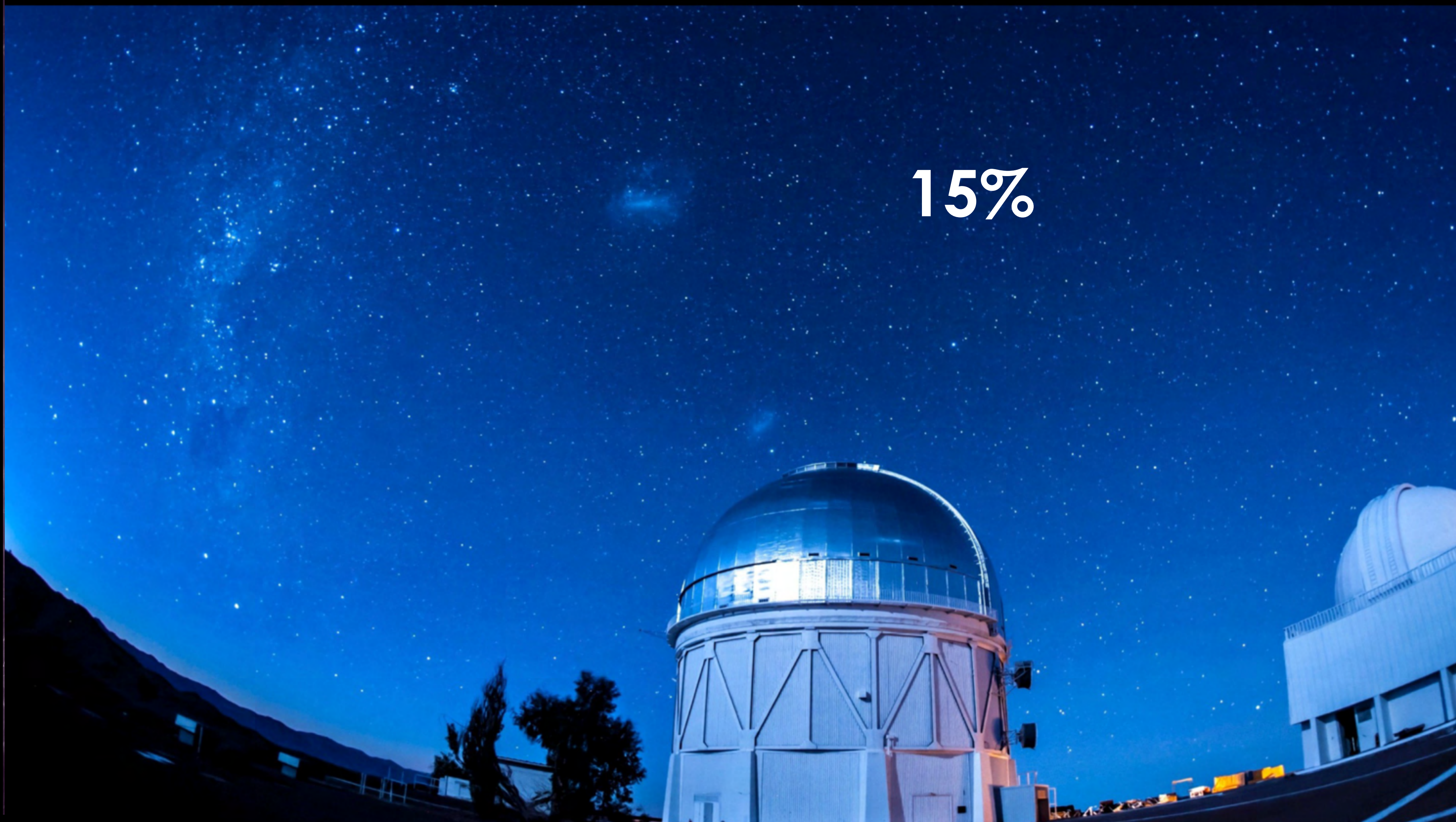
Dark matter cosmology

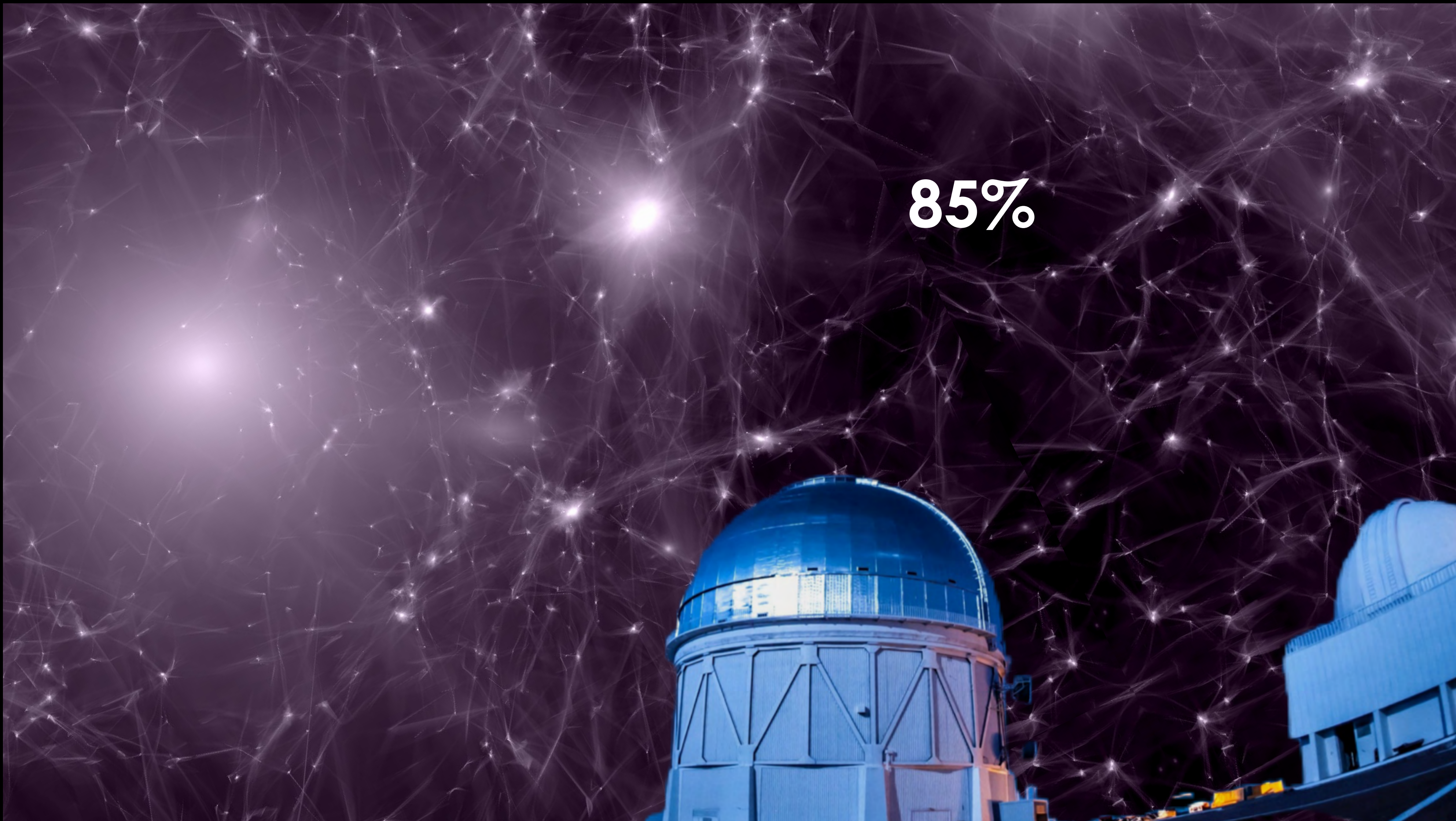
from the early Universe to the Milky Way

Vera Gluscevic

University of Southern California



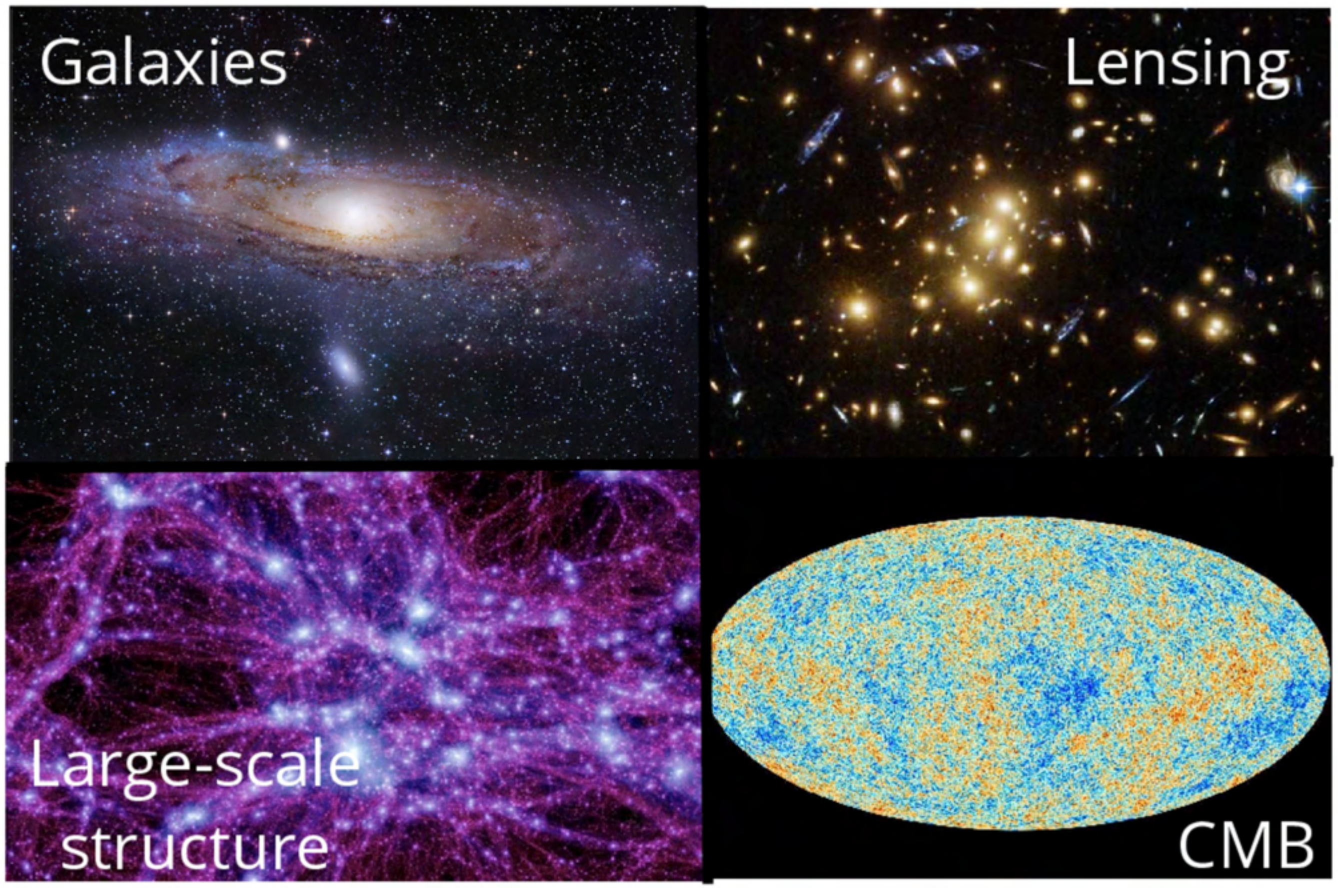
Slide by E. Nadler



Slide by E. Nadler

Lots of evidence points to a **consistent picture**:

there is ~**6x more gravity** in the Universe than visible matter.



CMB and dark matter

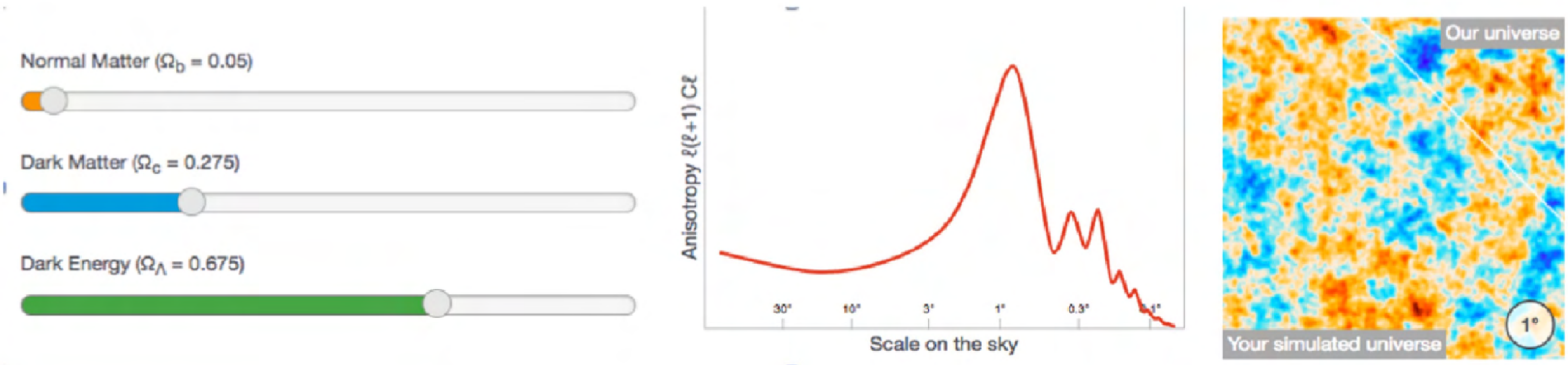
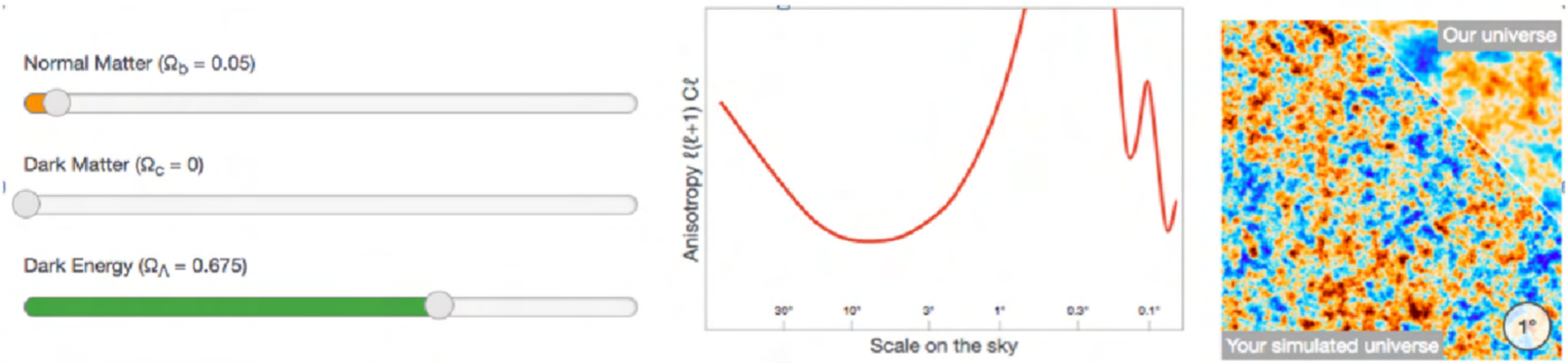


Image credits: Amanda Yoho, Planck

CMB and dark matter



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CMB and dark matter

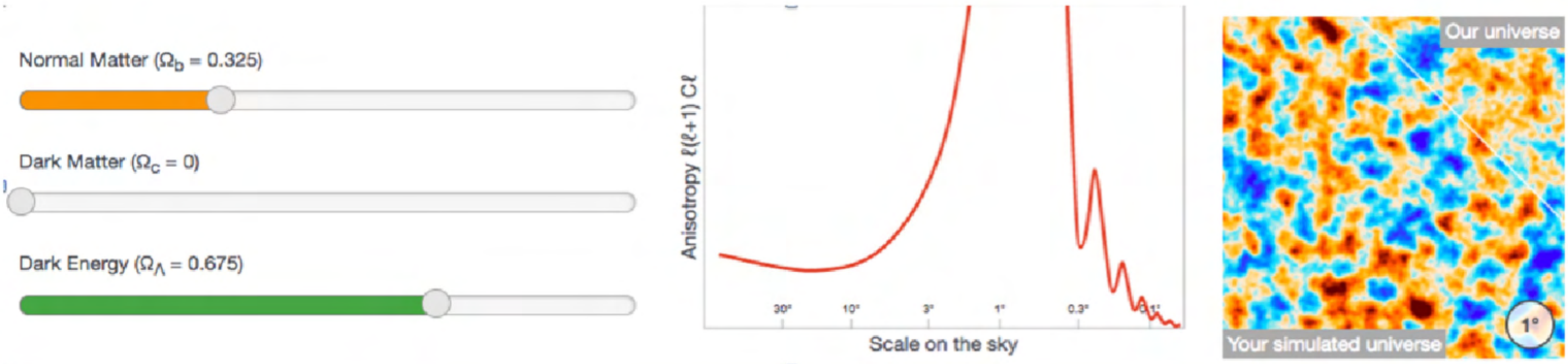


Image credits: Amanda Yoho, Planck

Direct detection – status of nuclear recoil searches

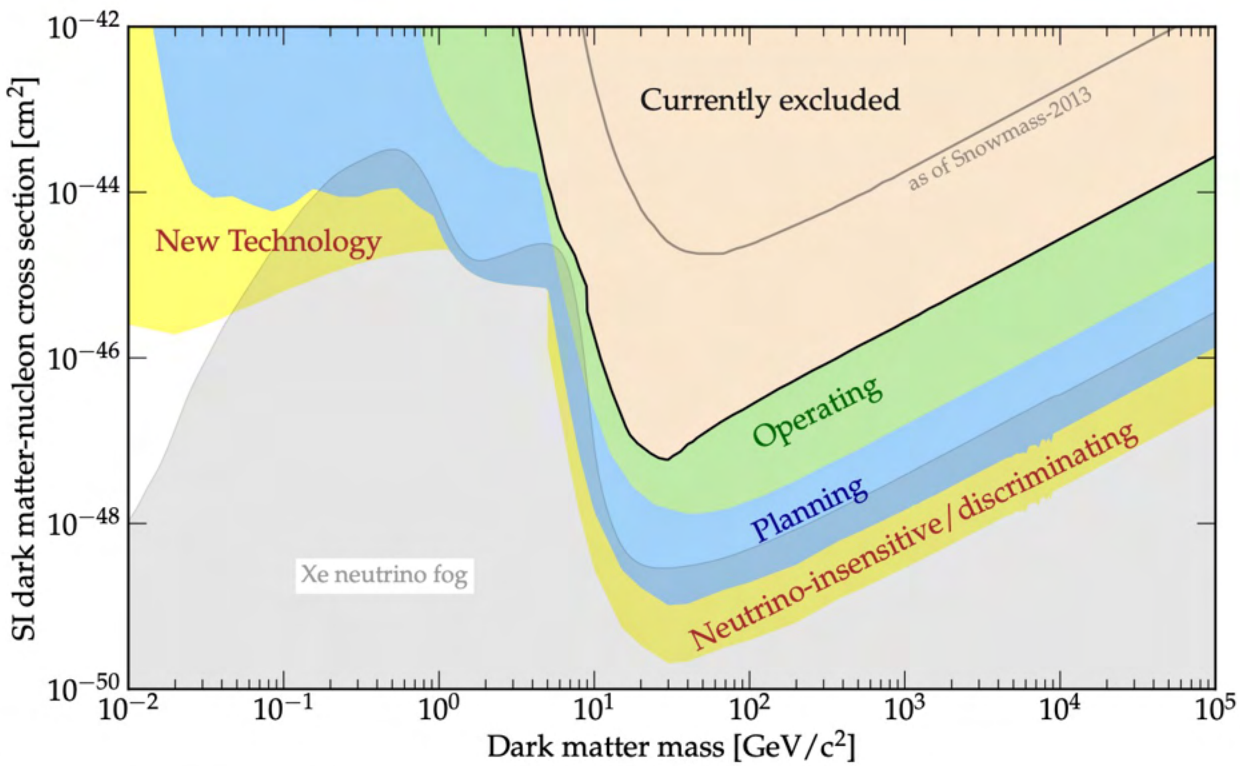
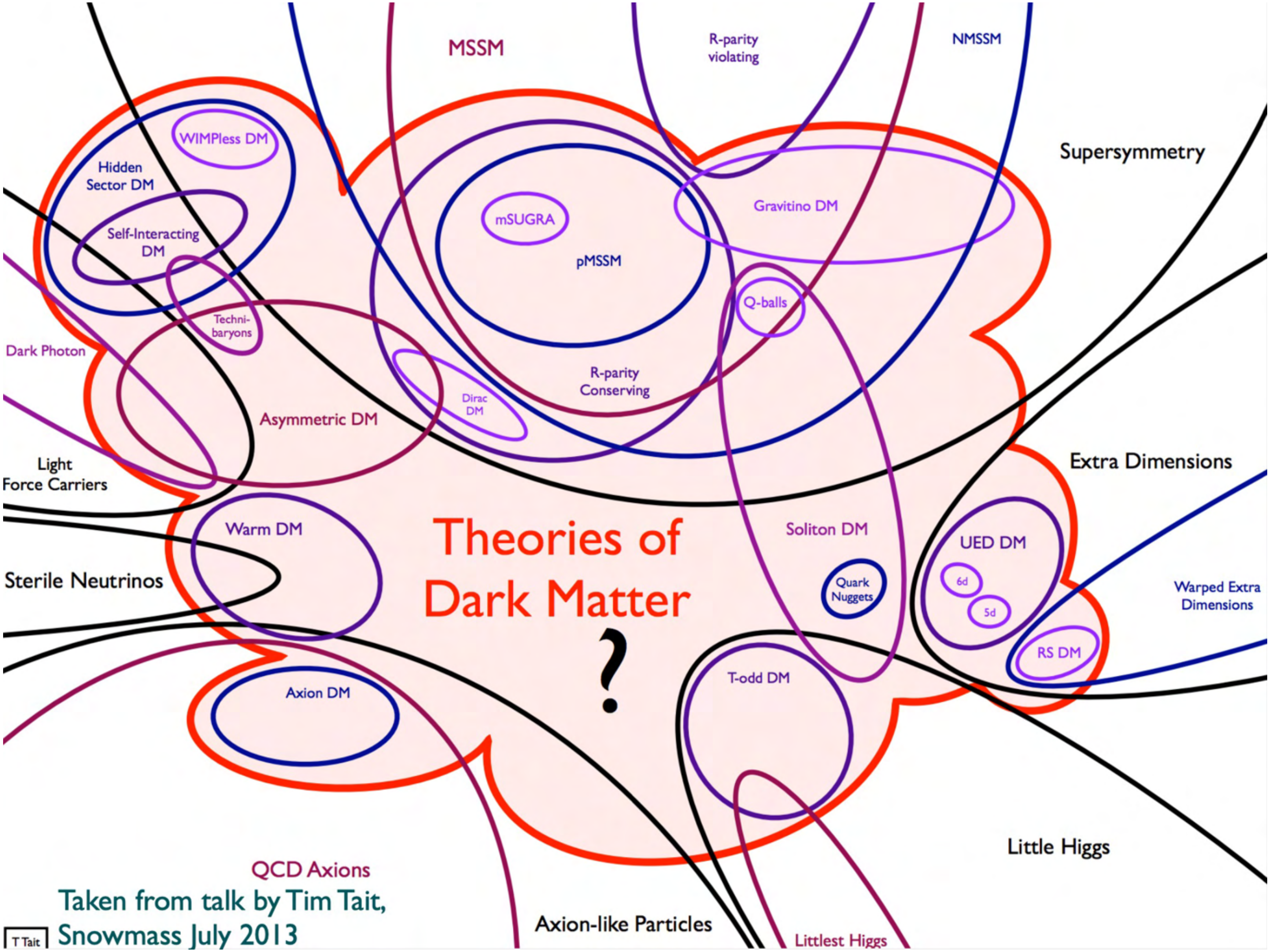


Figure 5-18. *Combined Spin-independent dark-matter nucleon scattering cross section space. Current 90% c.l. constraints are shaded beige, while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). Future experiments are shown in blue (SuperCDMS, DarkSide-20k, DarkSide-LowMass, SBC, XLZD, ARGO) and yellow (Snowball and Planned× 5). The neutrino fog for a xenon target is shaded light grey. From Ref. [97].*

Snowmass Cosmic Frontier 2023 report



Taken from talk by Tim Tait, Snowmass July 2013

State of knowledge

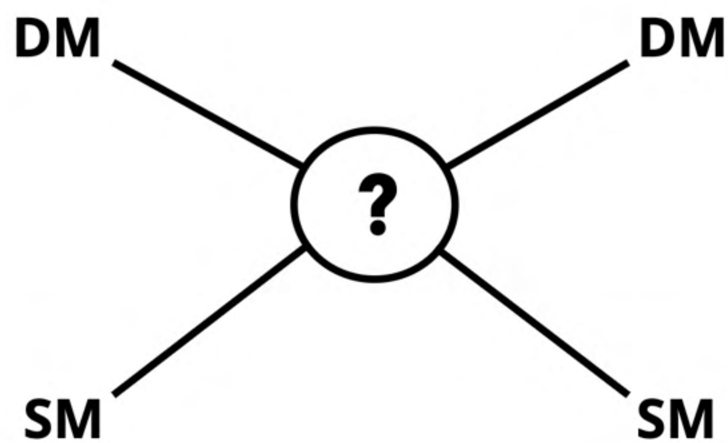
It's ***not*** a lot of things

(~~relativistic~~, ~~interacting much~~, ~~decaying fast~~) ✗

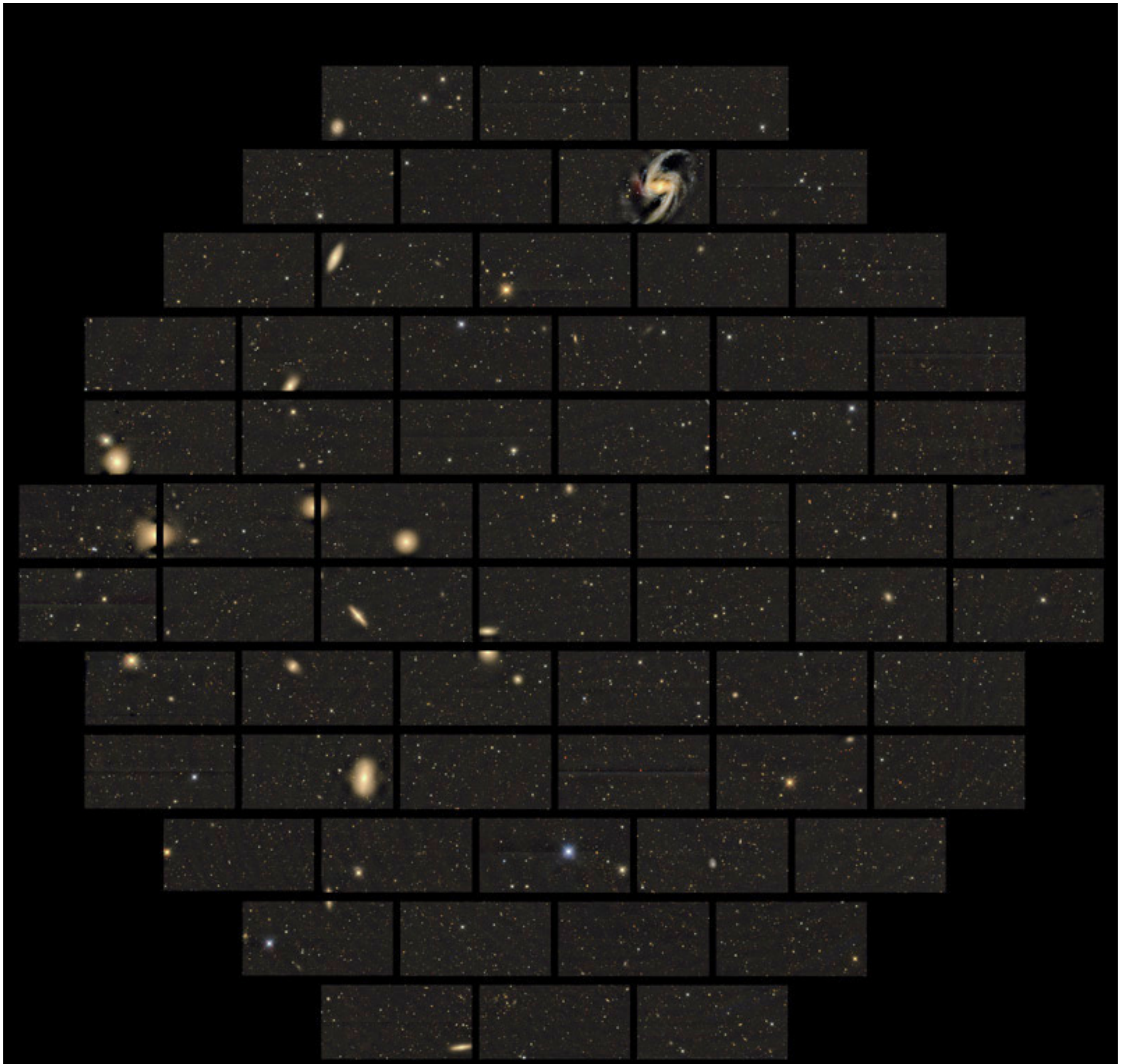
It could be a lot of things

(WIMPs, axions, hidden sector, etc.) ✓

? mass, spin, interactions, production ?

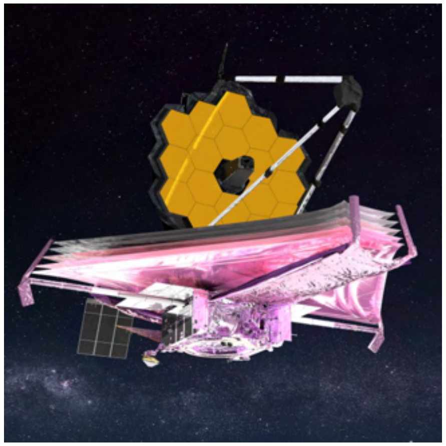
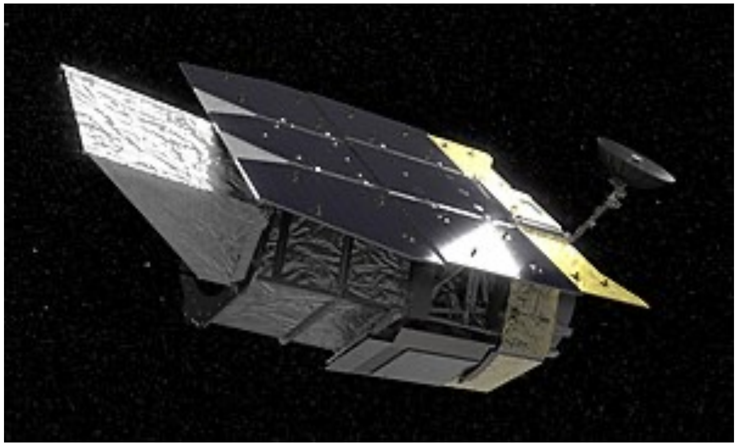


Data

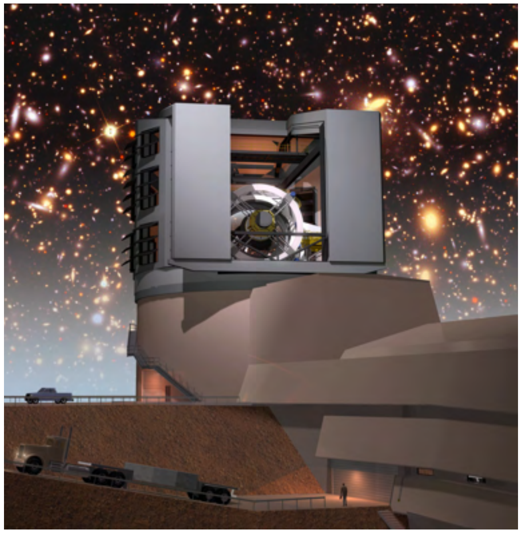


Images taken by the DES Collaboration with the DECam mounted on the Blanco Telescope. (DES Collaboration.)

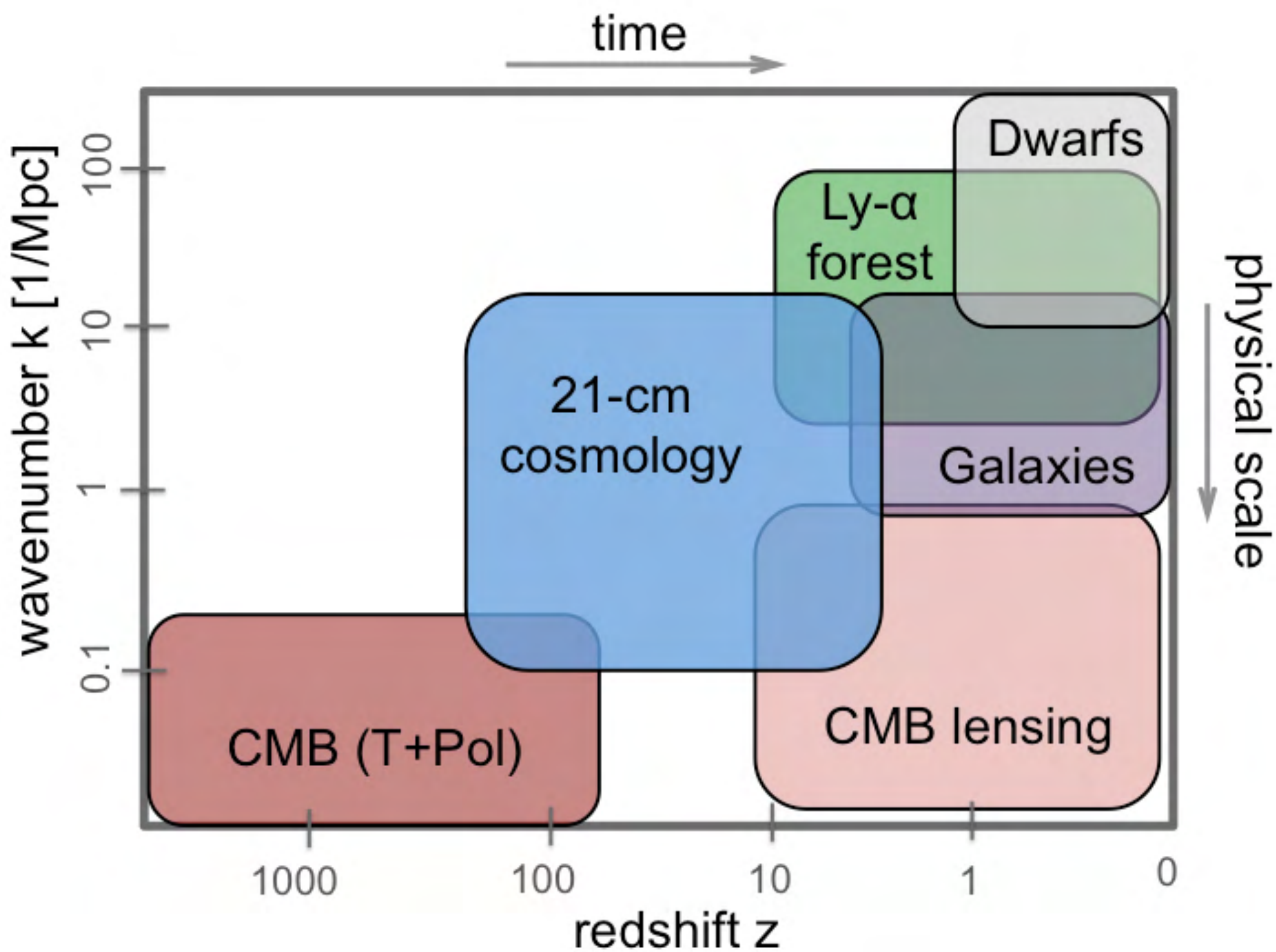
Data





Observables



Arxiv: 1903.05140 (Astro2020 decadal)

The plan

- **Ultra-brief ~~overview~~ recap of computational tools**

- **Mass** -- Lessons from BBN
- **Spin** -- Lessons from cosmic structures
- **Interactions** -- Lessons from large and small scales

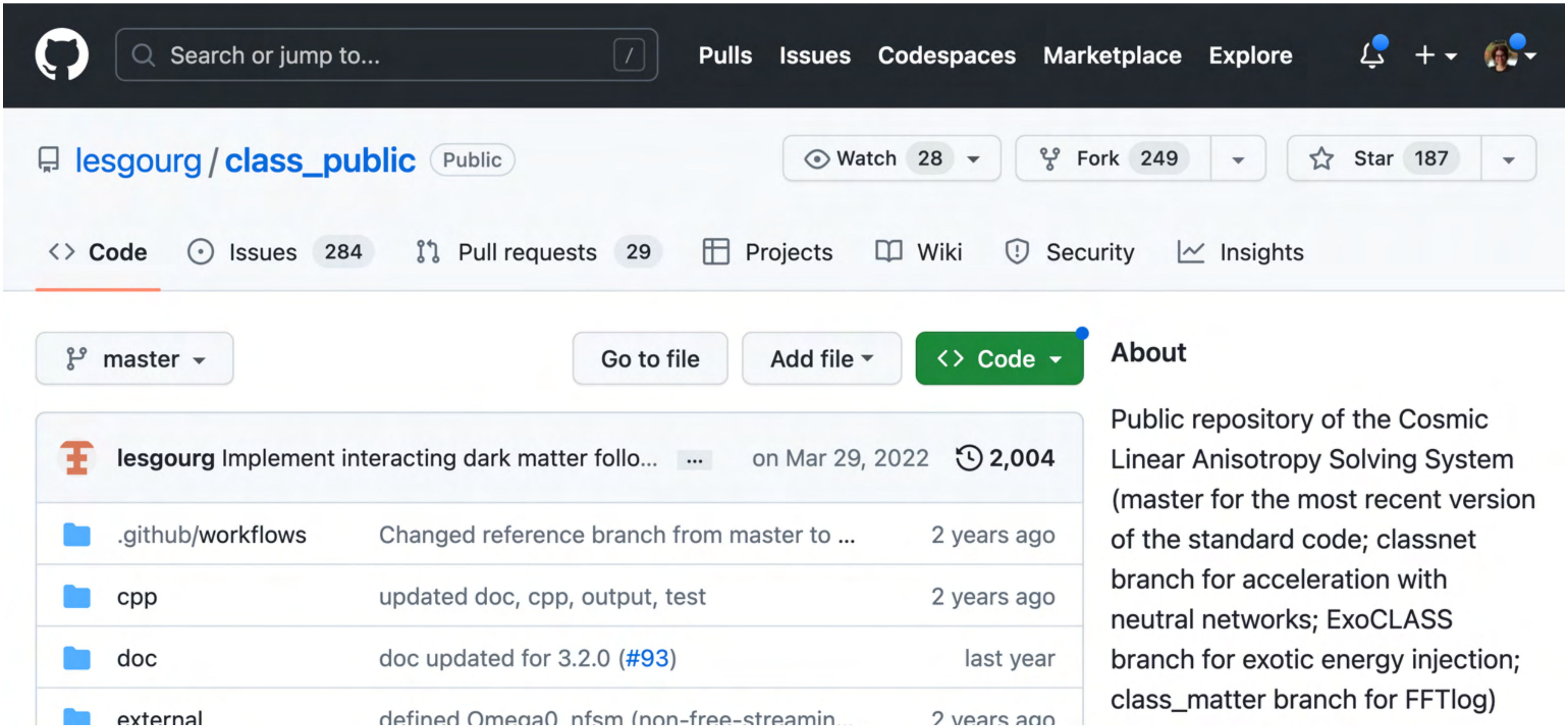
- **BONUS: Thermal history** -- Lessons from 21-cm cosmology

Computational tools

ultra-brief review

Linear cosmology --- CLASS/CAMB

https://arxiv.org/abs/1104.2932



Cosmological background

fluids + gravity

Dark matter
& Baryons (p+e+nuclei)

$$\rho_m \sim (1+z)^3$$

Radiation

$$\rho_\gamma \sim (1+z)^4$$

Dark energy

$$\rho_{de} \sim const$$

Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

Cosmological background

fluids + gravity

Dark matter

& Baryons (p+e+nuclei)

$$\rho_m \sim (1+z)^3$$

E&M
(Thomson
scattering)

Radiation

$$\rho_\gamma \sim (1+z)^4$$

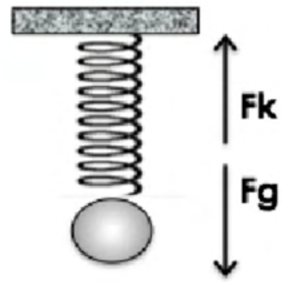
Dark energy

$$\rho_{de} \sim const$$

Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

Matter perturbations



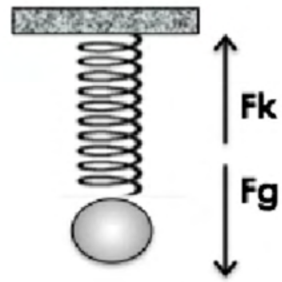
$$\frac{df}{dt} = C[f] \quad \Rightarrow$$

$$\dot{\delta}_\chi = \qquad -\frac{\dot{h}}{2}, \qquad \dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2},$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma \left(\theta_\gamma - \theta_b\right)$$

e.g. arxiv:1803.00070, arxiv:9506072

Matter perturbations



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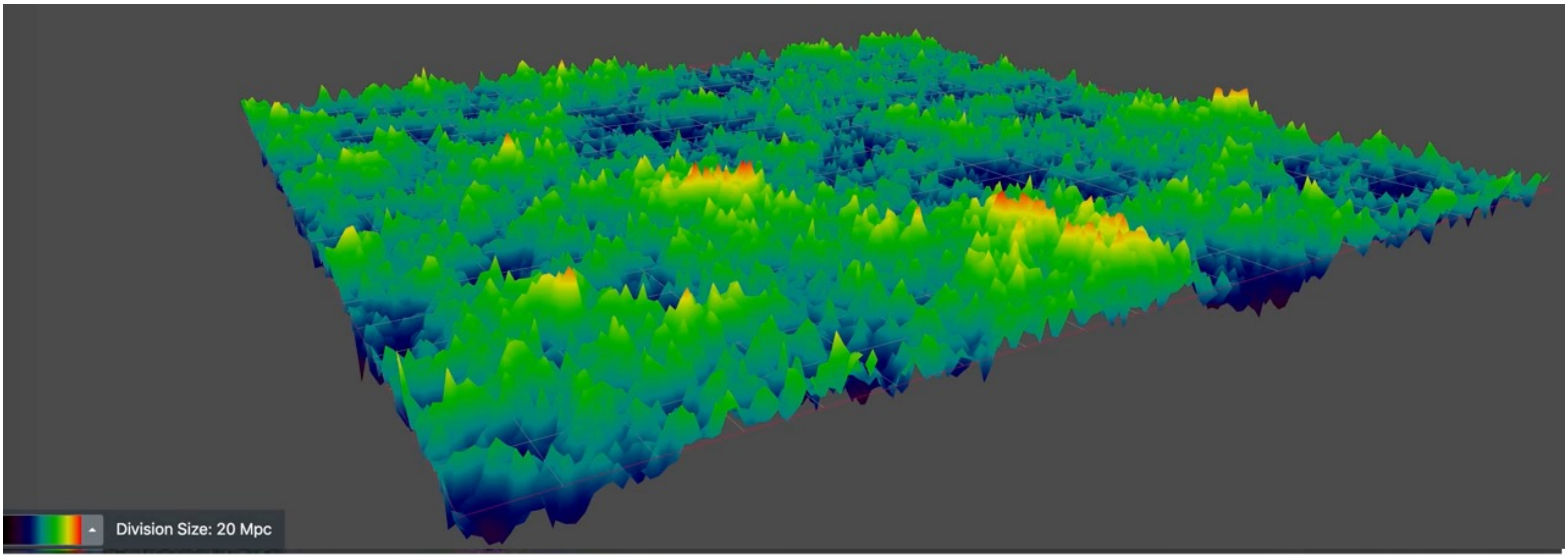
Early universe is a linear system!

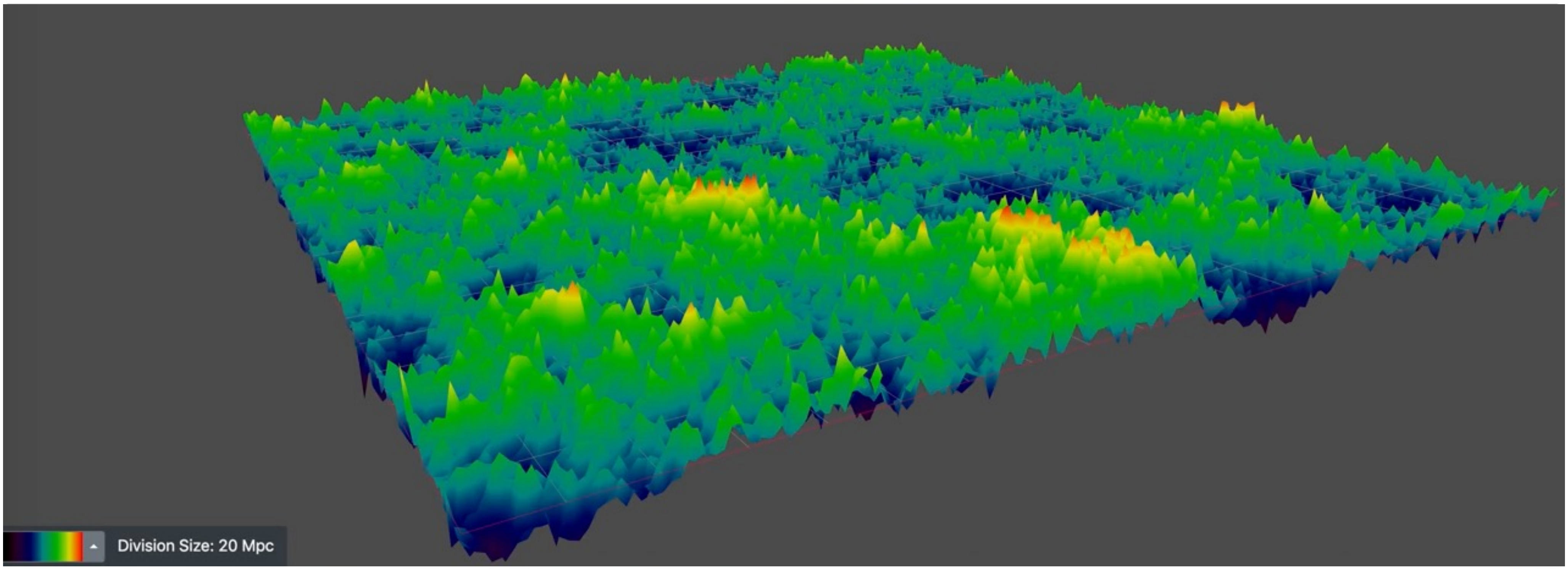
e.g. arxiv:1803.00070, arxiv:9506072

Matter perturbations: baryons



Created using CLASS Real Space Interface [J. Lesgourges]

Matter perturbations: CDM

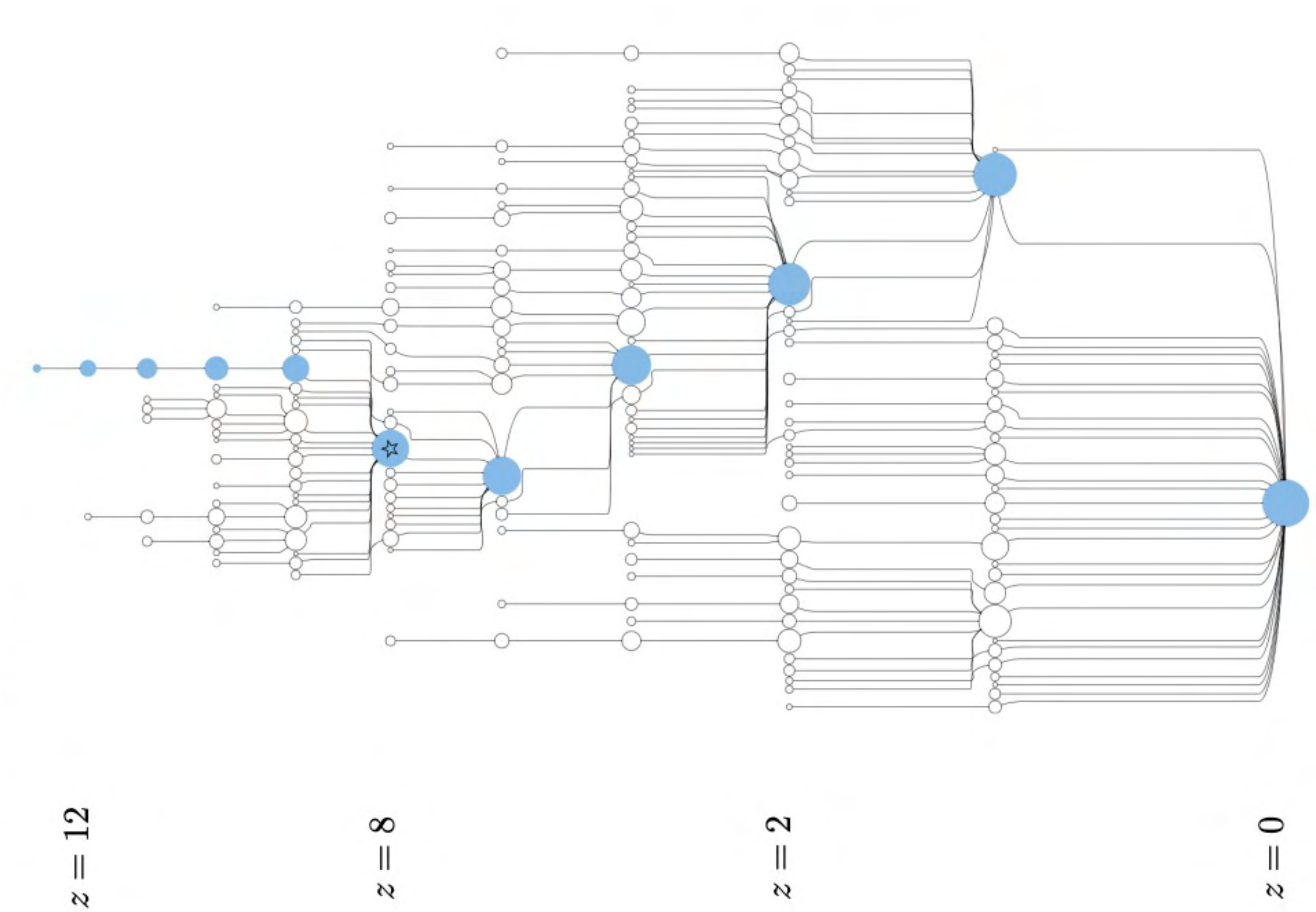


Created using CLASS Real Space Interface [J. Lesgourges]

Structure formation --- simulations

Ethan Nadler/Risa Wechsler/R. Kaehler/SLAC National Accelerator Laboratory/Stanford University

Structure formation --- semi analytic models



Nadler+ 2022

And also… baryons….

Need to compute/measure nuclear reaction rates for BBN:

https://alterbbn.hepforge.org/
https://parthenope.na.infn.it/

n decay

$n \to \mathrm{p}$

$^3\mathrm{H} \to \mathrm{e}^- + \overline{\nu}_e + {}^3\mathrm{He}$

$^8\mathrm{Li} \to \mathrm{e}^- + \overline{\nu}_e + 2\,{}^4\mathrm{He}$

$^{12}\mathrm{B} \to \mathrm{e}^- + \overline{\nu}_e + {}^{12}\mathrm{C}$

$^{14}\mathrm{C} \to \mathrm{e}^- + \overline{\nu}_e + {}^{14}\mathrm{N}$

$^8\mathrm{B} \to \mathrm{e}^+ + \nu_e + 2\,{}^4\mathrm{He}$

$^{11}\mathrm{C} \to \mathrm{e}^+ + \nu_e + {}^{11}\mathrm{B}$

$^{12}\mathrm{N} \to \mathrm{e}^+ + \nu_e + {}^{12}\mathrm{C}$

$^{13}\mathrm{N} \to \mathrm{e}^+ + \nu_e + {}^{13}\mathrm{C}$

$^{14}\mathrm{O} \to \mathrm{e}^+ + \nu_e + {}^{14}\mathrm{N}$

$^{15}\mathrm{O} \to \mathrm{e}^+ + \nu_e + {}^{15}\mathrm{N}$

$\mathrm{H} + \mathrm{n} \to + {}^2\mathrm{H}$

$^2\mathrm{H} + \mathrm{n} \to \gamma + {}^3\mathrm{H}$

$^3\mathrm{He} + \mathrm{n} \to \gamma + {}^4\mathrm{He}$

$^6\mathrm{Li} + \mathrm{n} \to \gamma + {}^7\mathrm{Li}$

$^3\mathrm{He} + \mathrm{n} \to \mathrm{p} + {}^3\mathrm{H}$

$^7\mathrm{Be} + \mathrm{n} \to \mathrm{p} + {}^7\mathrm{Li}$

$^6\mathrm{Li} + \mathrm{n} \to \alpha + {}^3\mathrm{H}$

$^7\mathrm{Be} + \mathrm{n} \to \alpha + {}^4\mathrm{He}$

$^2\mathrm{H} + \mathrm{p} \to \gamma + {}^3\mathrm{He}$

$^3\mathrm{H} + \mathrm{p} \to \gamma + {}^4\mathrm{He}$

$^6\mathrm{Li} + \mathrm{p} \to \gamma + {}^7\mathrm{Be}$

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$^2\mathrm{H} + \alpha \to \gamma + {}^6\mathrm{Li}$

$^3\mathrm{H} + \alpha \to \gamma + {}^7\mathrm{Li}$

$^3\mathrm{He} + \alpha \to \gamma + {}^7\mathrm{Be}$

$^2\mathrm{H} + \mathrm{d} \to \mathrm{n} + {}^3\mathrm{He}$

$^2\mathrm{H} + \mathrm{d} \to \mathrm{p} + {}^3\mathrm{H}$

$^3\mathrm{H} + \mathrm{d} \to \mathrm{n} + {}^4\mathrm{He}$

$^3\mathrm{He} + \mathrm{d} \to \mathrm{p} + {}^4\mathrm{He}$

$^3\mathrm{He} + {}^3\mathrm{He} \to 2\mathrm{p} + {}^4\mathrm{He}$

$^7\mathrm{Li} + \mathrm{d} \to \mathrm{n} + \alpha + {}^4\mathrm{He}$

$^7\mathrm{Be} + \mathrm{d} \to \mathrm{p} + \alpha + {}^4\mathrm{He}$

$^3\mathrm{He} + {}^3\mathrm{H} \to \gamma + {}^6\mathrm{Li}$

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$^3\mathrm{He} + {}^3\mathrm{H} \to \mathrm{d} + {}^4\mathrm{He}$

I. Spin

lessons from cosmic structures

Tremaine-Gunn bound (~1970s)

- Measure LOS velocity dispersion =>
  mass profile **M(r)** and density profile ***ρ*(r).**

- +Jeans stability => **escape velocity**

$$v_{esc} \approx \sqrt{\frac{2GM(r)}{r}}$$

- +Pauli exclusion => **fermi velocity**

$$v_F(r) = \hbar\left(\frac{6\pi^2\rho(r)}{gm^4}\right)^{1/3}$$

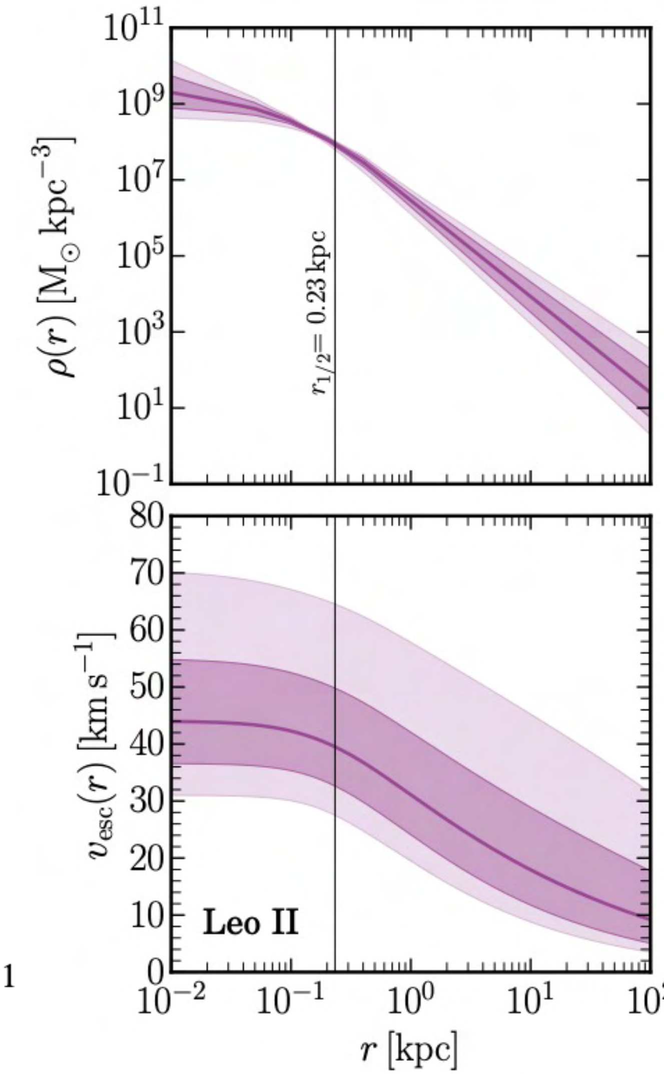
$$\boxed{v_F < v_{esc}}$$

https://arxiv.org/abs/astro-ph/0004381

Teamwork time

Teamwork time

https://arxiv.org/pdf/2010.03572.pdf



Estimate the lower bound on fermionic dark matter mass, from Leo II dwarf spheroidal galaxy, using the measurements of the escape velocity and density at half light radius, shown in the figure.

How does your result compare to the result of the paper linked at the top of the figure?

How would you improve this bound?

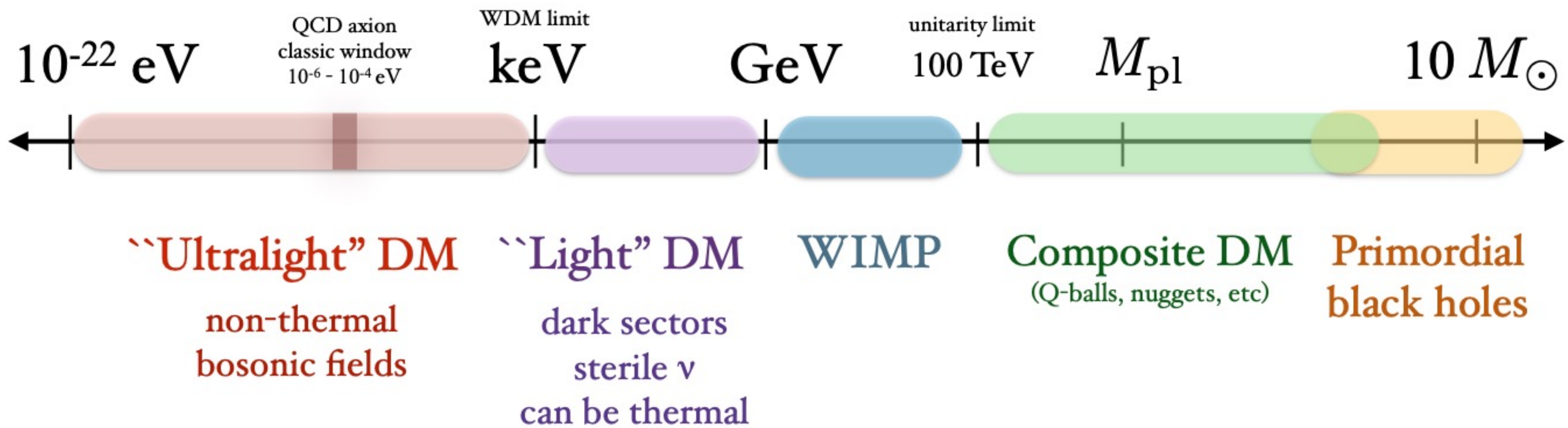
Hint: You will need formulas from the previous slide, and possibly also the following constants:

parsec	pc	3.086×10^{18} cm	
reduced Planck's constant	$\hbar = h/2\pi$	1.0546×10^{-27} cm^2 g s^{-1}	
Solar mass	$M_\odot$	1.989×10^{33} g	
erg (unit of energy)	erg	1 cm^2 g s^{-2}	6.2415×10^{11} eV

II. Mass

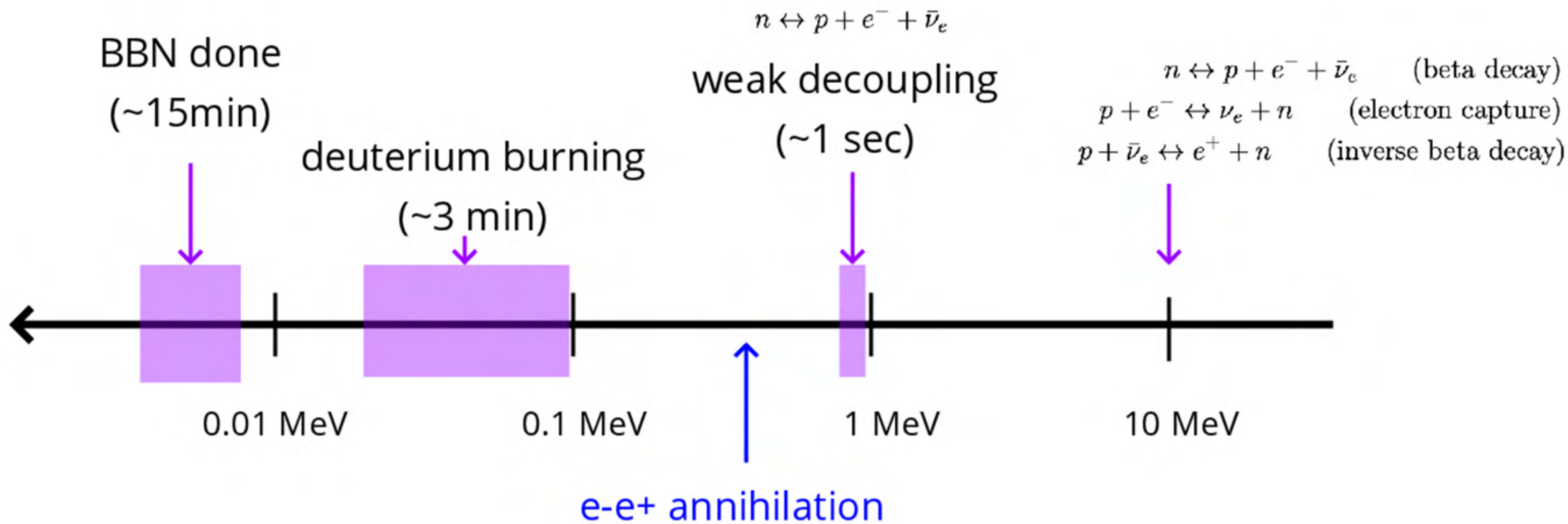
lessons from BBN

Allowed range of DM mass is huge.



Plot by T. Lin.

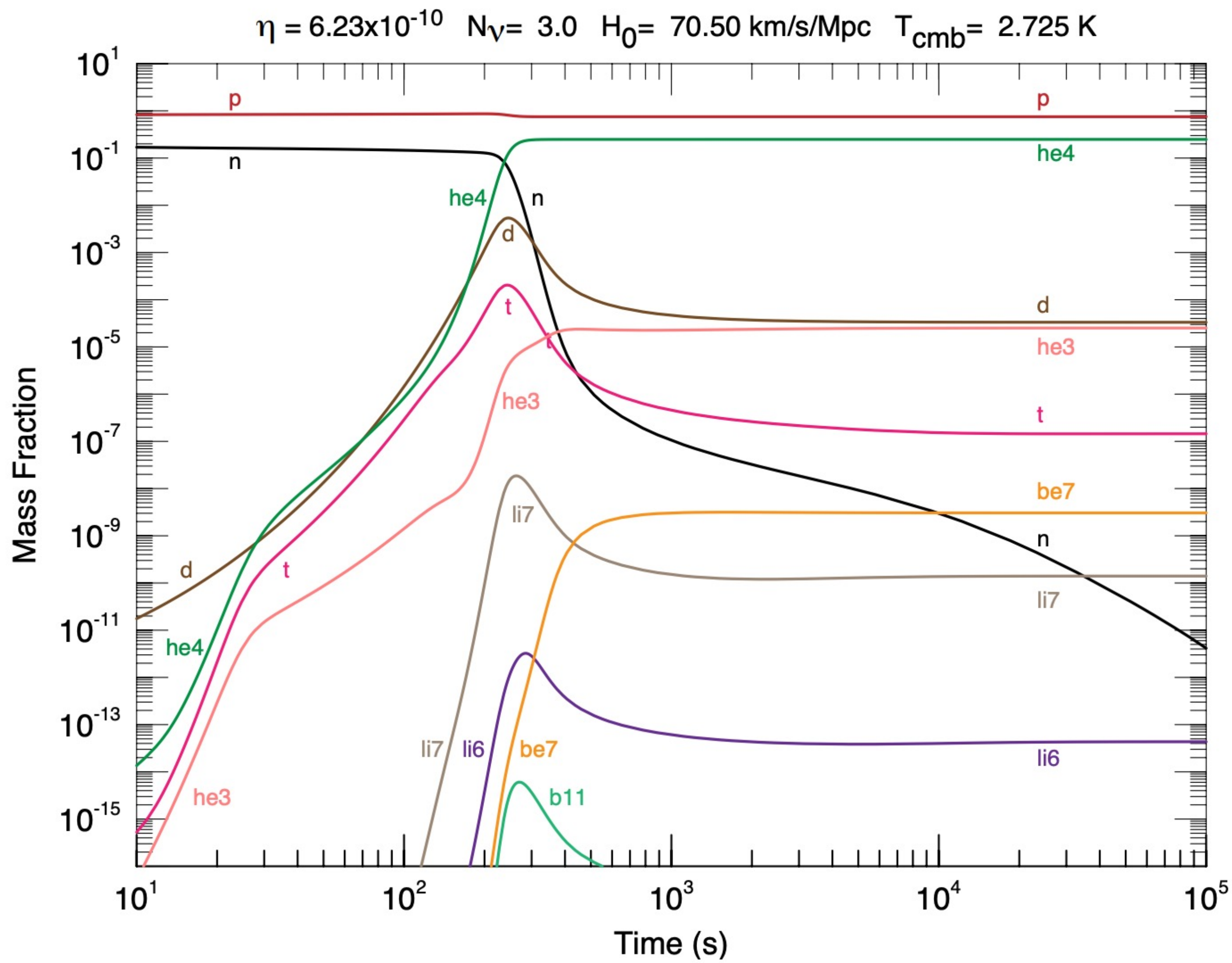
BBN



Big Bang Nucleosynthesis = a race to capture free neutrons left over after weak decoupling, into nuclei, before they decay away.

For a review: https://arxiv.org/pdf/1903.09187.pdf

Primordial element abundances

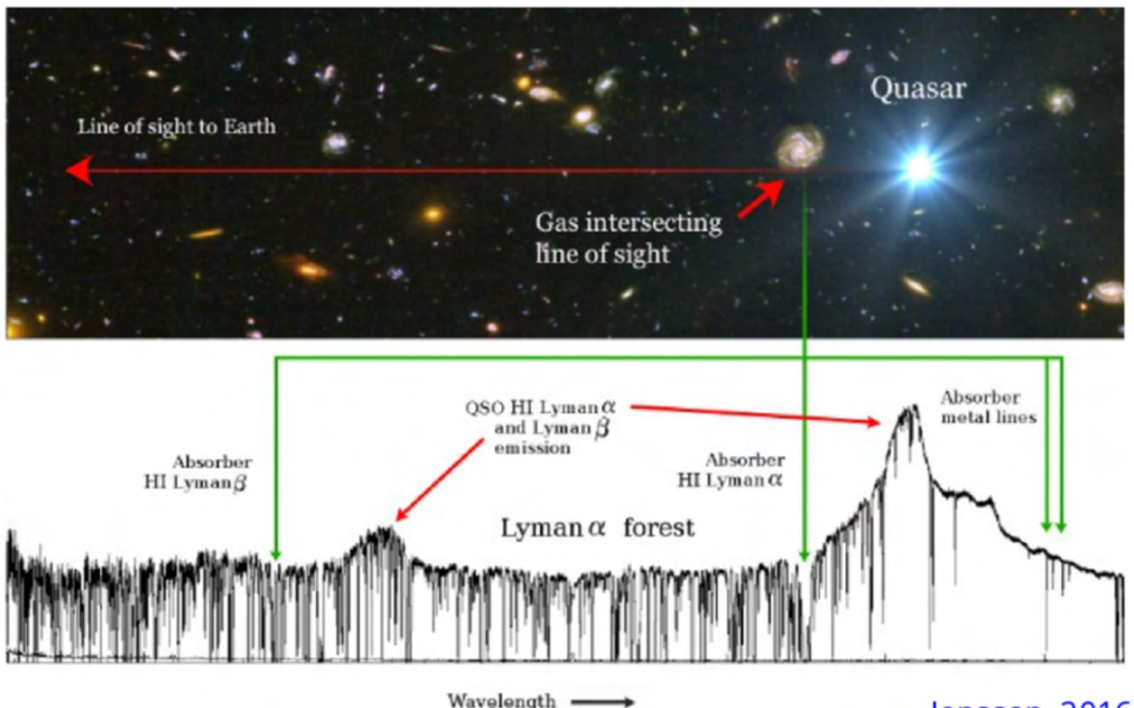


Jenssen, 2016
https://arxiv.org/abs/1803.00070

For a review: https://arxiv.org/pdf/1903.09187.pdf

We can measure primordial element abundances in pristine circumgalactic gas (using Lyman-alpha forest absorption in quasar spectra)

D, He-4, He-3, Li-7



Jenssen, 2016

For a review: https://arxiv.org/pdf/1903.09187.pdf

What about dark matter?

Thermal relic

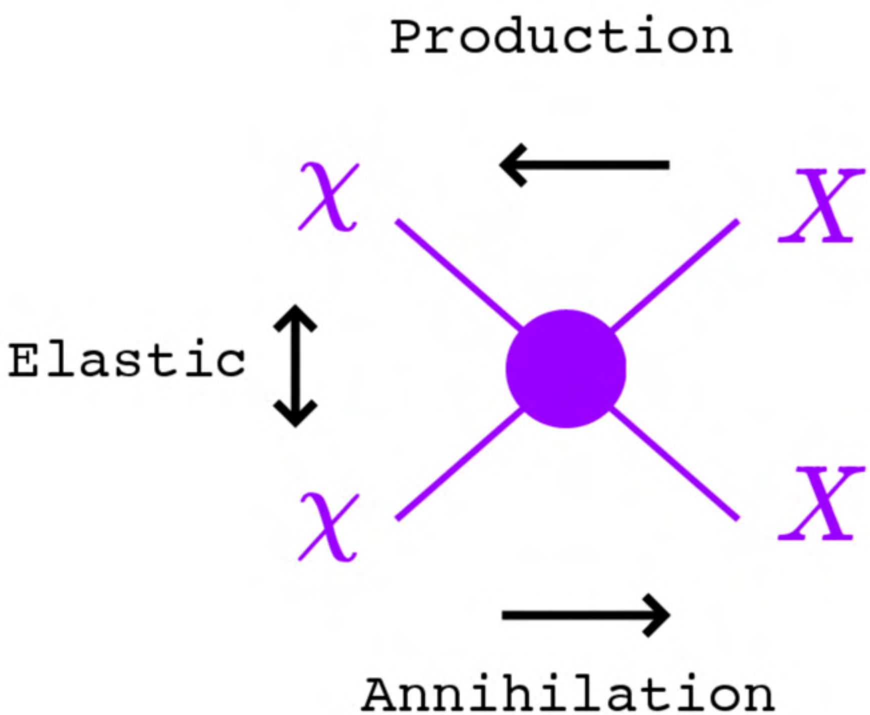
~concepts of **decoupling** and **freeze-out**~

Thermal relic particle starts off in thermal, kinetic, and chemical equilibrium with the rest of the universe at early times.

Thermal relic

~concepts of **decoupling** and **freeze-out**~

Thermal relic particle starts off in thermal, kinetic, and chemical equilibrium with the rest of the universe at early times.

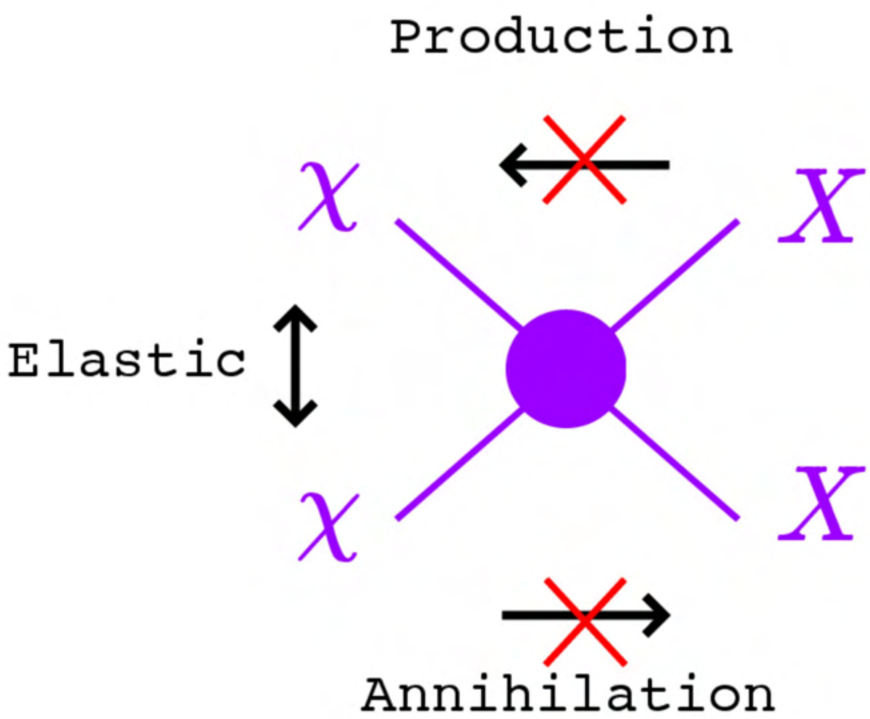


$$\chi\chi \leftrightharpoons XX$$

$$\chi X \leftrightharpoons \chi X$$

Thermal relic

chemical decoupling → freeze-out



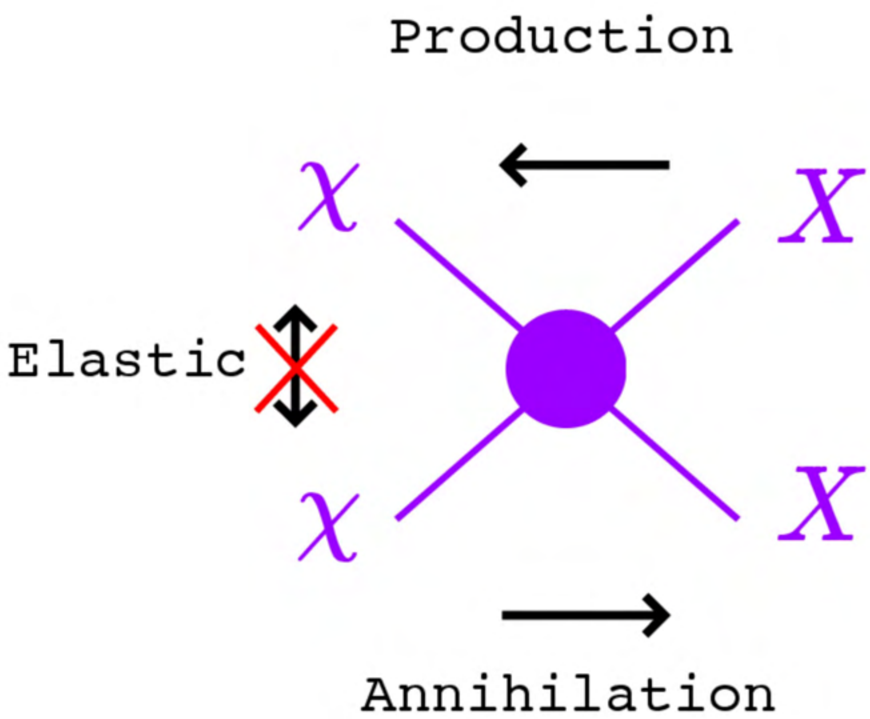
$$\chi\chi \not\rightleftharpoons X X$$

$$\Gamma_{\text{inelastic}} = n_\chi \langle \sigma v \rangle \sim H$$

$$H \sim \frac{T^2}{M_{\text{pl}}}$$

Thermal relic

kinetic decoupling



$$\chi X \not\rightleftharpoons \chi X$$

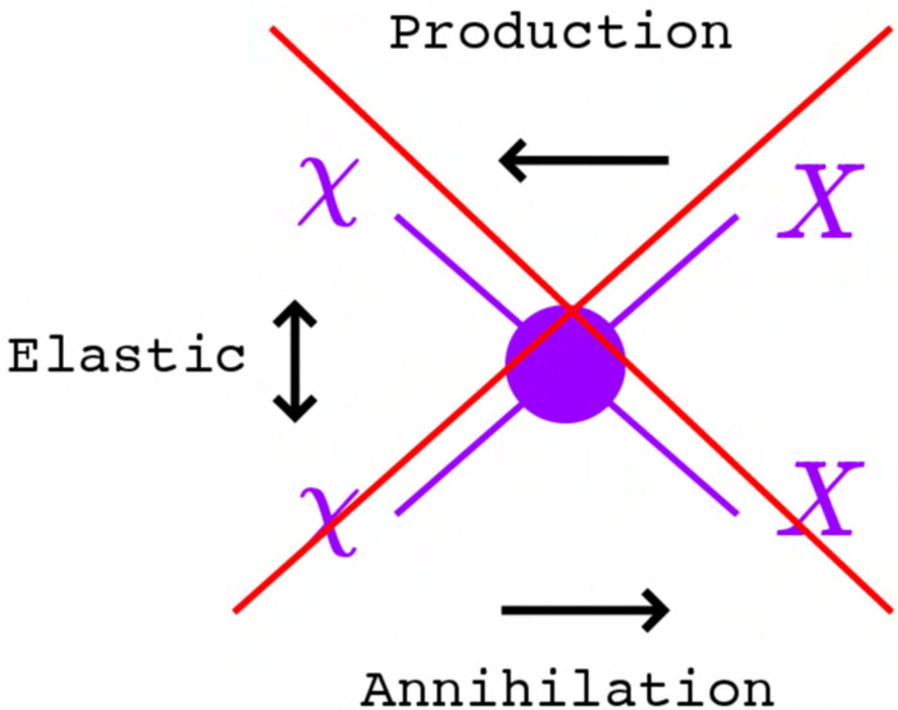
$$\Gamma_{\text{elastic}} = n_X \langle \sigma v \rangle \sim H$$

$$H \sim \frac{T^2}{M_{\text{pl}}}$$

Thermal relic

thermal decoupling

followed by free-streaming



$$\chi\chi \rightleftharpoons XX$$
$$\chi X \rightleftharpoons \chi X$$

Thermal relic abundance

$$f(p) = \frac{1}{e^{(E(p)-\mu)/T} \pm 1}$$

$$n = \frac{\zeta(3)}{\pi^2} g T^3 \begin{cases} 1 & \text{bosons} \\ \frac{3}{4} & \text{fermions} \end{cases}$$

$$n = g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

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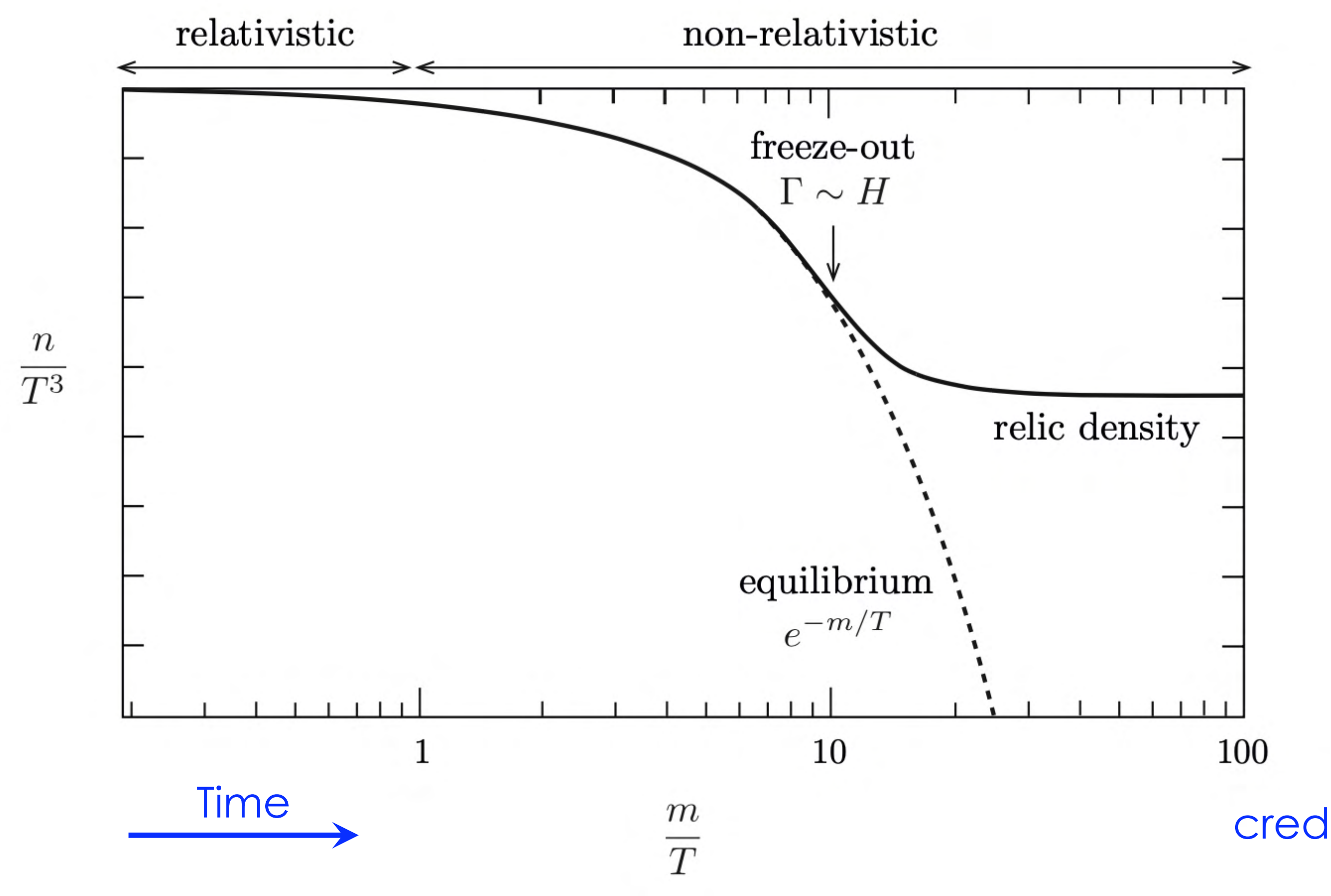

credit: D. Baumann

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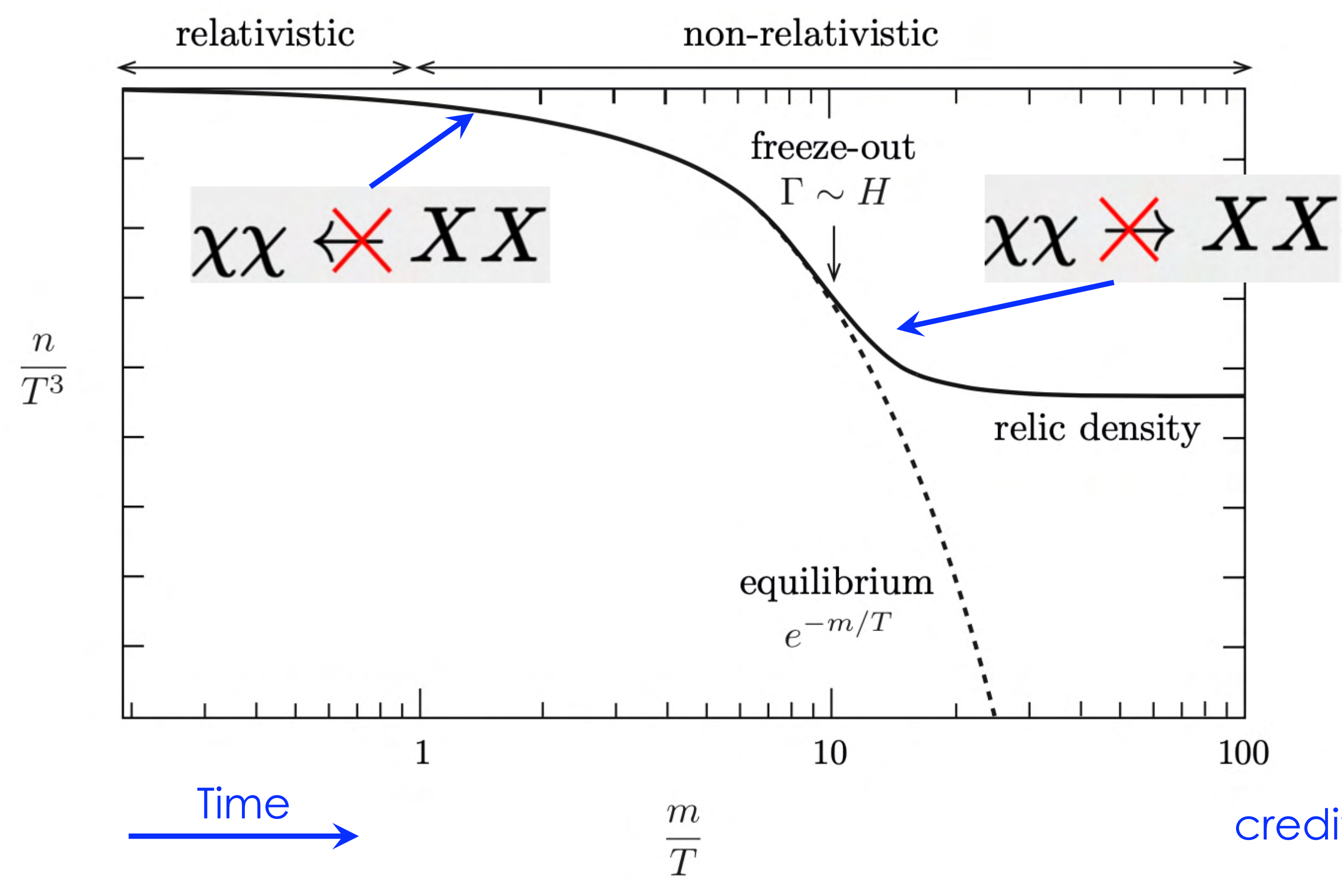


credit: D. Baumann

Question for you

A

B

C

D

Question for you

What happens to the temperature of the universe when a particle falls out of equilibrium (*by becoming non-relativistic*)?

A) It stays constant

B) It increases

C) It decreases

D) It depends on the particle interactions

E) I have no idea

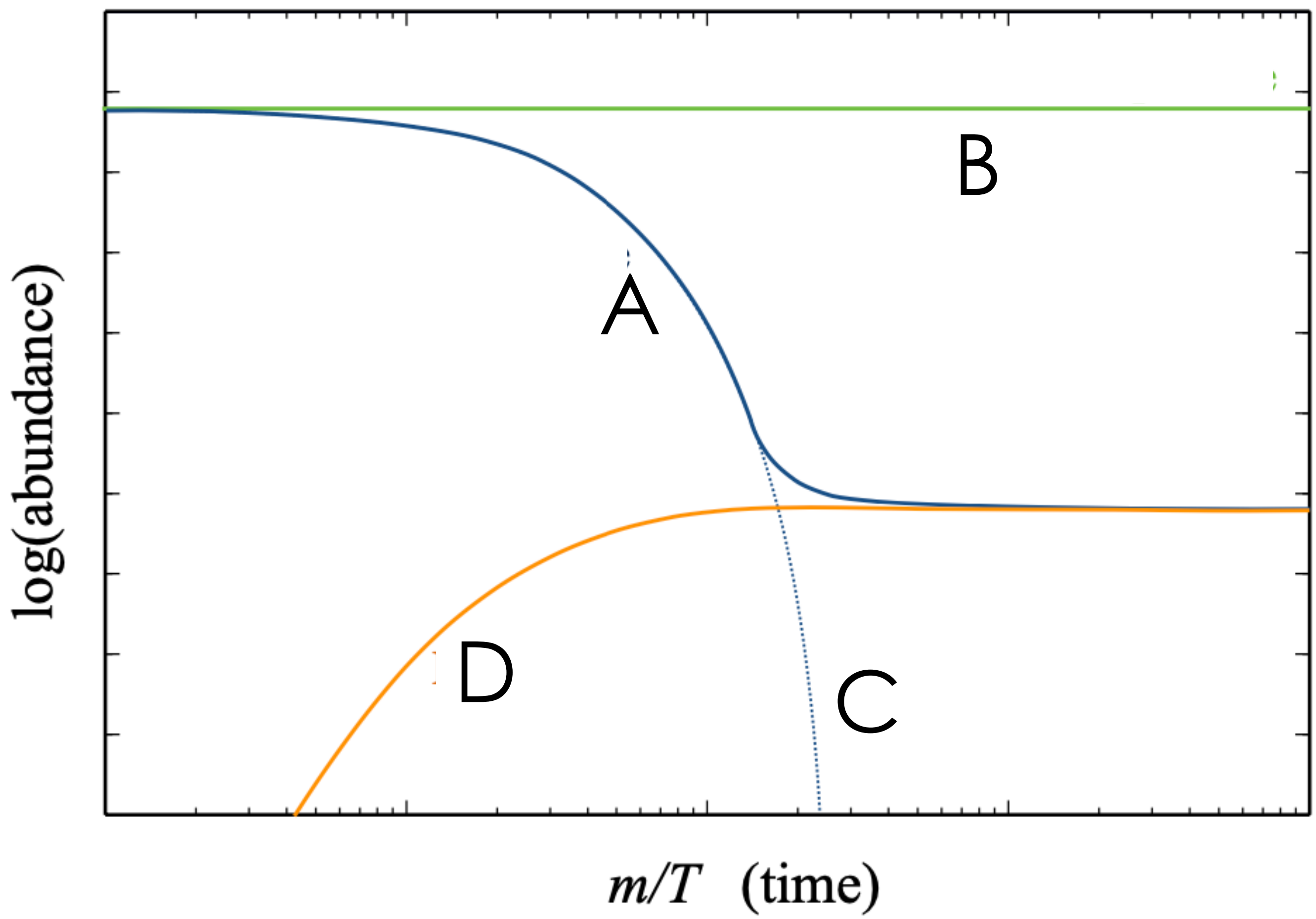
The quantity $g_{*S}(T)\, T^3 a^3$ is conserved throughout the expansion history of the universe.

A B
C D

Question for you

Which of the four scenarios occurs if H > Γ while T>>m?

(m=particle mass, T=temperature, Γ=rate of particle production/annihilation)

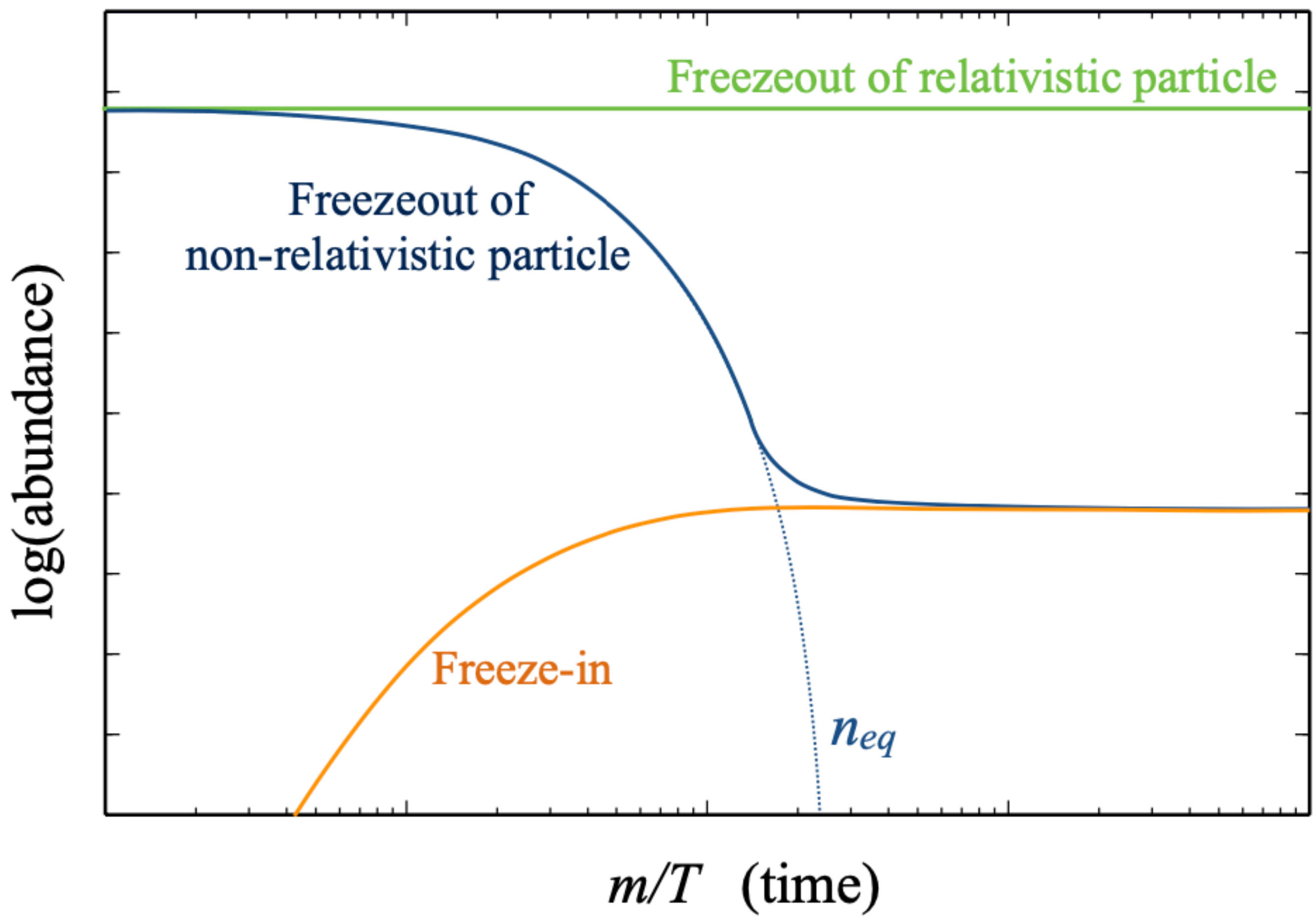


A B
C D

Question for you

Which of the four scenarios occurs if $H > \mathbf{\Gamma}$ while $T >> m$?

(m=particle mass, T=temperature, $\mathbf{\Gamma}$=rate of particle production/annihilation)



Plot by T. Lin

In case of DM annihilation:

S = const

Heating

Expansion speeds up

Yp increases*

Neutron half life is ~15 min

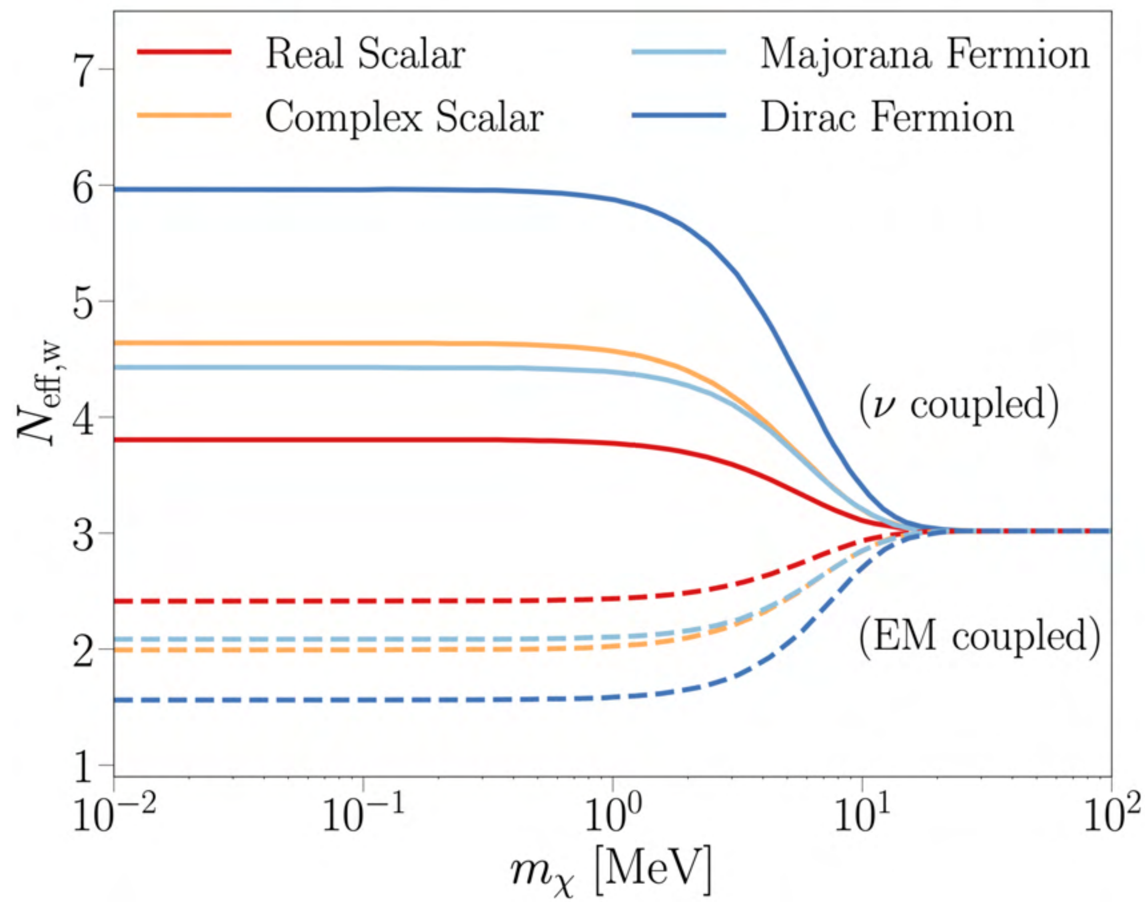
BBN with light dark matter

$$N_{\rm eff,w} \equiv 3\left[\frac{11}{4}\left(\frac{T_\nu}{T_\gamma}\right)_0^3\right]^{\frac{4}{3}}$$

Contribution from SM + dark matter or other light relics

Contribution from *other* relativistic d.o.f.

$$N_{eff}(m_\chi, \Delta N_\nu) \equiv N_{eff,w}(m_\chi)(1+\Delta N_\nu/3)$$

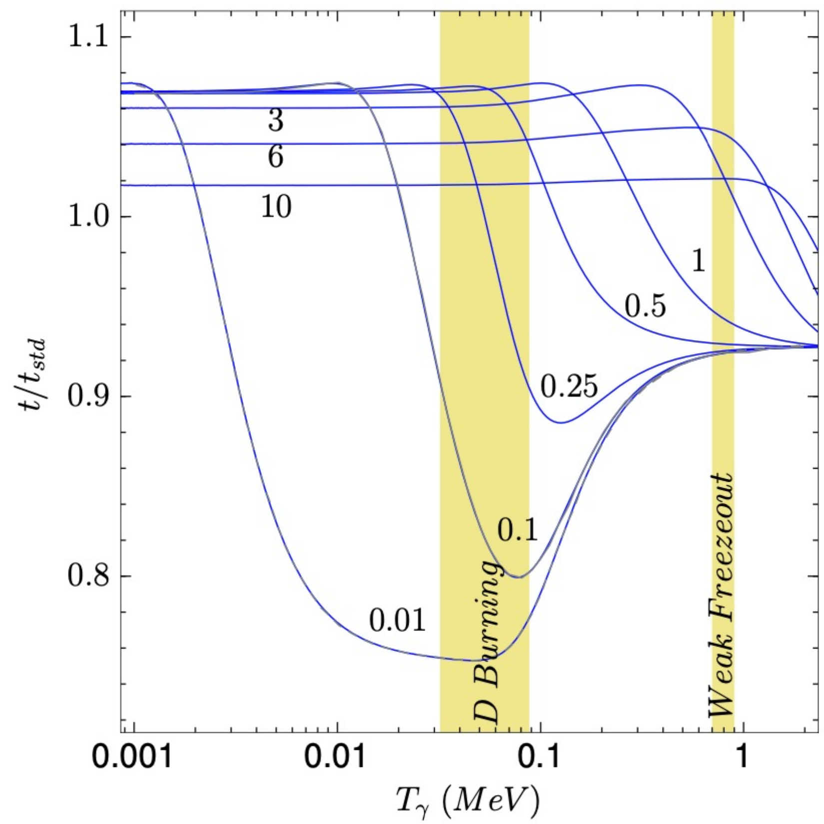


An+ 2022
Jenssen, 2016; Sabti+. 2019.

A **light thermal relic** can alter both early and late expansion history.

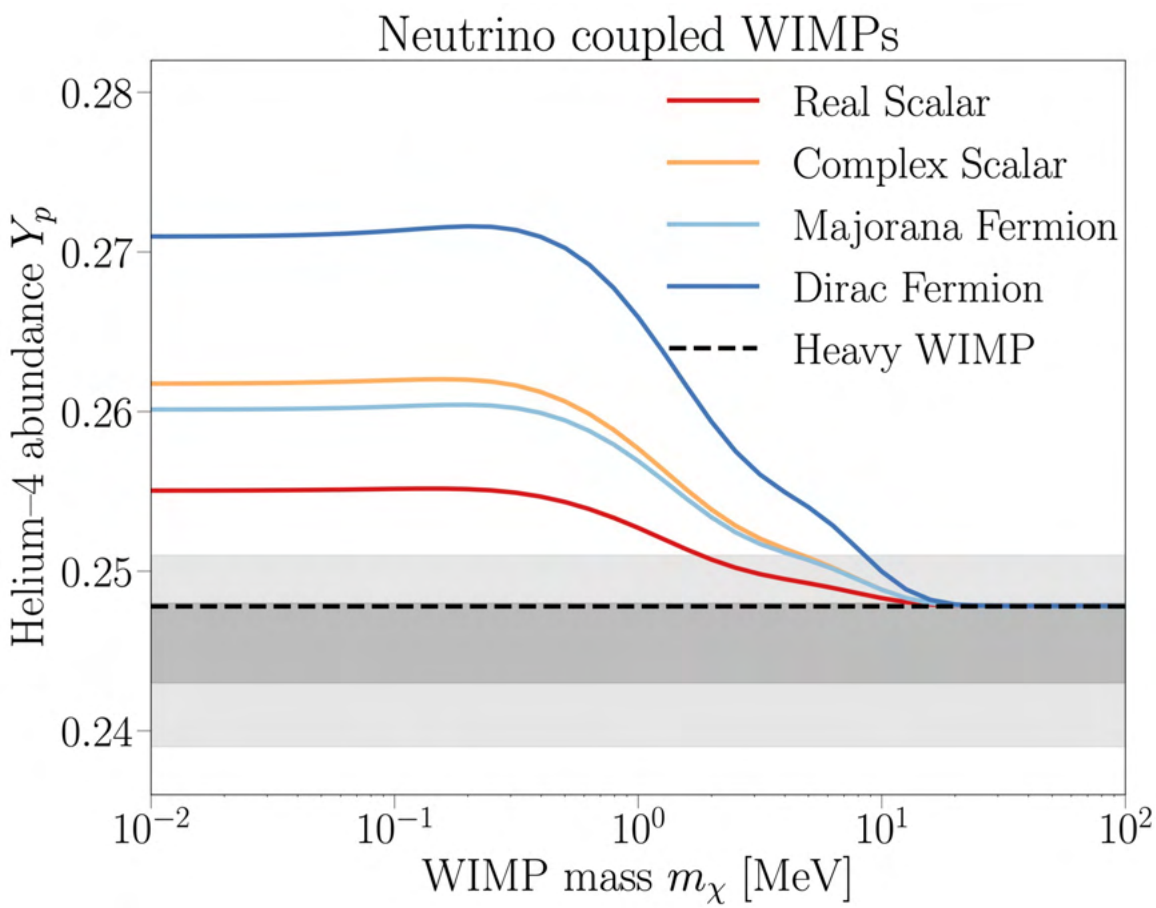
Light enough to become non-relativistic during BBN (while annihilating into photons or neutrinos):

0.1 MeV < mχ < 20 MeV



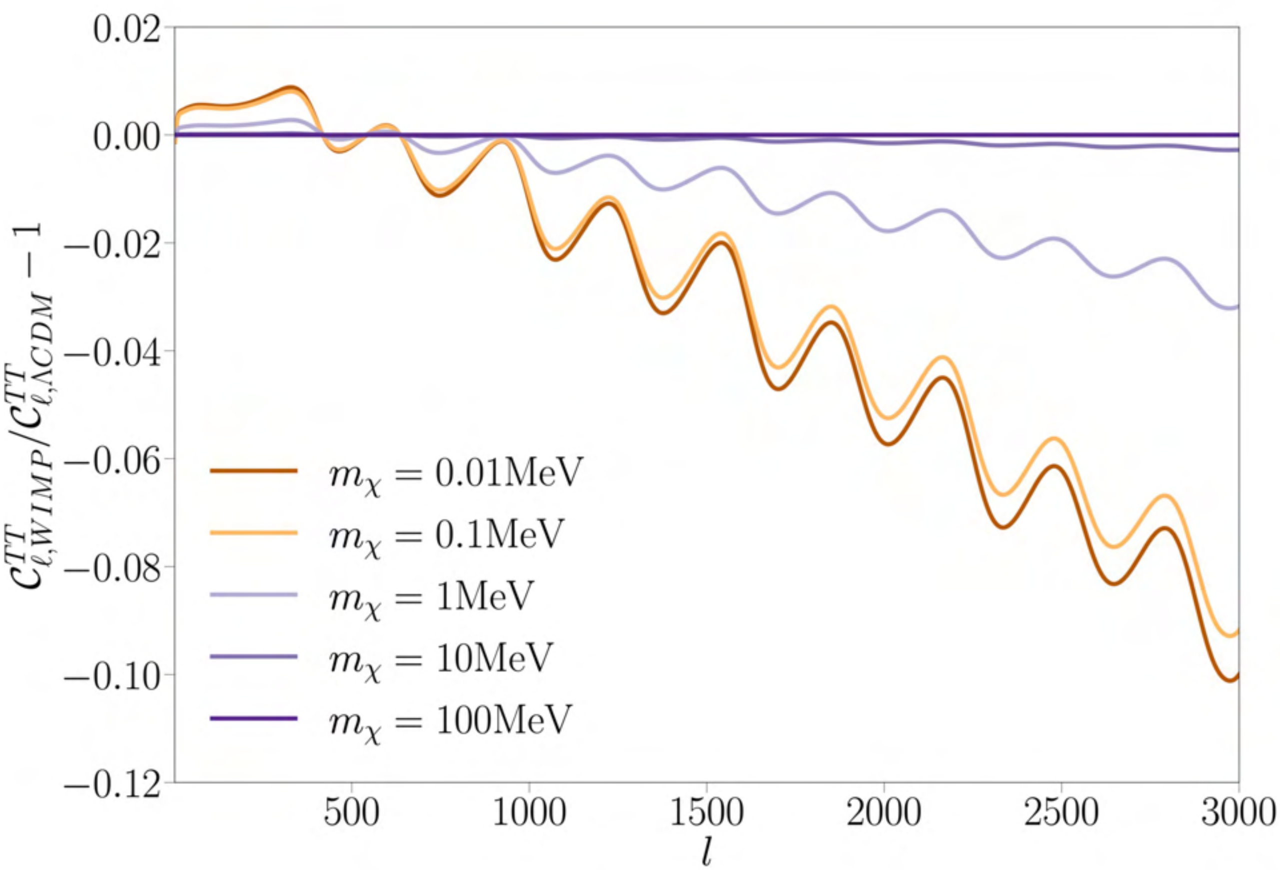
Nollett+Steigman, 2014, 2015
Jenssen, 2016
https://arxiv.org/abs/1803.00070

BBN with light dark matter



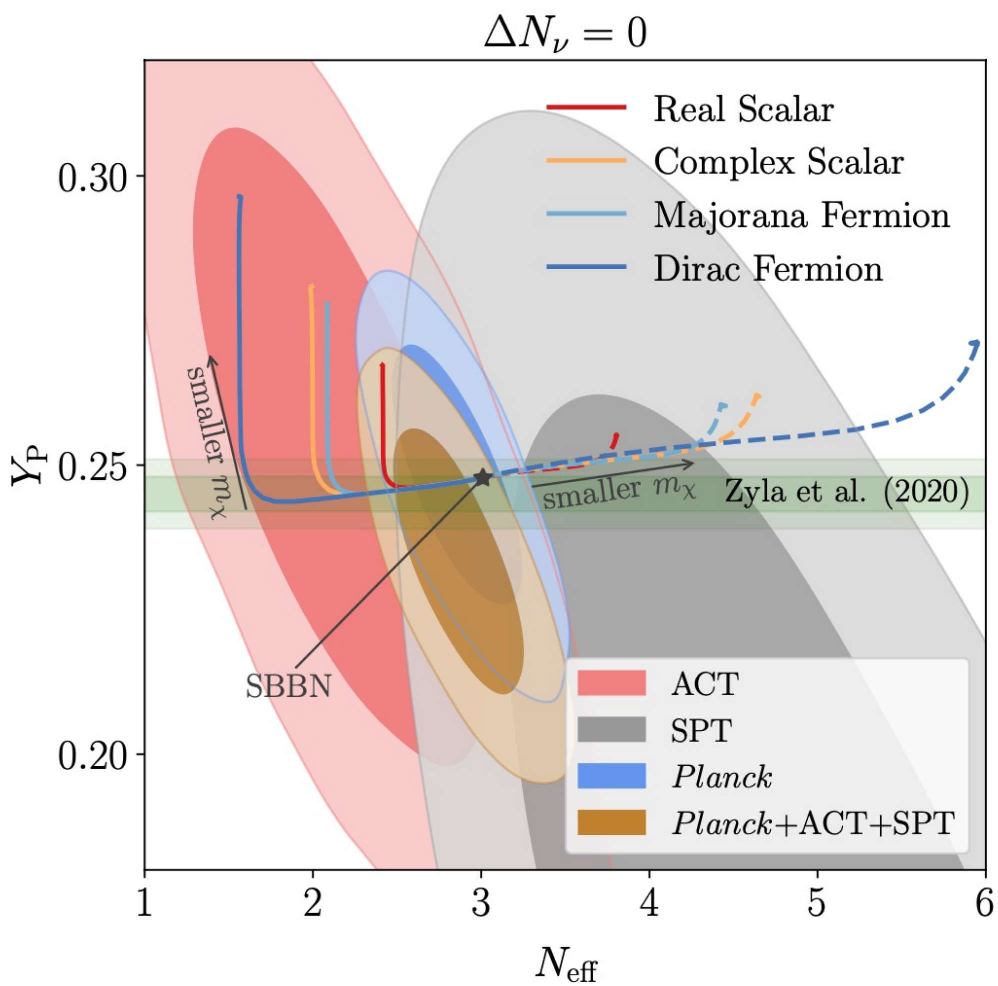
An+ 2022; Giovanetti+, 2021; Krnjaic+McDermott, 2019; Nollett+Steigman, 2014, 2015; Jensen, 2016; Sabti+, 2019.

CMB with light dark matter



An+ 2022; Giovanetti+, 2021; Krnjaic+McDermott, 2019; Nollett+Steigman, 2014, 2015; Jensen, 2016; Sabti+, 2019.

CMB with light dark matter



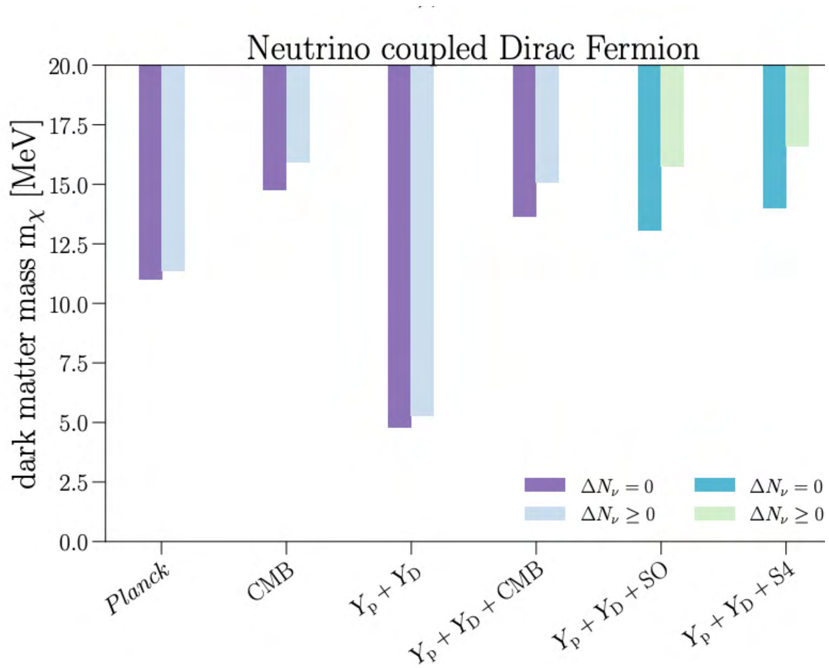
Dark matter mass bounds are sensitive to small shifts in best-fit values of Neff and Yp.

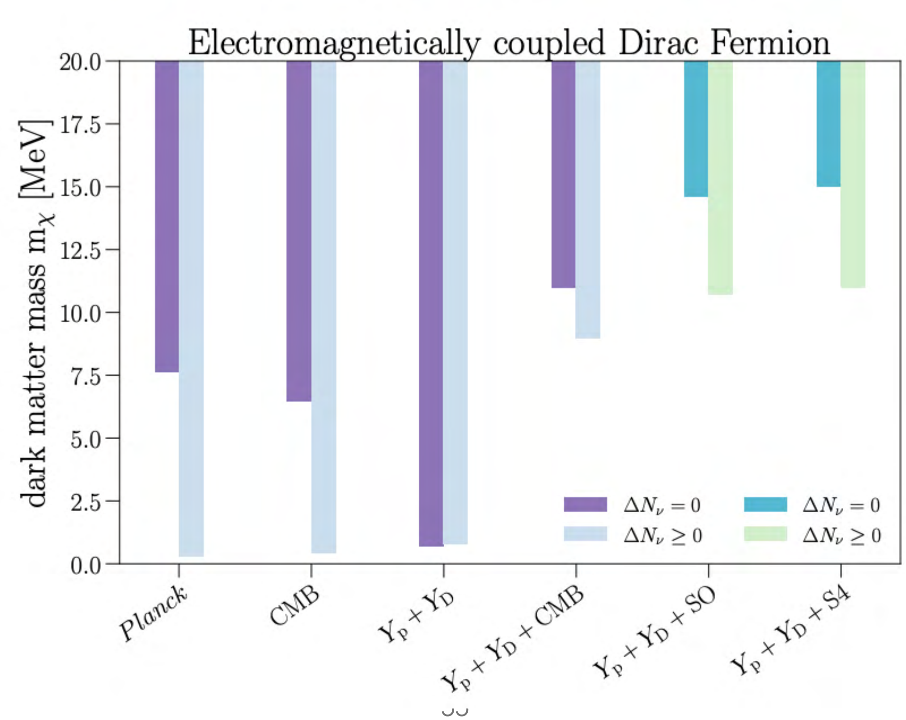
An+ 2022; Giovanetti+, 2021; Krnjaic+McDermott, 2019; Nollett+Steigman, 2014, 2015; Jensen, 2016; Sabti+, 2019.

DM mass bounds

*Colored = allowed mass ranges
(95% CL)

An+ (2022)

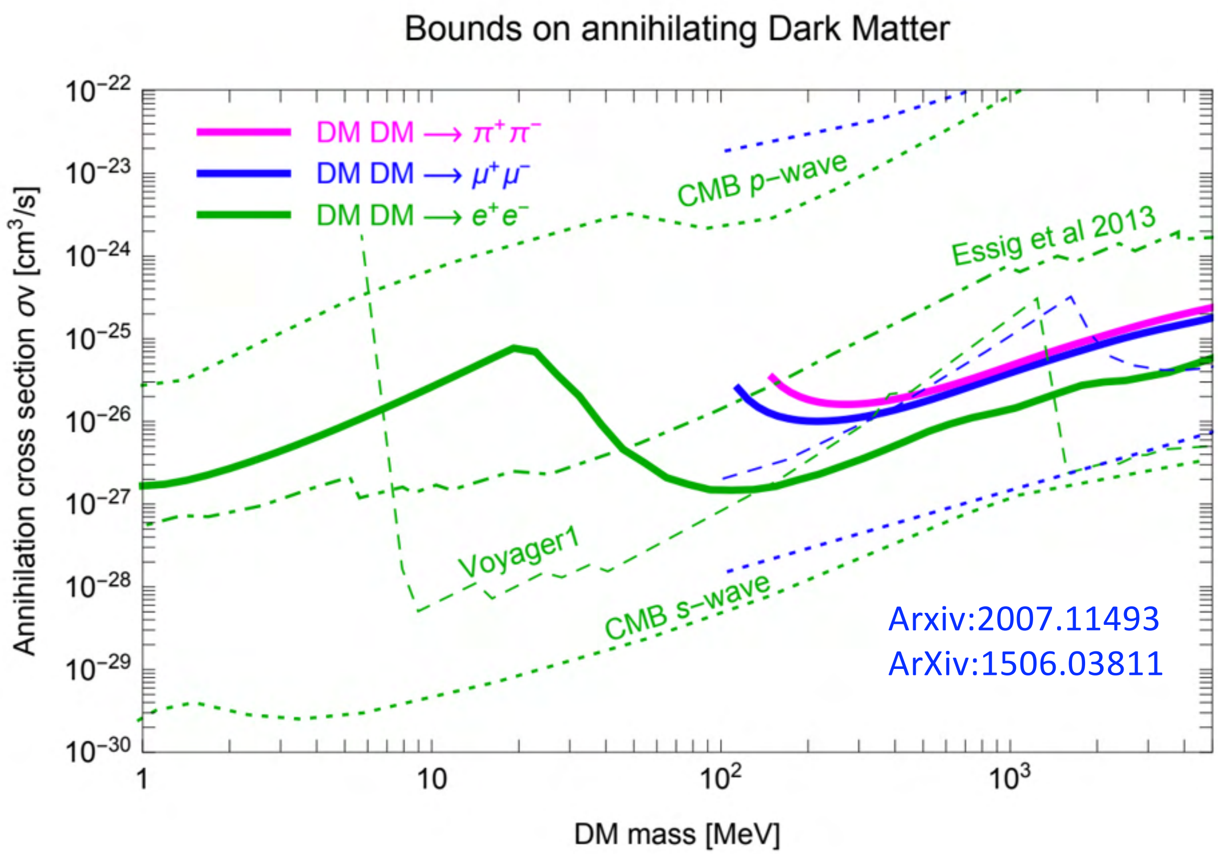




-CMB is more constraining than primordial abundances.
-Strongest bound is from CMB + primordial abundances, around 15 MEV
-Weakest bound is around 100 keV
-Addition of ACT+SPT to Plank improves bounds by up to 80% for neutrino coupled
-Bounds on EM coupled DM sensitive to choice of data: small inconsistency between CMB data sets in value of Neff.

-SO will either exclude thermal relics lighter than 20 MeV, or provide evidence for non-standard BBN.

Digression:
late-time (residual) annihilation bounds

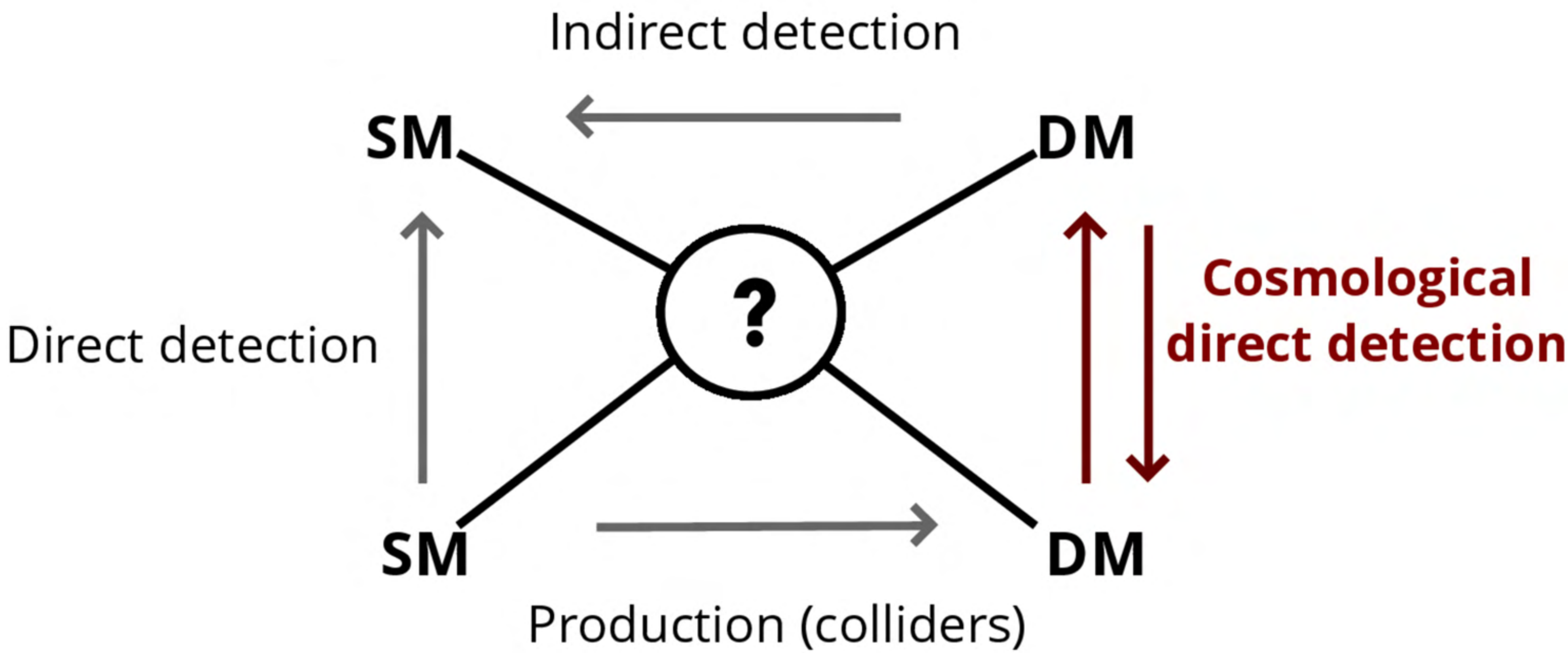


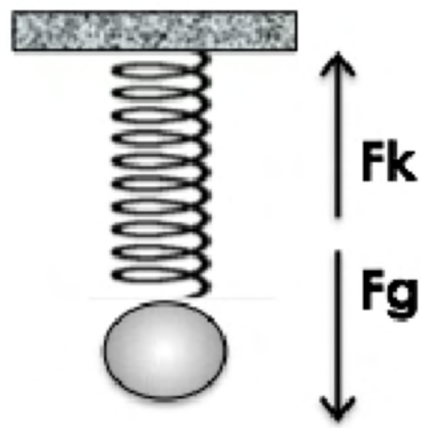
- If DM is a thermal relic, its annihilation is related to relic abundance!
- There are bounds from CMB and X-rays.

III. Interactions

lessons from small and large scales

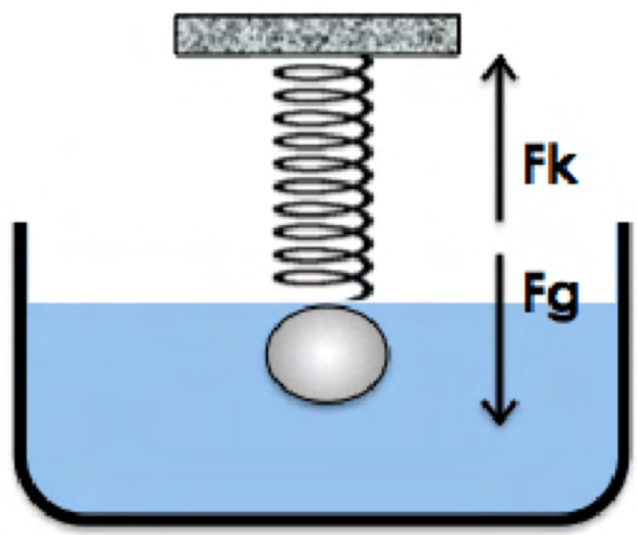
Interacting dark matter (IDM)



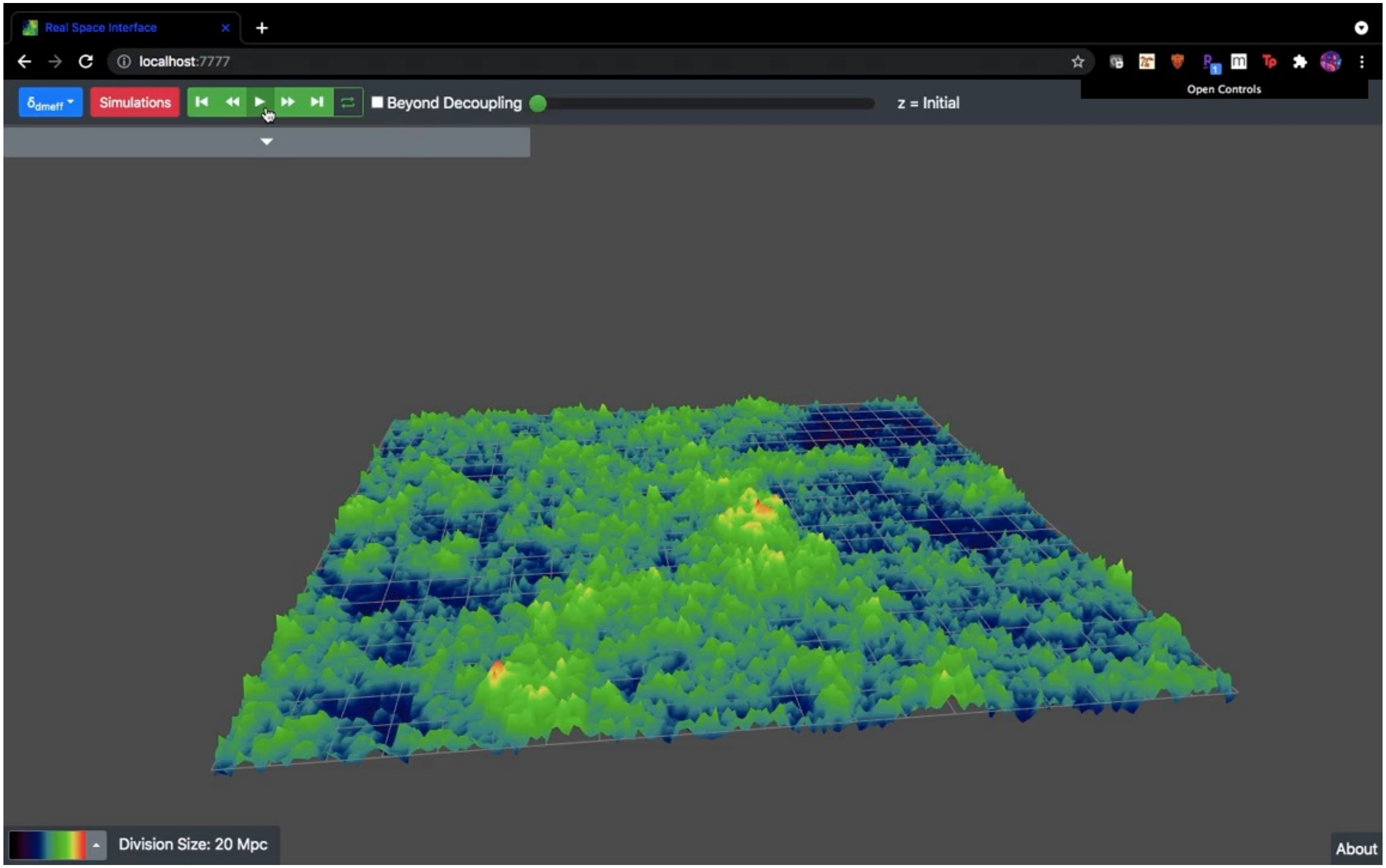

Fk
Fg

DM-baryon elastic scattering

fluids + gravity **+ drag** = **damped** baryonic acoustic oscillations



IDM cosmology: dark acoustic oscillations



Credit: Dimple Sarnaaik (USC), using CLASS Real Space Interface

Cosmology with DM-baryon elastic scattering

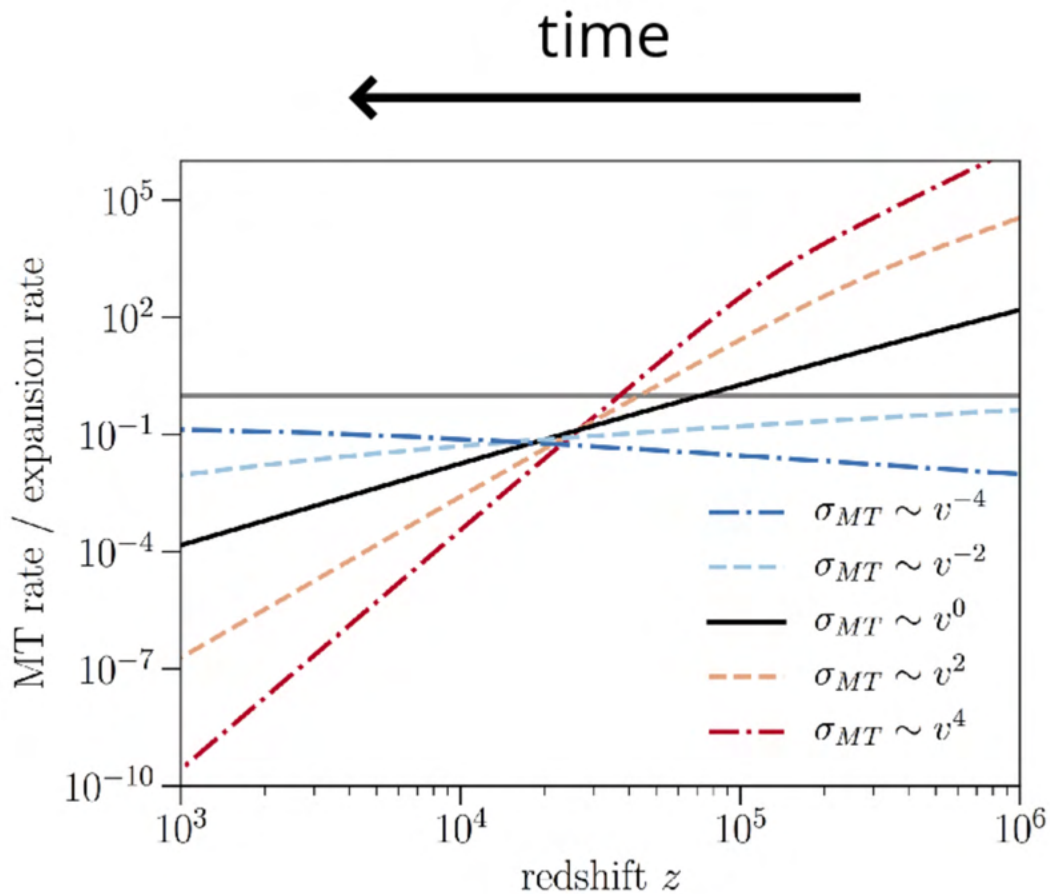
momentum-transfer
cross section

$$\sigma_{MT} = \sigma_0 v^n$$

↓

momentum-transfer rate

$$R_\chi = a\rho_{\mathrm{b}} \frac{\mathcal{N}_n \sigma_0}{m_\chi + m_{\mathrm{b}}} \left(\frac{T_\chi}{m_\chi} + \frac{T_b}{m_{\mathrm{b}}} \right)^{(n+1)/2}$$



See also: Boehm+ (2002), Chen+ (2002), Dubovsky+ (2004), Sigurdson+ (2004), Dvorkin+ (2014);

Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018).

Non-relativistic EFT in a nutshell

Goal:

Model-independently categorize pheno at low energy.

Method:

Instead of a model, use Galilean Hermitian invariants:

relative particle velocity $\vec{v}_\perp = \vec{v} + \vec{q}/2\mu_{p\chi}$

momentum transfer $i\vec{q}$

spins $\vec{S}_\chi \quad \vec{S}_p$

and construct non-relativistic operators for elastic scattering through a scalar or a vector mediator, up to second order in momentum transfer.

Result: Total of 14 operators (free: coupling and DM mass).

Fan et al, 2010; Fitzpatrick et al, 2012; Anand et al, 2013

EFT in cosmological context

theory → differential cross section → momentum-transfer cross section

$$\mathcal{O}_i(m_\chi, c_i) \longrightarrow \frac{d\sigma}{d\Omega} \longrightarrow \boxed{\sigma_{MT}(v^n)} = \int d\Omega \frac{d\sigma}{d\Omega}(1 - cos\theta)$$

$$\longrightarrow R_\chi \longrightarrow \text{Boltzmann Eqs.} \longrightarrow C_\ell, P(k)$$

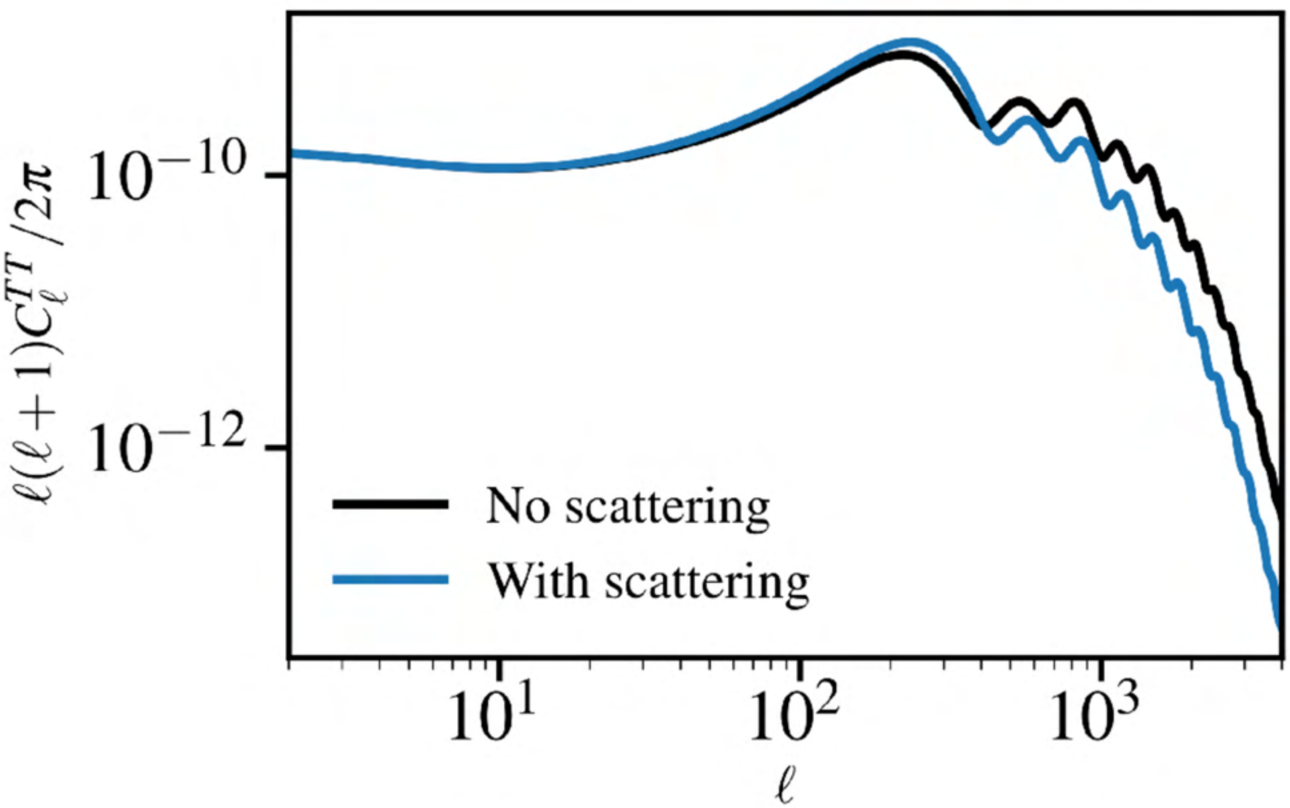
momentum-transfer rate

evolution of cosmological perturbations

observable!

Boddy and VG (2018)

CMB anisotropy with IDM



See also: Boehm+ (2002), Chen+ (2002), Dubovsky+ (2004), Sigurdson+ (2004), Dvorkin+ (2014);

Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018).

Cosmology with DM-baryon elastic scattering

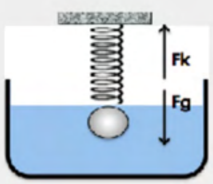
Heat and momentum transfer between DM and baryons affects:

Thermal history

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + \underline{2R'_\chi}(T_b - T_\chi)$$

$$\dot{T}_b = -2\frac{\dot{a}}{a}T_b + \frac{2\mu_b}{m_\chi}\frac{\rho_\chi}{\rho_b}\underline{R'_\chi}(T_\chi - T_b) + \frac{2\mu_b}{m_e}R_\gamma(T_\gamma - T_b)$$

Matter distribution



$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}, \qquad \dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2},$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + \underline{R_\chi}(\theta_b - \theta_\chi),$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b}\underline{R_\chi}(\theta_\chi - \theta_b)$$

See also: Boehm+ (2002), Chen+ (2002), Dubovsky+ (2004), Sigurdson+ (2004), Dvorkin+ (2014);

Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018).

EFT in cosmological context

unknown params

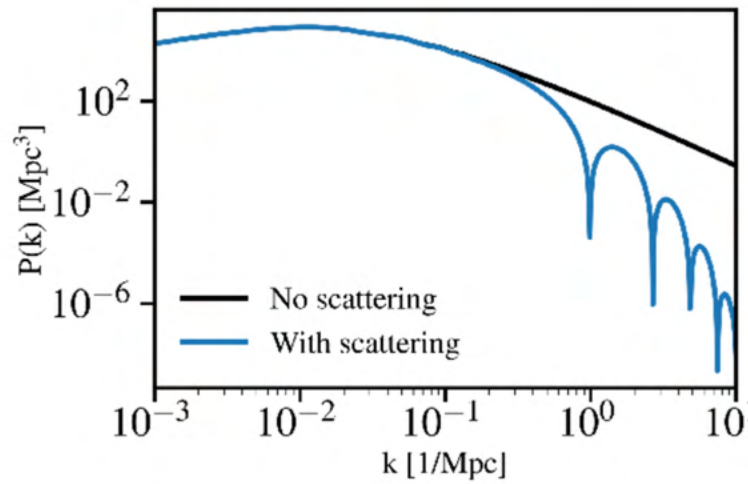
theory

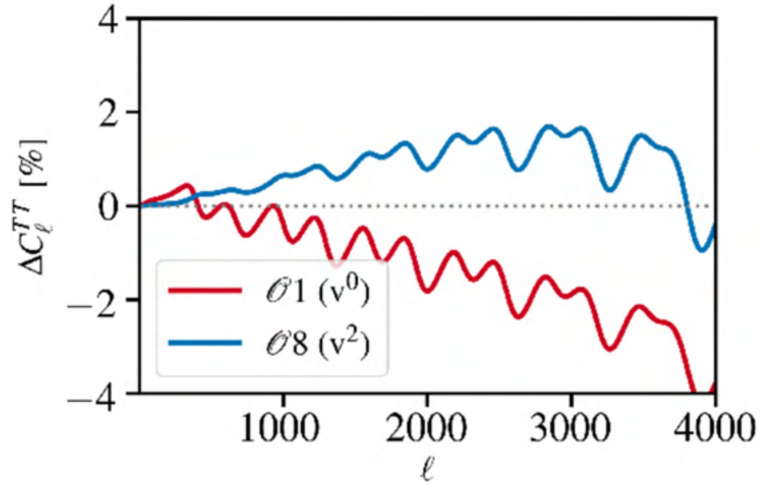
$$\mathcal{O}_i(m_\chi, c_i) \rightarrow$$

observables

$$P(k)$$

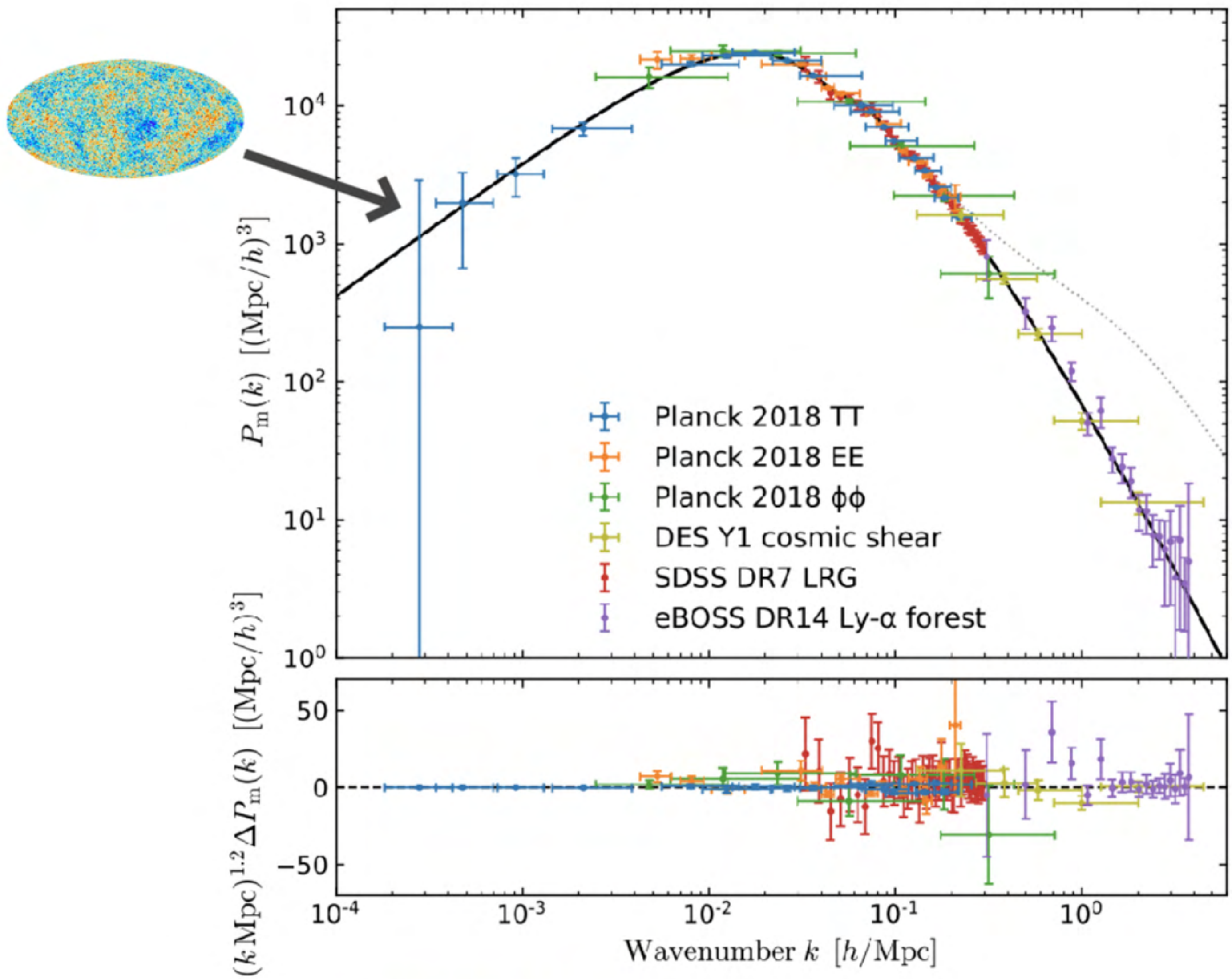
$$C_\ell$$





https://arxiv.org/abs/1801.08609

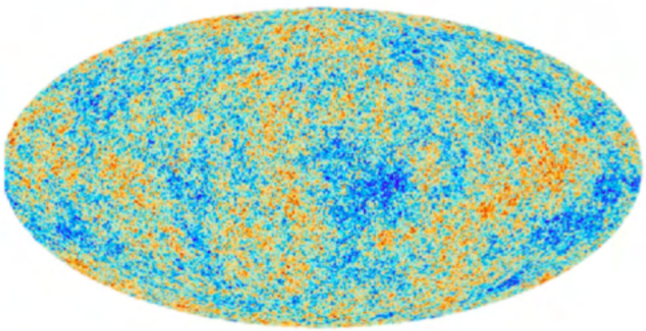
Matter distribution is captured on various scales by different visible tracers.



Chabanier+ 2019

CMB anisotropy

Observables = temperature + polarization + lensing

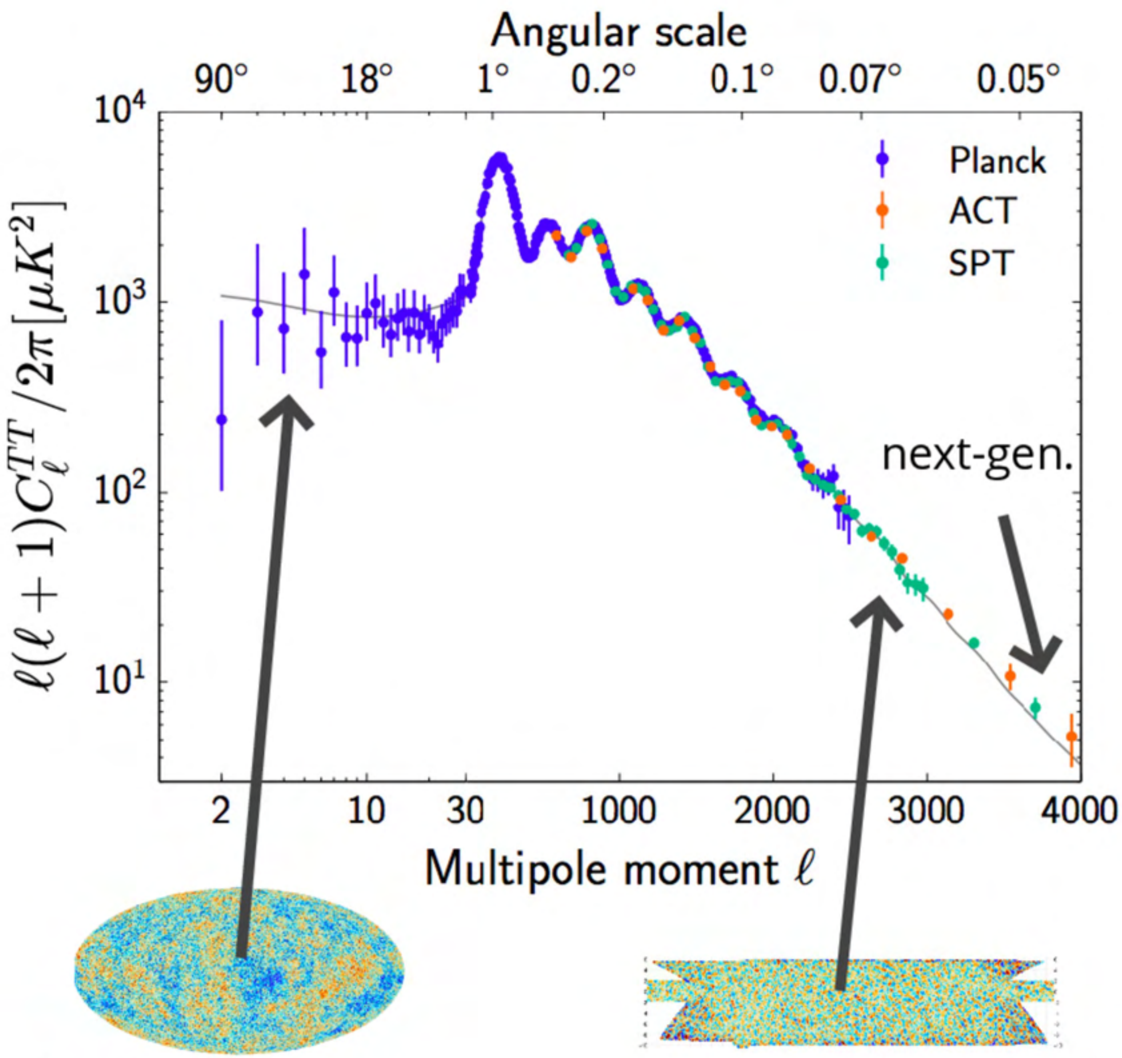


$$T(\widehat{n}) = \Sigma a_{\ell m} Y_{\ell m}(\widehat{n})$$

$$C_\ell^{TT} = \frac{1}{2\ell+1} \sum \langle |a_{\ell m}|^2 \rangle$$

https://arxiv.org/abs/1907.12875

https://arxiv.org/abs/2007.07289



Planck Collaboration 2015

Actpol Collaboration 2016

Question for you

A

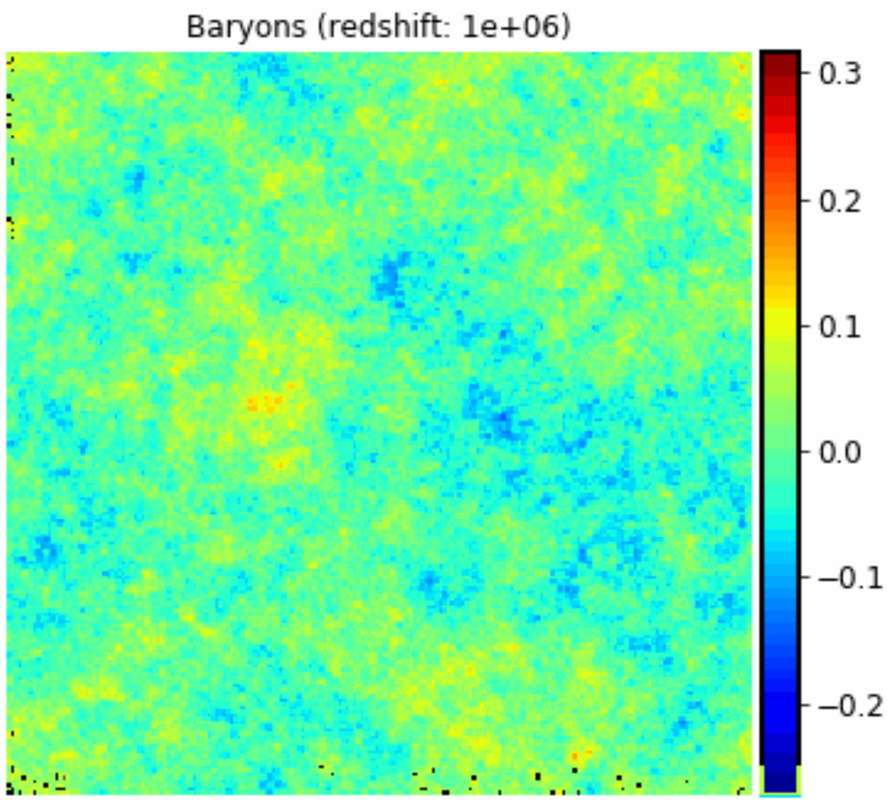
B

C

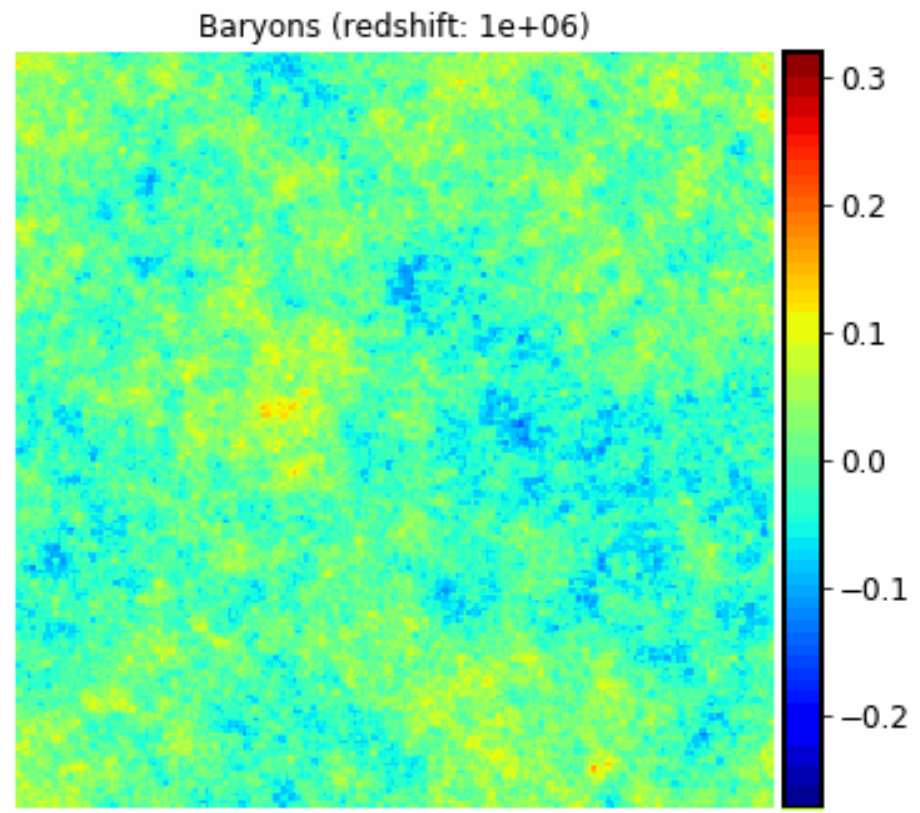
D

Question for you

Which panel features DM-baryon scattering?

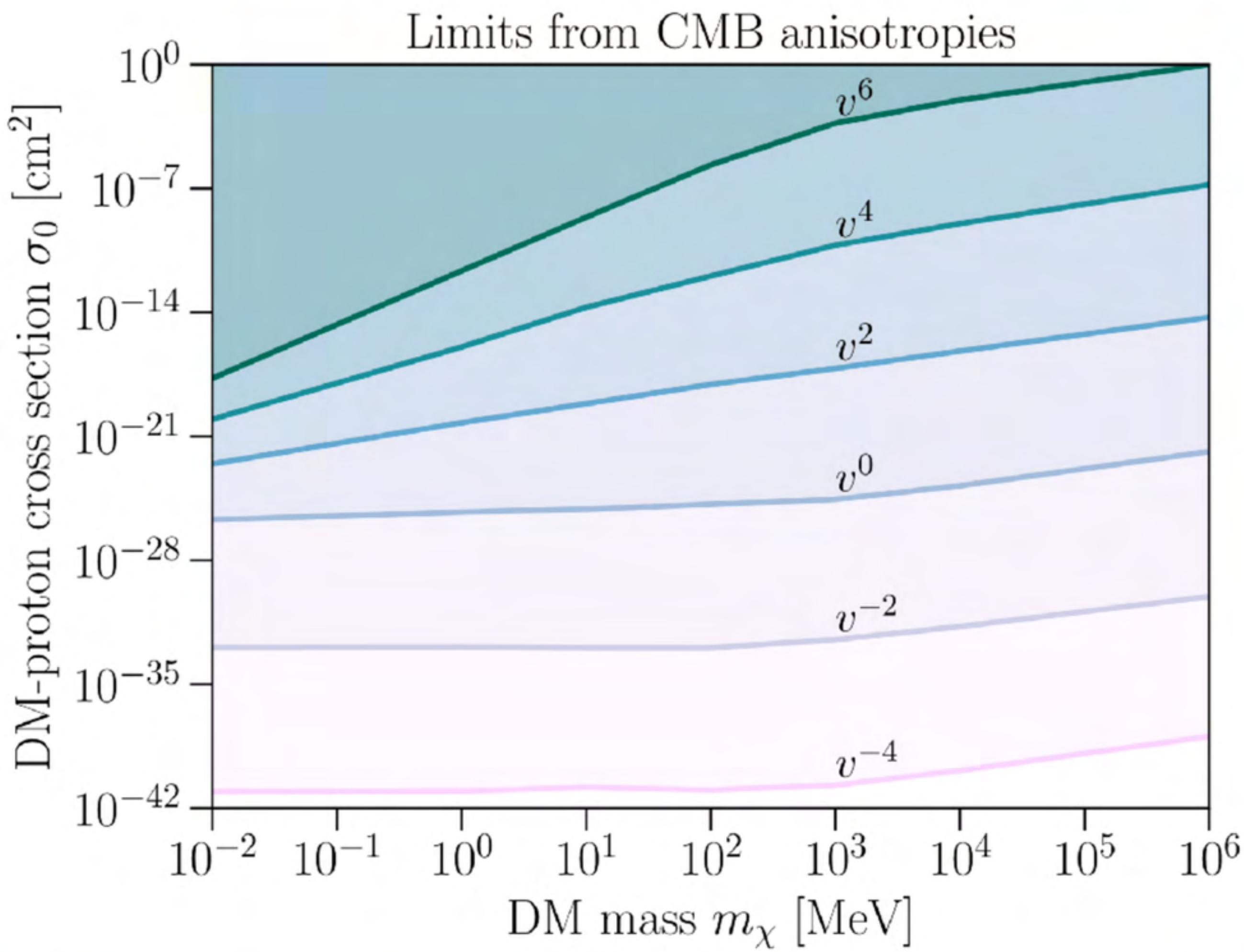


A



B

Planck limits on EFT of DM-proton scattering

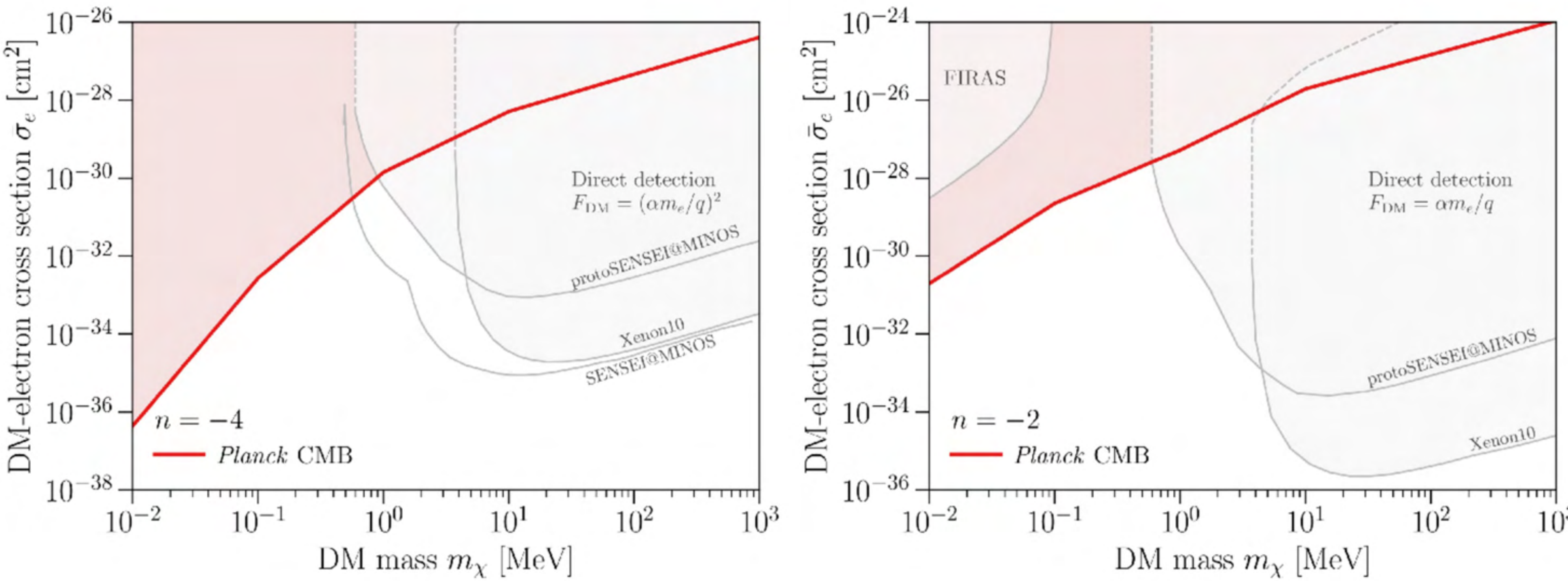


Nguyen+ (2021)

@age of the Universe ~1000 years:

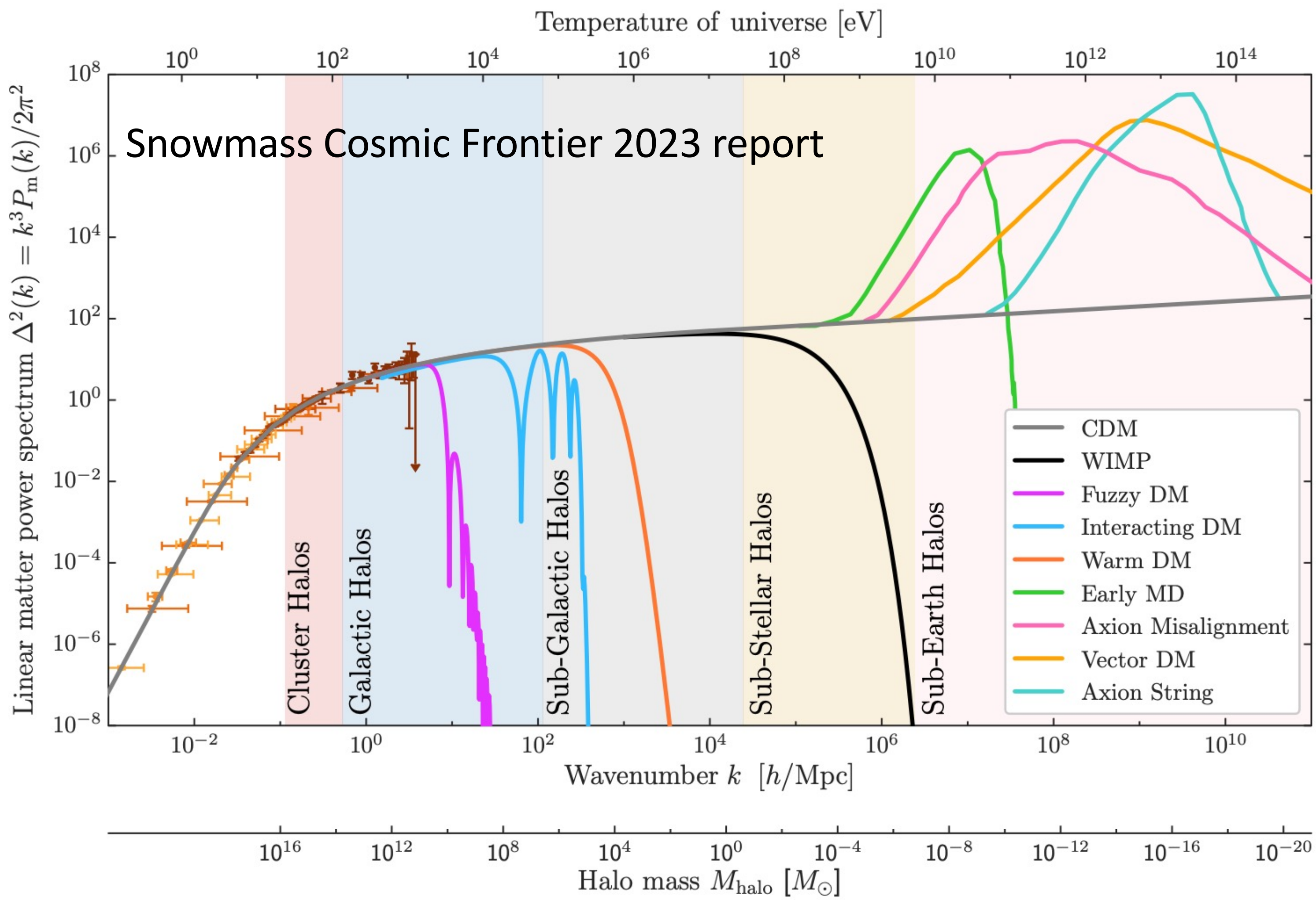
less than 1 in 100 000 proton scatterings is with DM.

Planck limits on DM-electron scattering



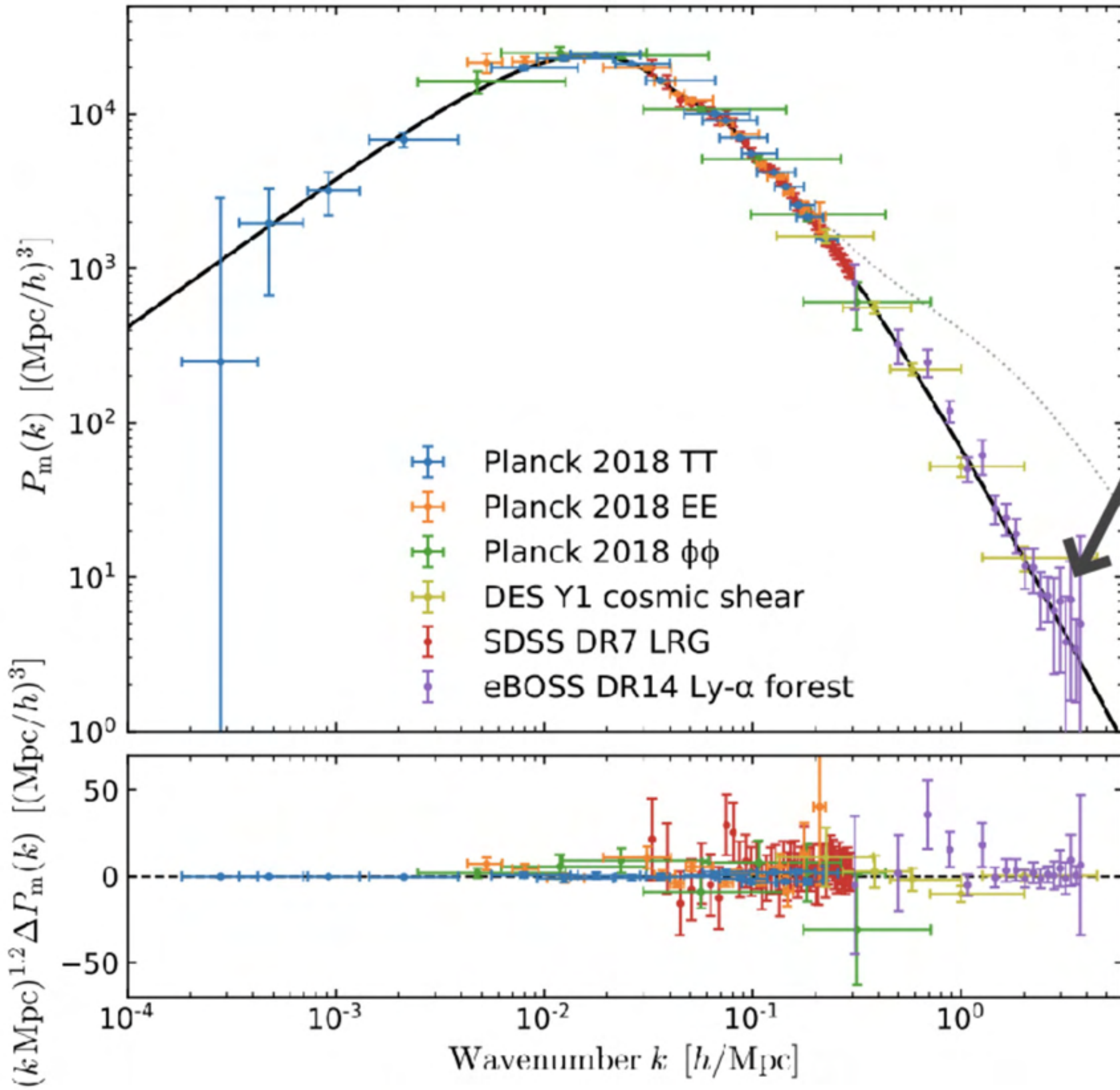
Nguyen+ (2021)

DM microphysics at the small-scale frontier



Lyman-alpha forest, dwarf galaxies, stellar streams, galaxy clustering, strong and weak lensing, intensity mapping, etc.

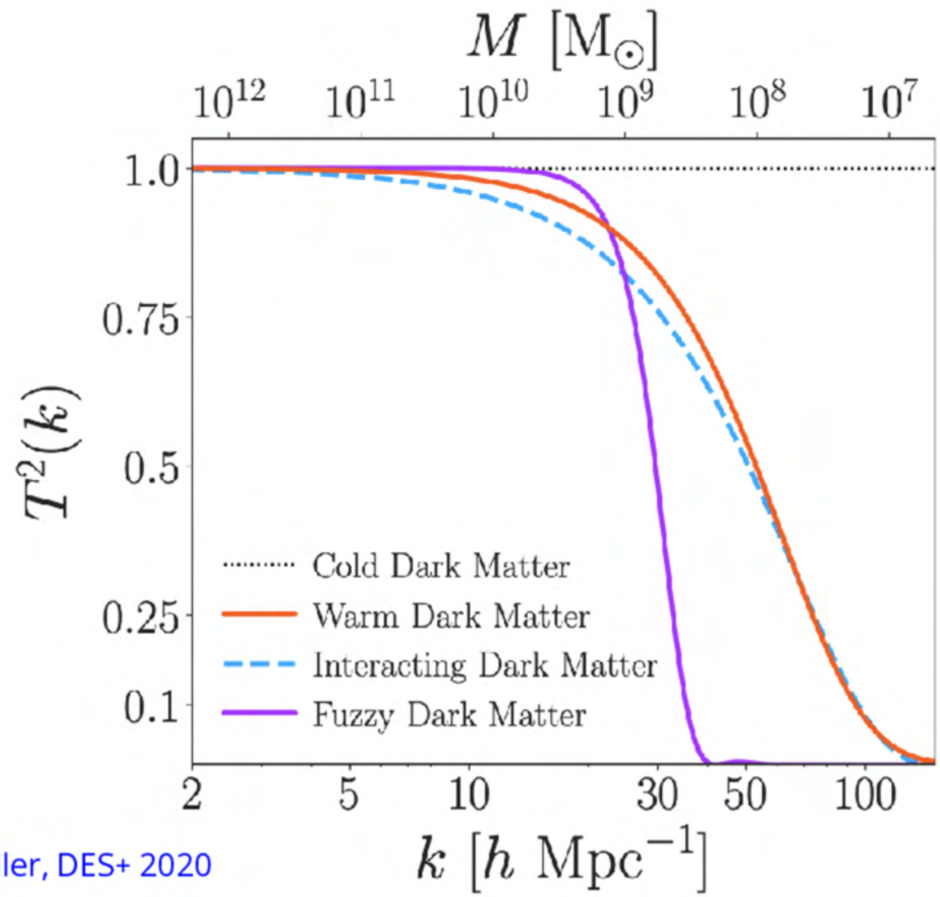
Observables : Lyman-alpha spectrum (from quasar spectra), dwarf galaxies, ultra-faint galaxies, stellar streams, galaxy clustering and lensing, etc.



Bullock and Boylan-Kolchin (2017)

Chabanier+ 2019

DM microphysics can suppress structure on small scales.



Nadler, DES+ 2020

Suppression of power at small scales leads to under-abundance of small dark matter halos throughout cosmic history.

Damping of Pk

Case studies

non-collisional damping

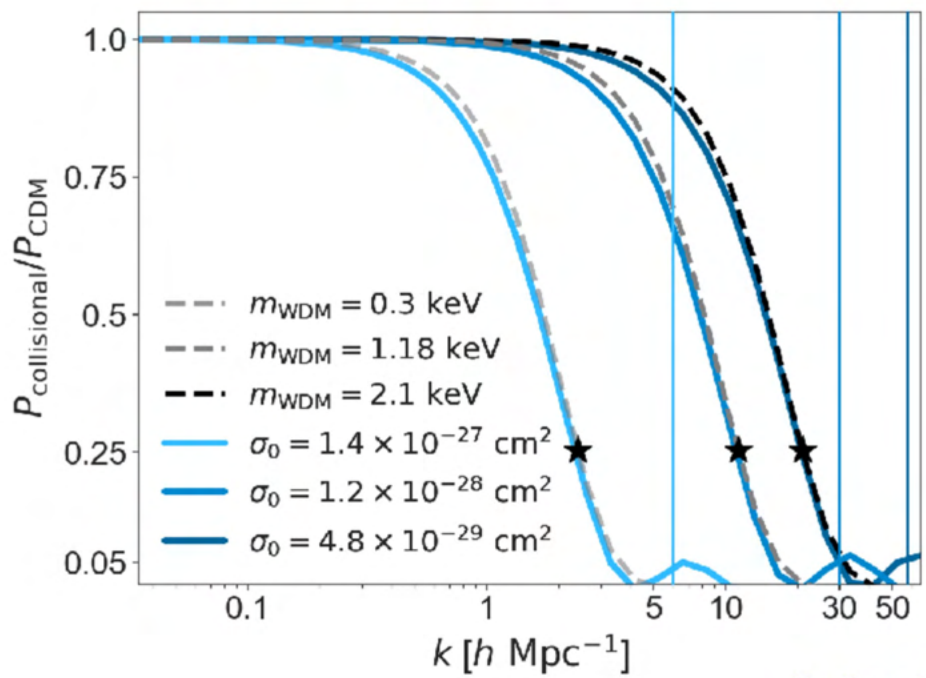
collisional damping

WDM

https://arxiv.org/abs/1702.01764
https://arxiv.org/pdf/1601.07553.pdf
https://arxiv.org/pdf/2008.00022.pdf
https://www.zora.uzh.ch/id/eprint/75587/1/20131701.pdf
https://arxiv.org/pdf/1603.03797.pdf

IDM

https://arxiv.org/abs/2010.02936
https://arxiv.org/abs/1904.10000
https://arxiv.org/pdf/astro-ph/0504112.pdf
https://arxiv.org/pdf/astro-ph/0309621.pdf
https://arxiv.org/pdf/astro-ph/0603373.pdf



Nadler+ 2019

WDM = (thermal relic) warm dark matter

WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

WDM = (thermal relic) warm dark matter

*just like neutrinos!

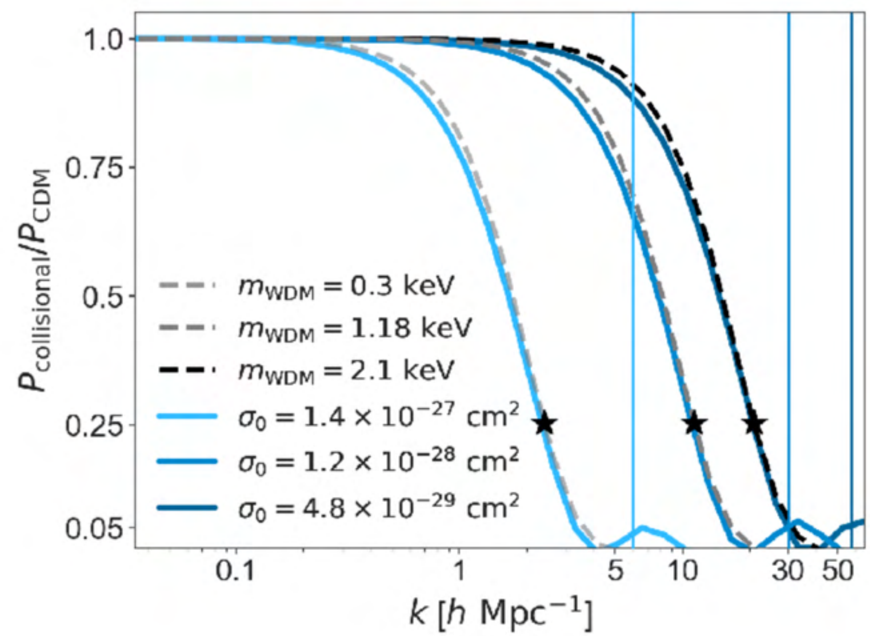
WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

WDM = (thermal relic) warm dark matter

WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

Free-streaming => **collisionless** damping of small-scale structure

$$\lambda_{FS} \approx \int_{\text{dec.}}^{\text{non-rel.}} c\,dt/a$$



Nadler+ 2019

WDM = (thermal relic) warm dark matter

WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

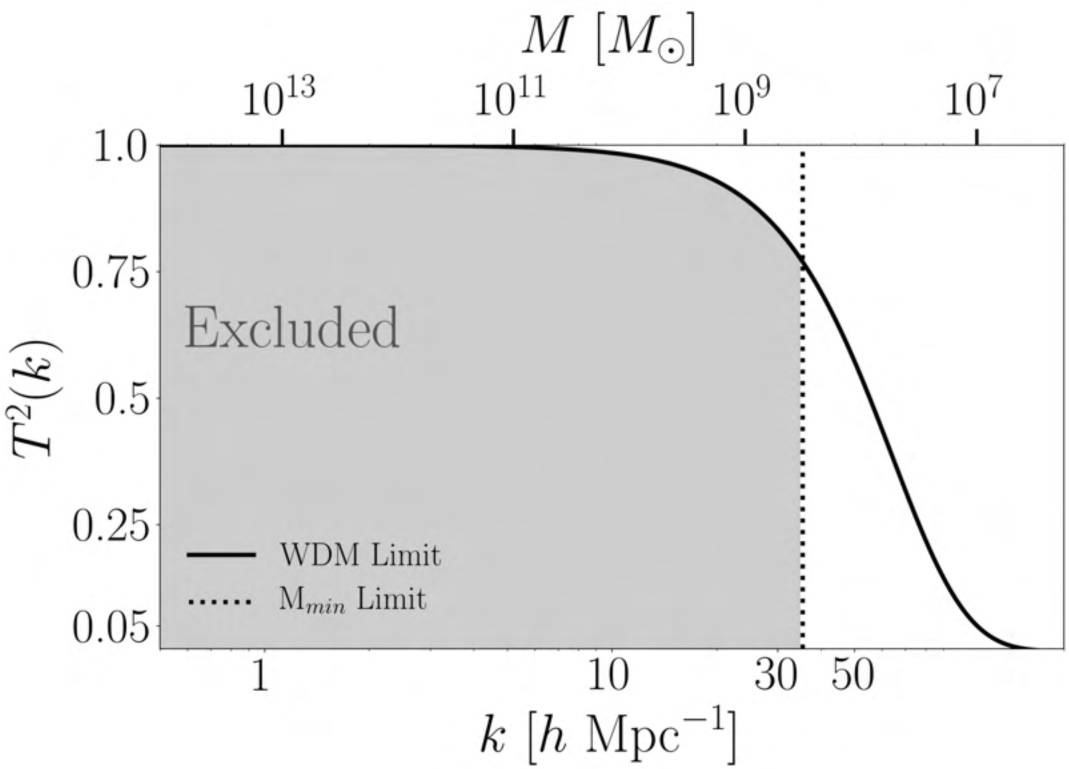
Free-streaming => **collisionless** damping of small-scale structure

Lovell+ 2014

WDM = (thermal relic) warm dark matter

Lower bounds (Lyman-alpha forest, Milky Way substructure, 95% confidence):

$$m_{\rm WDM} > 6.5\,{\rm keV}$$



$$\lambda_{\rm fs} \lesssim 10\ h^{-1}\,{\rm kpc}$$

https://arxiv.org/pdf/hep-ph/0612238.pdf

https://arxiv.org/pdf/1702.01764.pdf

Question for you

A

B

C

D

A B
C D

Question for you

Neutrinos are much lighter than WDM. Their transfer function is shown in top panel, WDM transfers are shown at the bottom.

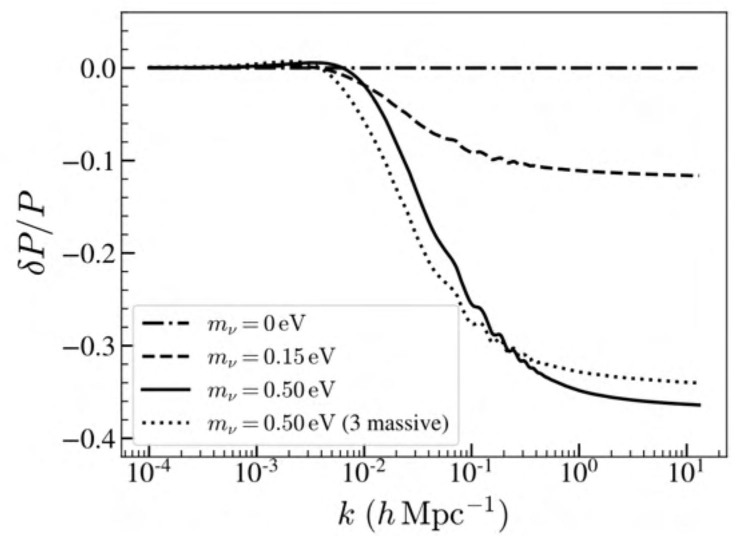
Why is the shape of the damping so different in the two cases?

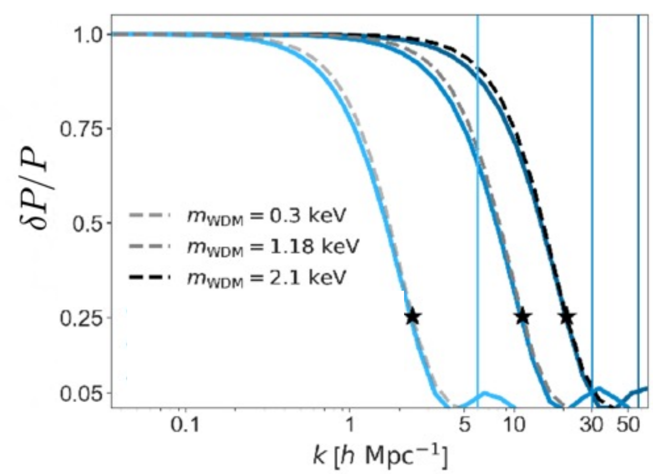
A) Because neutrinos are still weakly coupled to other particles, while WDM is not.

B) Because WDM has a different phase space density.

C) Because neutrinos contribute much less to the overall energy energy density than DM.

D) Because neutrinos decouple earlier and are thus colder than WDM.





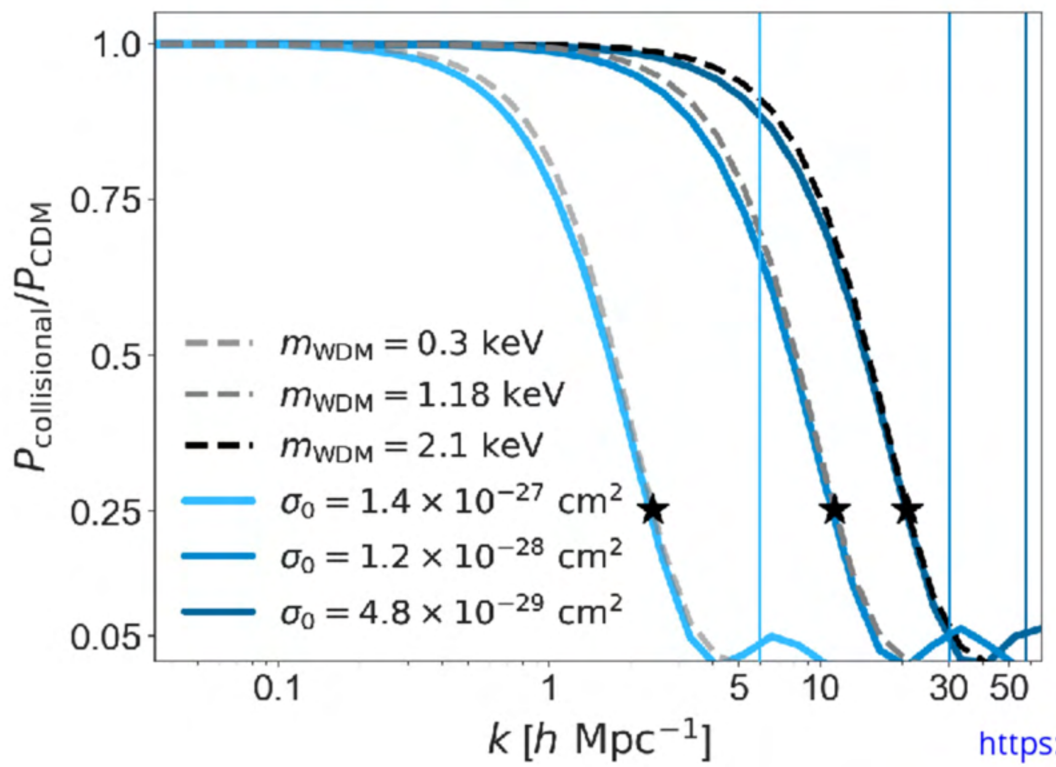
IDM = elastically interacting dark matter

Assumes elastic scattering at some point in cosmic history
(not necessary to be coupled at early times)

IDM = elastically interacting dark matter

Assumes elastic scattering at some point in cosmic history
(not necessary to be coupled at early times)

Interactions with photon-baryon fluid => **collisional** damping of small-scale structure



https://arxiv.org/pdf/2008.00022.

Teamwork time

Teamwork time

Estimate the comoving wavenumber k at which Pk is suppressed due to DM-baryon elastic scattering, assuming DM particle mass of 1 GeV and velocity-independent interaction cross section of 2e-28 cm^2. How does that scale compare to the scale of the modes corresponding to the smallest halos detected in galaxy surveys today?

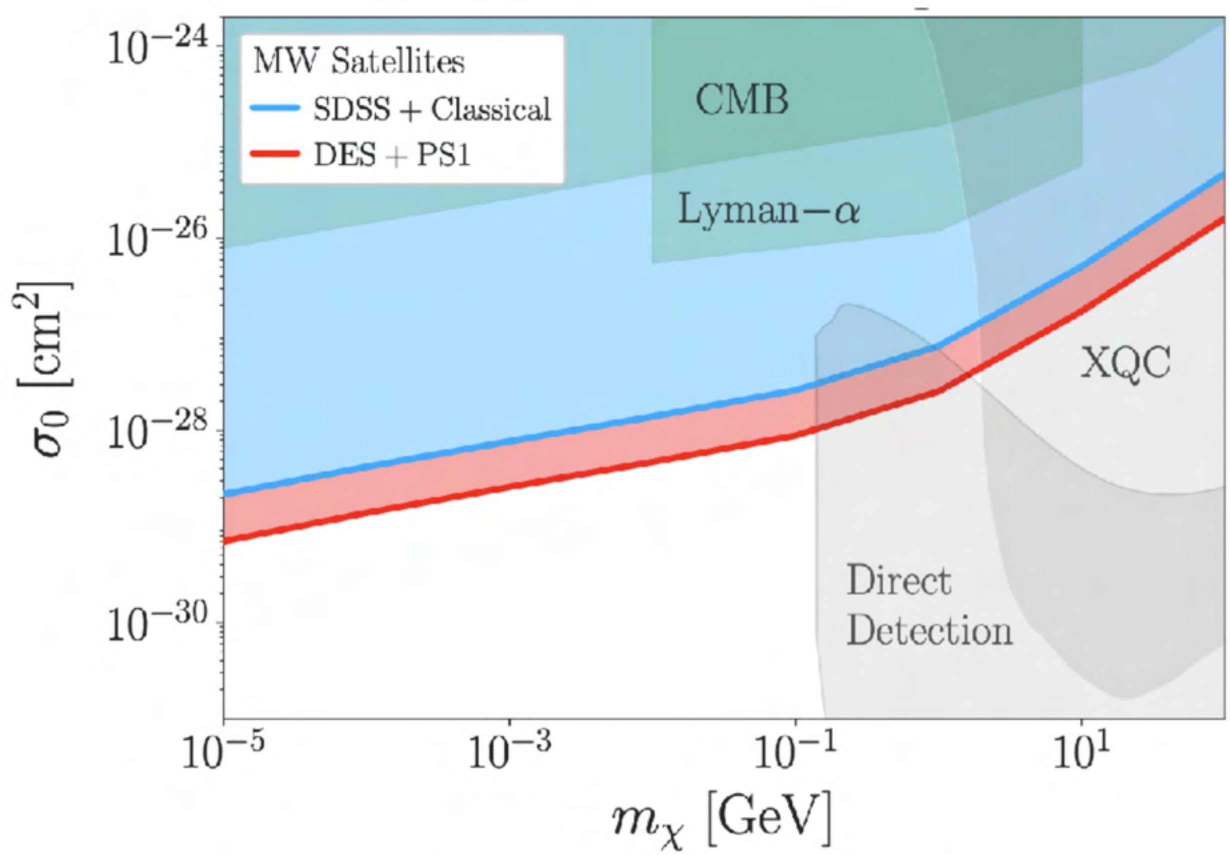
Hints: First, assume that DM is tightly coupled to baryons until the rate of scattering (per DM particle) drops below the Hubble rate, at which point instantaneous decoupling occurs. Assume that decoupling takes place during radiation domination. Take the average mass of baryons to be about 1GeV (proton mass). What was the size of the mode that entered the horizon at this time?

To relate this size to a halo mass scale, assume a spherical collapse of a small overdensity, 2\pi/k in diameter; assume that all the mass enclosed within that diameter ends up in one halo. Remember that ~25% of the critical density today is in dark matter. Also remember that the comoving horizon is aH, where H=Hubble parameter. Assume a flat universe.

https://arxiv.org/pdf/1904.10000.pdf https://github.com/eonadler/DMBaryonScattering/

IDM limits from MW Satellites (DES+PS1)

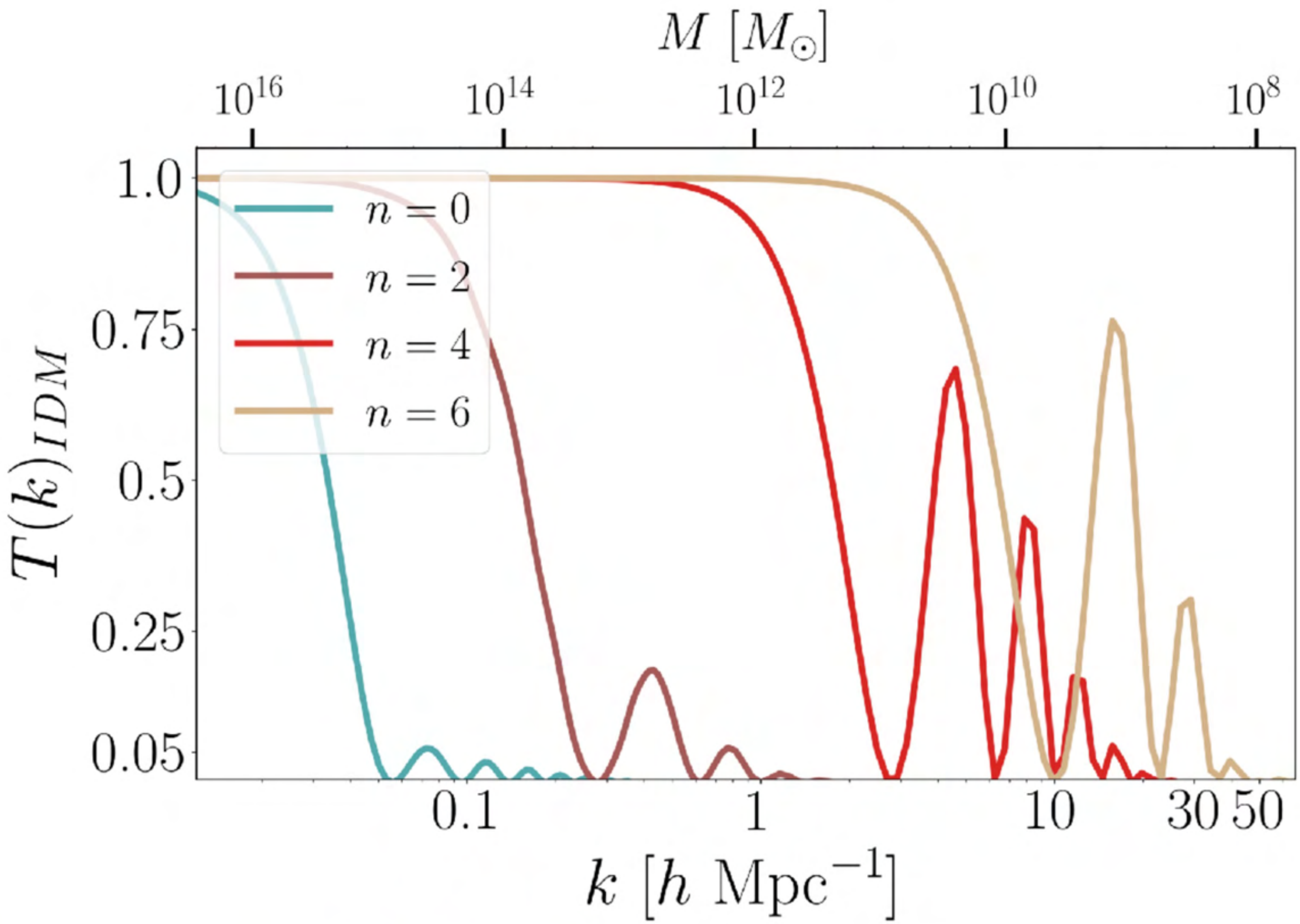
v-independent scattering



Including: realistic modeling of galaxy-halo connection and mock observations of the satellite abundance (luminosity, size, and radial distribution)

Nadler, + (ApJ Letters 2019); DES collaboration, + (2020)

DM-proton scattering: $\sigma \sim v^n$



Maamari, + (ApJ Letters 2020), arXiv:2010.02936

see also: 2008.00022

What if DM is NOT a thermal relic?

Case of sterile neutrinos

Dodelson-Widrow mechanism

$$\nu_4 = \cos\theta\, \nu_s + \sin\theta\, \nu_a$$

Dodelson-Widrow mechanism

$$\nu_4 = \cos\theta\,\nu_s + \sin\theta\,\nu_a$$

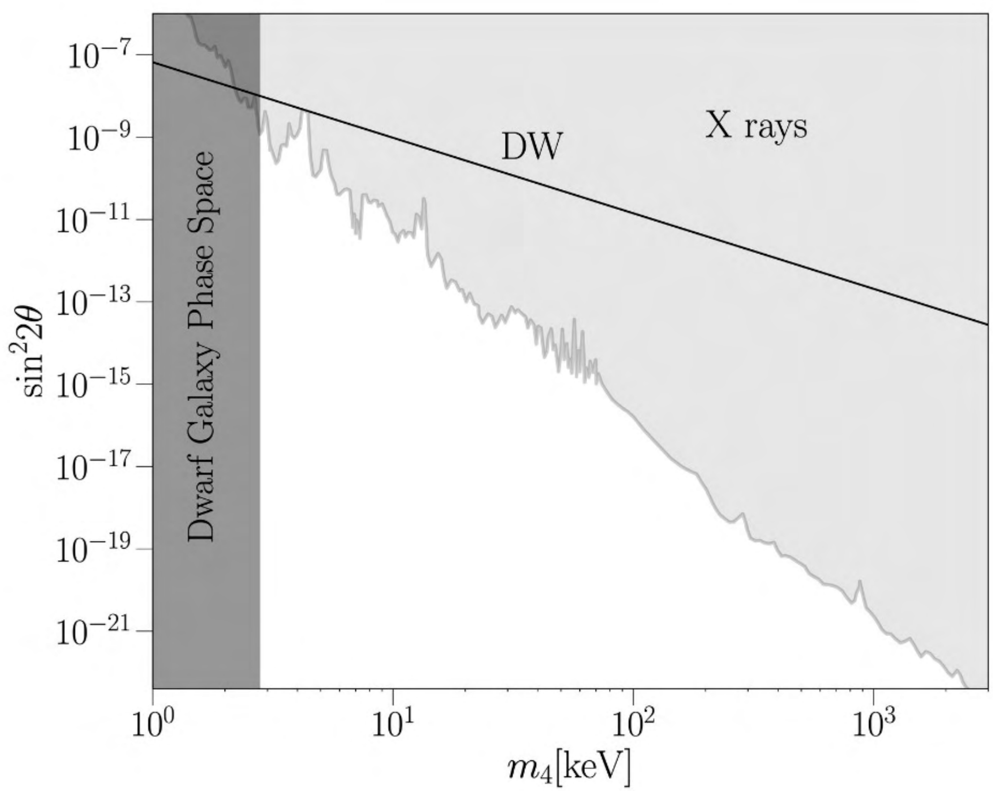
$$n \leftrightarrow p + e^- + \nu_e$$

$$p + e^- \leftrightarrow \nu_e + \mathrm{n}$$

$$p + \nu_e \leftrightarrow e^+ + n$$

Dodelson-Widrow mechanism

$$\nu_4 = \cos\theta\,\nu_s + \sin\theta\,\nu_a$$



…ruled out, due to decay and X-ray production.

Question for you

A

B

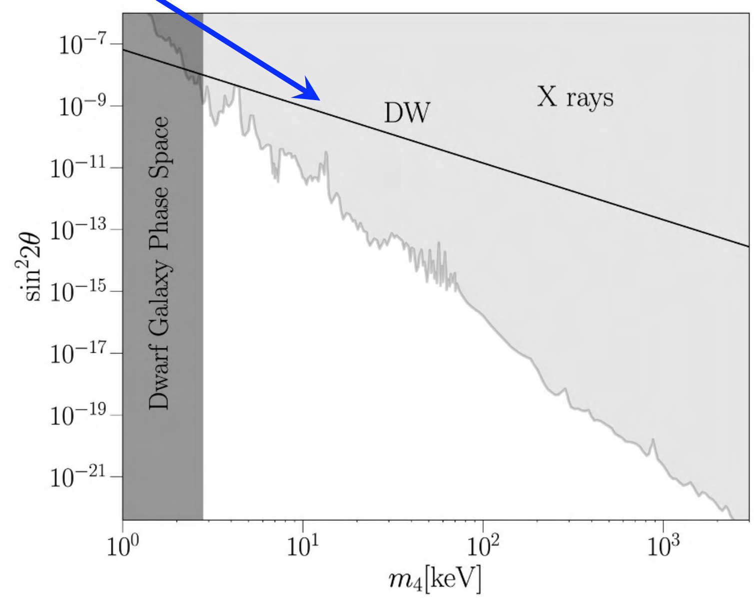
C

D

A B
C D

Question for you

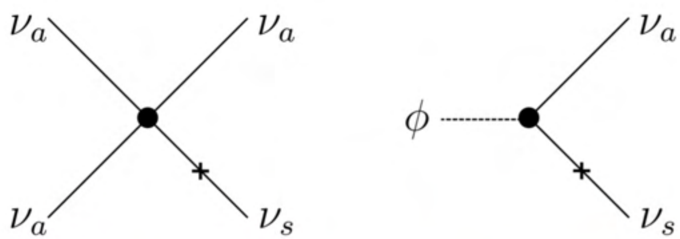
How will the abundance line in this plot change, if only 10% of DM are sterile neutrinos?



A) It will move up.
B) It will move down.
C) It depends on the cosmology.

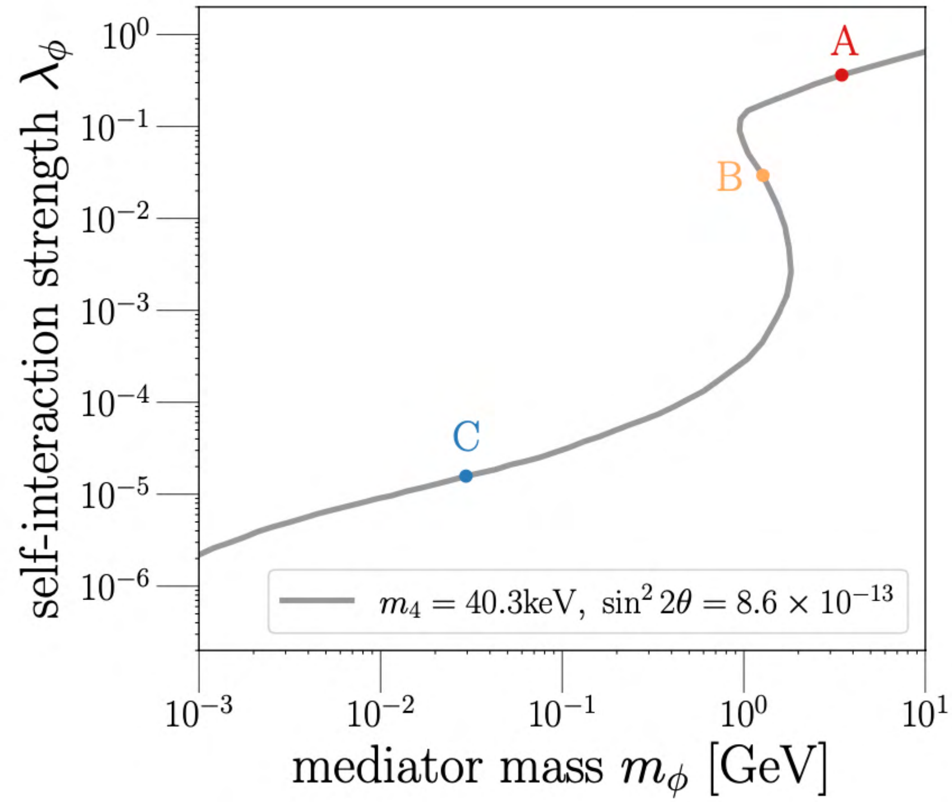
Sterile neutrinos + **neutrino self-interactions**

$$\mathcal{L} \supset \frac{\lambda_\phi}{2} \nu_a \nu_a \phi + \text{h.c.}$$



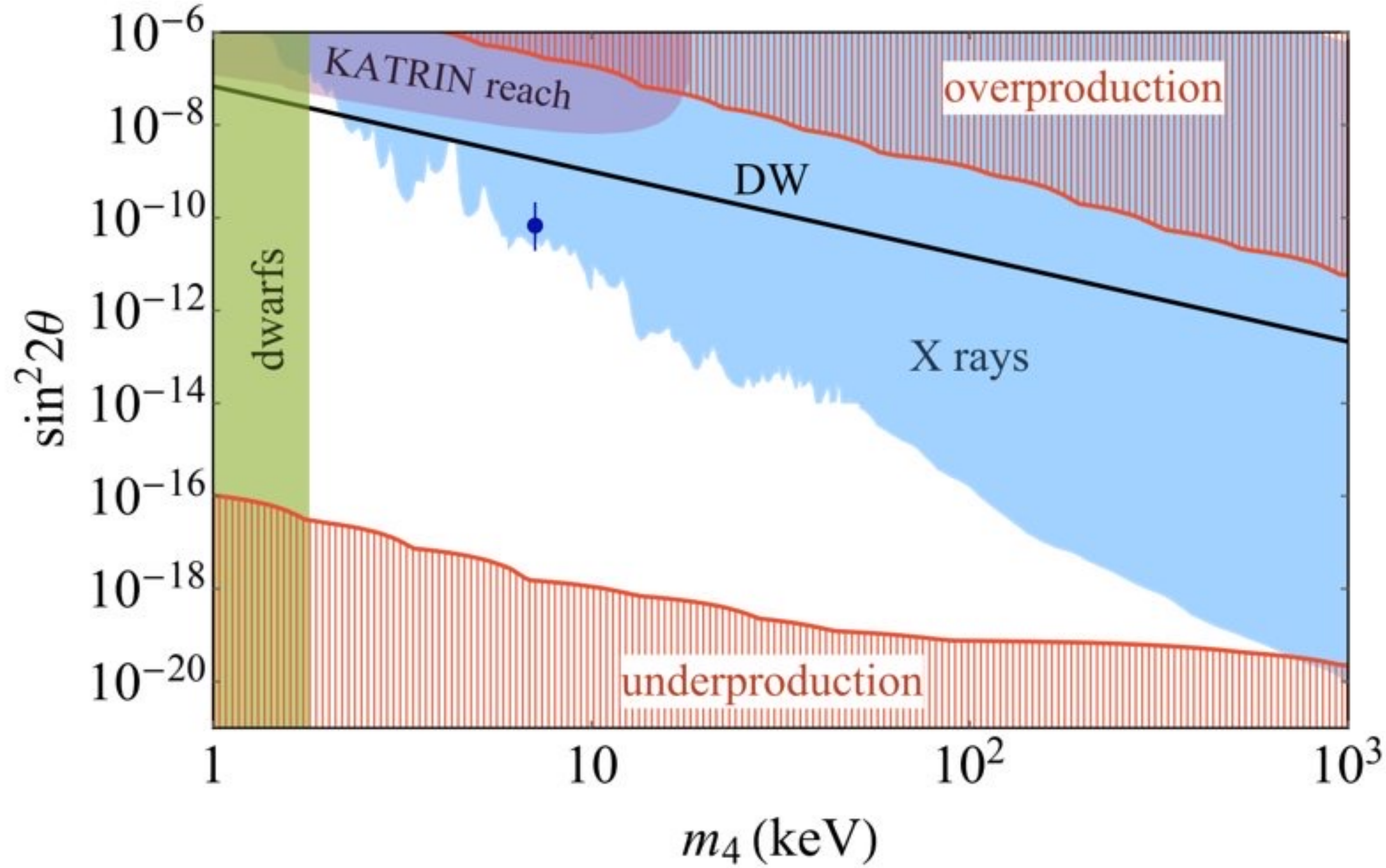
Case A (heavy ϕ)

Case B (light ϕ)
Case C (light ϕ)



de Gouvea + (2019), etc.

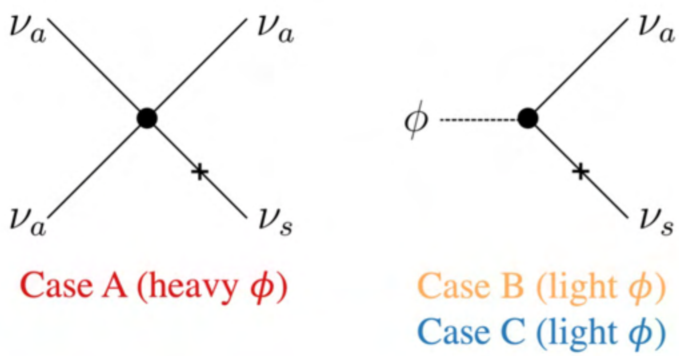
Sterile neutrinos + **neutrino self-interactions** = allowed?

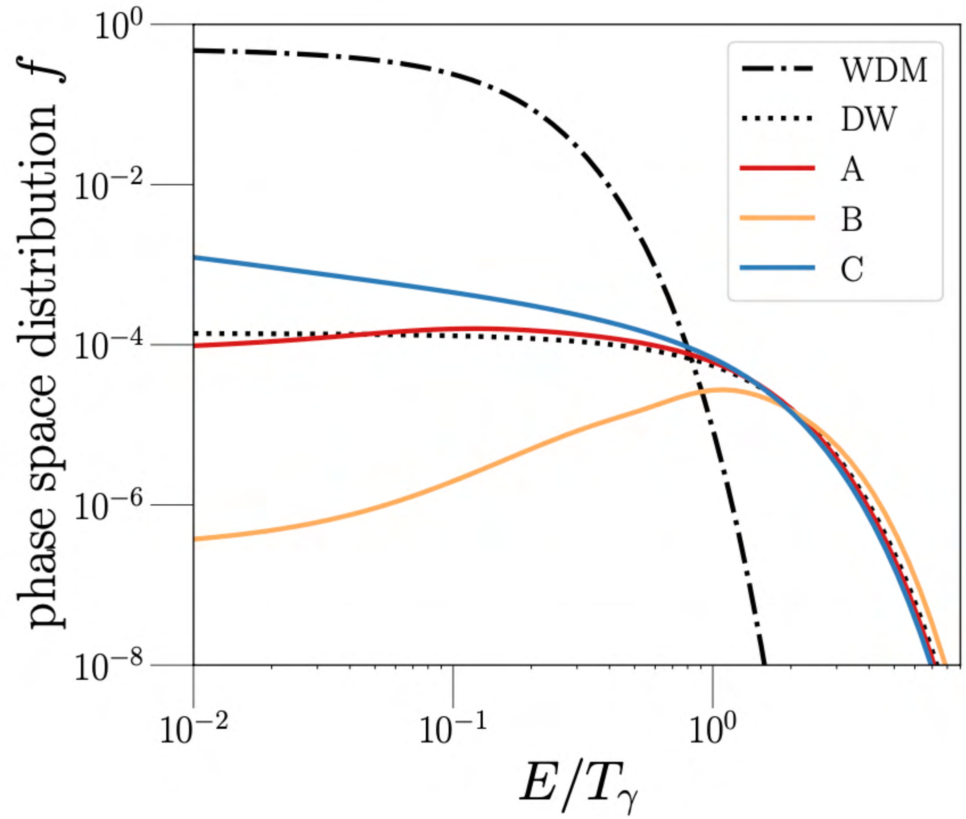


DM mass

de Gouvea + (2019), etc.

Sterile neutrinos + **neutrino self-interactions**

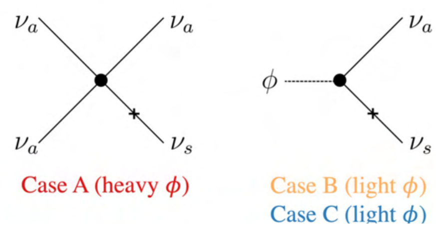


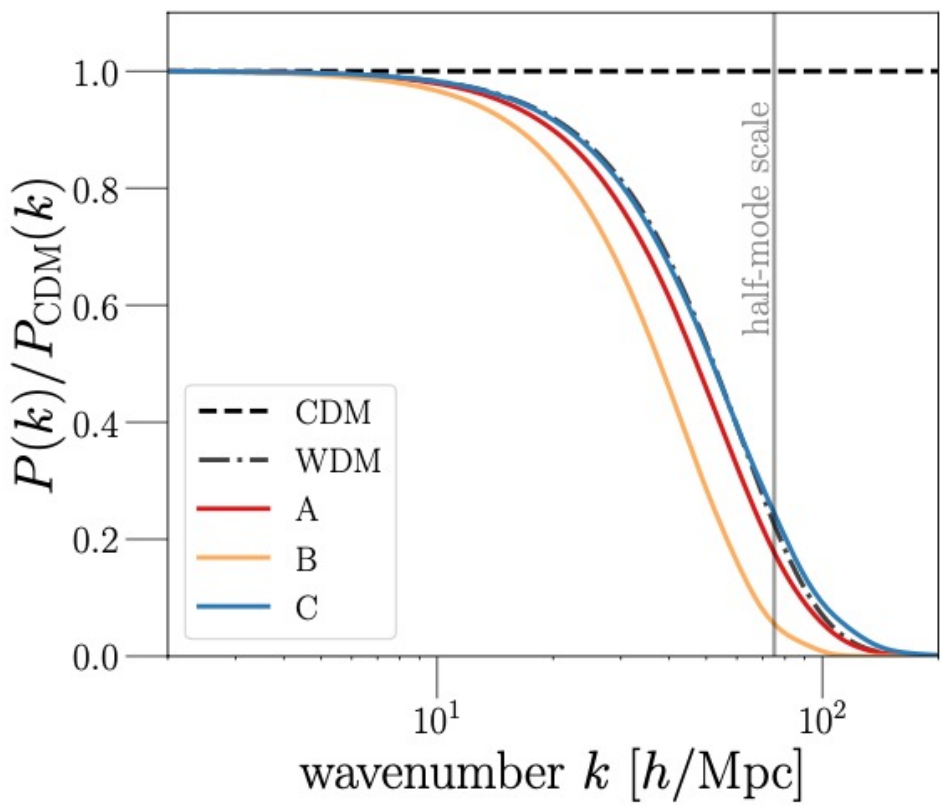


NB: Class assumes specific PSD!!

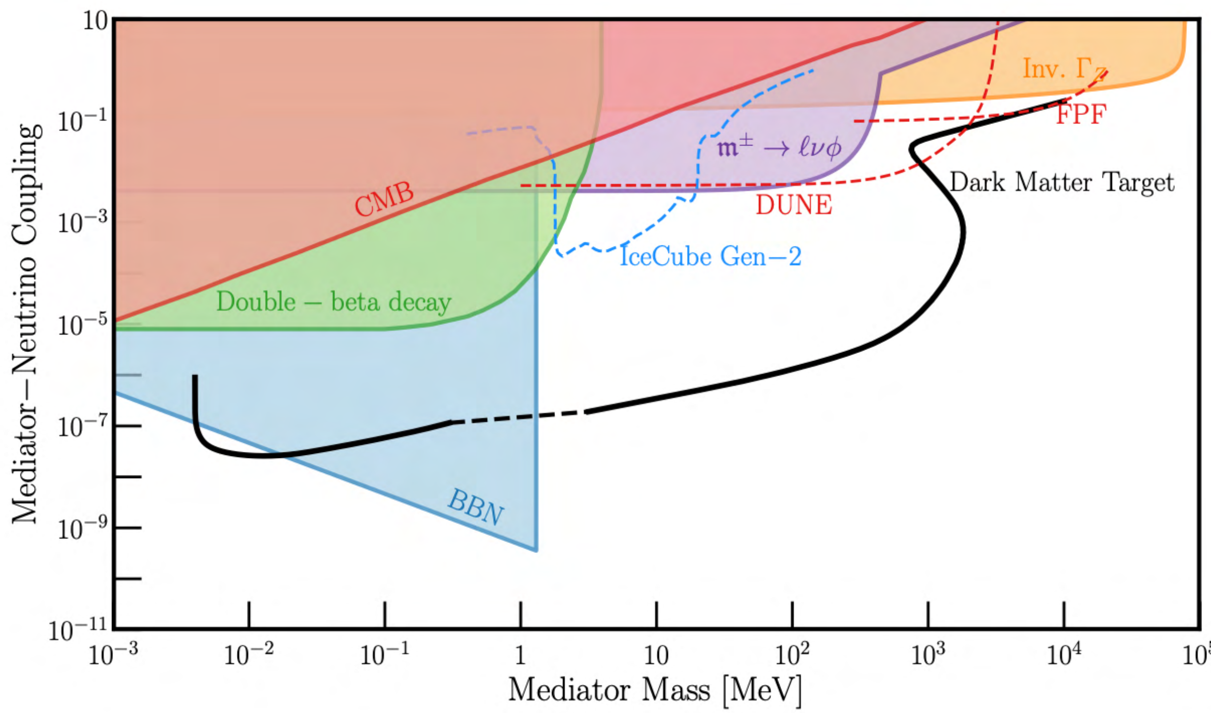
de Gouvea + (2019), etc.

Power suppression from sterile neutrino free streaming:





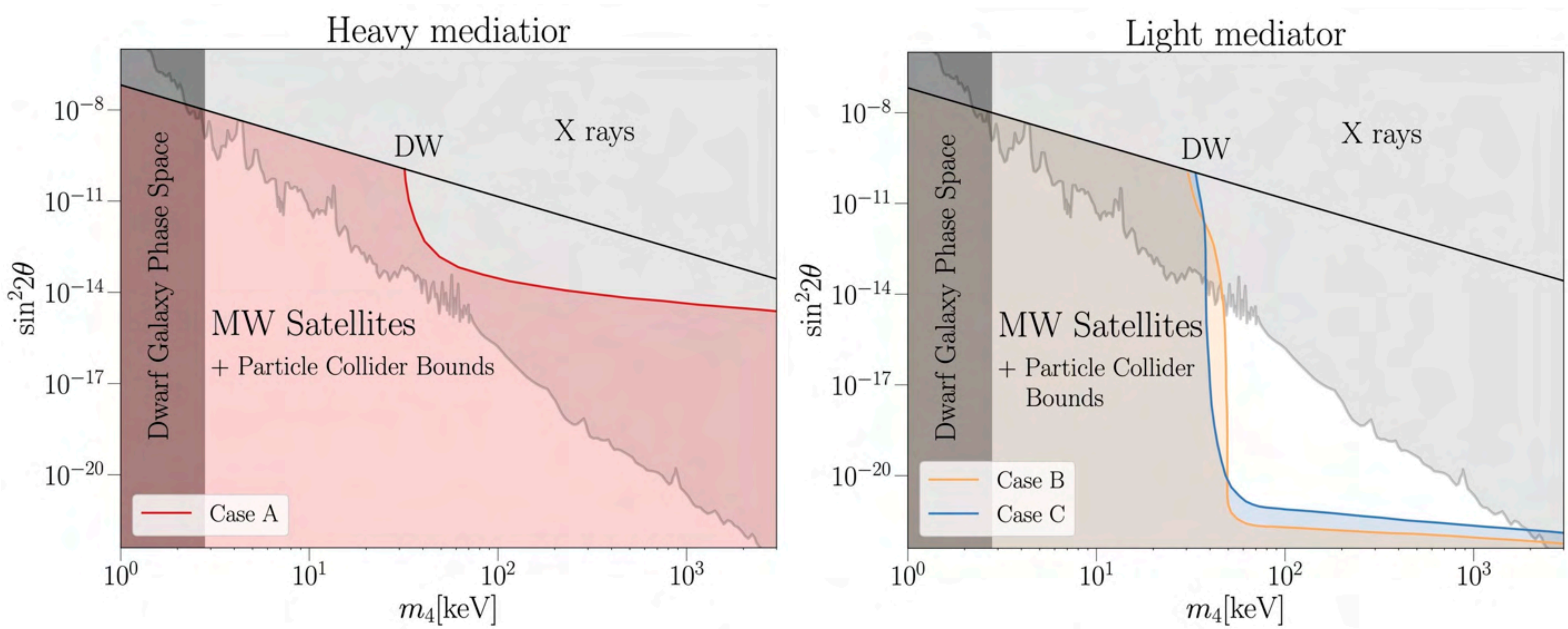
Lab bounds on neutrino self-interactions:



https://arxiv.org/pdf/2203.01955.pdf

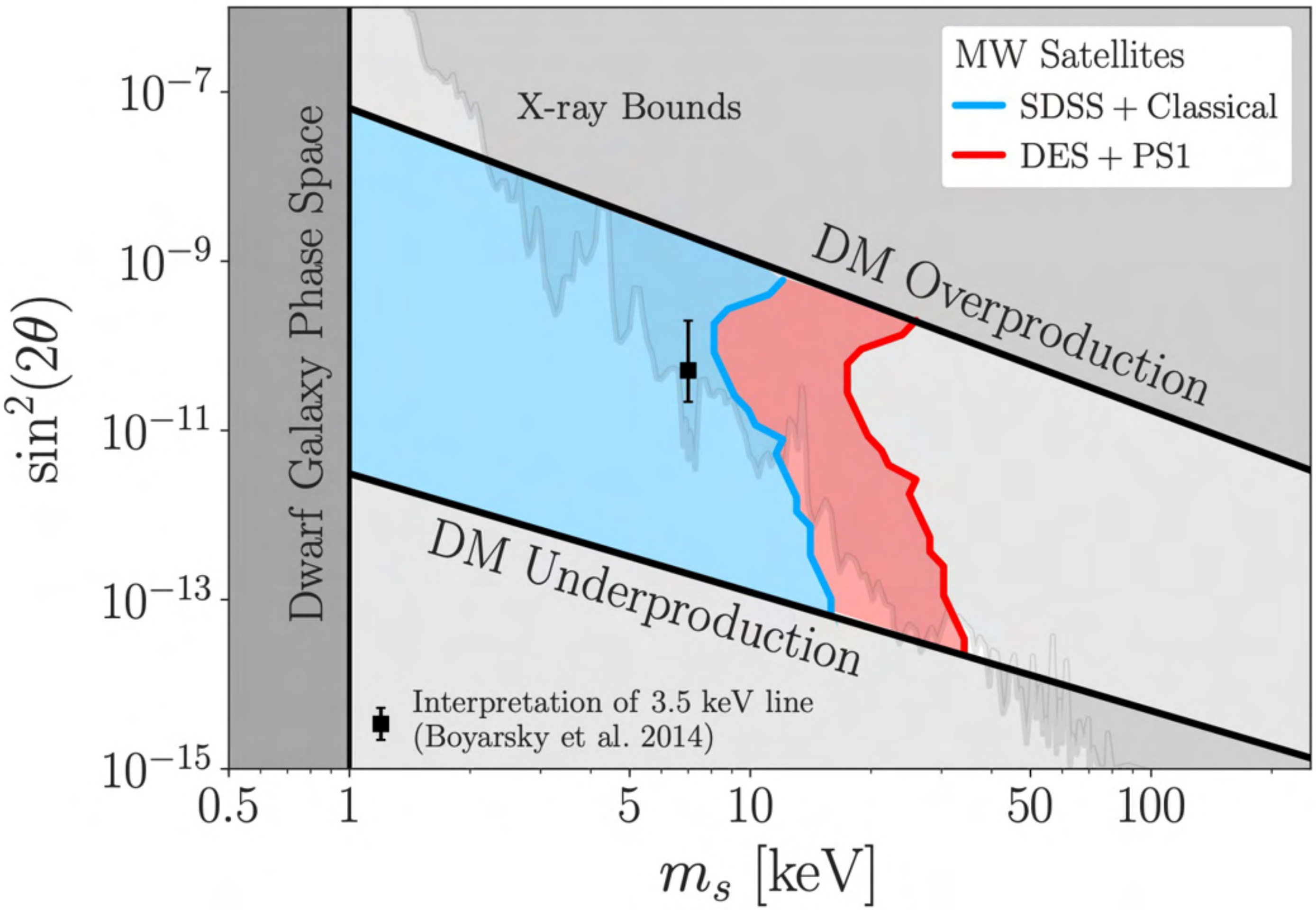
Hard to escape thermal constraints…

Mediators > 1GeV are ruled out.



An, Gluscevic, Nadler, Zhang (2023)

Bounds on resonantly-produced sterile neutrino



Nadler, DES+, 2021
For a review: https://arxiv.org/pdf/1602.04816.pdf

Near-field cosmology

Using small-scale structure to study fundamental physics

Galaxy surveys: **SDSS, DES;** Upcoming: **LSST,DESI,...**

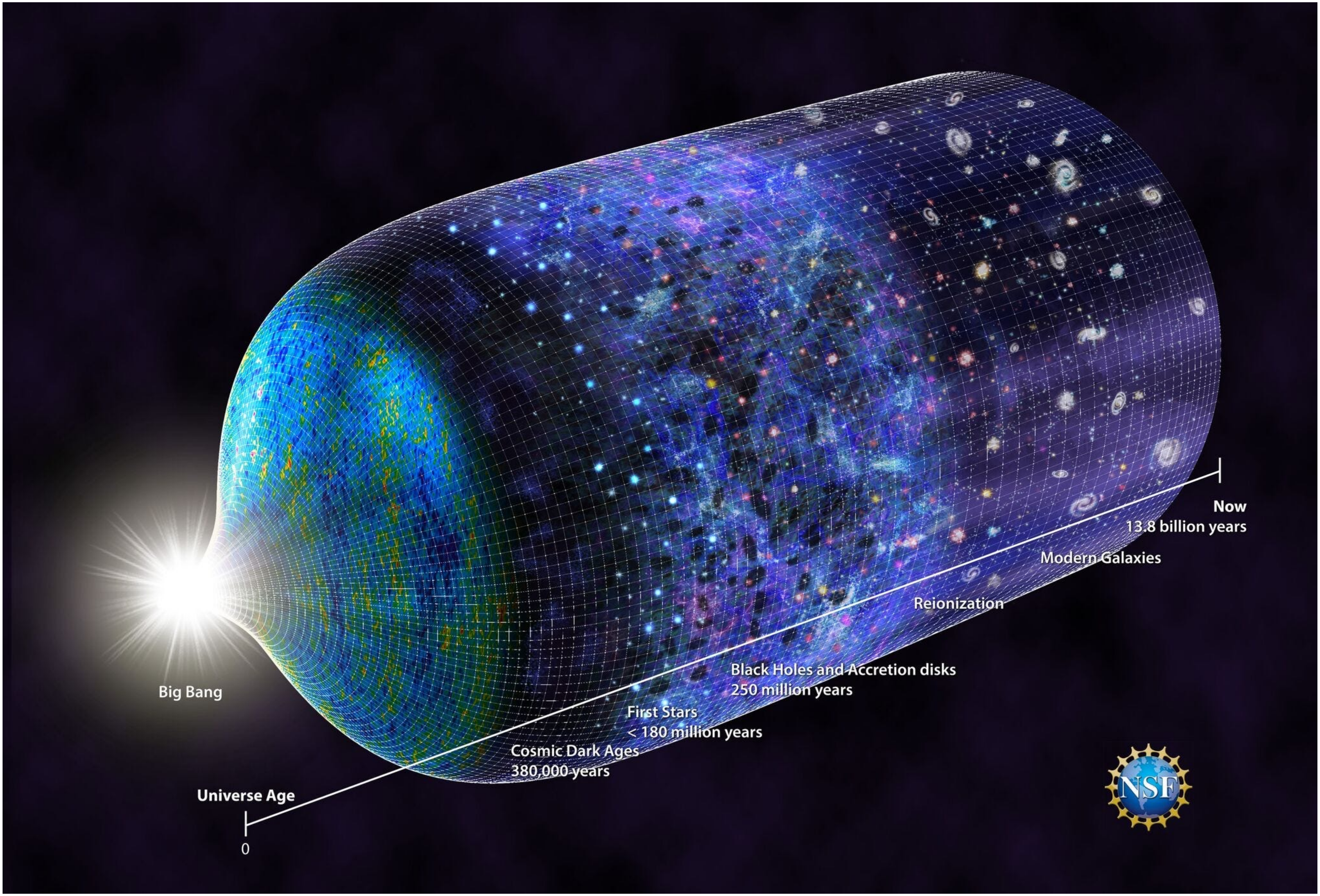
Challenges:

- **Observational**: smaller halos host fainter galaxies [completeness correction]
- **Theoretical**: understanding of baryonic physics and substructure formation [galaxy-halo connection]
- **Analysis**: fast forward modeling of observables [parameter inference]

BONUS!

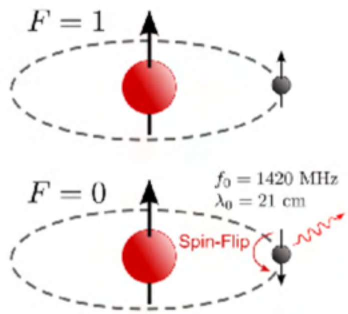
IV. Thermal history

lessons from 21-cm cosmology



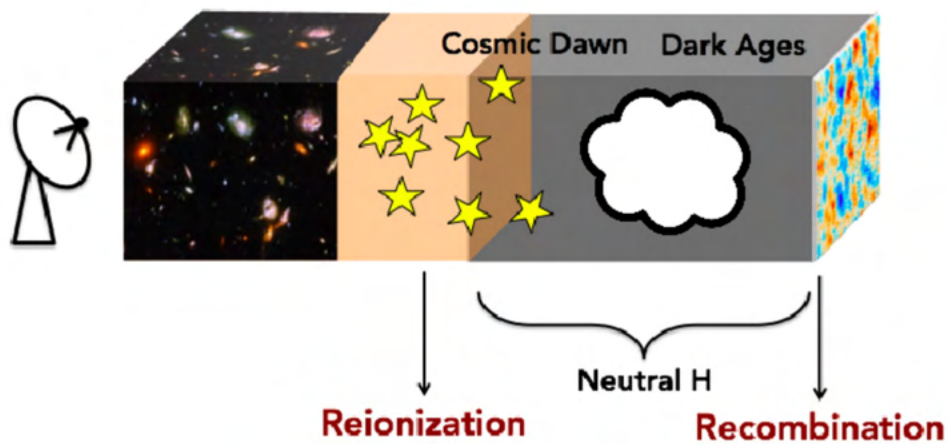
Big Bang
Universe Age
0
Cosmic Dark Ages
380,000 years
First Stars
< 180 million years
Black Holes and Accretion disks
250 million years
Reionization
Modern Galaxies
Now
13.8 billion years
NSF

21-cm intensity mapping



occupation number of hyperfine levels determines intensity of 21-cm line radiation given off by the hydrogen cloud:

$$\frac{n_1}{n_0} = 3\exp(-T_*/T_{spin})$$



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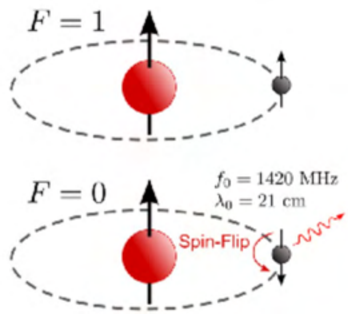

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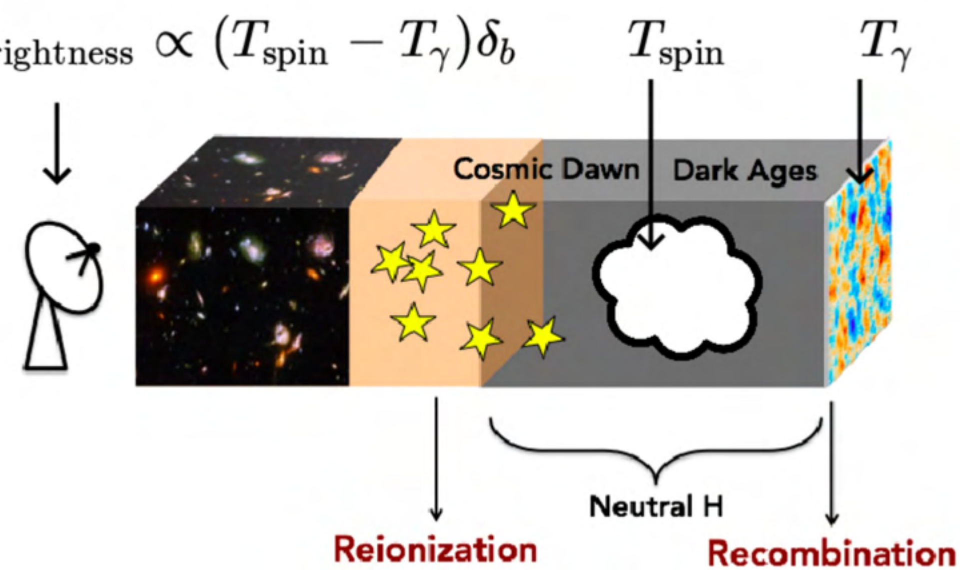
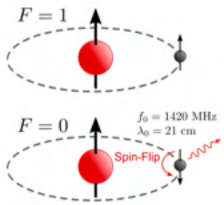
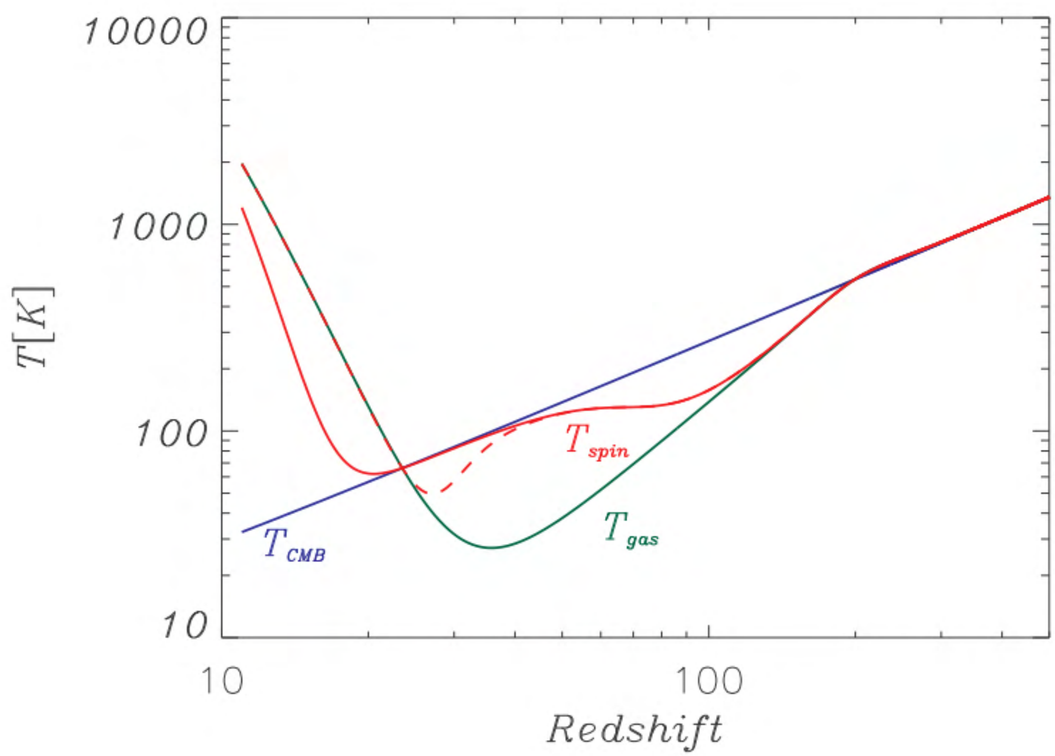
$$T_{\text{brightness}} \propto (T_{\text{spin}} - T_\gamma)\delta_b$$



21-cm global signal





Occupation number of hyperfine levels determines the intensity of the 21-cm line.

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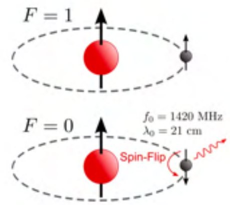
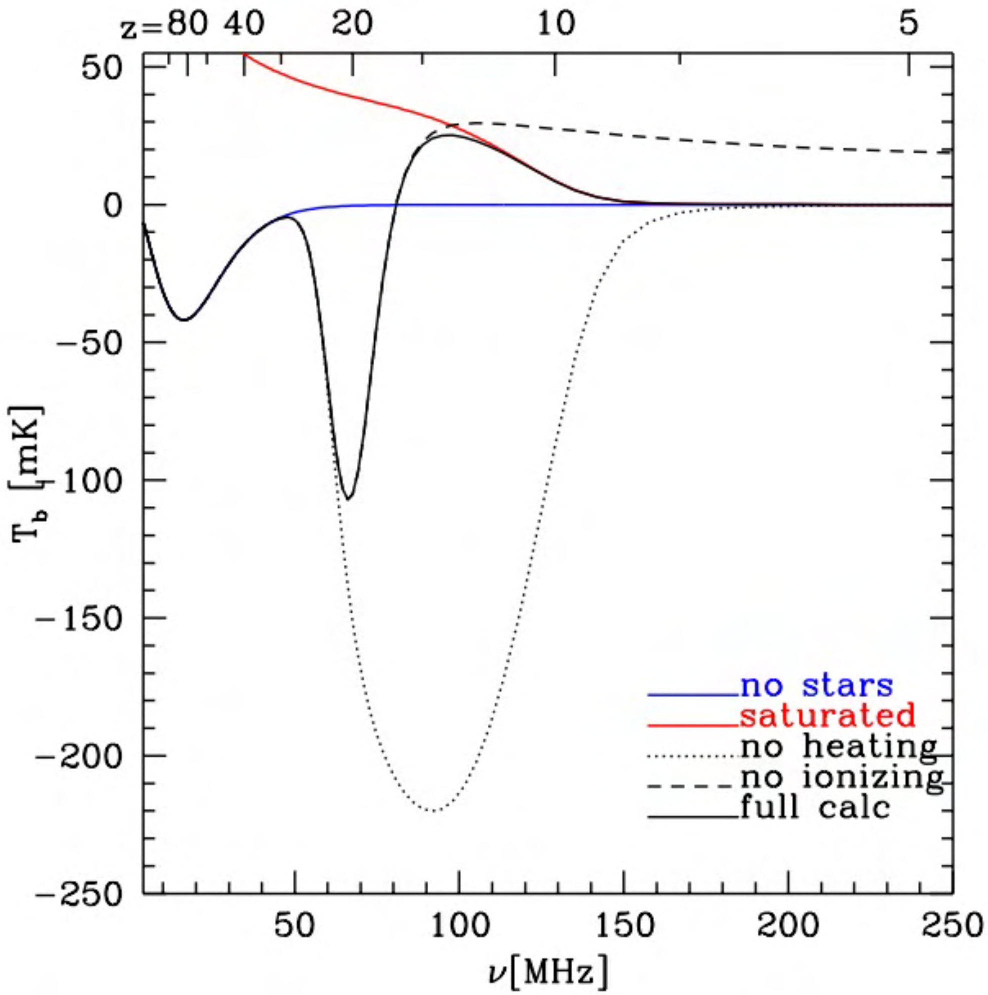
Spin temperatures is controlled by:

- radiative transitions (CMB temperature)
- atomic collisions (i.e. gas temperature)
- Lyman-alpha background (Wouthuysen–Field effect)

https://arxiv.org/pdf/1005.4057.pdf
https://arxiv.org/pdf/1206.0267.pdf

21-cm global signal





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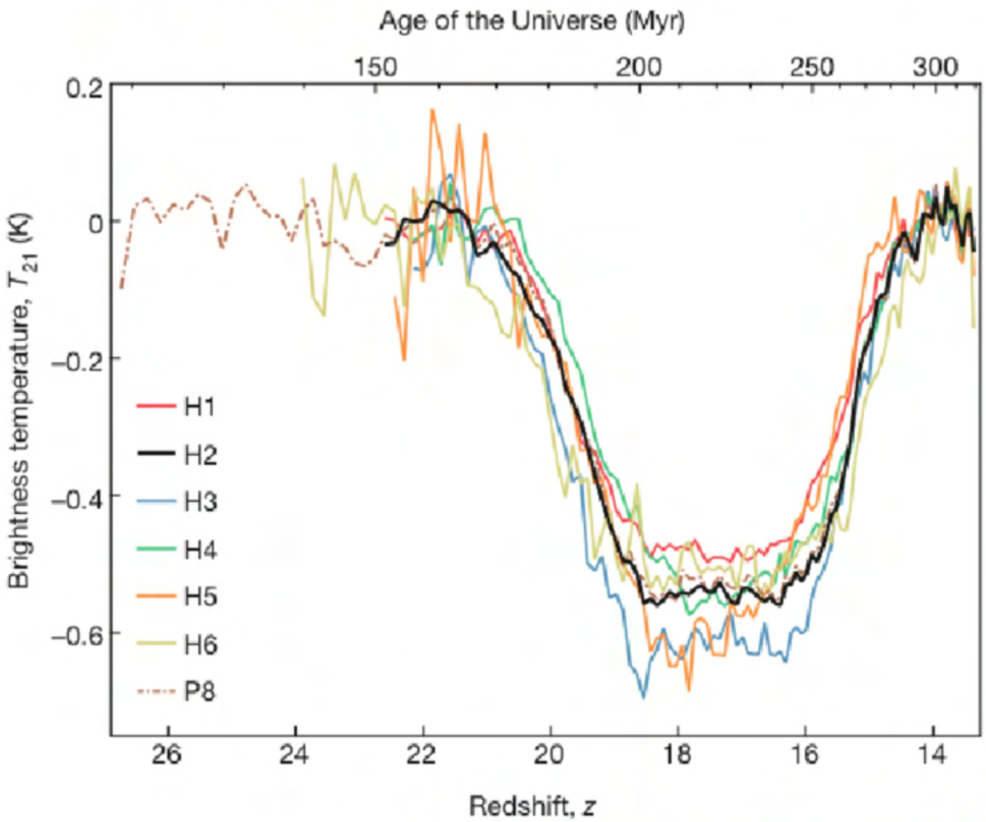
Case study: EDGES

[Experiment to Detect the Global Epoch of reionization Signature]

Bowman, + (2018).



NB: Is it in the sky? Is it cosmological?

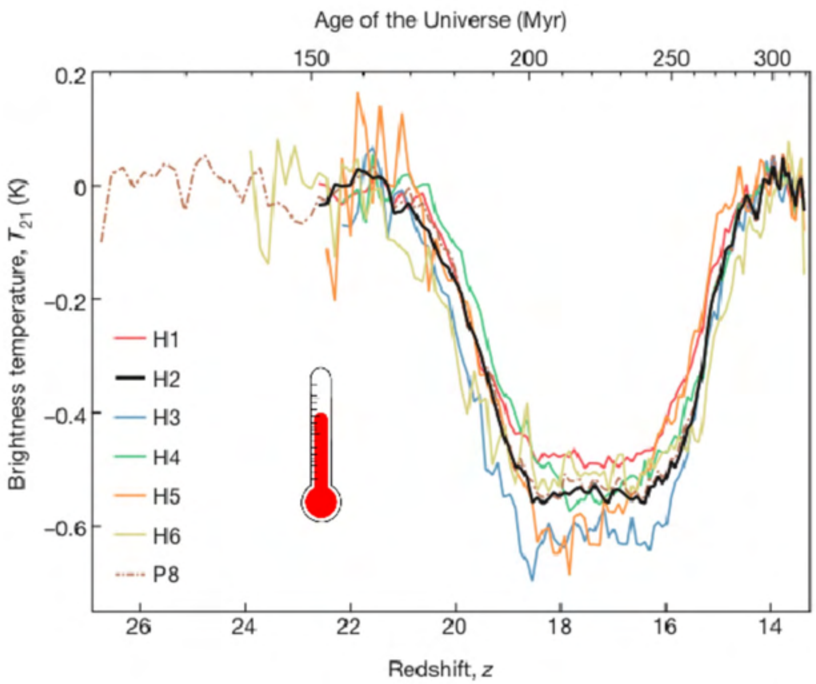
In any case: trough is too deep!

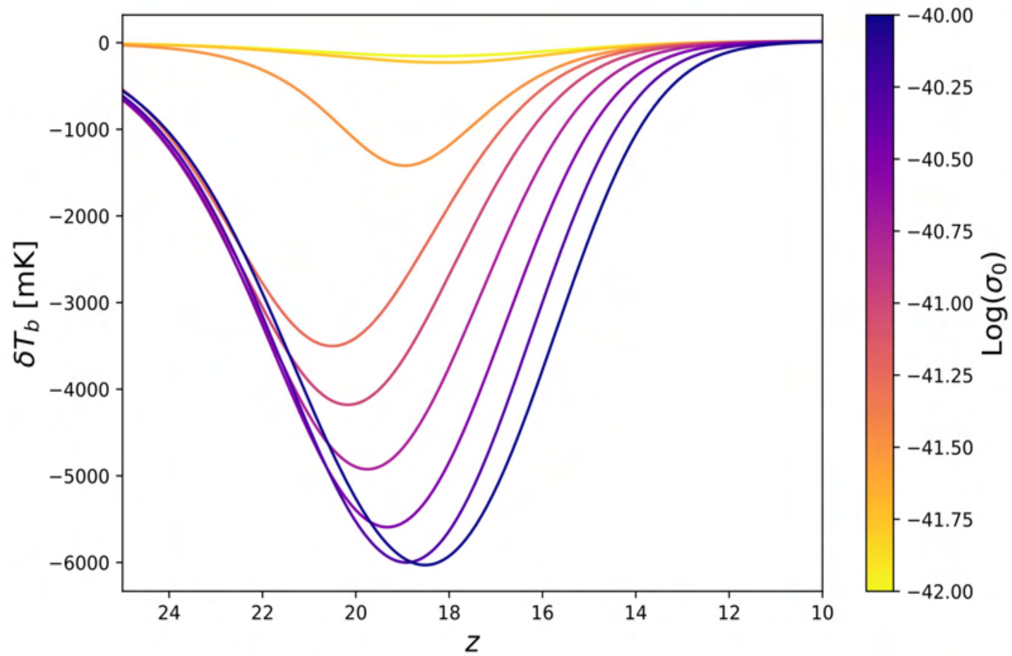
Case study: EDGES

Possible interpretation: baryons are too cold.

Late-time dark matter-baryon elastic scattering?!

Millicharge: $\sigma \sim v^{-4}$





Driskell + (2022)
Munoz+ (2016)

Bowman + (2018)
Barkana+ (2018)

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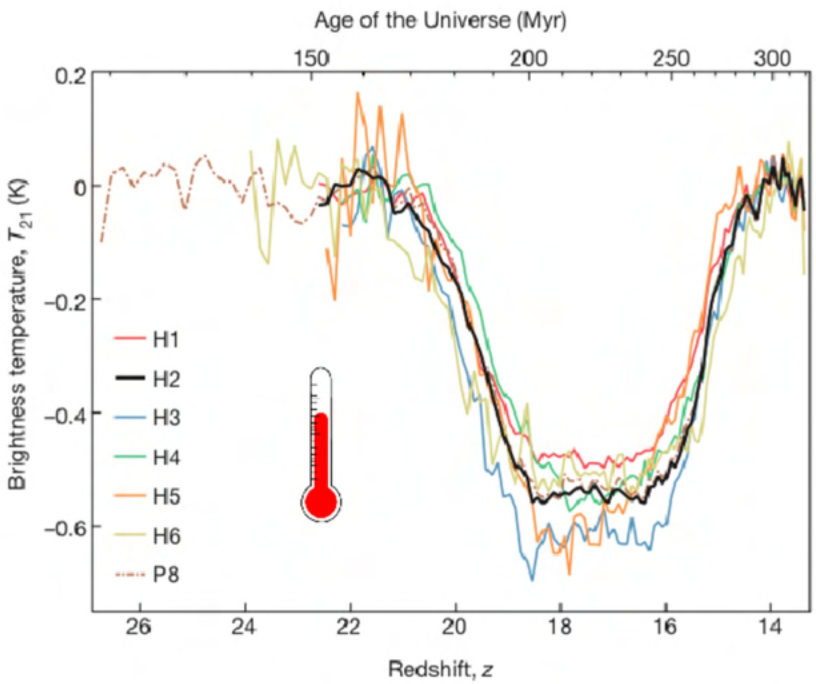
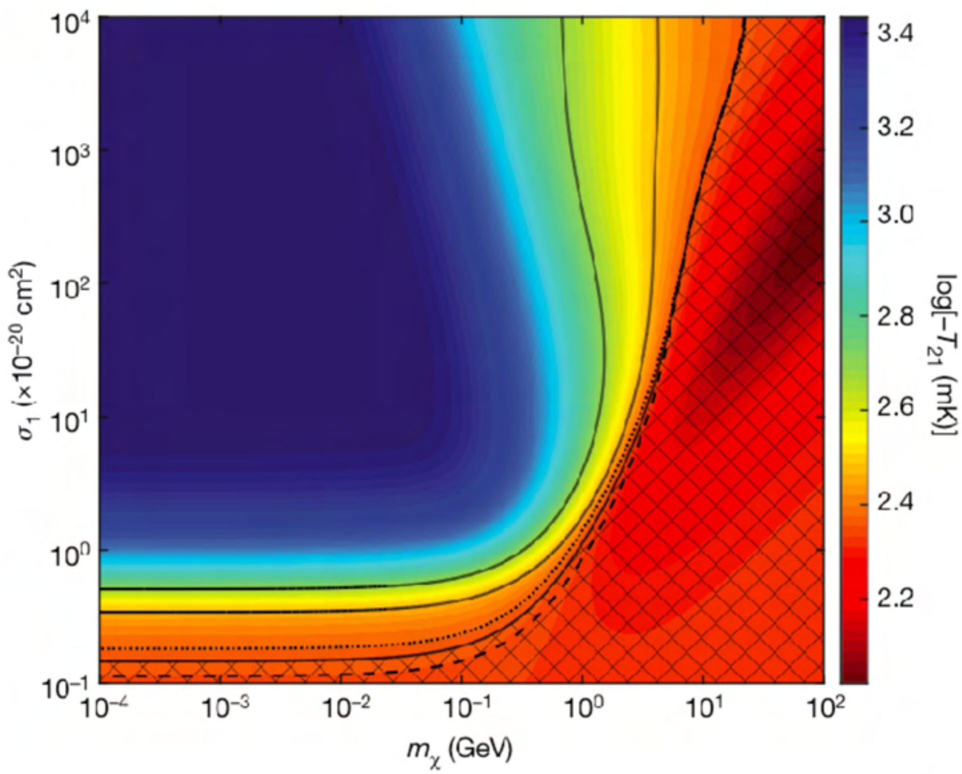


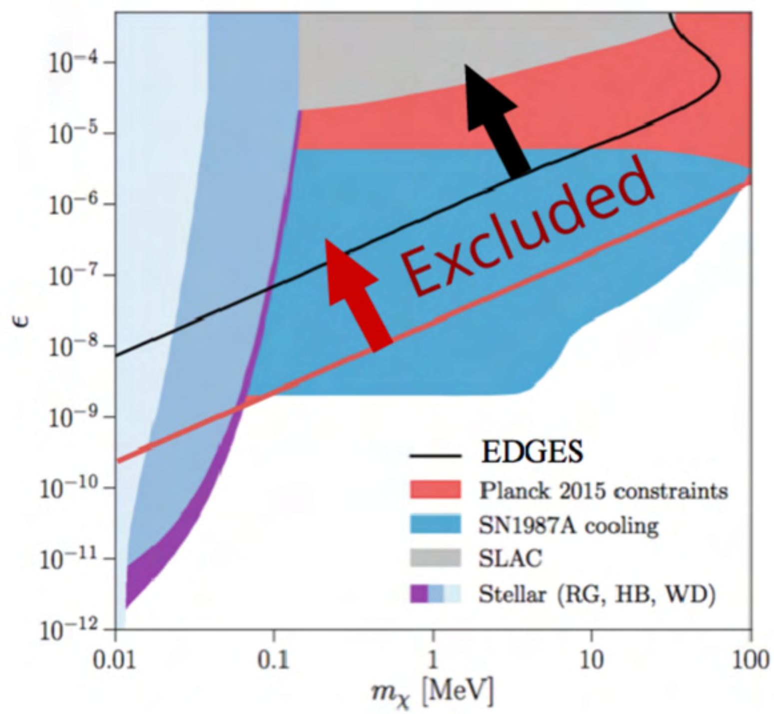


Bowman, + (2018)

Barkana (2018)

Planck and EDGES are *inconsistent* for millicharge accounting for >0.5% of dark matter

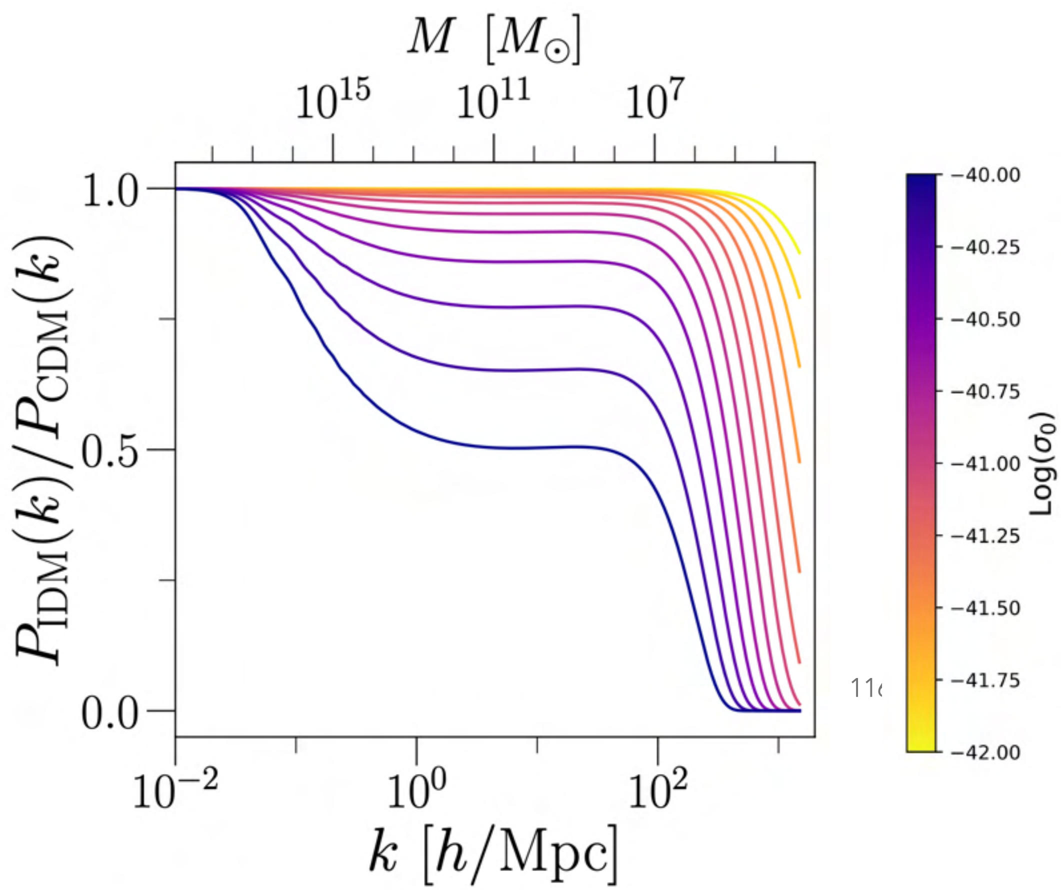
$$\sigma \sim v^{-4}$$



Boddy, + (2018); Kovetz, + (2018)

Global 21-cm signal with IDM

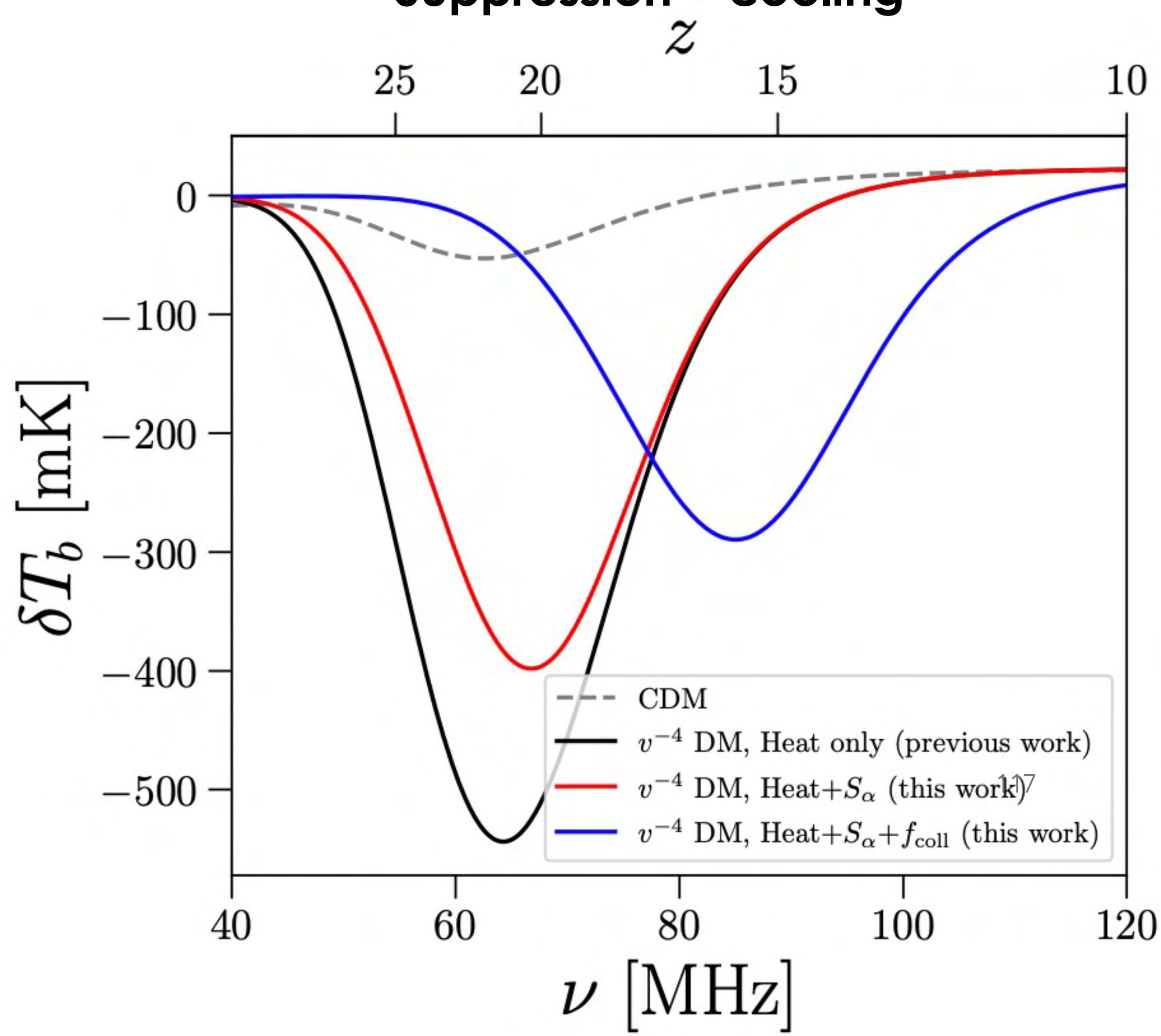
Suppression of structure:
(Not included in previous modeling)



Driskell + (2022)

Global 21-cm signal with IDM

Suppression + cooling

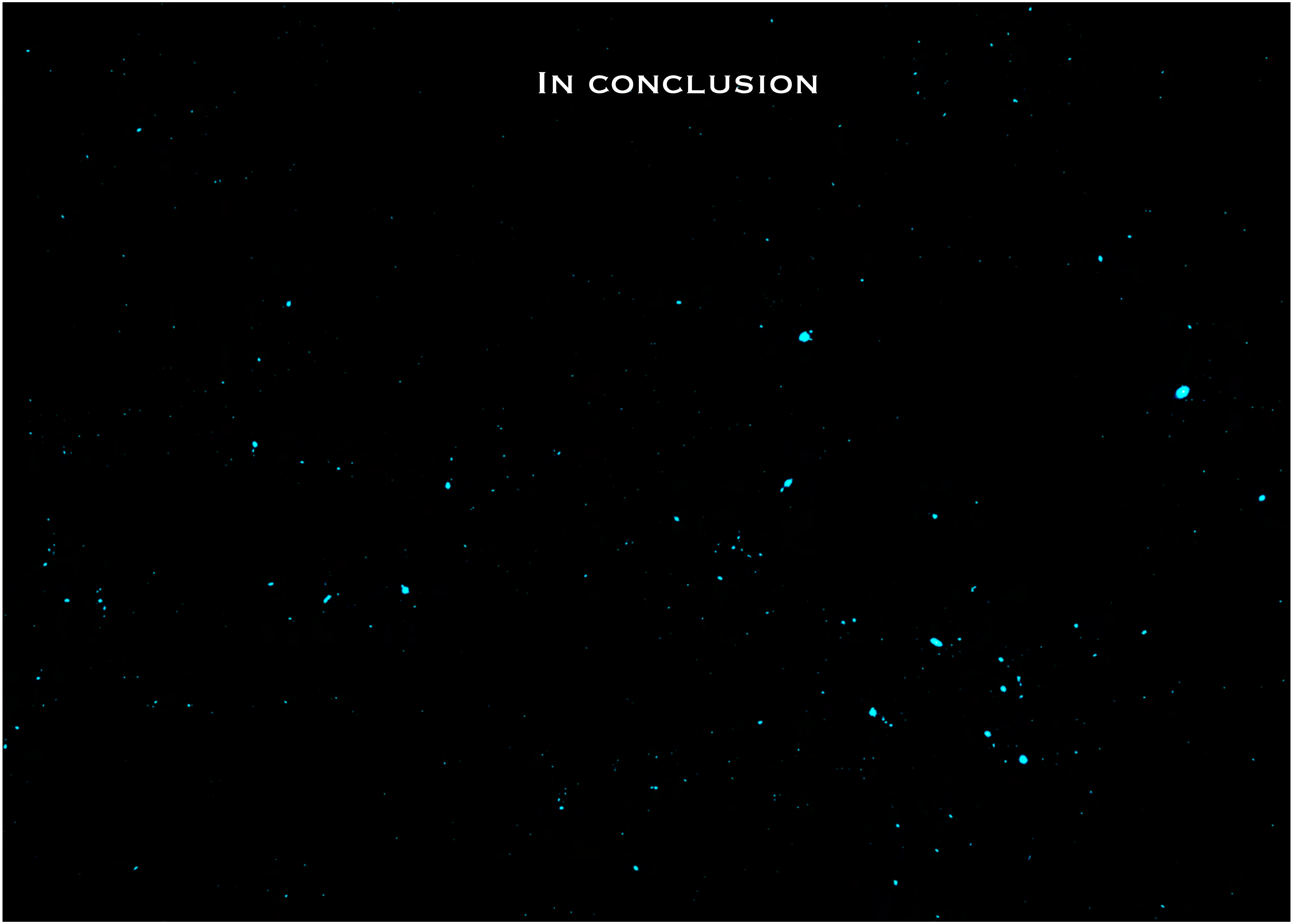


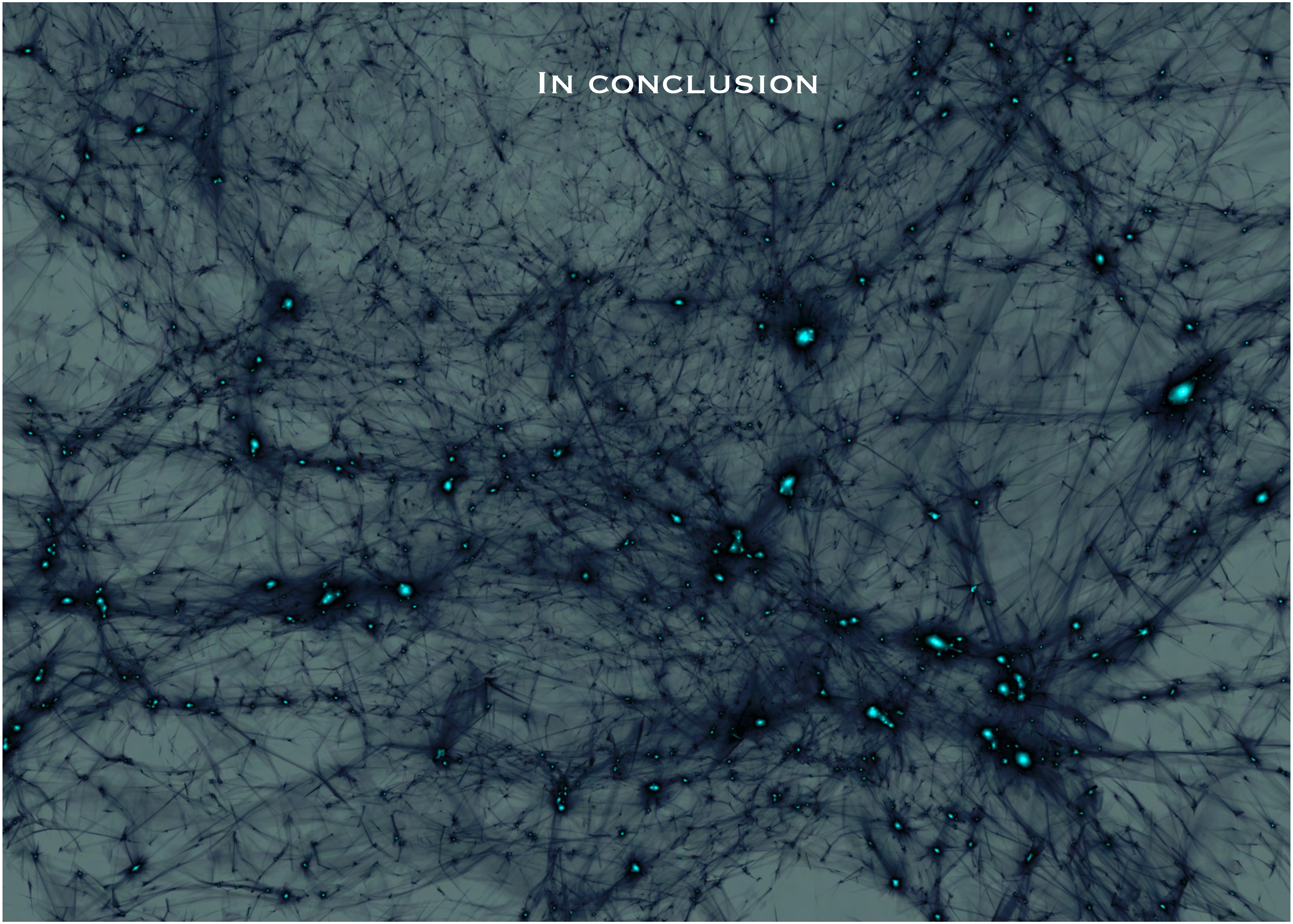
Driskell + (2022)

Cosmological probes are sensitive.

Comprehensive analyses are essential to establish a discovery.

In conclusion

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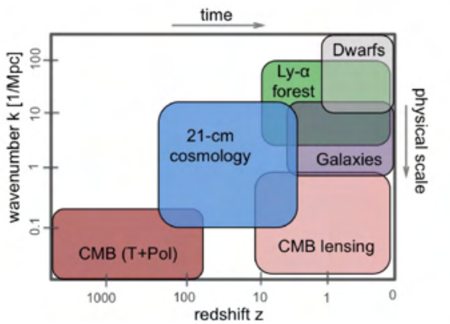
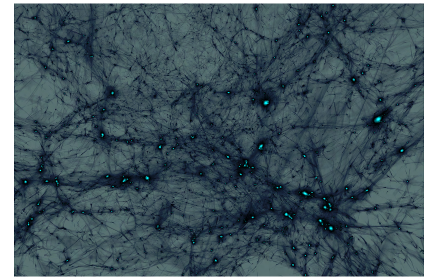


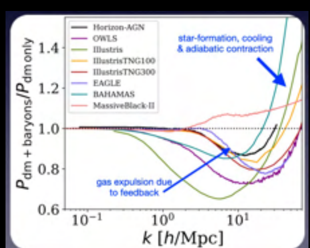
Key points

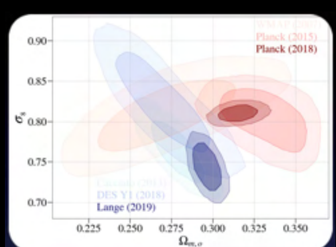


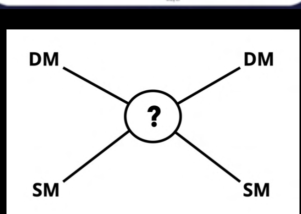
- Dark matter dominates matter content of the universe today, and also signals existence of new physics.
- There are many viable theoretical models.
- Cosmological observables probe different aspects of DM microphysics, but smallest scales enter cosmological horizon at earliest times and thus are typically sensitive to particle physics at higher energies.
- CMB and BBN probe the early universe, mass and production mechanisms.
- LSS and 21-cm signal can probe interactions and thermal history.
- Discovery might require evidence across observables…

Cosmological discoveries* in this decade?

SO (being deployed);CMB-S4; JWST (in operation);LSS surveys: DESI (in operation),
Rubin/LSST (start 2025?), Euclid (launch July 1?), Roman (2027) , SphereX (2025).







* Measurements:

sum of neutrino masses (SO/CMB-S4/LSS).

minimum halo mass (Rubin, DESI, Roman etc).

Large scale B-modes (CMB).

* Stress-tests:

cosmological tensions (SPT/ACT, SO + LSS surveys).

DE equation of state (LSS).

Tests of GR (LSS).

structure formation (baryonic effects, bias+) (LSS).

* Large New Open Space:

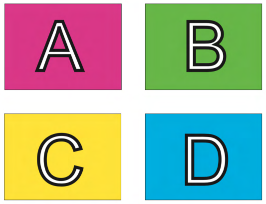
light relics and BBN (CMB).

small-scale DM physics (clustering/stellar streams/lensing).

astrophysics of the first galaxies (JWST).

black holes and neutron stars (LIGO/Virgo).

Non-gaussianity (LSS+CMB).



A) Teamwork time?

B) Nap time?

https://arxiv.org/pdf/1904.10000.pdf
https://github.com/eonadler/DMBaryonScattering/

The end.

Solutions to teamwork problems

V. Gluscevic

Michigan summer school 2023

TEAM EXERCISE SOLUTIONS

(1) Fermi energy (in SI units): (for $g=2$)

$$E_F = \frac{\hbar^2}{2m} \cdot (3\pi^2 \cdot n)^{1/2} \Rightarrow \boxed{V_F = \sqrt{\frac{2E_F}{m}} = \hbar \left[\frac{6\pi^2 \rho}{2m^4}\right]^{1/3}}$$

n = # density, m = particle mass.

$$\hbar \approx 6.58\times10^{-16}\,\text{eV}\cdot\text{s} = 1.054\times10^{-27}\,\frac{\text{cm}^2\text{g}}{\text{s}}$$

From the plot: $\rho_{1/2} \simeq 10^8 \frac{M_\odot}{\text{kpc}^3}$ @ $r_{1/2} = 0.23\,\text{kpc}$

$$V_{esc}(r_{1/2}) = 30\,\frac{\text{km}}{\text{s}} = 3e6\,\frac{\text{cm}}{\text{s}}$$

$M_\odot \approx 3.75\times10^{52}$ keV $\approx 1.989\times10^{33}$ g, $1\,\text{kpc} = 3.08\times10^{16}$ km

$\Rightarrow$ $V_F < V_{esc}$?

$$\Rightarrow \boxed{m > \left[\frac{\hbar^3}{V_{esc}^3(r)} \frac{6\pi^2 \rho(r)}{2}\right]^{1/4}} \simeq \boxed{170\,\text{eV}}$$

(2)

$$k_{dec.} = \frac{2}{\lambda_{dec.}} \qquad M = \frac{\pi}{3} \bar{\rho} \cdot \lambda_{dec.}^3$$

$\bar{\rho} \to \rho_{crit.} \cdot \Omega_m$

$$\lambda_{dec.} \approx z_{dec.} \cdot \frac{c}{H(z_{dec.})}$$

$\lambda_{dec.}$ → comoving size of horizon

$$m_x \approx m_p = m$$

$\Gamma = H$ @ $z_{dec.}$

$$\Gamma = n \sigma V \qquad (\sigma \to 3 \cdot 10^{-26}\, cm^2) \qquad H(\text{in R.D}) = H_0 \sqrt{\Omega_{r_0}} \cdot z^2$$

($H_0 \to 70 \frac{km}{s \cdot Mpc}$, $\Omega_{r_0} \to 10^{-4}$)

$$n = \frac{\rho}{m} = \frac{\rho_{crit.} \cdot \Omega_b \cdot z^3}{m} \qquad (\rho_{crit.} \to 10^{-29} \frac{g}{cm^3},\ \Omega_b \to 0.05)$$

$$\frac{1}{2} m V^2 = k T_{CMB,0} \cdot z \Rightarrow V = \sqrt{\frac{2 \cdot k T_{CMB,0} \cdot z}{m}}$$

($k T_{CMB,0} \sim 10^{-4}\, eV$)

$$\Rightarrow \frac{\rho_c \cdot \Omega_{b,0} \cdot z_{dec}^3}{m} \sigma \cdot \sqrt{\frac{2 k T_{CMB,0} \cdot z}{m}} = H_0 \sqrt{\Omega_{r,0}} \cdot z_{dec}^2$$

$$\Rightarrow z_{dec.} = \left[H_0 \sqrt{\Omega_{r,0}} \cdot \frac{\sqrt{m^3}}{\sigma \cdot \Omega_{b,0}\, \rho_c \sqrt{2 k T_{CMB,0}}} \right]^{2/3}$$

$\boxed{z_{dec} \simeq 10^7} \Rightarrow \boxed{k_{dec} \simeq 60\ Mpc^{-1}} \Rightarrow \boxed{M \simeq 10^{8} M_\odot}$