Title: Probing dark matter mass and interactions: from the early universe to near-field cosmology

Speakers: Vera Gluscevic

Series: Cosmology & Gravitation

Date: October 26, 2021 - 11:00 AM

URL: https://pirsa.org/21100003

Abstract: Dark matter constitutes 85% of the matter content in the Universe, but its physical nature remains unknown and requires new physics to explain. I will review the status of the recent early-universe and late-universe searches for the identity of dark matter, summarizing the best current limits on scattering between dark matter and baryons, and discussing cosmological limits on the mass of thermal-relic dark matter. I will highlight the interplay between the thermal history of the universe and the formation of structure as complementary probes of dark matter physics, using the example of the 21-cm signal from the Cosmic Dawn. Finally, I will discuss the prospects for unveiling the physics of dark matter in the coming decade.

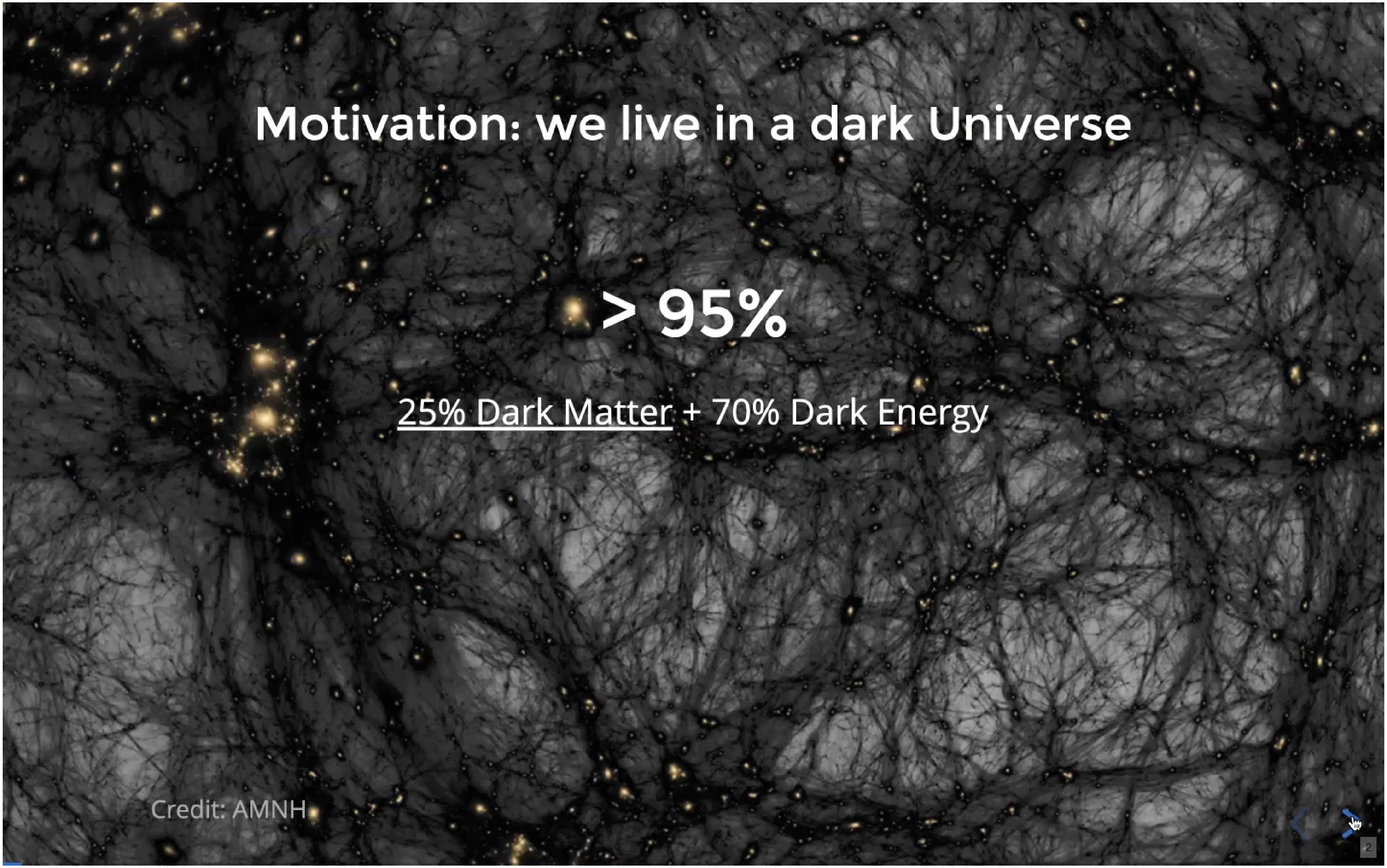
Probing dark matter mass and interactions:

from the early universe to near-field cosmology

Vera Gluscevic

University of Southern California (USC)

PI Seminar (via Zoom), Waterloo - October 26, 2021.


Motivation: we live in a dark Universe
> 95%
25% Dark Matter + 70% Dark Energy
Credit: AMNH
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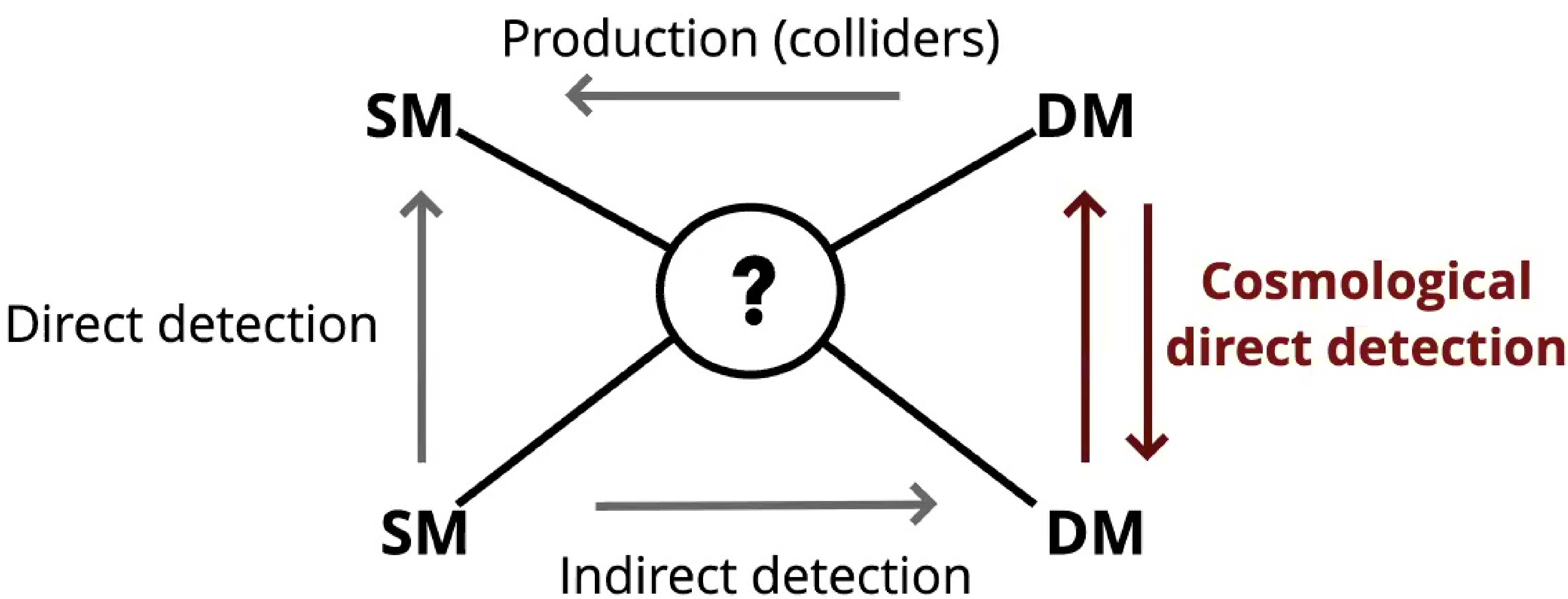
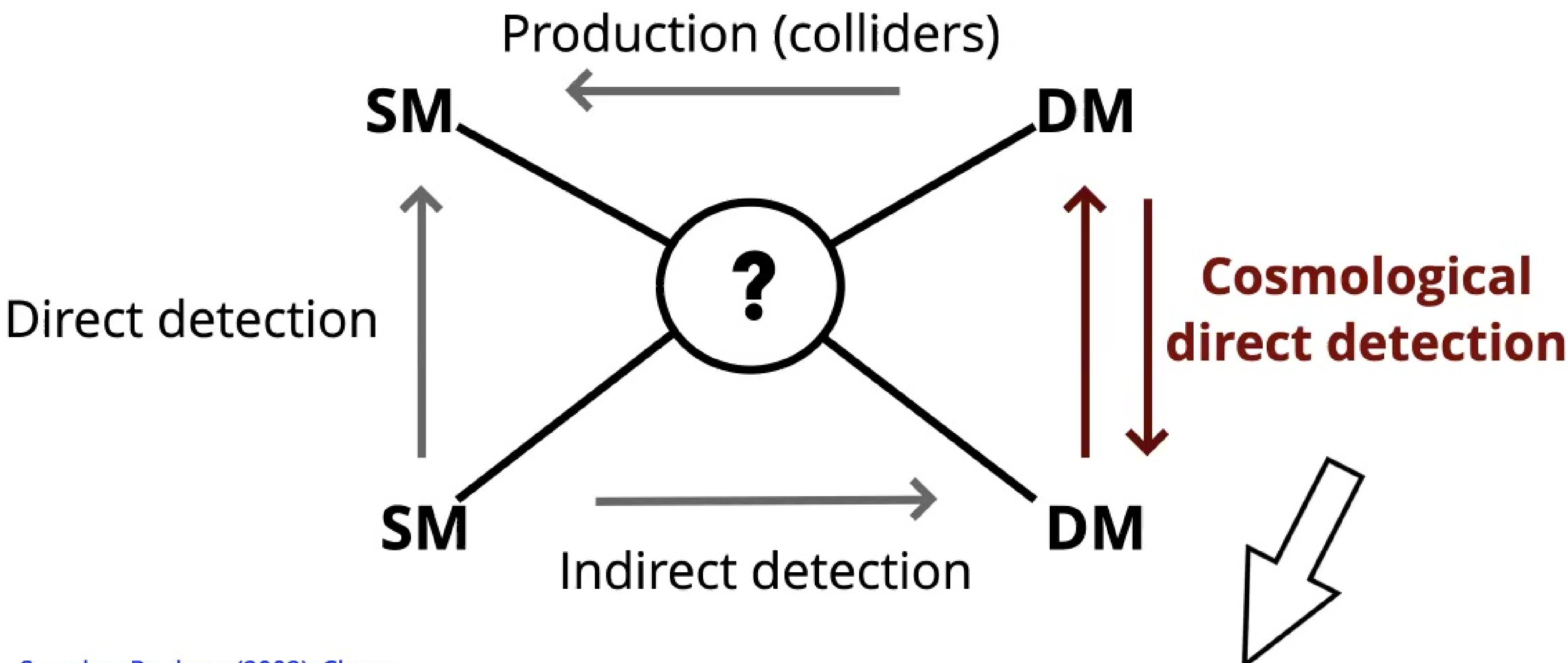
Context: interacting dark matter (IDM)



See also: Boehm+ (2002), Chen+ (2002), Dubovsky+ (2004), Sigurdson+ (2004), Dvorkin+ (2014); Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018); Giovanetti+ (2021), etc.

Context: interacting dark matter (IDM)



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*** Tests cosmological DM**

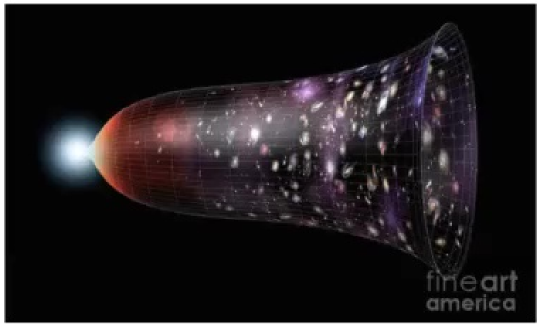
*** Independent on local f(v)**

*** Explore low m and high sigma**

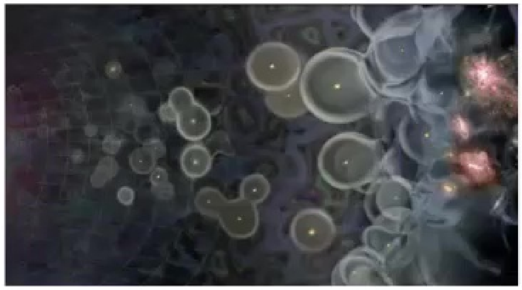
Cosmology with IDM

Early expansion & element abundances

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



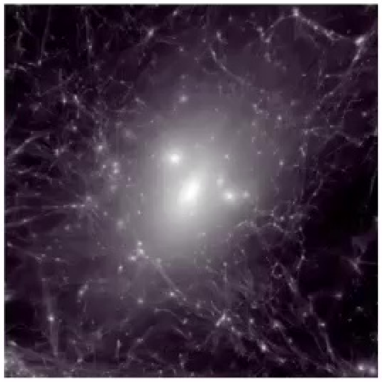
Thermal & ionization history



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

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

Matter distribution & structure formation



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

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

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

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Roadmap

Tools:

1. Large-scale cosmology
2. Near-field cosmology
3. 21-cm cosmology
4. Big Bang Nucleosynthesis

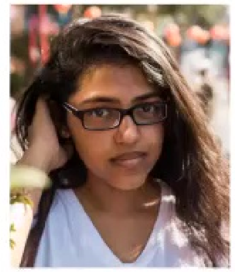
⇩ (beyond CDM)

Objectives:

- **Mass** (e.g. thermal relic, WDM)
- **Interactions** (e.g. scattering with SM)

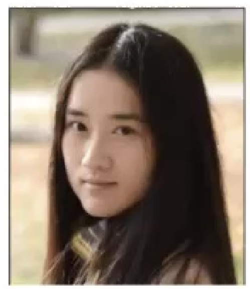
Key contributors


David Nguyen


Dimple Sarnaaik


Karime Maamari


Trey Driskell


Rui An


Ethan Nadler

Also: Zack Li, Jordan Mirocha, Kim Boddy, Andrew Benson, Risa Wechsler, and the ACT collaboration.

1. Large-scale cosmology

lessons from the CMB

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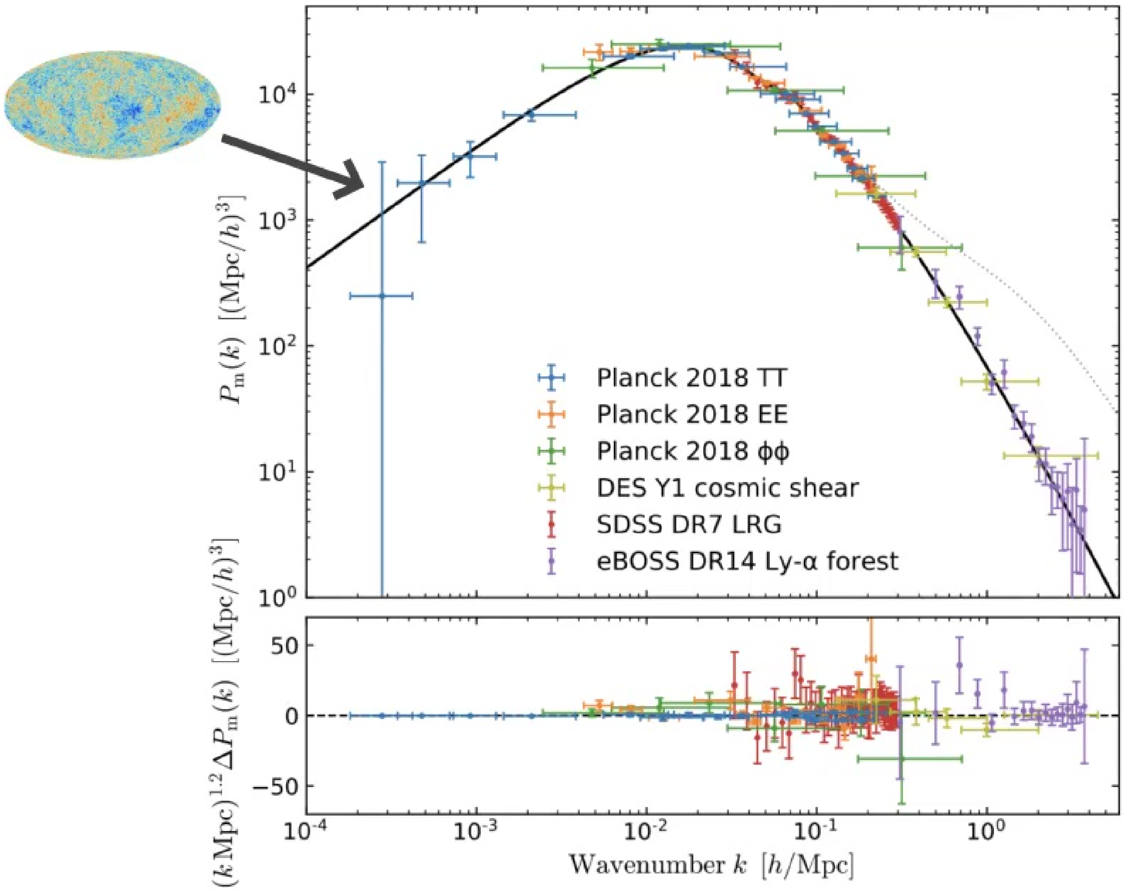
Matter distribution is captured on various scales by different visible tracers.



Chabanier+ 2019

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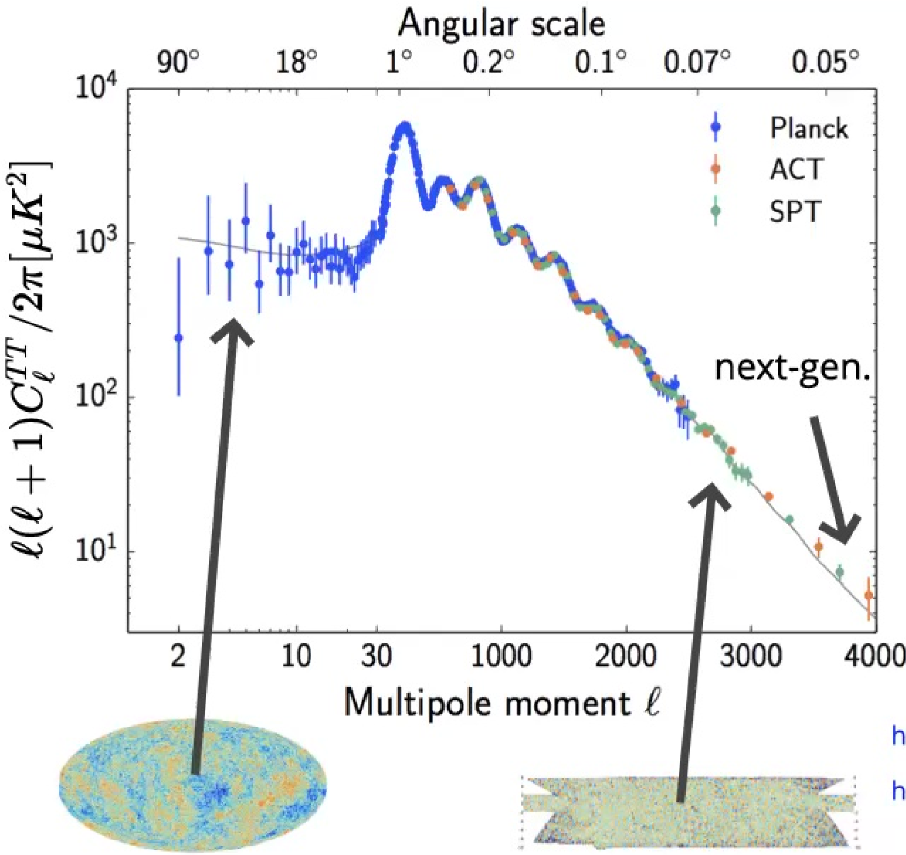
CMB anisotropy

Observables = temperature + polarization + lensing



https://arxiv.org/abs/1907.12875

https://arxiv.org/abs/2007.07289

Actpol Collaboration 2016

Planck Collaboration 2015

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Cosmology with DM-baryon elastic scattering

momentum-transfer cross section

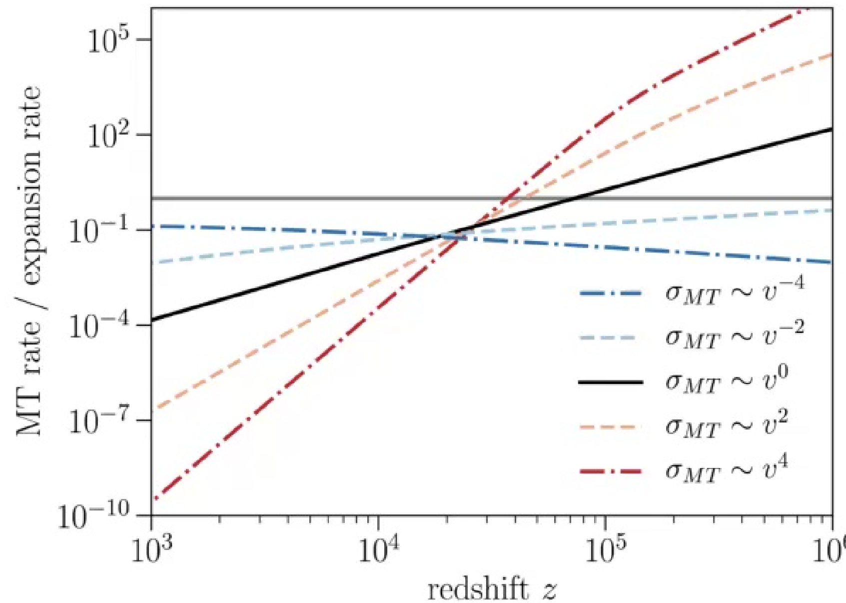
$$\sigma_{MT} = \sigma_0 v^n$$

↓

momentum-transfer rate

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

time ←



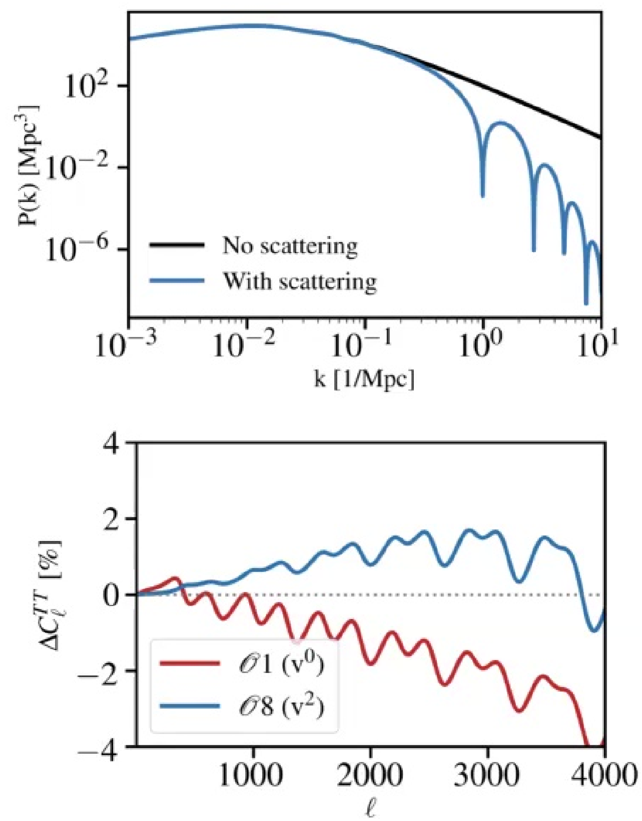
Non-relativistic effective theory operators describing contact interactions at low energy map to n>=0 cases, while n<0 arises due to interactions with very light mediators.

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

EFT in context of the CMB

unknown params

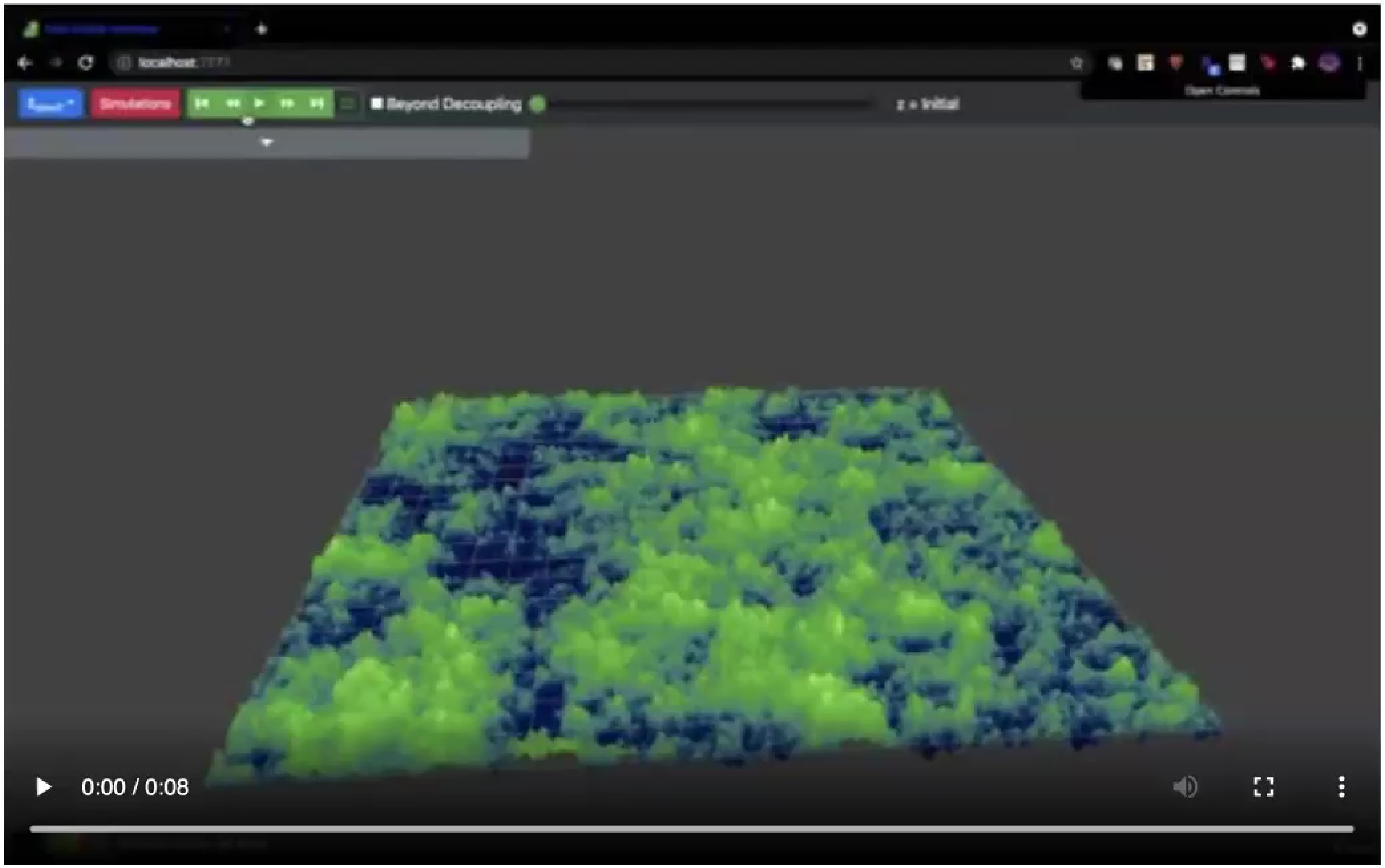
theory $\mathcal{O}_i(m_\chi, c_i)$ $\longrightarrow$ **observables** $P(k)$ C_ℓ



Boddy, VG, 2018

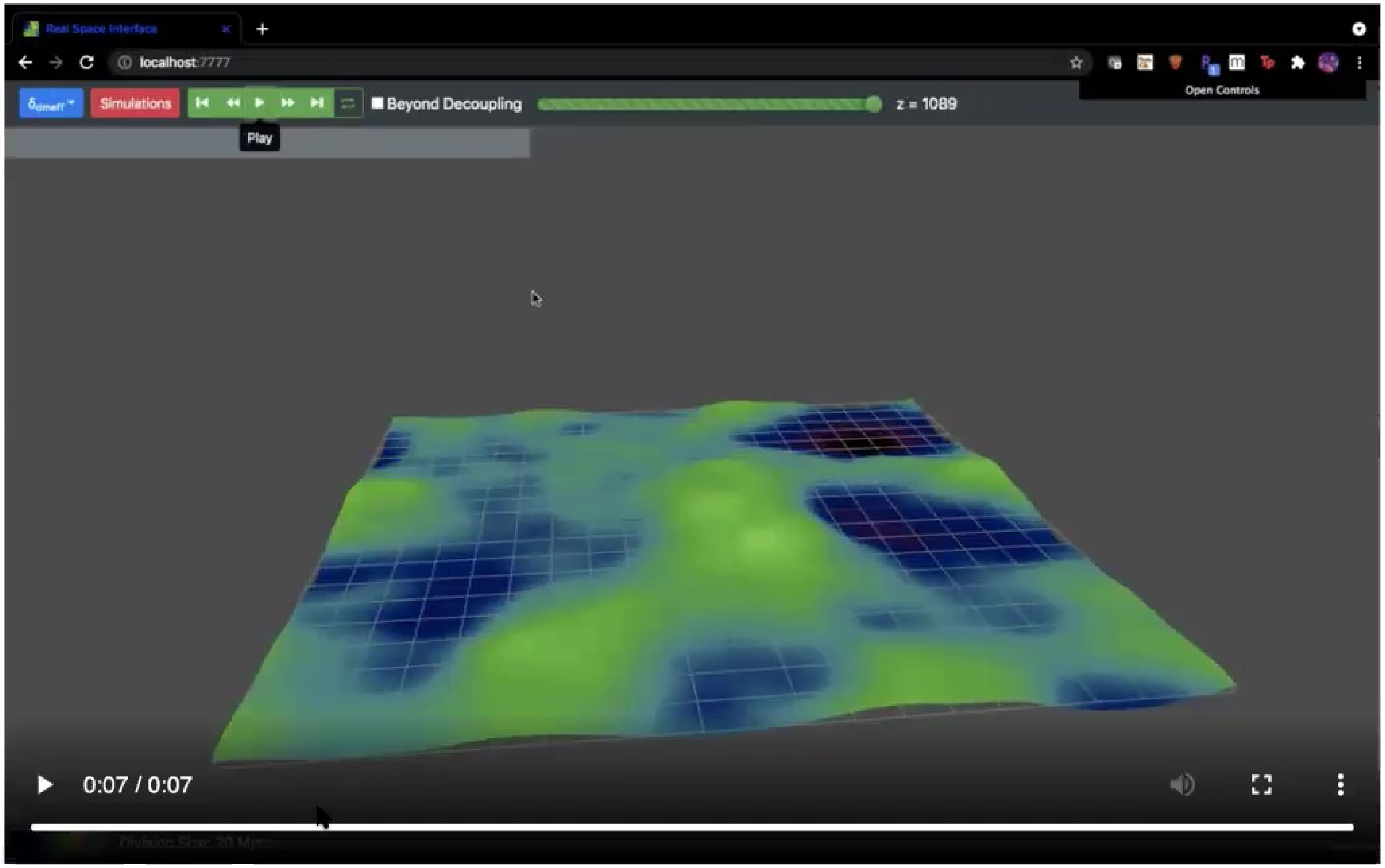
https://arxiv.org/abs/1801.08609

CDM cosmology



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

IDM cosmology: dark acoustic oscillations



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

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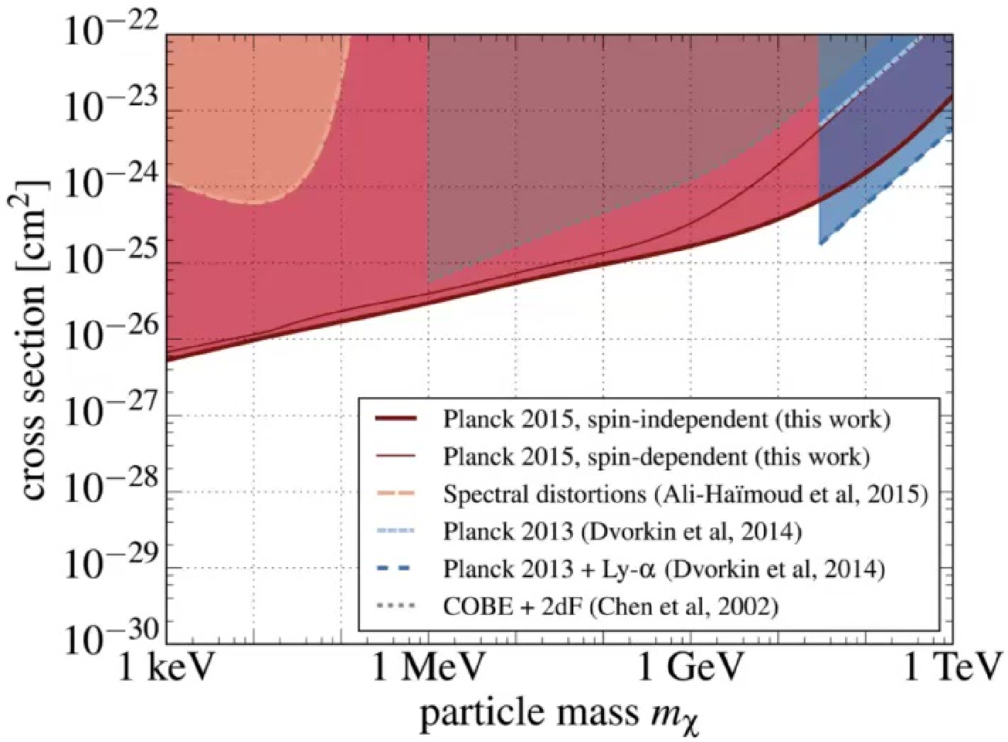
Planck limits on DM-proton scattering

[velocity-independent spin-independent interaction]

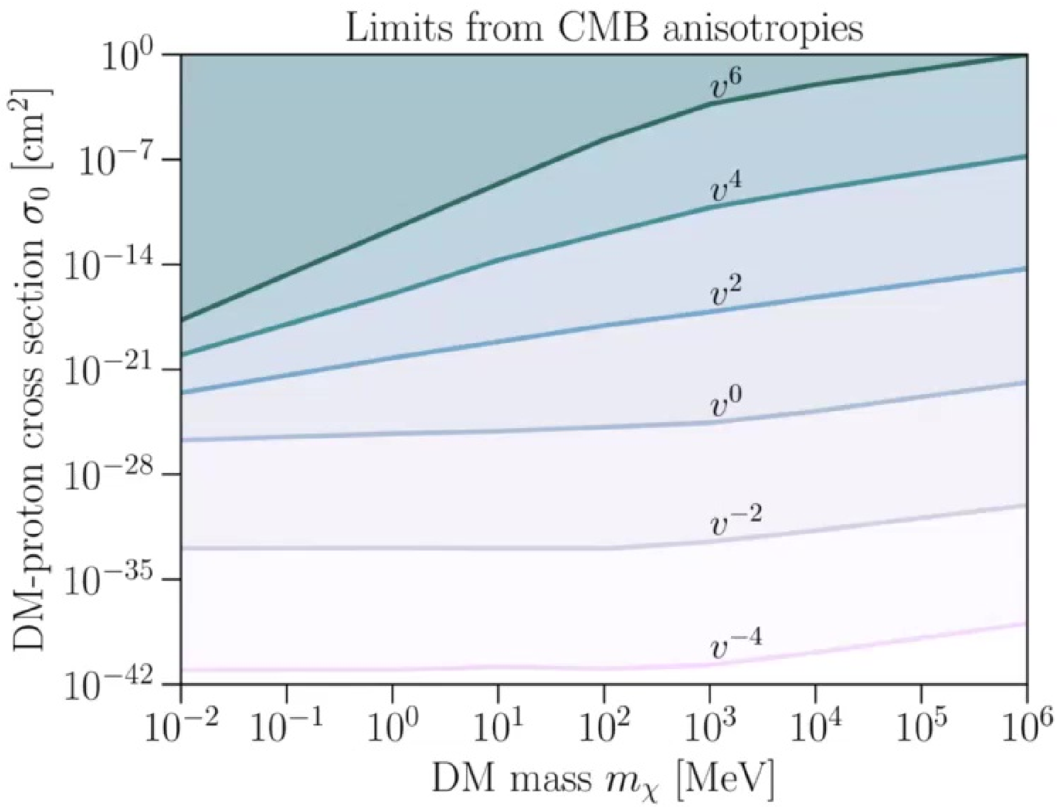


Boddy and VG, PRL 2018;

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

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

Planck limits on DM-proton scattering



Boddy and VG (2018);
Nguyen+ (PRD, 2021)

@age of the Universe ~1000 years:

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

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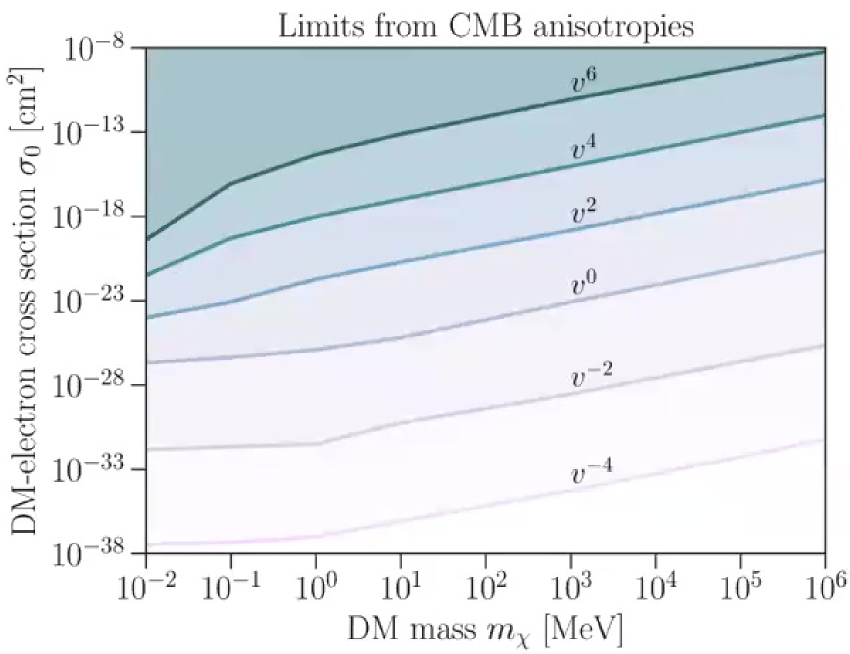
Planck limits on DM-electron scattering

David Nguyen and Dimple Sarnaaik



Nguyen+ (PRD, 2021)

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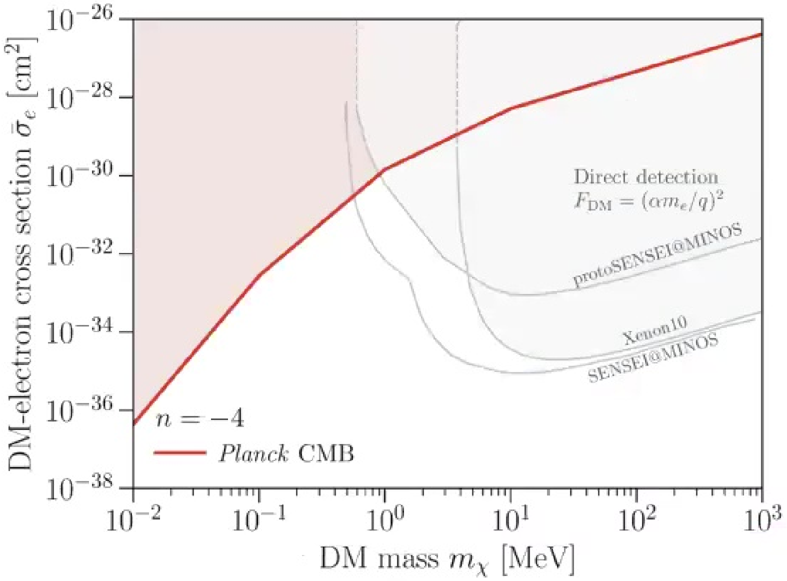
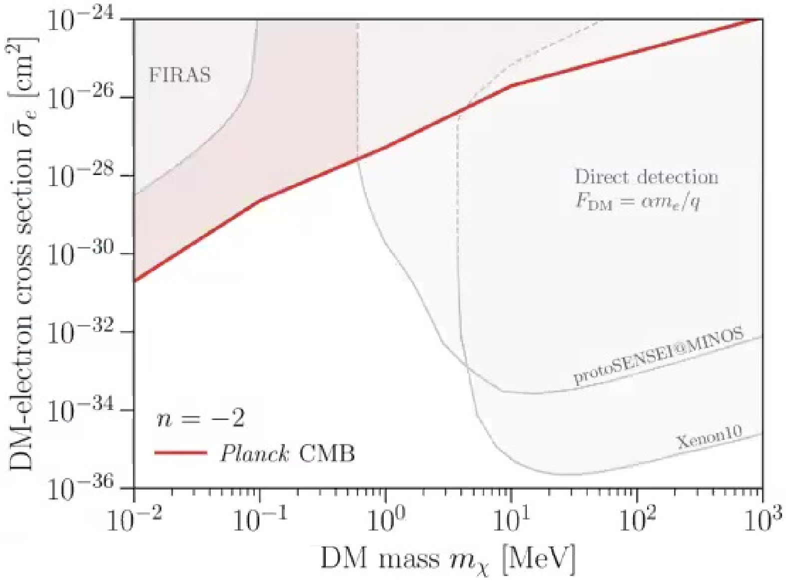
Planck limits on DM-electron scattering

Comparison with direct detection bounds from electronic recoils.

David Nguyen and Dimple Sarnaaik



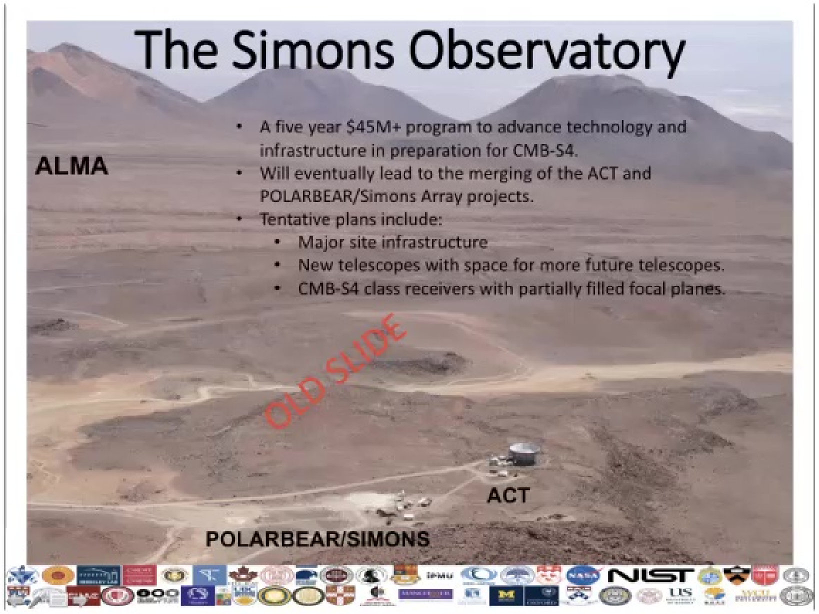


Nguyen+ (PRD, 2021)

$$\sigma_{\rm MT} = \bar{\sigma}_e \frac{4}{4+n}\left(\frac{2\mu_{\chi e}}{\alpha m_e}\right)^n v^n \qquad \sigma_0 = \bar{\sigma}_e \times \begin{cases} 1 & \text{for } n = 0 \\ \frac{\alpha^2 m_e^2}{2\mu_{\chi e}^2} & \text{for } n = -2 \\ \left(\frac{\alpha^2 m_e^2}{2\mu_{\chi e}^2}\right)^2 \ln\left(\frac{2}{\theta_D}\right) & \text{for } n = -4\,. \end{cases}$$

Next-generation ground-based CMB observatories
=> high-resolution measurements.

CMB-S4 (proposed) and Simons Observatory (first light 2022)

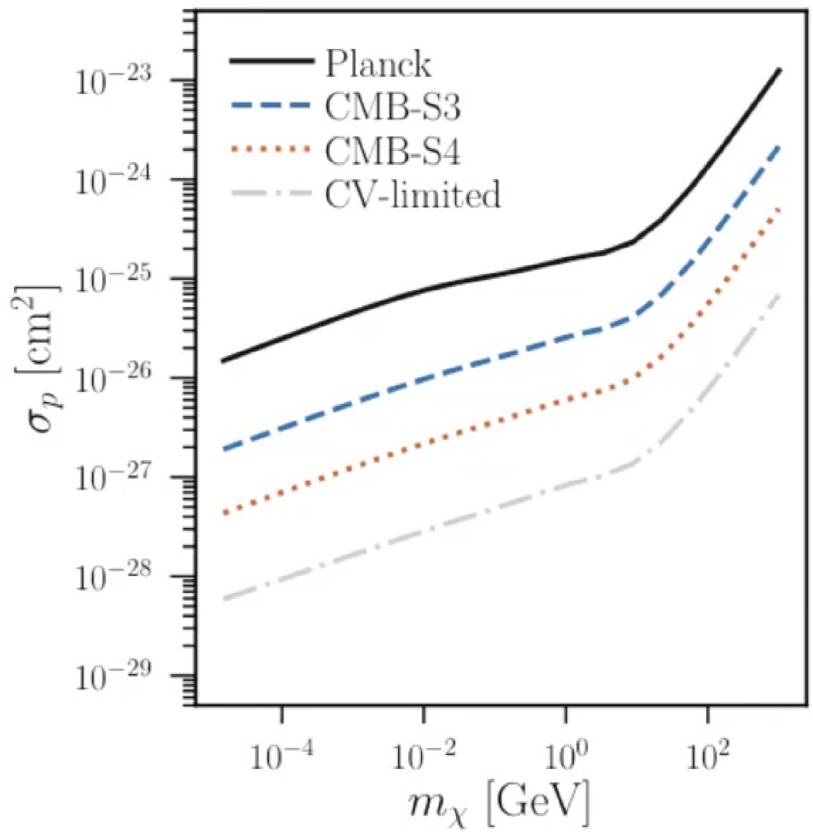


CMB-S4:
https://arxiv.org/abs/1610.02743

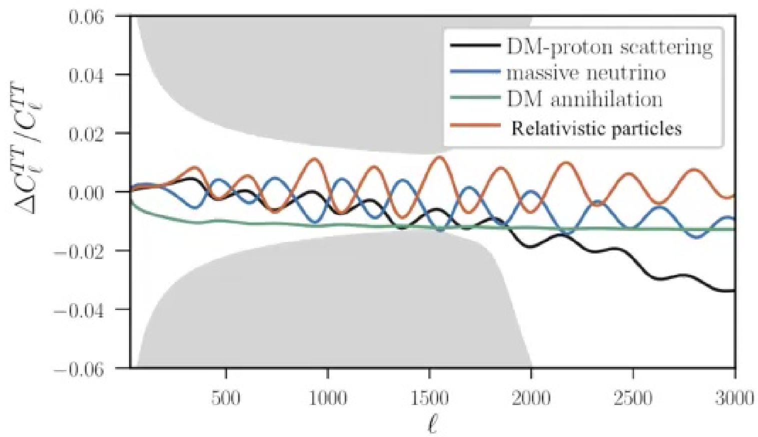
SO forecasts:
https://arxiv.org/abs/1808.07445

Forecasts

(velocity-independent scattering)



IDM does NOT look like other science targets, given well-measured lensing.

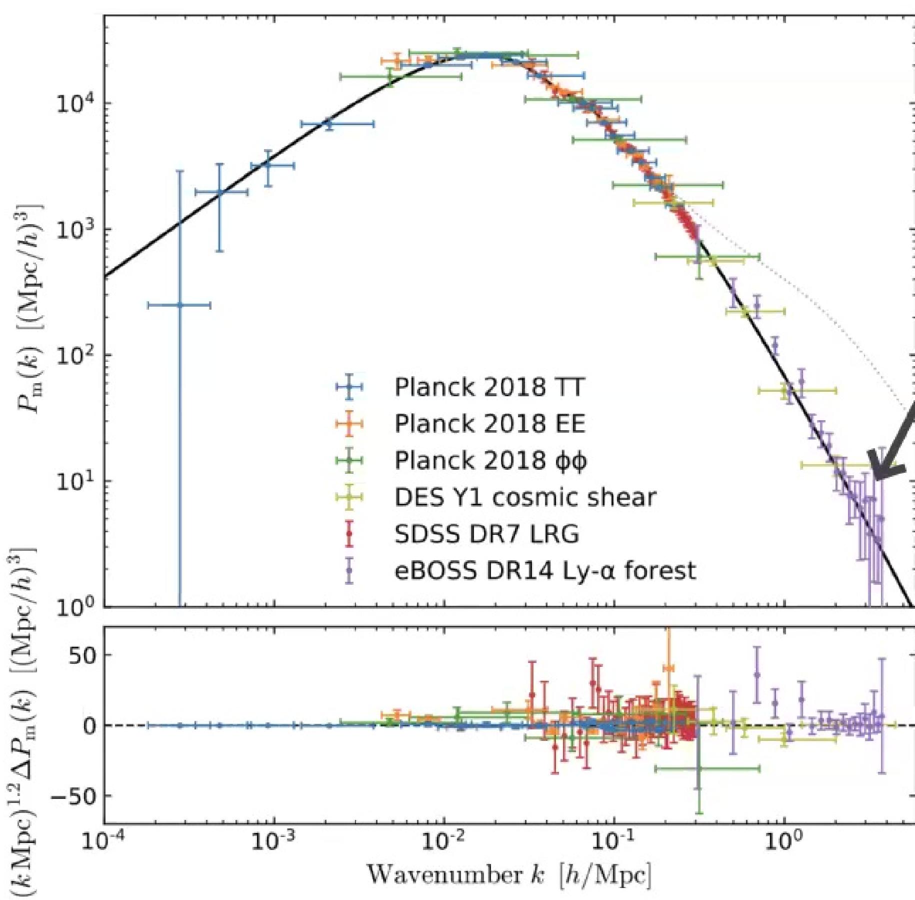


Li+ (2018); see also: [1808.07445]

2. Near-field cosmology

lessons from the smallest galaxies

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

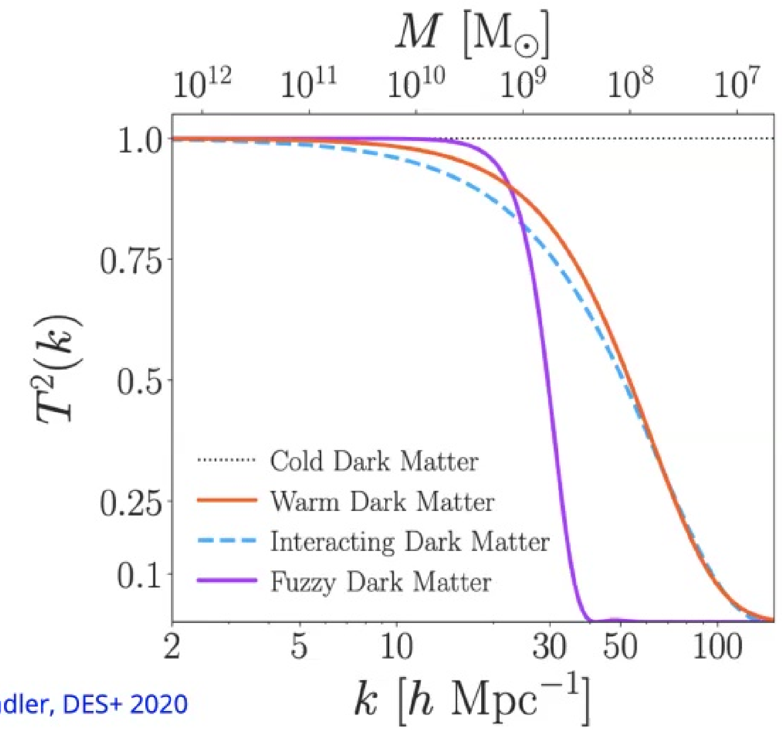
Surveys

Current: Dark Energy Survey, DESI

Upcoming: Vera C. Rubin Observatory (first light 2021), Roman Space Telescope

https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/
https://arxiv.org/abs/1902.01055; lsst.org

DM microphysics can affect 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.

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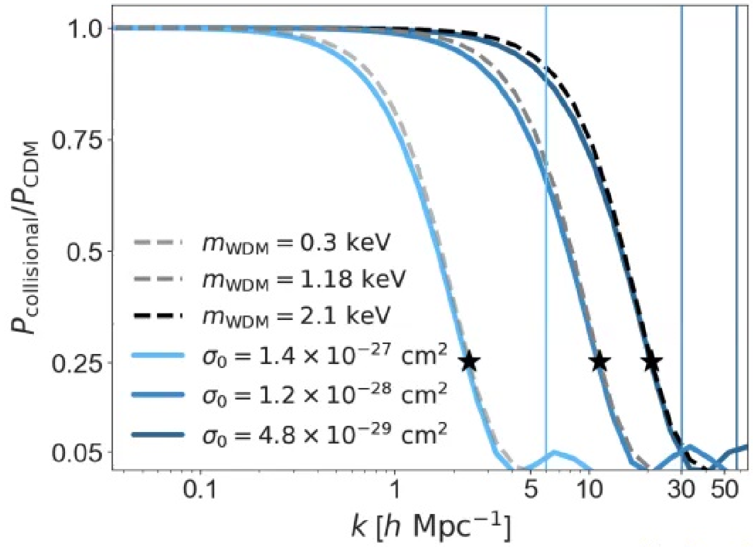
Case studies

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

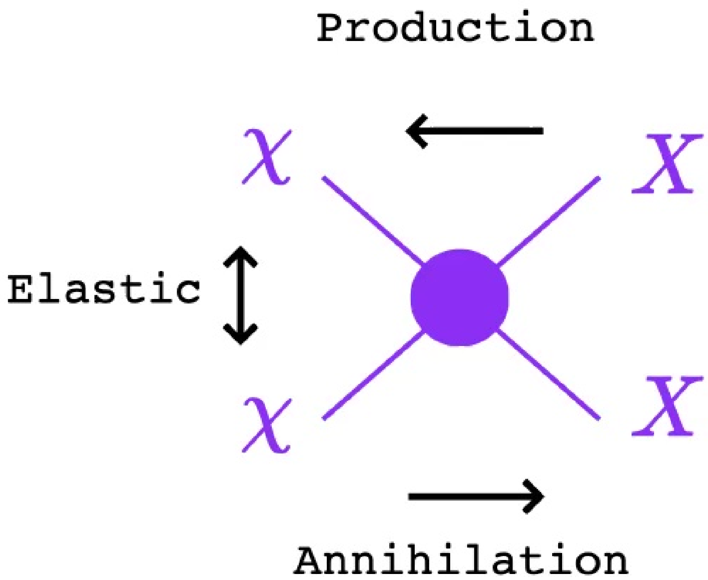


Nadler+ 2019

Context: 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.

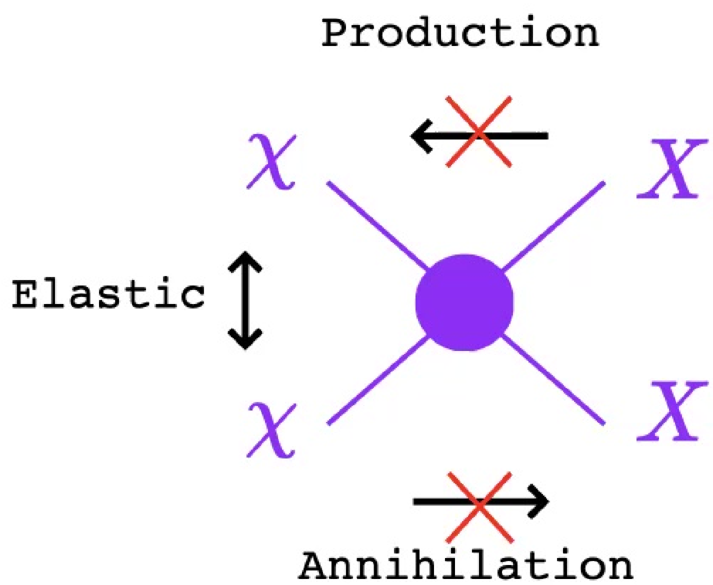


$$\chi\chi \leftrightharpoons XX$$

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

Context: Thermal relic

chemical decoupling = freeze-out

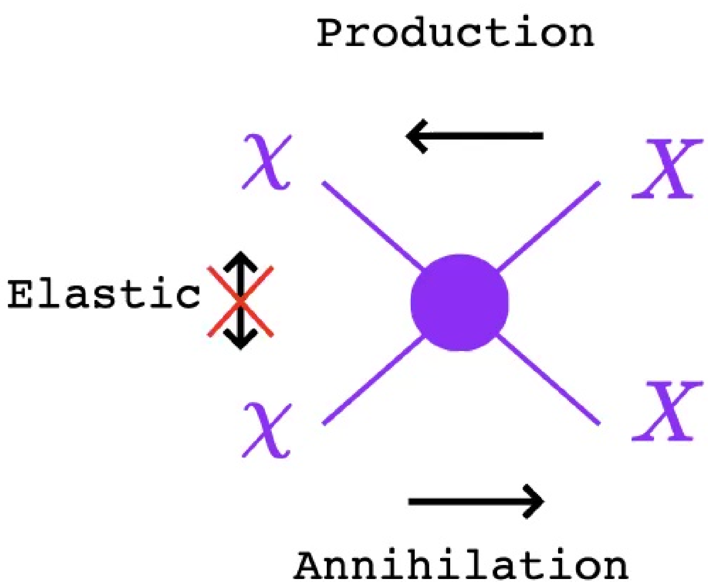


$$\chi\chi \not\rightleftharpoons XX$$

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

Context: Thermal relic

kinetic decoupling



$$\chi X \not\leftrightharpoons \chi X$$

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

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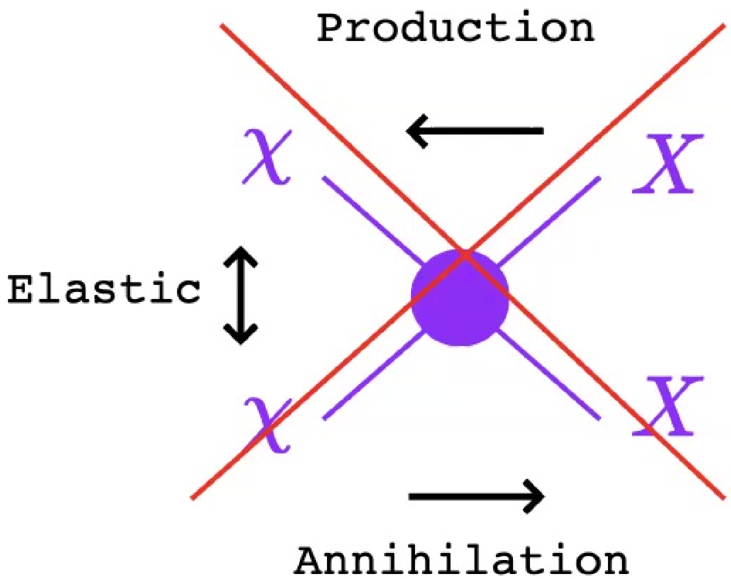
Context: Thermal relic

thermal decoupling

followed by free-streaming



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

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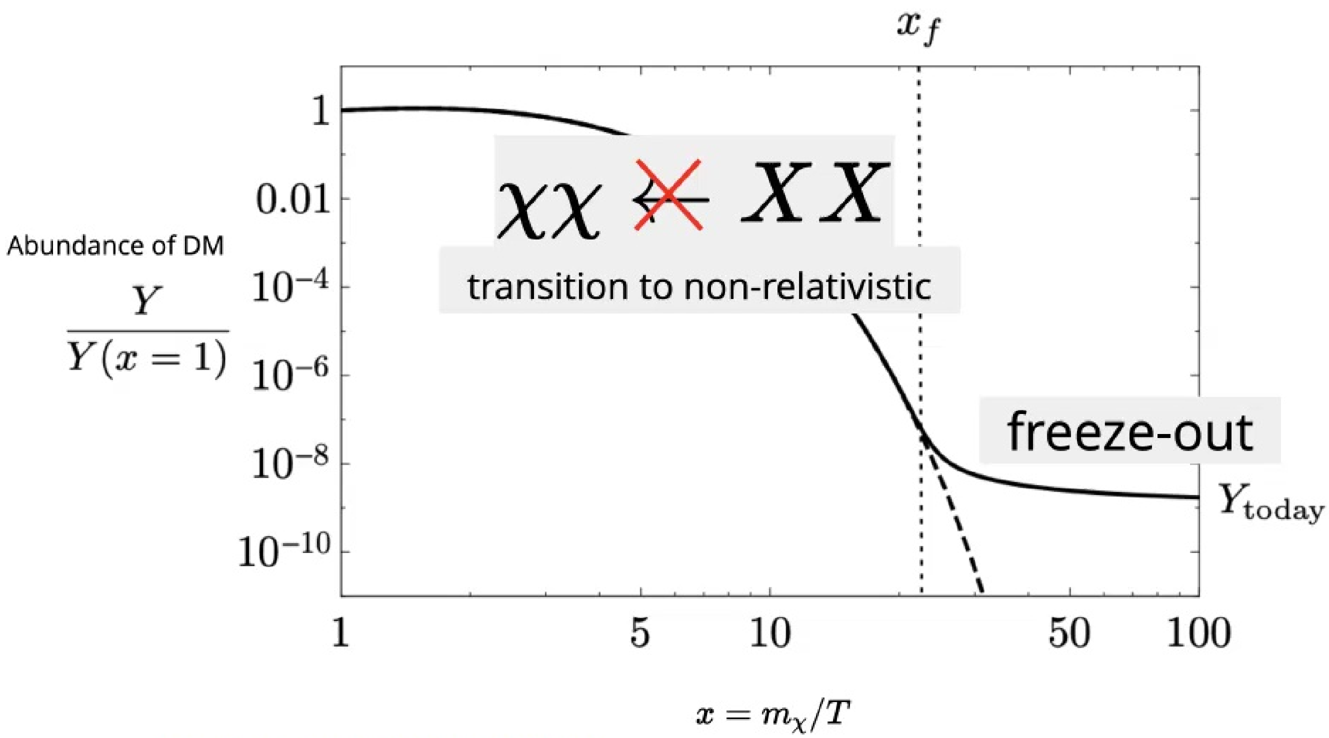
Cold thermal relic (WIMP)



https://arxiv.org/pdf/1603.03797.pdf

WDM = (thermal relic) warm dark matter

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

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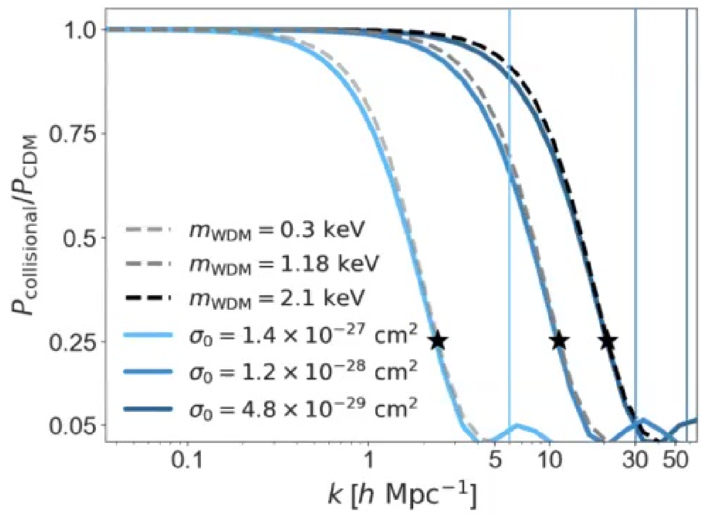
WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

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



Nadler+ 2019

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

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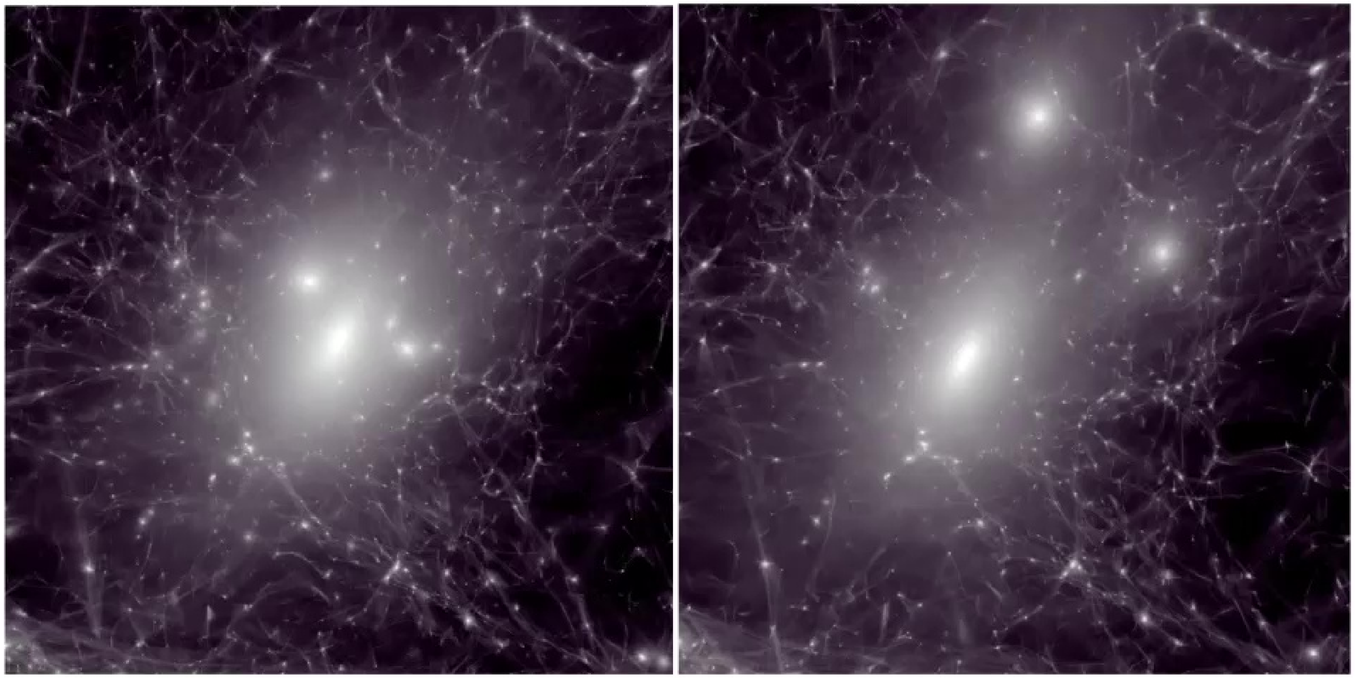


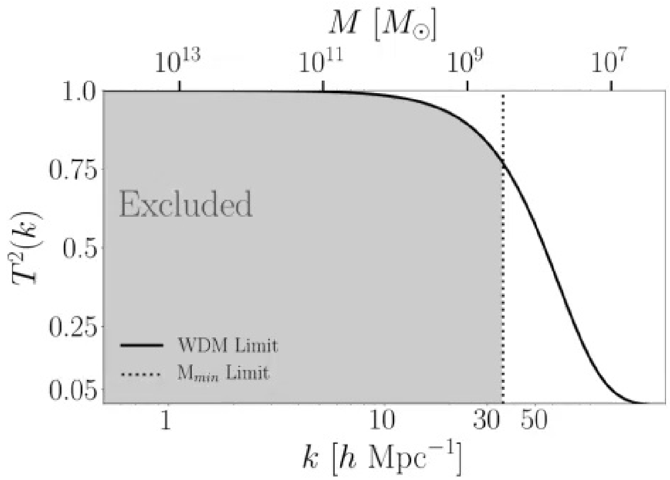
Plots and simulations by Rui An and Ethan Nadler

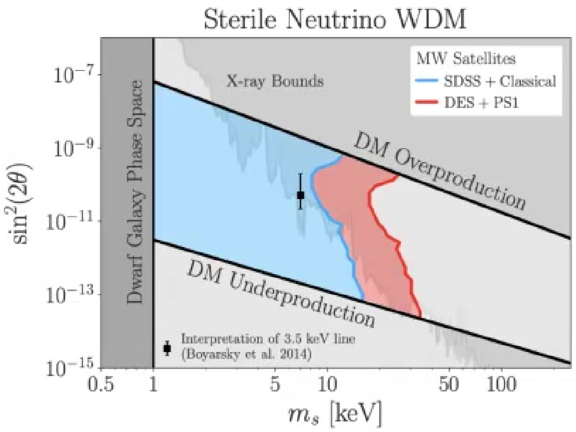
WDM = (thermal relic) warm dark matter

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

$$m_{WDM} \sim 7\text{keV}$$

$$(\lambda_{fs} < 10h^{-1}\text{kpc})$$





Nadler+, 2020

IDM = dark matter-baryon elastic scattering

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

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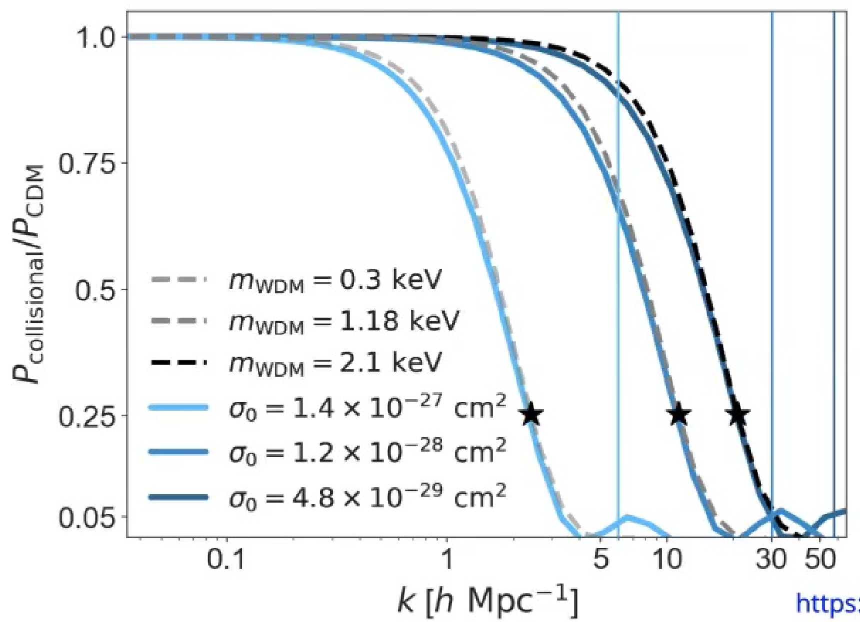
Assumes elastic scattering at some point in cosmic history
(not necessary to be coupled at early times)

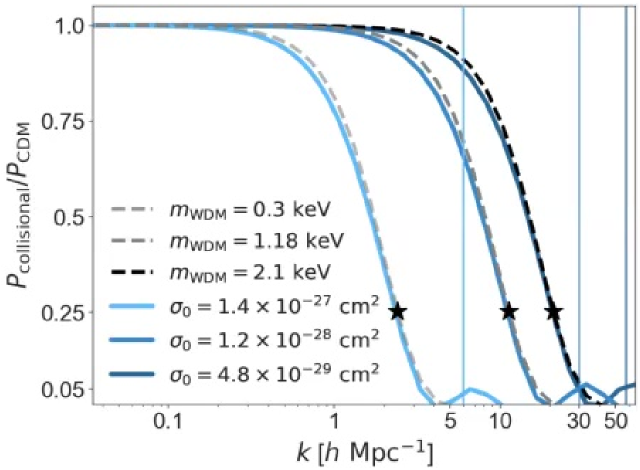
Interactions with photon-baryon fluid => **collisional** damping of small-scale structure



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

IDM = dark matter-baryon elastic scattering

Momentum transfer (σ_0, m_χ) = Hubble rate



IDM = dark matter-baryon elastic scattering

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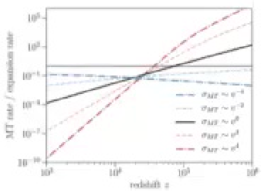
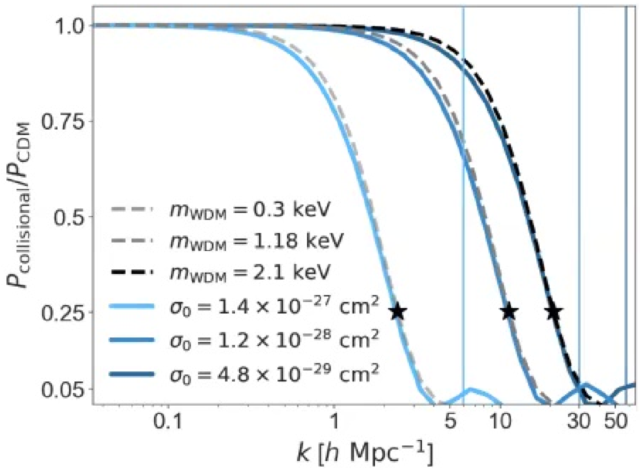


$R_\chi(z) \sim n_\chi \sigma_0 v$

z_{crit}

Horizon size (z_{crit}) = $2\pi / k_{crit}$



IDM = dark matter-baryon elastic scattering

DES+PanSTARRS1 result:

abundance of Milky Way satellite galaxies is consistent with CDM down to a minimum halo mass of:

$$M_{min} < 3.2 \times 10^8 M_{\rm sun}$$

$$k_{crit}(\sigma_0, m_\chi)$$

IDM = dark matter-baryon elastic scattering

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$$\boxed{M_{crit}(\sigma_0, m_\chi)}$$

$$\uparrow$$

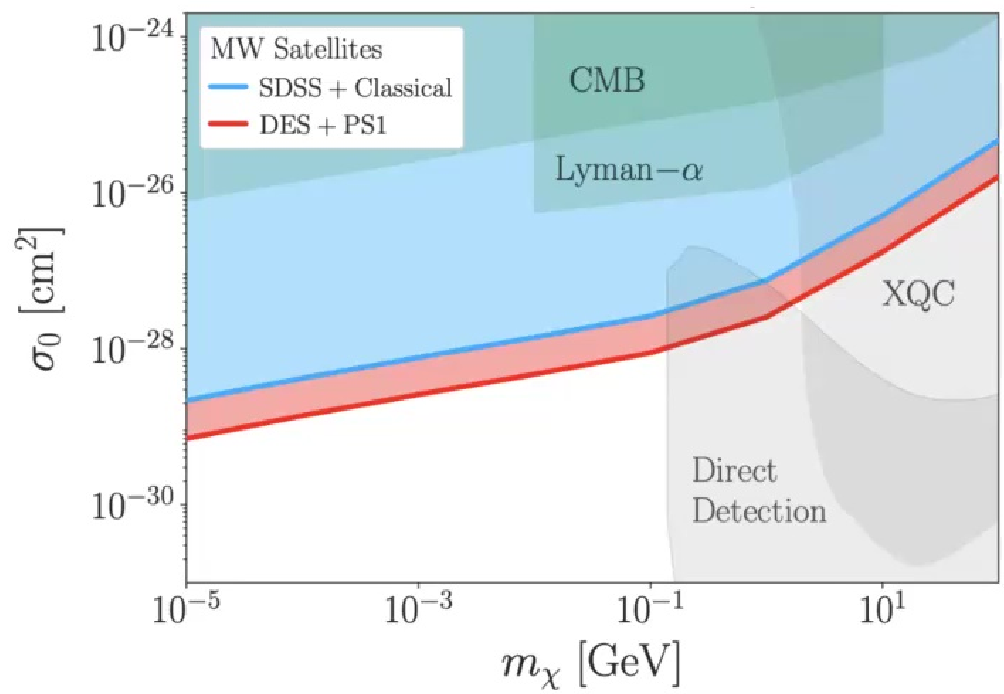
$$M_{crit} = \frac{4\pi}{3}\bar{\rho}(\lambda_{crit})^3$$

$$\uparrow$$

$$k_{crit}(\sigma_0, m_\chi)$$

IDM limits from MW Satellites (DES+PS1)

v-independent scattering



Ethan Nadler (USC/Carnegie)

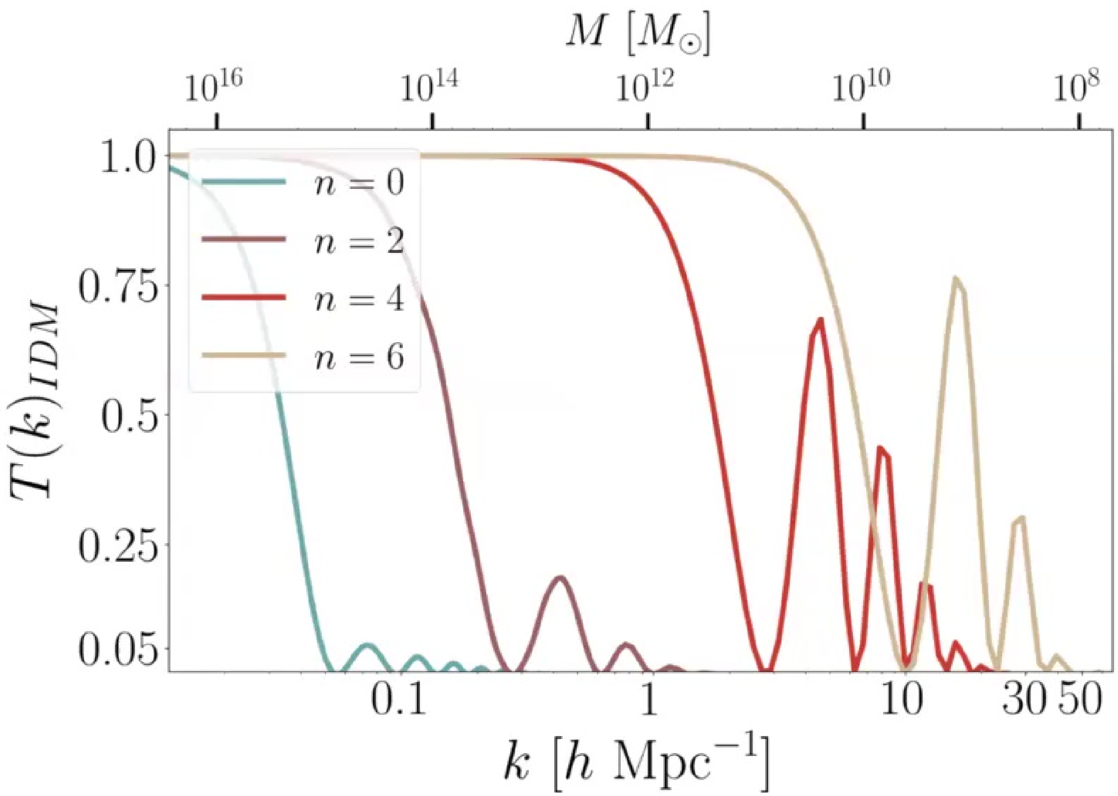
Bonus: fuzzy DM mass bound (95% CL):

$$m_\phi > 2.9 \times 10^{-21} \text{ eV}$$

Including: realistic modeling of galaxy-halo connection (incl. disruption of subhalos by the Milky Way disk) and mock observations of the satellite abundance (luminosity, size, and radial distribution).

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

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



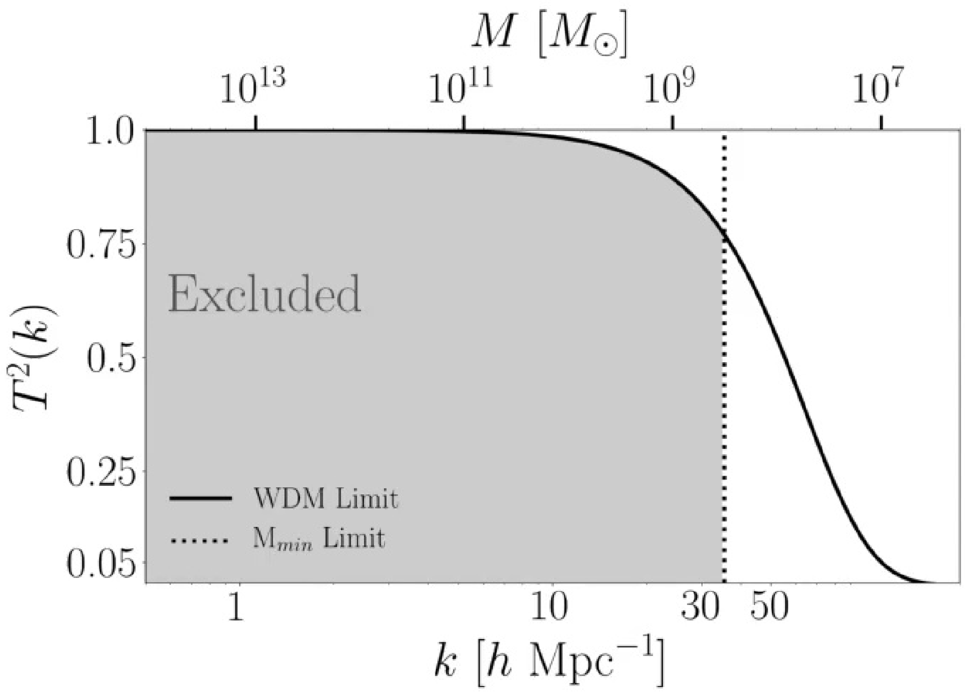
Karime Maamari (USC)

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

see also: 2008.00022

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

DES + PanSTARRS1



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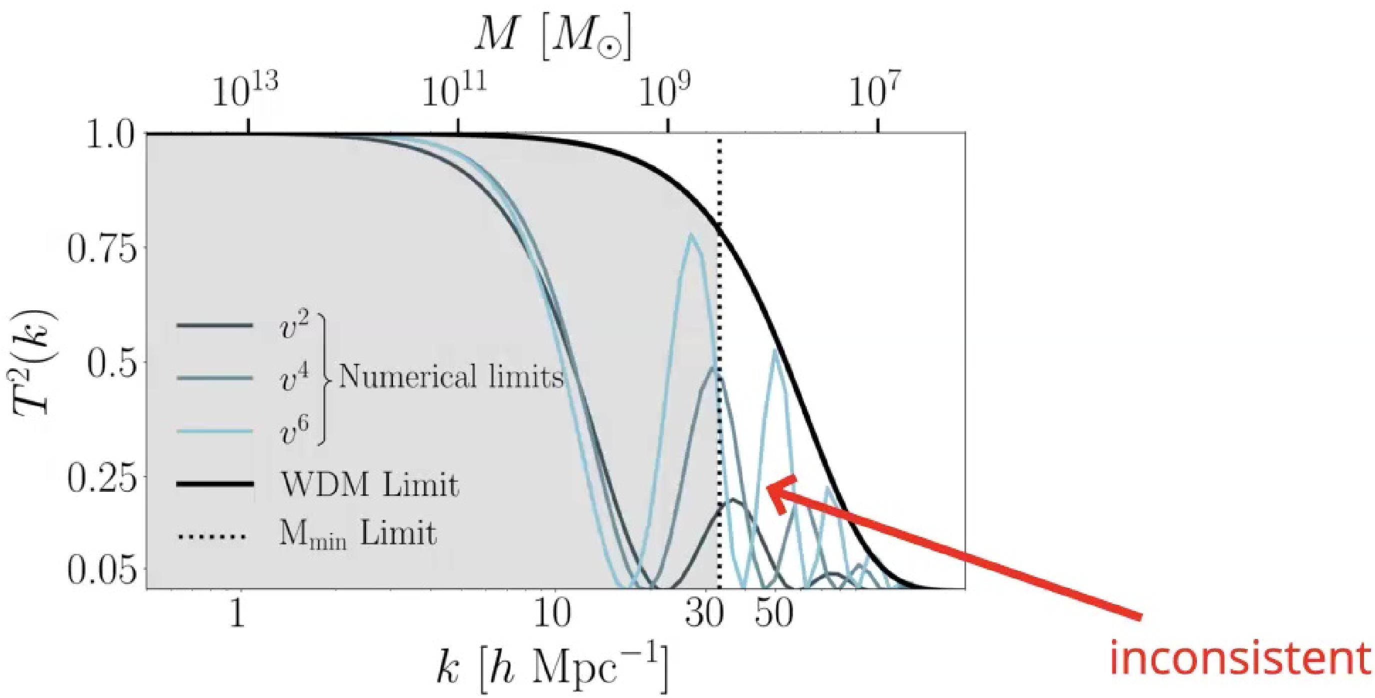

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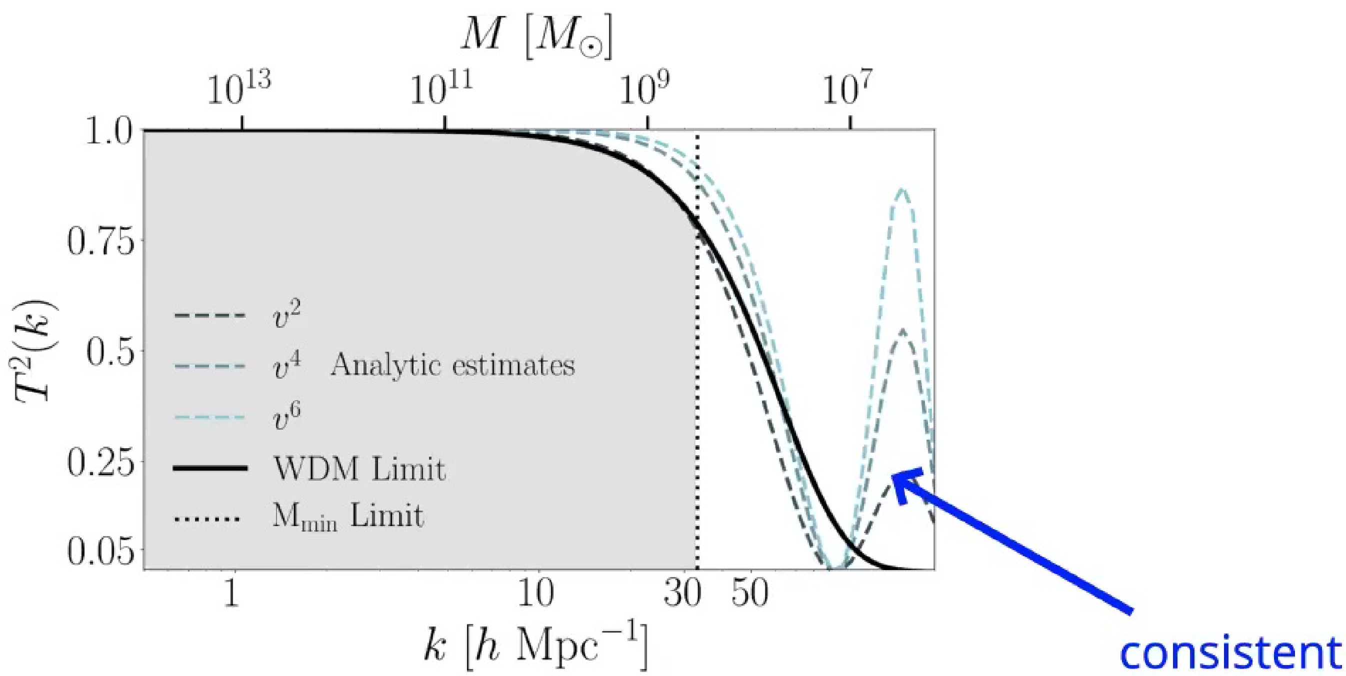
DES + PanSTARRS1

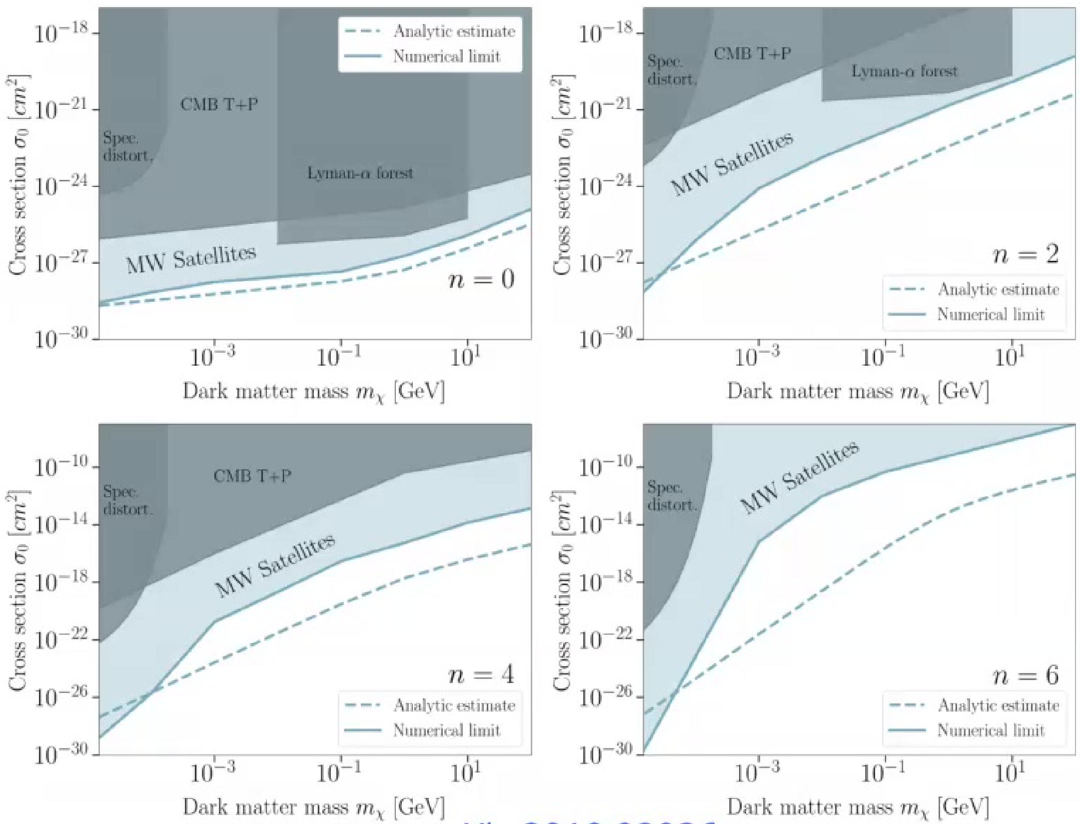


Maamari, + (ApJ Letters 2020), arXiv:2010.02936

see also: 2008.00022

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

DES + PanSTARRS1



Karime Maamari
(USC)

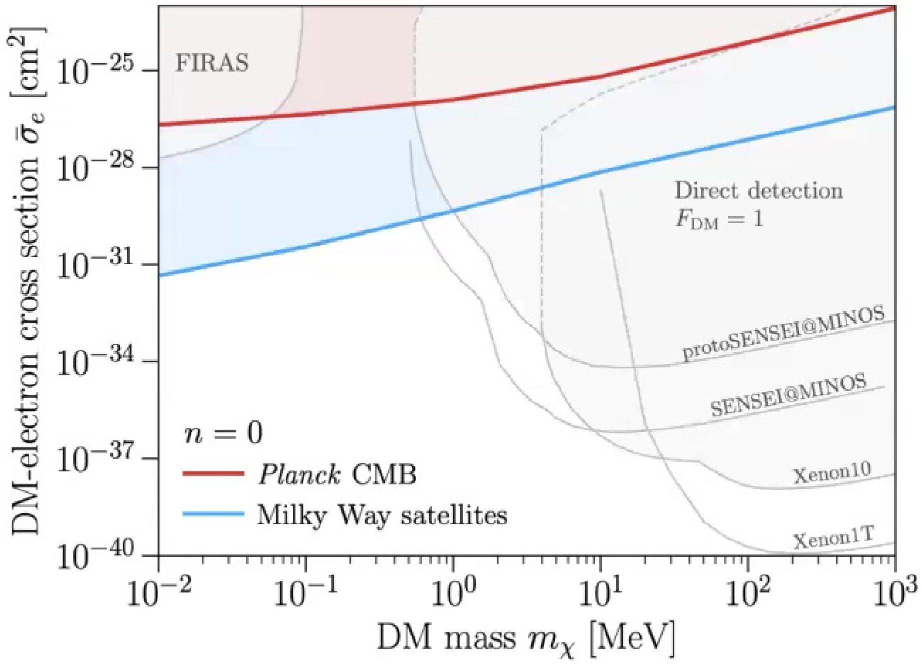
$\Longrightarrow$ **@ ~1 month after the Big Bang**

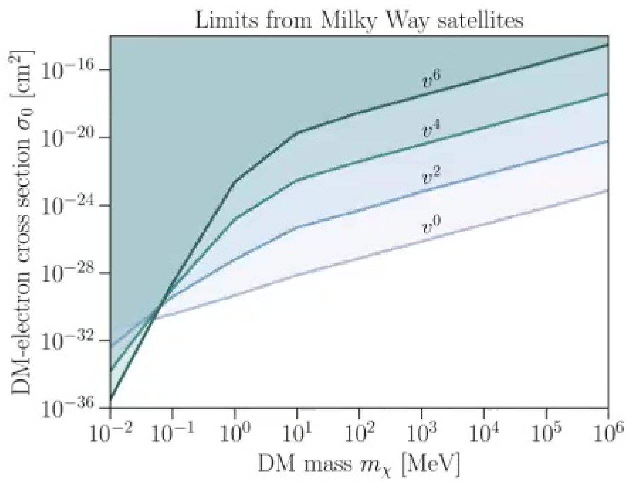
3-5 OOM improvement.

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

see also: 2008.00022

DM-electron scattering





Nguyen+ (PRD, 2021)

Near-field cosmology

Using small-scale structure to study fundamental physics

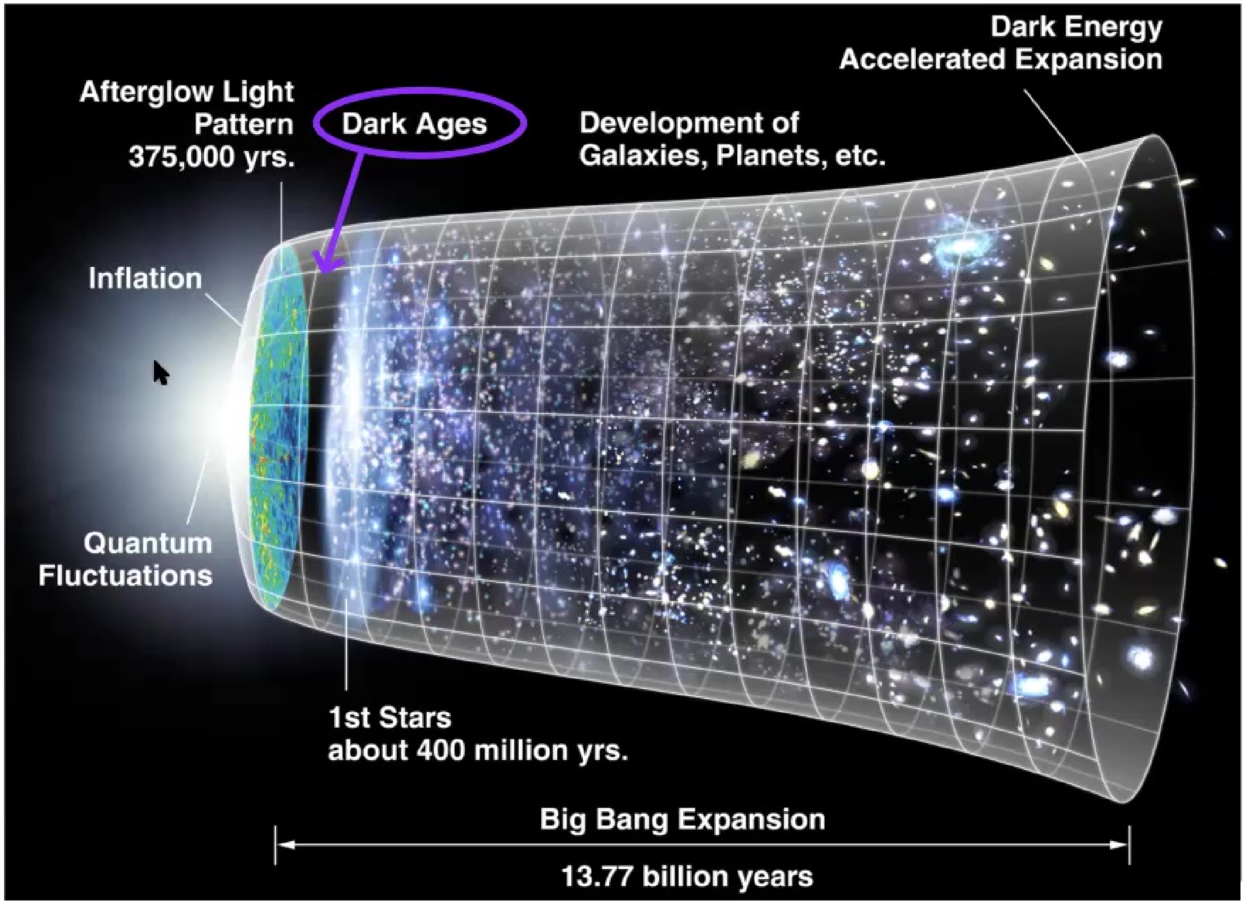
Galaxy surveys: **SDSS, DES;** Upcoming: **LSST,DESI,...**

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]

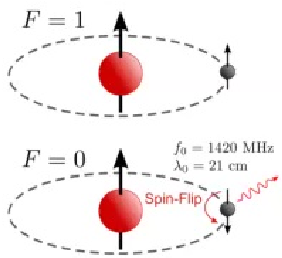
3. 21-cm intensity mapping

lessons from the global signal


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

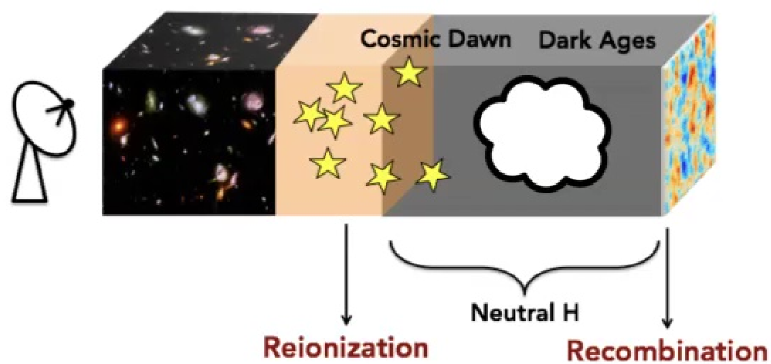
47

21-cm intensity mapping



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

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

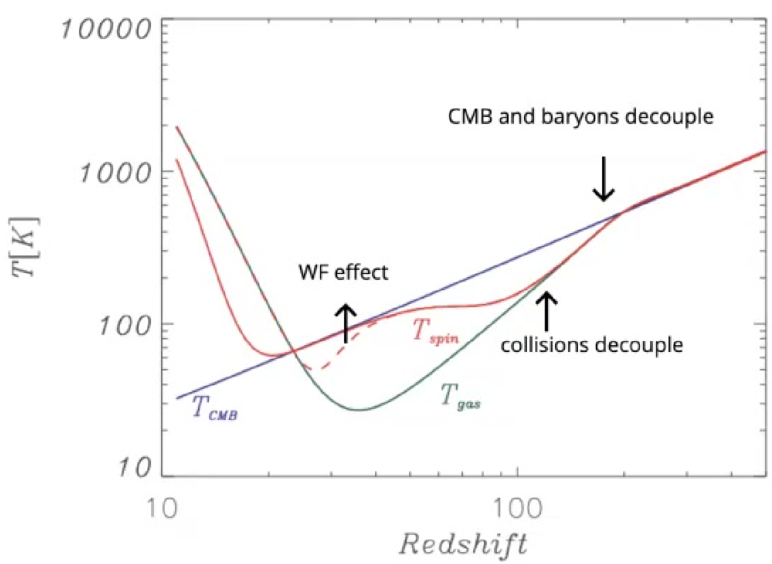


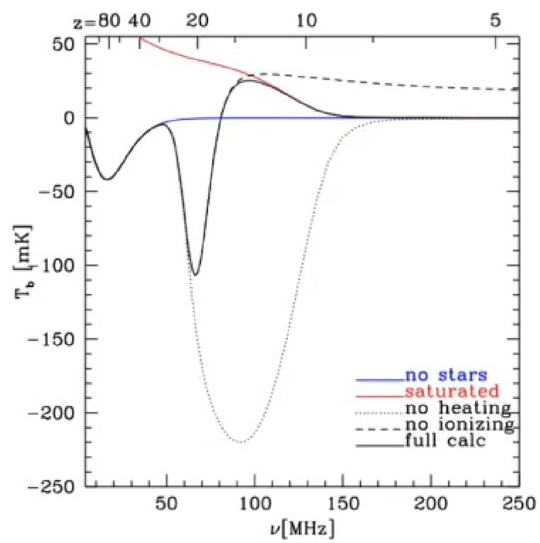
48

Global signal and thermal history

Spin temperatures is controlled by:

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



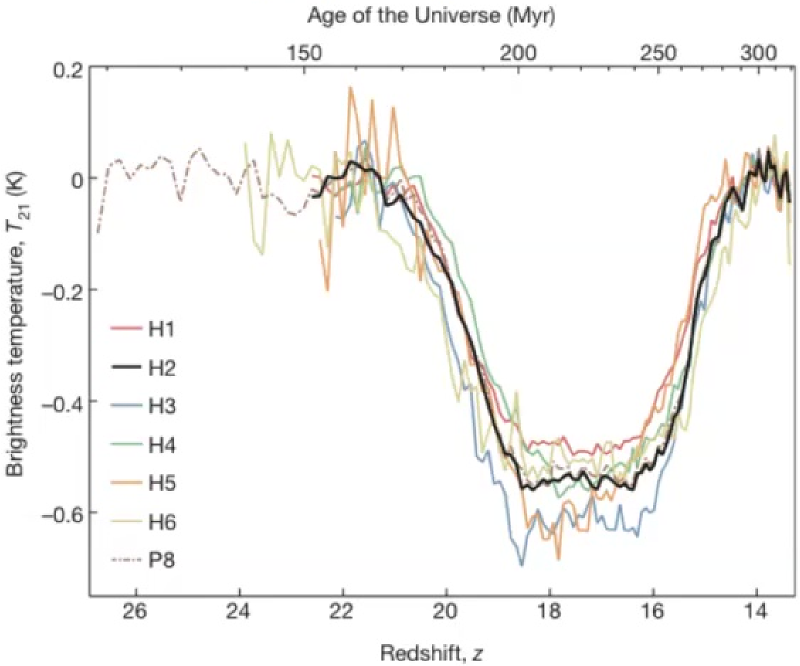


https://arxiv.org/pdf/1005.4057.pdf
https://arxiv.org/pdf/1206.0267.pdf

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!

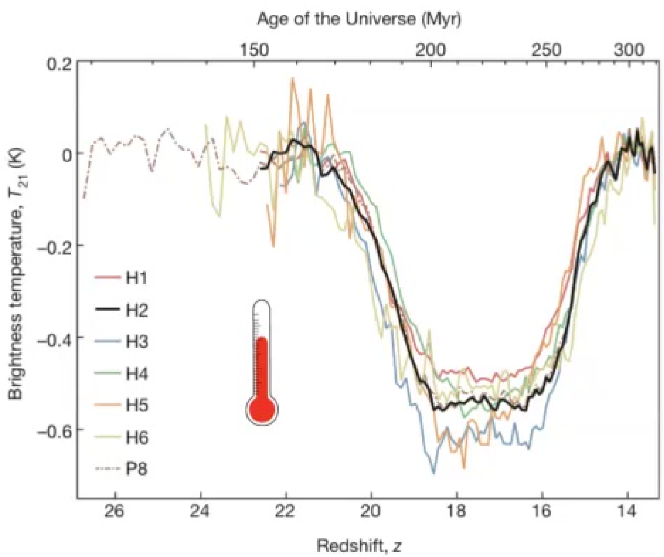
50

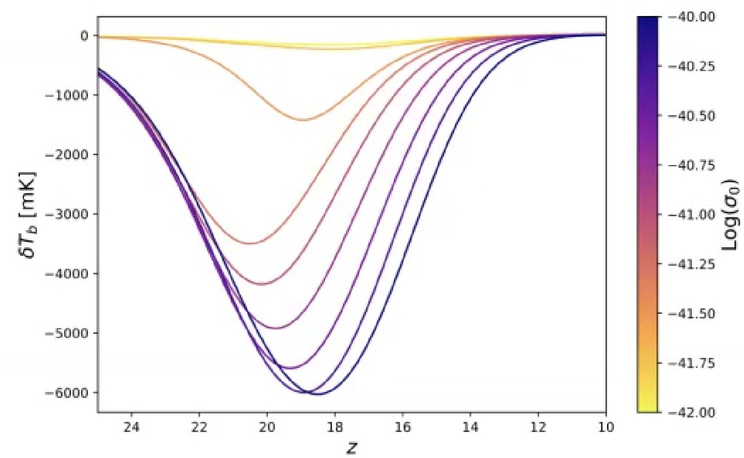
Case study: EDGES

Possible interpretation: baryons are too cold.

Late-time dark matter-baryon elastic scattering?!

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





Plot credit: Trey Driskell

Bowman, + (2018)
Barkana (2018)

Case study: EDGES

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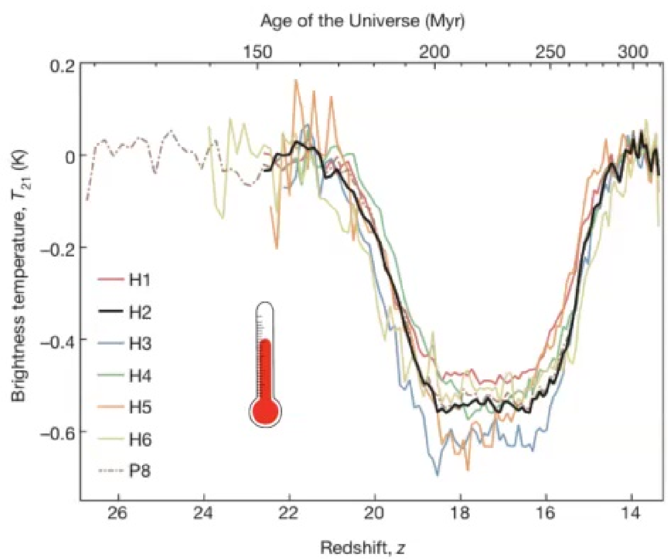
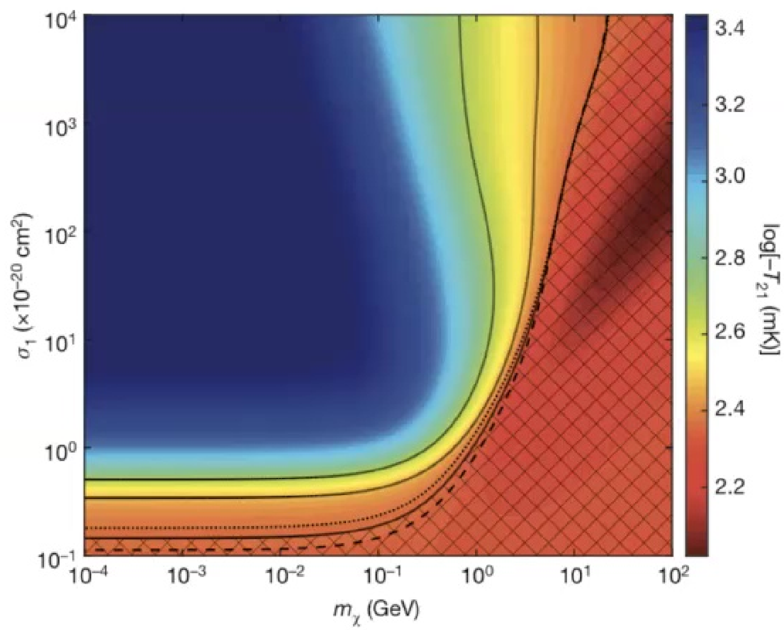
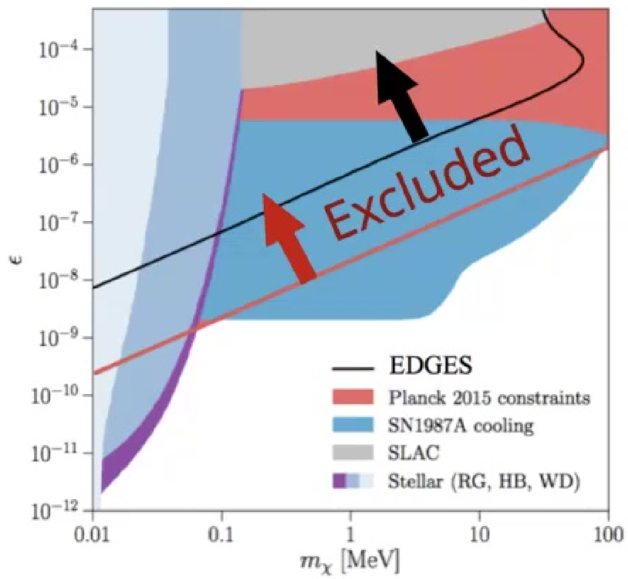




Bowman, + (2018)
Barkana (2018)

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

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

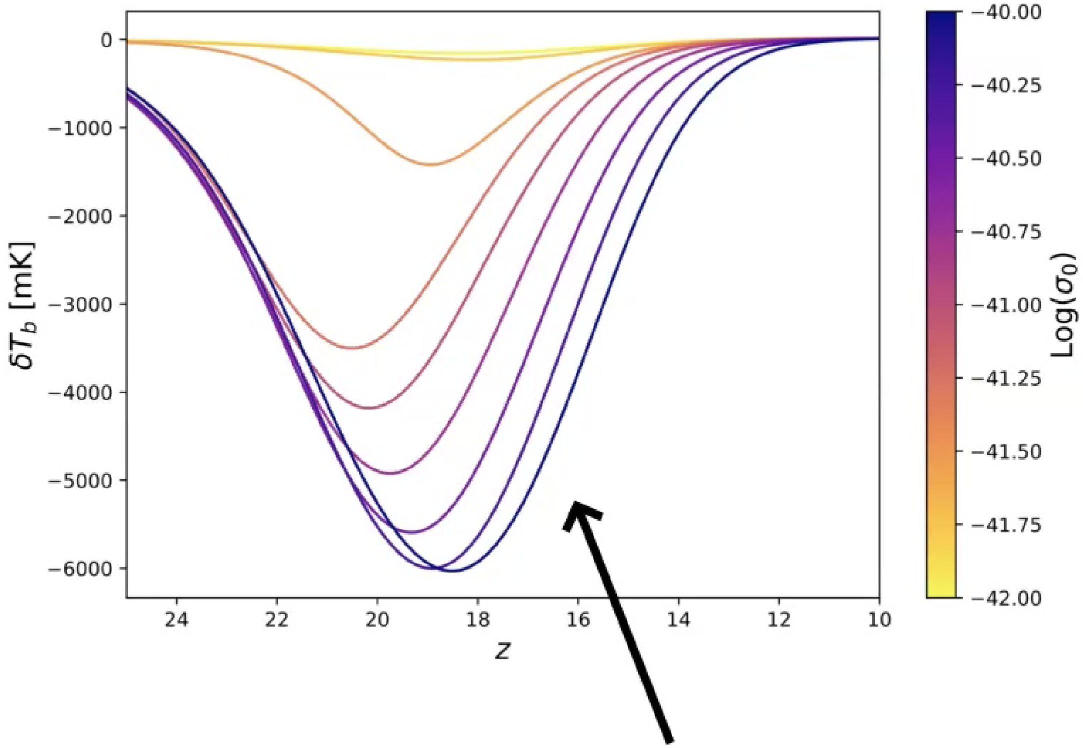


Boddy, + (2018); Kovetz, + (2018)

Cosmological probes are sensitive.

Comprehensive analyses are essential to establish a discovery.

Global 21-cm signal with DM scattering



Trey Driskell

Heat transfer

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

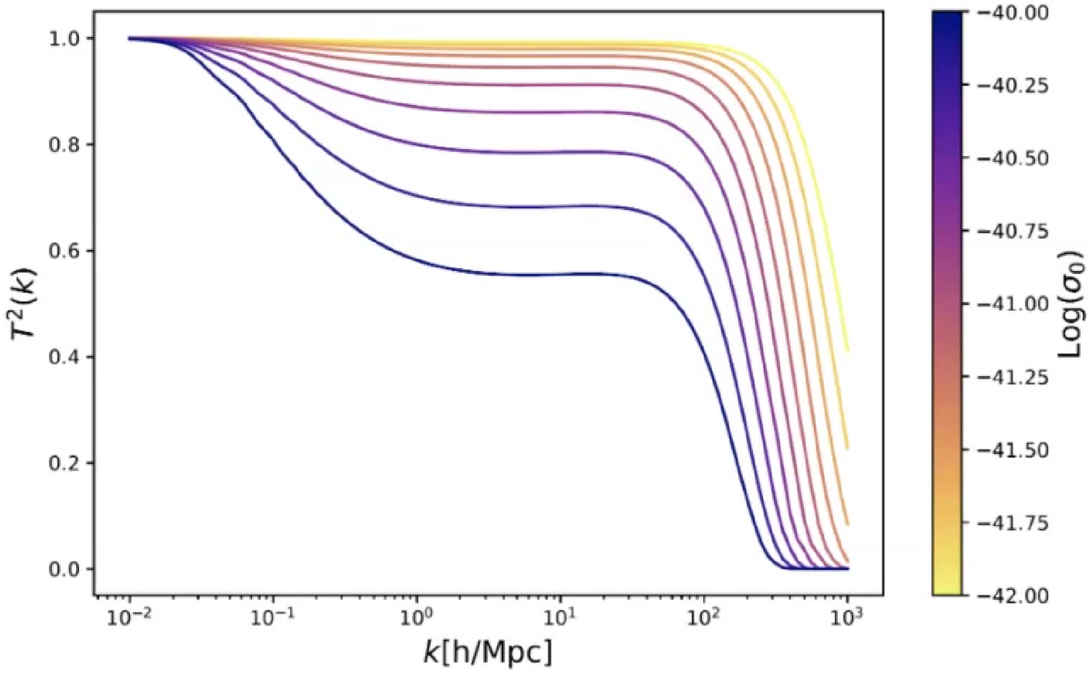
$$\dot{T}_b = -2\frac{\dot{a}}{a}T_b + \frac{2\mu_b}{m_\chi}\frac{\rho_\chi}{\rho_b}R'_\chi(T_\chi - T_b) + \frac{2\mu_b}{m_e}R_\gamma(T_\gamma - T_b)$$

Driskell, VG, + (In prep, 2021)

Global 21-cm signal with DM scattering

Transfer function (from modified CLASS):

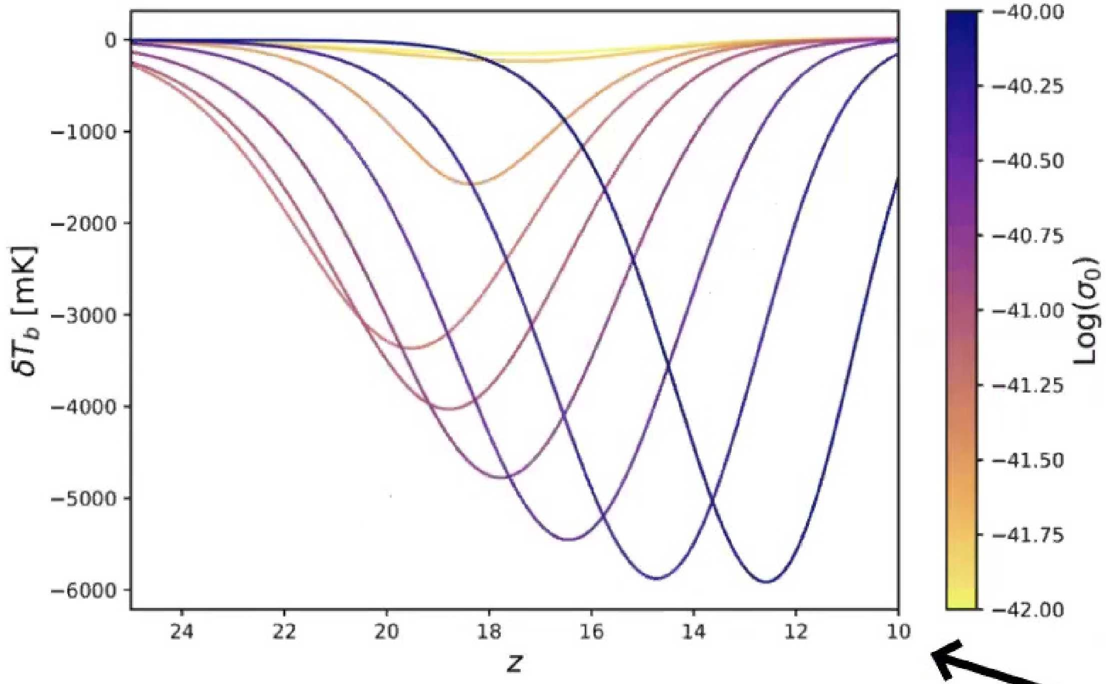
strong suppression that does not resemble other DM models…



Trey Driskell

Driskell, VG, + (In prep, 2021)

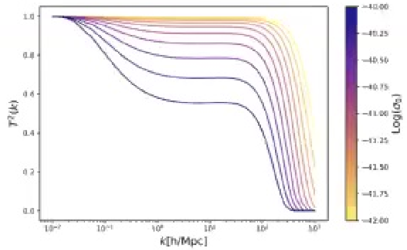
Global 21-cm signal with DM scattering



Trey Driskell

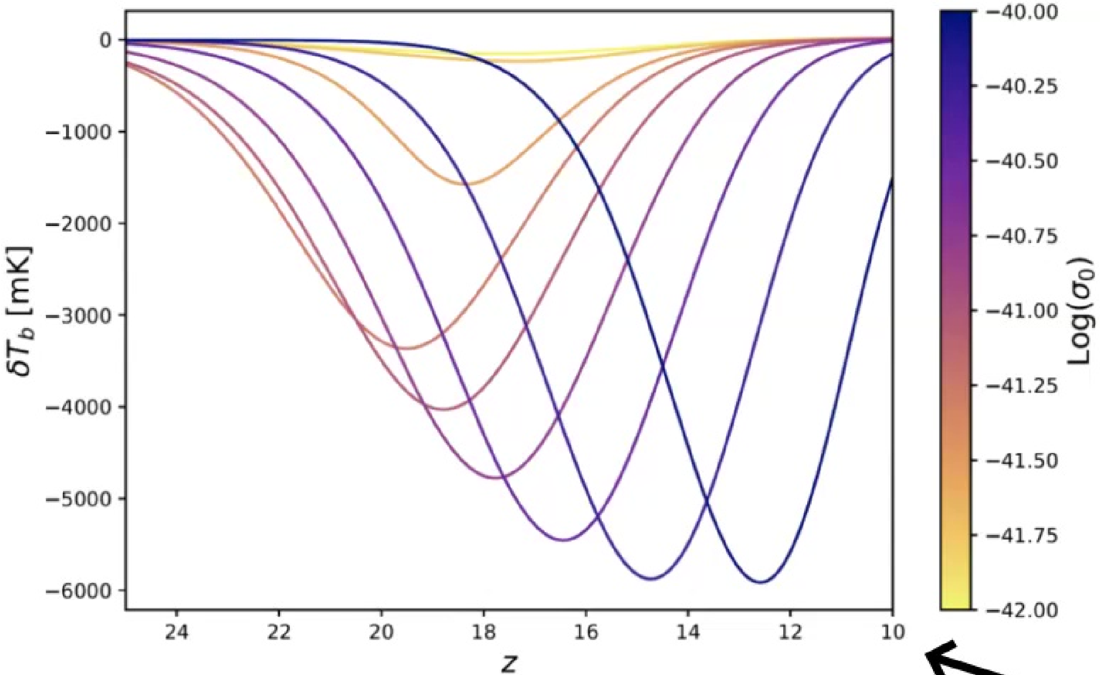
PRELIMINARY

With suppressed power:



Driskell, VG, + (In prep, 2021)

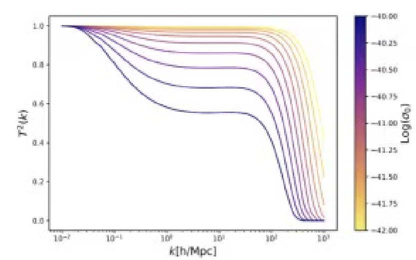
Global 21-cm signal with DM scattering



Trey Driskell

PRELIMINARY

With suppressed power:



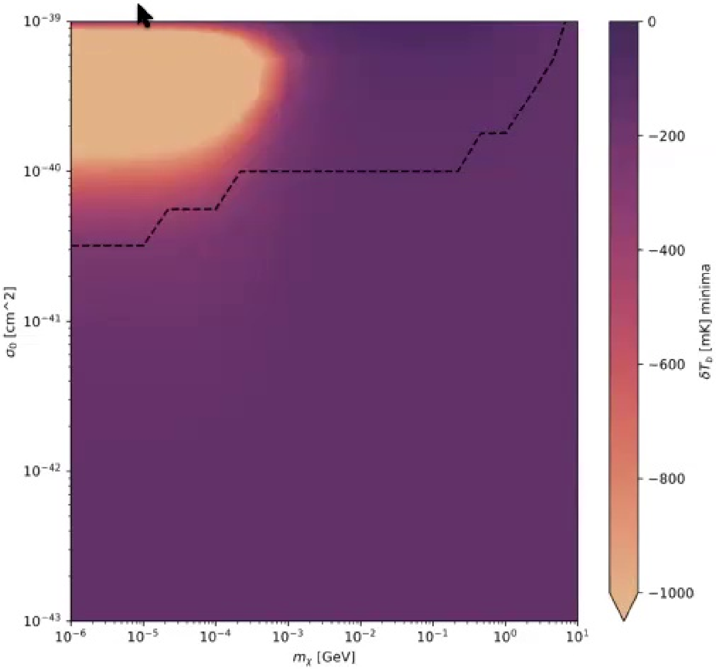
Driskell, VG, + (In prep, 2021)

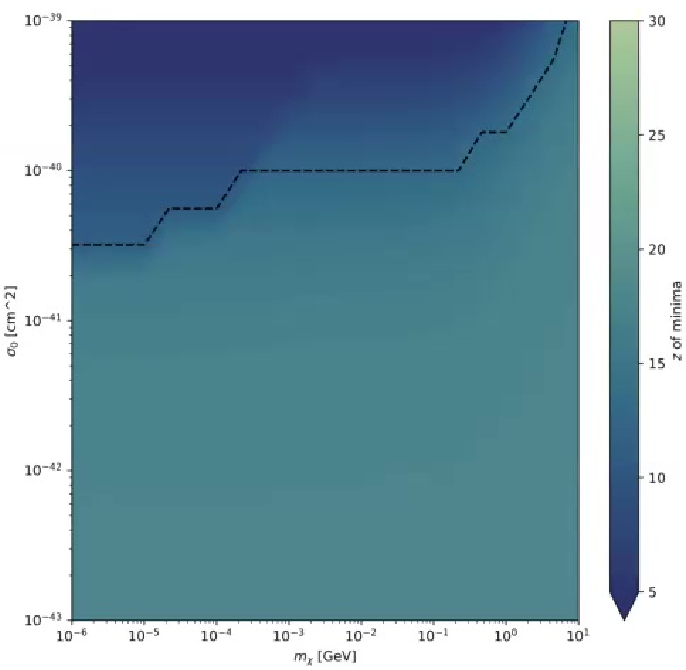
Global 21-cm signal with DM scattering

Scattering with ions

EDGES is inconsistent with millicharge-like IDM.

PRELIMINARY





Driskell, VG, + (In prep, 2021)

Key points

- CMB already probes new parameter space for IDM (elastic scattering with protons and electrons, as well as the mass).
- Near-field cosmology is promising [e.g. Milky Way satellite abundance], but we need new modeling tools to enable detection.
- Primordial abundances and the CMB small-scale anisotropy are extremely sensitive to dark matter mass, better data is needed to probe light particles robustly.
- **Lots of data coming:** Simons Observatory, CMB-S4, LSST, DESI, HERA, SKA, EDGES, SARAS, next gen. direct detection, etc.
- **Key for discovery: comprehensive searches and joint analyses.**
- **To-address: non-linearities in non-standard cosmologies, frameworks for joint analyses of multiple observables, assessment of limitations and degeneracies in new data sets.**