Title: Dark Matter: A Cosmological Perspective

Speakers: Katherine Mack

Series: Colloquium

Date: April 15, 2020 - 2:00 PM

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Abstract: While it is considered to be one of the most promising hints of new physics beyond the Standard Model, dark matter is as-yet known only through its gravitational influence on astronomical and cosmological observables. I will discuss our current best evidence for dark matter's existence as well as the constraints that astrophysical probes can place on its properties, while highlighting some tantalizing anomalies that could indicate non-gravitational dark matter interactions. Future observations, along with synergies between astrophysical and experimental searches, have the potential to illuminate dark matter's fundamental nature and its influence on the evolution of matter in the cosmos from the first stars and galaxies to today.


Dark Matter:
A Cosmological Perspective
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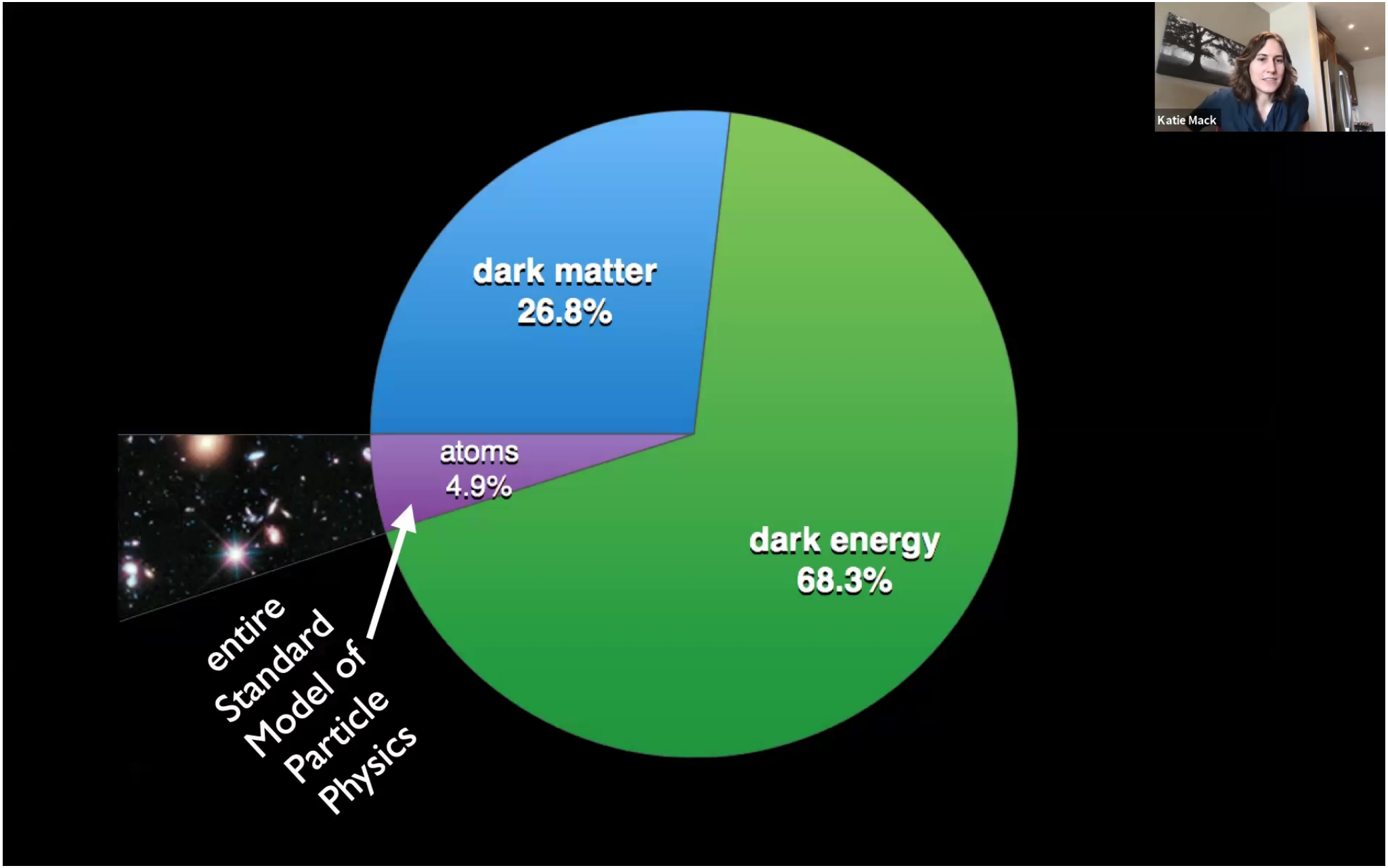

Katie Mack
dark matter
26.8%
atoms
4.9%
dark energy
68.3%
entire Standard Model of Particle Physics

Dark Matter

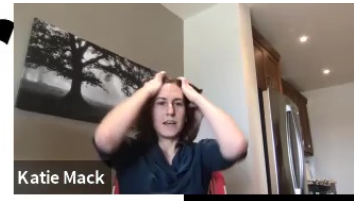
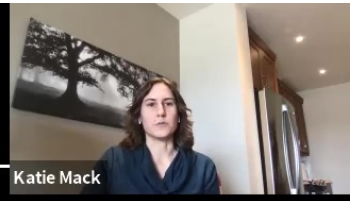


Image: dark matter: K. Mack; Andromeda Galaxy: GALEX, JPL-Caltech, NASA

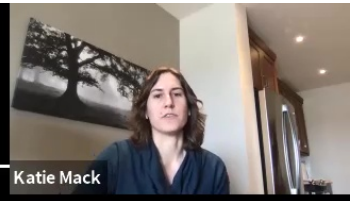
What We Don't Know



- Origin / particle type
- Particle mass
- Thermal history

Particle Zoo

What We Don't Know

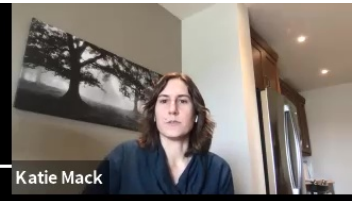


- Origin / particle type
- Particle mass
- Thermal history
- Non-trivial evolution?

Particle Zoo

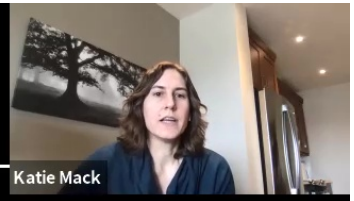
- One component or many?
- Non-gravitational interactions (self or SM)?
- Small-scale behavior (mass of smallest halos)

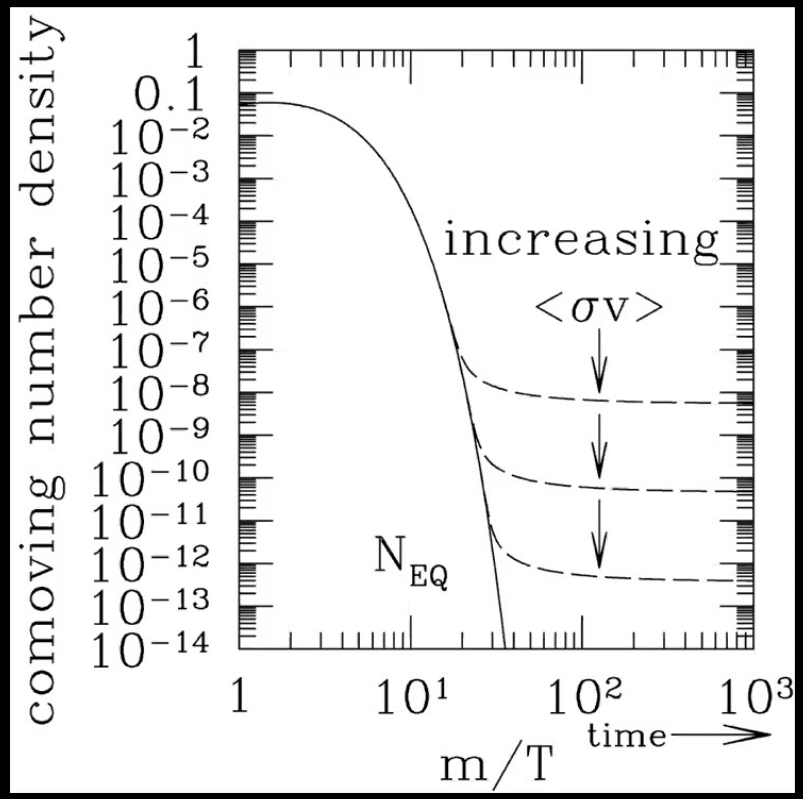
Candidates (incomplete list)



- Weakly Interacting Massive Particles (WIMPs)
  - Something not included in the Standard Model of Particle Physics, generally with weak interactions
  - May be thermally produced (or not)
- Annihilating (e.g., SUSY neutralino WIMP)

WIMP Miracle



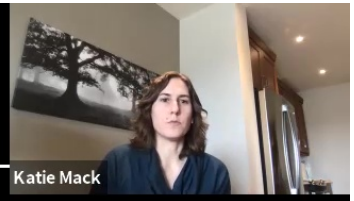


Kolb & Turner 1990

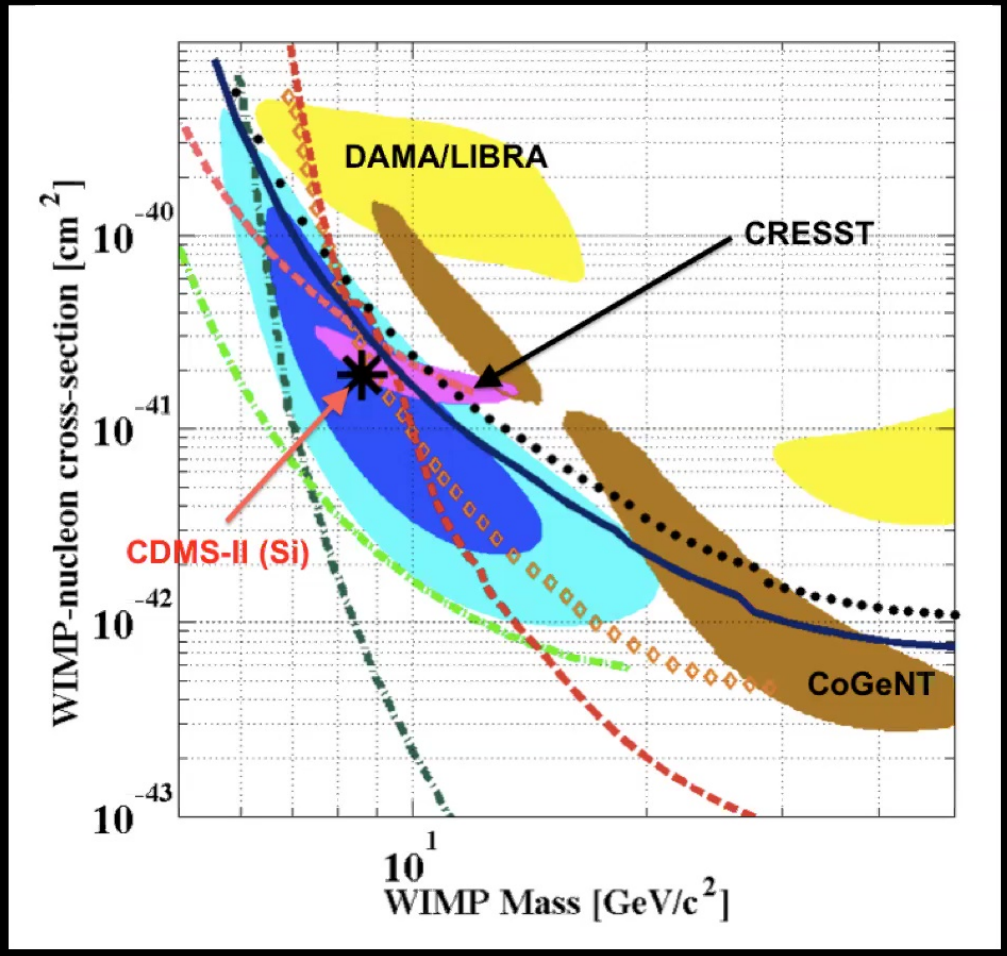
Standard thermal WIMP dark matter

- freezes out when no longer in thermal equilibrium with baryons
- for weak-scale mass and cross-section, predict correct abundance of DM
- discovery opportunities: annihilation, scattering, production

WIMP Direct Detection



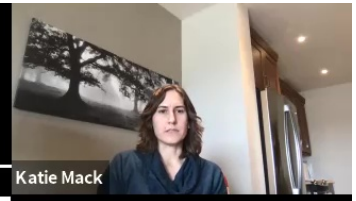
strength of interaction with nucleus

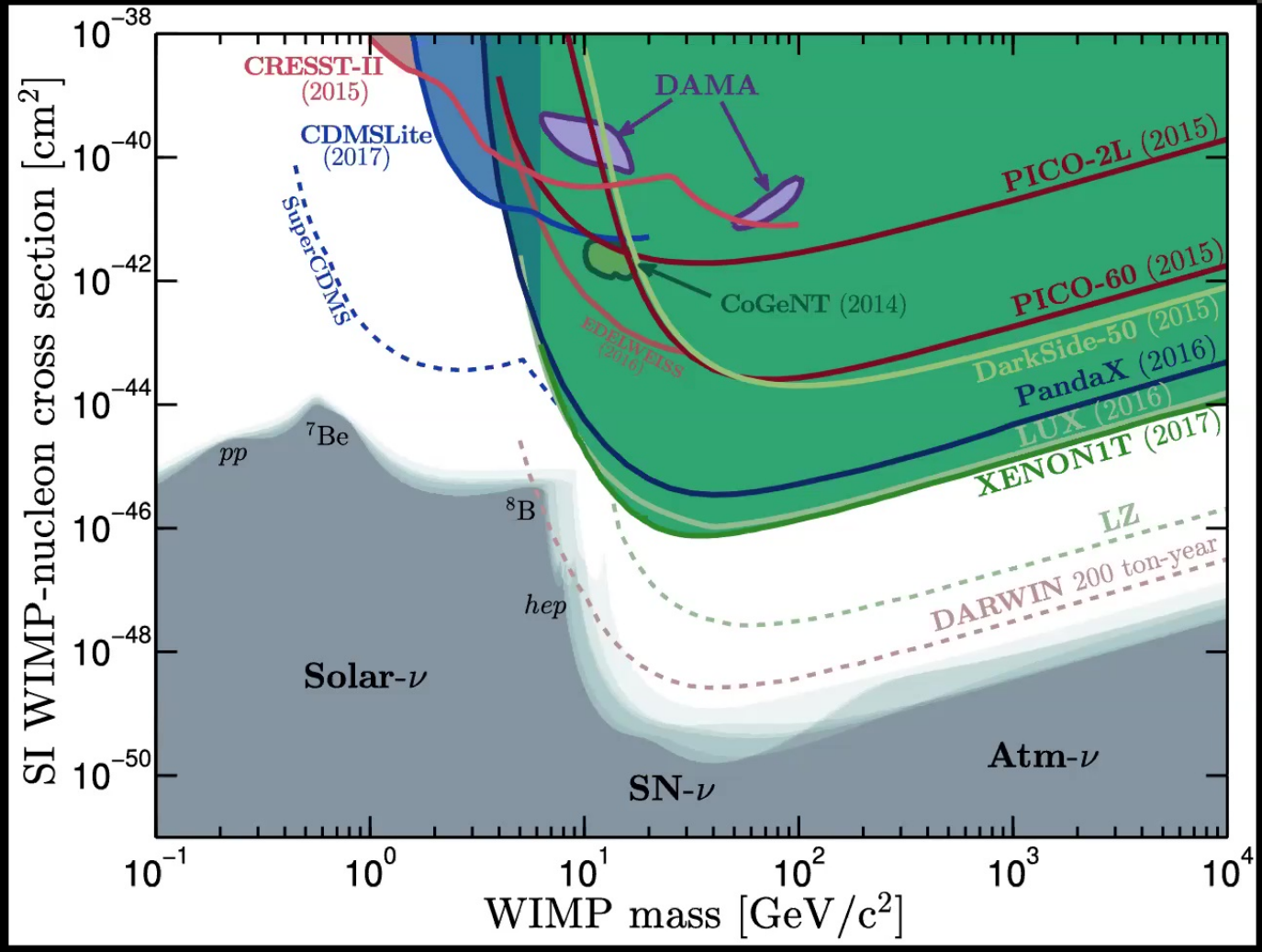


mass of dark matter particle

CDMS Collaboration, 2013

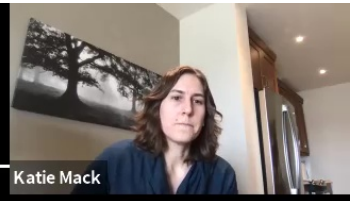
WIMP Direct Detection





plot via Ciaran O'Hare

Candidates (incomplete list)



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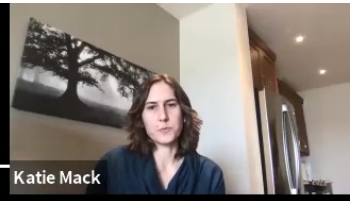
- Decaying (e.g., sterile neutrino)
- Warm (WDM) (e.g., axino)
- Self-interacting (SIDM) (particle + dark sector force)
- Axion (e.g., QCD axion / string axion) (Mack 2011; Mack & Steinhardt 2011)
- Fuzzy DM (tiny mass, large deBroglie wavelength)

Candidates (incomplete list)



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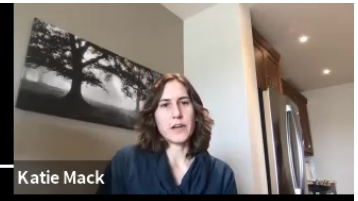
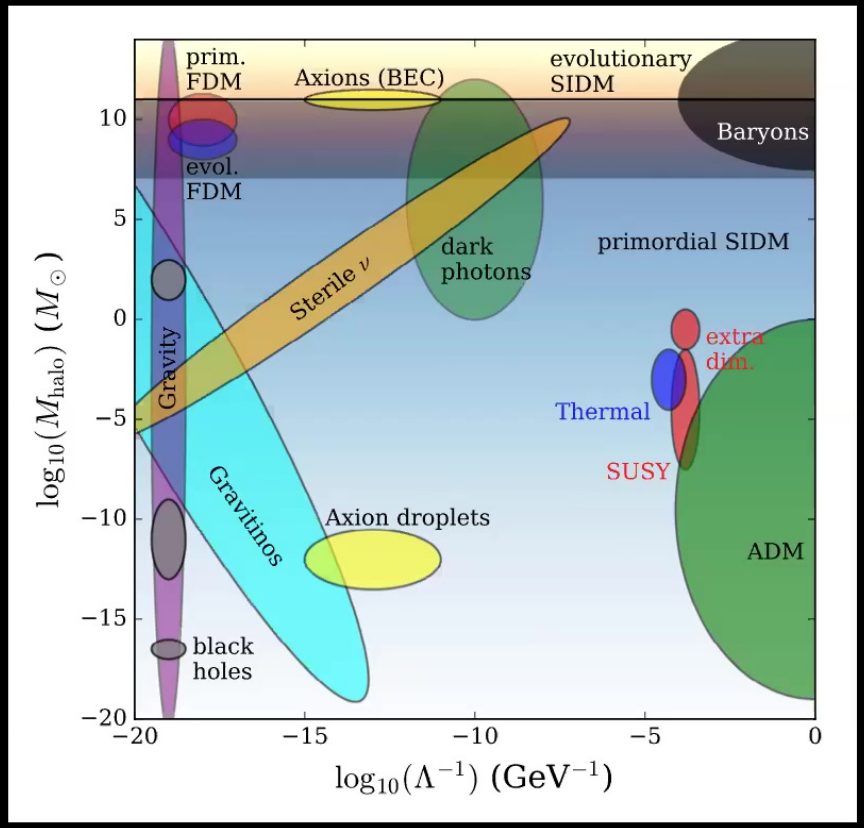
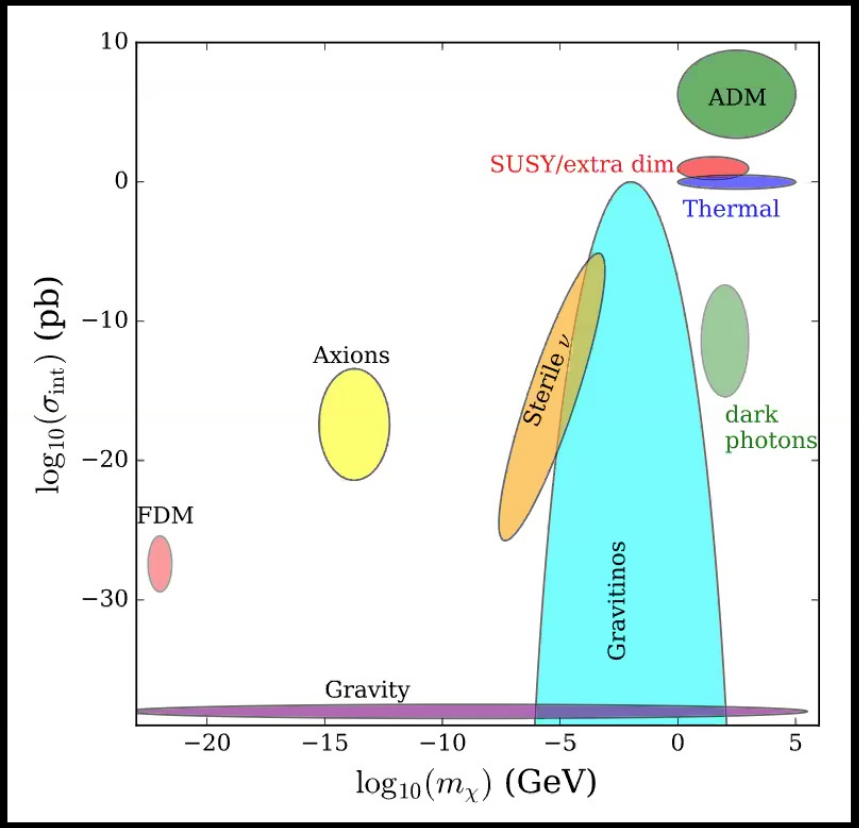
- Axion (e.g., QCD axion / string axion) (Mack 2011; Mack & Steinhardt 2011)
- Fuzzy DM (tiny mass, large deBroglie wavelength)
- MACHO (e.g., primordial black holes) (Mack, Ostriker & Ricotti 2007; R,O,M 2008)

Candidates (incomplete list)







halo mass vs SM interaction

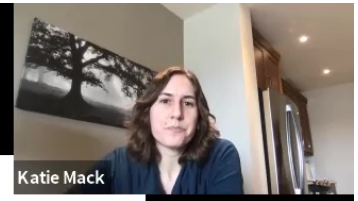
↗

(where we expect to see a deviation from CDM)

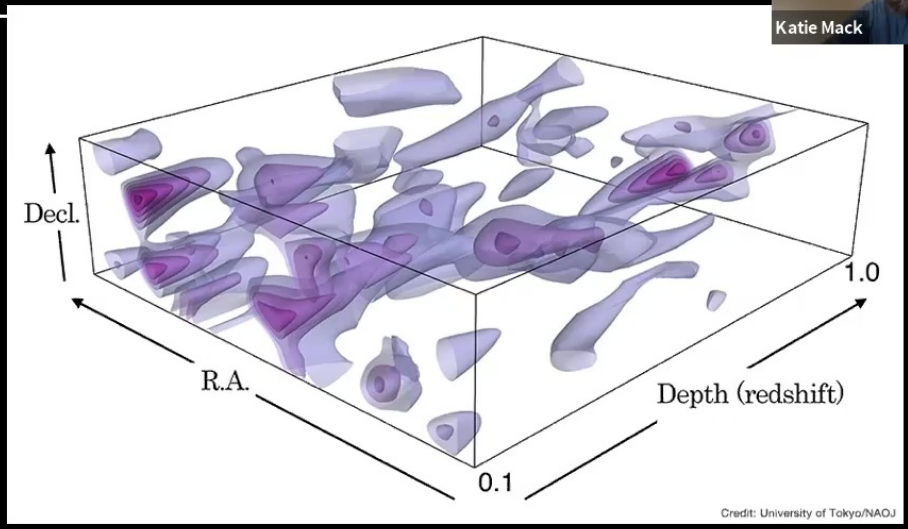
SM cross section vs particle mass

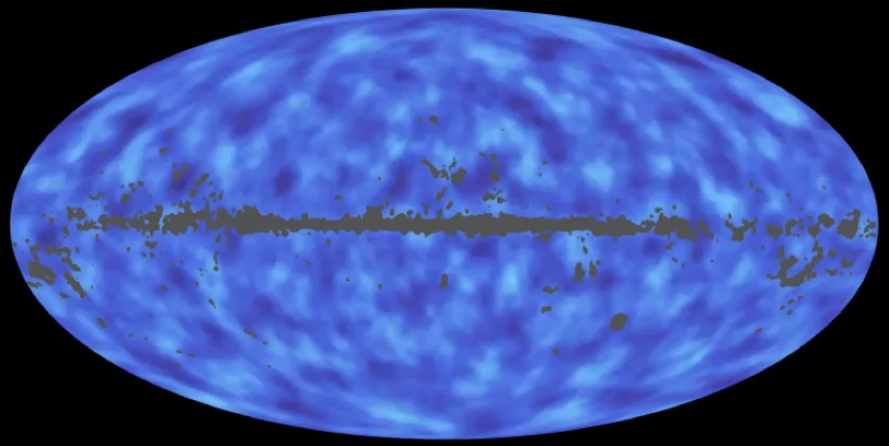
Peter & Buckley 2018

What We Do Know

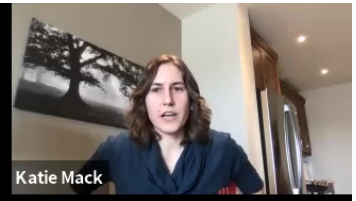


- Where it is
- How much is out there
- What it's doing
- (to some degree) what it isn't



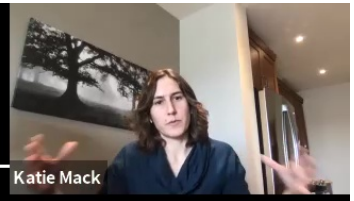


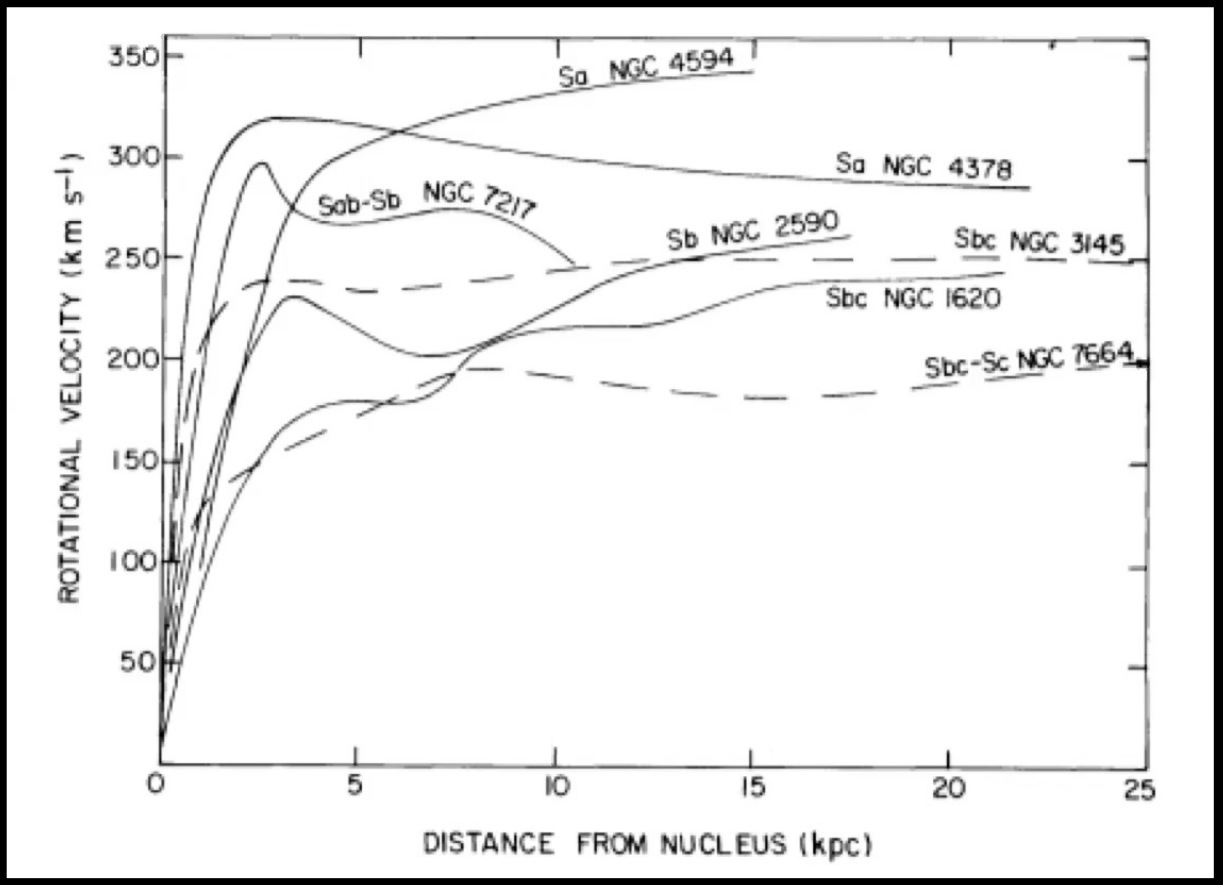
Planck Collaboration



Dark matter…
How do I know thee?
Let me count the ways…

1. Rotation Curves



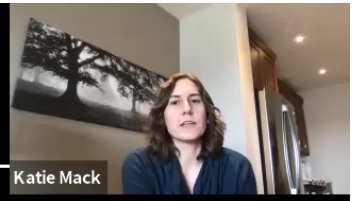


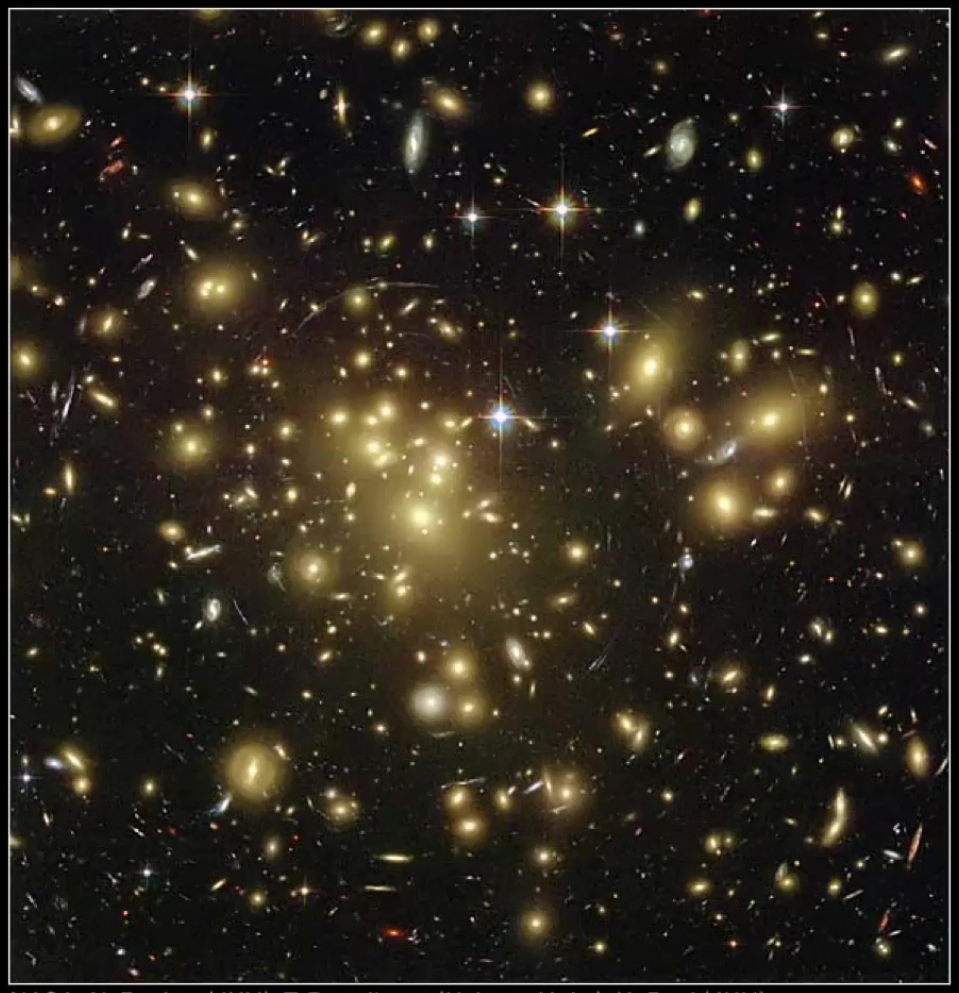
Rubin, Ford & Thonnard 1978

<u>What we learn:</u>

mass fraction distribution

2. Cluster Dynamics



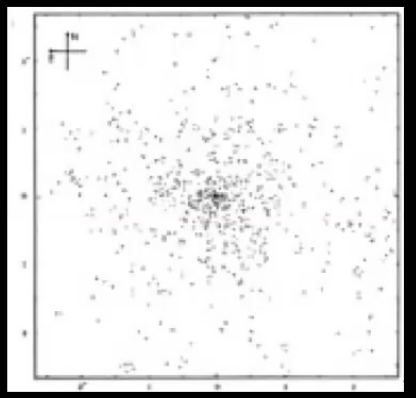


NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU),
M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory),
the ACS Science Team and ESA STScI-PRC03-01a

<u>What we learn:</u>

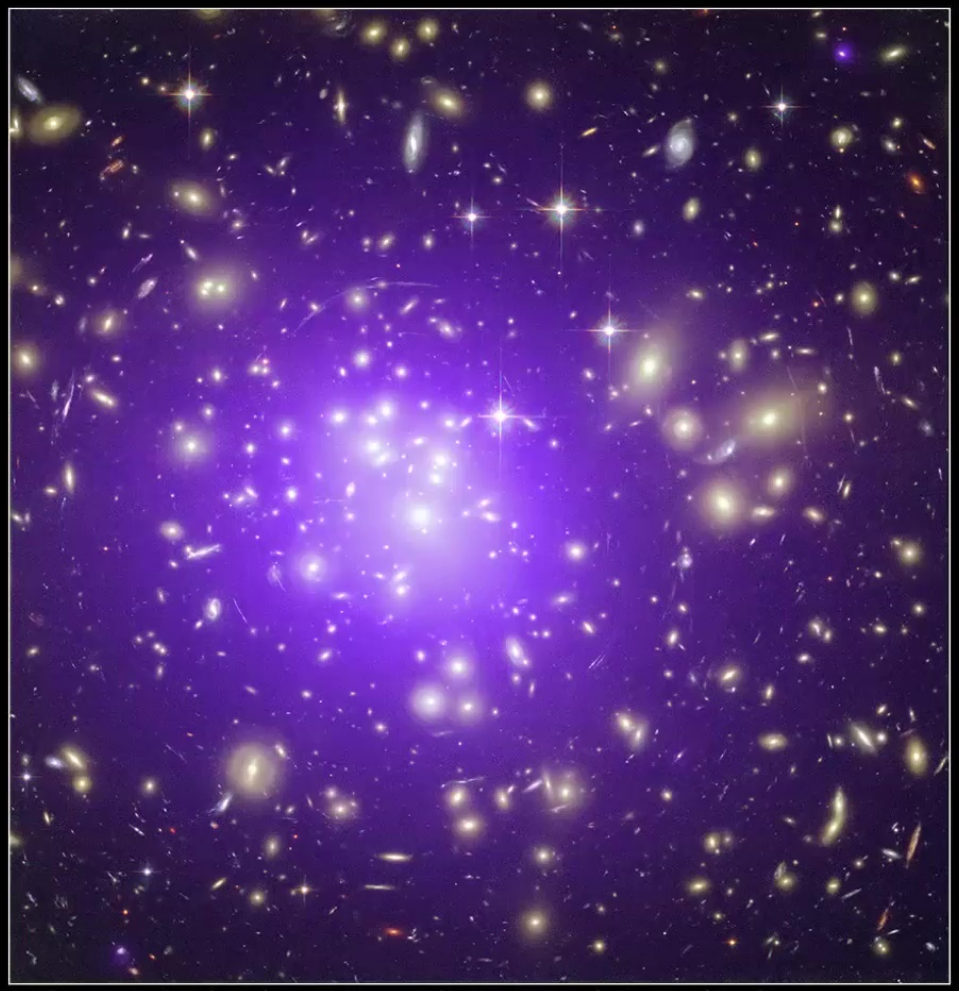
mass fraction

distribution



Zwicky 1937

3. Cluster Gas



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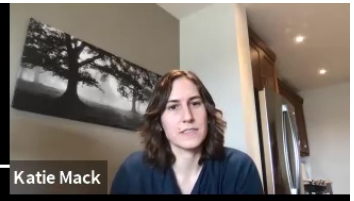

<u>What we learn:</u>

mass fraction

distribution

3. Cluster Gas

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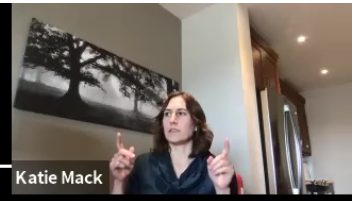
<u>What we learn:</u>

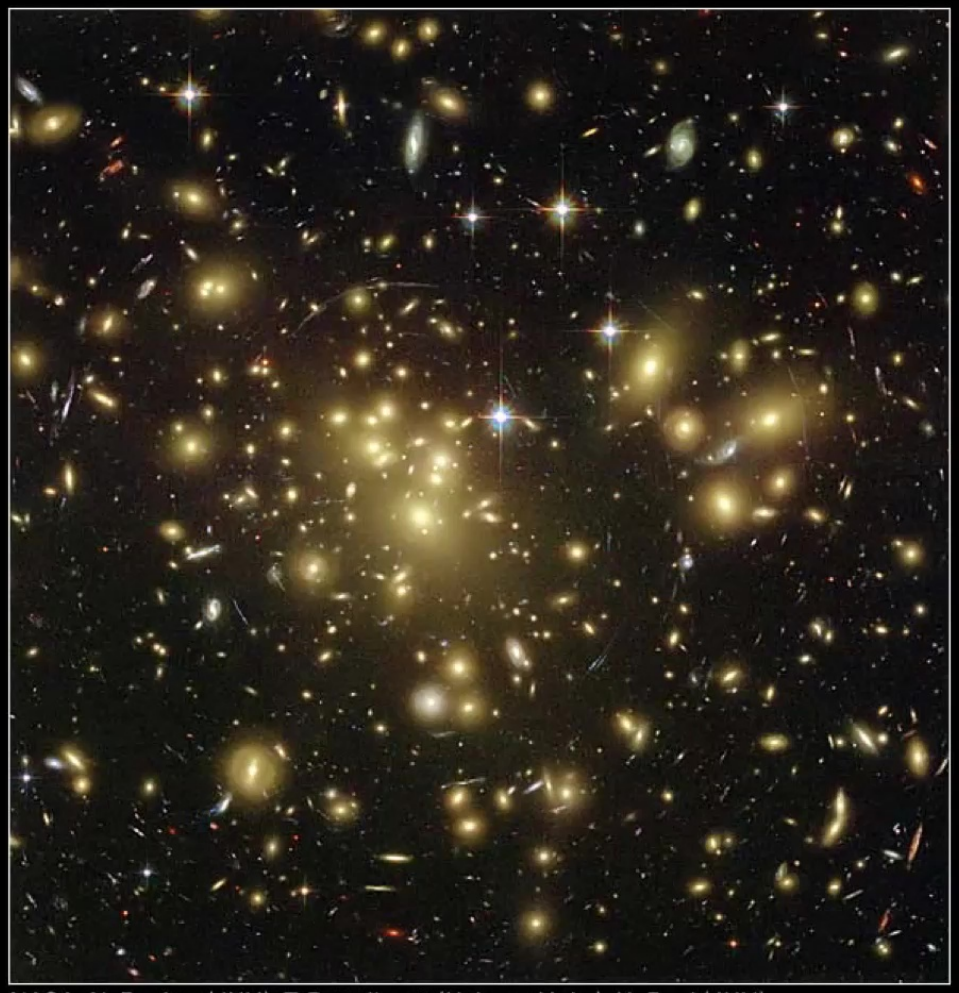
mass fraction

distribution

~90% of the *luminous* matter in a cluster is hot gas

4. Strong Gravitational Lensing





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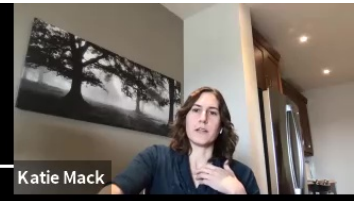
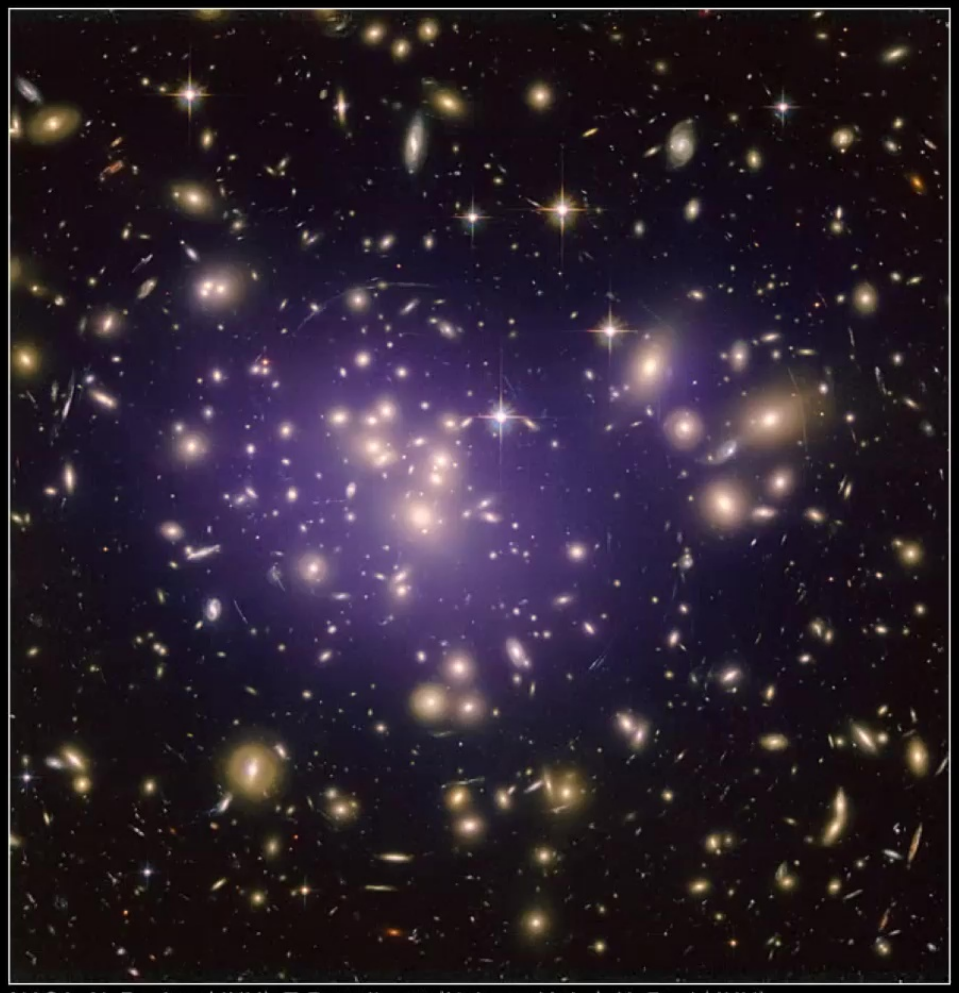
<u>What we learn:</u>

mass fraction

distribution

4. Strong Gravitational Lensing





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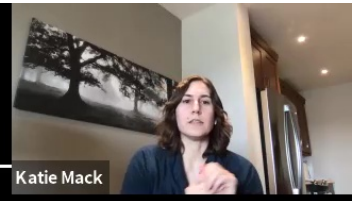
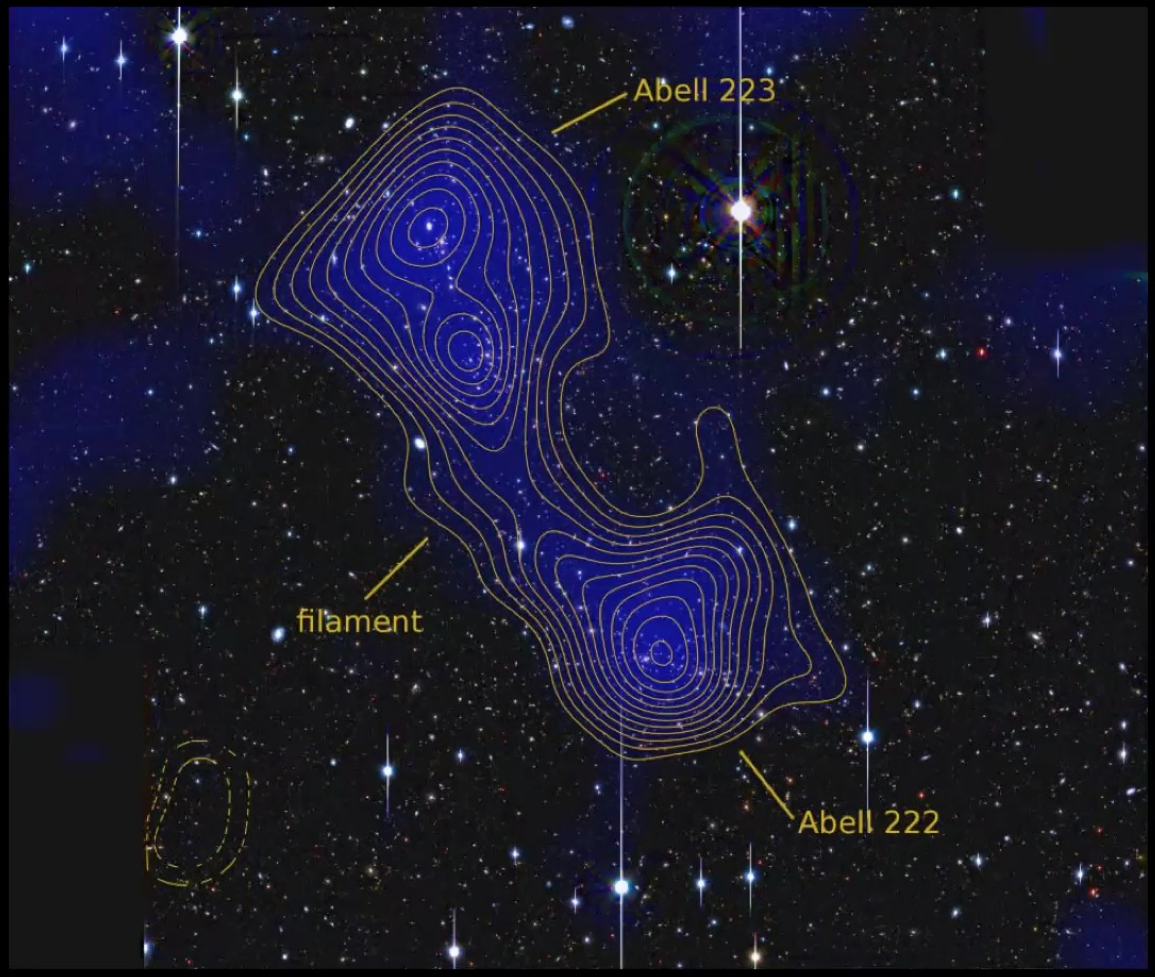
<u>What we learn:</u>

mass fraction

distribution

5. Weak Gravitational Lensing





Dietrich et al. 2016

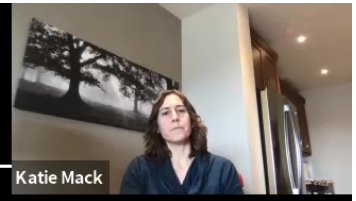
<u>What we learn:</u>

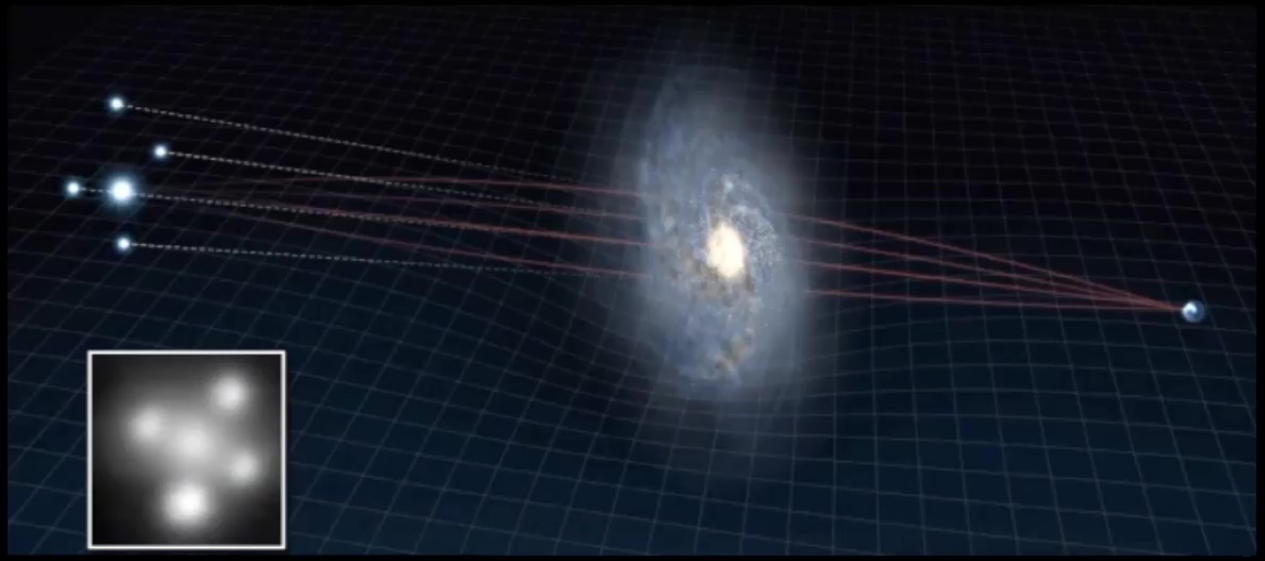
distribution

shape

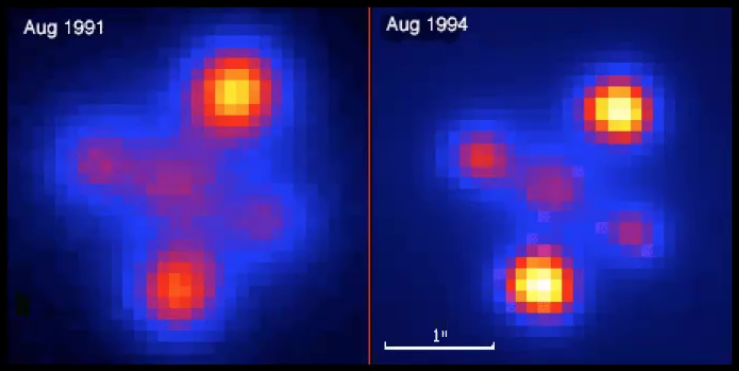
structure

6. Cosmological Microlensing





Lewis & Irwin 1996

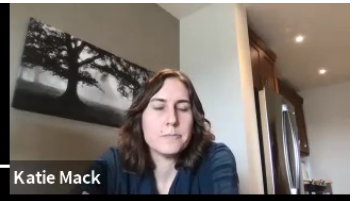


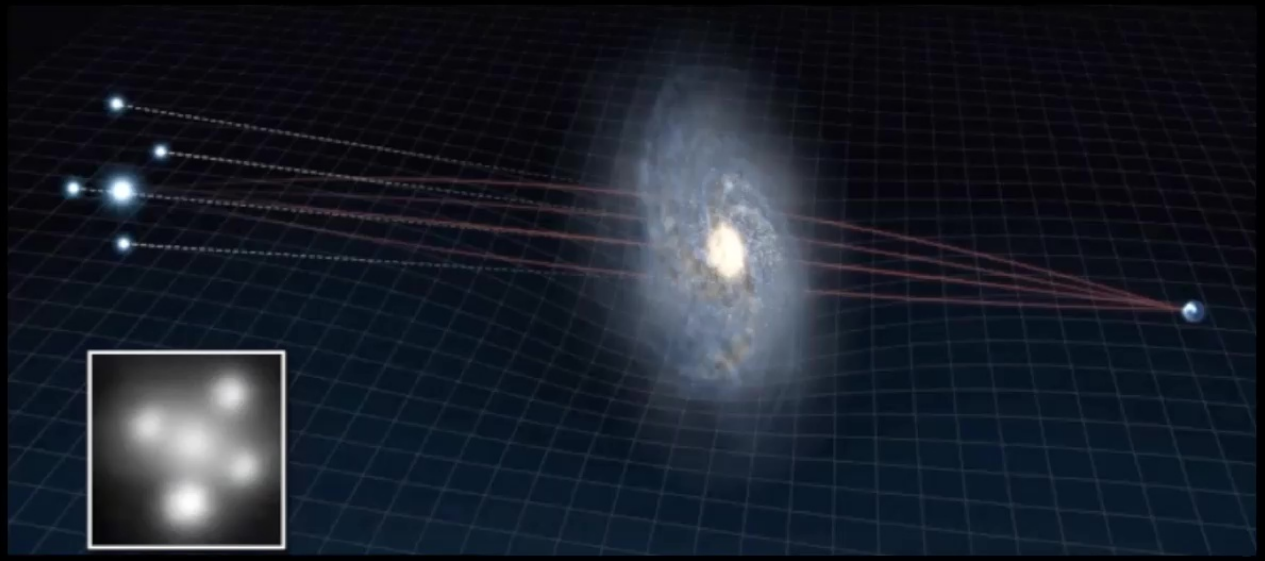
<u>What we learn:</u>

mass fraction

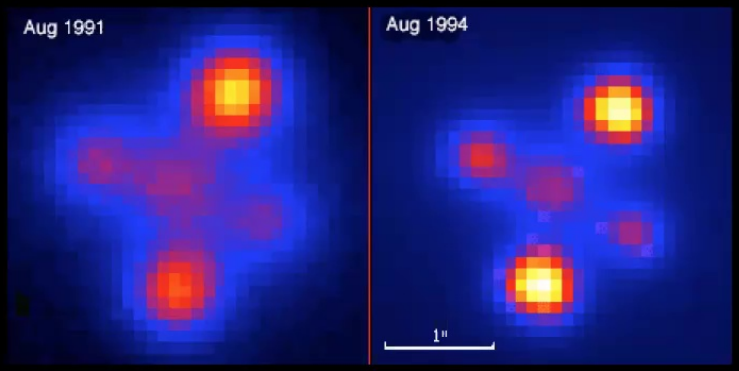
smoothness

6. Cosmological Microlensing





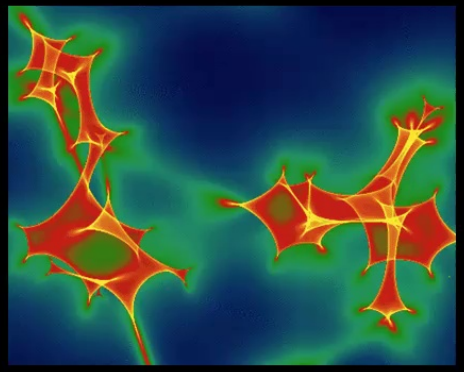
Lewis & Irwin 1996



<u>What we learn:</u>

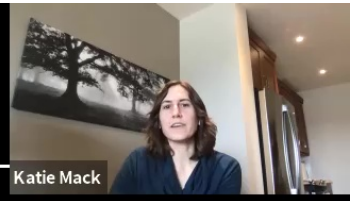
mass fraction

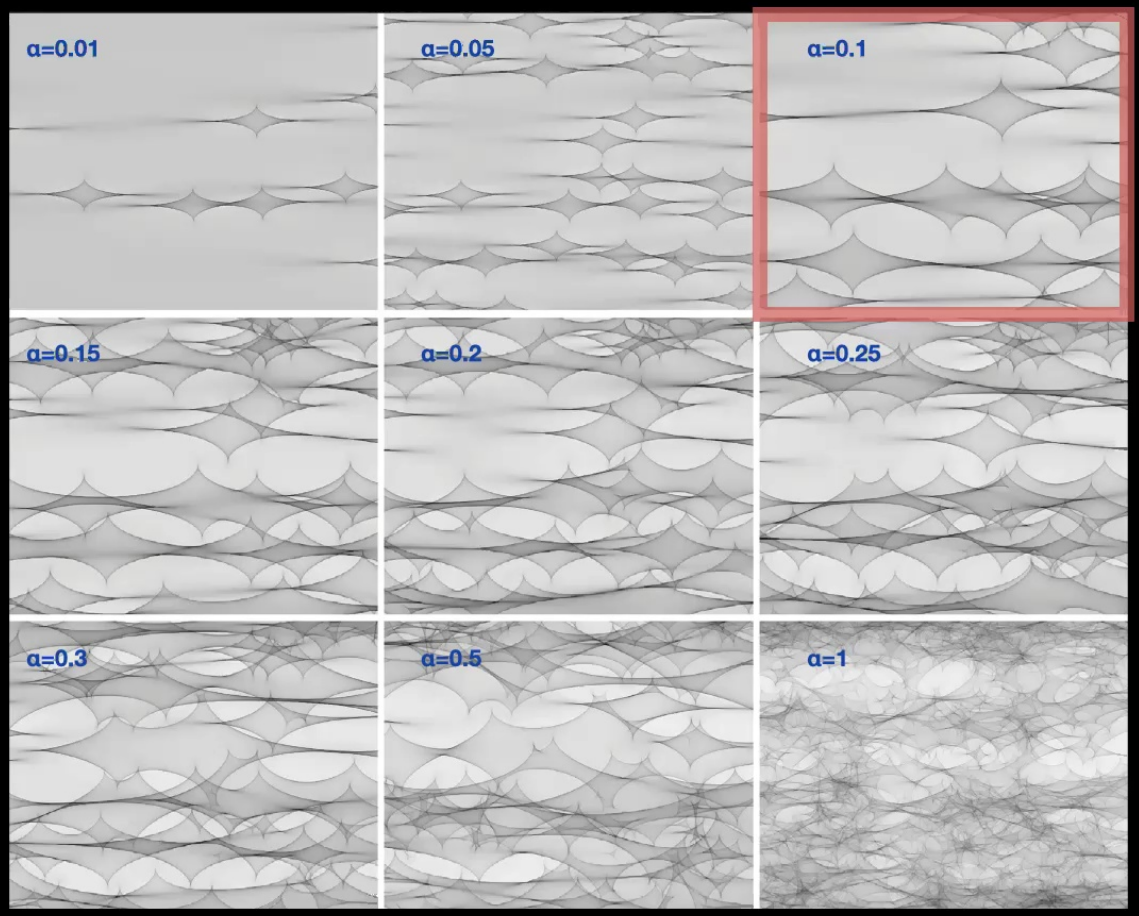
smoothness



Joachim Wambsganss

6. Cosmological Microlensing





Mediavilla et al. 2009

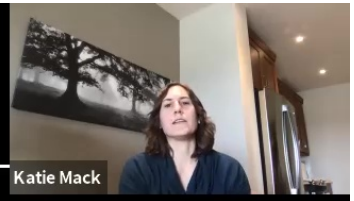
What we learn:

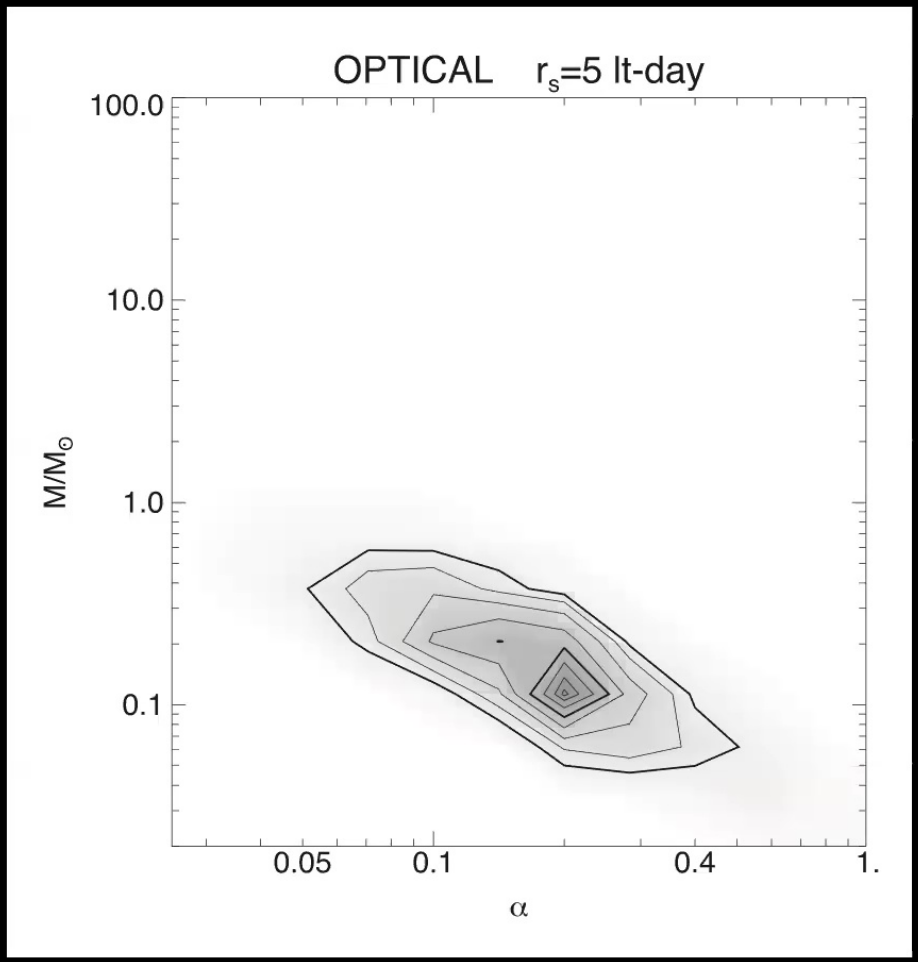
mass fraction

smoothness

Can constrain the fraction α of matter in compact objects (stars/black holes)

6. Cosmological Microlensing





Mediavilla et al. 2017

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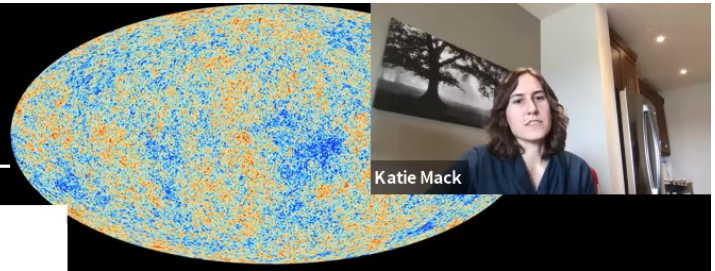
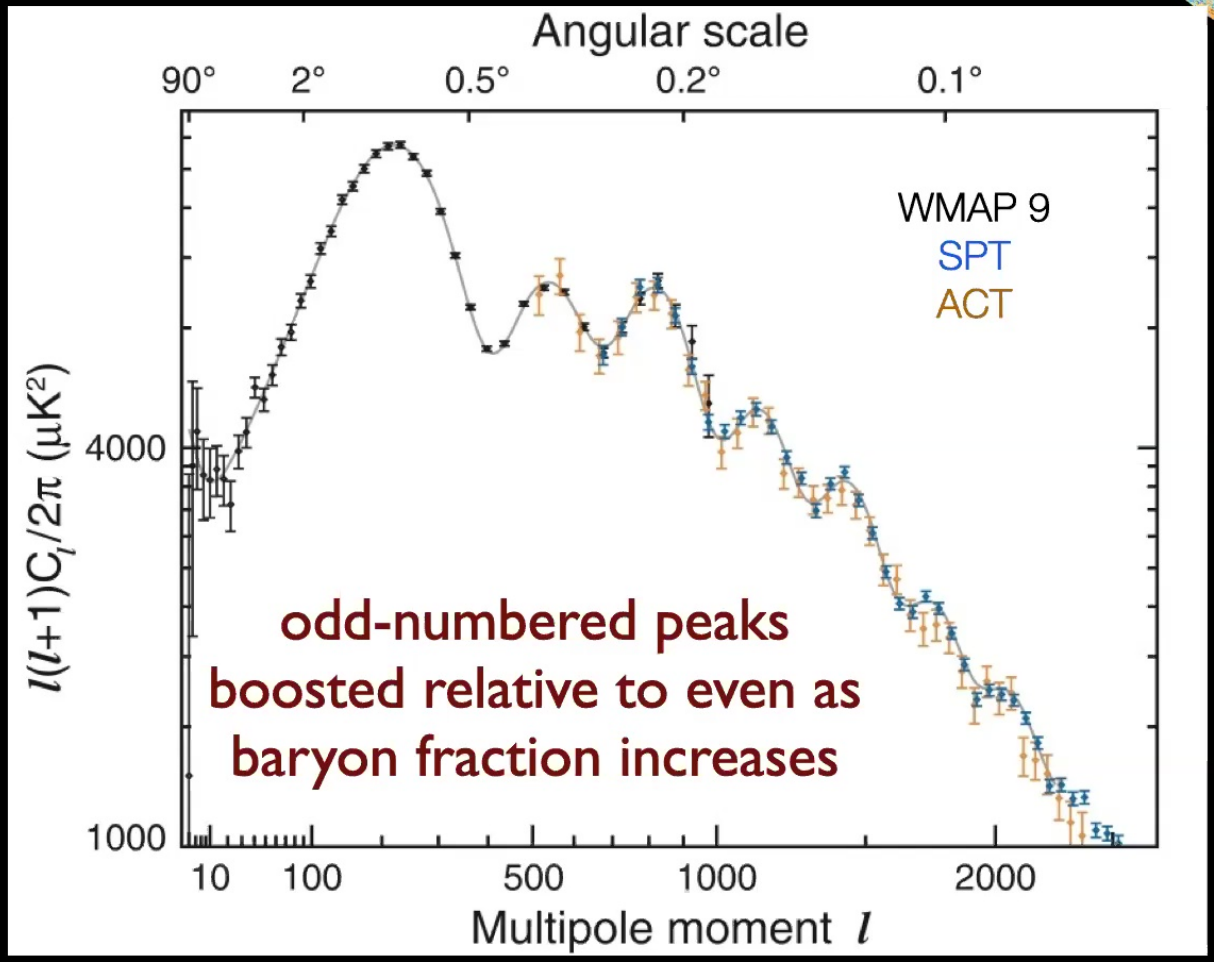
7. CMB Acoustic Peaks





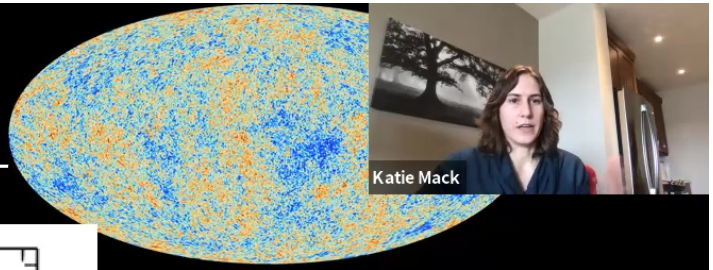
Hinshaw et al. 2013

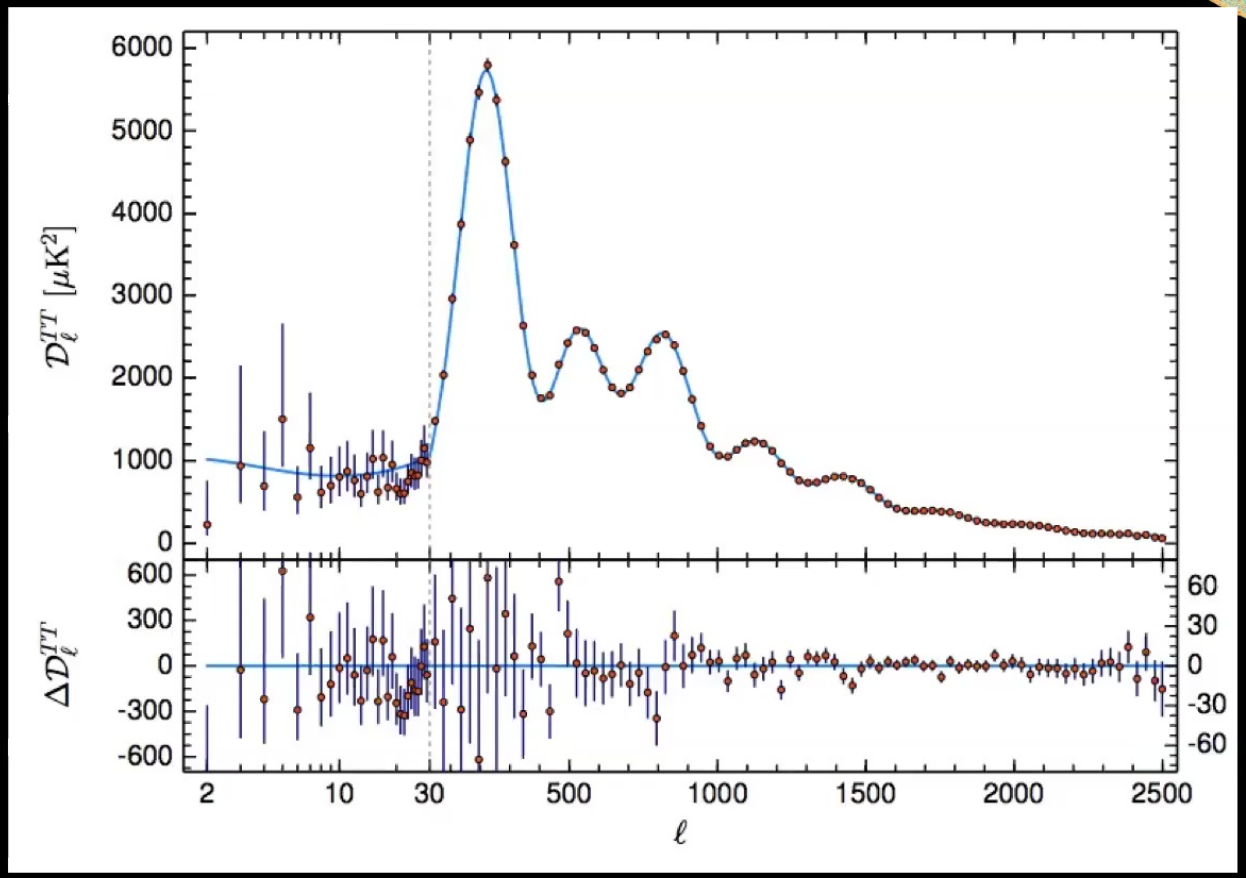
<u>What we learn:</u>

ratio of DM/ collisional matter

thermal history

7. CMB Acoustic Peaks





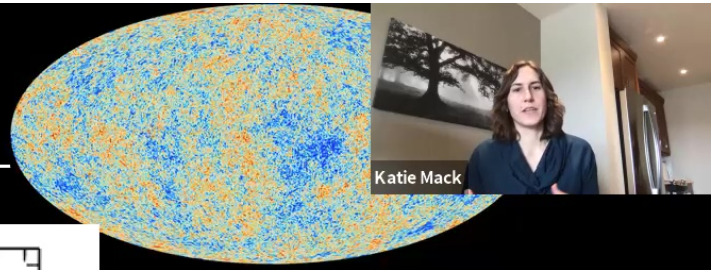
Planck 2018

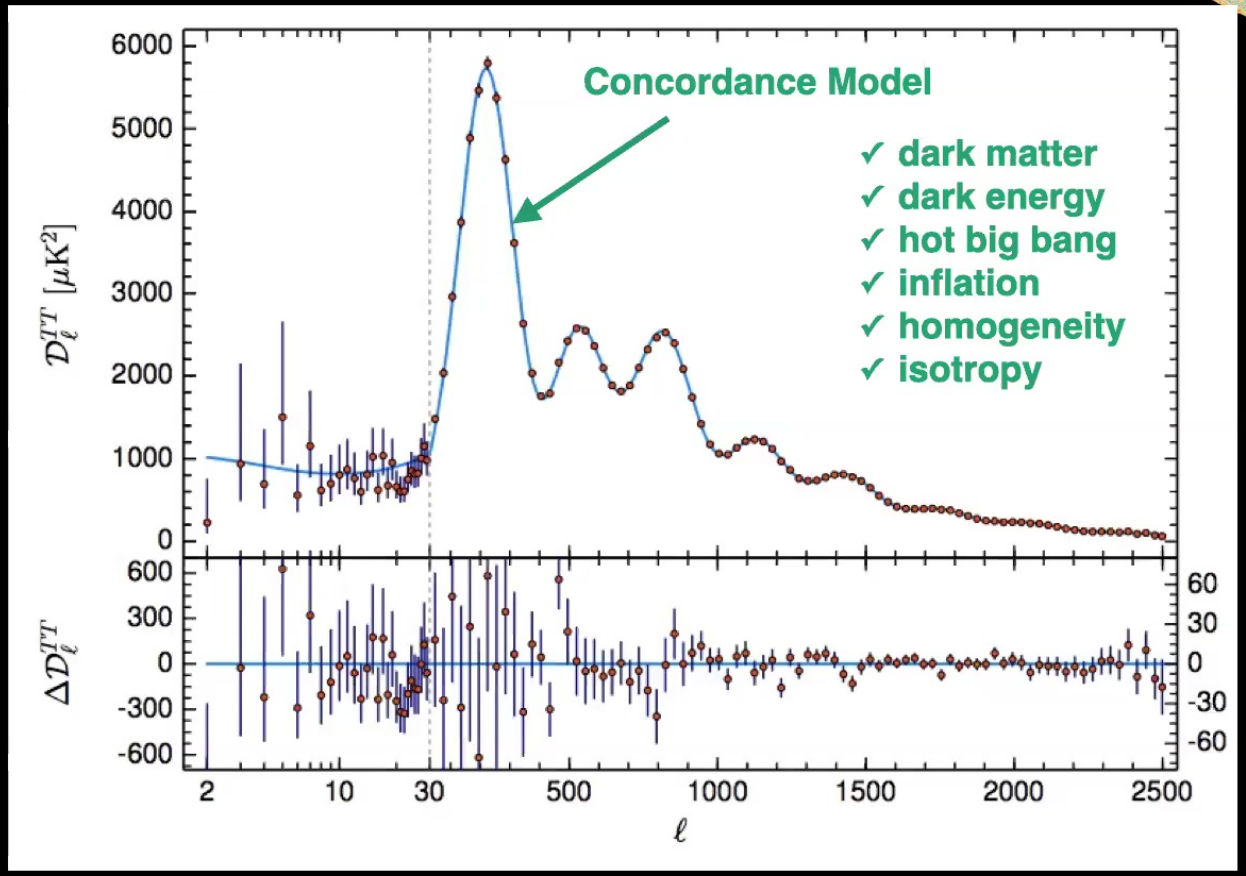
What we learn:

ratio of DM/ collisional matter

thermal history

7. CMB Acoustic Peaks





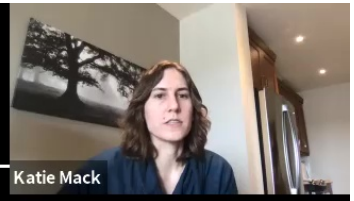
Planck 2018

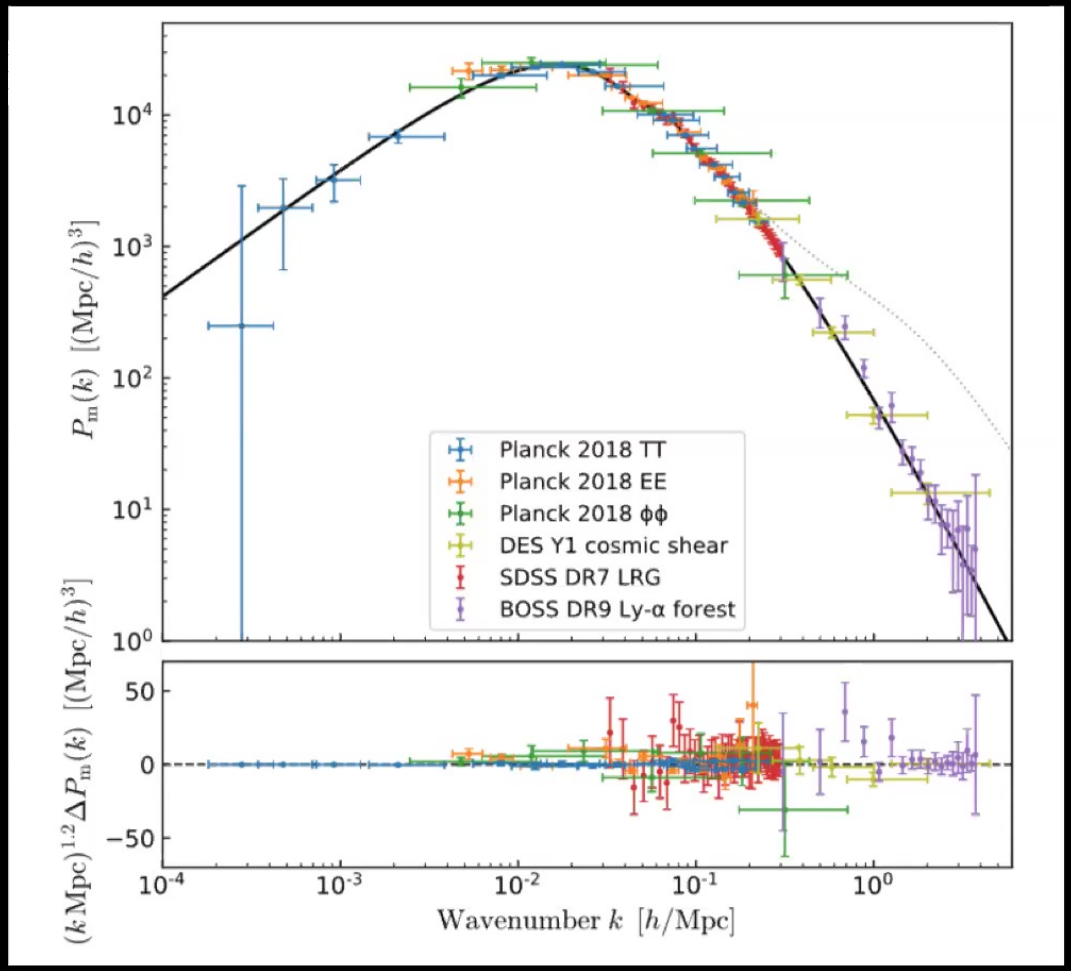
What we learn:

ratio of DM/ collisional matter

thermal history

8. Matter Power Spectrum





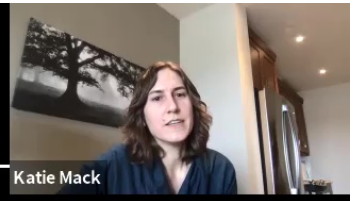
Chabanier et al. 2019

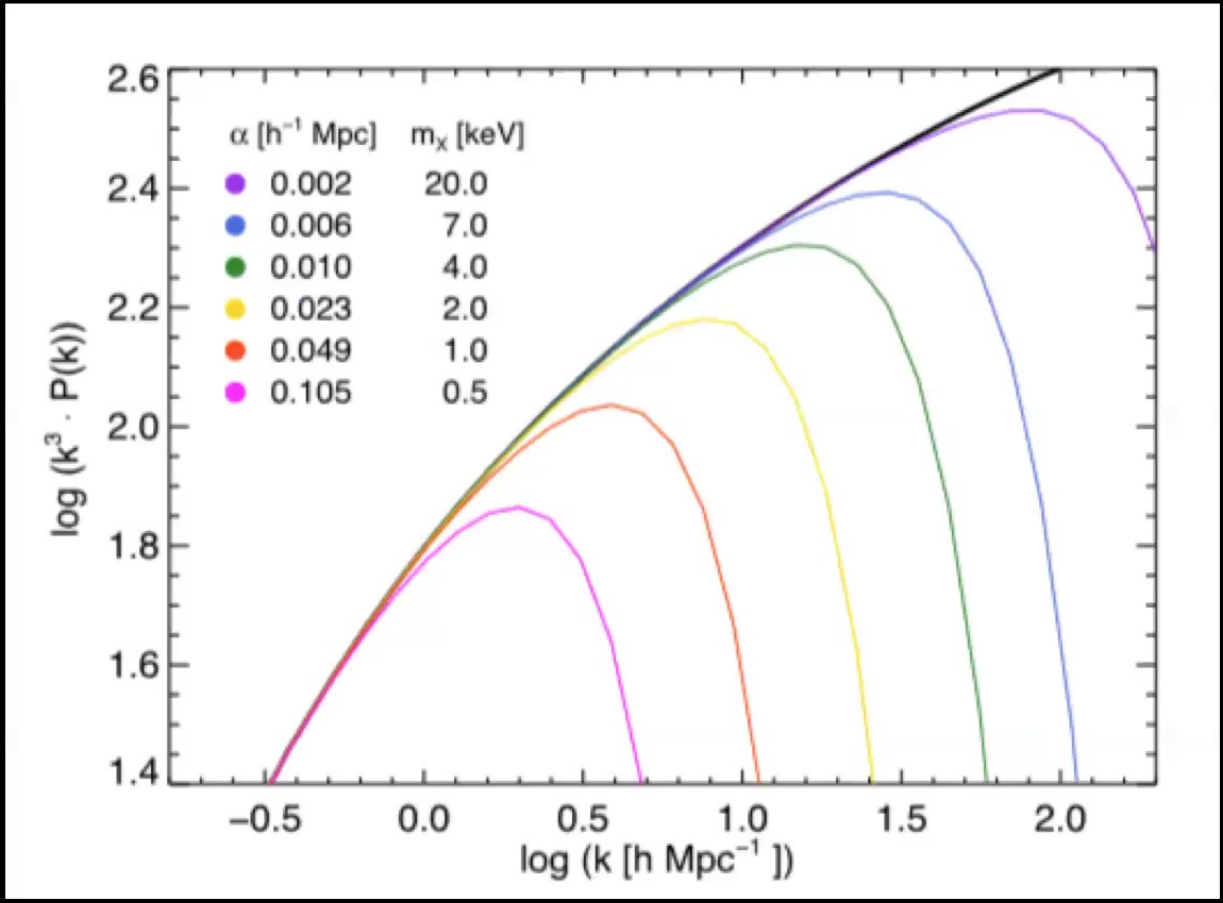
<u>What we learn:</u>

ratio of DM/ collisional matter

thermal history

8. Matter Power Spectrum





Kennedy et al. 2013

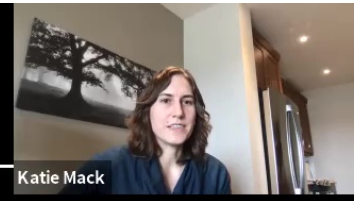
What we learn:

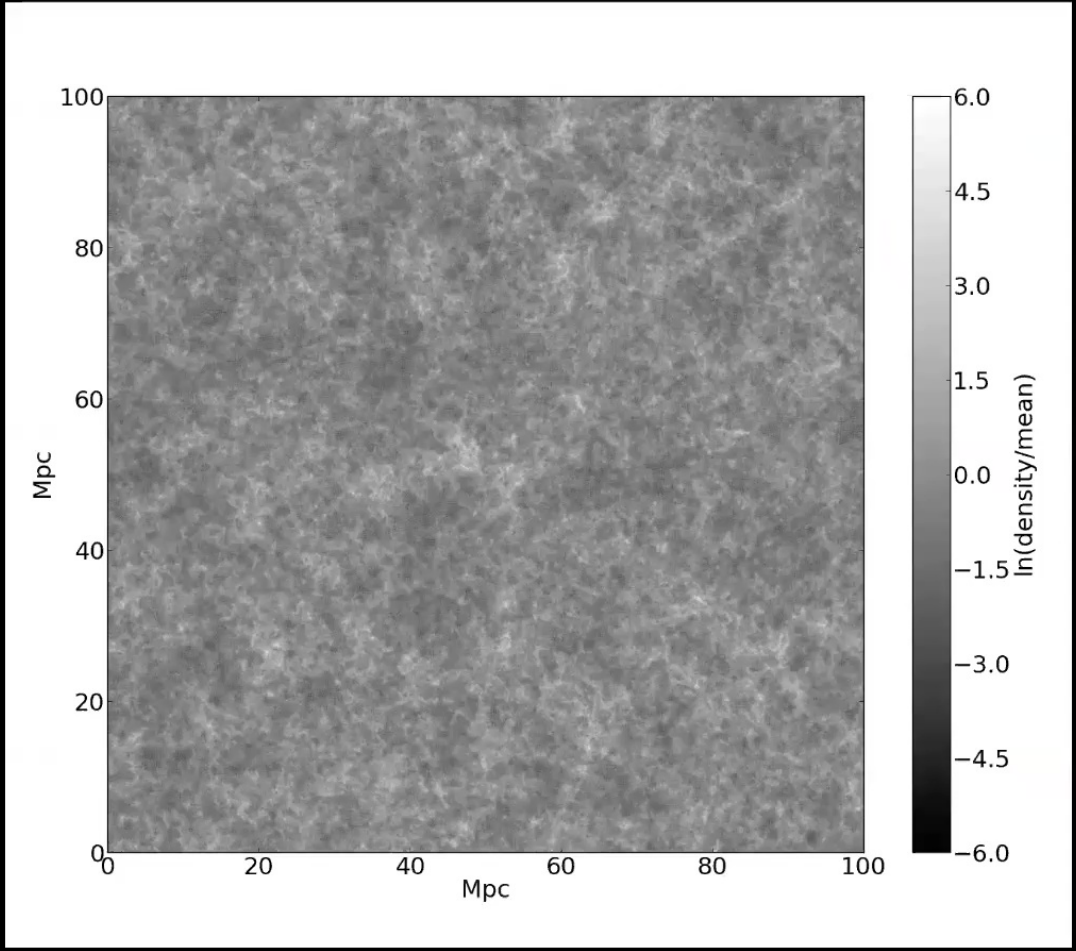
ratio of DM/ collisional matter

thermal history

Current limits:
m_X > few keV

9. Large Scale Structure





Paul Angel, Tiamat Simulation

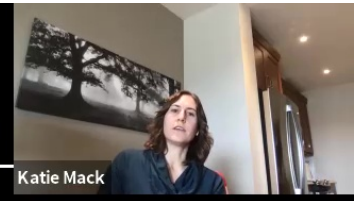
What we learn:

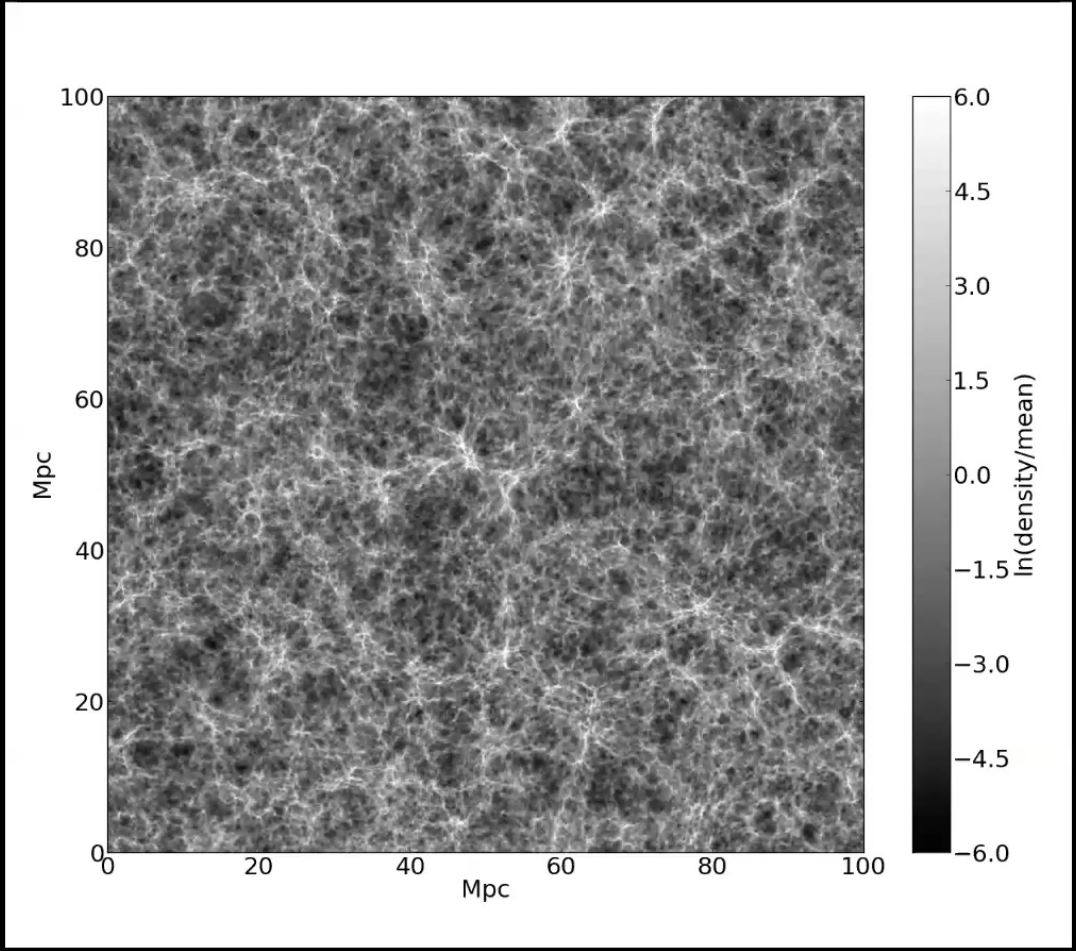
ratio of DM/ collisional matter

thermal history

Excellent agreement between simulations and galaxy distribution on the largest scales

9. Large Scale Structure





Paul Angel, Tiamat Simulation

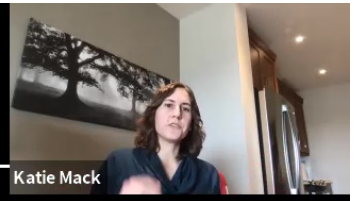
What we learn:

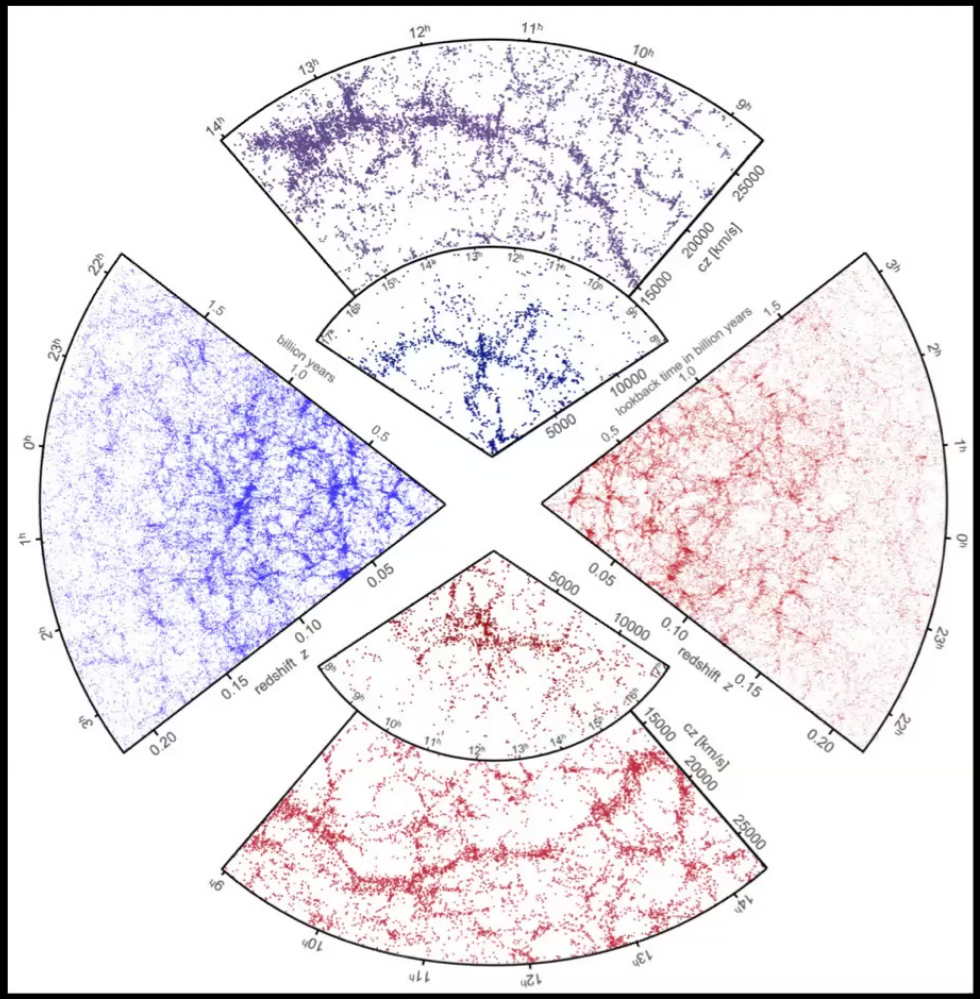
ratio of DM/ collisional matter

thermal history

Excellent agreement between simulations and galaxy distribution on the largest scales

9. Large Scale Structure





Frenk & White 2012

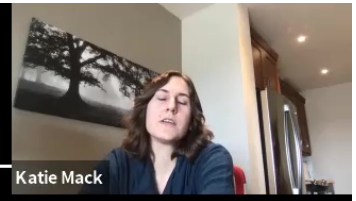
What we learn:

ratio of DM/ collisional matter

thermal history

Excellent agreement between simulations and galaxy distribution on the largest scales

10. Galaxy/Cluster Collisions



NASA/Clowe et al. 2006

<u>What we learn:</u>

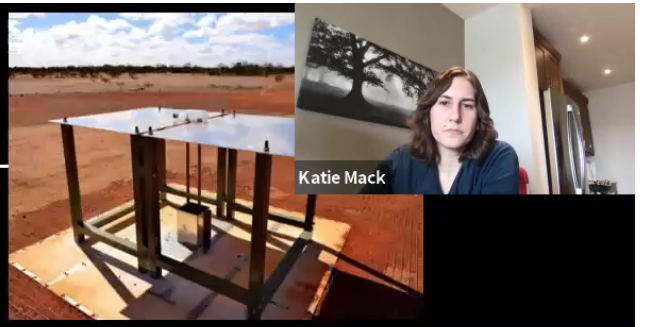
distribution

separation from collisional matter

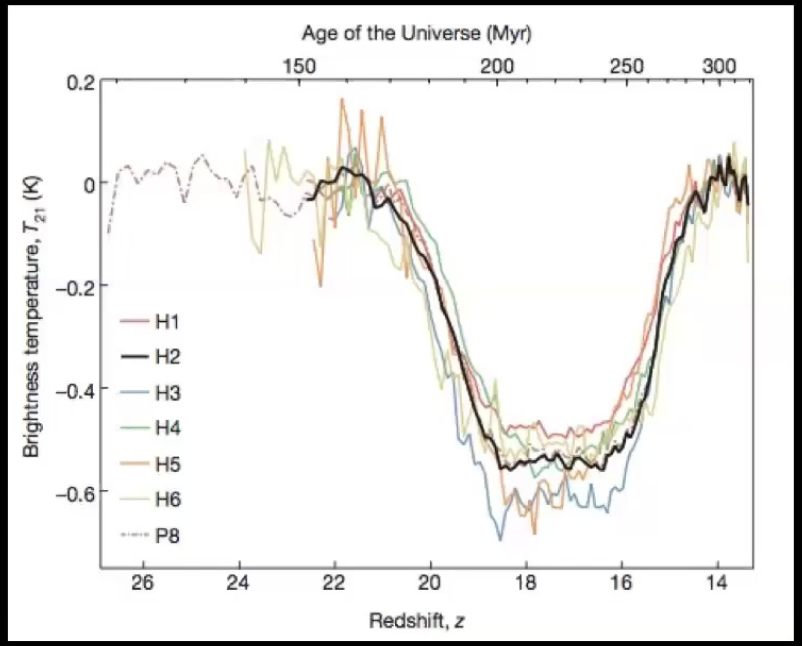
self-interaction

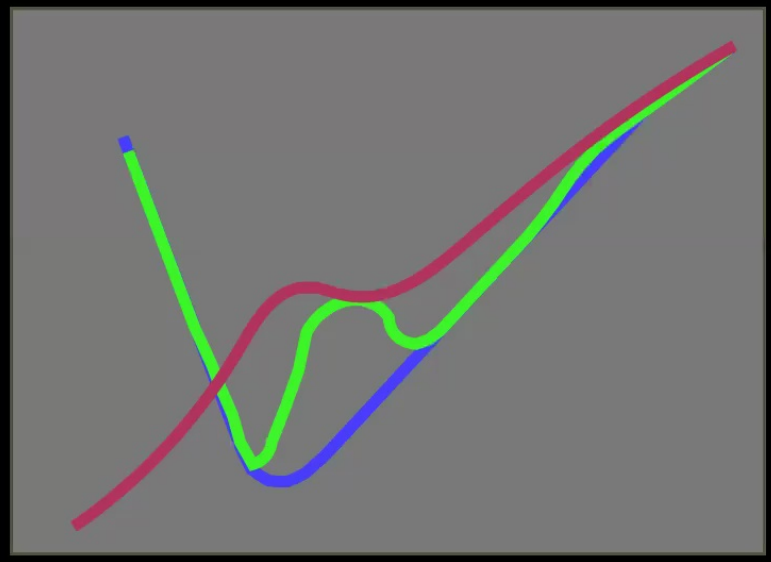
Difficult to explain without collisionless matter

EDGES



EDGES Experiment

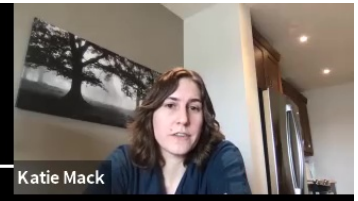


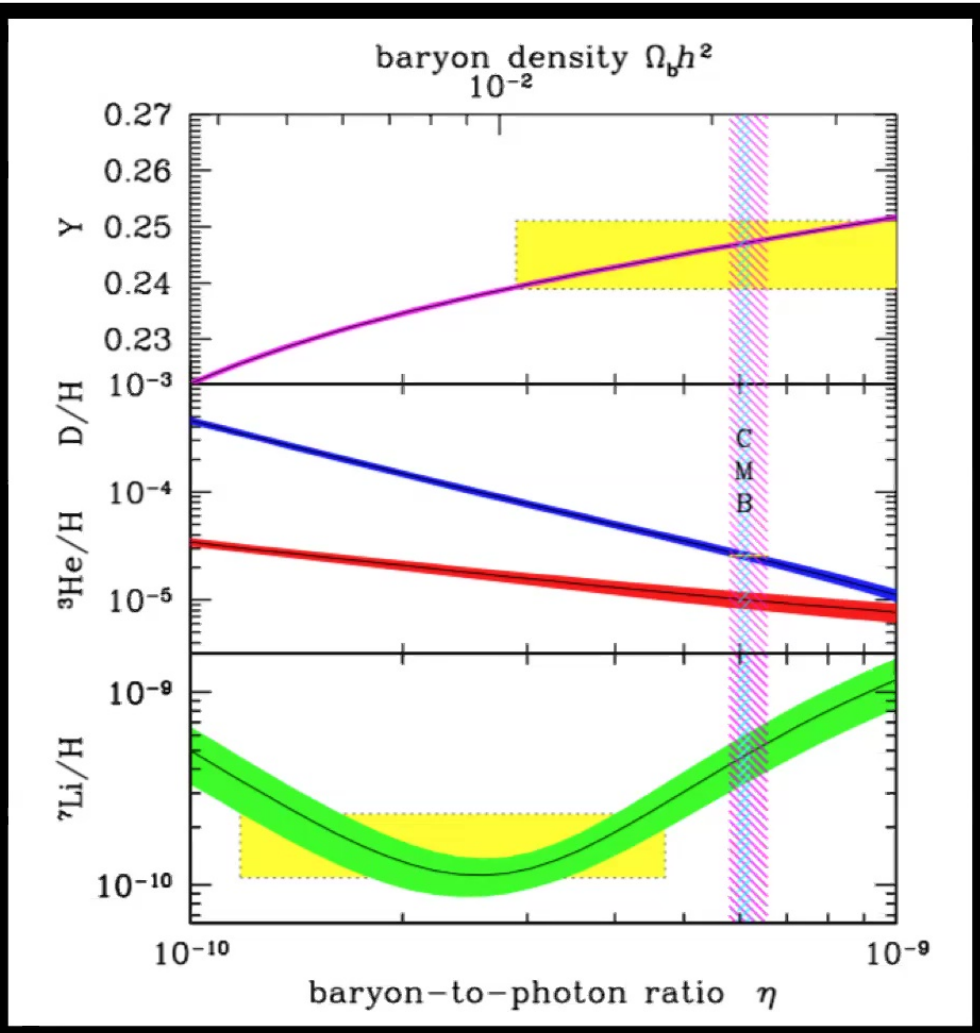


Bowman et al. 2018

Higher radiation background?

11. Big Bang Nucleosynthesis





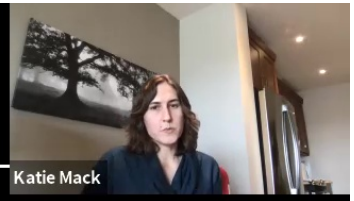
PDG 2018

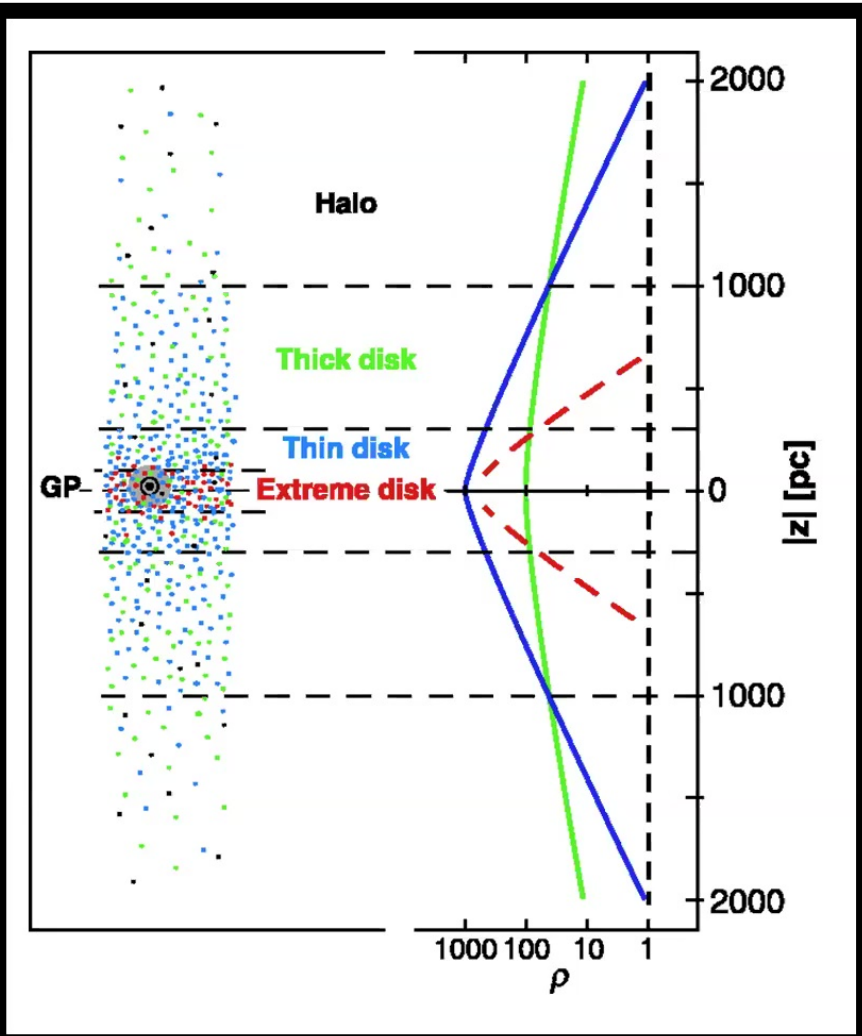
What we learn:

amount of baryonic matter

Remaining mystery: lithium abundance (but still need low baryon fraction)

12. Local Stellar Motions





Buser 2000

What we learn:

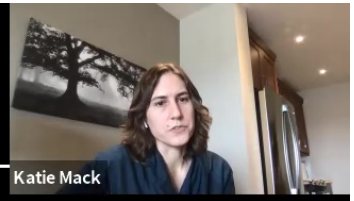
local dark matter density

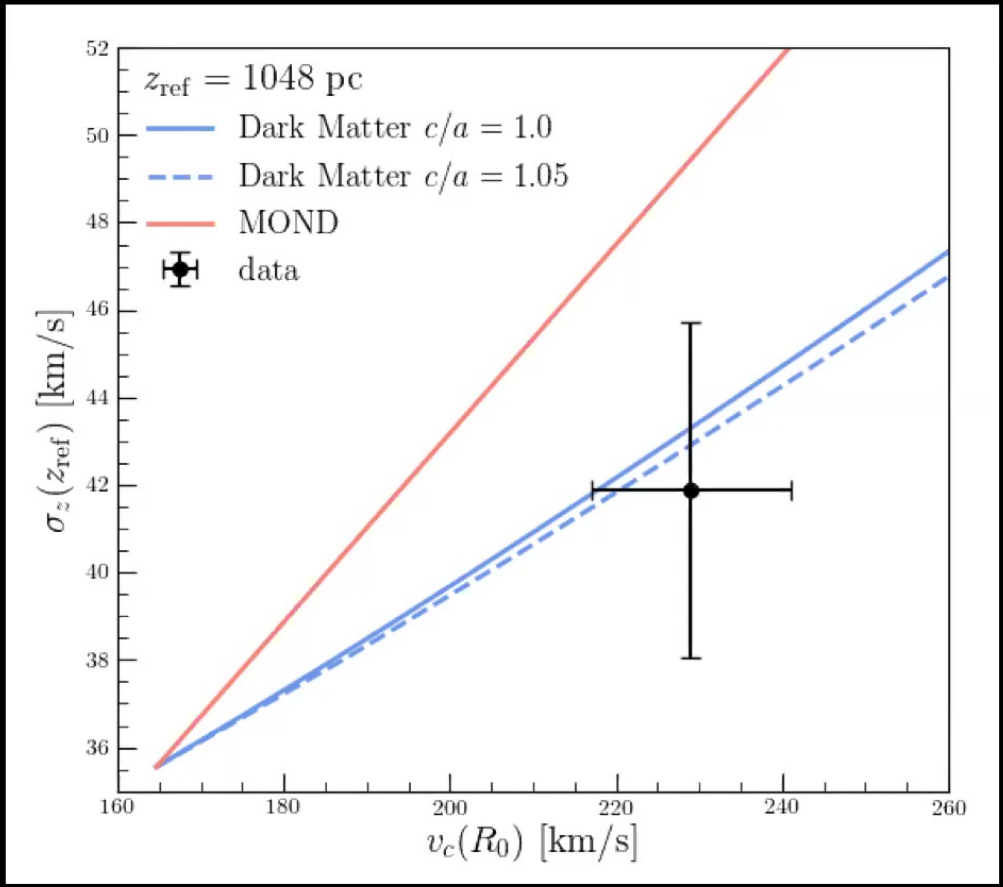
Estimates:

$\rho_{DM} \sim 0.3$ GeV/cm^3

~ 0.008 M_{Sun}/pc^3

12. Local Stellar Motions





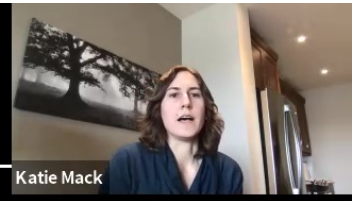
Lisanti et al. 2019

What we learn:

local dark matter density

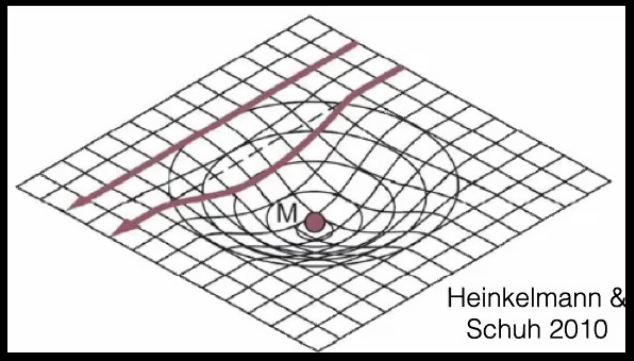
Measurements in strong tension with MOND explanations

13. Gravitational Waves

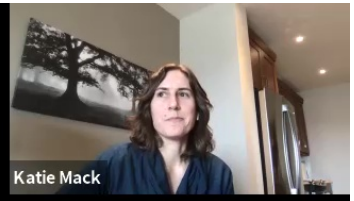


<u>What we learn:</u>

rules out some DM emulators

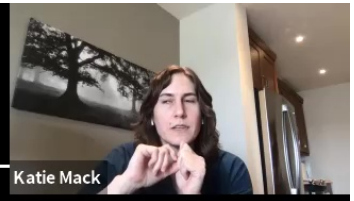


Near-simultaneous arrival of light & gravitational waves in GW170817 inconsistent with models where GWs and light follow different geodesics (Boran et al. 2018)

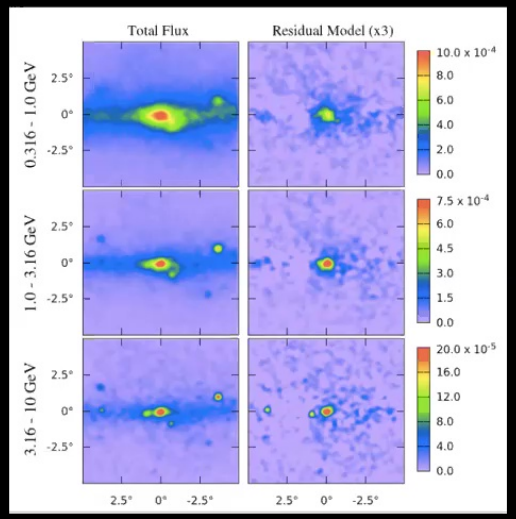


Possible Hints/Signals

Annihilation?



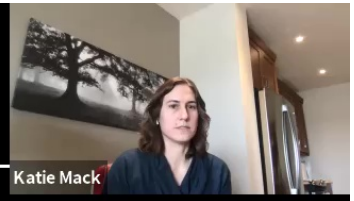
Gamma rays in the Galactic Center



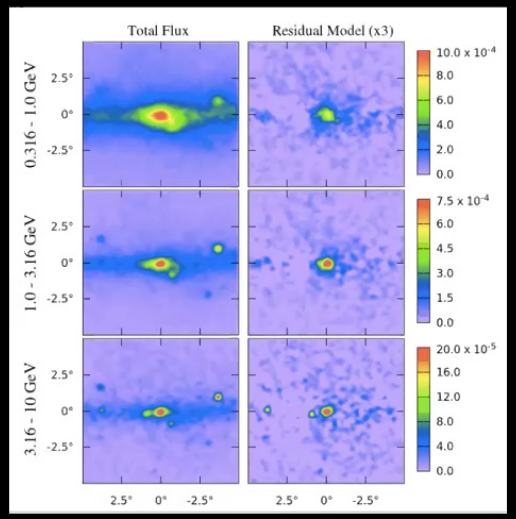
Daylan et al. 2014

... but maybe pulsars

Annihilation?

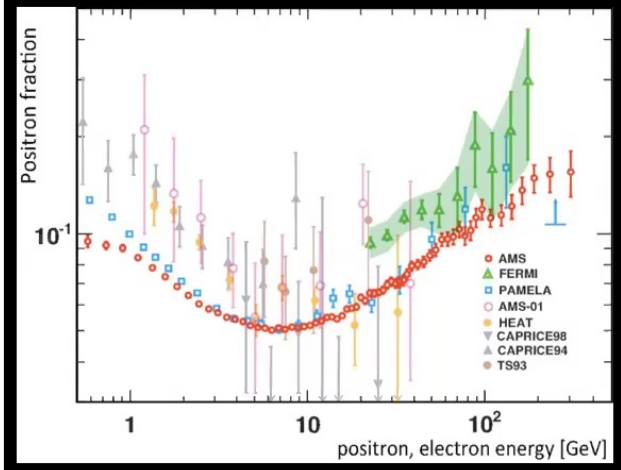


Gamma rays in the Galactic Center



Daylan et al. 2014

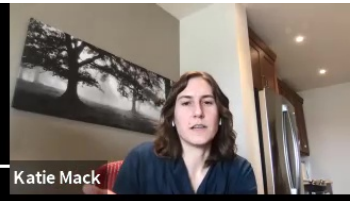
Excess positrons at high energy



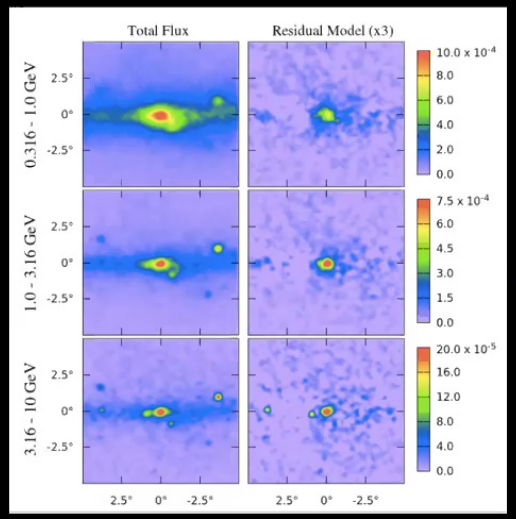
AMS Collaboration 2013

... but maybe pulsars

Annihilation?

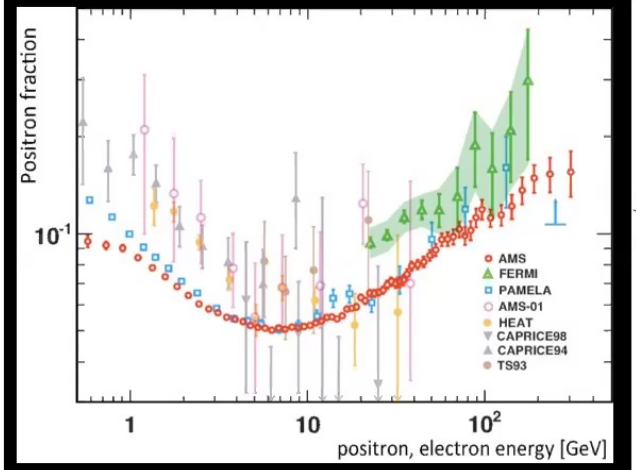


Gamma rays in the Galactic Center



Daylan et al. 2014

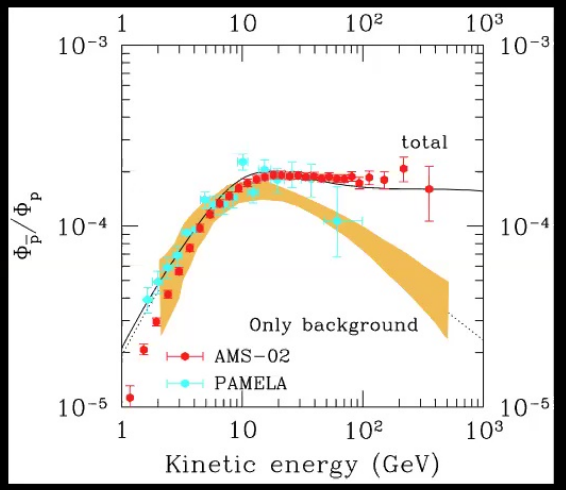
Excess positrons at high energy



AMS Collaboration 2013

... but maybe pulsars

Excess antiprotons at high energy

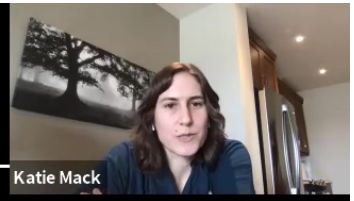


Kohri et al. 2015

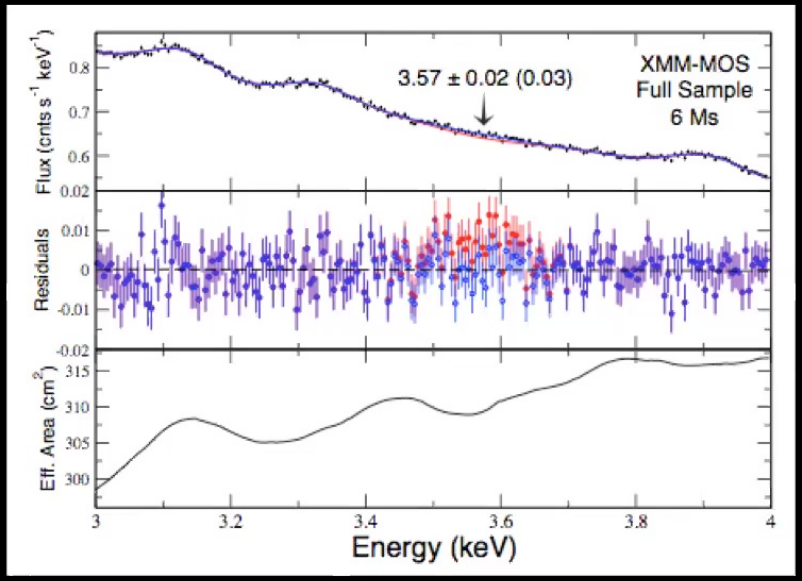
Not pulsars!

... but maybe supernova remnant

Decay?

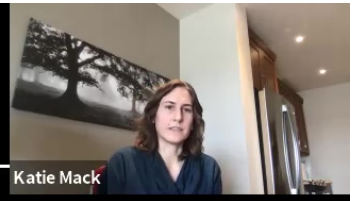


Excess x-rays in galaxy clusters

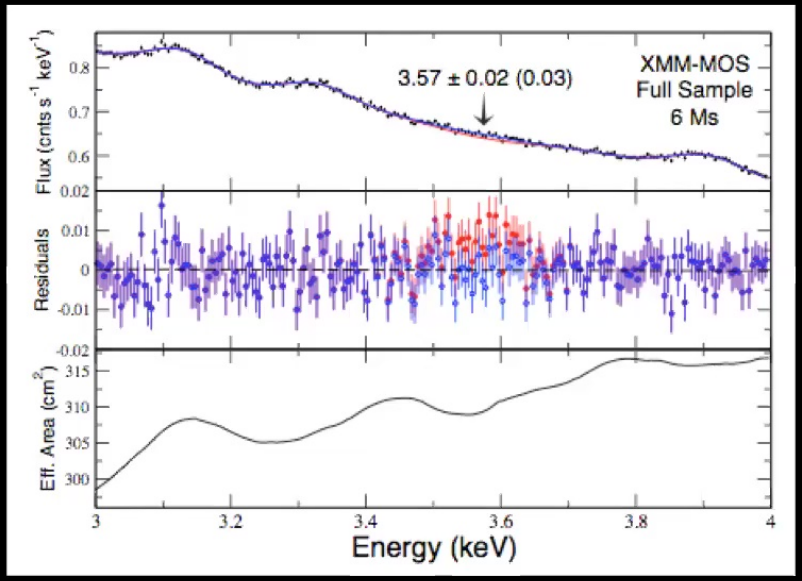


Bulbul et al. 2014

Decay?



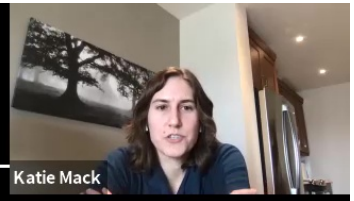
Excess x-rays in galaxy clusters



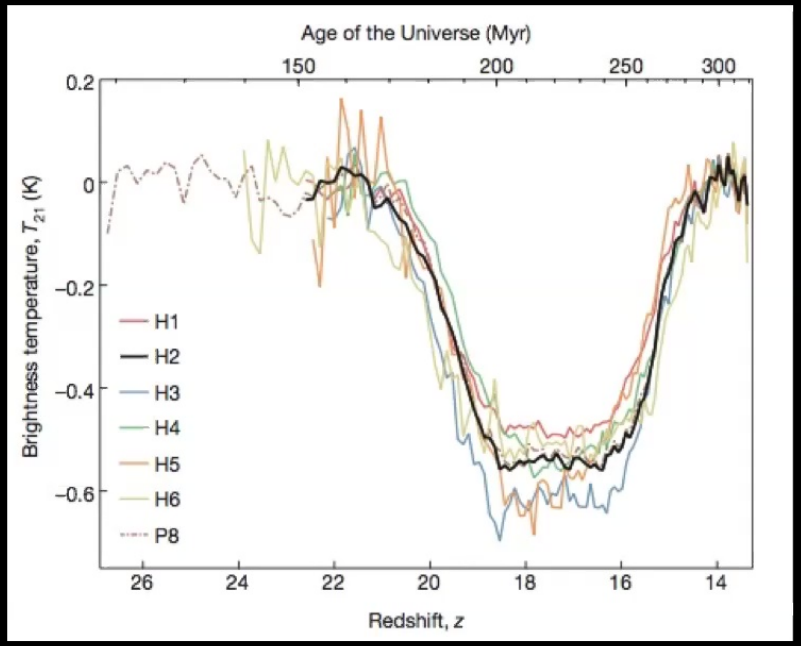
Bulbul et al. 2014

... but maybe line contamination

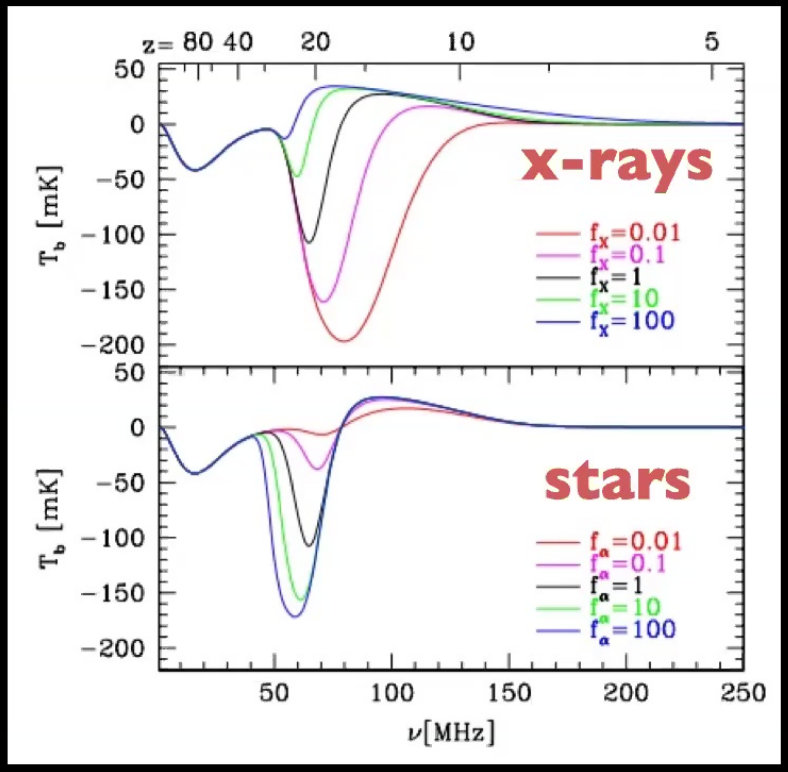
Scattering?



Super-cold neutral hydrogen at high redshift

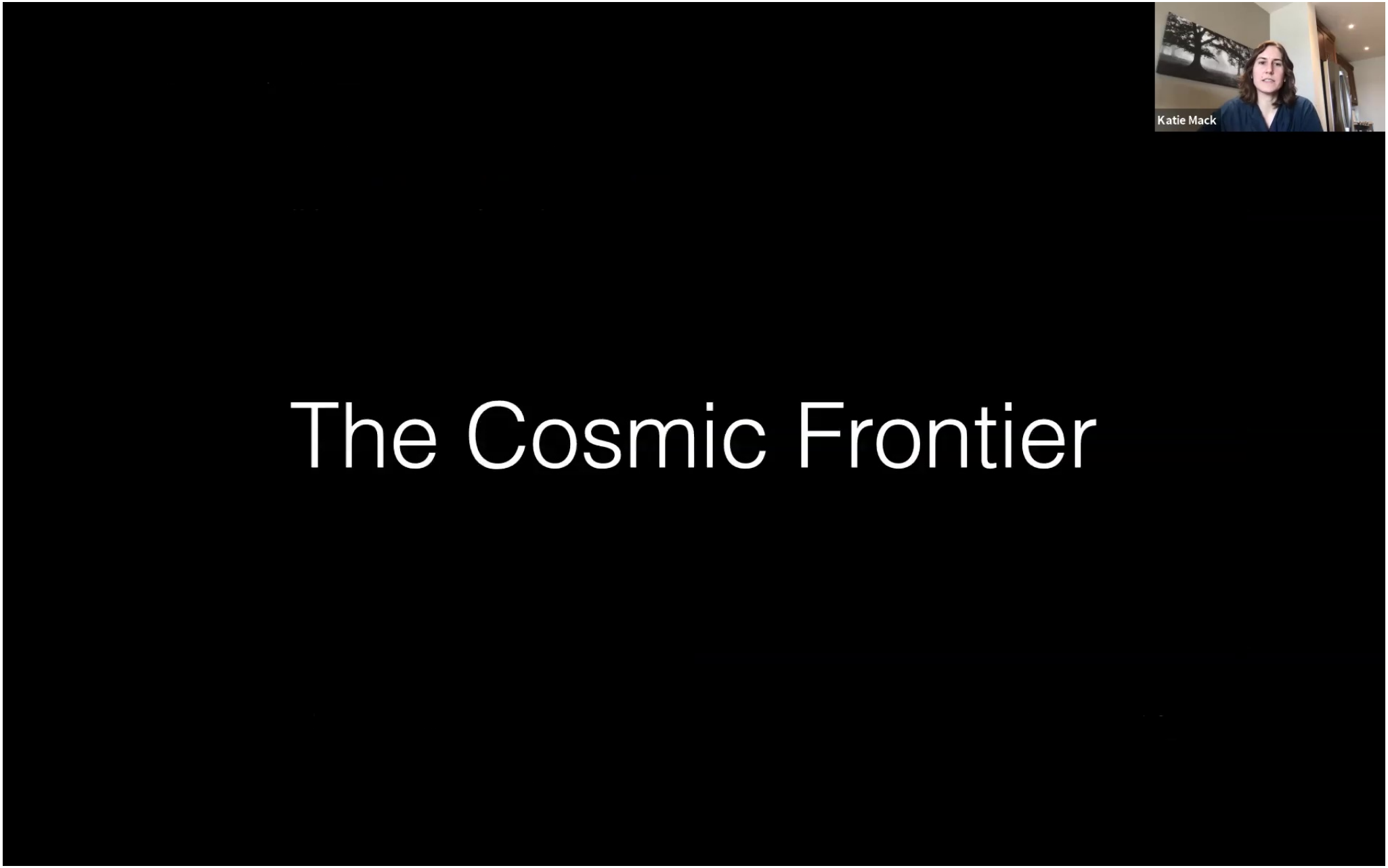


Bowman et al. 2018

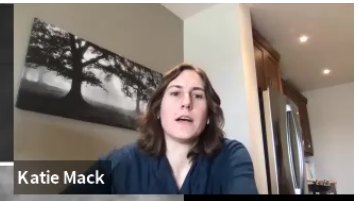


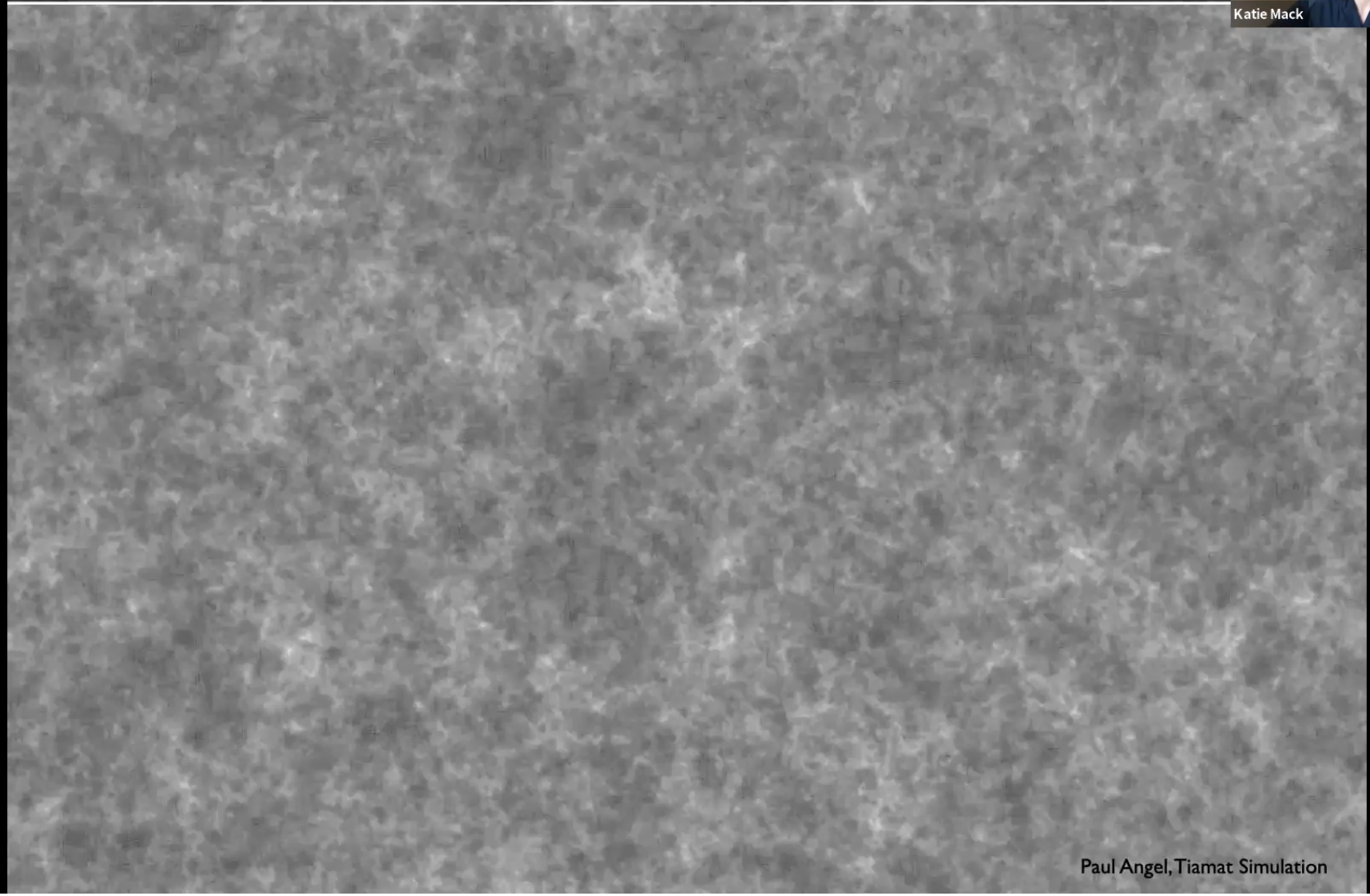
Pritchard & Loeb 2010

... but maybe a foreground subtraction problem

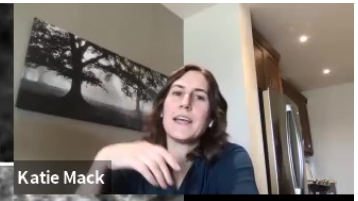

Katie Mack
The Cosmic Frontier

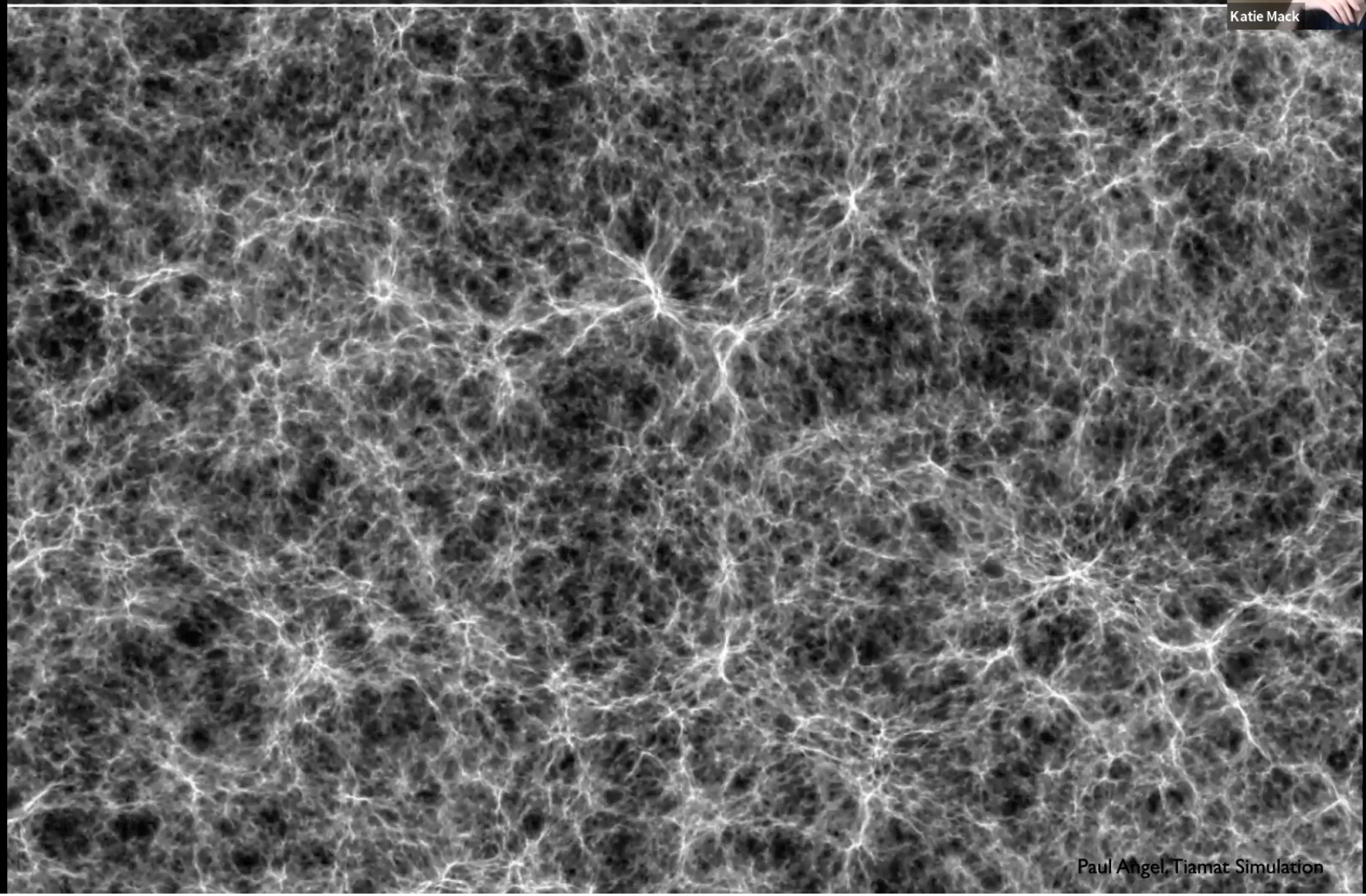
Dark Matter: Cosmology



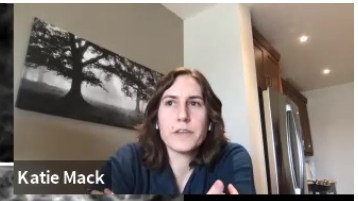


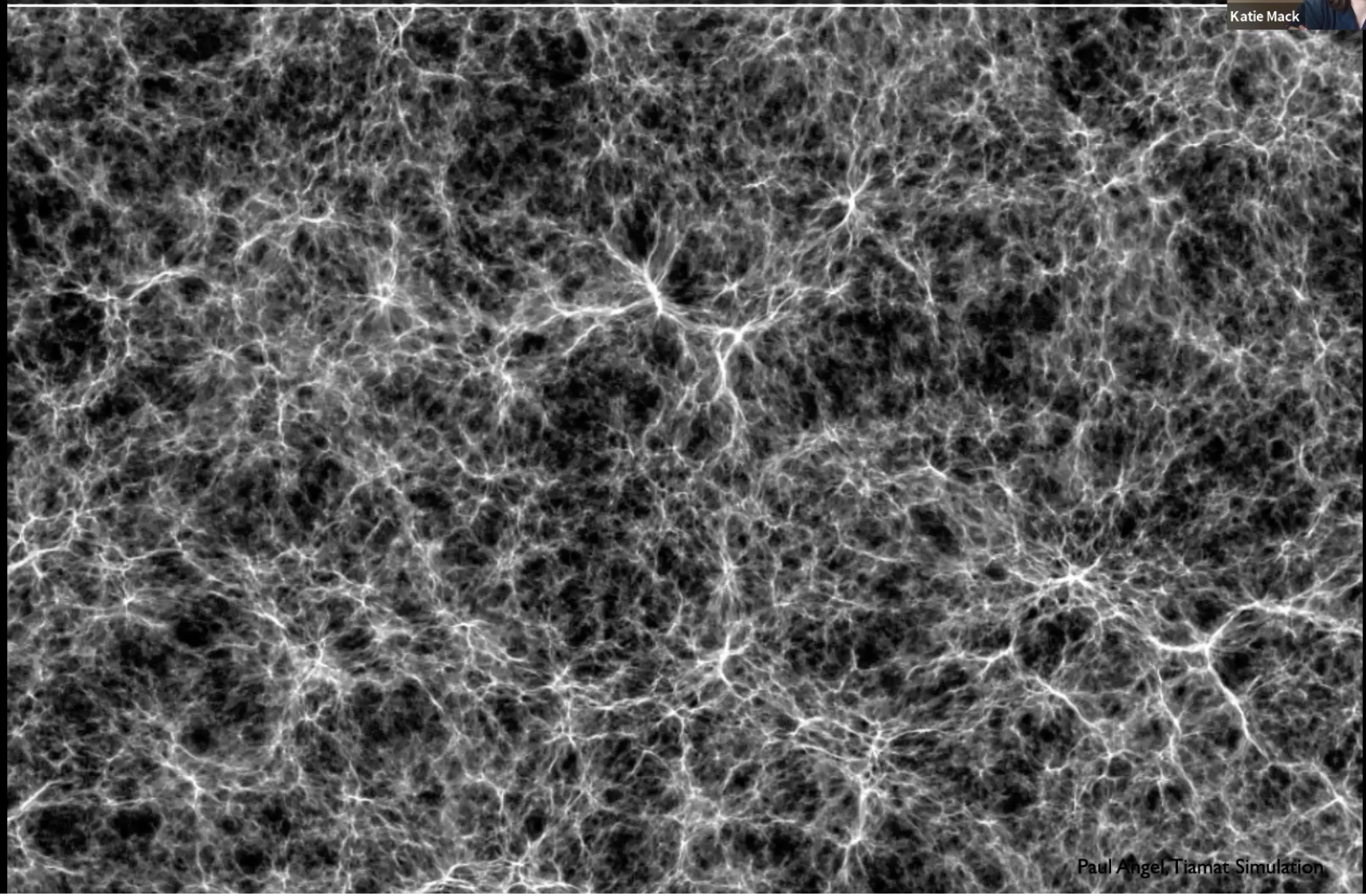
Dark Matter: Cosmology



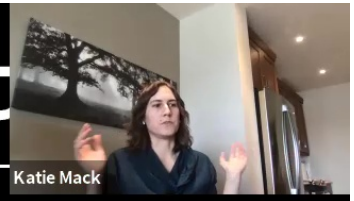


Dark Matter: Cosmology



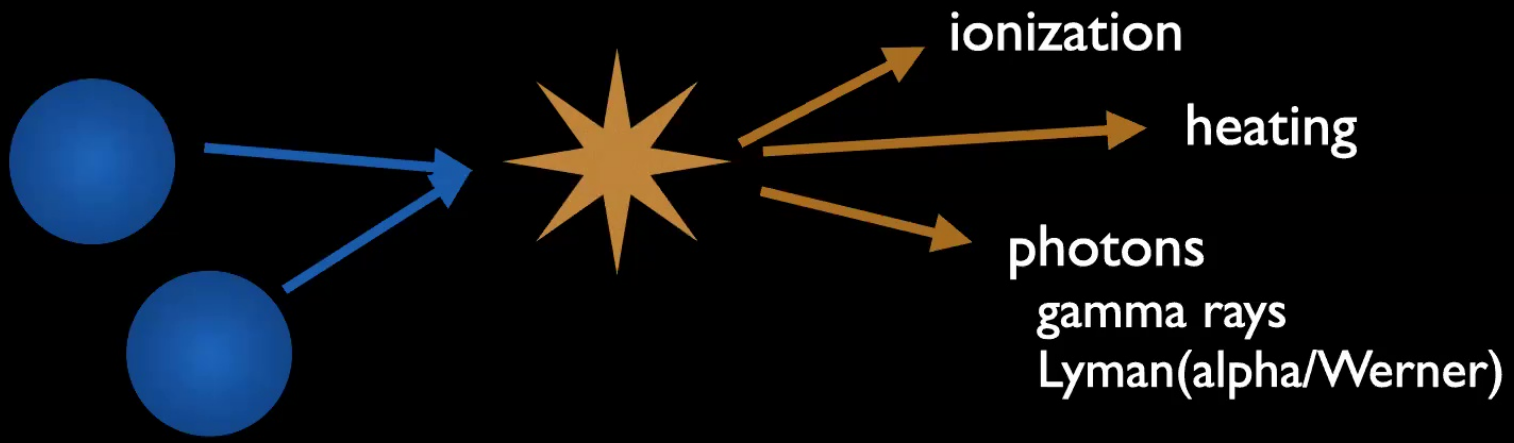


Impact of Dark Matter Annihilat

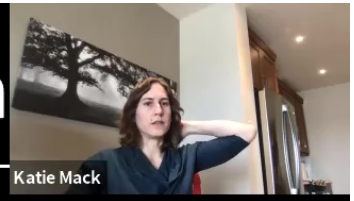


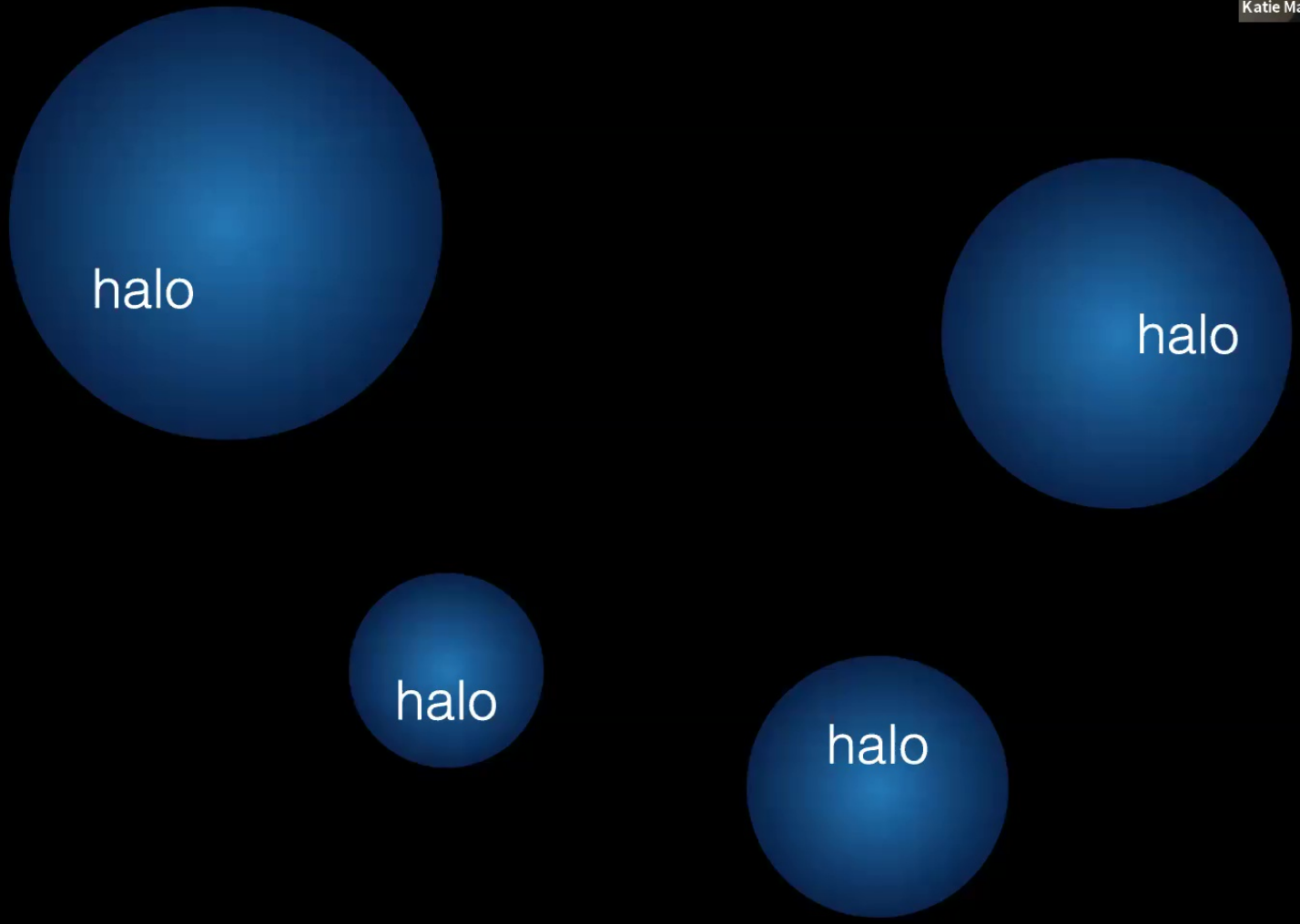
Major unanswered question:

If dark matter **annihilates** across all of cosmic time, **how does it affect the first stars and galaxies?**

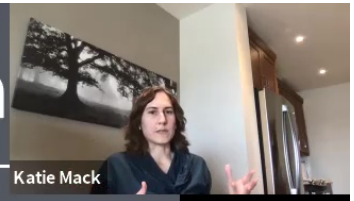


Annihilation in the Intergalactic Medium





Annihilation in the Intergalactic Medium



halo

halo

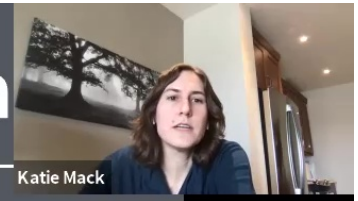
halo

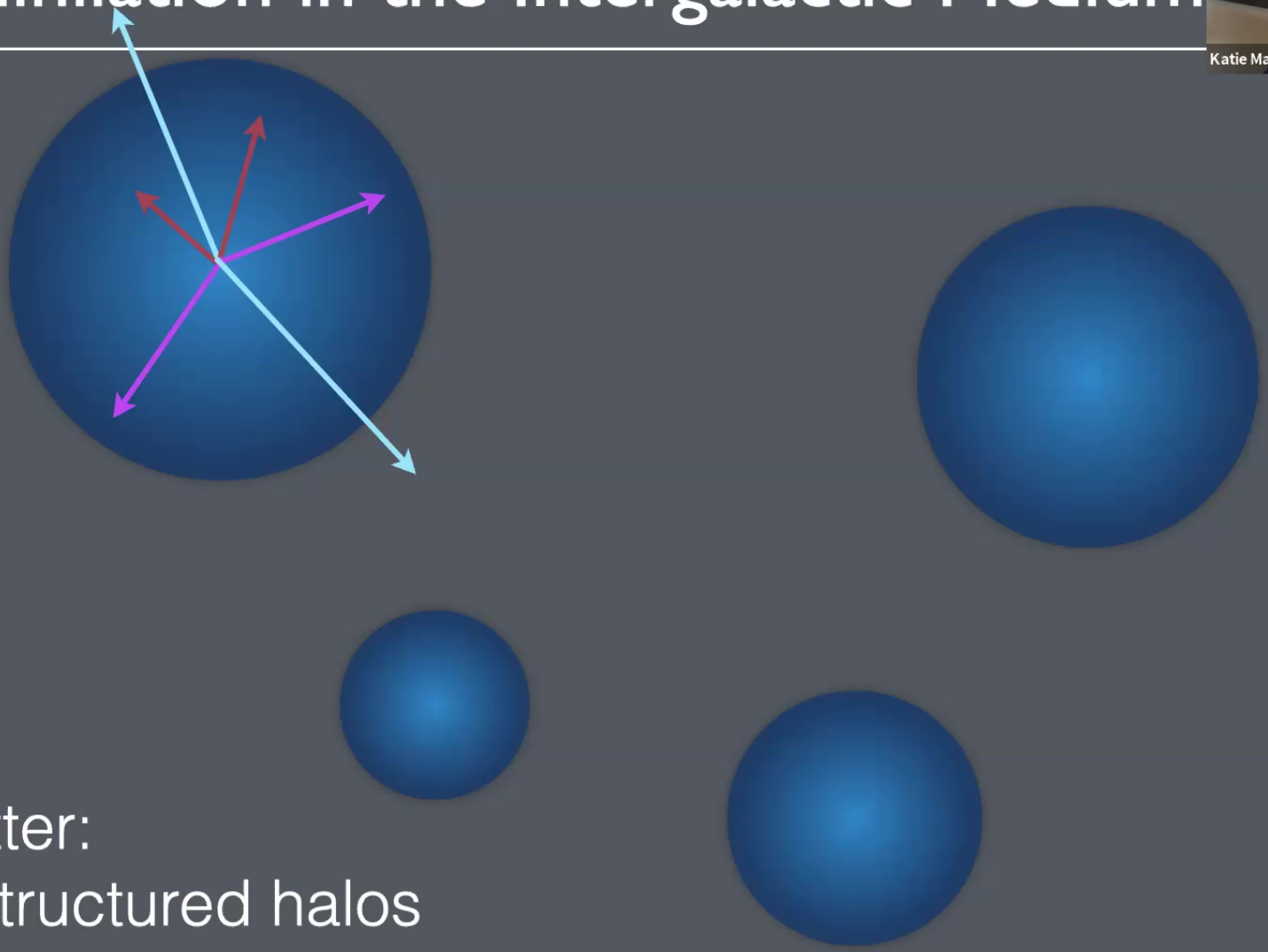
halo

Usual treatment:

- monolithic halos
- immediate uniform energy deposition

Annihilation in the Intergalactic Medium

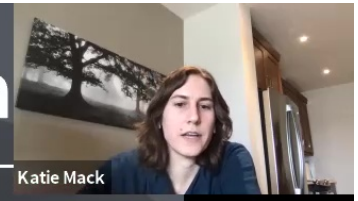


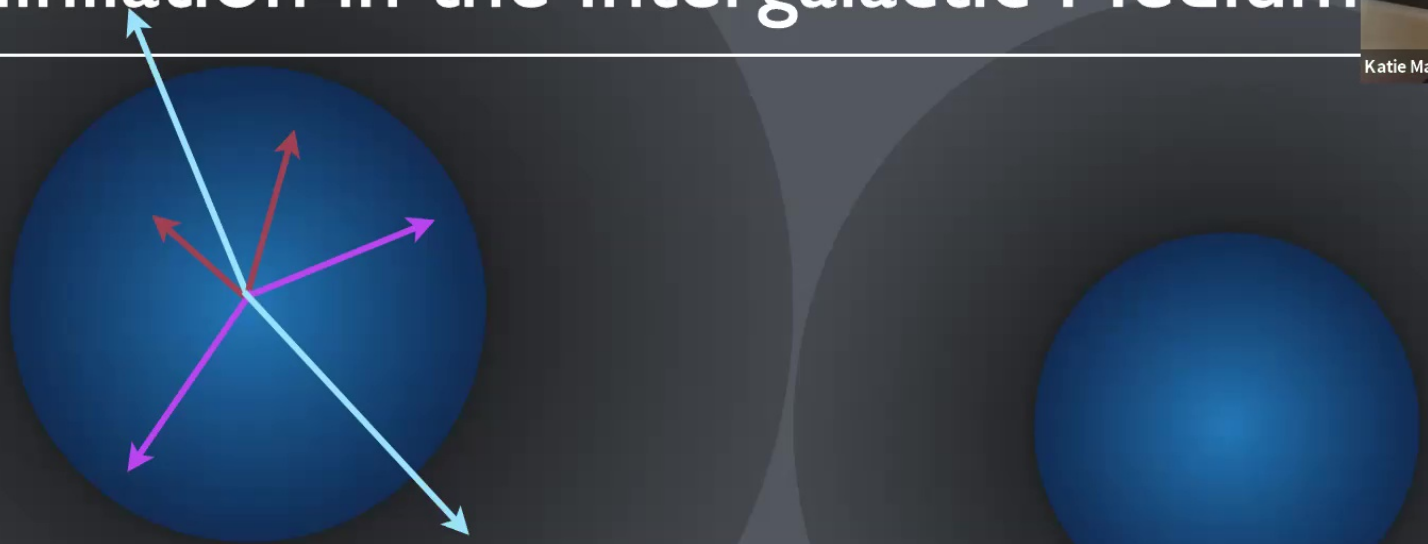


Better:

- structured halos

Annihilation in the Intergalactic Medium

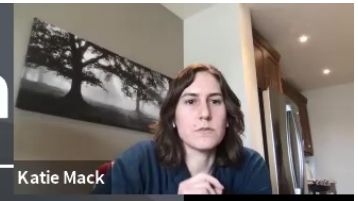


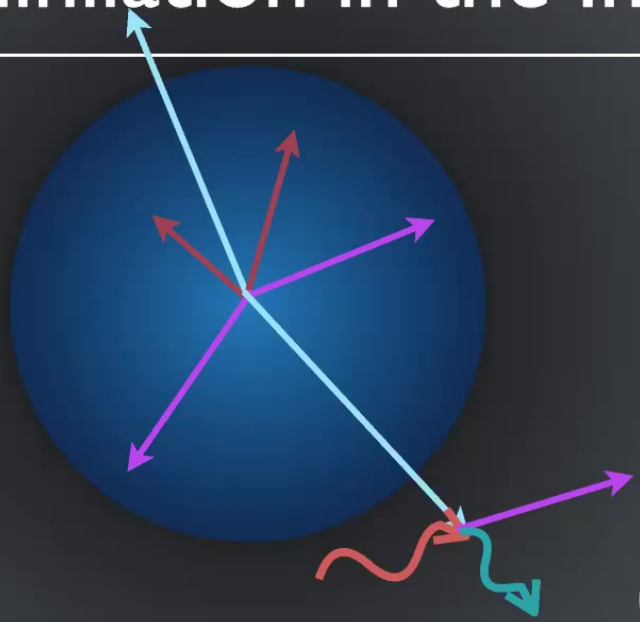


Better:

- structured halos
- delayed energy deposition

Annihilation in the Intergalactic Medium



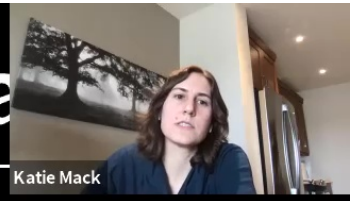


inverse Compton scattering

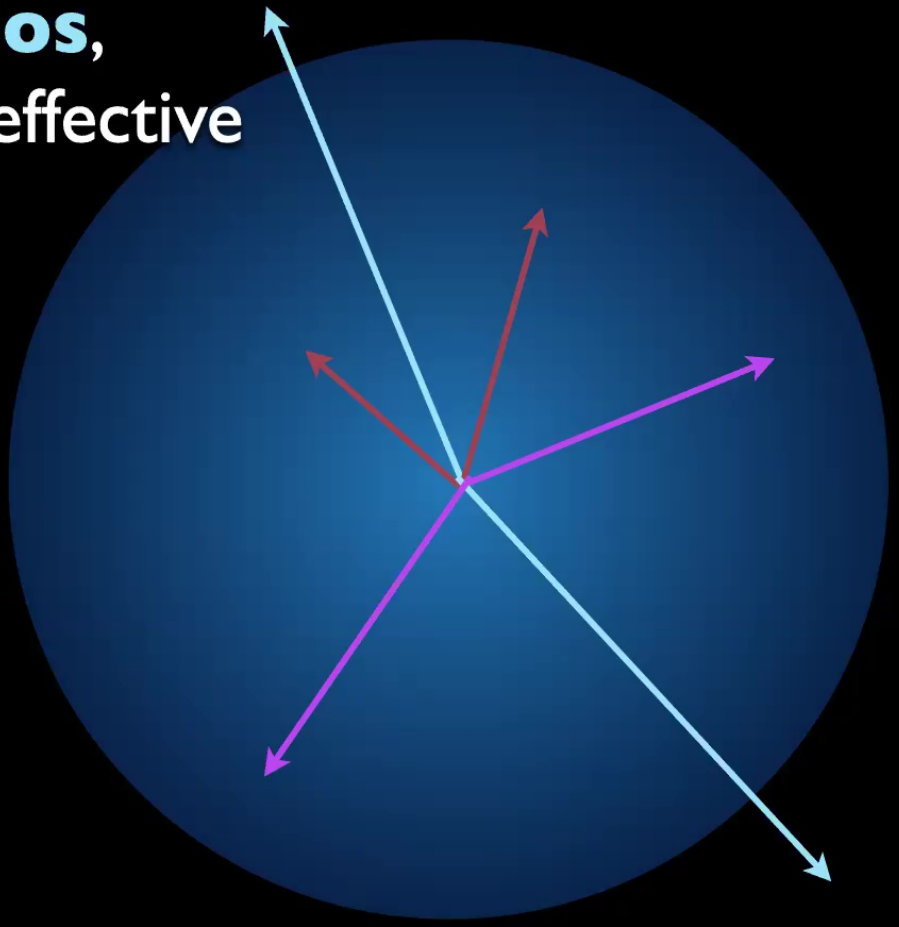
Better:

- structured halos
- delayed energy deposition

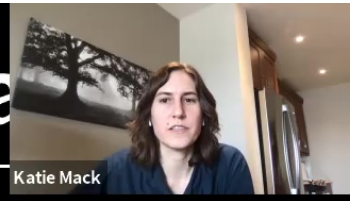
Annihilation Feedback on Halo Ga



If dark matter is annihilating **within baryonic halos**, does this constitute an effective **"feedback"** process?



Annihilation Feedback on Halo Ga



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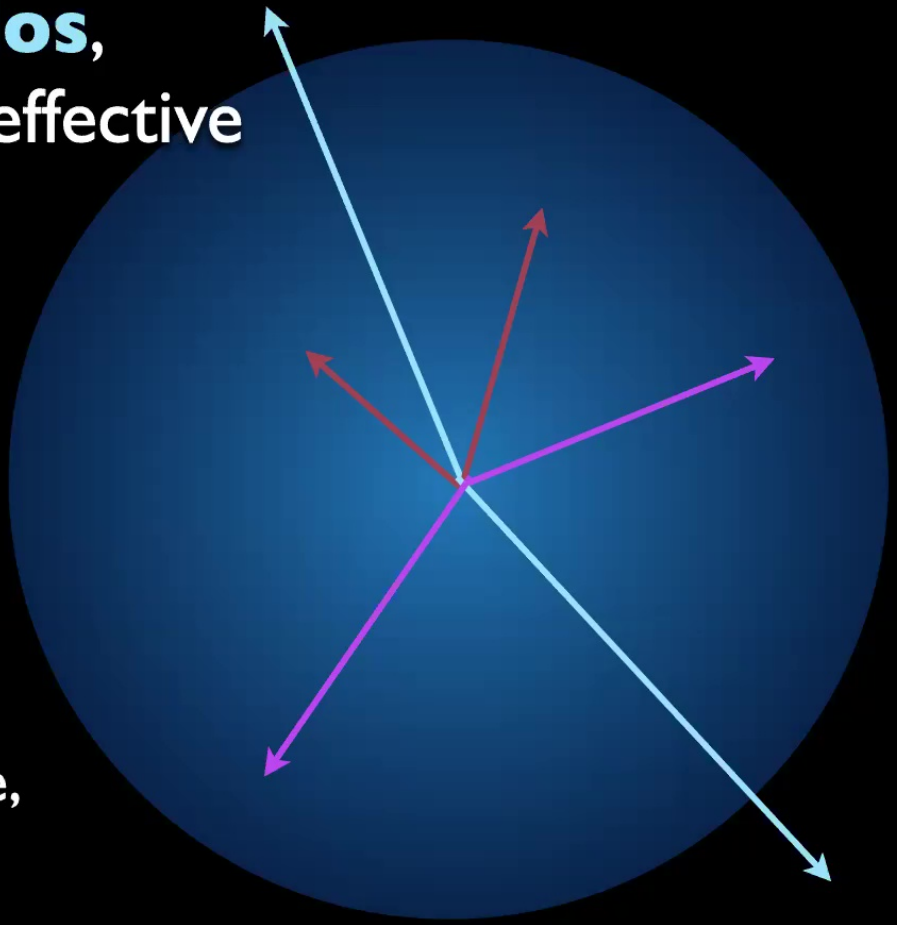
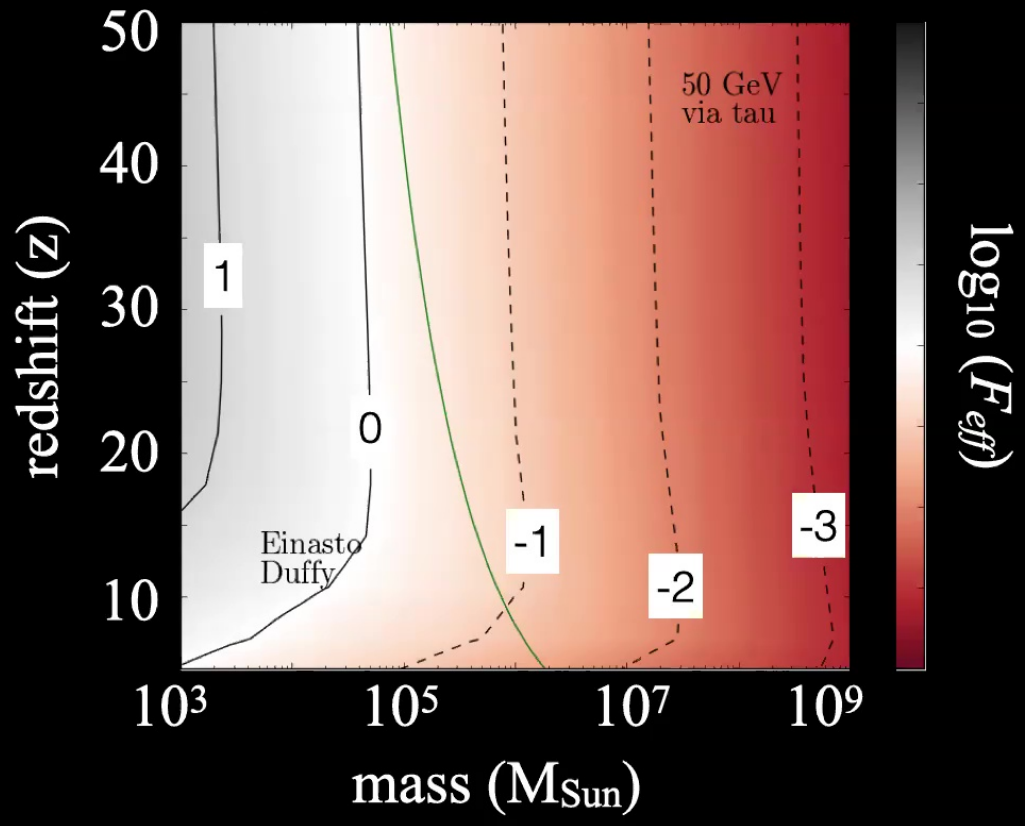


PYTHIA code: dark matter annihilation events

MEDEA2 code: energy transfer to baryons

Halo models: density profile, mass-concentration

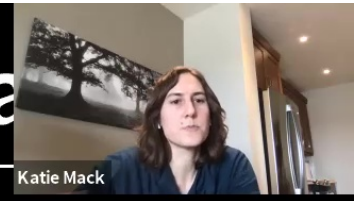
Annihilation Feedback on Halo Ga

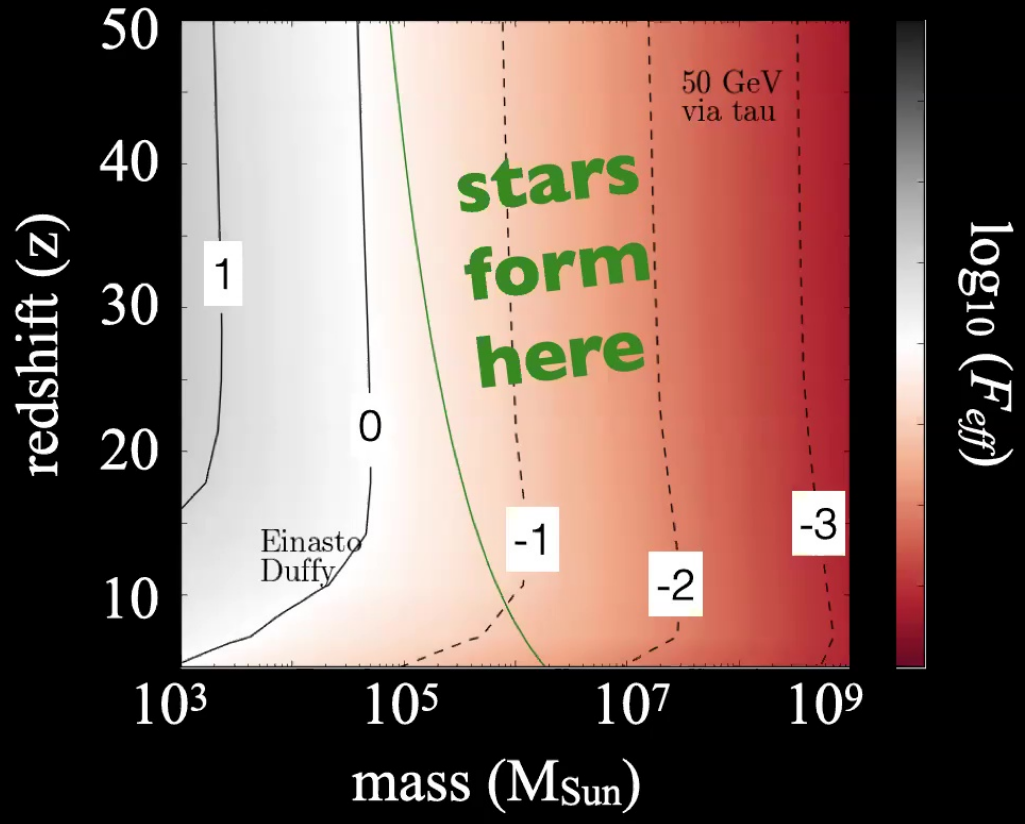


Comparing:
dark matter annihilation energy
(over Hubble time)
to:
gas binding energy

Schon, Mack+ 2015, MNRAS [arxiv: 1411.3783]

Annihilation Feedback on Halo Ga





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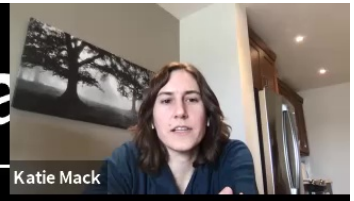

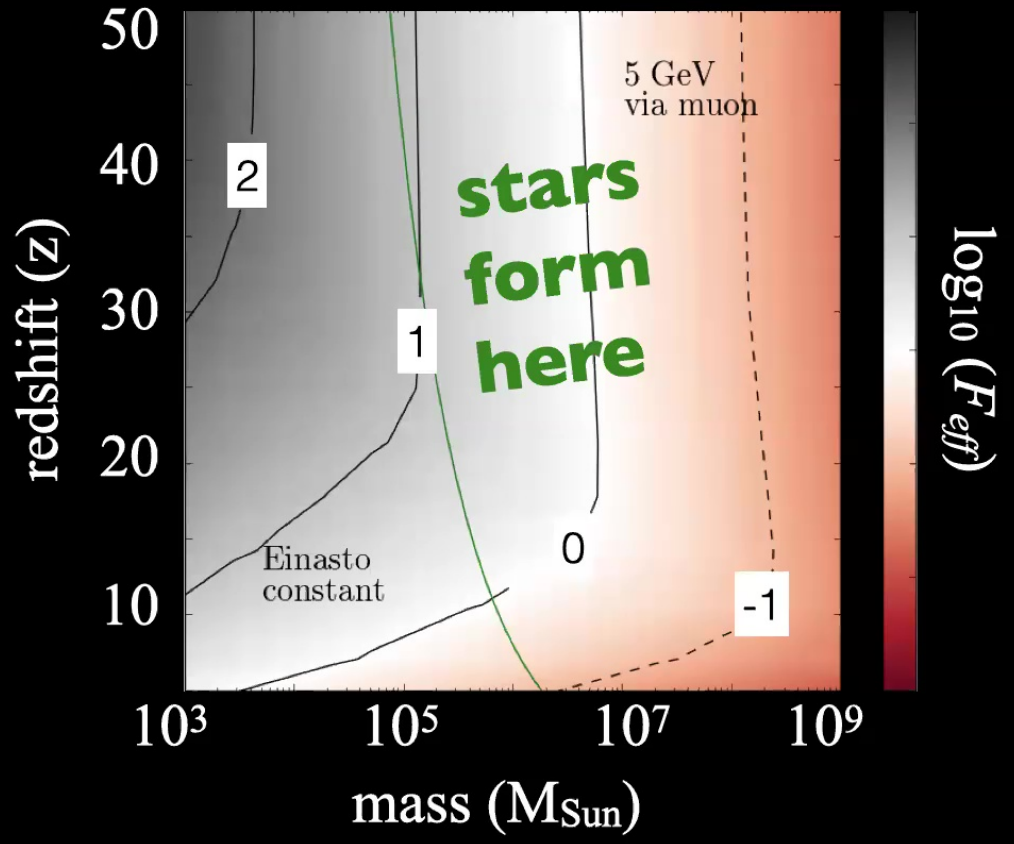

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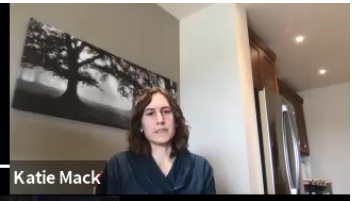
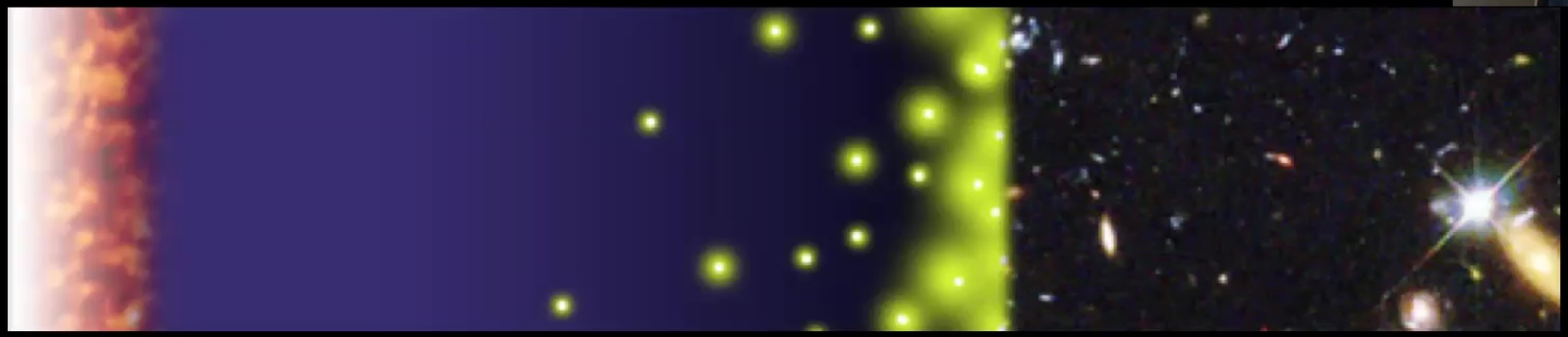
+ Schon, Mack+ 2018, MNRAS [arxiv: 1706.04327]

Probing Cosmic Dawn

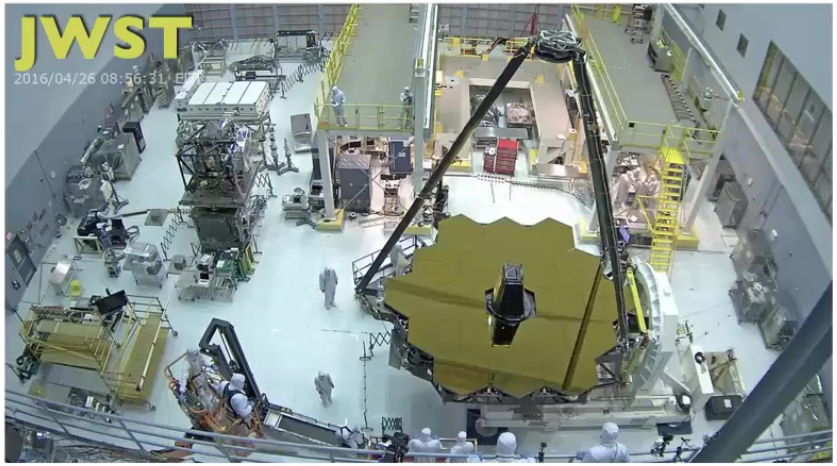


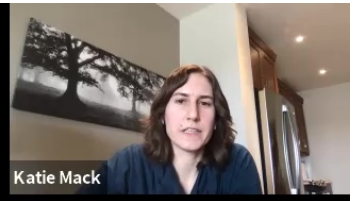


Djorgovski et al., Caltech

current instruments

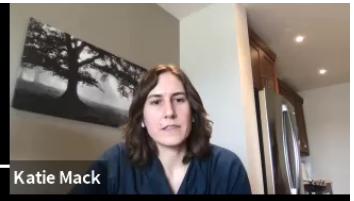
next decade

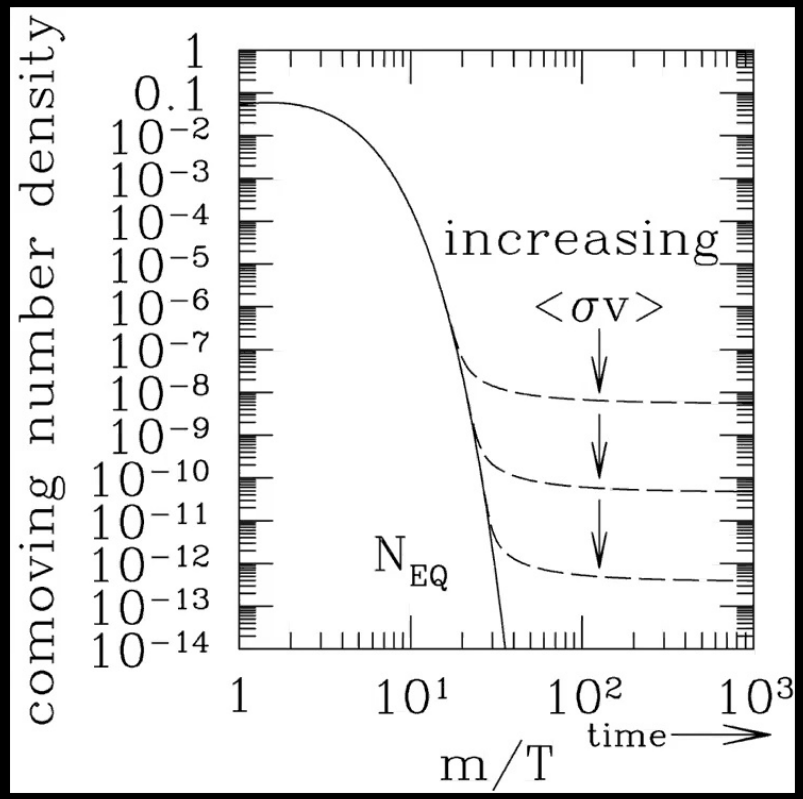




Work in Progress

Alternative DM Thermal Histories

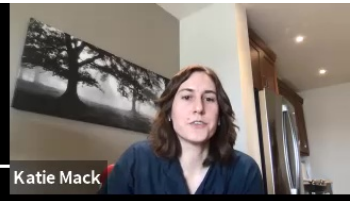


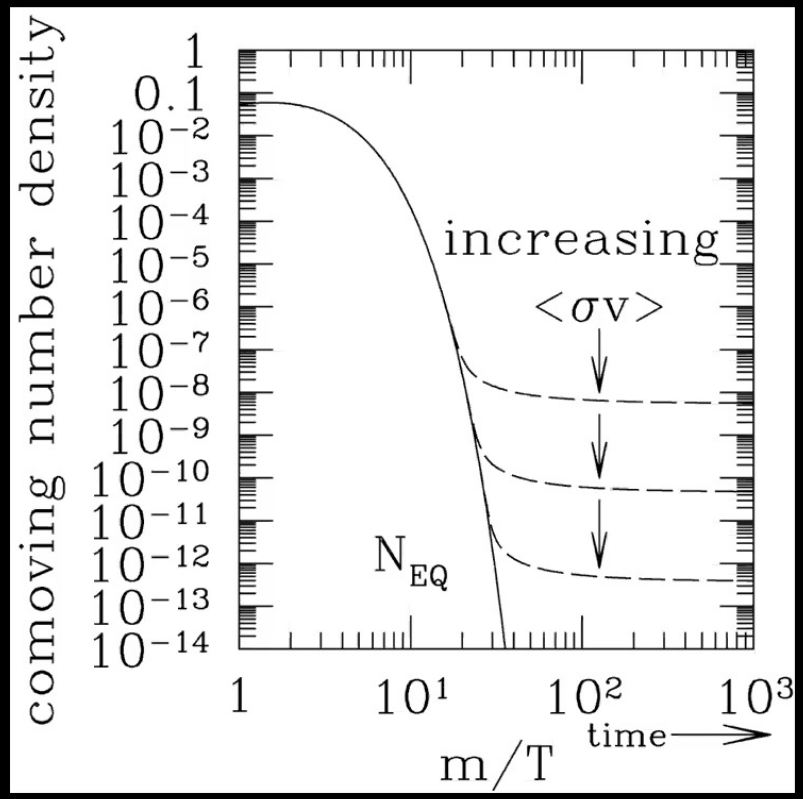


Kolb & Turner 1990

Standard thermal WIMP dark matter

Alternative DM Thermal Histories



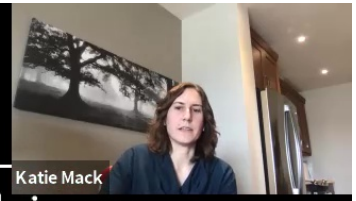


Kolb & Turner 1990

Standard thermal WIMP dark matter

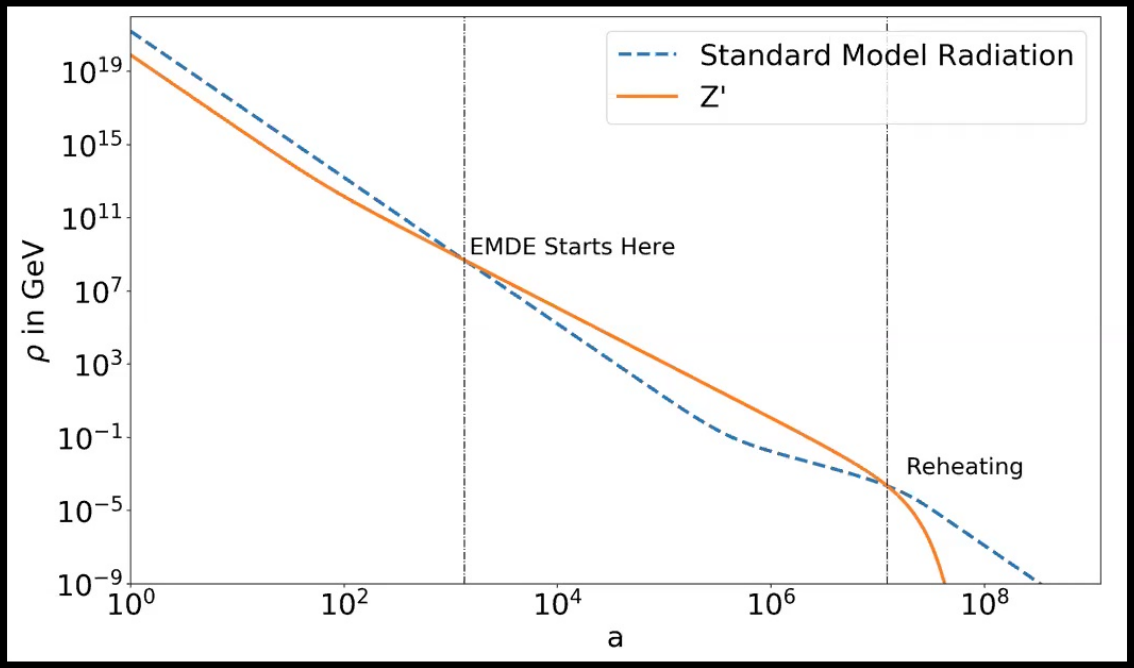
- WIMP-interaction-strength cross section mostly ruled out
- ➡ consider alternative histories

Alternative DM Thermal Histories



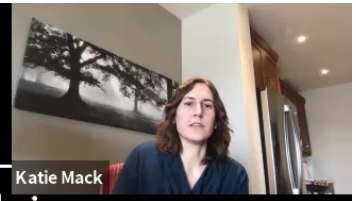
A. Erickcek, H. Ganjoo et al., in prep

Early matter-dominated epoch



- dark matter coupled to Standard Model only via mediator

Alternative DM Thermal Histories



A. Erickcek, H. Ganjoo et al., in prep

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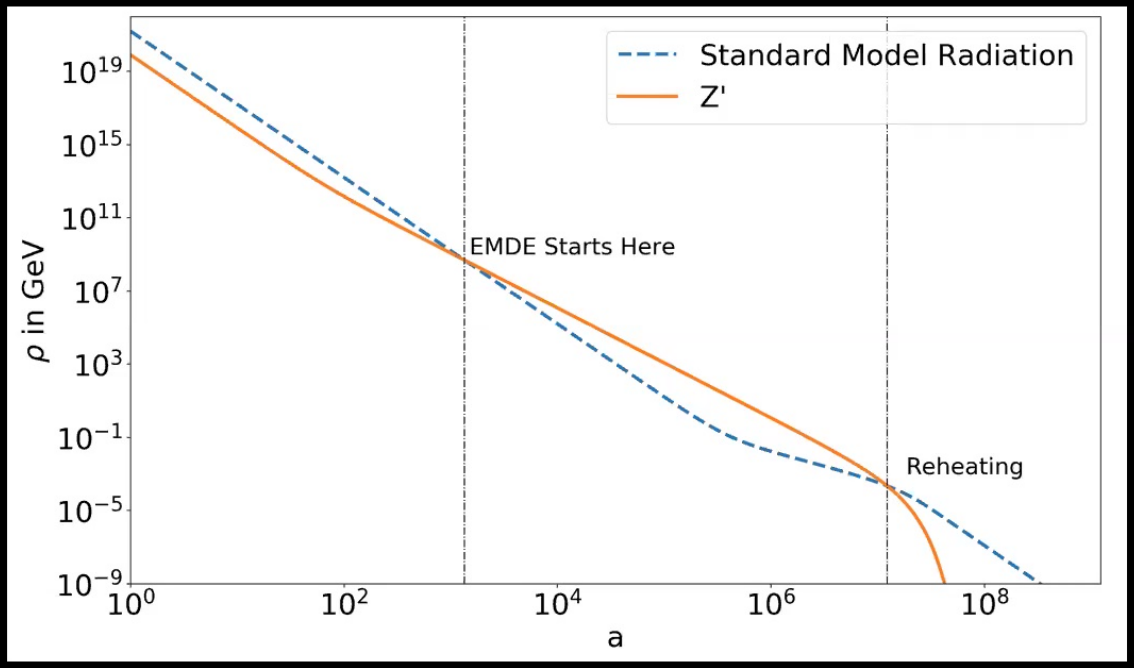
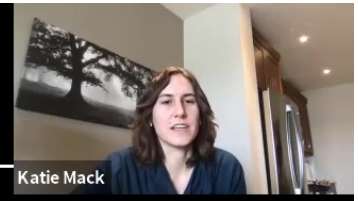
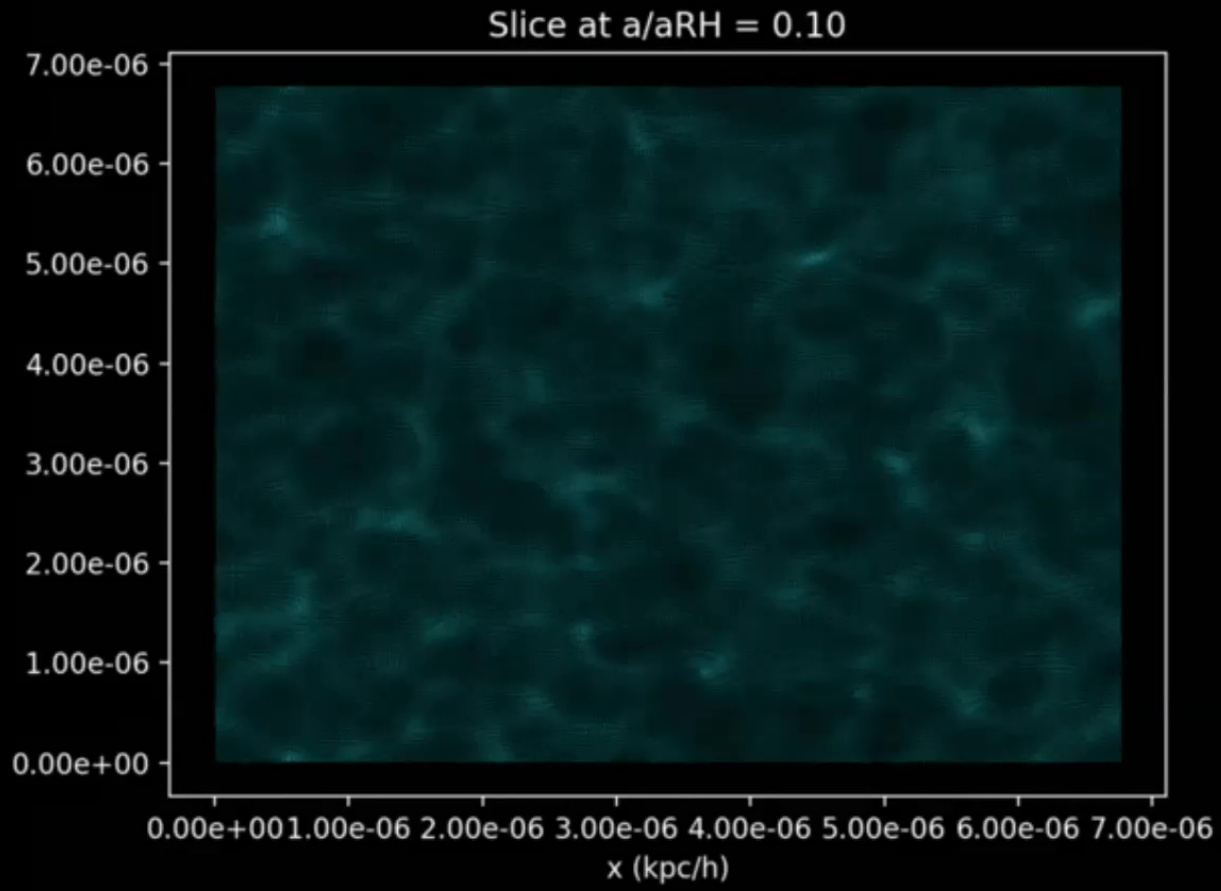


- dark matter coupled to Standard Model only via mediator
- mediator dominates during radiation domination, initiating temporary matter-dominated era
- mediator decays, heating dark matter

Alternative DM Thermal Histories





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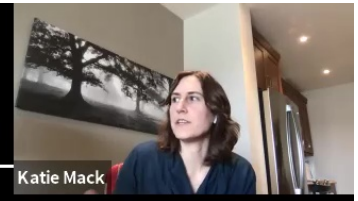

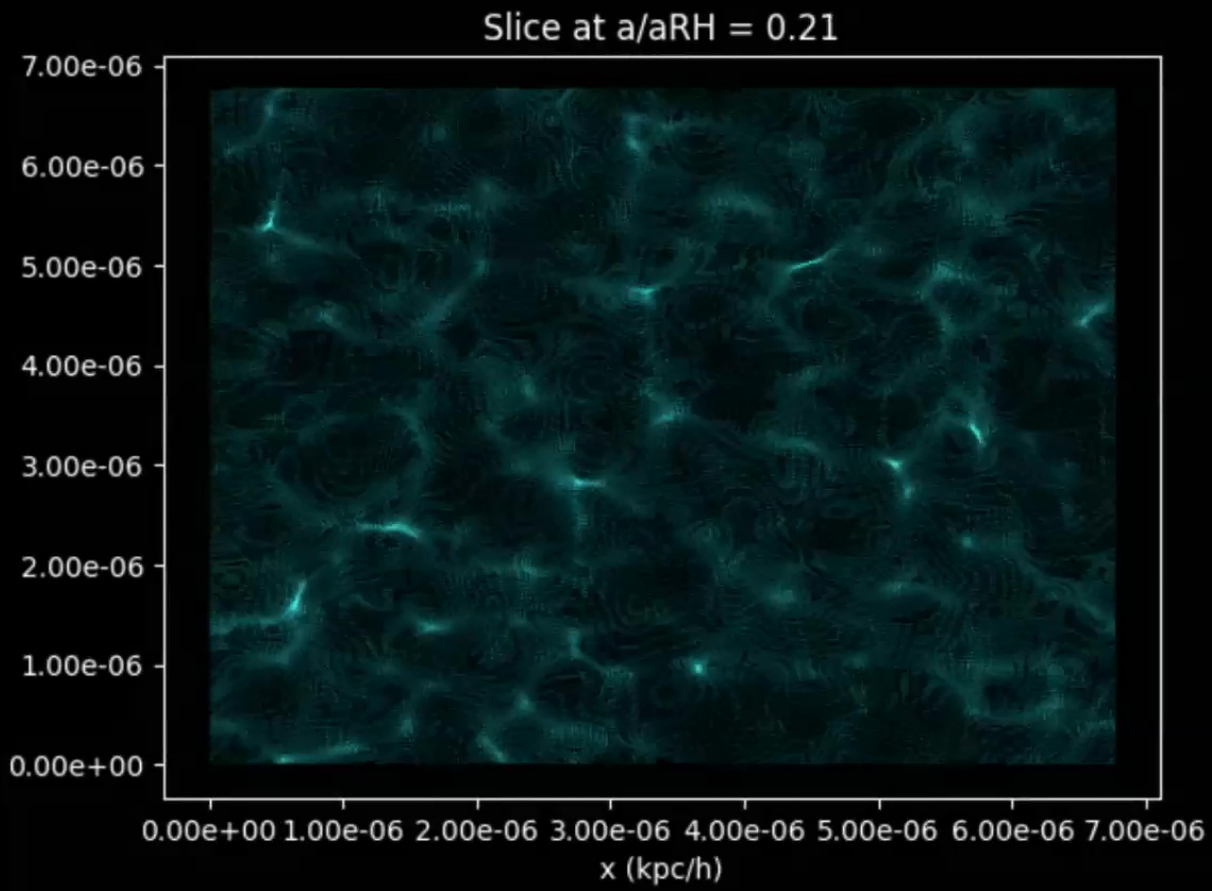

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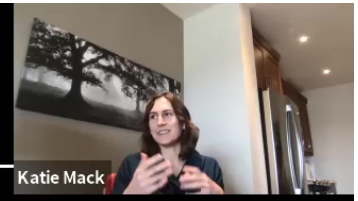

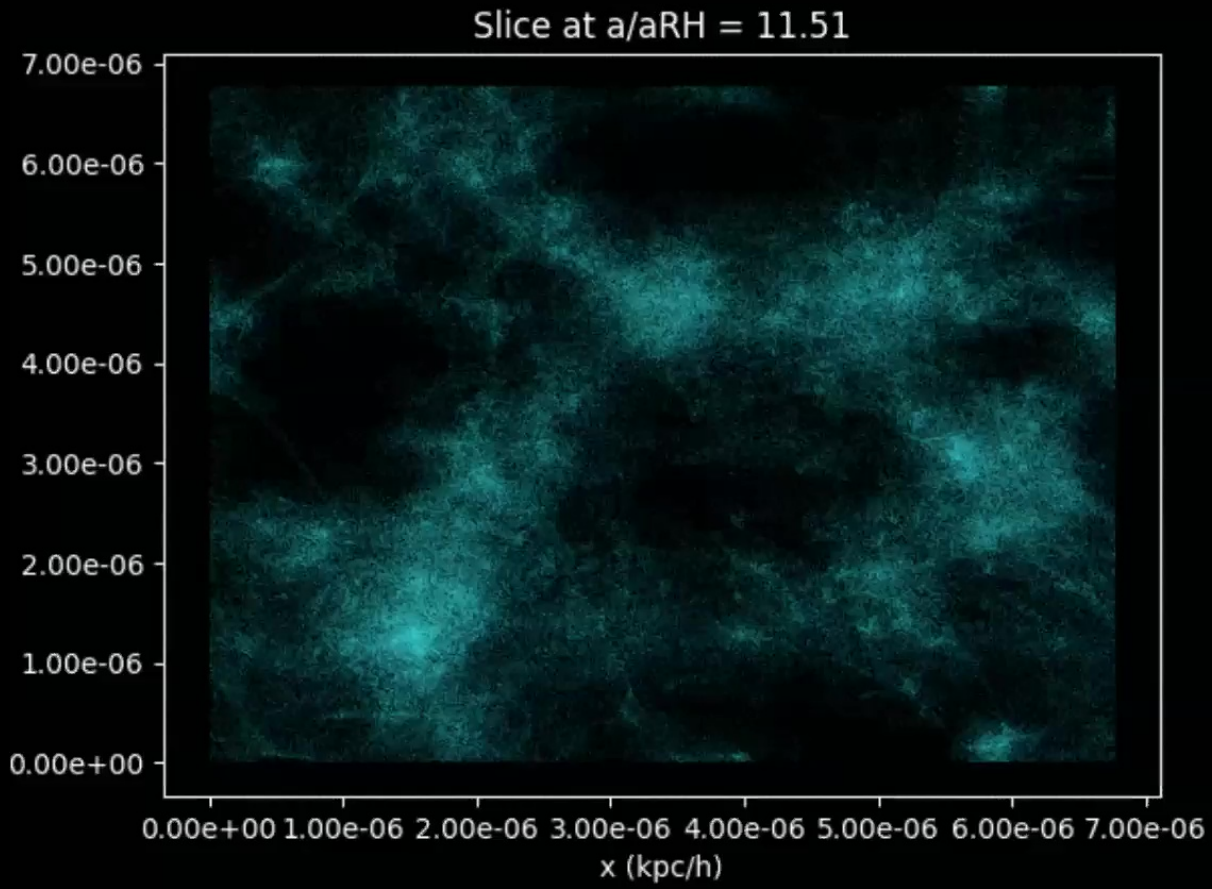

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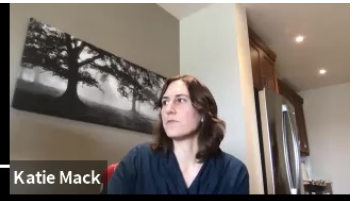
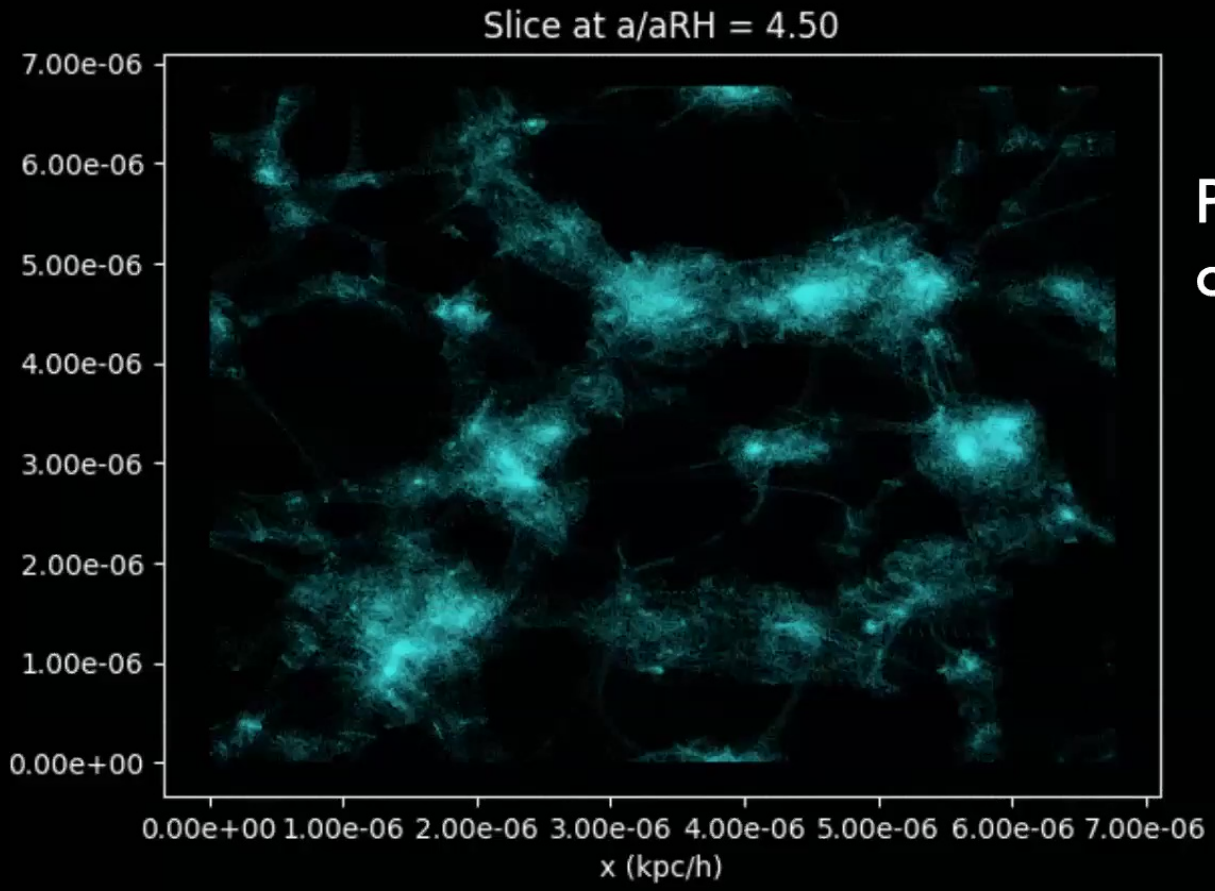
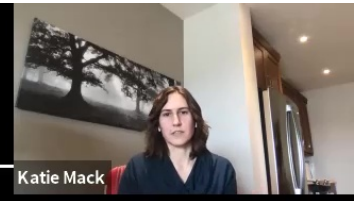


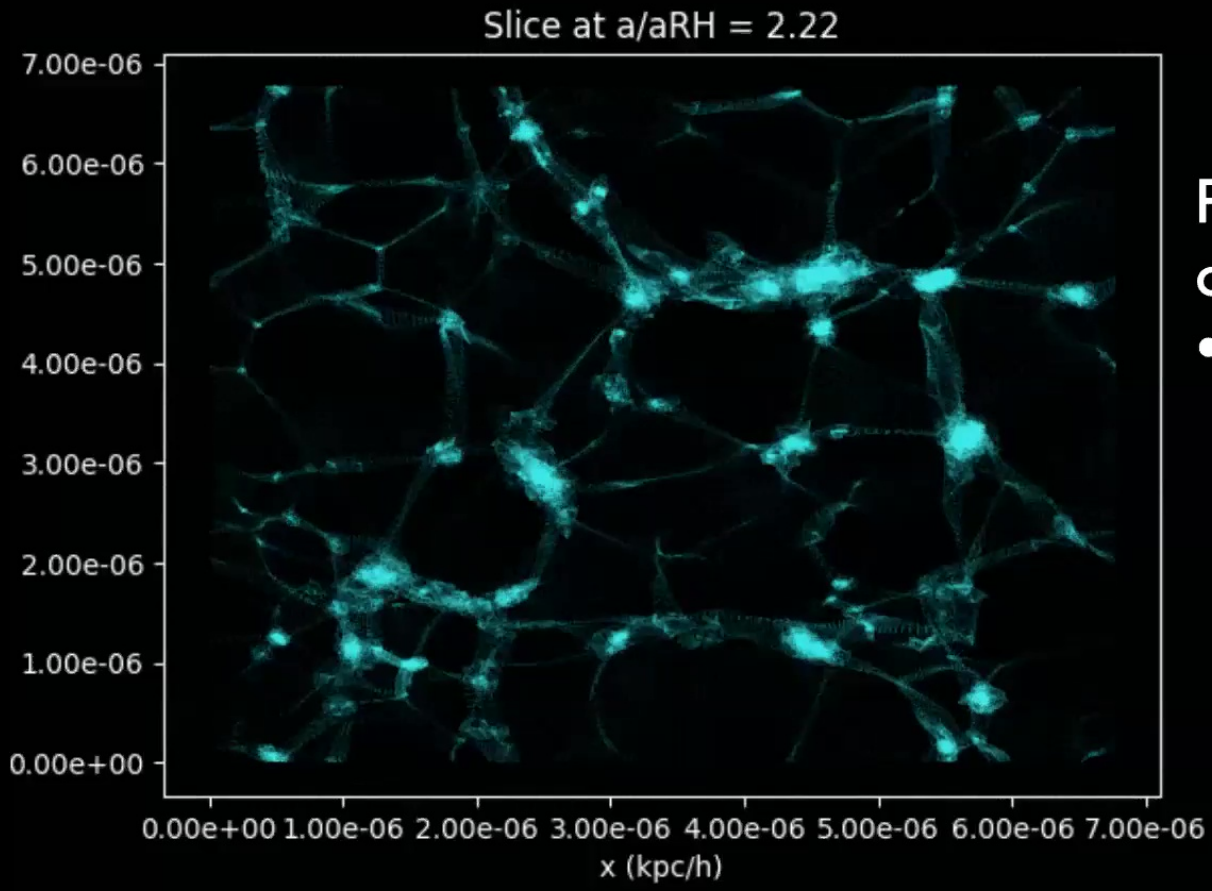


Potential impacts on:

A. Erickcek, H. Ganjoo et al., in prep

Alternative DM Thermal Histories



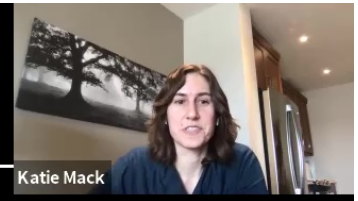


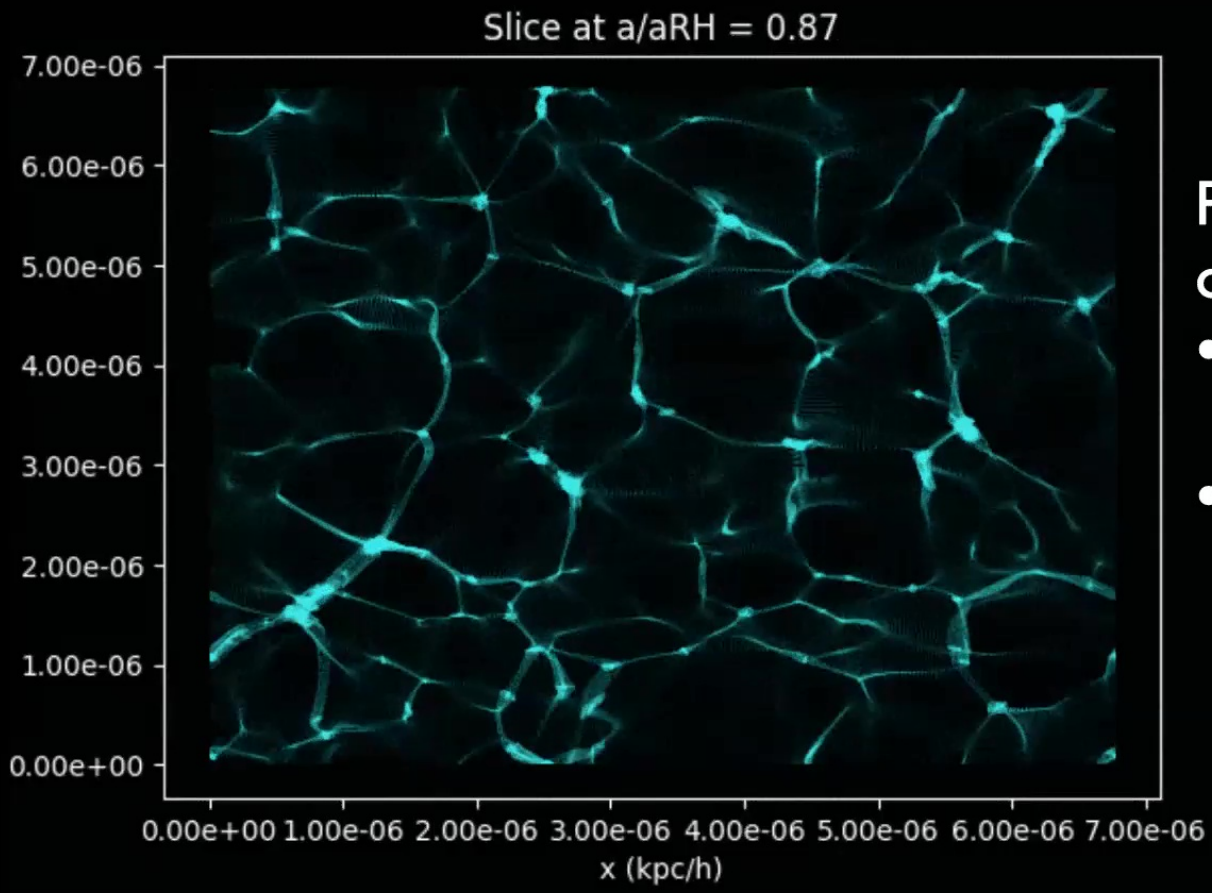
Potential impacts on:

- annihilation signal

A. Erickcek, H. Ganjoo et al., in prep

Alternative DM Thermal Histories

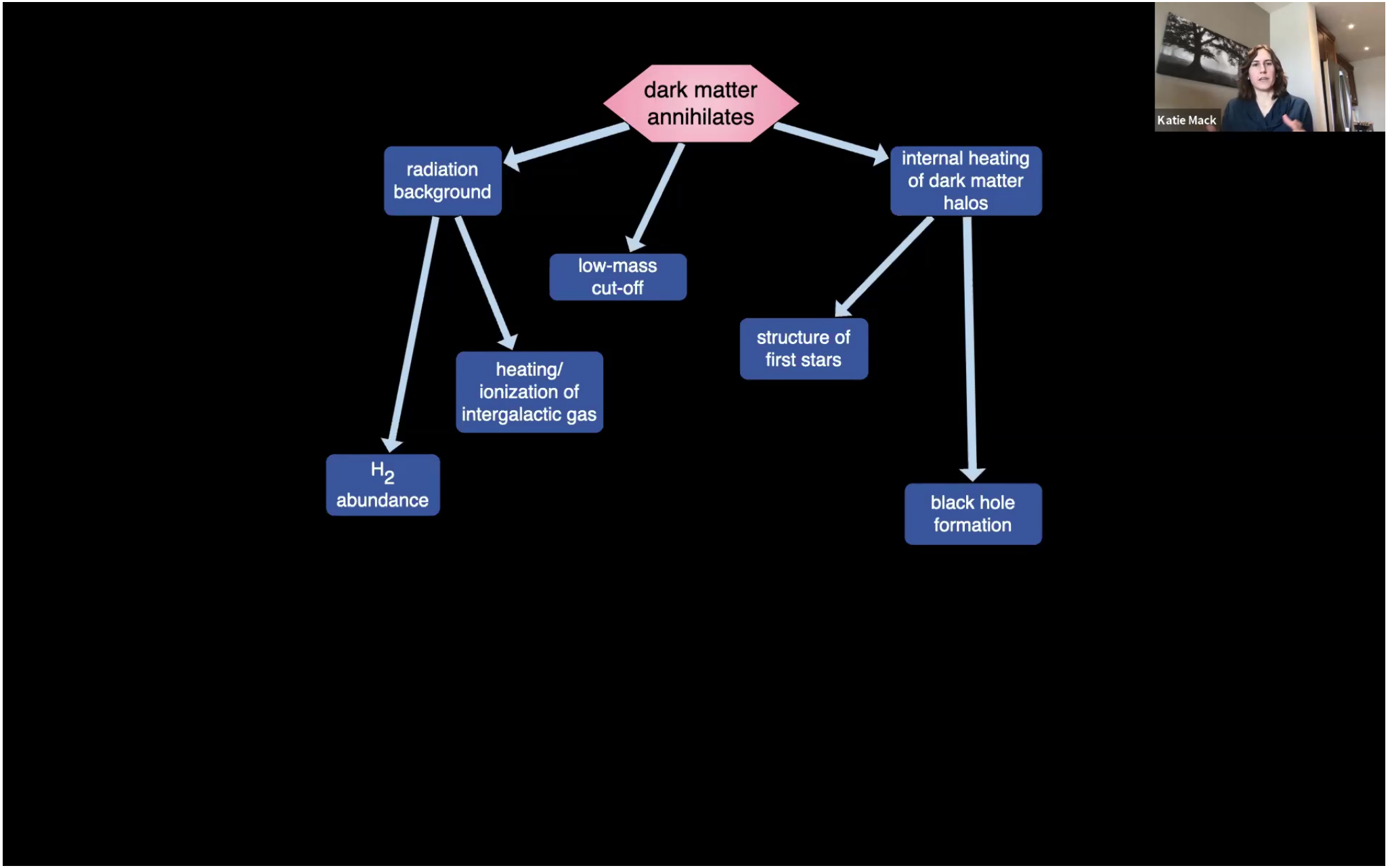


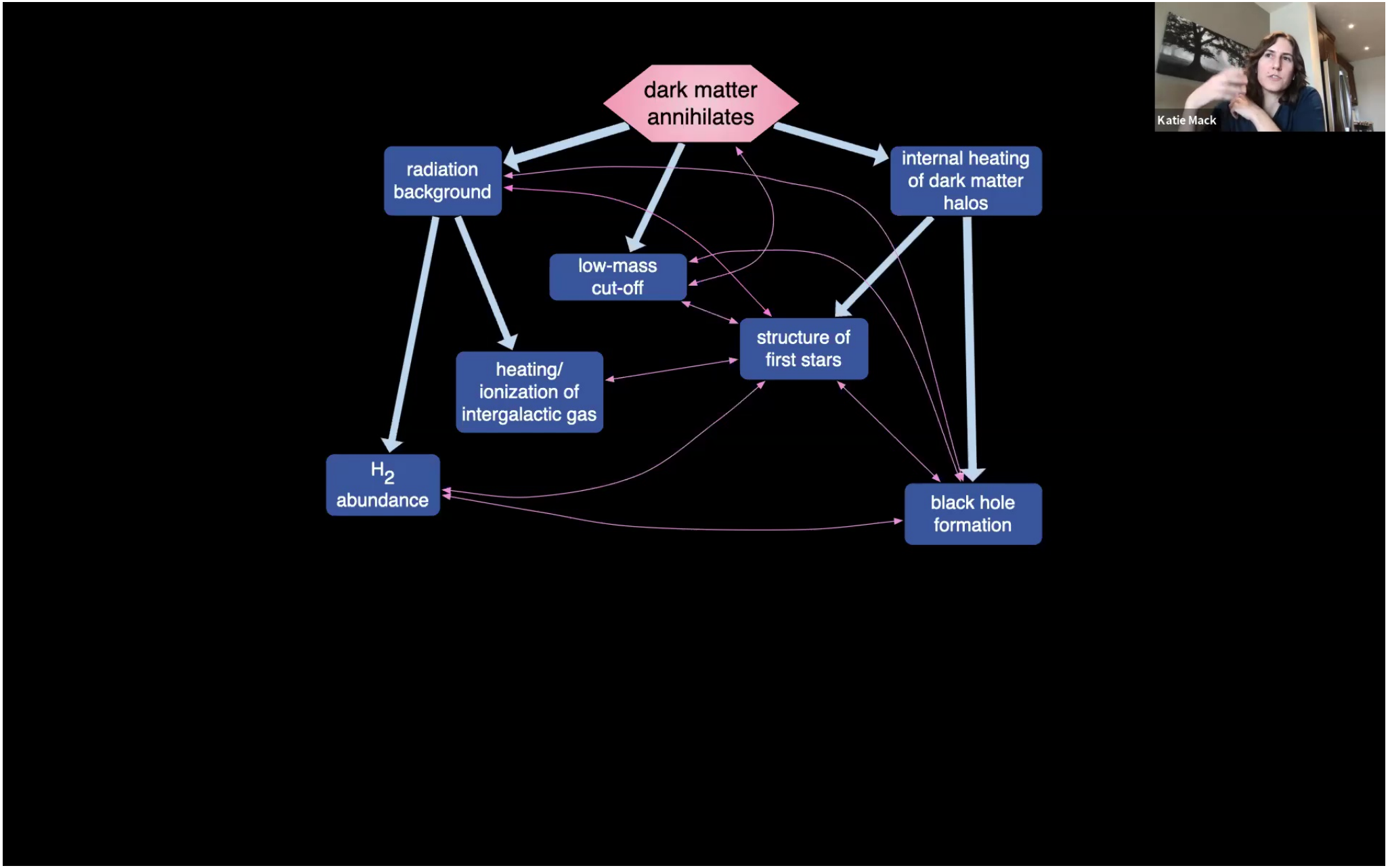


Potential impacts on:

- annihilation signal
- small-scale matter power spectrum

A. Erickcek, H. Ganjoo et al., in prep


dark matter annihilates
radiation background
low-mass cut-off
internal heating of dark matter halos
heating/ ionization of intergalactic gas
structure of first stars
H_2 abundance
black hole formation
Katie Mack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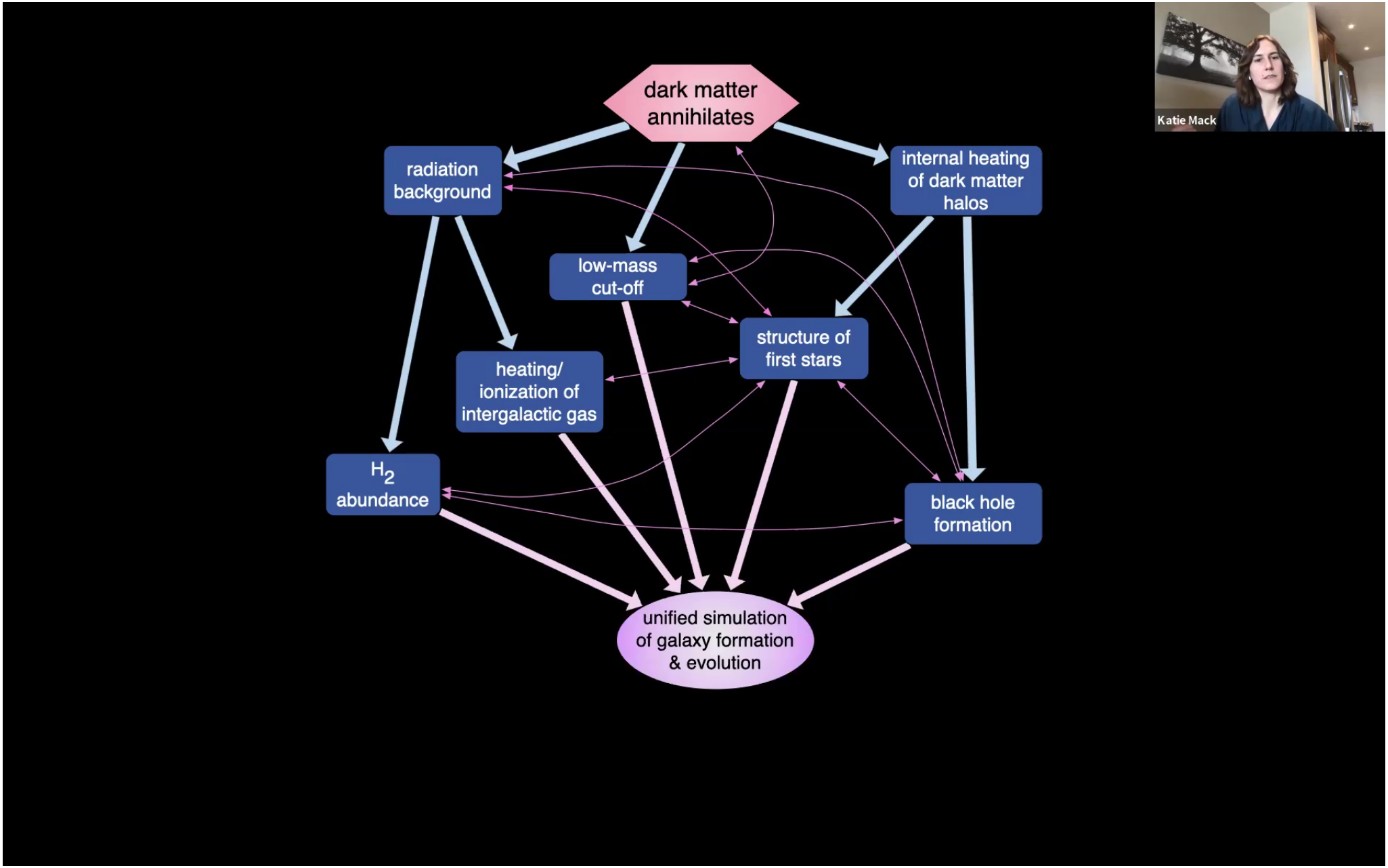
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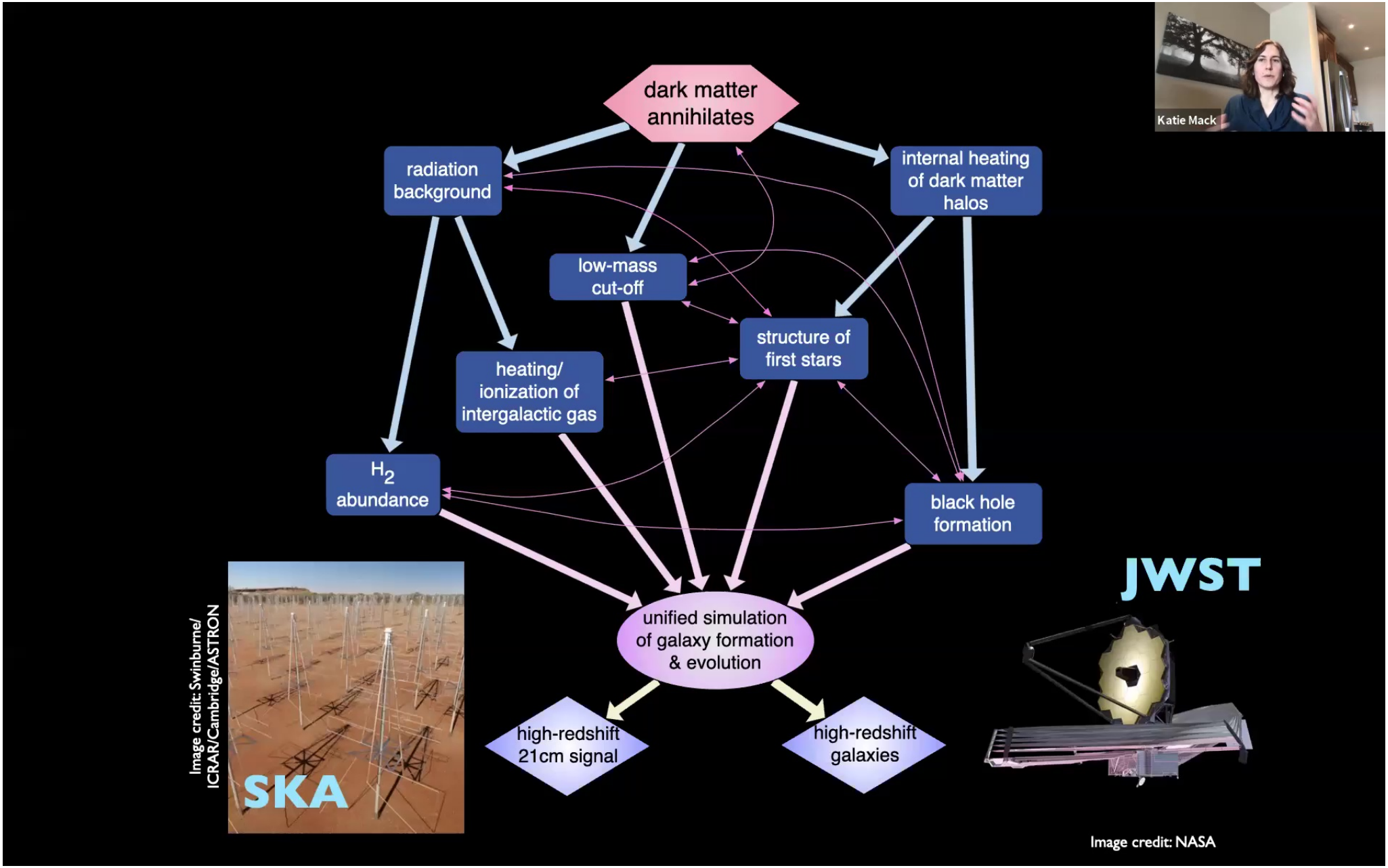
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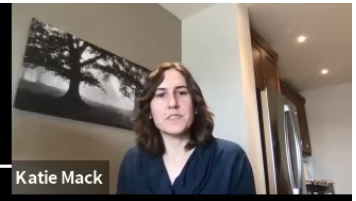
high-redshift 21cm signal
high-redshift galaxies
Katie Mack
Image credit: Swinburne/ ICRAR/Cambridge/ASTRON
SKA
JWST
Image credit: NASA

Take-Home Messages



- The **fundamental nature of dark matter** is still a mystery
  - but it is almost certainly real
  - and we are getting clues
- To identify dark matter from astrophysics, we need **multi-messenger signals** and a solid understanding of **astrophysical foregrounds**
- Future surveys can probe the **particle physics of dark matter** and produce a more consistent picture of cosmology