Dark Matter in the Cosmic Context

Katie Mack

University of Melbourne

(soon: North Carolina State University)

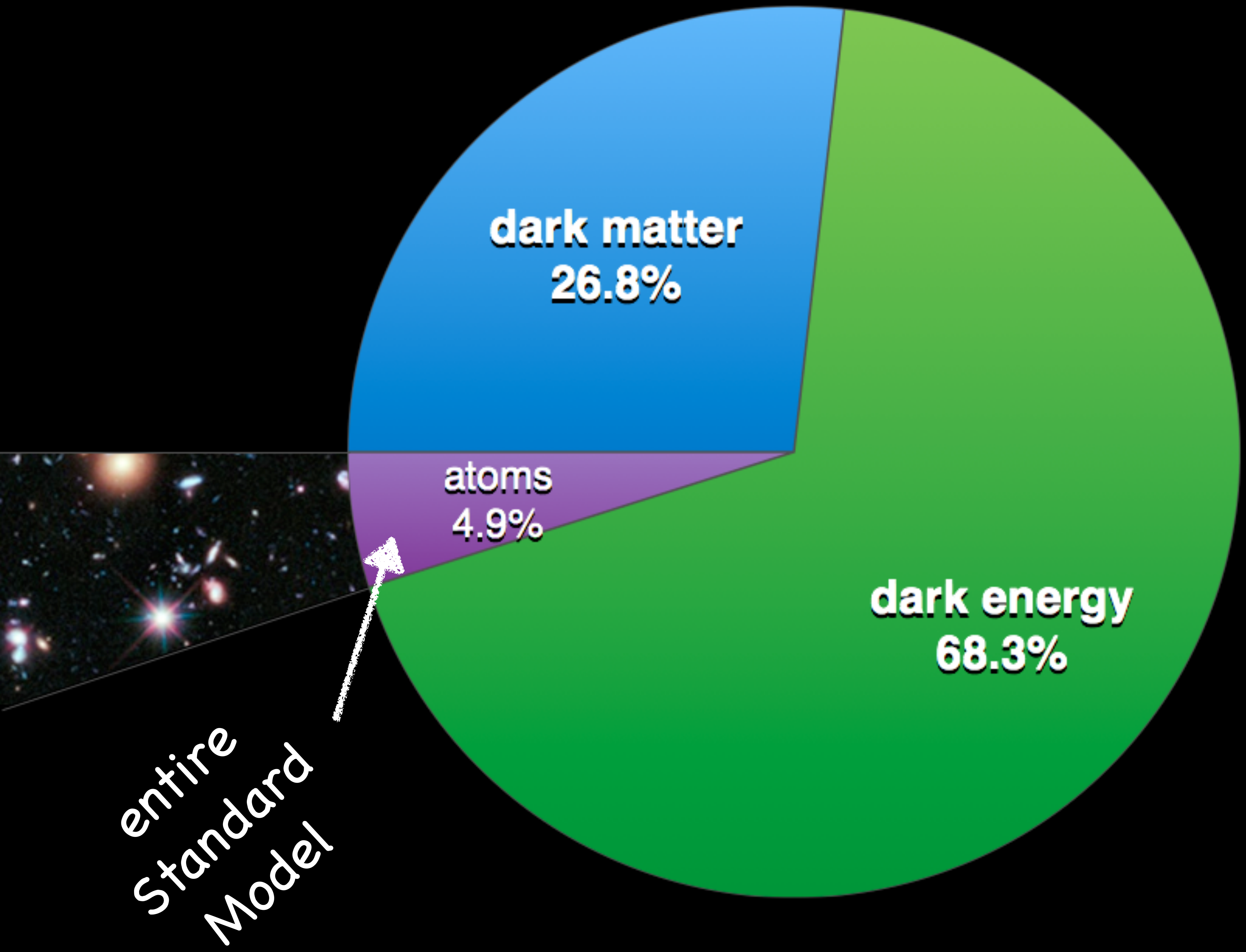
CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

THE UNIVERSITY OF MELBOURNE

CoEPP

www.ph.unimelb.edu.au/~kmack

: @AstroKatie

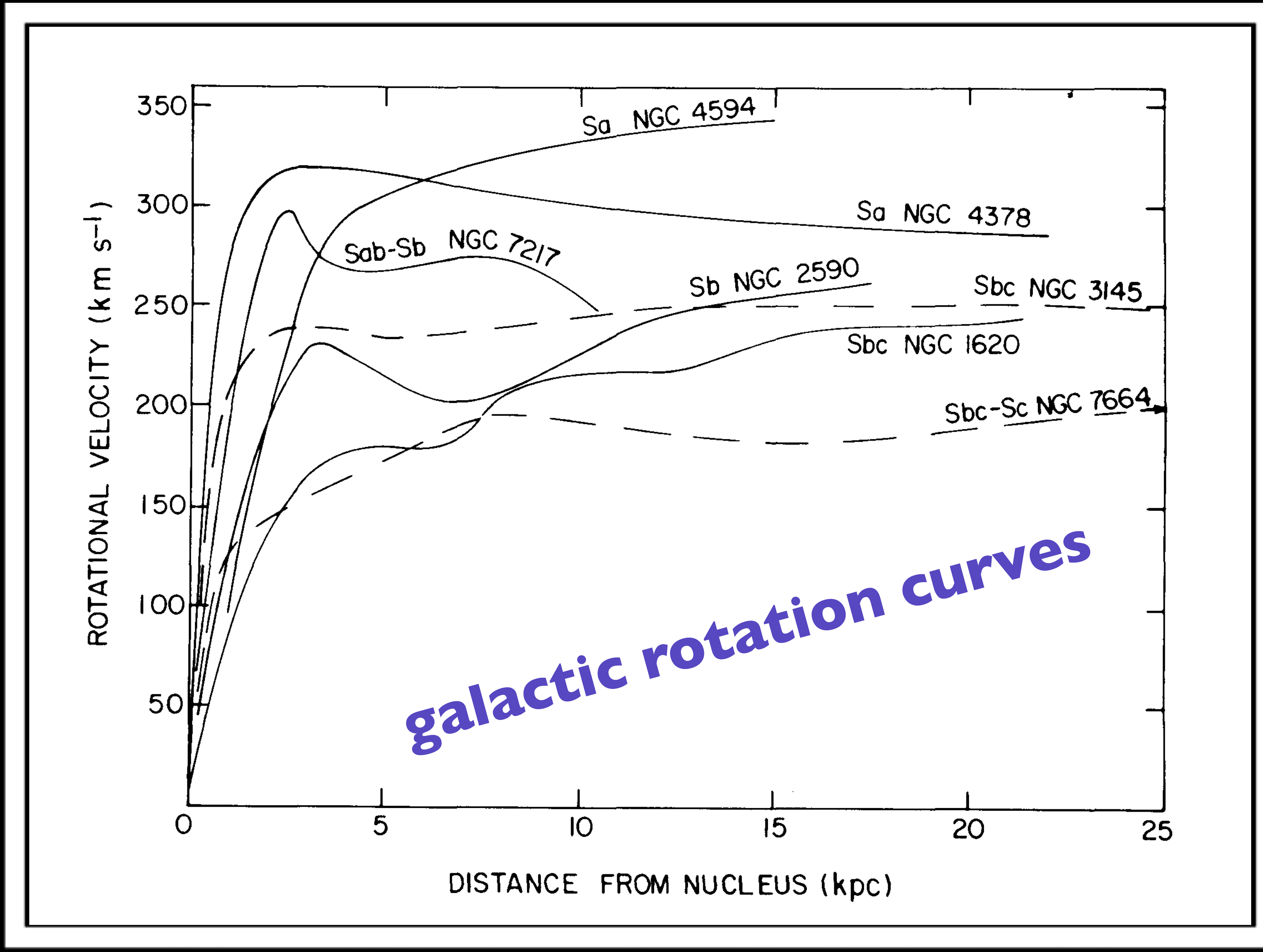

dark matter
26.8%
atoms
4.9%
dark energy
68.3%
entire
Standard
Model

Dark Matter

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

Evidence and Properties

massive



Evidence and Properties

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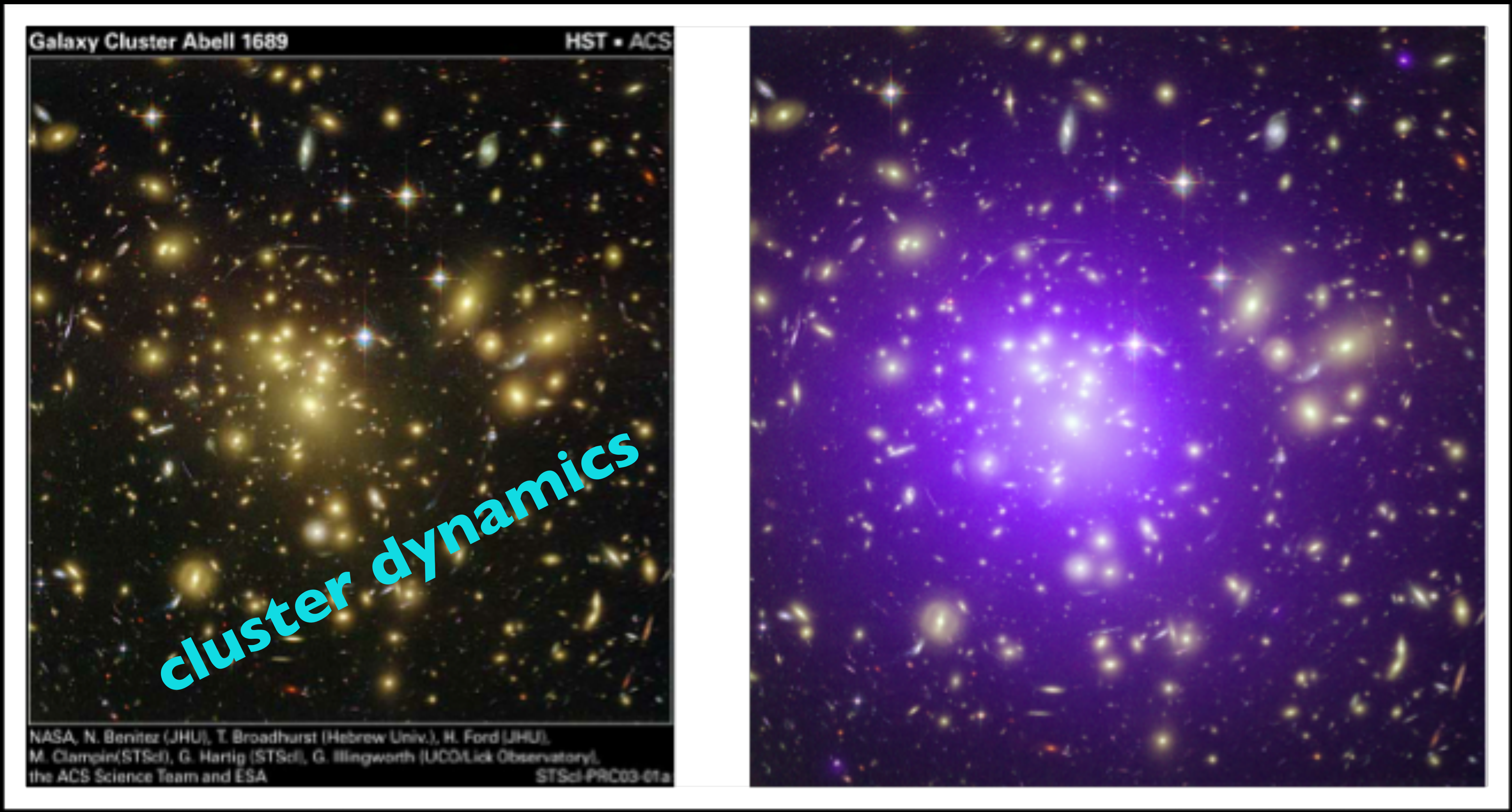
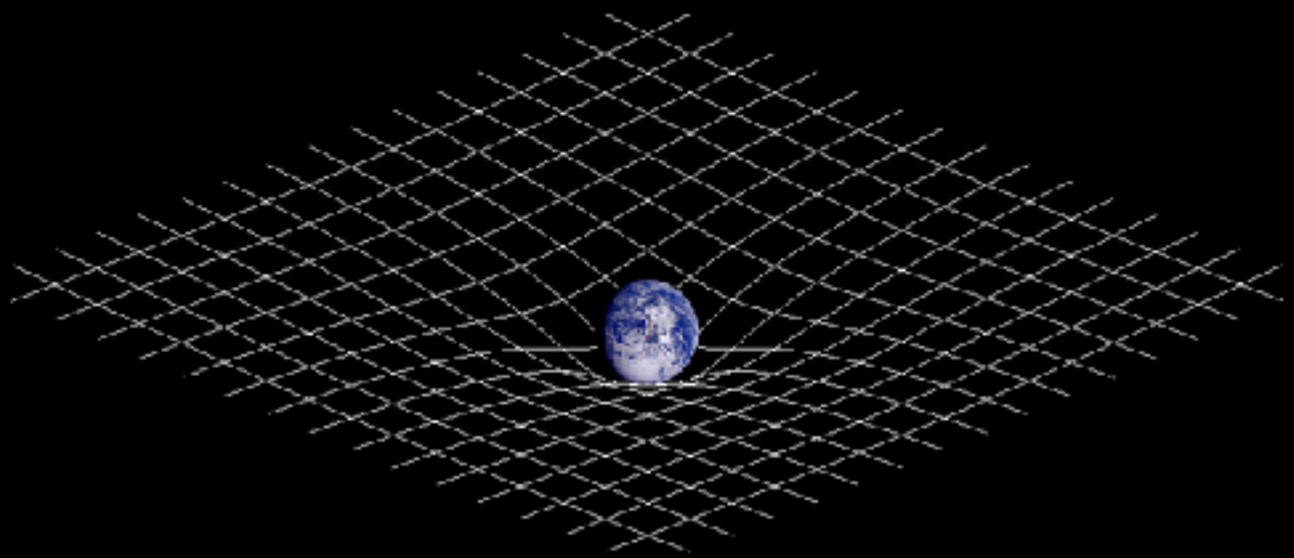
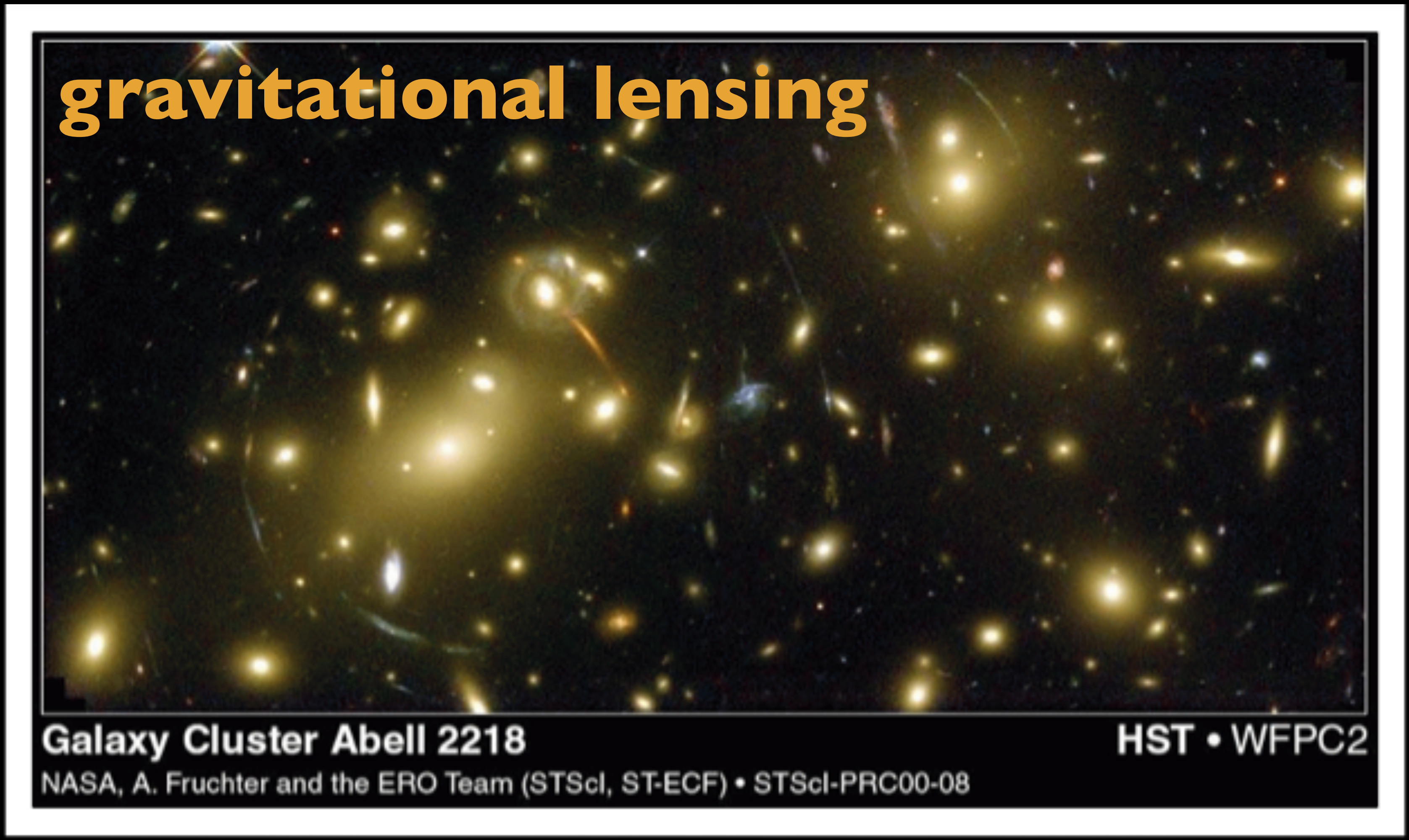


Evidence and Properties

massive

ubiquitous



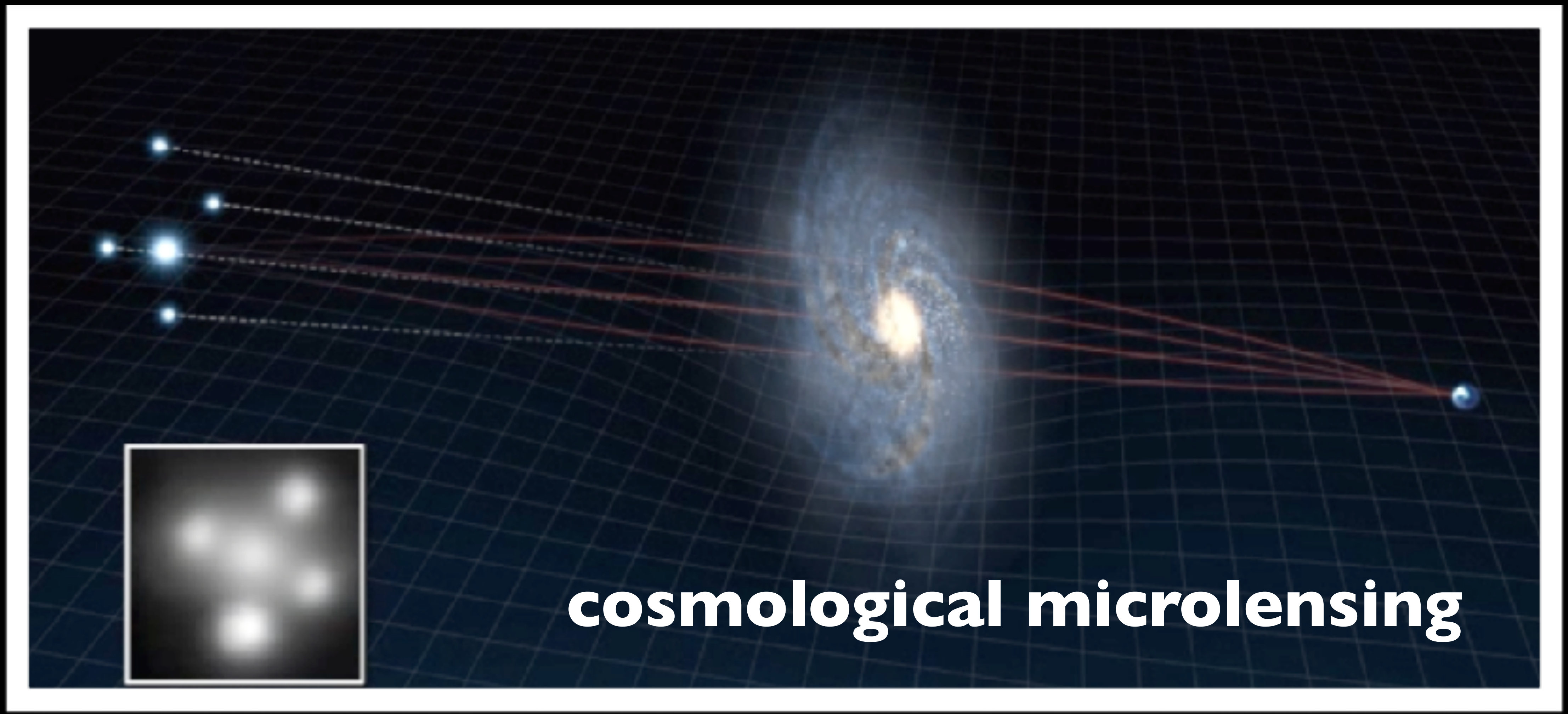


Evidence and Properties

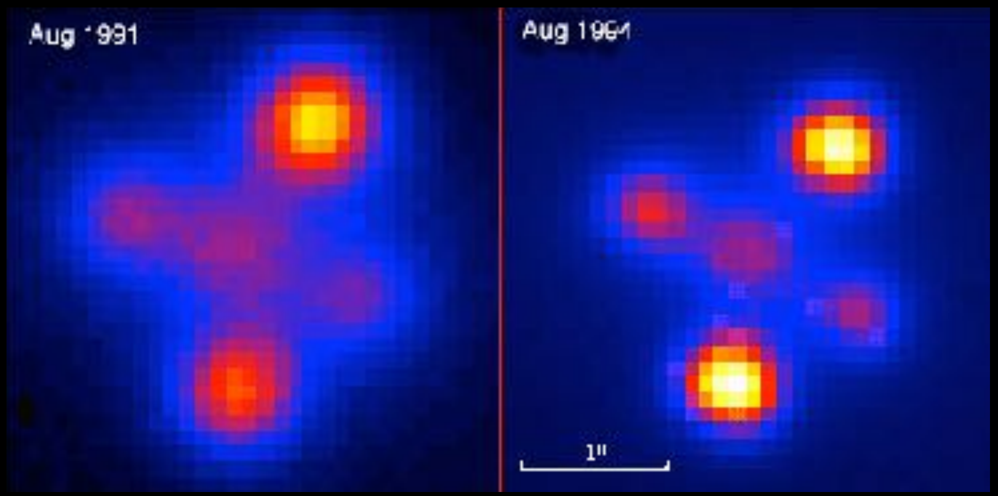
massive

ubiquitous

smooth



Lewis & Irwin 1996



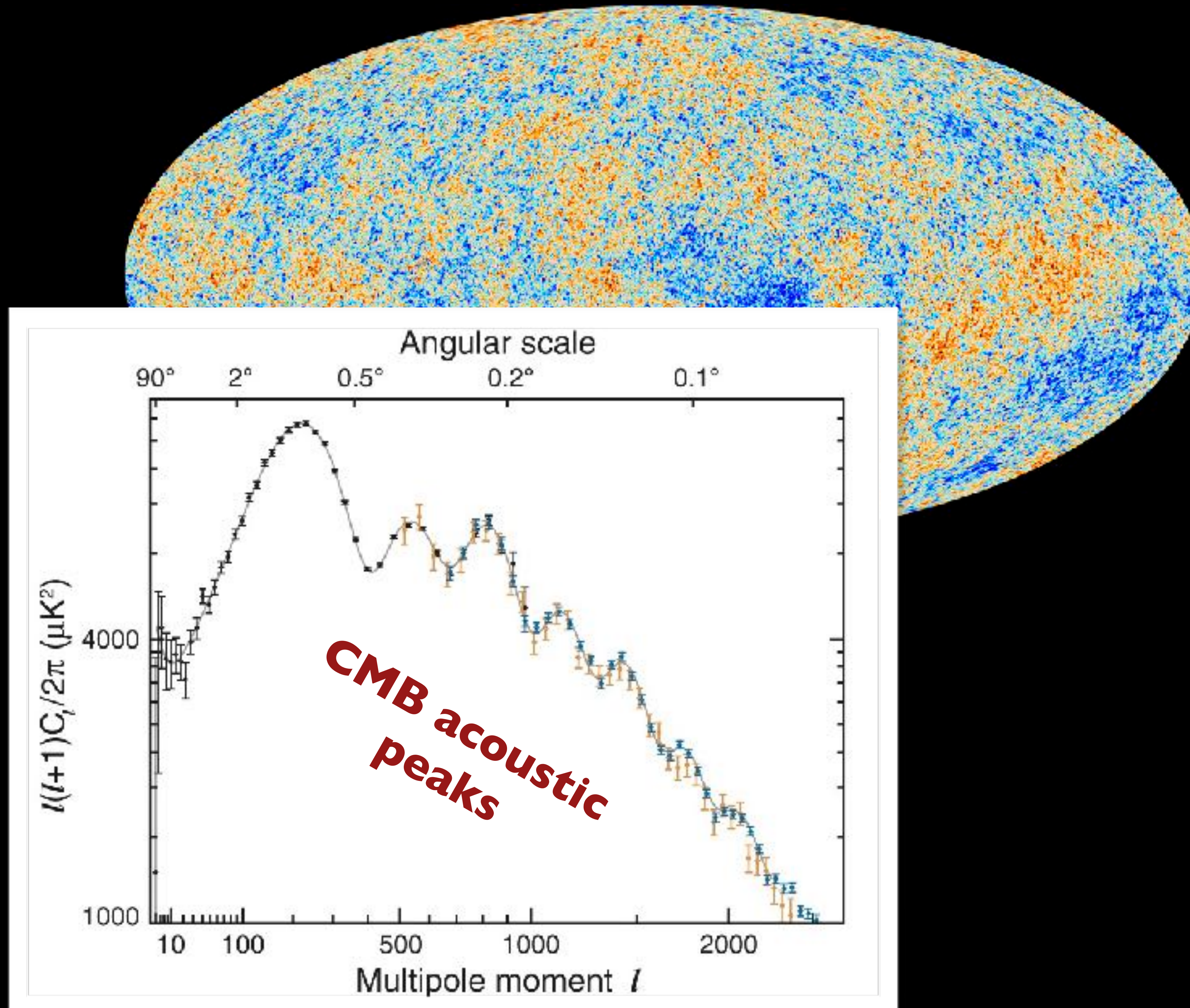
Evidence and Properties

massive

ubiquitous

smooth

collisionless



Evidence and Properties

massive

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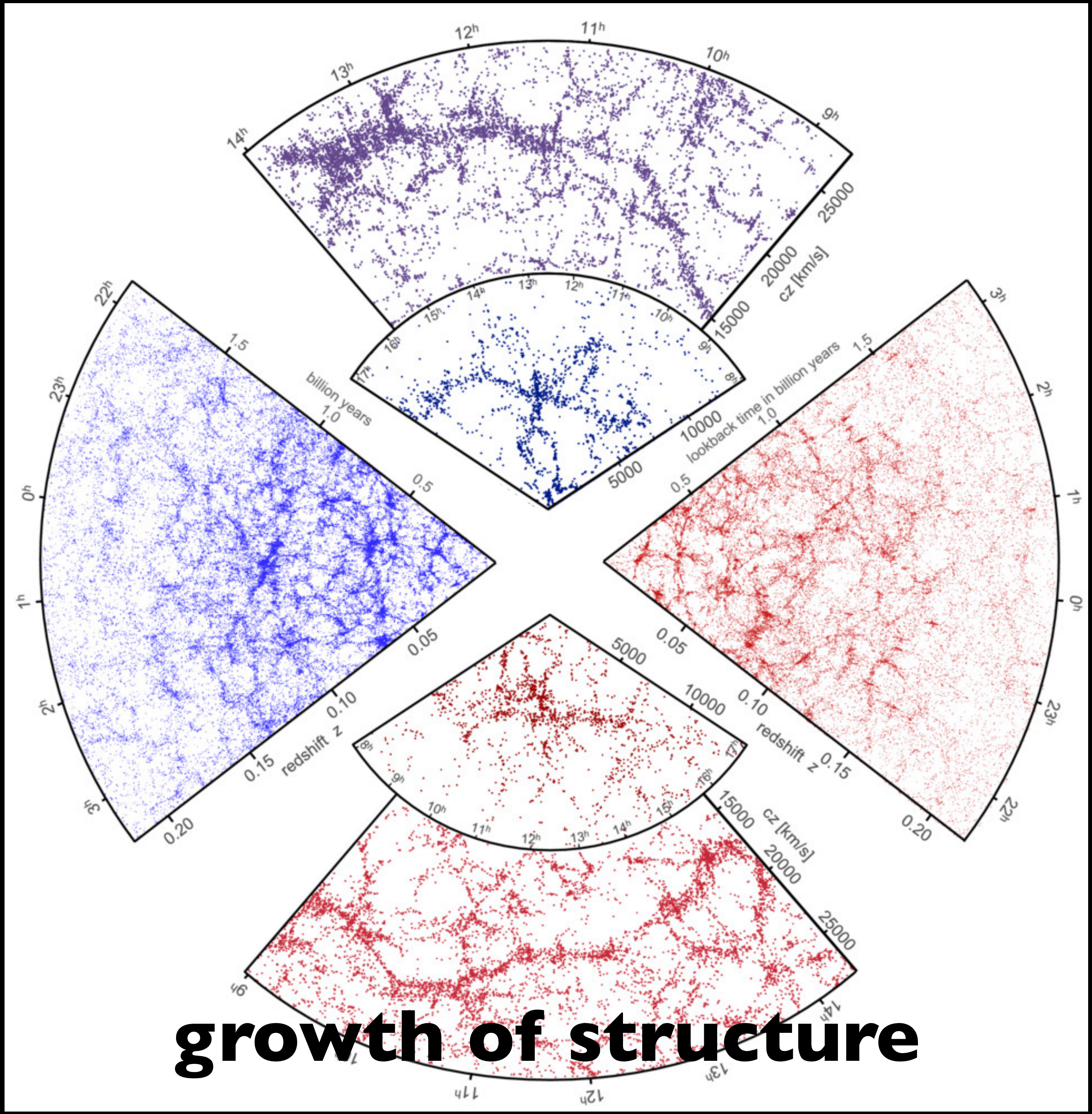


Evidence and Properties

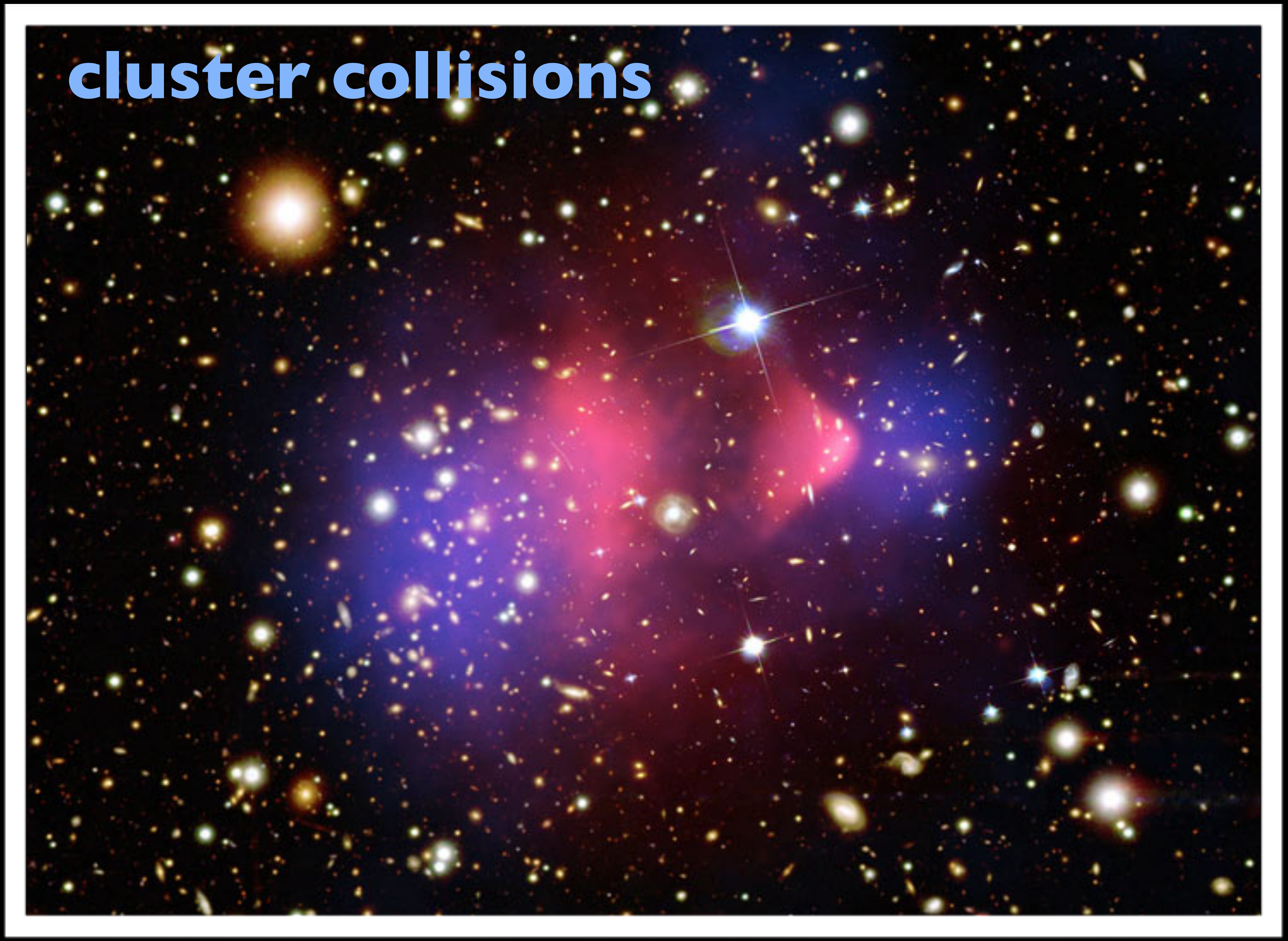
massive

ubiquitous

smooth

collisionless

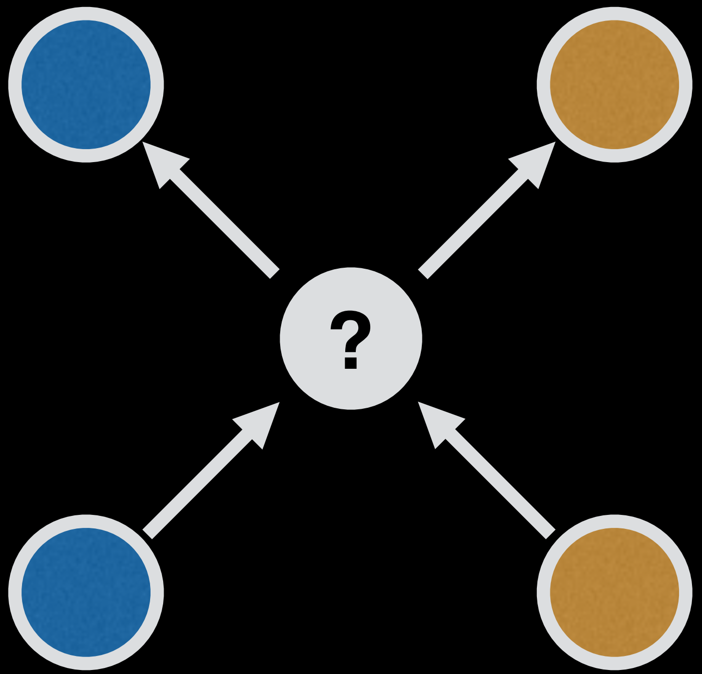
new component



Candidates (incomplete list)

- ✦ MACHOs (e.g., primordial black holes)
  - Mack, Ostriker & Ricotti 2007, Ricotti, Ostriker & Mack 2008, Mack & Wesley 2008
- ✦ Axions/axion-like particles
  - Mack & Steinhardt 2011, Mack 2011
- ✦ **W**eakly **I**nteracting **M**assive **P**articles (a.k.a., WIMPs)
  - Something not included in the Standard Model of Particle Physics

Annihilating WIMPS

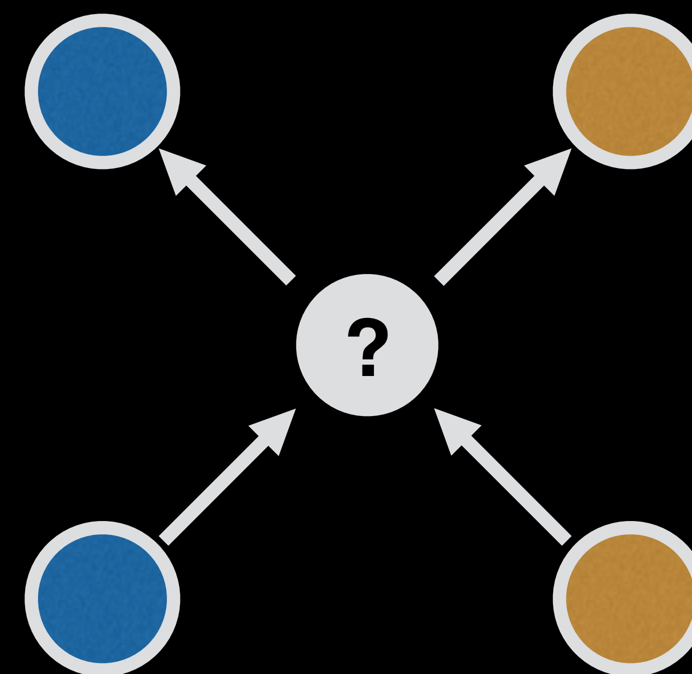


Key detection signature: WIMP annihilation

Why **annihilating** dark matter?

- Good candidates in *supersymmetry* (e.g. neutralino), *Kaluza-Klein theory* (e.g. B^1)
- Early thermal equilibrium and freeze-out gives natural production mechanism

Dark Matter: Indirect Detection



- signature: cosmic rays, gamma rays, neutrinos (annihilation products)

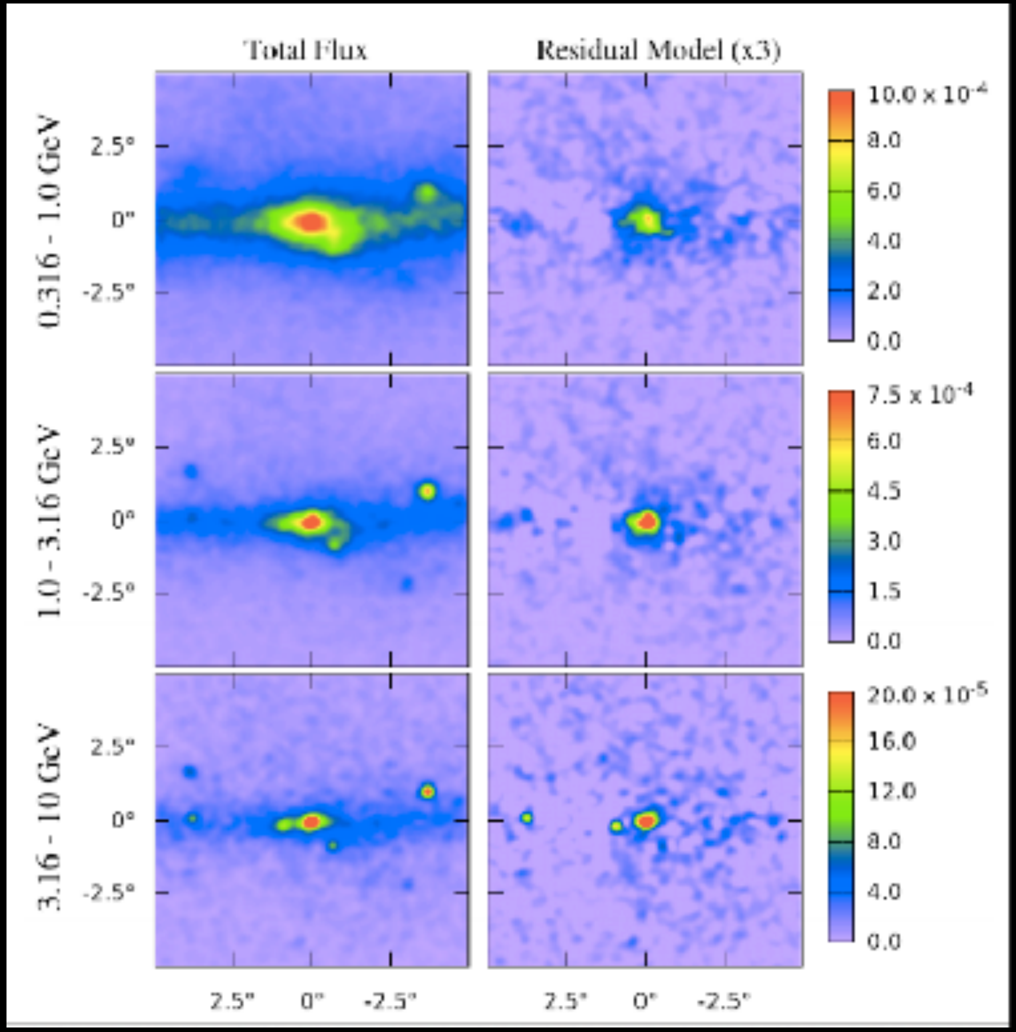
Gamma Rays

Gamma-ray excess in Galactic Center at 1-3 GeV

31-40 GeV WIMP annihilation?

In favor: **spatial distribution** looks plausible; fairly **simple WIMP model,** possible new hints seen in Andromeda

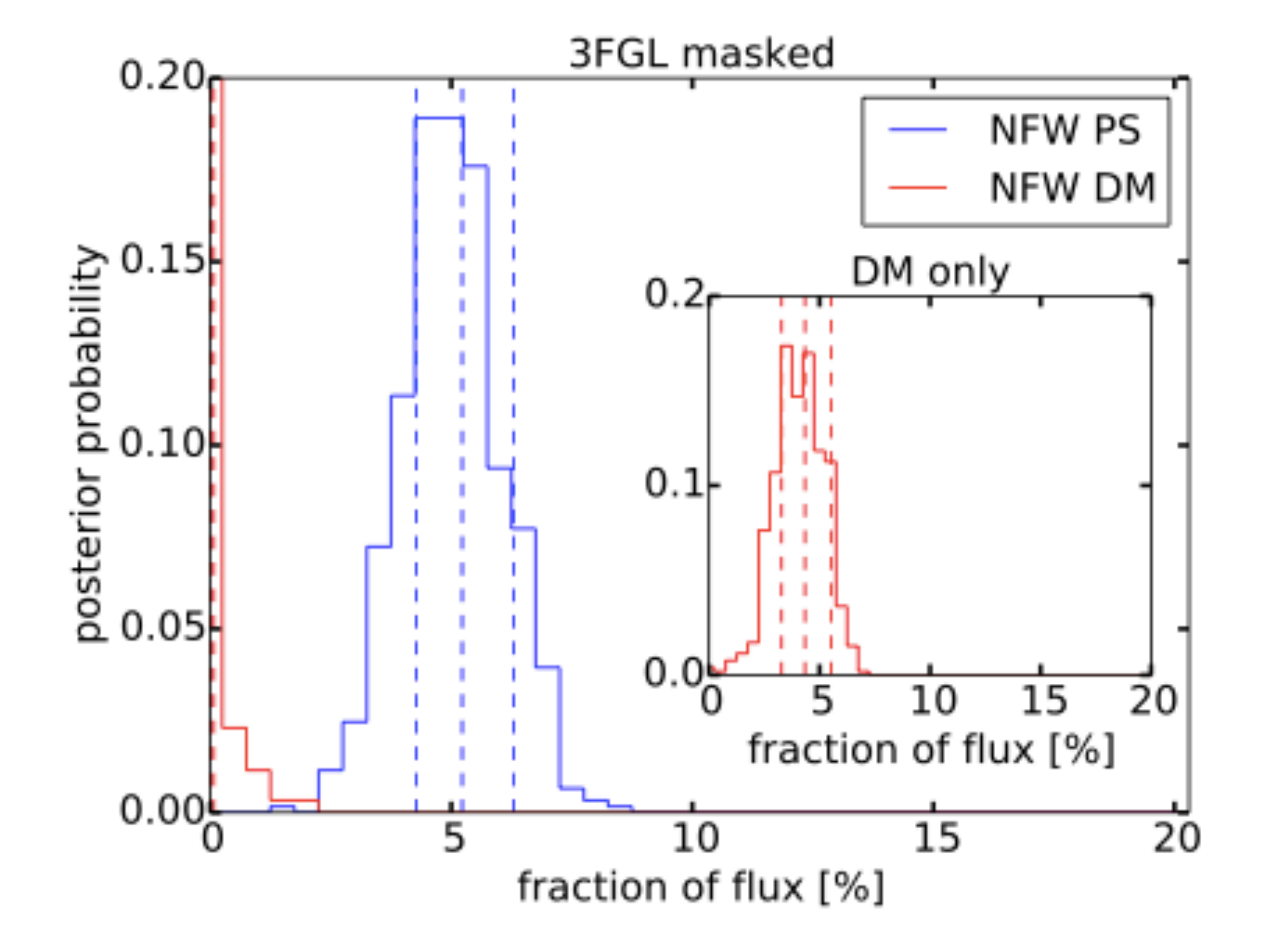
Against: Galactic Center is **messy**; **complicated analysis**; statistics favor **point sources** (Lee et al. 2015)



Daylan et al. 2014

Gamma Rays

However: Statistical distribution appears to be more consistent with point sources (probably pulsars)



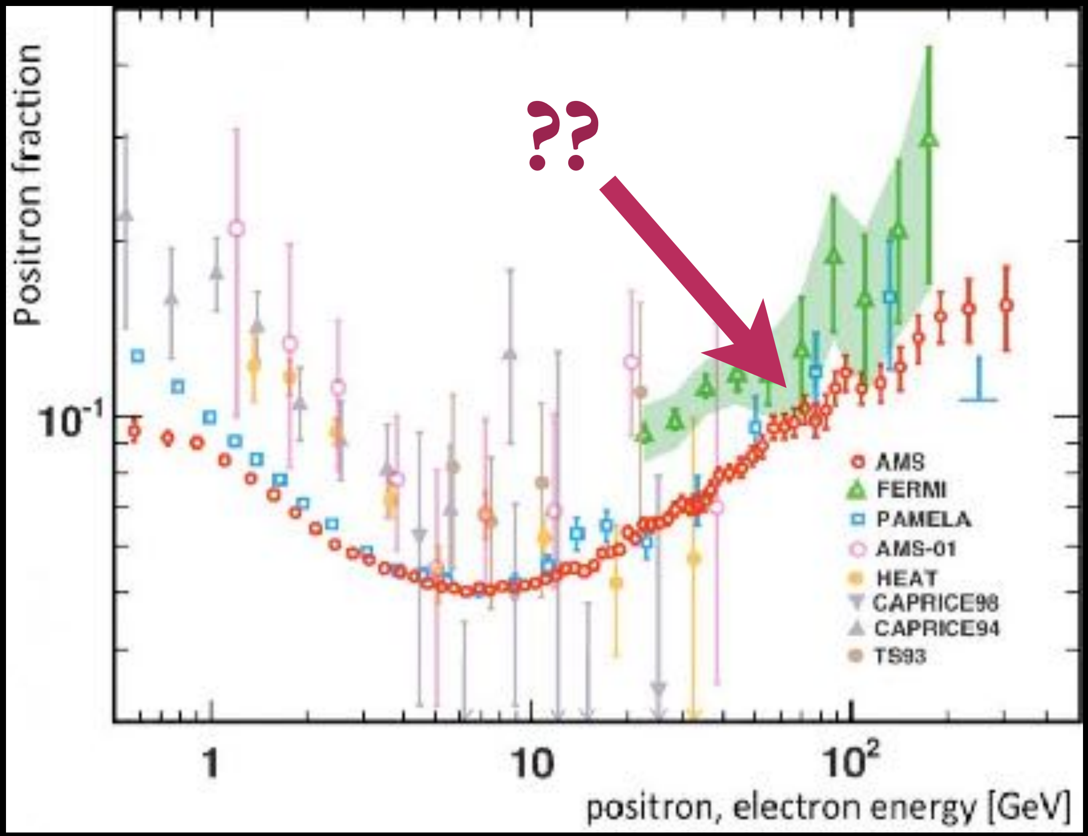
Lee et al. 2015

Cosmic Rays

Image credit: PAMELA Collaboration

Image credit: NASA

PAMELA and the **AMS instrument** (and several others) saw an excess of positrons in their measurements -- could it be dark matter annihilation?



3 TeV DM with **high cross-section** proposed as explanation

AMS Collaboration, 2013

Cosmic Rays

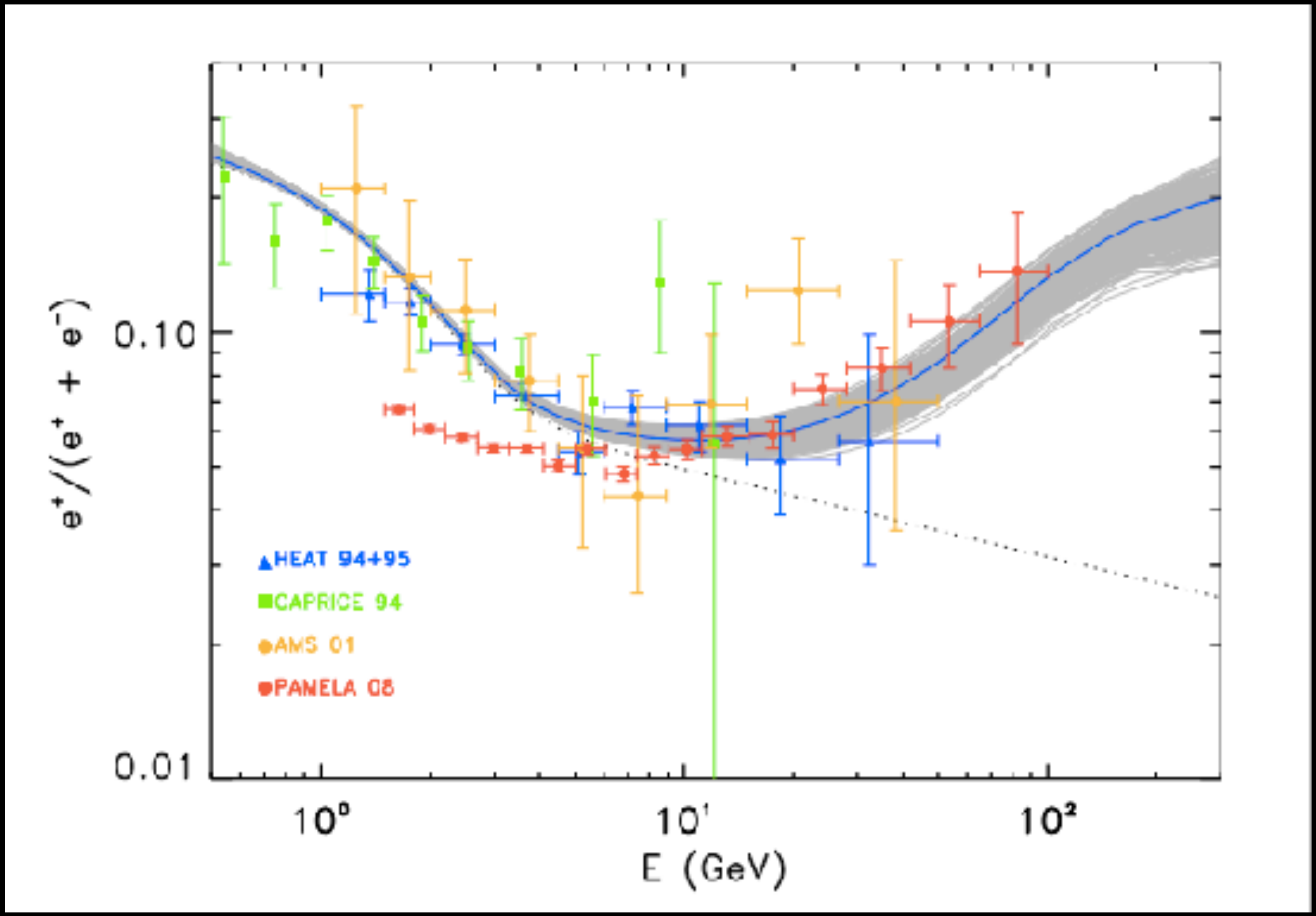
Image credit: PAMELA Collaboration

Image credit: NASA

But: **pulsars** also make electron-positron pairs

Limited **directional information**

A couple of nearby pulsars could produce entire signal

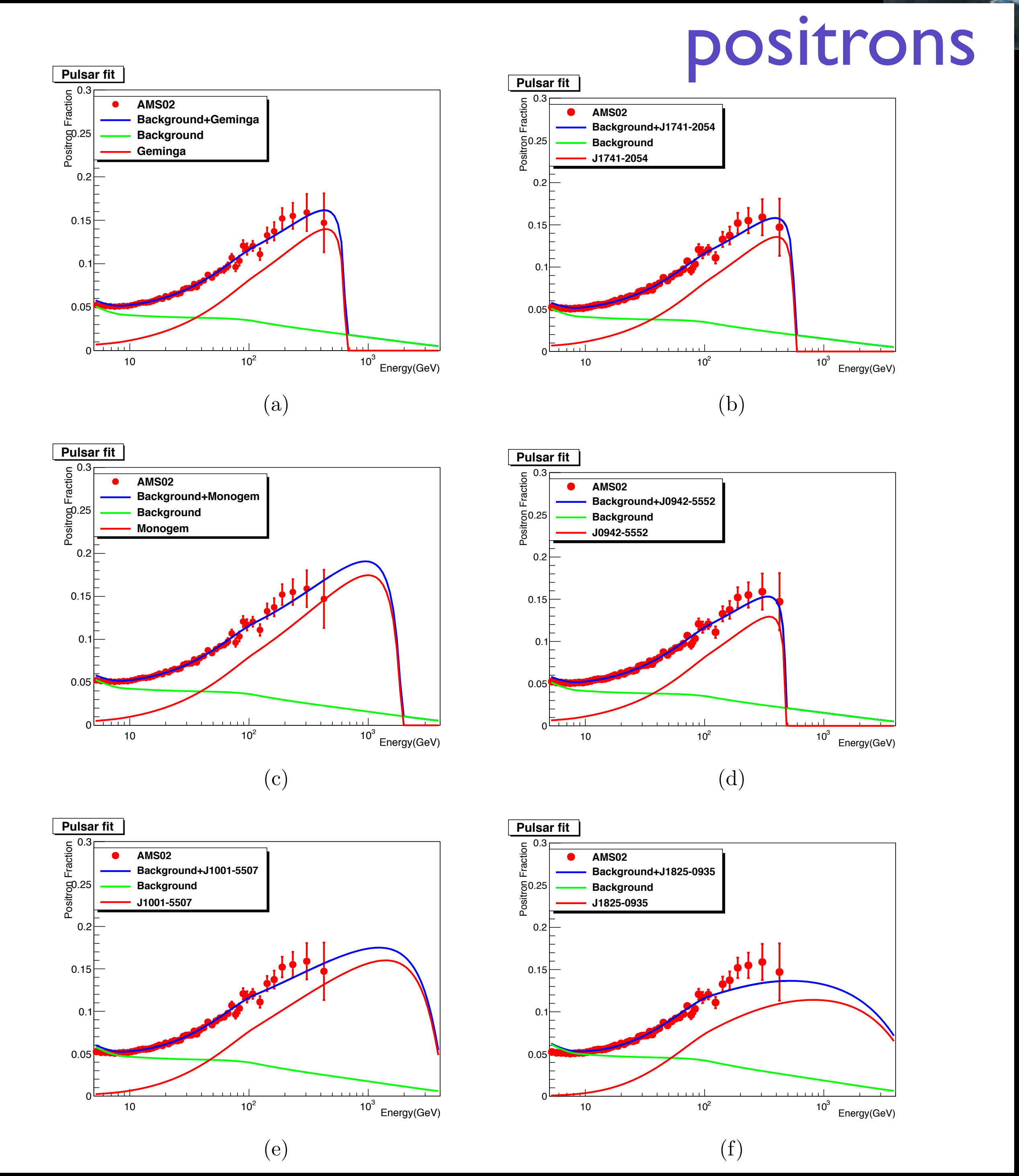


Grasso et al. 2009

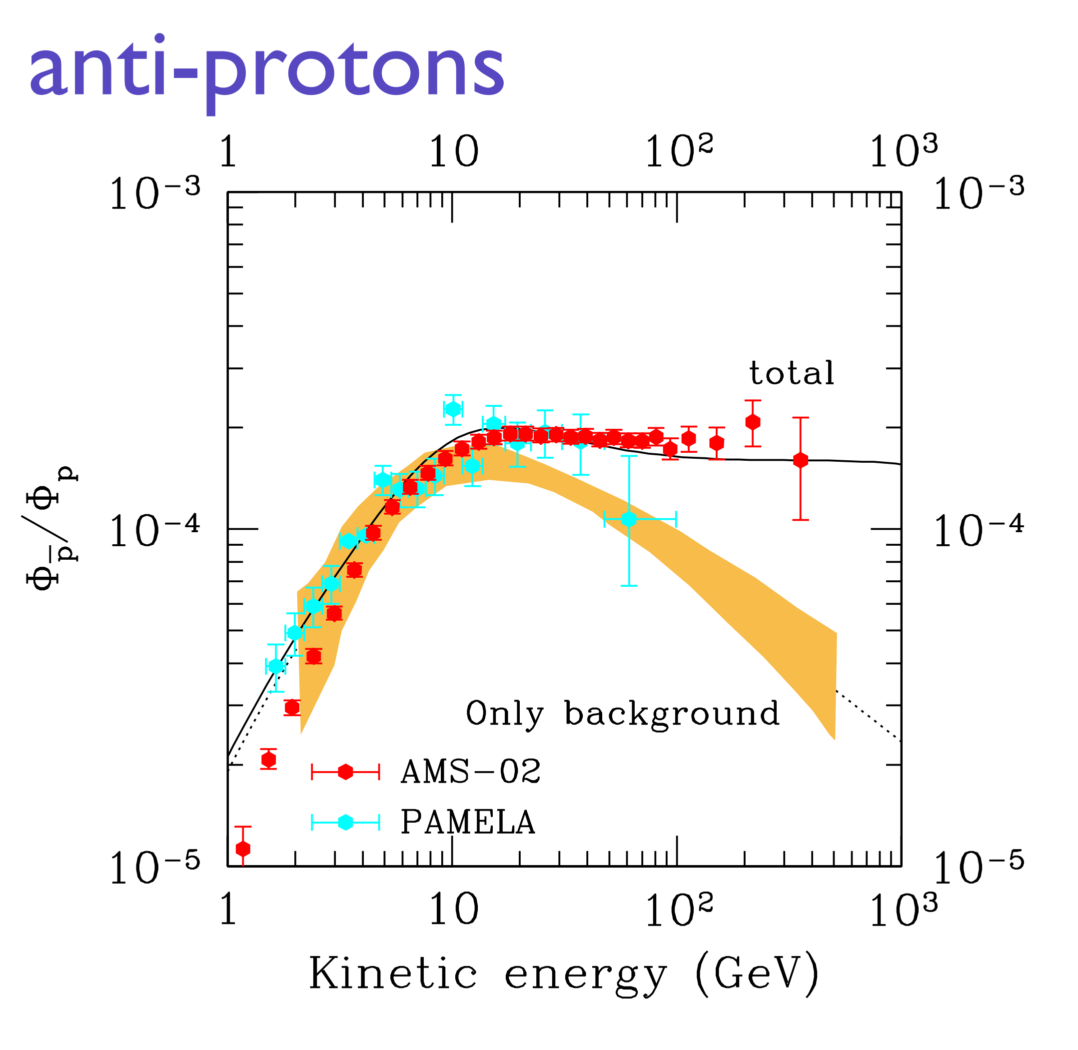
Cosmic Rays

Image credit: PAMELA Collaboration

Image credit: NASA

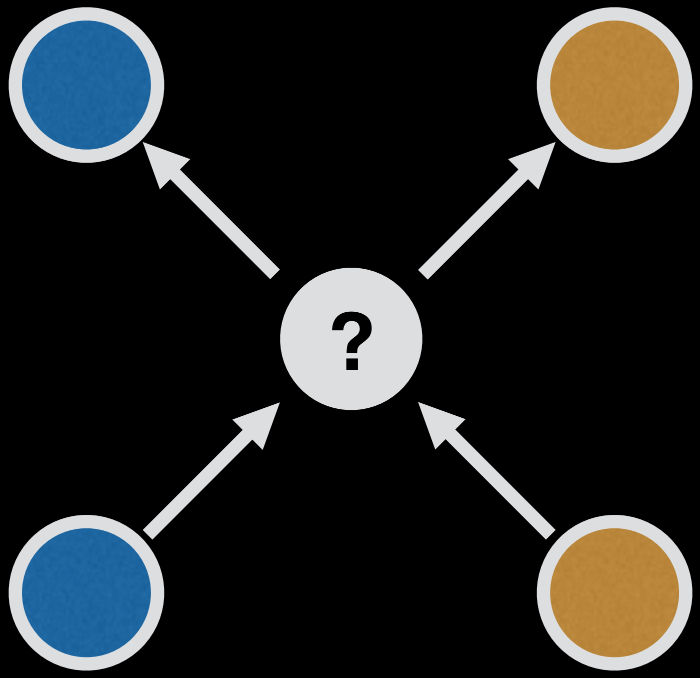


Feng & Zhang 2015



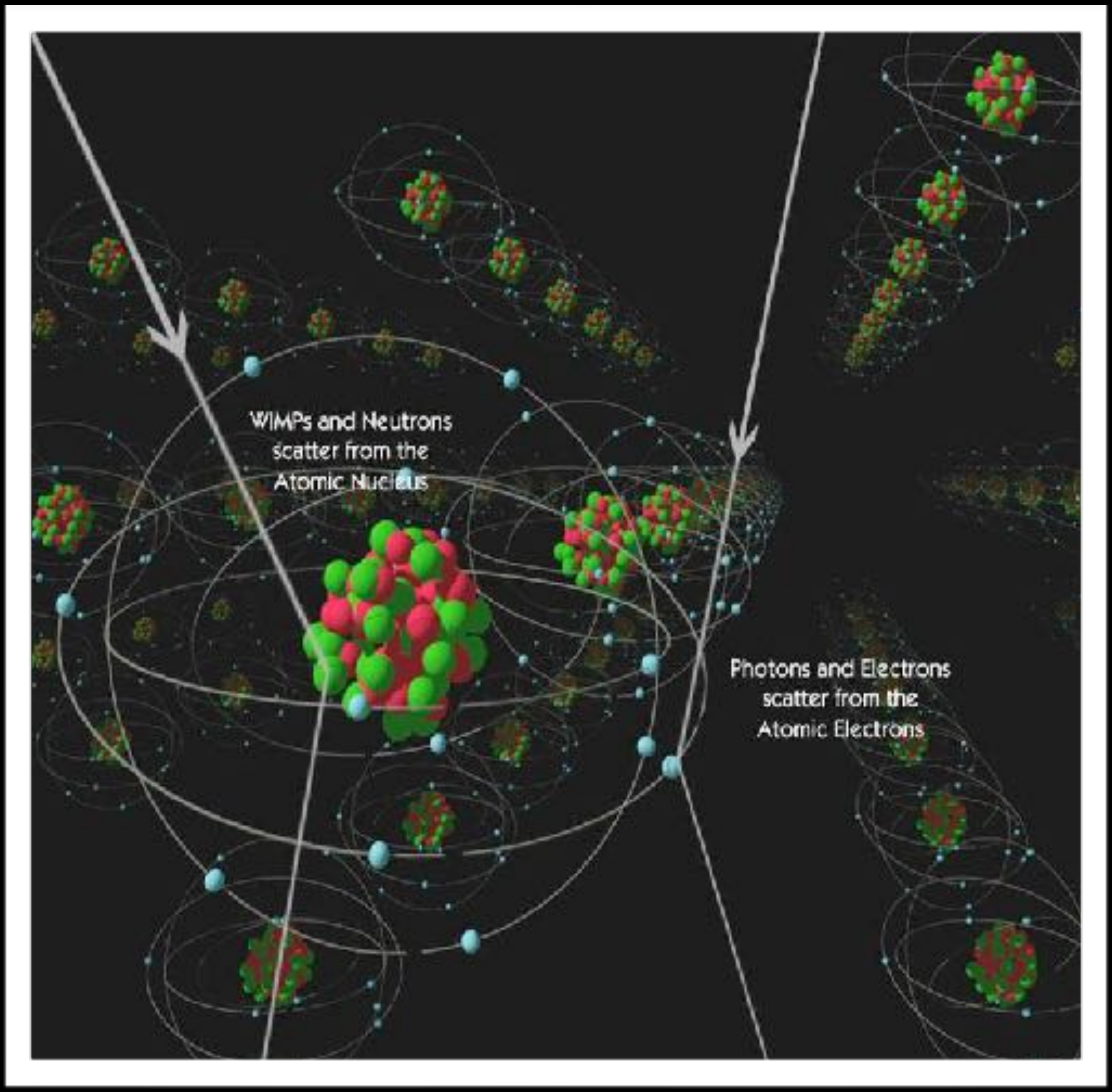
Kohri et al. 2015

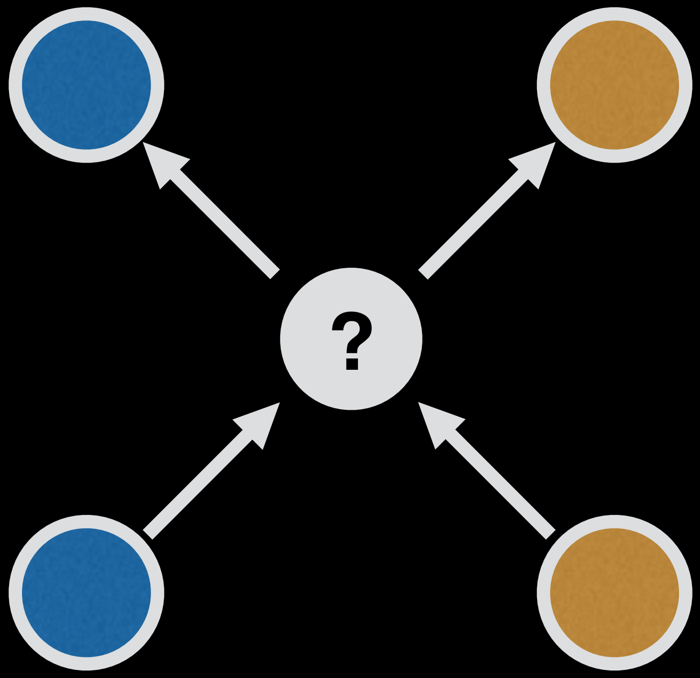
Dark Matter: Indirect Detection



- signature: cosmic rays, gamma rays, neutrinos (annihilation products)
- results: inconclusive
- the future: giant cosmic ray array (CTA), high-resolution gamma-ray astronomy

Dark Matter: Direct Detection

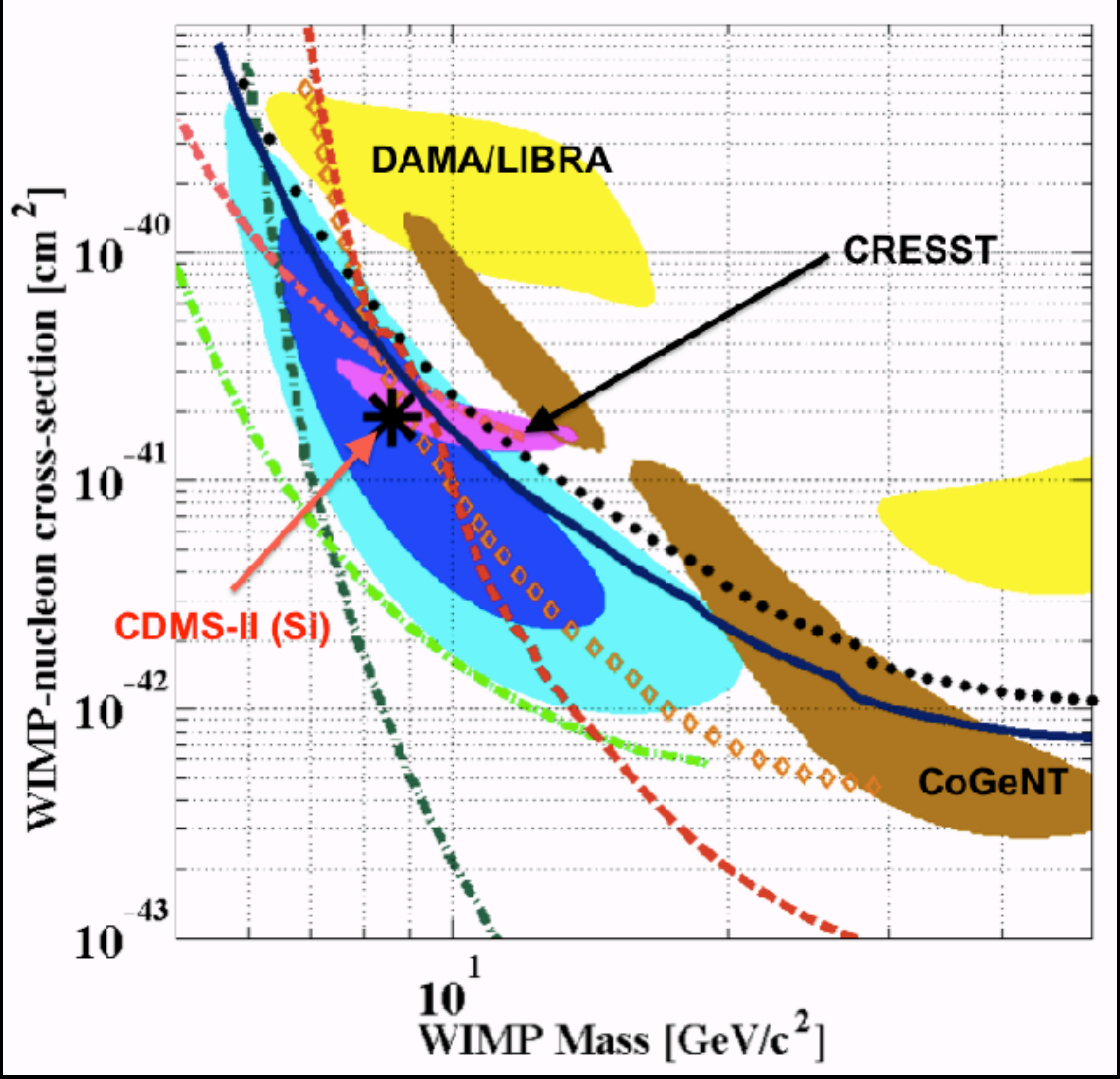




- signature: nuclear recoil

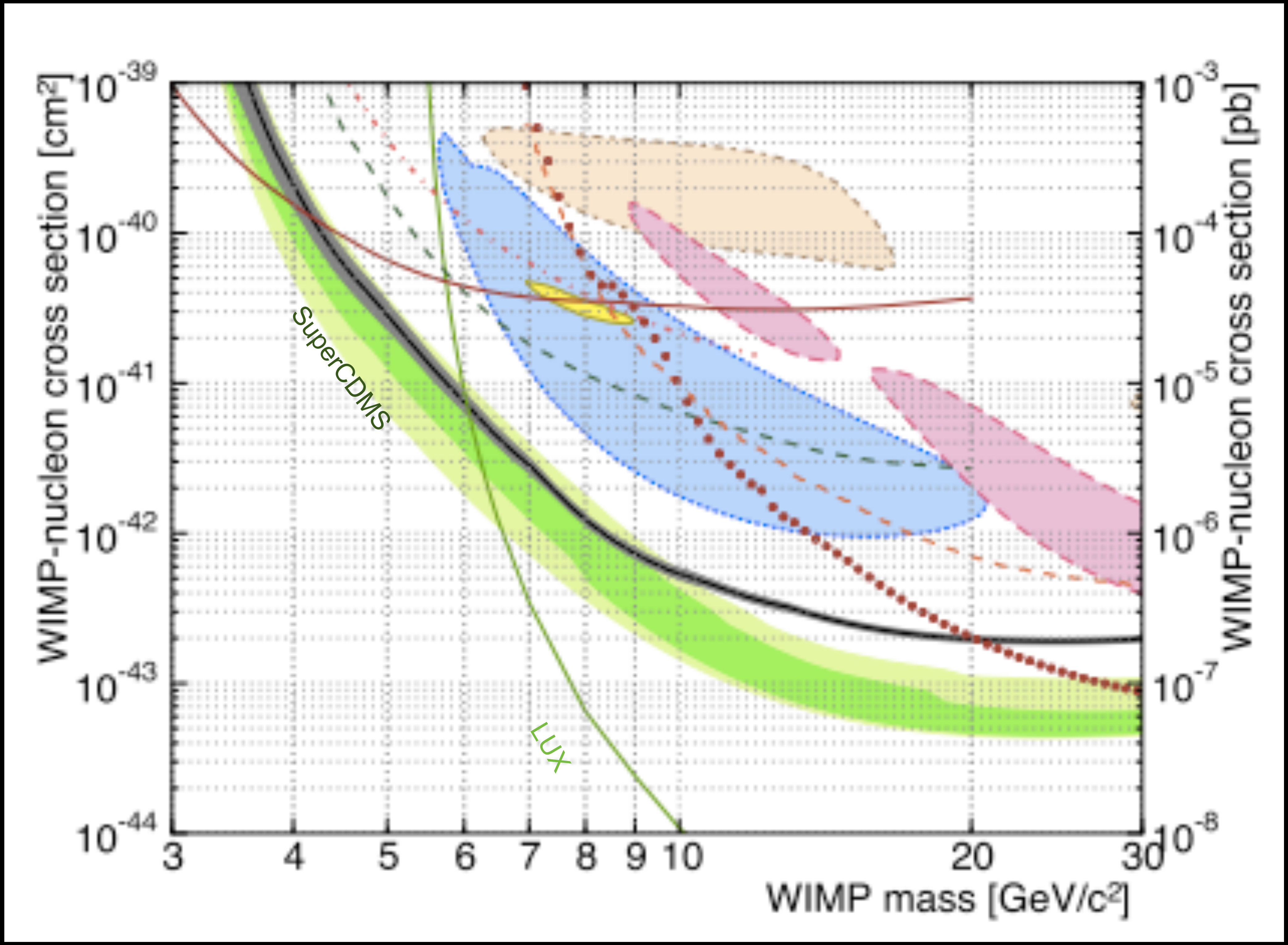
Image credit: UC Berkeley

Direct Detection



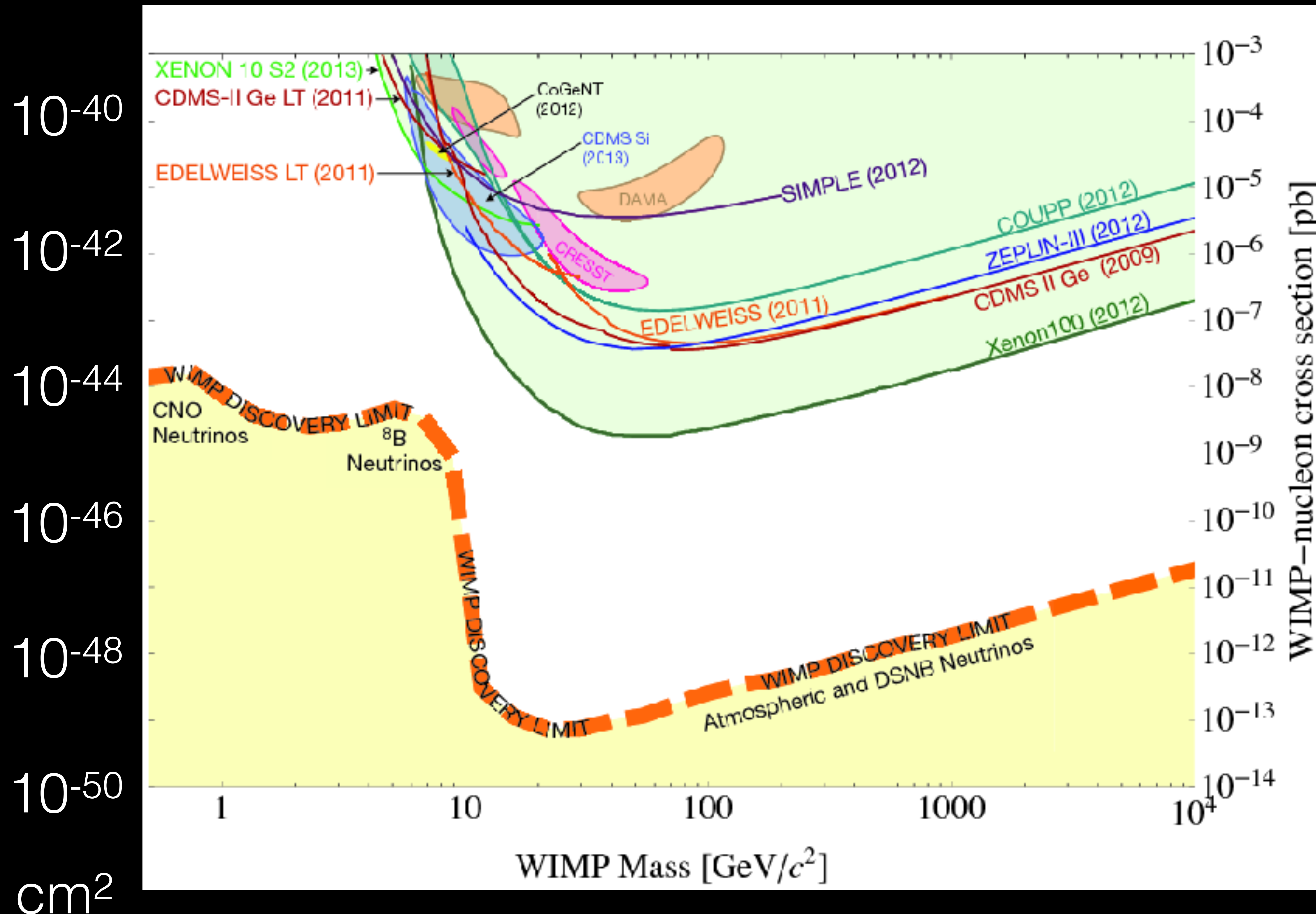
CDMS Collaboration, 2013

Direct Detection



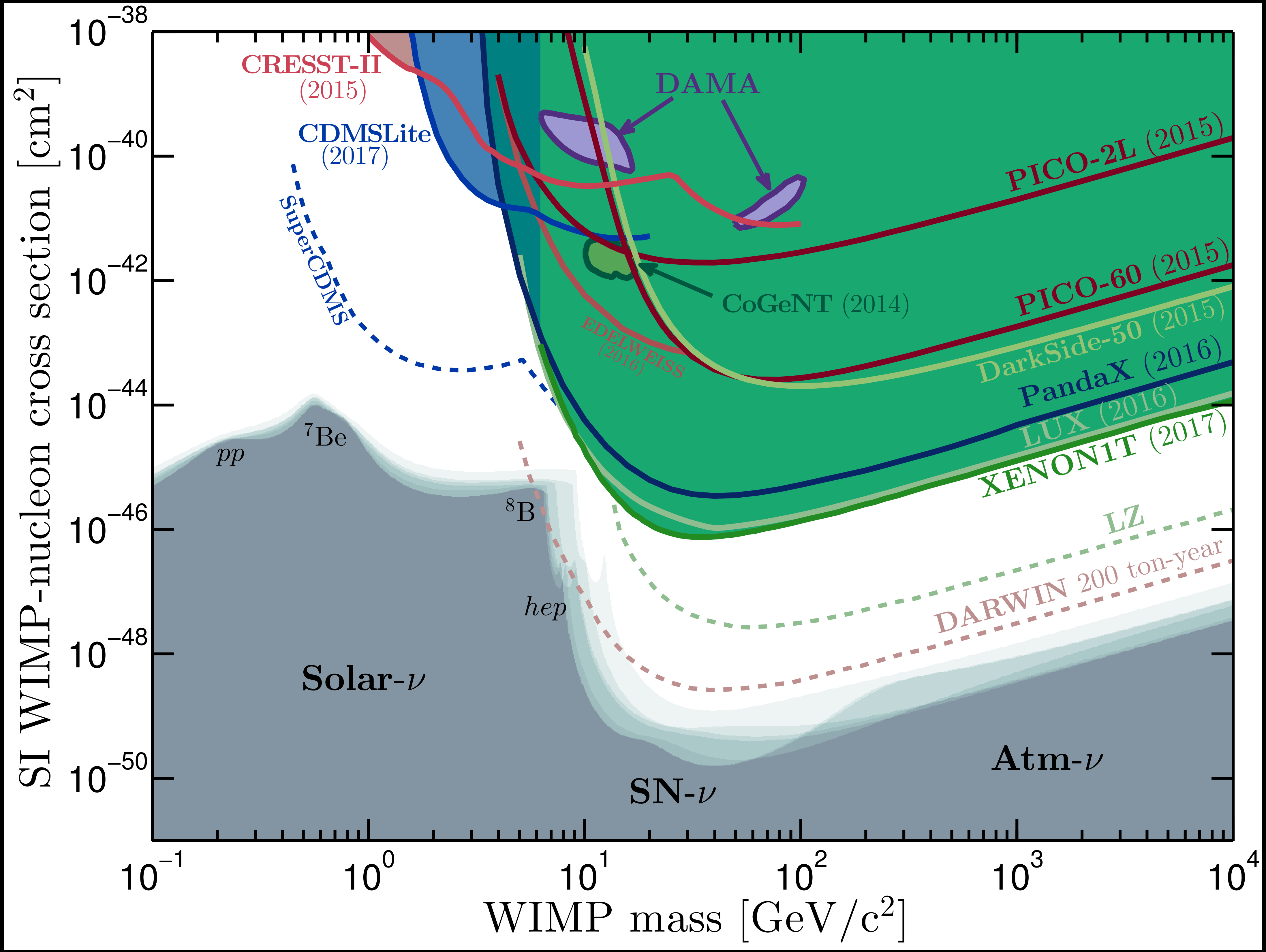
SuperCDMS Collaboration, 2014

Neutrino Wall



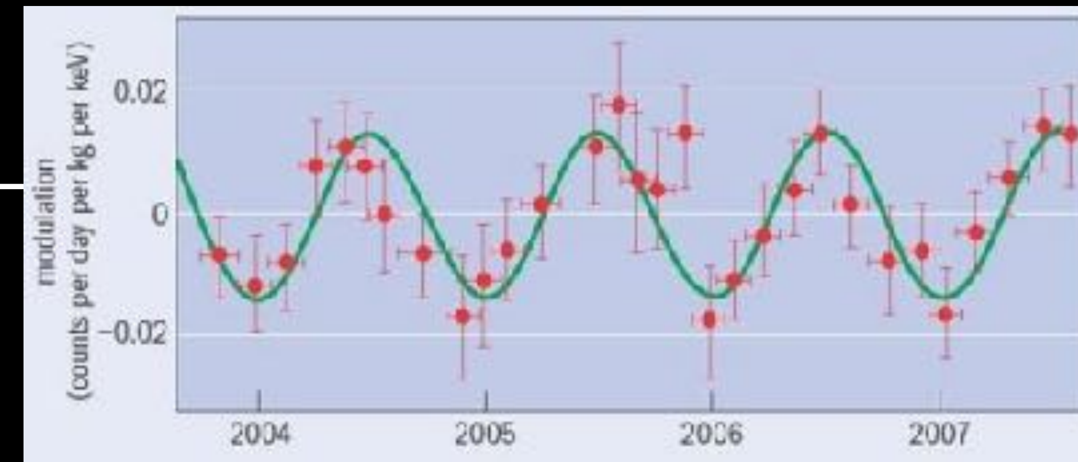
Billard et al. 2013

Neutrino Wall

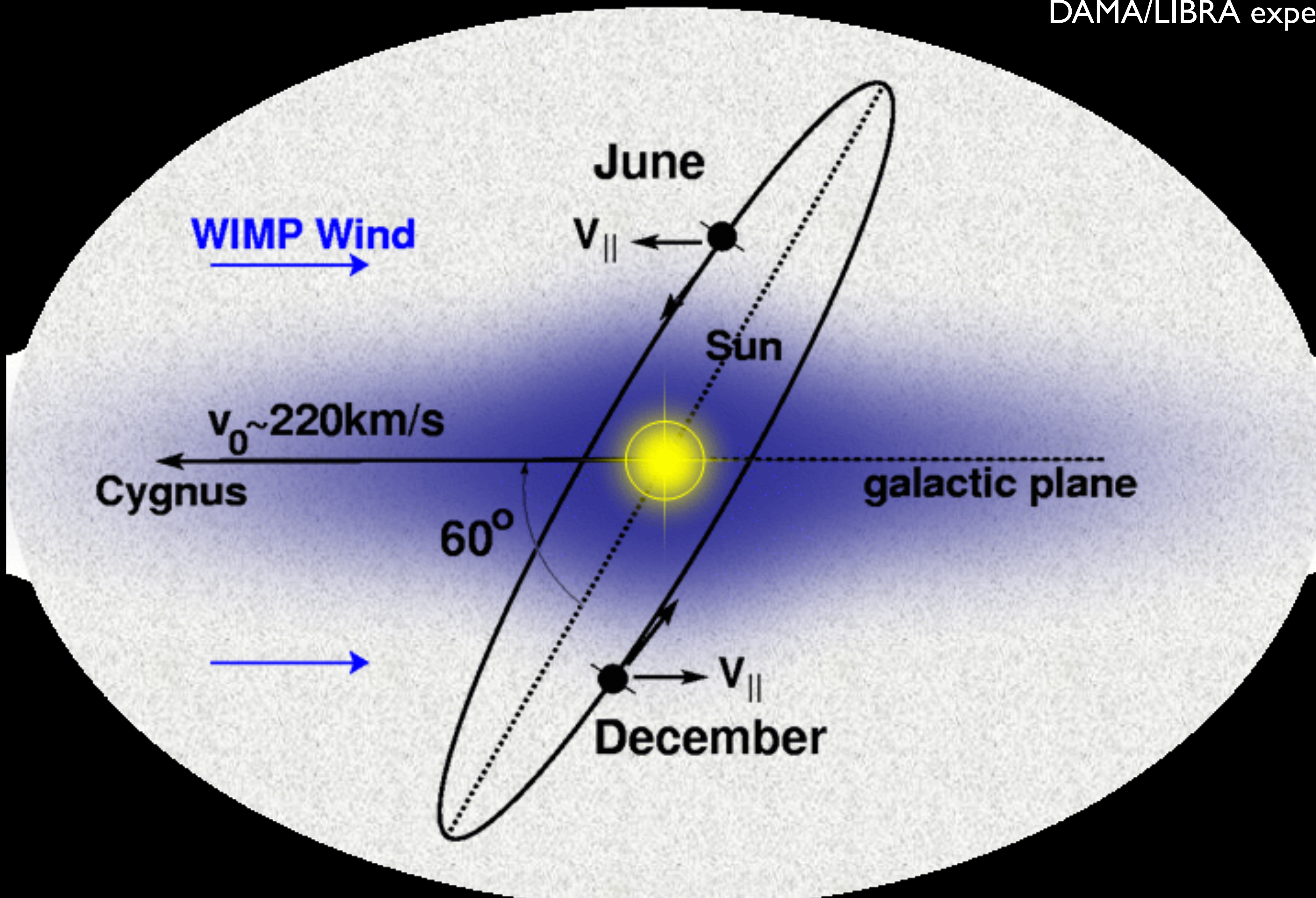


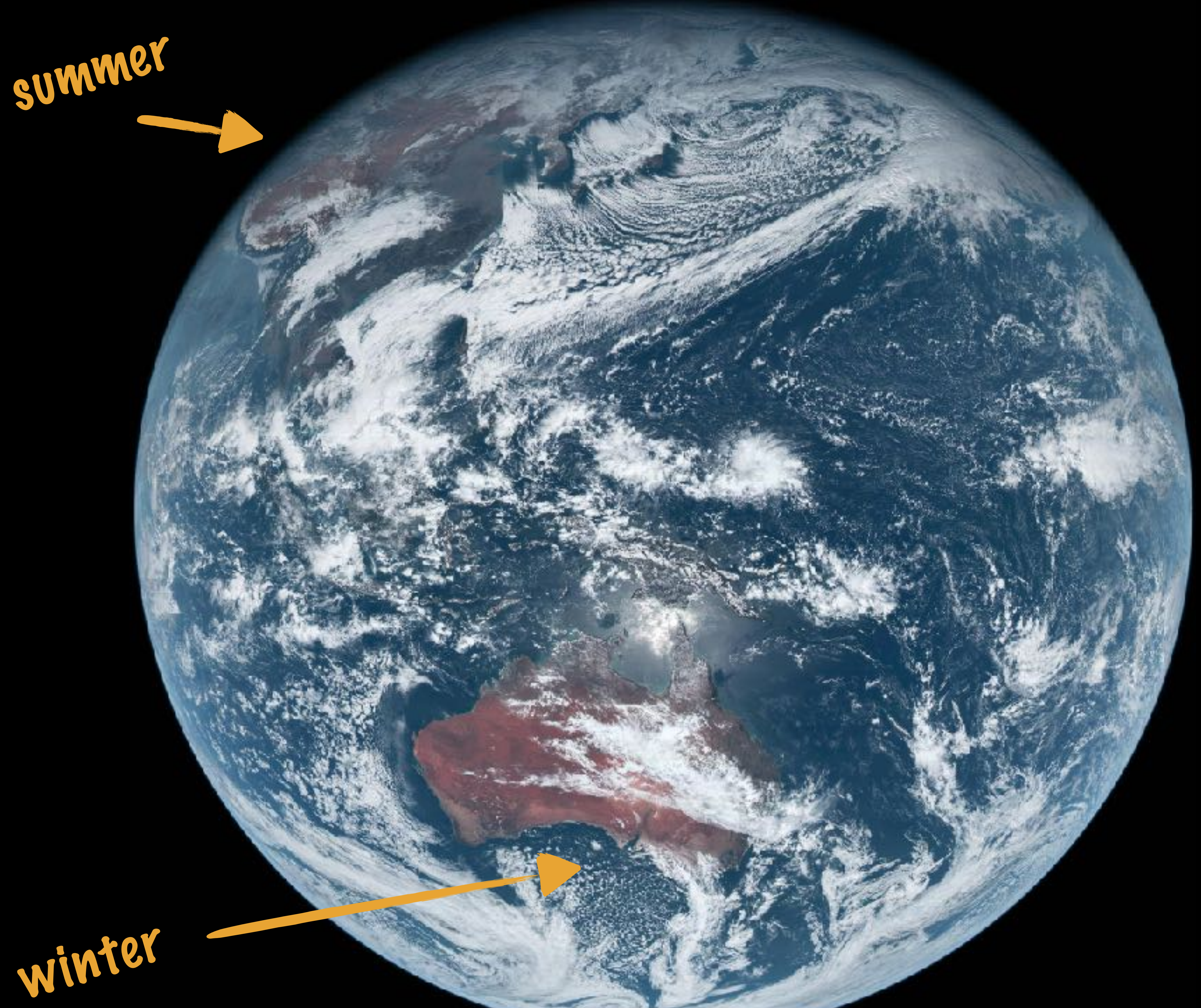
O'Hare, from paper in prep

Annual Modulation



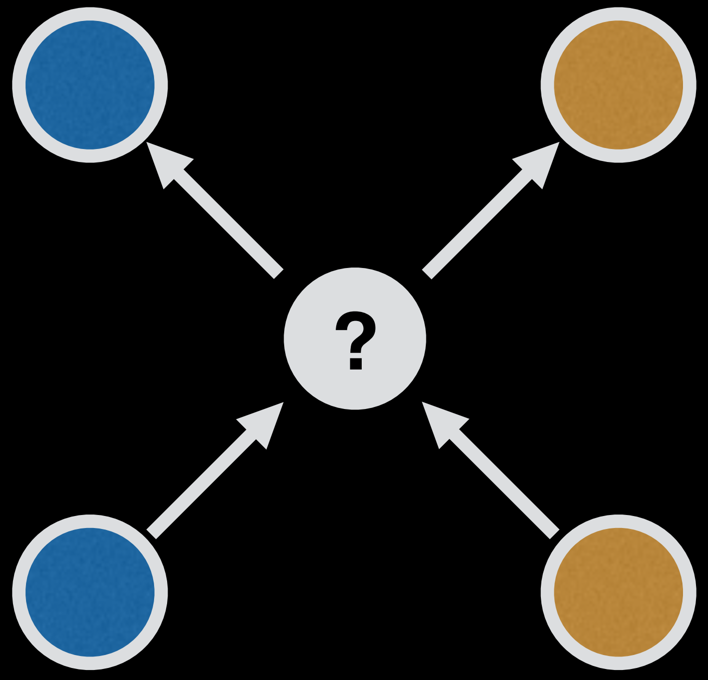
DAMA/LIBRA experiment results





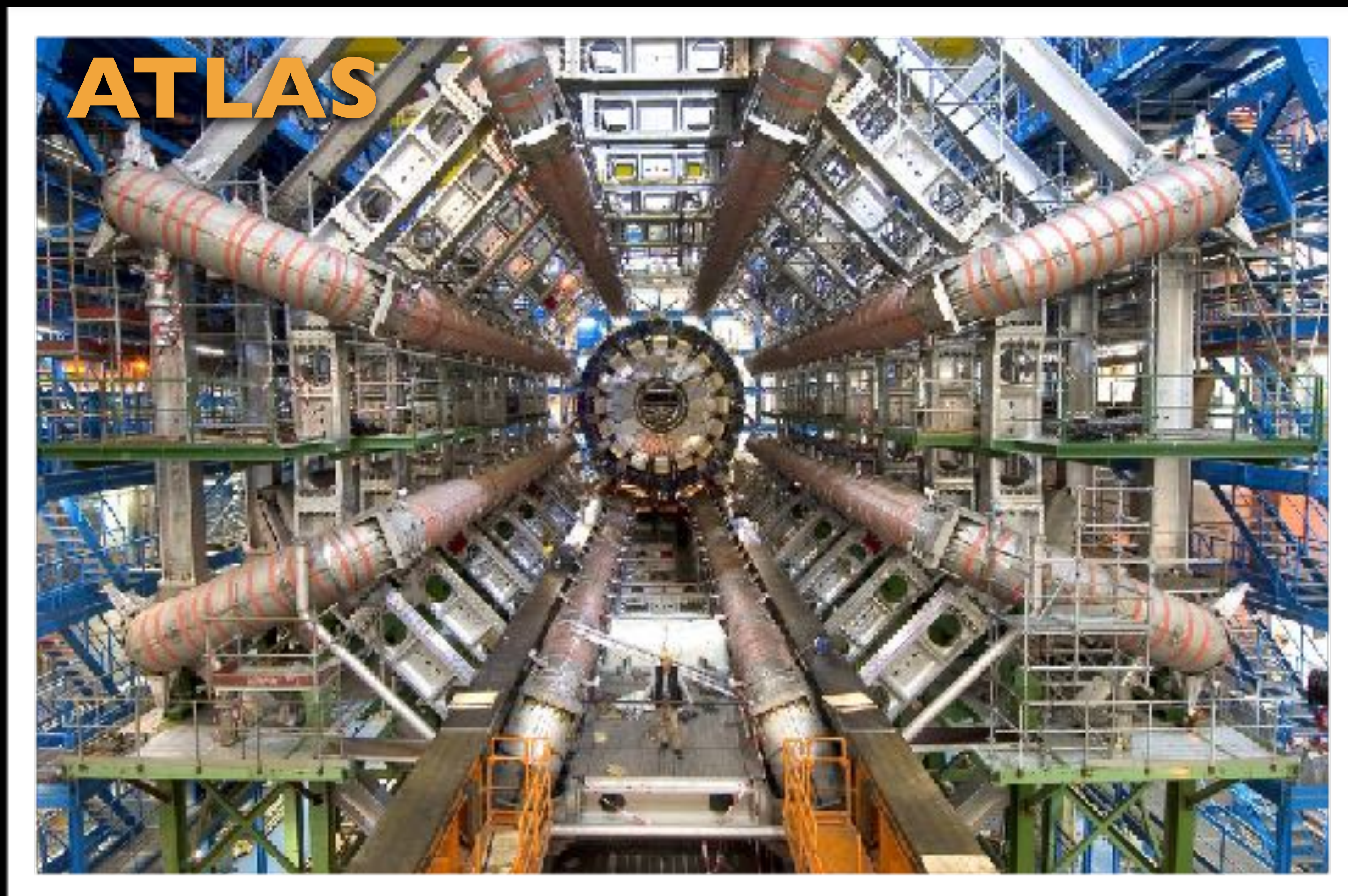
Himawari 8 satellite image

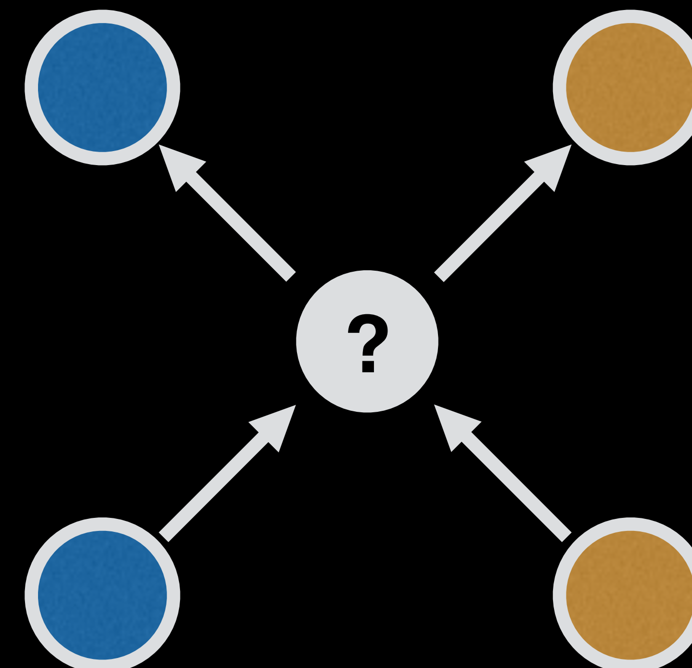
Dark Matter: Direct Detection



- signature: nuclear recoil
- results: inconclusive
- the future: SABRE, directional detection (see: CYGNUS project)

Dark Matter: Production



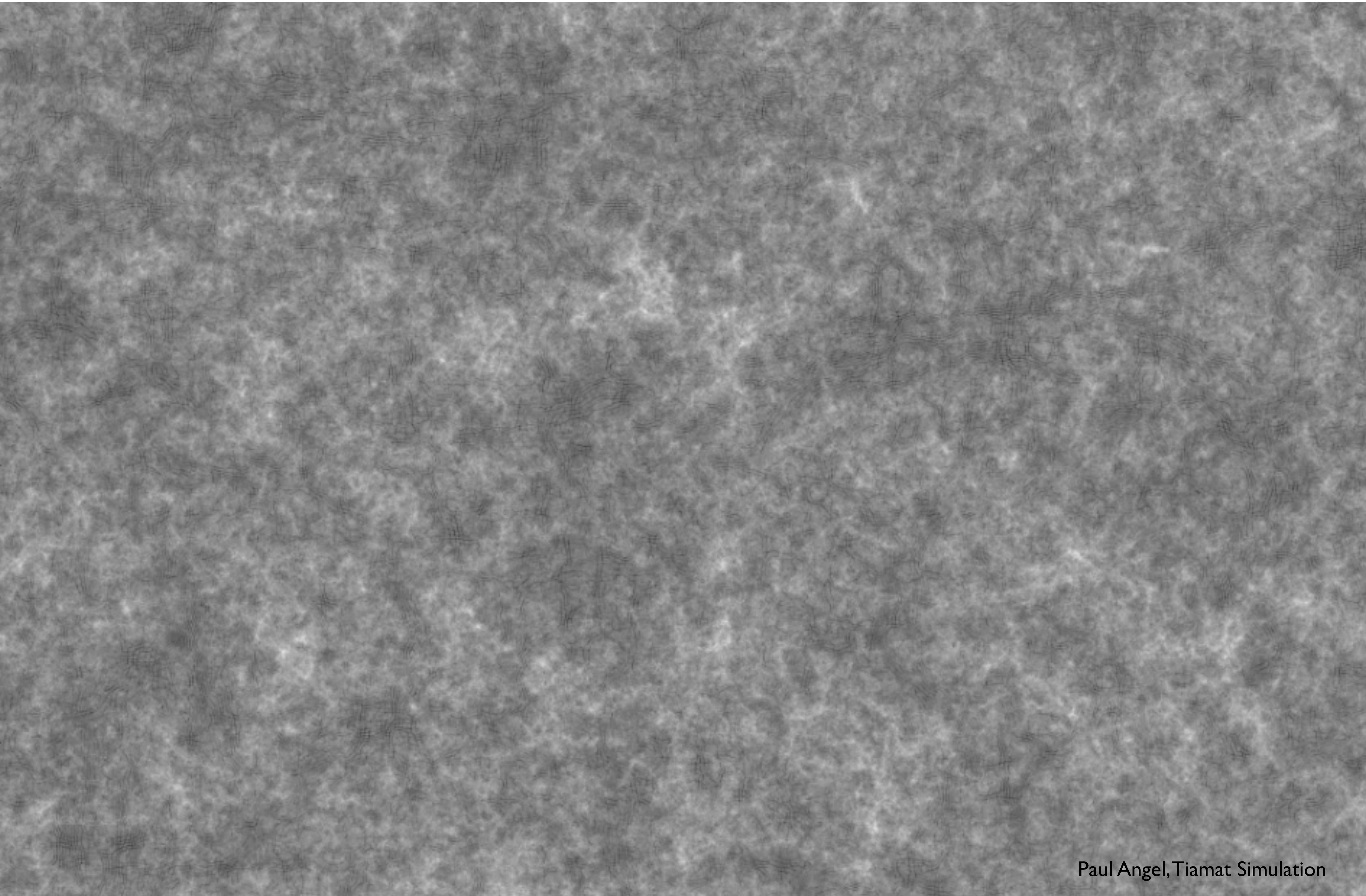


- signature: missing energy
- results: no signal (yet)
- the future: more LHC data, future colliders

Cosmological DM Signatures

- Density field
  - angular dependence of 21cm power spectrum
  - lensing (CMB, LSS)
- **Energy injection (annihilation, decay)**
- Structure formation
  - velocity offset between dark matter & baryons
- Small-scale structure and bias (warm dark matter)
- Radio counterparts (axions, annihilation)

Dark Matter: Cosmology

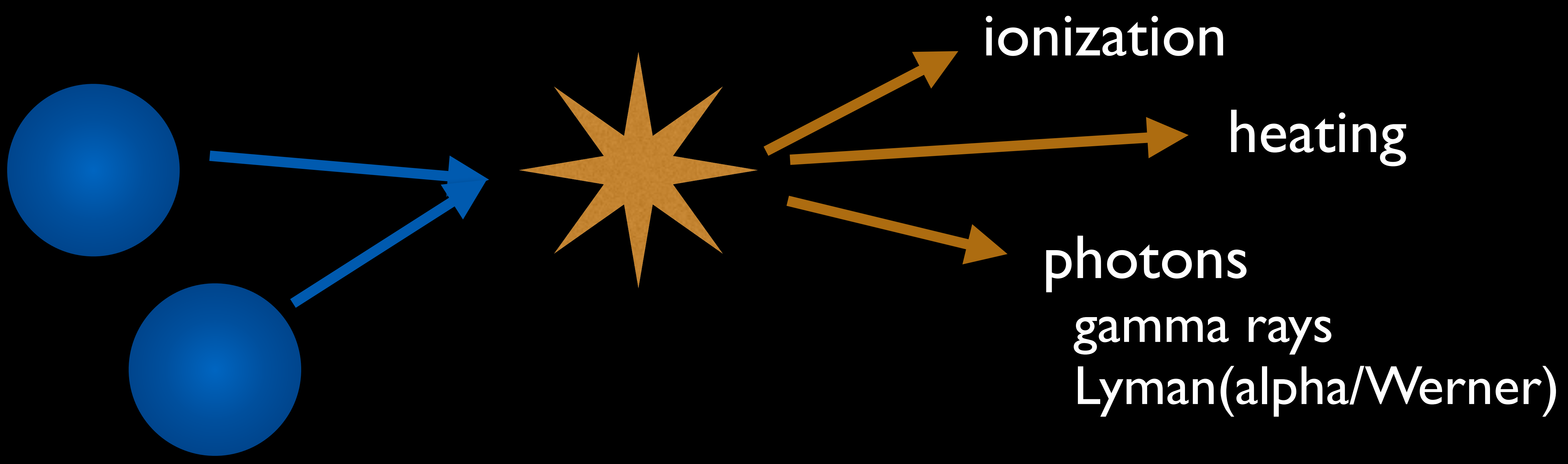


Paul Angel, Tiamat Simulation

Annihilation “Feedback”

Major unanswered question:

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



Annihilation Over Cosmic Time

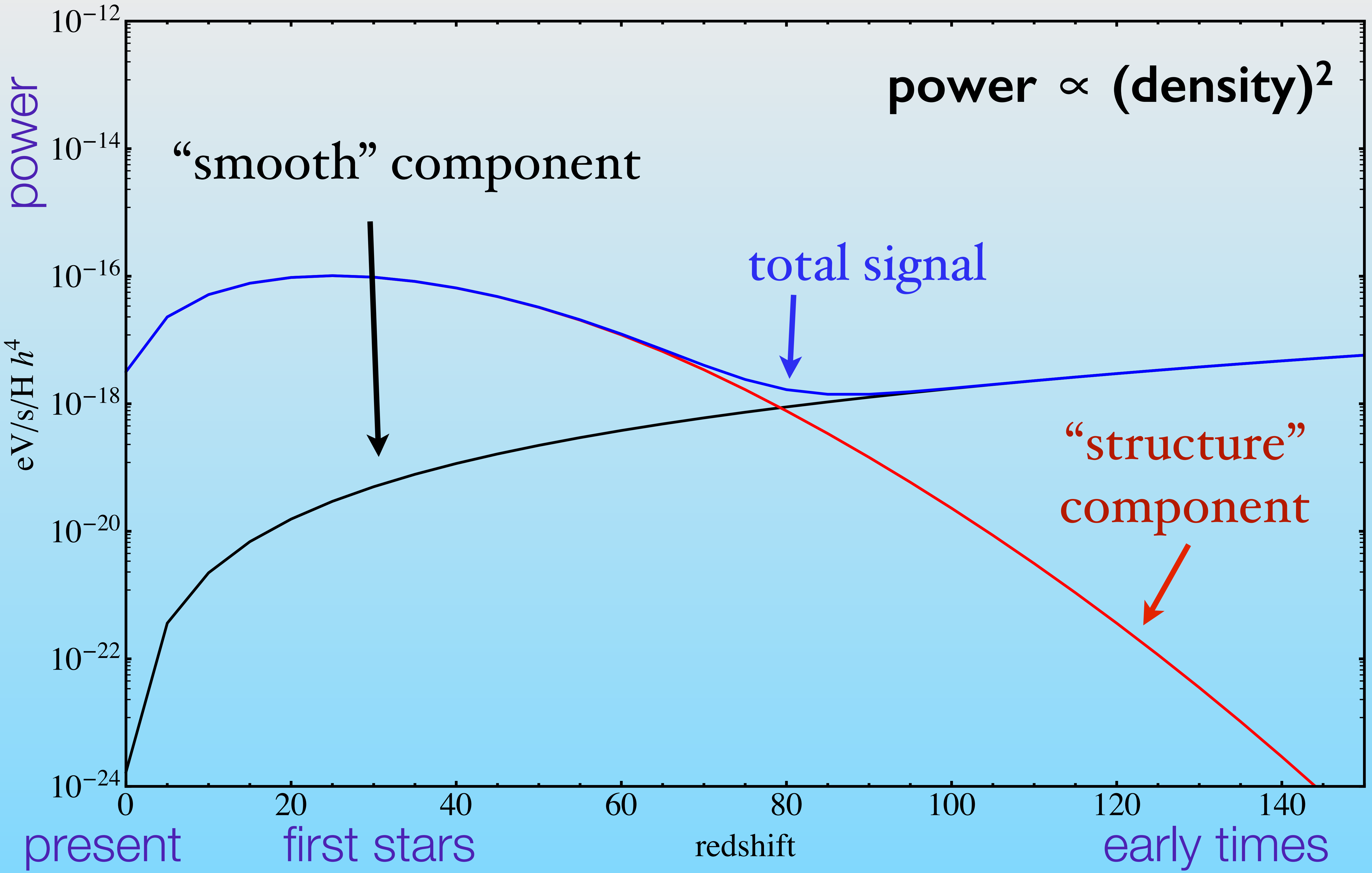
First question to ask:
When is annihilation power **strongest**?

Balance:
density of universe
(decreasing with time)
vs
growth of structure
(increasing with time)

$$\frac{\text{power}}{\text{volume}} = \frac{\langle \sigma v \rangle \rho_\chi^2}{m_\chi}$$

$\langle \sigma v \rangle$	velocity-averaged self-annihilation rate
ρ_χ	dark matter density
m_χ	dark matter particle mass

Annihilation Over Cosmic Time



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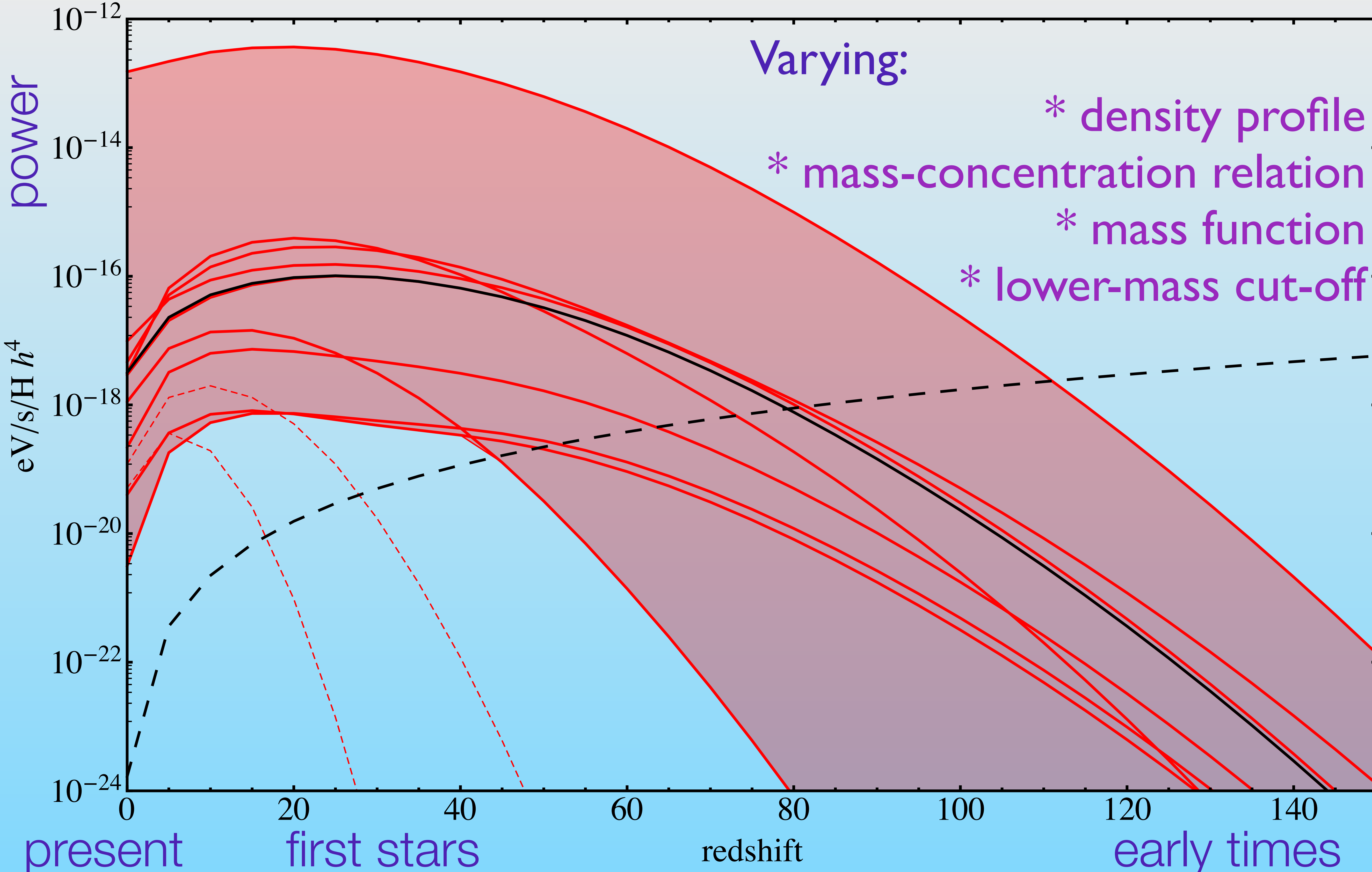
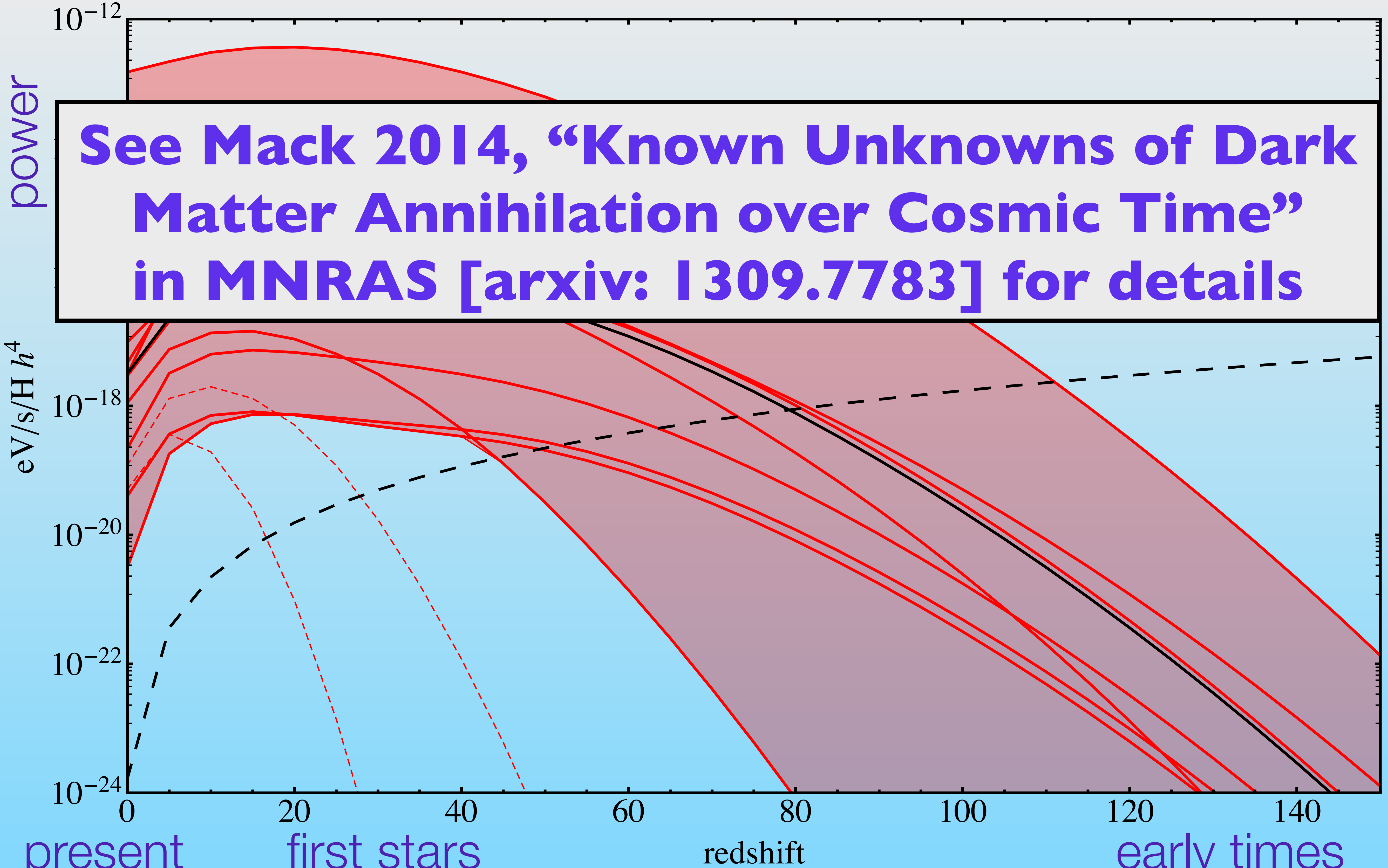
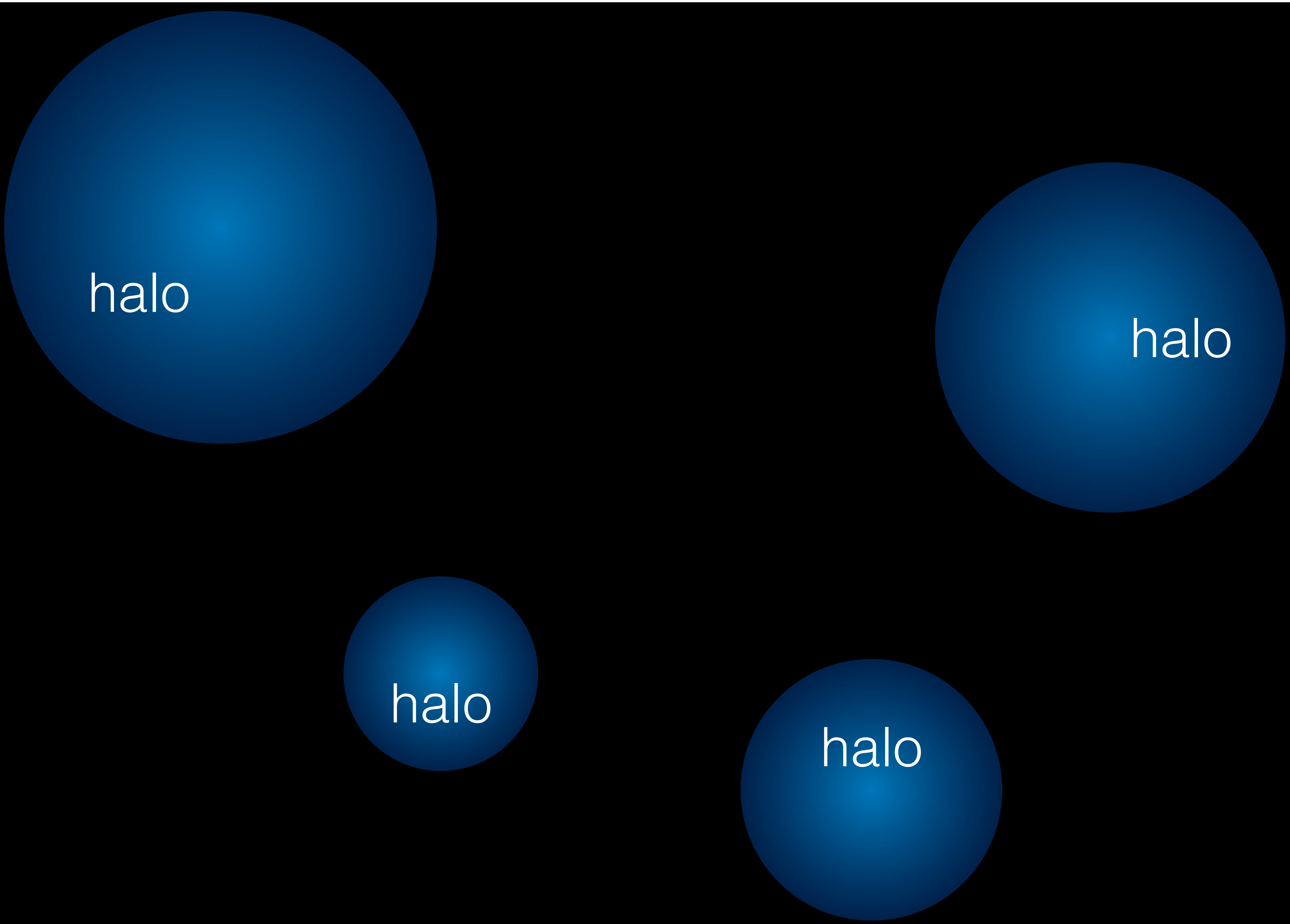


Annihilation Over Cosmic Time



See Mack 2014, "Known Unknowns of Dark Matter Annihilation over Cosmic Time" in MNRAS [arxiv: 1309.7783] for details

Annihilation in the Intergalactic Medium



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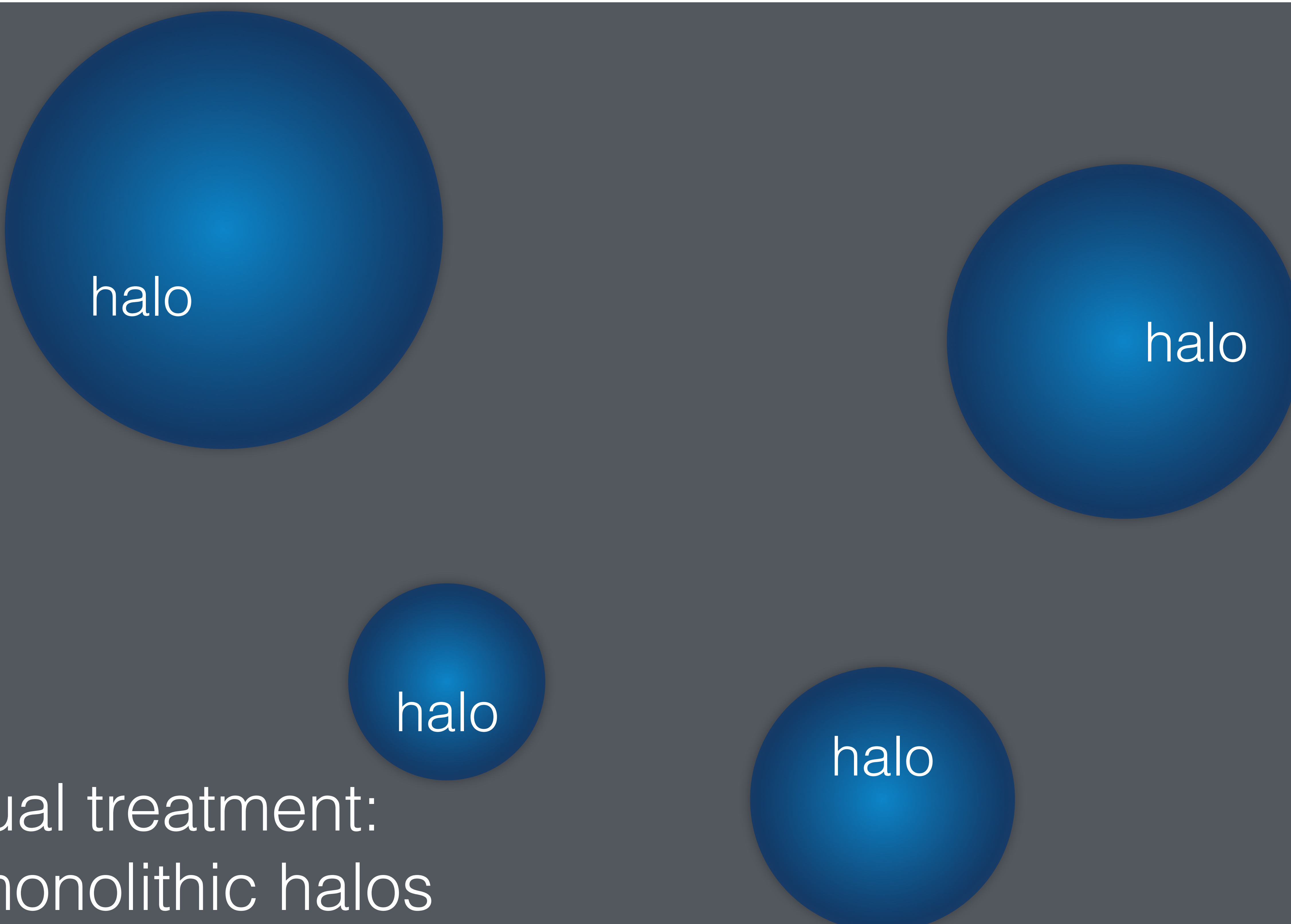
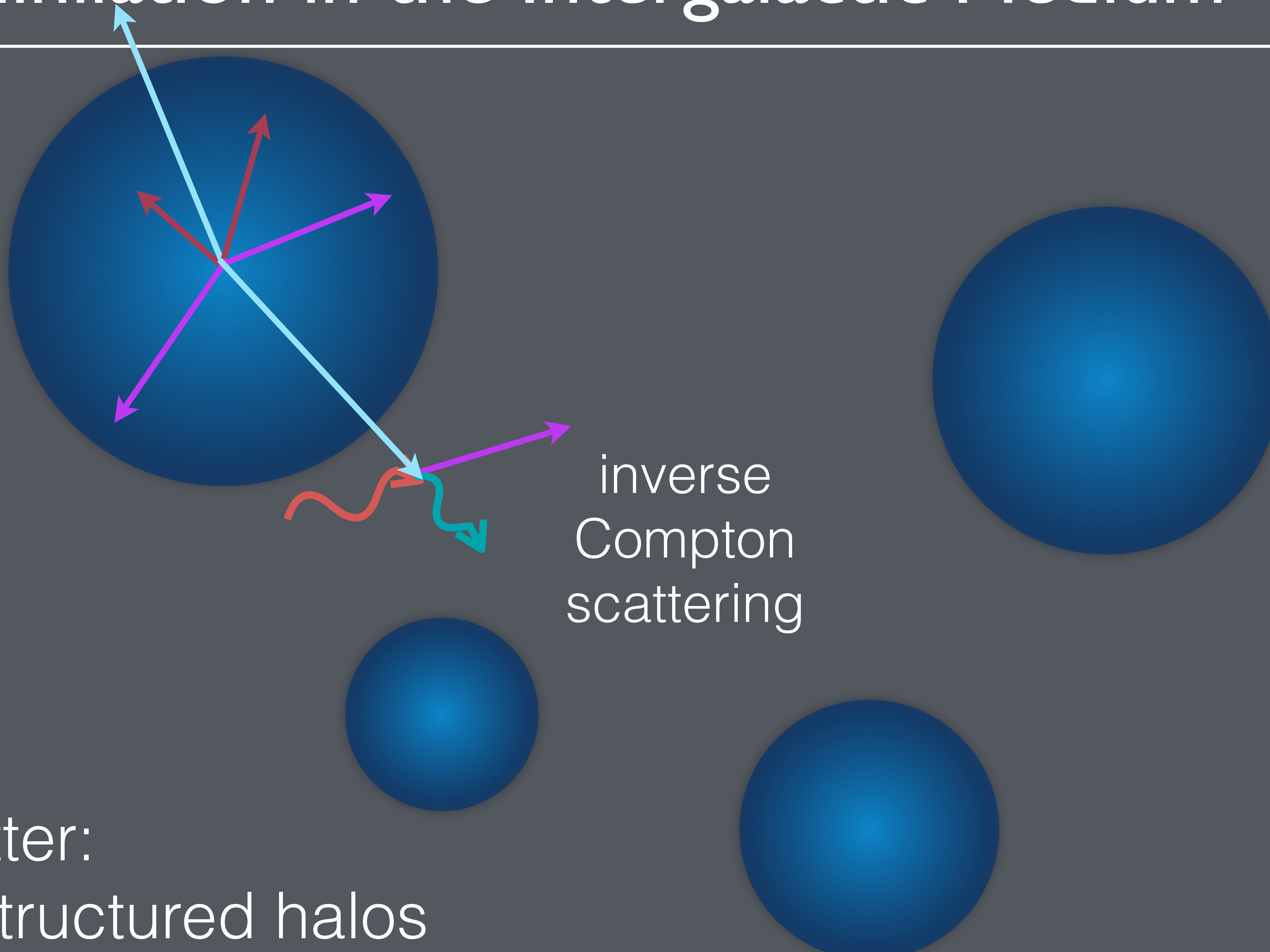


Usual treatment:

- monolithic halos
- immediate uniform energy deposition

Annihilation in the Intergalactic Medium



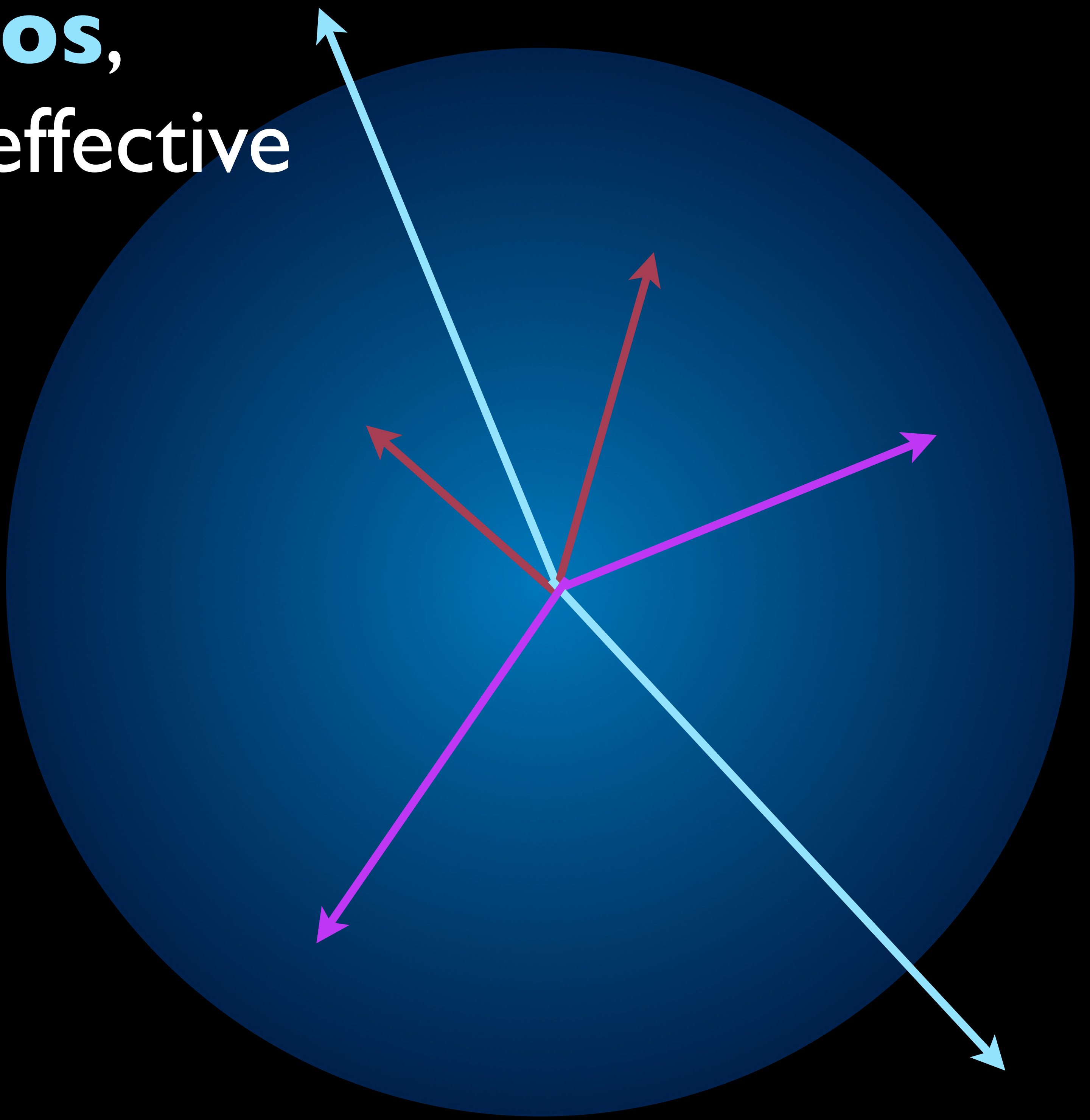
Better:

- structured halos
- delayed energy deposition

Annihilation Feedback on Halo Gas

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

Sarah Schon, very-soon-to-be-PhD



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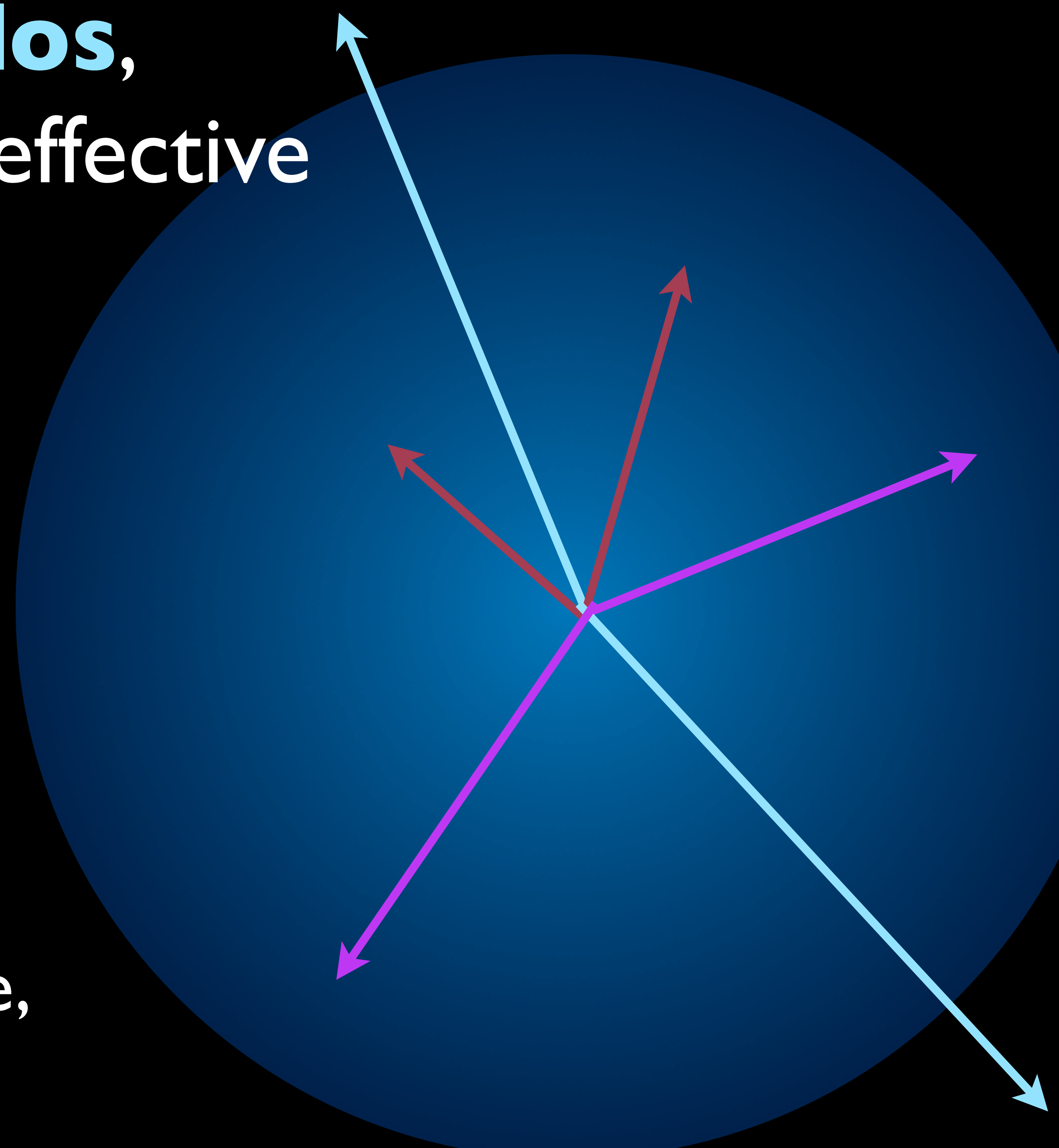
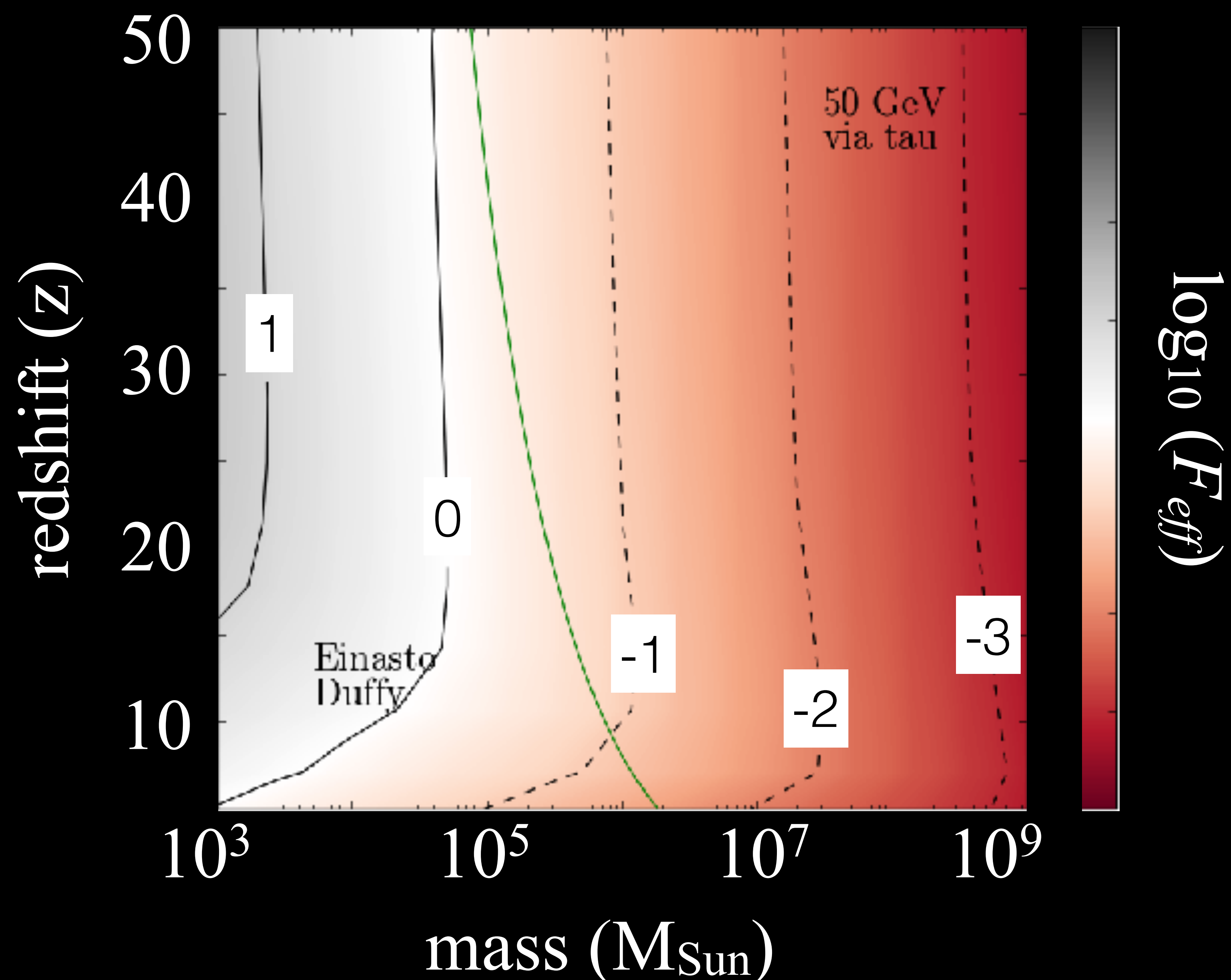


PYTHIA code: dark matter annihilation events

MEDEA2 code: energy transfer to baryons

Halo models: density profile, mass-concentration

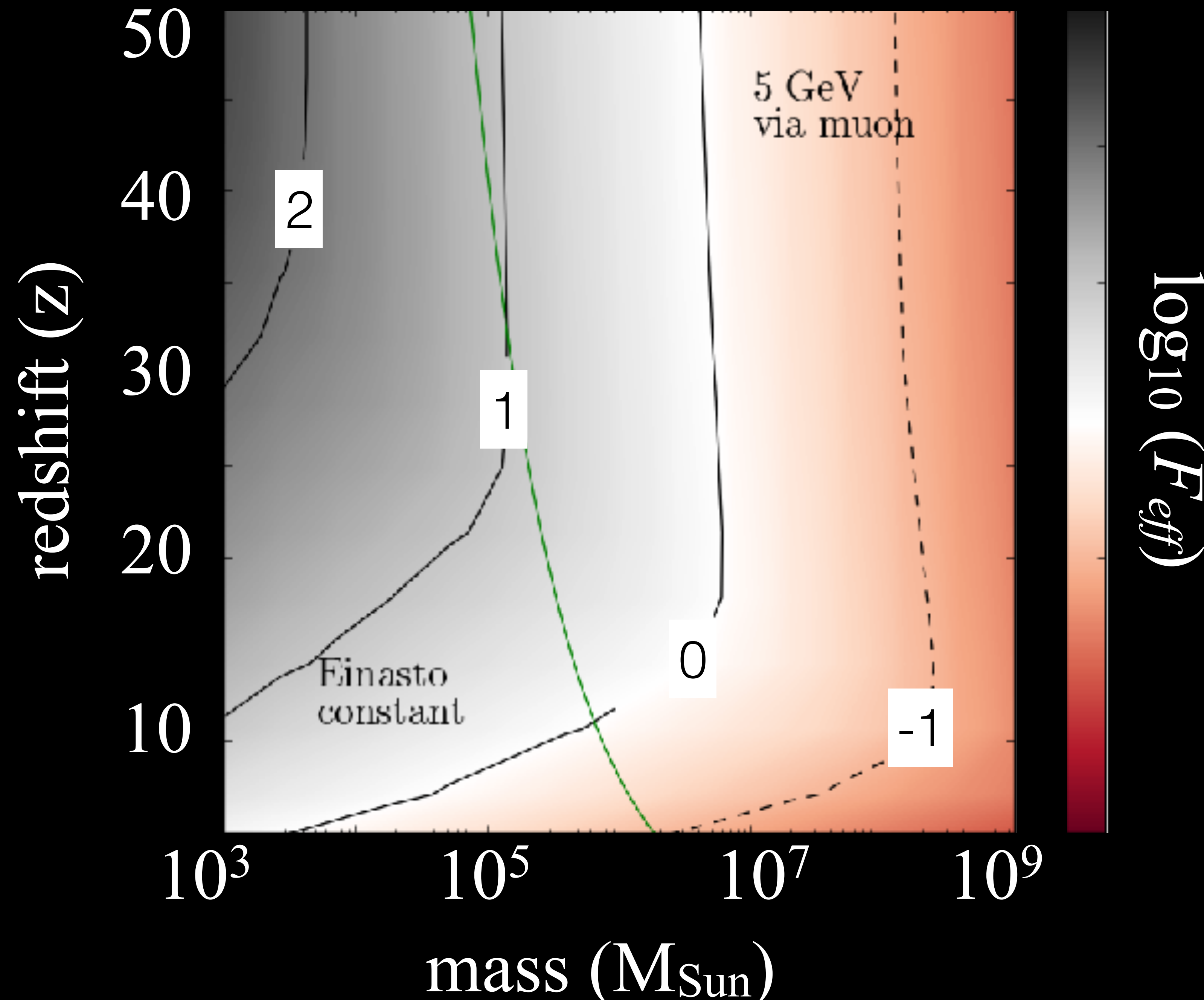
Annihilation Feedback on Halo Gas



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

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

Annihilation Feedback on Halo Gas



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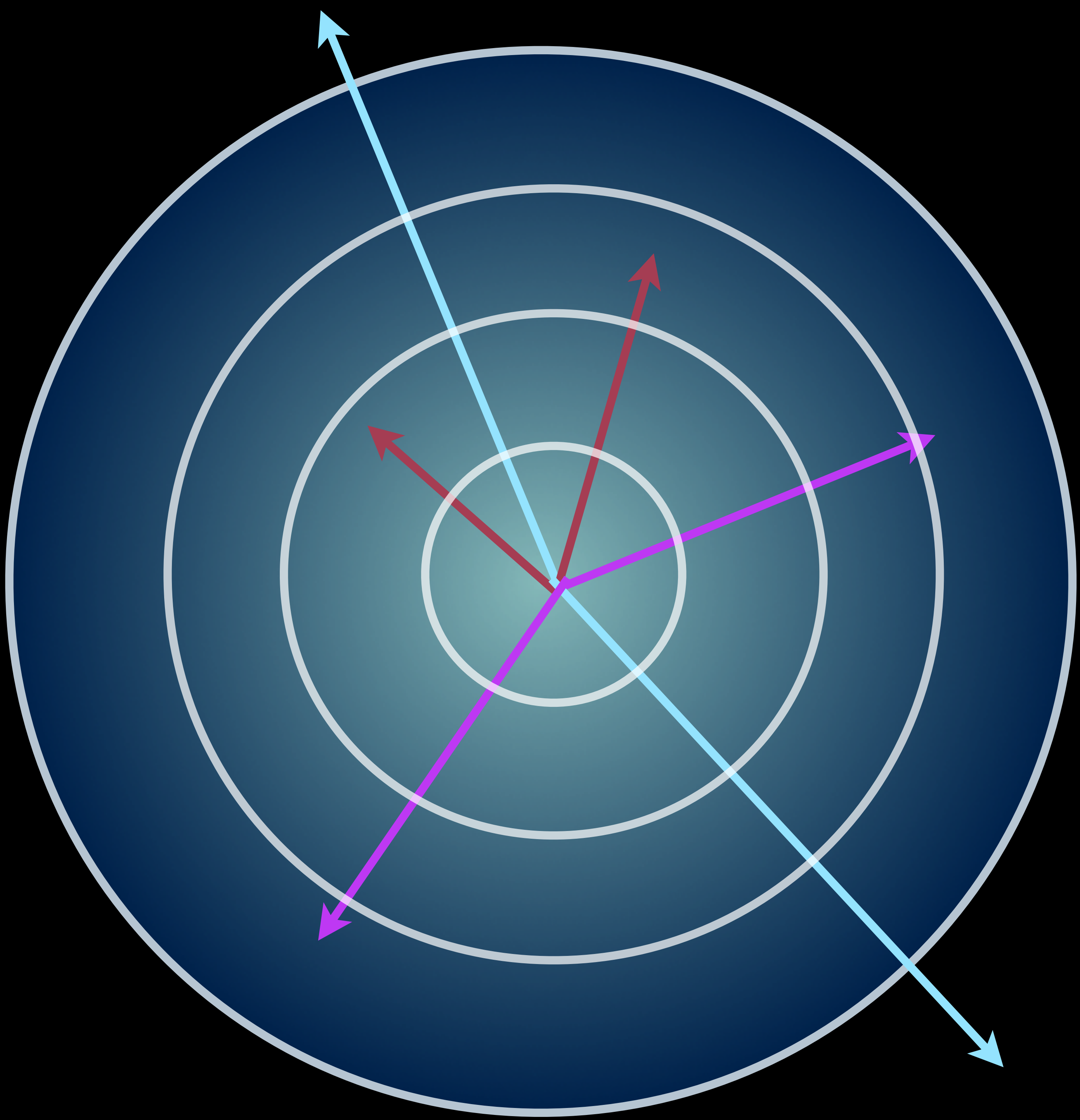
Halo Structure and Environment

Improved code: tracks full particle cascades & deposition within halos



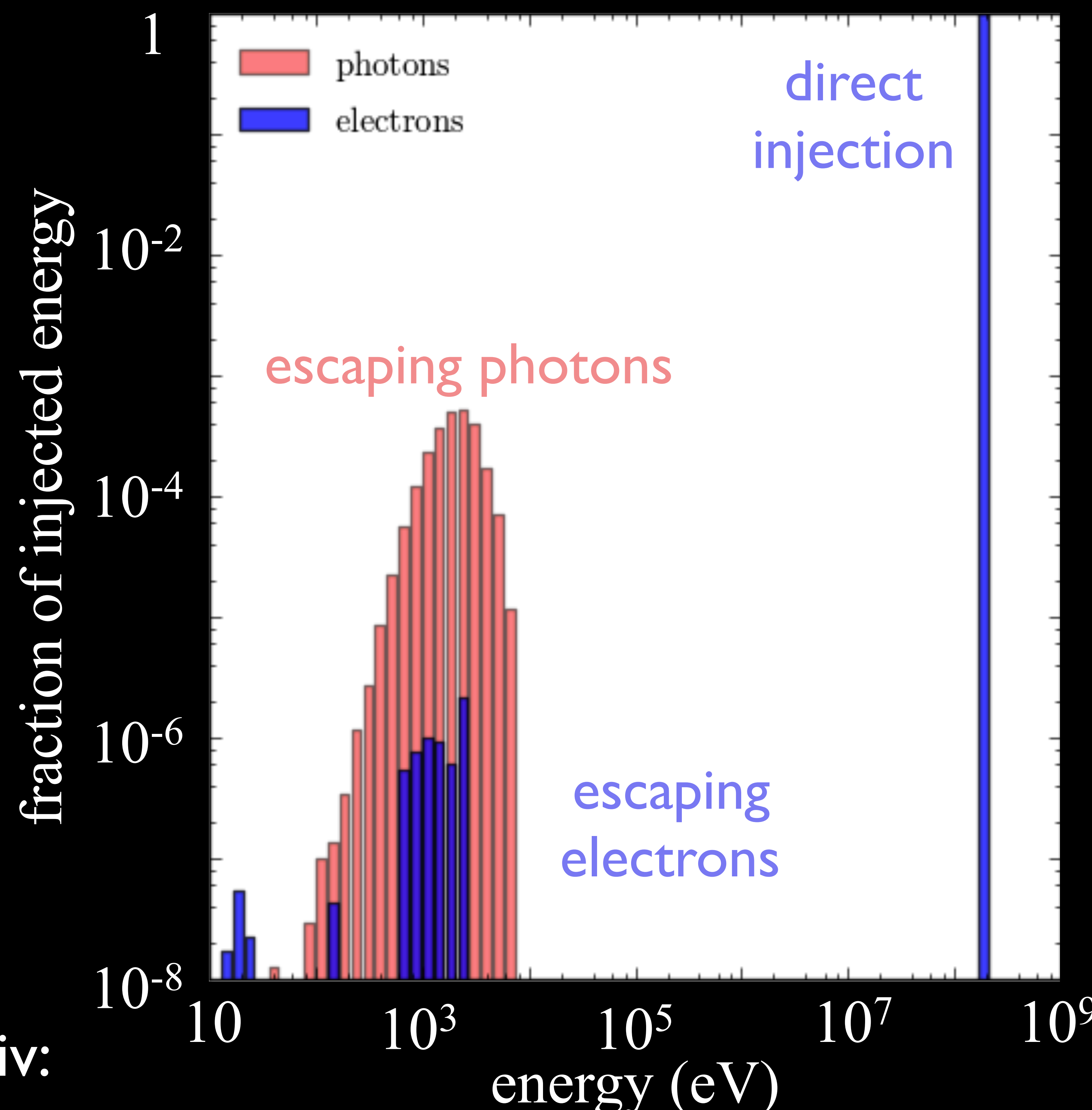
Main questions:

- Where is the energy deposited?
- What is the effect on the halo environment?

Schon, Mack & Wyithe 2017 [arxiv:1706.04327]

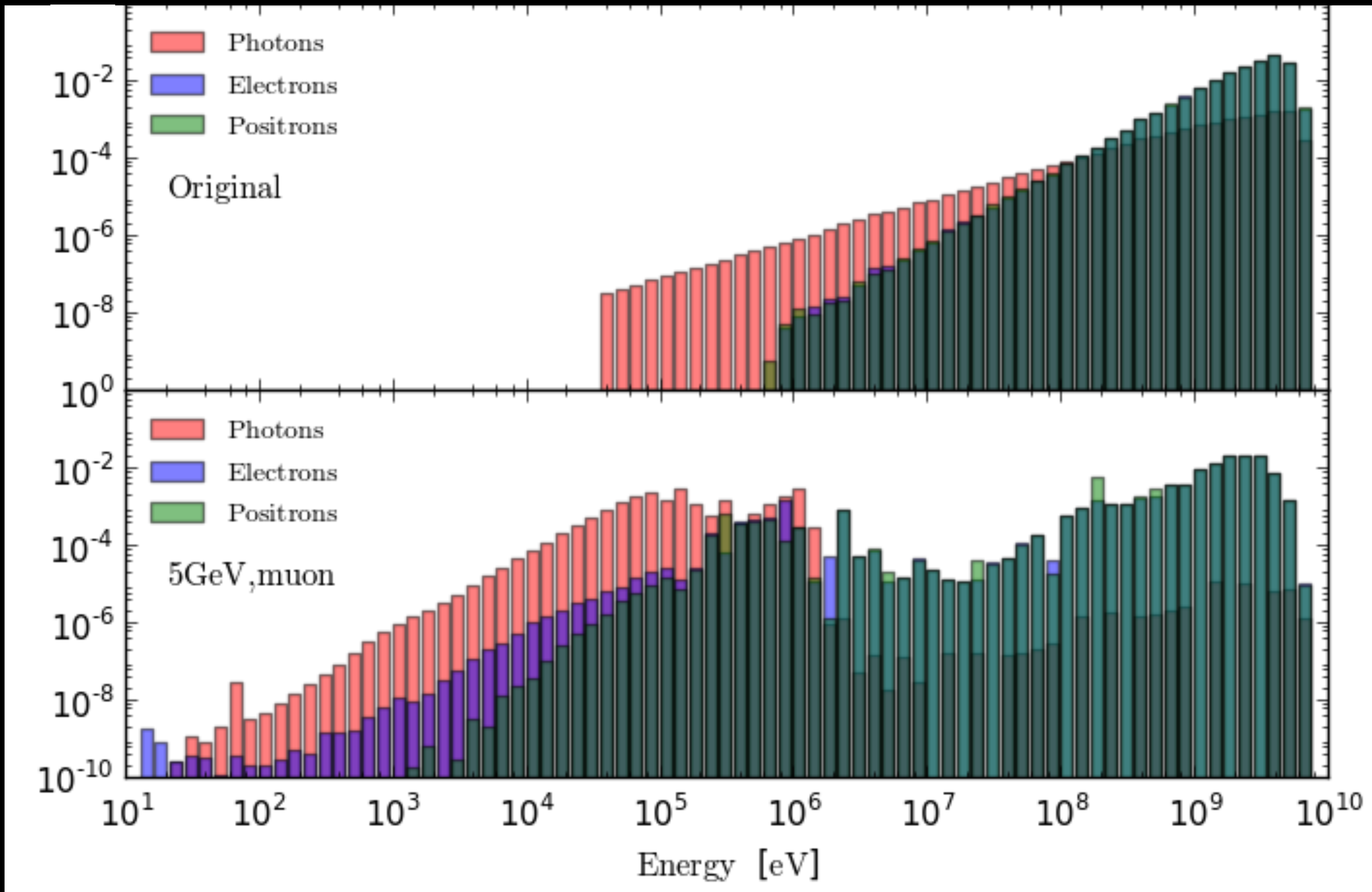
Halo Structure and Environment

Annihilation products **filtered** through halo baryons



Schon, Mack & Wyithe 2017 [arxiv: 1706.04327]

Halo Structure and Environment



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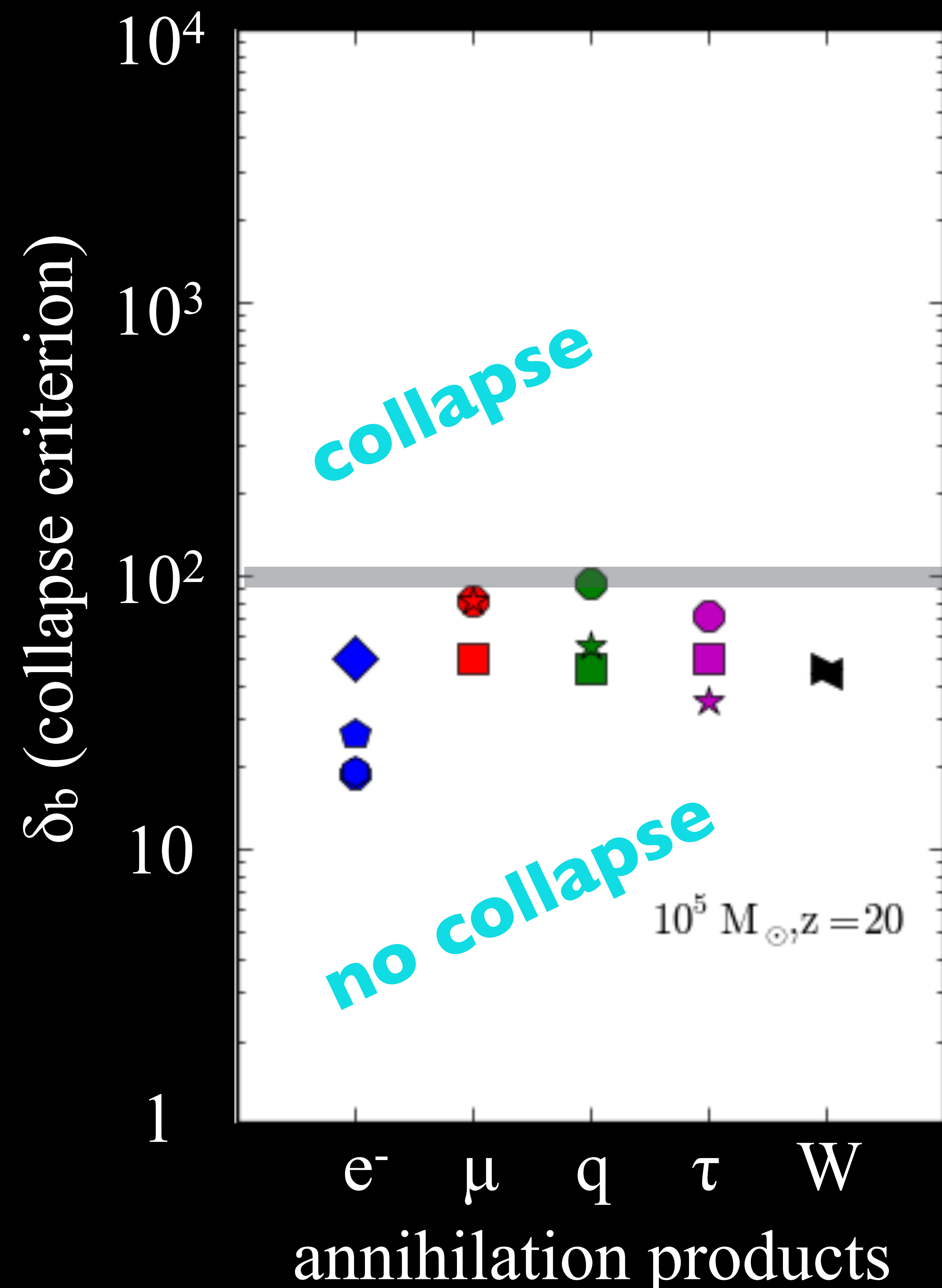
Alteration of halo collapse

Heating of halos alters Jeans mass (mass at which collapse possible)

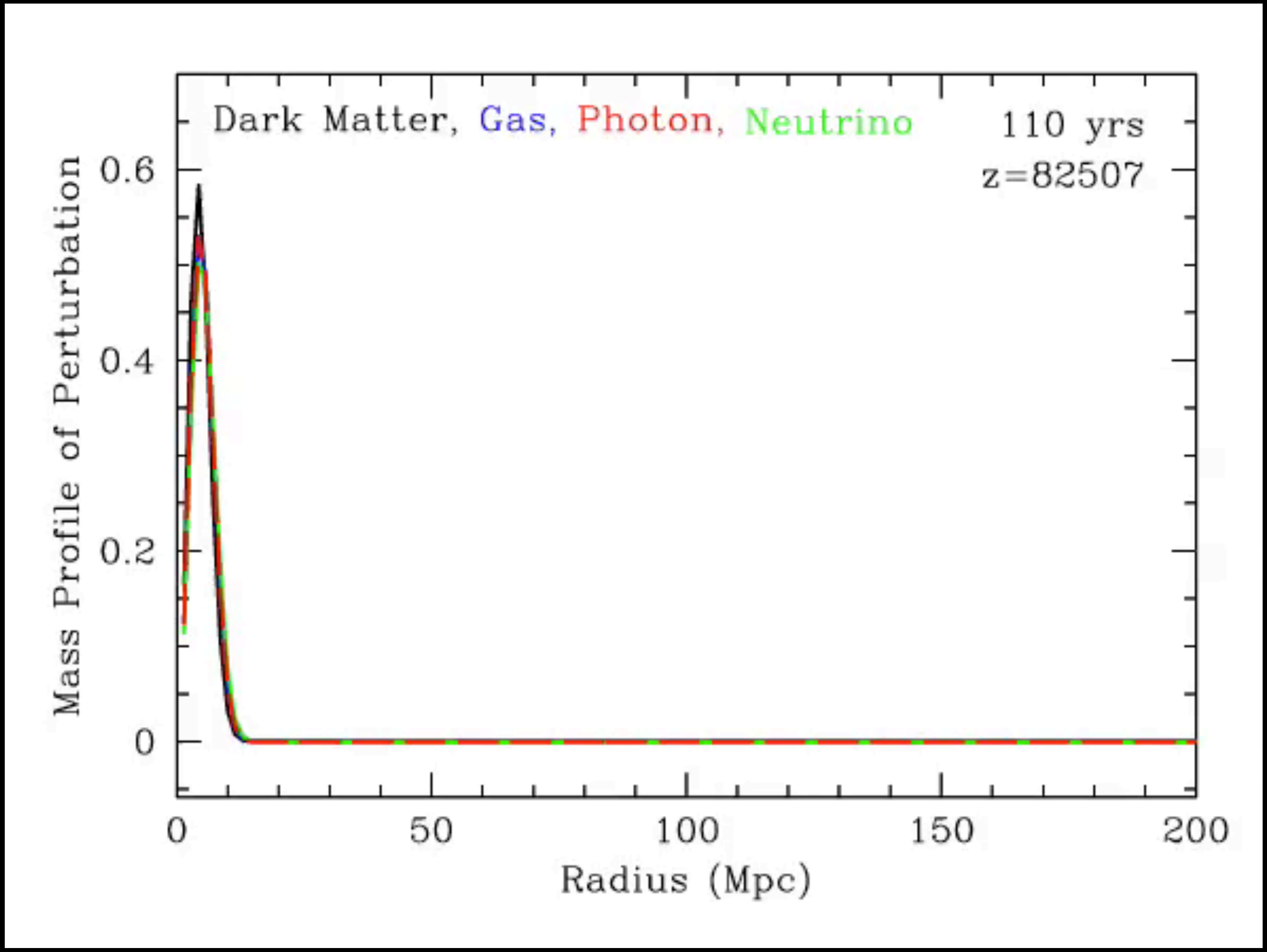
This can **prevent or delay collapse** for small halos at high redshift



Schon, Mack & Wyithe 2017 [arxiv:1706.04327]

Velocity Offsets

Tseliakhovich & Hirata 2010
McQuinn & O'Leary 2012
Fialkov et al. 2014
Ali-Haimoud et al. 2014



animation by Daniel Eisenstein

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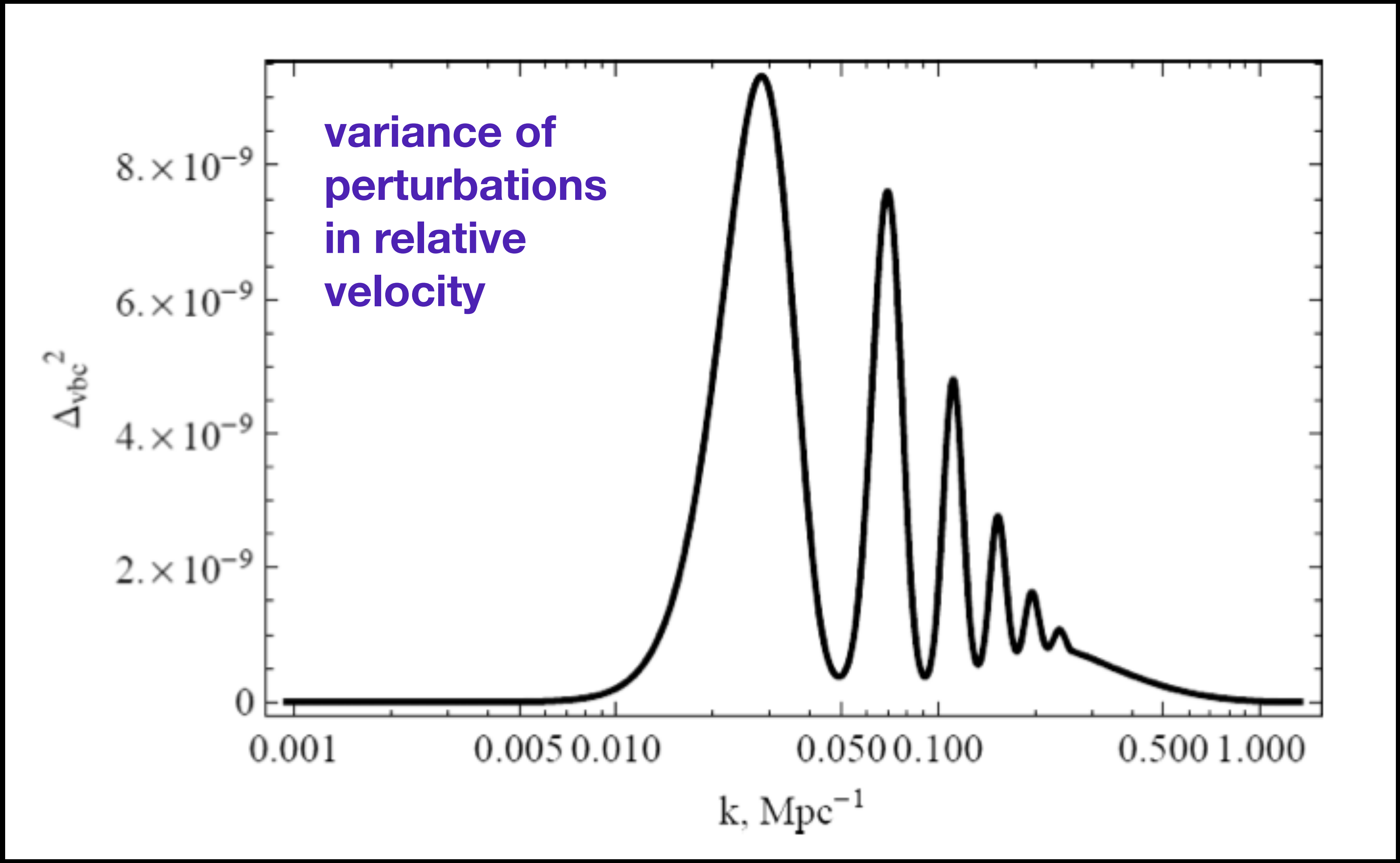

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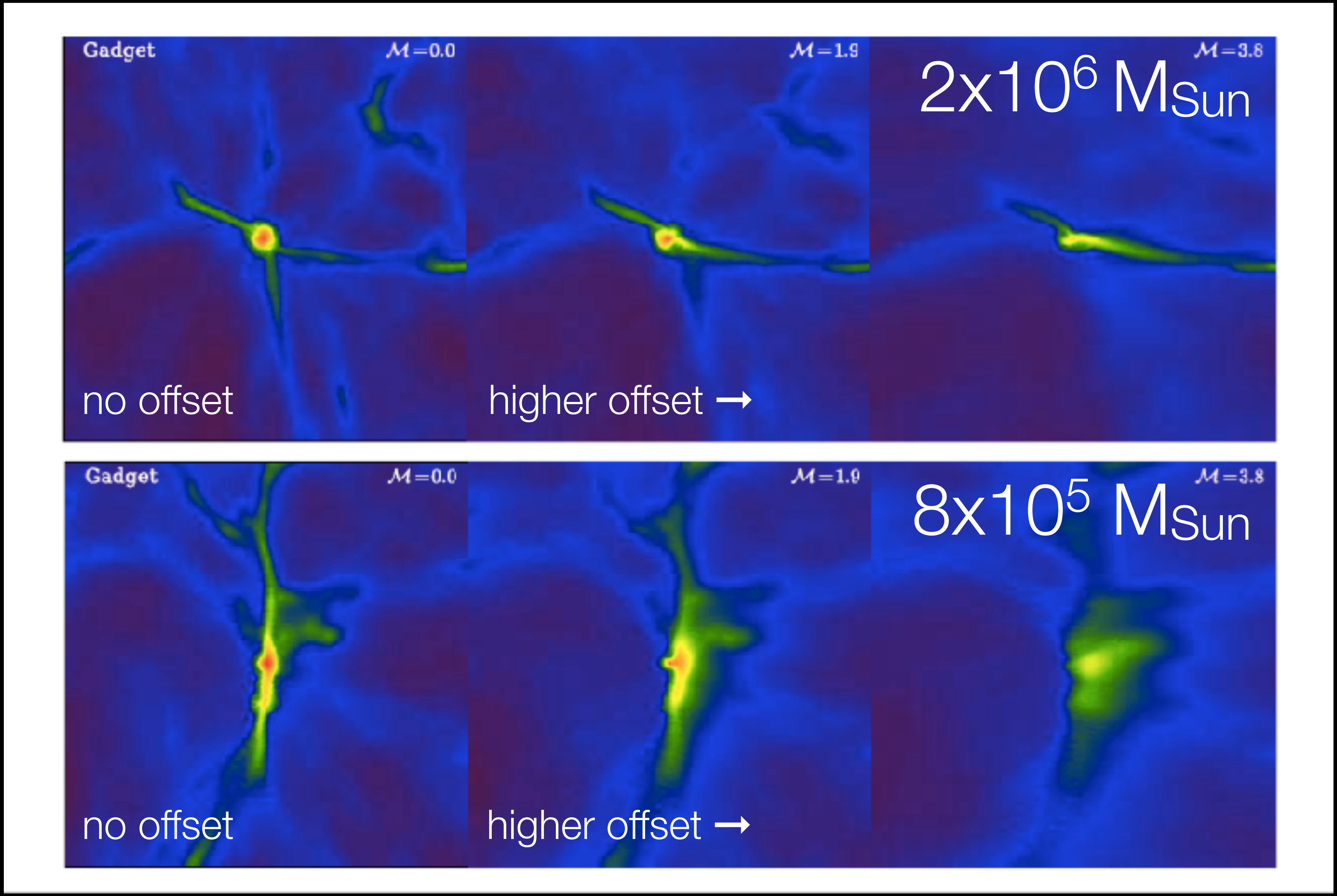

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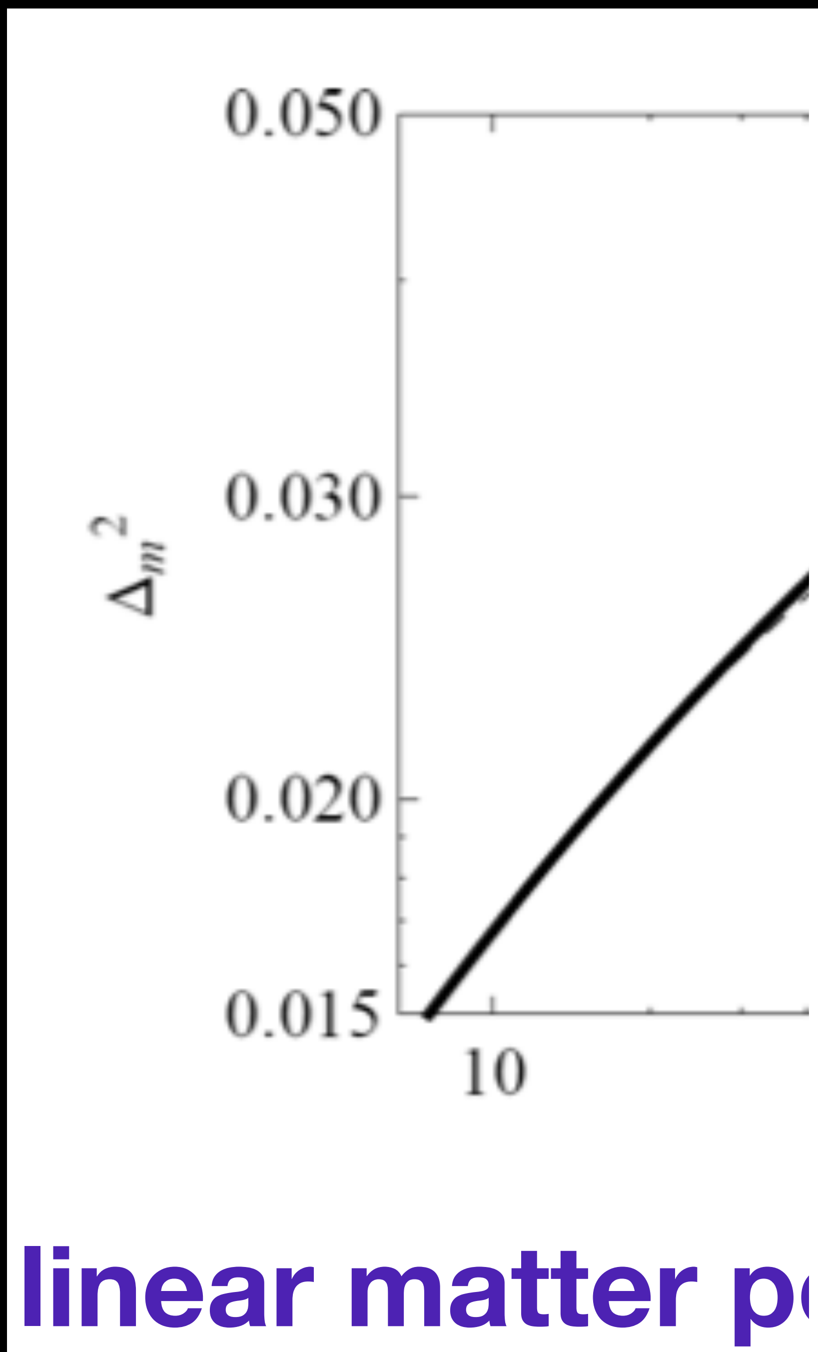
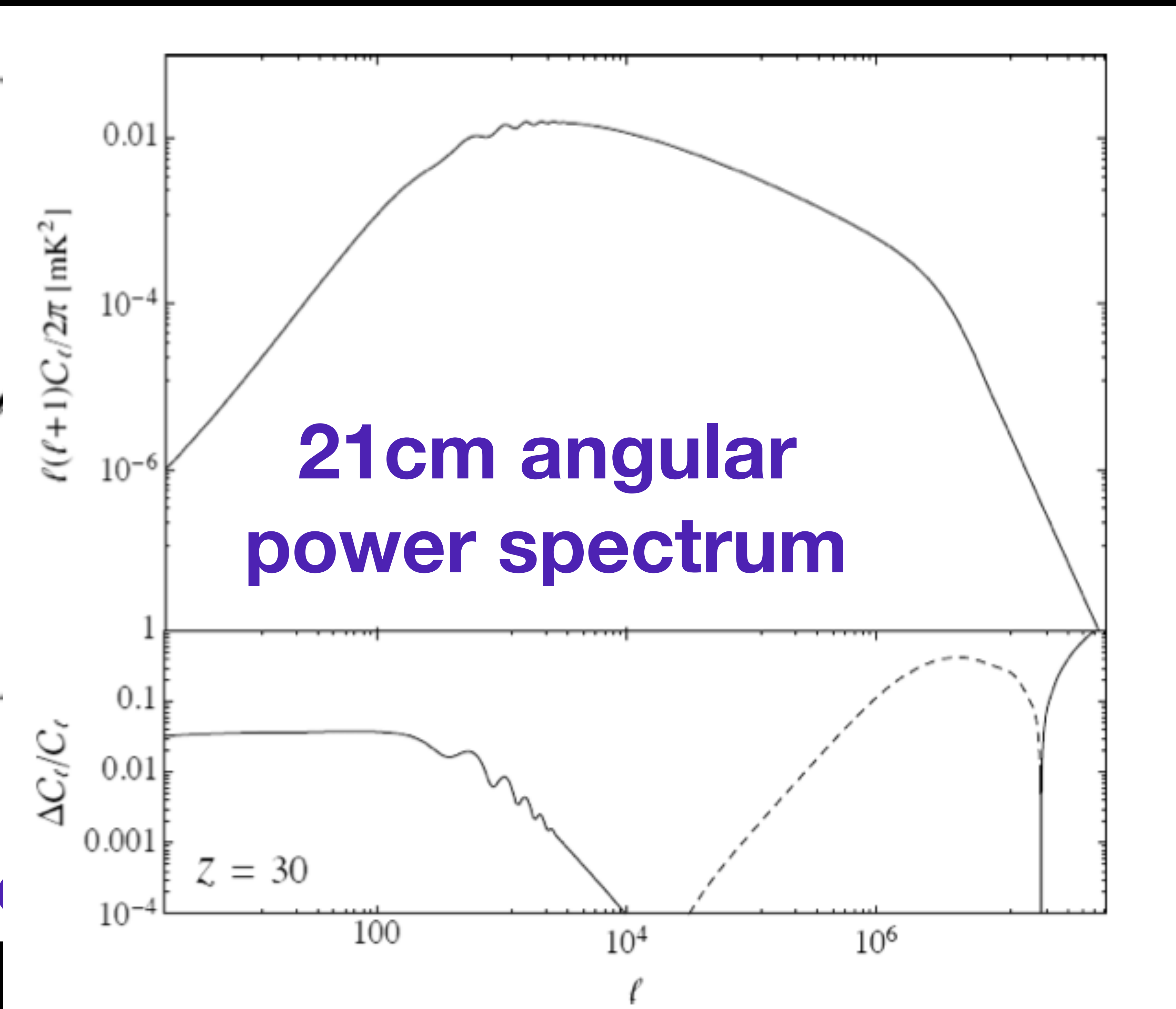


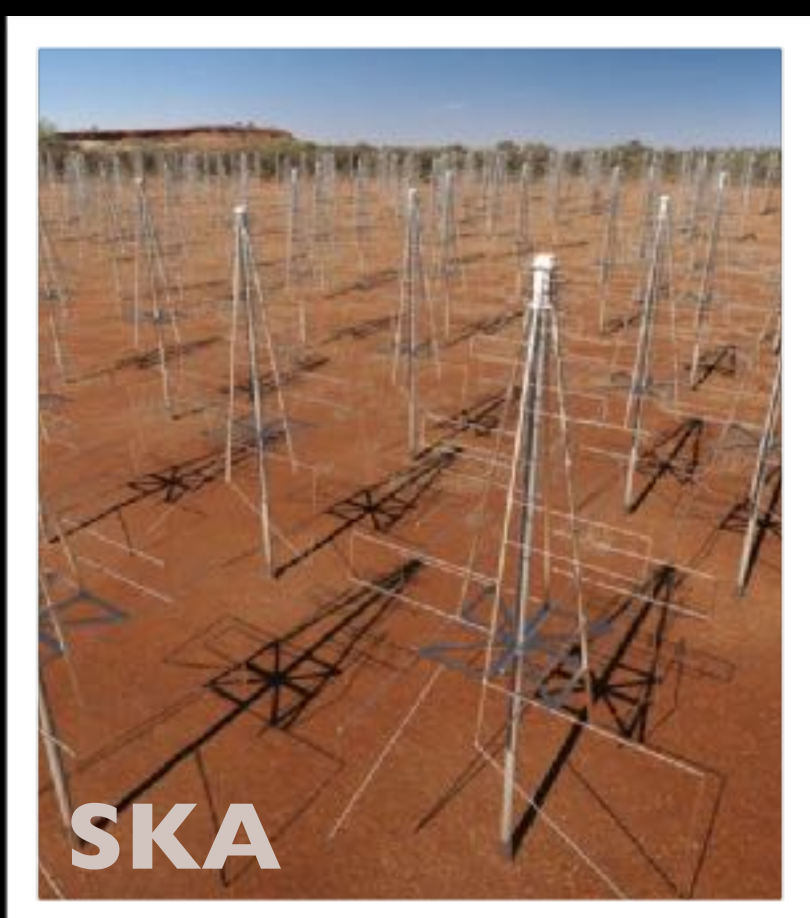


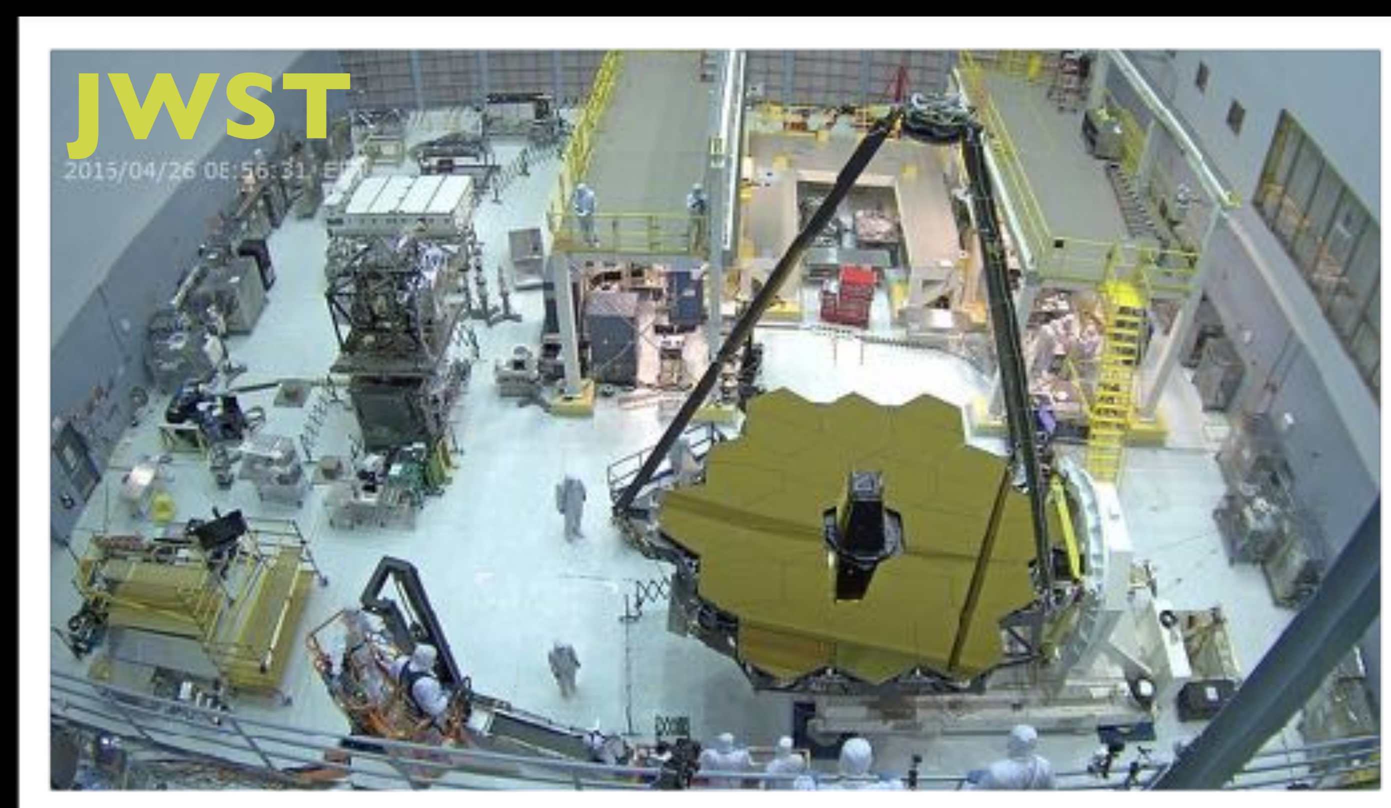
Probing "Cosmic Dawn"

Djorgovski et al., Caltech

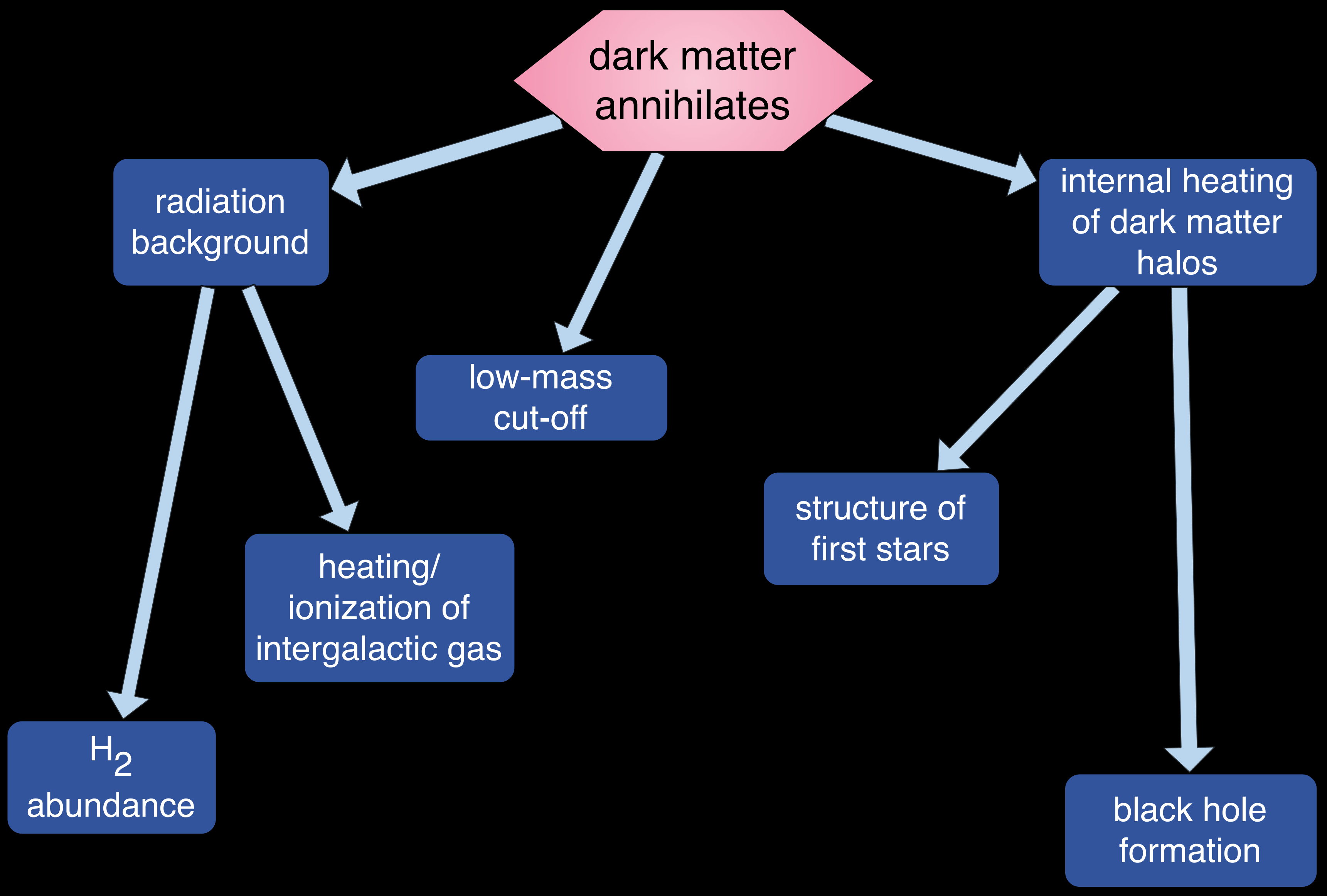
current instruments

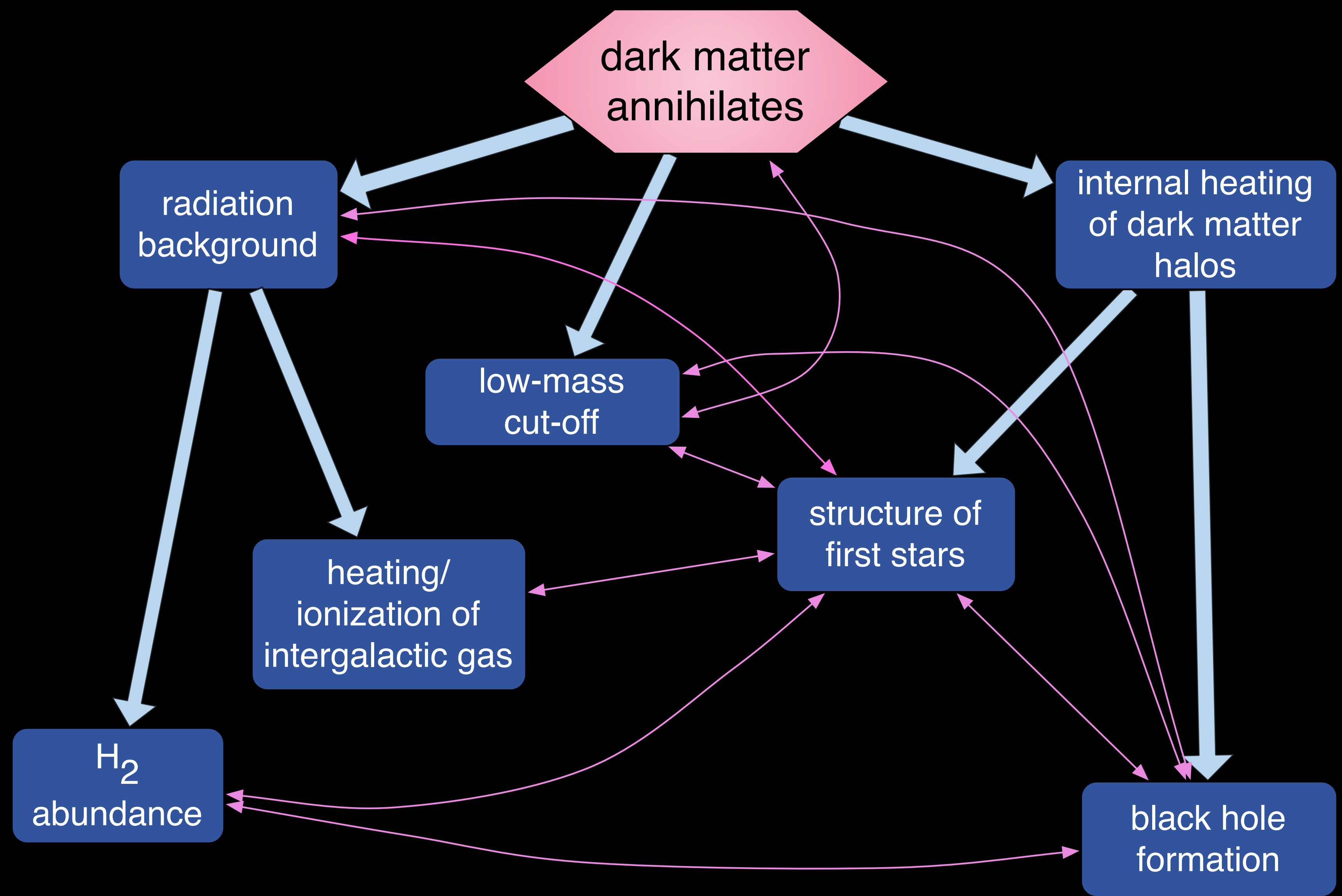
next decade





dark matter
annihilates


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



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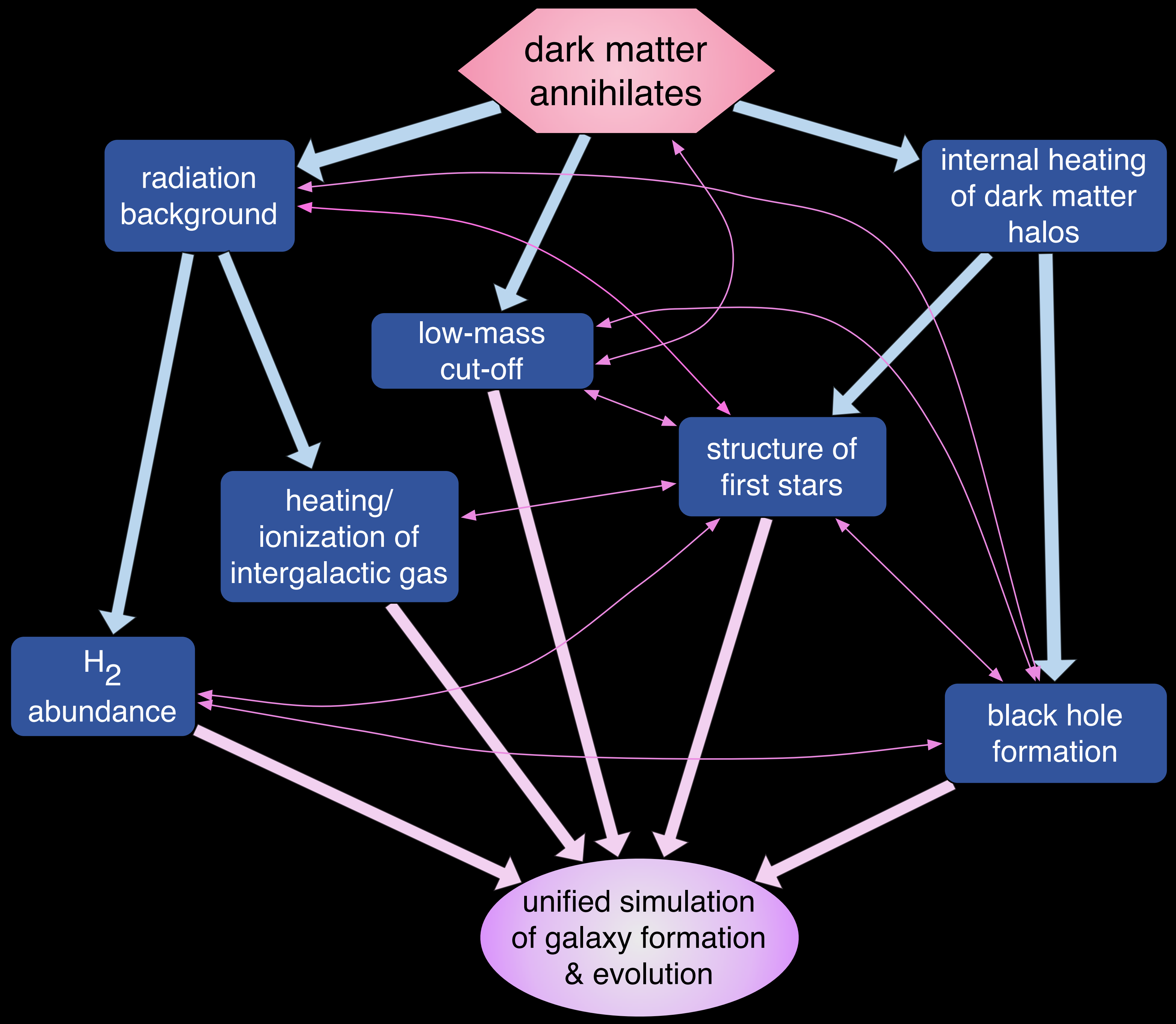
H_2 abundance
black hole formation


dark matter annihilates
radiation background
internal heating of dark matter halos
low-mass cut-off
structure of first stars
heating/ ionization of intergalactic gas
H_2 abundance
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unified simulation of galaxy formation & evolution


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high-redshift 21cm signal
high-redshift galaxies

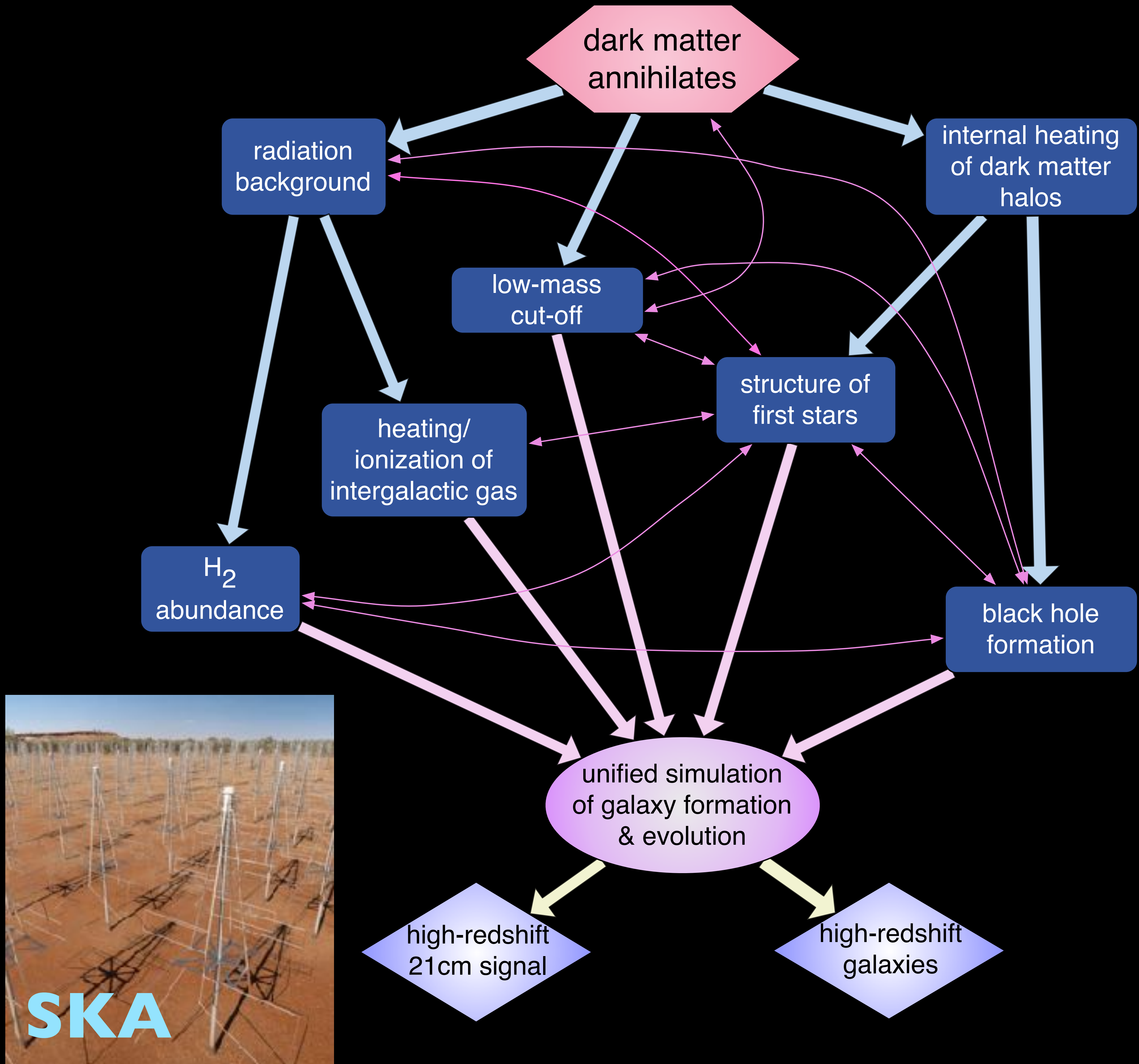

Image credit: Swinburne/
ICRAR/Cambridge/ASTRON

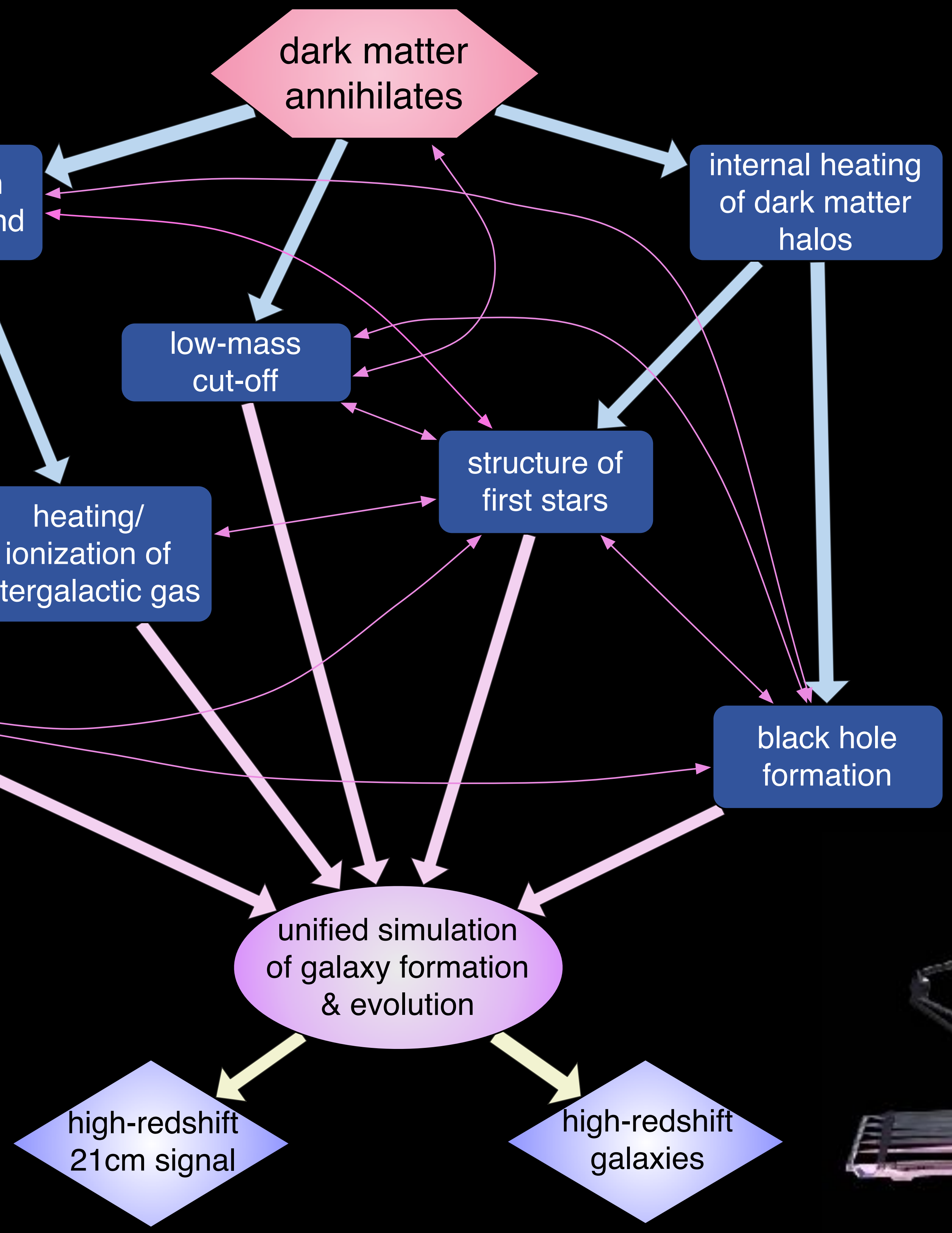

Image credit: Swinburne/ ICRAR/Cambridge/ASTRON

JWST

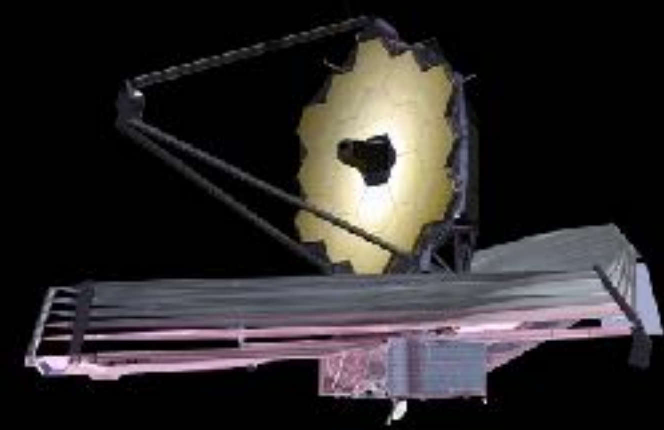

Image credit: NASA

Take-Home Messages

- The **fundamental nature of dark matter** is still a mystery (but 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

end