Cosmology, Dark Matter and New Physics

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Perimeter Institute for Theoretical Physics

Image: A. Loeb/Scientific American


Camille Flammarion 1888

THE STANDARD MODEL • SAWANGWIT, SHANKS: QUESTIONING THE STANDARD MODEL

Is everything we know about the universe wrong?

In the first of a pair of articles, Utane Sawangwit and Tom Shanks play devil's advocate, ... the standard ... missing

One of the ... for cos- mology ... origin ... cosmic micro... CMB is the ... and theref... on cosm... the sta... perfec... the W... me... la...

the atoms in the ordinary material that we see around us (figure 1). This model produces a largest ripple size of about 1° on the microwave sky and this is well matched by the ripples seen in the WMAP maps (figure 2). These WMAP ripples have a size that is roughly twice the size of the full Moon as they appear on the sky. Models that don't have dark energy or dark matter tend ... produce CMB ripples that are smaller, only ... the standard model size and so just ... the full Moon.

... sources to test how ... these CMB ... beam

Some things we know about the universe are probably right

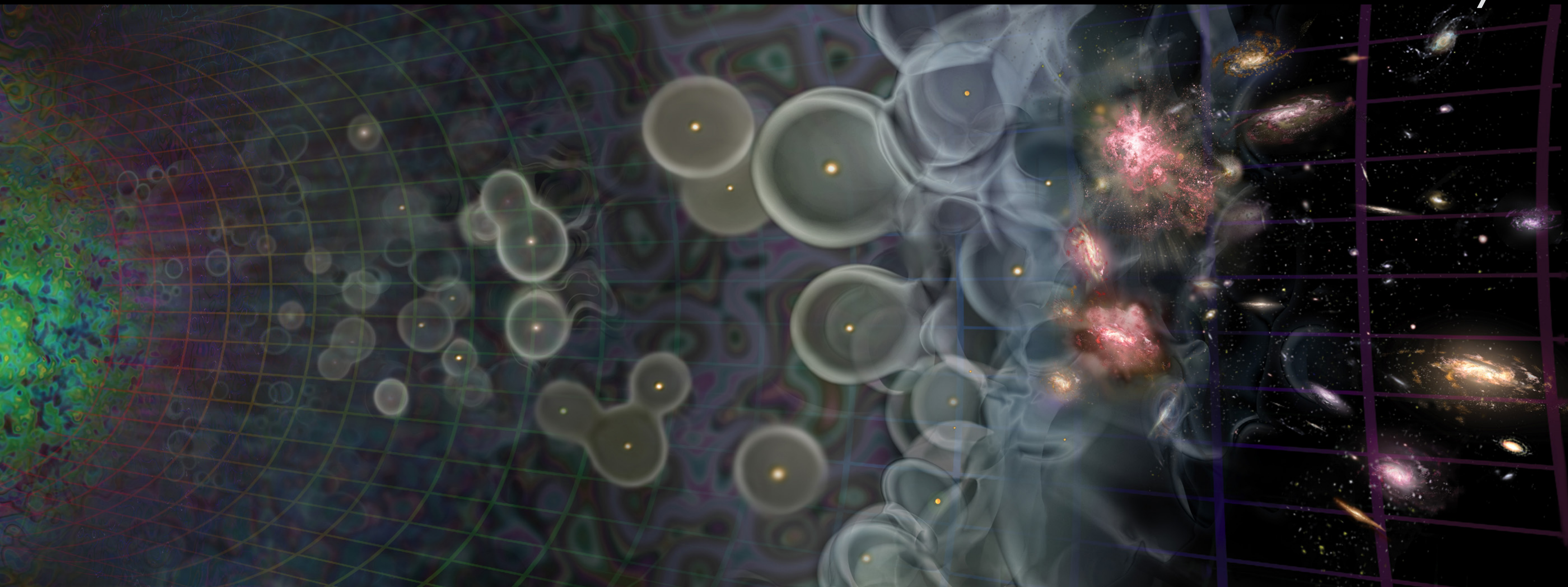
Tommaso Giannantonio, Antony Lewis and Robert Crittenden summarize our present standard model of cosmology, which does include some poorly understood and as yet unobserved components, known as dark matter and dark energy. Here they argue why these ingredients, whose nature thus far is elusive, are probably here to stay.

Modern cosmology is a consequence of Einstein's general relativity, which describes gravity as the interplay of mass (or energy) and geometry: the geometrical bending of the space-time tells matter where to fall, while matter bends the space-time itself. General relativity, which is well tested in local phenomena such as the planets' motion within the solar system, can be applied to the study of the universe as a whole with the introduction of *the cosmological principle*; this modern version of the Copernican principle states that the universe is homogeneous and isotropic on very large scales, greater than about 100 Megaparsecs, and is supported by observations (Sarkar *et al.* 2009). Under this assumption, general relativity predicts that the universe expands at a rate determined by its curvature and its total energy density.

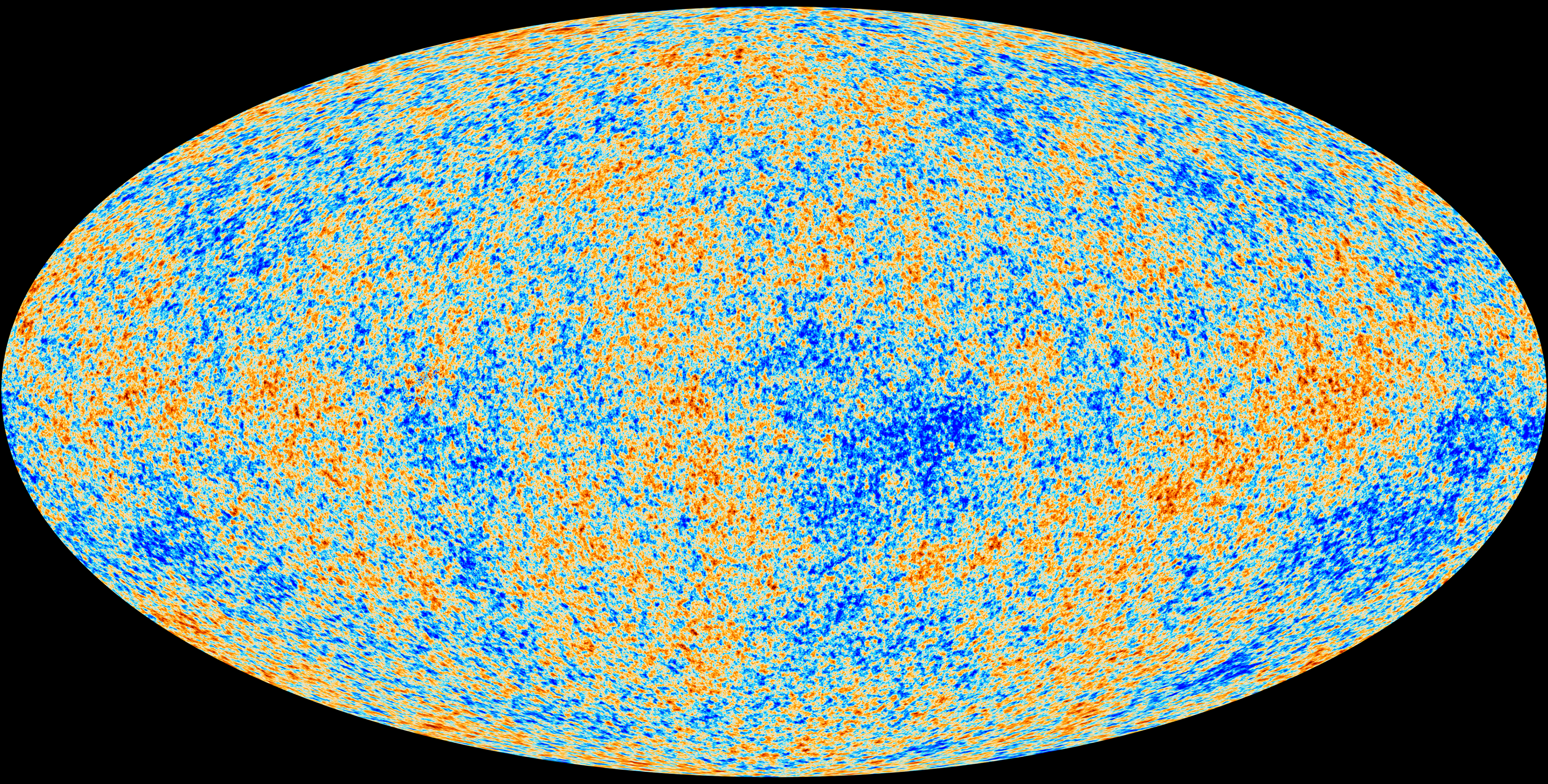
The universe's expansion was detected in the 1920s from the observation of spectral redshifts of distant galaxies. It is more recent news that the expansion rate is currently increasing with time. Since the action of gravity on ordinary matter can only be attractive, and thus only slows down the expansion, this accelerating expansion provides evidence for the mysterious dark energy. By dark energy we mean a component of the universe with a very smooth (unclustered) positive energy density that acts as though it has a negative pressure. ...

Astronomy & Geophysics, 2010

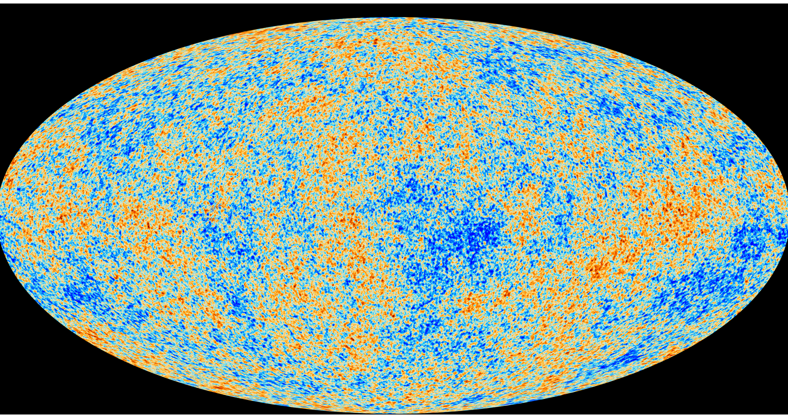

Credits: NASA, ESA, CSA, and STScI

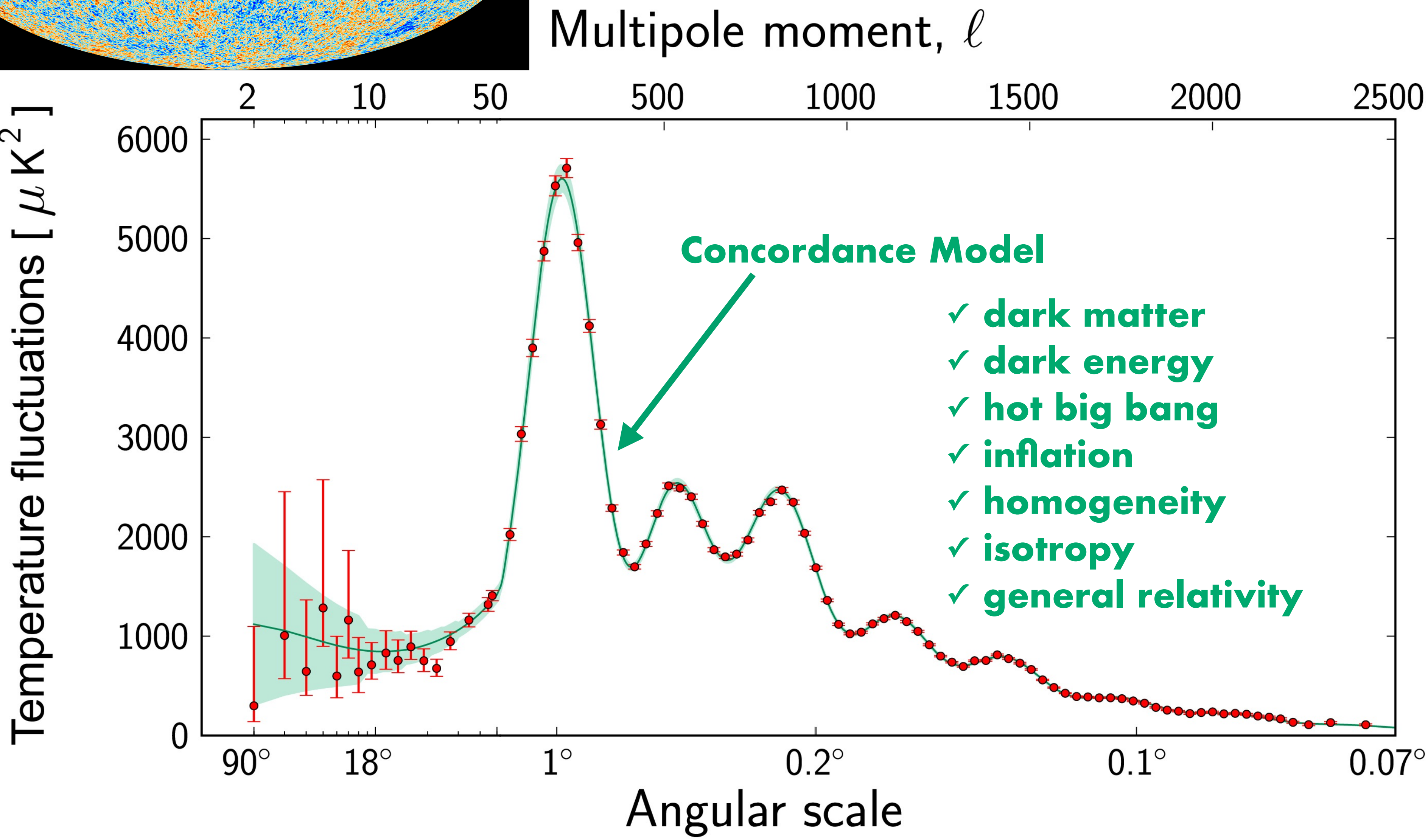


Credits: A. Loeb, Scientific American



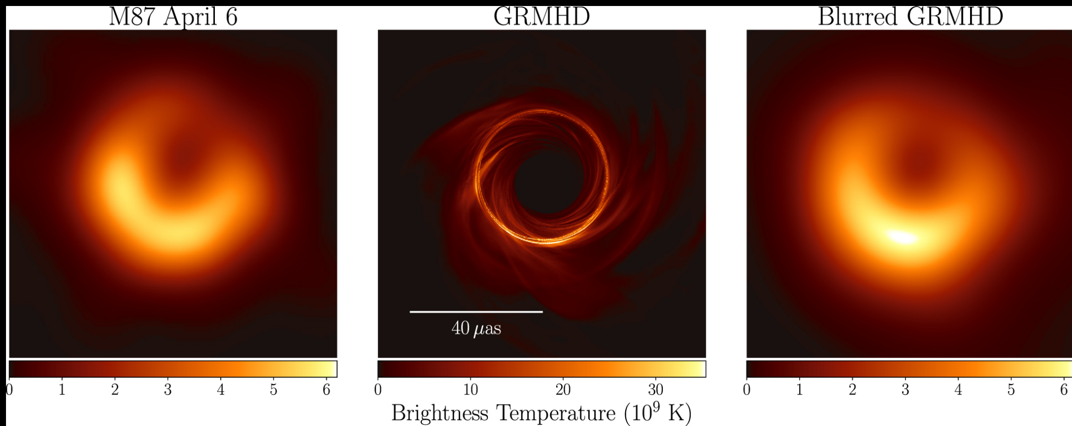
Credit: Planck/ESA



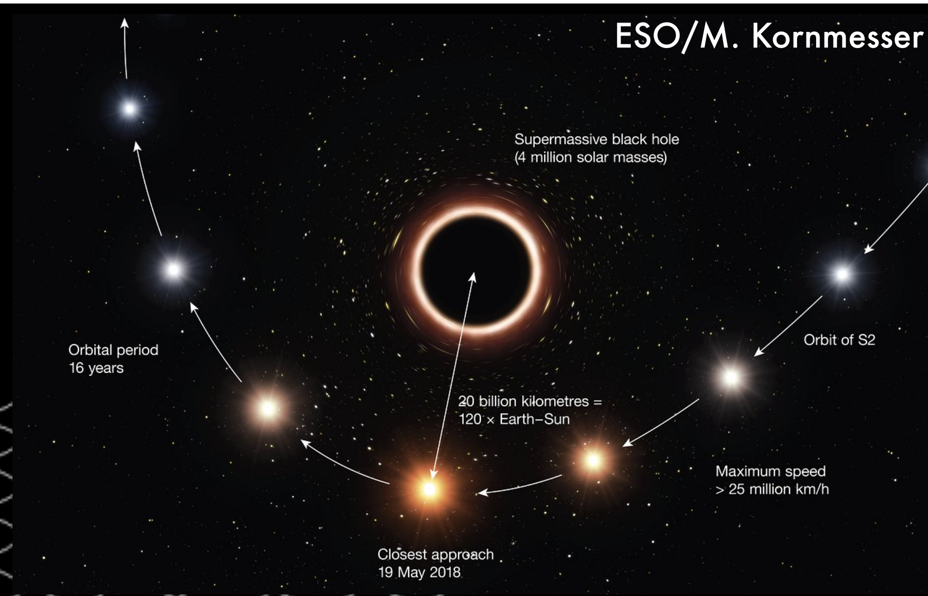


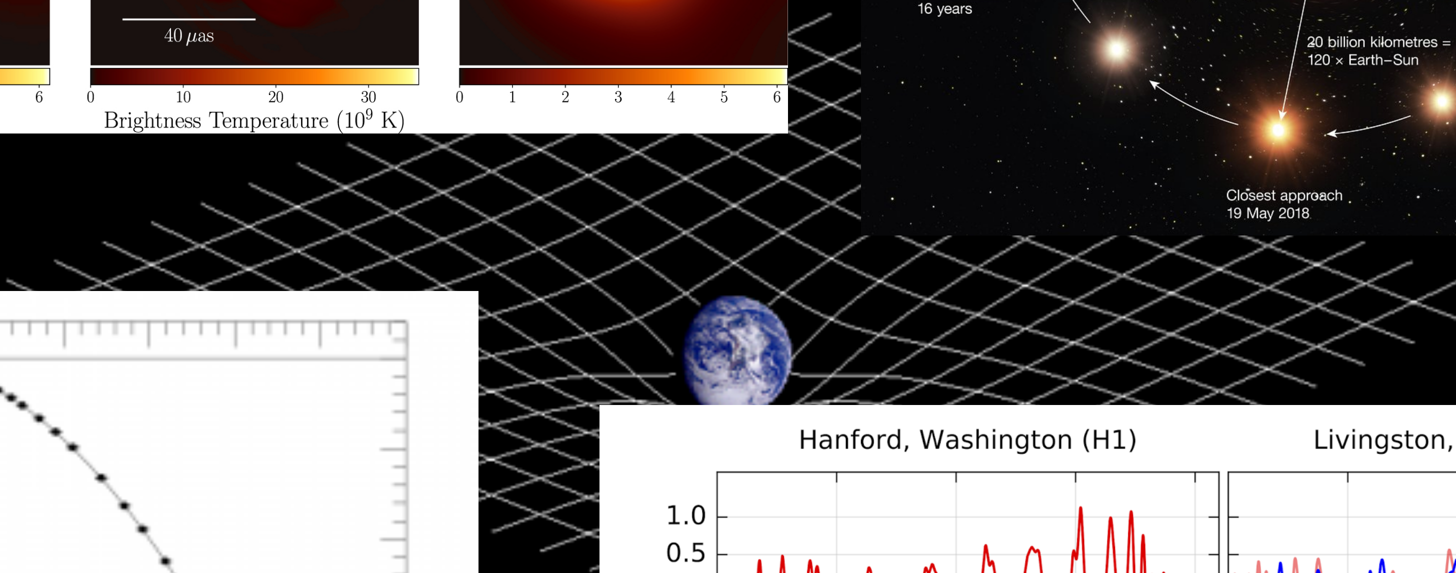
Credit: Planck/ESA

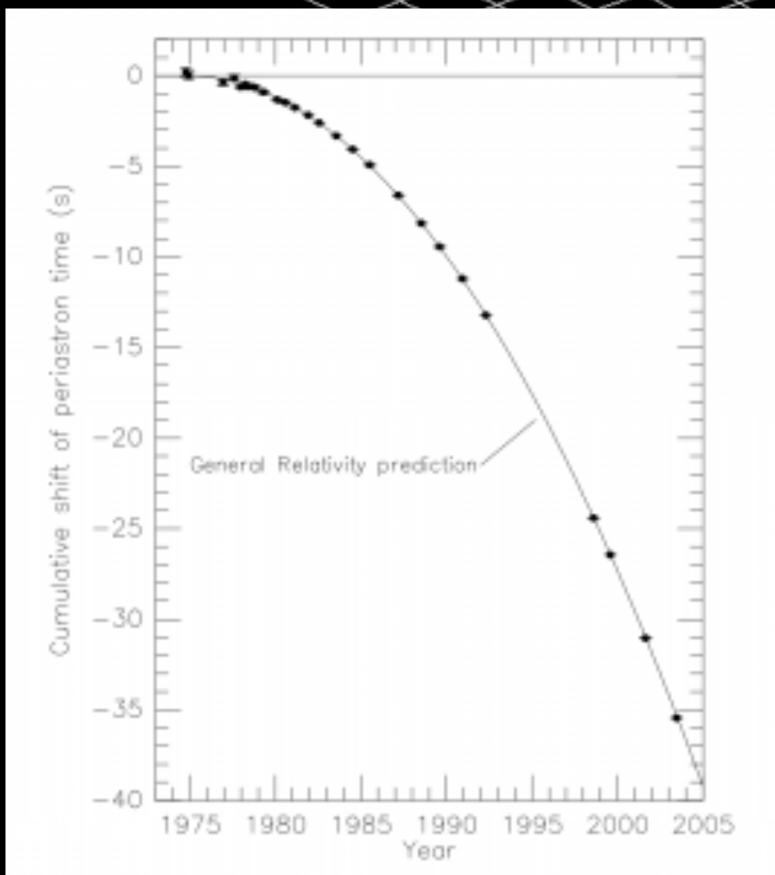
Event Horizon Telescope

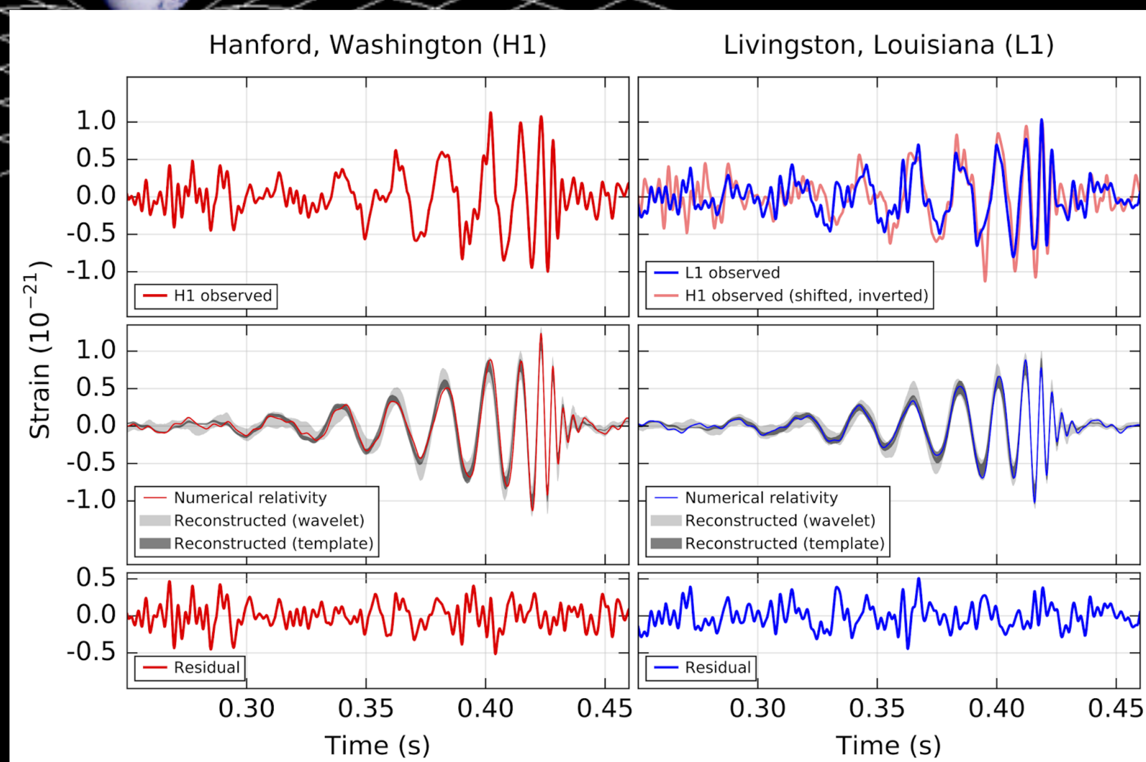


ESO/M. Kornmesser



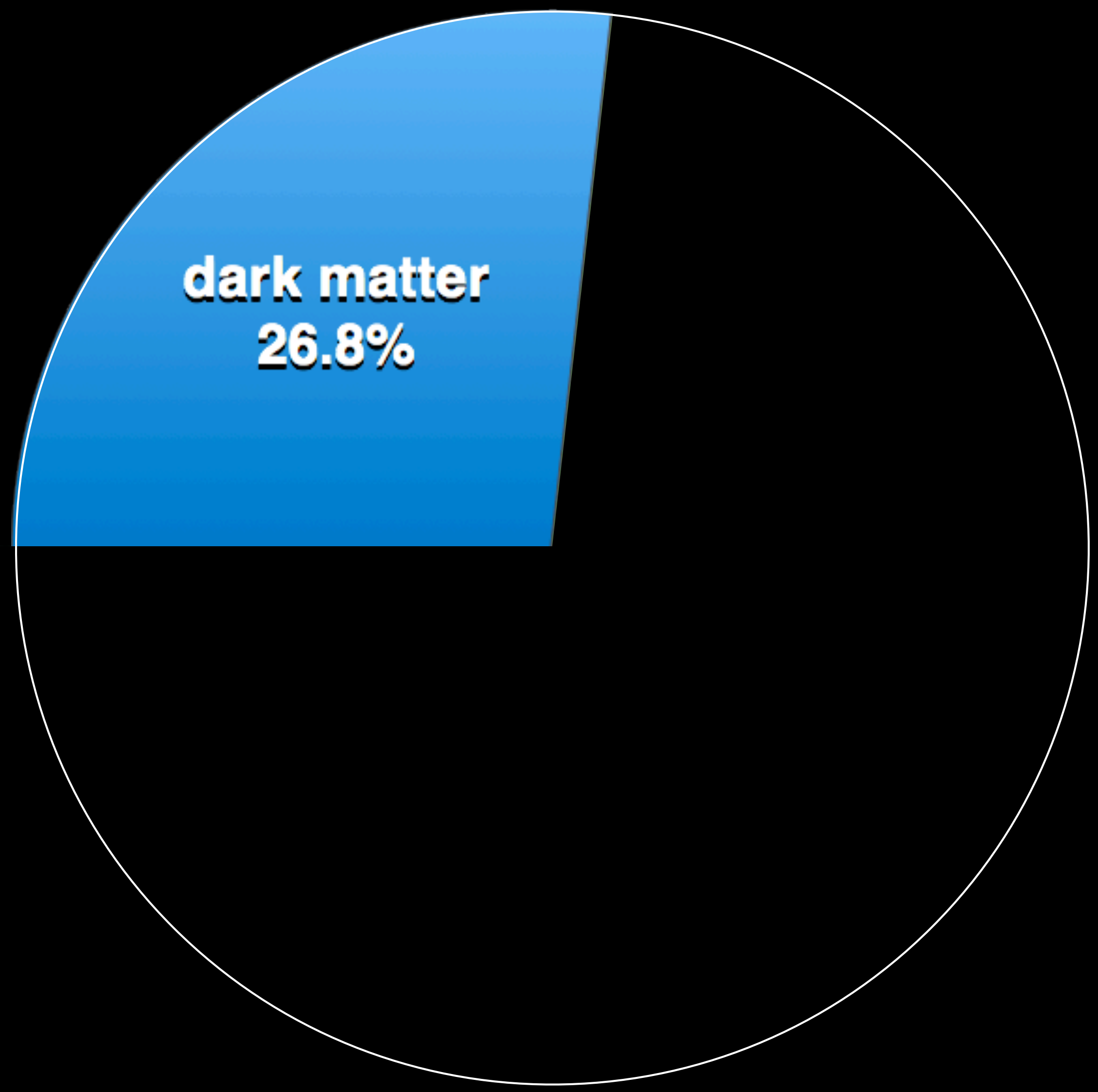


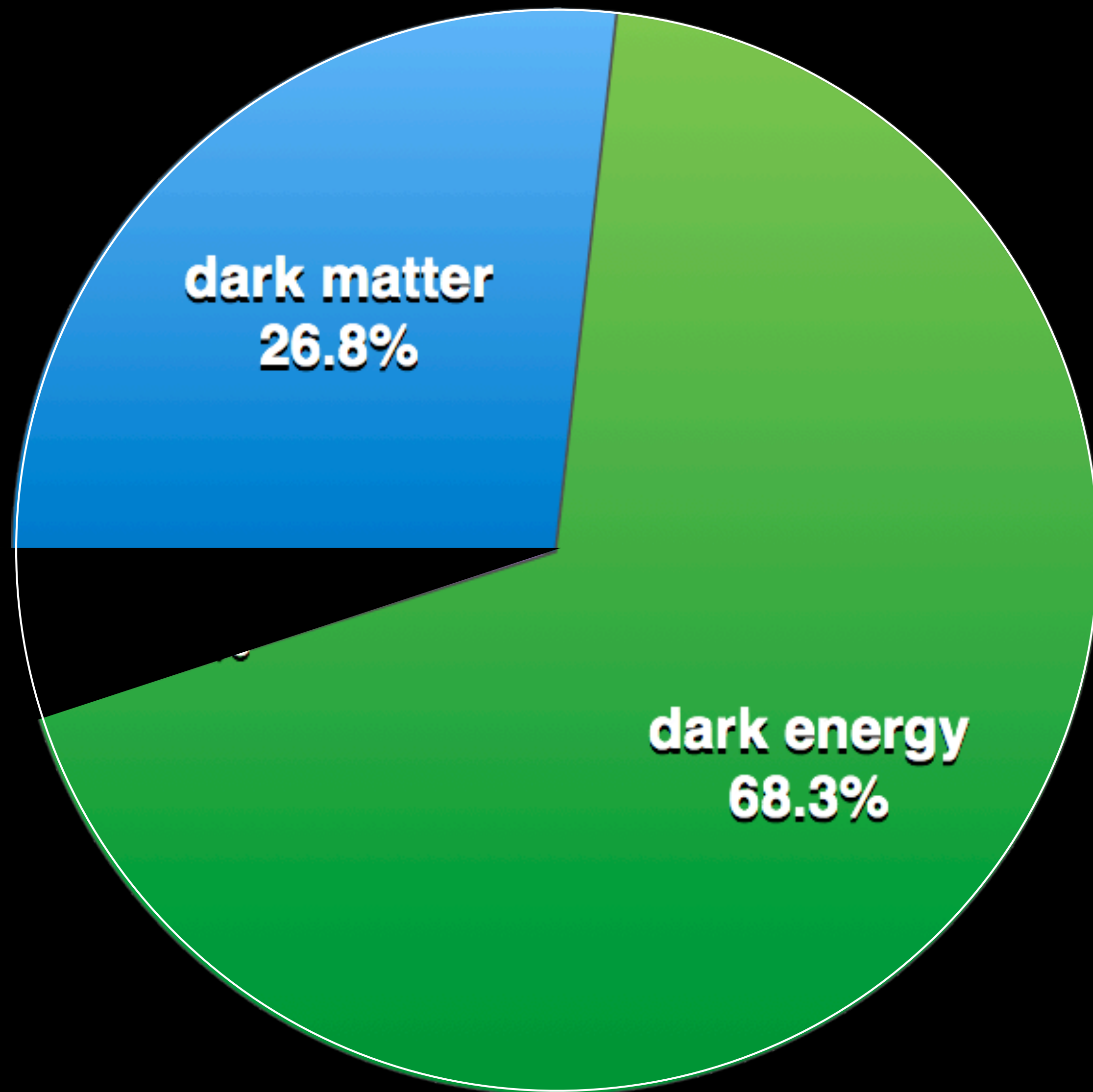


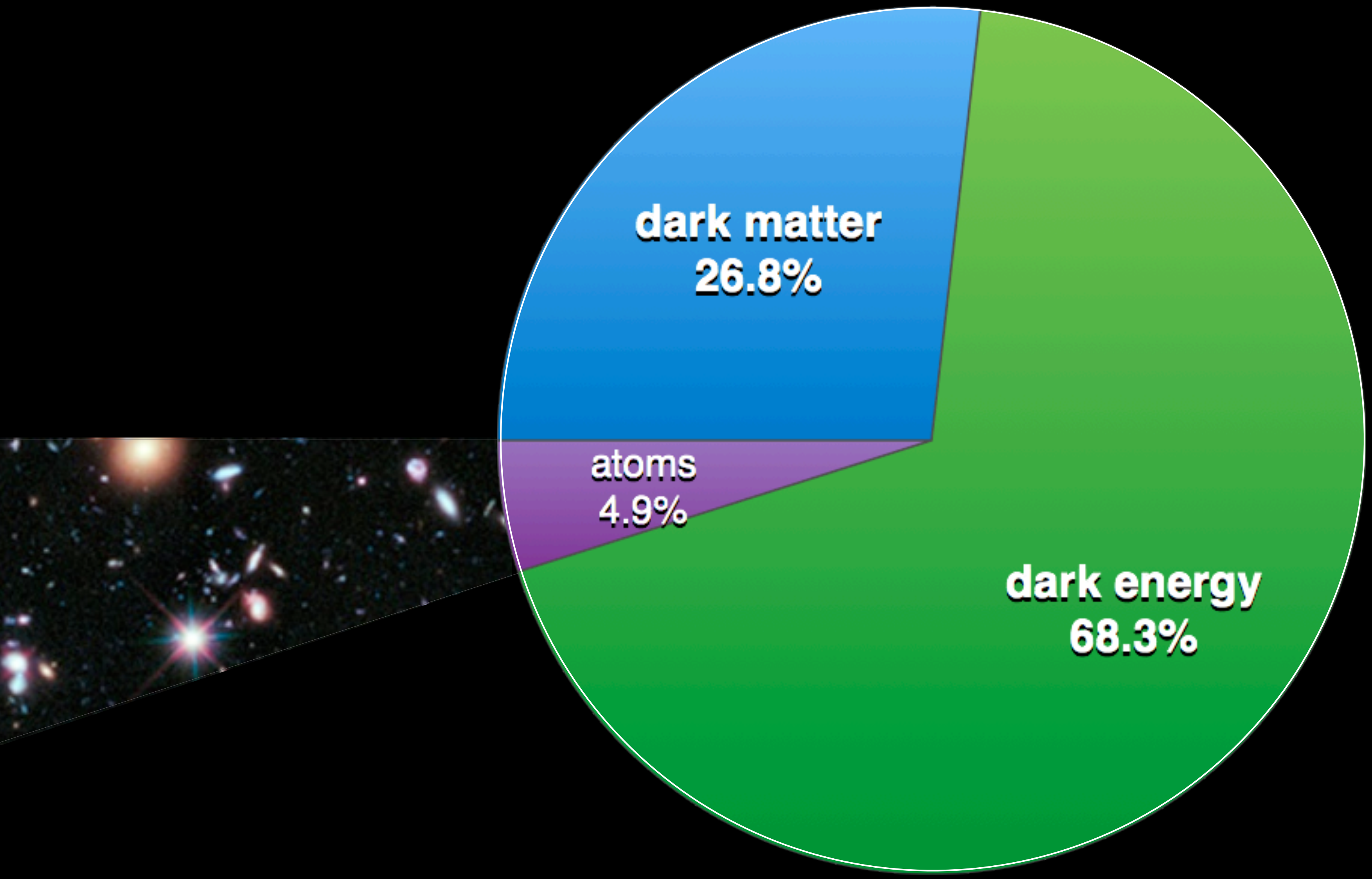


The Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis

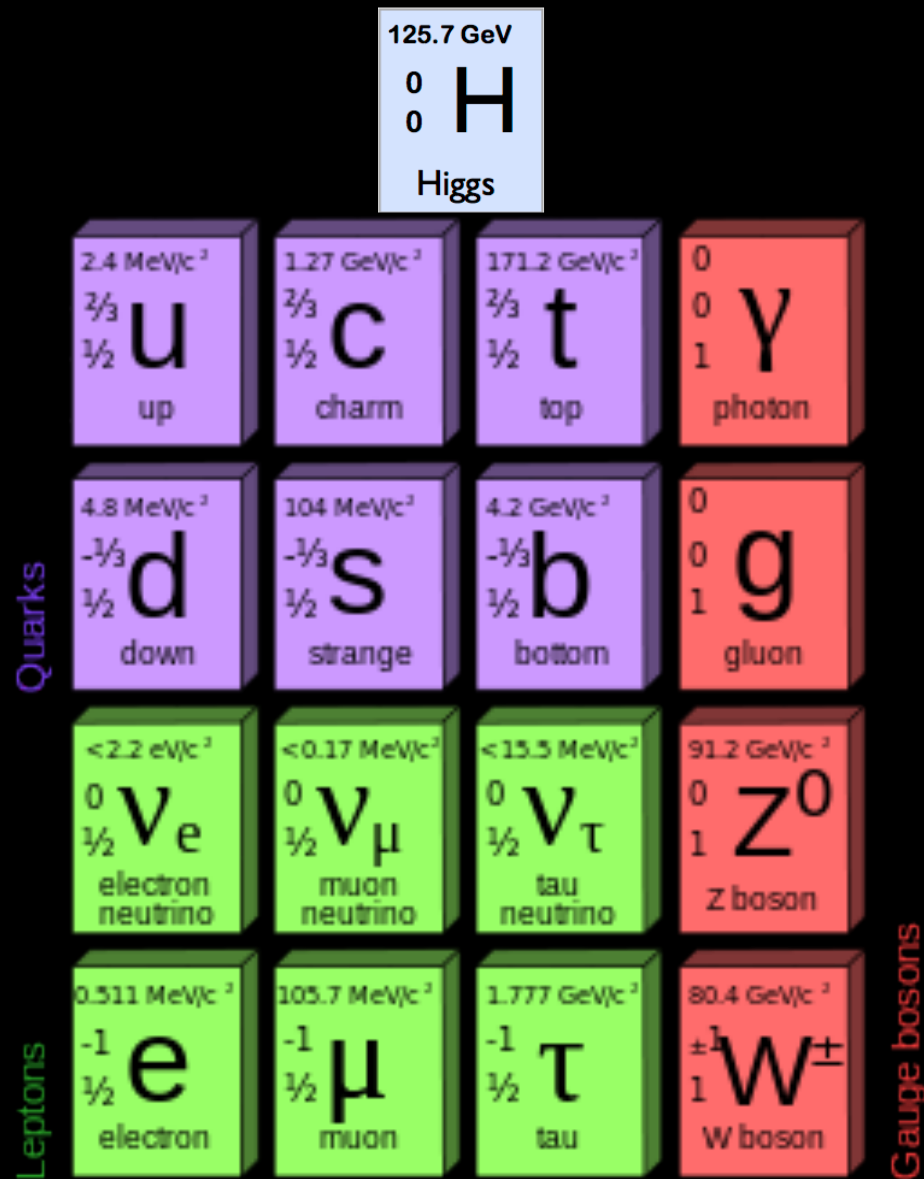
LIGO

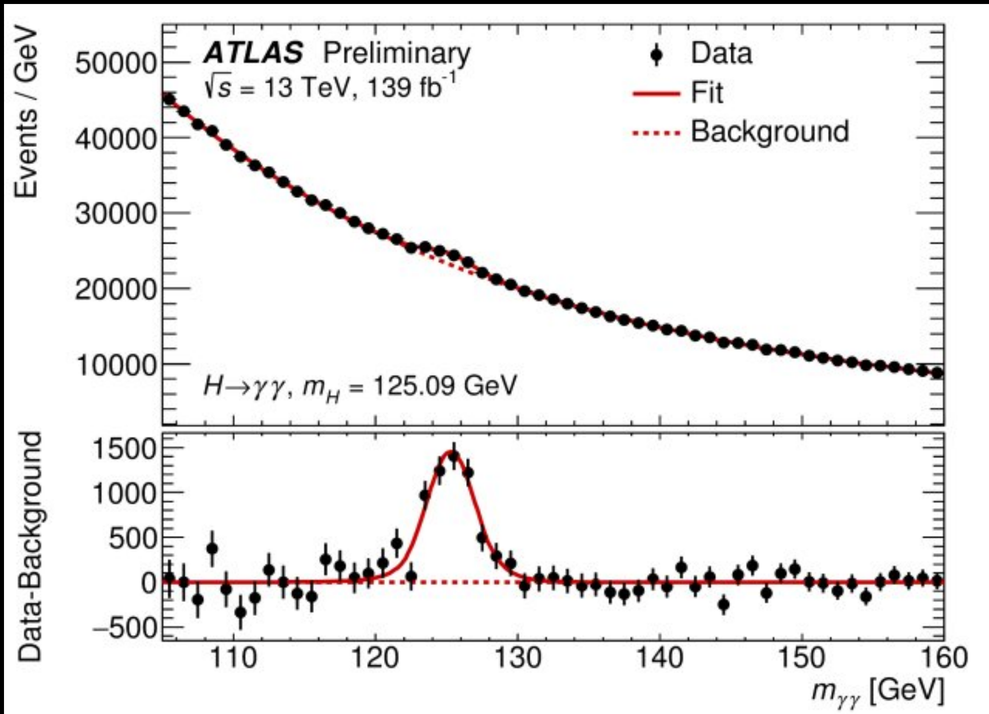

dark matter
26.8%


dark matter
26.8%
dark energy
68.3%


dark matter
26.8%
atoms
4.9%
dark energy
68.3%

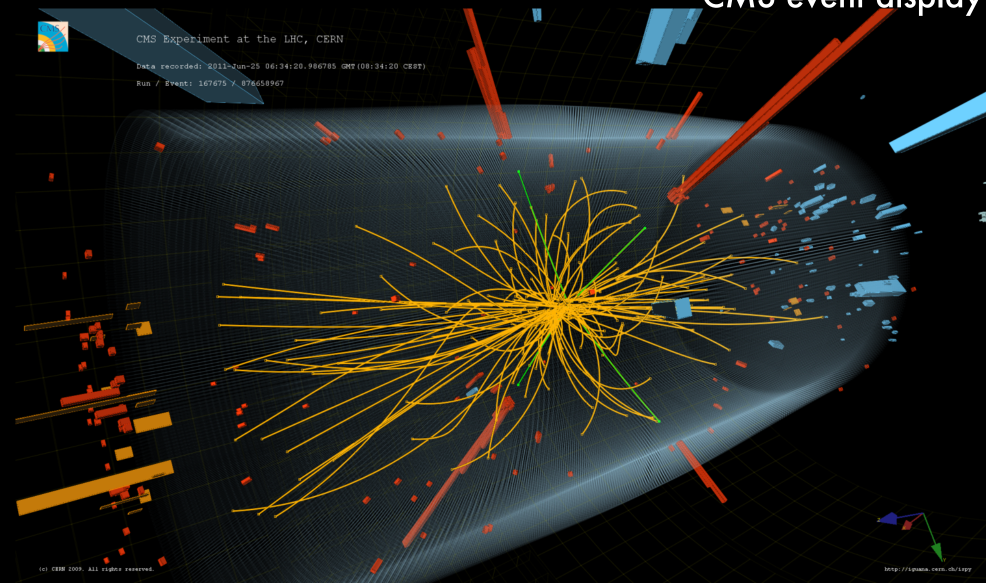
The Standard Model of Particle Physics

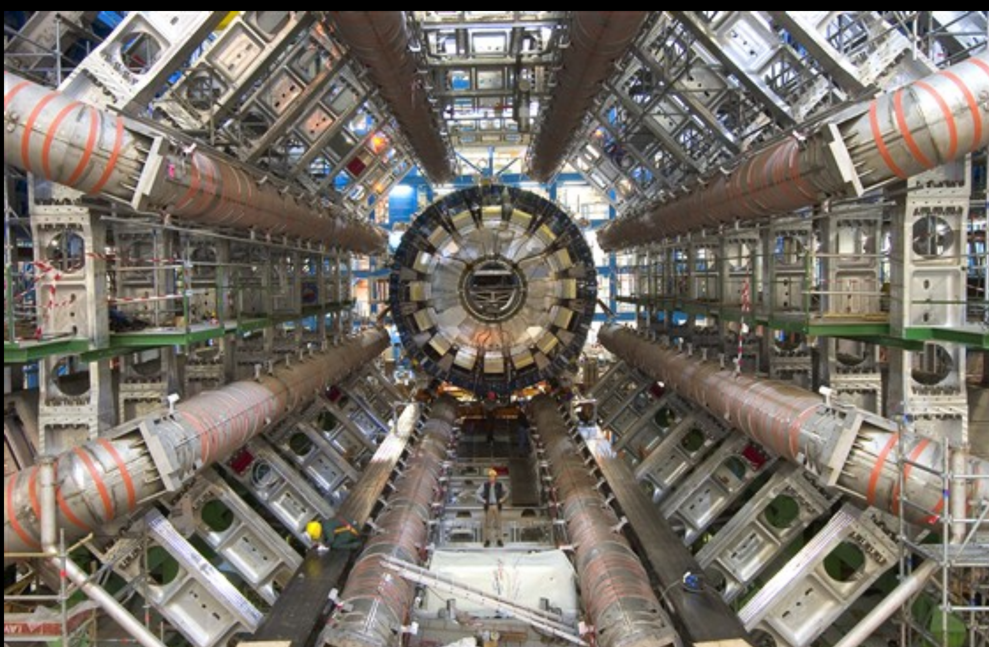




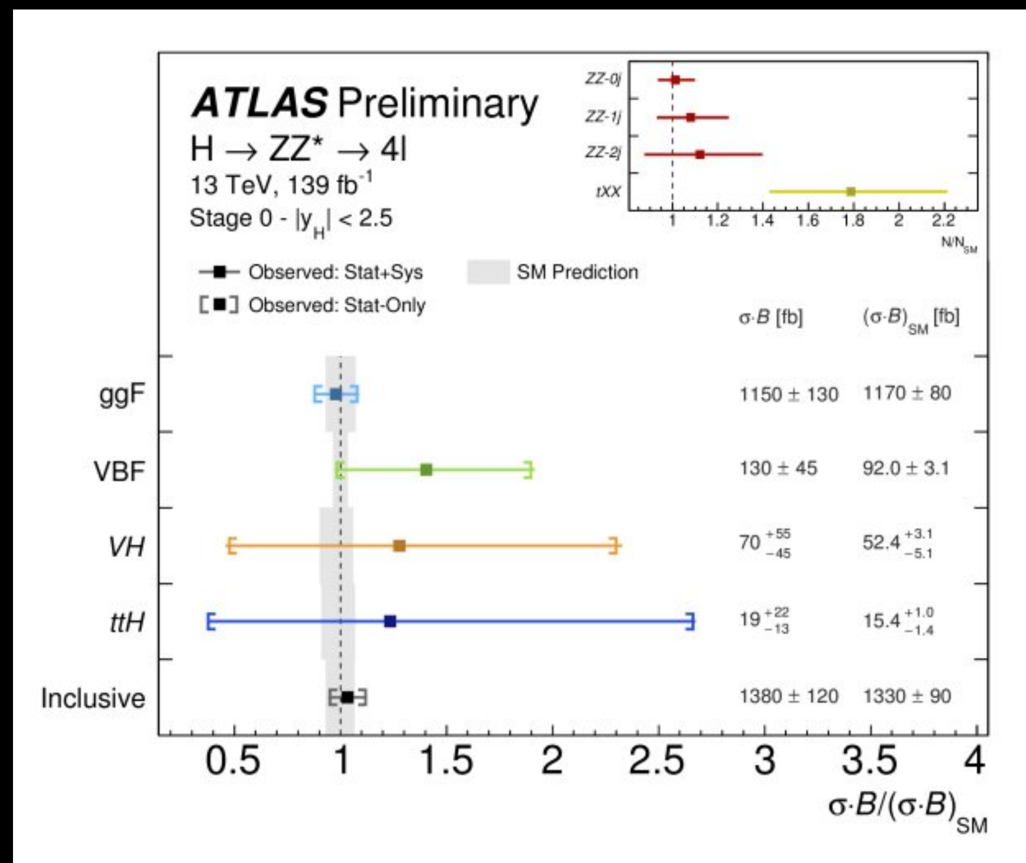
ATLAS, 2019

CMS event display

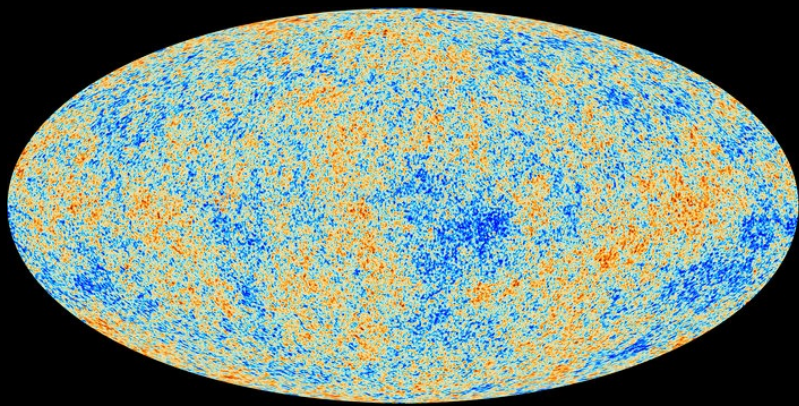




ATLAS detector

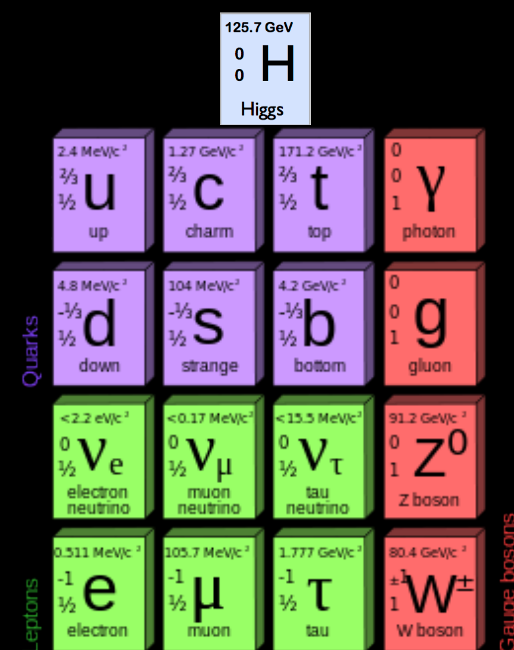


ATLAS, 2020



"Maximally Boring Universe"

"Nightmare Scenario"



So what now?

- Test the paradigm in new regimes, in new ways; find the edges of validity

  (Look for the most promising ways to break things.)

- Dark matter: Concordance cosmology, but ***not*** Standard Model

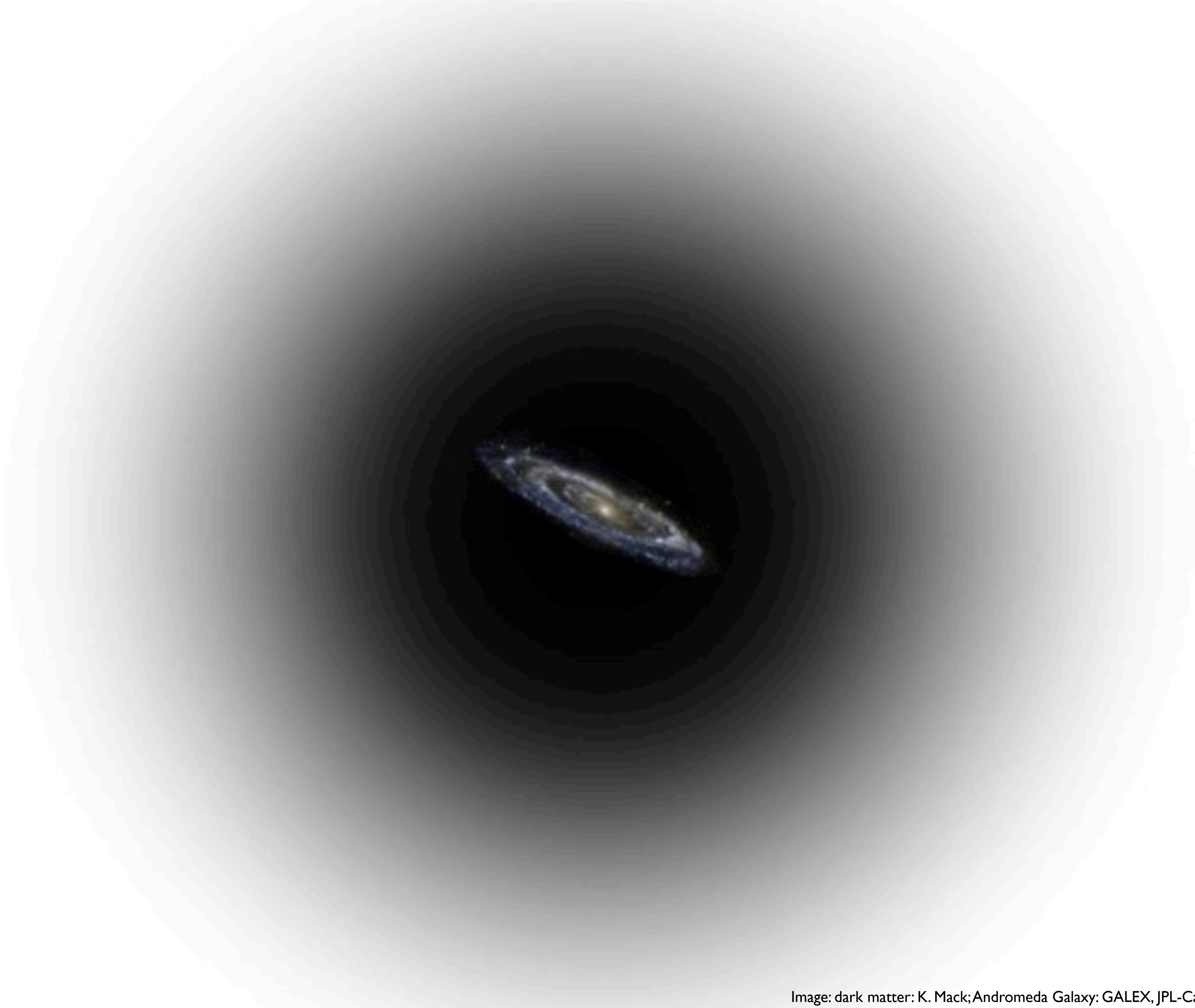


Image: dark matter: K. Mack; Andromeda Galaxy: GALEX, JPL-Caltech, NASA

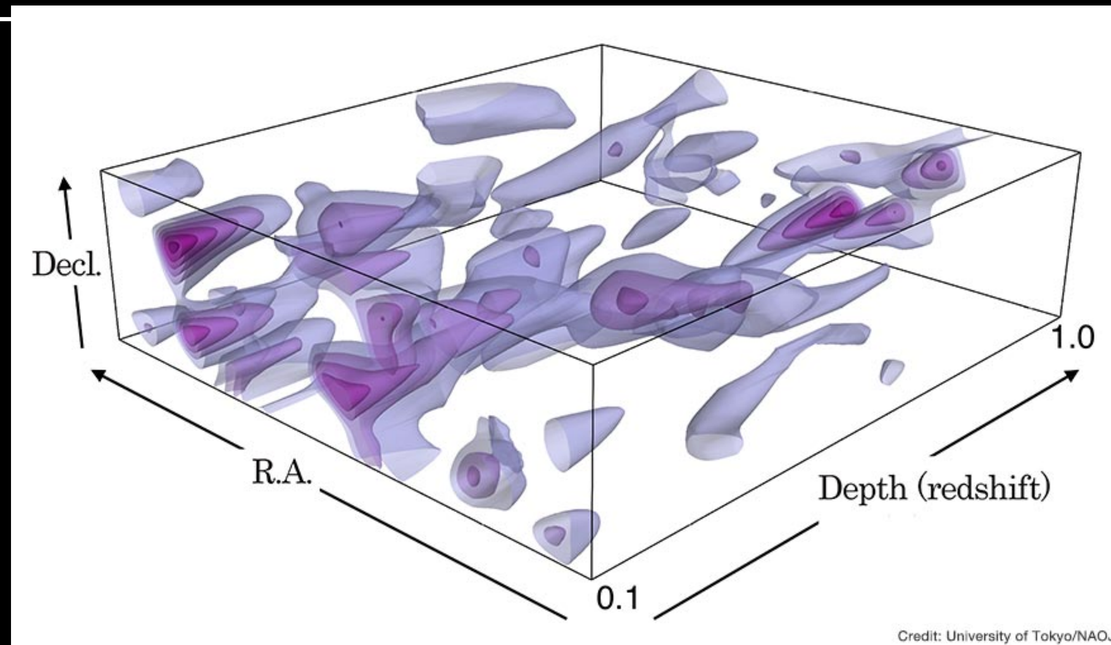
What We Don't Know

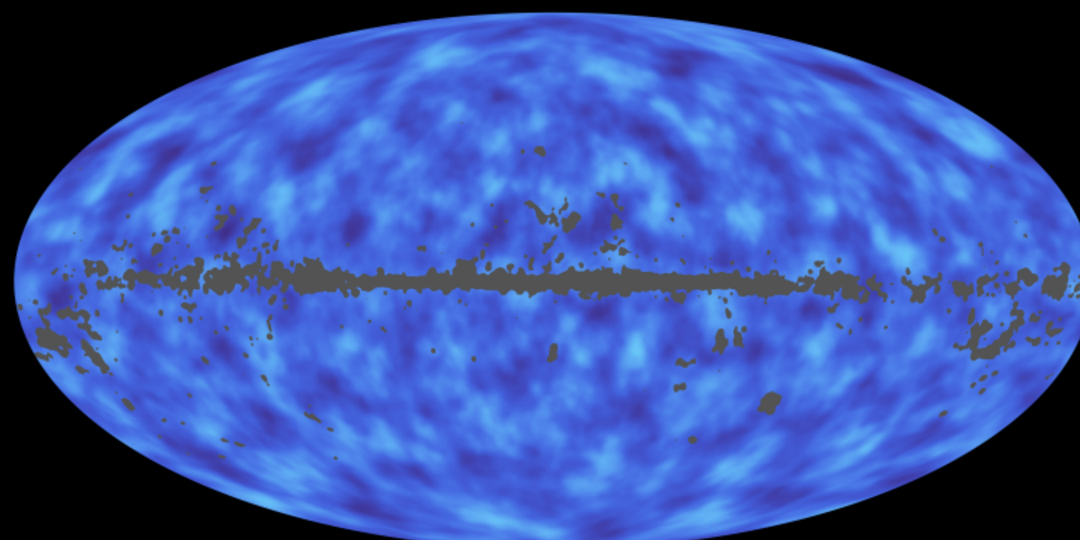
- Origin / particle type
- Particle mass
- Thermal history
- Non-trivial evolution?
- One component or many?
- Non-gravitational interactions (self or SM)?
- Small-scale behavior (mass of smallest halos)

Particle Zoo

What We Do Know

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





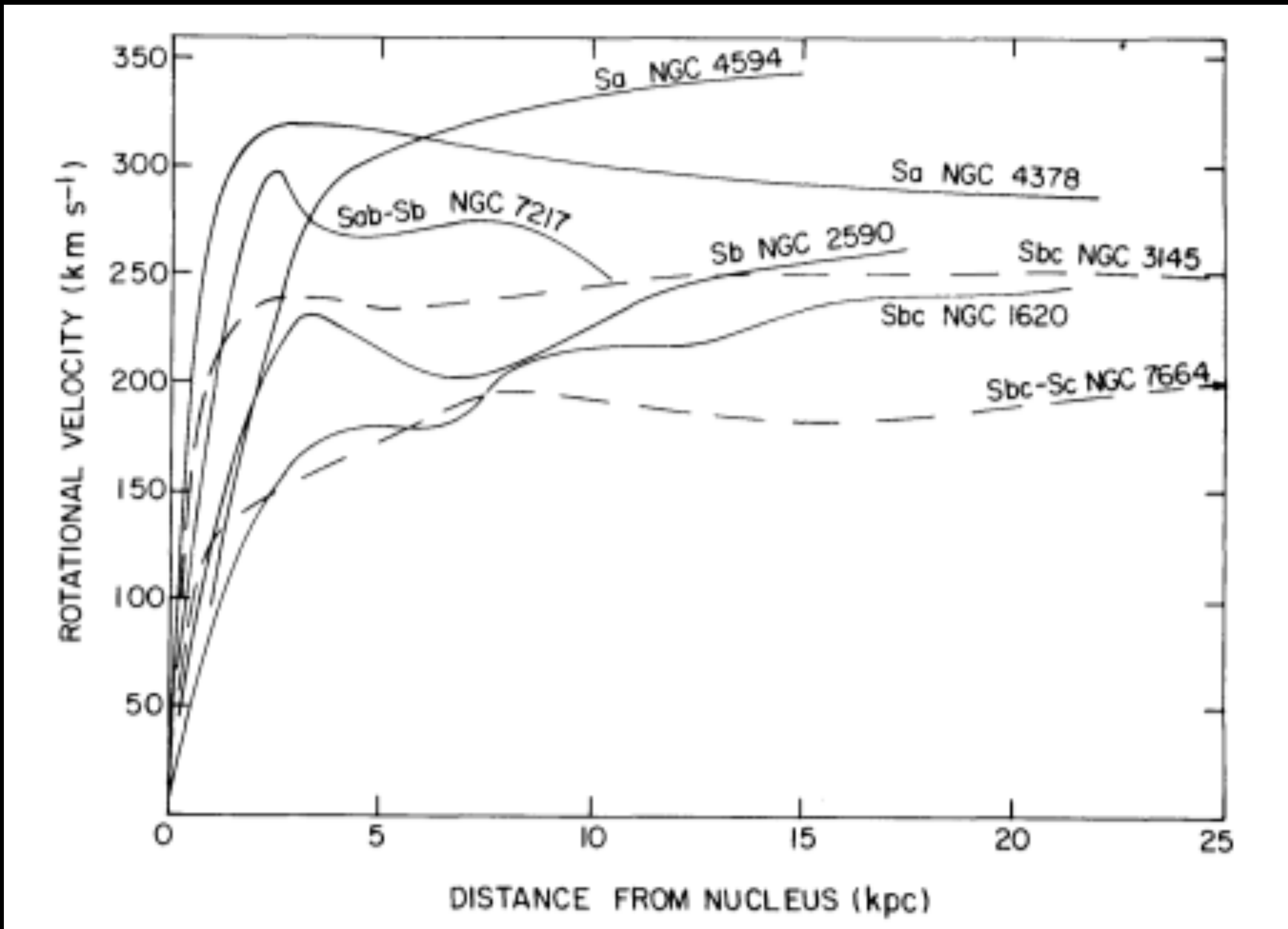
Planck Collaboration

Dark matter…

How do I know thee?

Let me count the ways…

1. Rotation Curves



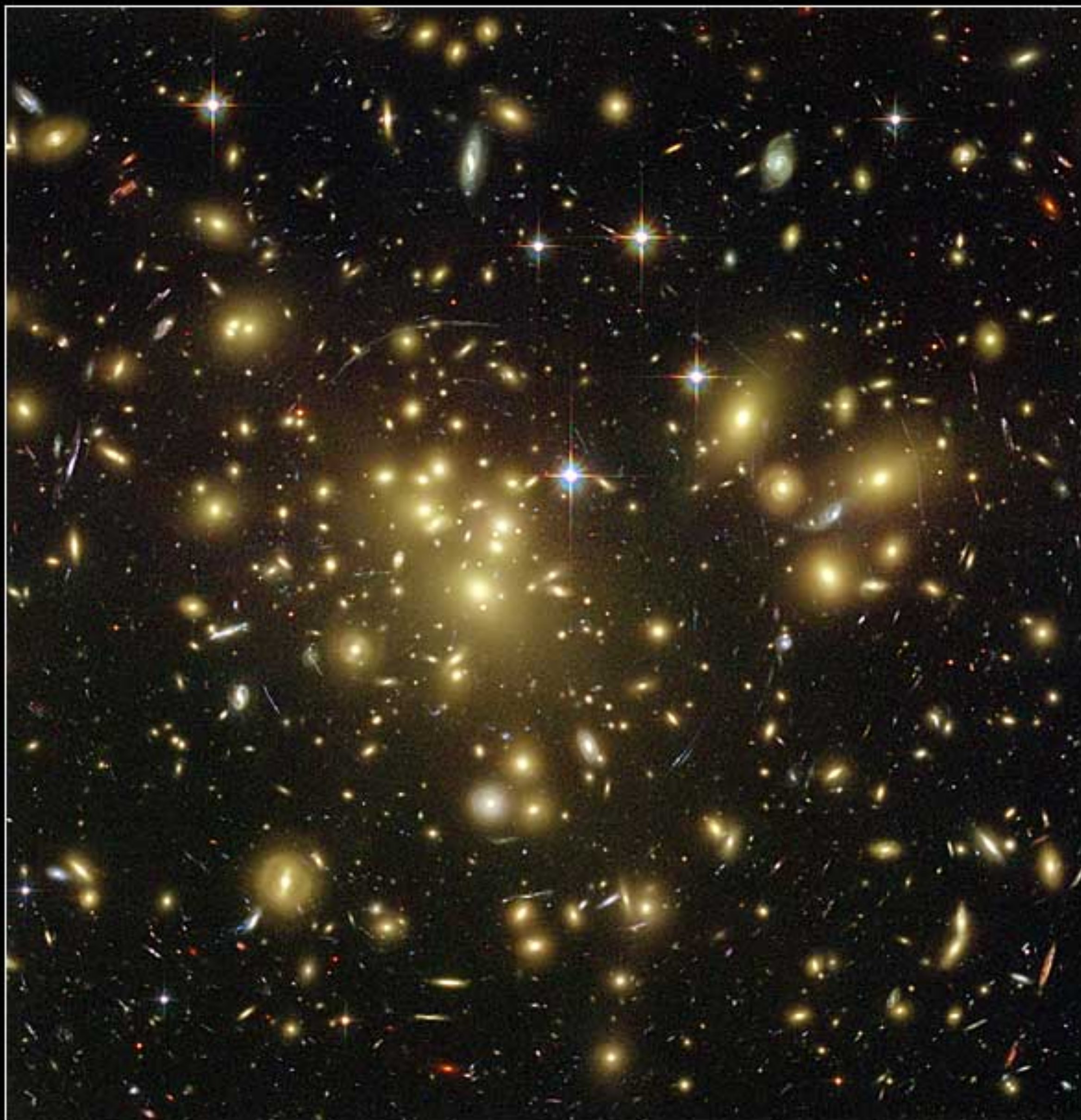
Rubin, Ford & Thonnard 1978

<u>What we learn:</u>

mass fraction

distribution

2. Cluster Dynamics

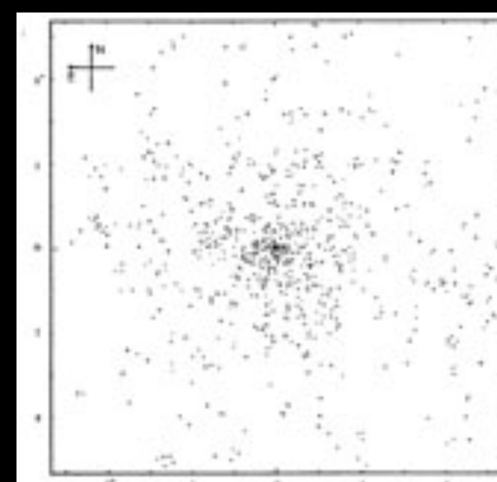


NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU),
M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory),
the ACS Science Team and ESA STScI-PRC03-01a

What we learn:

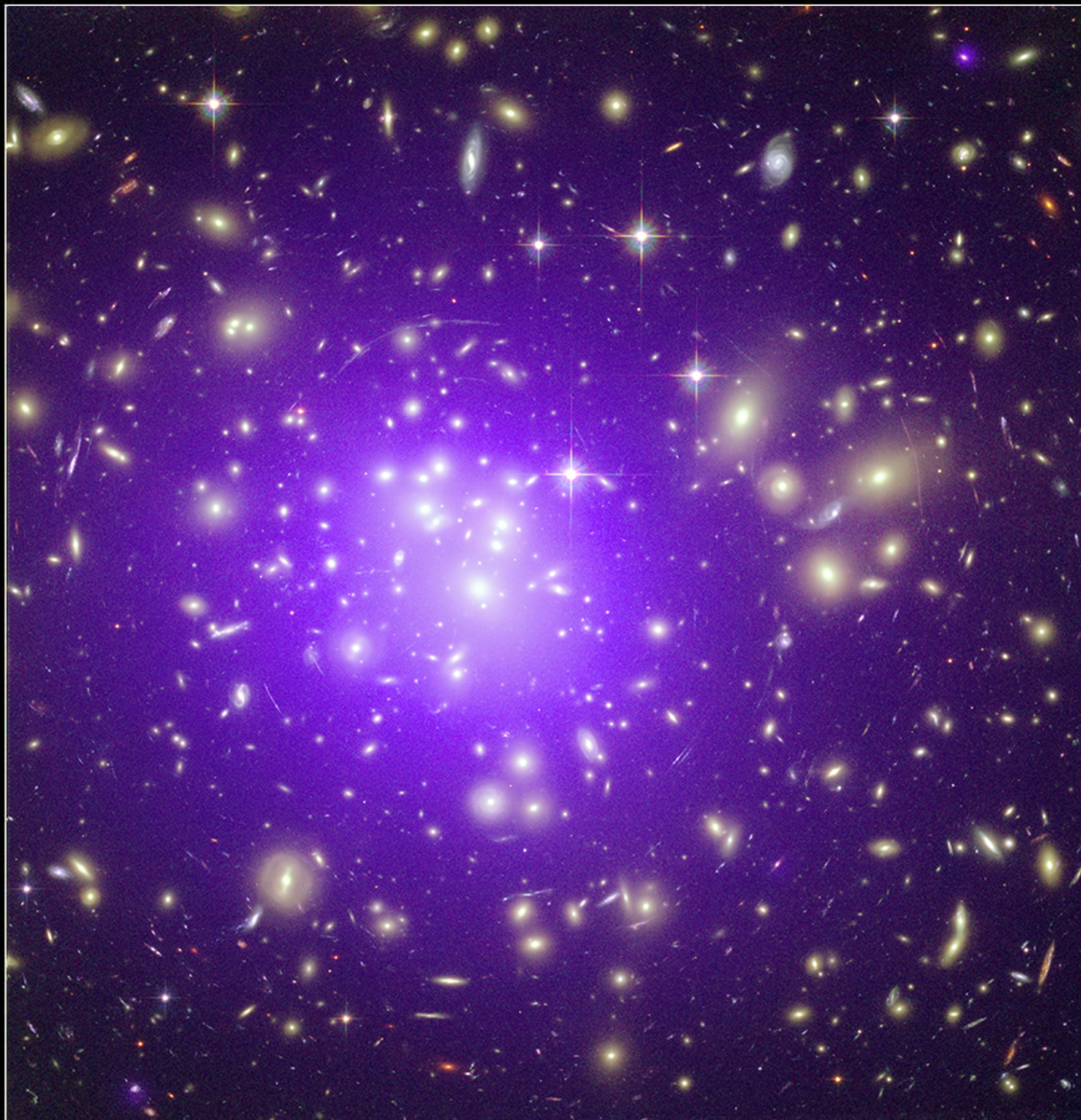
mass fraction

distribution



Zwicky 1937

3. Cluster Gas



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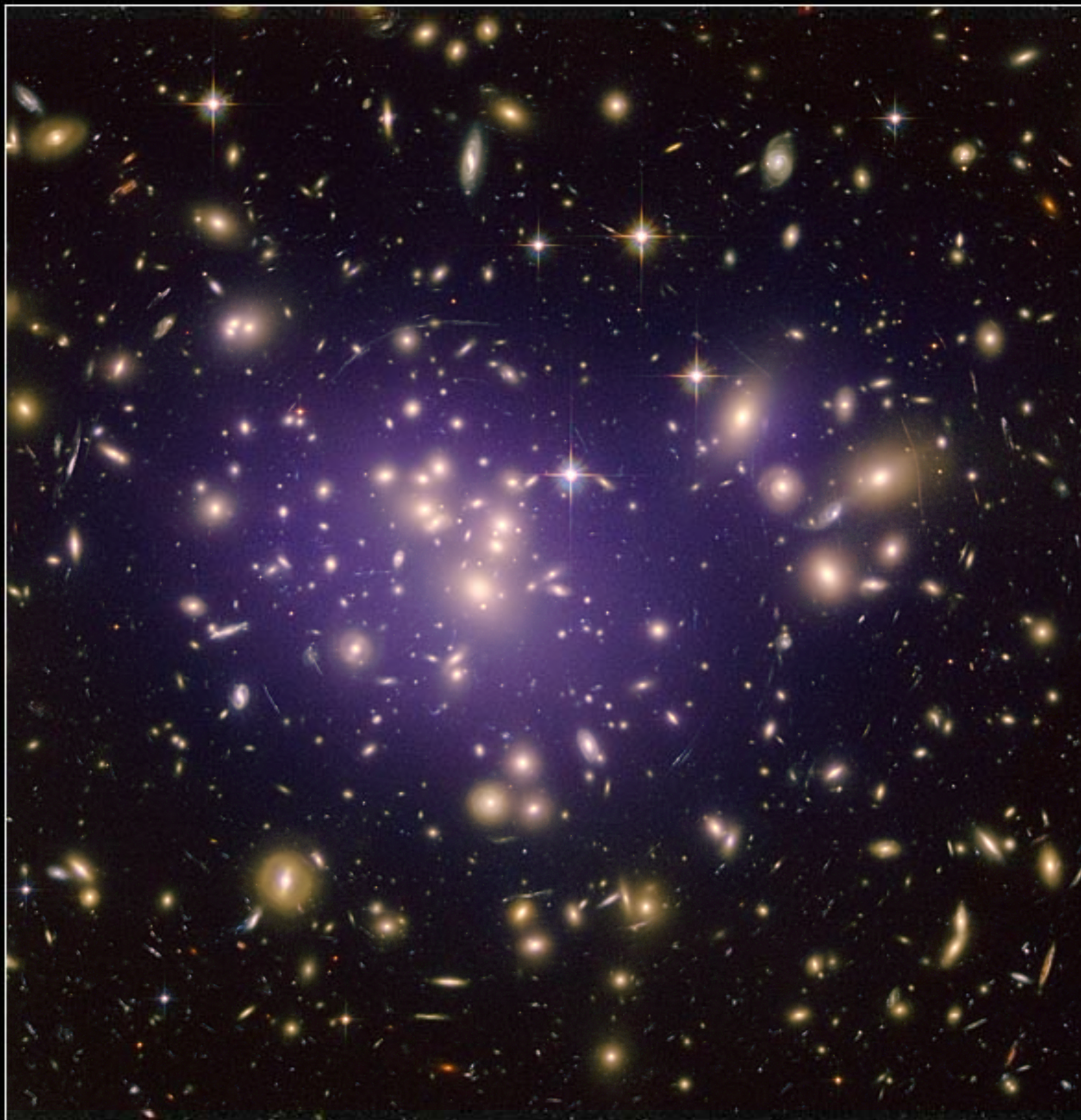
What we learn:

mass fraction

distribution

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

4. Strong Gravitational Lensing



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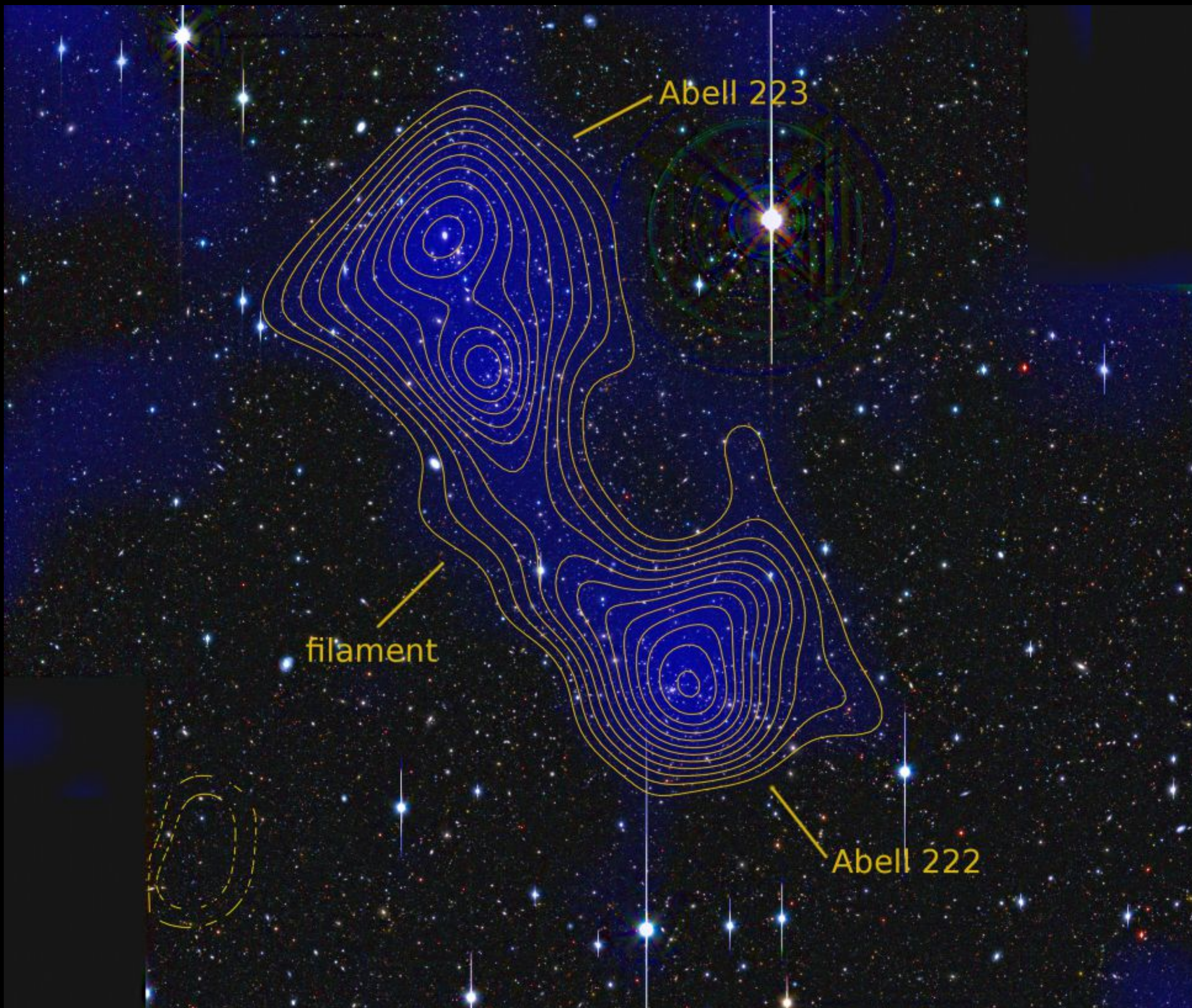
What we learn:

mass fraction

distribution

5. Weak Gravitational Lensing



Dietrich et al. 2016

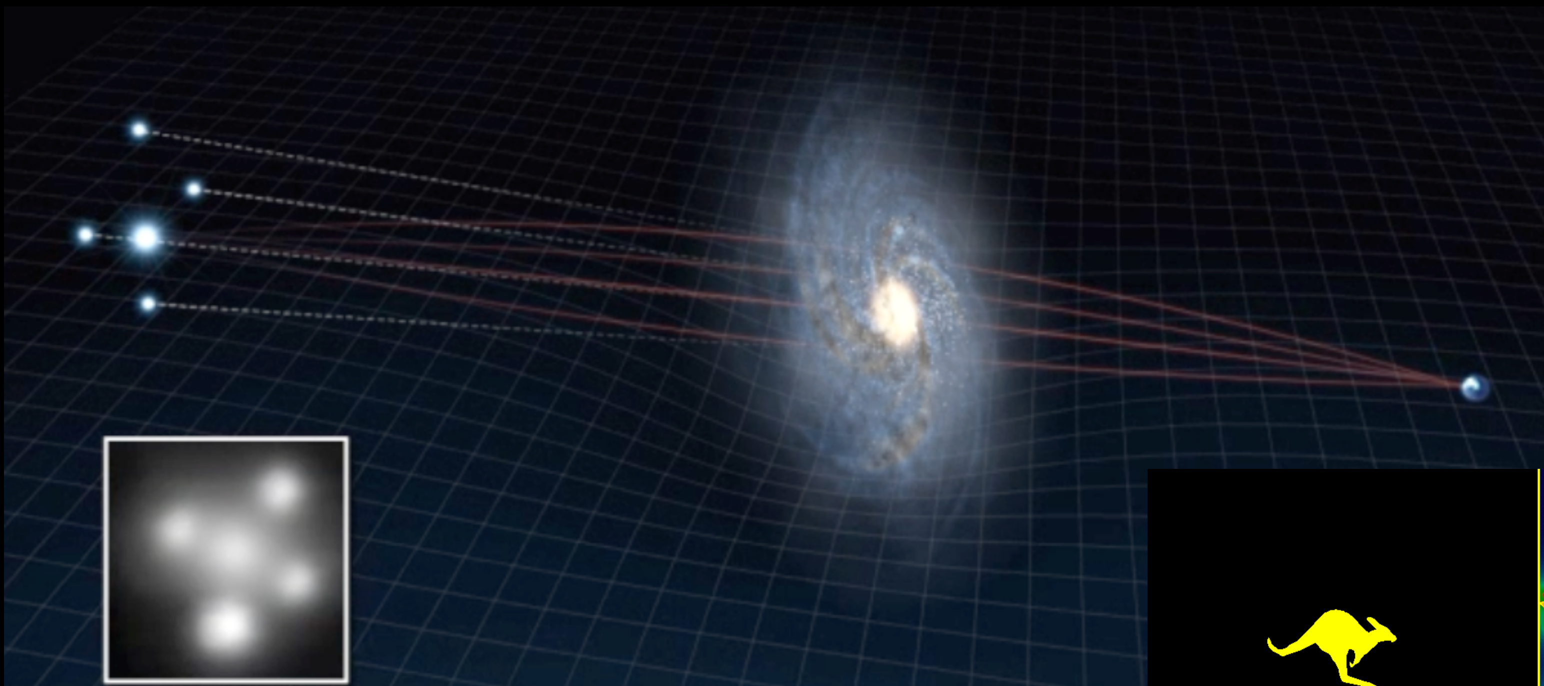
What we learn:

distribution

shape

structure

6. Cosmological Microlensing

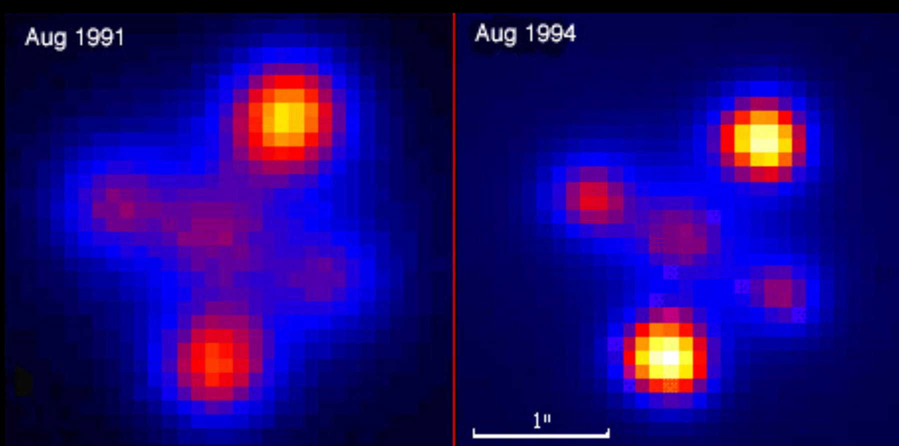


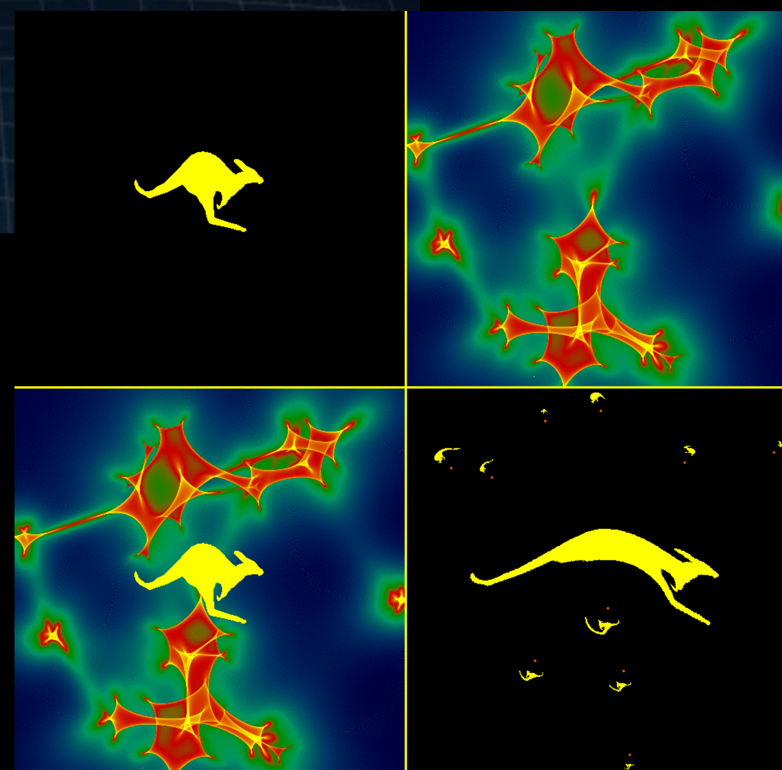
What we learn:

mass fraction

smoothness

Lewis & Irwin 1996





Joachim Wambsganss

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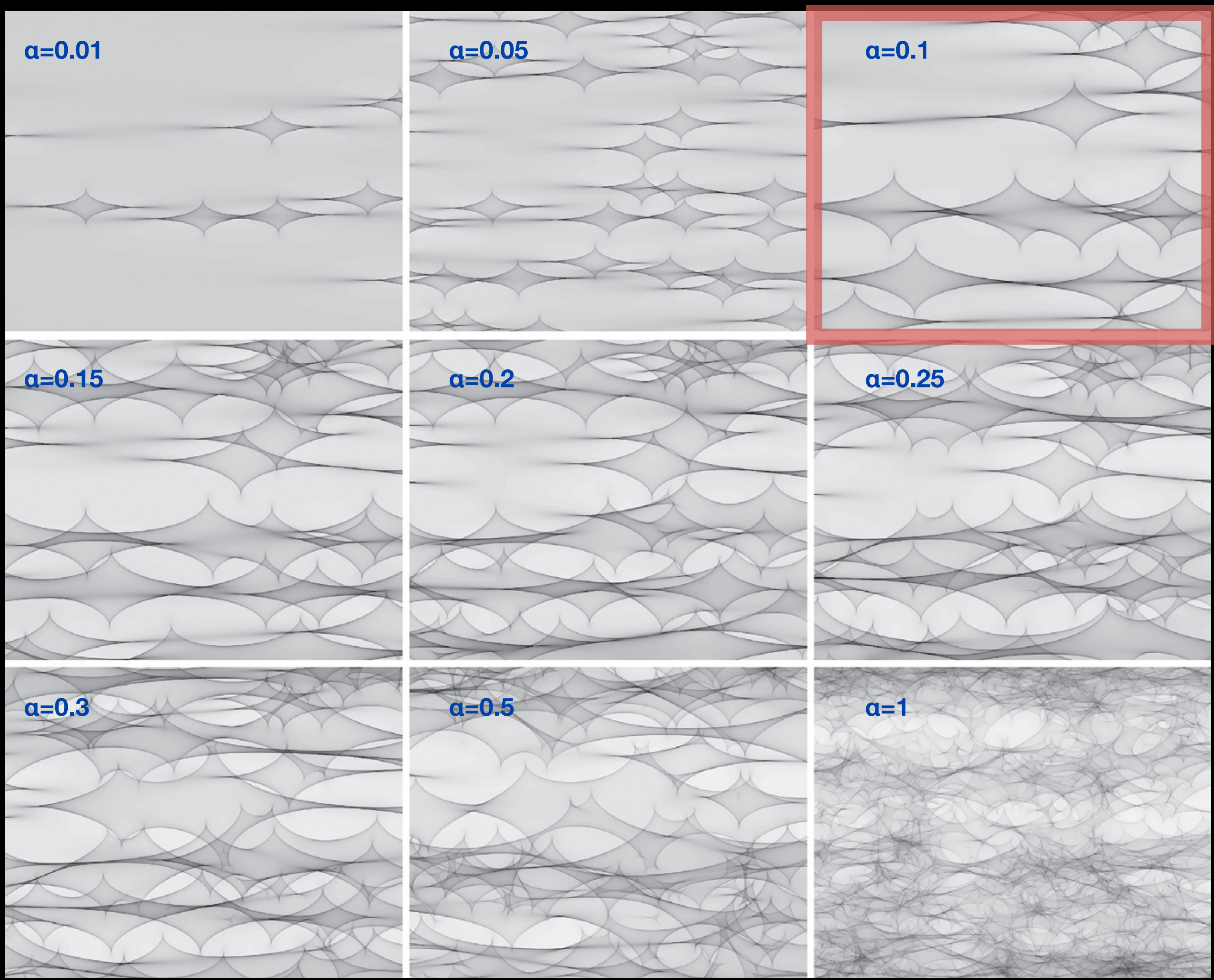

Mediavilla et al. 2009

What we learn:

mass fraction

smoothness

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

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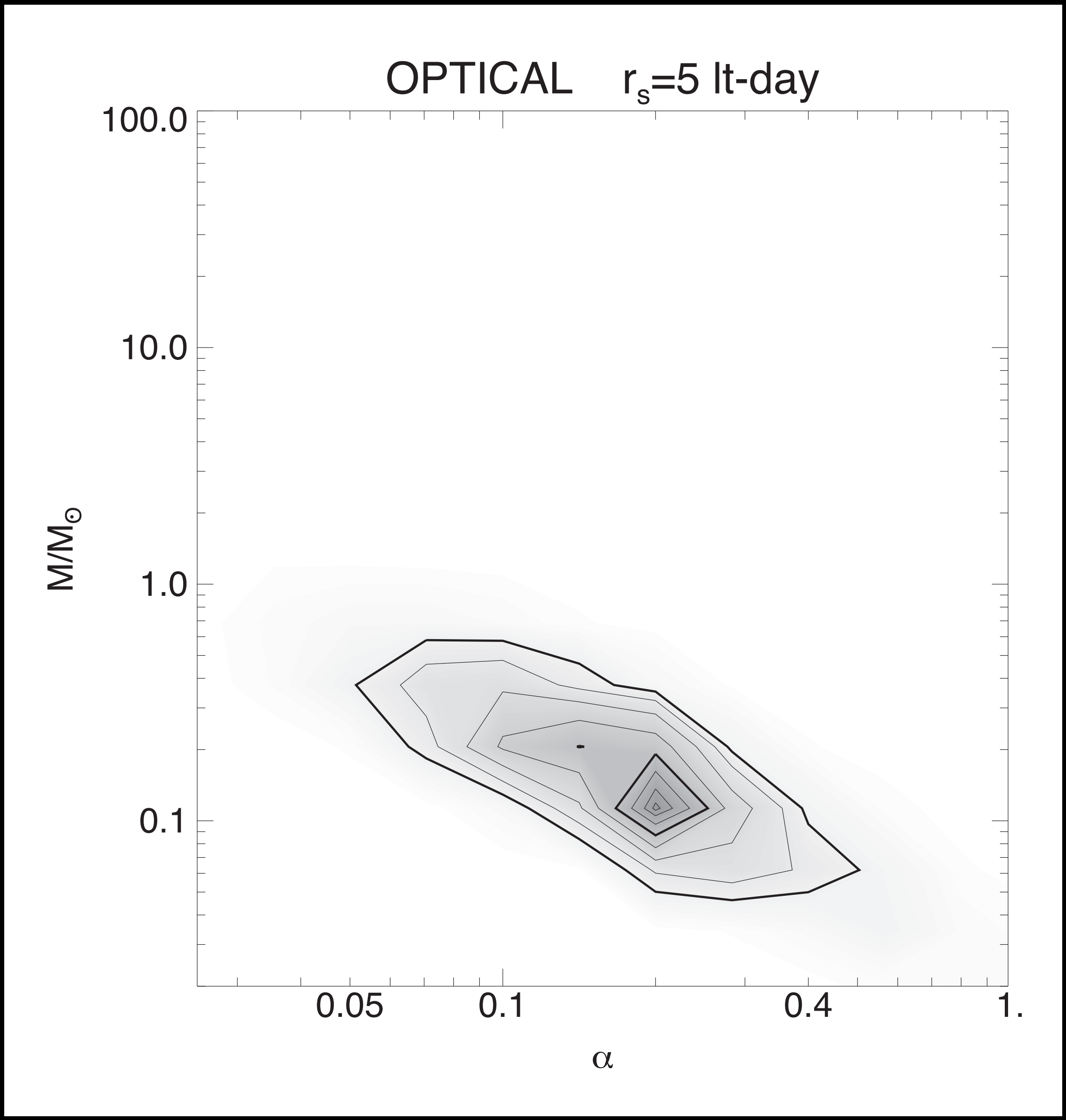

Mediavilla et al. 2017

What we learn:

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smoothness

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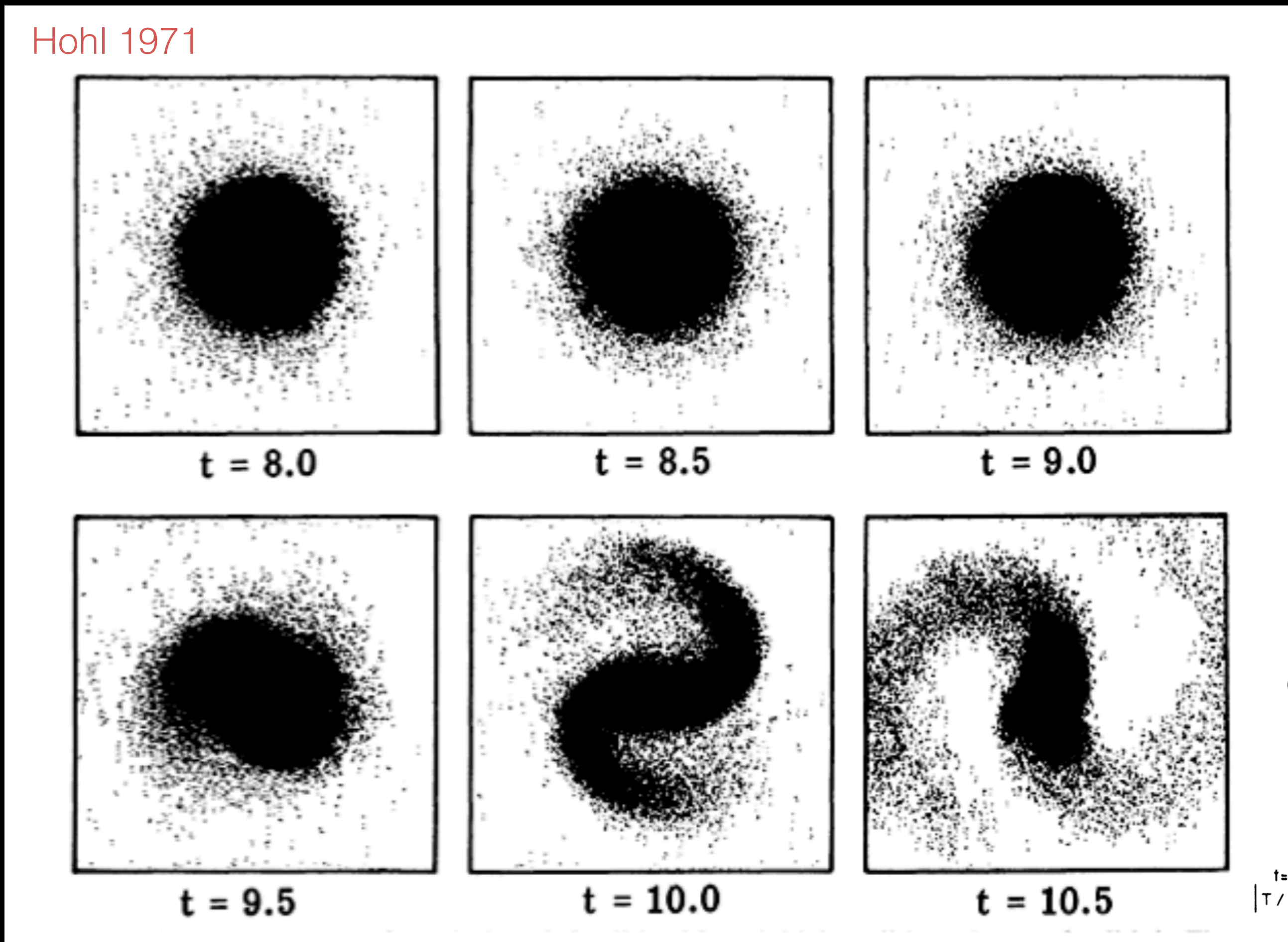
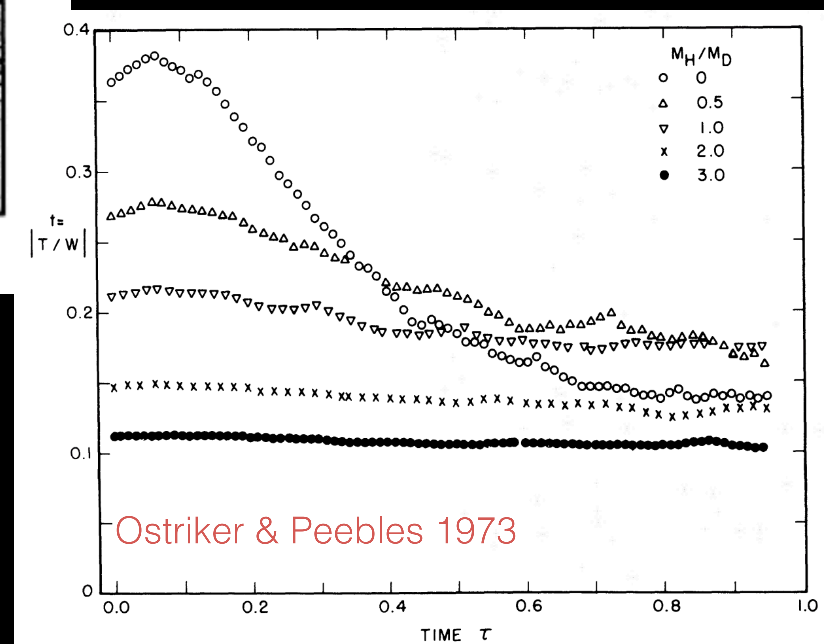
7. Disk Stability



What we learn:

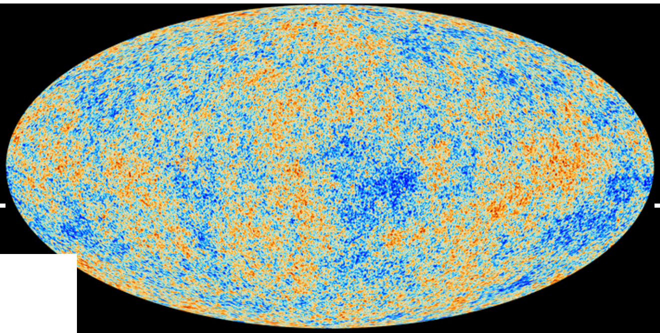
distribution

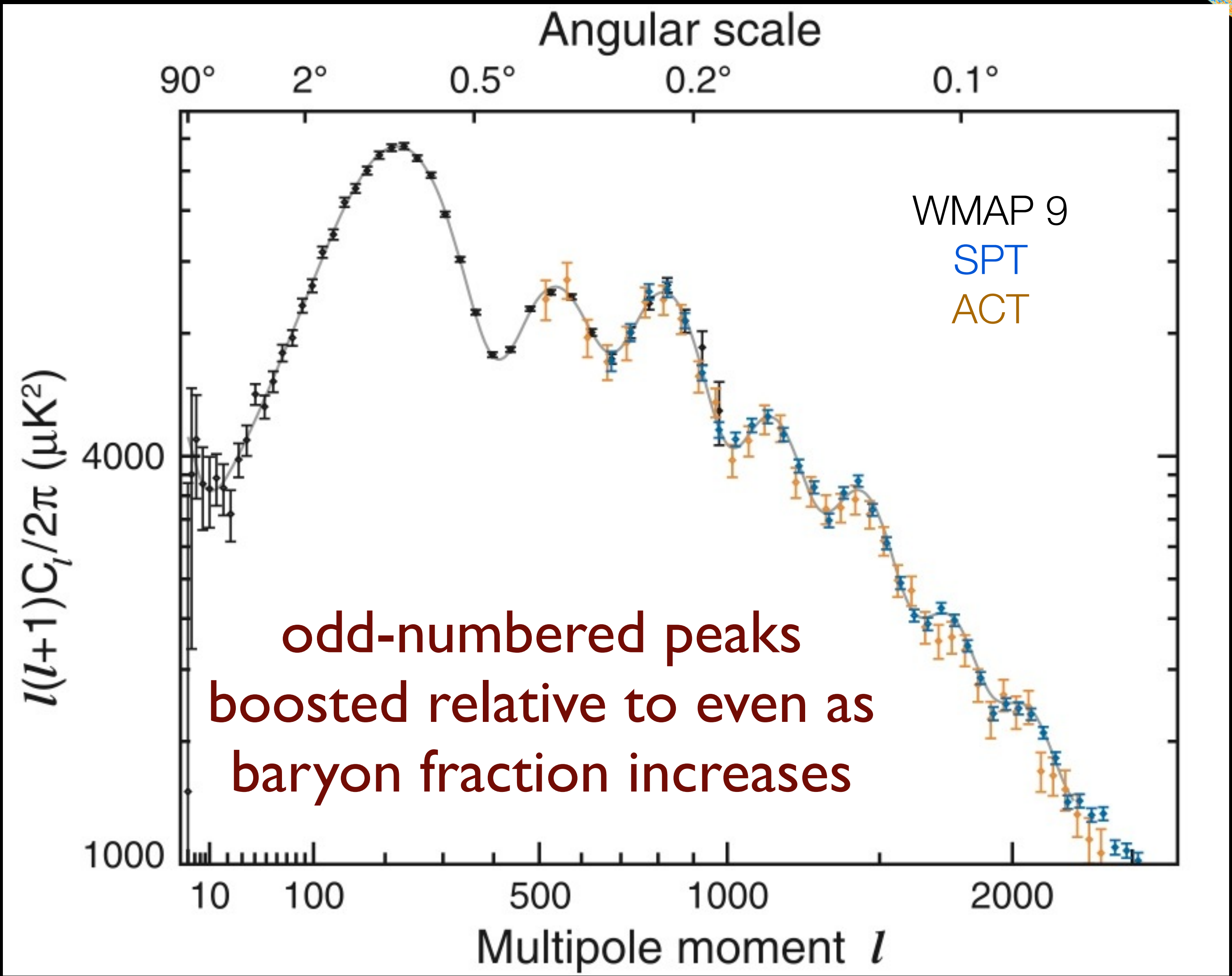
abundance



Flat stellar/gaseous disks are *unstable* to perturbations without dark matter halos extending beyond the stars

8. CMB Acoustic Peaks





Hinshaw et al. 2013

<u>What we learn:</u>

ratio of DM/ collisional matter

thermal history

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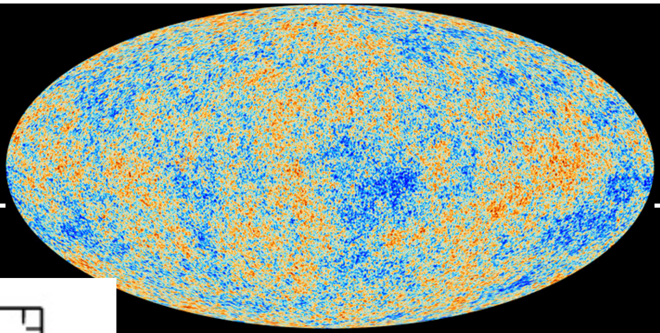
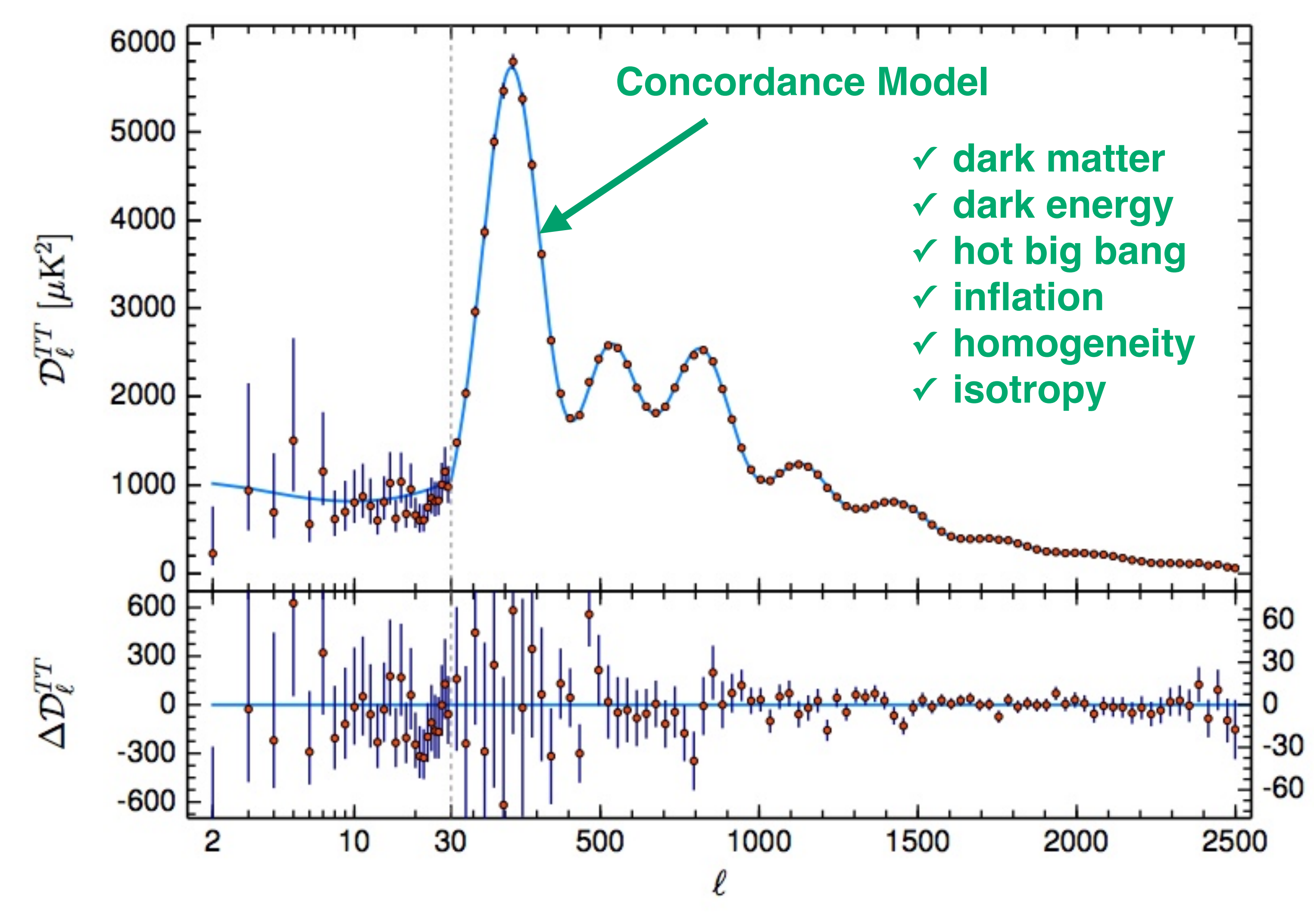




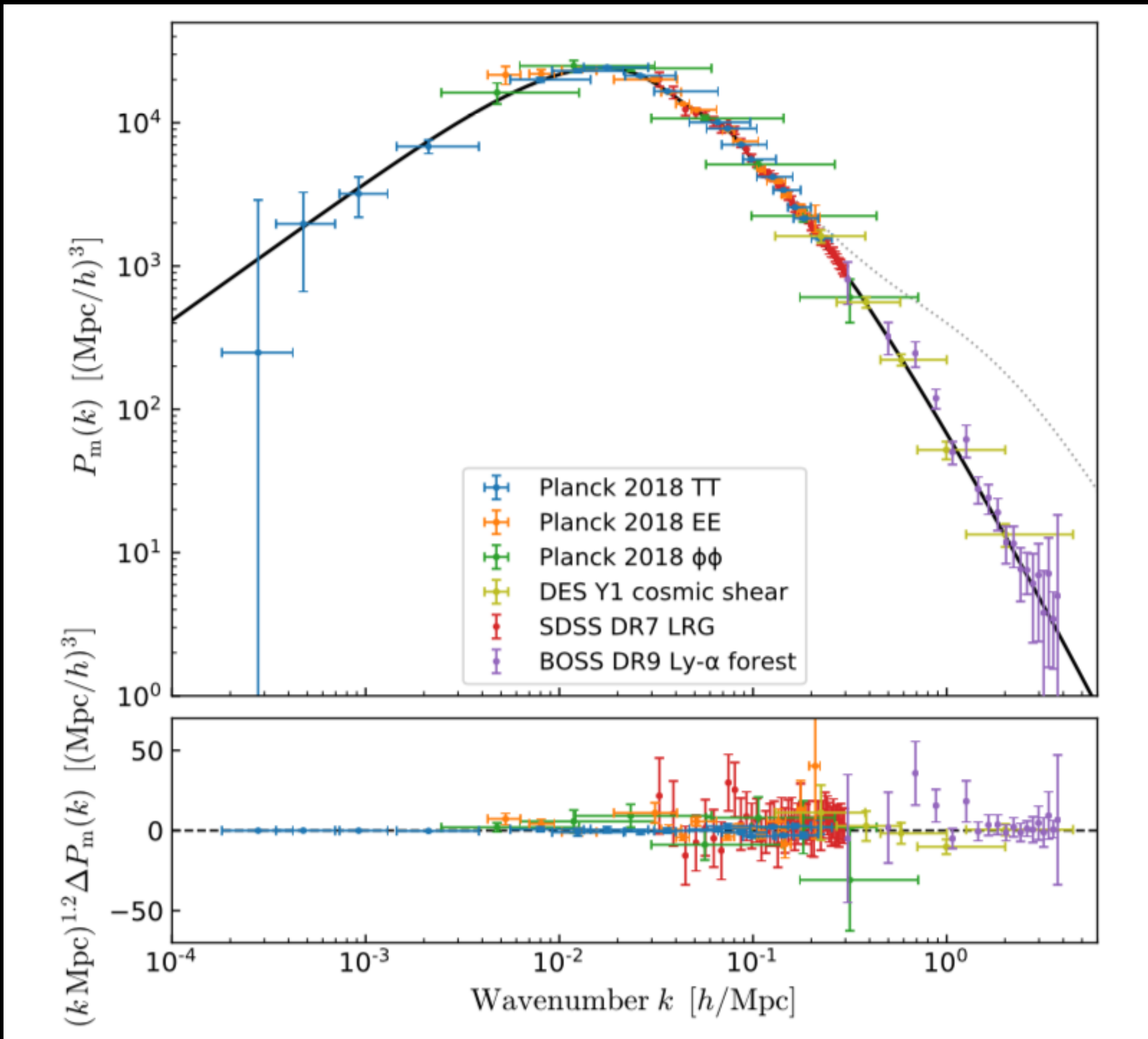
<u>What we learn:</u>

ratio of DM/ collisional matter

thermal history

Planck 2018

9. Matter Power Spectrum



Chabanier et al. 2019

<u>What we learn:</u>

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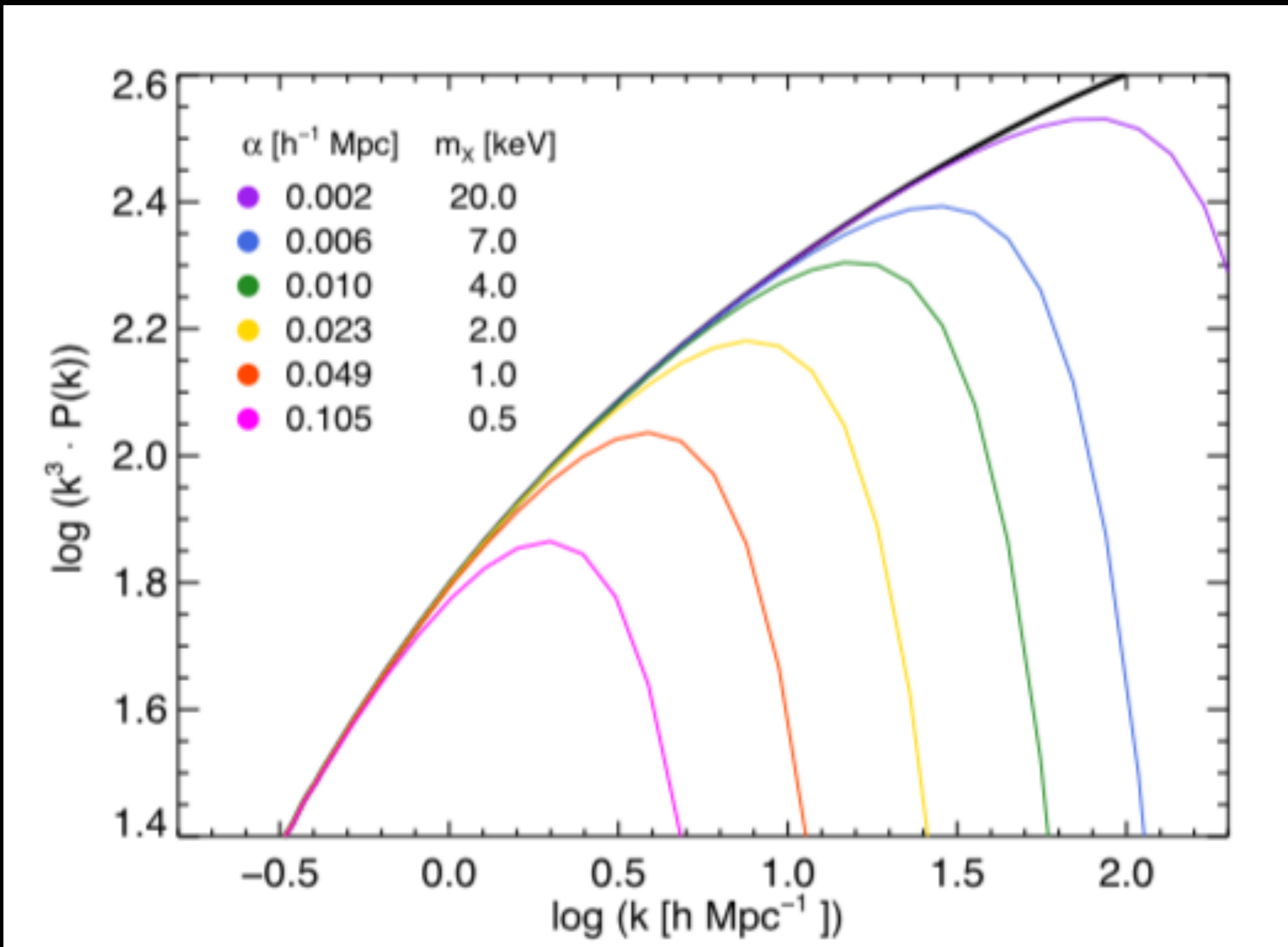


Kennedy et al. 2013

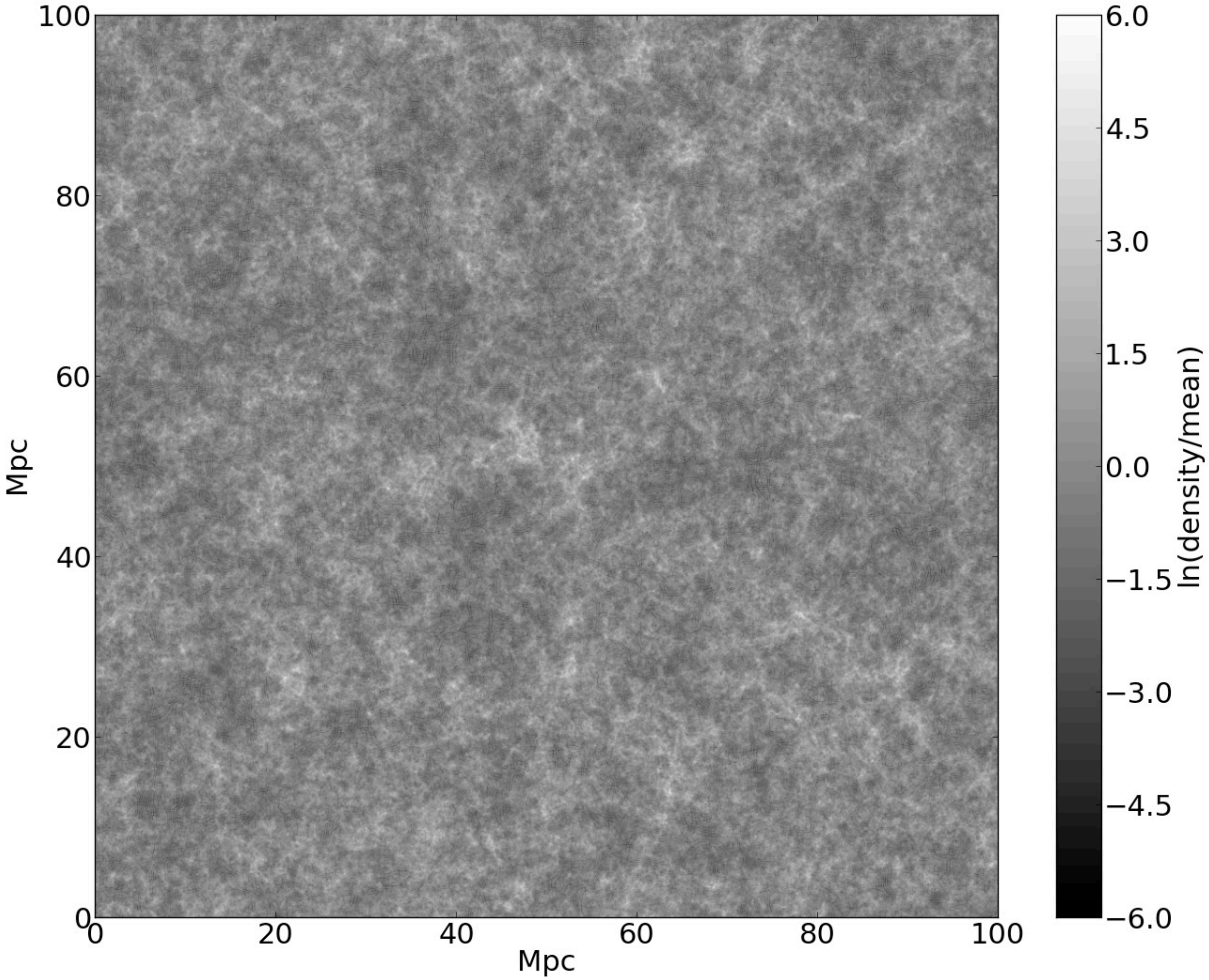
What we learn:

ratio of DM/ collisional matter

thermal history

Current limits: m_X > few keV

10. Large Scale Structure



Paul Angel, Tiamat Simulation

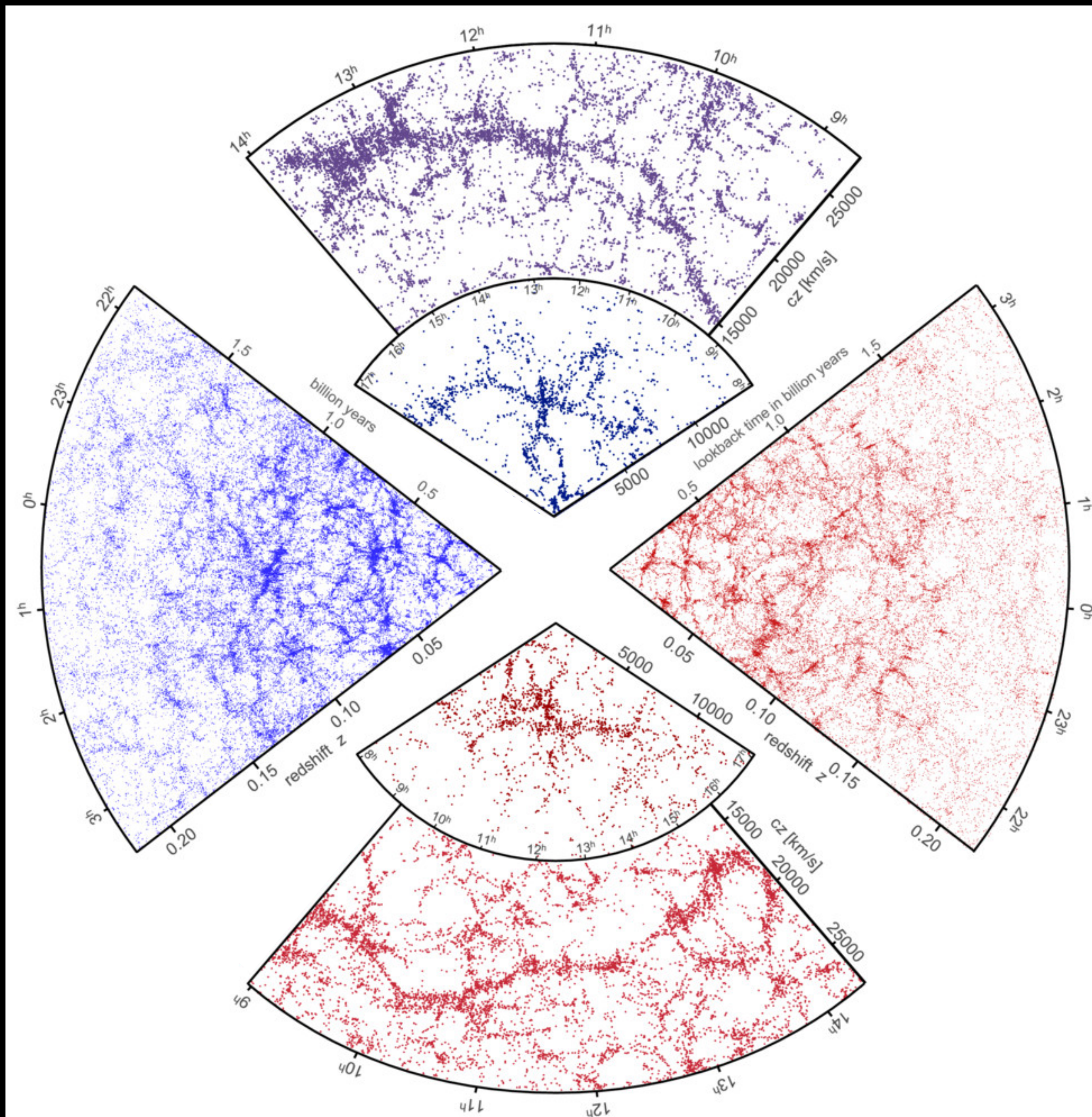
<u>What we learn:</u>

ratio of DM/ collisional matter

thermal history

Excellent agreement between simulations and galaxy distribution on the largest scales

10. Large Scale Structure



Frenk & White 2012

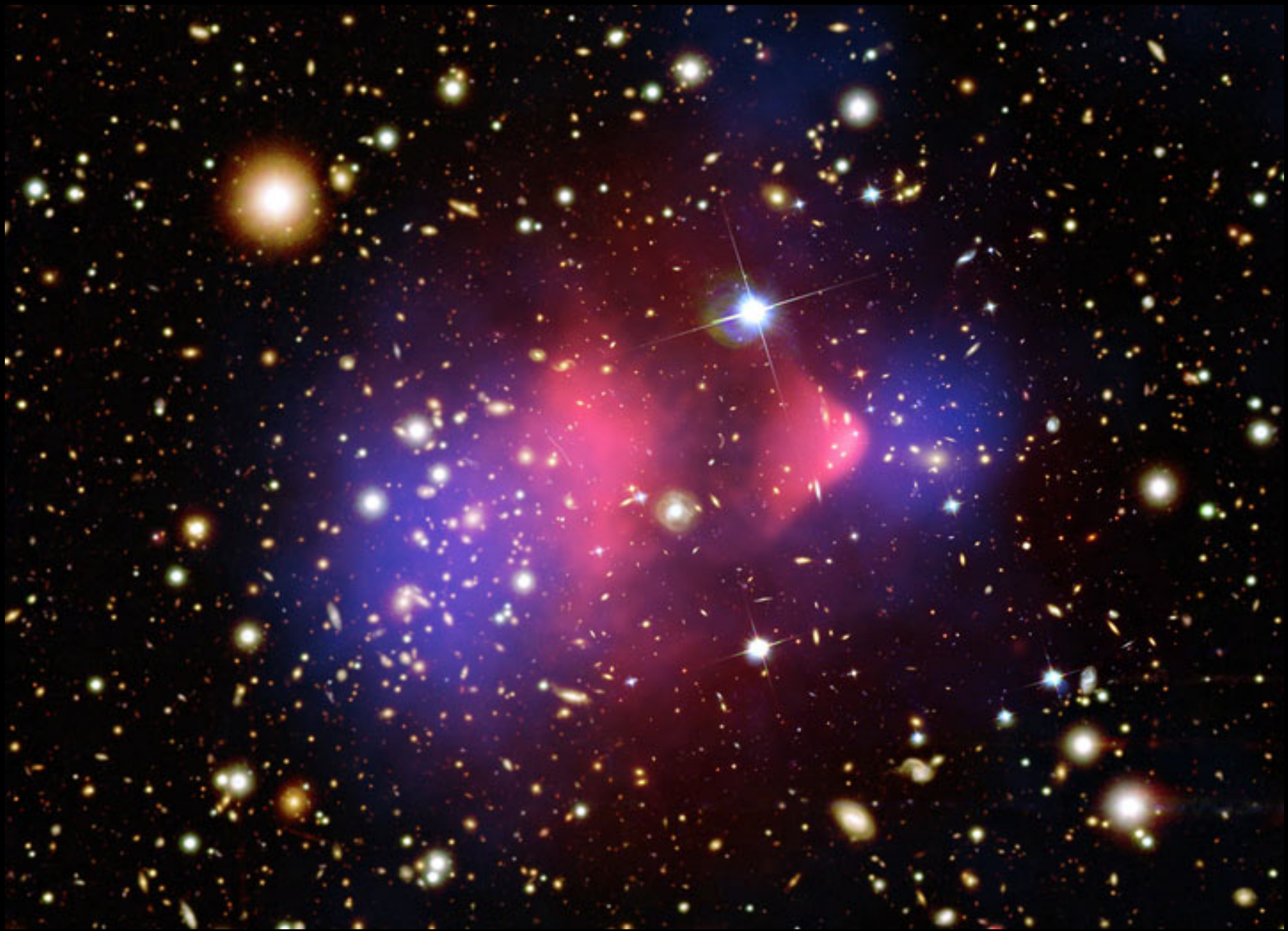
What we learn:

ratio of DM/ collisional matter

thermal history

Excellent agreement between simulations and galaxy distribution on the largest scales

11. Galaxy/Cluster Collisions



NASA/Clowe et al. 2006

What we learn:

distribution

separation from collisional matter

self-interaction

Difficult to explain without collisionless matter

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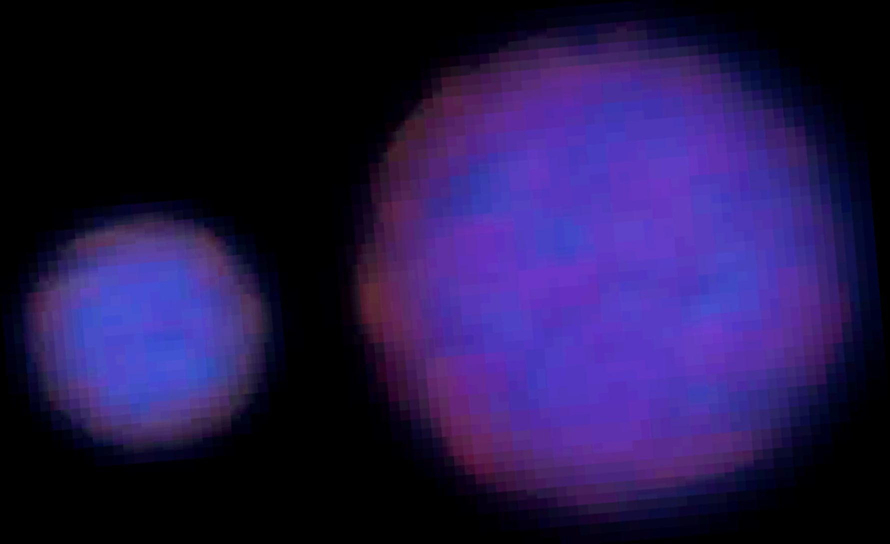

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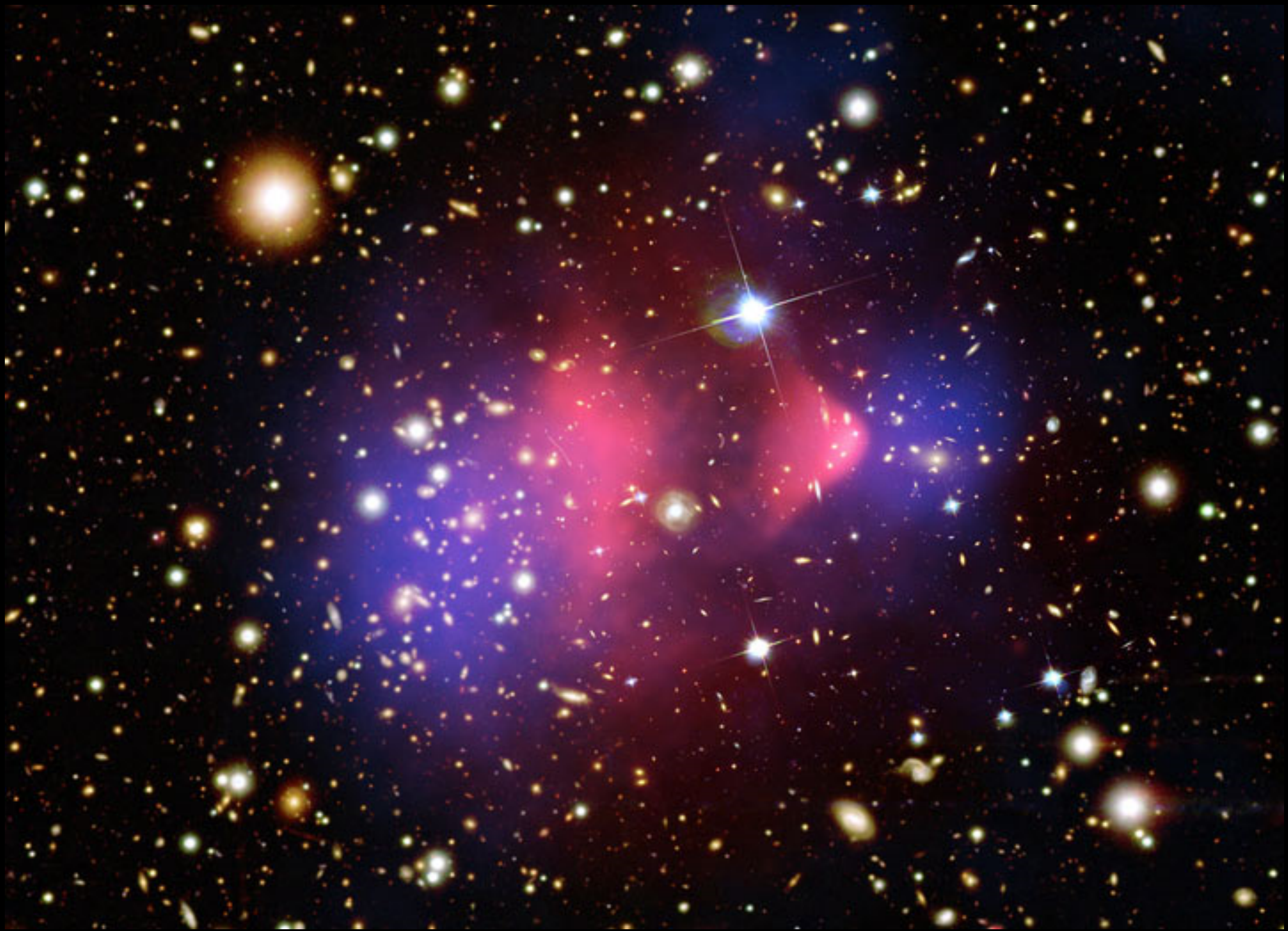

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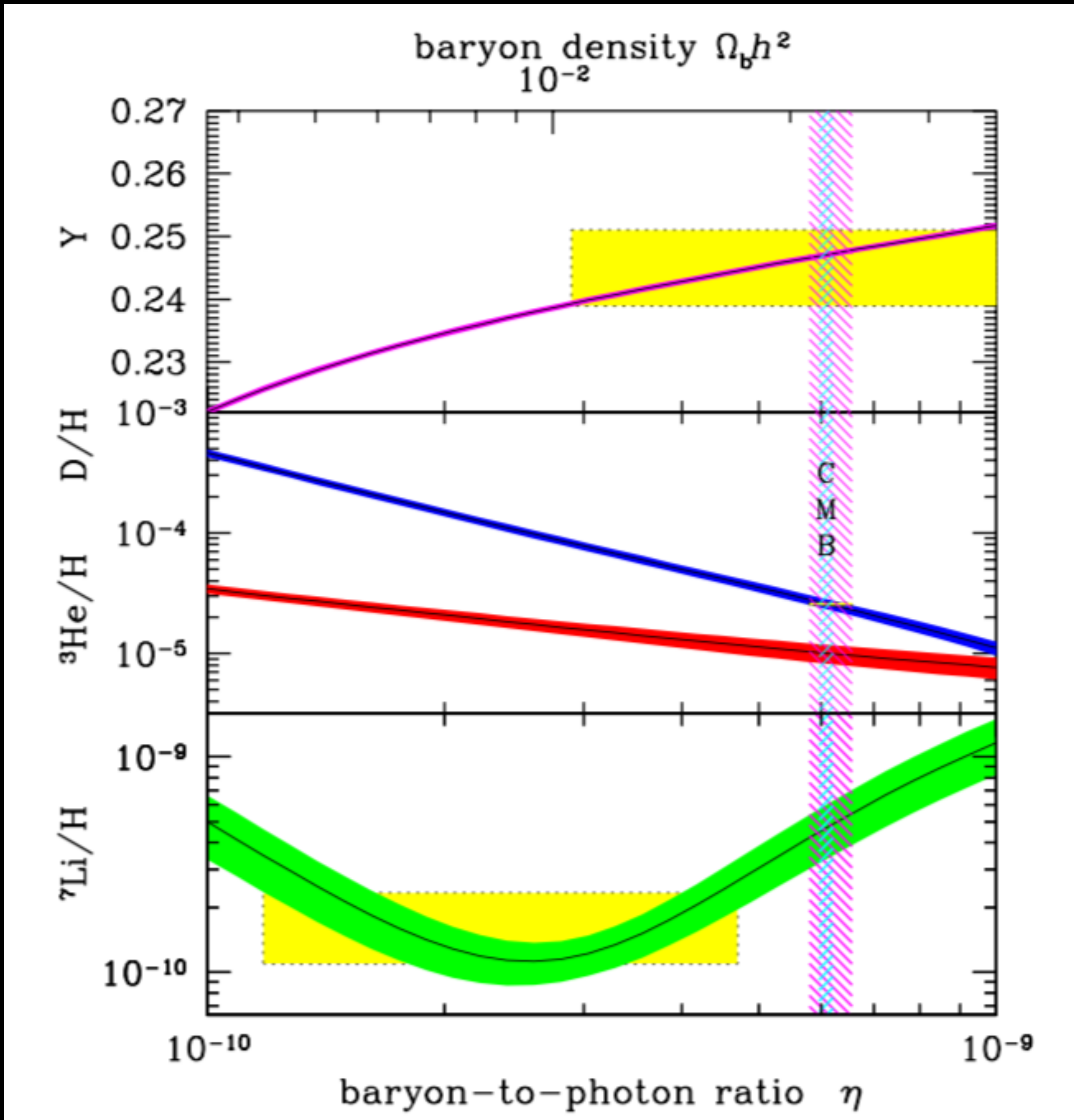
12. Big Bang Nucleosynthesis



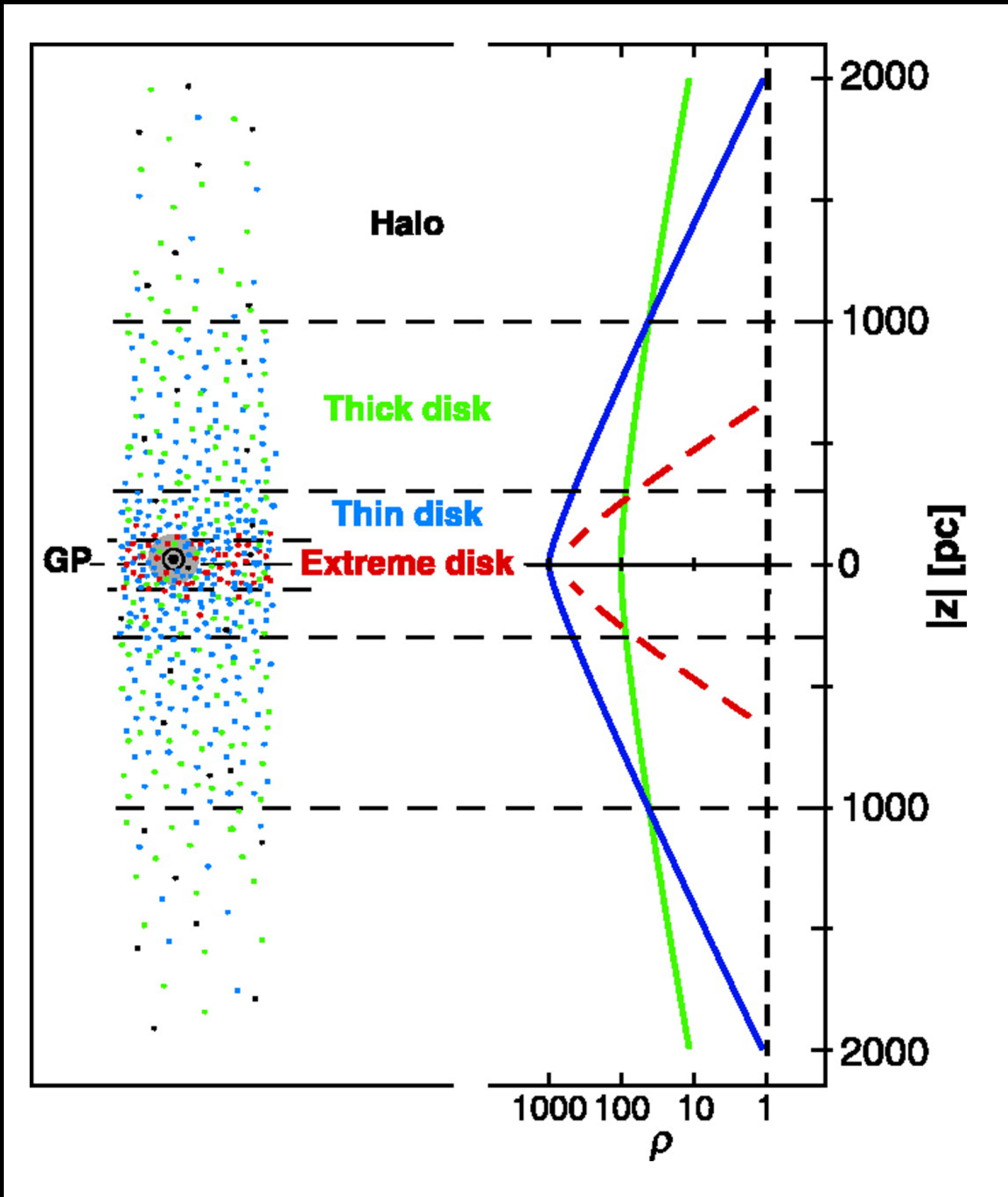
PDG 2018

What we learn:

amount of baryonic matter

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

13. Local Stellar Motions



Buser 2000

What we learn:

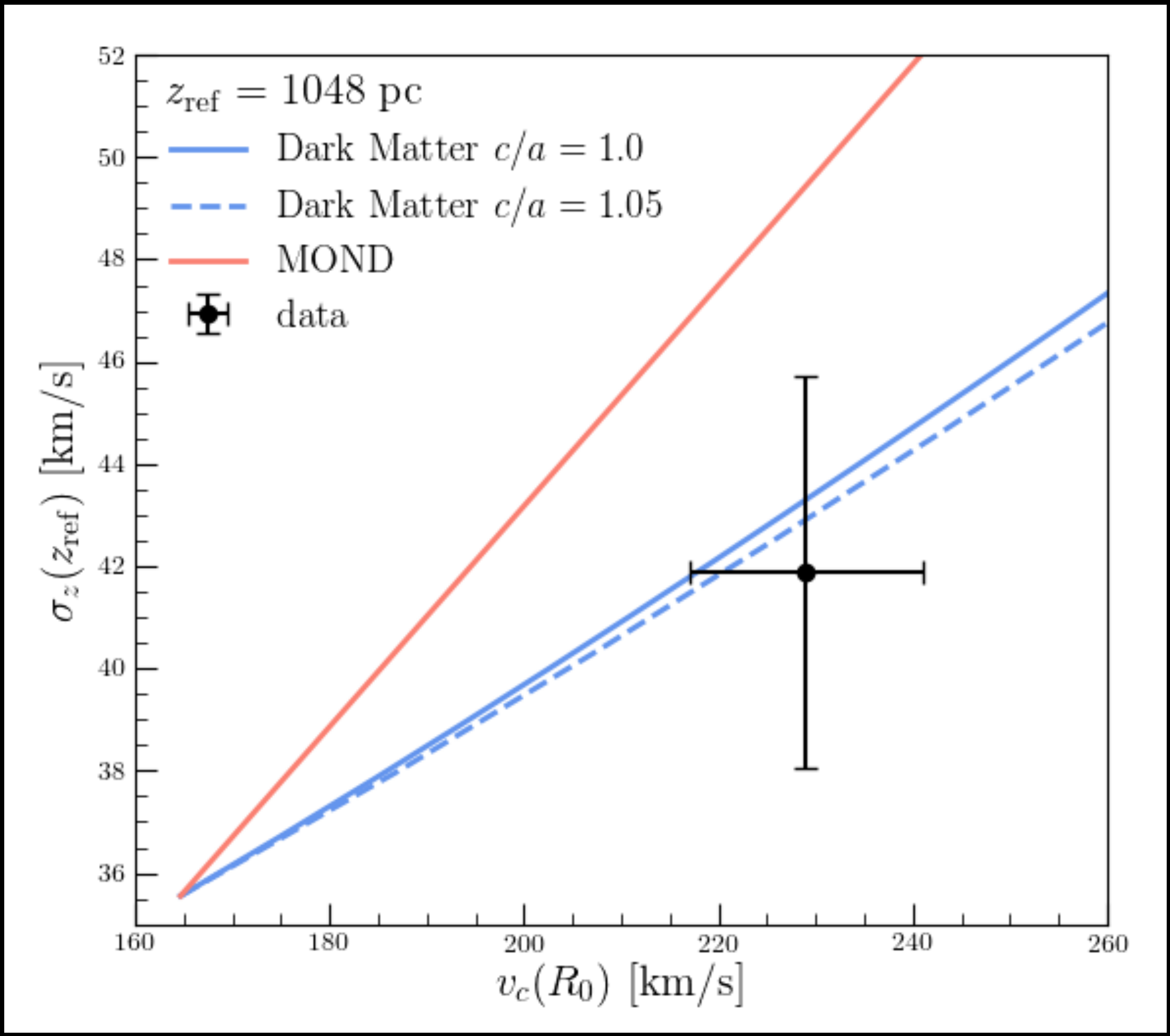
local dark matter density

Estimates:

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

$\sim 0.008\ M_{Sun}/pc^3$

13. Local Stellar Motions



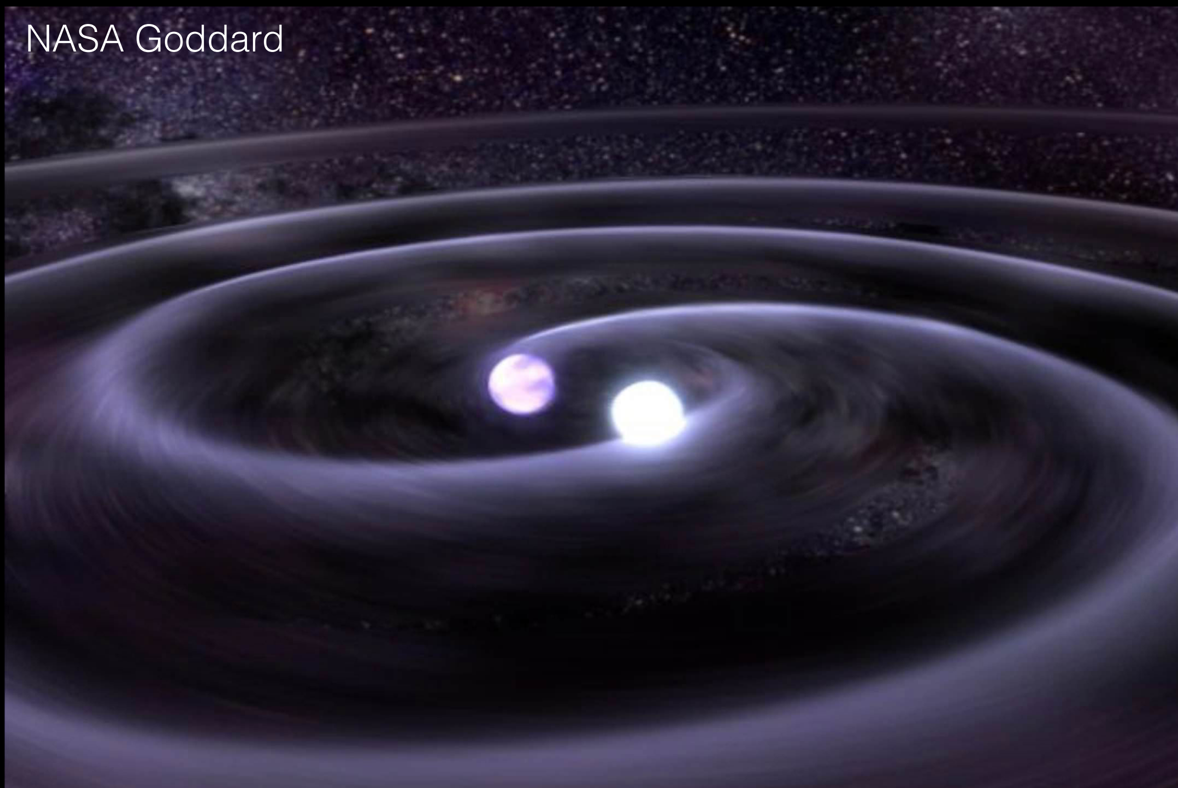
Lisanti et al. 2019

<u>What we learn:</u>

local dark matter density

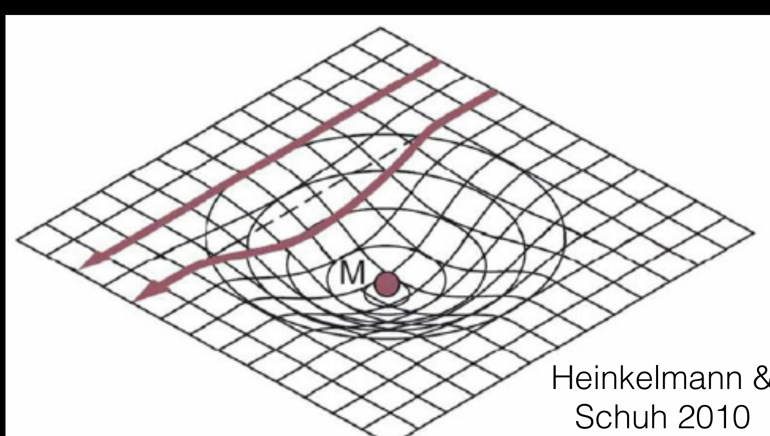
Measurements in strong tension with MOND explanations

Bonus: Gravitational Waves

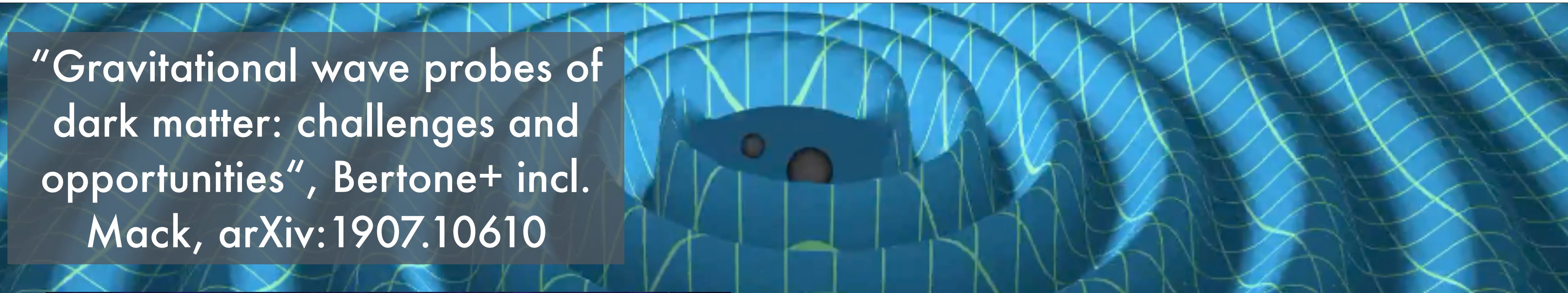


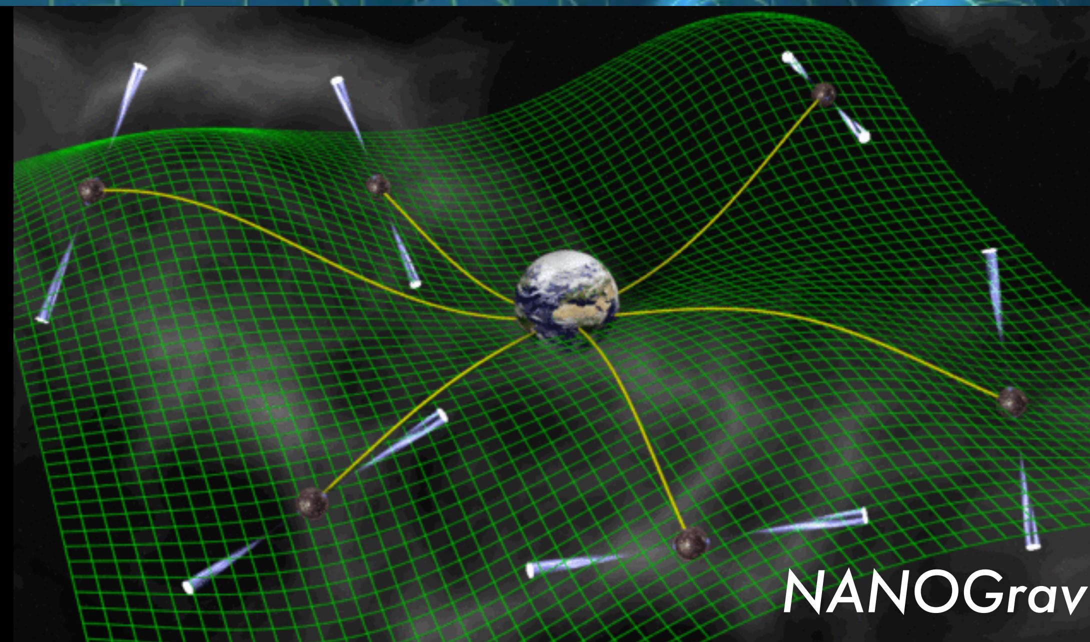
What we learn:

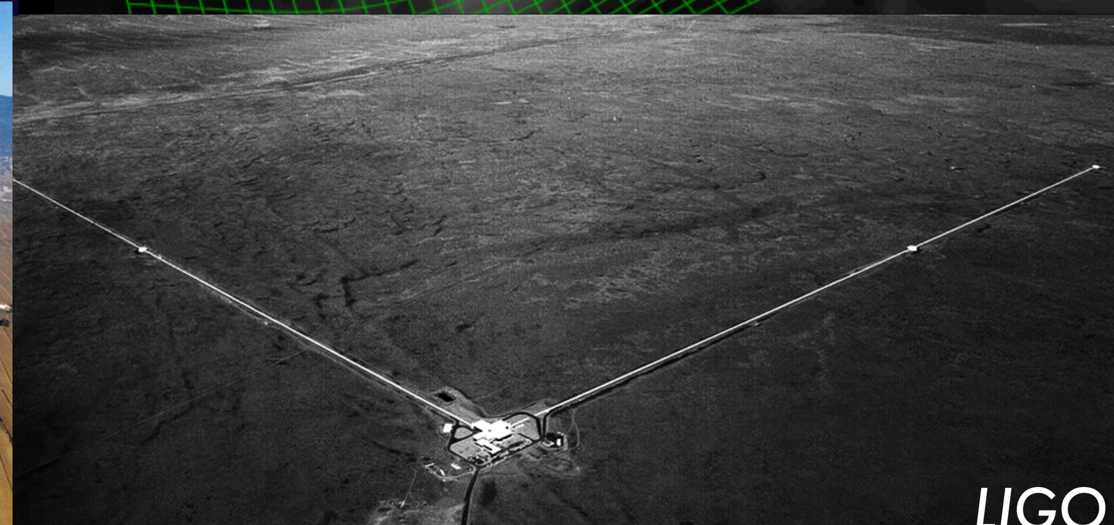
rules out some DM emulators

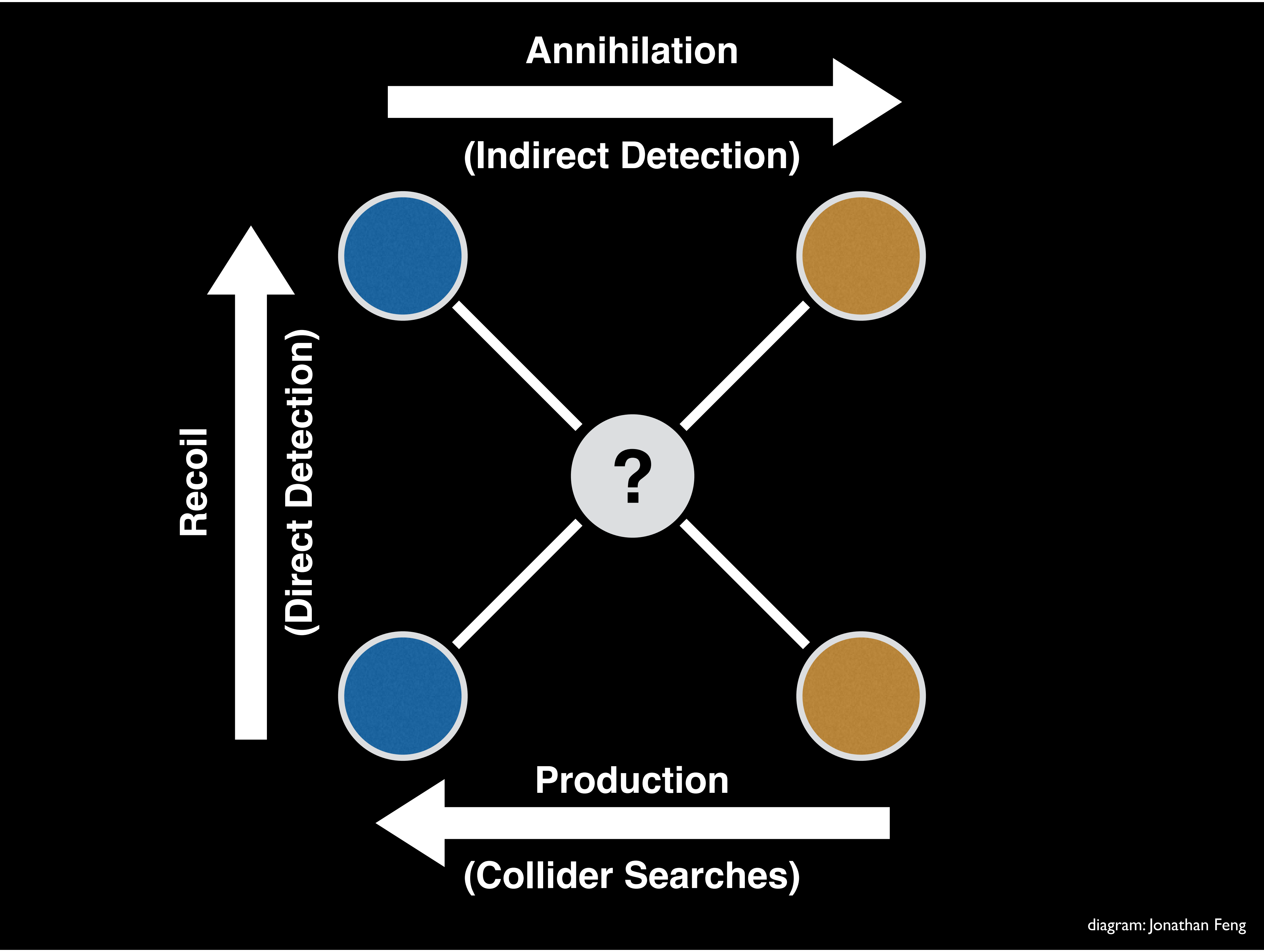


Near-simultaneous arrival of light & gravitational waves in GW170817 inconsistent with models where GWs and light follow different geodesics (Boran et al. 2018)


“Gravitational wave probes of dark matter: challenges and opportunities”, Bertone+ incl. Mack, arXiv:1907.10610

LISA

NANOGrav

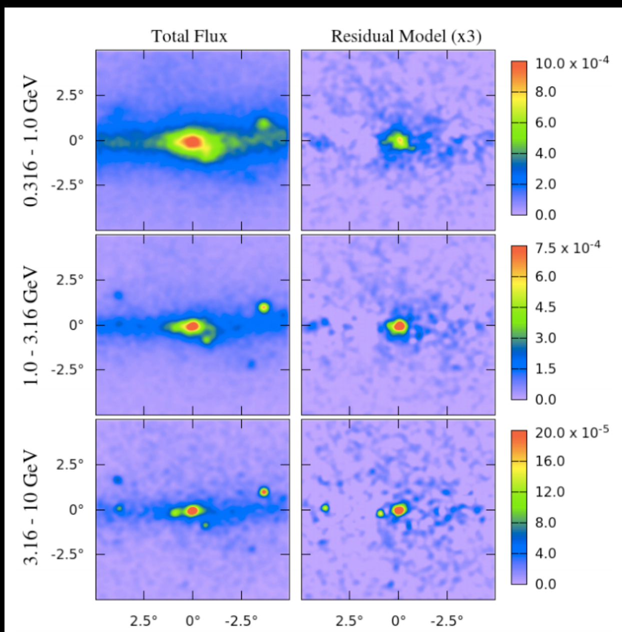
Virgo

LIGO


Annihilation
(Indirect Detection)
Recoil
(Direct Detection)
?
Production
(Collider Searches)
diagram: Jonathan Feng

Possible Hints/Signals

Annihilation?

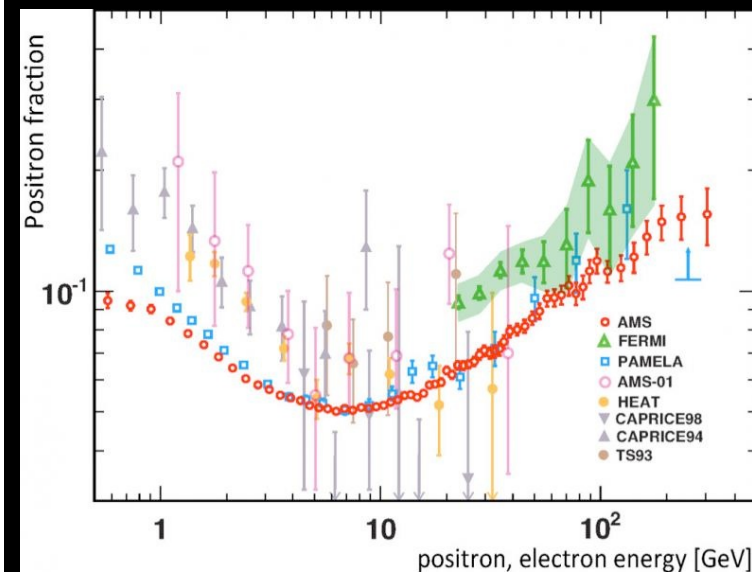
Gamma rays in the Galactic Center



Daylan et al. 2014

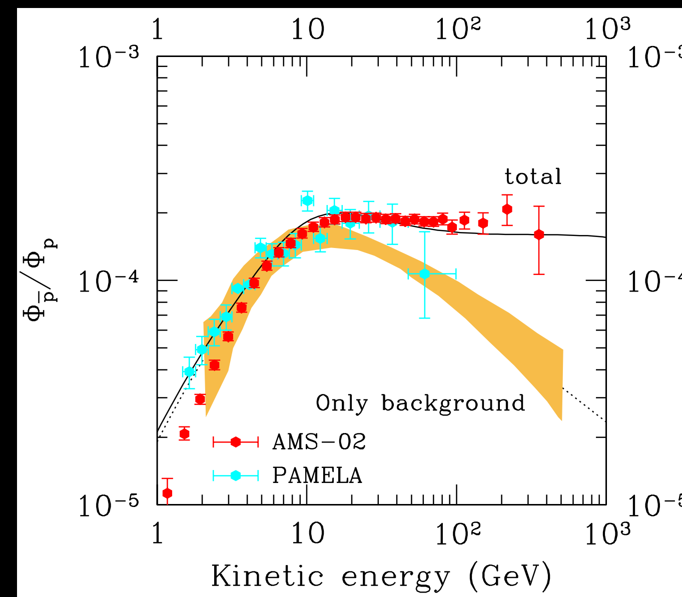
... but maybe pulsars

Excess positrons at high energy



AMS Collaboration 2013

Excess antiprotons at high energy



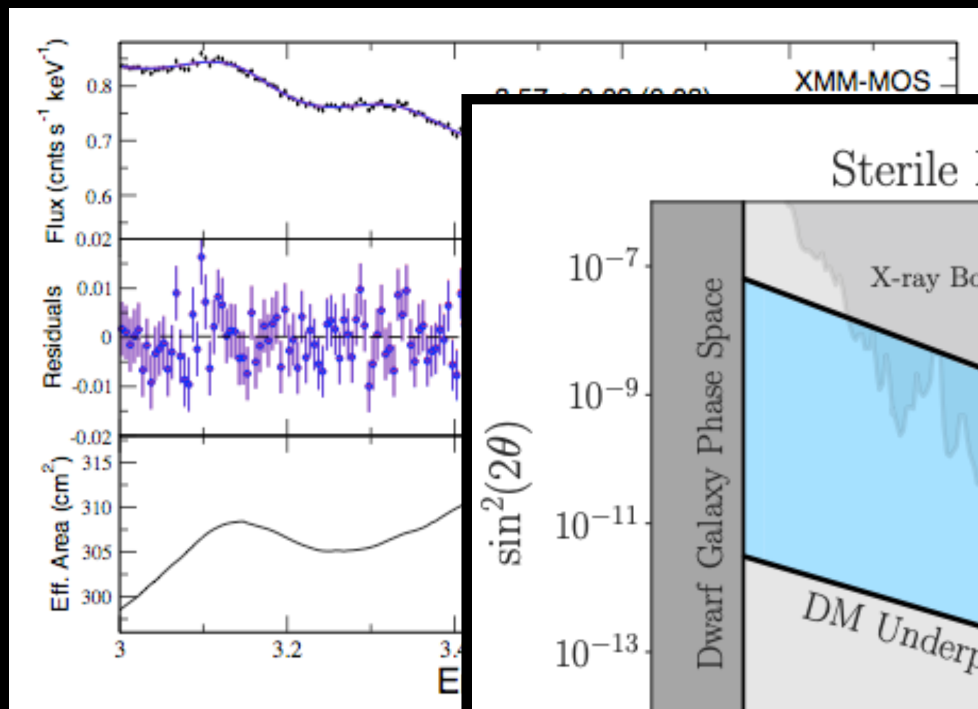
Kohri et al. 2015

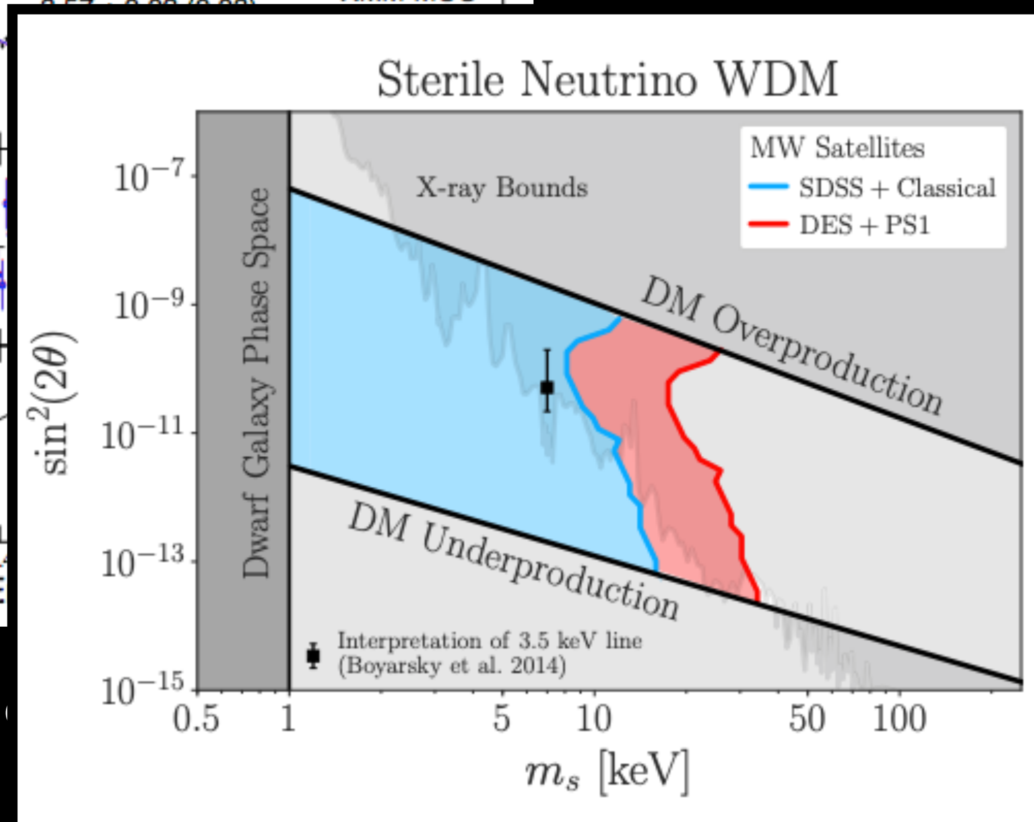
Not pulsars!

... but maybe supernova remnant

Decay?

Excess x-rays in galaxy clusters





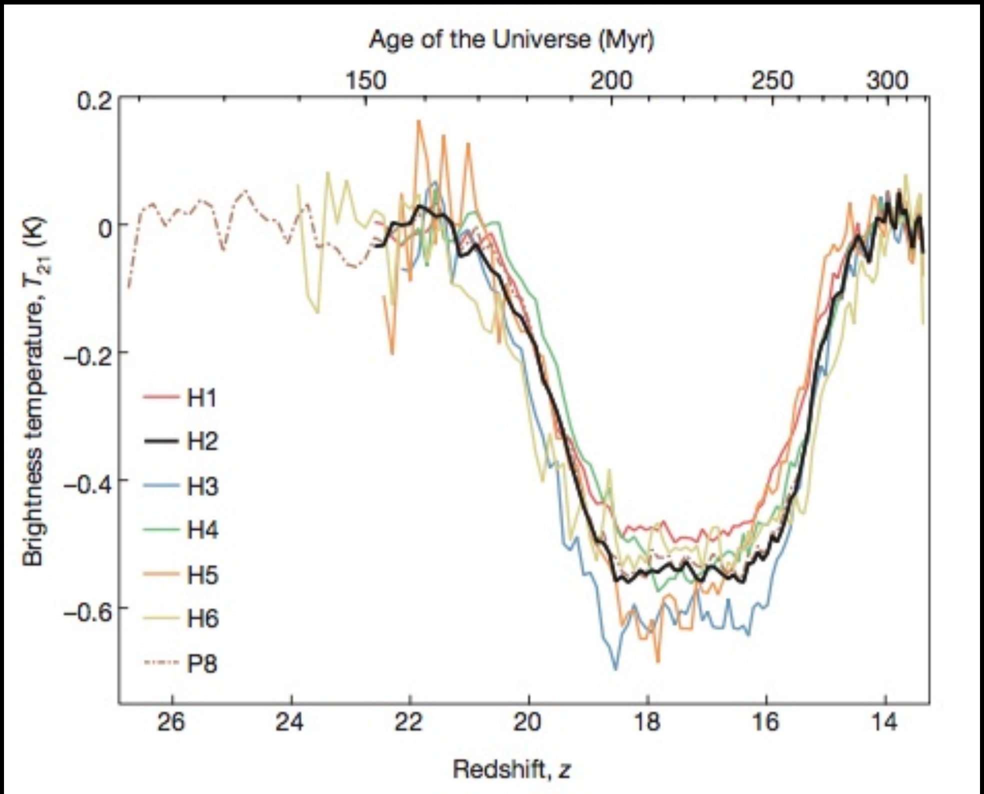
Bulbul

… but maybe line contamination

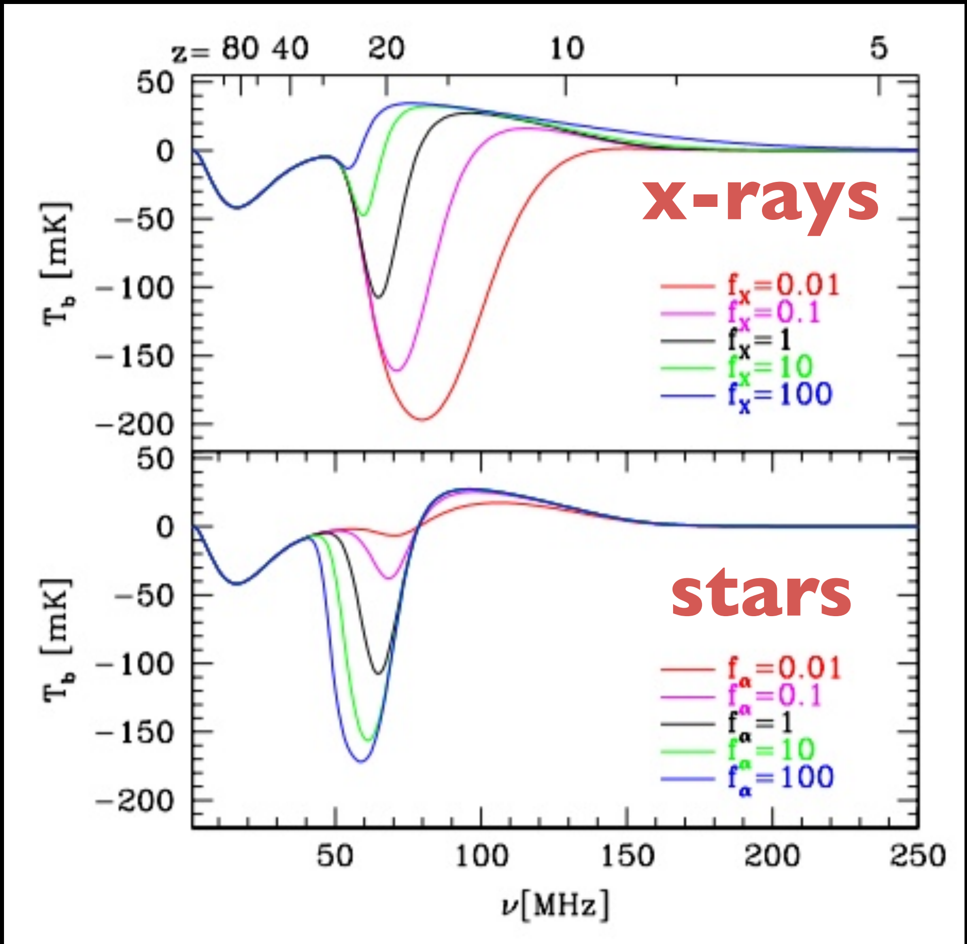
and see: Nadler+ (DES) 2021

Scattering?

Super-cold neutral hydrogen at high redshift



Bowman et al. 2018



Pritchard & Loeb 2010

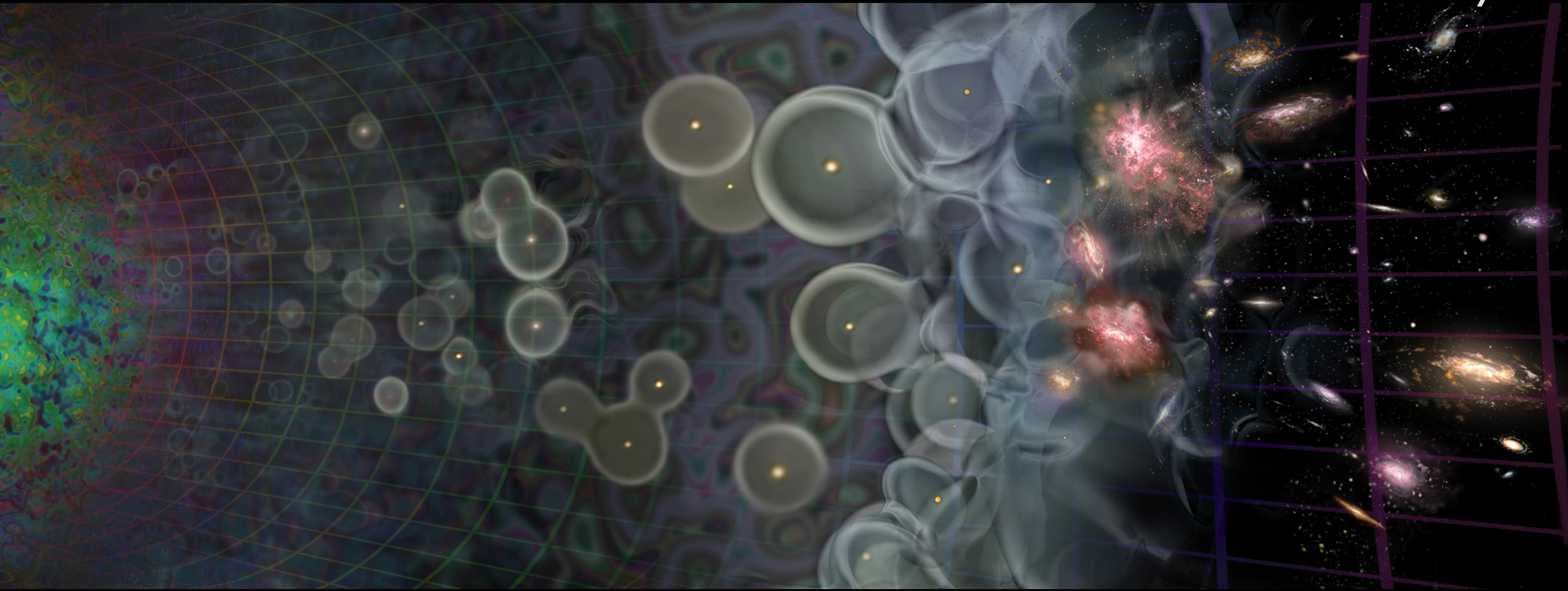
... but maybe a foreground subtraction problem

Scorecard

Direct Detection	**inconclusive**
Indirect Detection	**inconclusive**
Production	**no signal**
Astrophysical Evidence	**very strong**

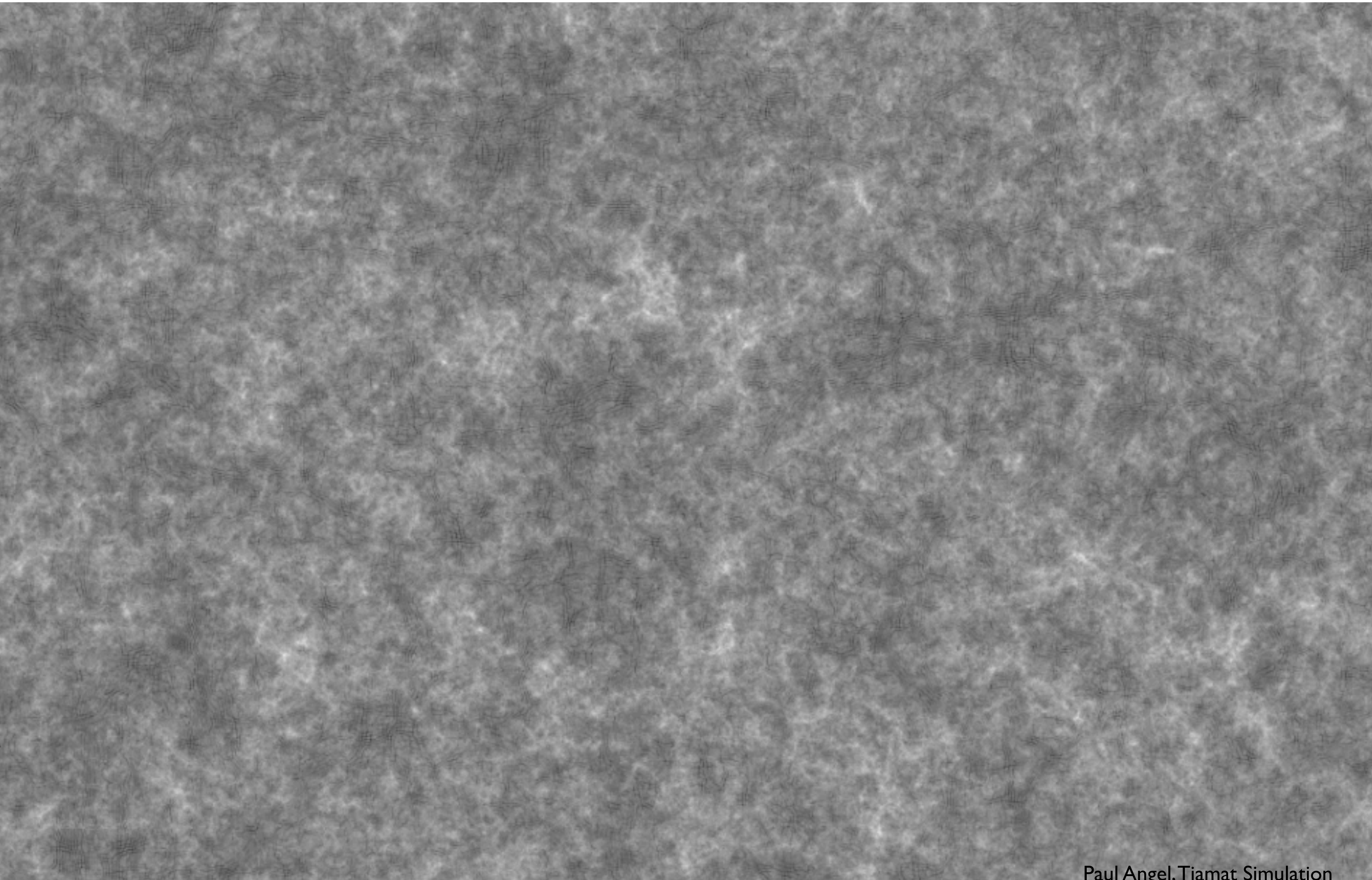
The Cosmic Frontier

CMB | Cosmic Dawn | Reionization | Today



redshift: 40 20 10 0

Dark Matter: Cosmology

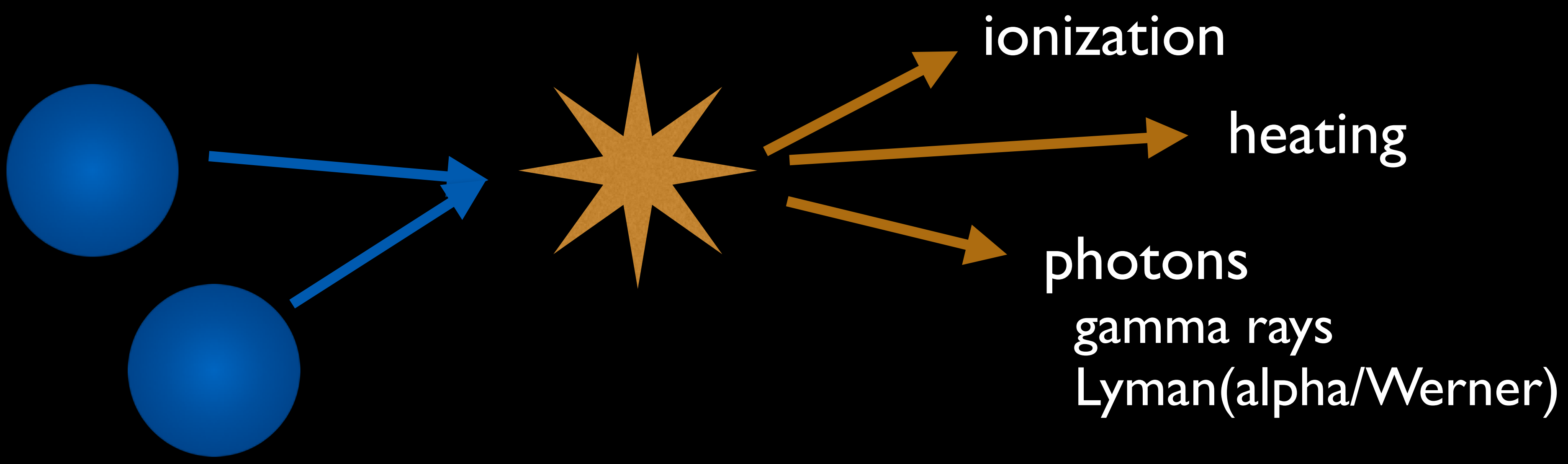


Paul Angel, Tiamat Simulation

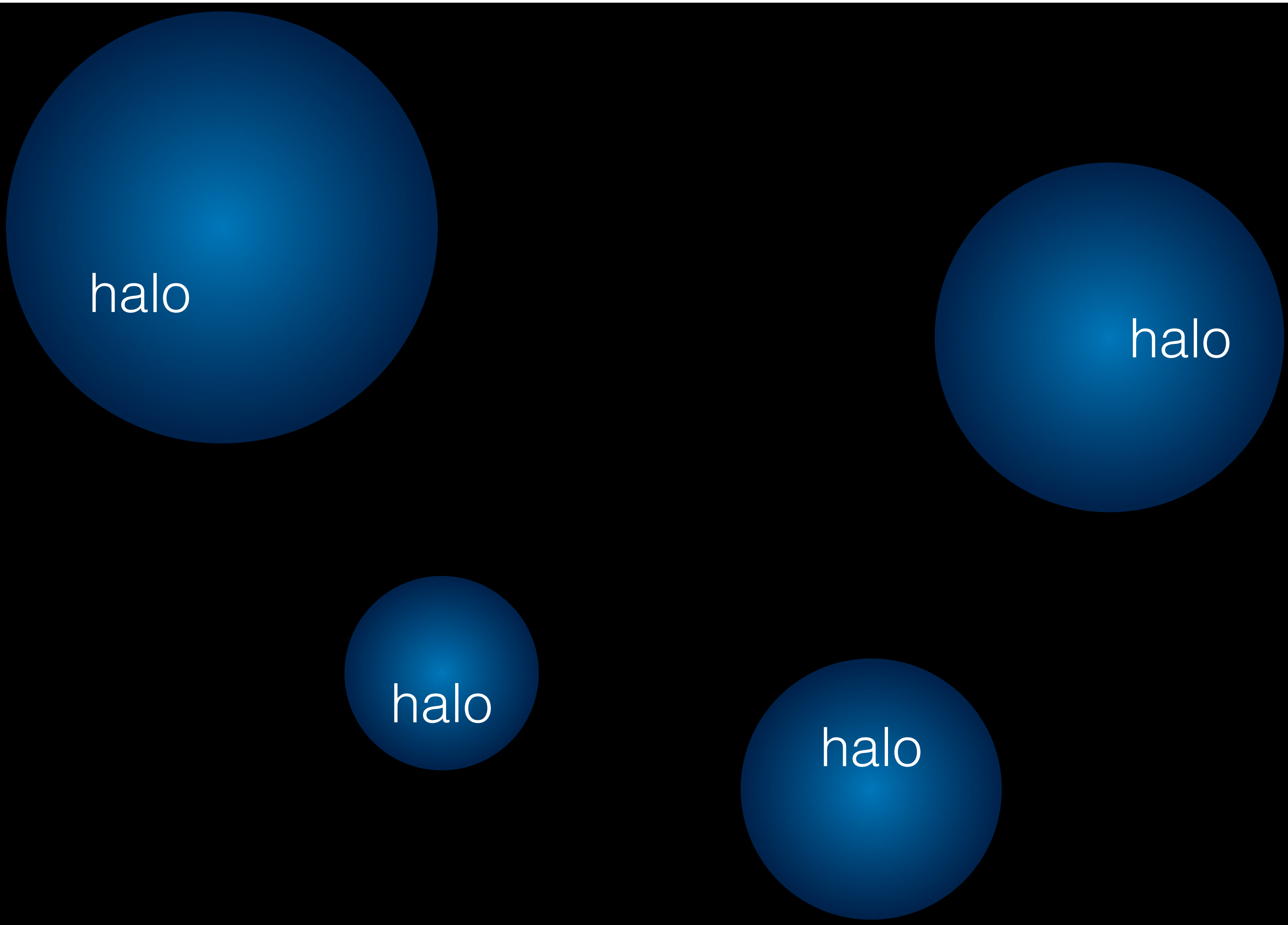
Impact of Dark Matter Annihilation

Major unanswered question:

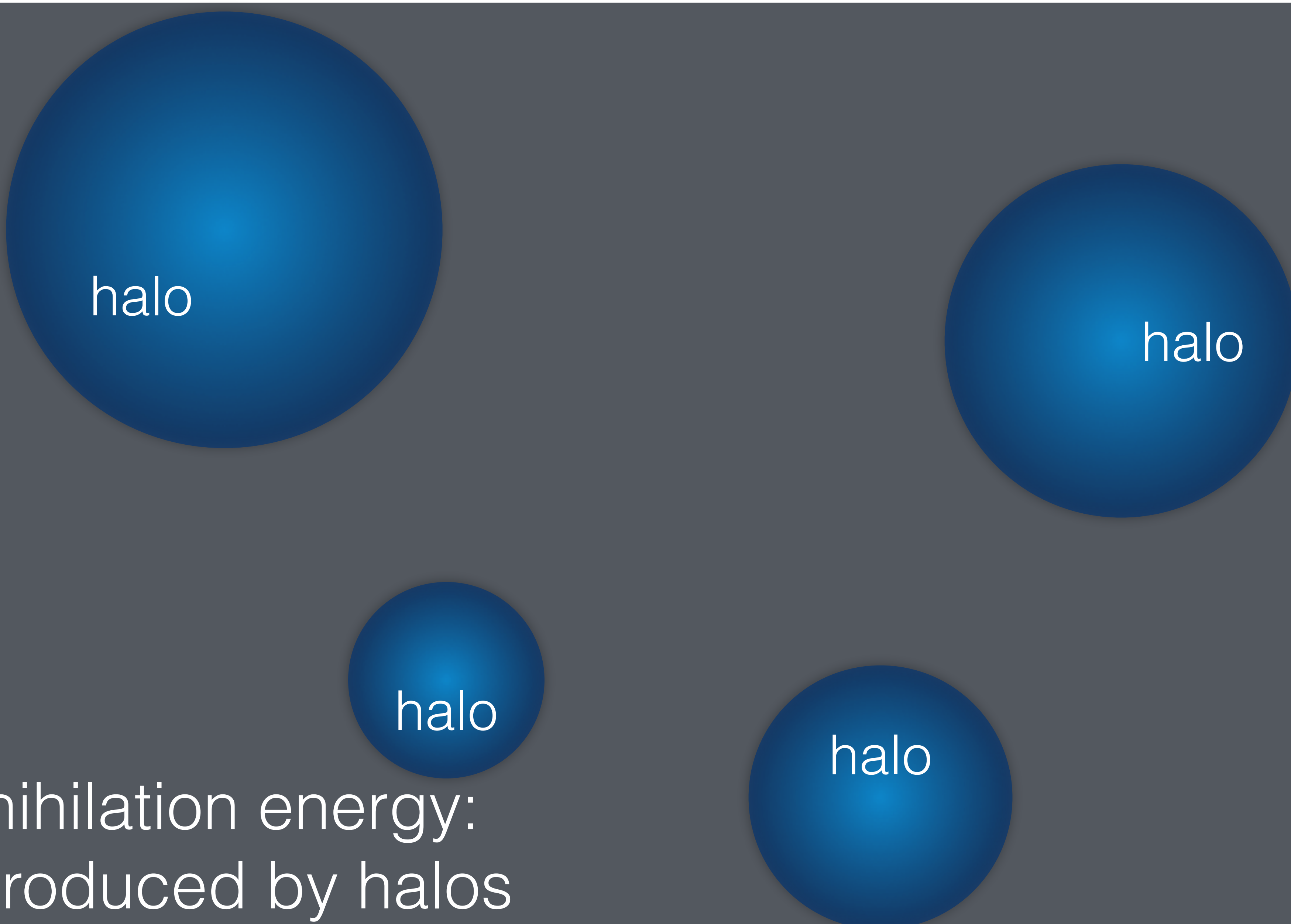
If dark matter **annihilates** across all of cosmic time, **how does it affect the first stars and galaxies?**



Annihilation in the Intergalactic Medium



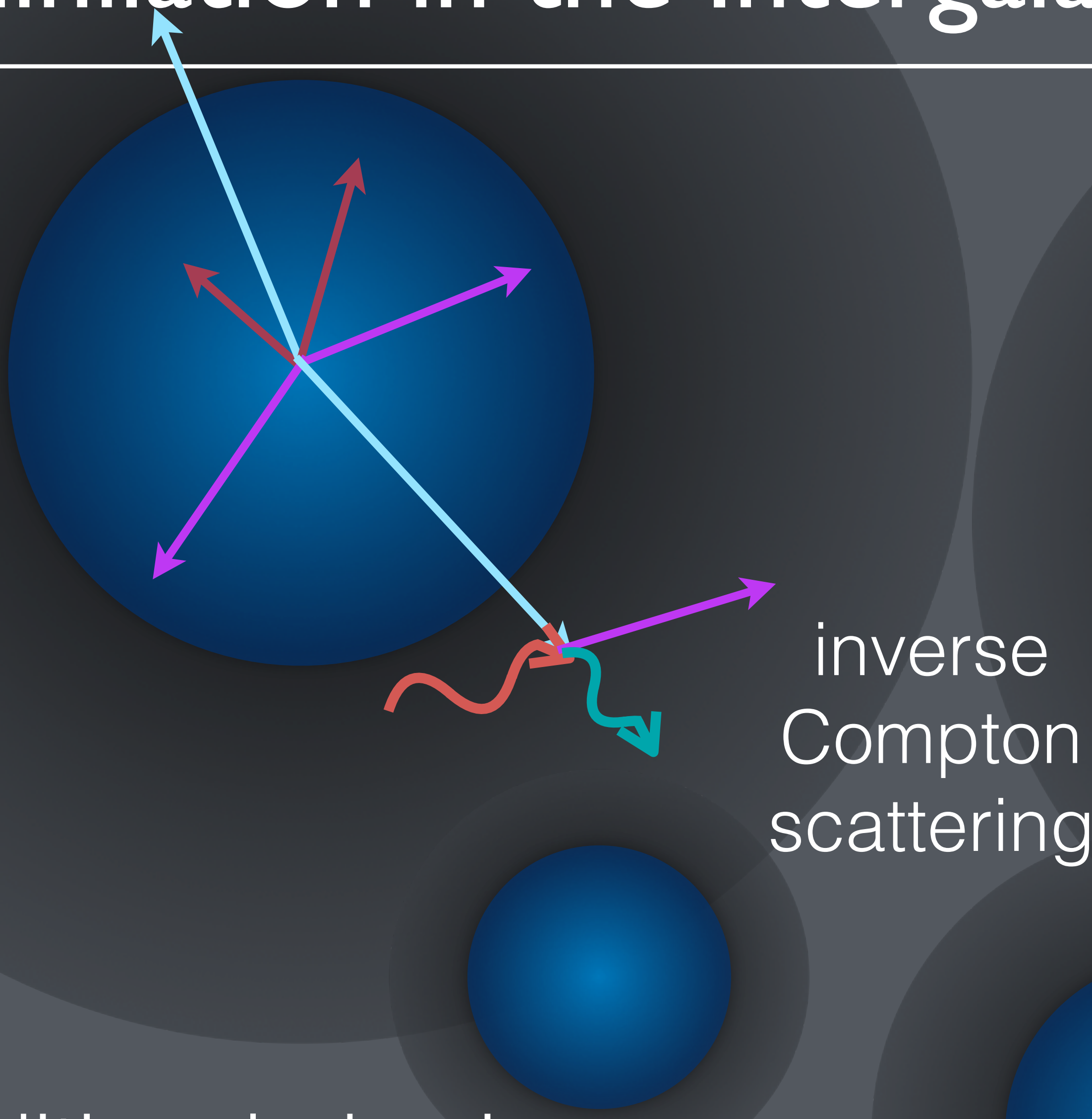
Annihilation in the Intergalactic Medium



Annihilation energy:

- produced by halos
- deposited in IGM — heat, ionization

Annihilation in the Intergalactic Medium



Additional physics:

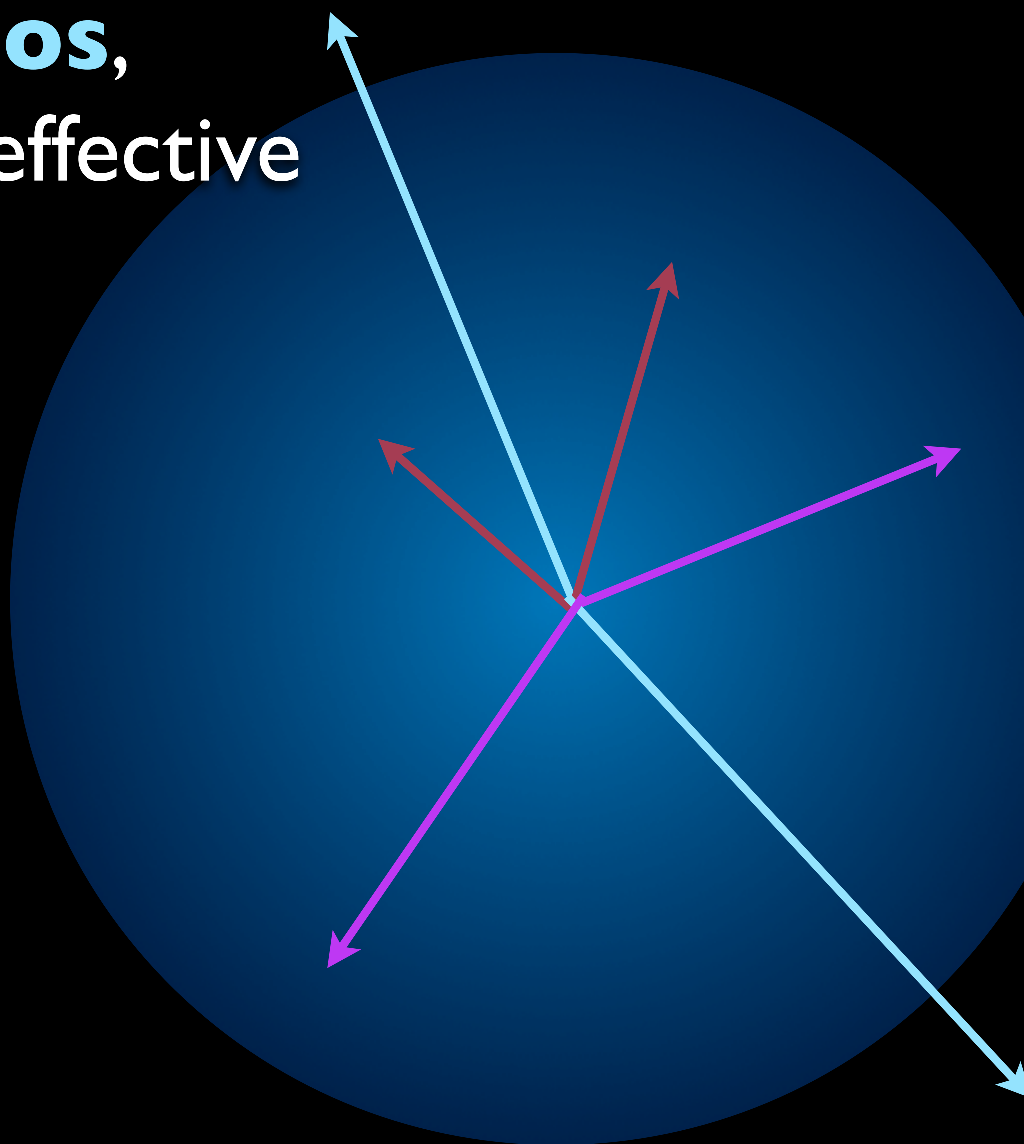
- structured halos
- delayed energy deposition

Annihilation Feedback on Halo Gas

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

CHIMERA code:
modified custom-built code (in collaboration with S. Schön) to calculate energy transfer to baryons

Preliminary results:
arxiv:1411.3783,
1706.04327

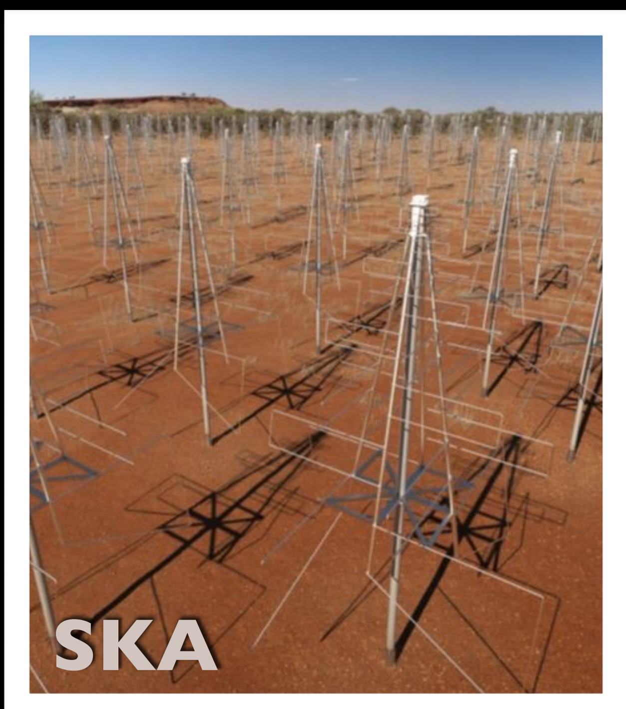


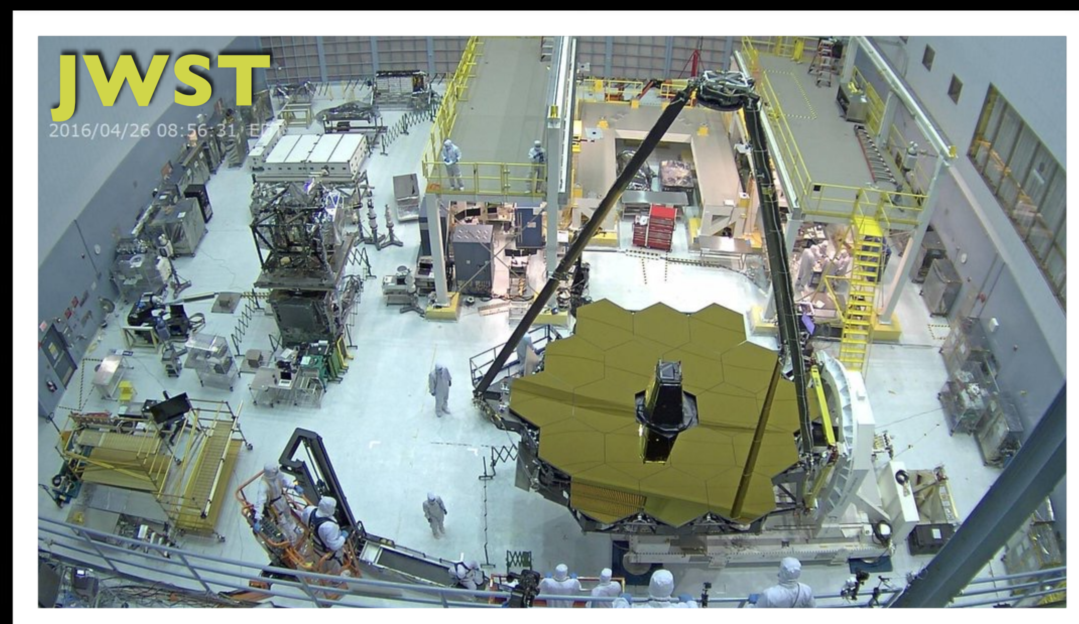
Probing Cosmic Dawn

Djorgovski et al., Caltech

current instruments

next decade






Nancy Grace Roman (IR)
JWST (vis/IR)
Euclid (vis/IR)
www.esa.int
European Space Agency
SKA (radio)
Vera Rubin Obs (vis)

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

end