

Confronting the Invisible Universe

Jesse Thaler



Intro to Modern Physics, MIT Lincoln Laboratory — March 25, 2022



Milky Way Chasers, Michael Bentz at Nubble Lighthouse

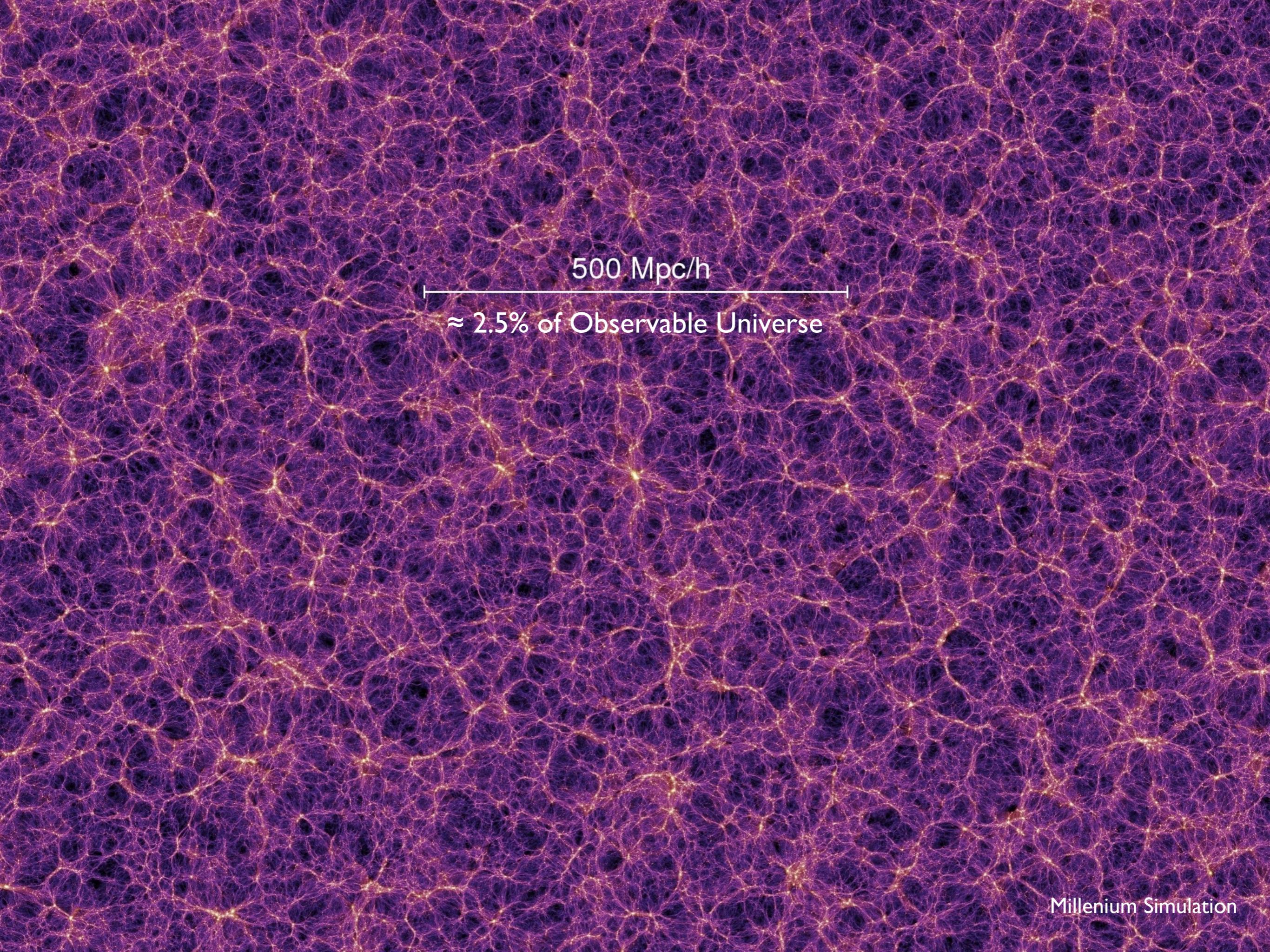
Stars

Dark Matter

Visible Matter (mostly H and He)

Dark Energy

Invisible Stuff



500 Mpc/h

$\approx 2.5\%$ of Observable Universe

Millenium Simulation

A tour of the universe



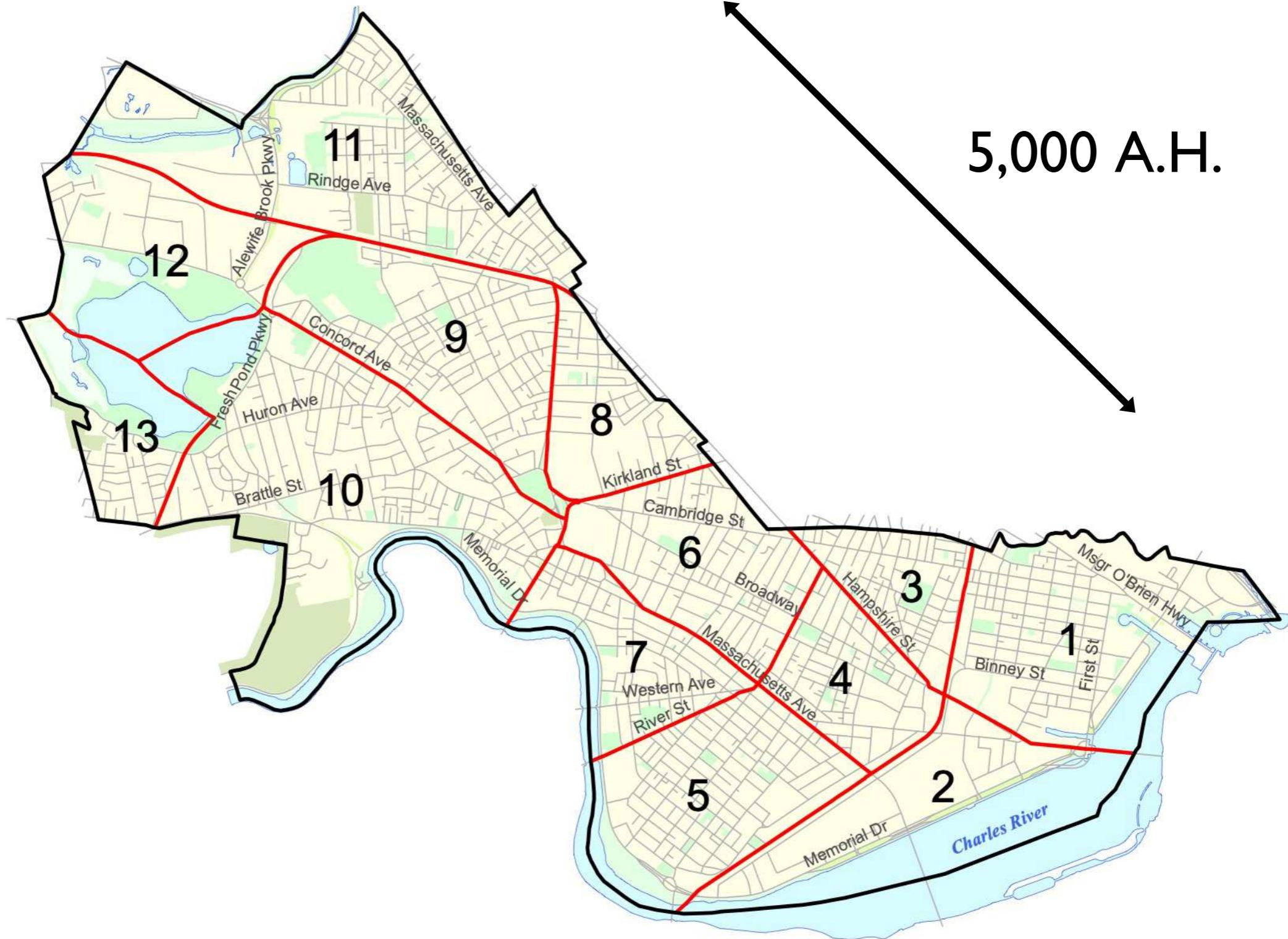
Adrian
Height

50 A.H.

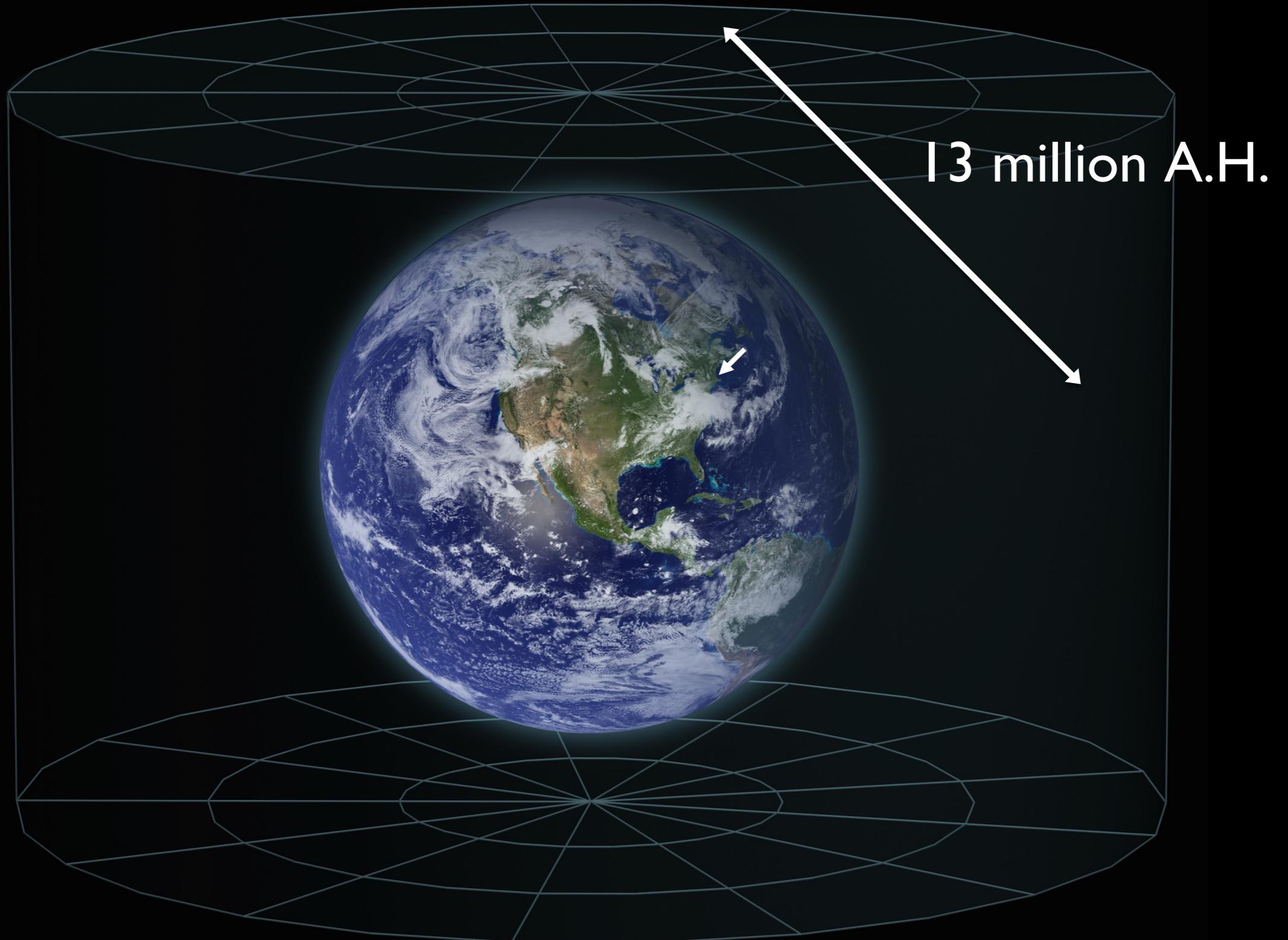


MCMXVI

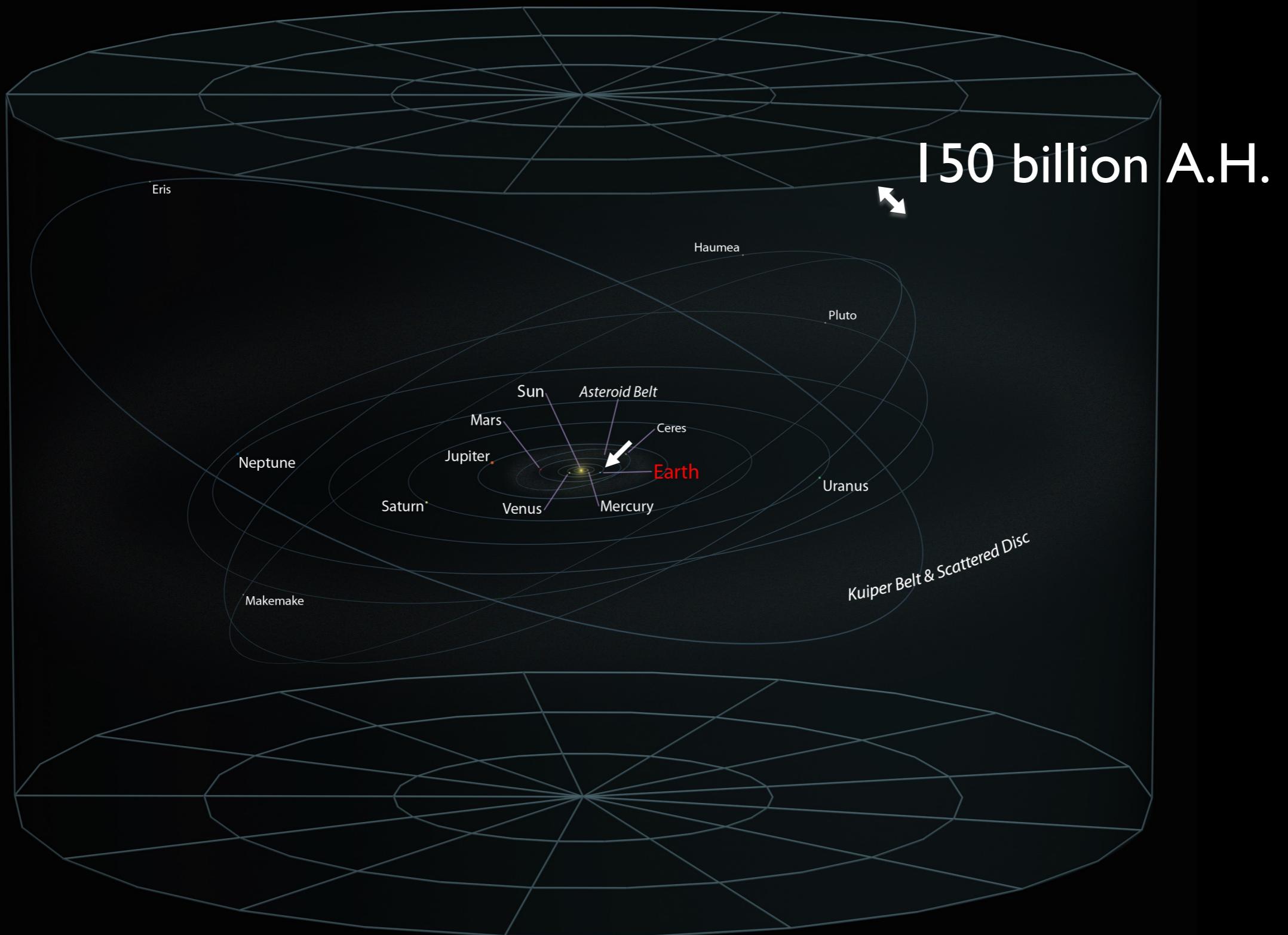
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



EARTH

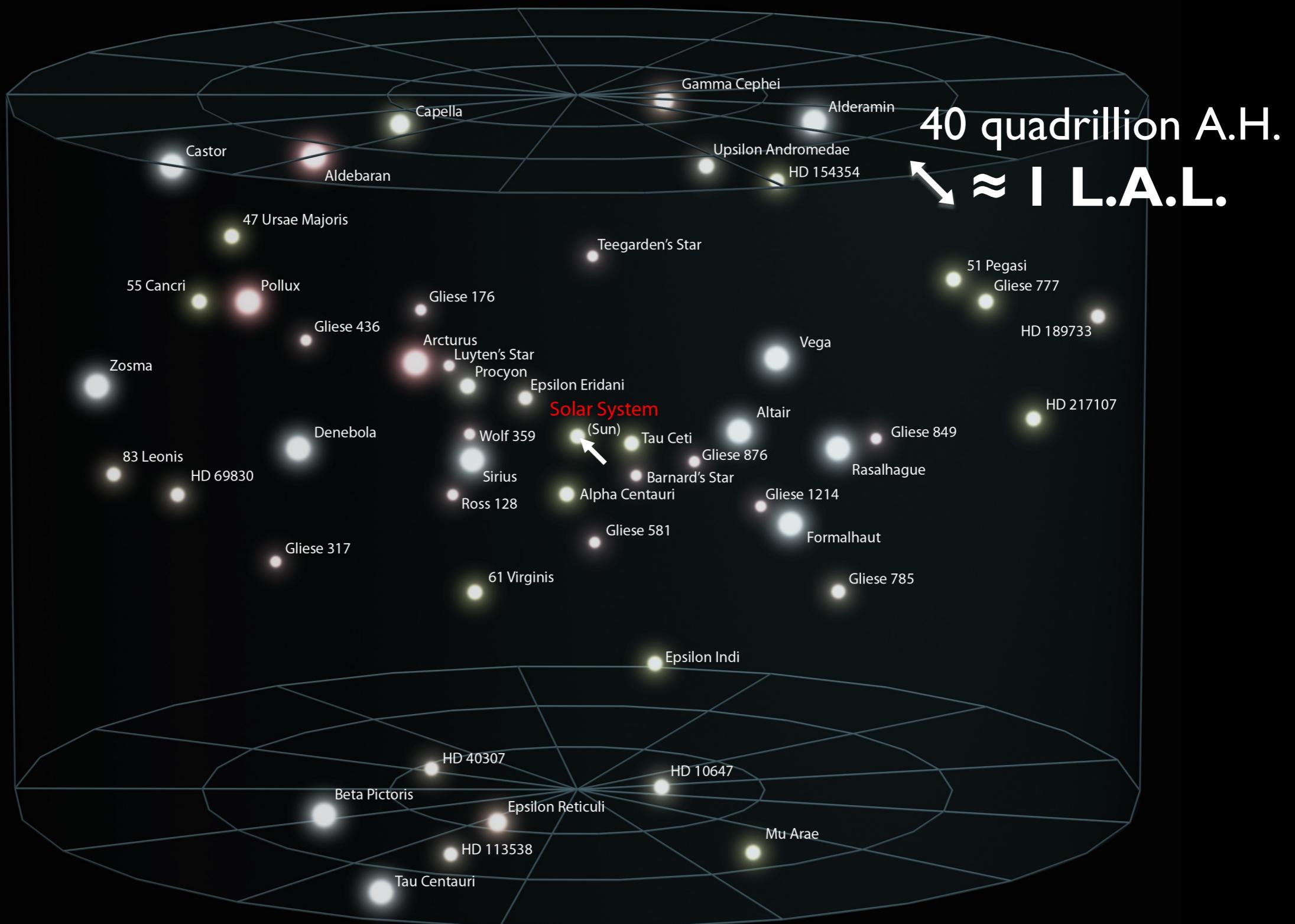


SOLAR SYSTEM

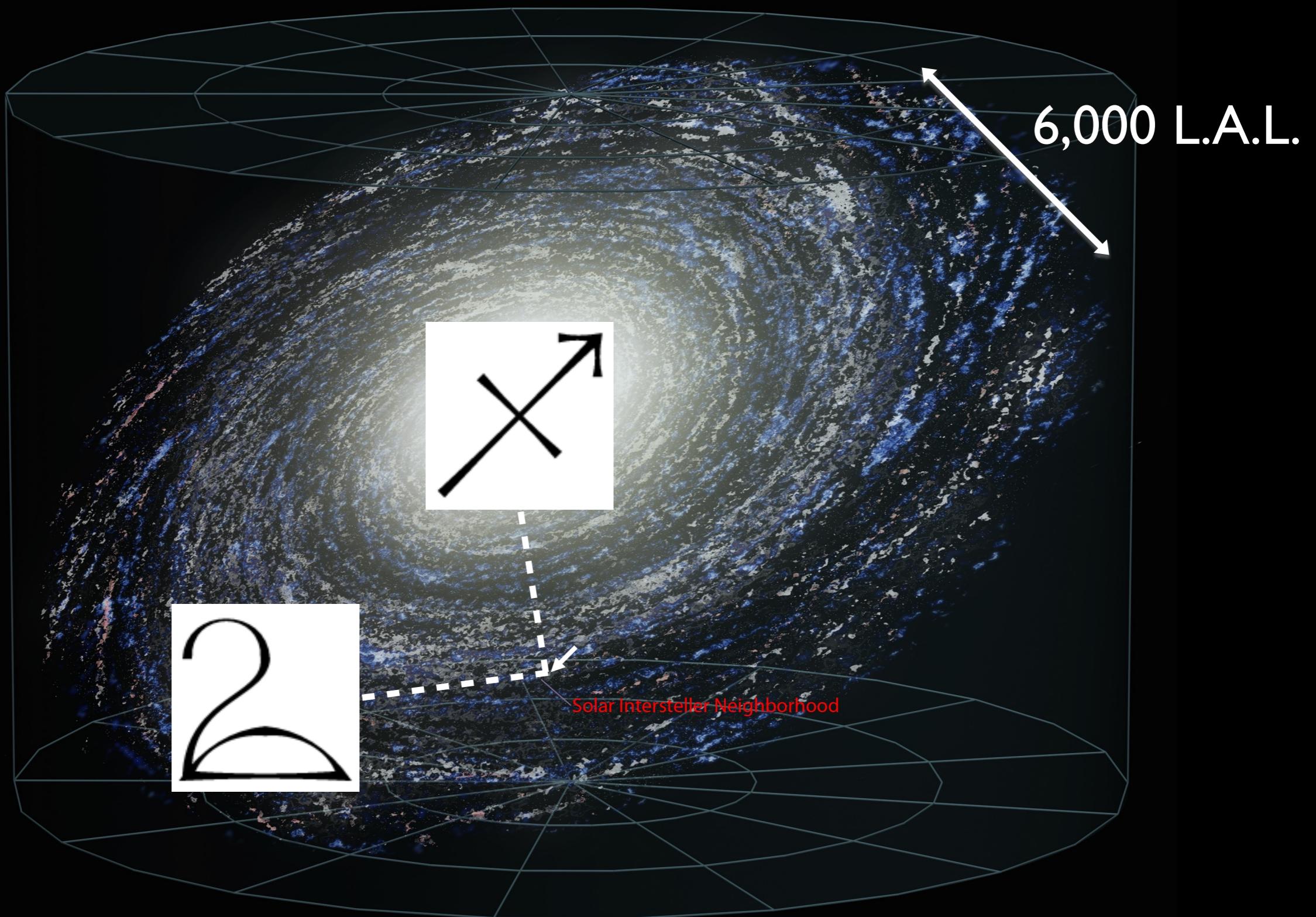


Andrew Z. Colvin

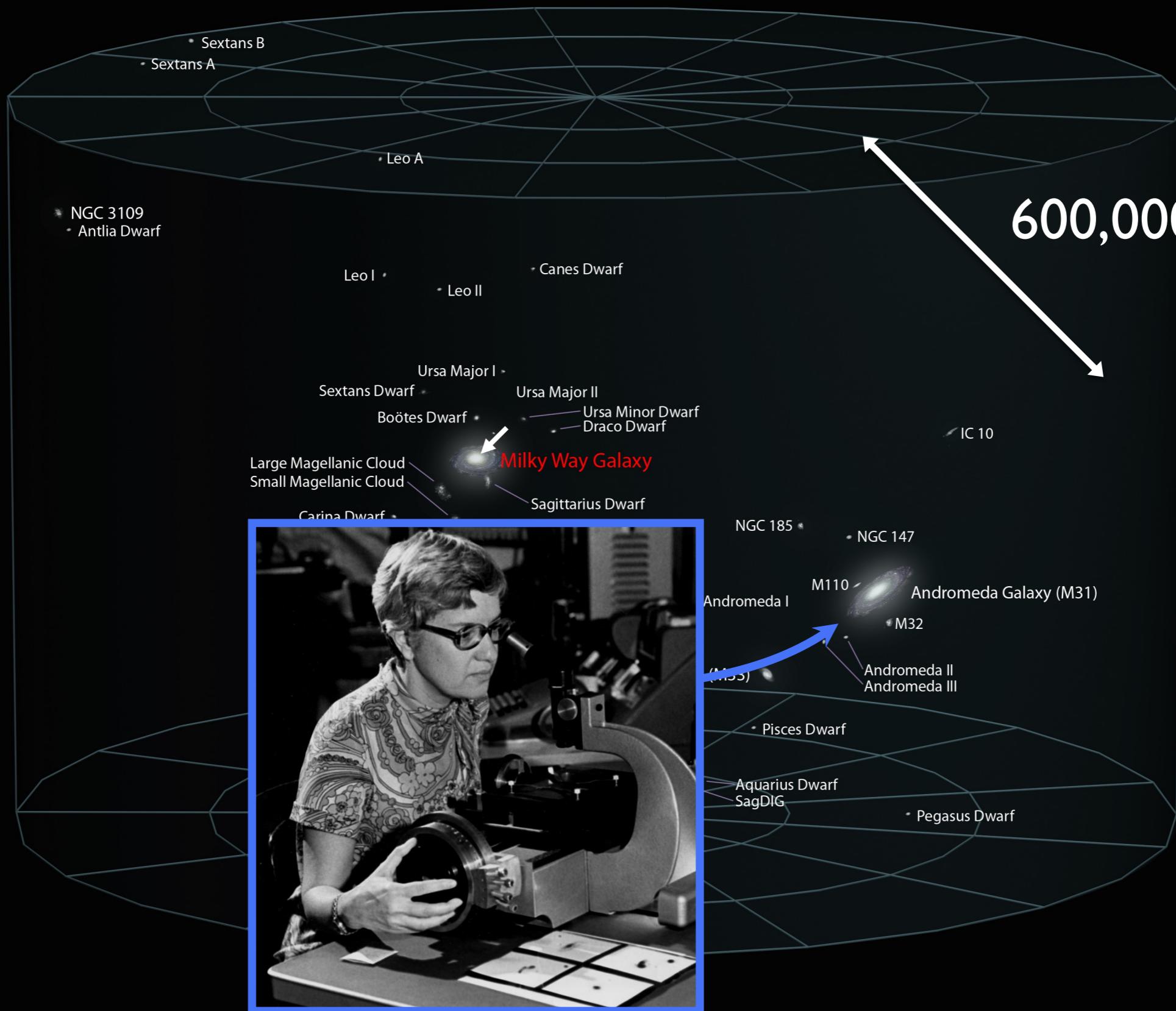
INTERSTELLAR NEIGHBORHOOD



MILKY WAY GALAXY

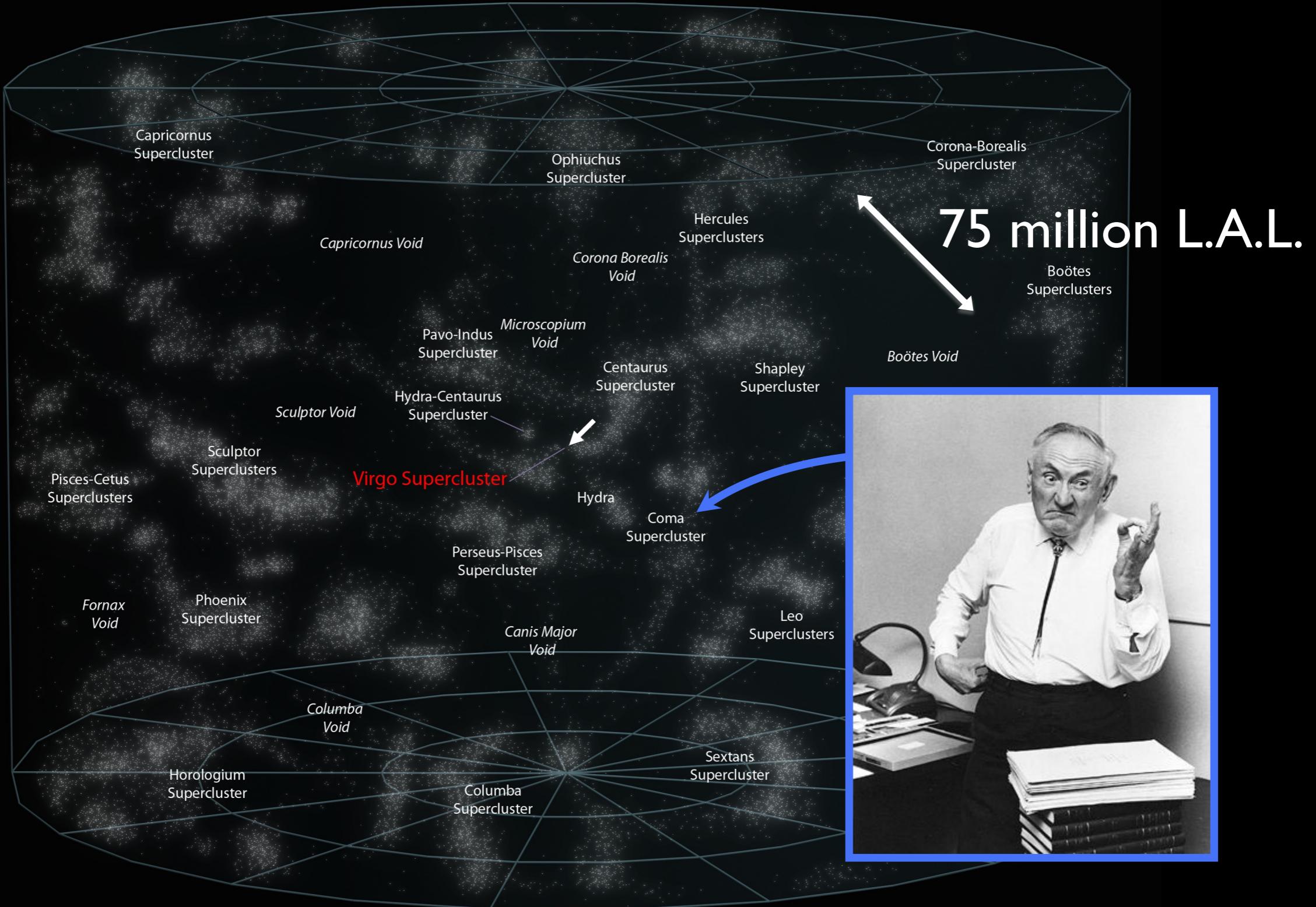


LOCAL GALACTIC GROUP



Andrew Z. Colvin

LOCAL SUPERCLUSTERS



Andrew Z. Colvin

OBSERVABLE UNIVERSE



Andrew Z. Colvin

Invisible Stuff

What?

Substance

Mechanism

Why?

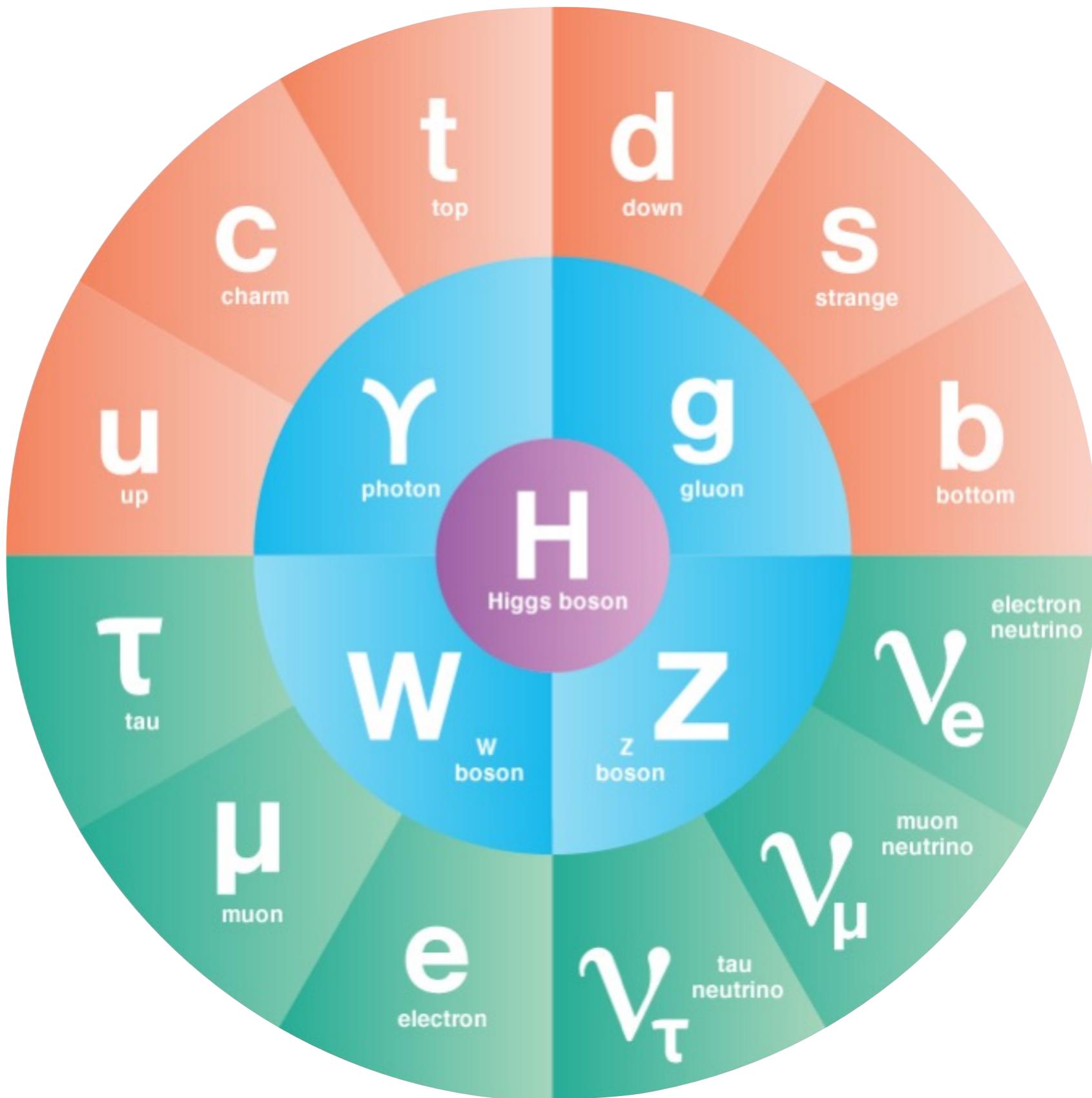
Purpose

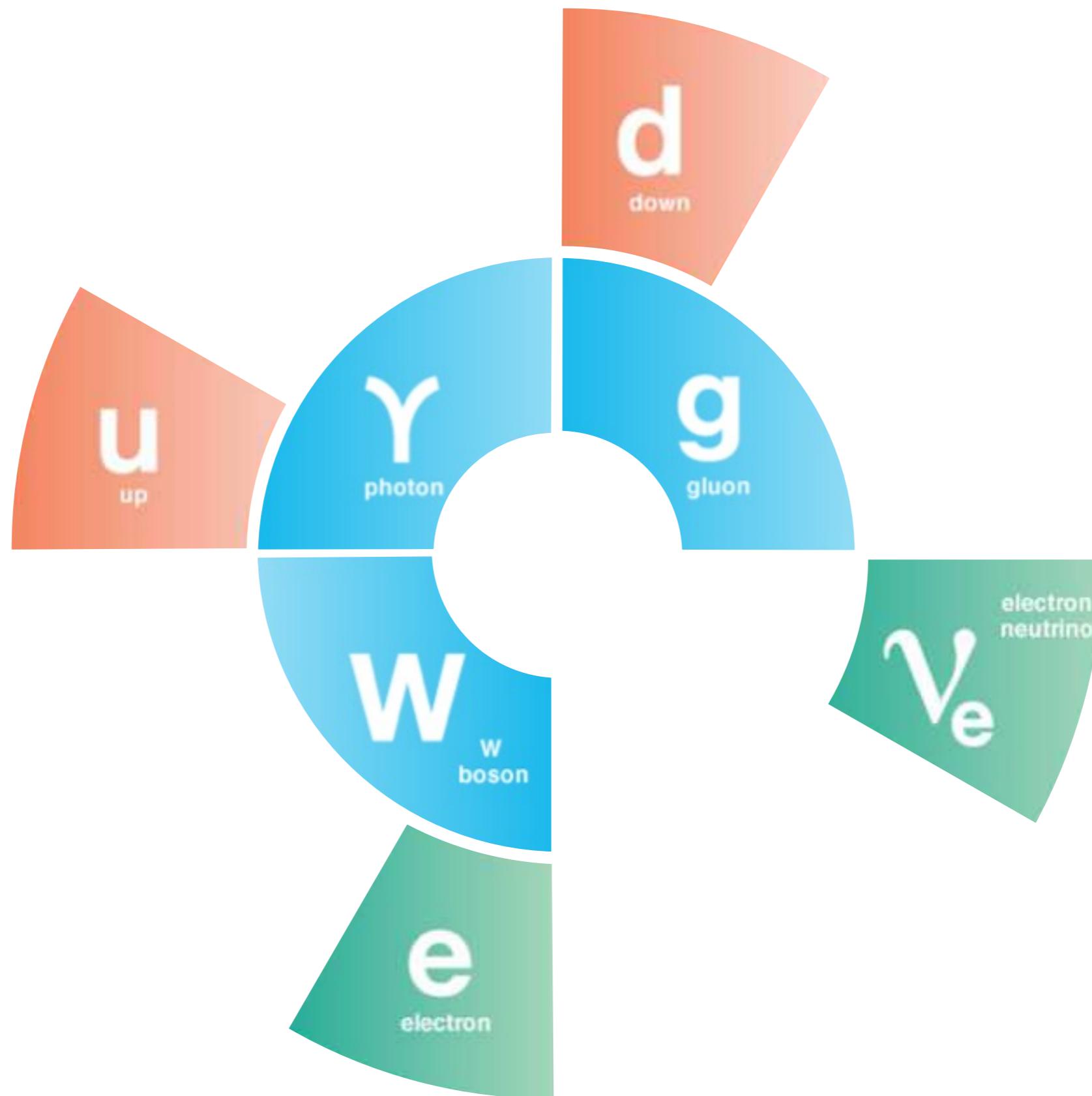
Implication

(And how do we know?)

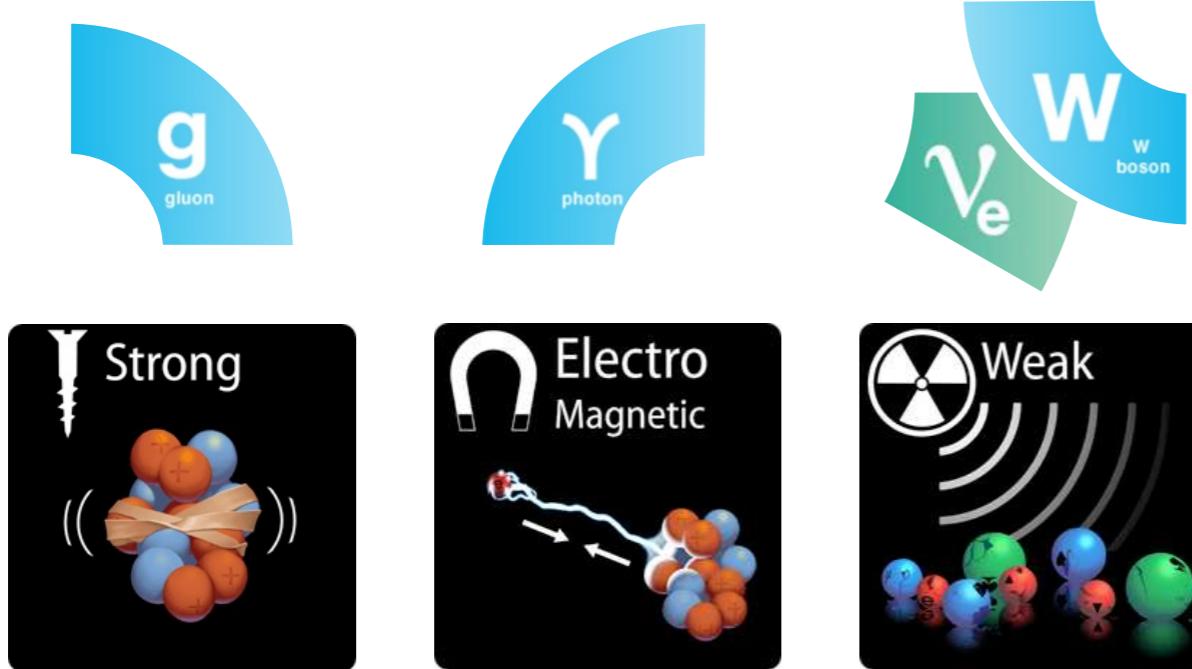
Evidence

What is Dark Matter?





Ordinary Matter



Invisible Stuff

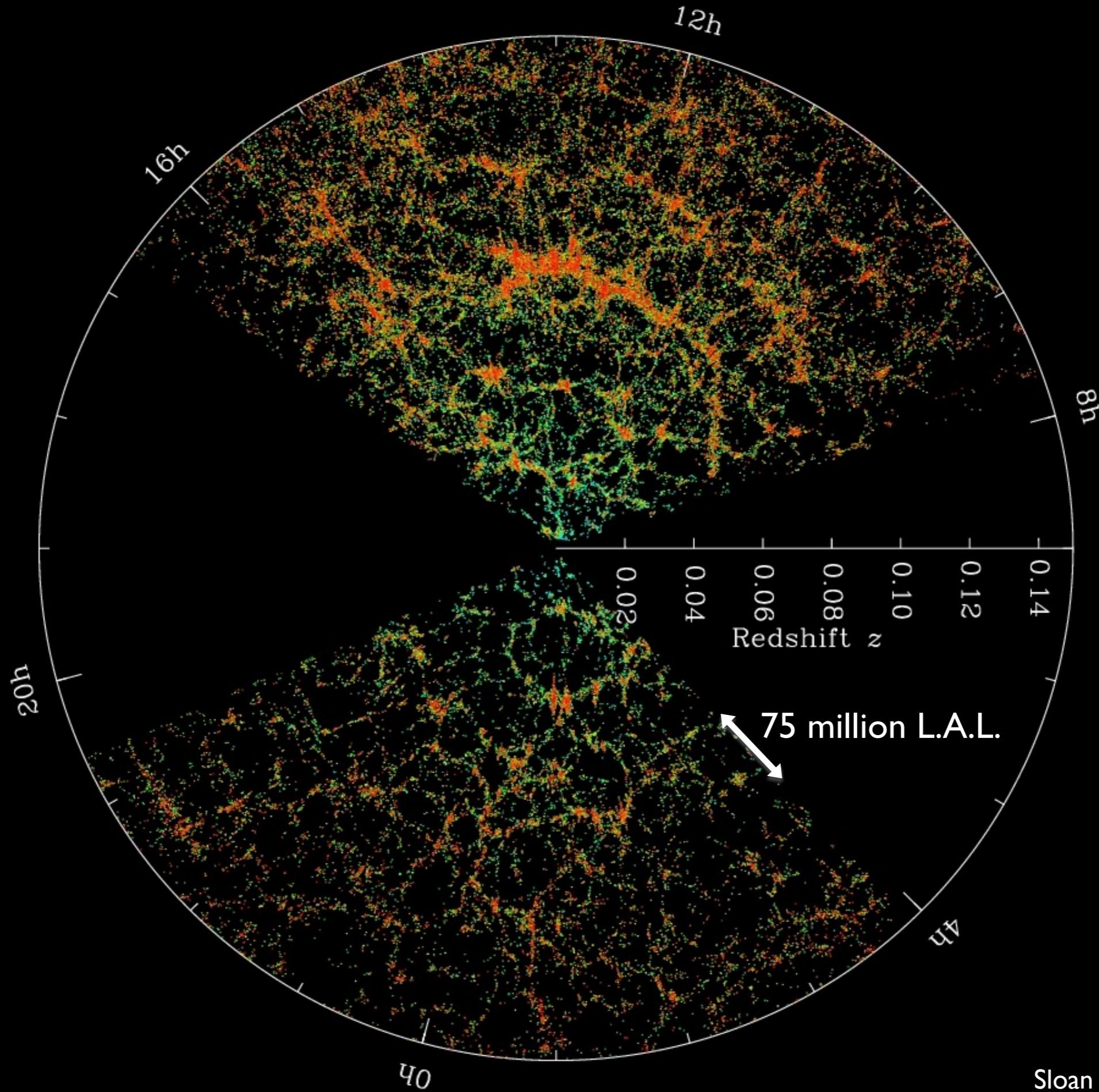
Inert

Stable

Slow

Who, me?

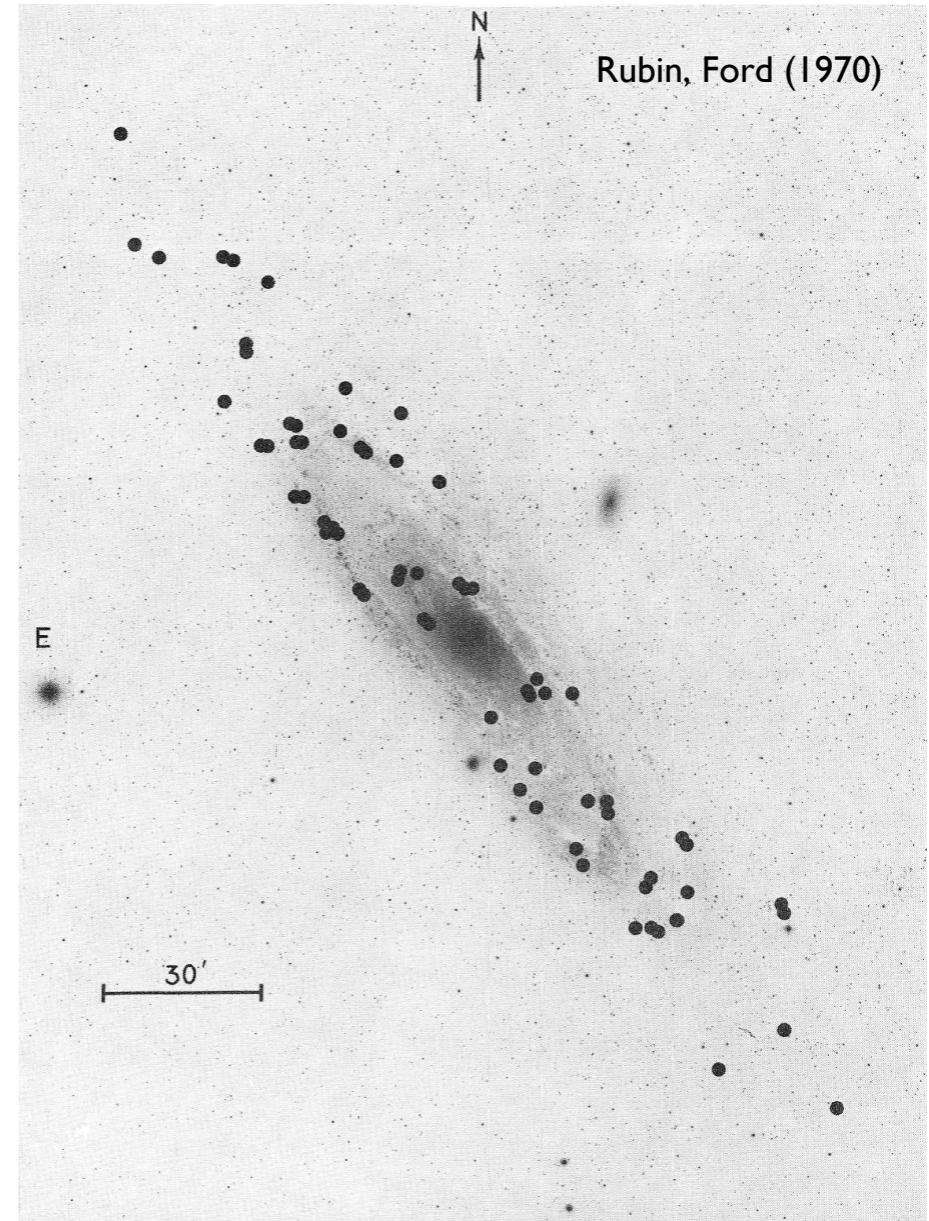




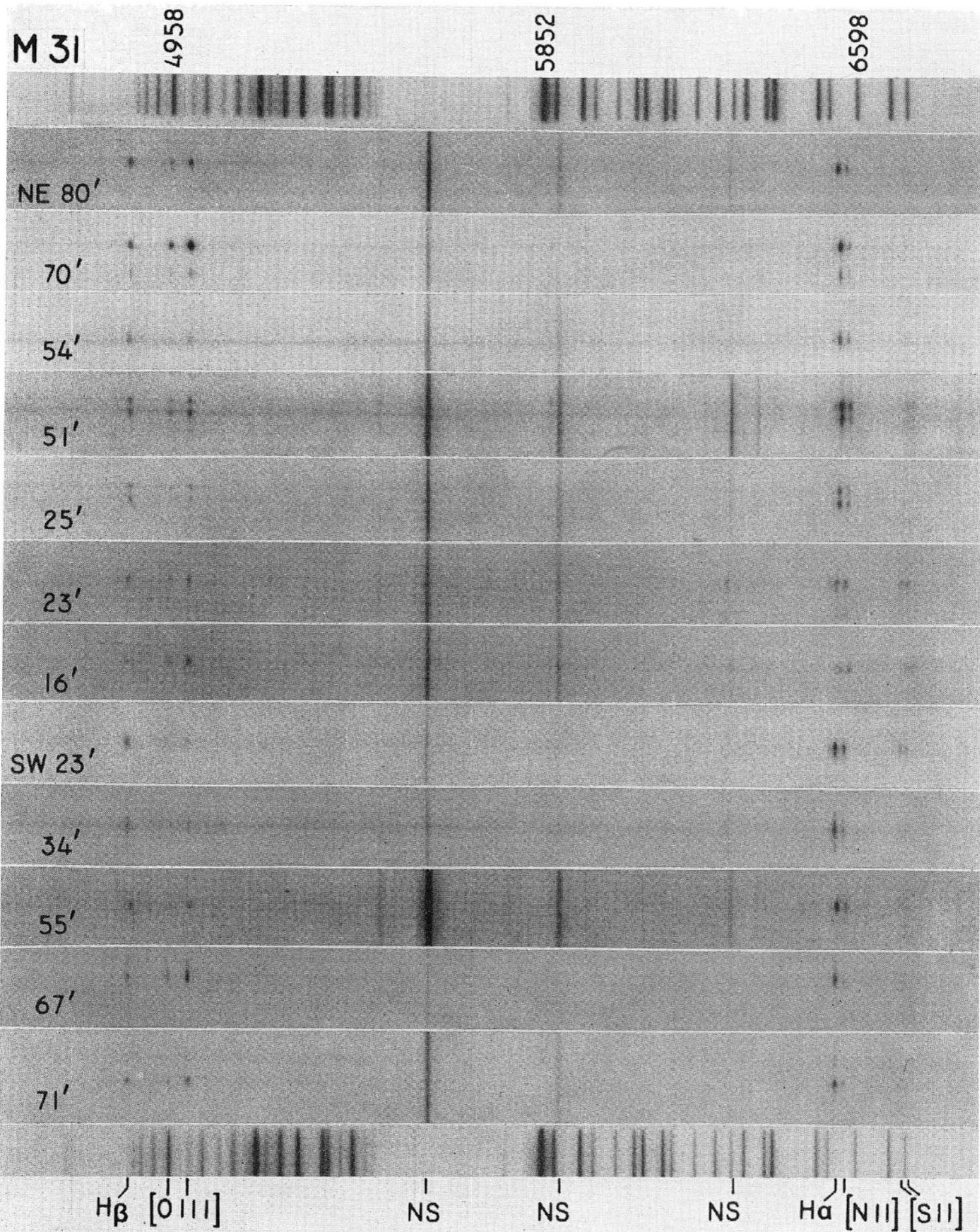
Sloan Digital Sky Survey



Vera Rubin, 1928–2016



Andromeda (M31)



Visible Only



Calculation break!

In the interest of time, this will be a homework assignment

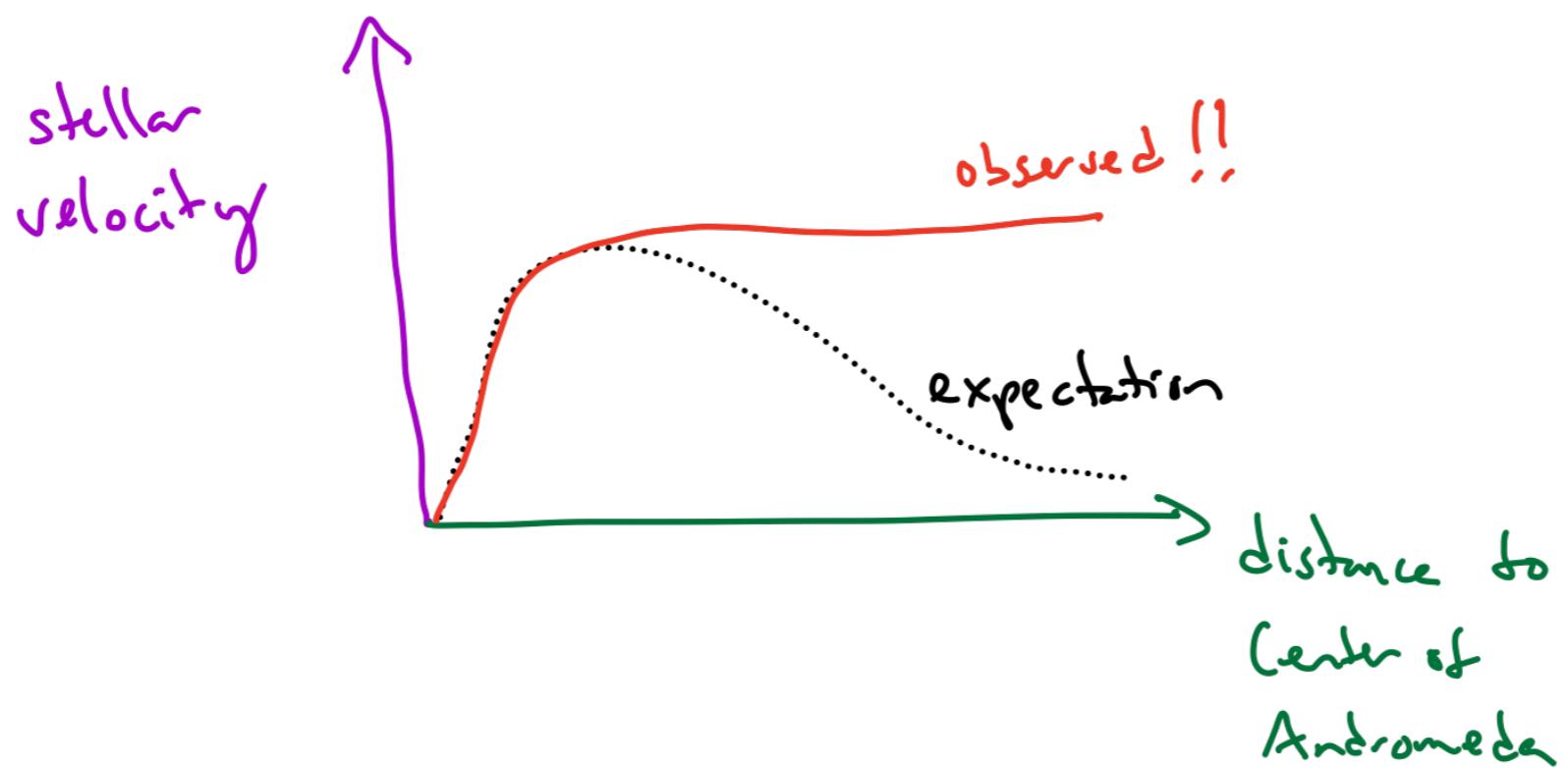
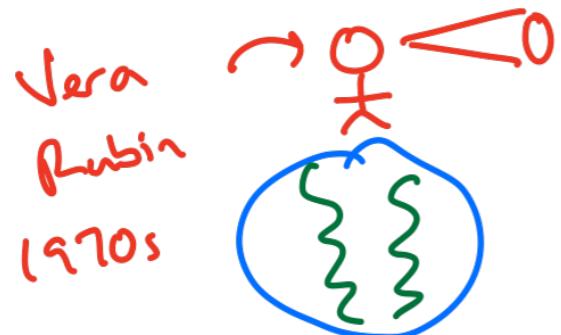
Lincoln Labs Dark Matter Exercise

Jesse Thaler, MIT

March 25, 2022



How surprised should you be about
flat galactic rotation curves?



Let's model the galaxy as a
"spherical cow"



Mass within a radius r
 $= M(r) = M_0 \left(\frac{r}{r_0}\right)^\alpha$

r_0 = some typical radius

M_0 = mass enclosed by r_0

α = how fast mass grows with r



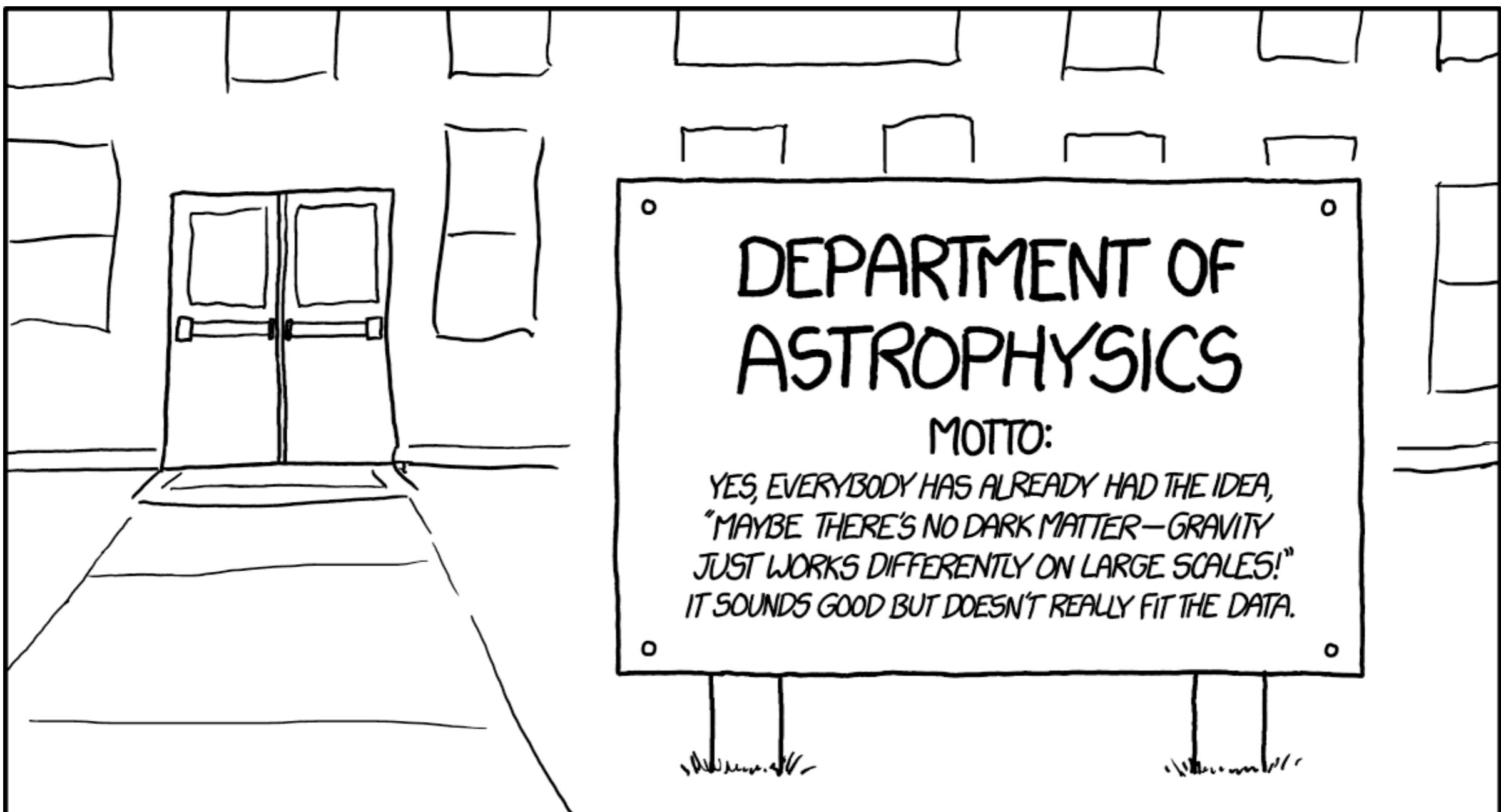
Mass within a radius r

$$= M(r) = M_0 \left(\frac{r}{r_0}\right)^{\alpha}$$

Beyond a certain distance, we don't expect mass to grow much, so $\alpha=0$ is a reasonable model as a starting point

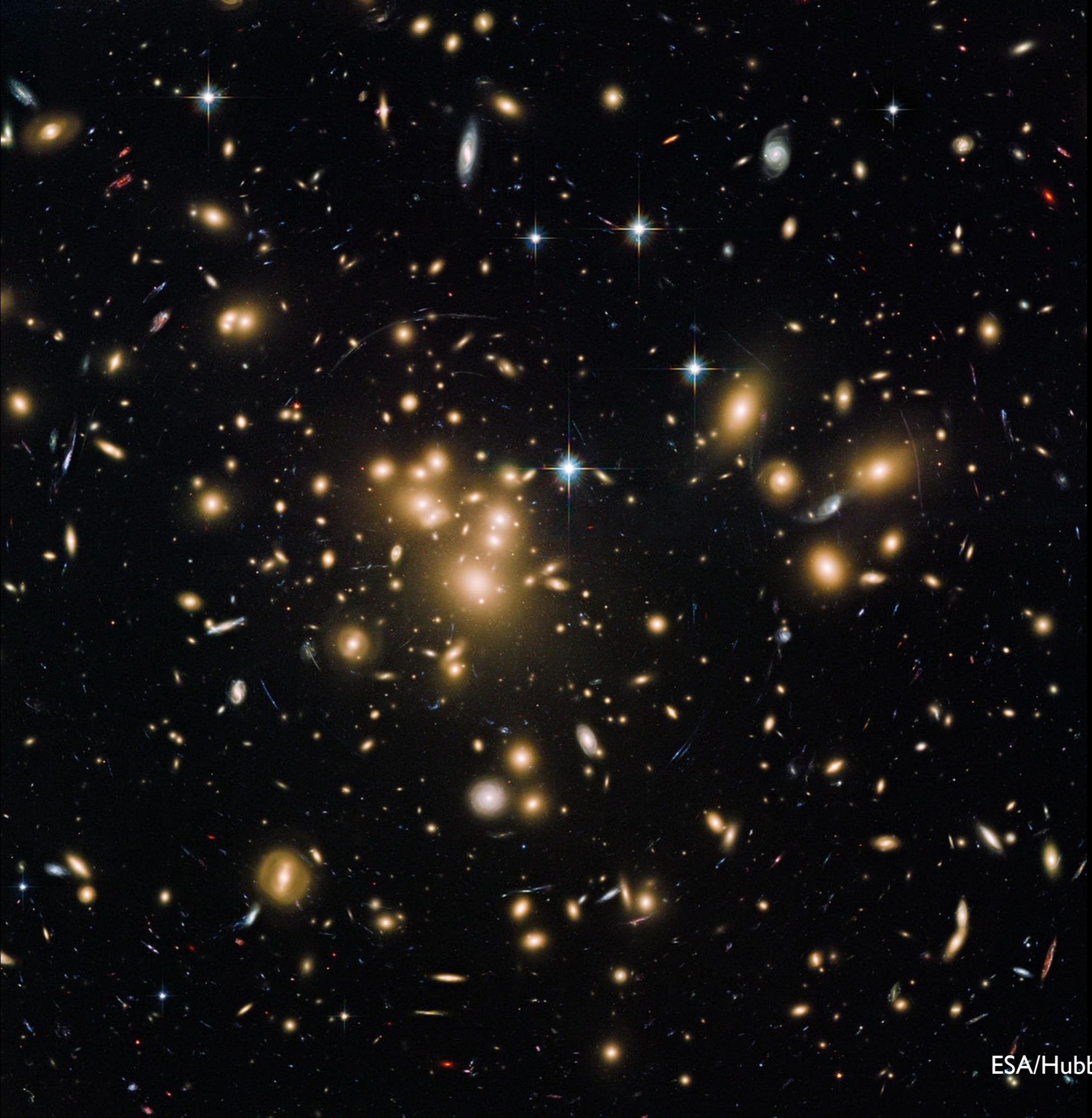
Q: what value of α yields flat rotation curves?

*“Maybe there’s no dark matter—gravity
just works differently on large scales!”*

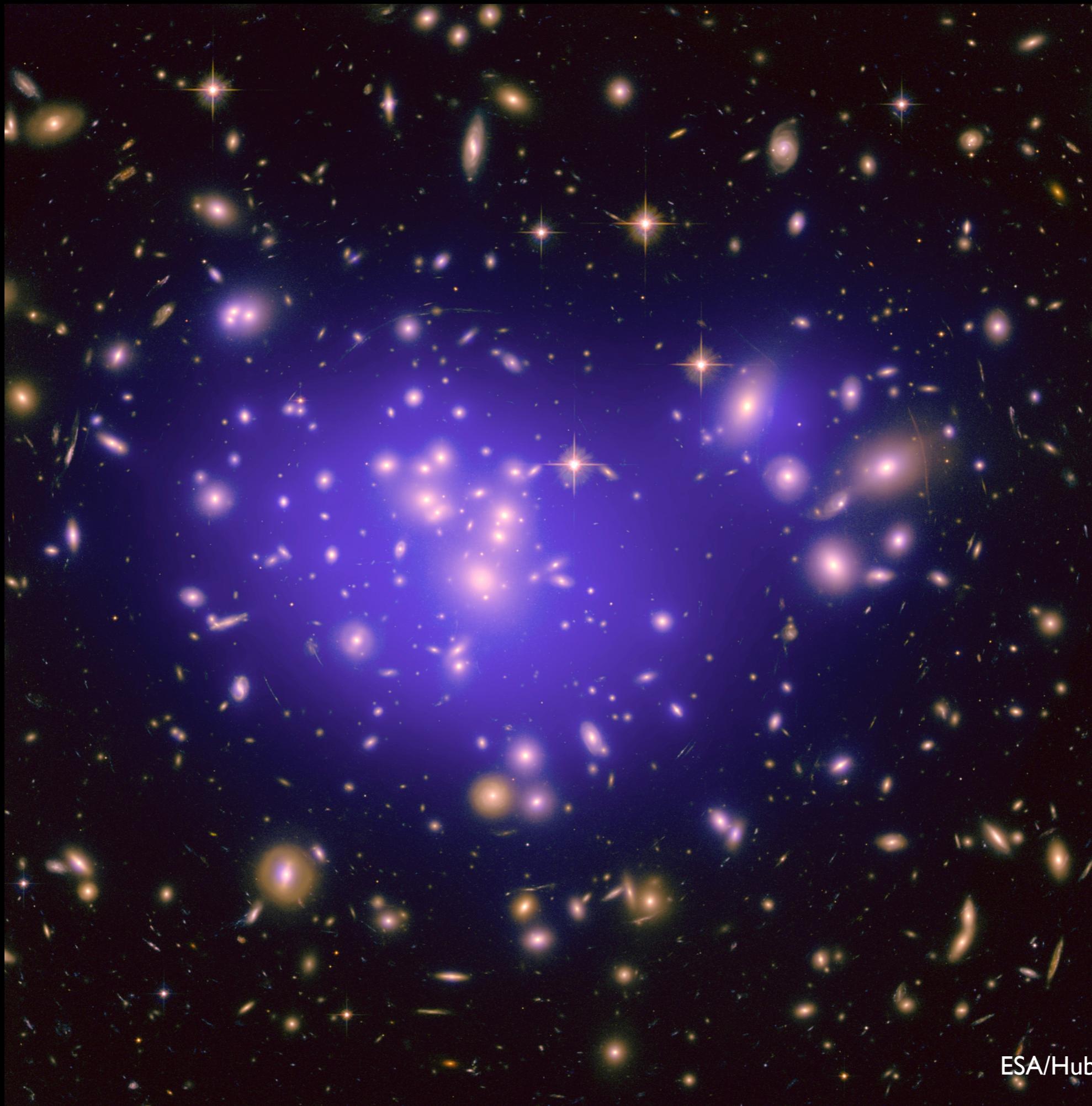




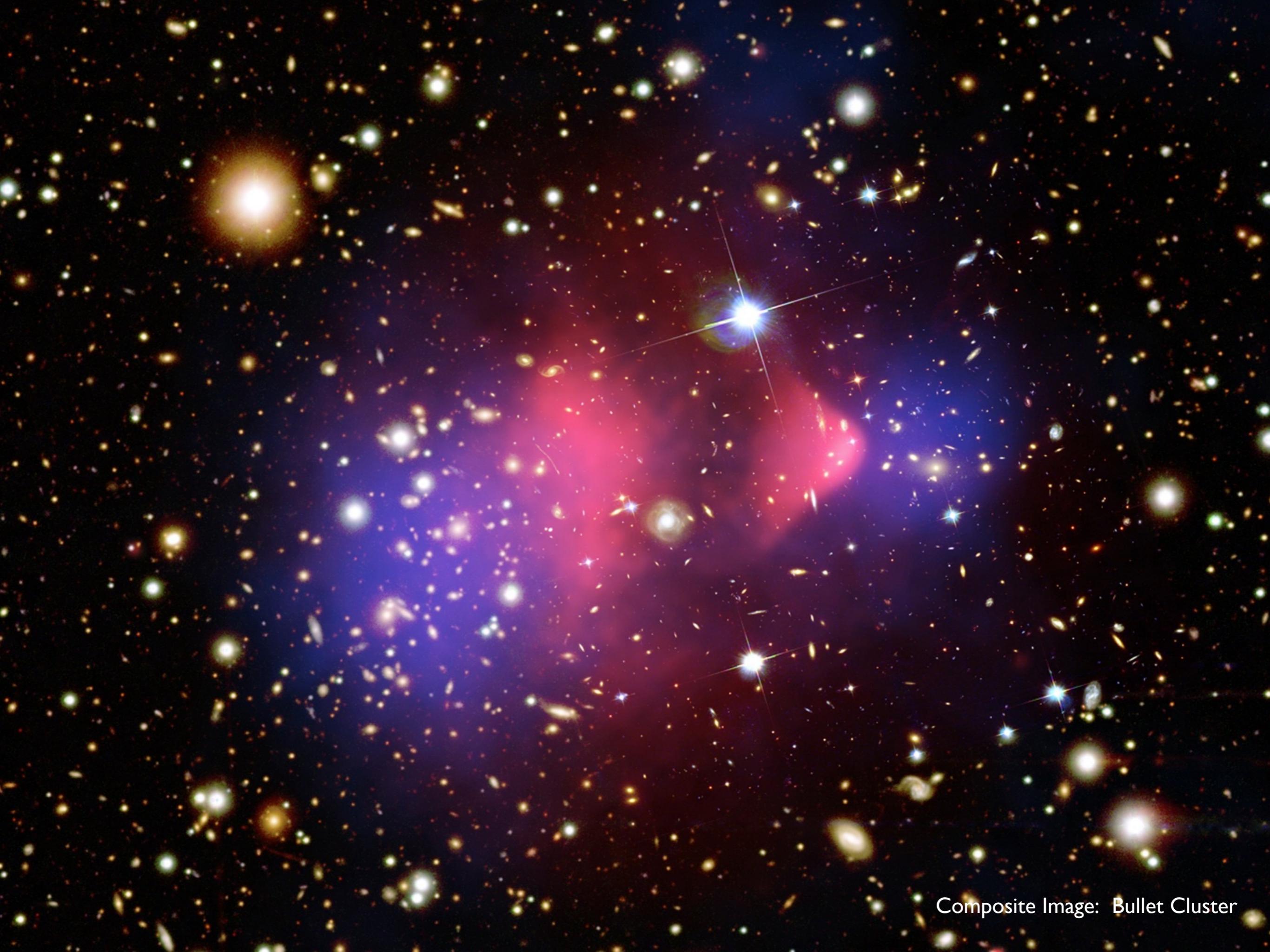
Kevin Hickerson



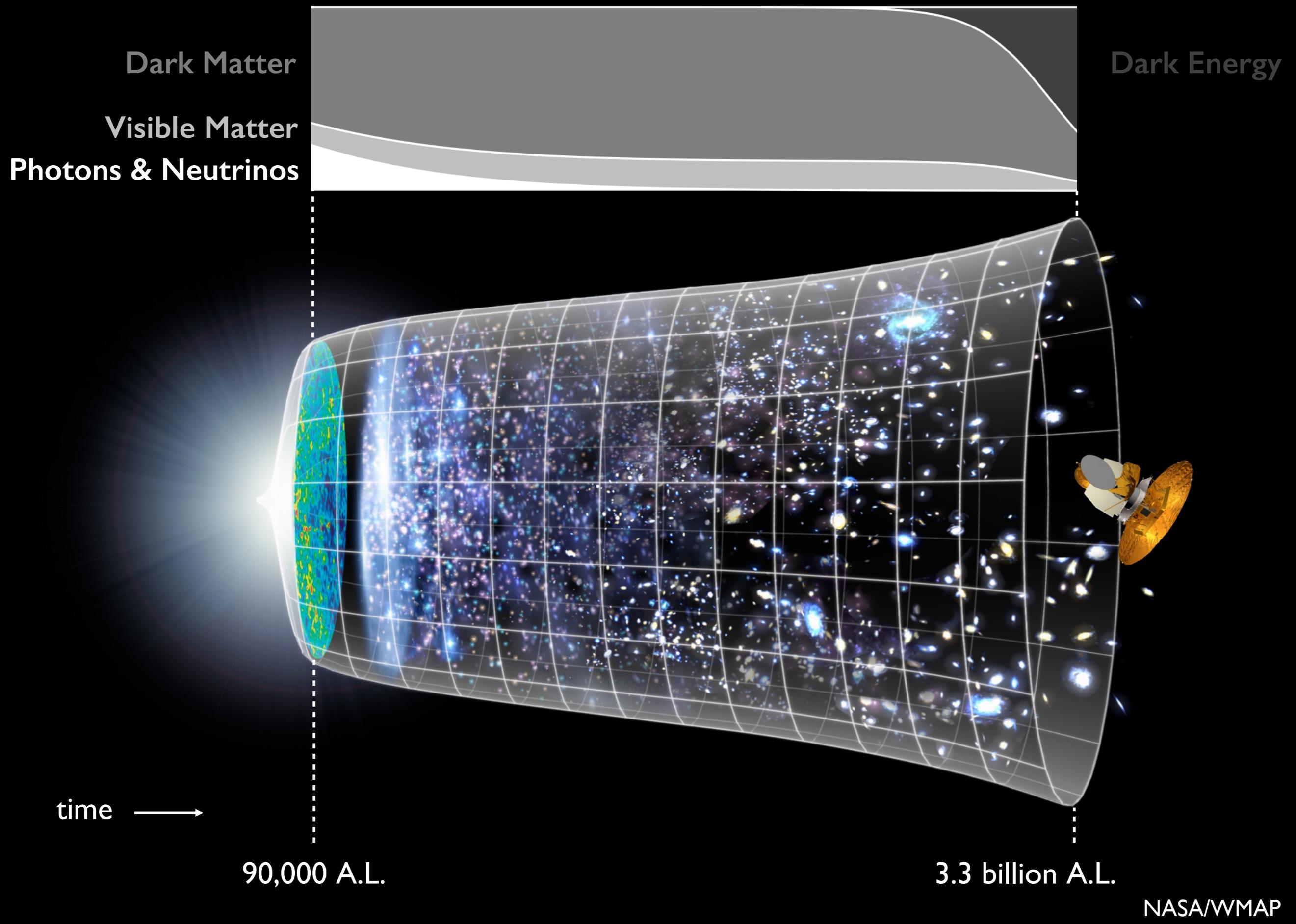
ESA/Hubble: Abell 1689

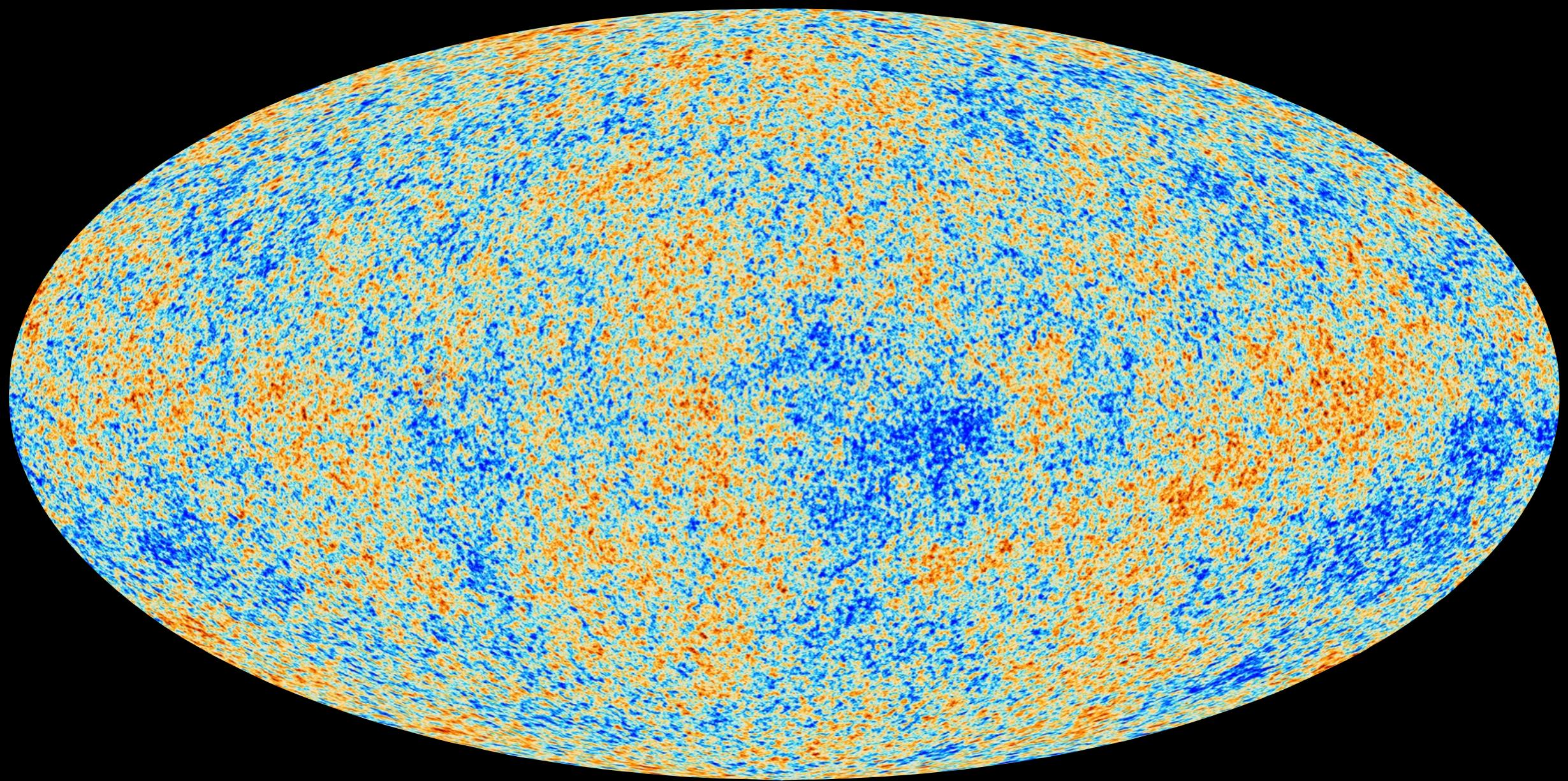


ESA/Hubble: Abell 1689

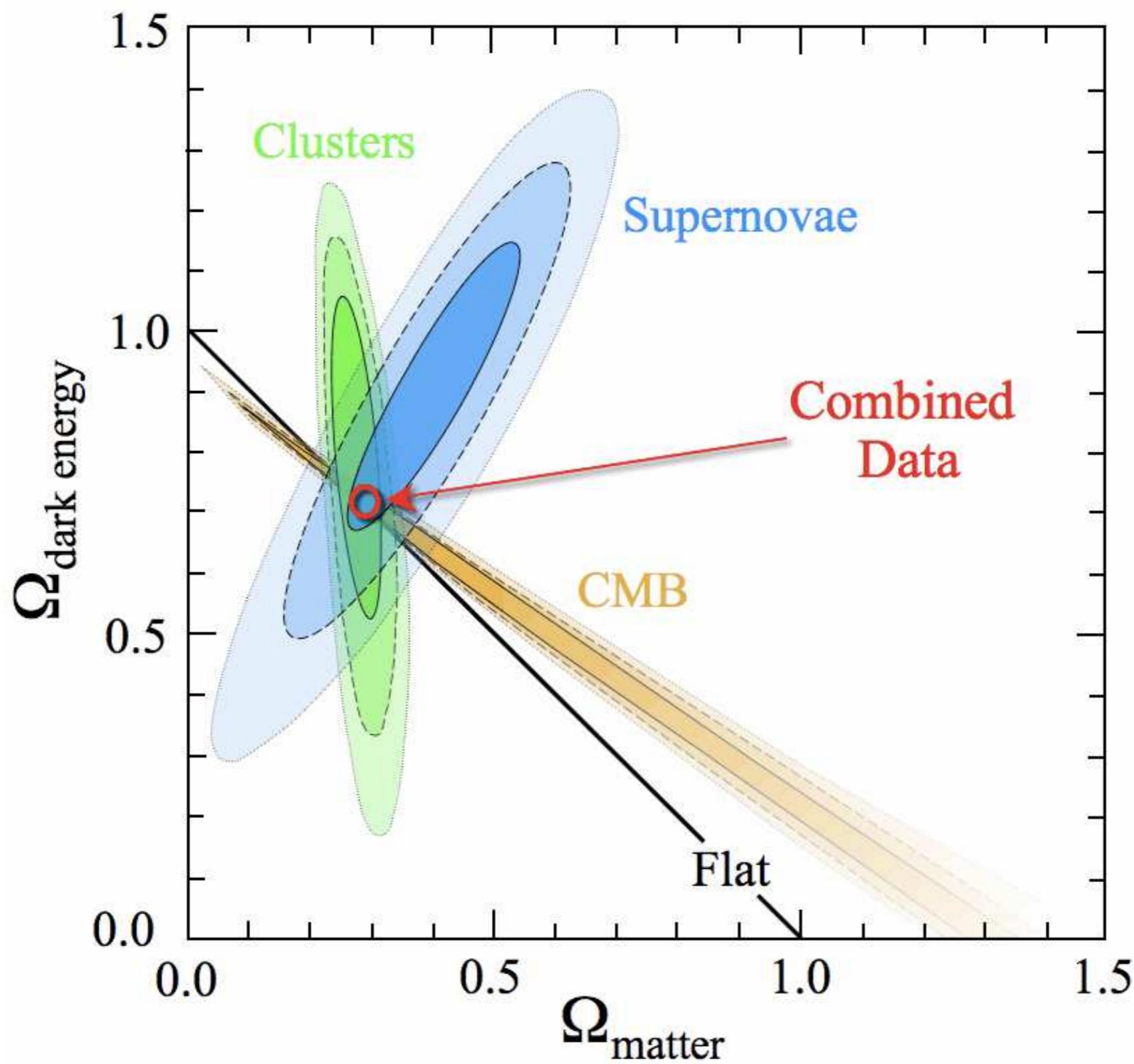


Composite Image: Bullet Cluster





ESA/Planck Cosmic Microwave Background



Simulation break!

<https://chrисnорt.github.io/planckapps/Simulator/>

What parameters match our observed universe?

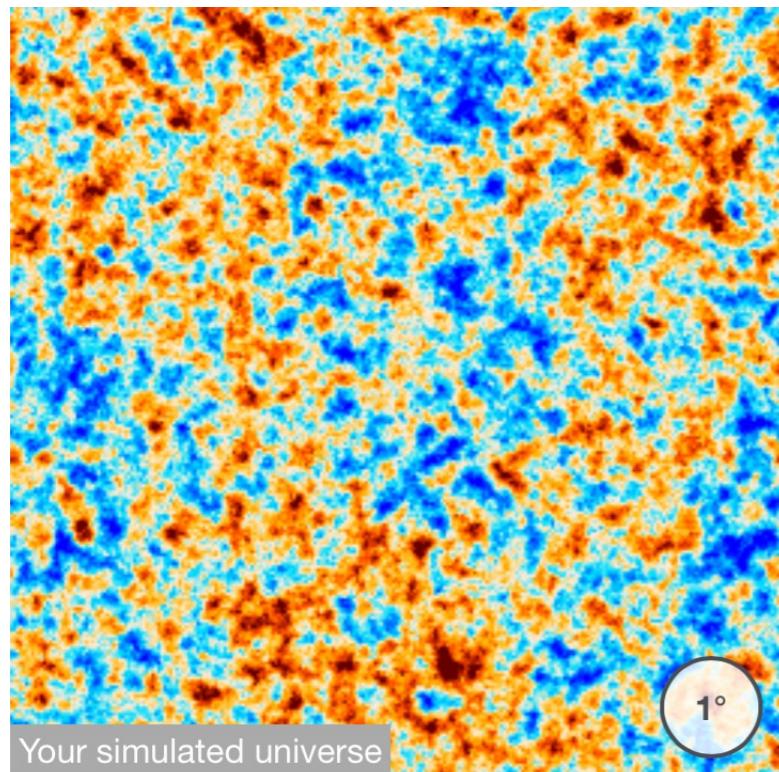
How close can you get if you set Ω_{DM} to zero?

Can you identify a parameter valley?

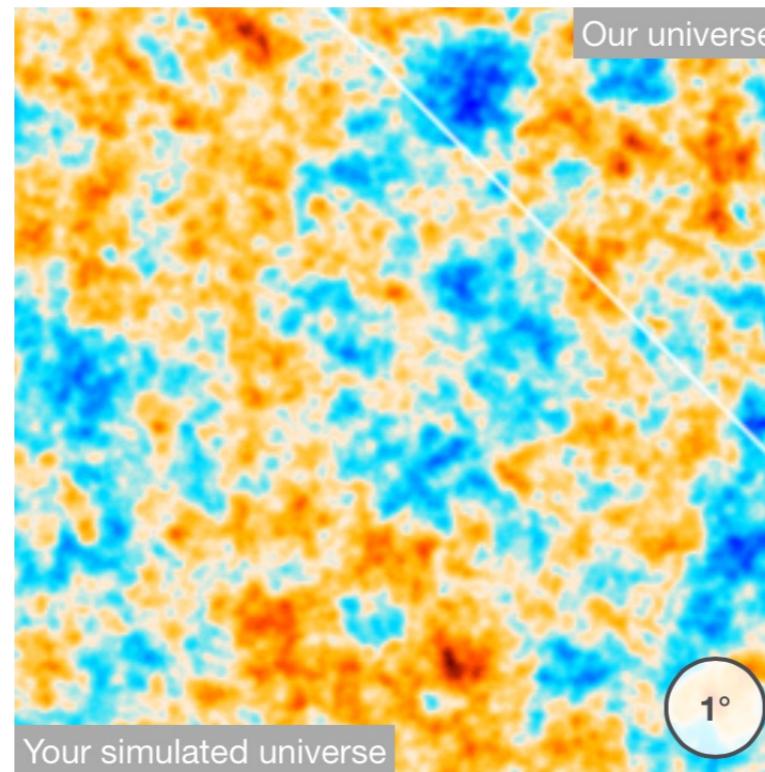
What can you learn from the “power spectrum”?



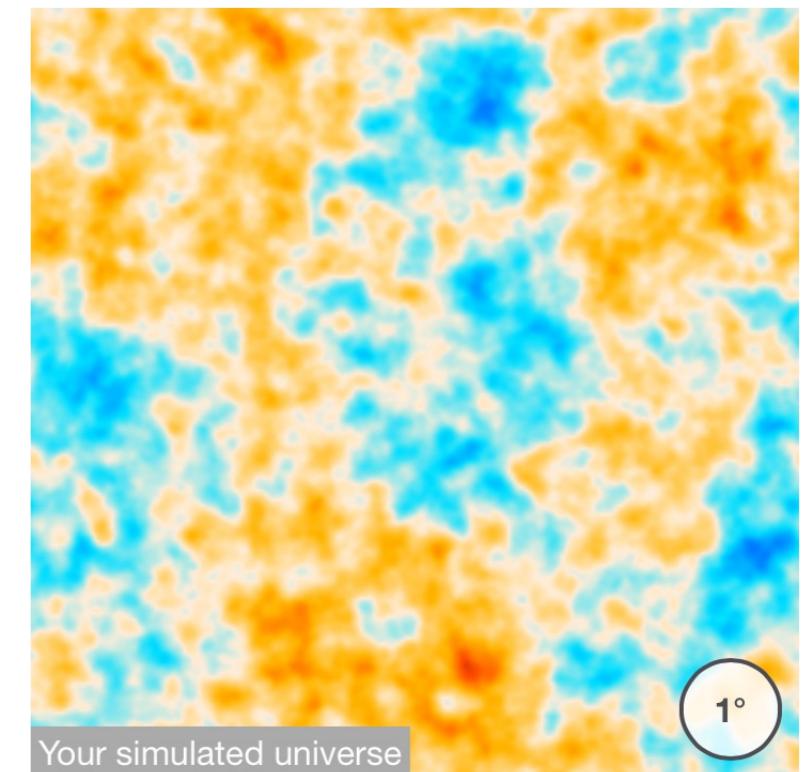
planck CMB Simulator



No Dark Matter



Measured Dark Matter



3x Dark Matter

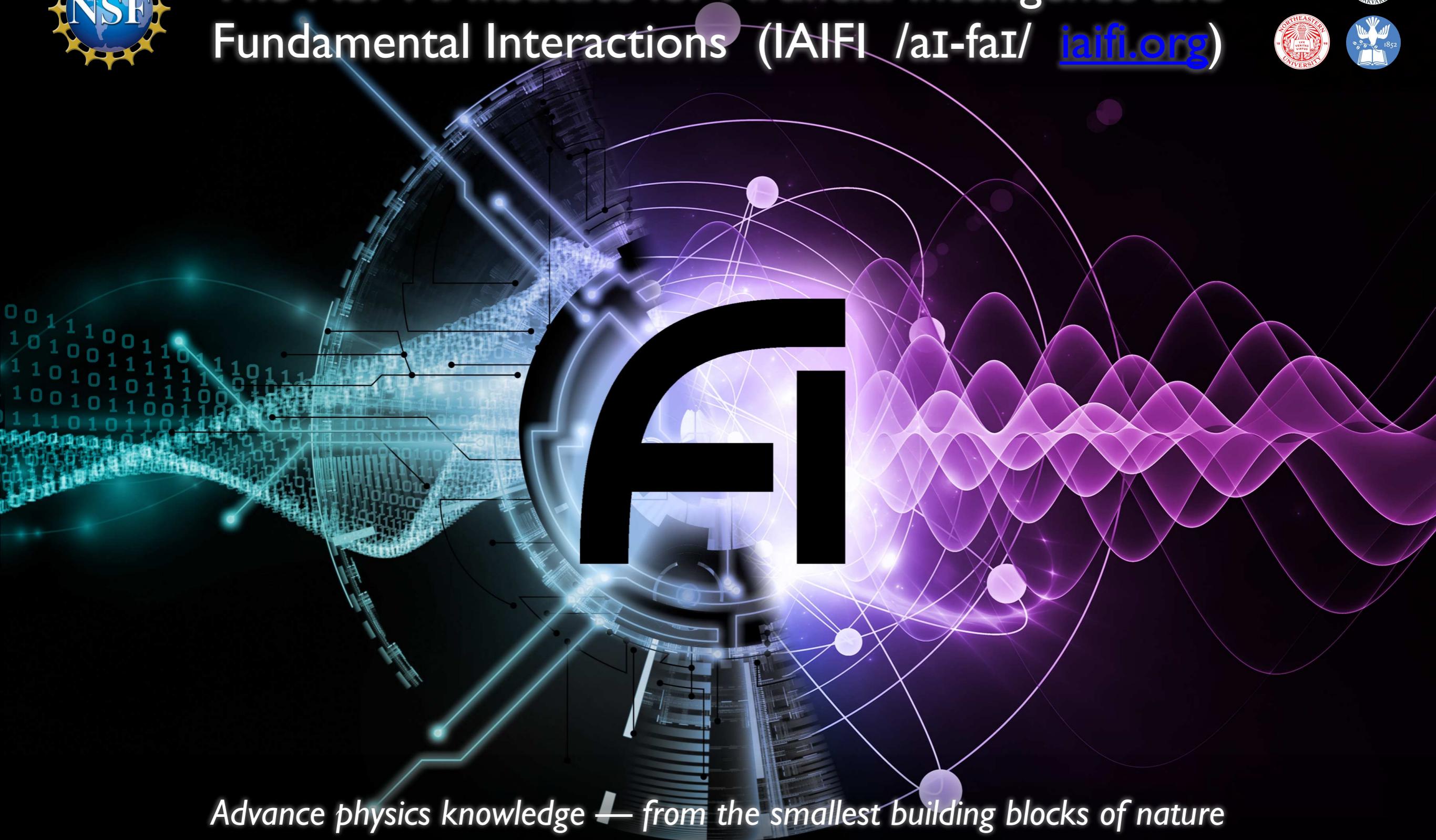
But what *is* Dark Matter?

Good question! In the interest of time, I'm skipping highlights of research efforts from my MIT colleagues

Advertisement break!



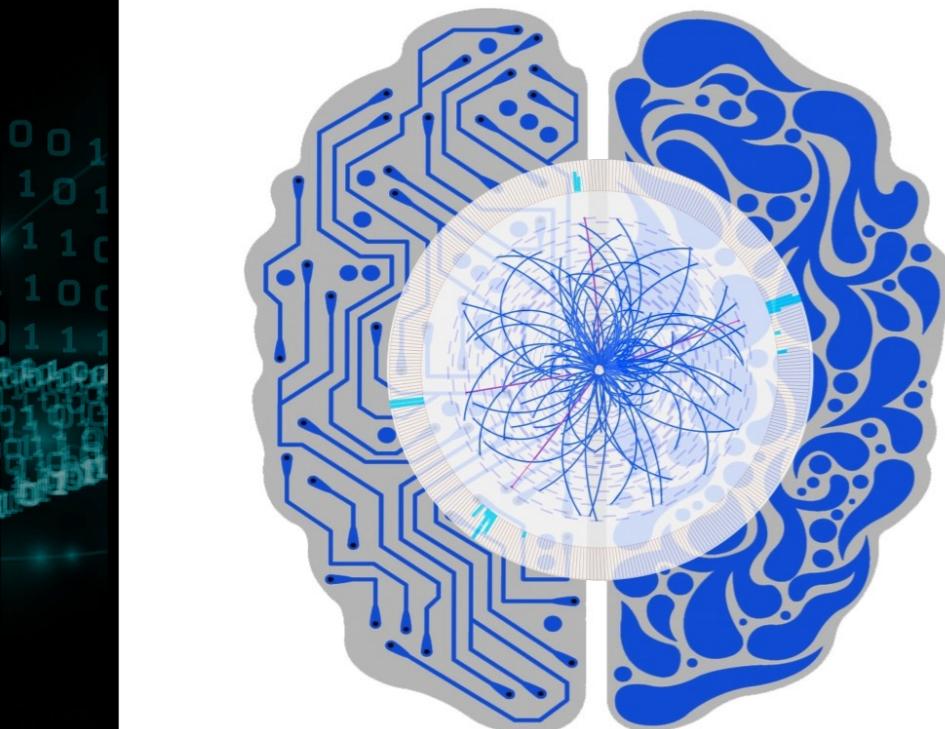
The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI /aI-faI/ iaifi.org)



*Advance physics knowledge — from the smallest building blocks of nature
to the largest structures in the universe — and galvanize AI research innovation*



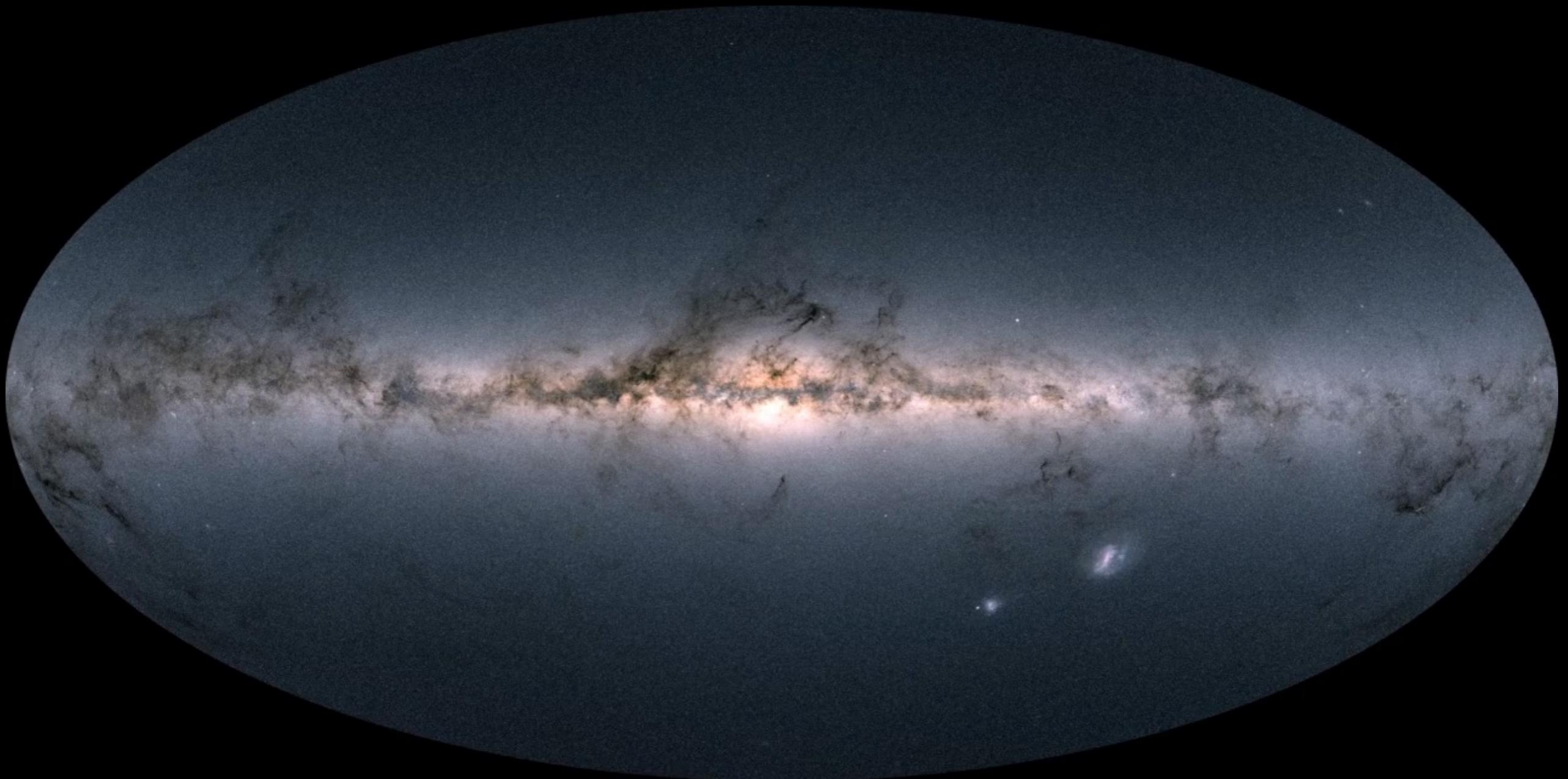
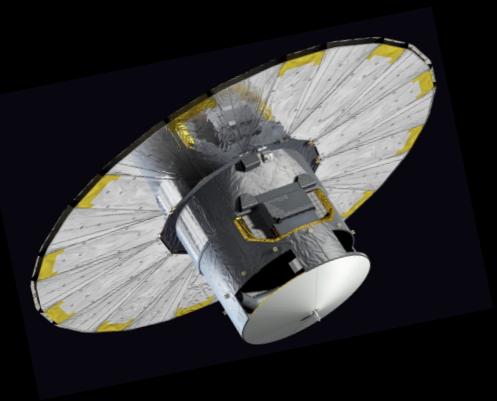
The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI /aI-faI/ iaifi.org)



For another talk...

***Infuse physics intelligence
into artificial intelligence***

*Advance physics knowledge — from the smallest building blocks of nature
to the largest structures in the universe — and galvanize AI research innovation*



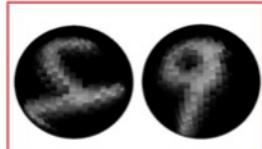
Gaia (Prof. Lina Necib)



IAIFI Fellow: Siddharth Mishra-Sharma

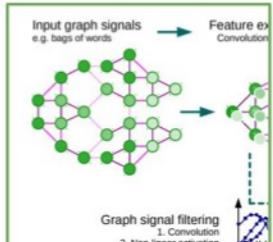


Cohen et al [ICLR 2018]



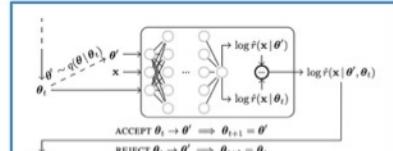
Spherical CNNs

Defferrard et al [NIPS 2016, ICLR 2020]



Graph signal processing

Hermans et al [ICML 2020]



Likelihood-free inference

Ai

fi

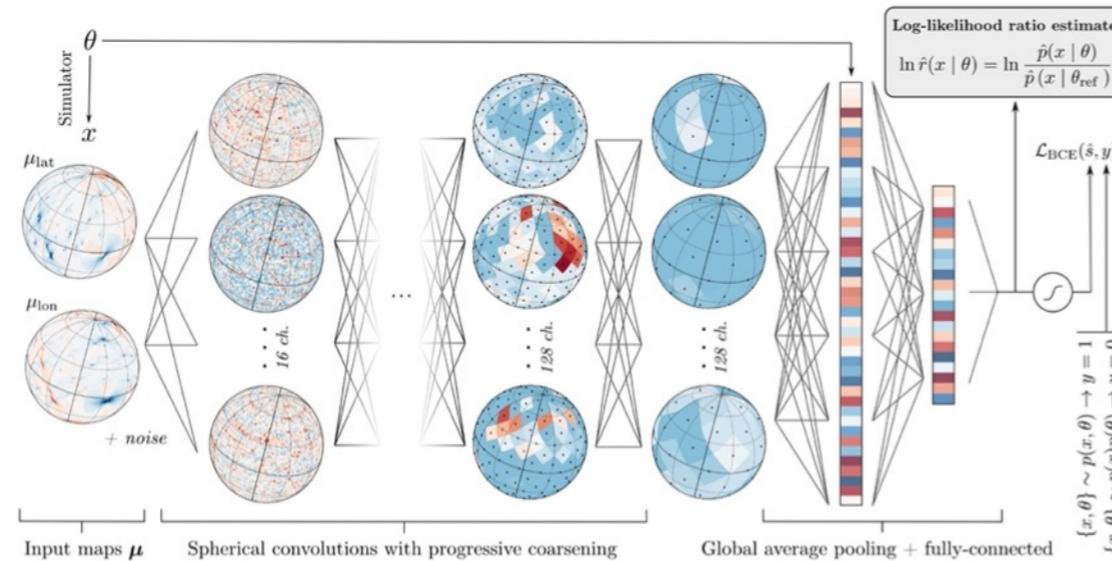


Gravitational lensing of background stars due to dark matter clumps as measured by e.g. the *Gaia* satellite

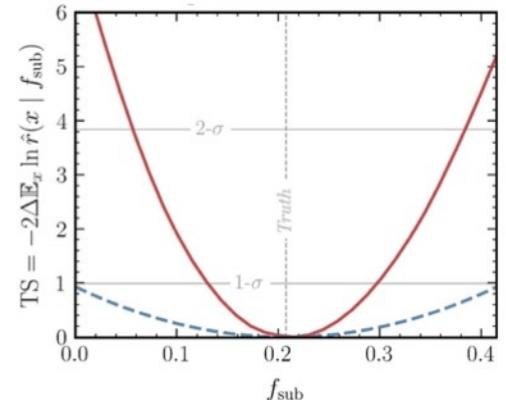


An architecture to extract the dark matter signal

- ★ Account for **structure of data domain** (observations on the celestial sphere)
- ★ Account for **physical symmetries** expected in signal
 - Rotational equivariance (*signal features are similar across the sky*)
 - Rotational invariance (*there is no preferred direction*)
- ★ Infer **statistically-meaningful** quantity: likelihood ratio



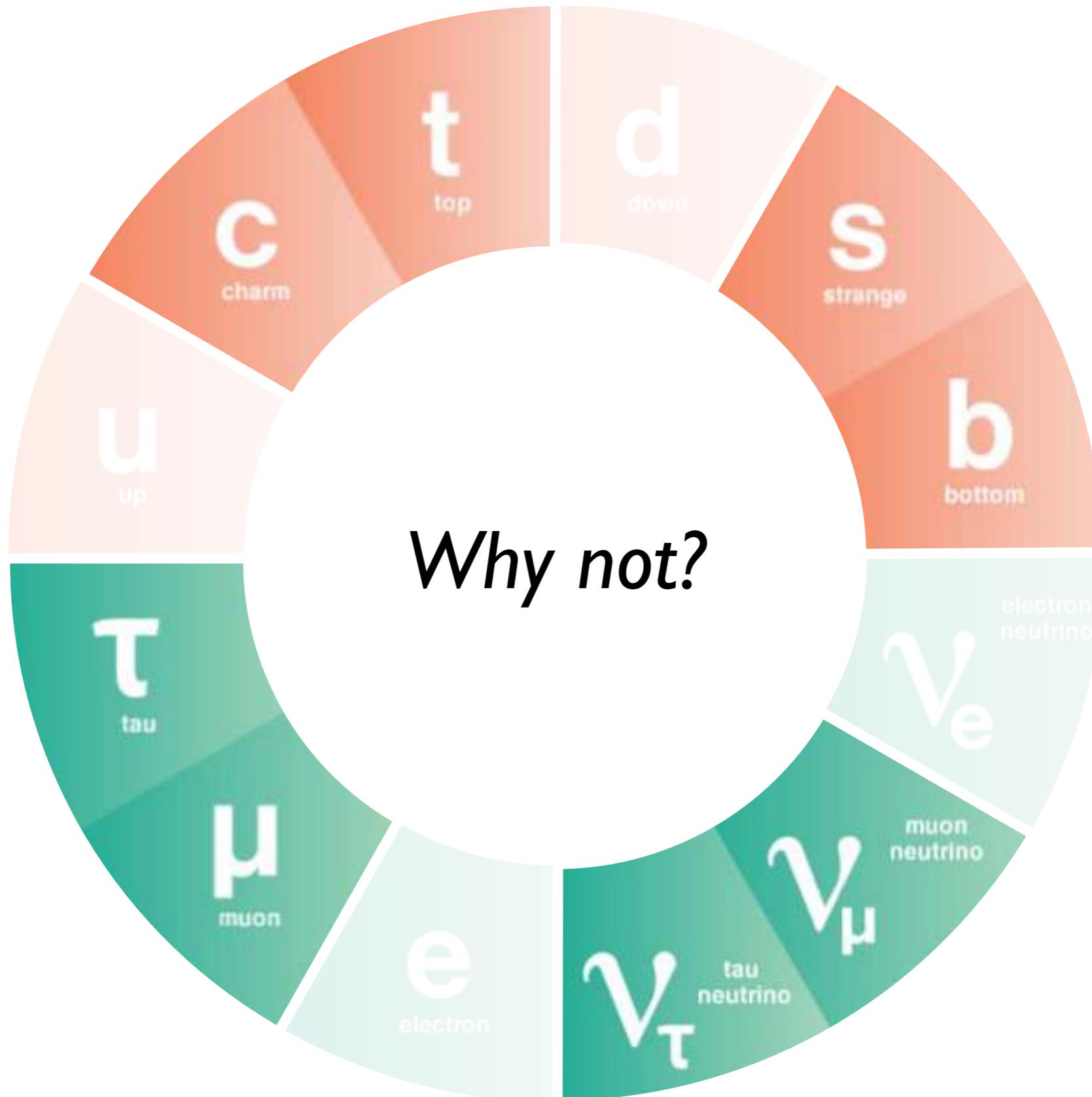
Significantly greater sensitivity to dark matter compared to traditional methods



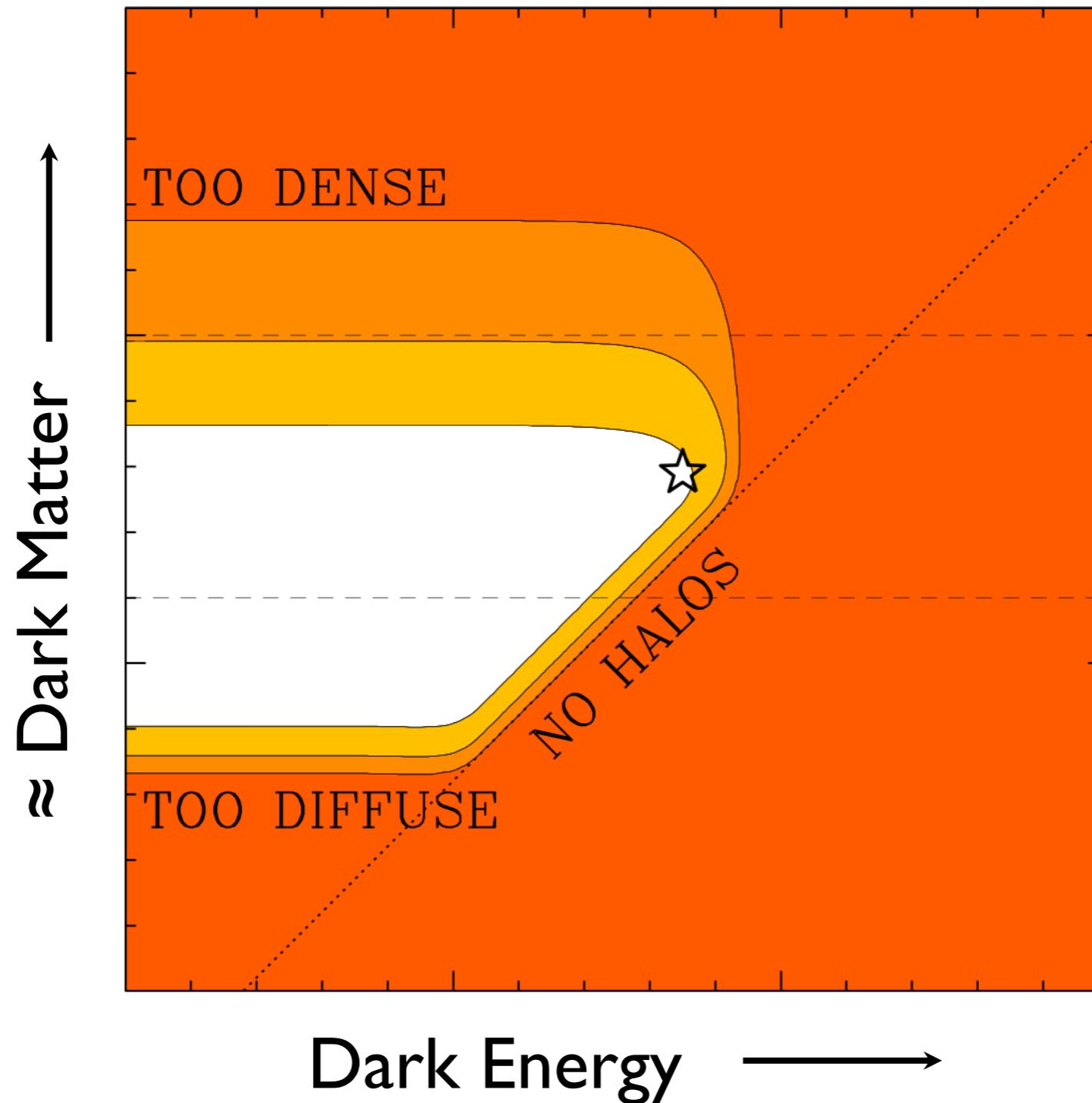
Reference: Mishra-Sharma [MLST 2022; arXiv:2110.01620]



Why is there Dark Matter?



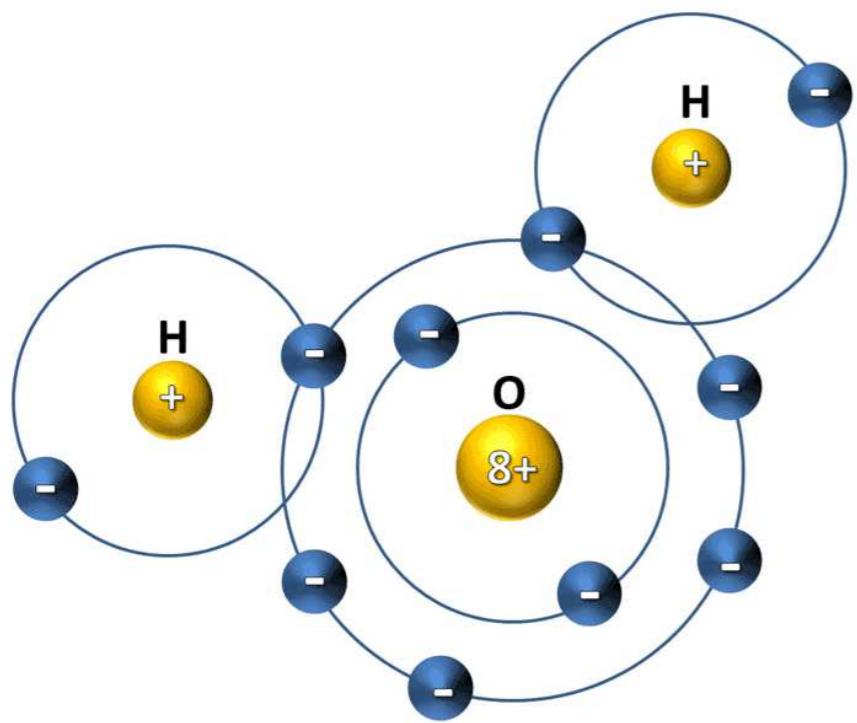
A Curious Coincidence



Tegmark, Aguirre, Rees, Wilczek (2005)

Is Dark Matter related
to other Mysteries
of the Universe?

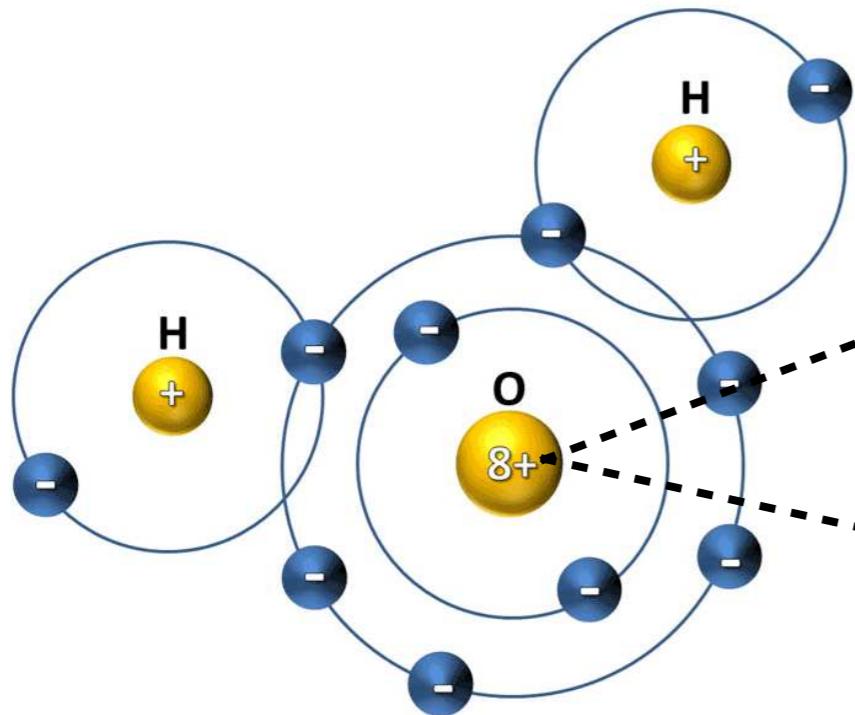
Water



1.85 D

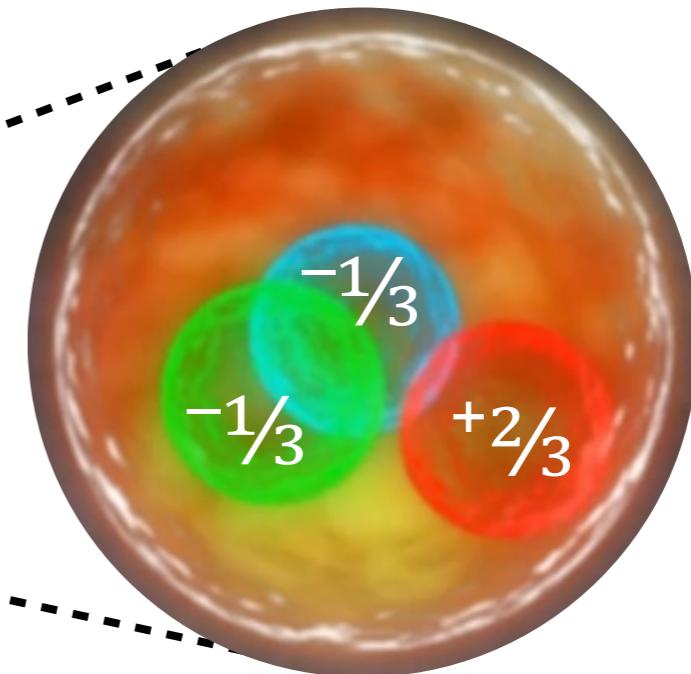


Water



1.85 D

Neutron

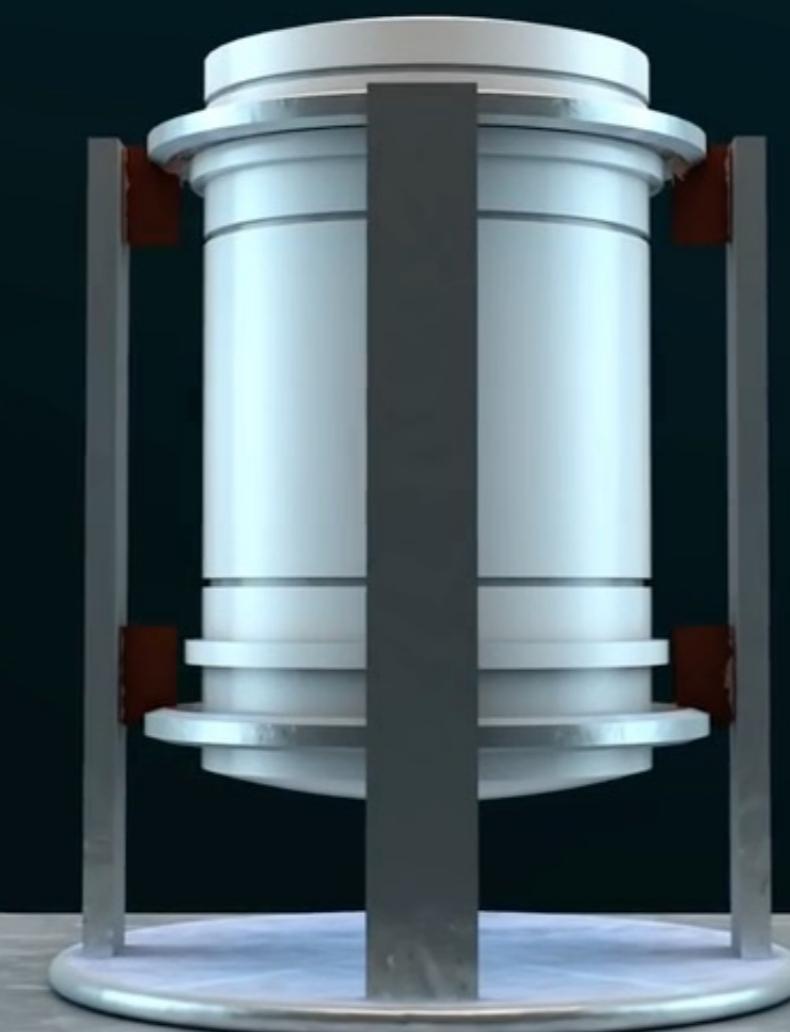


< 0.00000000000000 | 4 D





Peccei, Quinn; Weinberg; Wilczek; ...



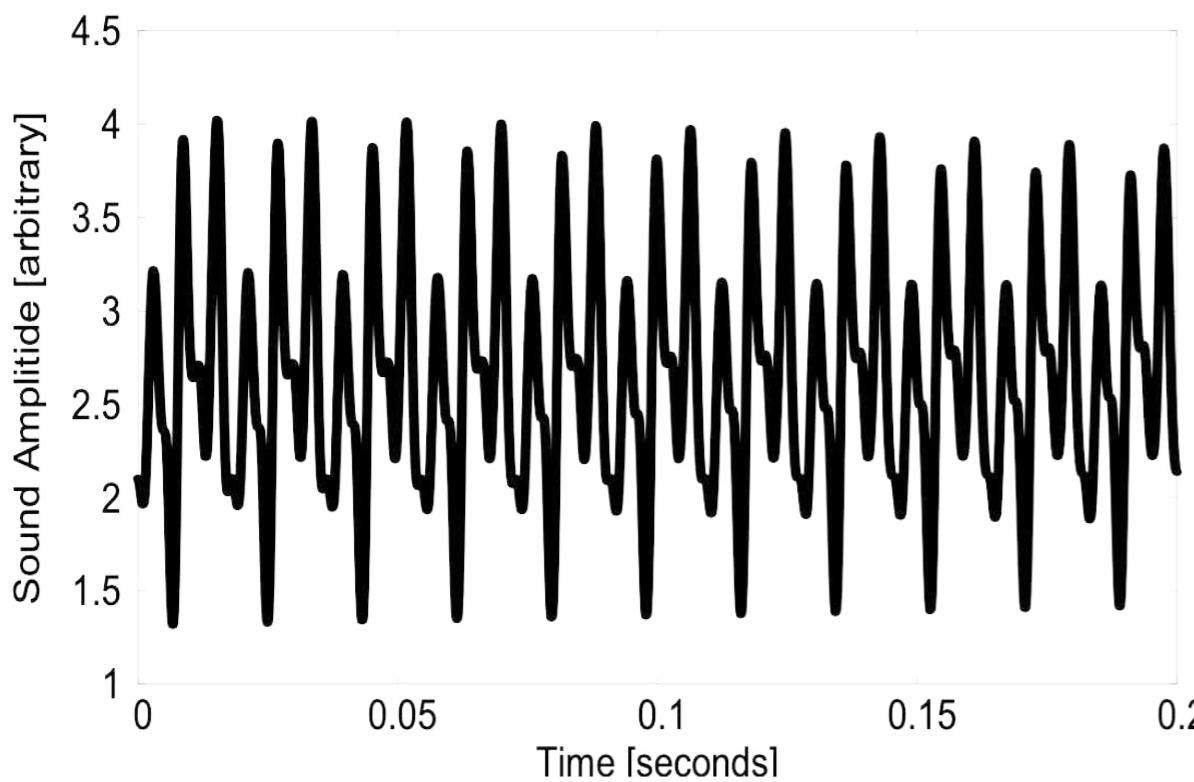
CASPER Experiment



Open A String

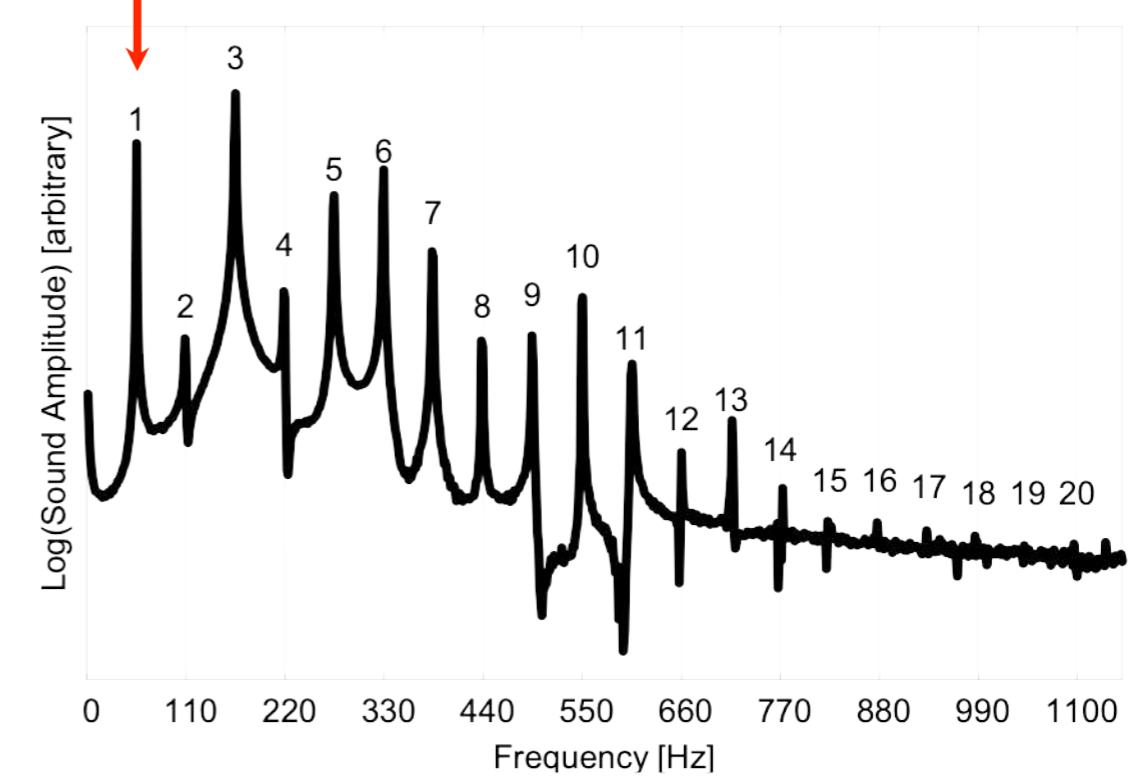


Waveform



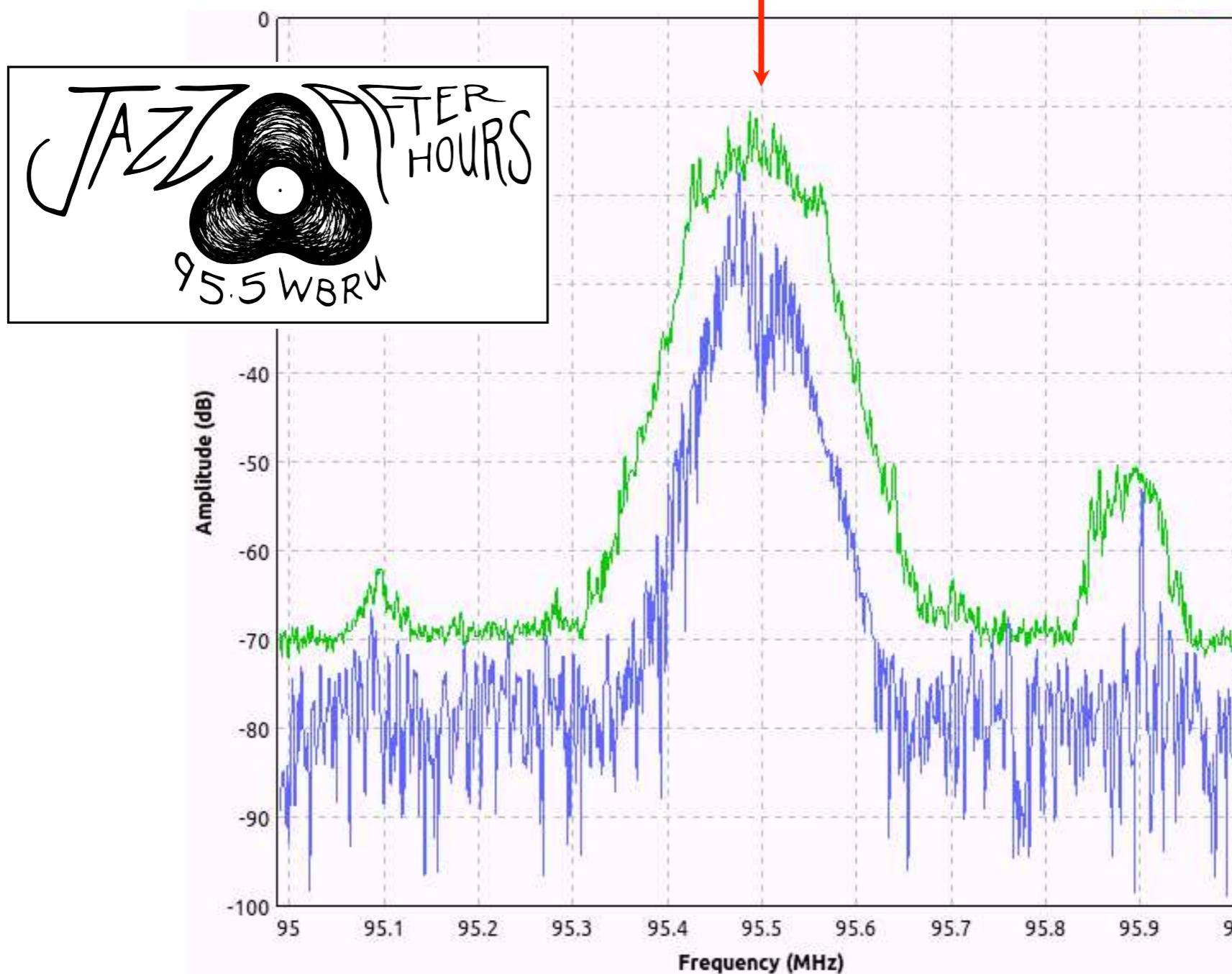
55 Hz

Spectrum



95,500,000 Hz

Electromagnetic waves
instead of sound



Broadband and Resonant Approaches to Axion Dark Matter Detection

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²*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 3 March 2016; published 30 September 2016)



! → First Results from ABRACADABRA-10 cm: A Search for Sub- μ eV Axion Dark Matter

Jonathan L. Ouellet,^{1,*} Chiara P. Salemi,¹ Joshua W. Foster,² Reyco Henning,^{3,4} Zachary Bogorad,¹ Janet M. Conrad,¹ Joseph A. Formaggio,¹ Yonatan Kahn,^{5,6} Joe Minervini,⁷ Alexey Radovinsky,⁷ Nicholas L. Rodd,^{8,9} Benjamin R. Safdi,² Jesse Thaler,¹⁰ Daniel Winklehner,¹ and Lindley Winslow^{1,†}

¹Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

²Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA

³University of North Carolina, Chapel Hill, North Carolina 27599, USA

⁴Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA

⁵Princeton University, Princeton, New Jersey 08544, USA

⁶Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA

⁷Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

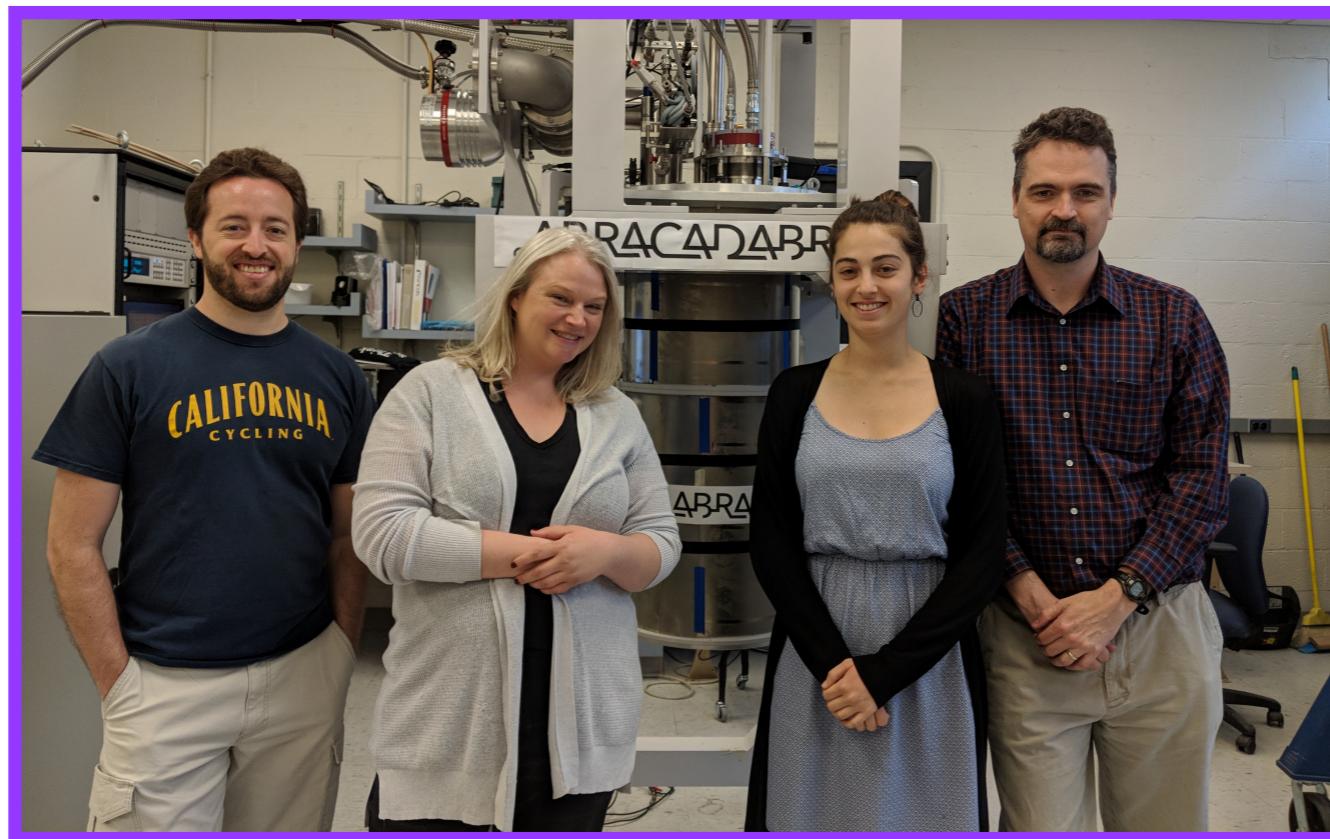
⁸Berkeley Center for Theoretical Physics, University of California, Berkeley, California 94720, USA

⁹Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

¹⁰Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA



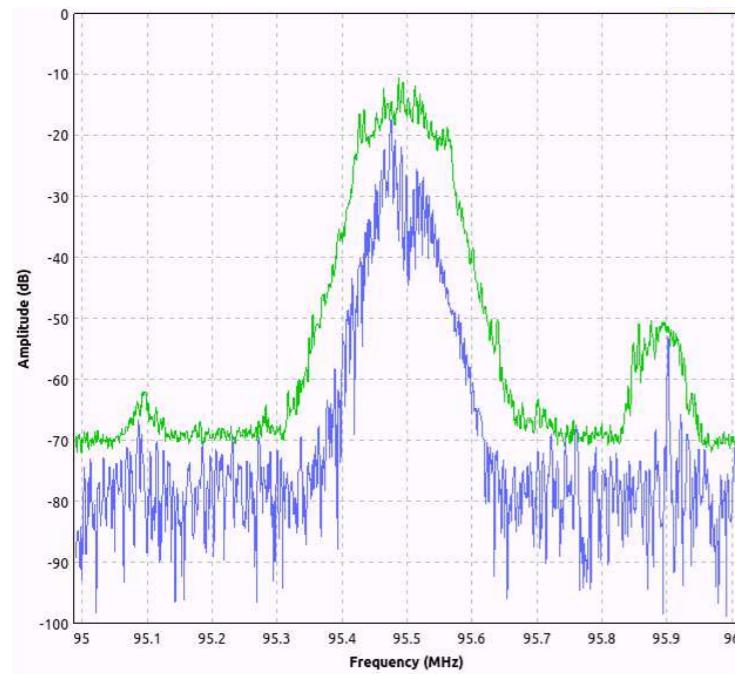
(Received 30 October 2018; published 29 March 2019)



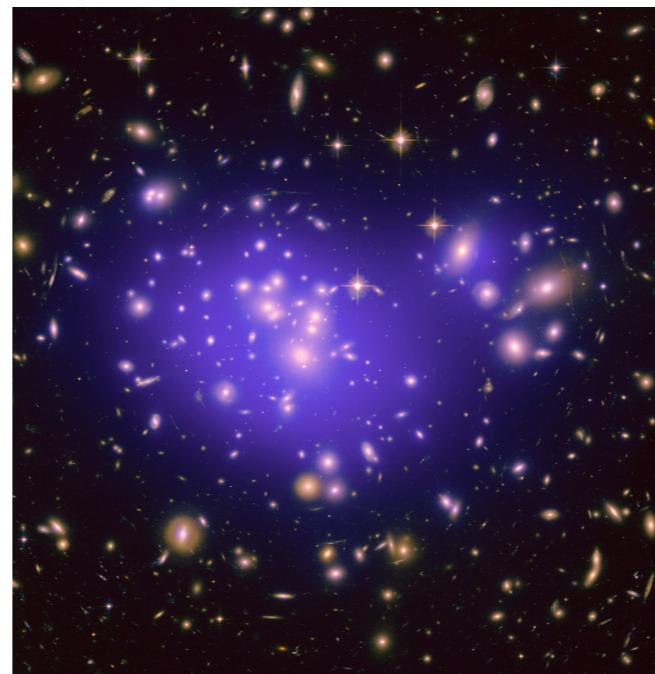
ABRACADABRA →

A Broadband or Resonant Approach to Cosmic Axion
Detection with an Amplifying B-field Ring Apparatus

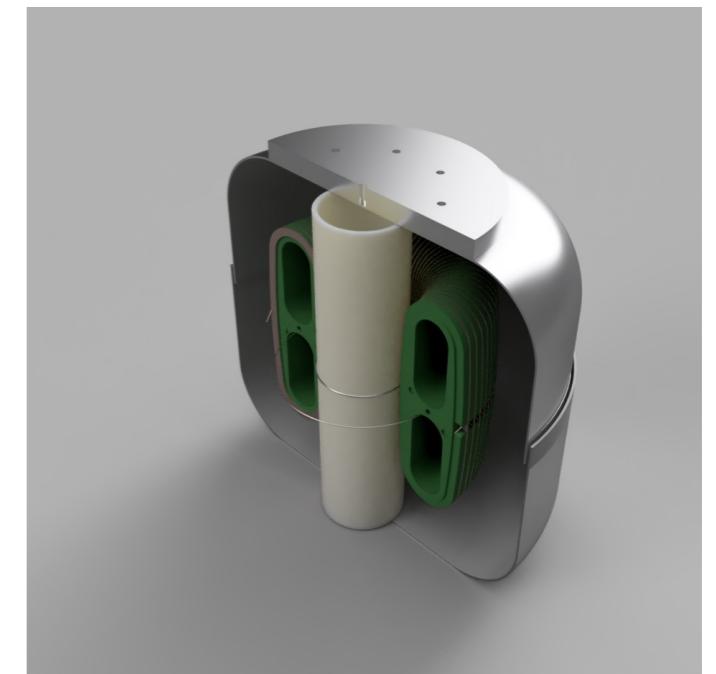
Listening...

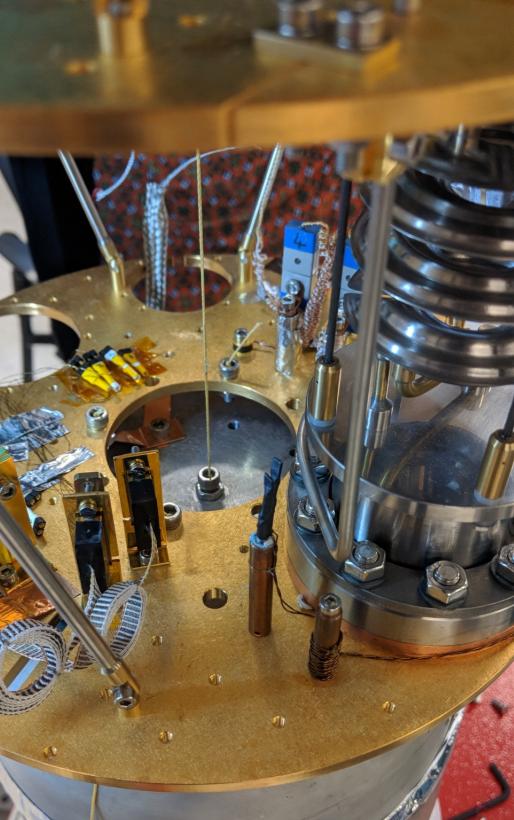
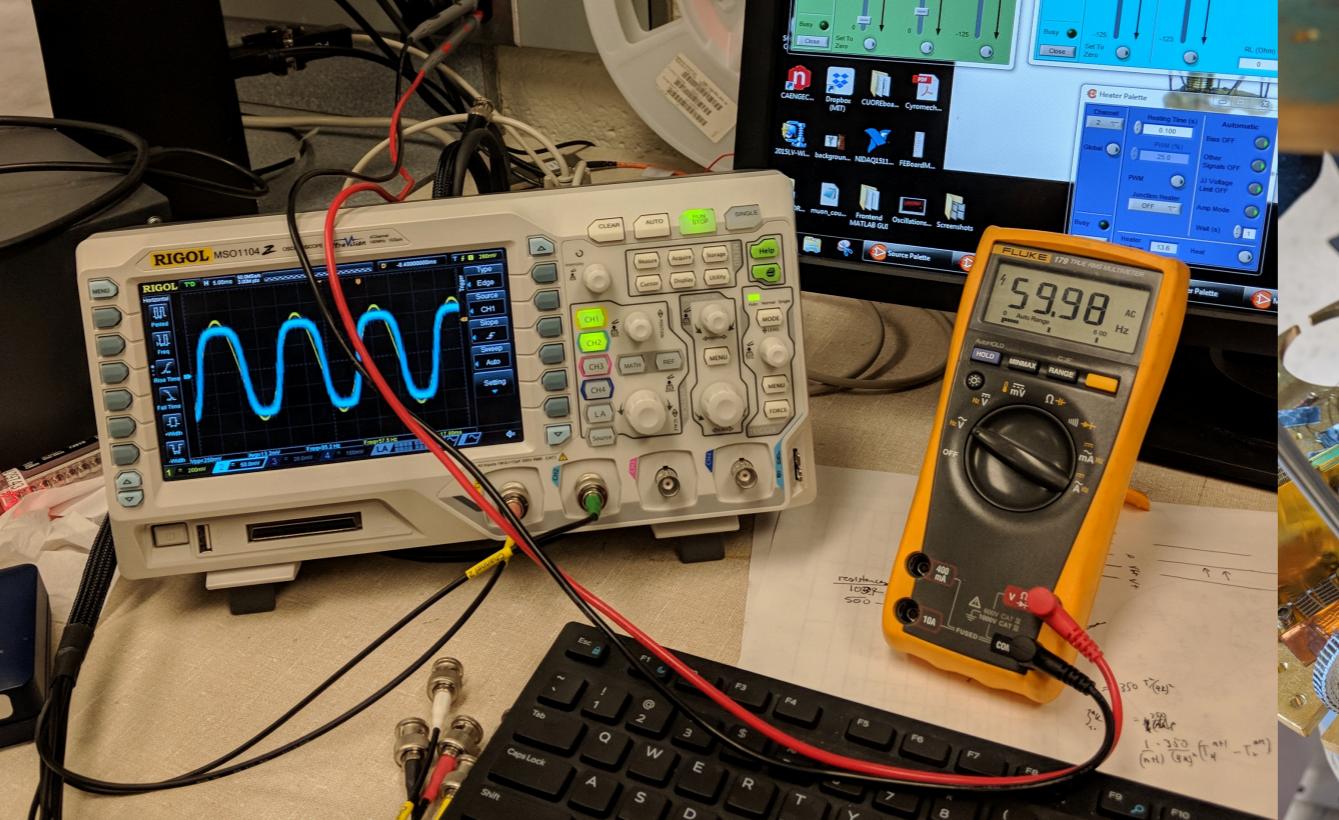
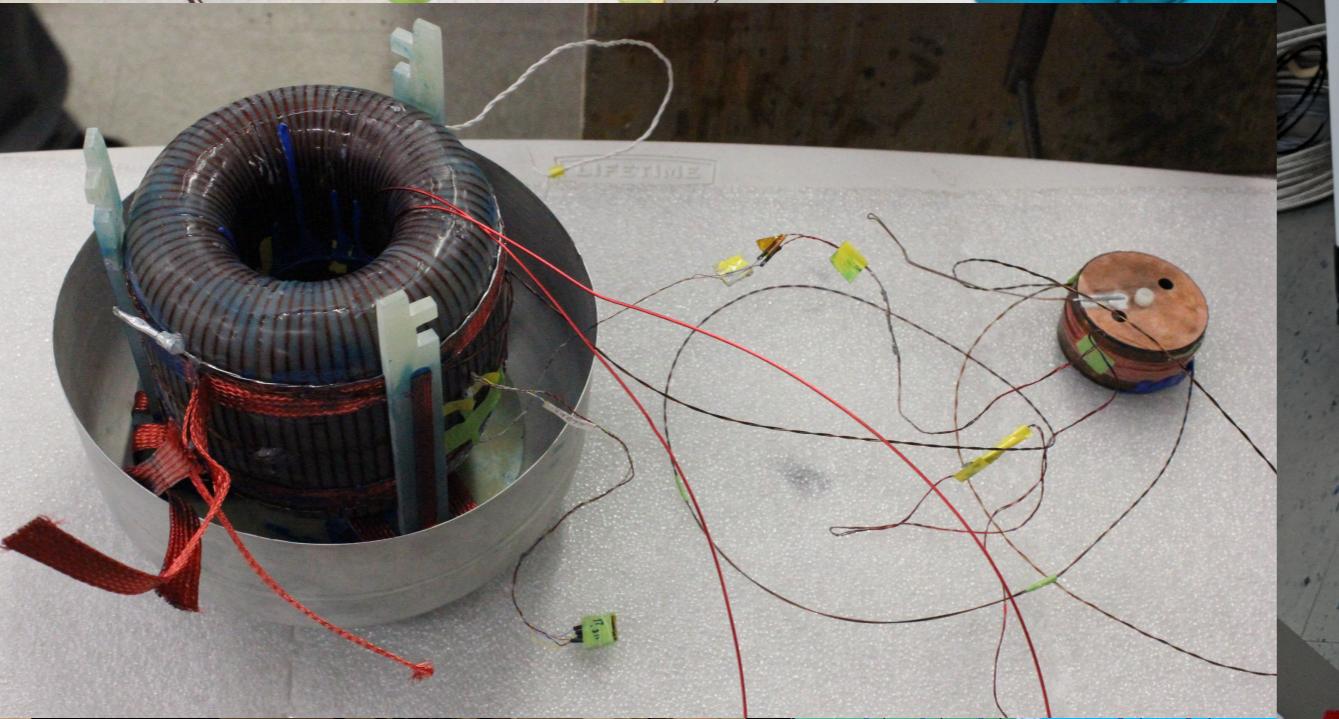
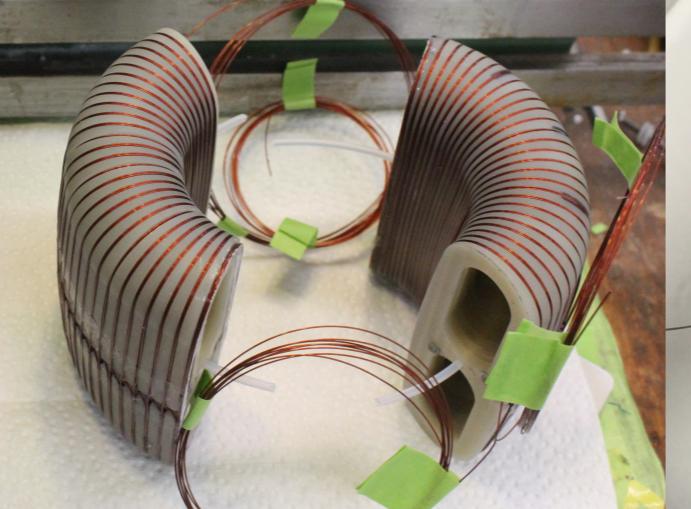


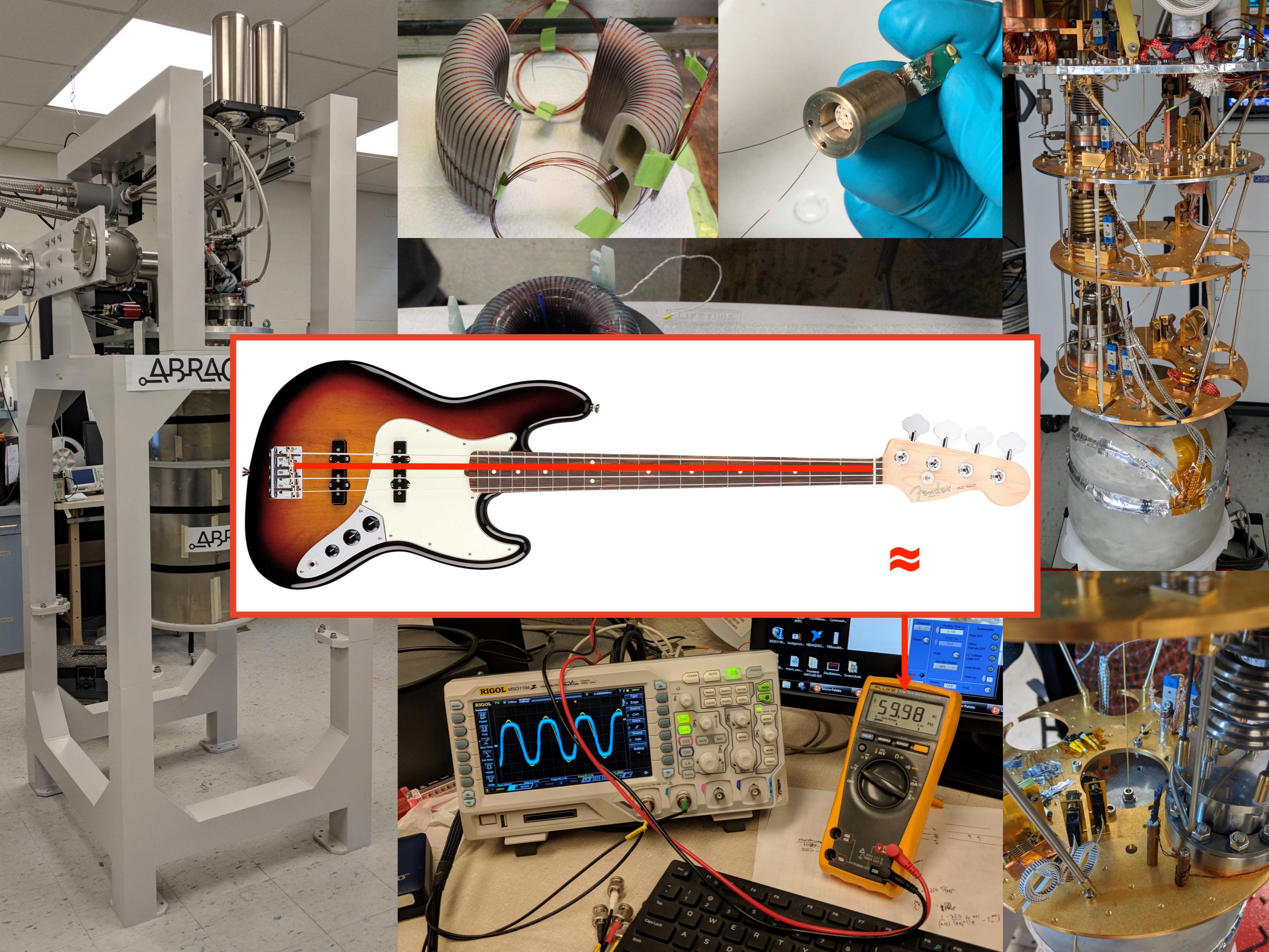
...to the universe...



...very carefully







Listening... to noise



Listening...

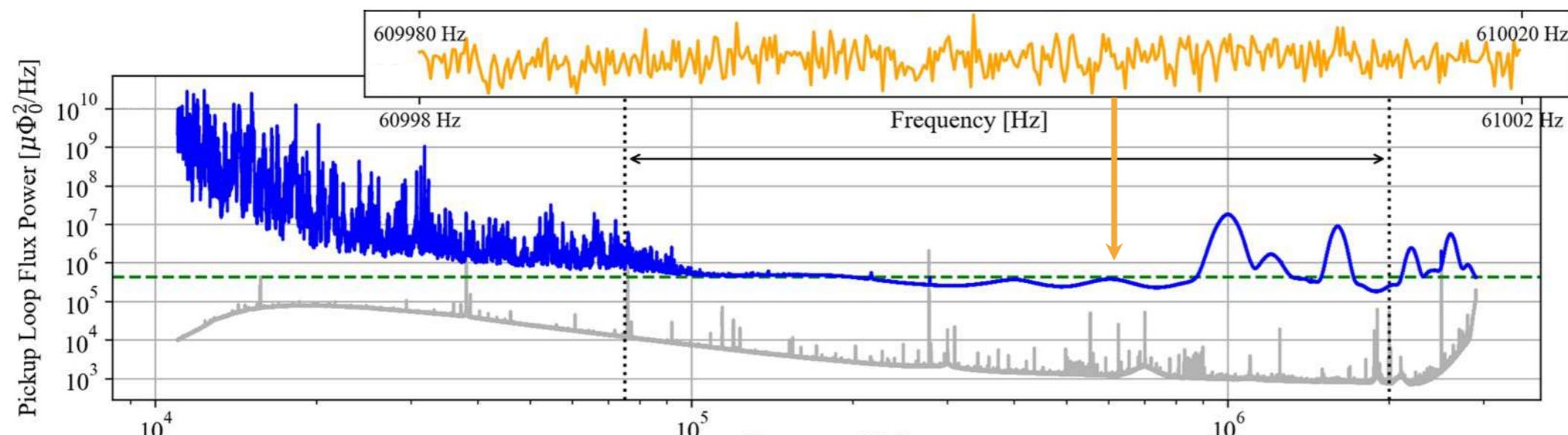
now with
noise-cancelling
headphones



The sound of dark matter?

610,000 Hz

ΔBRAČADABRA

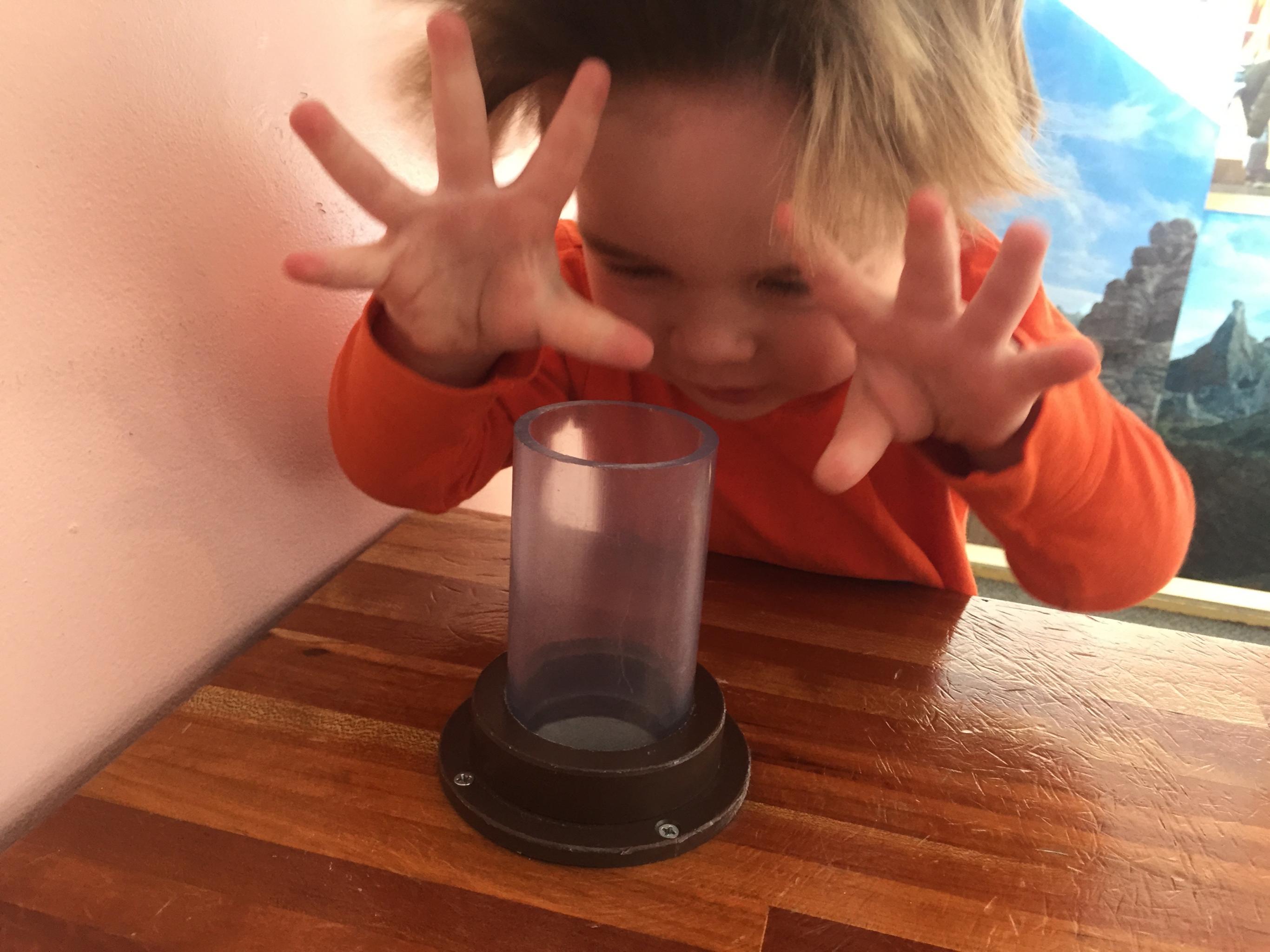


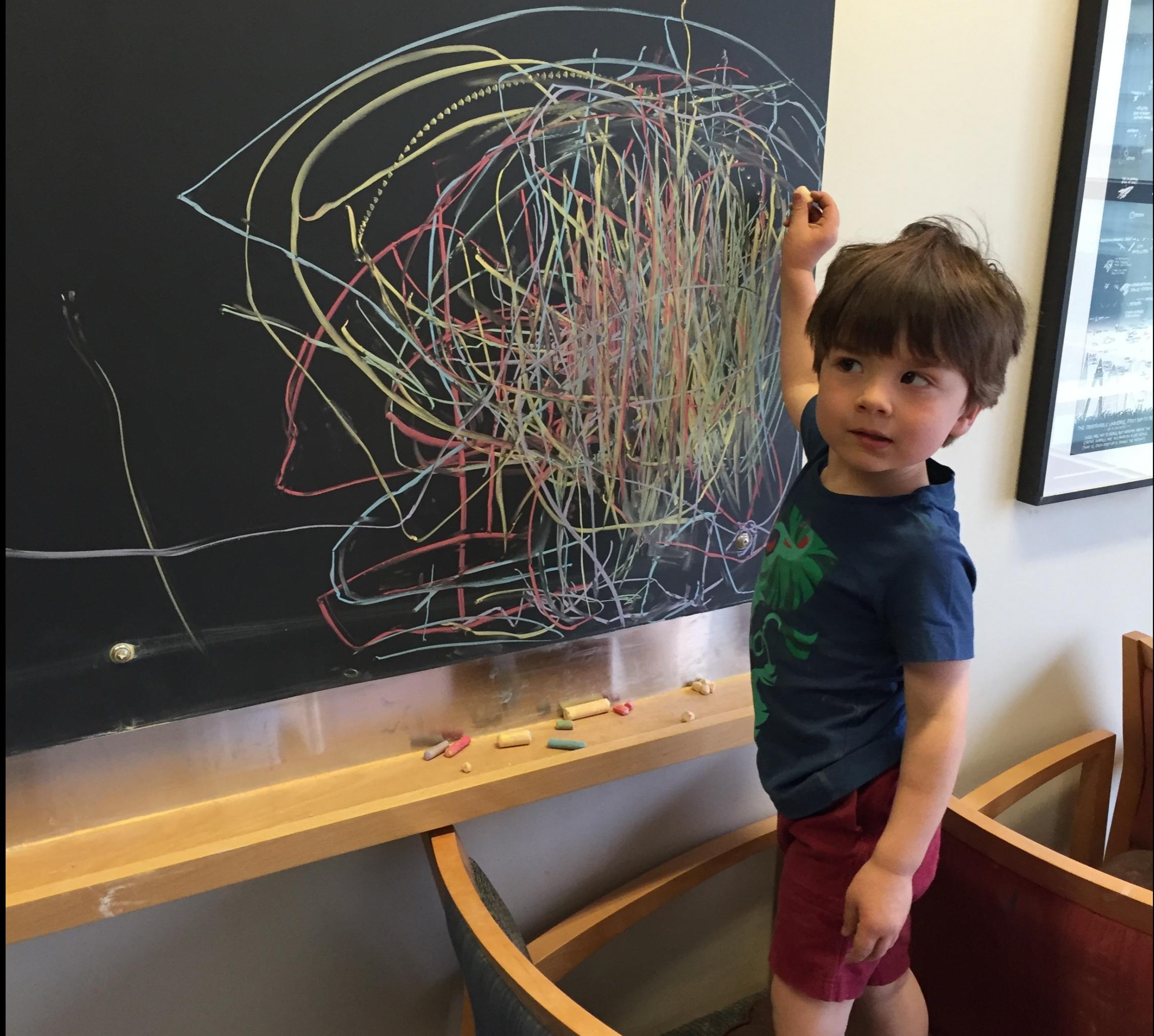
850,000 Hz

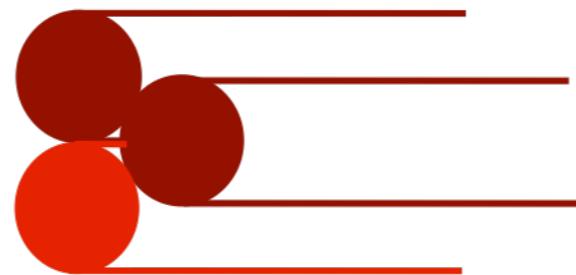
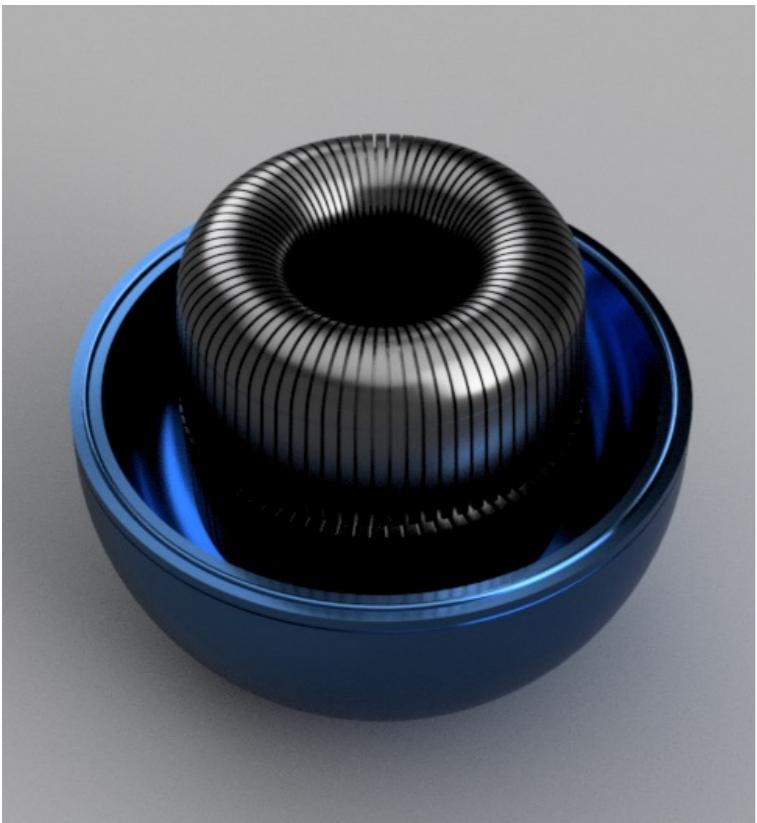
WEEI
((850))



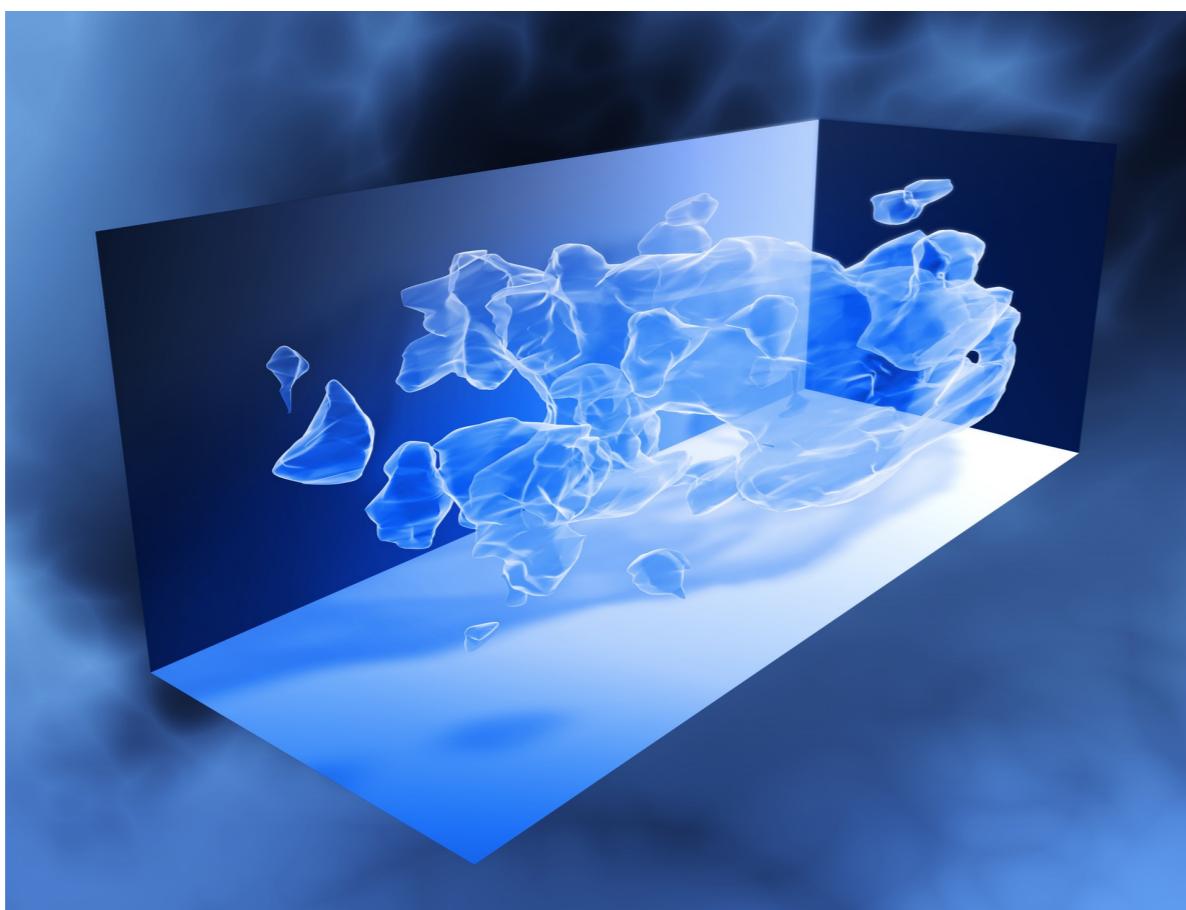
Why does
Dark Matter matter?







Superconducting Systems, Inc.



*Why has the pursuit of science for its own sake
had such a remarkable track record in
generating transformative new technology?*

The reason must be that Nature poses deeper and more challenging questions than humans can do, and the struggle to understand Nature forces us to invent better and deeper ideas than we would if left to our devices.

Invisible Stuff

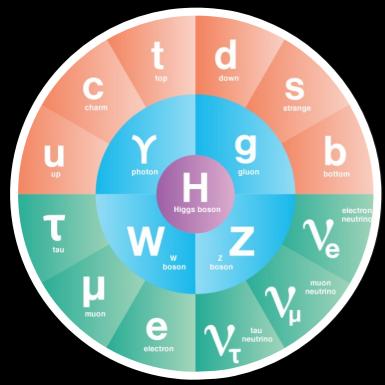
What?

Why?

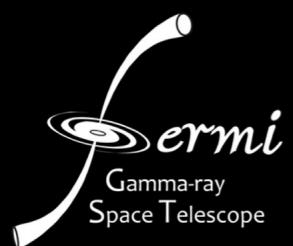
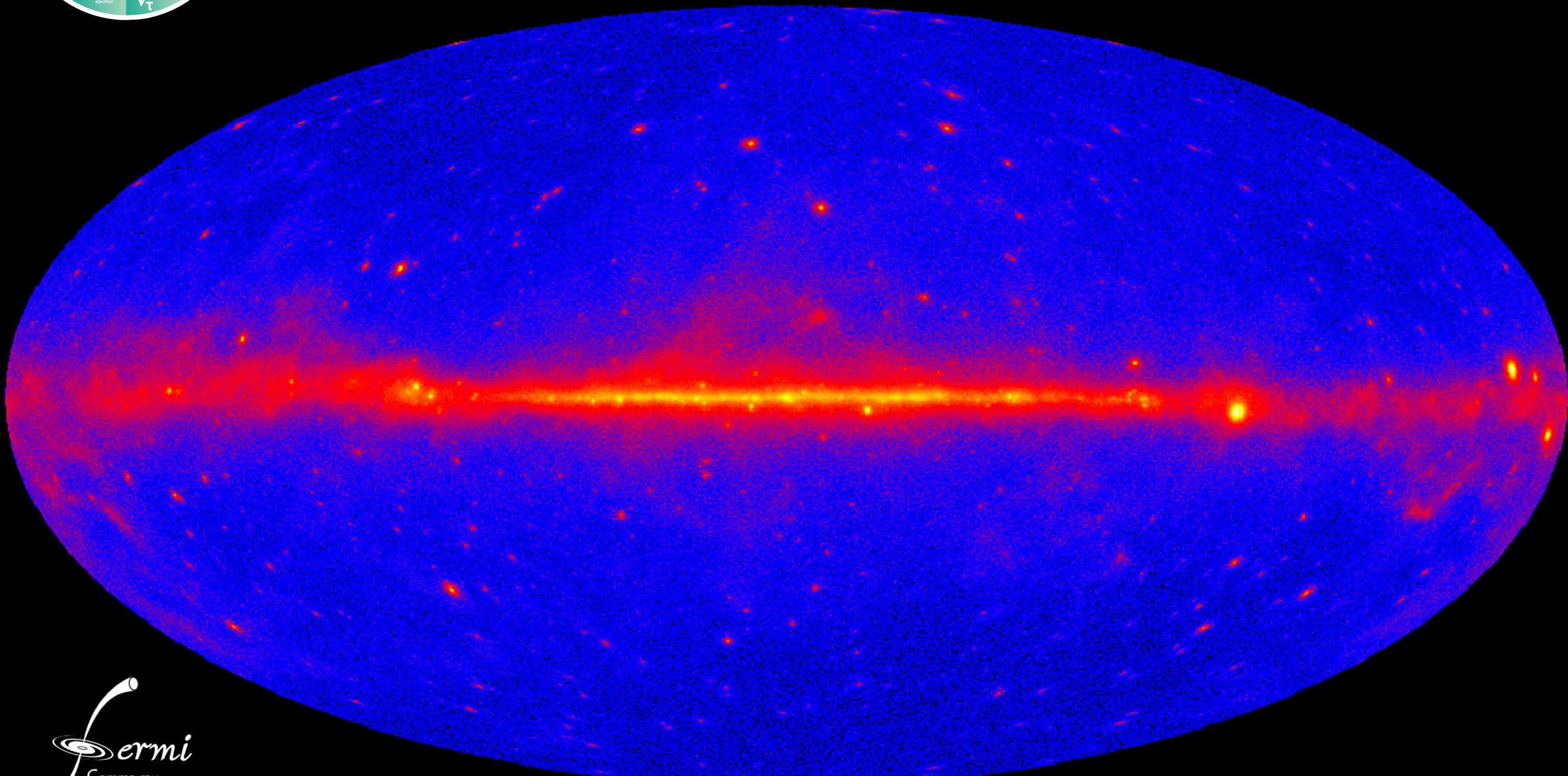
How do we know?

What will we know soon?

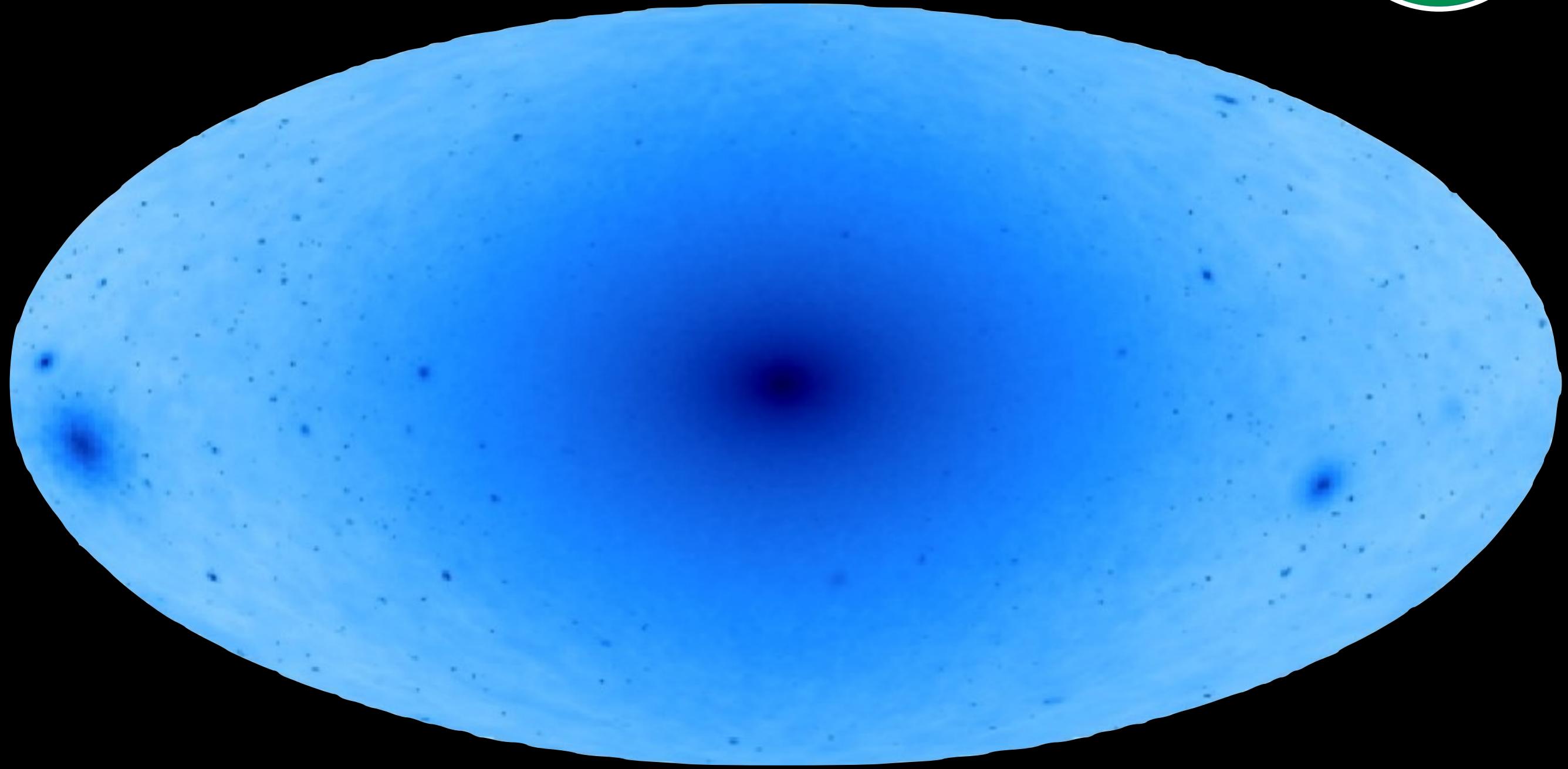
What more do you want to know?

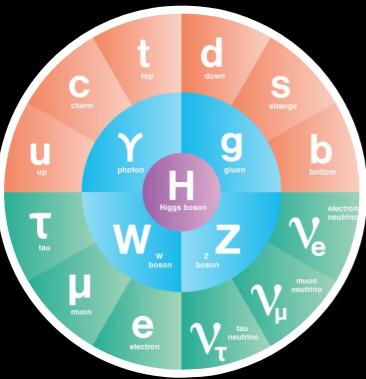


The Visible Milky Way

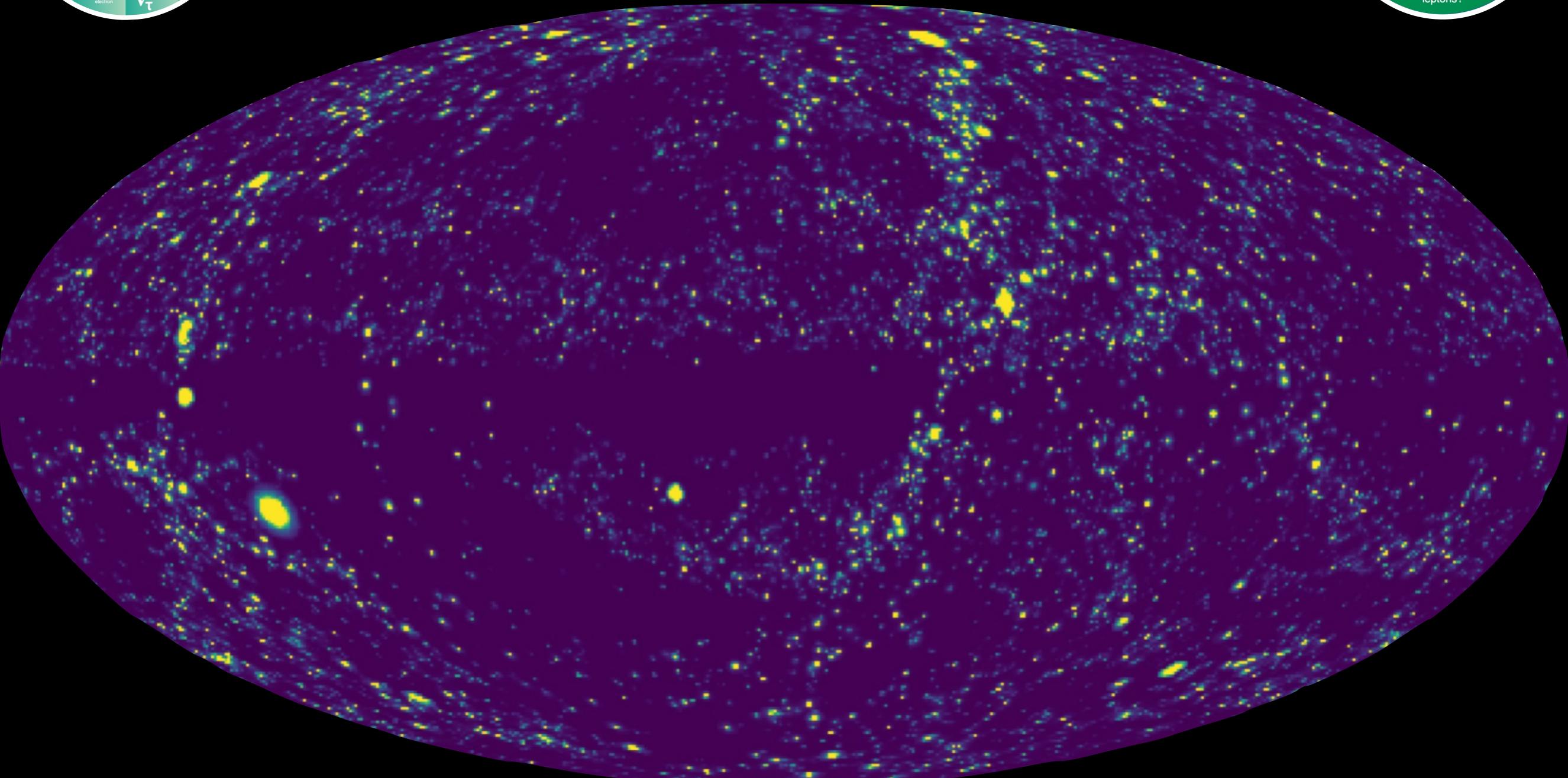
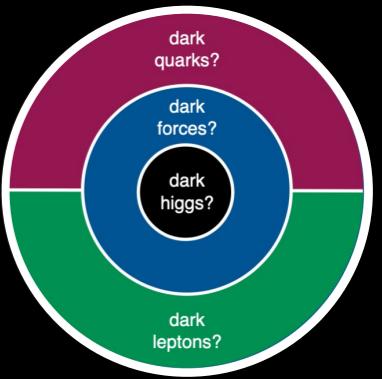


The Invisible Milky Way





The (In)visible Universe



from Dr. Nick Rodd (Ph.D. April 2018)