Chemistry and Dark Matter

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Dark Black Holes

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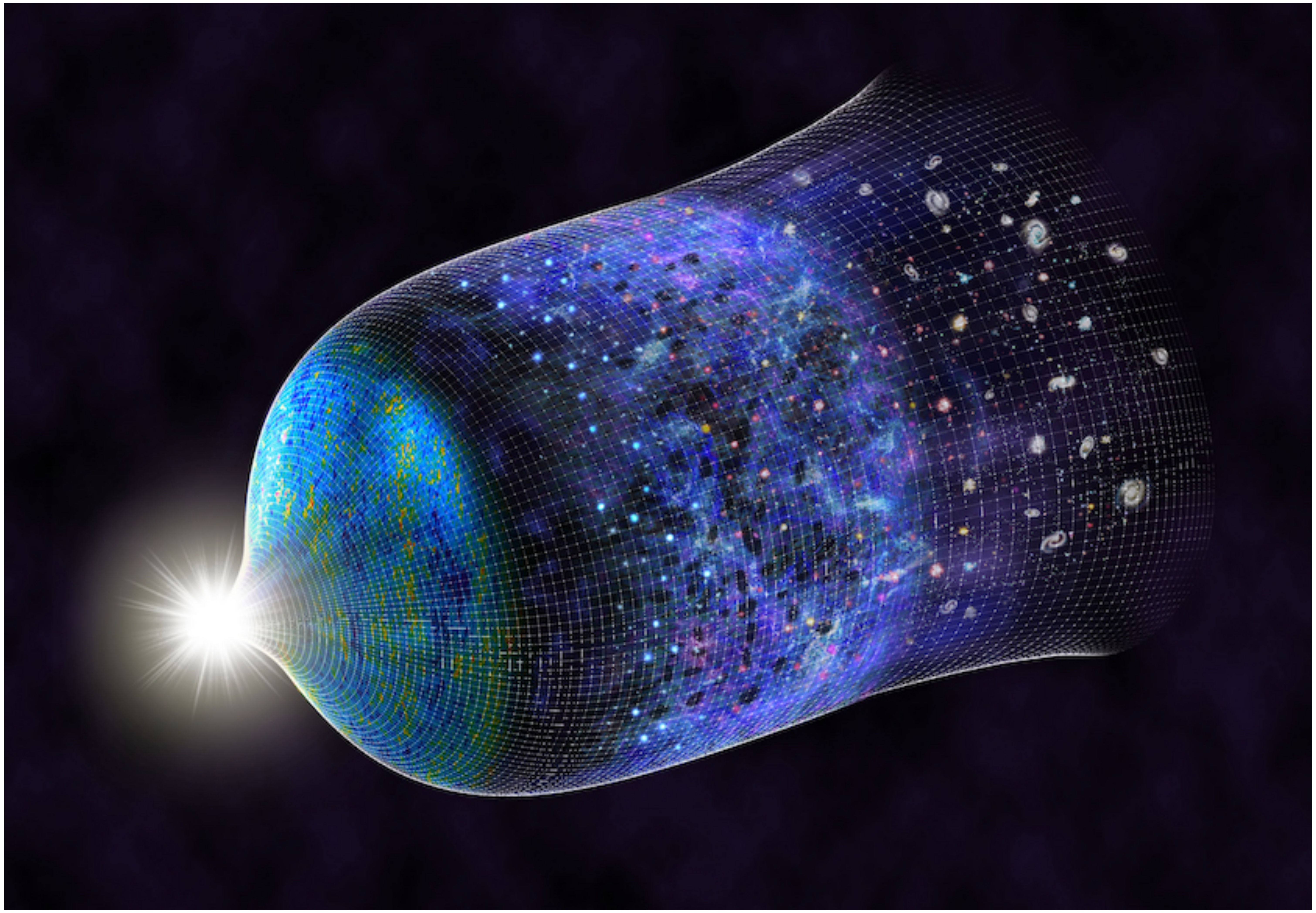
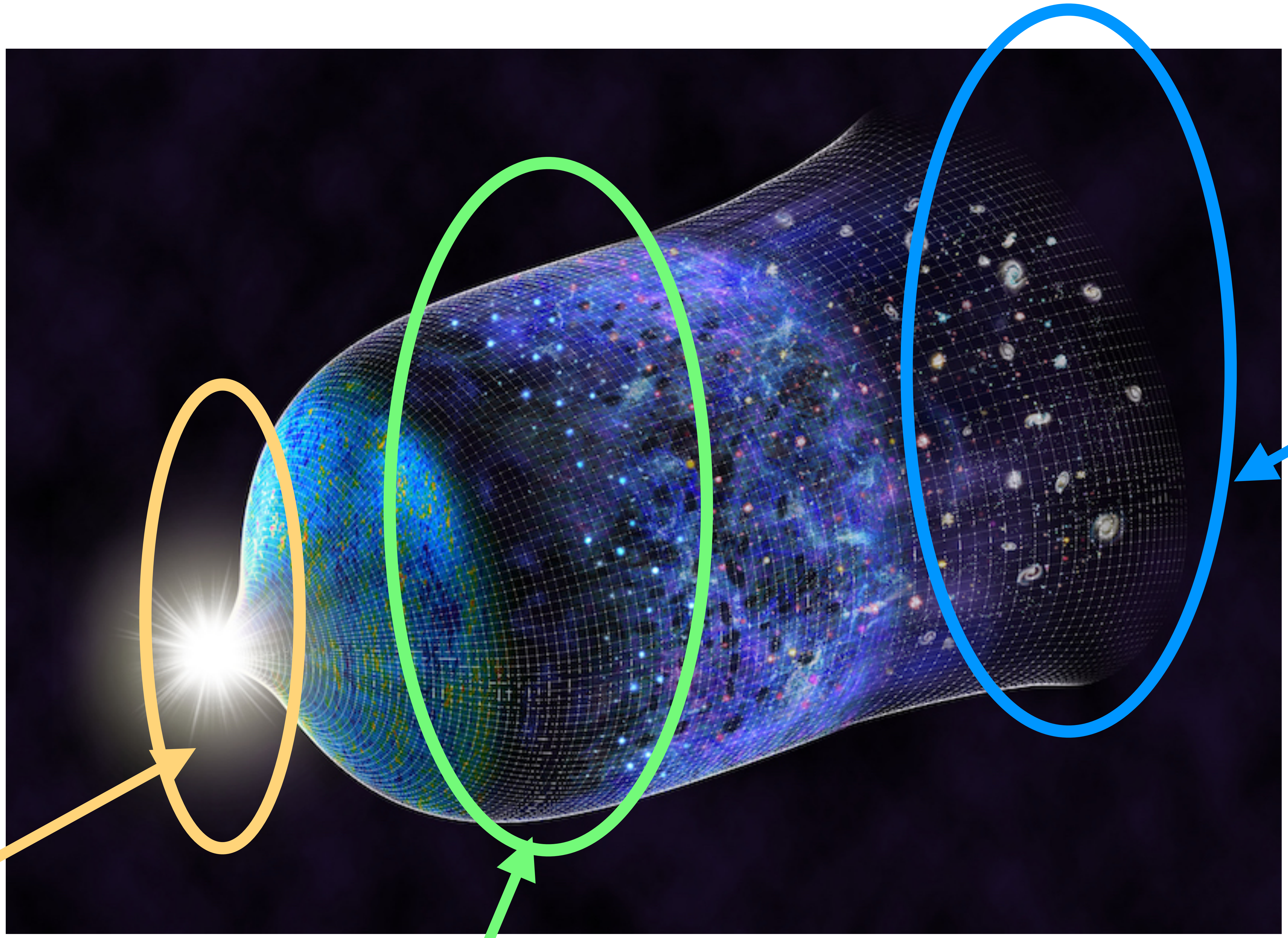
Big Universe, Big Questions



Nicole R. Fuller, NSF

Beyond the Standard Model with Cosmology



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What is causing the expansion of the universe to accelerate?

What can the enormously energetic phenomena reveal about particle physics?

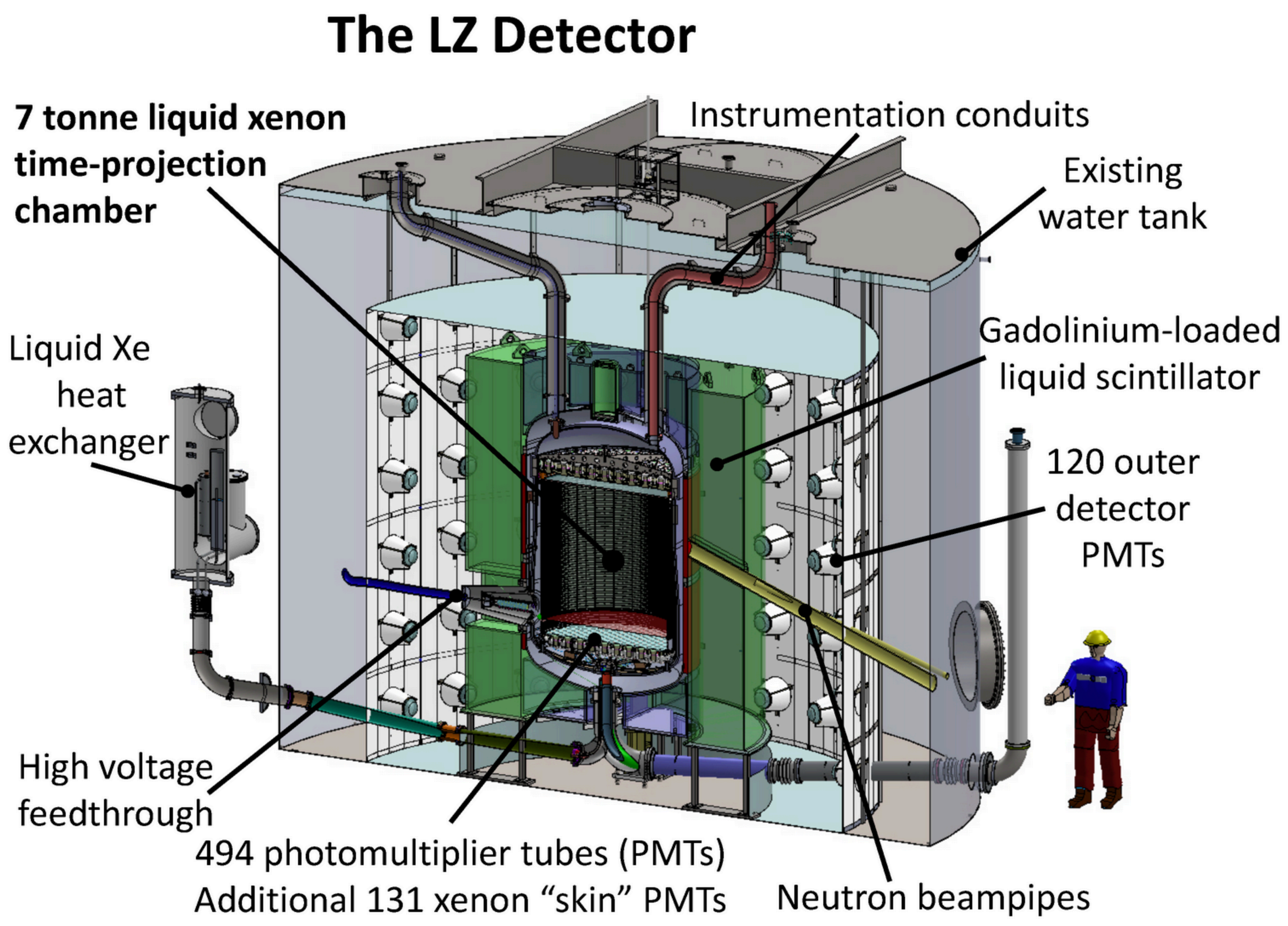
Why quantum?
Why gravity?

Inflation?

How does structure form? What is the dark matter?

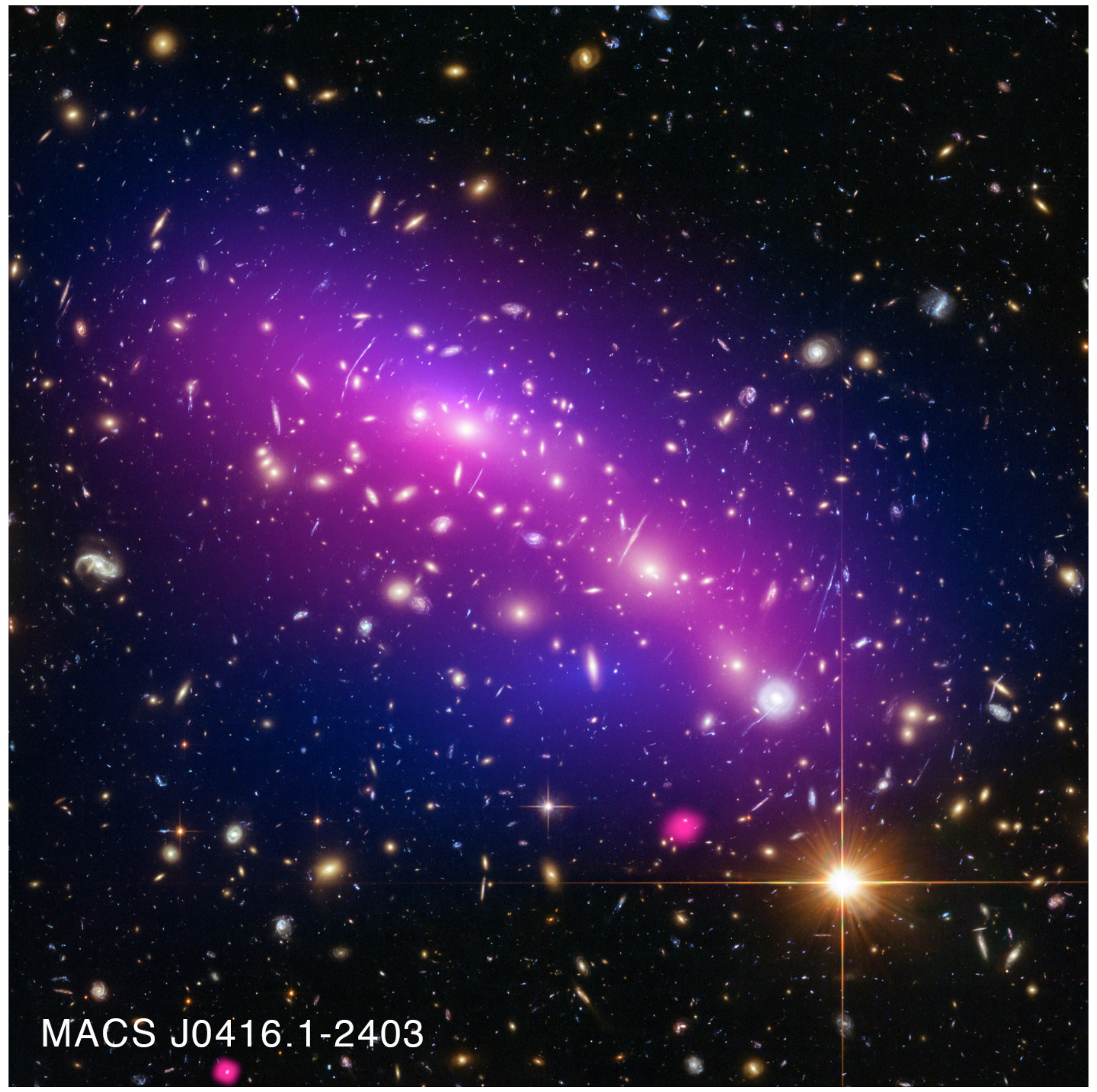
Cosmology vs Laboratory

Instead of understanding



https://lz.lbl.gov/detector/

We need to understand (model) this stuff:



Cosmology vs Laboratory

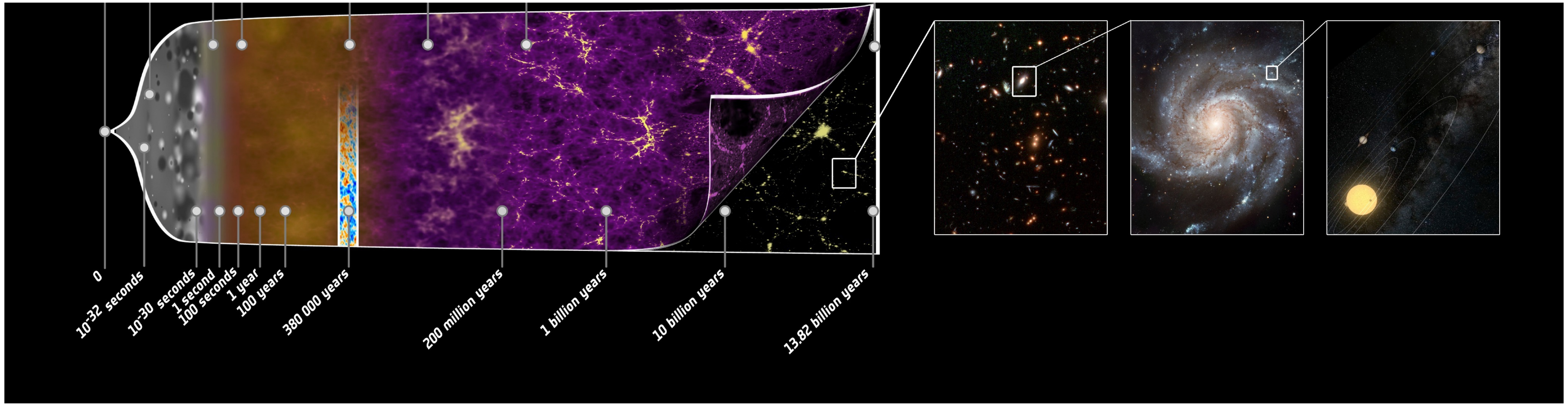


Image credit: ESA, Planck collaboration

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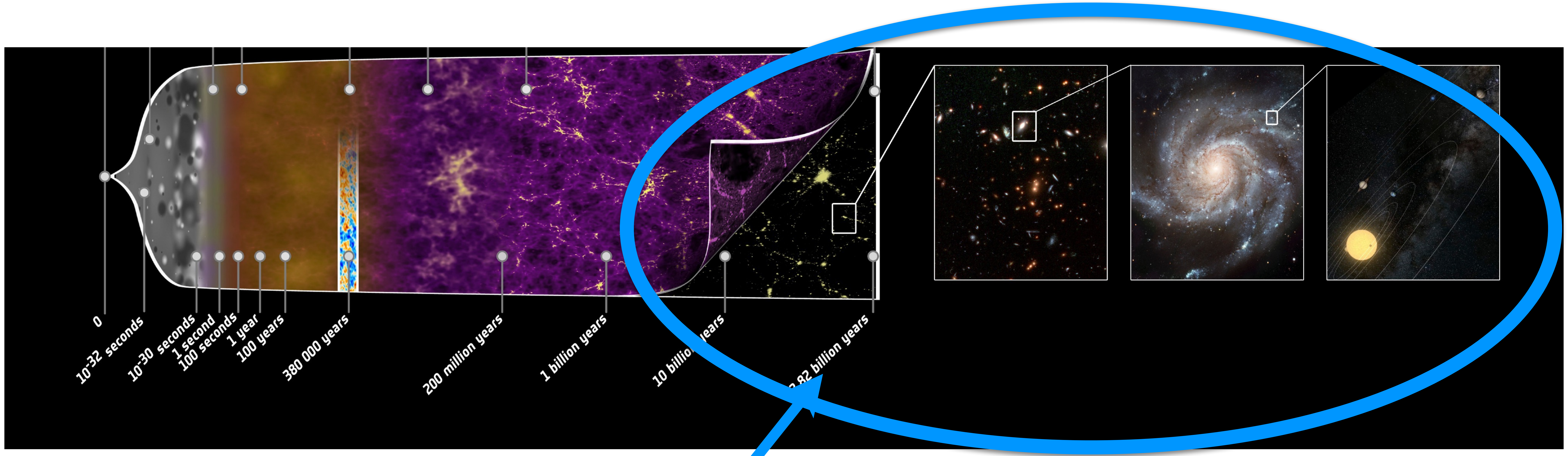

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Cosmological Principle

Our place is not special

Cosmology vs Laboratory

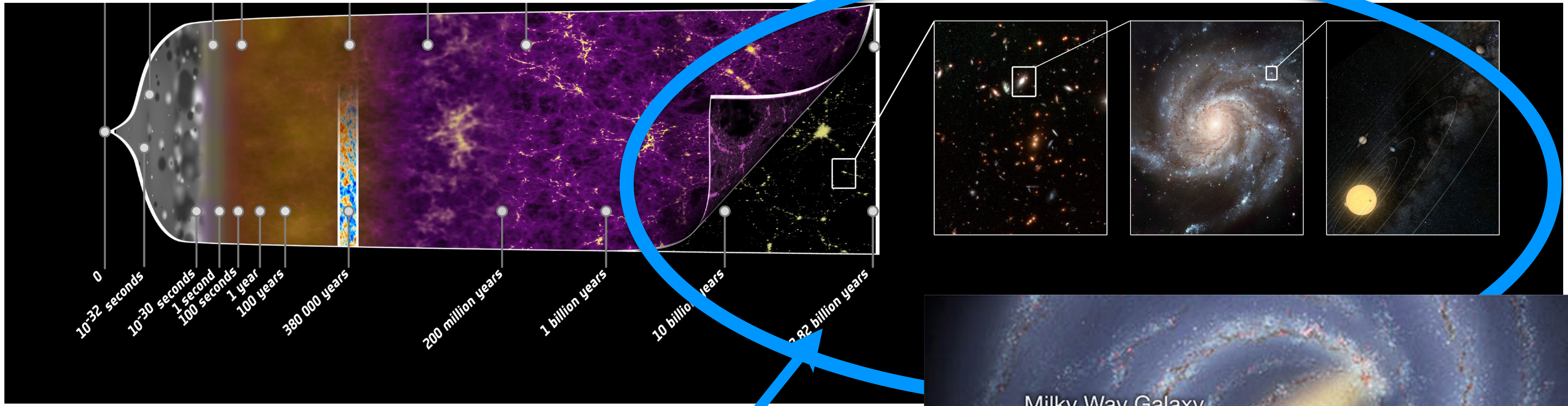


Image credit: ESA, Planck collaboration

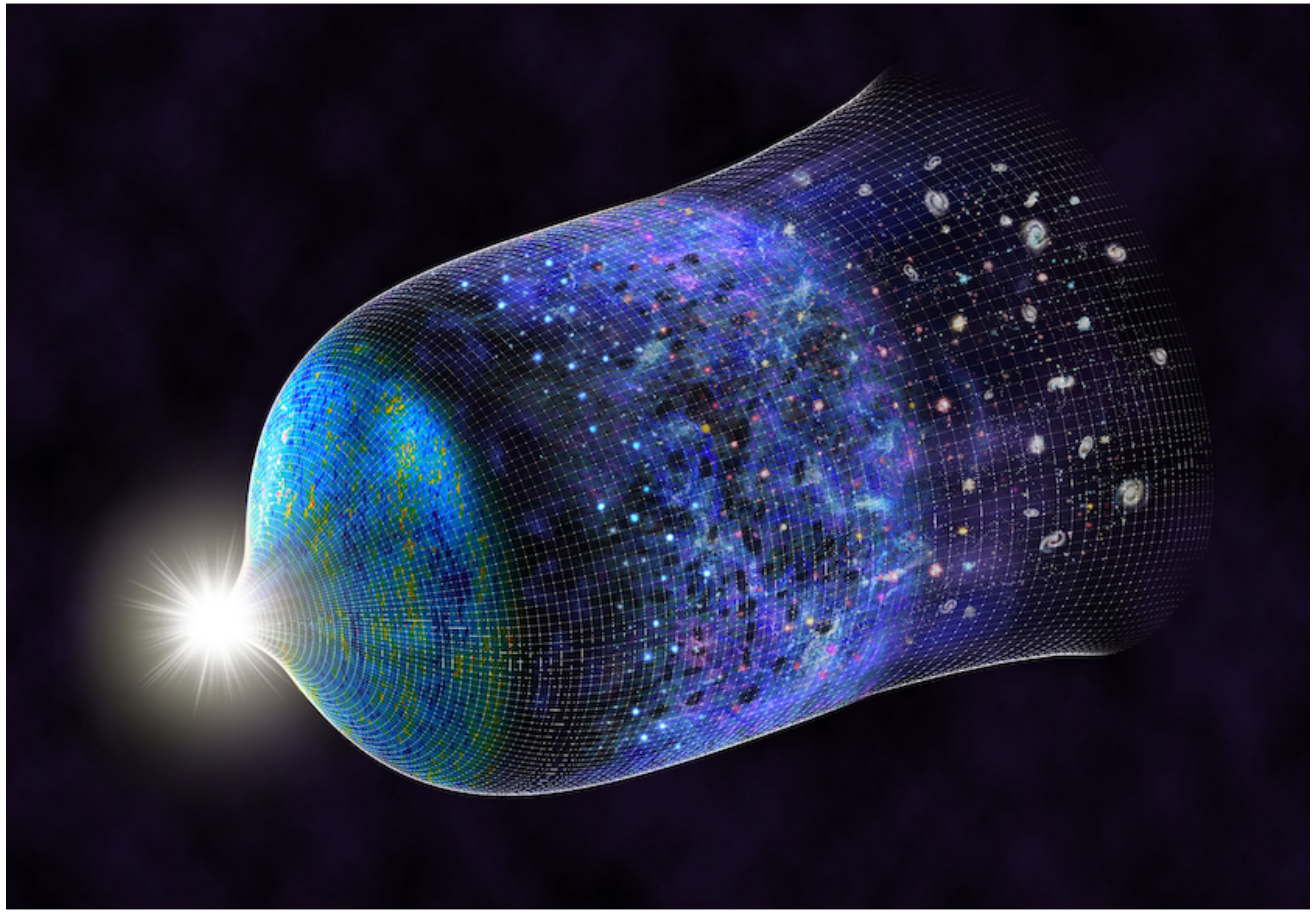
<u>Cosmological Principle</u>

Our place is not special

(Except, thermodynamically, maybe it is)

Image credit: NASA Ames/W. Stenzel and JPL-Caltech/R. Hurt

One example of how it works to wander through this space…



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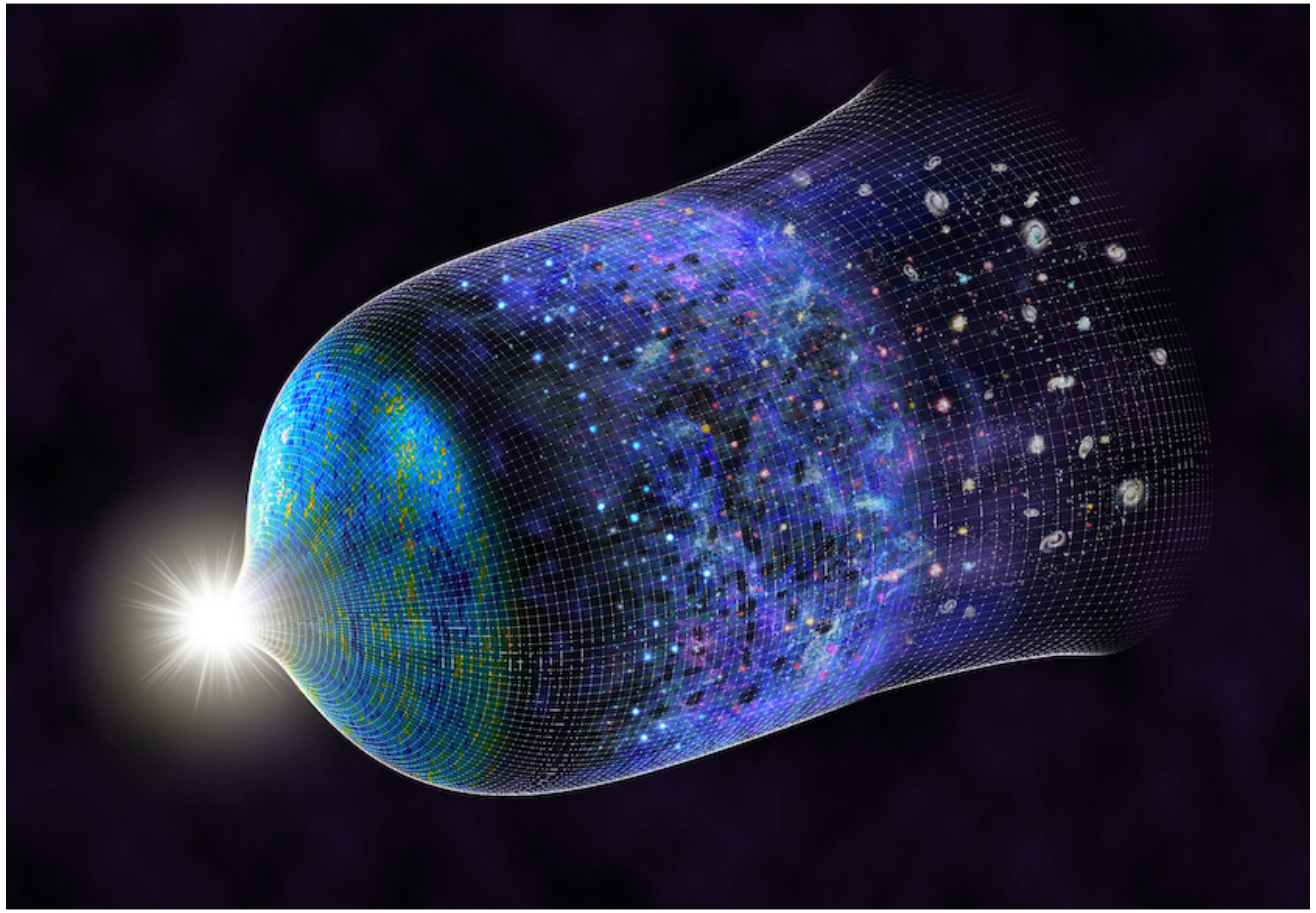

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WMAP data ~2004: very detailed view of CMB
Can we test BSM models of inflation? String theory?

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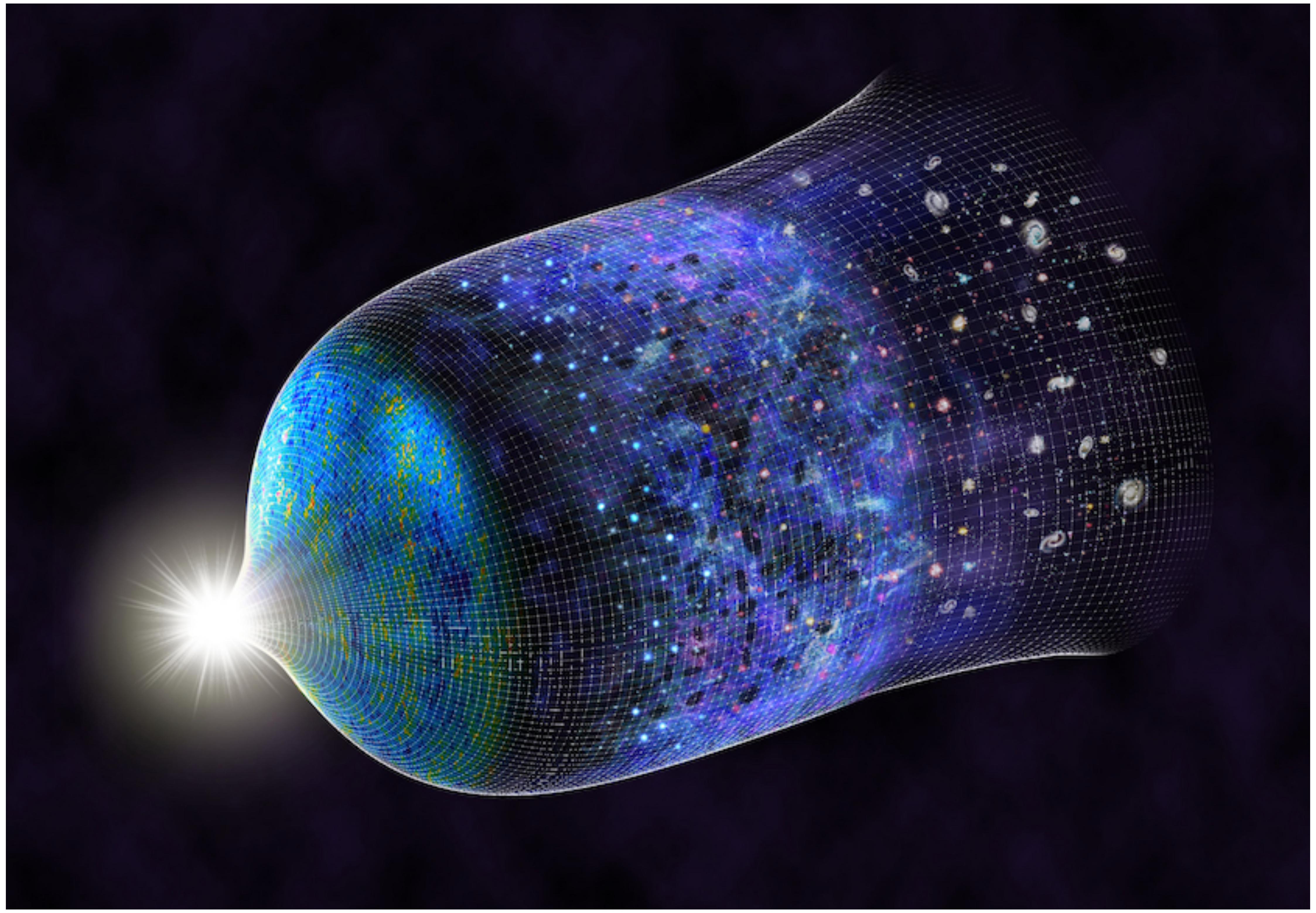

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Non-Gaussianity as a probe of particle interactions in the primordial universe
Lots of theory work
What about large-scale structure?
(Stay tuned for SPHERE-X!)

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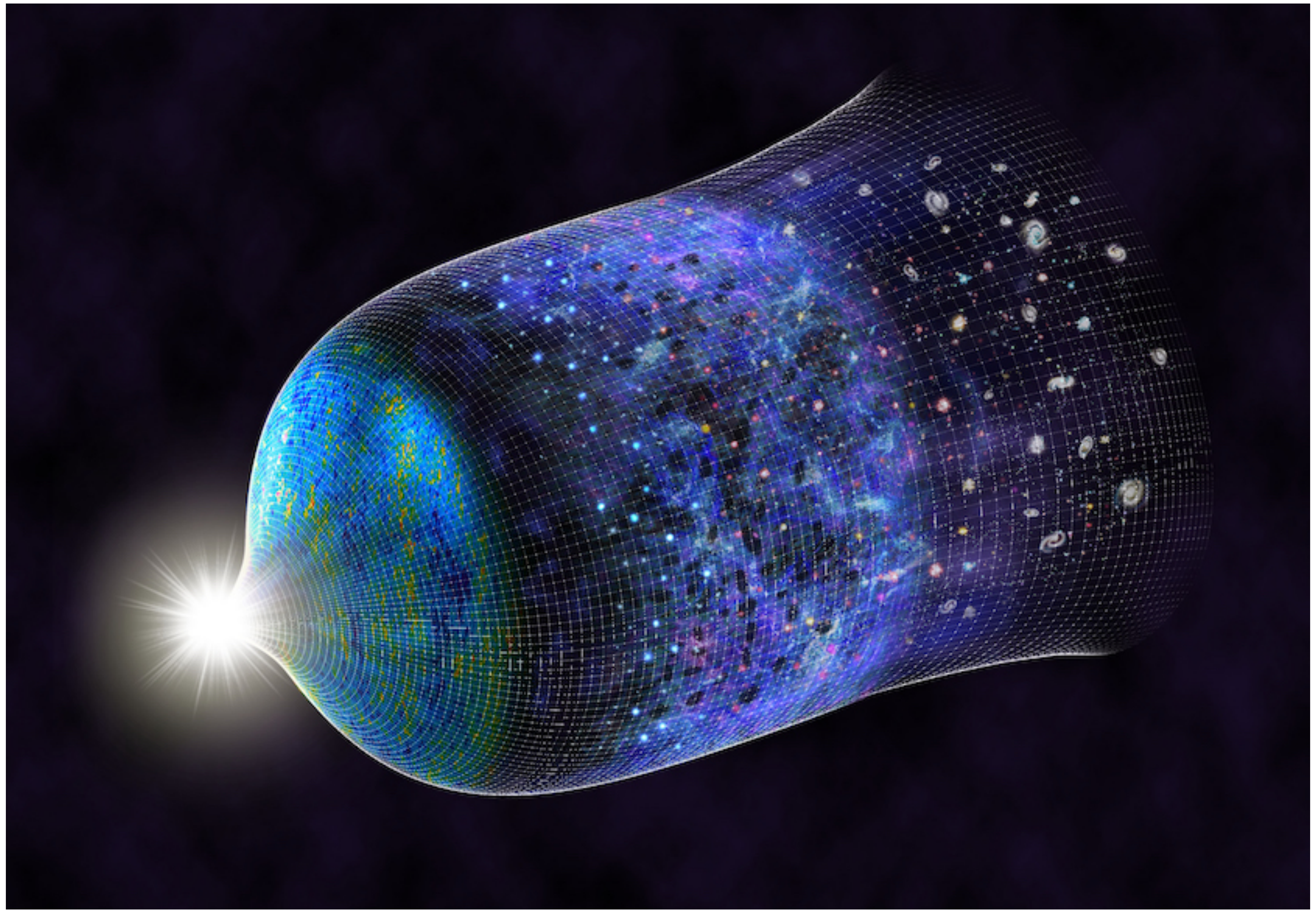

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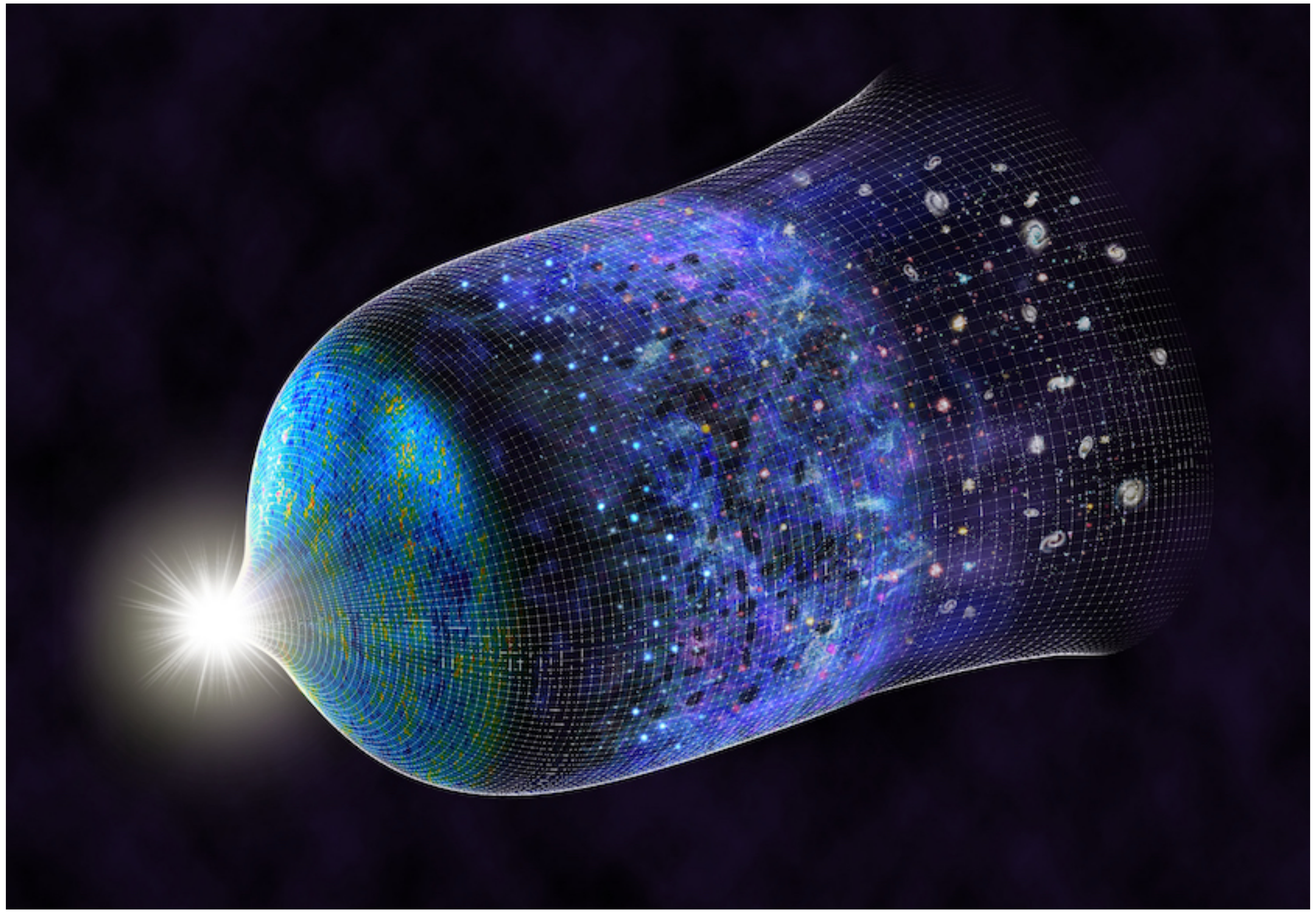

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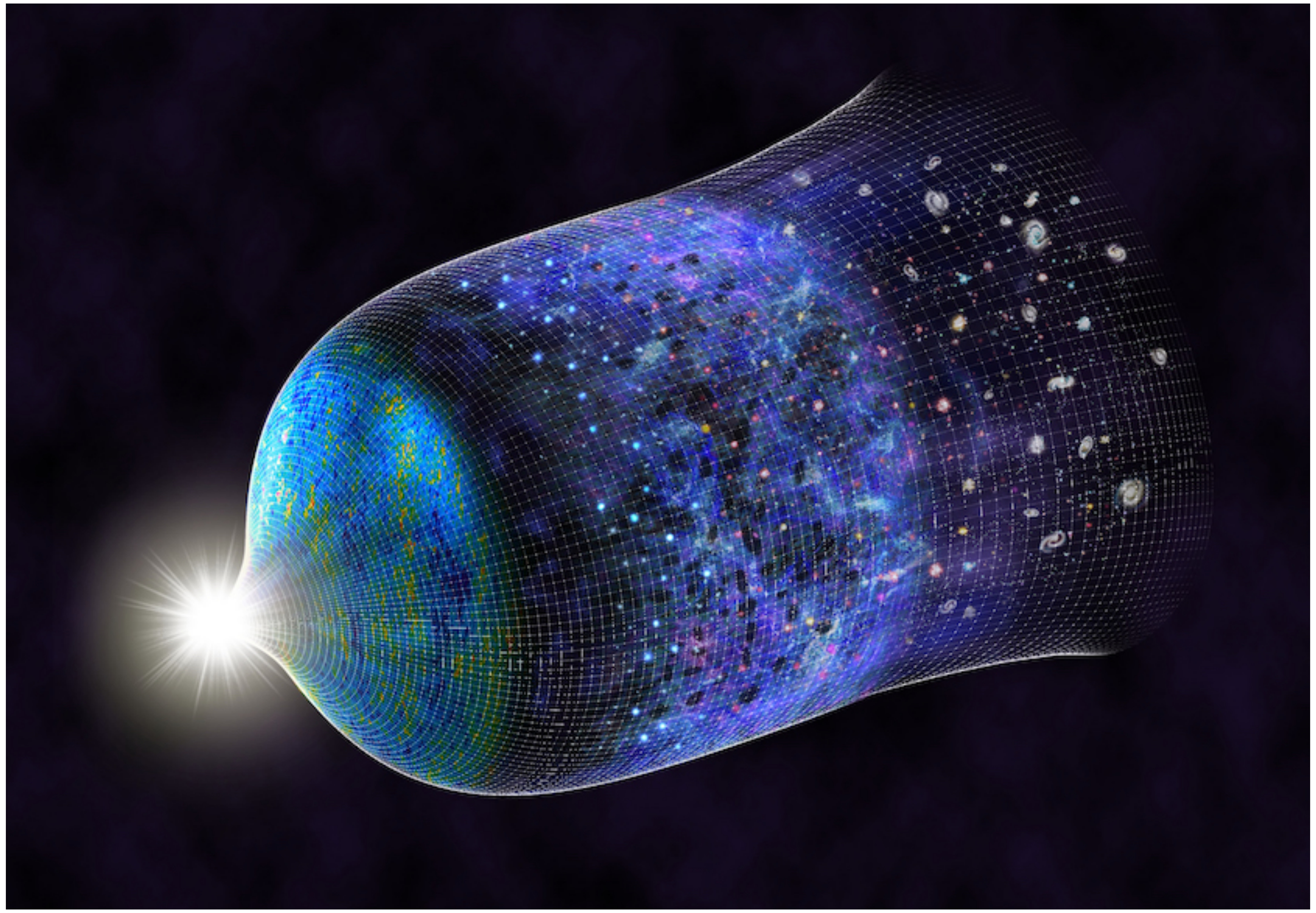

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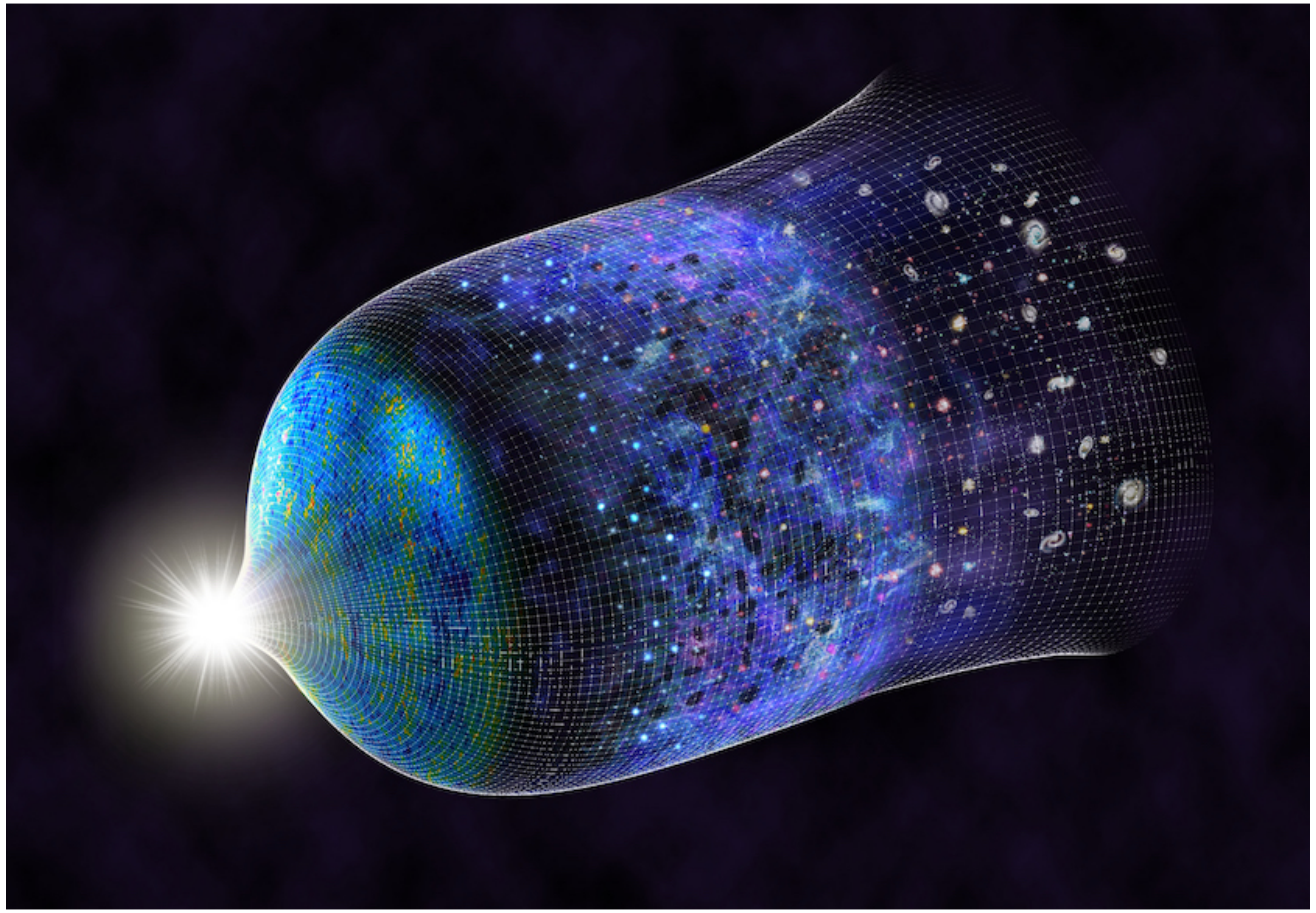

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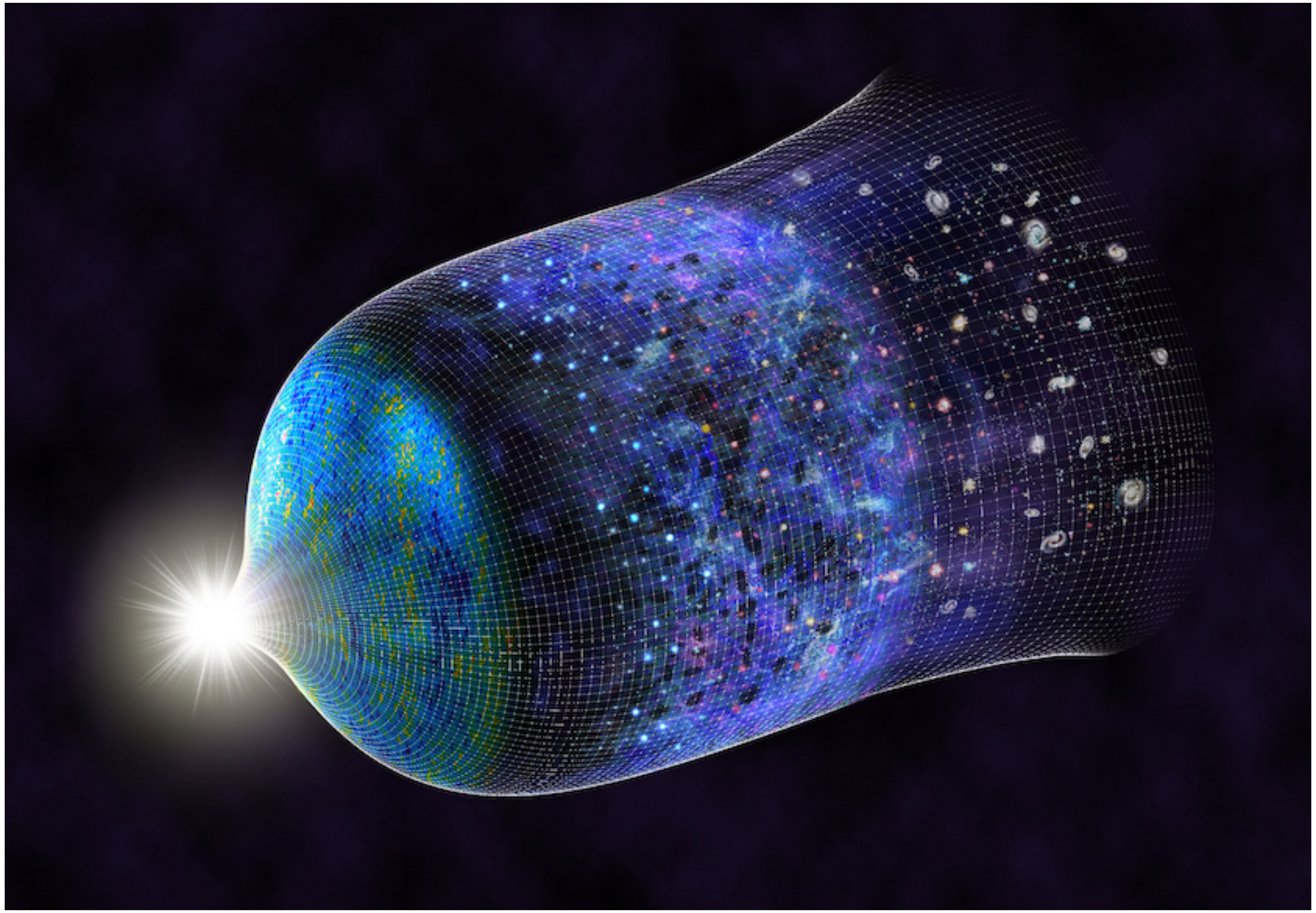
Collaborators are absolutely key. Be mindful of building good community -> better science

A (mostly) electromagnetic picture



Recently: + other messengers: cosmic rays, neutrinos, gravitational waves

The dark matter puzzle

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(Density, pressure)

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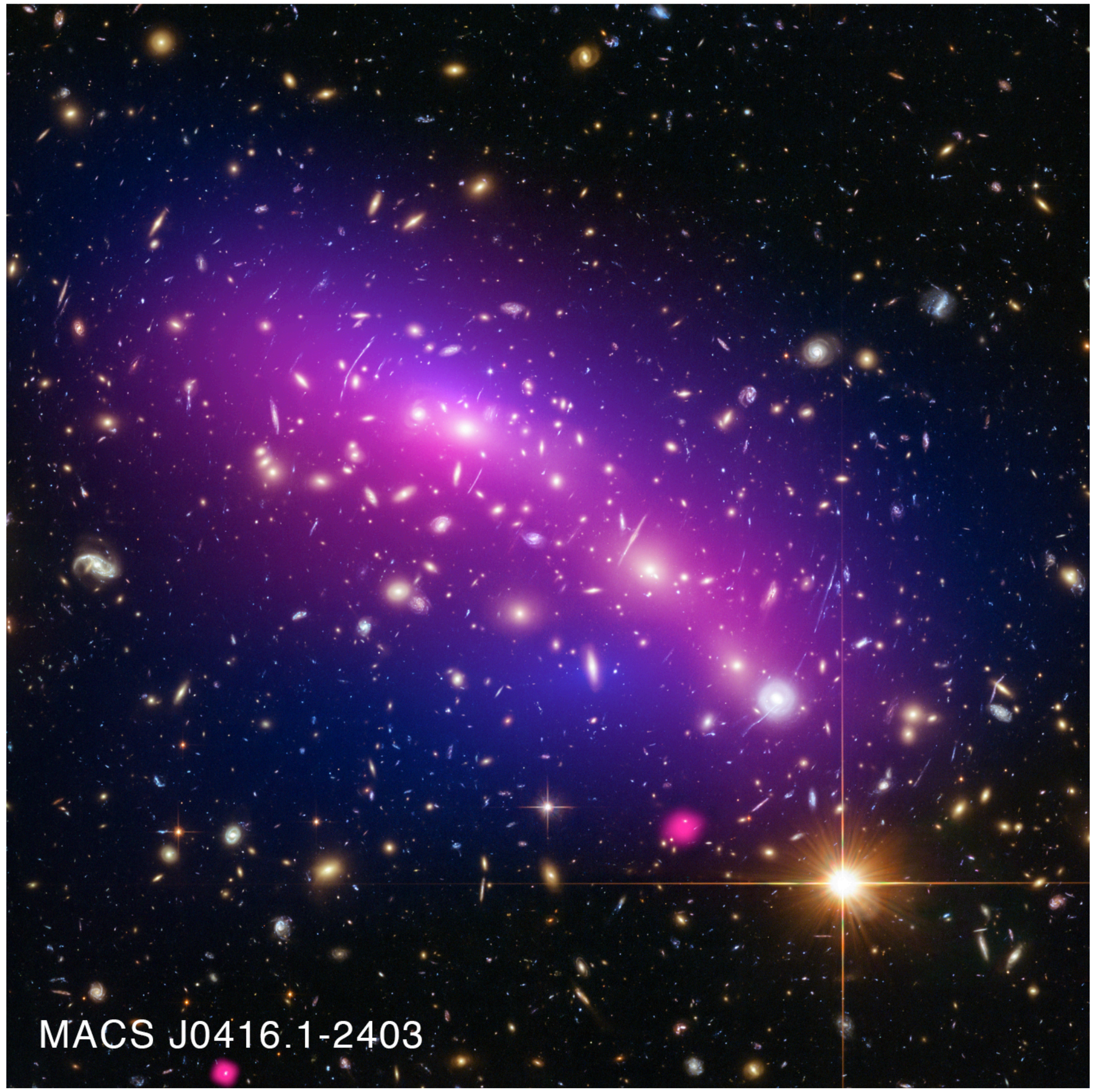


Visible light + hot gas (pink) + all matter (blue)

Image credit: X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)

(One way)

How do we know?

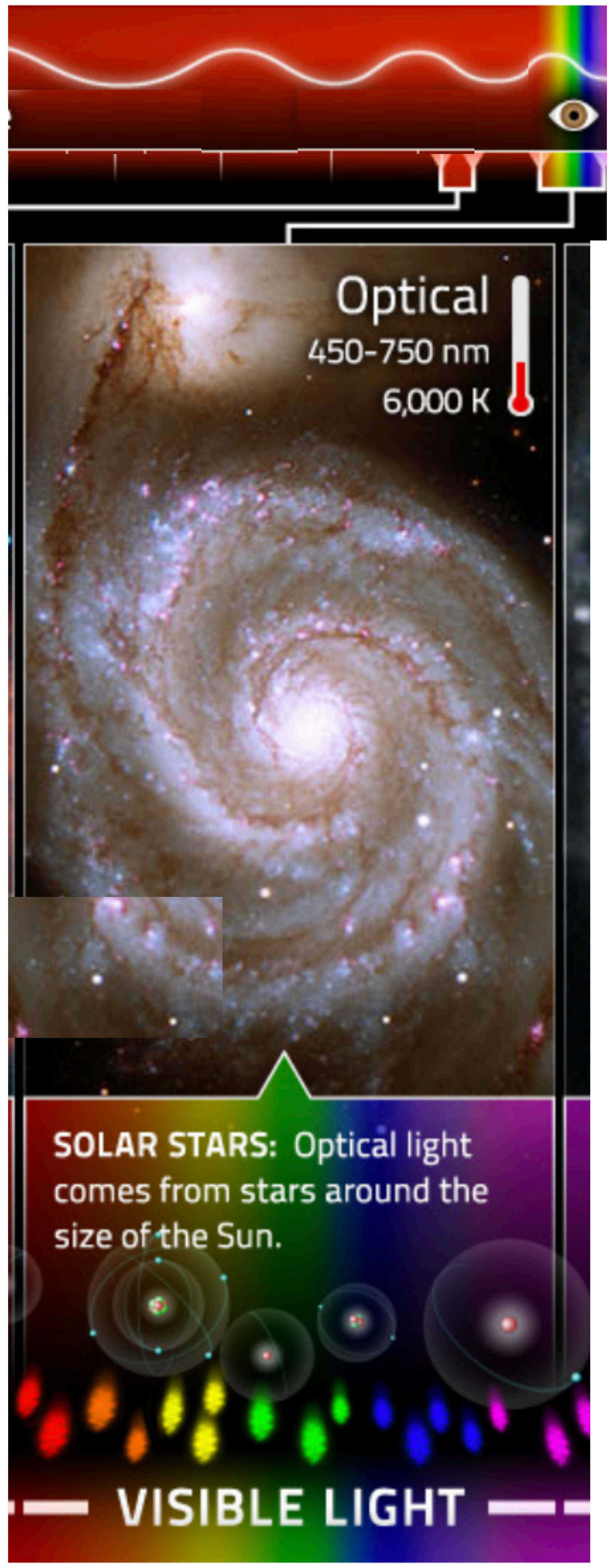


Image credit: U. Chicago Digital Library Project (eCUIP Multiwavelength Astronomy)

(One way)

How do we know?

Step 1: use the full electromagnetic spectrum

Image credit: U. Chicago Digital Library Project (eCUIP Multiwavelength Astronomy)

(One way)

How do we know?

Step 2: see how gravity bends light

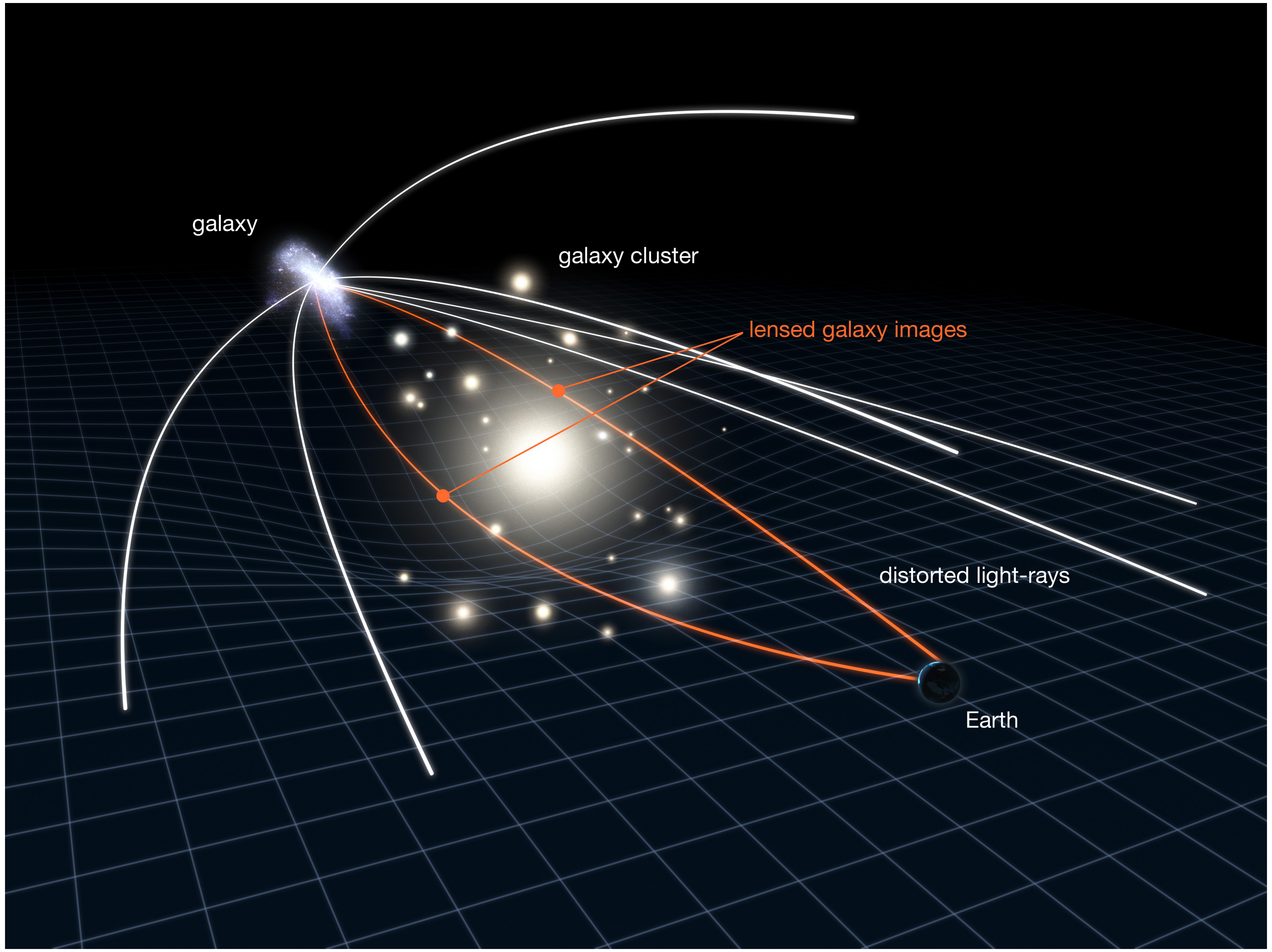
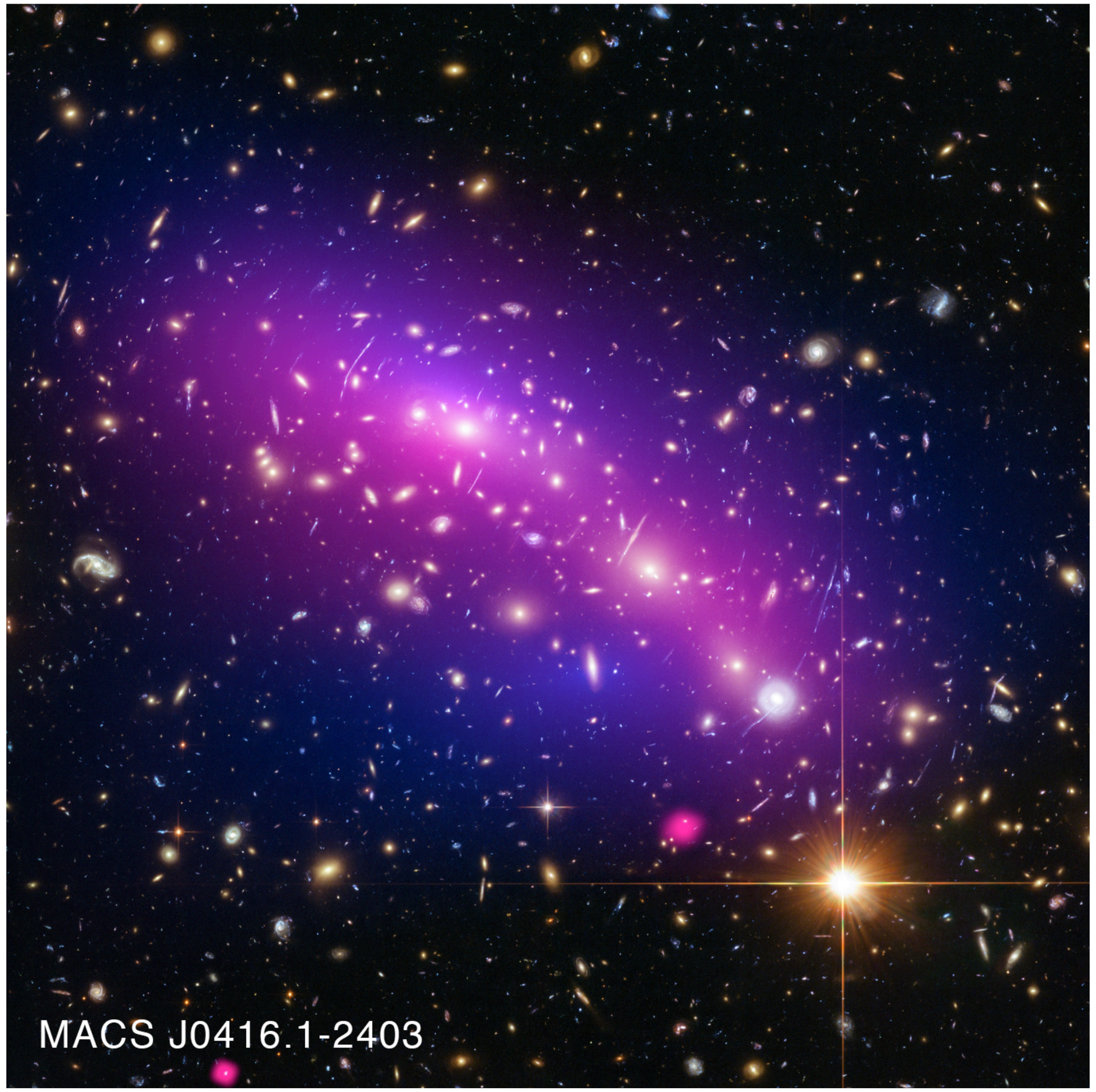


Image credit: NASA, ESA, and L. Calçada (lens is Abell 383)

The dark matter puzzle



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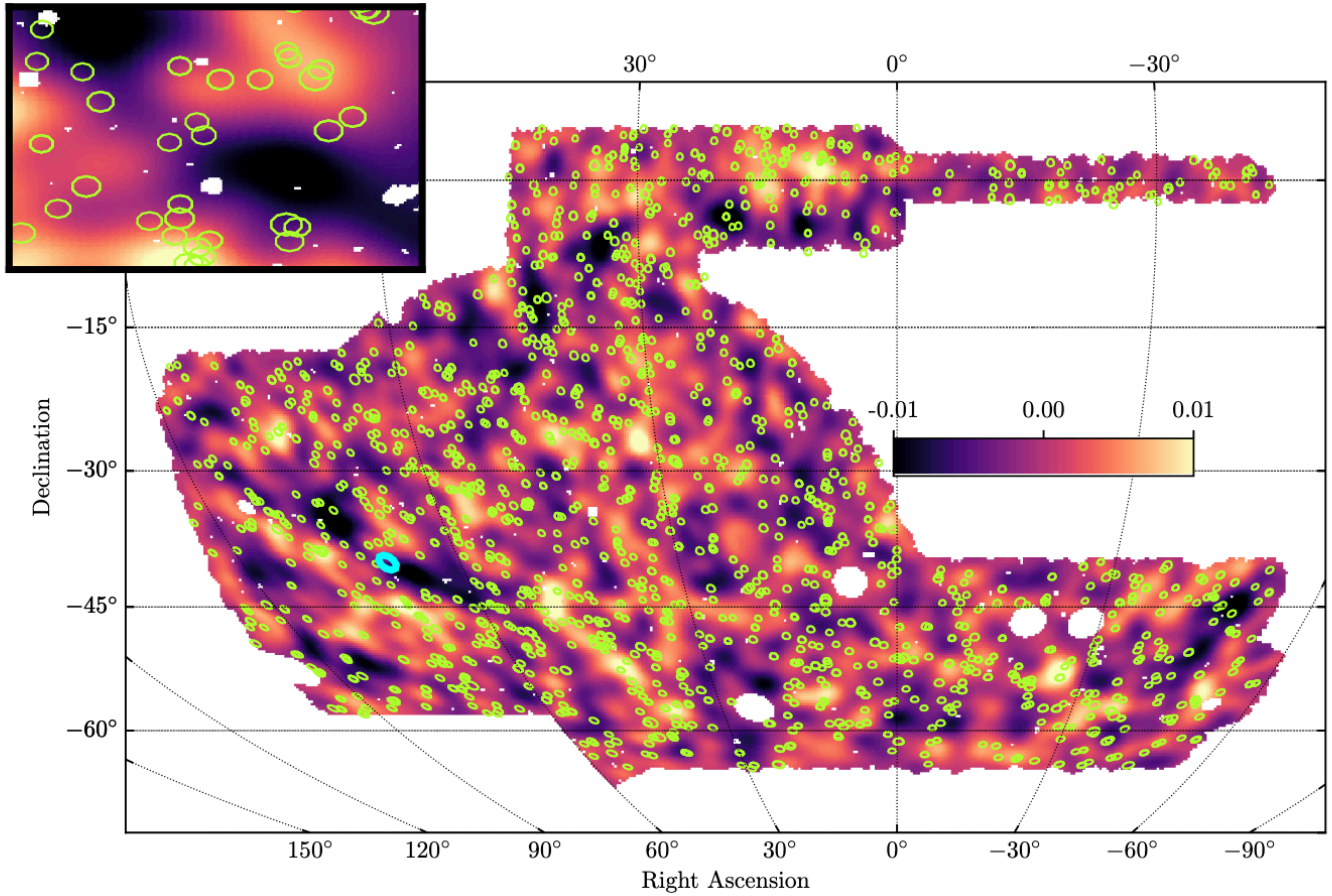
And, on a bigger scale

Each green circle is a galaxy cluster
Color shading is total mass



Dark Energy Survey Year 3 results: Curved-sky weak lensing mass map reconstruction, MNRAS 505, 4626-4645 (2021)

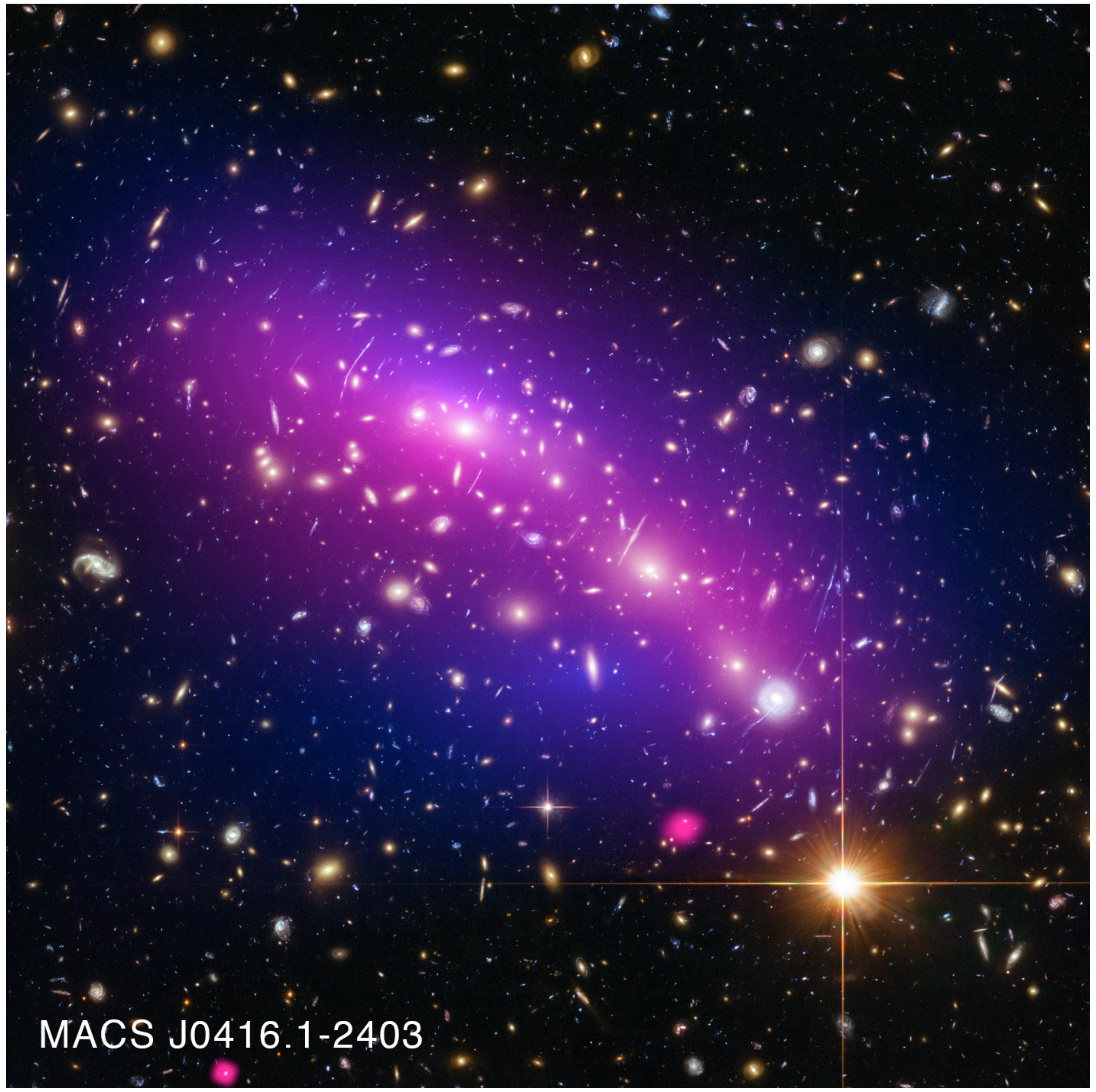
The dark matter puzzle

- Of the stuff that acts like matter, ~85% emits no light

$$G_{\mu\nu} \propto T_{\mu\nu}$$

(Density, pressure)

- Firmly established for ~45 years (Rubin, Thonnard, Ford, 1980; R&F 1970)



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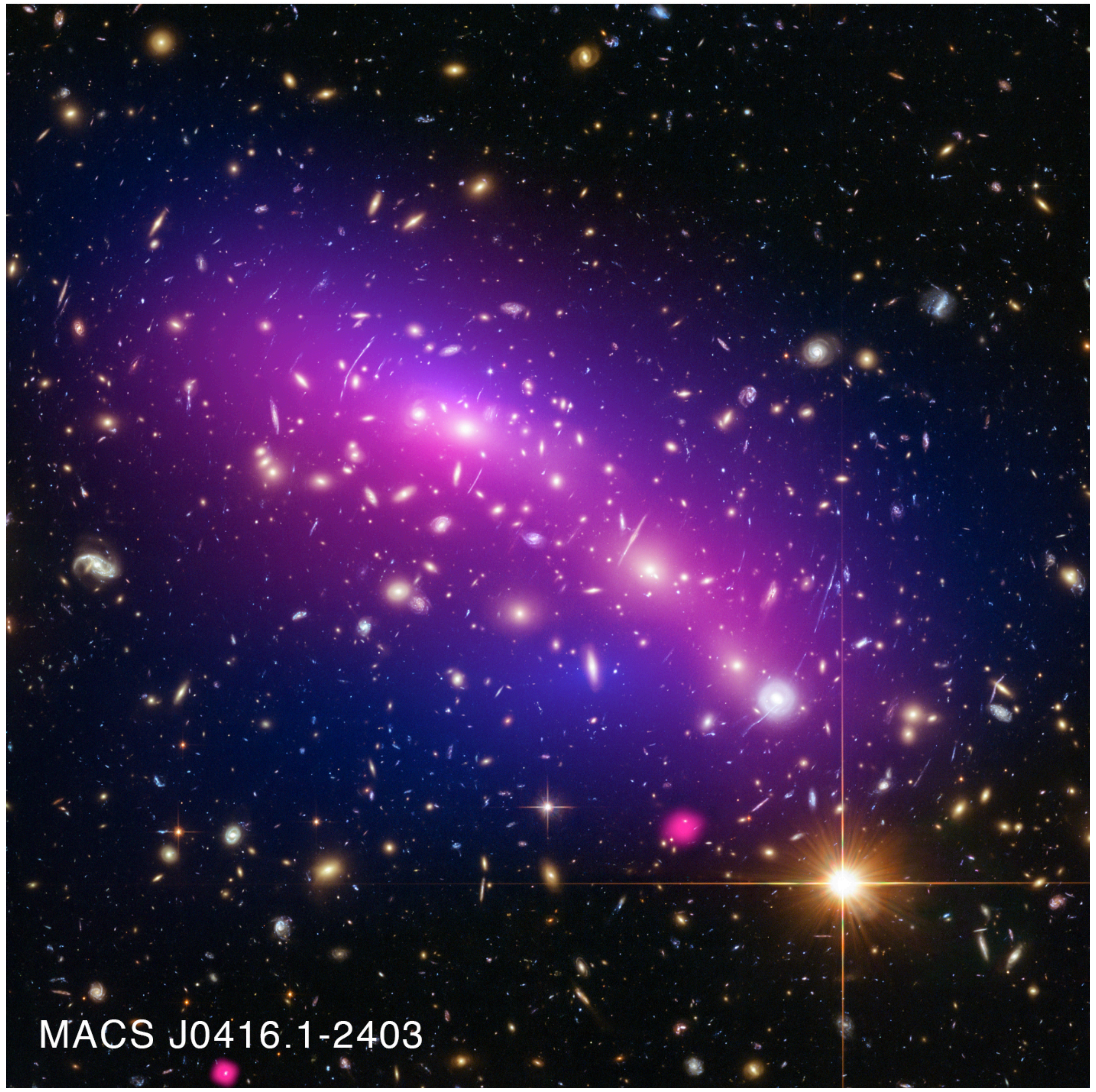

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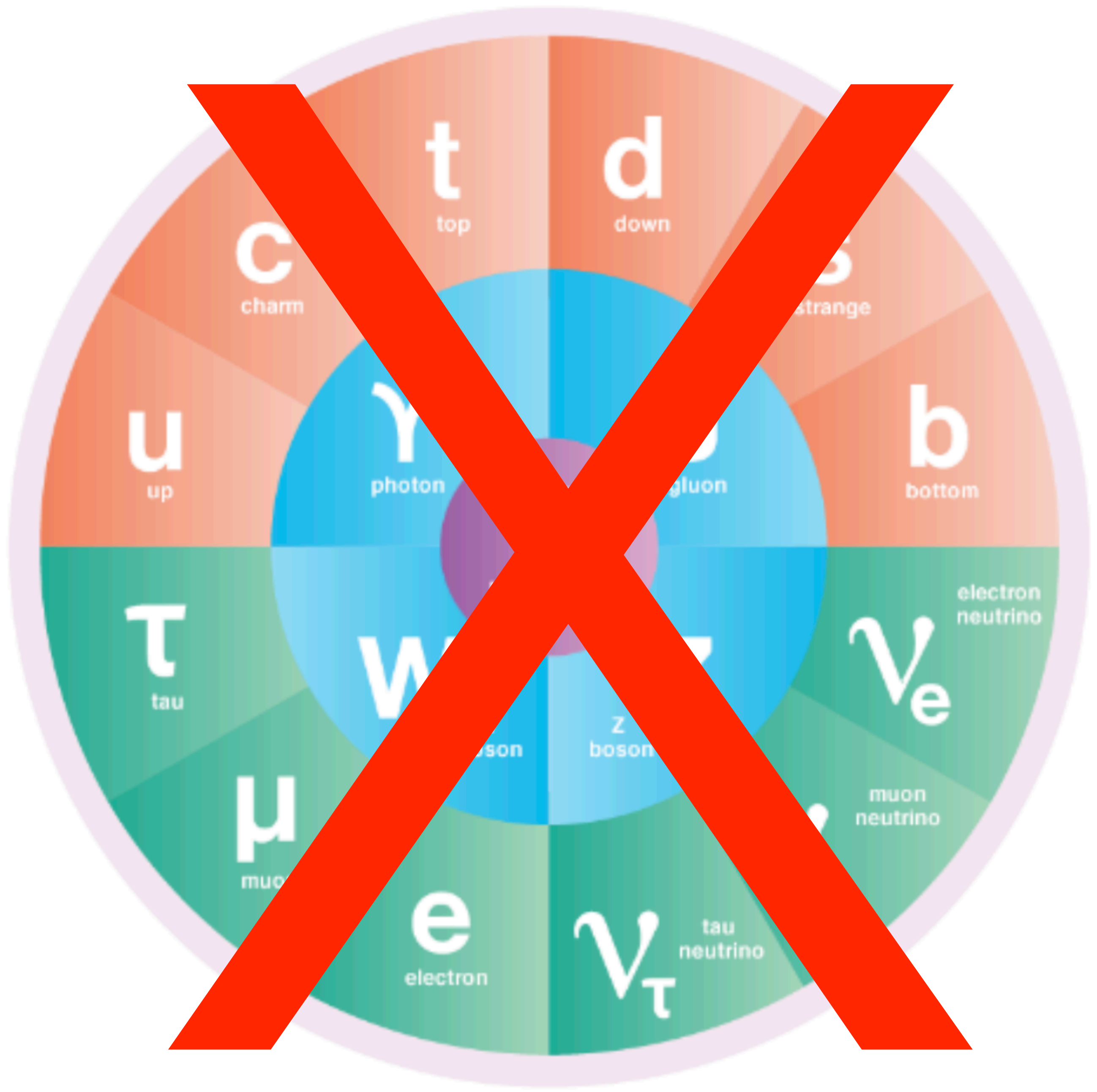

Not this!

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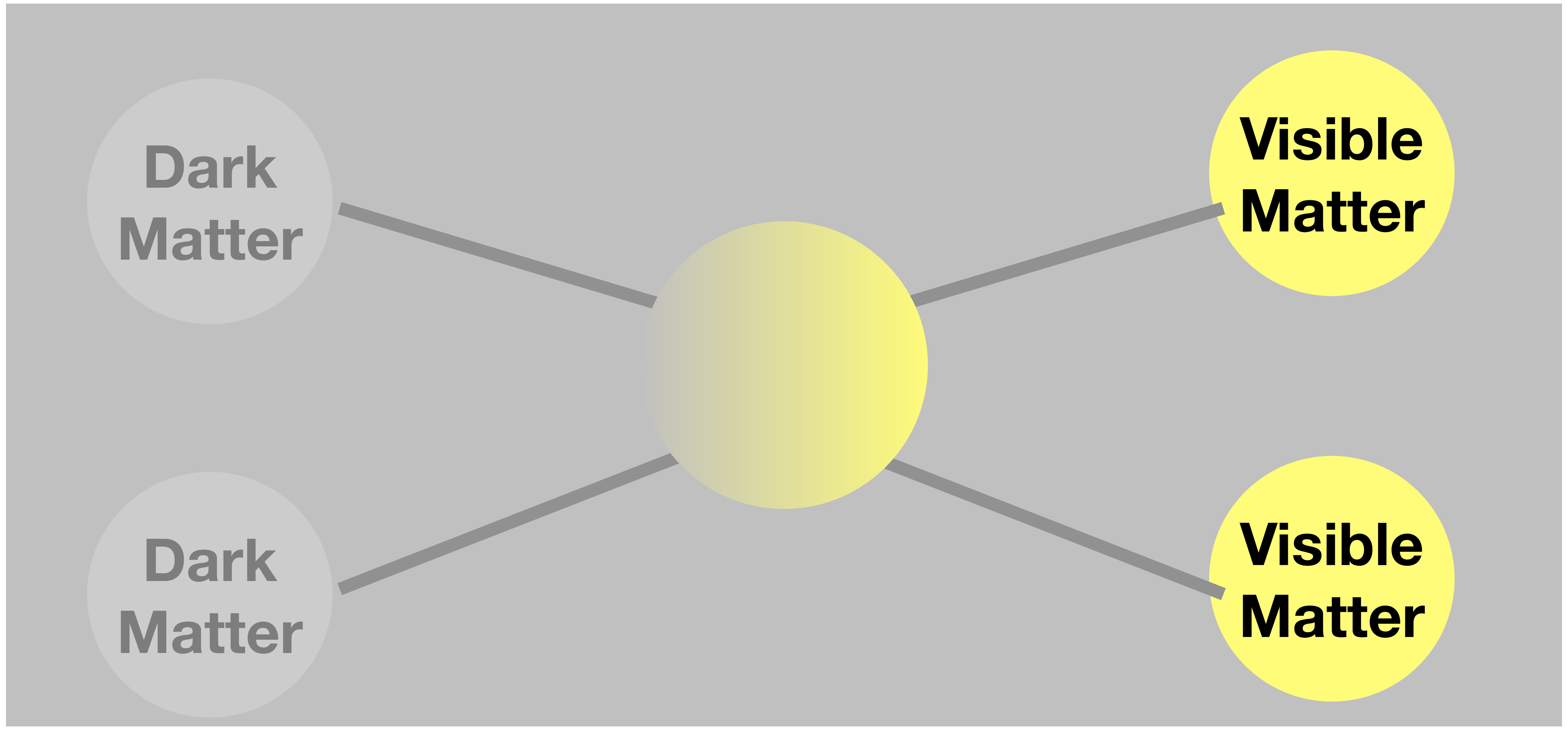
What is the dark matter?

Assume it interacts with the standard model particles



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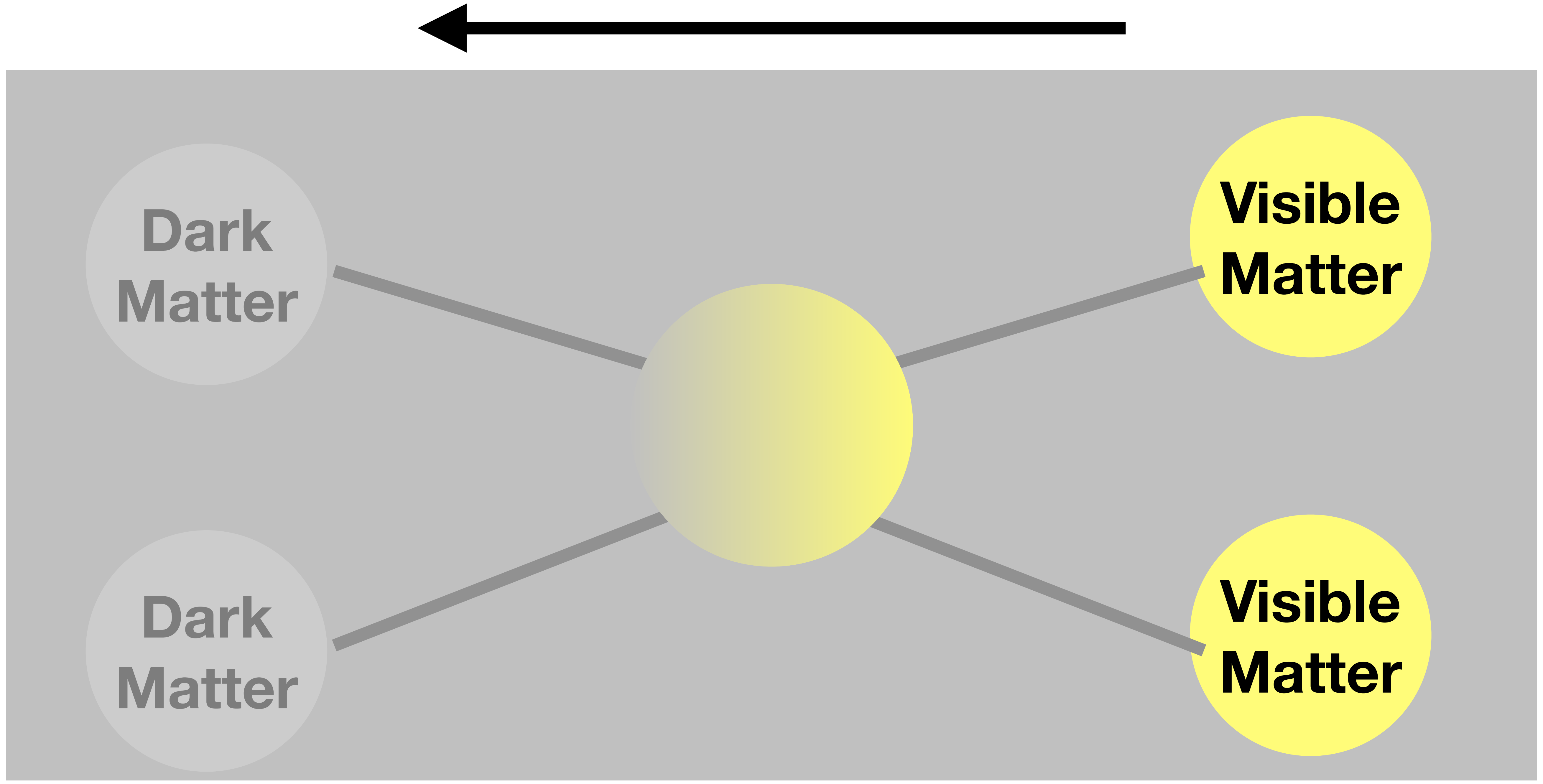
Production (colliders)



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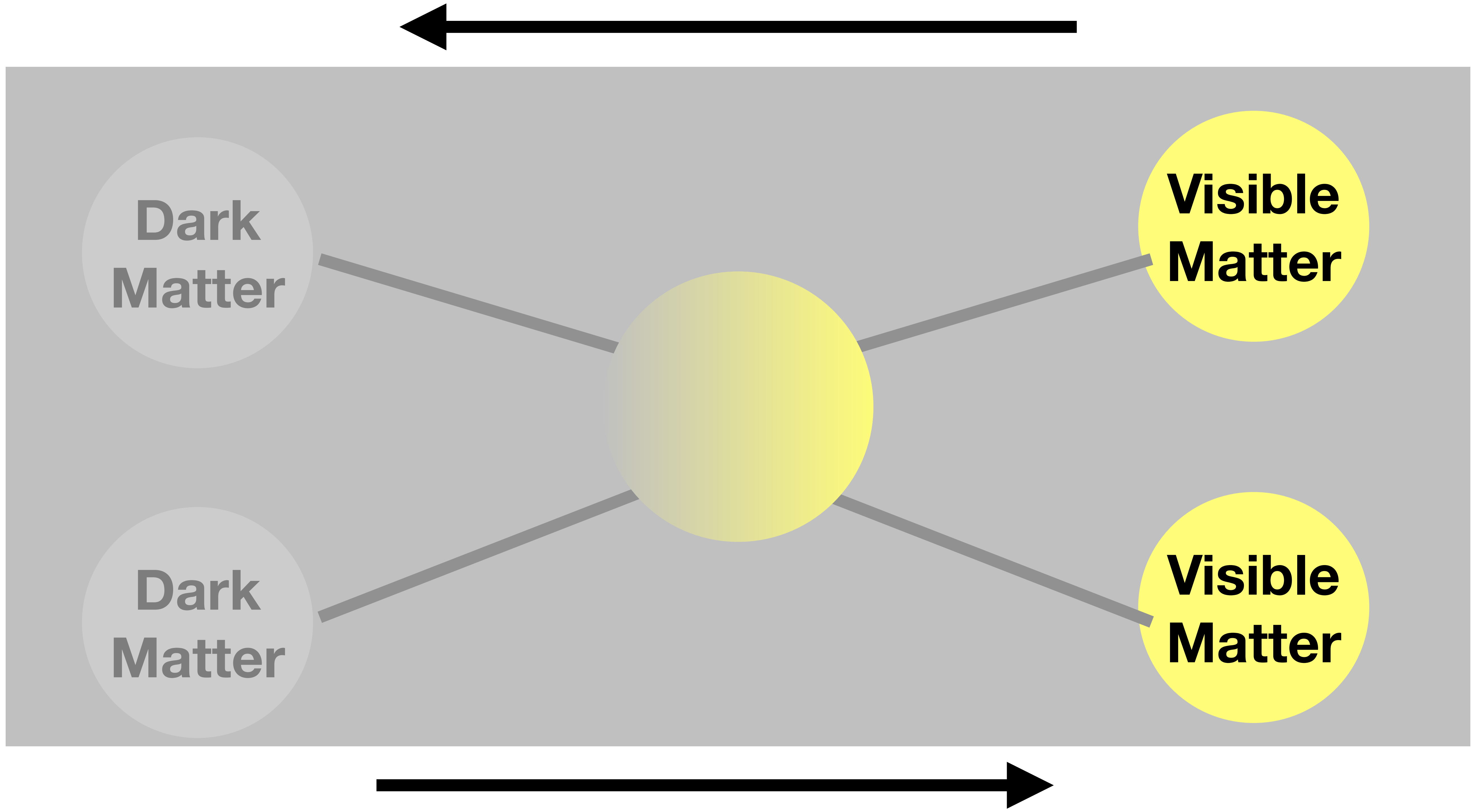

"Indirect" Detection
(look up at the sky for unexpected light)

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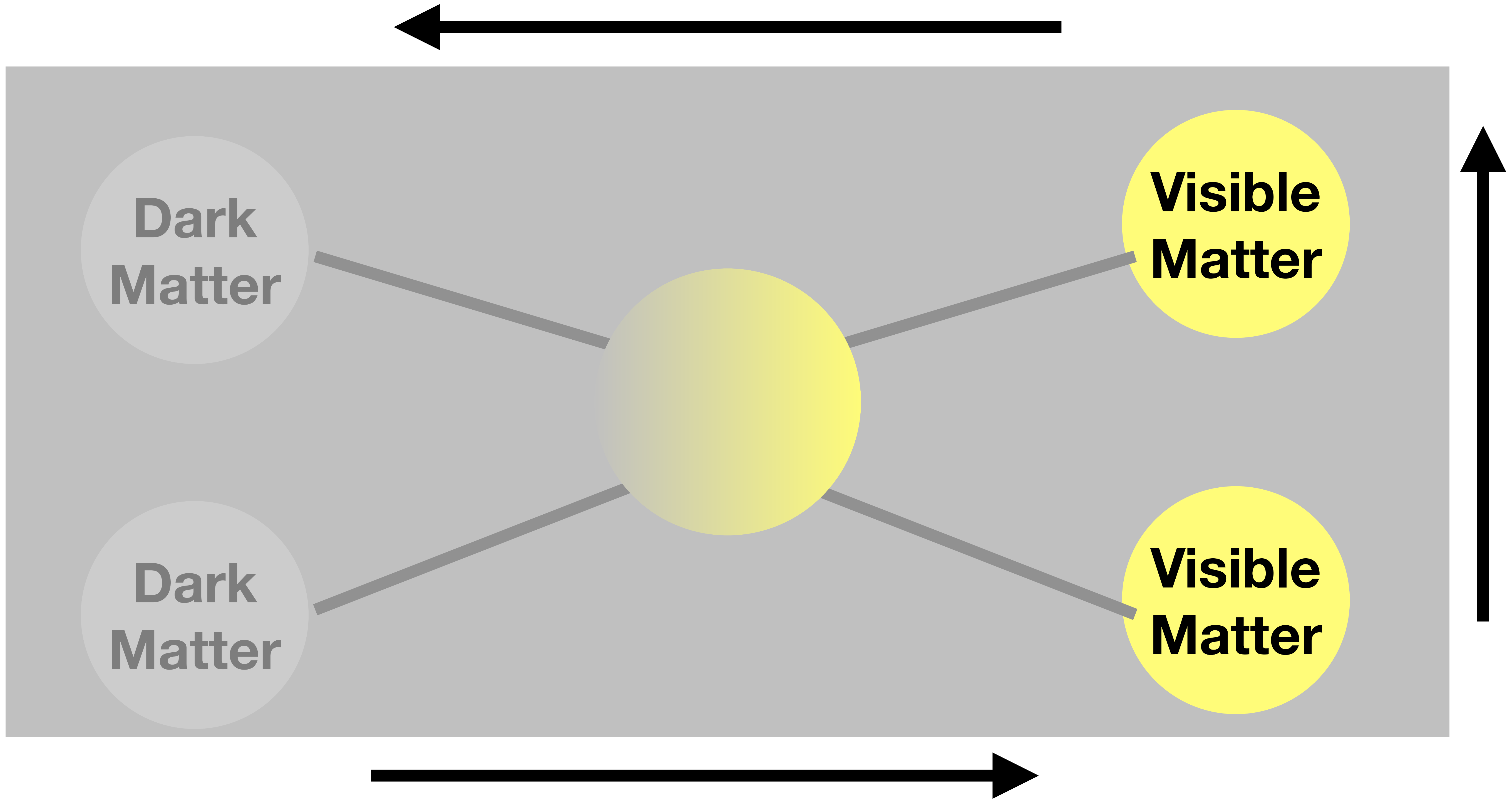
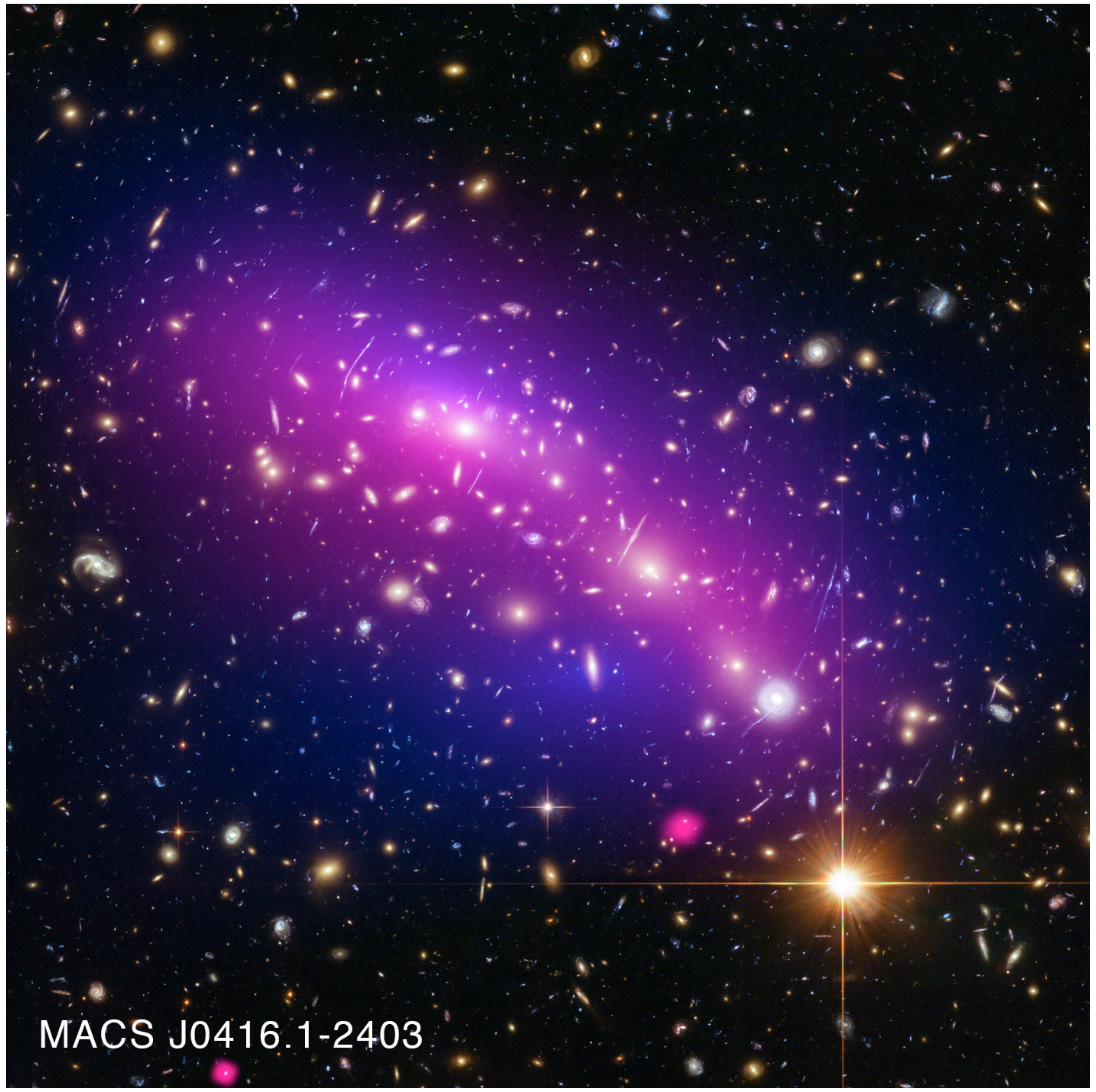


"Direct" Detection (watch big vats of Xenon)

"Indirect" Detection
(look up at the sky for unexpected light)

The Dark Matter Puzzle



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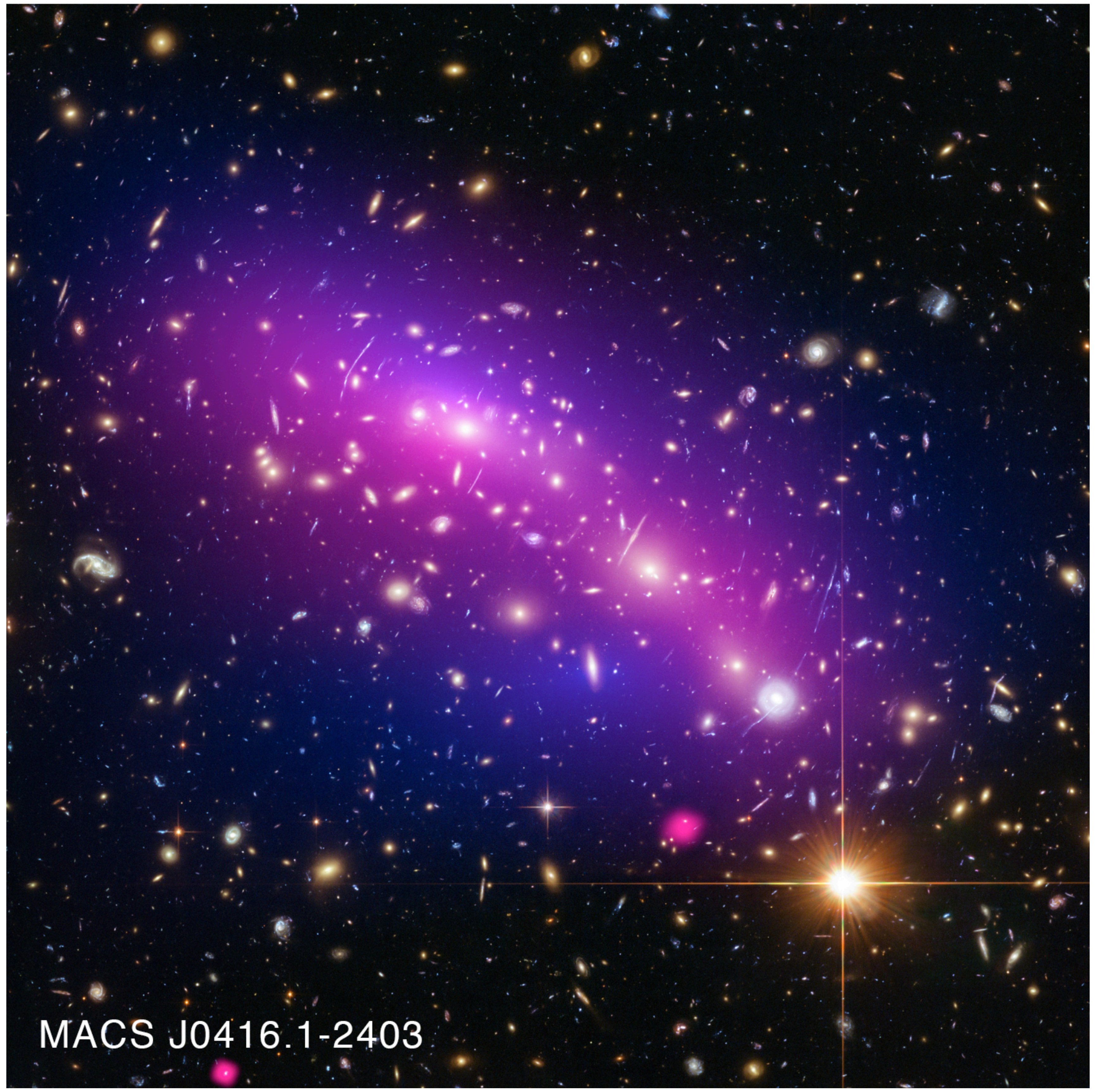
The Dark Matter Puzzle

We know very well how it gravitates



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The Dark Matter Puzzle

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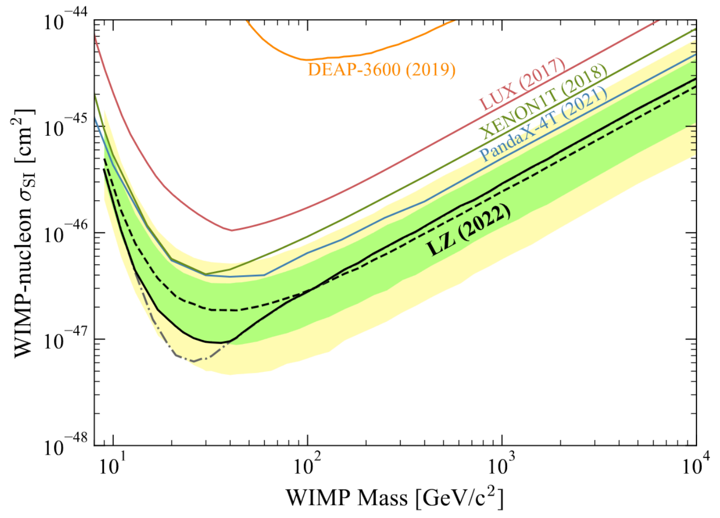
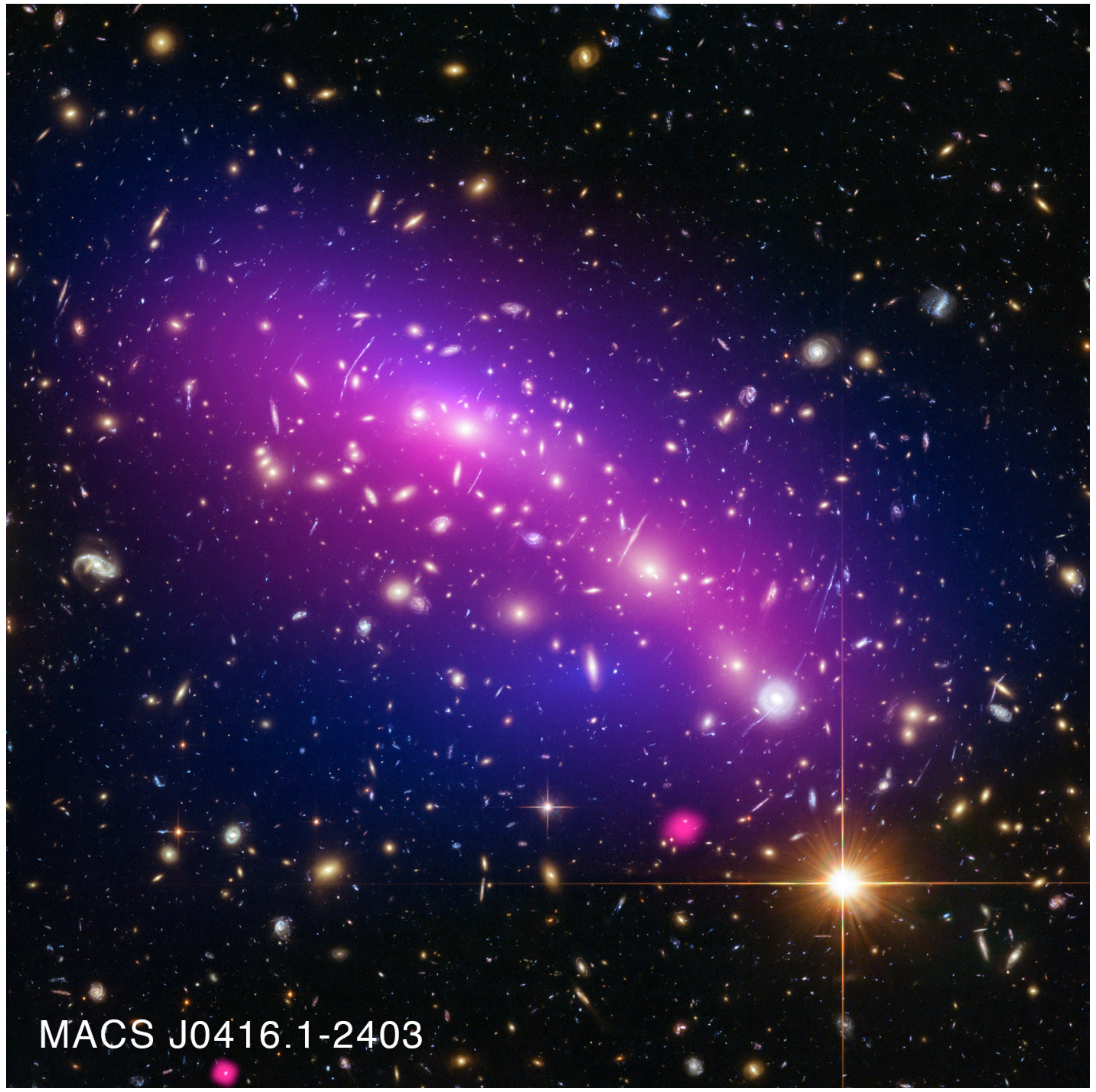
- No evidence for dark matter-visible matter interaction beyond gravity (yet?)





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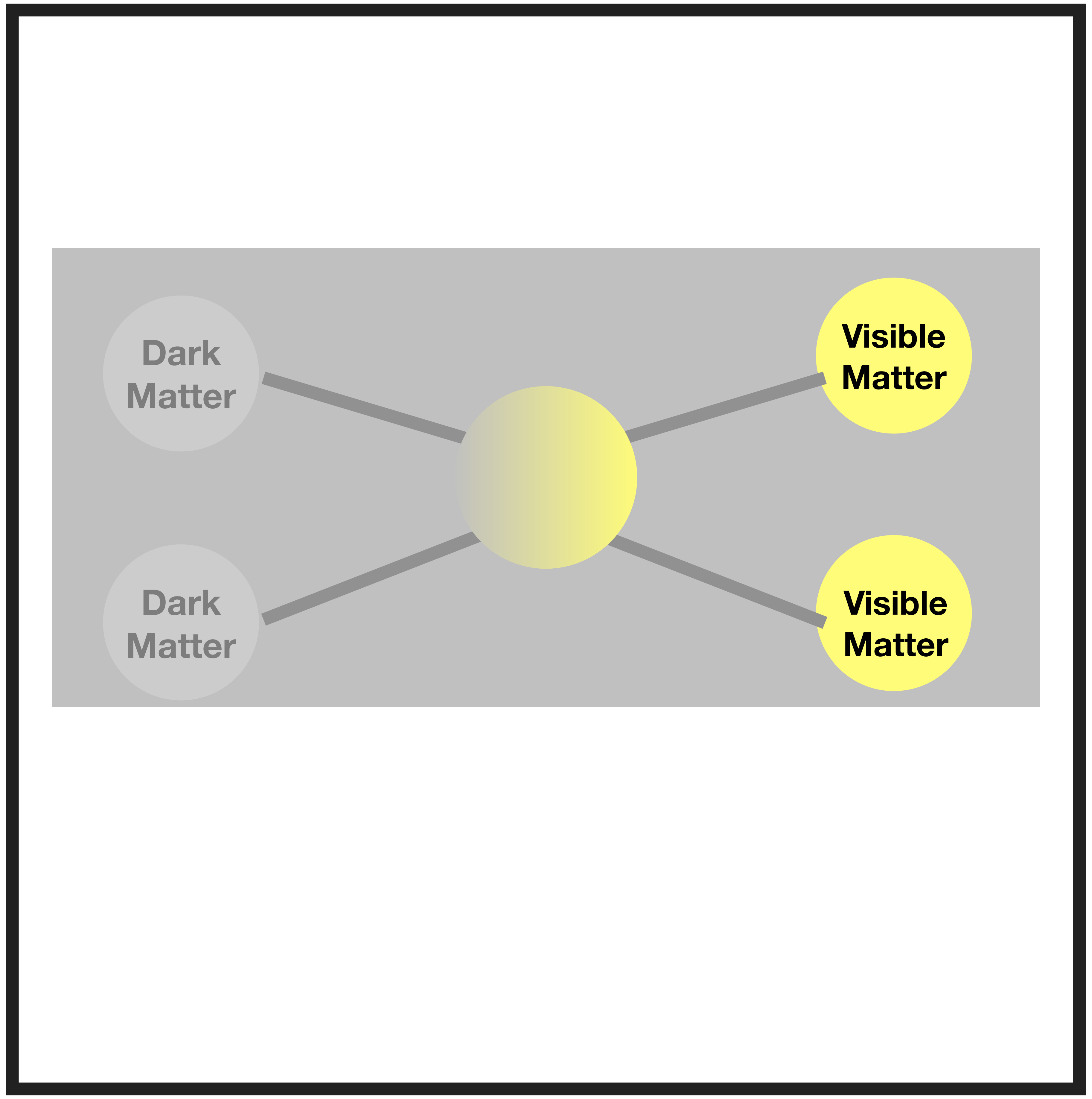
New perspectives on dark matter



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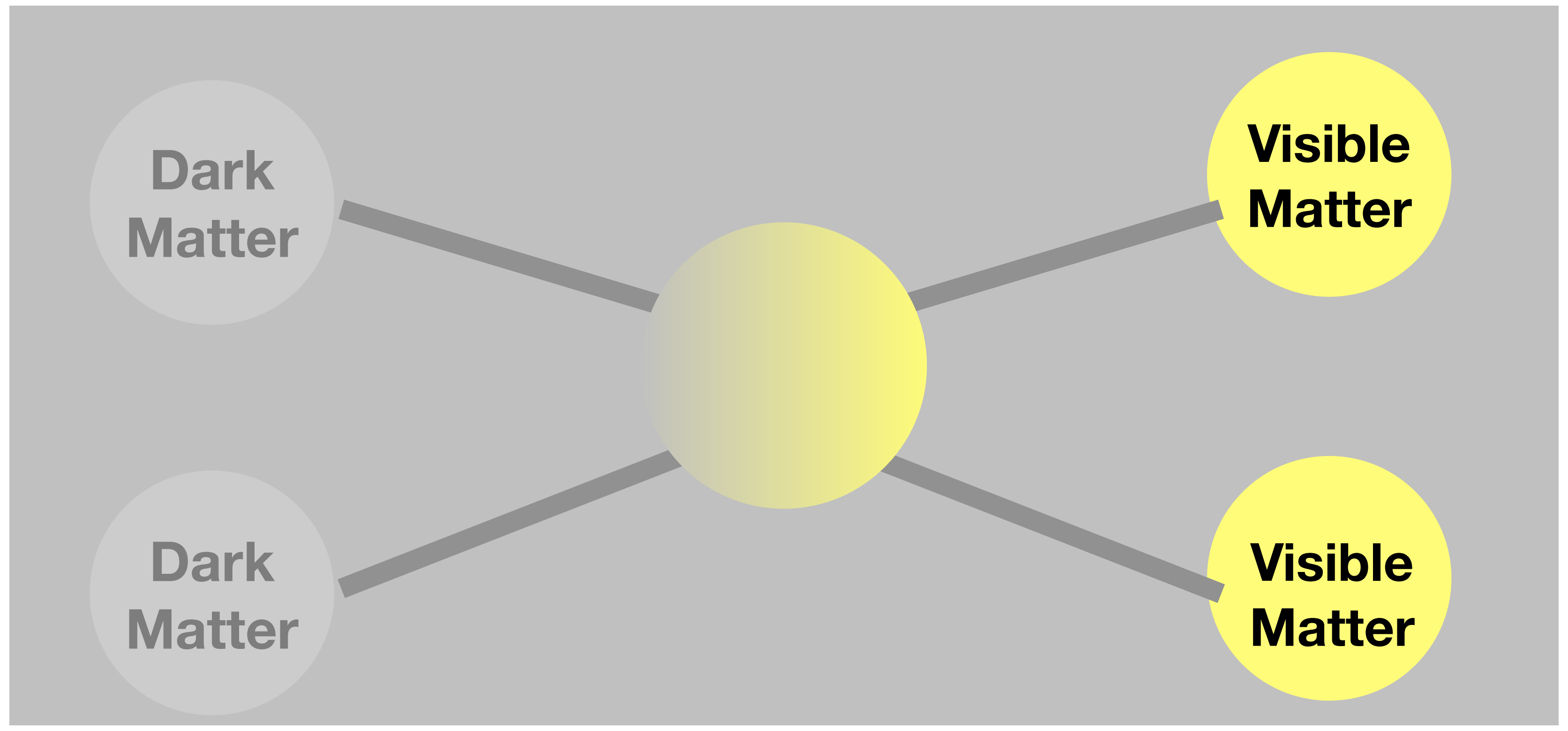

- Or -

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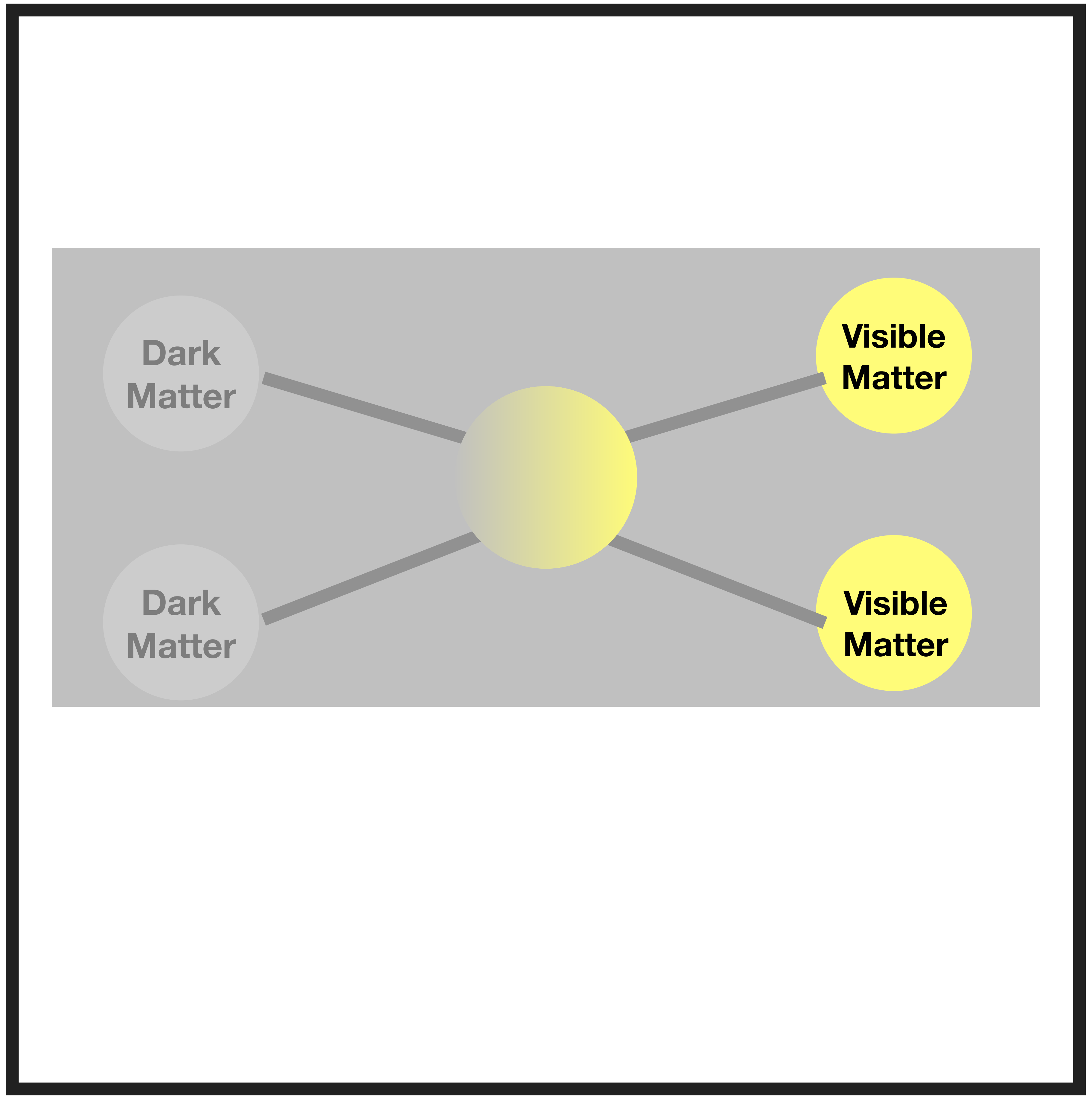

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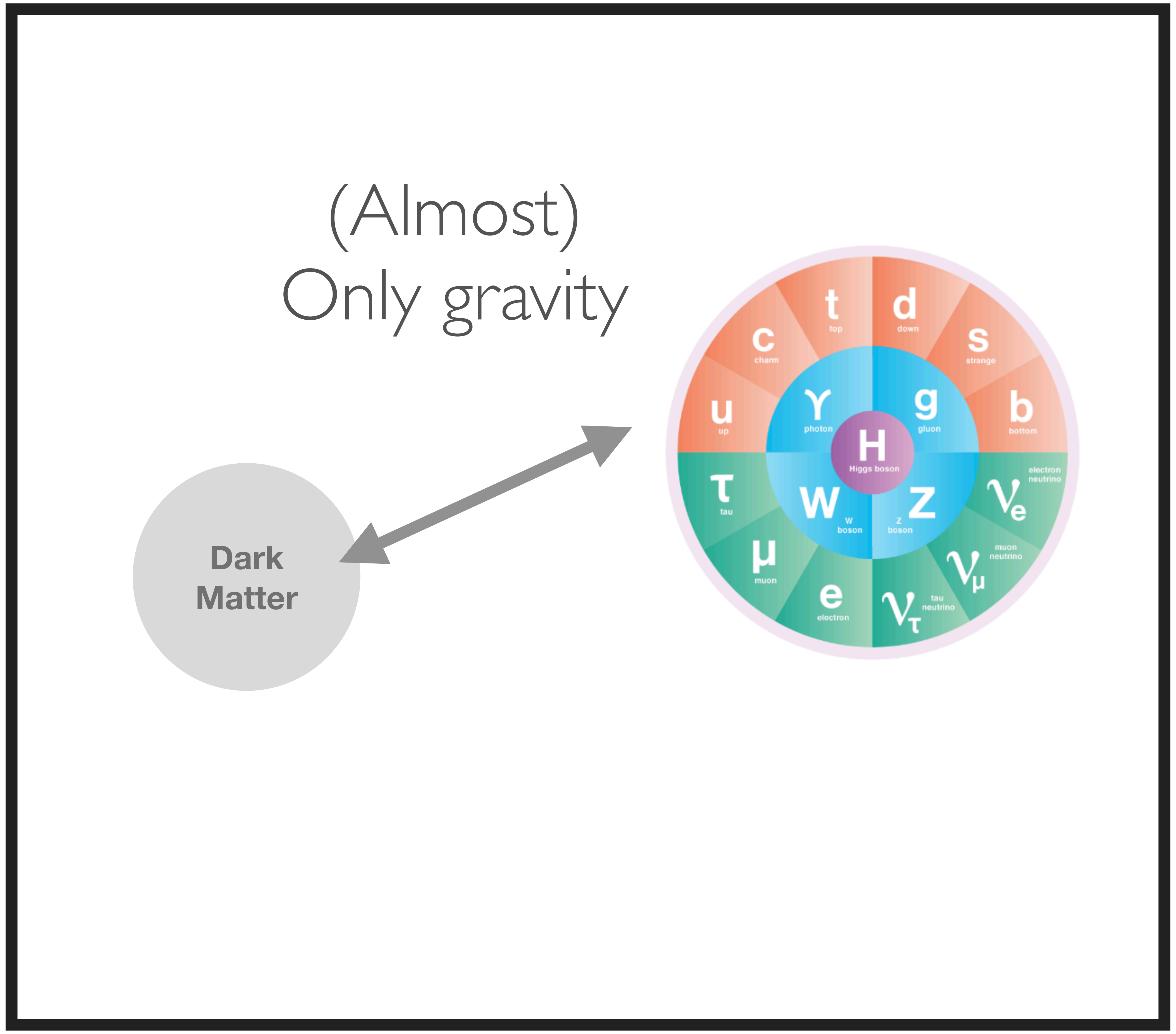
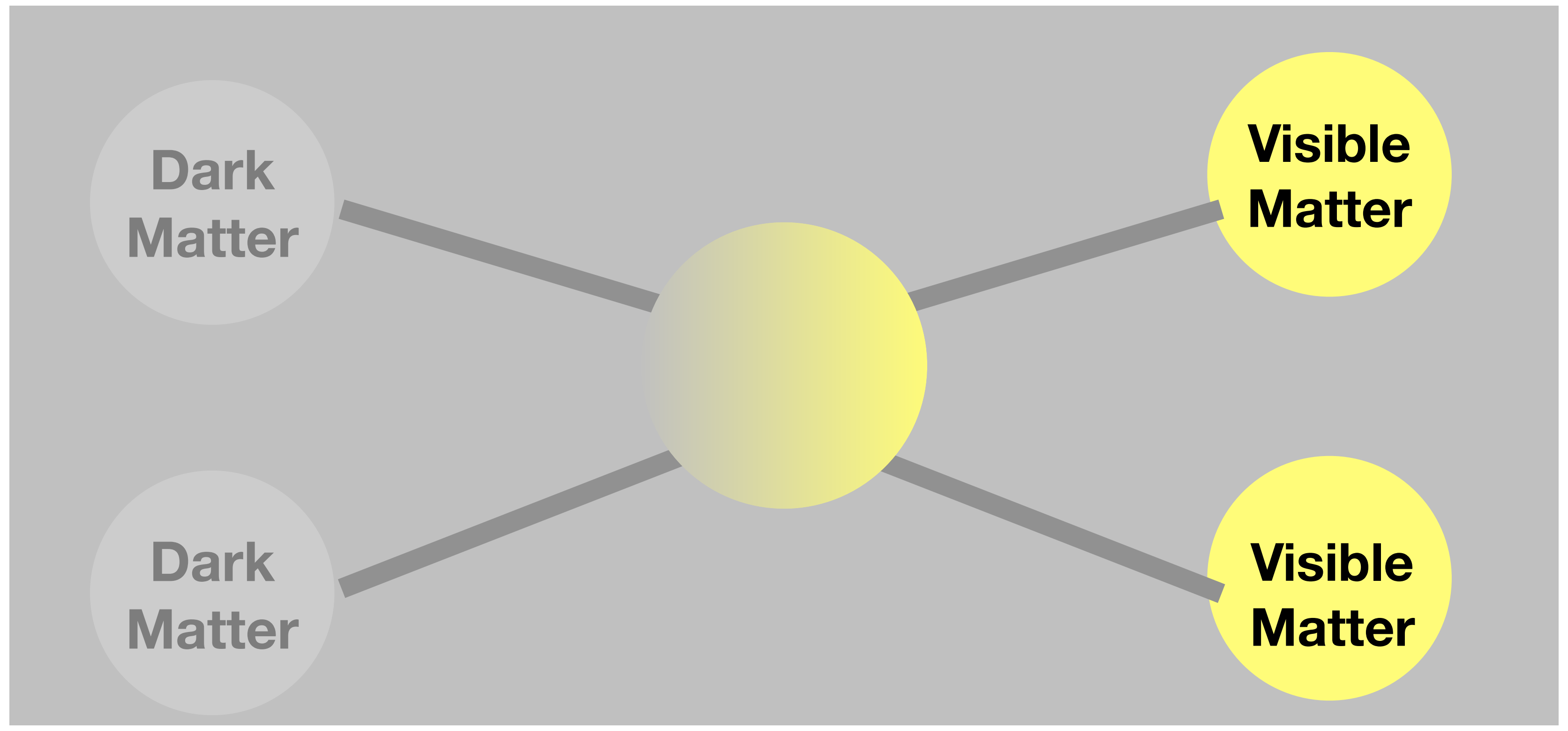


Shandera, TRISEP 2024

New perspectives on dark matter

“Complex” or “hidden sector” dark matter



Most important interaction is with the Standard Model

- Or -

(Almost)
Only gravity

New perspectives on dark matter

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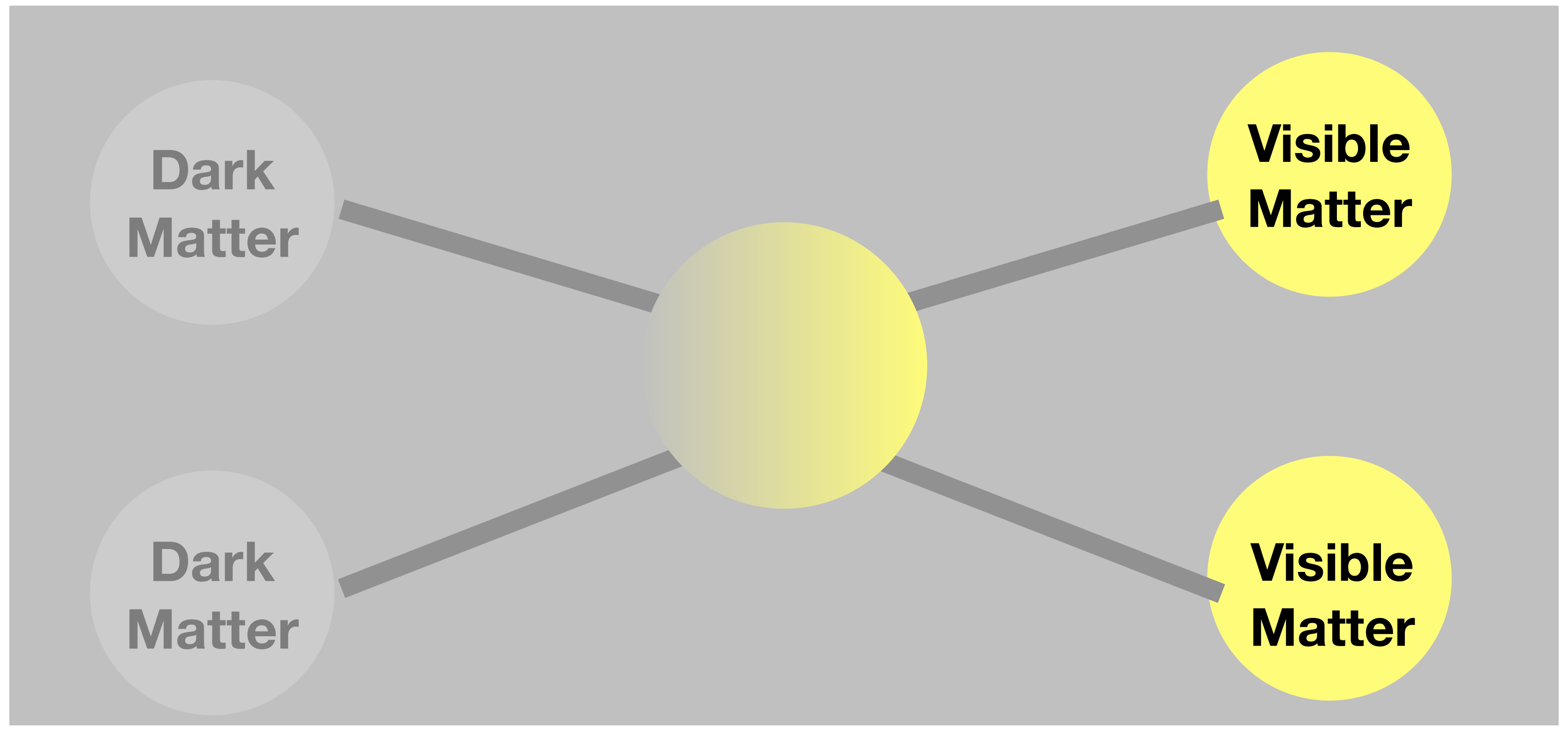

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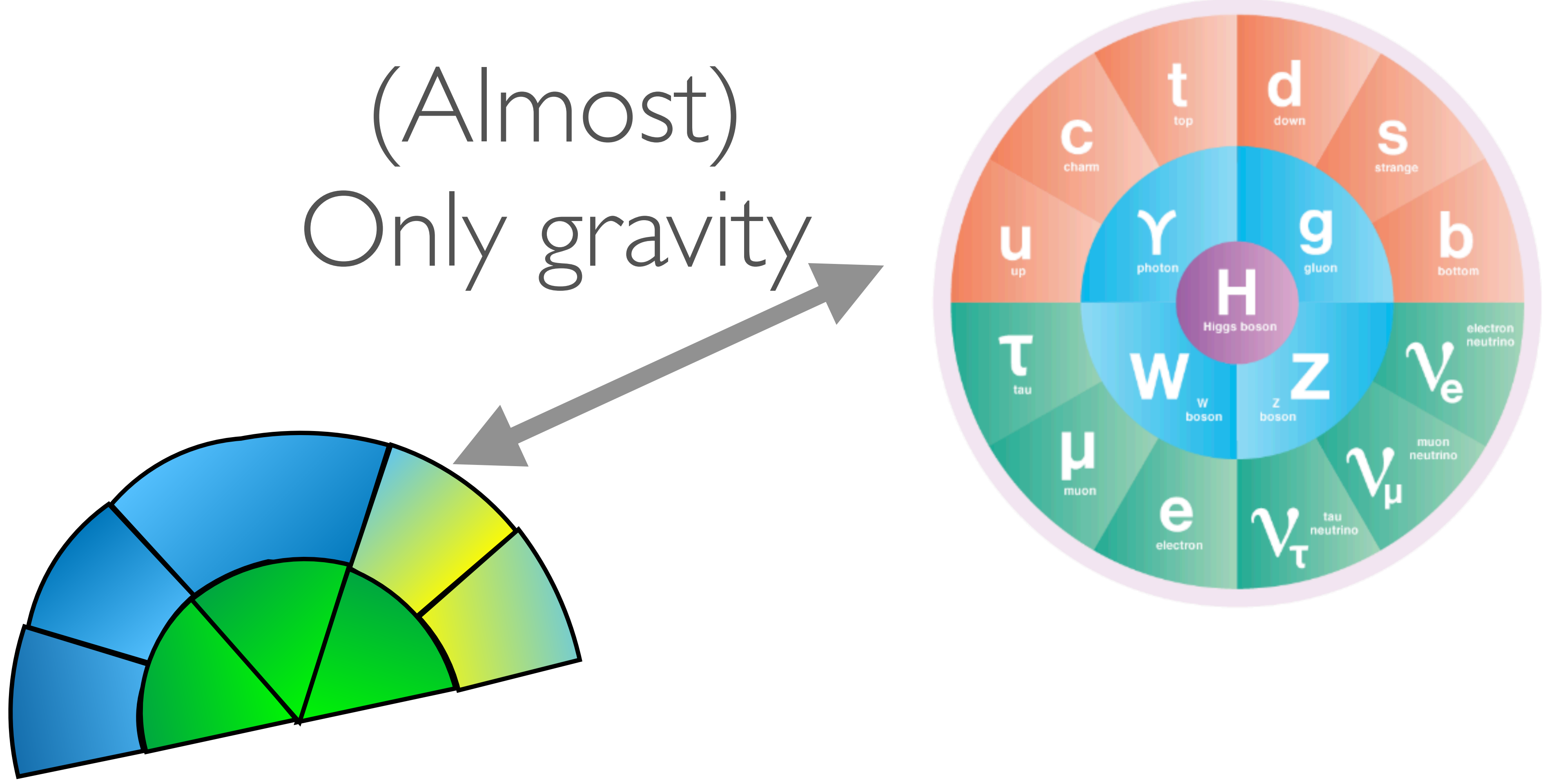
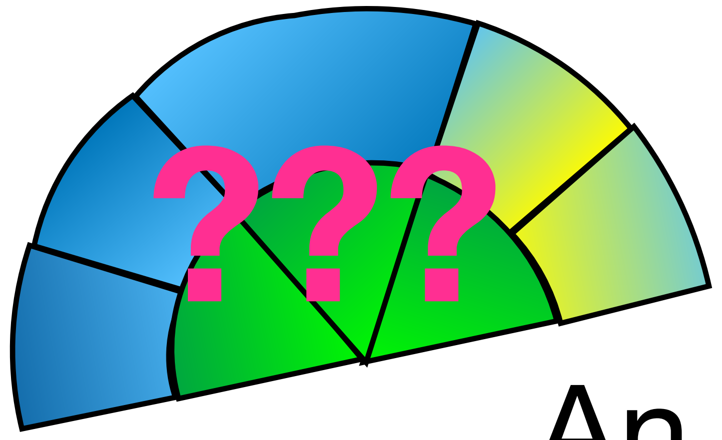


Most important interactions are between dark matter particles



Complex dark matter?

An old idea:

1965: Nishijima, Saffouri “CP Invariance and the Shadow Universe”

1966: Kobzarev, Okun, Ya, Pomeranchuk “On the possibility of experimental observation of mirror particles” (2014 review, Blinnikov, for Pomeranchuk’s 100th birthday)

1985: Gross, Harvey, Martinec, Rohm “Heterotic String” (“*shadow matter*”)

1986: Goldberg, Hall “A New Candidate for Dark Matter” (electromagnetic interactions with visible matter)

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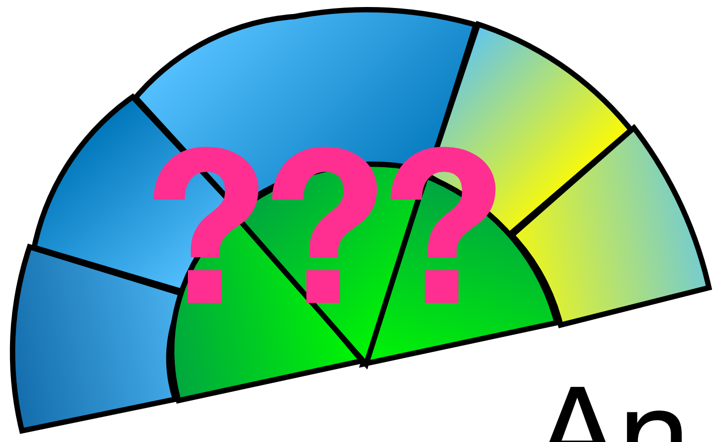

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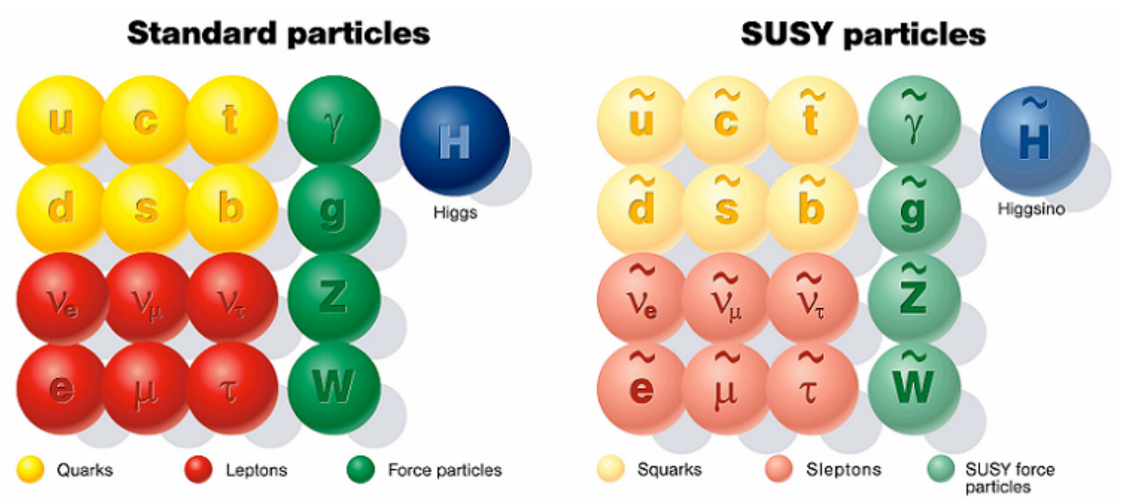
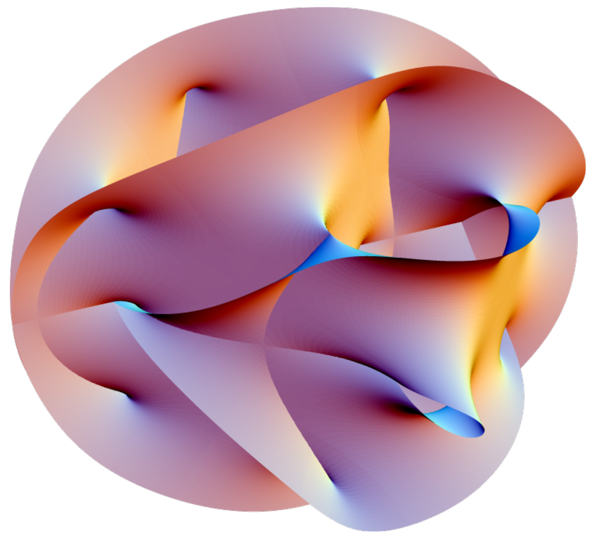
Went under the radar while these ideas were ascendent:

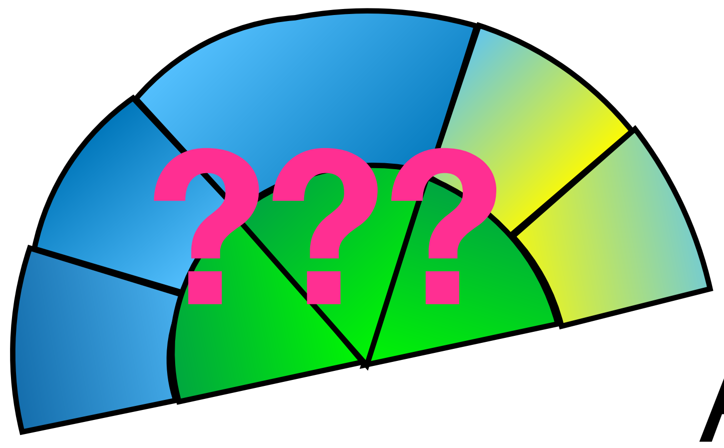


(WIMPs)



(Axions)

Shandera, TRISEP 2024



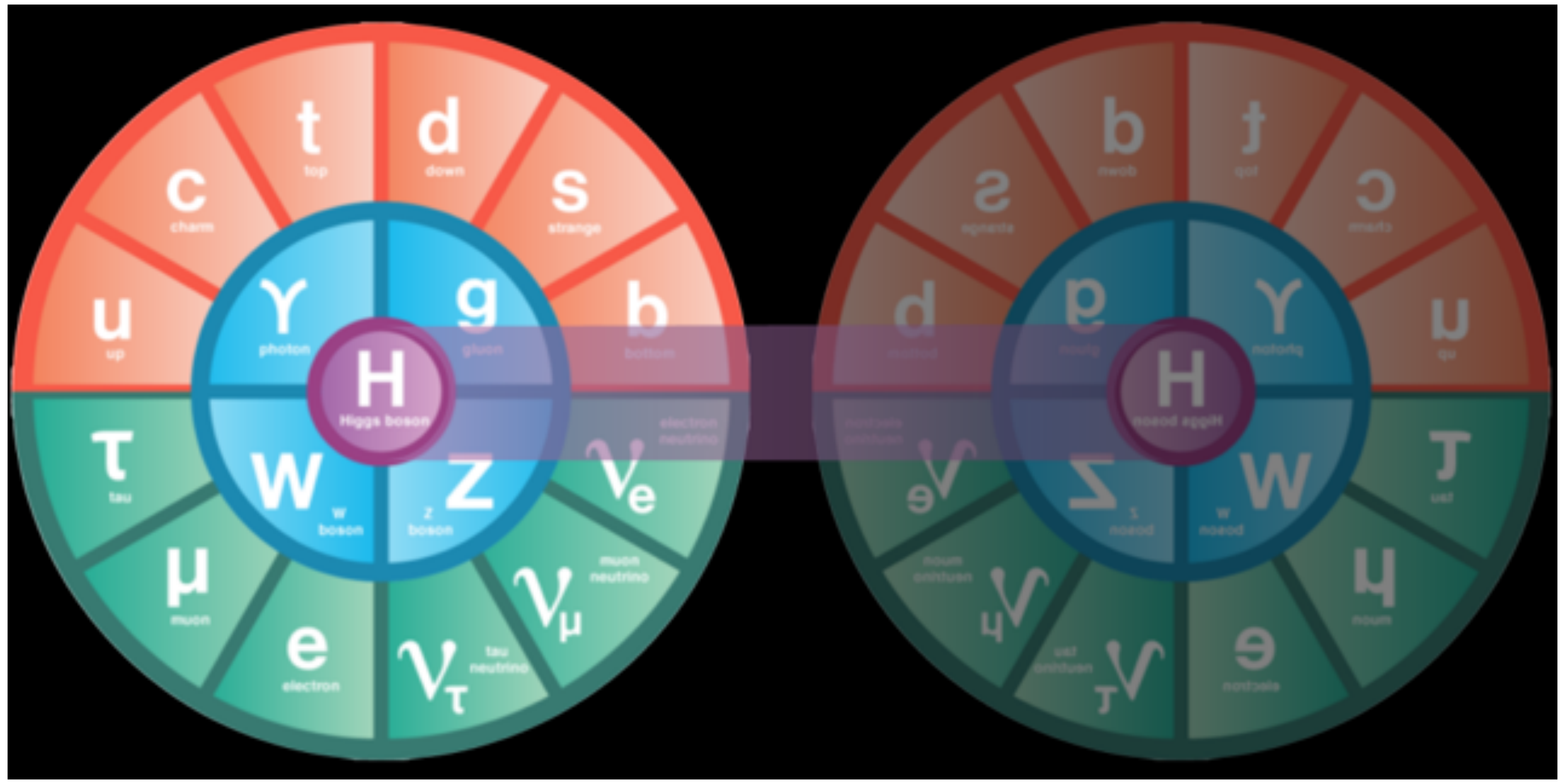
Complex dark matter?

An old idea, with new theory support:

Chacko, Goh, Harnik, “The Twin Higgs: Natural electroweak breaking from mirror symmetry” (hep-ph/0506256, *PRL*)

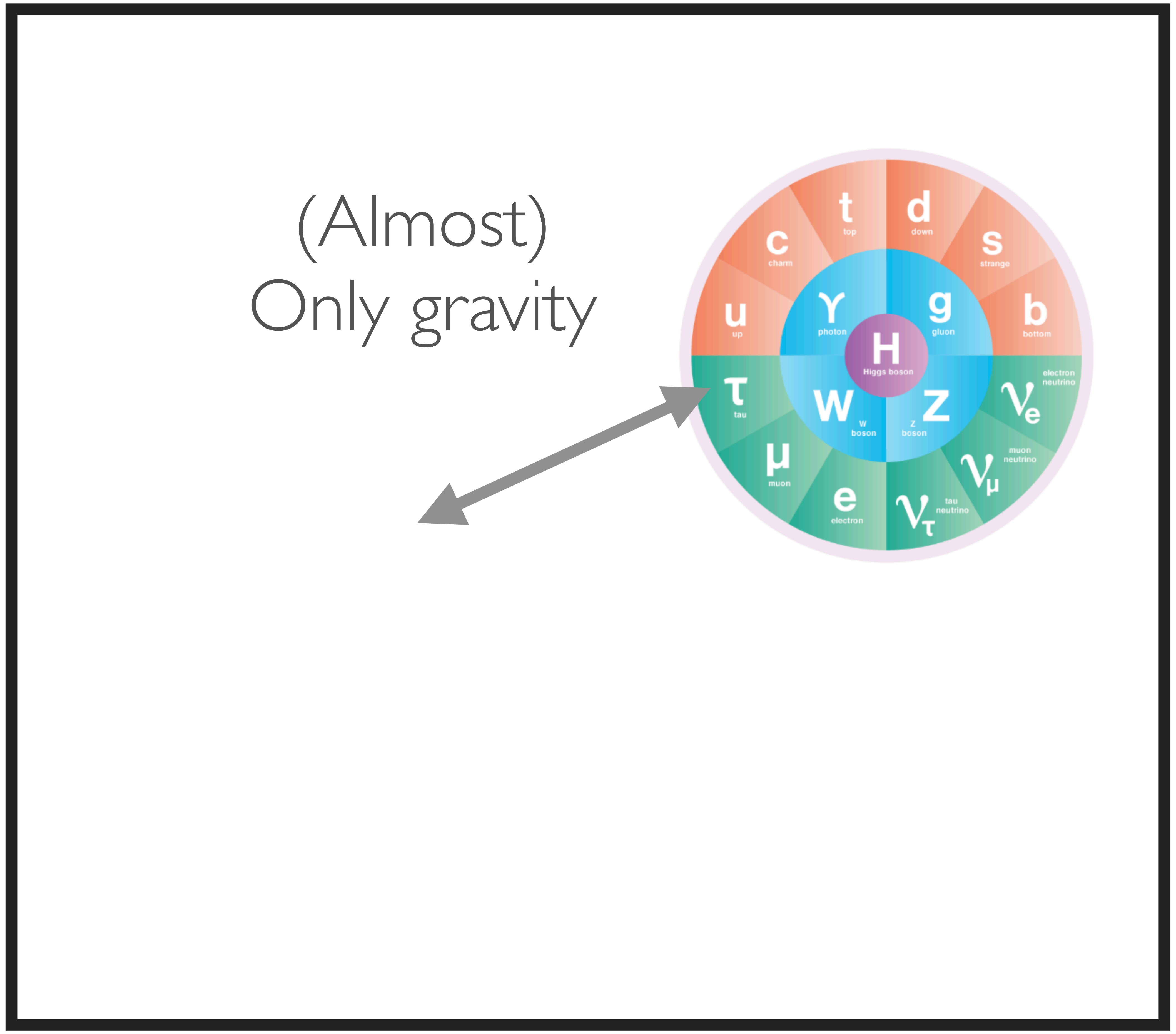
(~740 citations, mostly after discovery of the Higgs boson)

……



N. Craig; adapted from Symmetry Magazine
See discussion in 2205.05708

Keywords for complex dark matter



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- Dissipative
- Cooling
- Chemistry (bound states)

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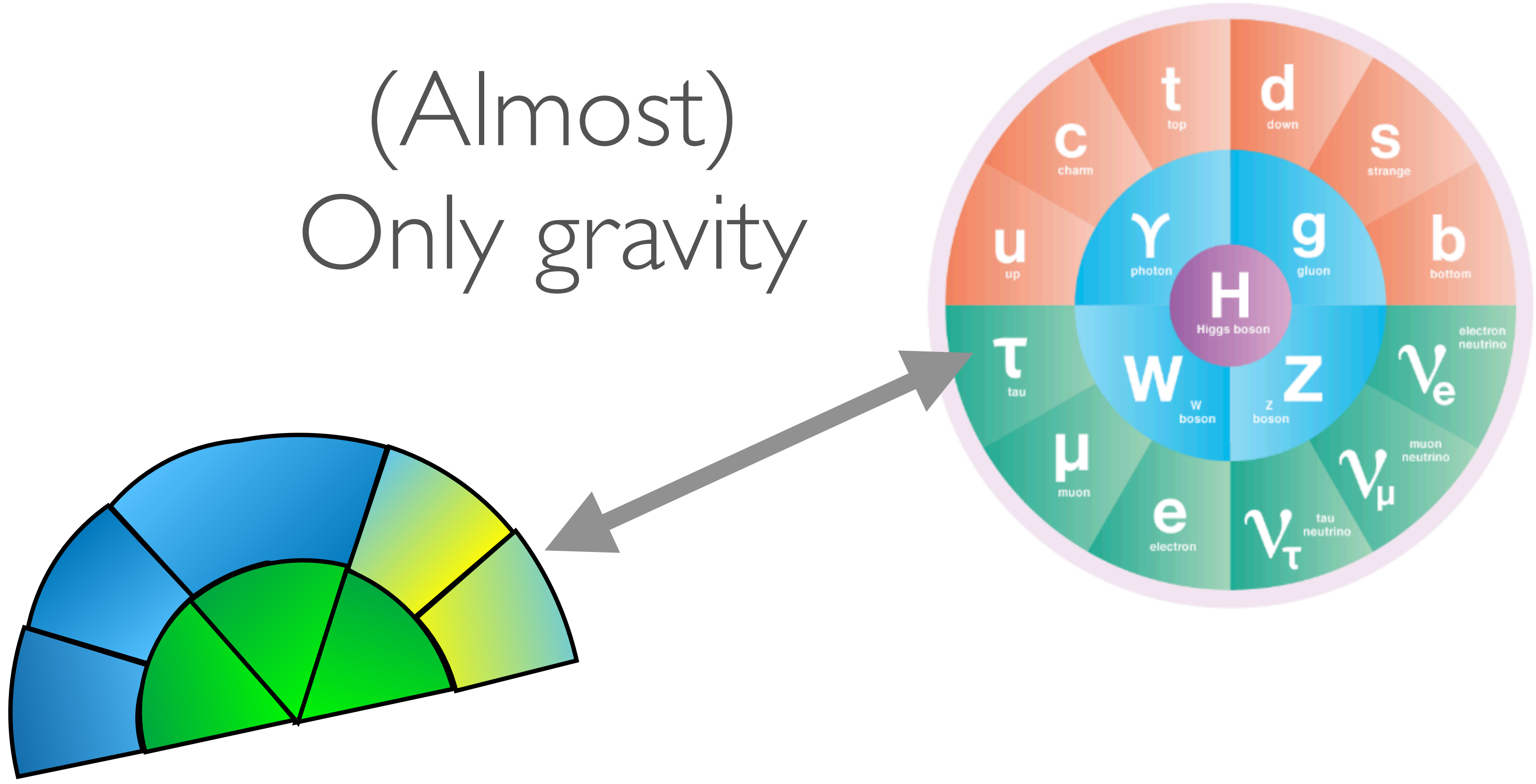

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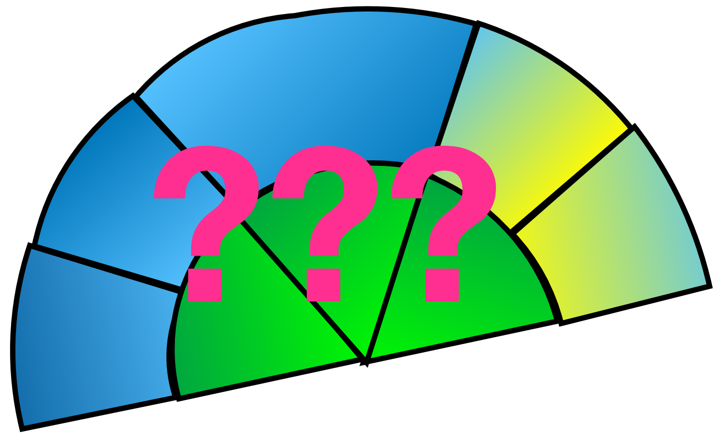
- Cooling
- Chemistry (bound states)



Complex dark matter?

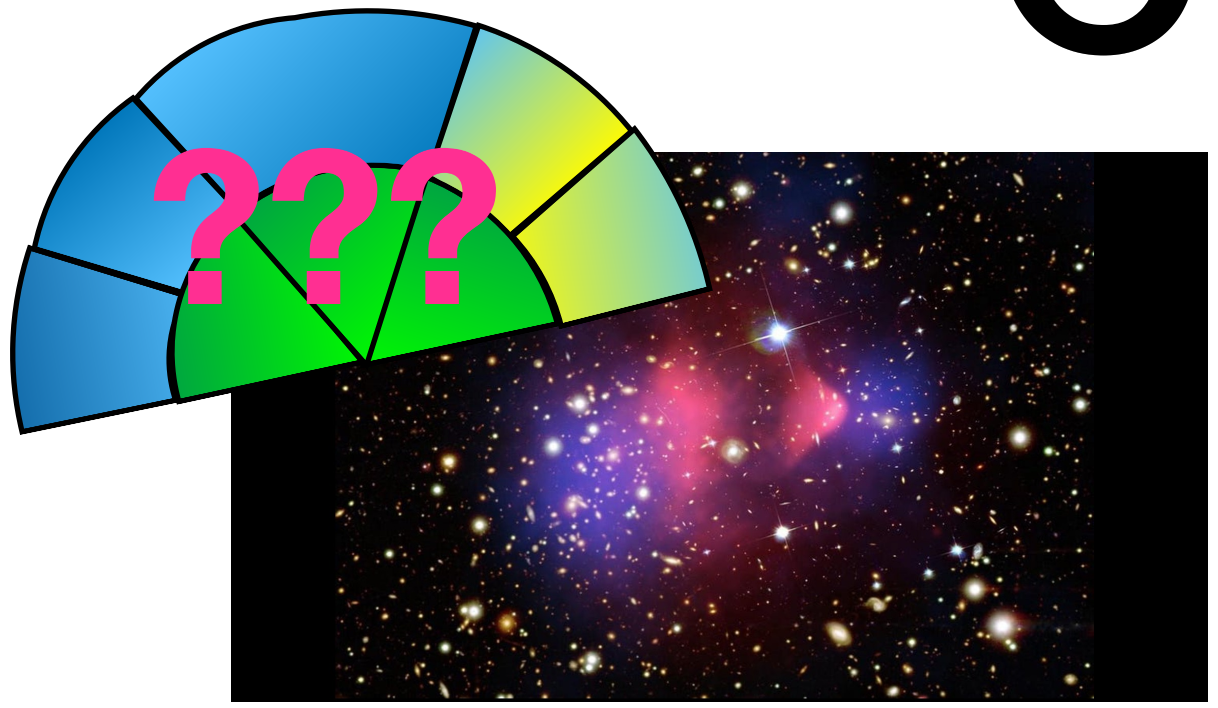
Data will decide

Consistency with what we know? Consider a famous constraint:

Dark matter experiences less drag than visible matter

Credit: NASA/CXC/CfA/M. Markevitch; Optical and lensing map: NASA/STScI, Magellan/U. of Arizona/D. Clowe; Lensing map: ESO WFI

Complex dark matter?



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Less drag? What interaction constraint?

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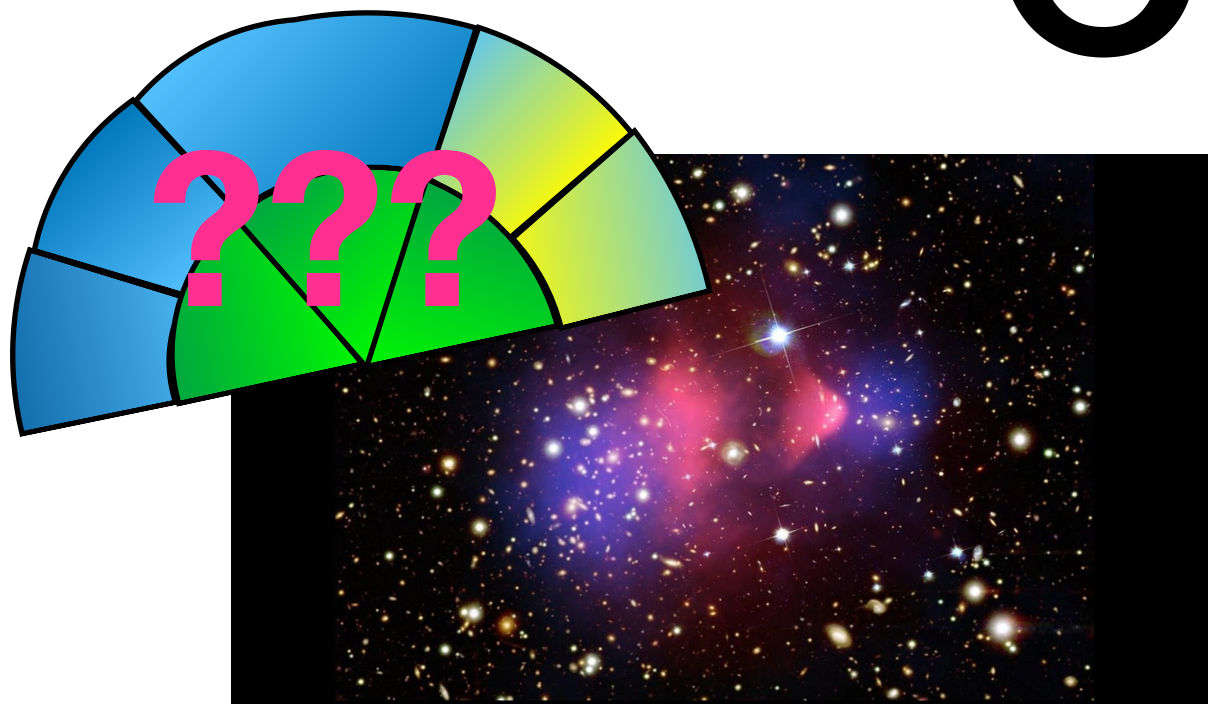

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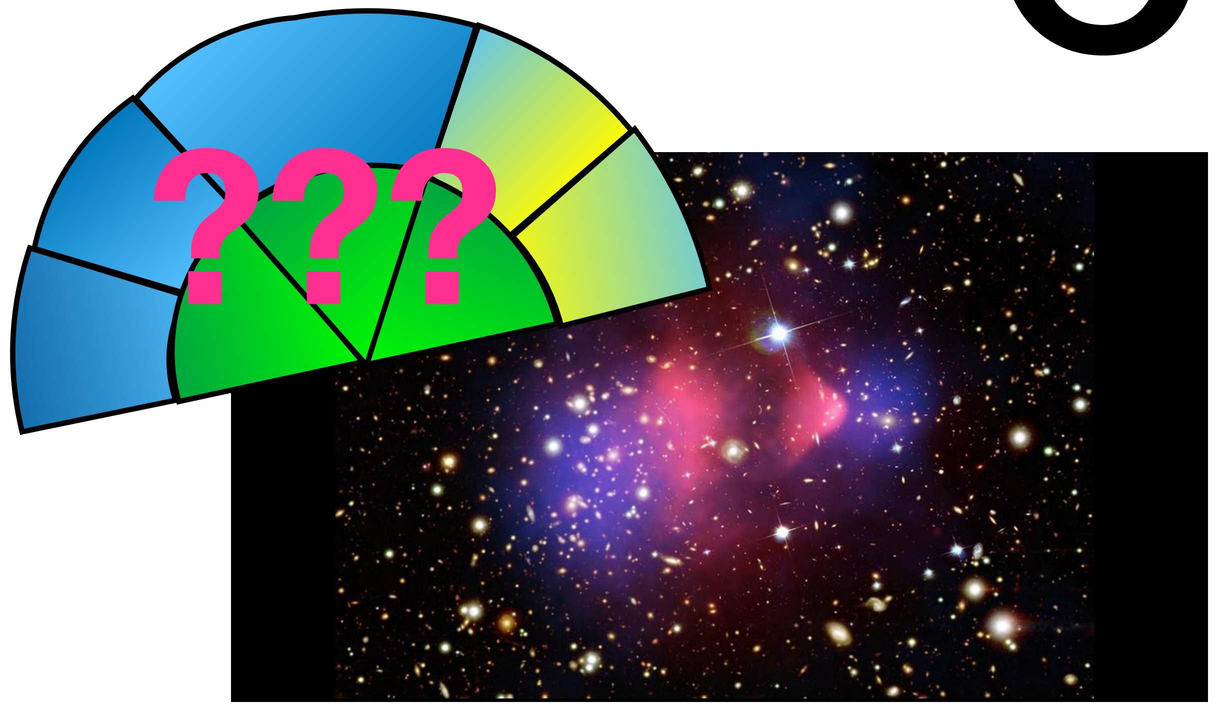
Less drag? What interaction constraint?

Assume elastic collisions:

$$\frac{\text{(Cross-section for momentum transfer)}}{\text{(Mass of the dark matter particle)}}$$

Complex dark matter?



Data will decide

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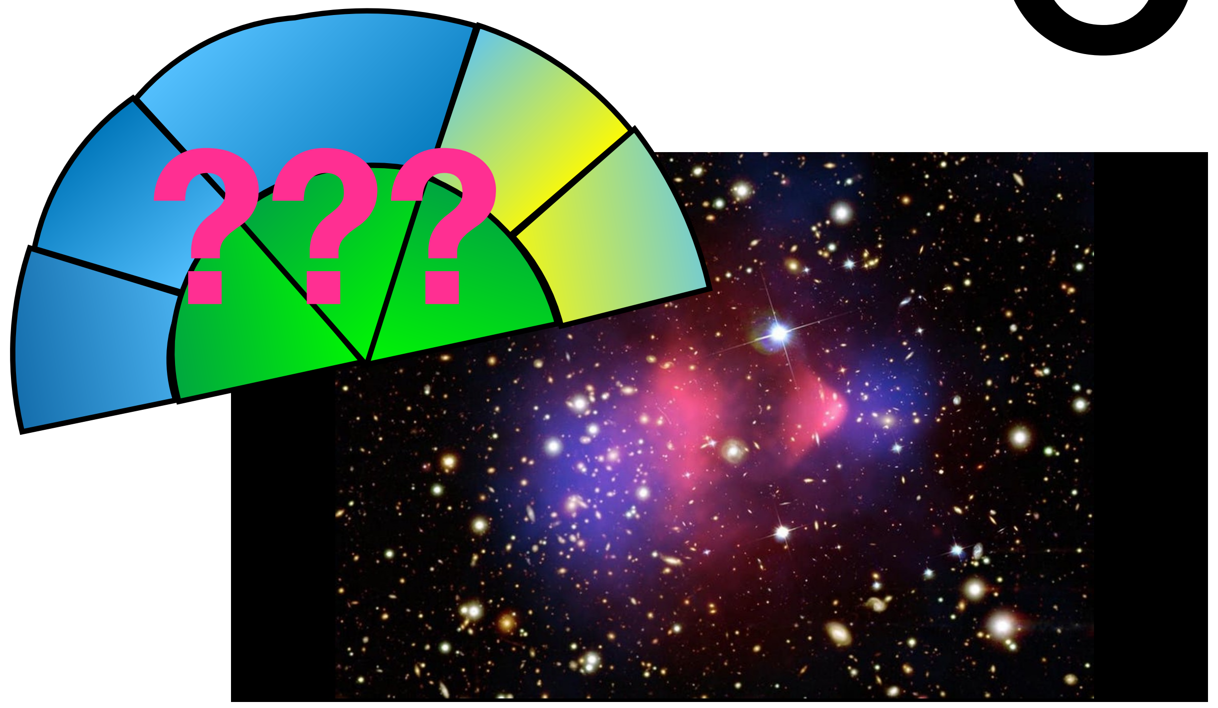
Assume elastic collisions:

$$\frac{\text{(Cross-section for momentum transfer)}}{\text{(Mass of the dark matter particle)}} = \frac{\sigma_T}{m} \lesssim [0.1 - 2]\ \mathrm{cm^2/g}$$

$1\ \mathrm{cm^2/g} \approx 2\ \mathrm{barns/GeV}$

Complex dark matter?



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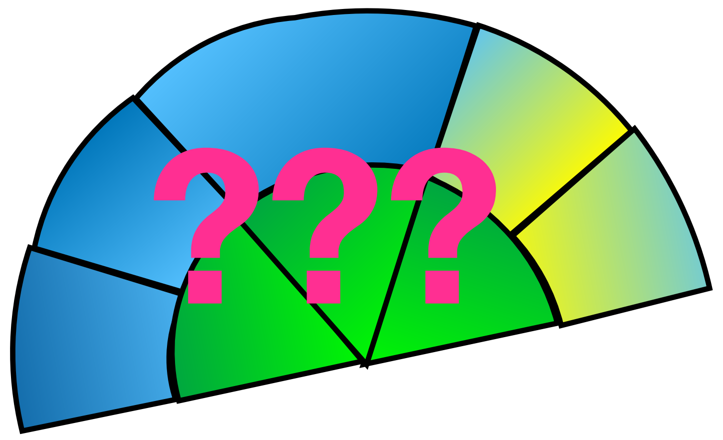
- Lots of different ways (data) to try to constrain this Markevitch et al, astro-ph/0309303
- Hard to get the bound right: simulations suggest factor of 10 changes over analytic estimates!

e.g. Kim et al 1608.08630; Adhikari et al 2207.10638 and 2401.05788

$1\ \mathrm{cm}^2/\mathrm{g} \approx 2\ \mathrm{barns}/\mathrm{GeV}$

Complex dark matter?

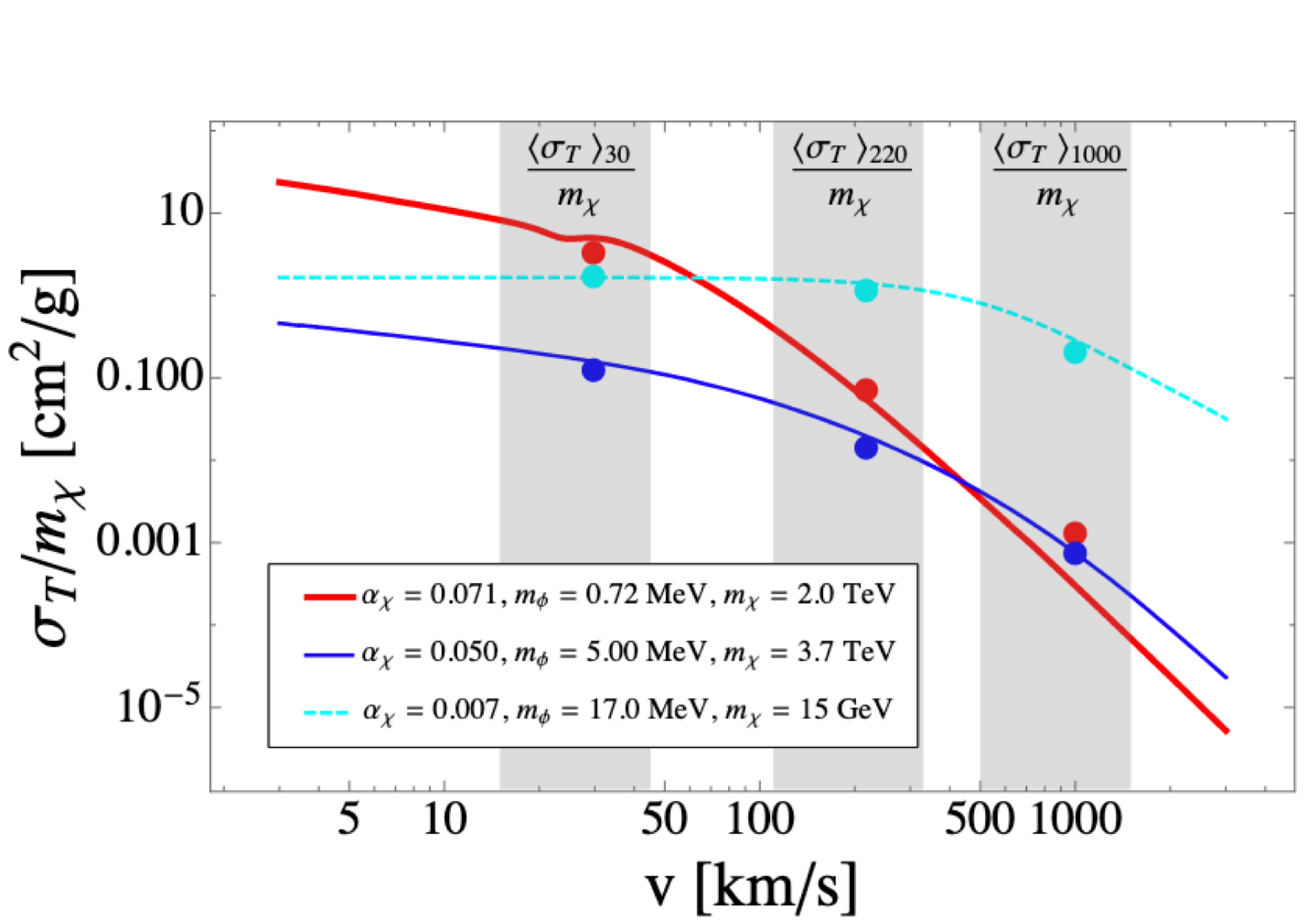


An old idea: Goldberg, Hall 1986

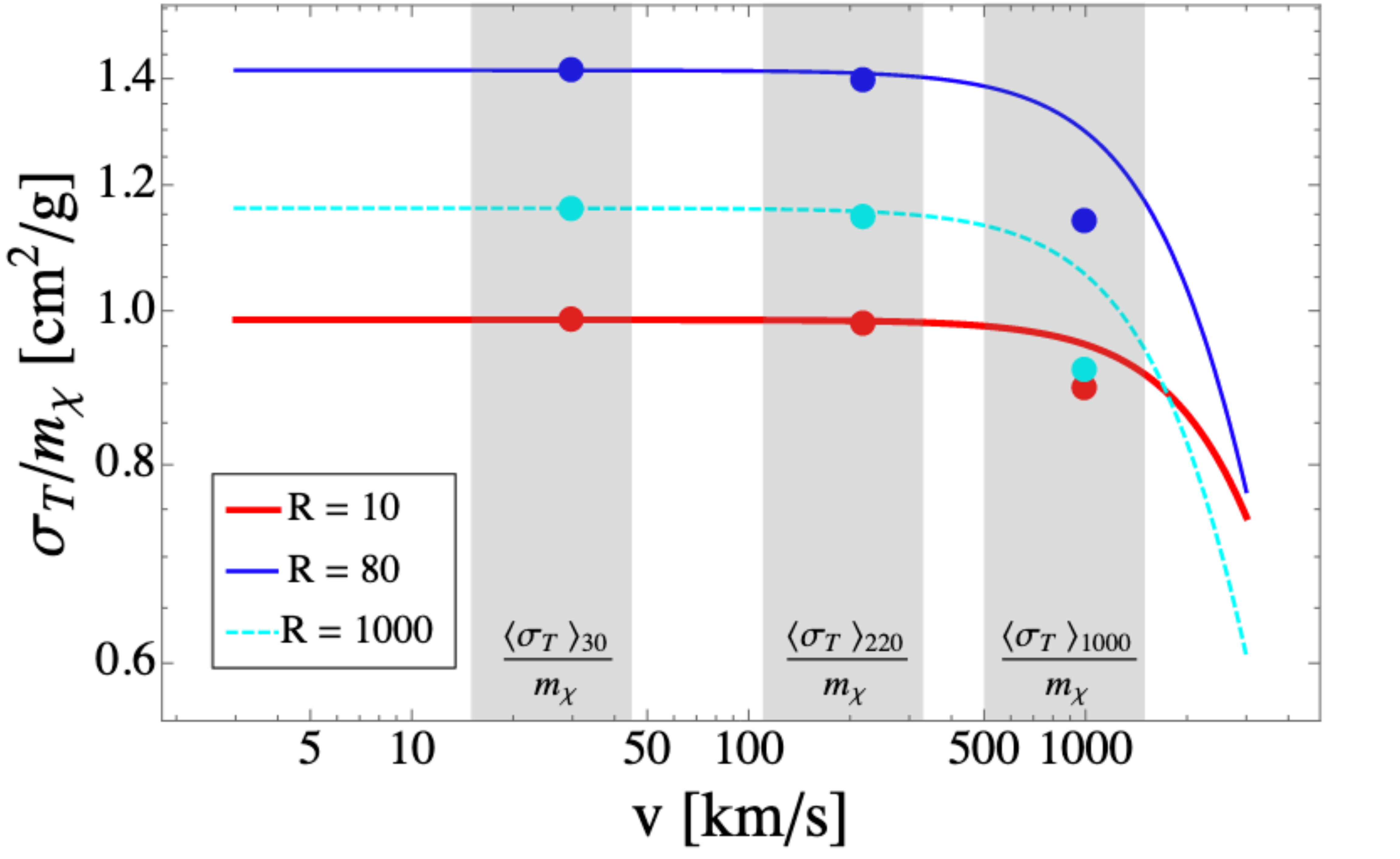
The presence of non-luminous matter in the halos of our own and othe galaxies is strongly indicated by observation [1]. Thus far, the most prominent elementary particle candidates for this dark matter have been weakly interacting (e.g. neutrinos, photinos, axions) [2]. This automatically makes the dark matter dissipationless, and hence allows the halo configuration. Much effort has been spent on designing experiments to detect the flux of such weakly interacting particles at the earth. The low counting rates make such experiments difficult, although for the first time experimental limits have been placed [3].

It is interesting to note that the criterion for a dissipationless halo is rather mild. Suppose the dark matter particles have a mass m,

Typical elastic cross-sections depend on velocity



Scenarios with Yukawa interactions



Scenarios with dark atoms

Examples plotted in 1512.05344 (Cyr-Racine et al)

Summary of constraints ~2023

	V (km/s)	$\frac{\sigma_T}{m_{\rm DM}}$ (cm²/g)	**Evidence for non-zero interactions?**
Cluster scales	1000-1500	$< 0.35, < 0.13$	Some claims of weak evidence
Galactic scales	200	> 3	Maybe
Dwarf/satellite galaxy scales	5-20	> 10	Maybe

Adhikari et al, 2207.10638 (see also references cited)

An older summary
1508.03339

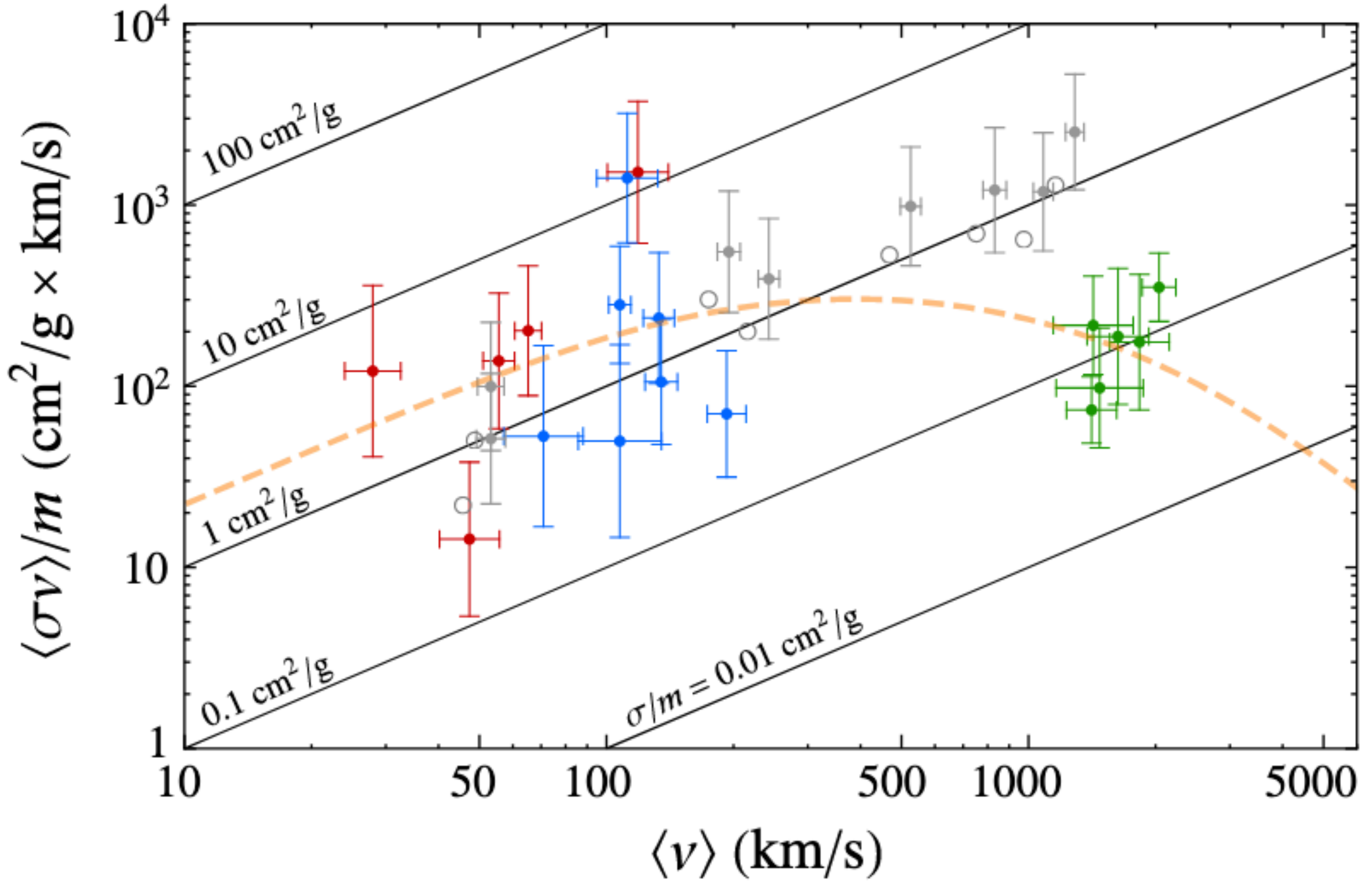


FIG. 1. Self-interaction cross section measured from astrophysical data, given as the velocity-weighted cross section per unit mass as a function of mean collision velocity. Data include dwarfs (red), LSB galaxies (blue), and clusters (green), as well as halos from SIDM N-body simulations with $\sigma/m = 1$ cm^2/g (gray). Diagonal lines are contours of constant σ/m and the dashed curve is the velocity-dependent cross section from our best-fit dark photon model (Sec. V).

But claiming evidence is tricky….

Use strong lensing to obtain dark matter density profile

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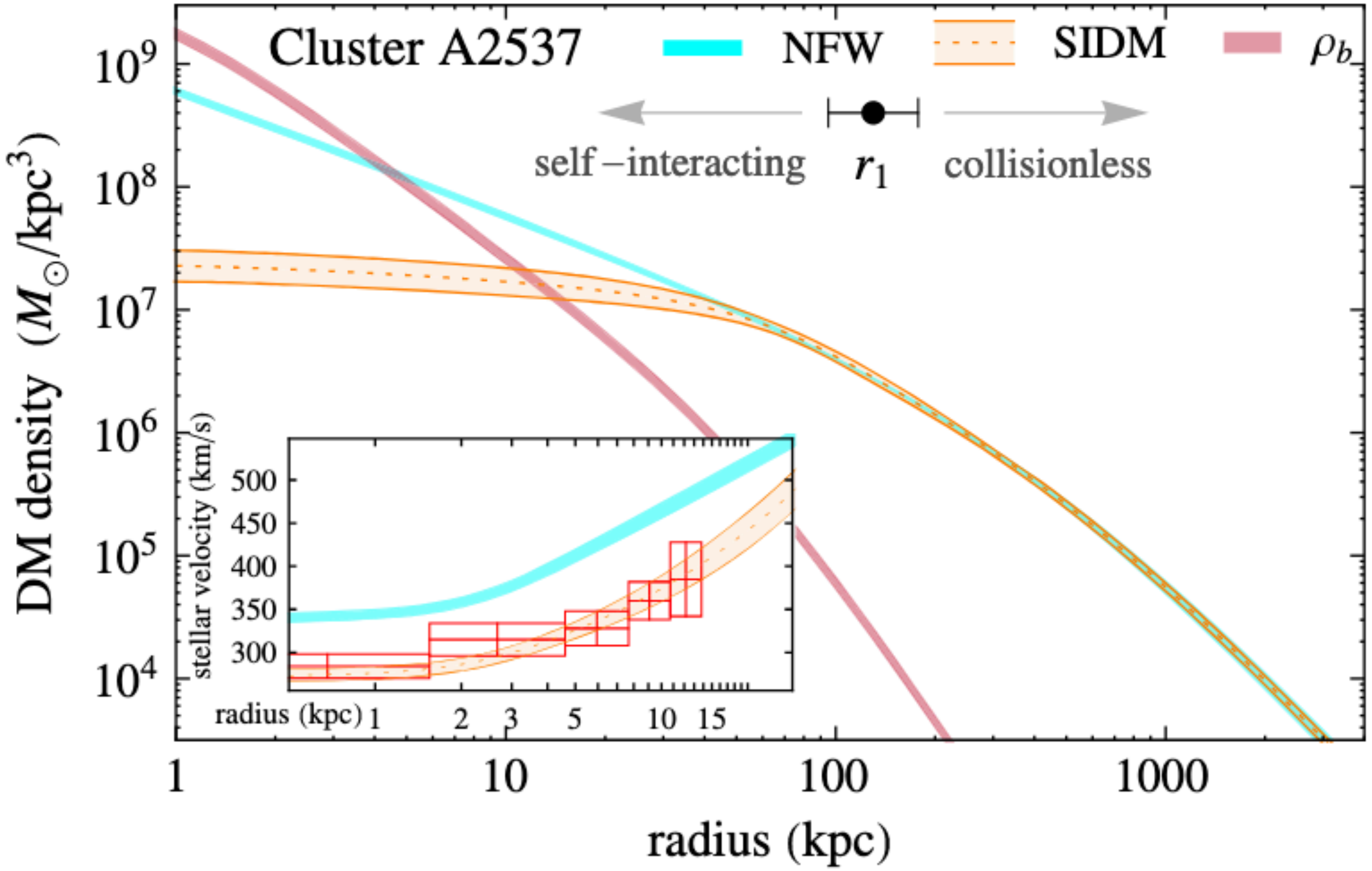

Compare to simulations of different models

Figure from Khaplinghat, Tulin, Yu, 1508.03339

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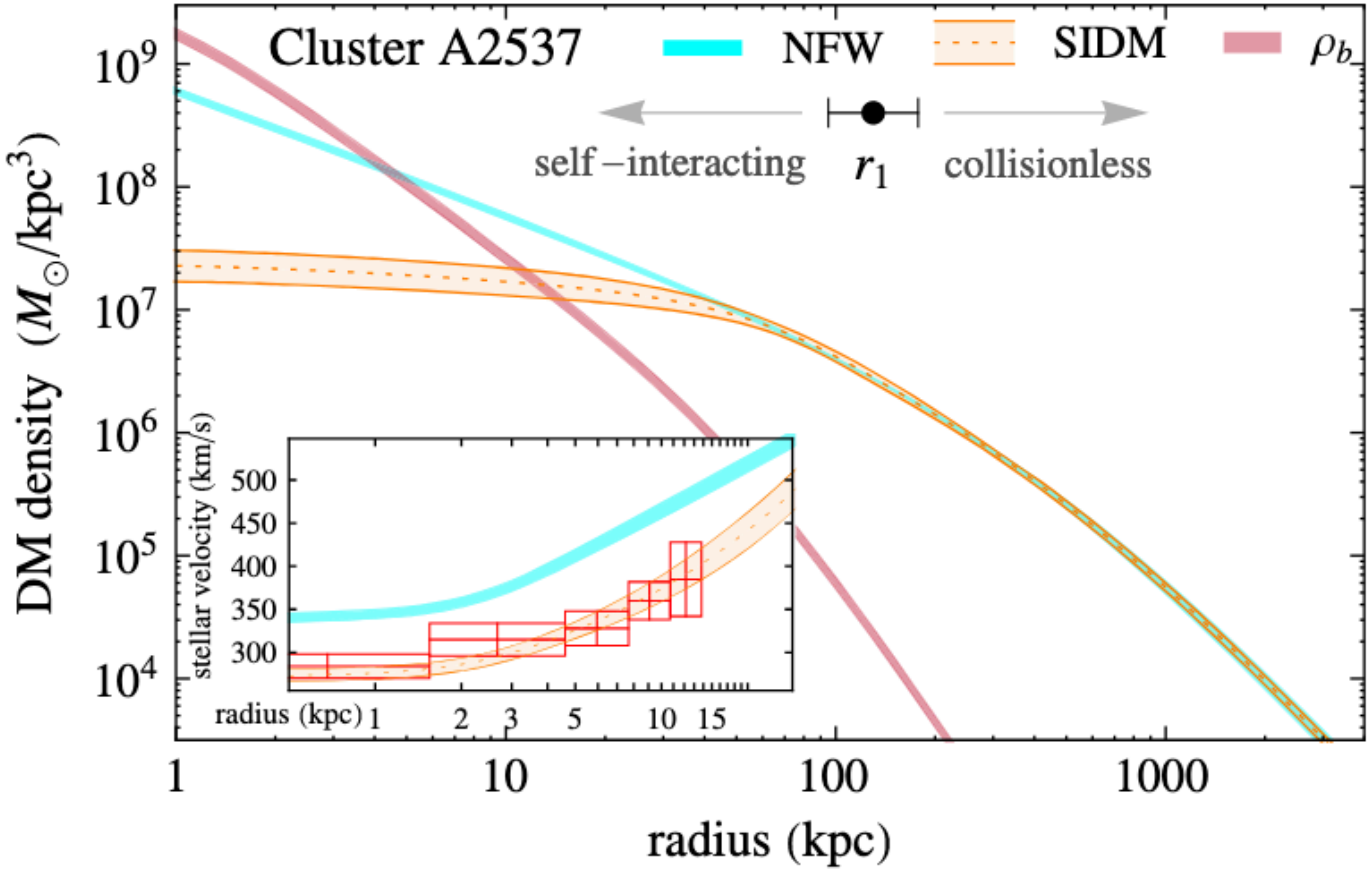

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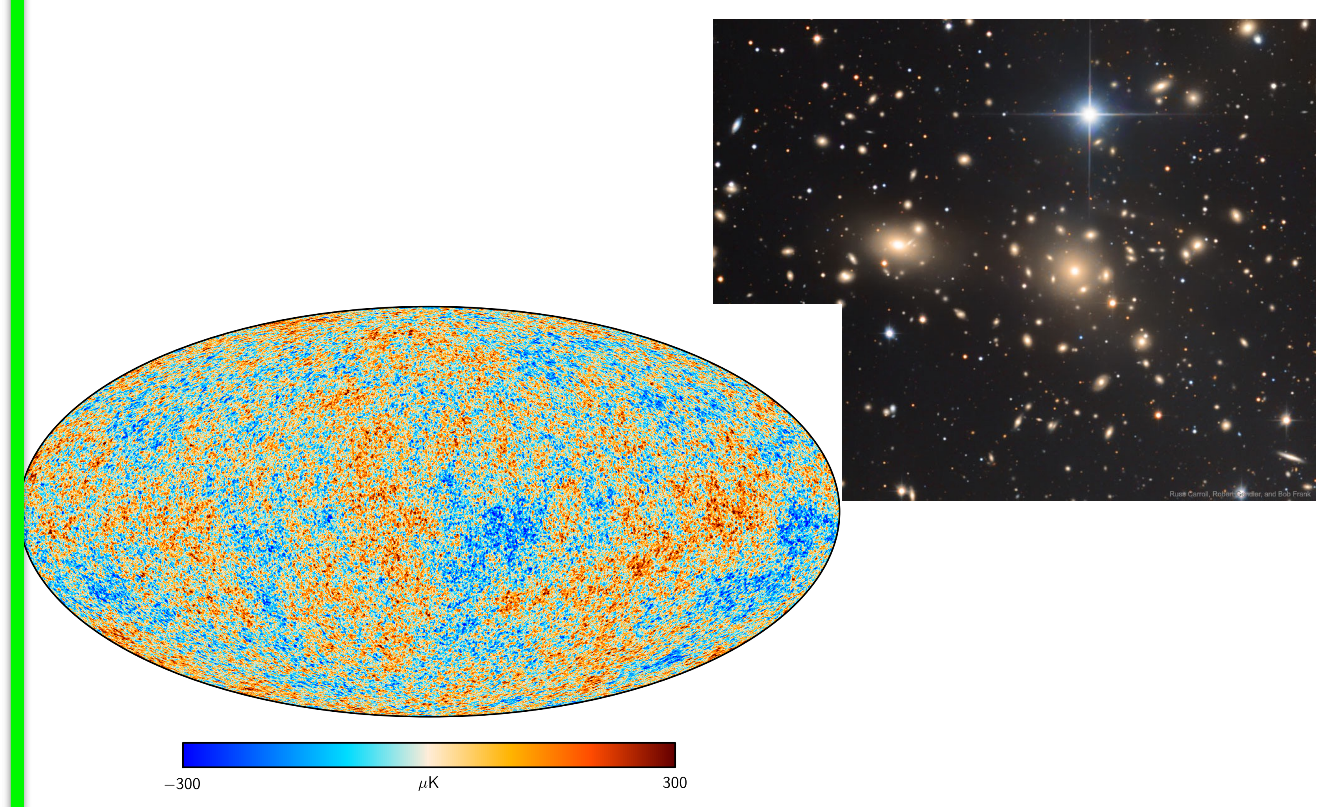
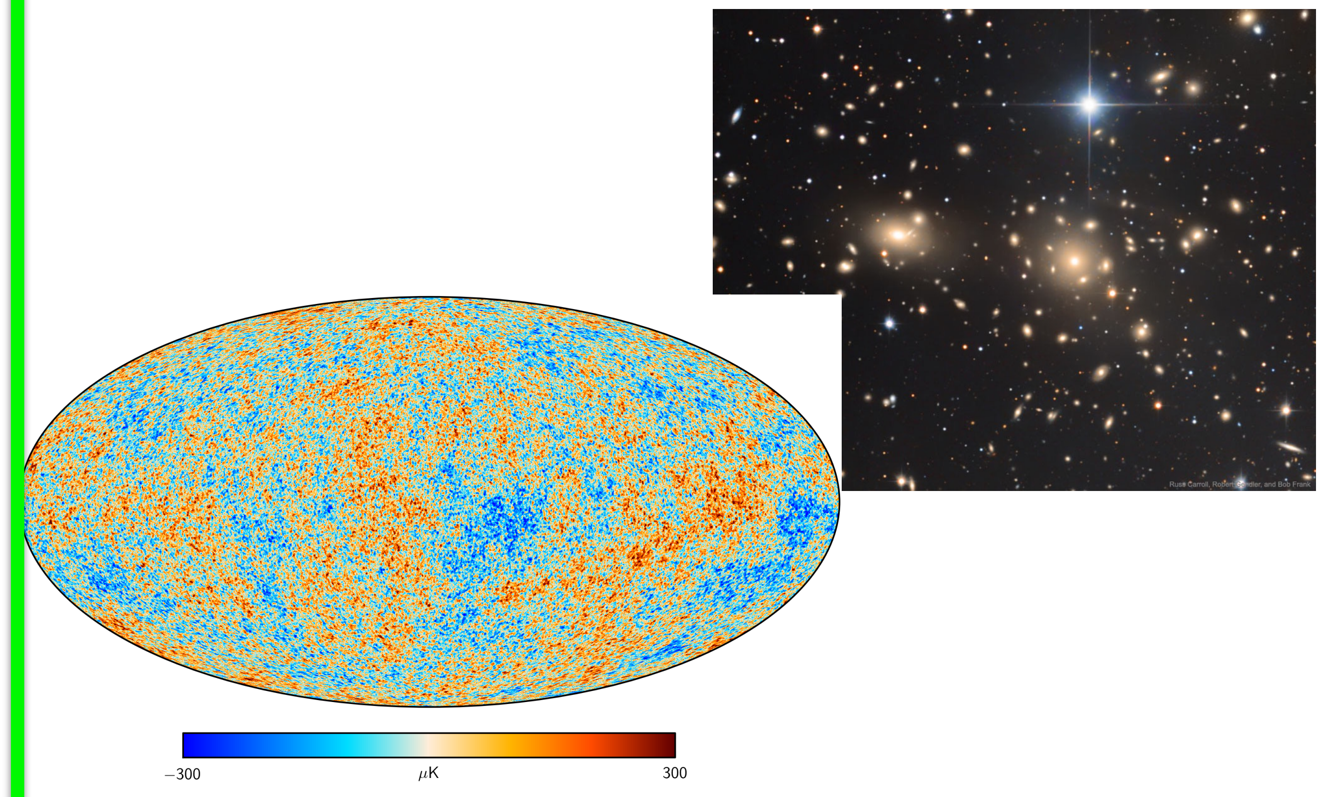
We rely on large simulations to understand structure formation

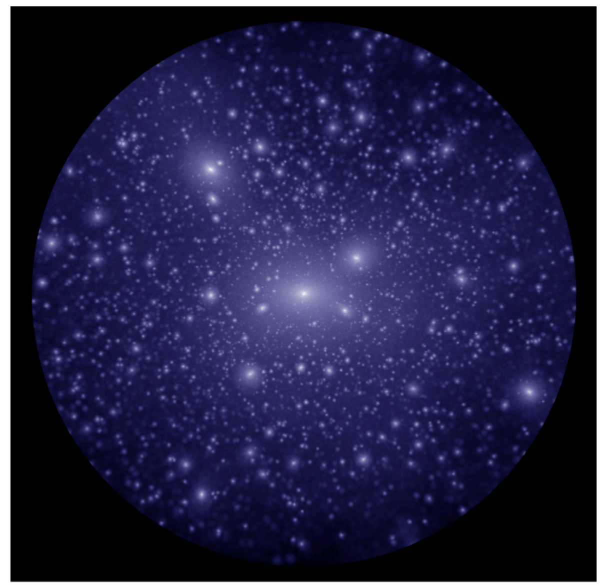


10^4 Mpc 1 Mpc 1 kpc 1 km

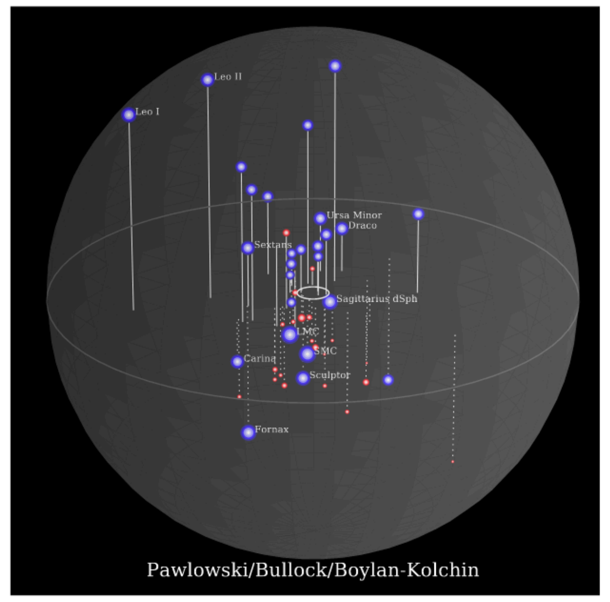
Large-Scale structure

Linear physics, clean probes





Simulations vs.
Observations



(Bullock, Boylan-Kolchin, 1707.04256)

10^4 Mpc — 1 Mpc — 1 kpc — 1 km

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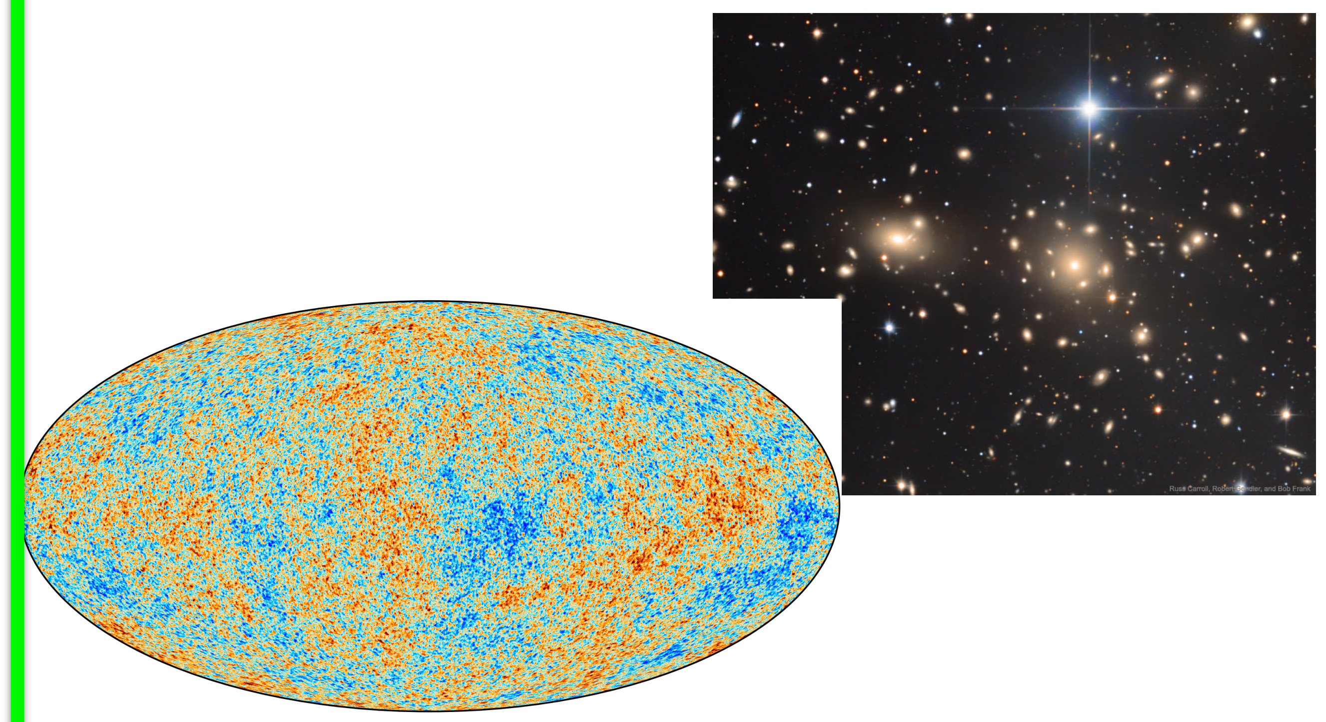
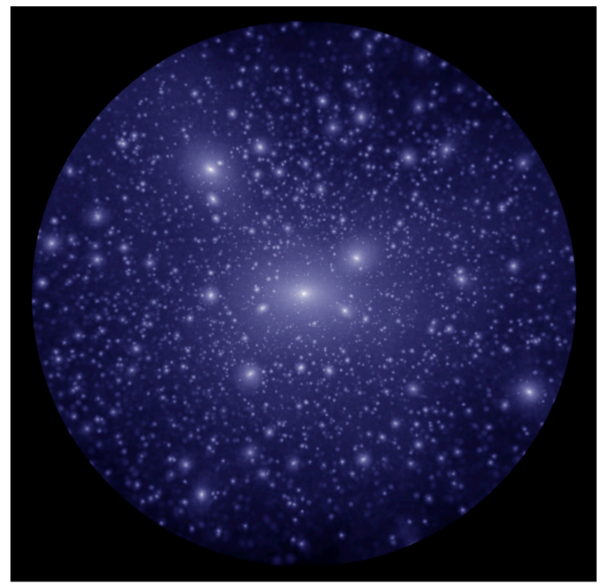
Linear physics, clean probes

Mid-Scale structure

Many complexities from visible matter.

Hints that more complex dark matter is better.





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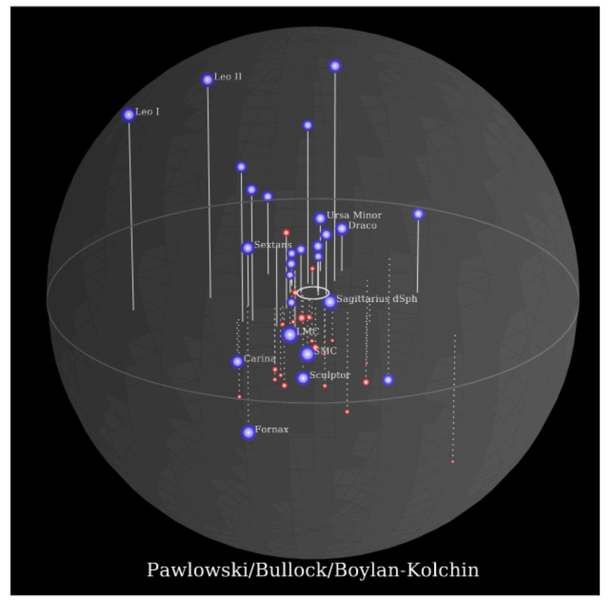

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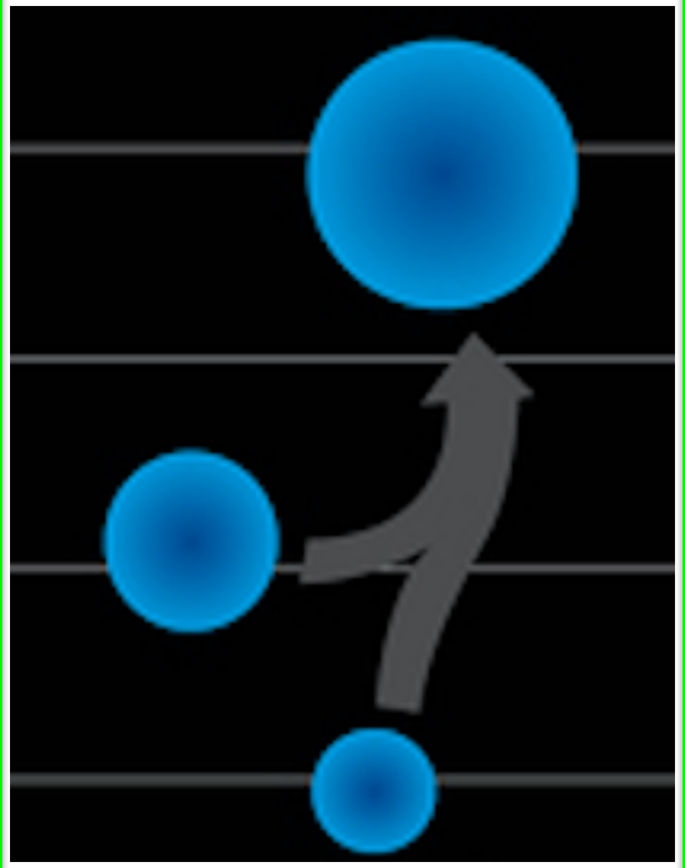


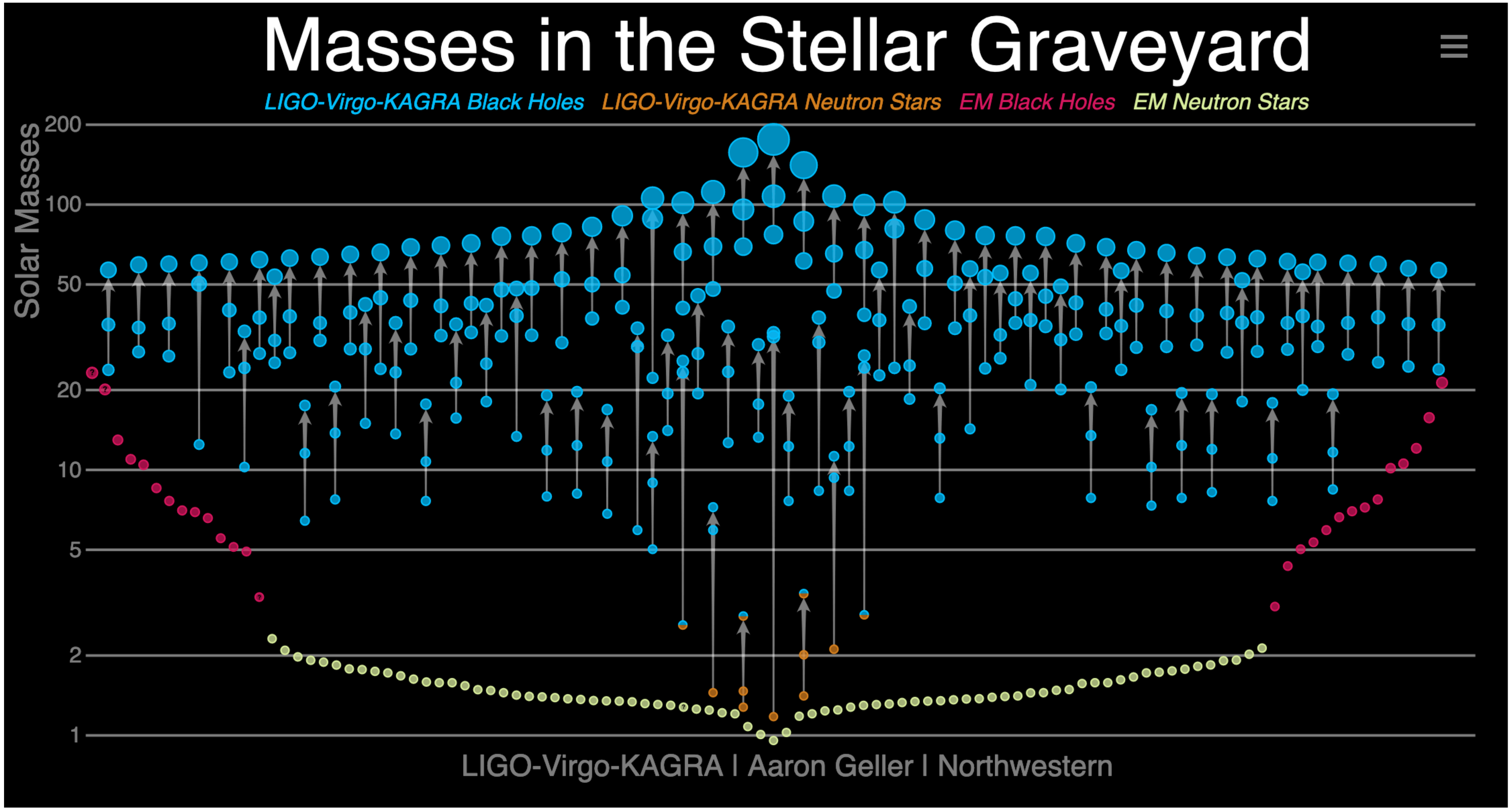
10^4 Mpc   1 Mpc   1 kpc   1 km

Large-Scale structure
Linear physics, clean probes

Mid-Scale structure
Many complexities from visible matter.
Hints that more complex dark matter is better.

Novel Compact objects
Existence is a clean probe

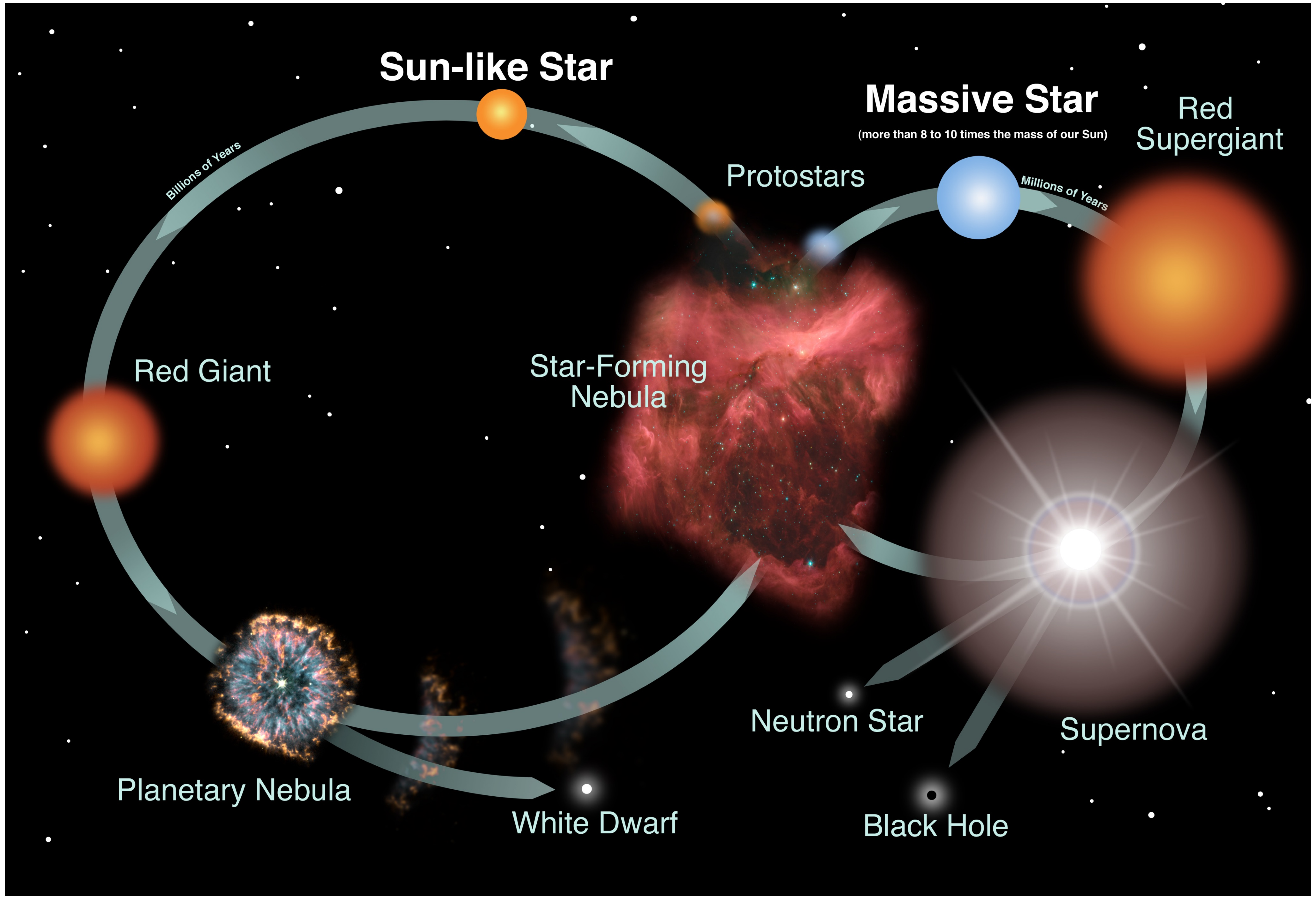
The context today



LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

+O4!

Ultra-compact objects in the standard model

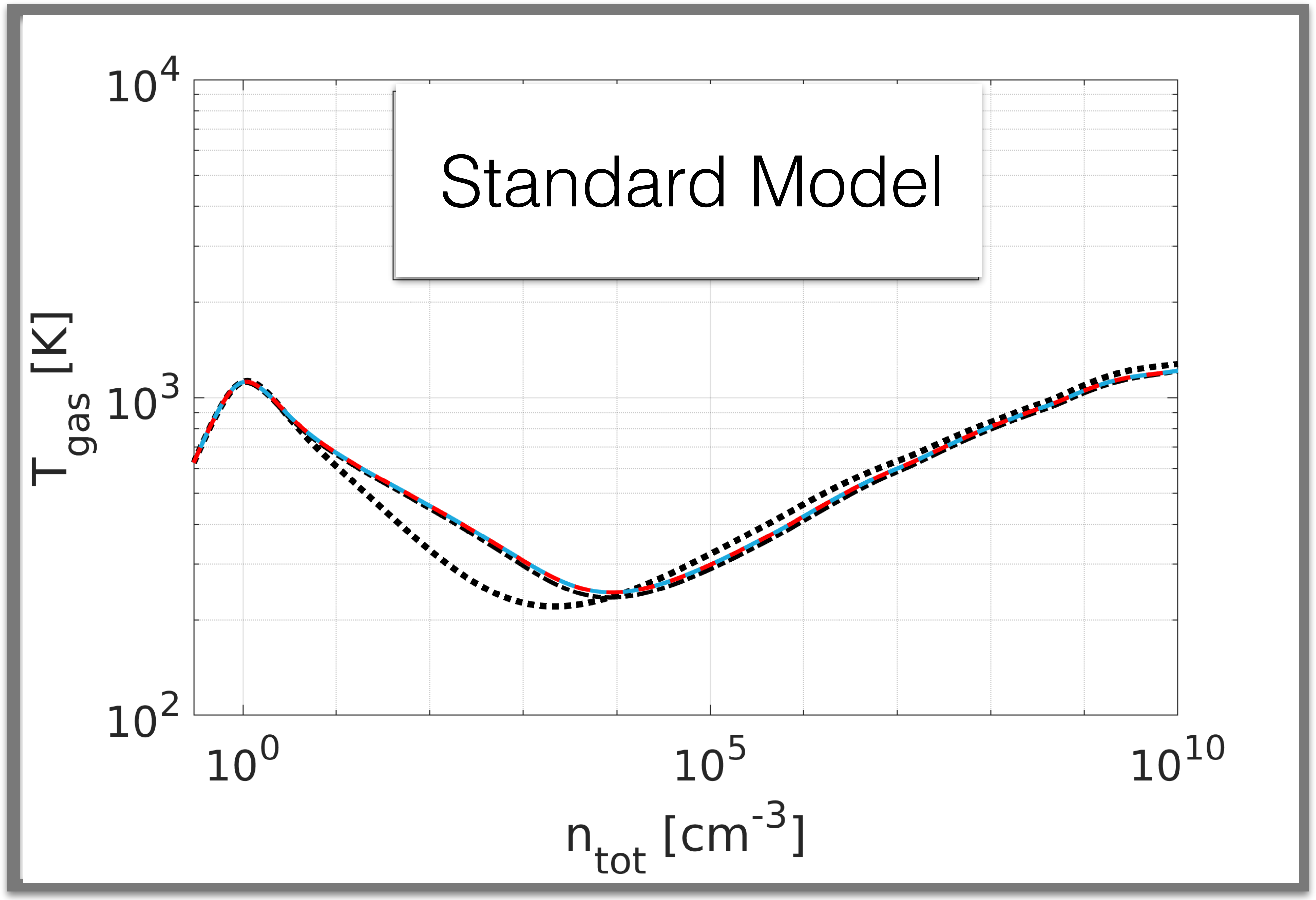


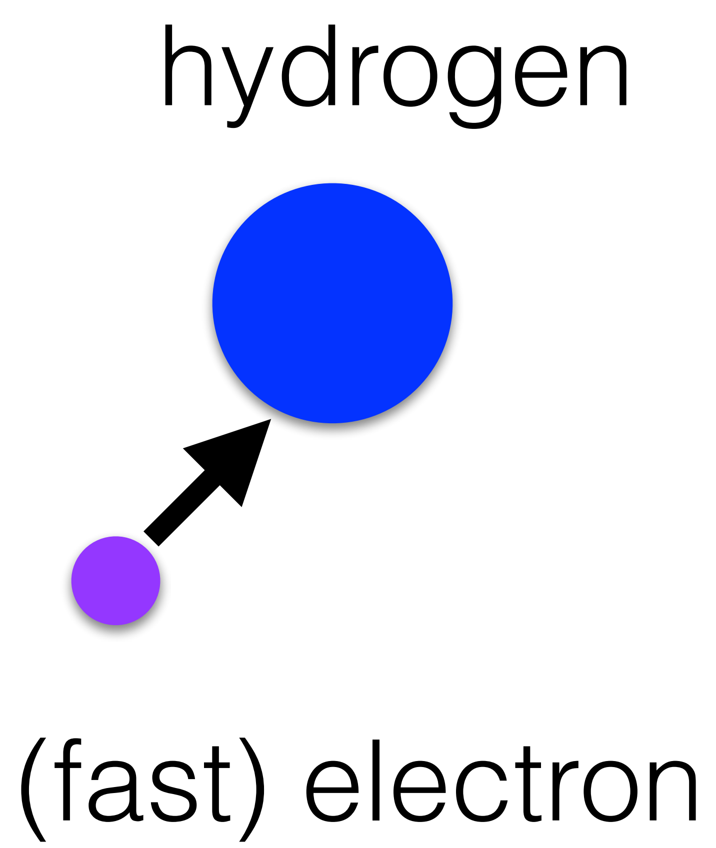
NASA and Night Sky Network

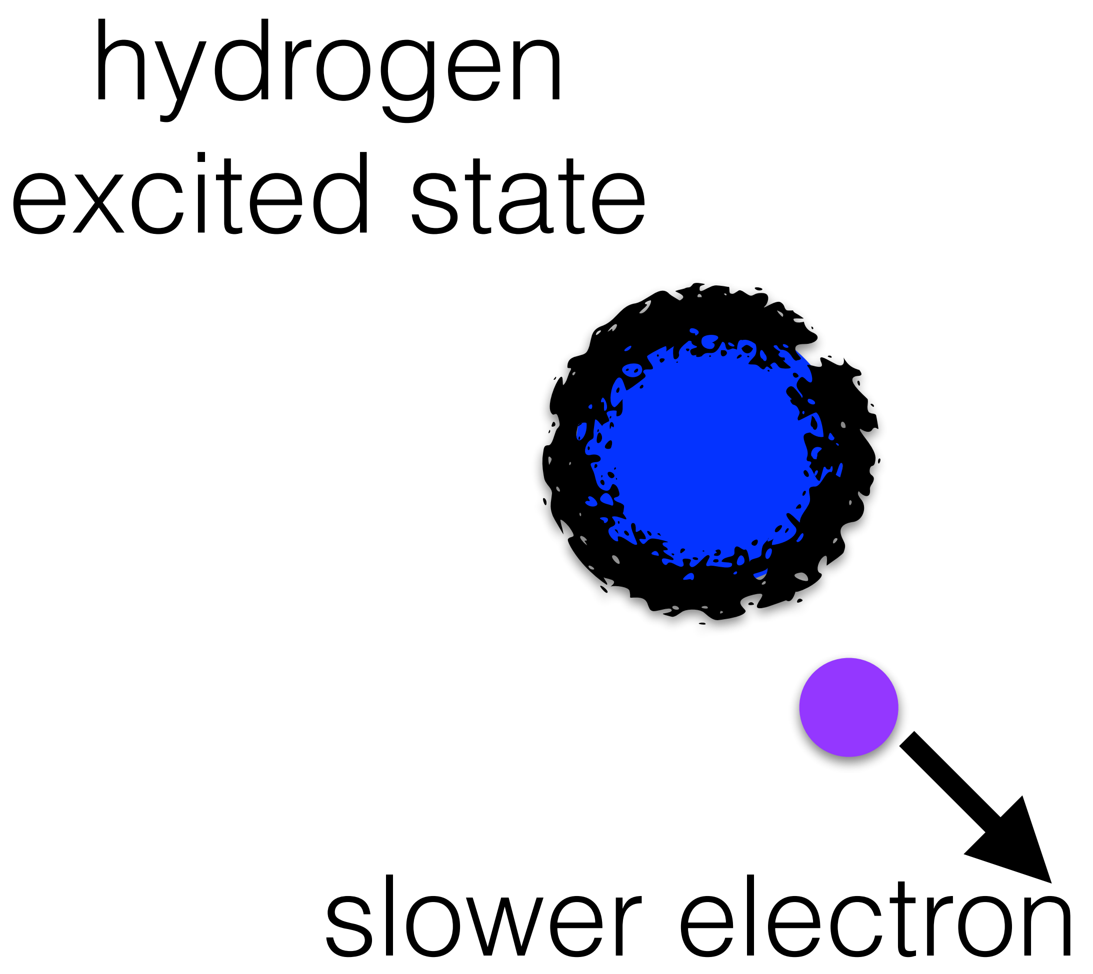
Why?

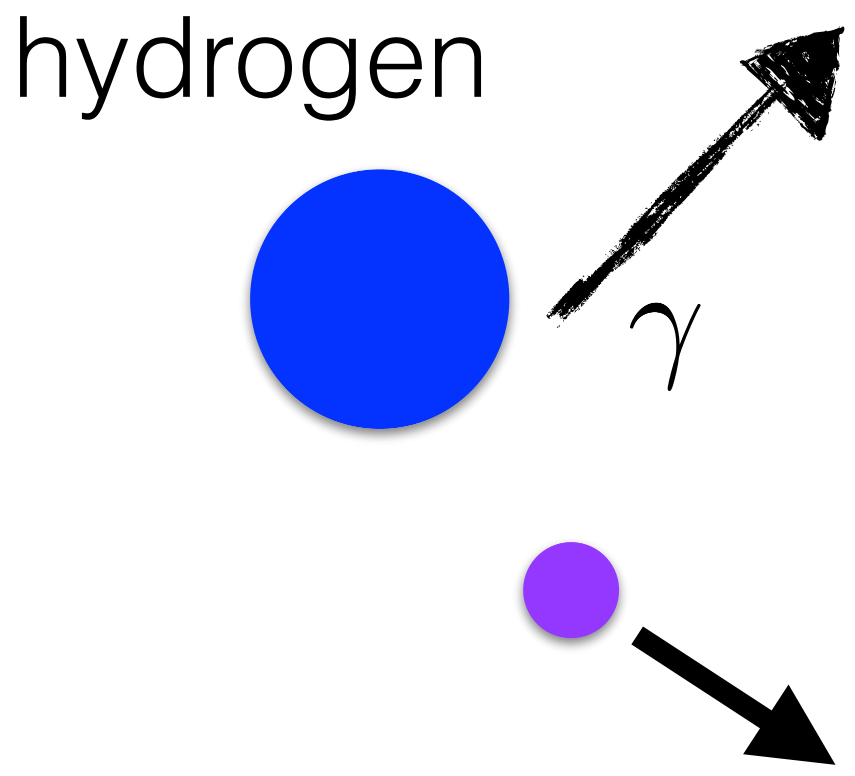
<u>Chemistry</u>

Processes that cool the gas



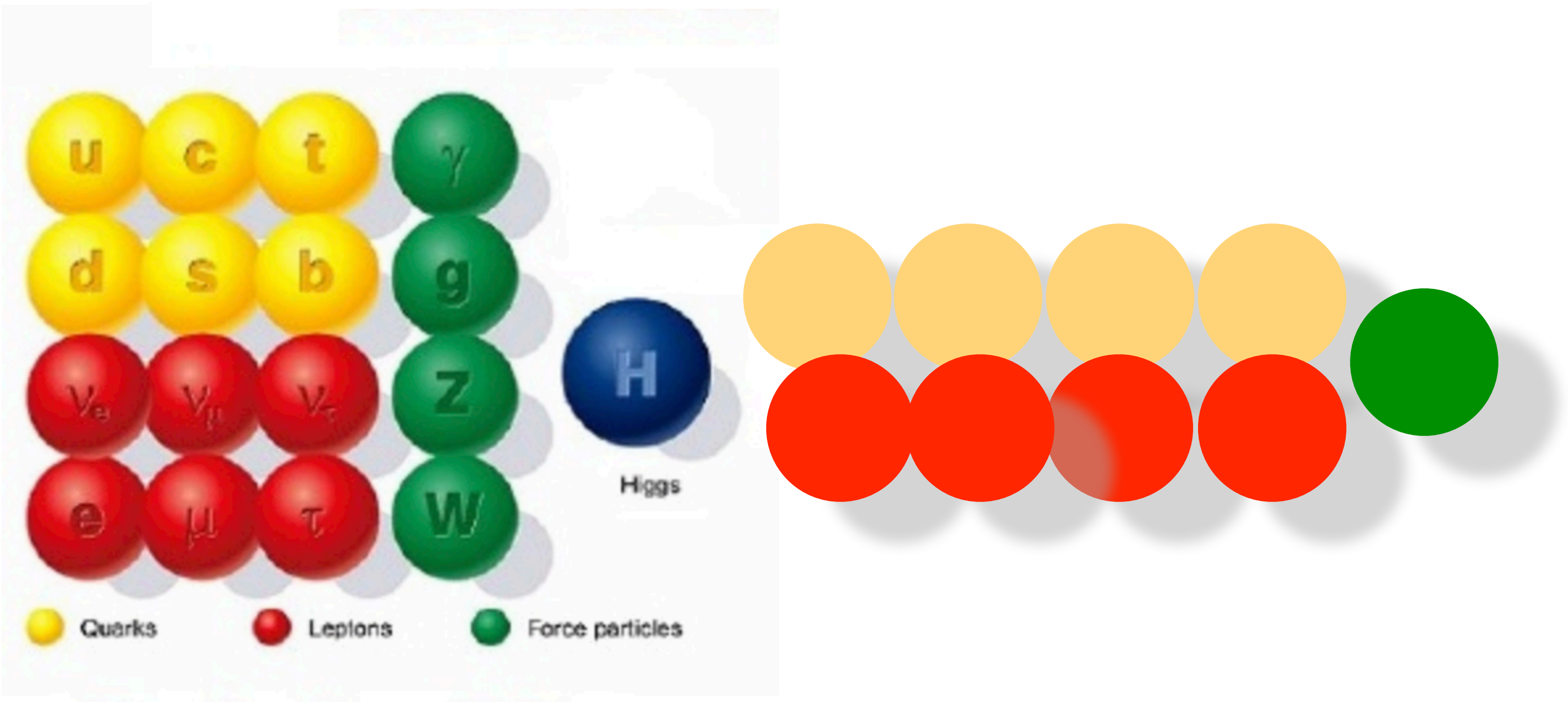






Shandera, TRISEP 2024

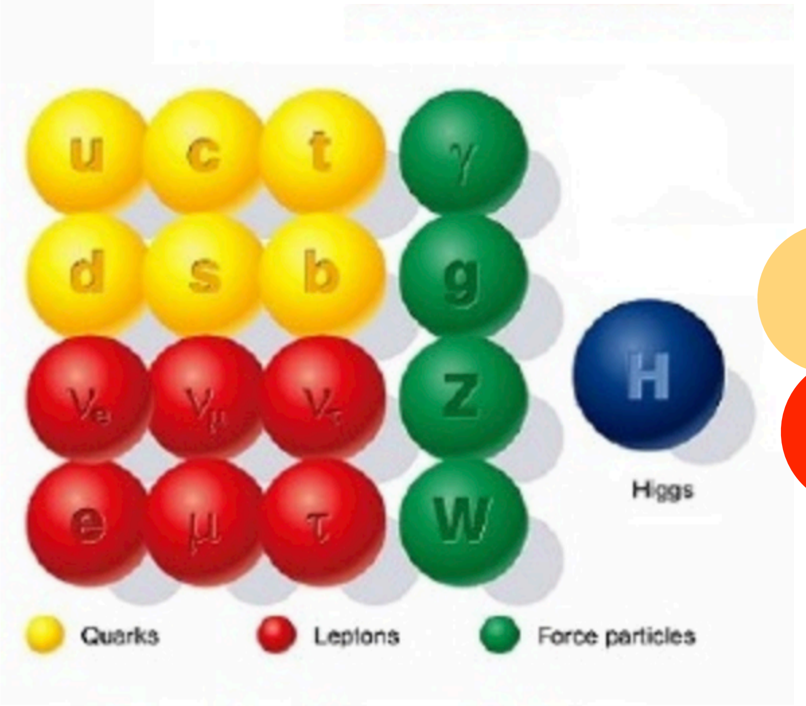
If dark matter has a rich spectrum of particles…



Standard particles

Dark particles
Includes light particles

Then it likely has a rich spectrum of small scale structures…



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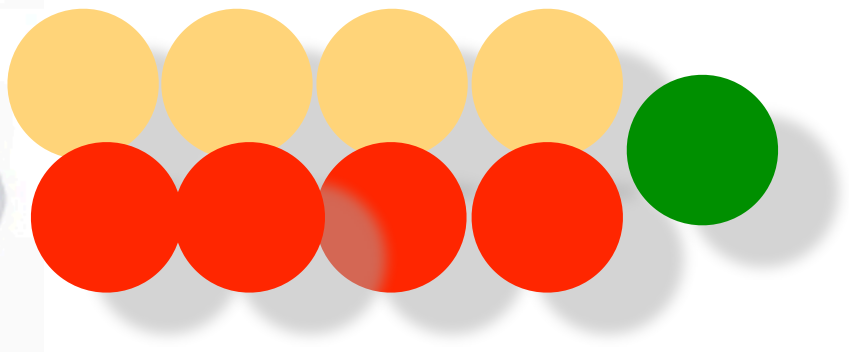

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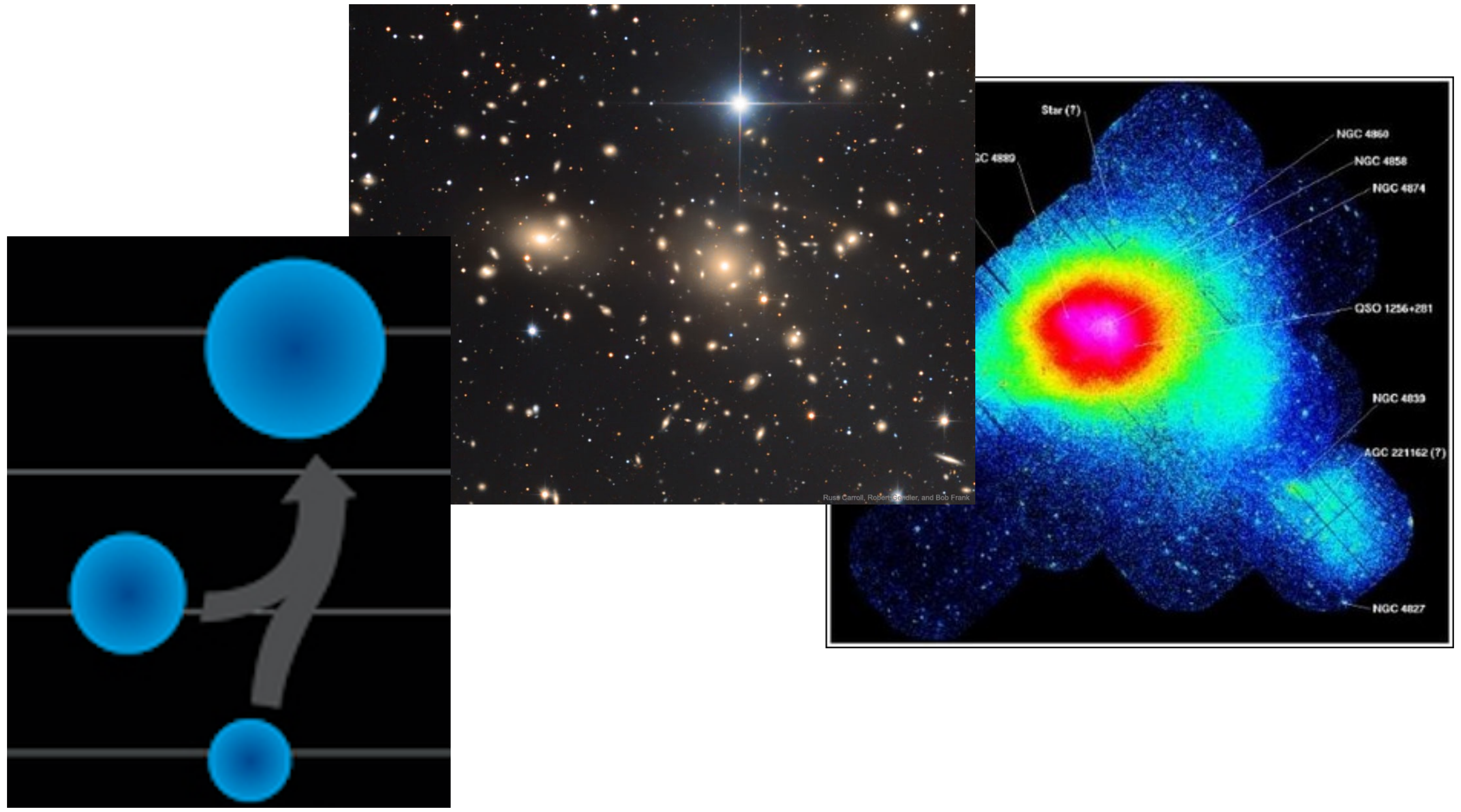

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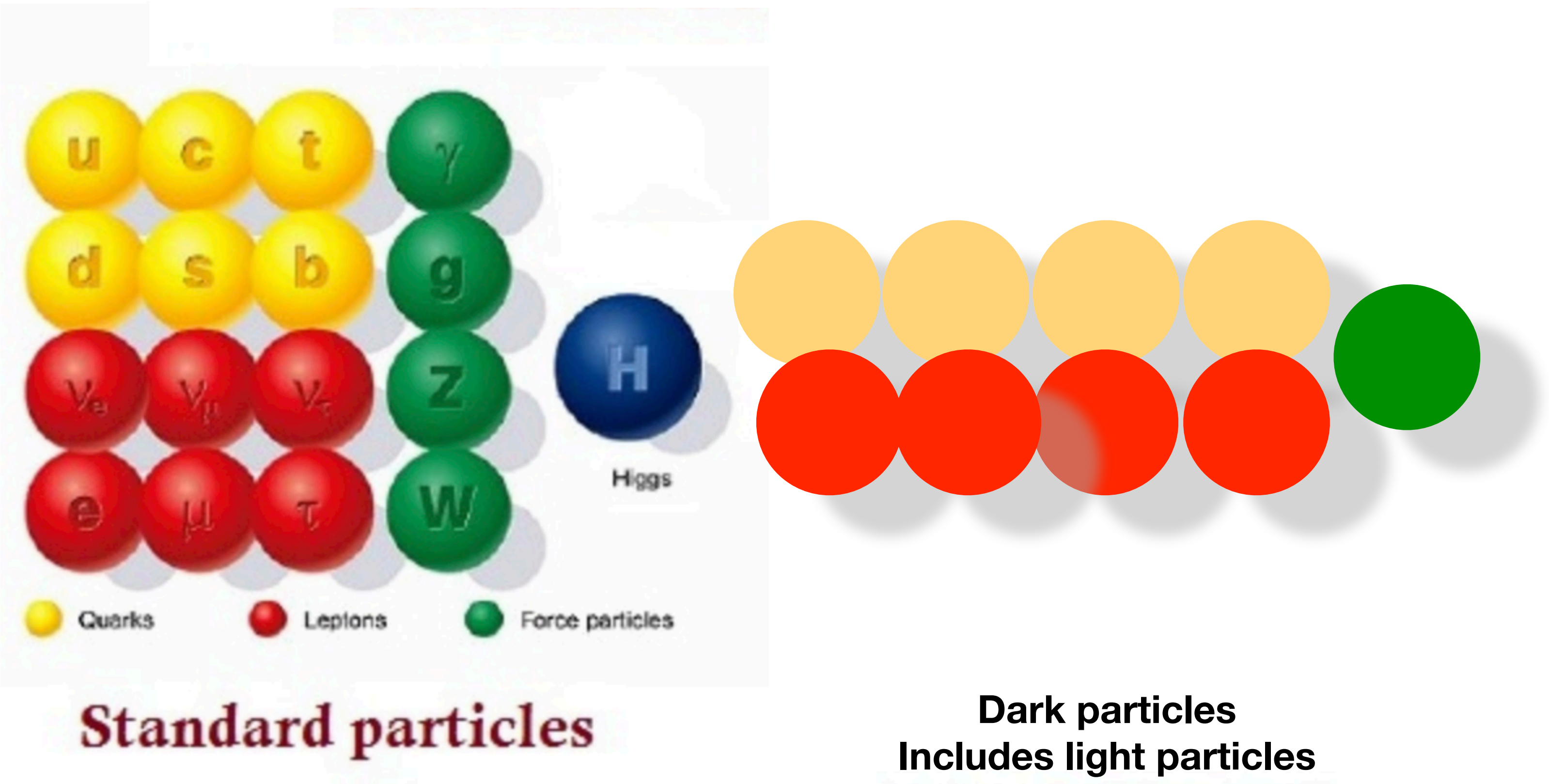

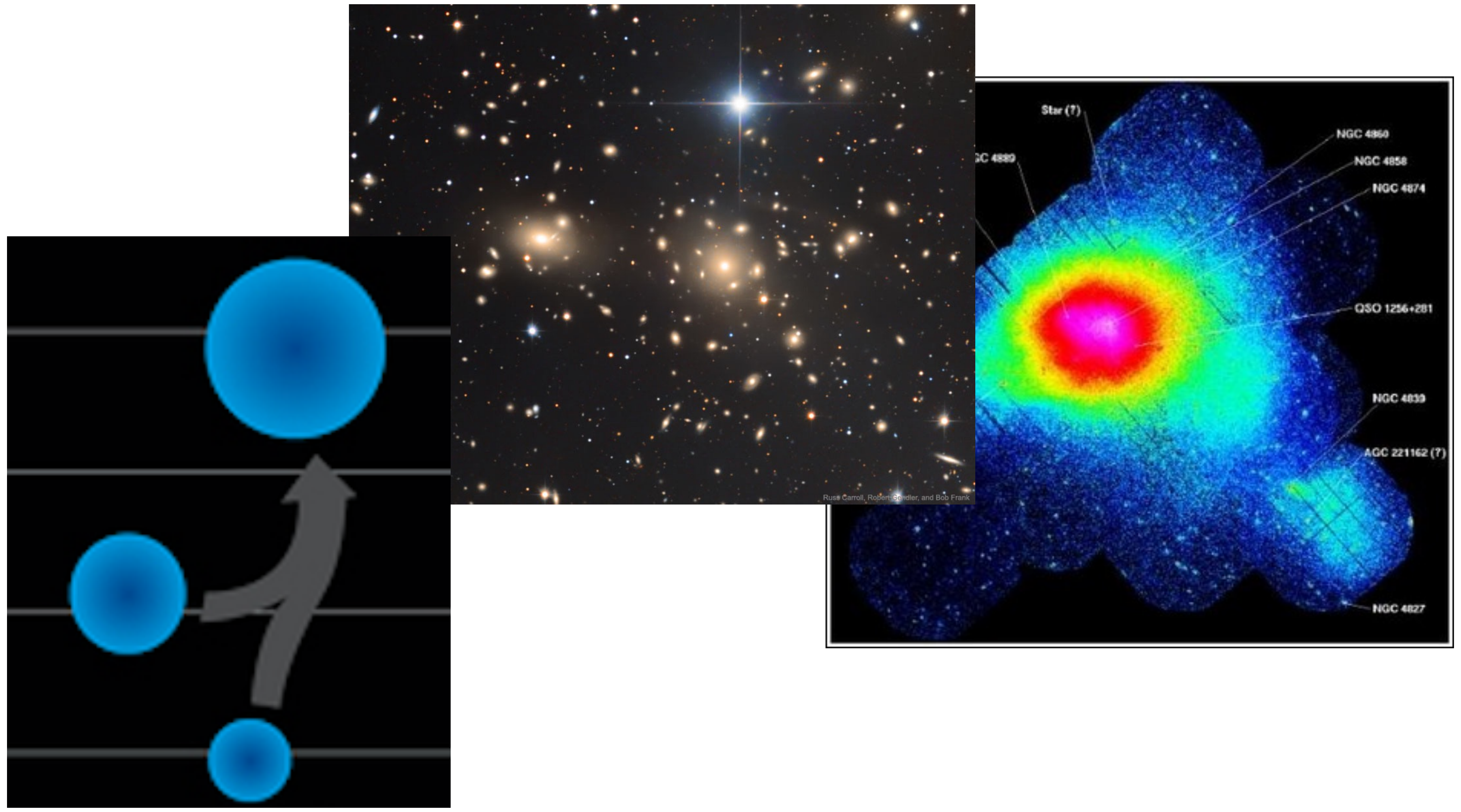

Details of this structure constrain the particle spectrum …

(See M. Buckley, A. Peter 1712.06615 for a nice review)

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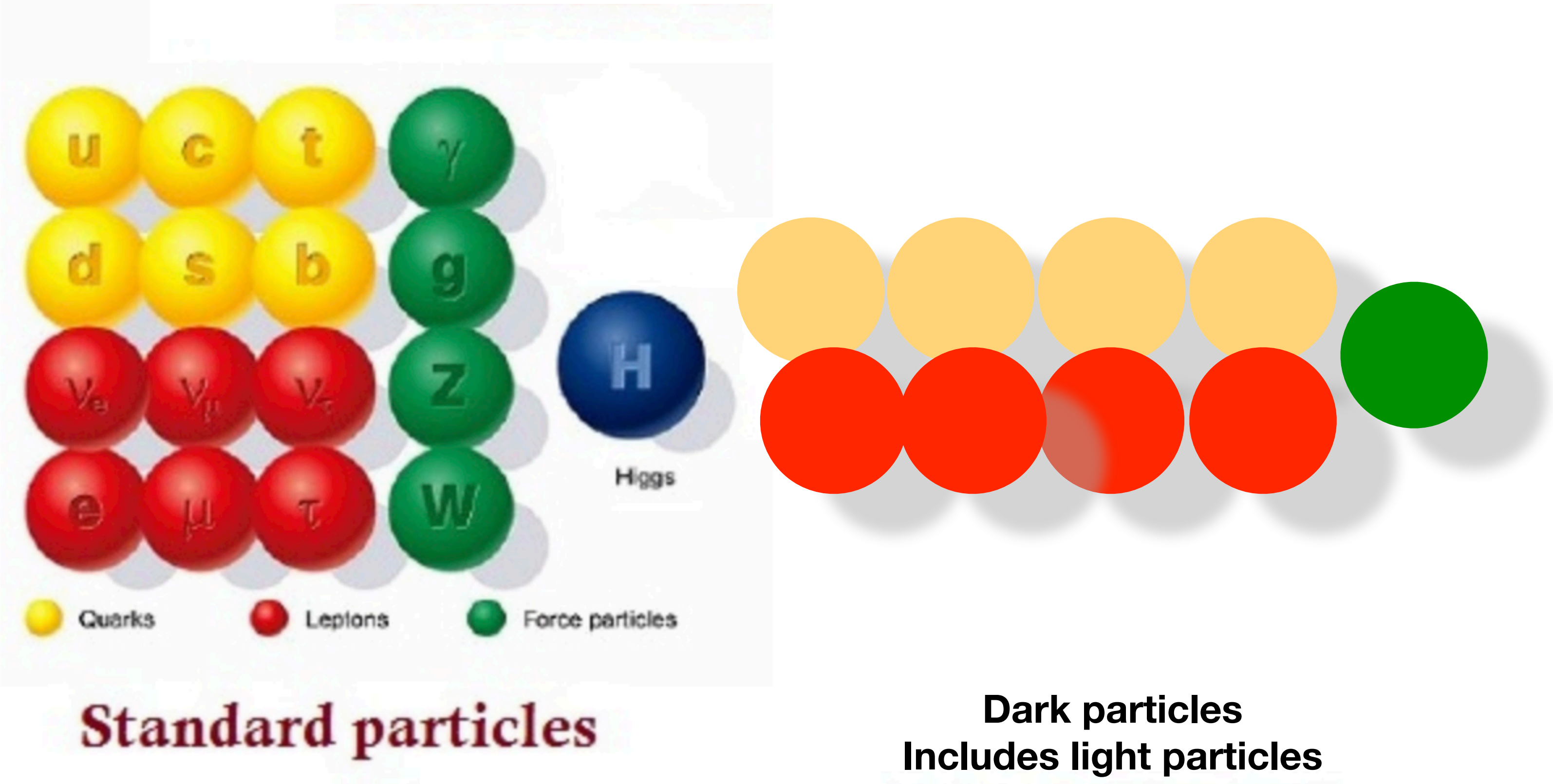

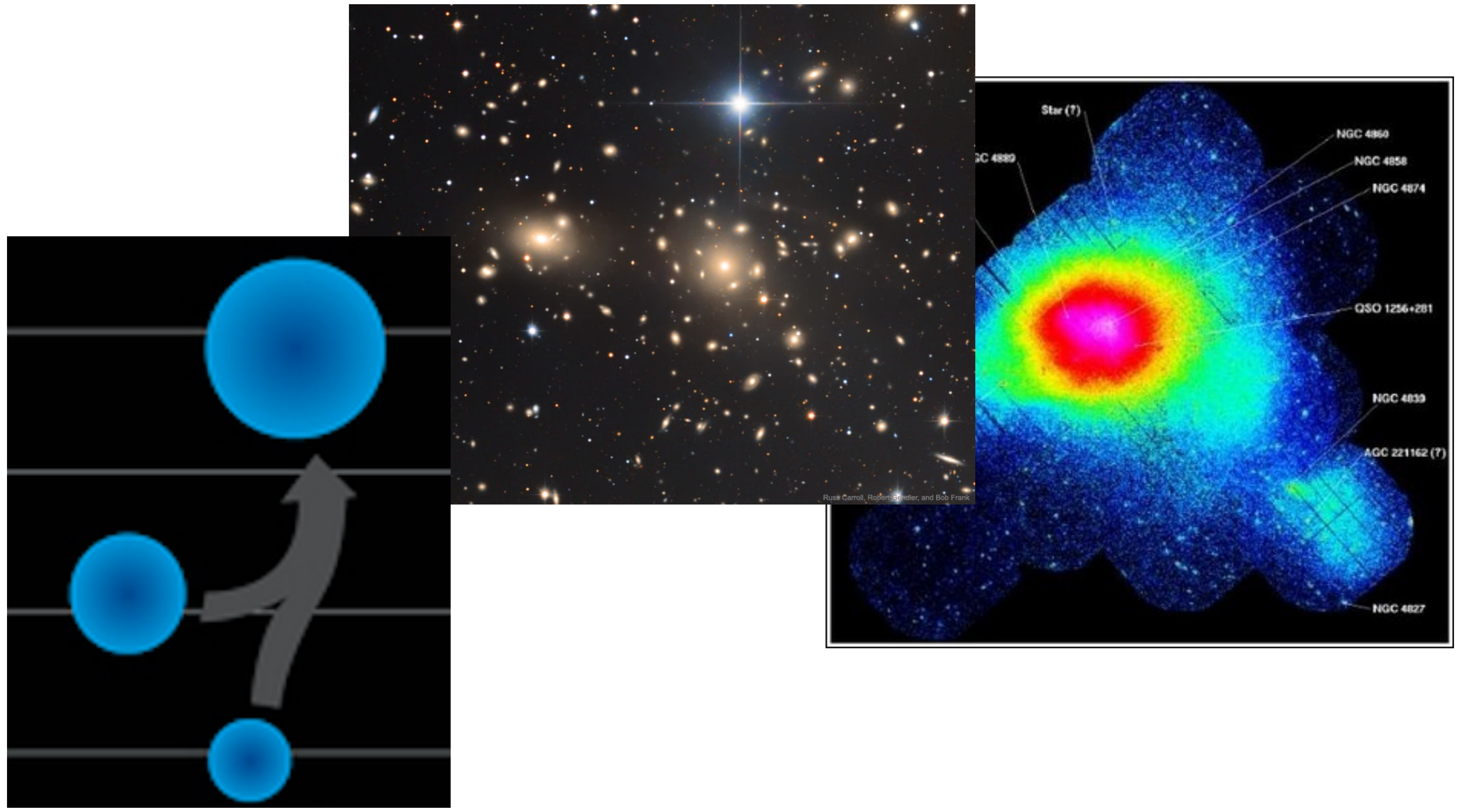

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…even if there is no non-gravitational interaction between dark matter and the standard model

(Simple) complex dark matter

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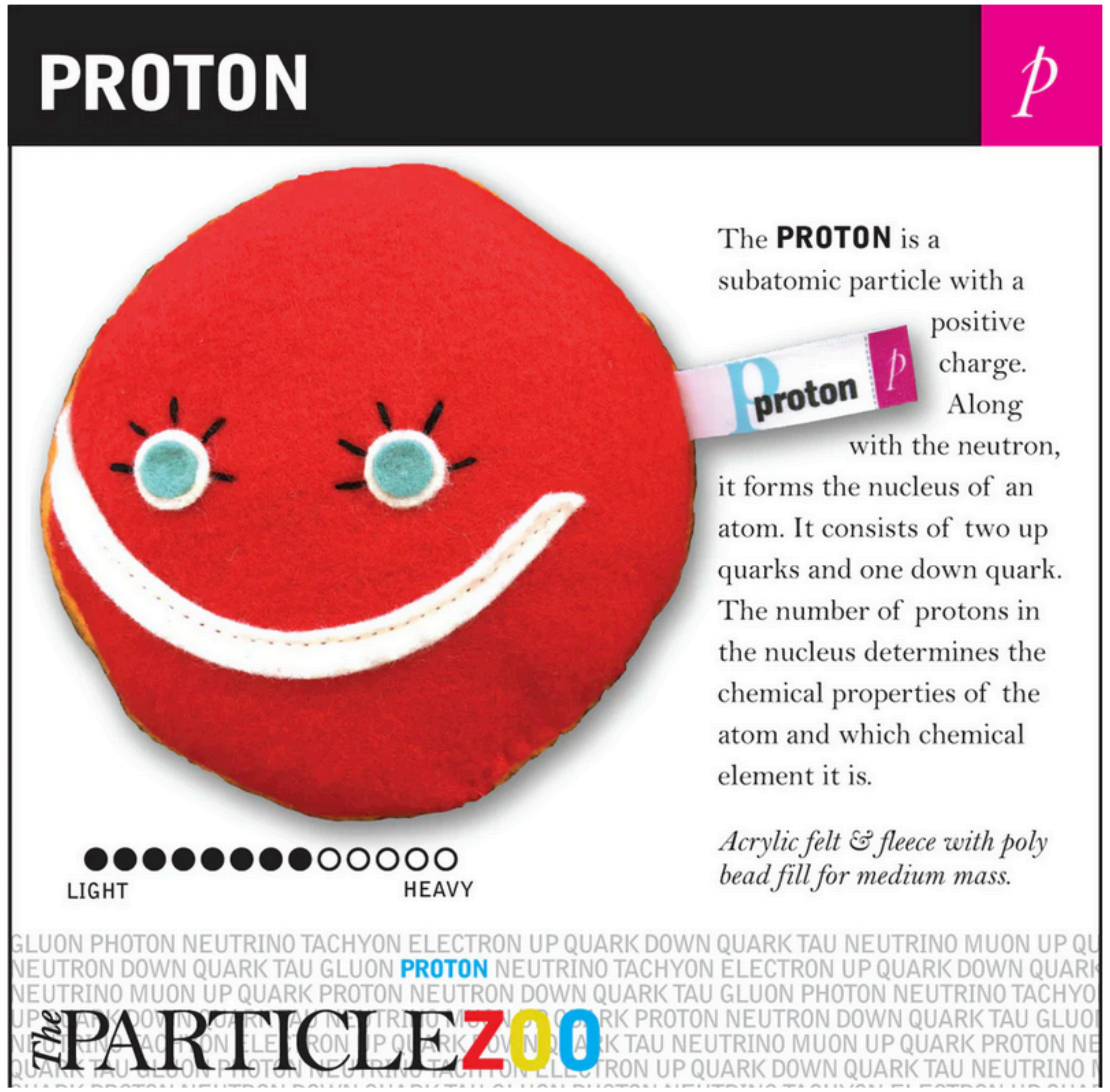
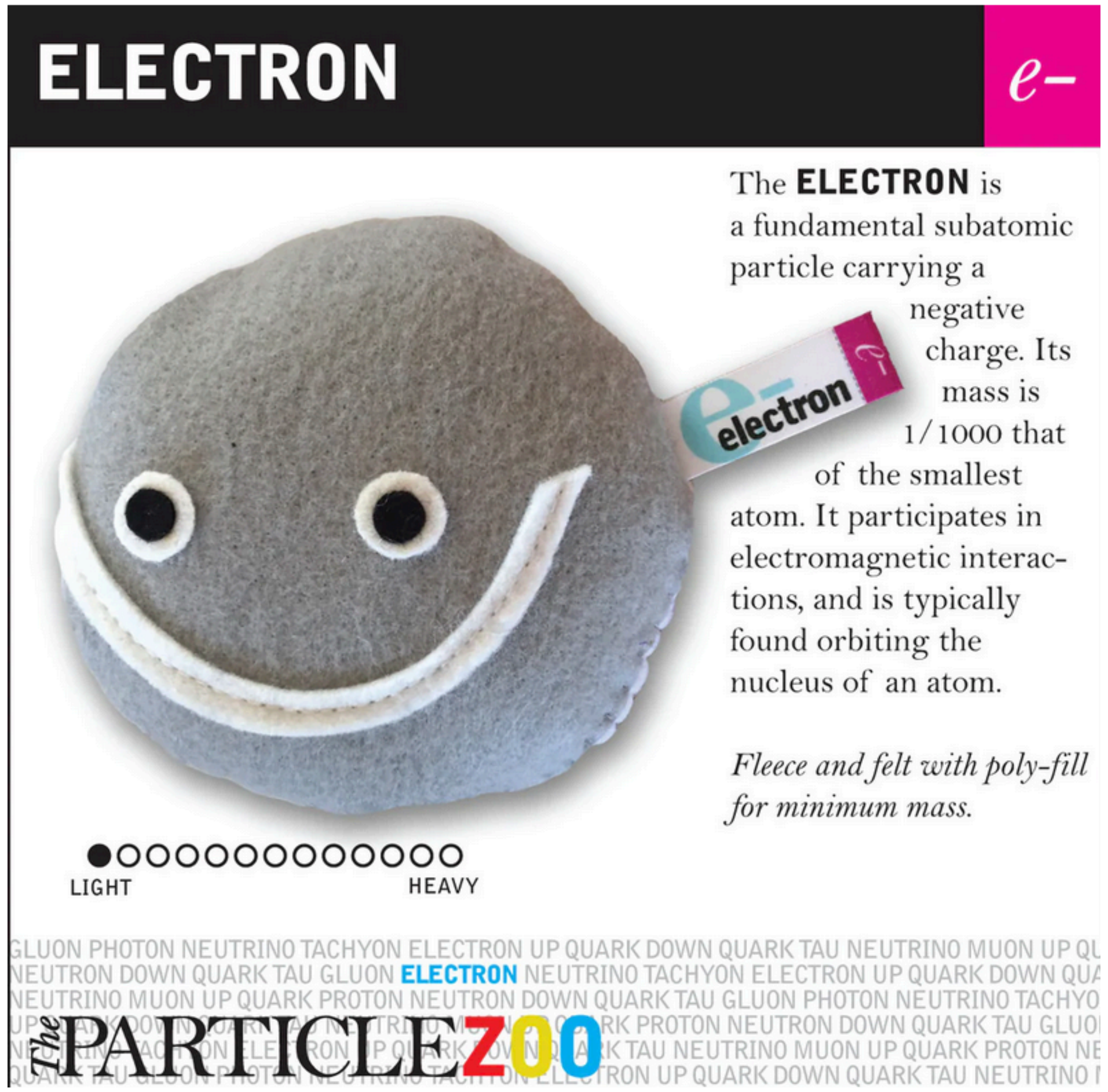
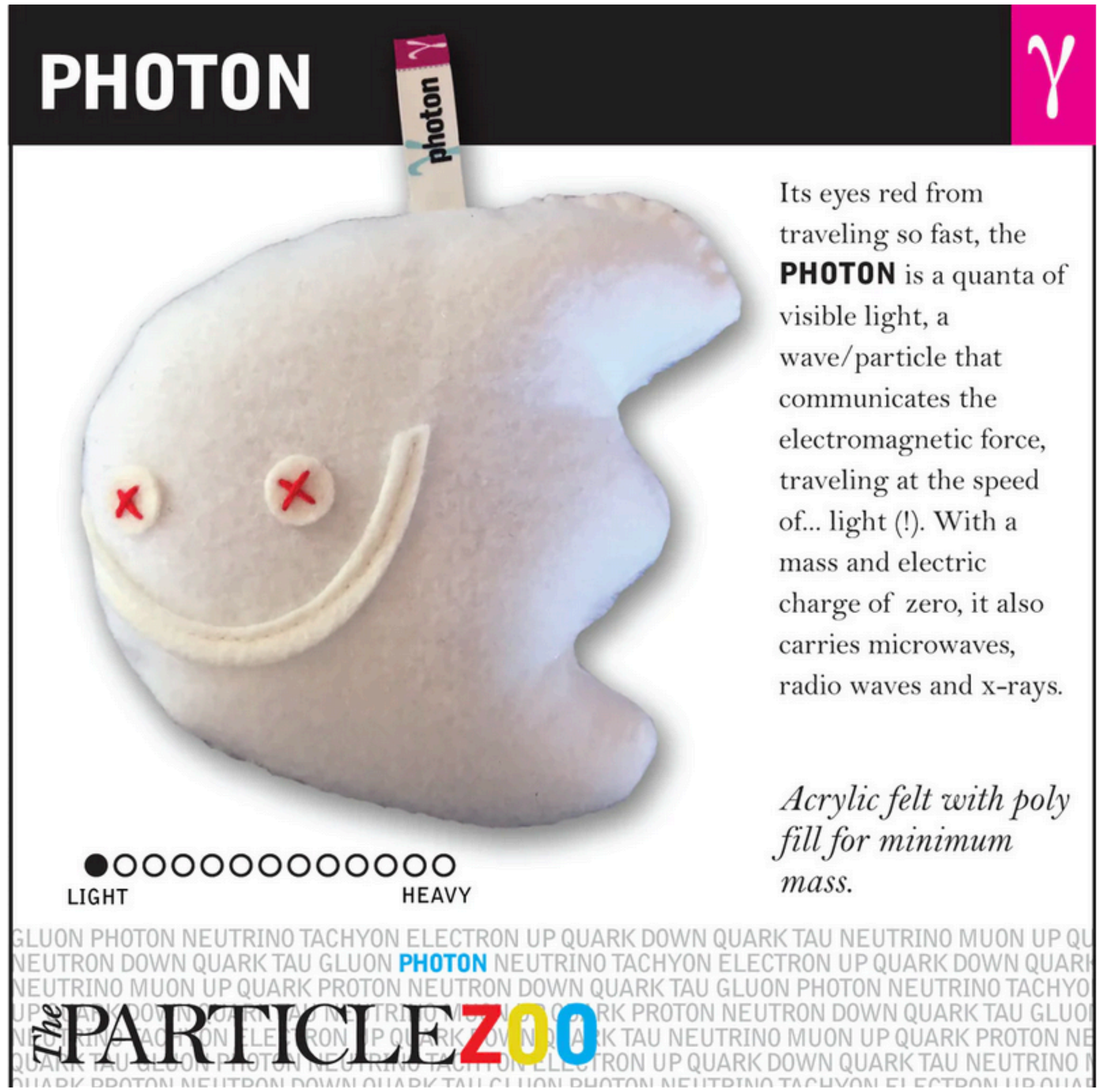
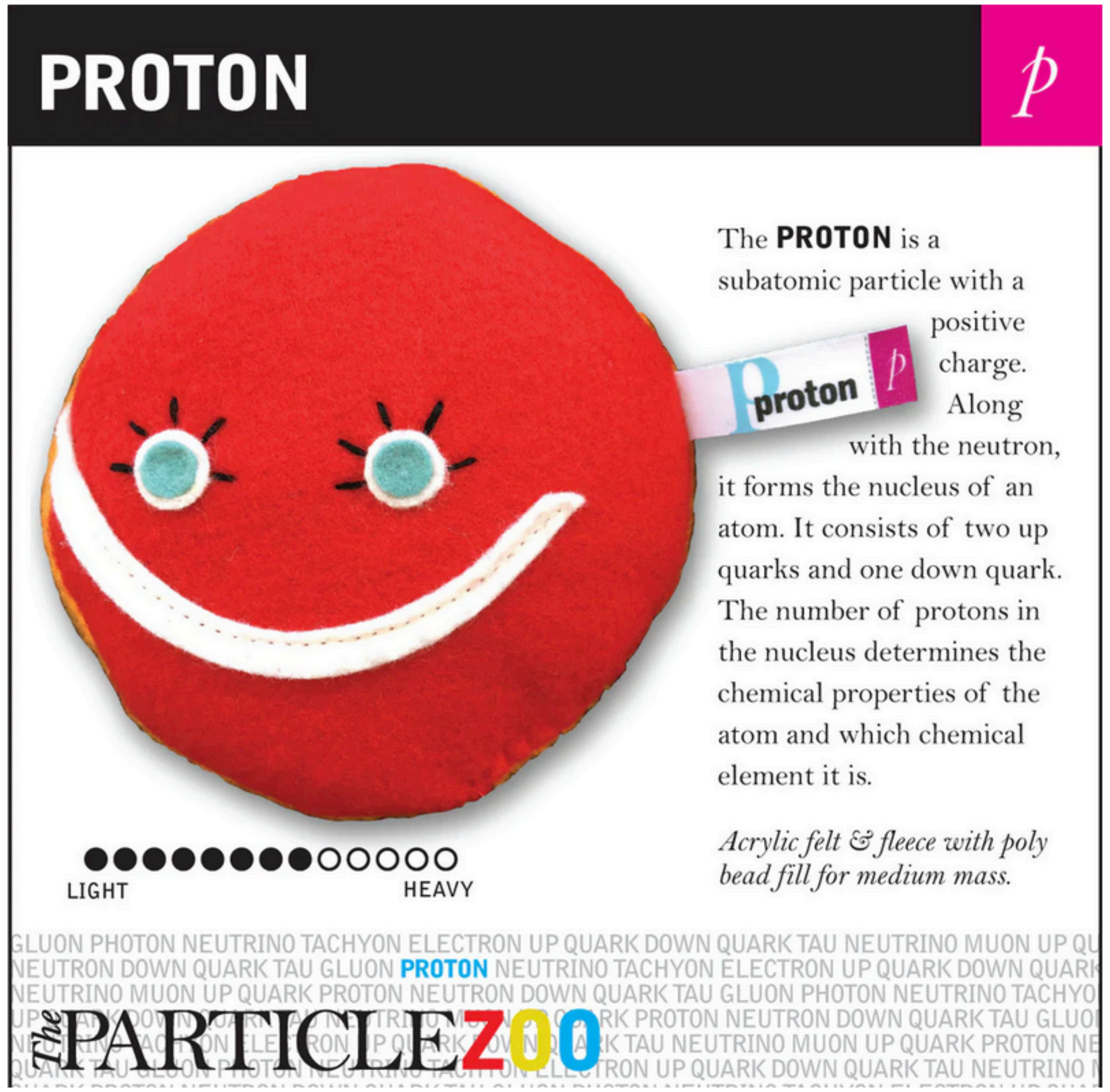




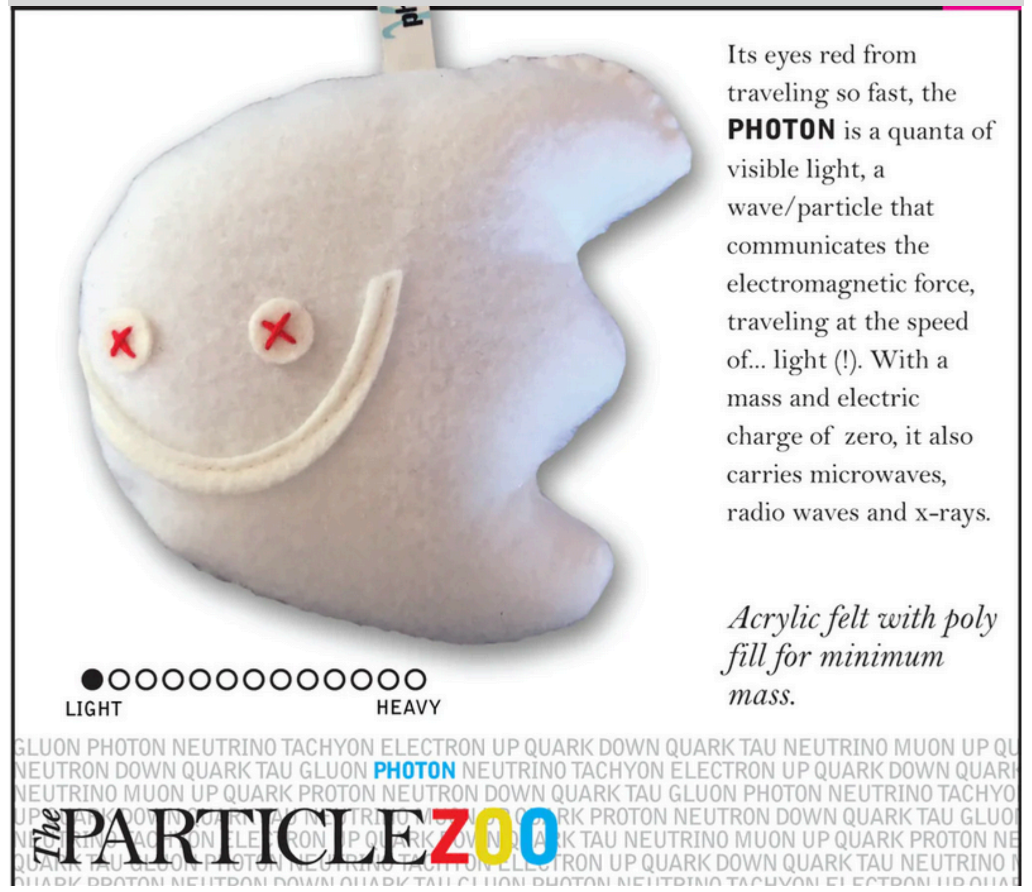


Shandera, TRISEP 2024

(Simple) complex dark matter



Dark Photon



Dark Electron

Shandera, TRISEP 2024

(Simple) complex dark matter

Too complicated!

Let this be a “fundamental” particle instead

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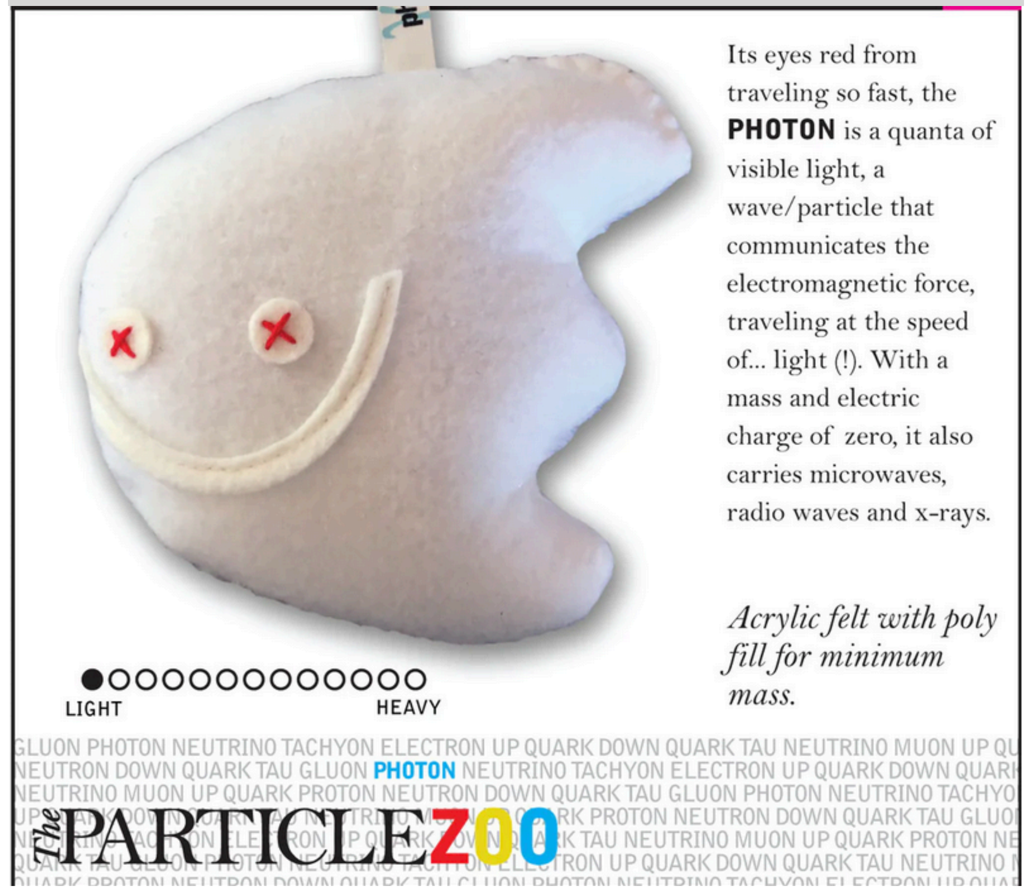
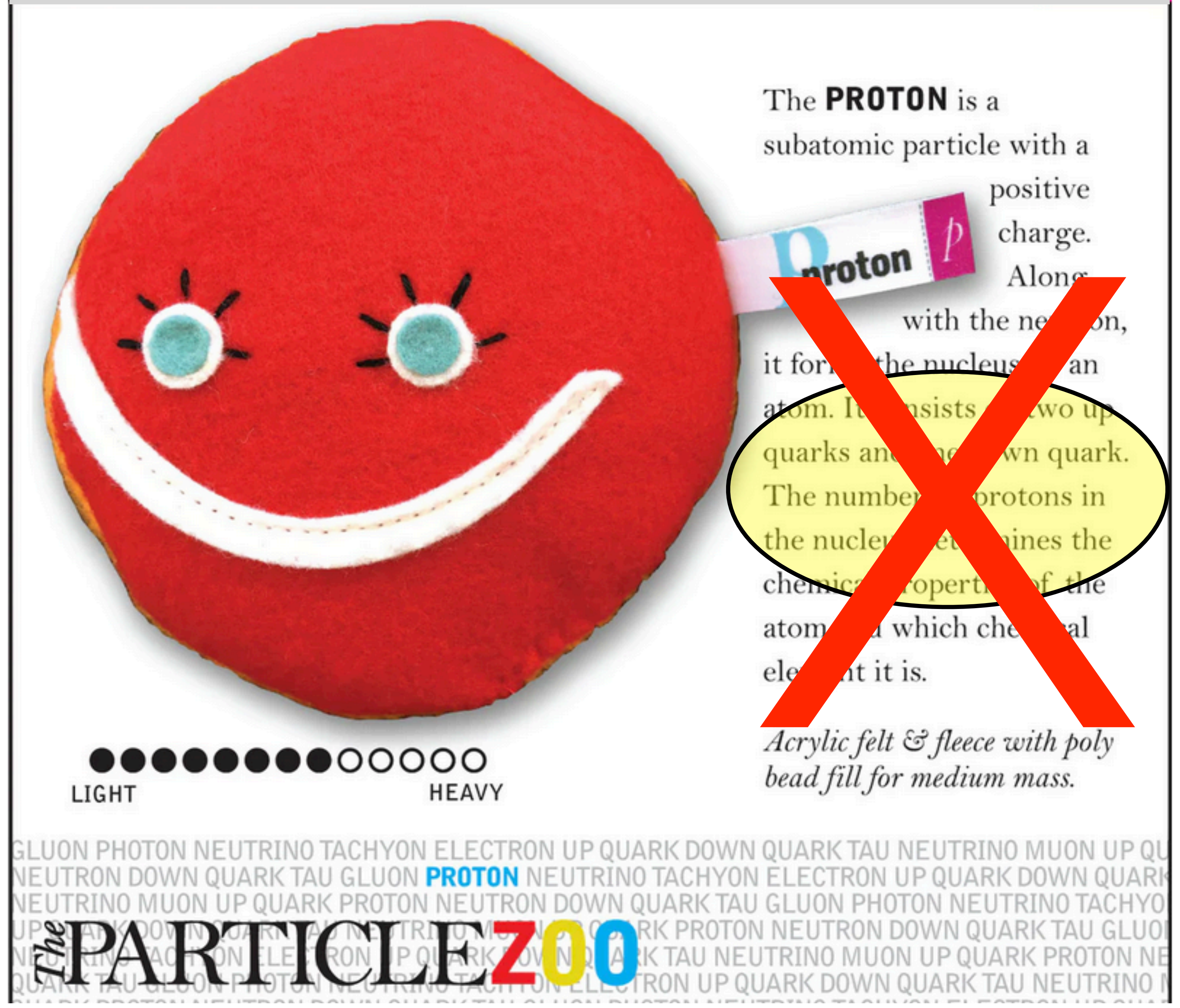


Dark Electron

Shandera, TRISEP 2024

(Simple) complex dark matter

Dark Pfermion



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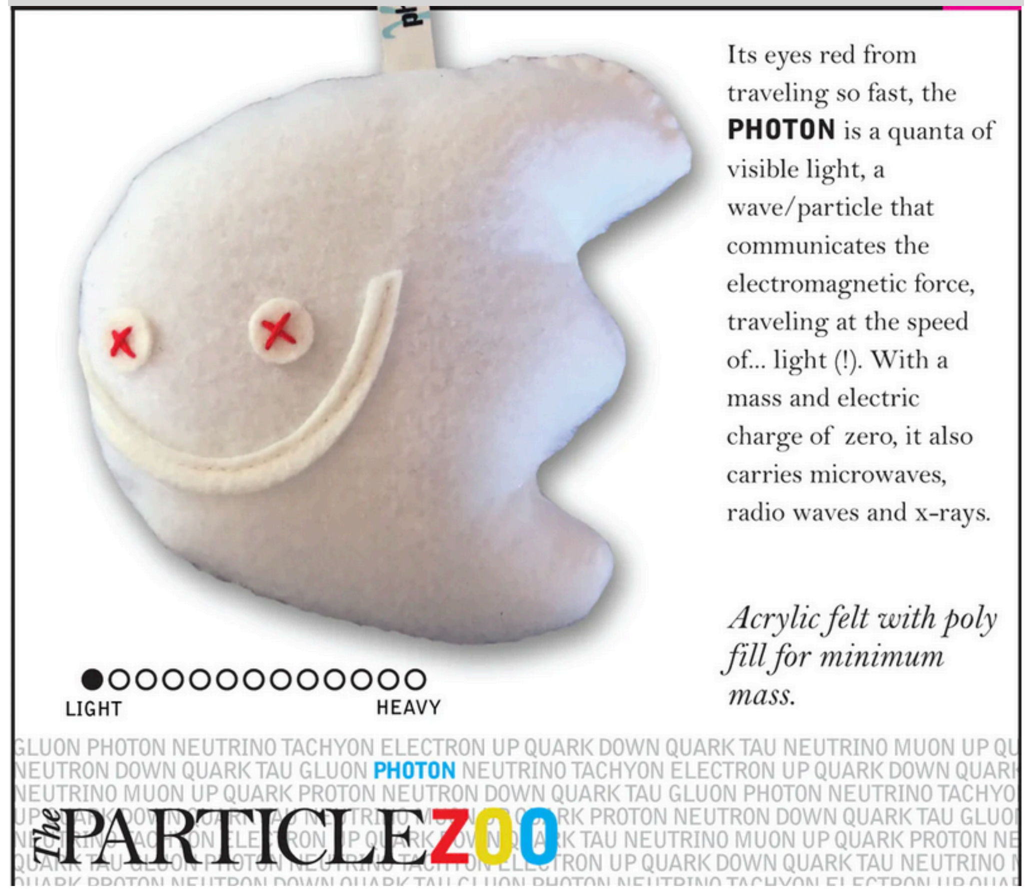

Dark Electron

Shandera, TRISEP 2024

A simple dark sector with distinctive black holes

Dark "electron" $0.01 \lesssim \frac{m}{m_{\rm electron}} \lesssim 100$

Dark "proton" $1 \lesssim \frac{M}{m_{\rm proton}} \lesssim 1000$

Dark "photon" massless

Dark fine structure constant

$$0.1 \lesssim \frac{\alpha}{\alpha_{\rm EM}} \lesssim 2$$

Interesting BH masses

$$M^{\rm Dark}_{\rm Chand.} \approx 1.4 M_\odot \left(\frac{m_{\rm prot.}}{M}\right)^2$$

No nuclear physics; No coupling to the standard model

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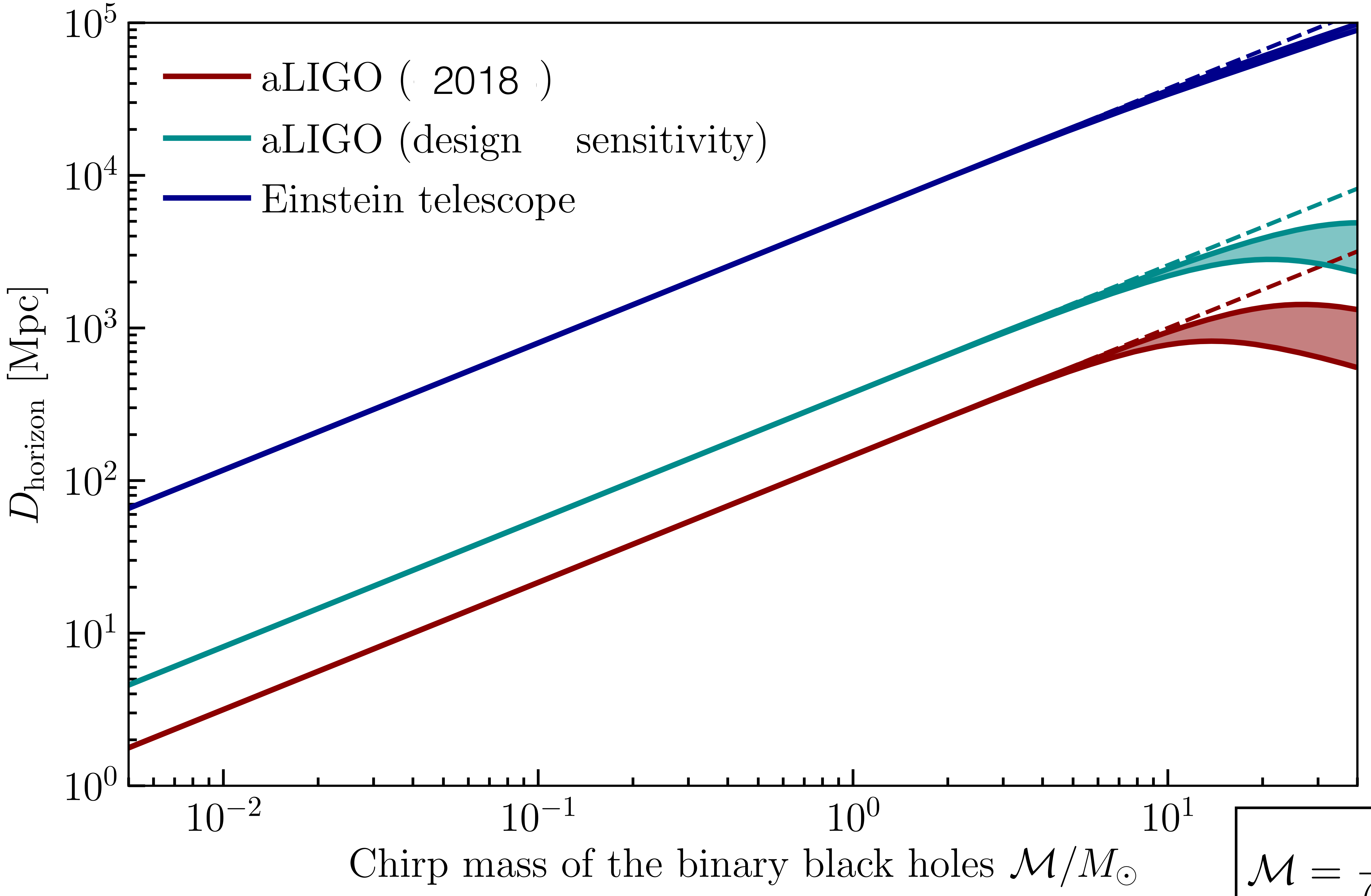
Dark "hydrogen" → Cooling channels

→ Allows BHs to form dynamically from dark matter

No nuclear physics; No coupling to the standard model

Clean new physics discovery space below ~1 solar mass



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Shandera, TRISEP 2024

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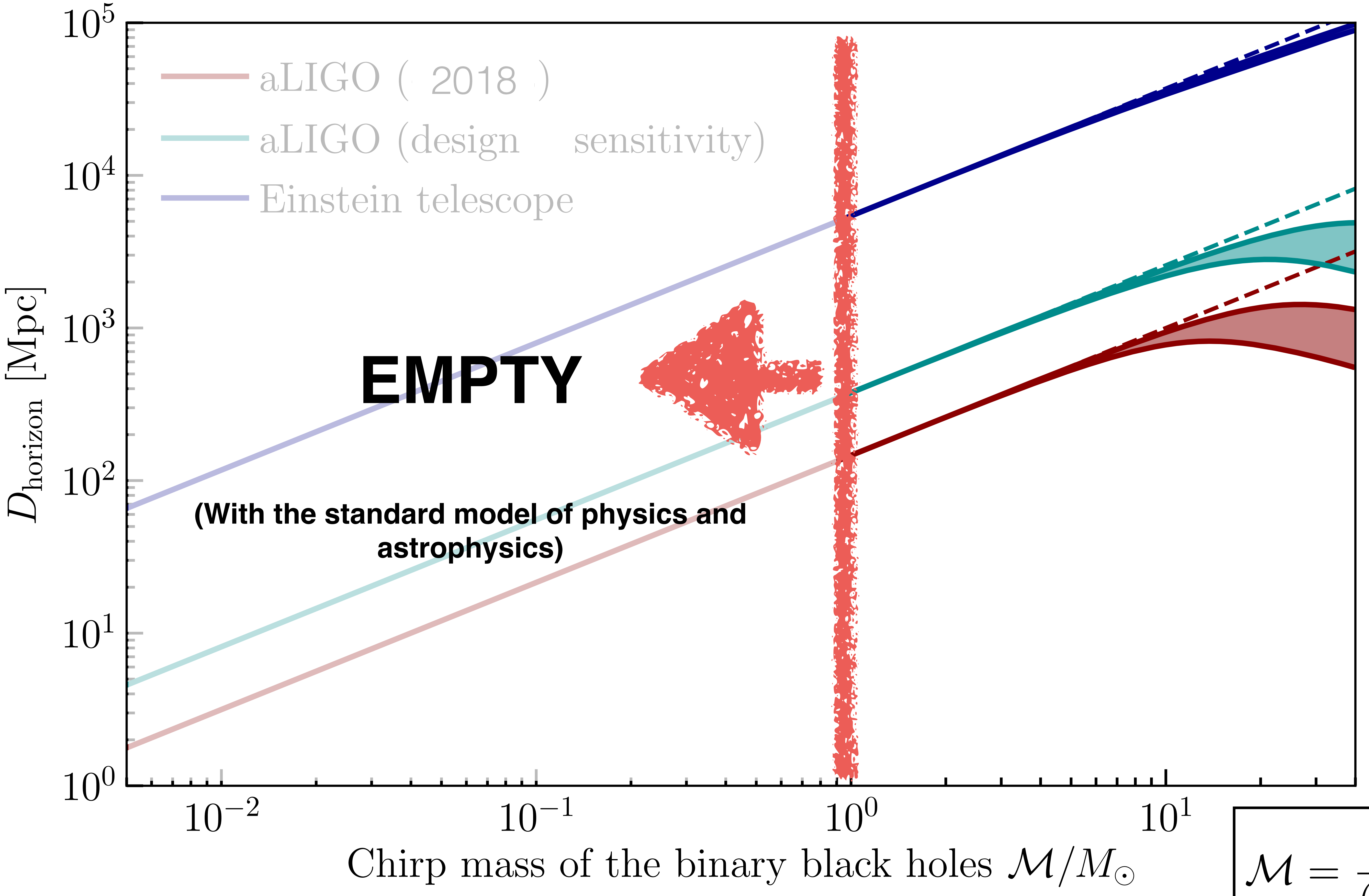

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Shandera, TRISEP 2024

How many dark black holes can form?

We need to estimate:

- Can dark matter cool sufficiently to collapse into black holes?

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Parameterizing the coalescence rate

$\propto$ (number of black holes) $\times$ (fraction in binaries)

$\times$ (merger rate of those binaries today)

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Depends on parameters of the binaries

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Total DM mass available
How much is in BHs

Depends on parameters of the binaries

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Rosenberg and Fan, 1705.10341;
Buckley and DiFranzo, 1707.03829;
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}

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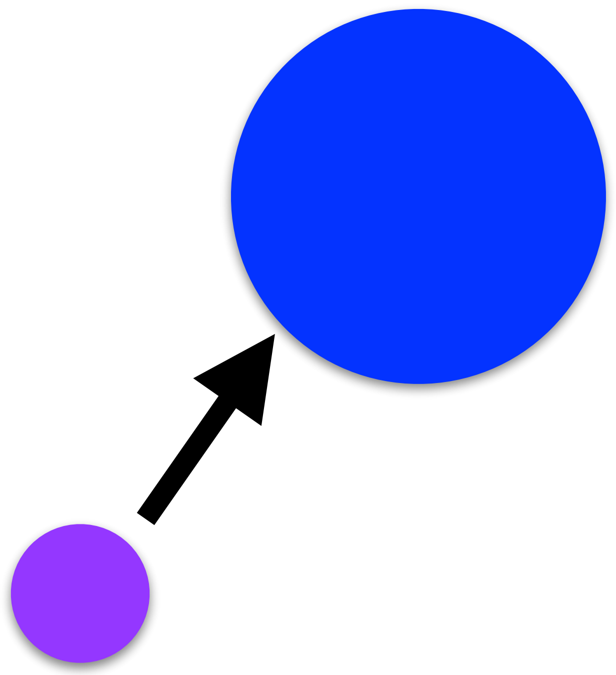
Now + molecular cooling

opacity limit arguments from 1970's
+
Pop III star literature;
Now + simulations

How much dark matter can cool?

Why is it cooling? Example: collisional excitation

dark hydrogen



(fast) dark electron

Detailed rates calculated by Rosenberg and Fan, 1705.10341;

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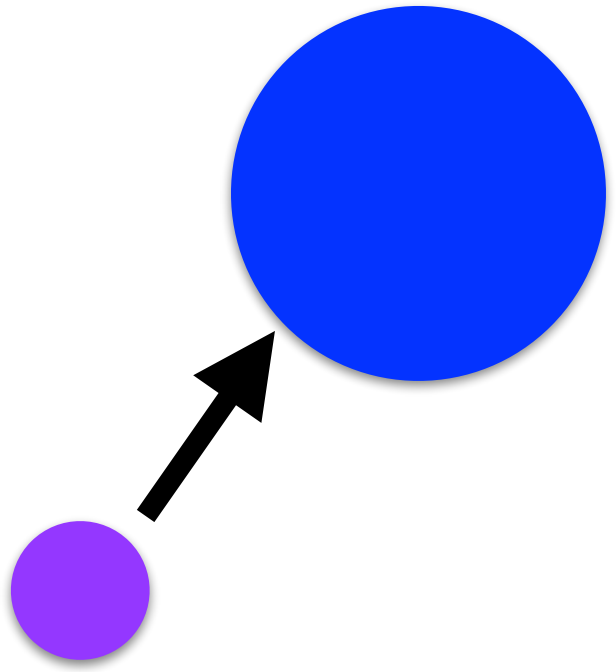

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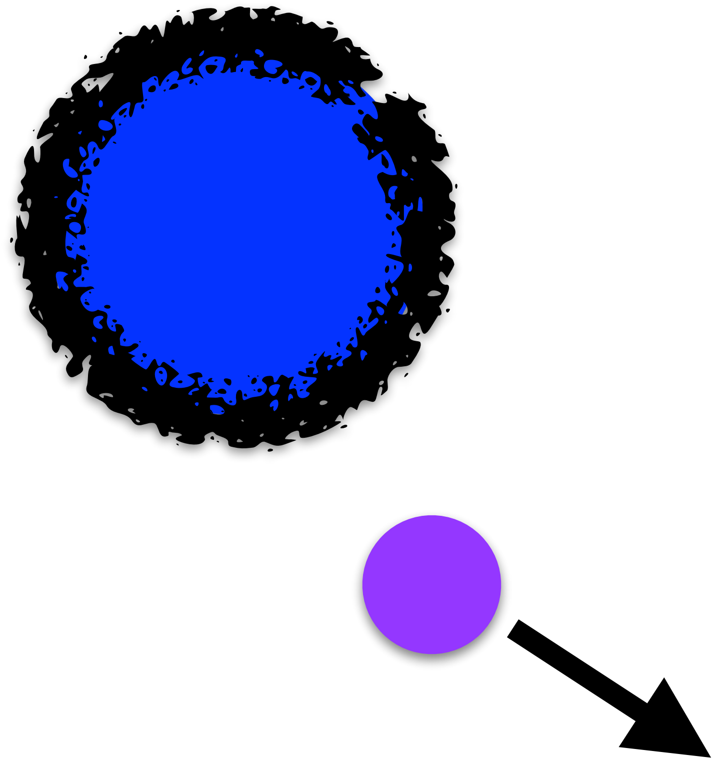
Example: collisional excitation

dark hydrogen
excited state

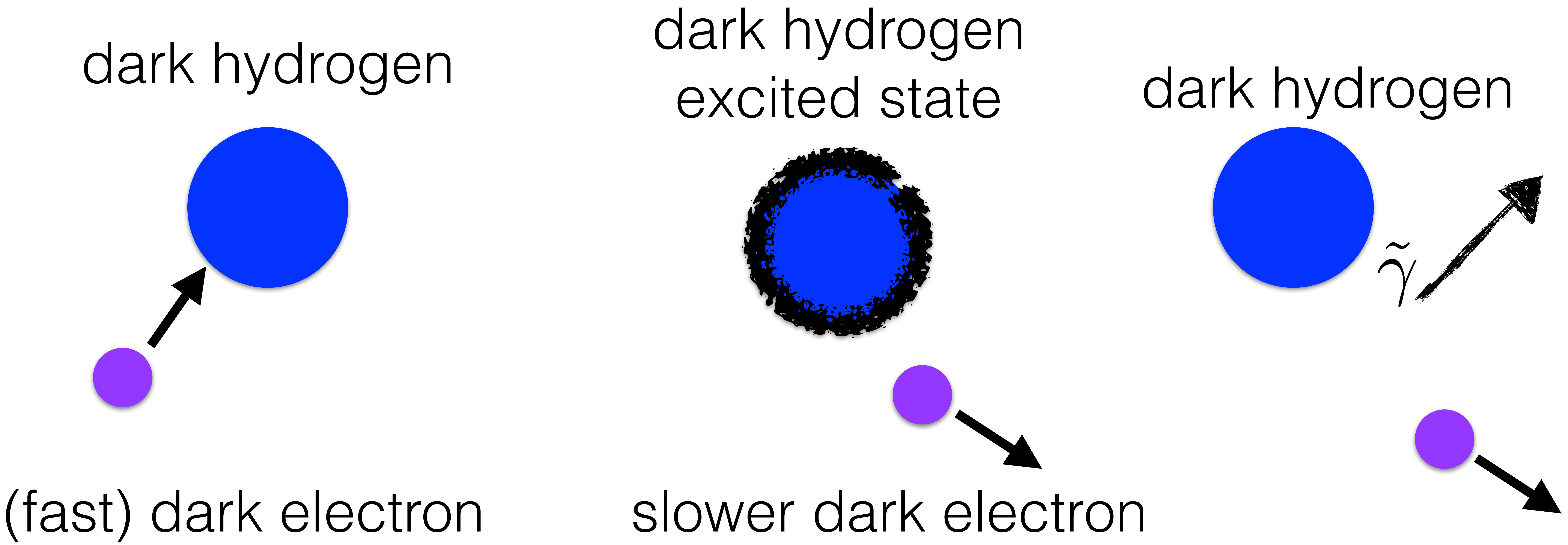


slower dark electron

Detailed rates calculated by Rosenberg and Fan, 1705.10341;

How much dark matter can cool?

Why is it cooling? Example: collisional excitation



Detailed rates calculated by Rosenberg and Fan, 1705.10341;

How much dark matter can cool?

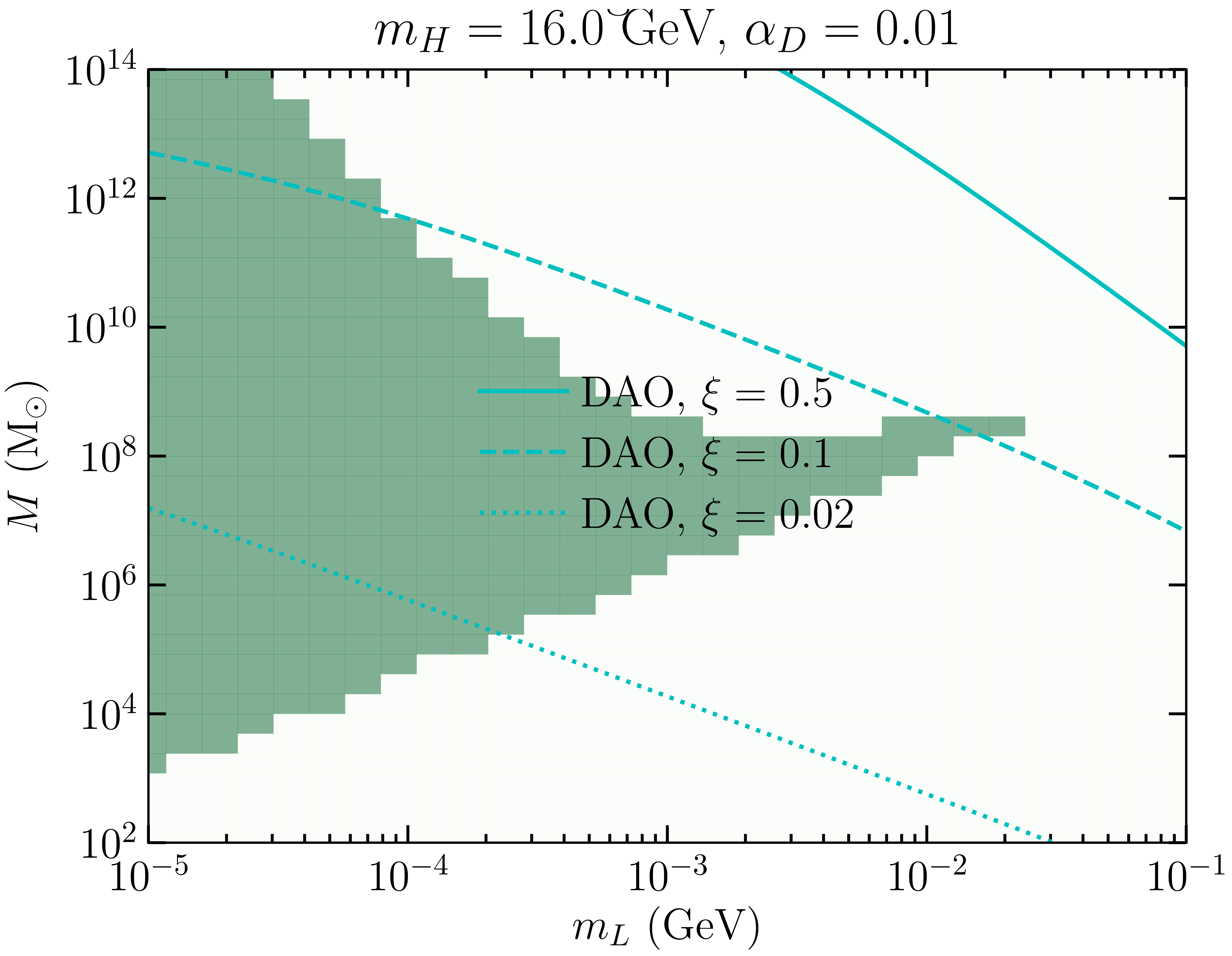
$$\frac{dT}{dt}\text{ (cooling processes)} > \frac{dT}{dt}\text{(kinematics in gravitational well)}$$

Cooling is more efficient for smaller dark matter halos:
can maintain “cold dark matter” success on large scales

Buckley and DiFranzo, 1707.03829

How much dark matter can cool?

Consider all the processes that involve dark atoms (not yet dark molecules)

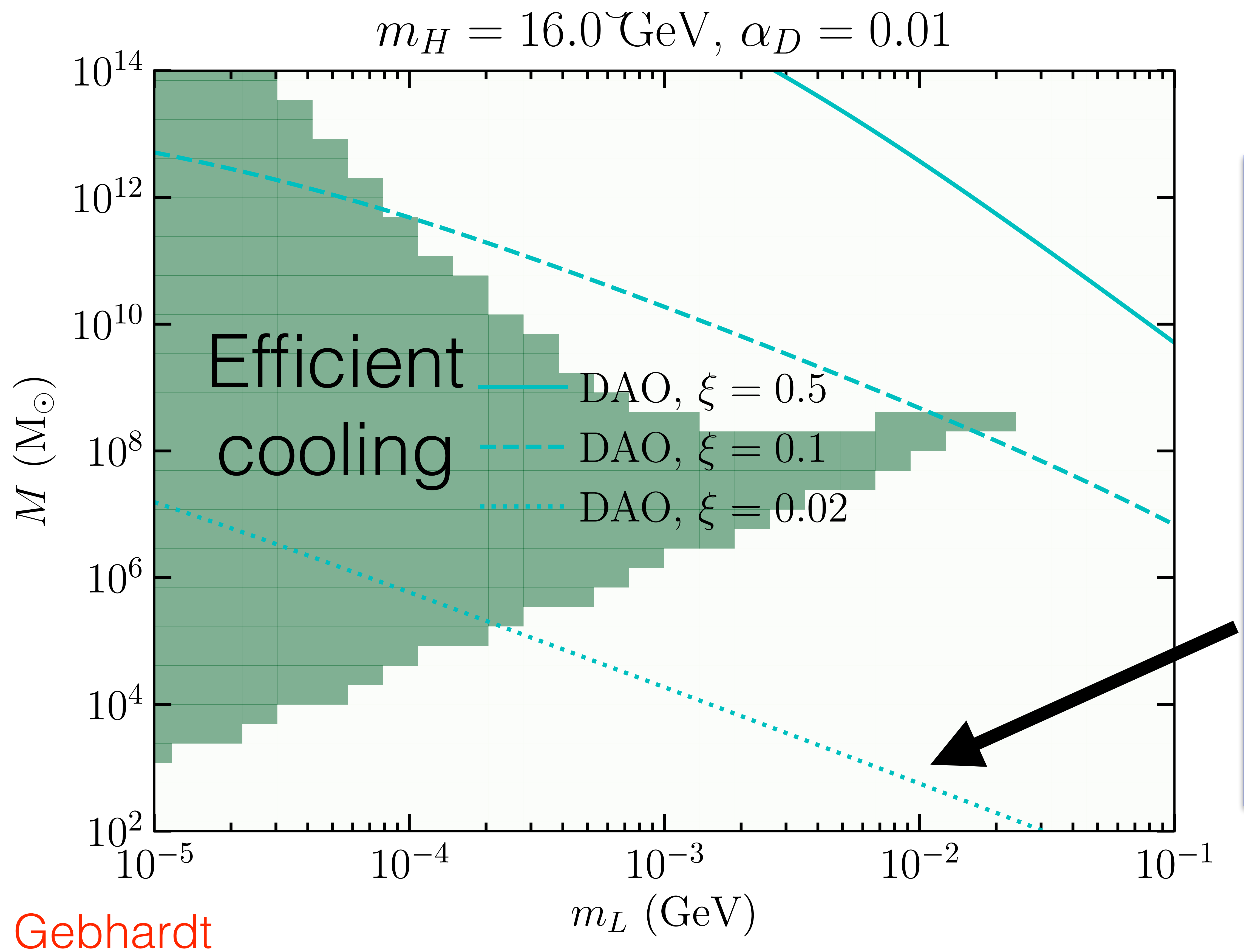


Plot: Henry Gebhardt

Rosenberg and Fan, 1705.10341; Buckley and DiFranzo, 1707.03829

Cooling dark matter

** But, must also maintain structure formation



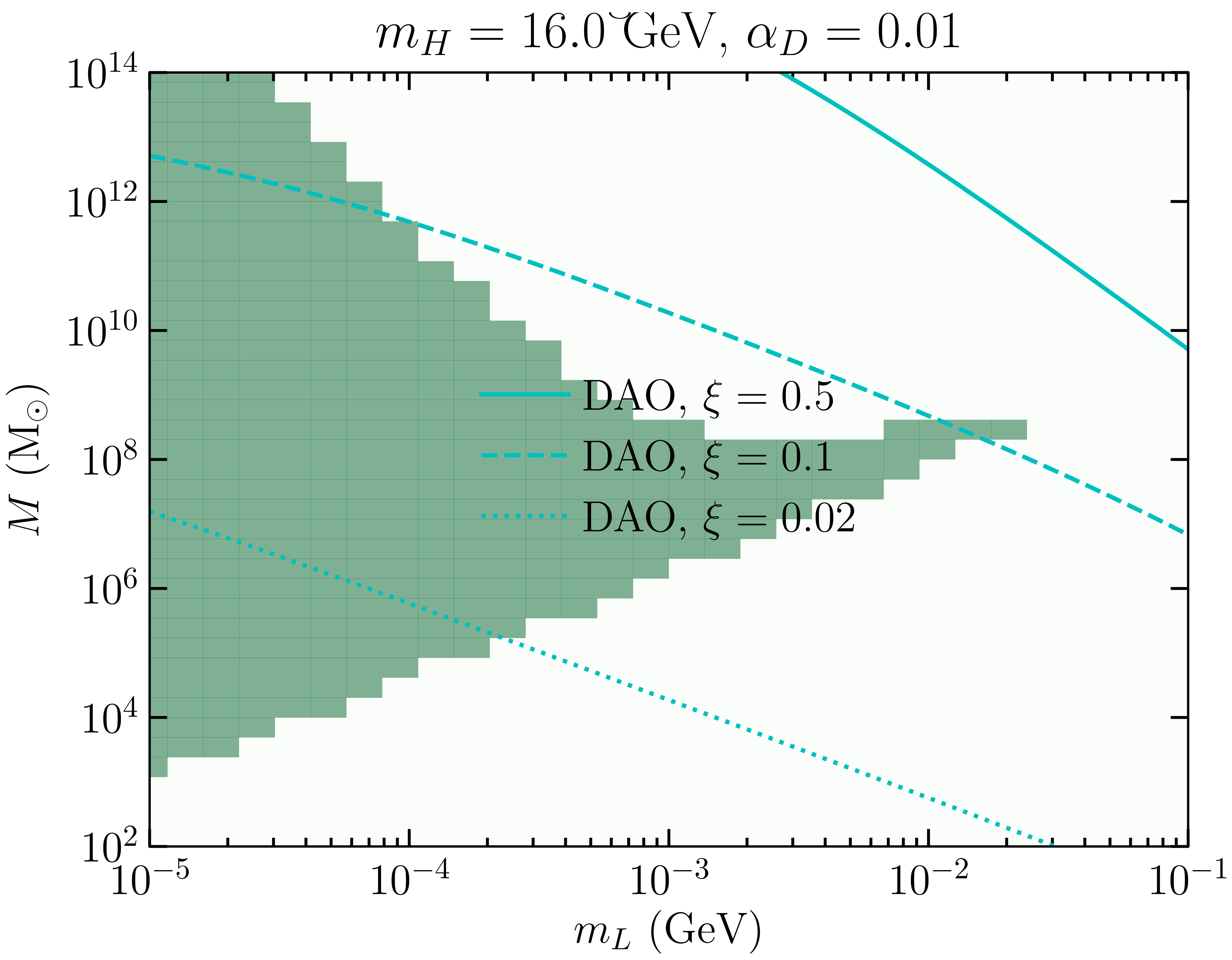
$$\xi = \frac{T_{\tilde{\gamma}}}{T_{\gamma, CMB}}$$

Require a rather cold dark sector

Plot: Henry Gebhardt

Cyr-Racine, de Putter, Raccanelli, Sigurdson 1310.3278

Cooling dark matter



This plot
+
sub-halo mass function:

$f_{\rm cool} \sim 0.01$

Plot: Henry Gebhardt

Rosenberg and Fan, 1705.10341; Buckley and DiFranzo, 1707.03829

How much of the dark matter that can cool ends up in black holes?

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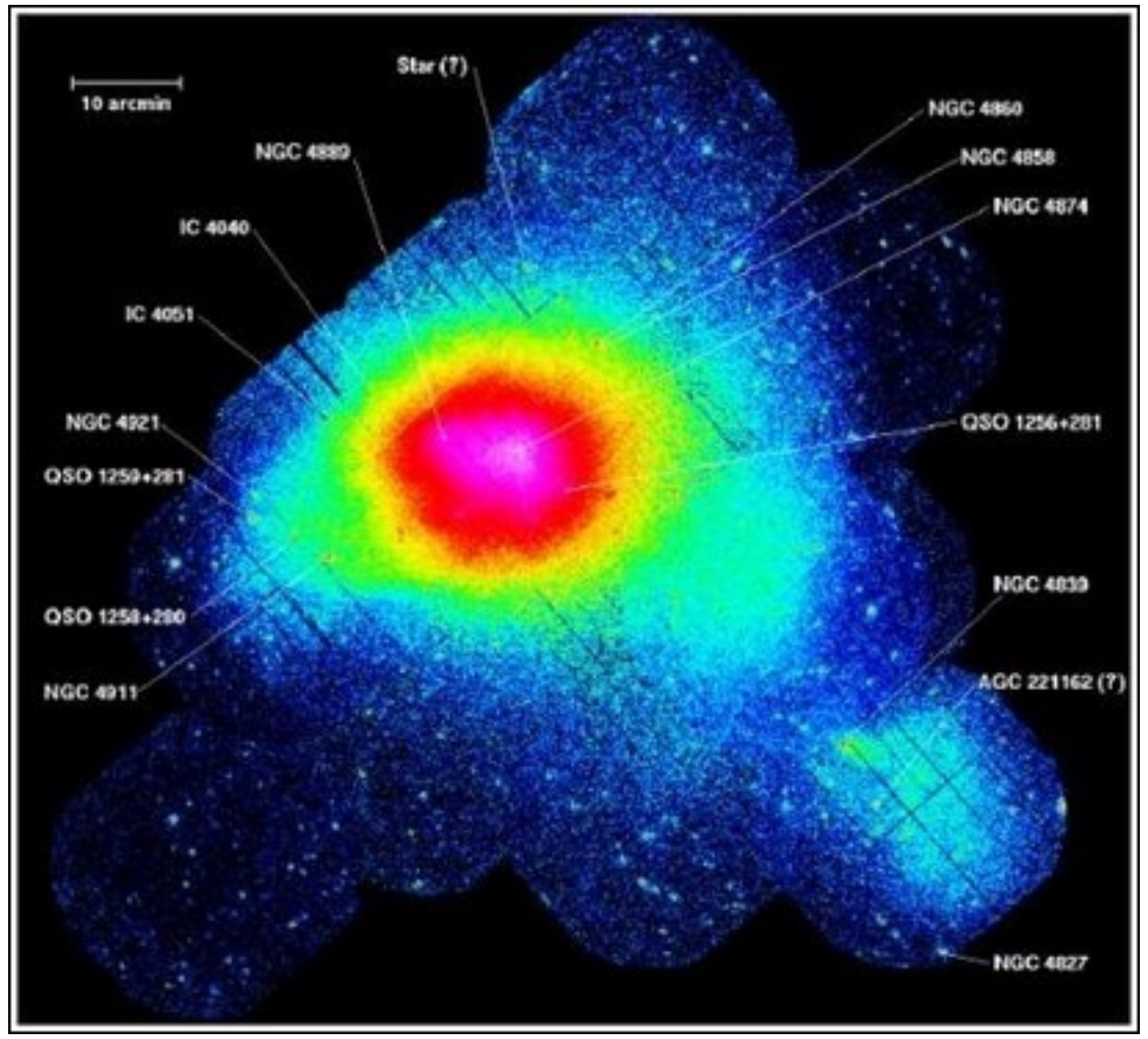
~2% of mass in stars



~10% of mass in gas

Shandera, TRISEP 2024

How much of the dark matter that can cool ends up in black holes?

Or, from literature on formation of first stars (in hydrogen gas, with a bit of helium):

$$f_{\rm form.\,eff.} \sim 10^{-3}$$

$$f_{\rm cool} \times f_{\rm form.\,eff.} \sim 10^{-5}$$

Optimistic: $$f_{\rm cool} \times f_{\rm form.\,eff.} \sim 10^{-3}$$

What is the mass of black holes formed by collapse of "atomic" dark matter?

"opacity limit" argument (Rees; Lynden-Bell, 1976)

$$M_{J,min} \propto \left(\frac{m_p}{m_X}\right)^{9/4} \left(\frac{T}{10^3 K}\right)^{1/4} M_\odot$$

Coefficient? Pop III star literature for proto-star masses:

$$M_{\mathrm{DBH,min}} \sim \left(\frac{m_p}{m_X}\right)^{9/4} \left(\frac{T}{10^3 K}\right)^{1/4} 10^3 M_\odot$$

What is the minimum temperature the gas can cool to?

What process allows cooling to lowest temperature?

Molecular hydrogen cooling

First excited state to ground state:

$$\Delta E = \left(\frac{m_p}{m_X}\right)\left(\frac{m_c}{511\,\mathrm{keV}}\right)^2\left(\frac{\alpha_D}{0.0073}\right)^2 \times 512\,K$$

This gives us minimum temperature.

The estimate was promising:

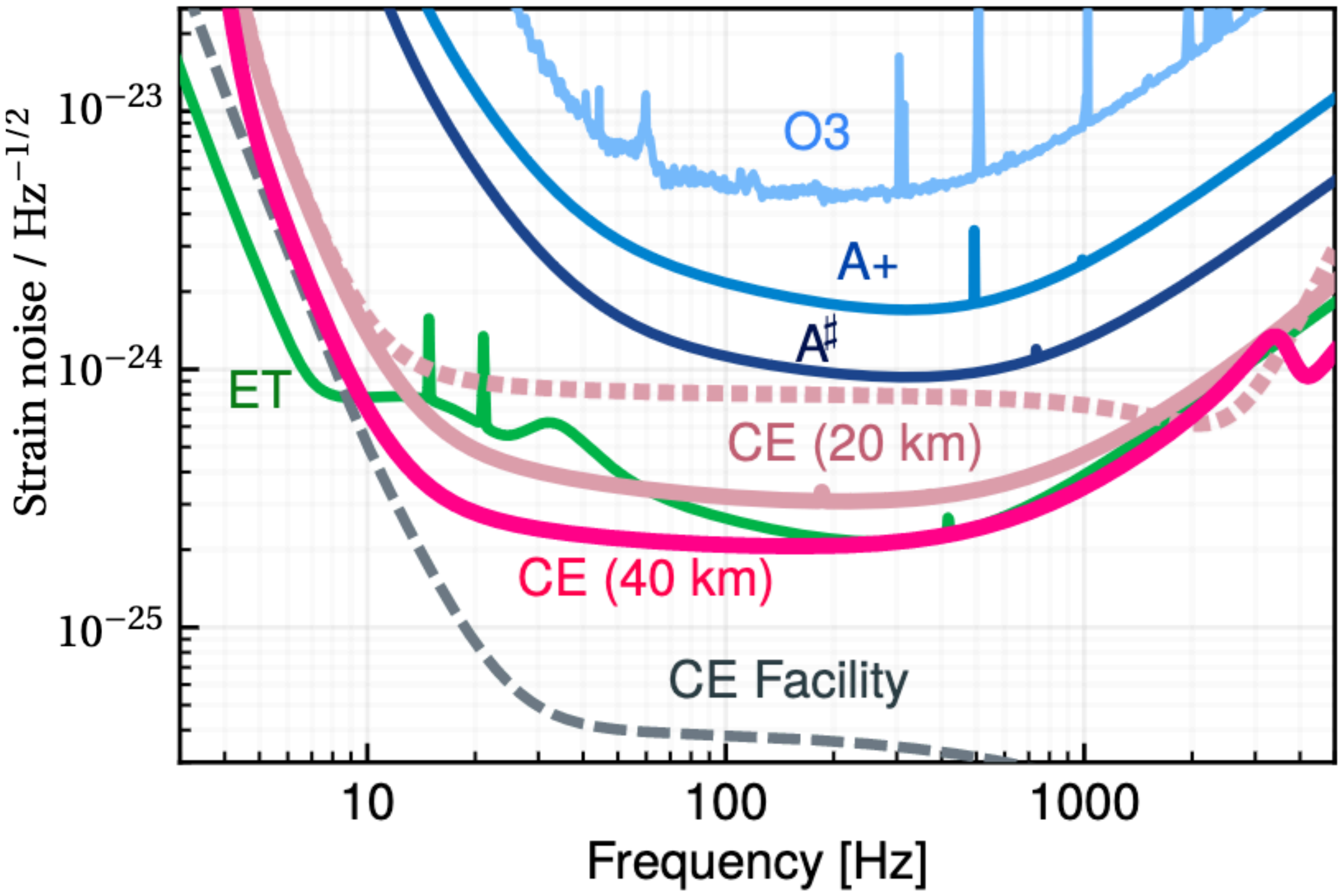
m_X [GeV]	m_c [keV]	$M^{\text{dark}}_{\text{Chand.}}$ $[10^{-5} M_\odot]$	M_{DBH} $[M_\odot]$	Rates per year: aLIGO (full)	Rates per year: Einstein T.	$m_1 < 1.4$ [%]	$m_1, m_2 < 1.4$ [%]
62	31	33	0.0068 – 0.68	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	0.016 – 1.6	0.11 (11)	330 (33k)	99%	79%
32	70	125	0.054 – 5.4	1.1 (110)	3500 (350k)	53%	9.3%
16	140	500	0.43 – 43	22 (2200)	92k (9200k)	9.8%	0.14%

Fraction of dark matter in Dark Black Holes: $f_{\text{cool}} \times f_{\text{form. eff.}} = 10^{-5} \, (10^{-3})$

S. Shandera, D. Jeong, H.Grasshorn Gebhardt (1802.08206, *PRL* **120**, 2018)

Similar results from others (Chang et al, Bramante et al, Fernandez et al)

Outlook for sub-solar mass searches



Figures + Projections from 2307.10421

LIGO Observing run 4: O4a May 24, 2023 - Jan 16 2024

LIGO Observing run 4: O4b March 27, 2024 - Nov 2024

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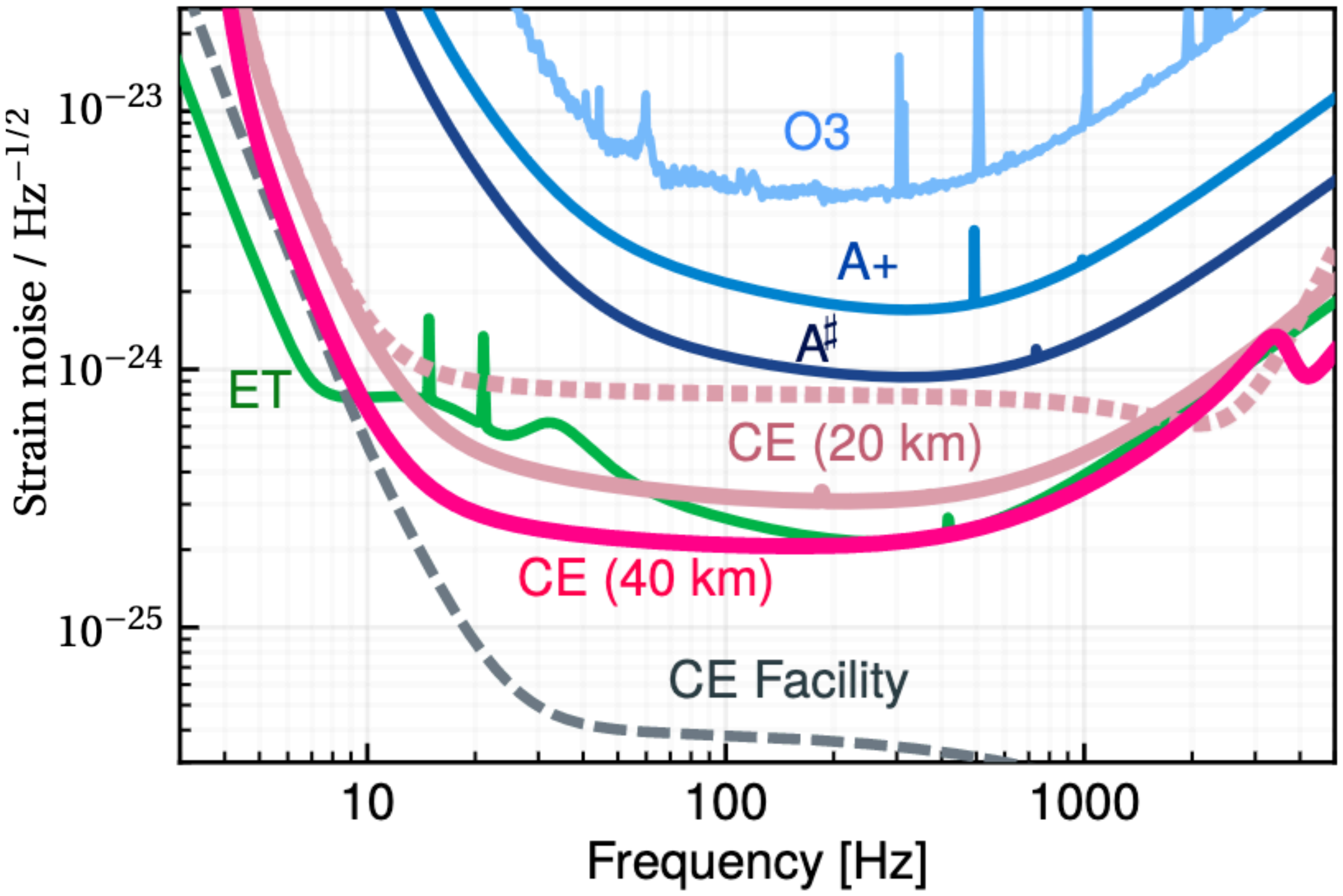

Figures + Projections from 2307.10421

Novel compact more generally:

- Ryan and Radice, 2201.05626, dark white dwarfs
- Hippert et al, 2103.01965, dark neutron stars

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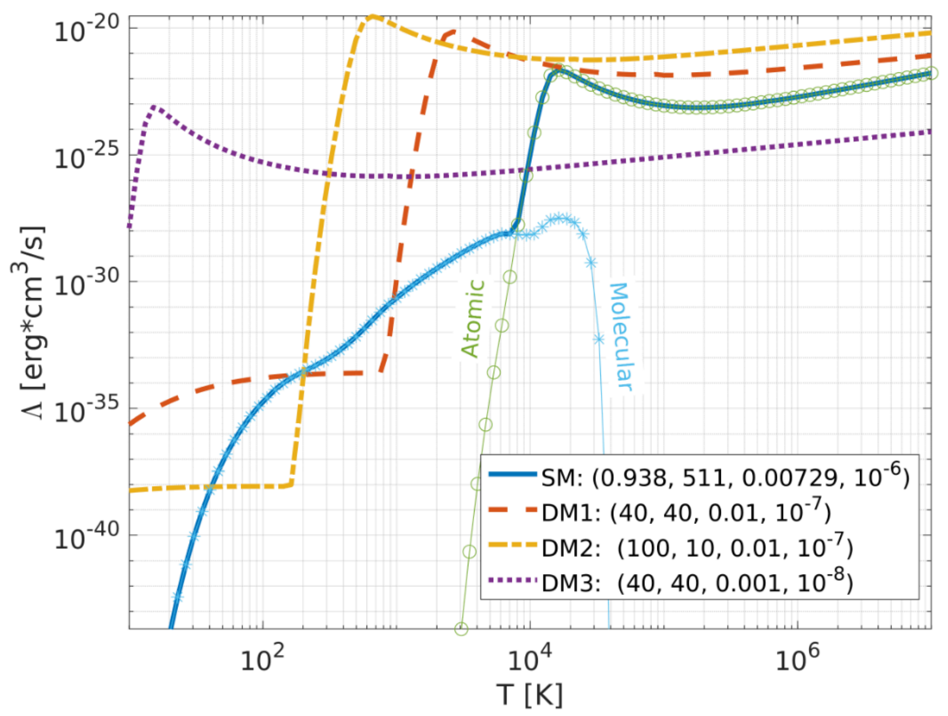
LIGO Observing run 4: O4b March 27, 2024 - Nov 2024

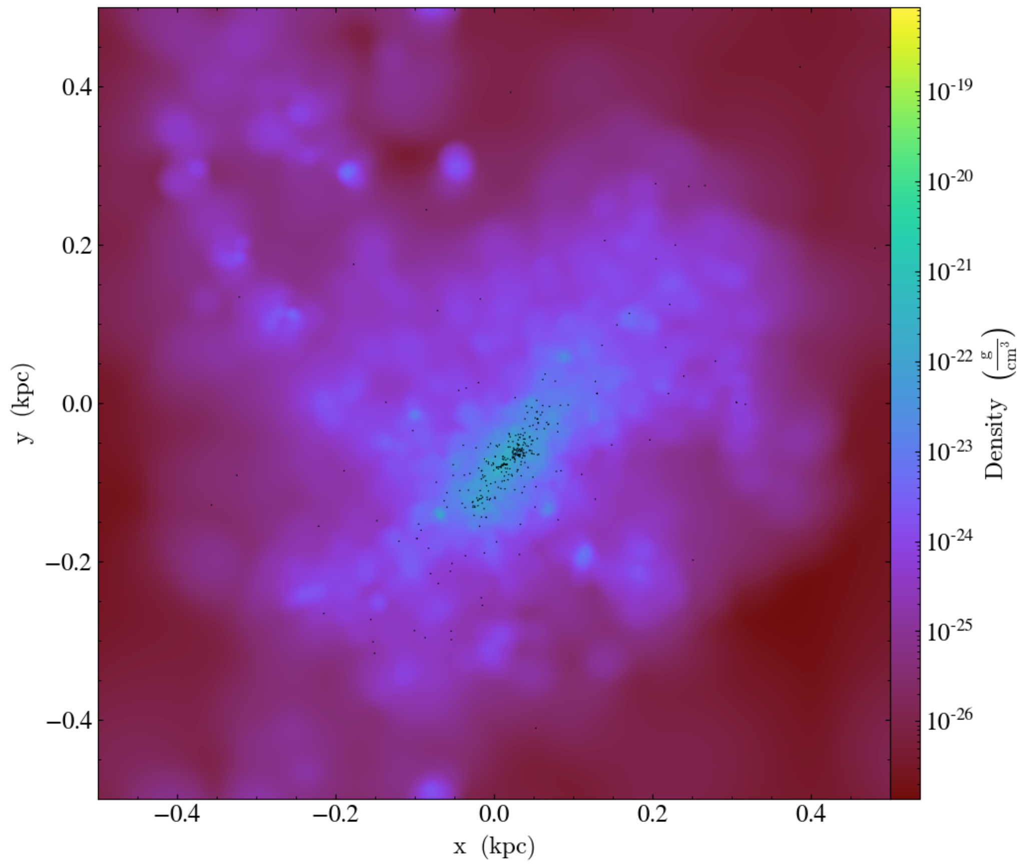
What next?

Particle Physics and Chemistry

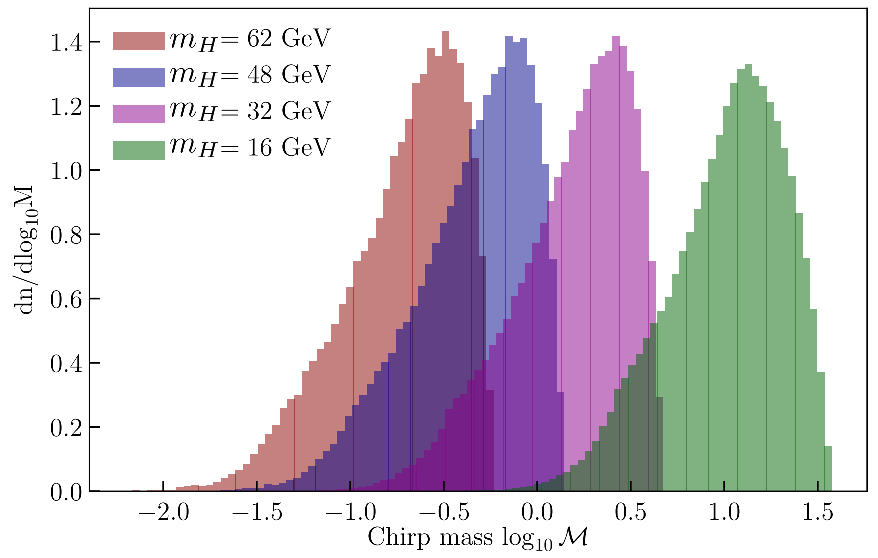


More precisely?

Structure formation



Population model for ultracompact objects



Shandera, TRISEP 2024

Prior work on atomic dark matter

Goldberg, Hall 1986
Ackerman et al 0810.5126
Feng et al 0905.3039
Kaplan et al 0909.0753, 1105.2073
Fan et al 1303.1521,1303.3271
Cyr-Racine et al 1209.5752, 1310.3278
Cline, Liu, Moore, Xue, 1311.6468
Foot, Vagnozzi 1409.7174, etc
Boddy et al, 1609.03592
Agrawal et al, 1610.04611
Ghalsasi and McQuinn, 1712.04779

Simulation work:

Vogelsberger et al 1805.03203
Huo et al 1912.06757
Todoroki et al 1711.11078
Shen et al, 2102.09580

Mirror dark matter:

Kobzarev et al, 1966,….more…..,
Mohapatra, Teplitz 1996 (“Structures in the Mirror Universe”)
Mohapatra, Teplitz 1999 (“Mirror Matter MACHOs”)
D’Amico et al, 1707.03419
Roux and Cline 2001.11504

Atomic physics of this model was known

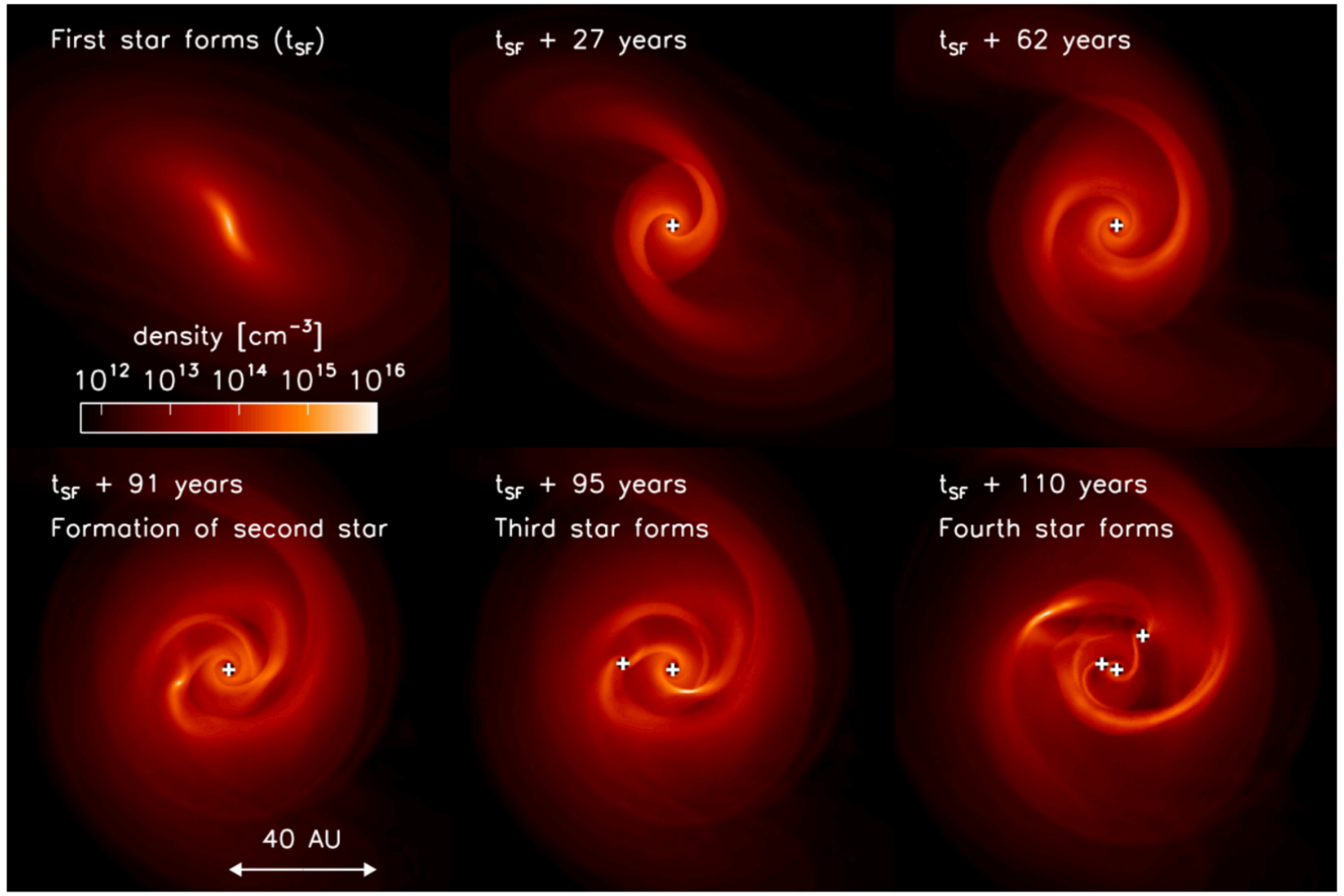
Detailed rates for atomic processes calculated by Rosenberg and Fan, 1705.10341
Basic argument about cooling: Buckley and DiFranzo, 1707.03829

But molecular physics is crucial for early universe abundances and for understanding cooling

Why molecular physics?

First stars:

Fragmentation depends on coldest temperature the gas can reach



Haemmerlé et al, 2003.10533

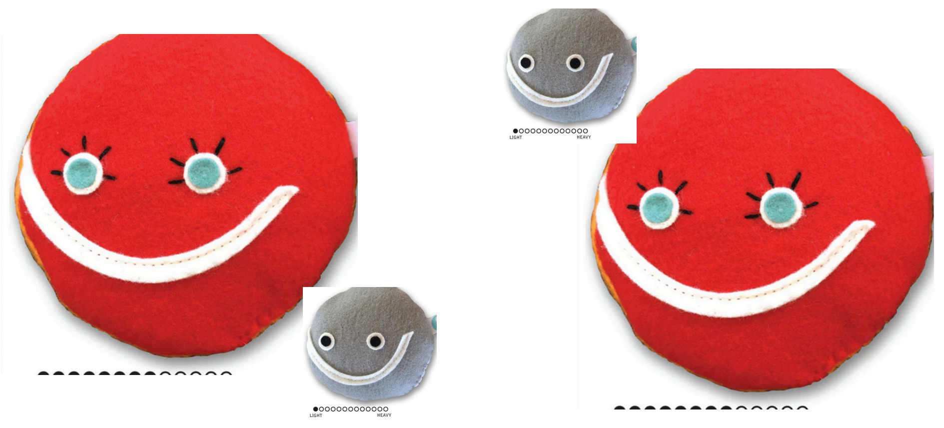
Standard Model:

- Atomic cooling ~ $10^4\,\mathrm{K}$
- Molecular cooling ~ $10^2\,\mathrm{K}$

Molecular physics

What do we need to compute gas cooling?

- Molecular energy levels
- Scattering processes



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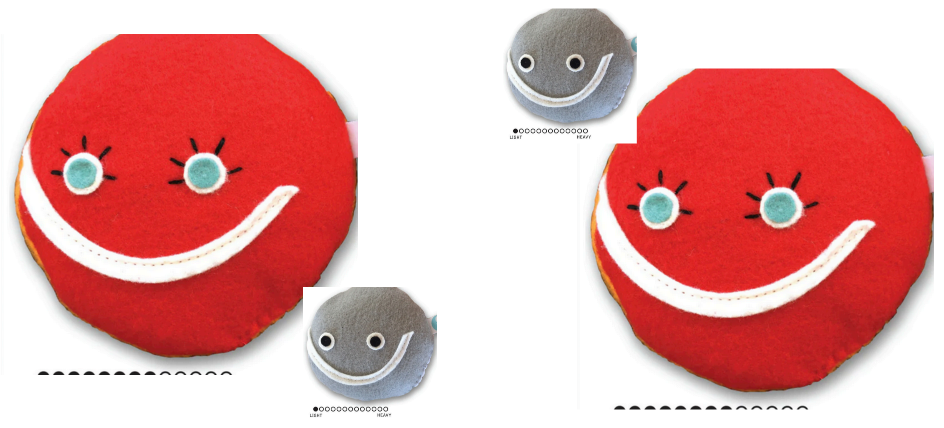
From first principles: solve the 4-body Schrödinger equation?

$$H\Psi(\mathbf{X}_A, \mathbf{X}_B; \mathbf{x}_1, \mathbf{x}_2) = E\Psi(\mathbf{X}_A, \mathbf{X}_B; \mathbf{x}_1, \mathbf{x}_2)$$



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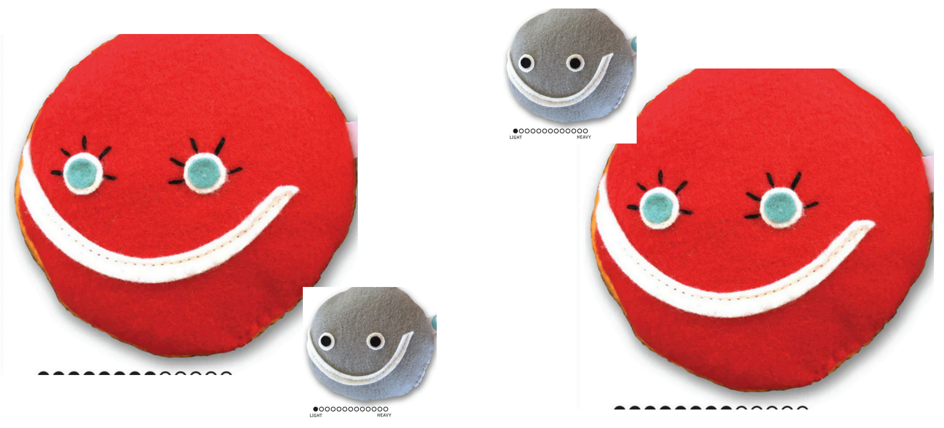
Easy to write down, hard to solve

$$H = -\frac{1}{2M}(\nabla_A^2 + \nabla_B^2) - \frac{1}{2m}(\nabla_1^2 + \nabla_2^2) + \alpha\left(\frac{1}{X_{AB}} + \frac{1}{x_{12}} - \frac{1}{x_{1A}} - \frac{1}{x_{2A}} - \frac{1}{x_{1B}} - \frac{1}{x_{2B}}\right)$$



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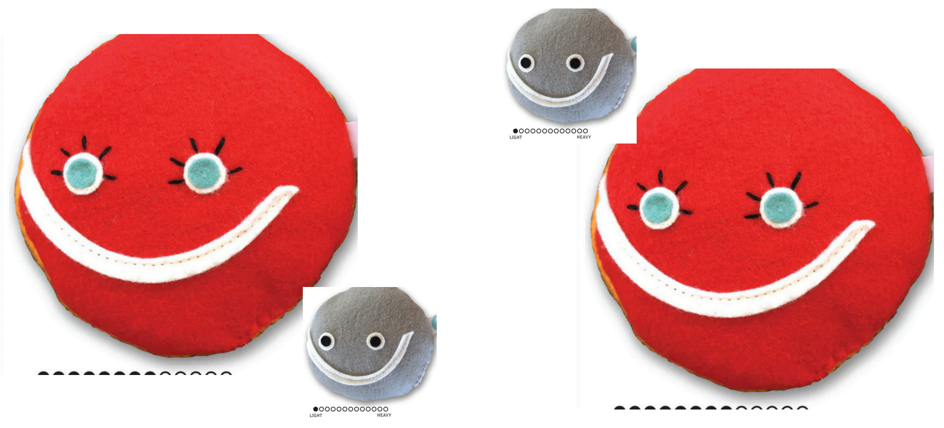

$$X_{AB} = |\mathbf{X}_A - \mathbf{X}_B|$$

Relative coords

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Molecular physics

Dimensional analysis!

Re-scale known standard model results using

$$r_m = \frac{m}{511\,\mathrm{keV}},\ r_M = \frac{M}{0.938\,\mathrm{GeV}},\ r_\alpha = \frac{\alpha}{137^{-1}}$$

James Gurian

Michael Ryan

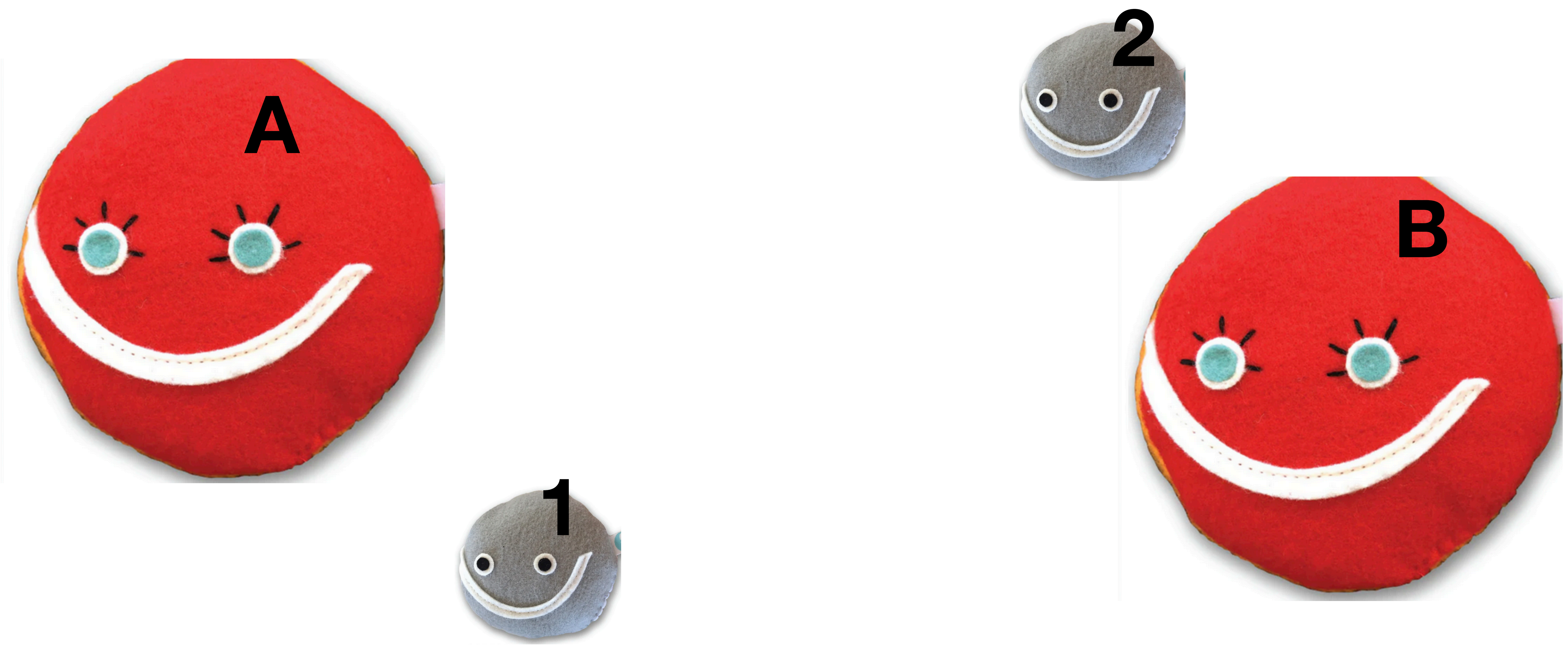
Solving the dark hydrogen molecule

Steps: look at the analytic steps that worked for usual hydrogen, write everything in terms of key parameters

1. Spell out assumptions
2. Carry out an approximate solution exactly to see relationship between visible and dark cases (re-scaling)
3. Understand how the re-scaling can be applied to more exact (numerical) solutions, with what limitations

Dark Hydrogen Molecule

$$H = -\frac{1}{2M}(\nabla_A^2 + \nabla_B^2) - \frac{1}{2m}(\nabla_1^2 + \nabla_2^2) + \alpha\left(\frac{1}{X_{AB}} + \frac{1}{x_{12}} - \frac{1}{x_{1A}} - \frac{1}{x_{2A}} - \frac{1}{x_{1B}} - \frac{1}{x_{2B}}\right)$$



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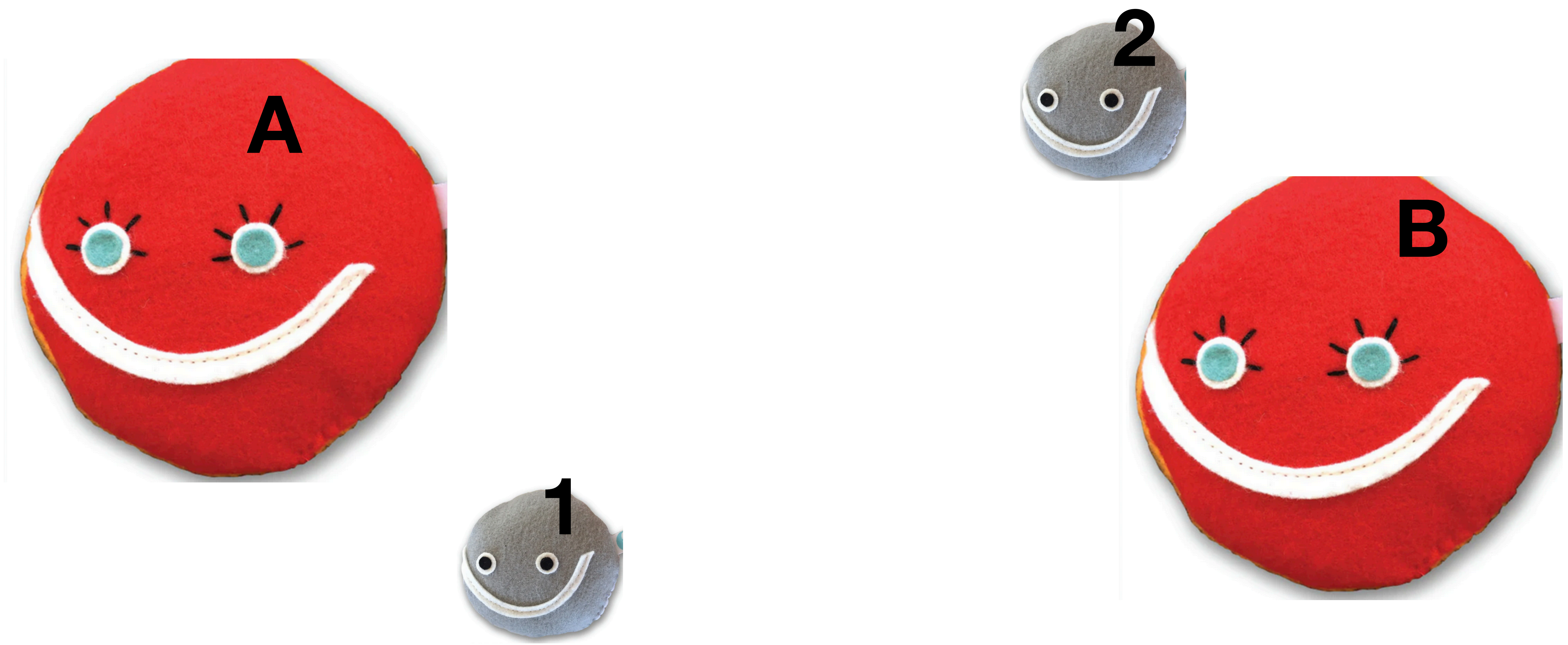

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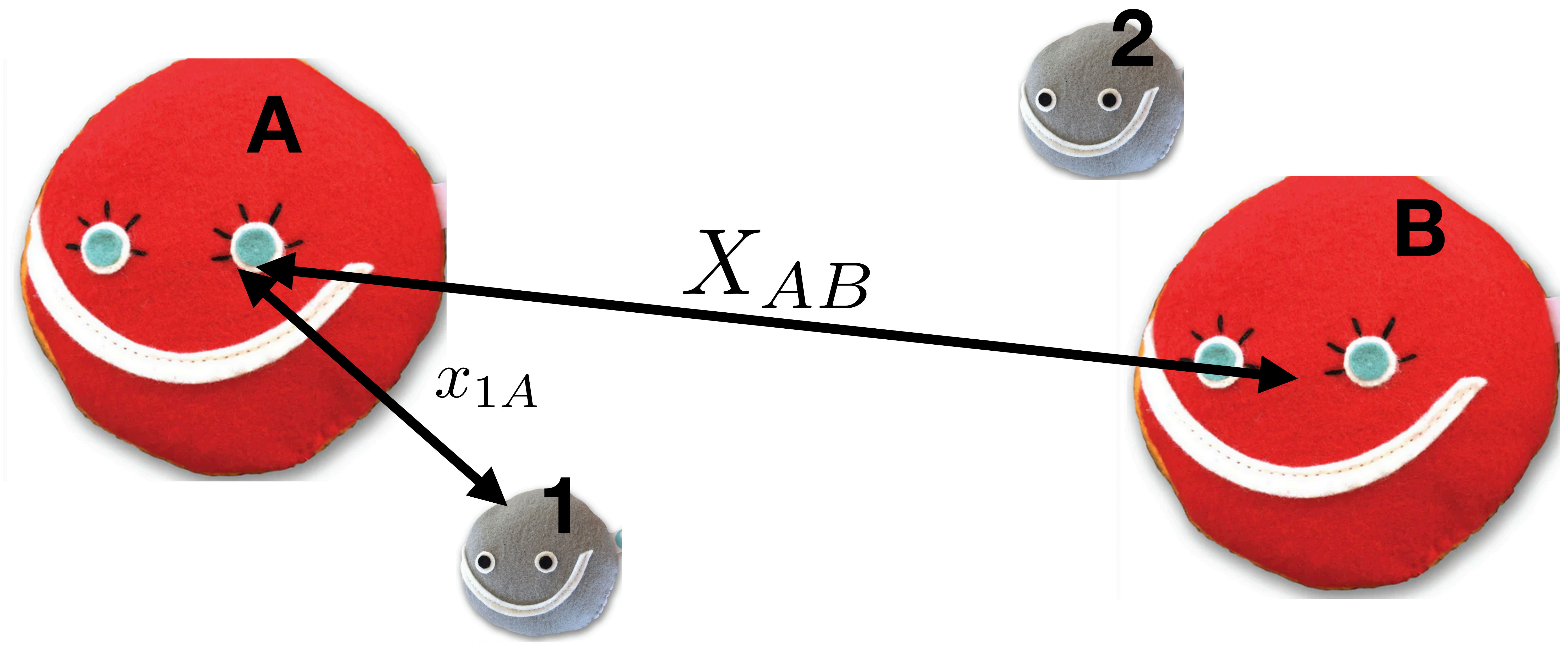
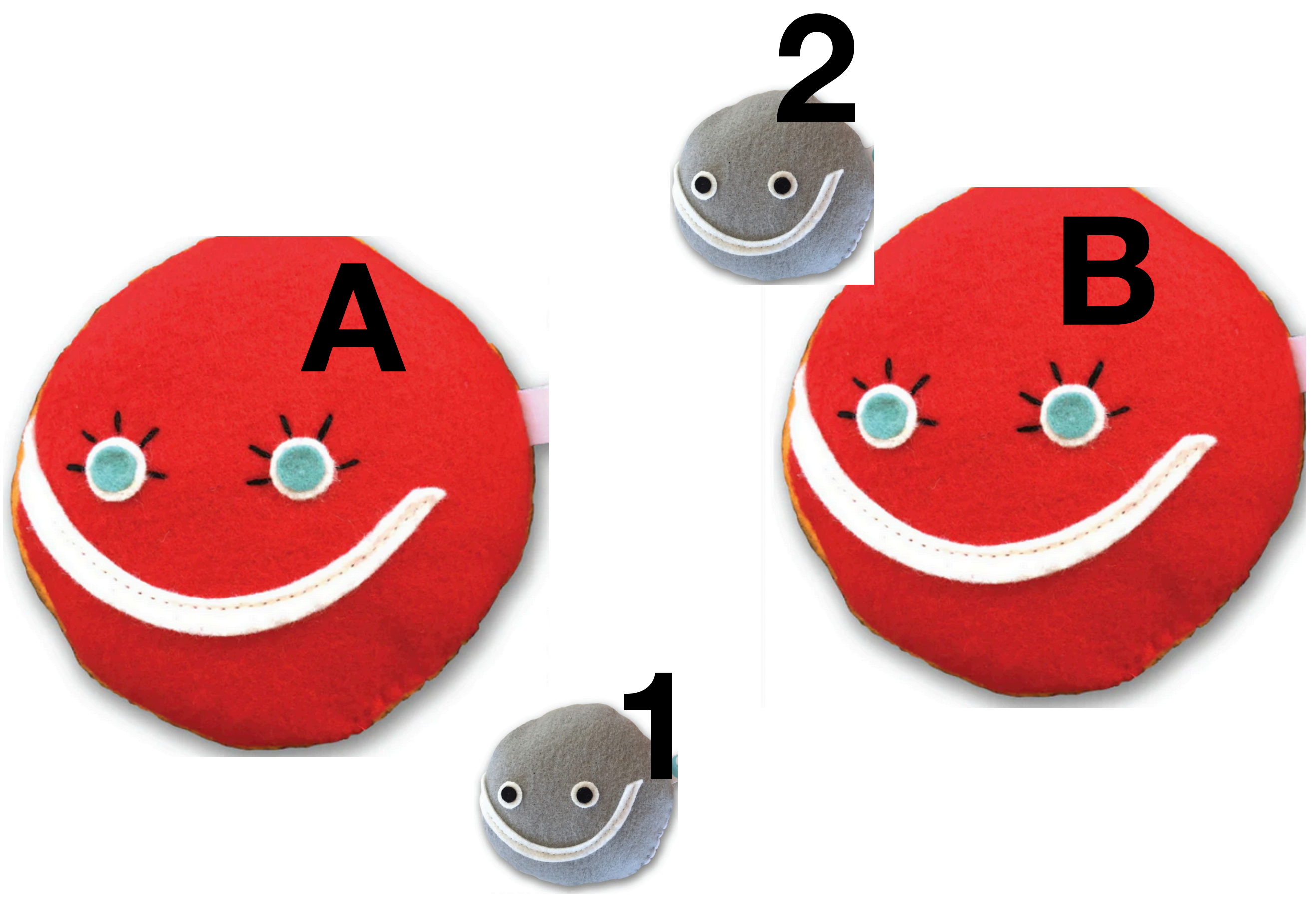


Shandera, TRISEP 2024

Solving the hydrogen molecule

1. For $M \gg m$, solve for (dark) electron wave functions, assuming (dark) protons remain stationary (Born-Oppenheimer approximation)



2. An ansatz for the electronic part, consider "Heitler-London"

$$\psi_{\text{electronic}} = \frac{1}{\sqrt{2}} \left[u_0(x_{1A}) u_0(x_{2B}) + u_0(x_{2A}) u_0(x_{1B}) \right]$$

Usual hydrogen atom ground state wave function

Only parameter = Bohr radius: $a_0 = \dfrac{1}{\alpha m}$

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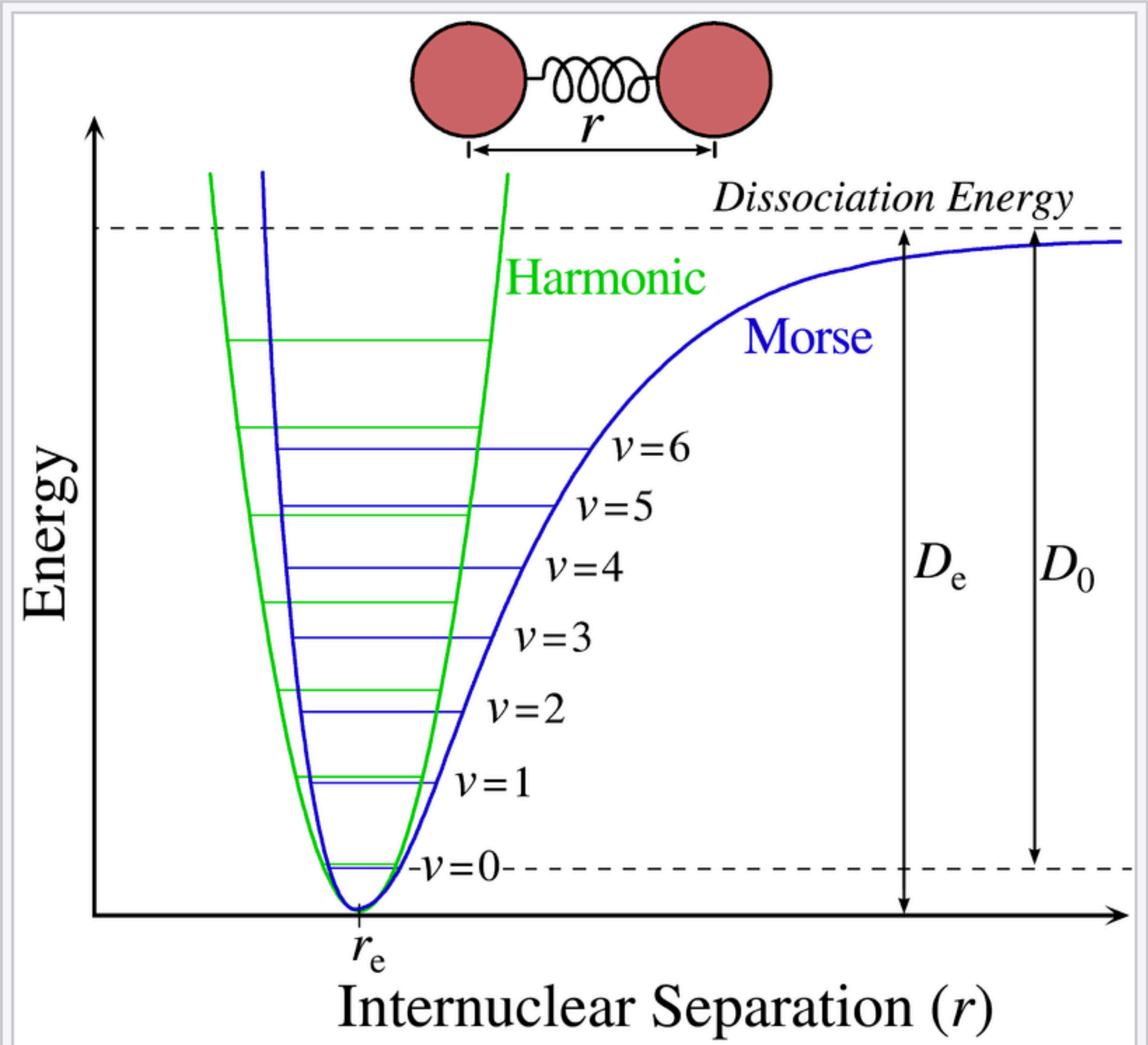
Solving the hydrogen molecule

With that ansatz, we have an effective potential for the dark "proton" pair: (nearly) the Morse potential



$$V_{\text{Morse}}(X_{\text{AB}}) = V_0 \left[e^{-2(X_{AB}-X_0)/b} - 2e^{-(X_{AB}-X_0)/b} \right]$$

$$V_0 \propto \frac{\alpha}{a_0} \propto m\alpha^2$$

$$X_0 \propto a_0$$

Separation at min of potential

$$b \propto a_0$$

Wikipedia

Solving the hydrogen molecule

The energy levels of the Morse potential can be calculated exactly

$$E_{\mathrm{rot,J}} = \frac{J(J+1)}{MX_0^2}$$

$$E_{\mathrm{vib},\nu} = -V_0 \left(1 - \frac{\nu + \frac{1}{2}}{b\sqrt{2MV_0}}\right)^2$$

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$$E_{\mathrm{mol.\,vib}} = \left[\frac{r_\alpha^2 r_m^{3/2}}{r_M^{1/2}}\right] E_{\mathrm{mol.\,vib,SM}}$$

$$E_{\mathrm{mol.\,rot}} = \left[\frac{r_\alpha^2 r_m^2}{r_M}\right] E_{\mathrm{mol.\,rot,SM}}$$

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Solving the hydrogen molecule

How to do better?

Get a better ansatz for the electronic wave-function. Work harder to solve for the energy levels (James-Coolidge, eg).

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$$E_{\mathrm{mol.\,rot}} = \left[\frac{r_\alpha^2 r_m^2}{r_M}\right] E_{\mathrm{mol.\,rot,SM}}$$

What else do we need?

To understand cooling, we need:

- Energy states available and their populations
- Transition probabilities
- Abundances of all species: reaction rates

$$\mathcal{C} = \sum_u n_u \sum_{\ell<u} A_{u\ell} \Delta E_{u\ell} \,,$$

Molecular properties

For $m \ll M$, leading order re-scaling can be calculated:

Quantity	Dependence	Re-scaling
a_0 (Bohr radius)	$\frac{1}{\alpha\, m}$	$r_\alpha^{-1}\, r_m^{-1}$
$E_{\rm H}$ (atomic energy level spacing)	$m\, \alpha^2$	$r_\alpha^2\, r_m$
$E_{\rm rot}$ (Molecular rotational energy)	$\frac{\alpha^2\, m^2}{M}$	$r_\alpha^2\, r_m^2\, r_M^{-1}$
$E_{\rm vib}$ (Molecular vibrational energy)	$\frac{\alpha^2\, m^{3/2}}{M^{1/2}}$	$r_\alpha^2\, r_m^{3/2}\, r_M^{-1/2}$
$\mathbf{d}$ (dipole moment)	0	0
$A_{\rm rot}$ (quadrupolar rotational Einstein coefficient)	$\frac{\alpha^7\, m^6}{M^5}$	$r_\alpha^7\, r_m^6\, r_M^{-5}$
$A_{\rm vib}$ (quadrupolar vibrational Einstein coefficient)	$\frac{\alpha^7\, m^{7/2}}{M^{5/2}}$	$r_\alpha^7\, r_m^{7/2}\, r_M^{-5/2}$
p_{ij} (polarizability)	$a_0^3 = \frac{1}{m^3\, \alpha^3}$	$r_\alpha^{-3}\, r_m^{-3}$

The same re-scaling can be applied to more exact numerical results for standard model hydrogen.

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)

Re-scaling a rate

$$\gamma_{J,J+2} = \langle \sigma v \rangle_{J \to J+2}$$

$$\gamma^{\mathrm{H(H_2)}}_{J,J-2,\mathrm{DM}}(T) = \left[r_\alpha^{-1}\, r_m^{-1}\, r_M^{-1} \right]\; \gamma^{\mathrm{H(H_2)}}_{J,J-2,\mathrm{SM}}(\tilde{T}_r),$$

$$\tilde{T}_r \equiv \left(\frac{r_M}{r_m^2 r_\alpha^2} \right)\; T,$$

Important reaction rates

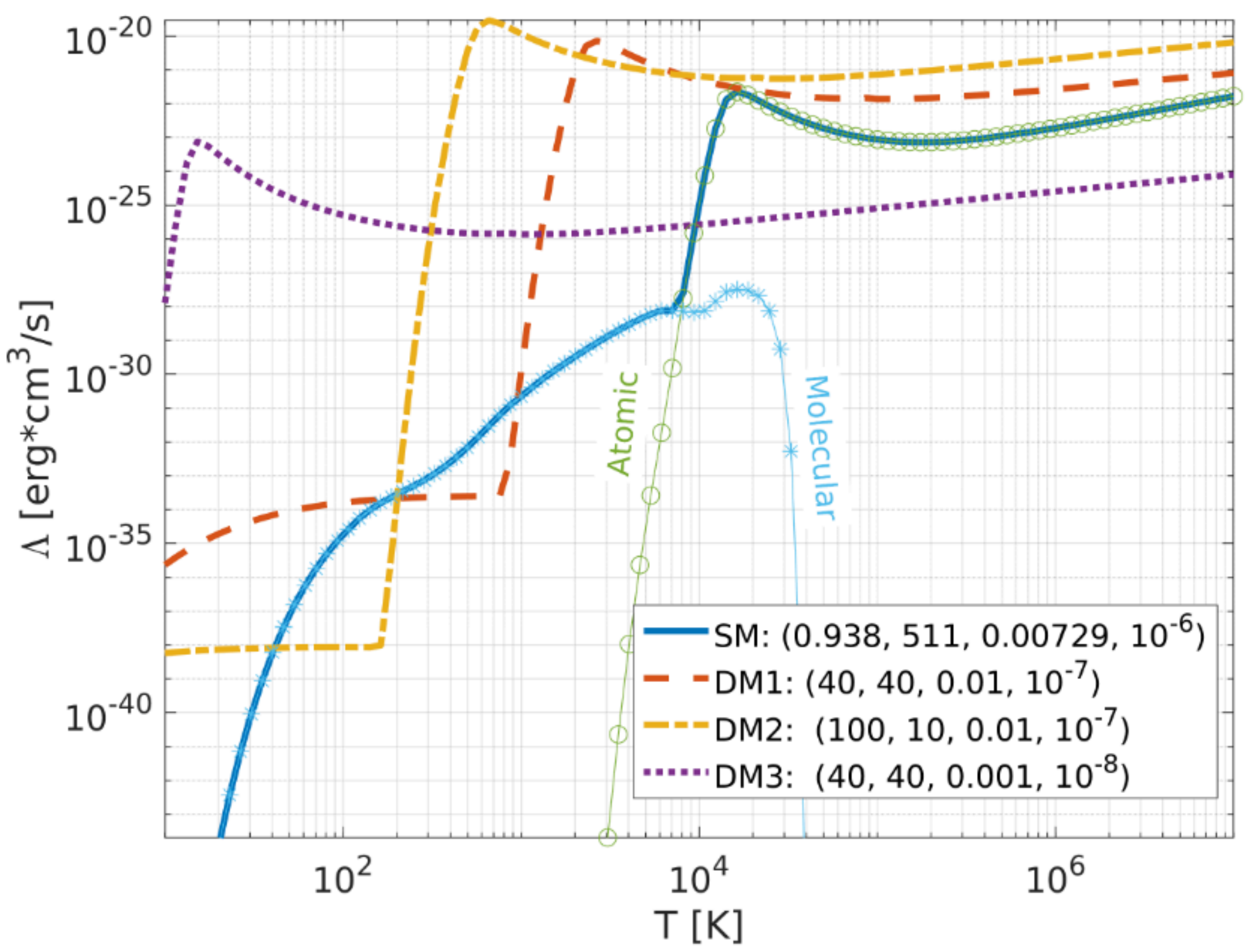
#	Reaction	Cross section source	σ	Re-scaling pre-factor $g(r_\alpha, r_m, r_M)$	b	Additional notes
1	$p + e \to \mathrm{H} + \gamma$(4.2)	Mo et al. (2010)	$\frac{\alpha^5}{\mathrm{K.E.}(\mathrm{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$	$-0.62, -1.15$	a, b
2	$\mathrm{H} + \gamma \to p + e$(4.2)	Mo et al. (2010)	$\mu\, \alpha^5 \frac{1}{(\mathrm{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$	0.88, 0.35	c
3	$\mathrm{H} + e \to \mathrm{H}^- + \gamma$ (4.3)	de Jong (1972)	$\frac{\alpha}{\mu^2} \frac{\Delta E^{1/2}\, \mathrm{K.E.}^{1/2}}{(\mathrm{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$	0.928	a, d
4	$\mathrm{H}^- + \gamma \to \mathrm{H} + e$	Armstrong (1963)	$\frac{\alpha}{\mu} \frac{\Delta E^{1/2} K^{3/2}}{(\mathrm{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$	2.13	c, d
5	$\mathrm{H}^- + \mathrm{H} \to \mathrm{H}_2 + e$	Browne & Dalgarno (1969)	$\sqrt{\frac{\alpha\, a_0^3}{\mathrm{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	e, f, g
7	$\mathrm{H}^- + p \to 2\mathrm{H}$ (4.4)	Bates & Lewis (1955)	$\alpha\, a_0^2 \sqrt{\mu}\, \frac{\sqrt{\mathrm{K.E.}+\Delta E}}{\mathrm{K.E.}\, \Delta E}$	$r_\alpha^{-3}\, r_m^{-3}$	$-\frac{1}{2}$	e, h
8	$\mathrm{H} + p \to \mathrm{H}_2^+ + \gamma$	Stancil et al. (1993)	$\frac{(\mathrm{K.E.}+\Delta E)^3 \alpha^4}{E_\mathrm{H}^3\, \mathrm{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^2\, r_m^{-1}\, r_M^{-1}$	1.8	i
9	$\mathrm{H}_2^+ + \gamma \to \mathrm{H} + p$	Stancil et al. (1993)	$\left(\frac{\mu\, v}{h\, \nu}\right)^2 \frac{(\mathrm{K.E.}+\Delta E)^3 \alpha^4}{E_\mathrm{H}^3\, \mathrm{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^5\, r_m^{1/2}\, r_M^{1/2}$	1.59	c, j
10	$\mathrm{H}_2^+ + \mathrm{H} \to \mathrm{H}_2 + p$(4.5)	Galli & Palla (1998)	$\sqrt{\frac{\alpha\, a_0^3}{\mathrm{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	g
13	$\mathrm{H}_2^+ + \mathrm{H}_2 \to \mathrm{H}_3^+ + \mathrm{H}$	—"—	—"—	—"—	0	g
15	$\mathrm{H}_2 + p \to \mathrm{H}_2^+ + \mathrm{H}$(4.5)	—"—	—"—	—"—	0	g, j
20	$\mathrm{H}_3^+ + e \to \mathrm{H} + \mathrm{H}_2$	Draine (2011)	$\frac{\alpha\, a_0}{\mathrm{K.E.}}$	$r_\alpha^{-1}\, r_m^{-2}\, r_M$	-0.65	k
*	$\mathrm{H}_2 + \mathrm{H} \to 3\mathrm{H}$ (4.6)	Hard Sphere	a_0^2	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	l
3B1	$3\mathrm{H} \to \mathrm{H}_2 + \mathrm{H}$ (4.7)	Hard Sphere/Detailed Balance	$a_0^2 \left[\frac{n_{\mathrm{H}_2}}{n_\mathrm{H}^2}\right]_\mathrm{LTE}$	$r_\alpha^{-4}\, r_m^{-4}\, r_M^{-1}$	-1	j, m
3B2	$\mathrm{H}_2 + 2\mathrm{H} \to 2\mathrm{H}_2$ (4.7)	—"—	—"—	—"—	-1	j, m
3B3	$2\mathrm{H} + \mathrm{H}^+ \to \mathrm{H}_2 + \mathrm{H}^+$ (4.7)	—"—	—"—	—"—	-1	j, m
3B4	$2\mathrm{H} + \mathrm{H}^+ \to \mathrm{H}_2^+ + \mathrm{H}$ (4.7)	—"—	—"—	—"—	-1	j, m

$$\gamma = \langle \sigma v \rangle \propto g(r_\alpha, r_m, r_M) \left(\frac{T}{r_{\Delta E}} \right)^b$$

(But choose your favorite modern reaction rate for a more precise rate)

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)
Some previous estimates in 1712.04779 (A. Ghalsasi, M. McQuinn)

Atomic + molecular cooling rates



Legend: $(M[\mathrm{GeV}], m[\mathrm{keV}], \alpha, x_{\mathrm{H_2}})$

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)

Now we can revisit how atomic dark matter cools, how structure forms

DarkKROME

Solve the chemical network for atomic dark matter

One-zone collapse (free-fall)

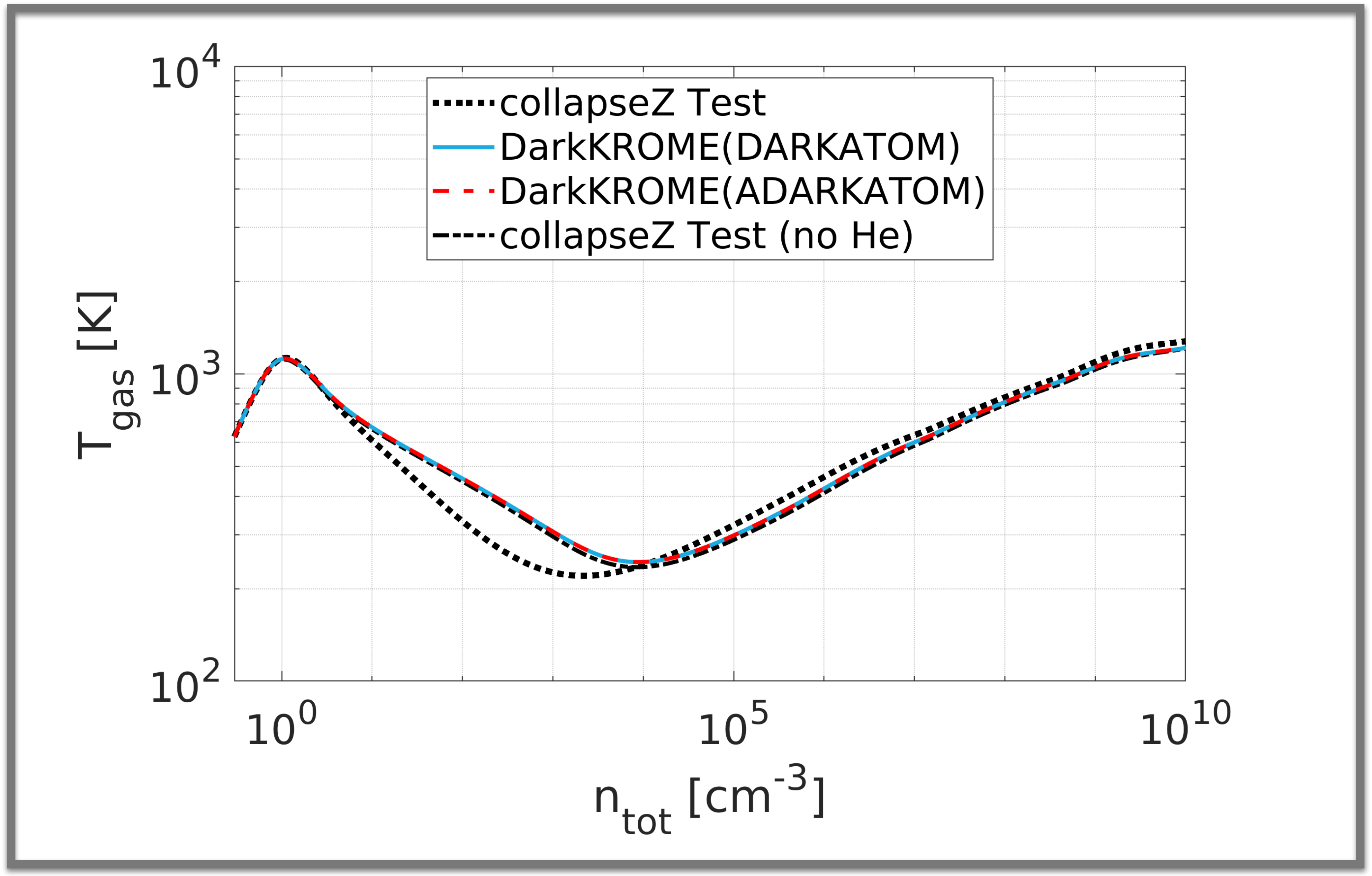
$$\frac{d\rho}{dt} = \frac{\rho}{t_{ff}}$$

$$\frac{dT}{dt} = (\gamma - 1)\frac{\Gamma(T,\bar{n}) - \Lambda(T,\bar{n})}{k_B \sum_i n_i}$$

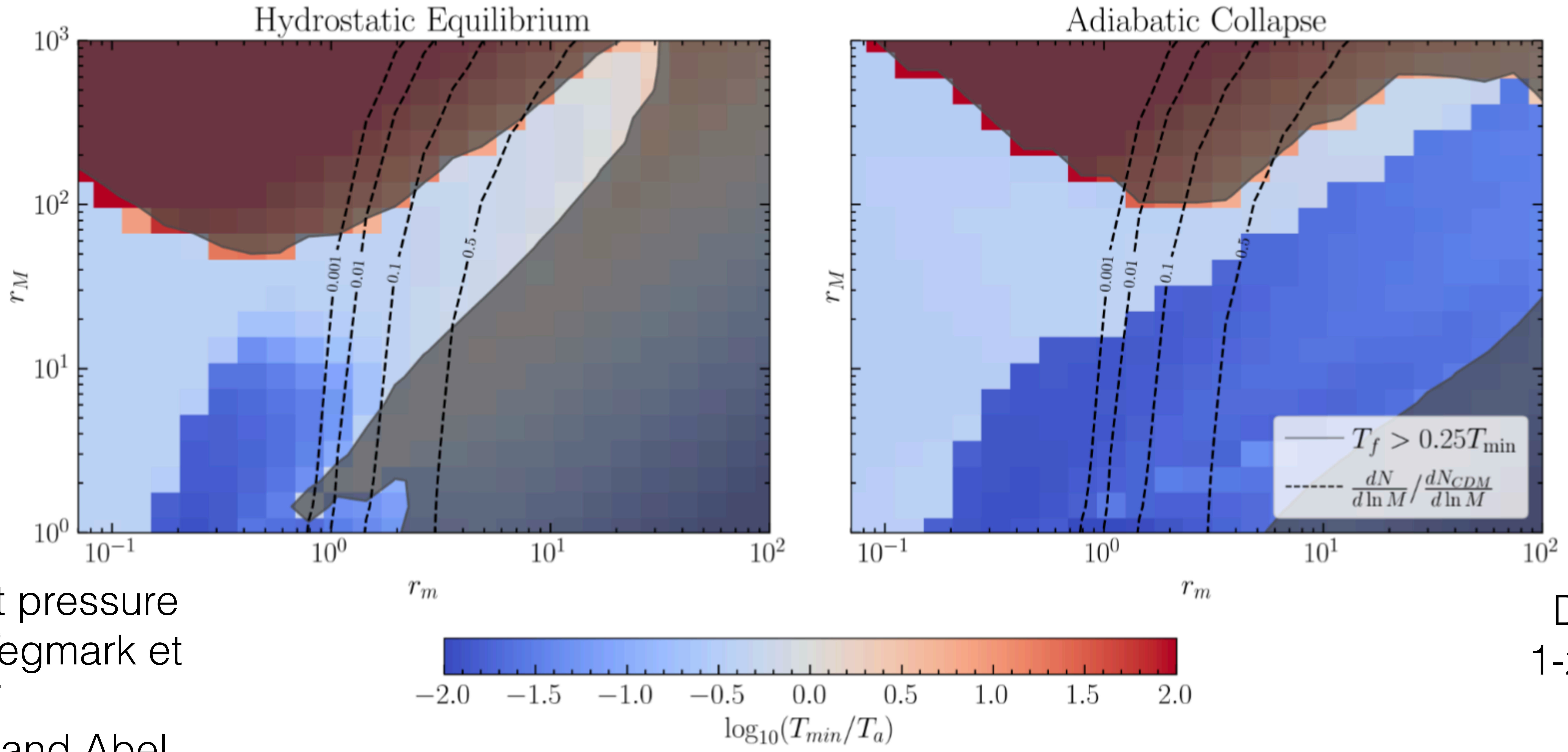
KROME: Grassi et al, 1311.1070 (kromepackage.org)

Molecular, atomic abundances: J. Gurian, M. Ryan, D. Jeong, S. Shandera, 2110.11964
Homogeneous cosmology of the early universe (Recfast ++)
(https://github.com/jamesgurian/RecfastJulia)

DarkKROME: https://bitbucket.org/mtryan83/darkkrome
2110.11971 (**M. Ryan**, S. Shandera, J. Gurian, D. Jeong)



Minimum temperature dark matter can reach?



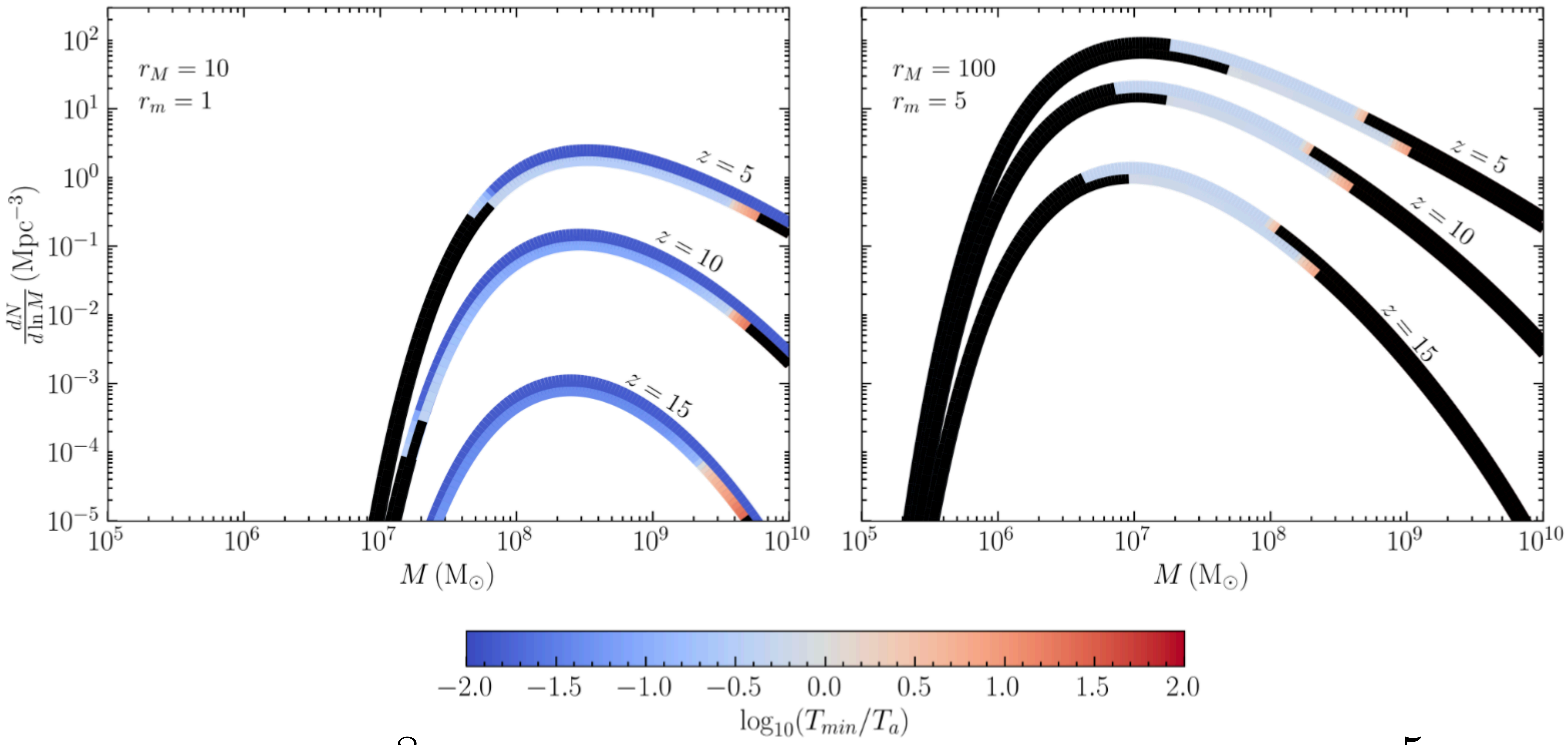
Maintain constant pressure (technique from Tegmark et al, 1997 ApJ 474; Glover and Abel 2008)

$10^8\,\mathrm{M}_\odot,\ z=10,\ r_\alpha=1,\ \xi=3\times10^{-5}$

Dark KROME
1-zone collapse

(Gurian et al 2209.00064)

How much dark matter can cool?

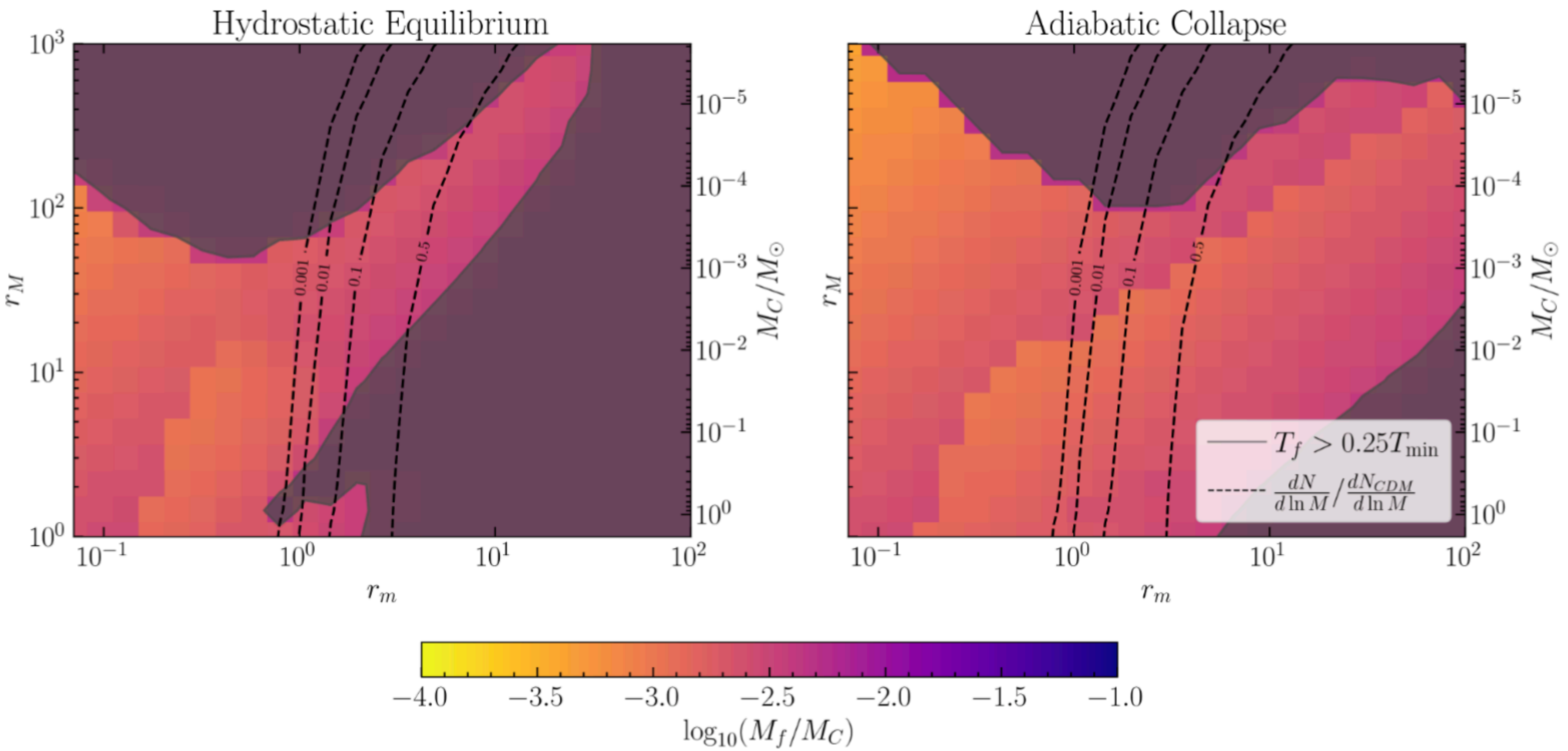


$$10^8\,\mathrm{M}_\odot,\ z = 10,\ r_\alpha = 1,\ \xi = 3\times 10^{-5}$$

Figure 2. The halo mass function for two representative choices of parameters (see Fig. 1). The bottom color band of each curve indicates the minimum temperature of those halos which collapse under hydrostatic evolution, while the top band illustrates the adiabatic density case. The black region fails to cool.

Gurian, Ryan, Schon, Jeong, Shandera 2209.00064

Fragmentation



$$10^8\,\mathrm{M}_\odot,\ z=10,\ r_\alpha=1,\ \xi=3\times10^{-5}$$

Opacity limit fragment mass

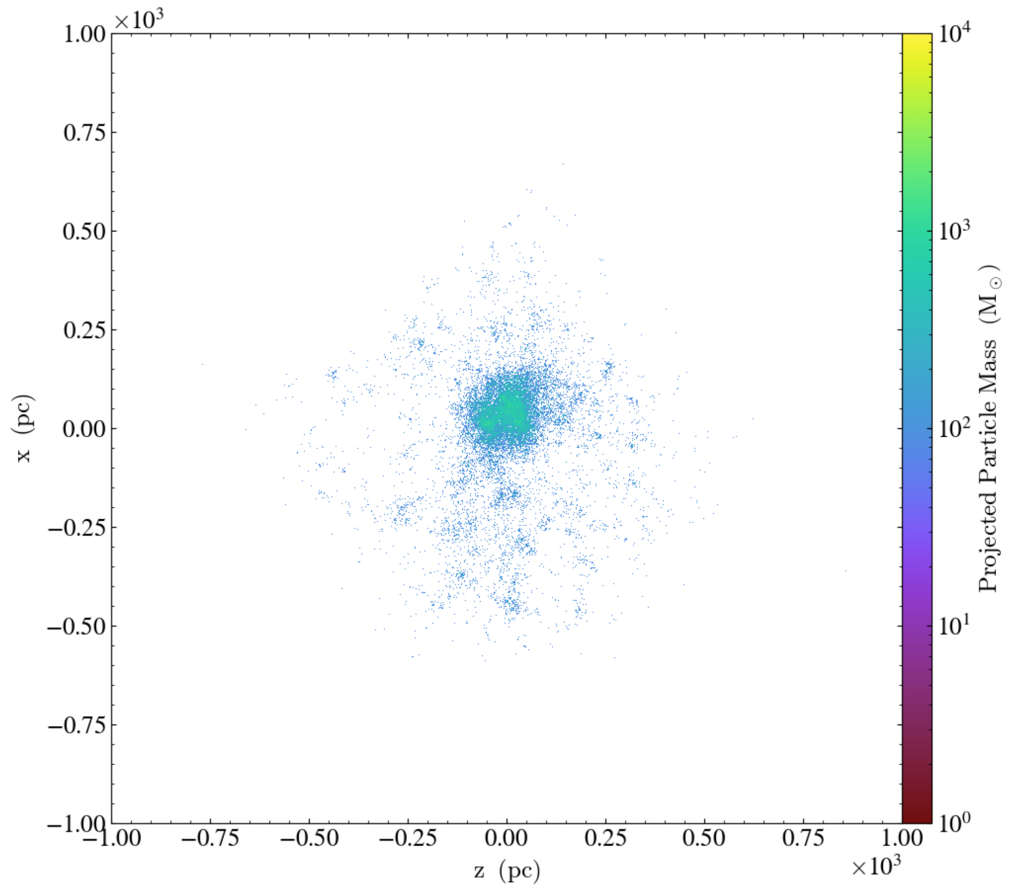
Accretion significantly adds to protostar mass

(Gurian et al 2209.00064)

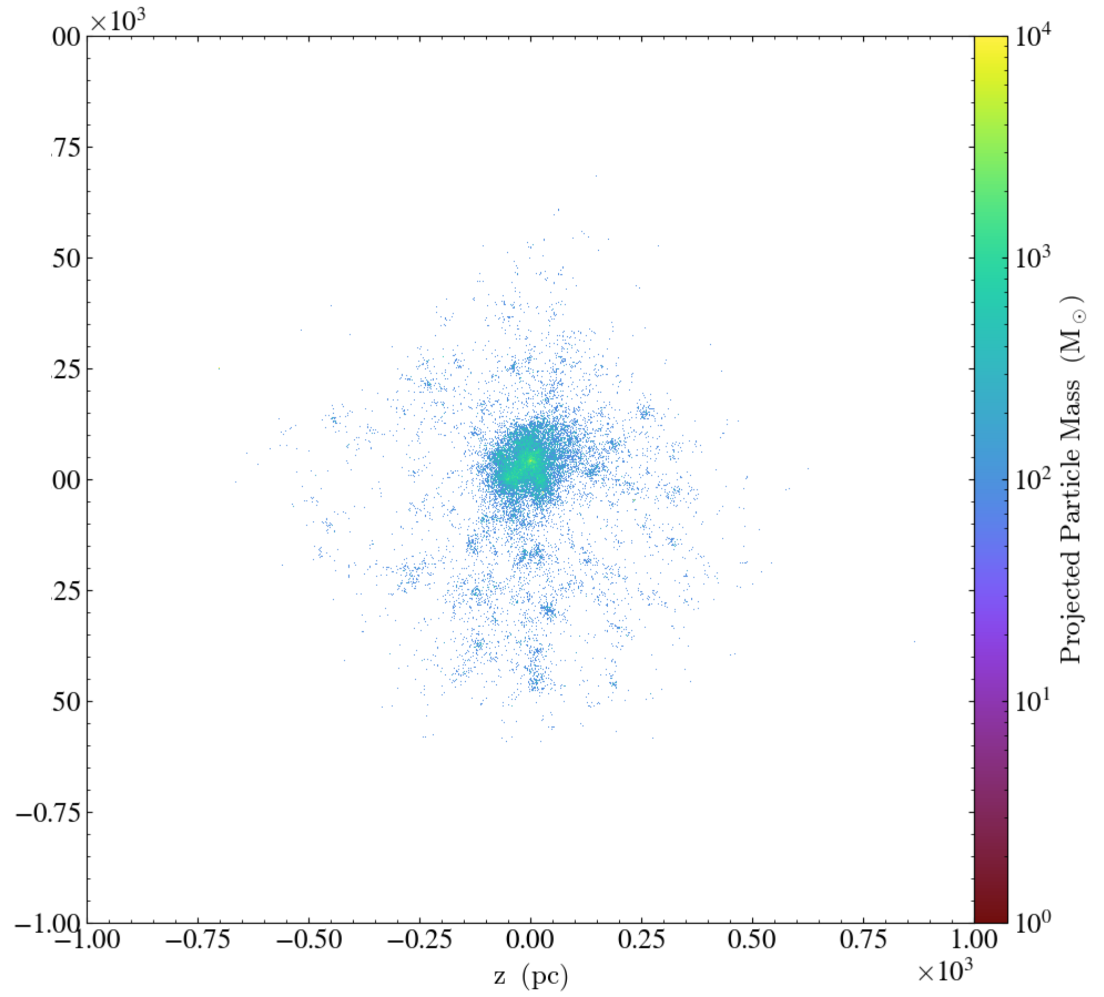
Next steps: full simulations

We have added DarkKROME to (modified) Gizmo: *hydrodynamical* atomic dark matter halo

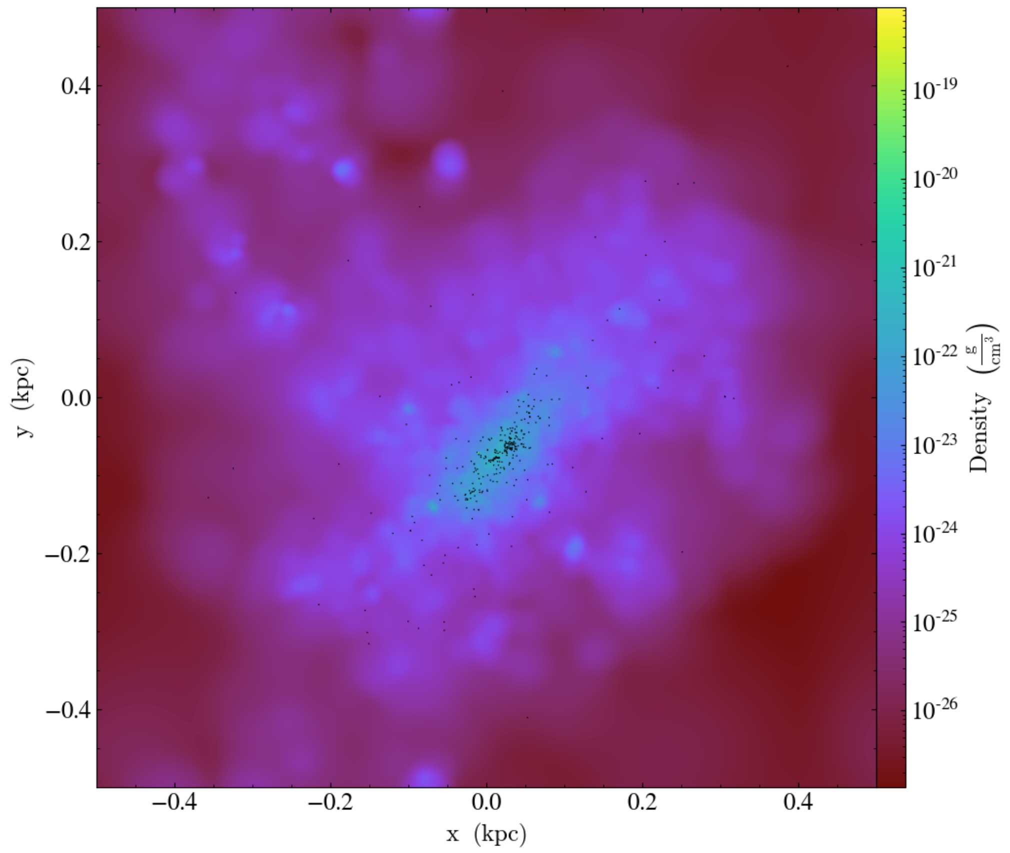
Simulations:
Sarah Schon



Cold dark matter



~ atomic dark matter



~ aDM proto-objects

Gizmo: P. Hopkins
Also: Roy, Shen, Lisanti, Curtin, Murray, Hopkins, 2304.09878, 2311.02148; 6% aDM

Next steps: full simulations

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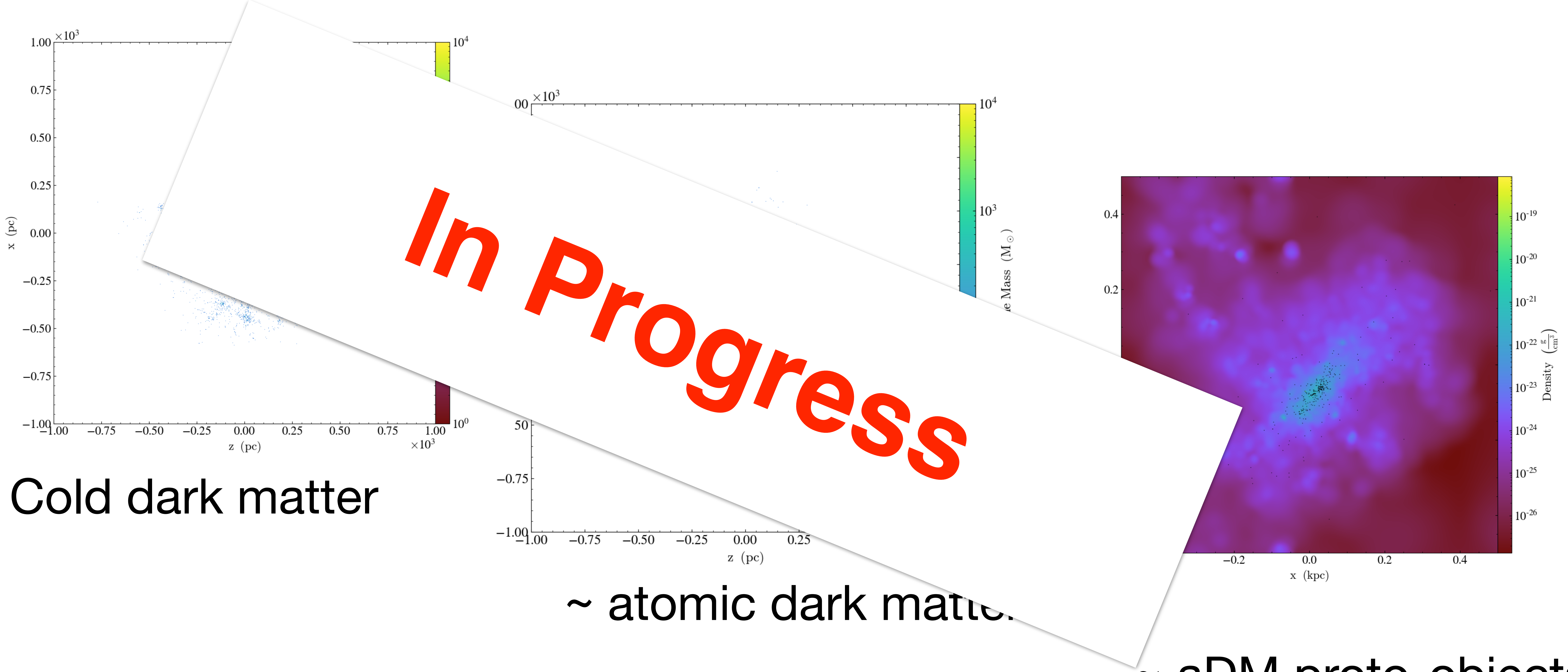

Cold dark matter

~ atomic dark matter

~ aDM proto-objects

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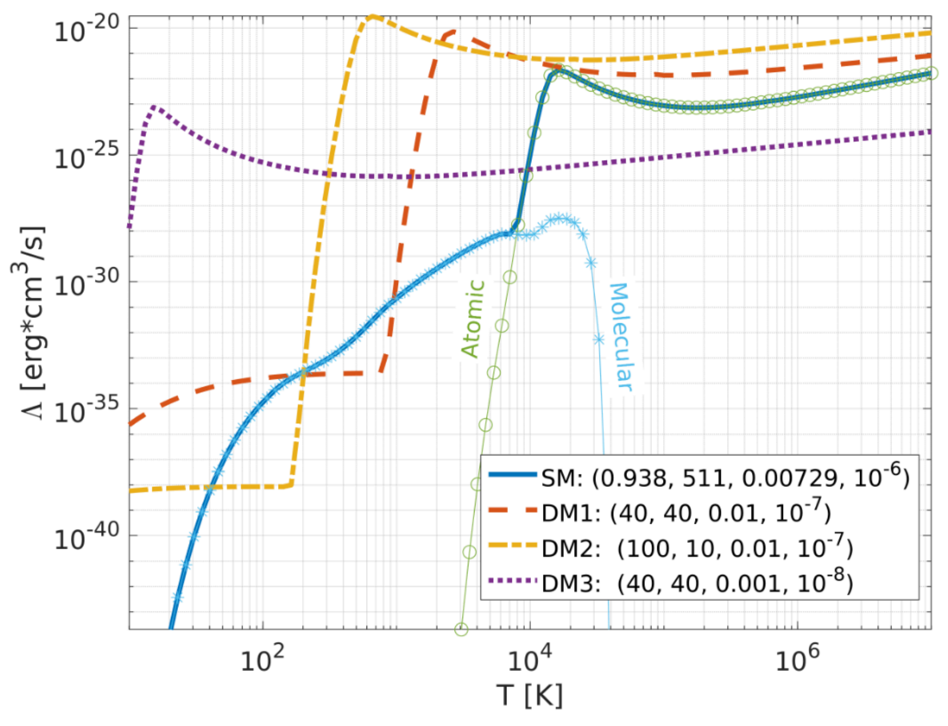
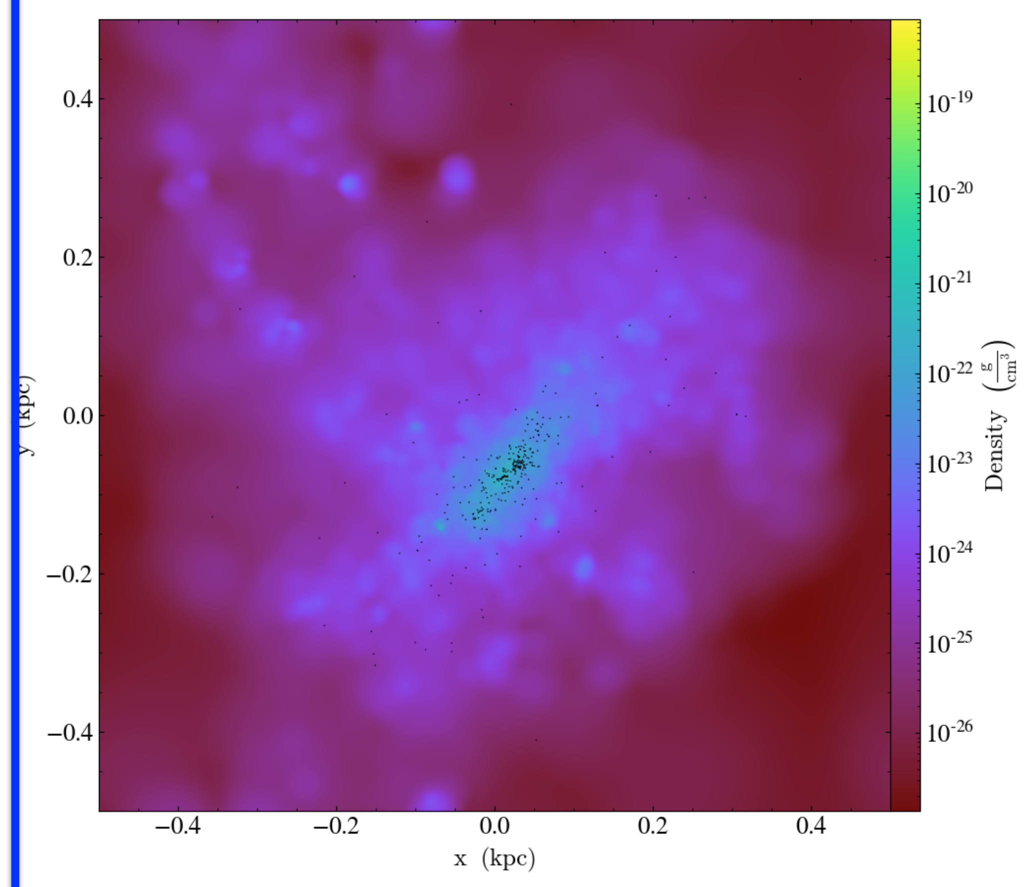
Particle Physics and Chemistry

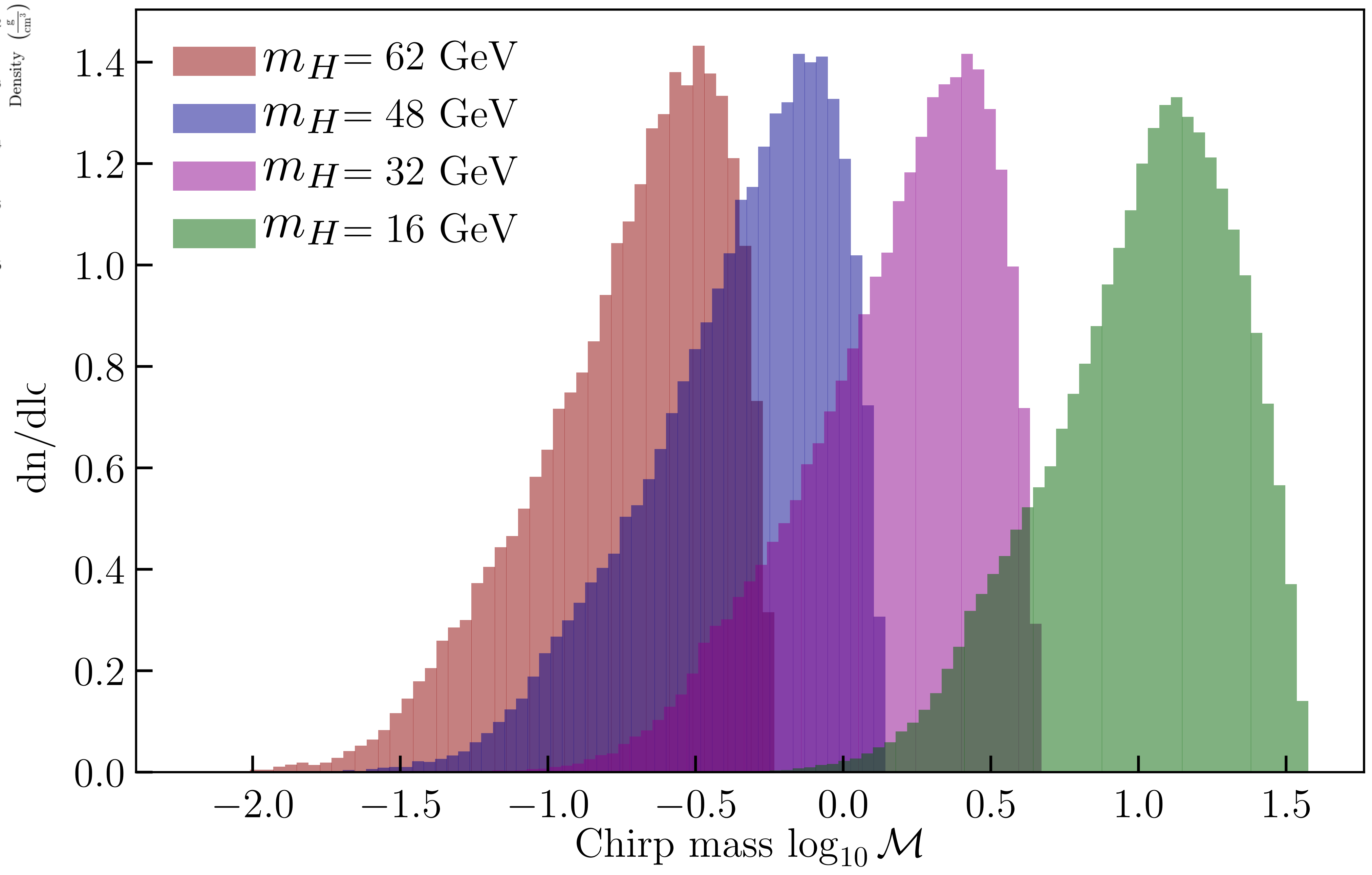


Hard!

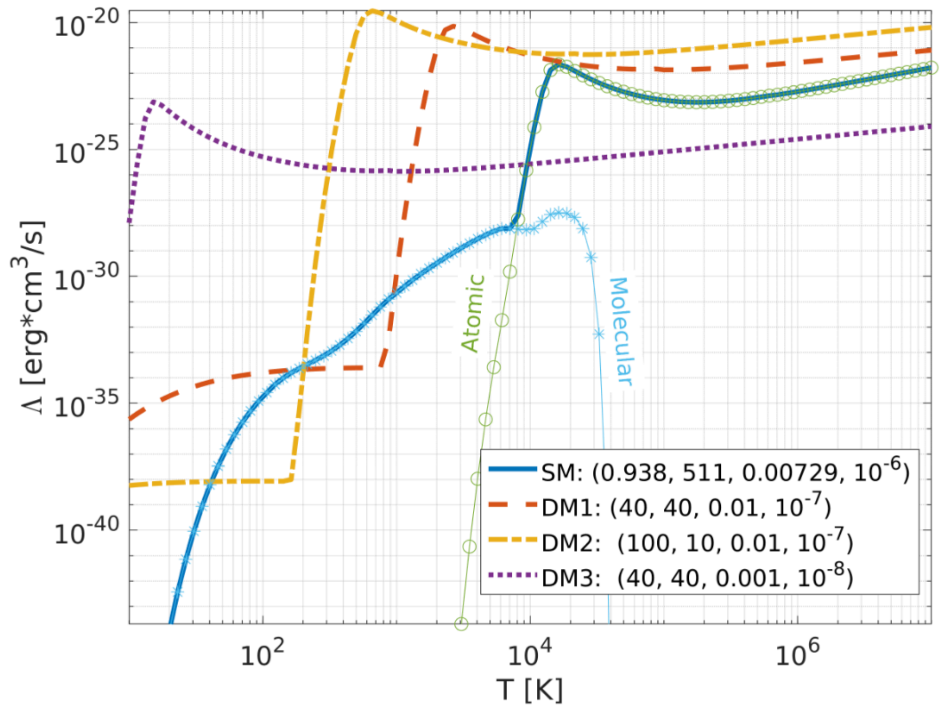
Structure formation



Population model for ultracompact objects

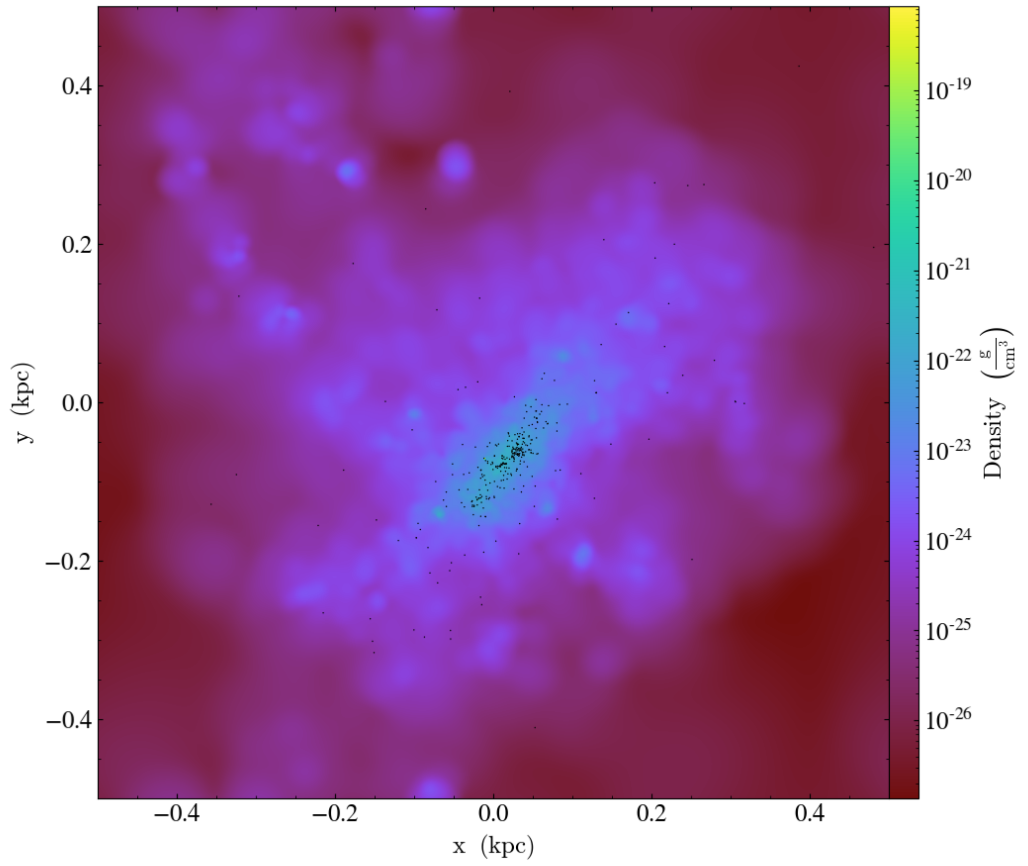


Particle Physics and Chemistry

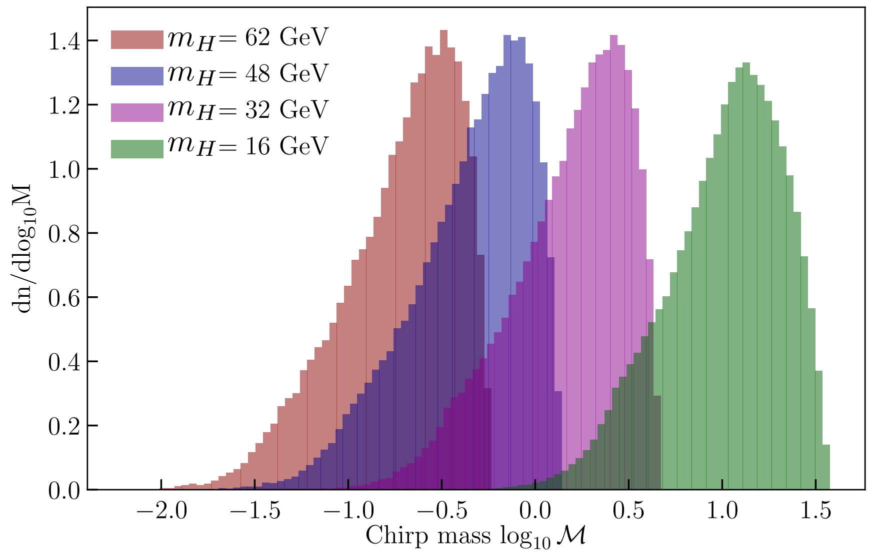


Hard!

Structure formation

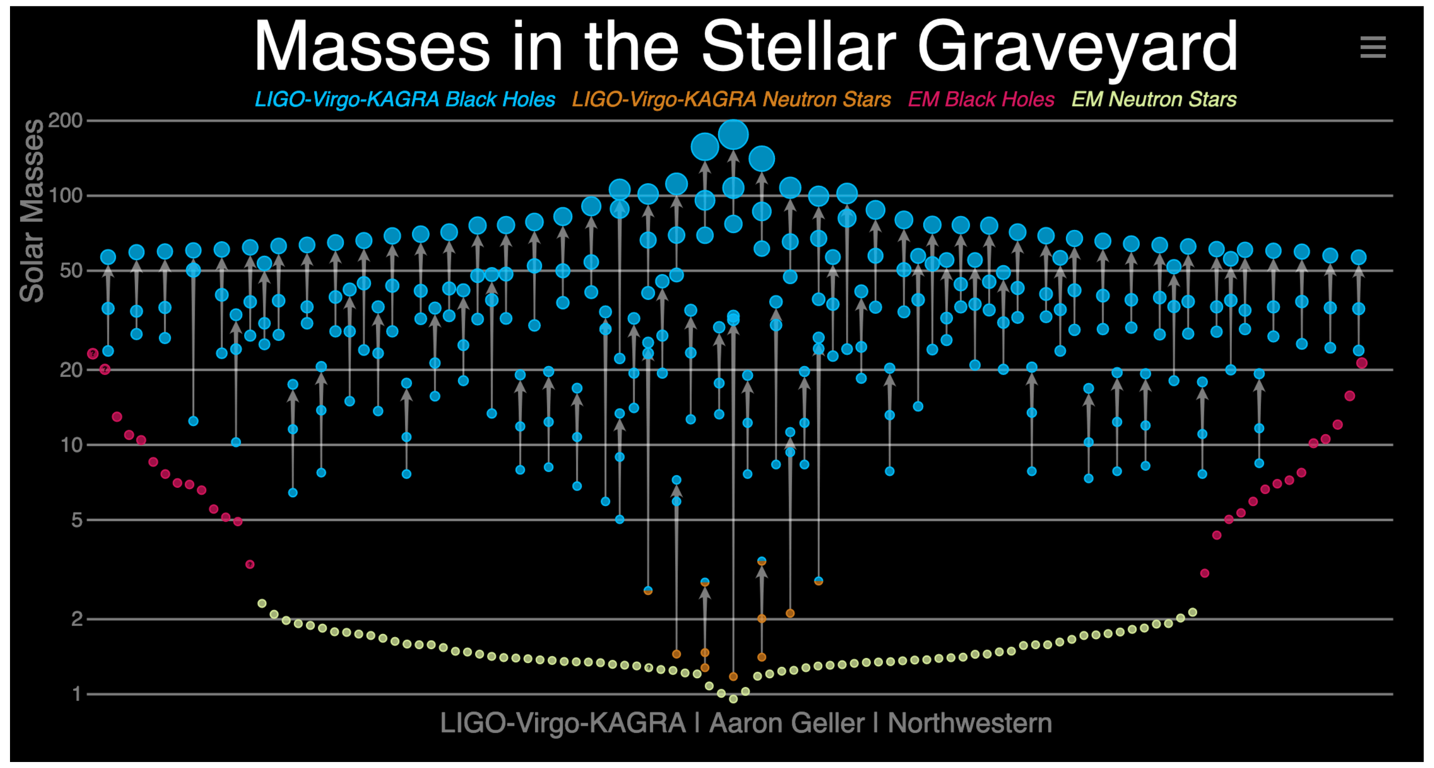


Population model for ultracompact objects



Not too hard

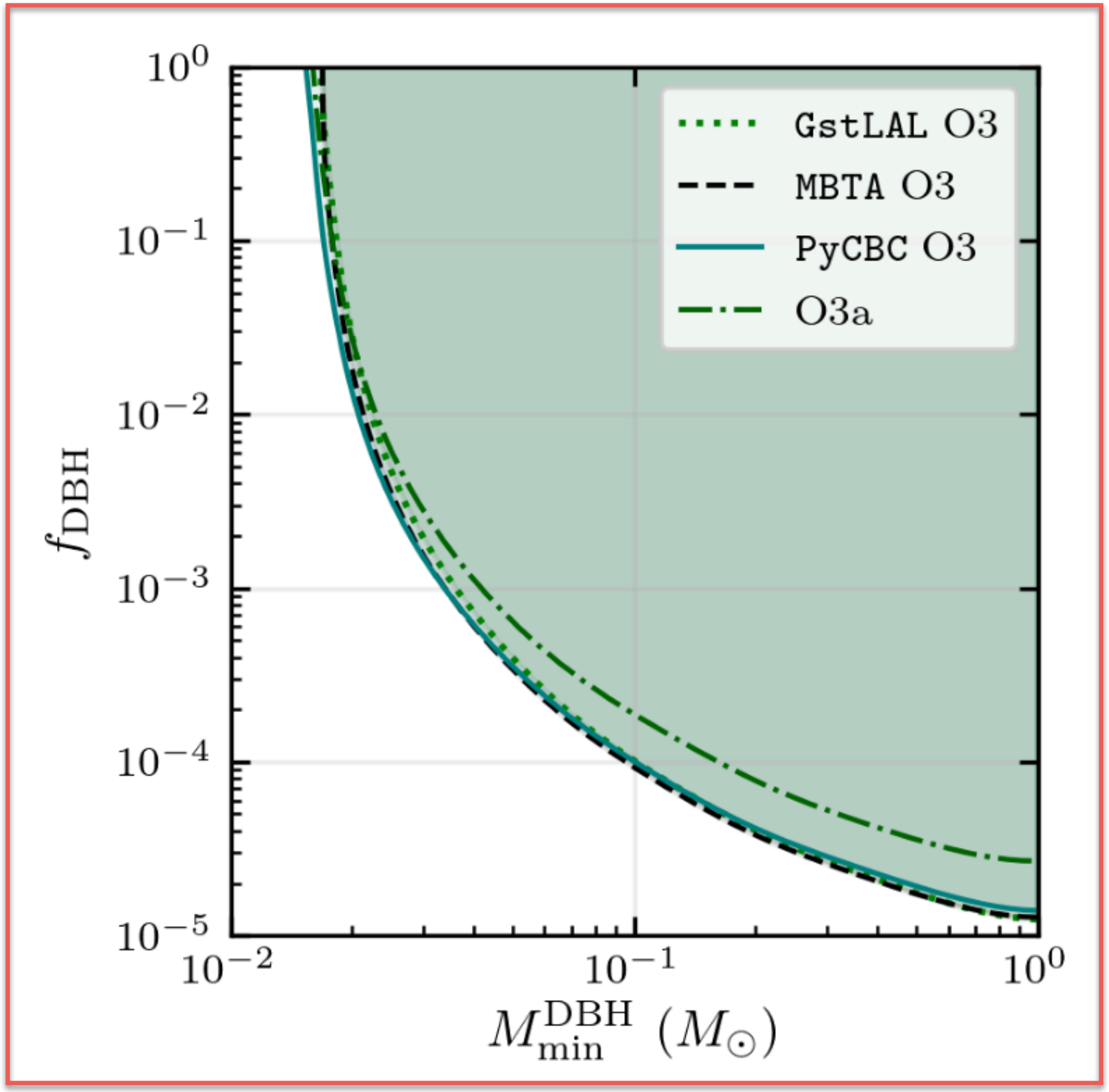
Gravitational wave data



Search for sub-solar mass black holes

- Search for sub-solar mass black holes: so far, no detect

Fourth observing run is in progress



LIGO, Virgo, KAGRA, D. Jeong, S. Shandera; (2212.01477, MNRAS; 2109.12197, PRL; 1904.08976 PRL;1808.04771 PRL); **R. Magee** et al 1808.04772, PRD;

Lots of interesting ways to look for compact objects

(Blackboard)

What would we learn if we found something?

GW190425: an intriguing event

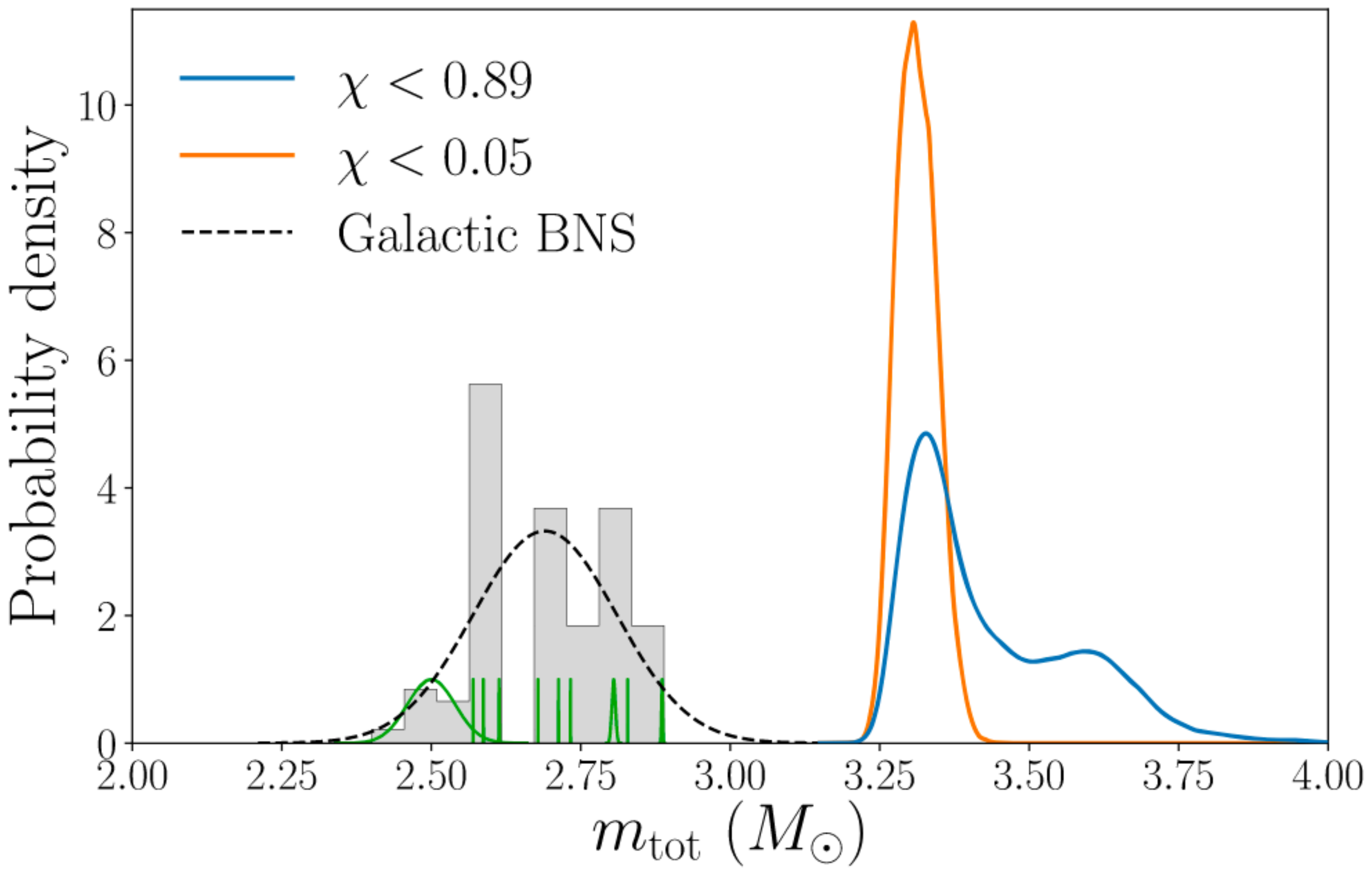


Figure 5. Total system masses for GW190425 under different spin priors, and those for the 10 Galactic BNSs from Farrow et al. (2019) that are expected to merge within a Hubble time. The distribution of the total masses of the latter is shown and fit using a normal distribution shown by the dashed black curve. The green curves are for individual Galactic BNS total mass distributions rescaled to the same ordinate axis height of 1.

LVC collaboration paper 2001.01761

$\gtrsim 5\sigma$ Outlier from known BNS systems

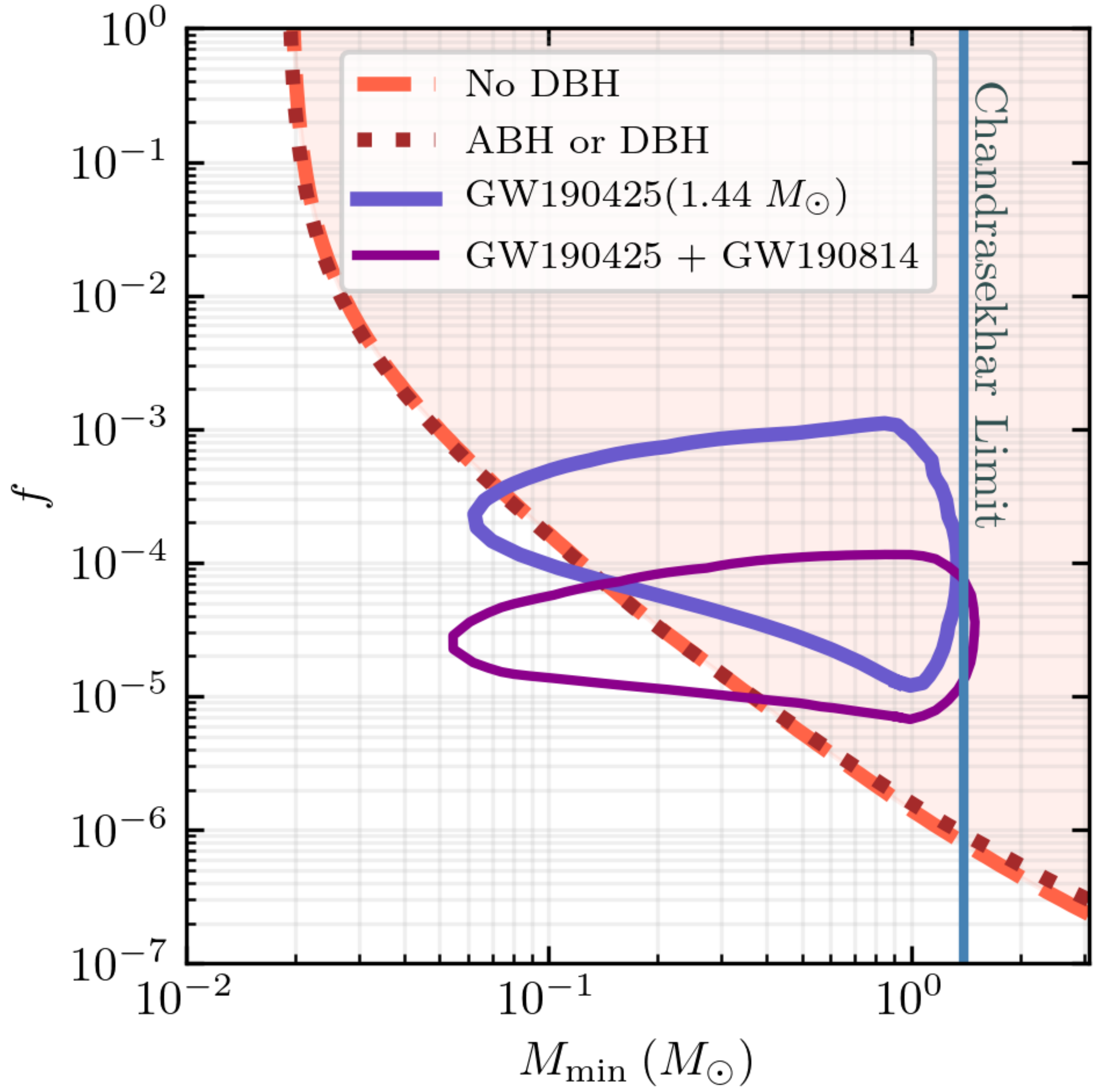
Component masses:

$$1.12 - 2.52\, M_\odot$$

“Neutron star” label currently applied based on mass alone, in absence of EM counterpart

If GW190425 is a dark black hole event:

Rates → Limits on source population



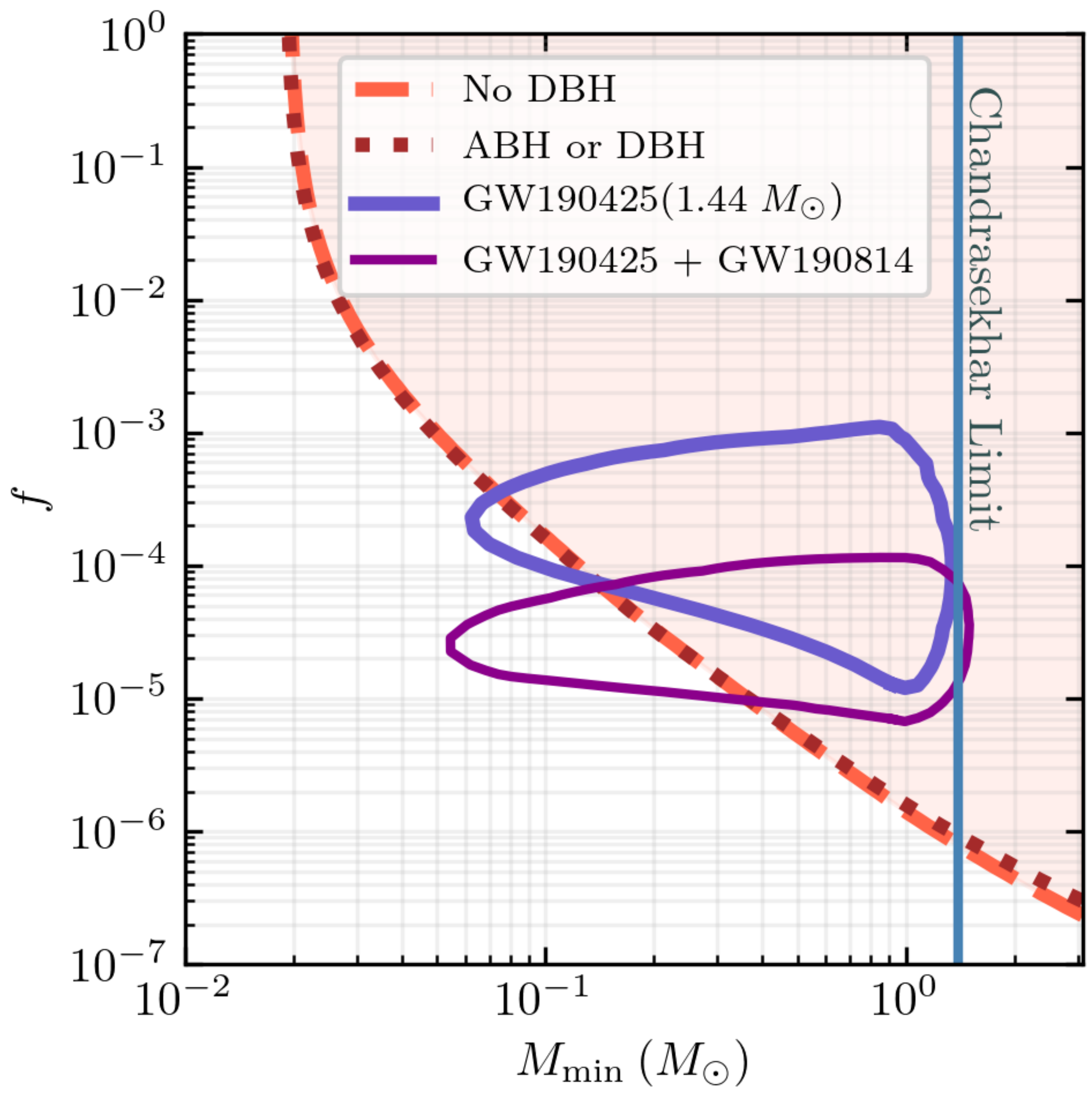
D. Singh, M. Ryan, R. Magee, T. Akhter, S. Shandera, D. Jeong, C. Hanna (2009.05209)

If GW190425 is a dark black hole event:

Rates ➡ Limits on source population

(A1) $M_{\rm min} \to M_{\rm D.Chand.} \to M_{\rm heavy\ fermion}$

$$M^{DM}_{\rm Chand.} < 1.4 M_\odot\,, \quad 99.9\%{\rm C.L.}$$



D. Singh, M. Ryan, R. Magee, T. Akhter, S. Shandera, D. Jeong, C. Hanna (2009.05209)

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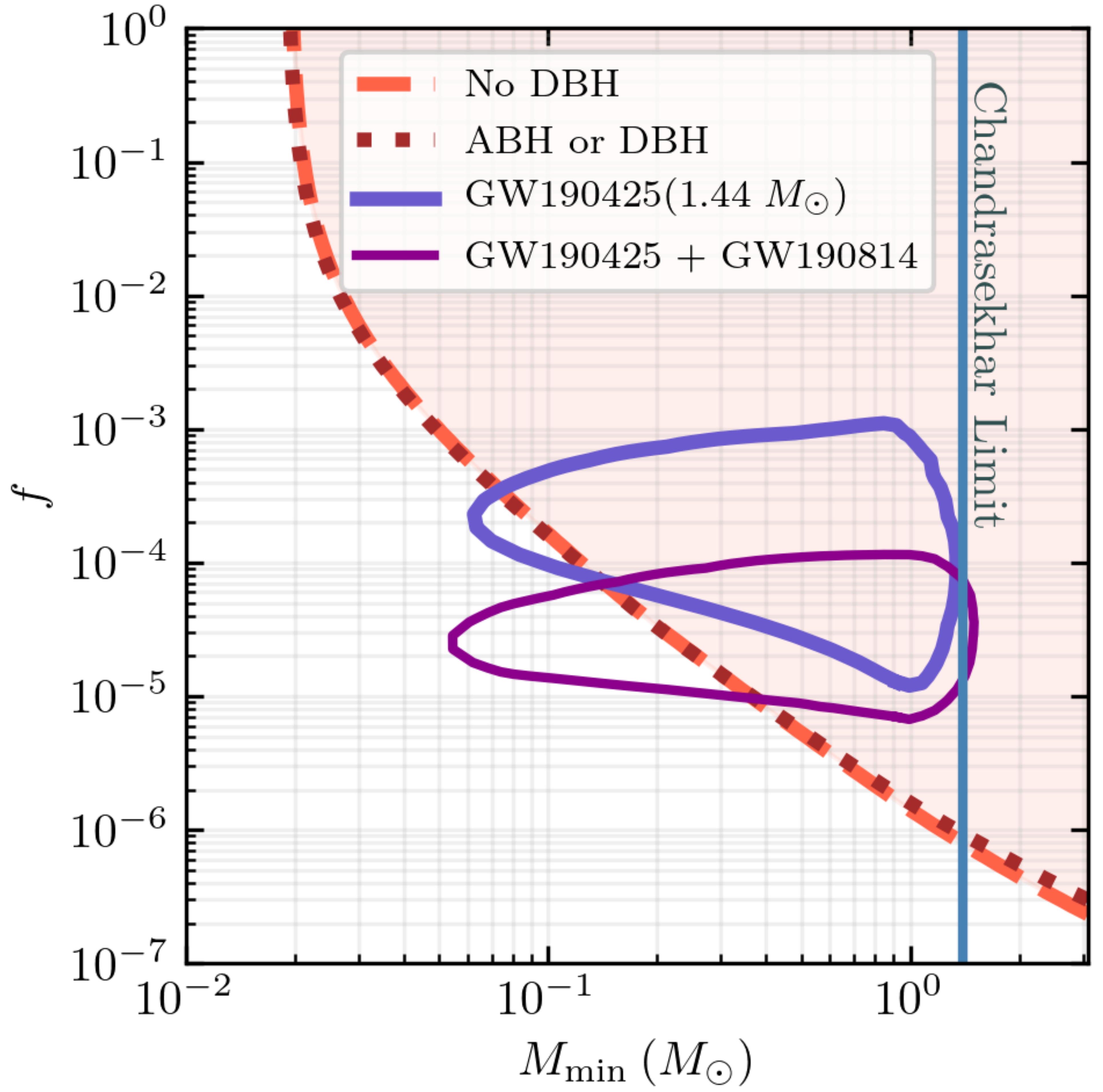
$$M^{DM}_{\rm Chand.} < 1.4 M_\odot\,, \quad 99.9\%{\rm C.L.}$$

(A2) $M_{\rm min} \to M_{\rm min\ gas\ fragment} \to \Delta E_{\rm molecular}$

$$\Delta E_{\rm mol.} \sim 10^{-3}\,{\rm eV} \propto \frac{\alpha^2 m^2}{M}$$



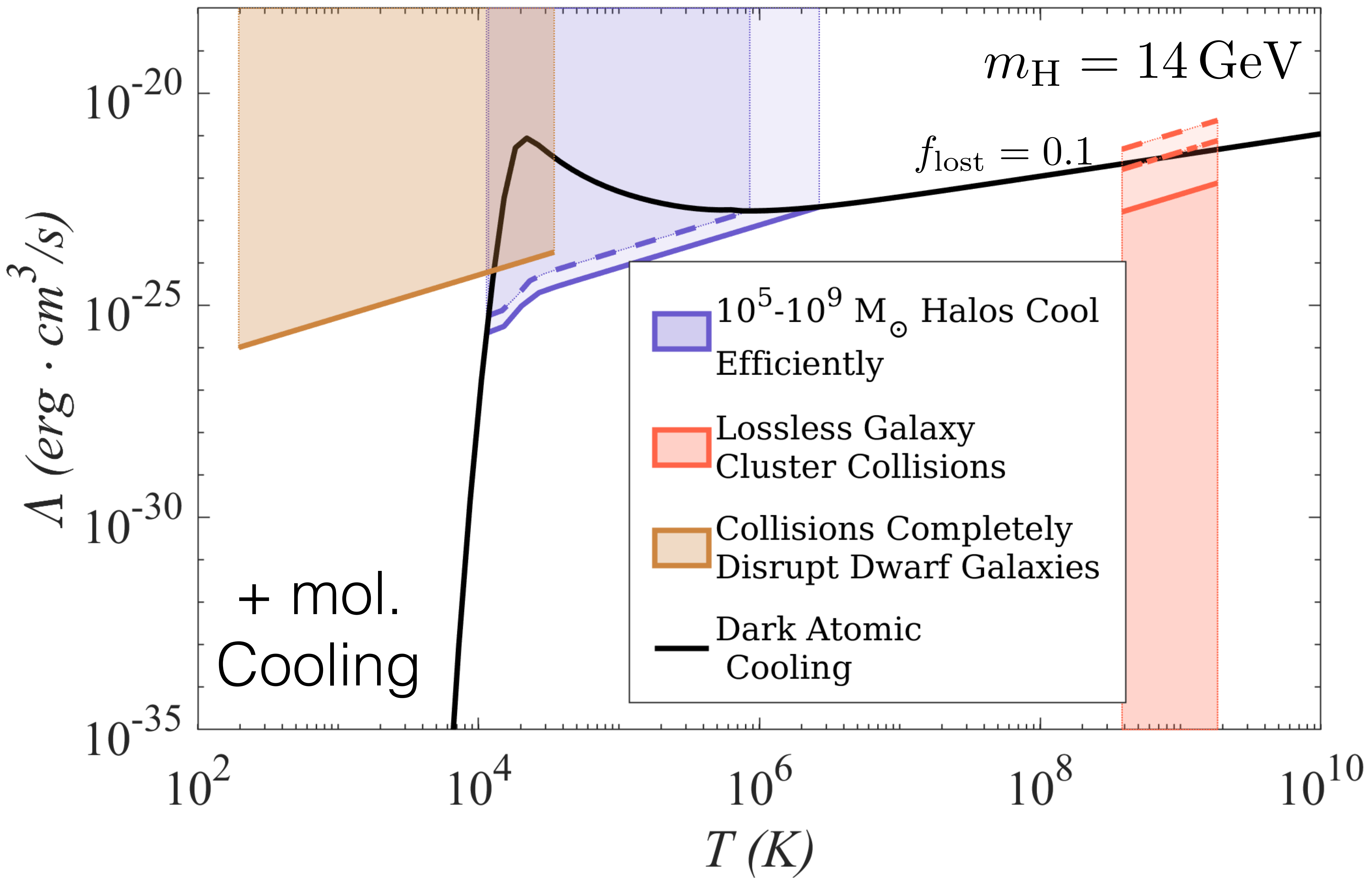
D. Singh, M. Ryan, R. Magee, T. Akhter, S. Shandera, D. Jeong, C. Hanna (2009.05209)

If GW190425 is a Dark Black Hole Event:

(B) Cooling rate (over number density) of dark matter

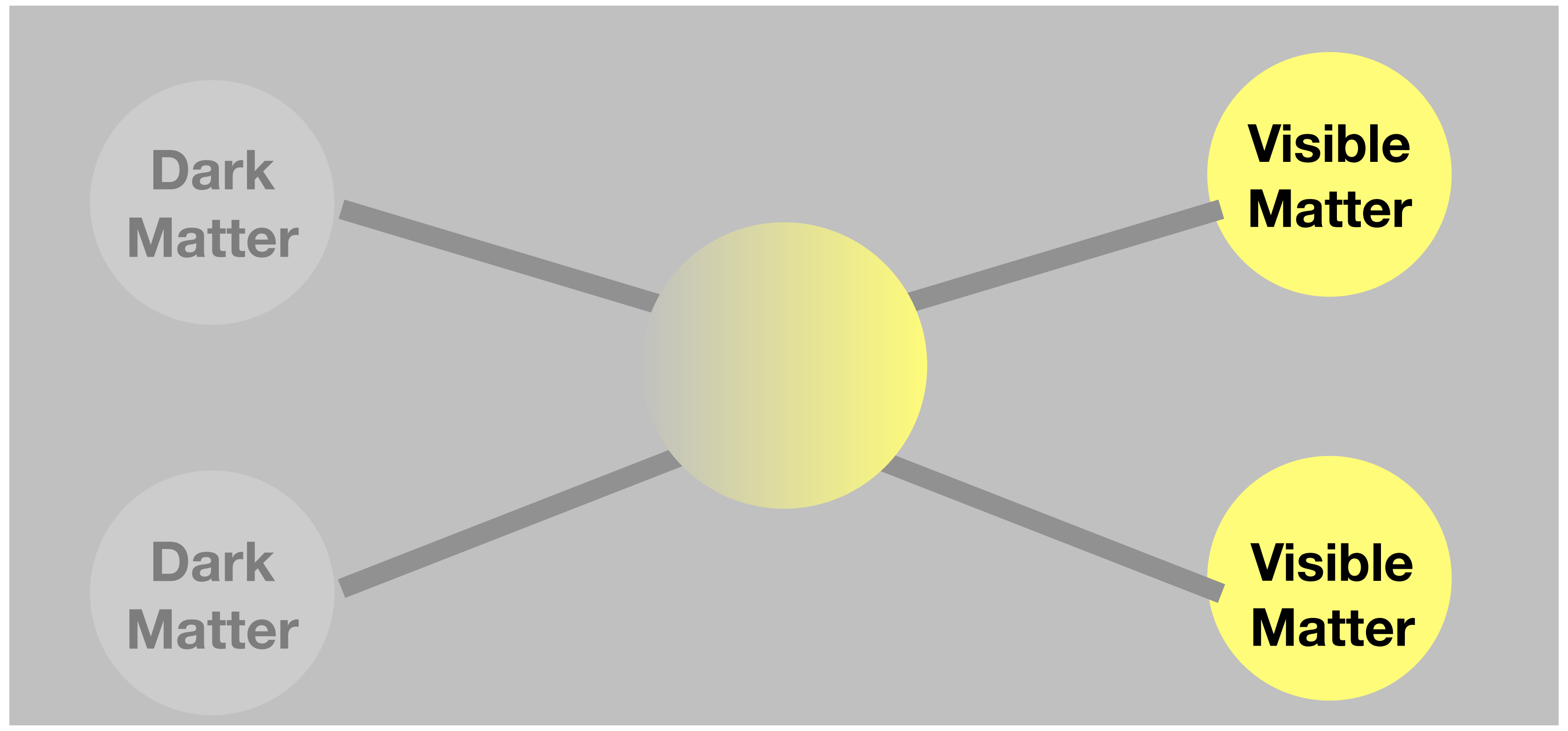
To form DBHs, need a minimum amount of cooling

Collisions in Bullet cluster give an upper bound on cooling (energy loss)



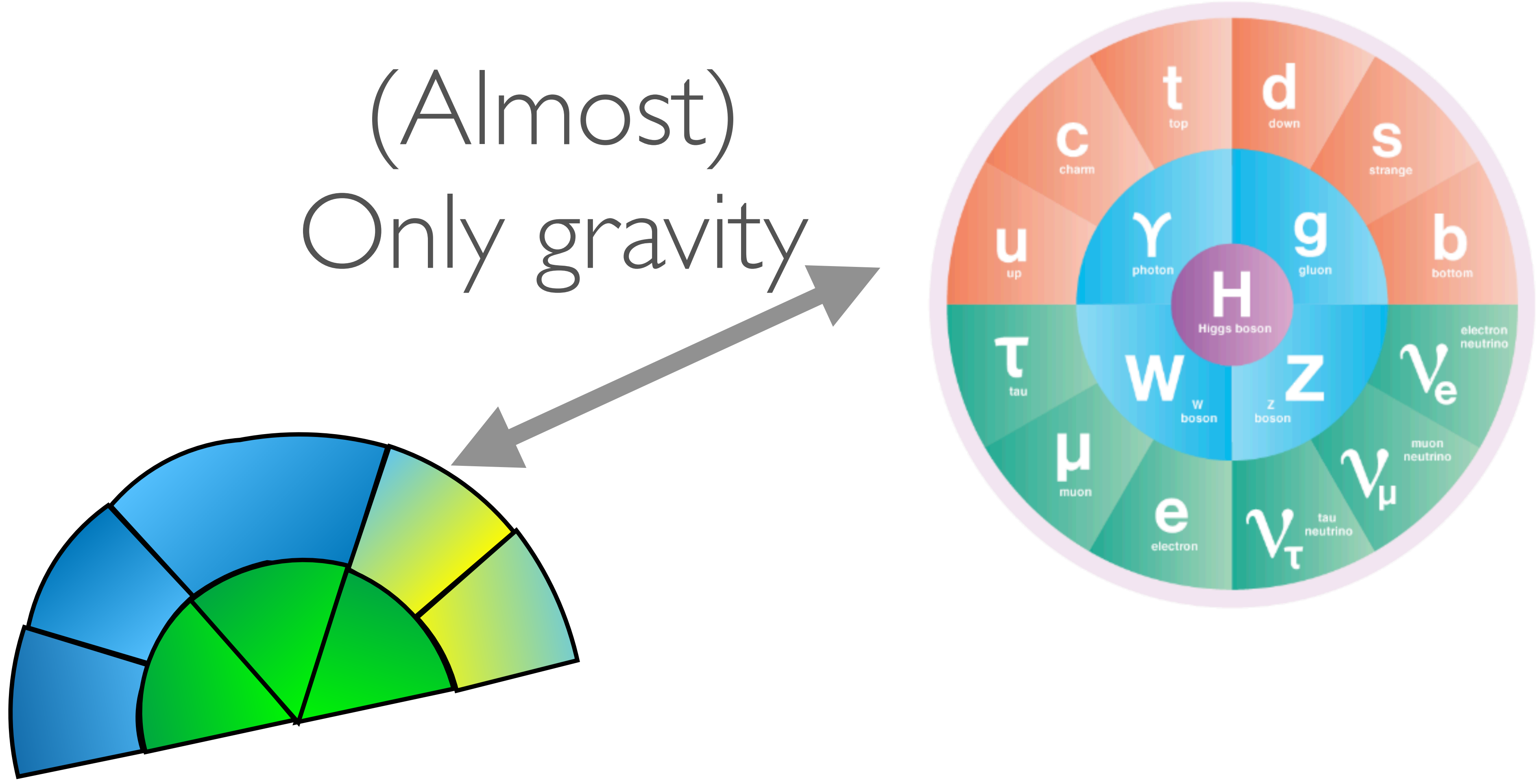
D. Singh et. al. 2009.05209

Summary: Perspective



Most important interaction is with the Standard Model

- Or -



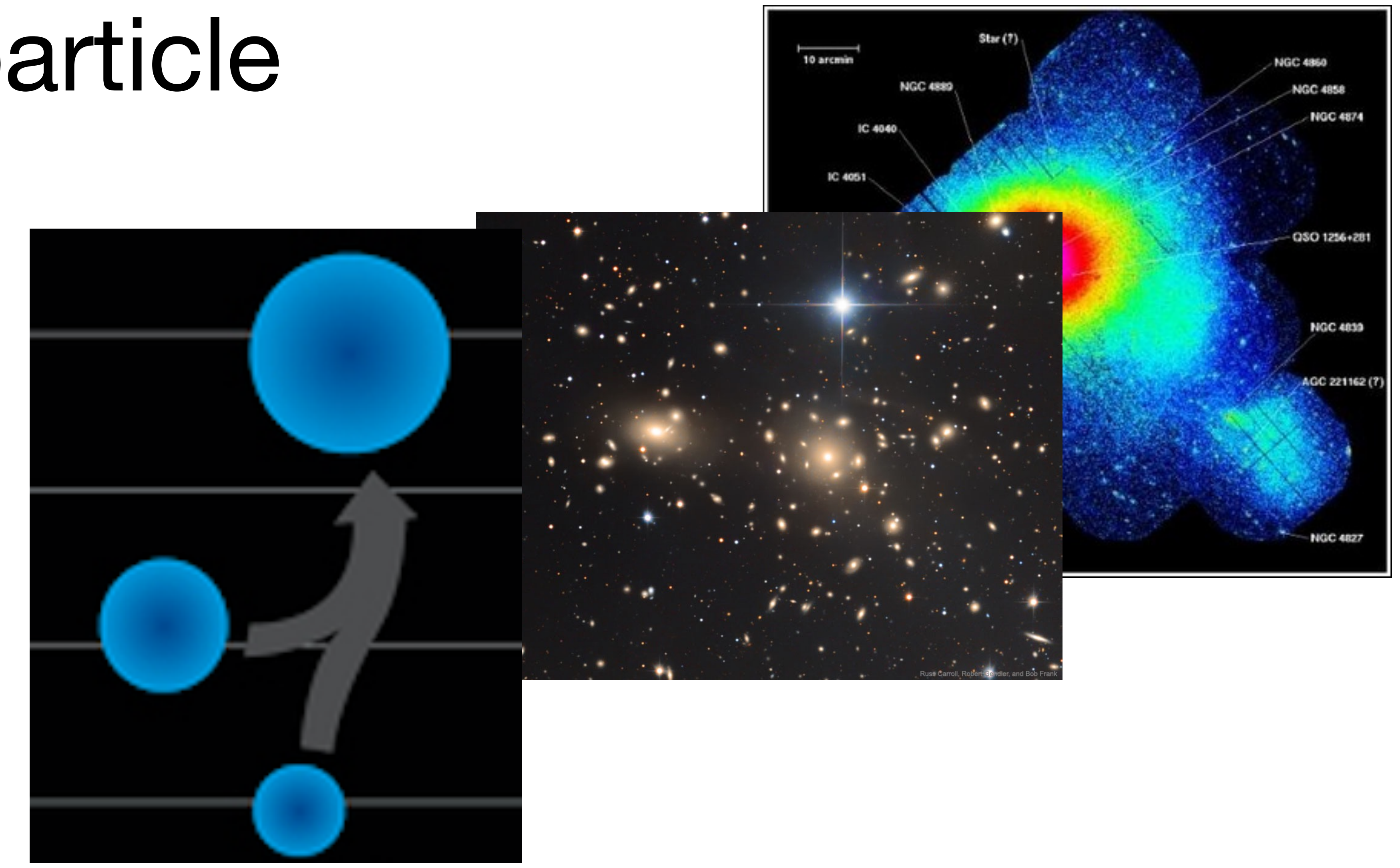
Most important interactions are between dark matter particles

Summary: Details

Black Holes: Sensitive to/constraining for dark matter physics (far beyond primordial black holes)

Compact objects: a gravitational probe with particle physics power for dissipative dark matter (chemistry!)

- Fermion mass (Chandrasekhar limit)
- Cooling rate
- Molecular energy gap



We have the tools now to do end-to-end simulations with a simple dissipative dark matter model