Light from Darkness? Searching for Dark Matter in the Sky

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What is dark matter?

We know it:

- Is roughly 84% of the matter in the universe.
- Has mass (and hence gravity).
- Doesn't scatter/emit/absorb light (really "transparent matter"!)
- Interacts with other particles weakly (except by gravity) or not at all.
- Can't be explained by any physics we currently understand.

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Tiny black holes?
- Where did it come from?
- Does it interact with ordinary particles? If so how?
- and many more…

Mystery of the Missing Mass

- 1933: astronomer Fritz Zwicky estimated the mass in the Coma cluster of galaxies.

Credit:NASA, ESA, and the Hubble Heritage Team (STScI/AURA).
Acknowledgment: D. Carter (Liverpool John Moores University) and the Coma HST ACS Treasury Team

HOW TO WEIGH A GALAXY CLUSTER:

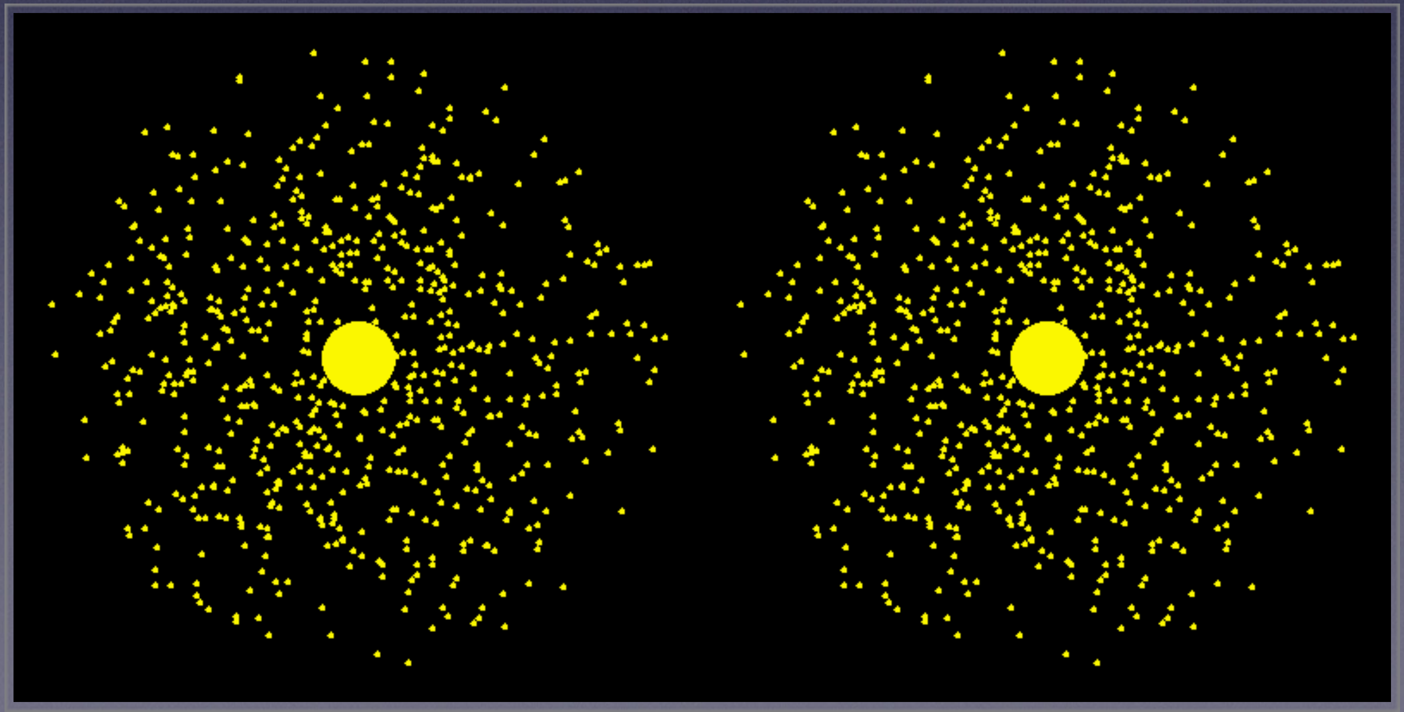
- Method 1: count galaxies, estimate mass of each, add it up.
- Method 2: measure gravitational pull on galaxies.

Problem: the two methods give very different answers! The second is much larger.

Mystery of the Missing Mass, Part II

- 1970s: astronomers Rubin, Ford and Thonnard measure the rotation speed of galaxies.
- Outer regions of galaxies are rotating faster than expected - suggests stronger gravity.

Expected



Actual

Credit: Clem Pryke

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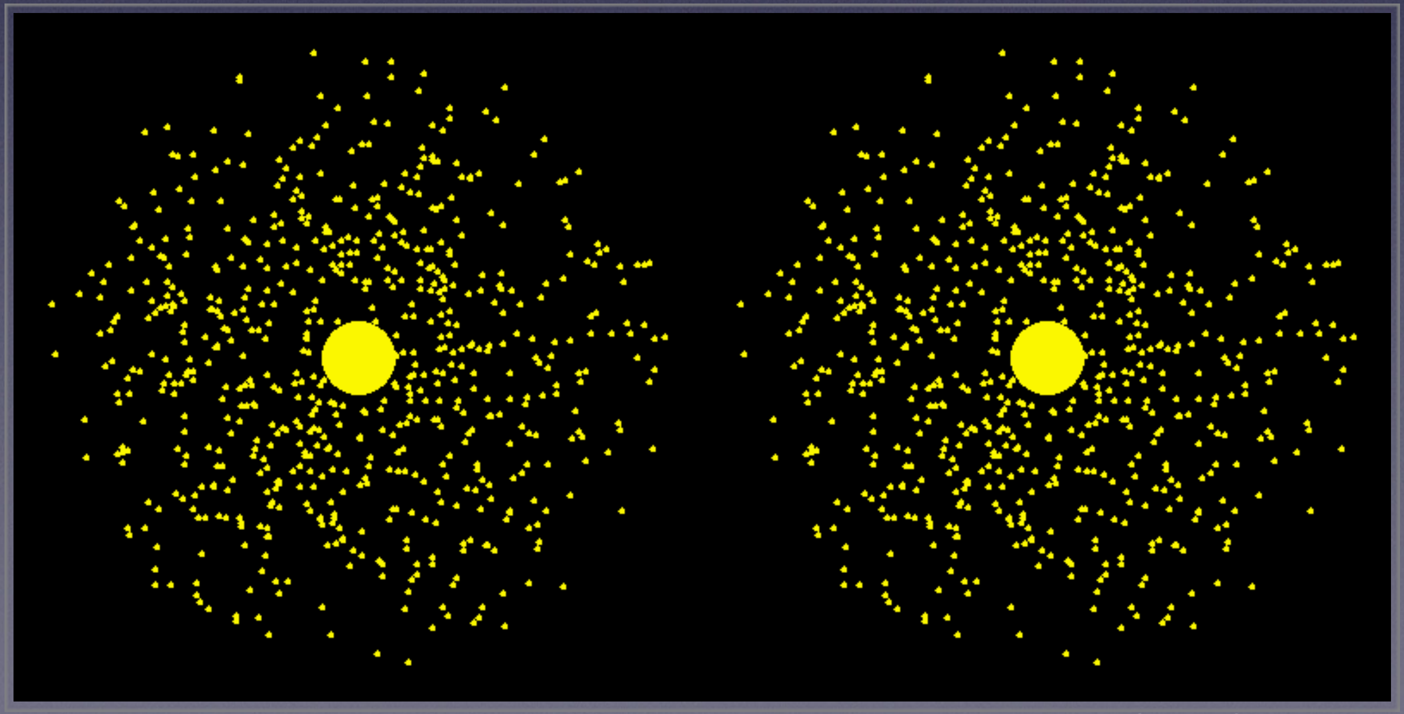

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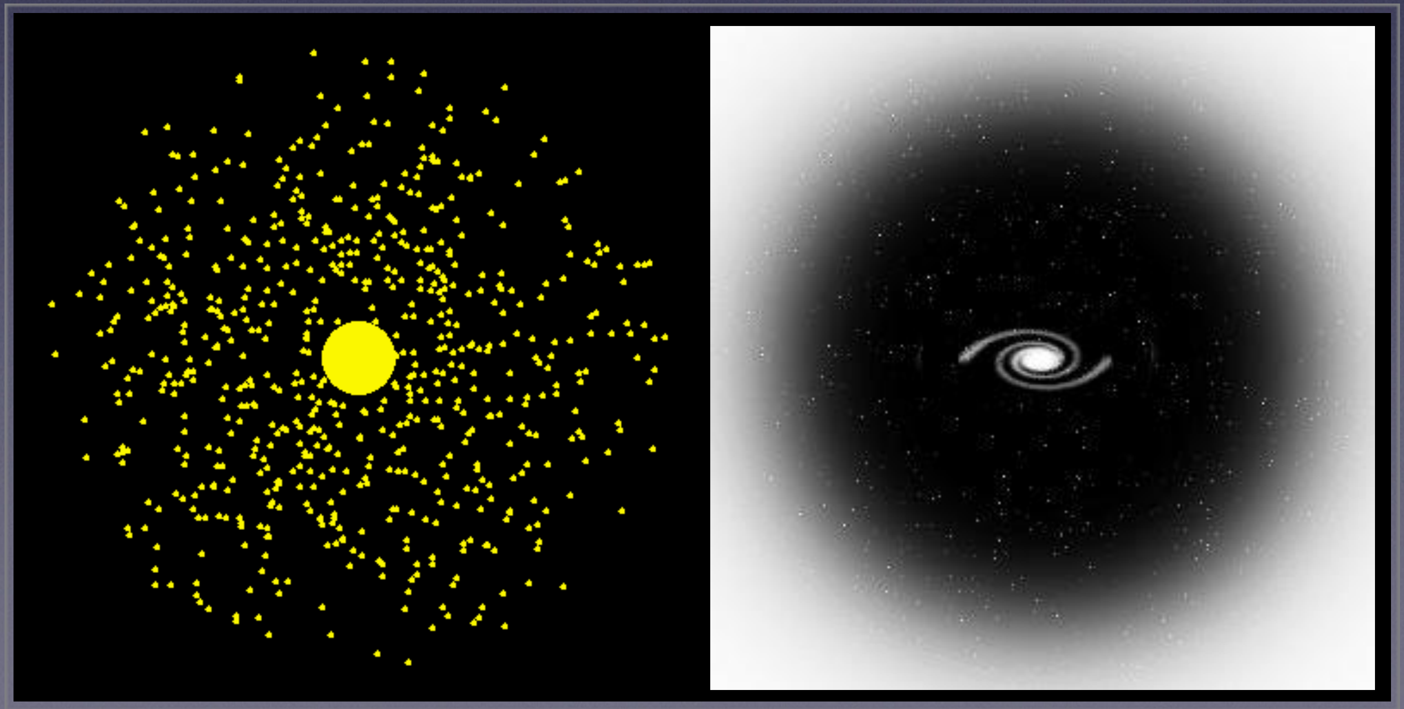

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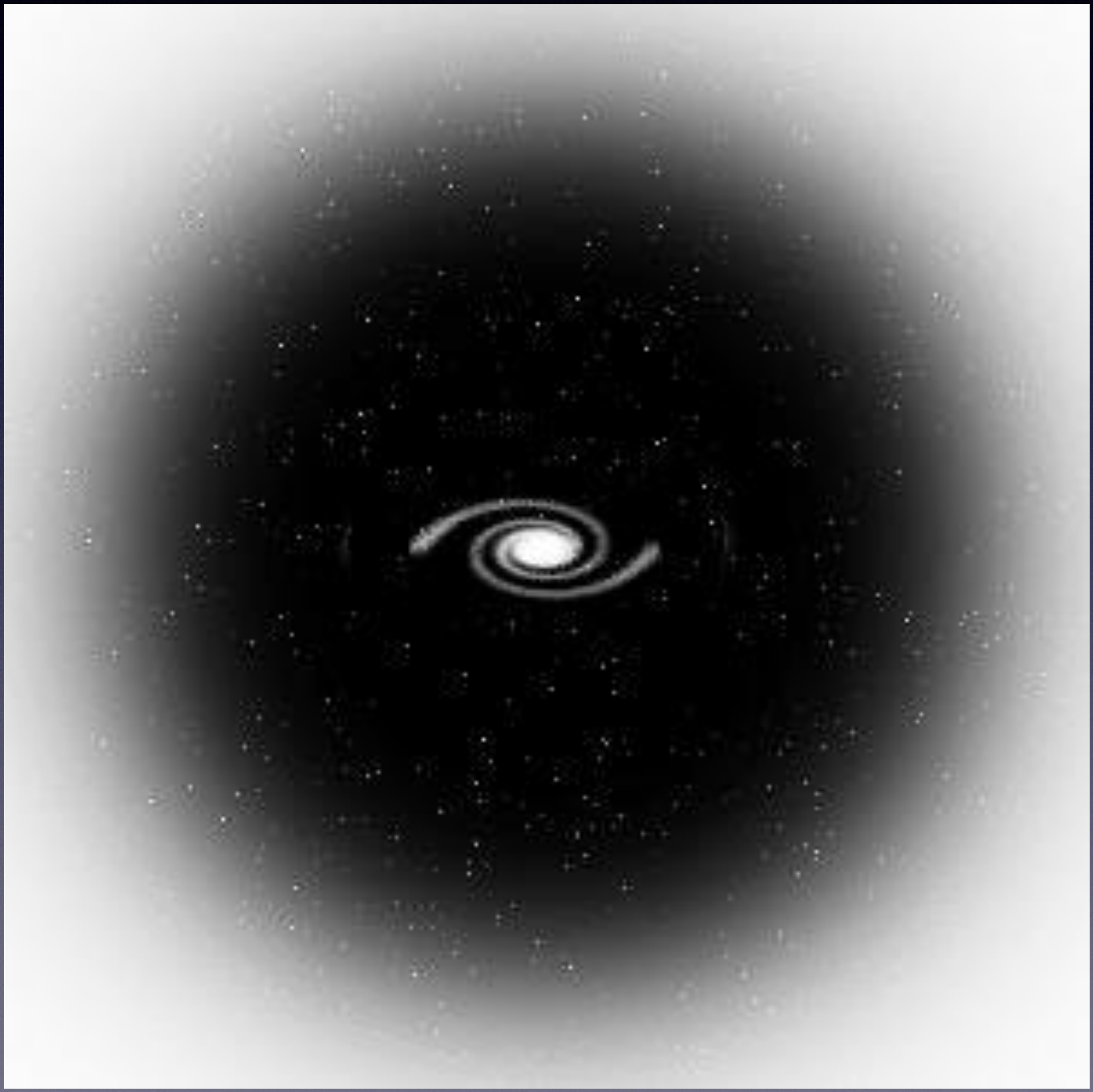
A "dark matter" halo…

- A new "dark" (not luminous) form of mass, in the outer part of galaxies?
- The different distribution suggests the dark matter behaves differently to ordinary matter in important ways.
- One possibility that works: matter with no interactions other than gravity.



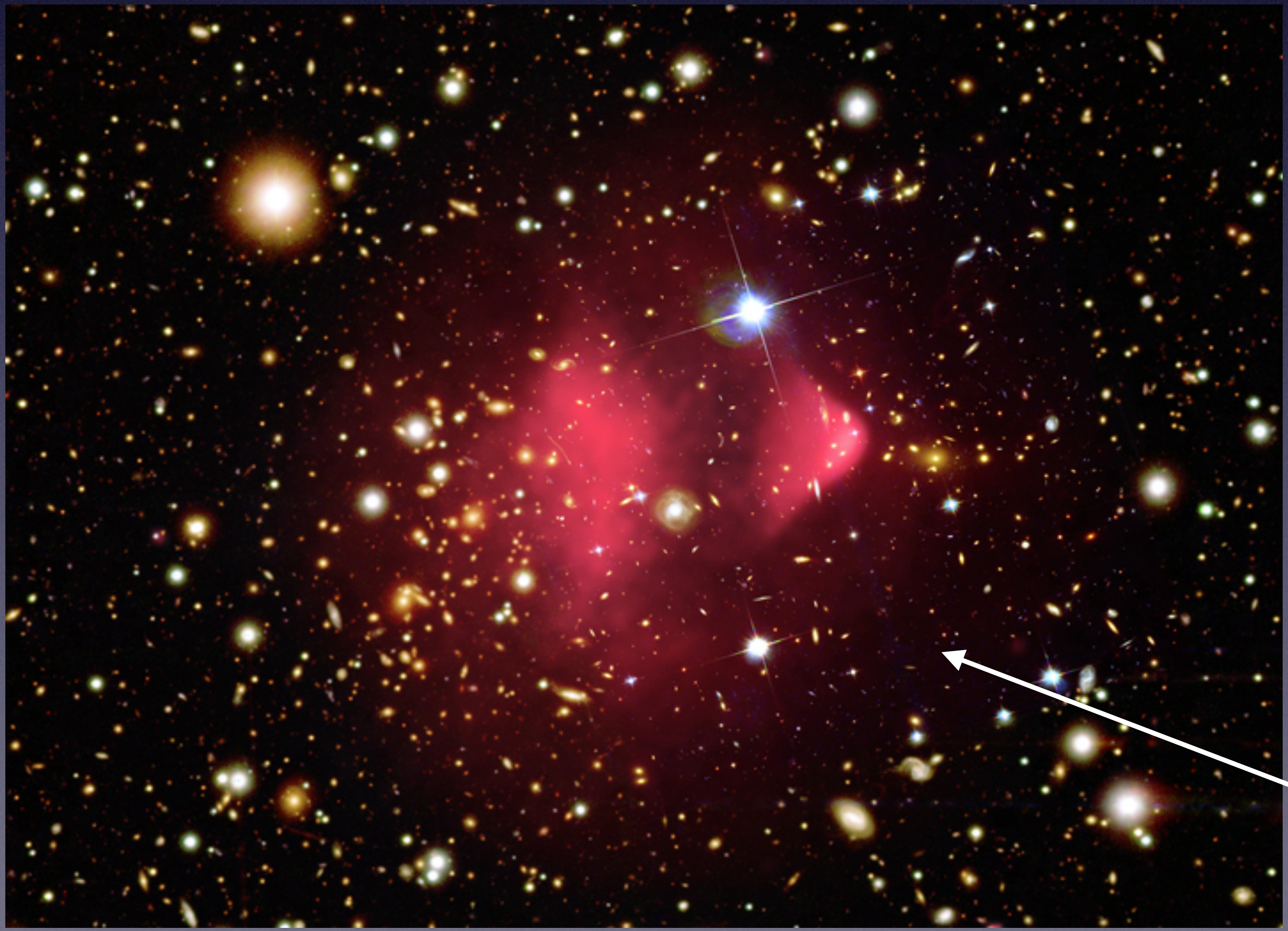
Credit: Jose Wudka

… or a change to gravity?

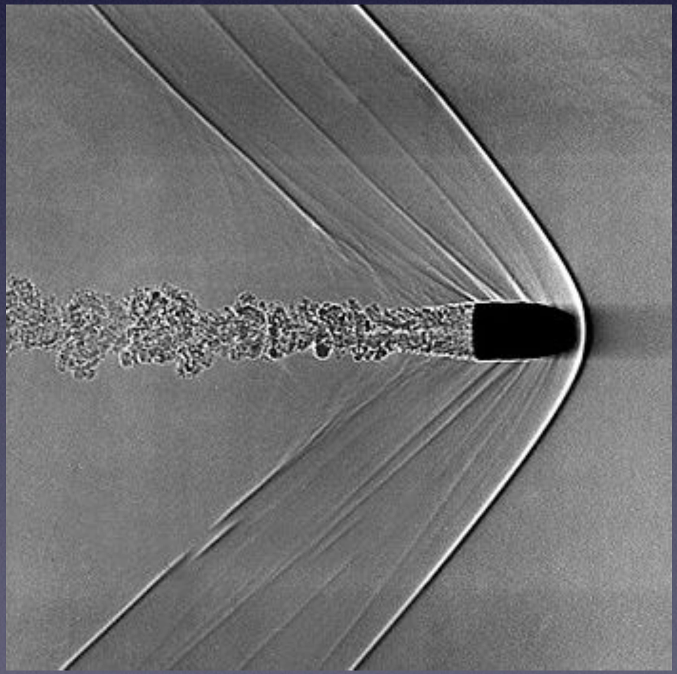
- Perhaps gravity is different on Galactic scales - doesn't weaken as quickly as expected with distance. How can we tell this apart from dark matter?
- Problem: dark matter and luminous matter are gravitationally bound to each other - tend to clump in the same places.
- Solution: look at systems where galaxy clusters are colliding.

Cosmic collisions

- In a collision between clouds of gas, there is compression and heating, producing X-ray radiation.



Credit: NASA/CXC/CfA/M.Markevitch et al.; NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

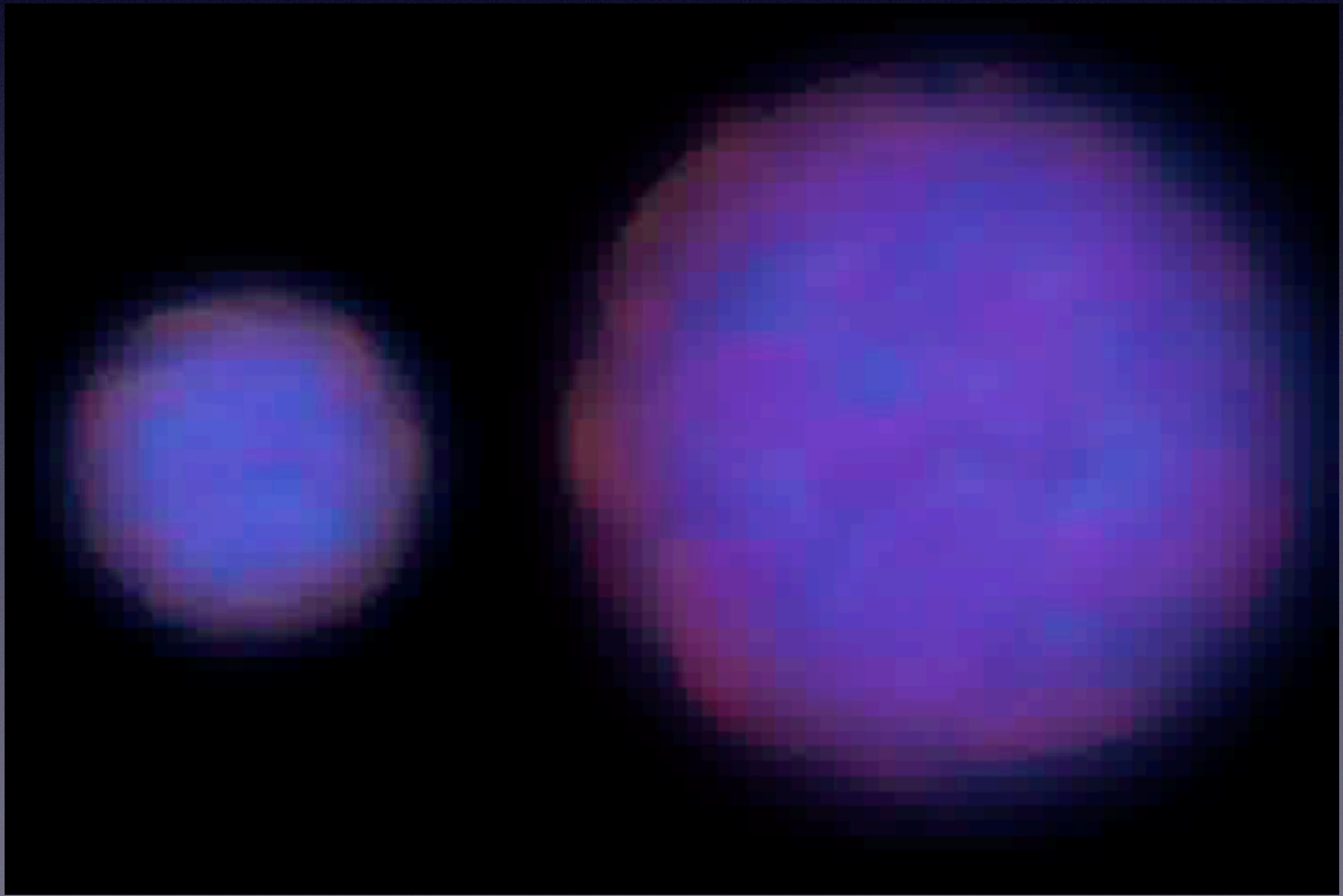


Credit: Andrew Davidhazy, Rochester Institute of Technology

the "Bullet Cluster"

Cosmic collisions (II)

- But dark matter doesn't interact and collide like ordinary matter - clouds of dark matter pass straight through each other!



Credit: NASA/CXC/M.Weiss

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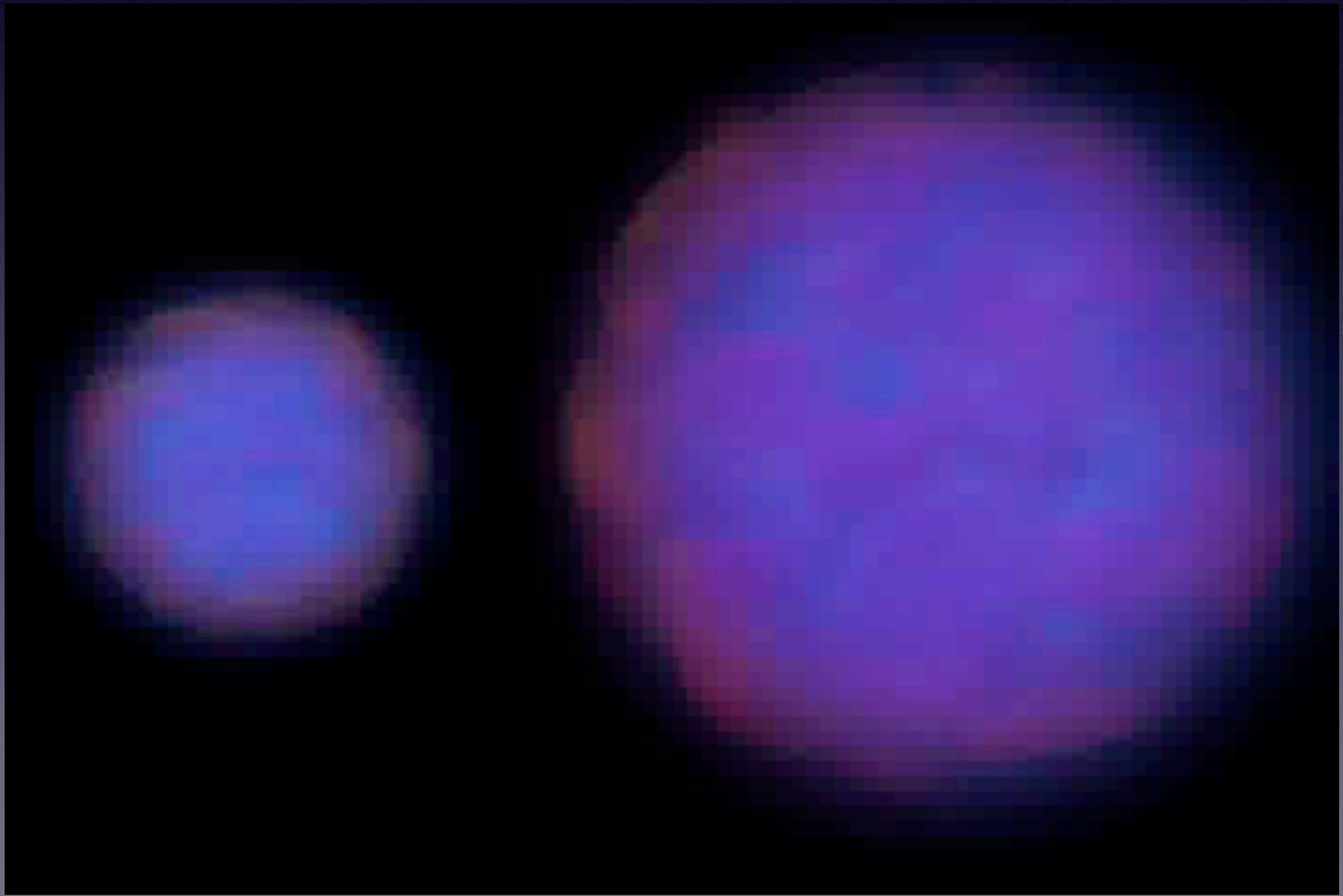

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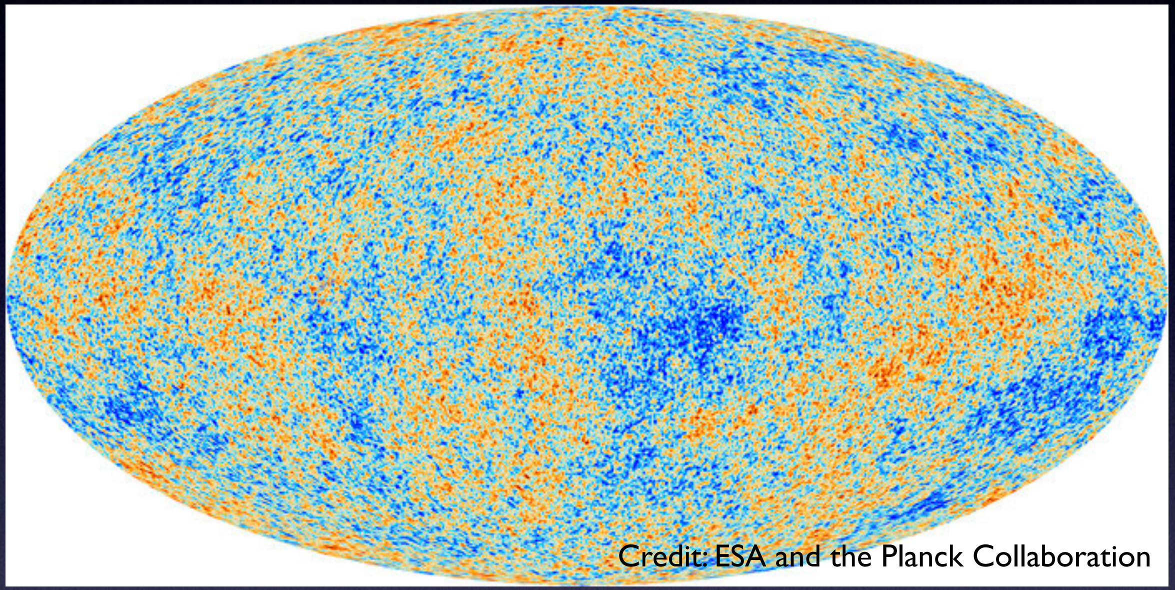
The Bullet Cluster

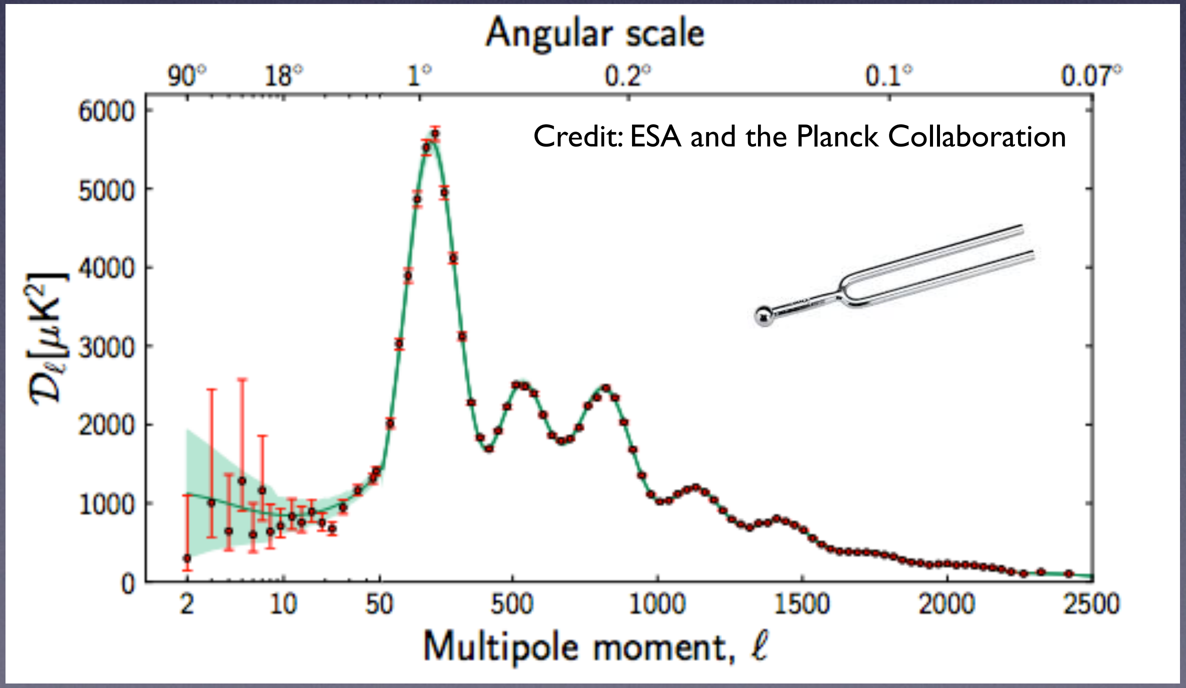
Credit: NASA/CXC/M. Weiss

- 2006: astronomers Clowe et al demonstrate just this effect - gravity measures distribution of mass (blue regions), X-rays measure visible matter (red regions).
- Most mass is distinctly separated from the visible matter! Hard to explain by modifying gravity - smoking gun for dark matter.

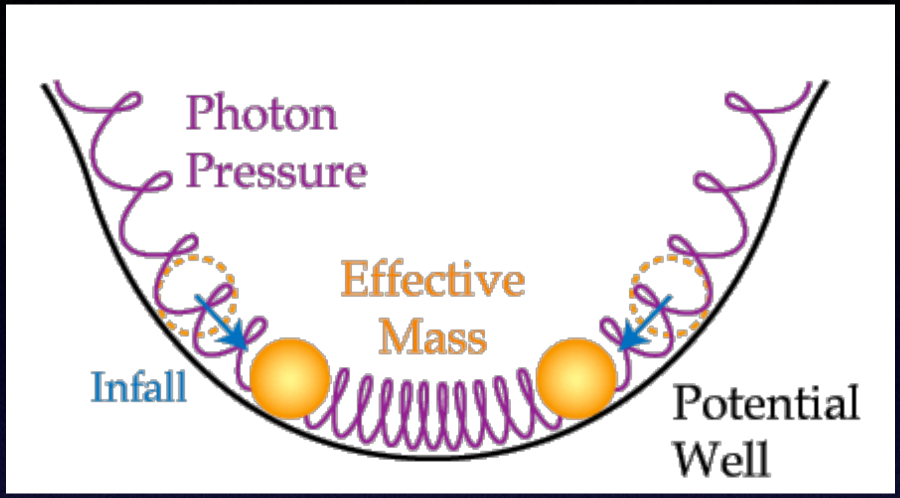
Dark matter in cosmic history

- When the universe was 400,000 years old, it was a hot, nearly perfectly smooth and uniform soup of light and atoms.
- There were oscillating ripples in the temperature/density.
- Photon temperature anisotropies today provide a "snapshot" of these ripples.
- We can measure the amount of power in these fluctuations as a function of their size - like measuring the intensity of sound at different frequencies

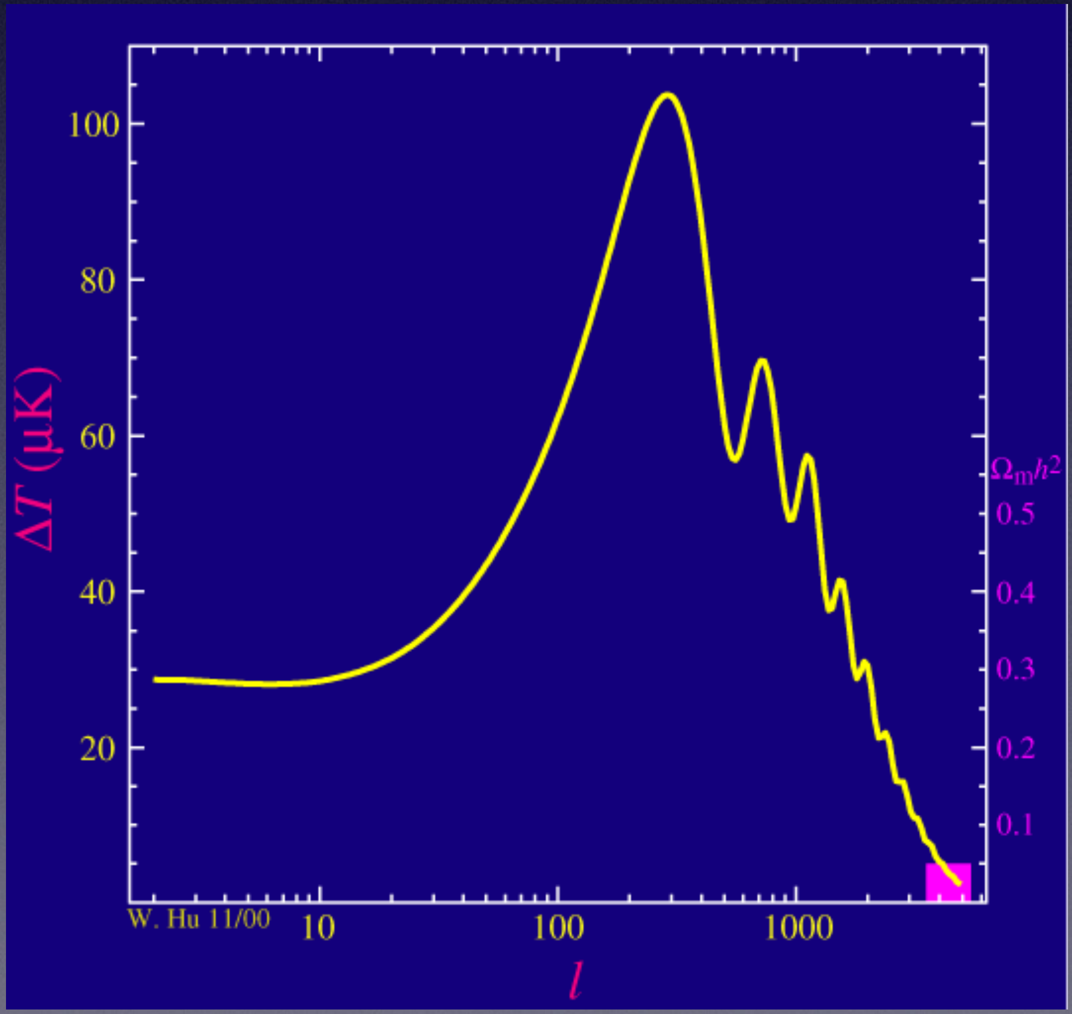




Measuring the dark matter content



- This "power spectrum" depends on the interplay between gravity and radiation pressure.
- Match to data is poor with just photons + visible matter.
- Add a dark component: does not experience radiation pressure, only gravity.
- To match data, need a dark matter component with 5x more total mass than ordinary matter.



Credit: Wayne Hu, http://background.uchicago.edu/~whu/

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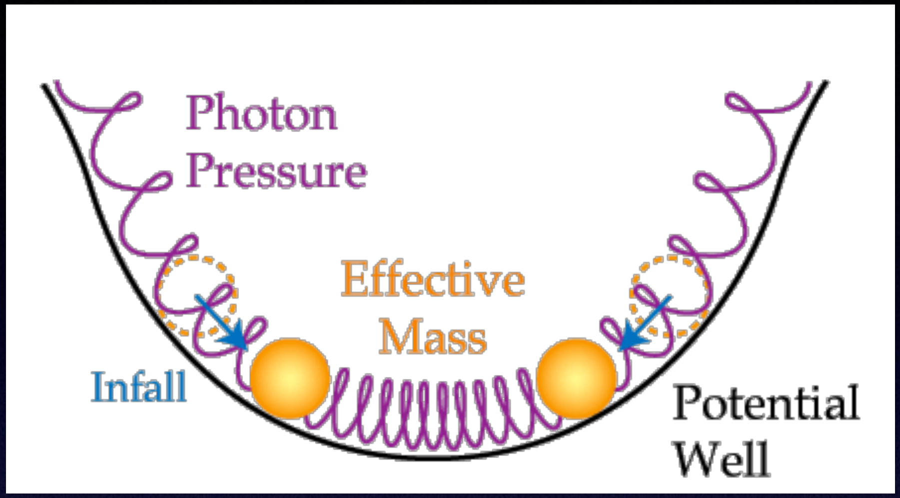

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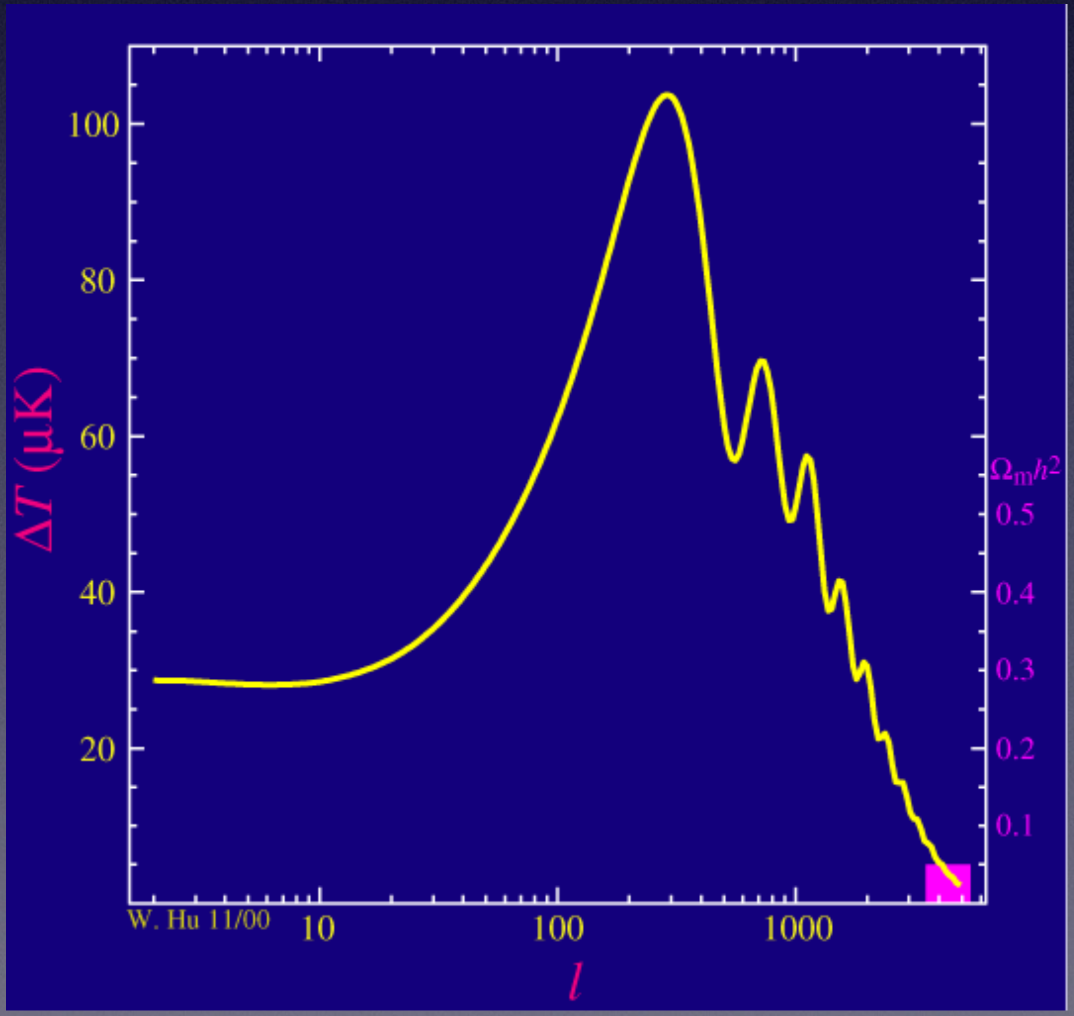
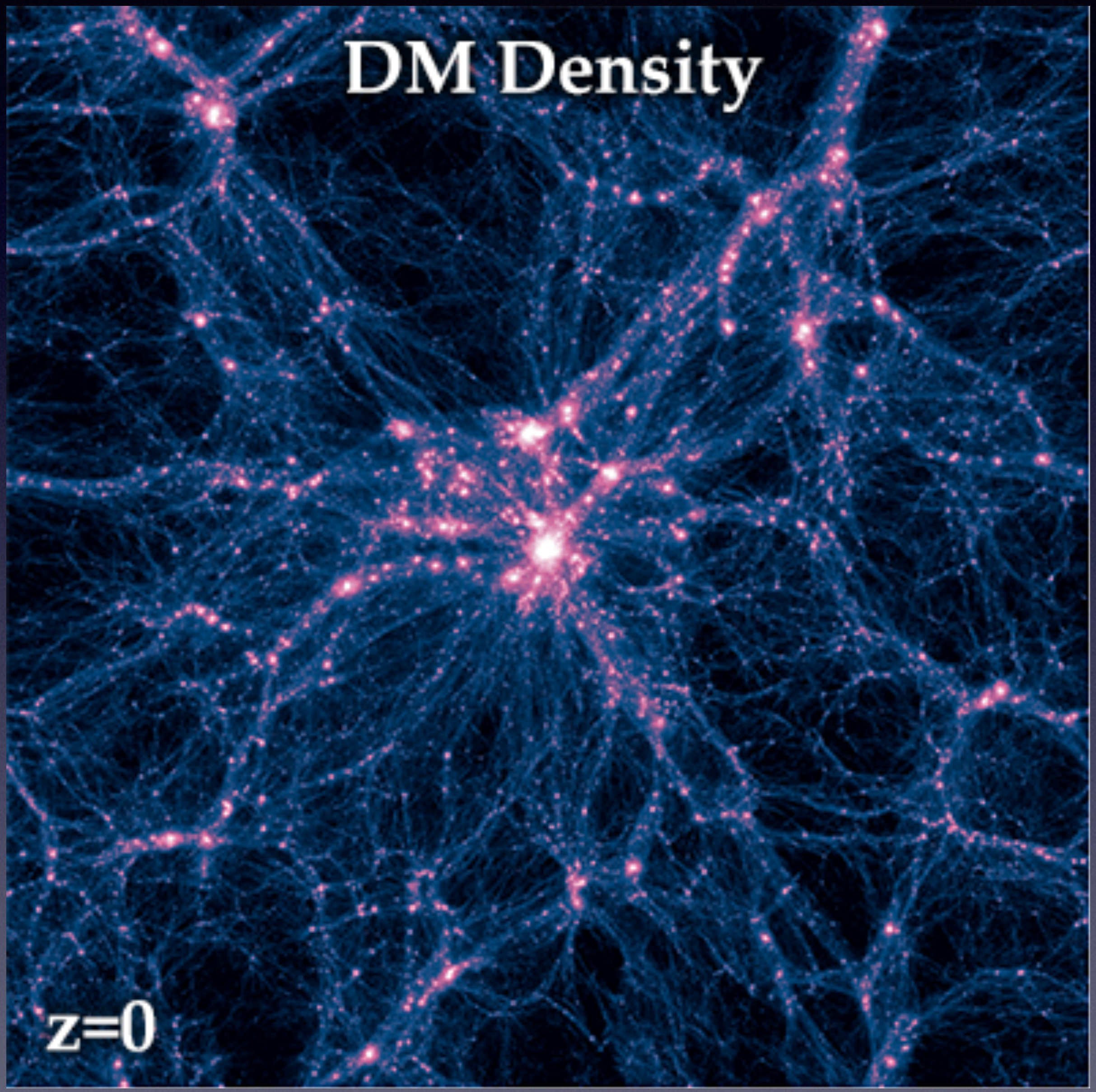


Credit: Wayne Hu, http://background.uchicago.edu/~whu/

The cosmic web

- CMB also maps out the initial conditions for cosmic structure formation - at later times, the ripples continue to grow.
- If dark matter is HOT - relativistic - then dark matter particles stream past each other at close to the speed of light.
  - This doesn't match the data - galaxies form too late.
- If dark matter is COLD, the slow-moving dark matter particles accrete into clumps.
  - Over time, these small clumps combine to form streams and halos.
  - This works to describe what we see!
  - Dark matter forms the "scaffolding" for the whole visible universe.

Credit: Illustris Collaboration



Dark matter as new physics

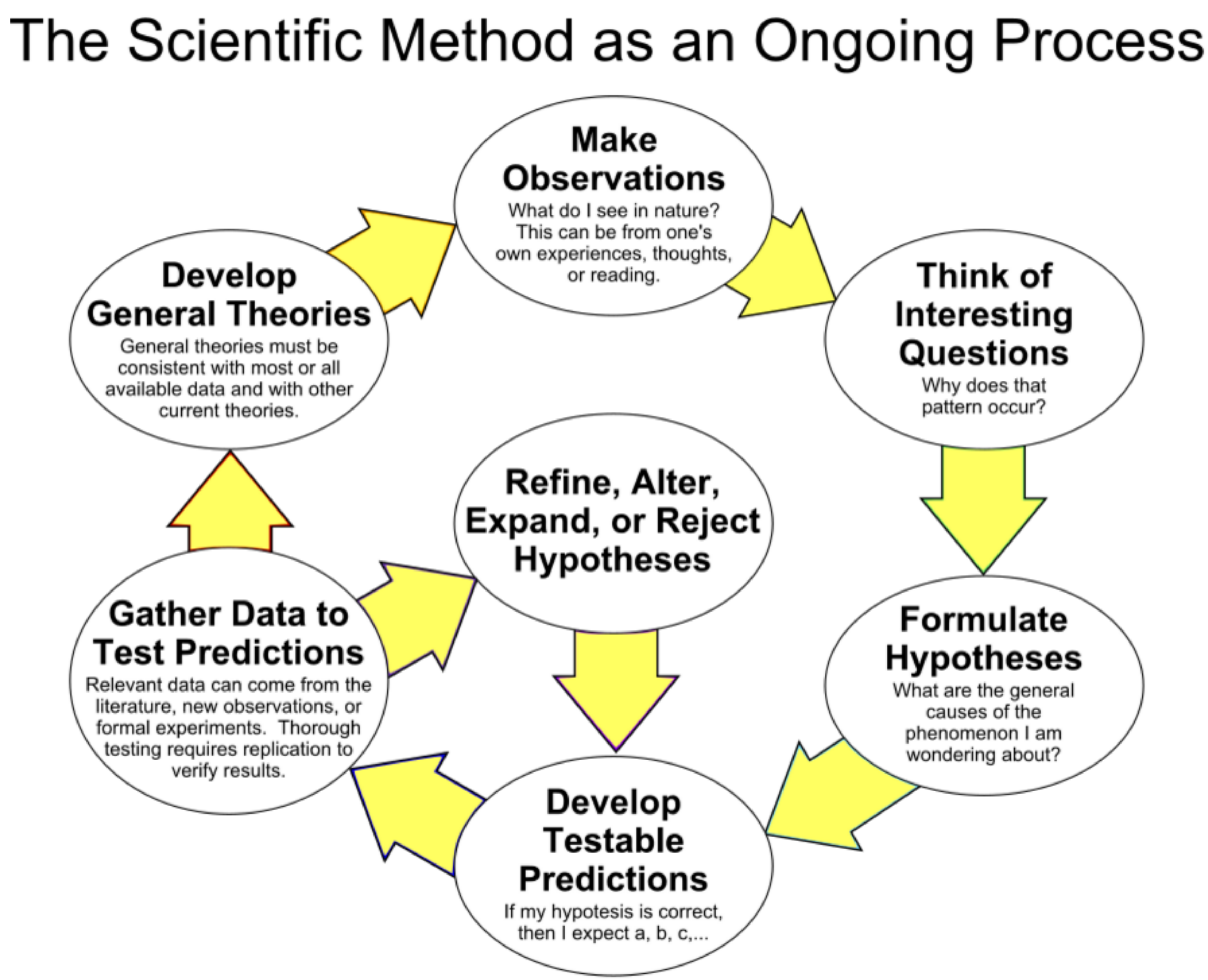
- The Standard Model (SM) of particle physics has been spectacularly successful - but no dark matter candidate. We need something:
  - Stable on cosmological timescales
  - Near-collisionless, i.e. electrically neutral
  - “Cold” or “warm” rather than “hot” - not highly relativistic during structure formation
- Only stable uncharged particles are neutrinos, and they would be hot dark matter.
- There is some possibility of using SM physics - e.g. tiny black holes - but would need to be formed very early in the universe, requiring currently-unknown physics there

- DM is one of the most powerful pieces of evidence for physics beyond the SM.
- Everything we have learned so far has come from studying the gravitational effects of dark matter, or from its inferred distribution.

Credit: NASA/CXC/M.Weiss

What could it be?

The DM hypothesis



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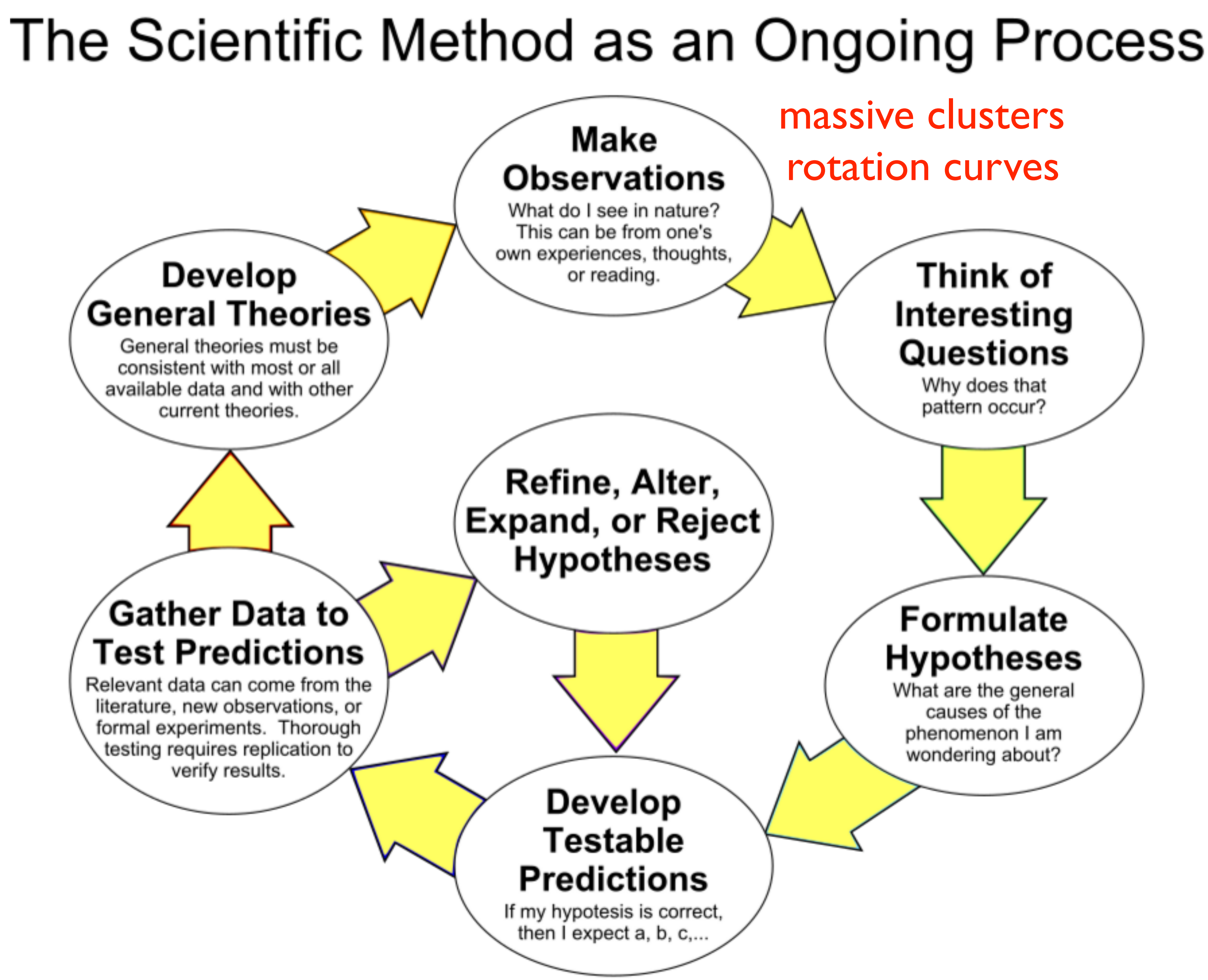

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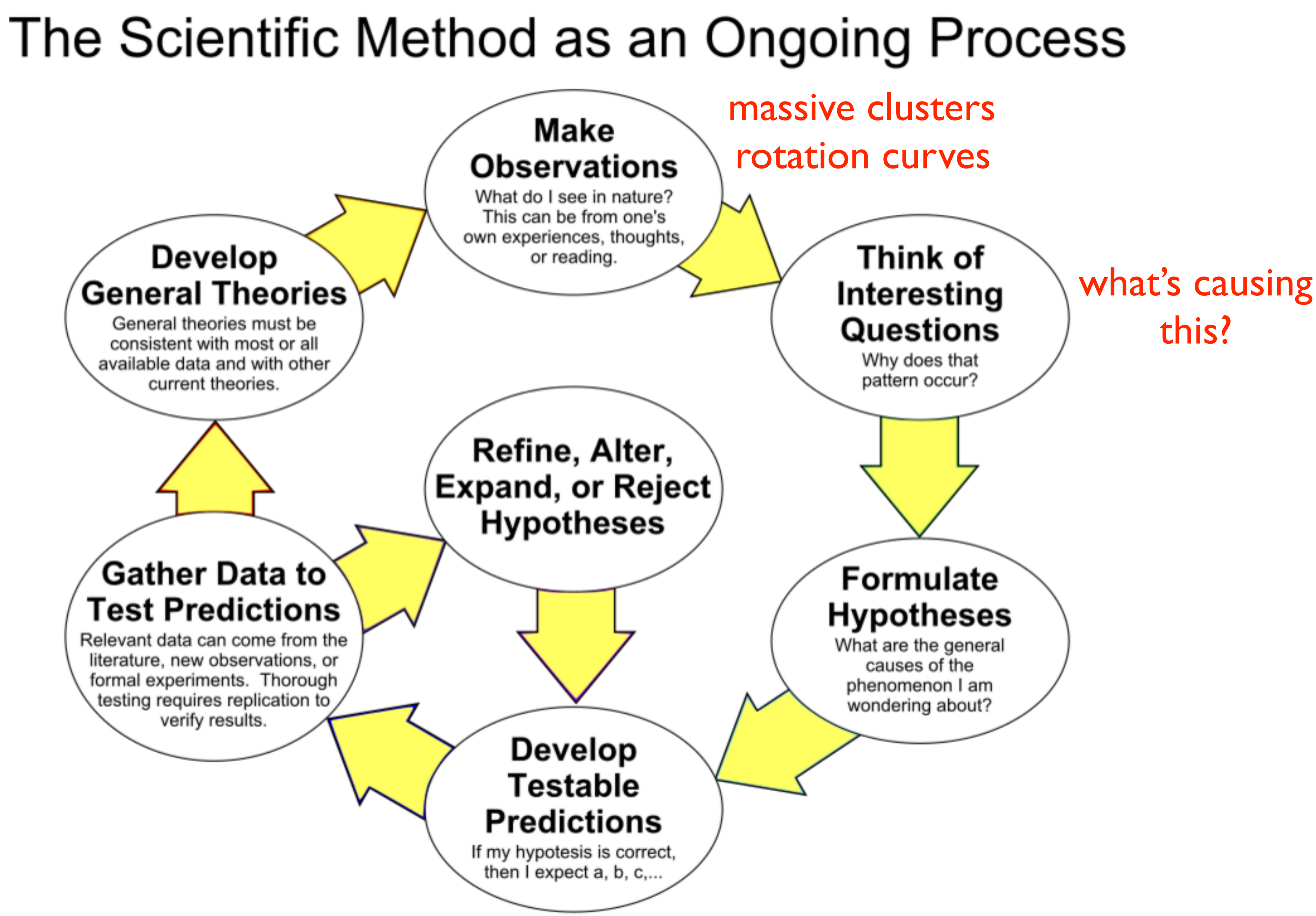

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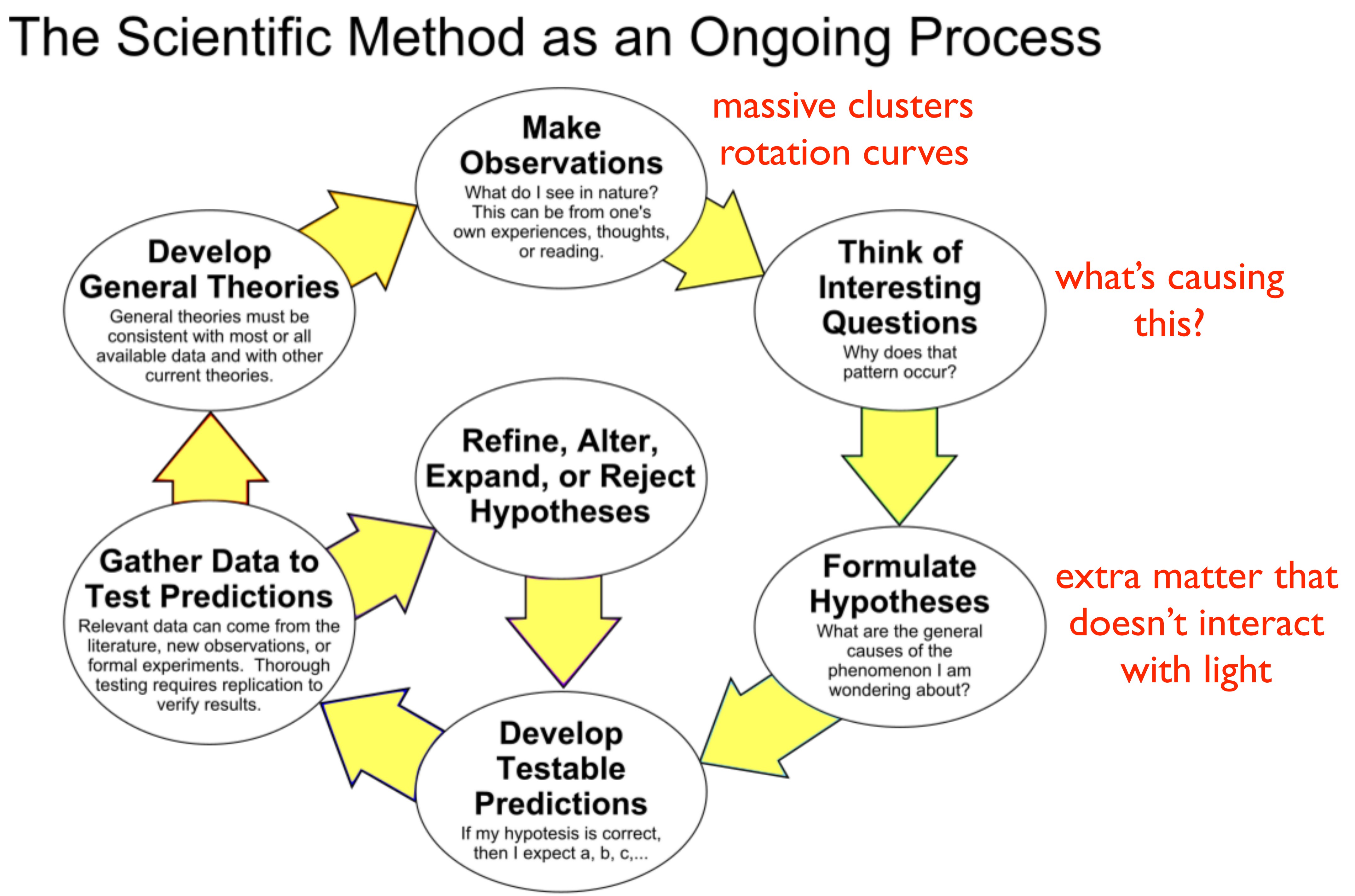

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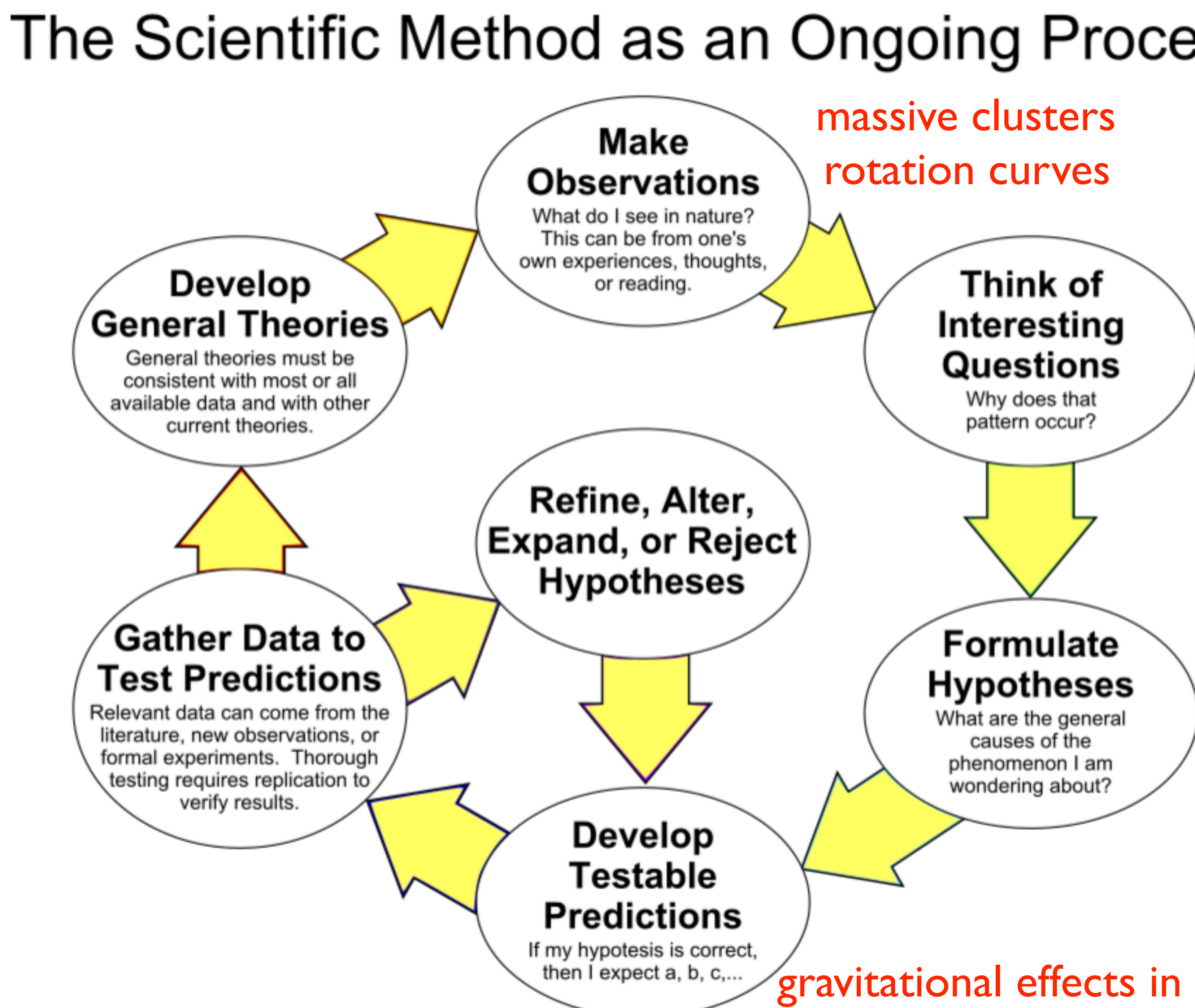

massive clusters
rotation curves

what's causing this?

extra matter that doesn't interact with light

gravitational effects in the absence of visible matter; modified cosmology

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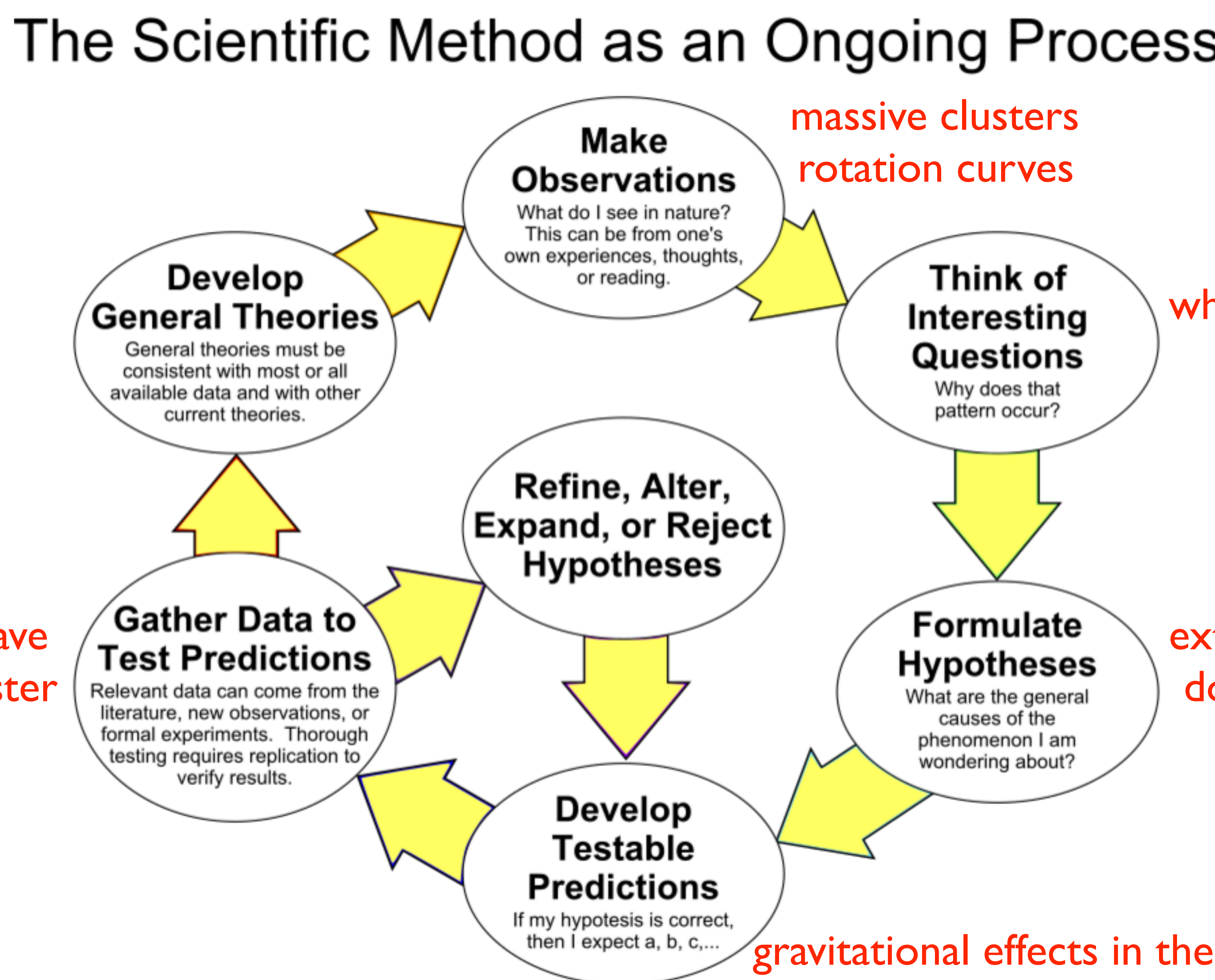

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cosmic microwave background, cluster observations

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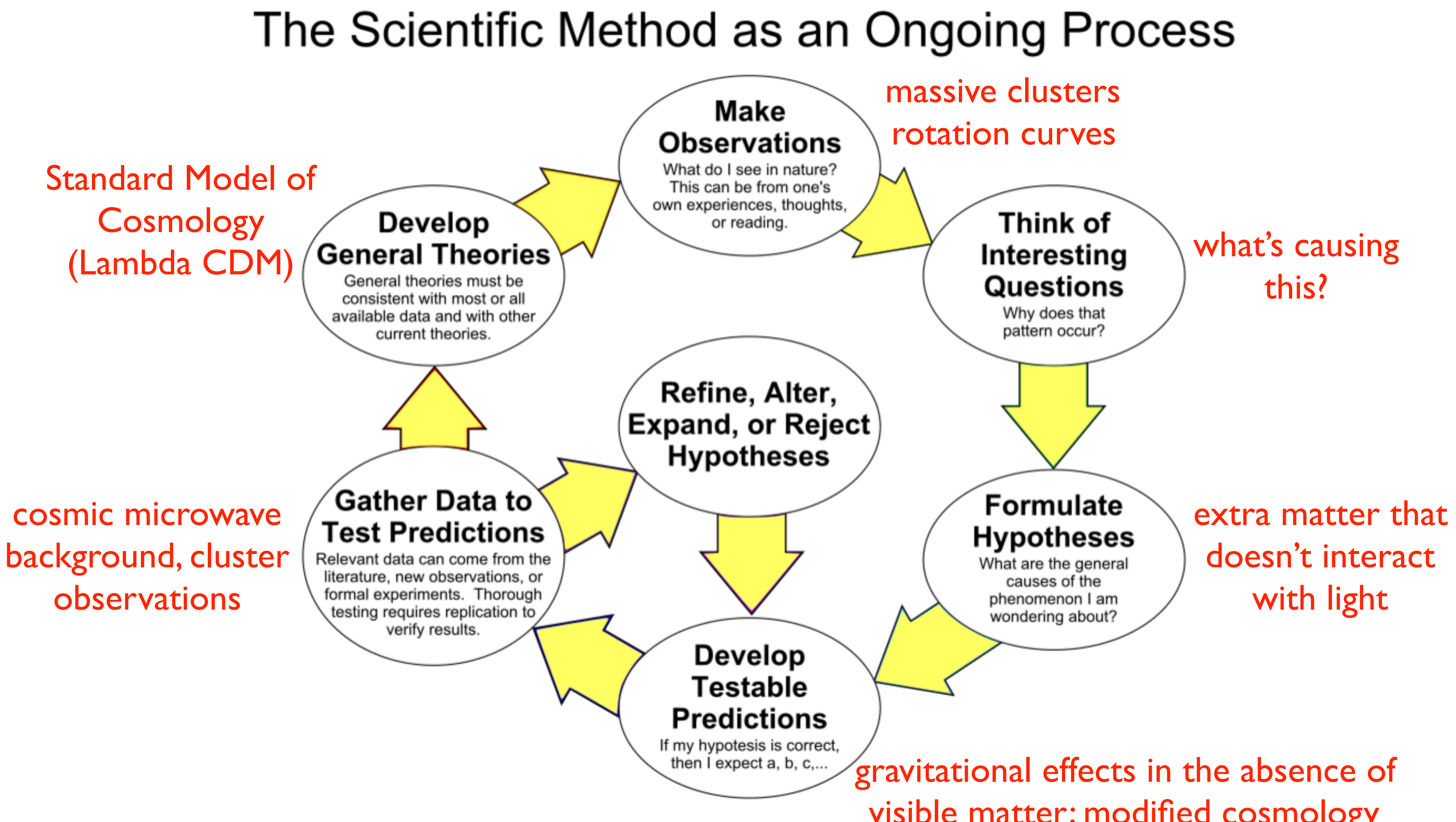

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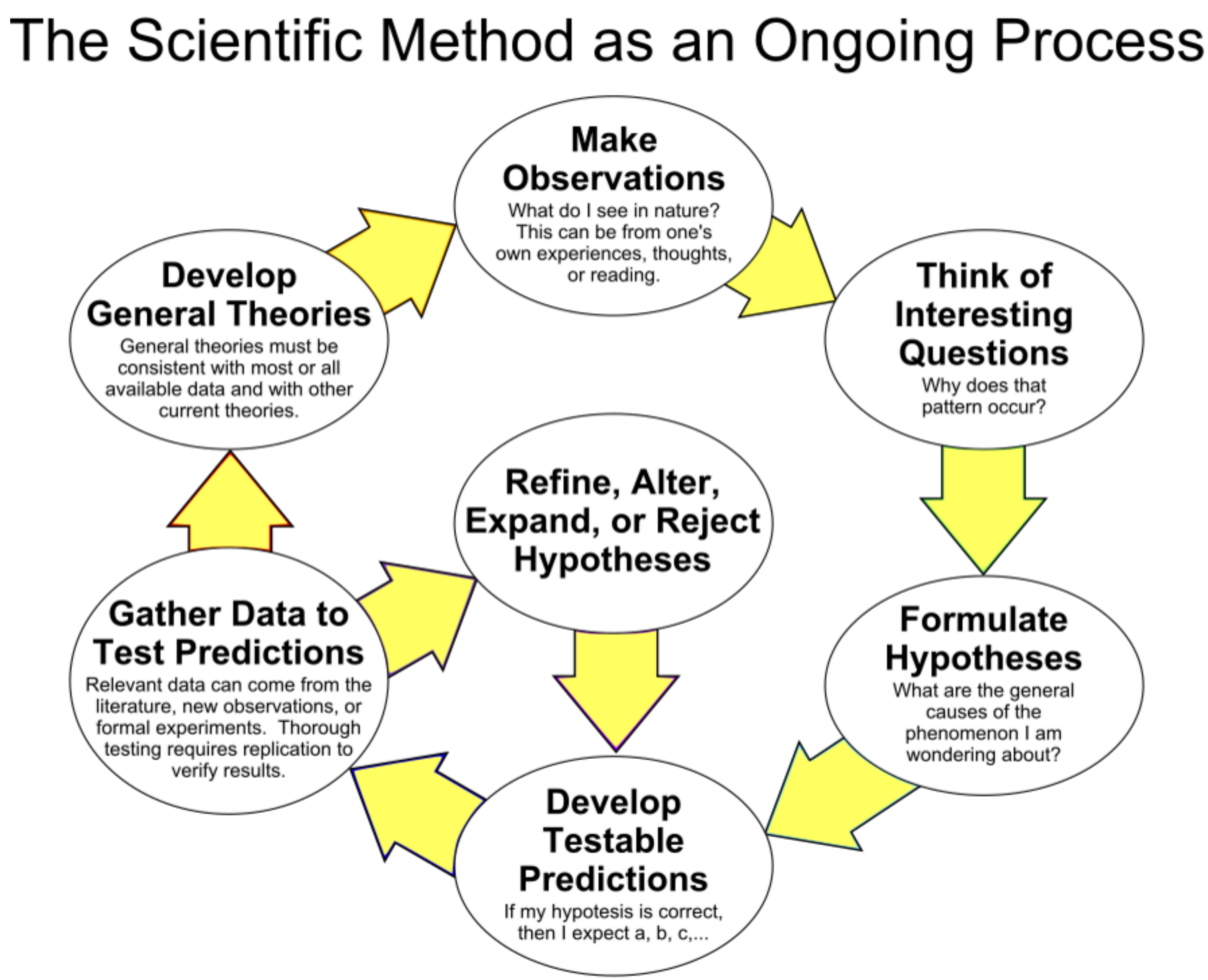

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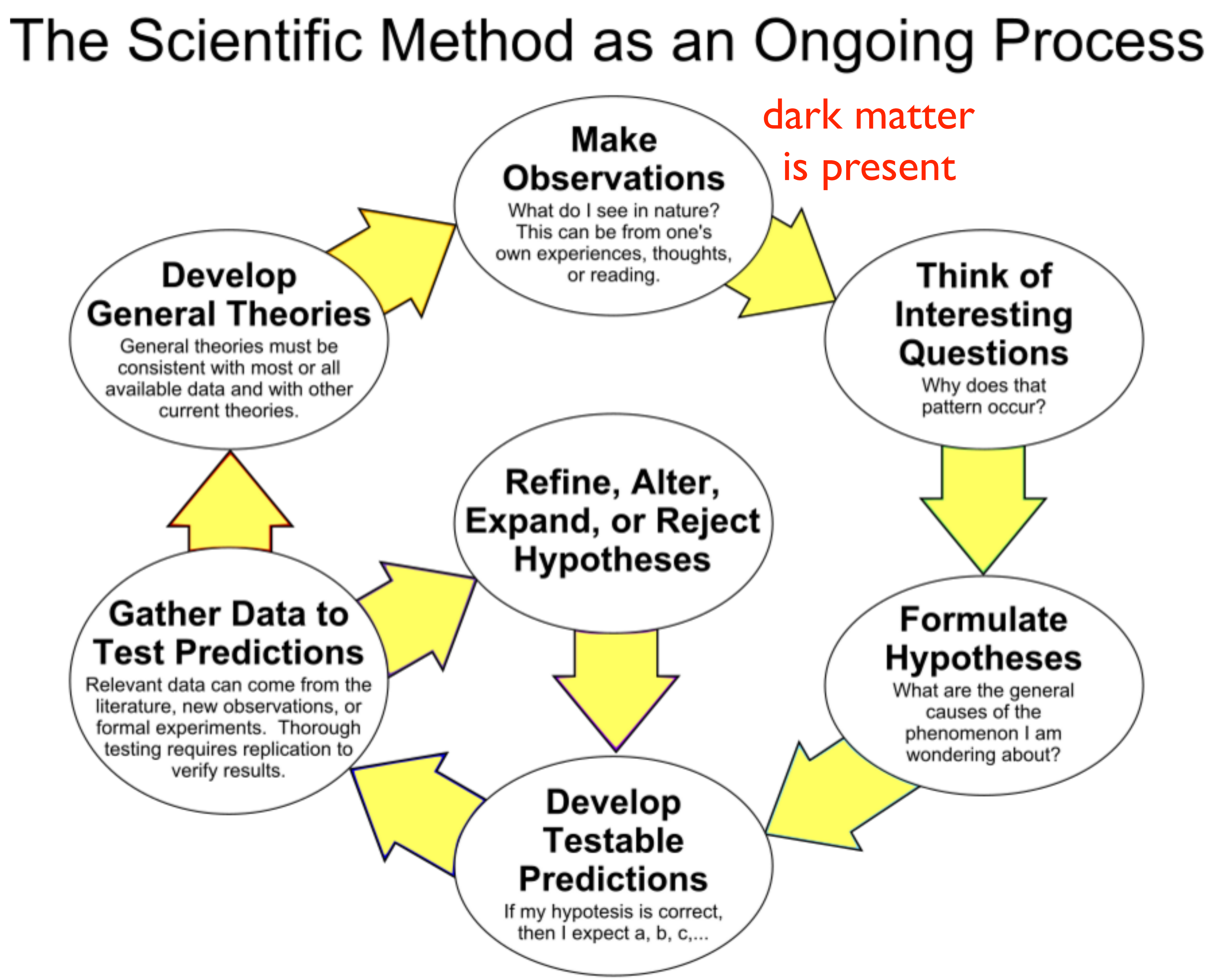

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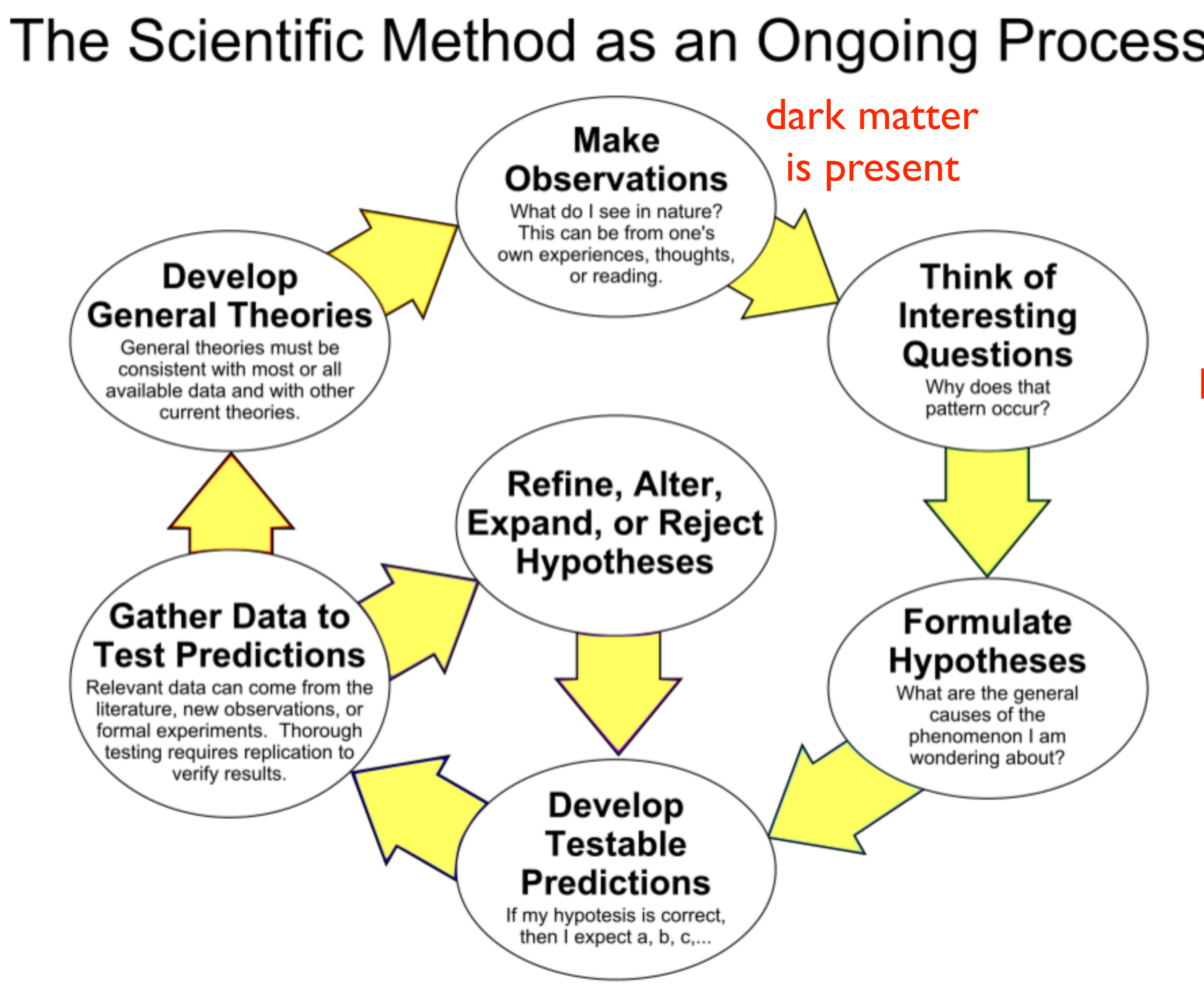

dark matter is present

Is it a new particle? Does it interact at all, except by gravity? How heavy is it? Can it decay? Is it connected to other fundamental puzzles?

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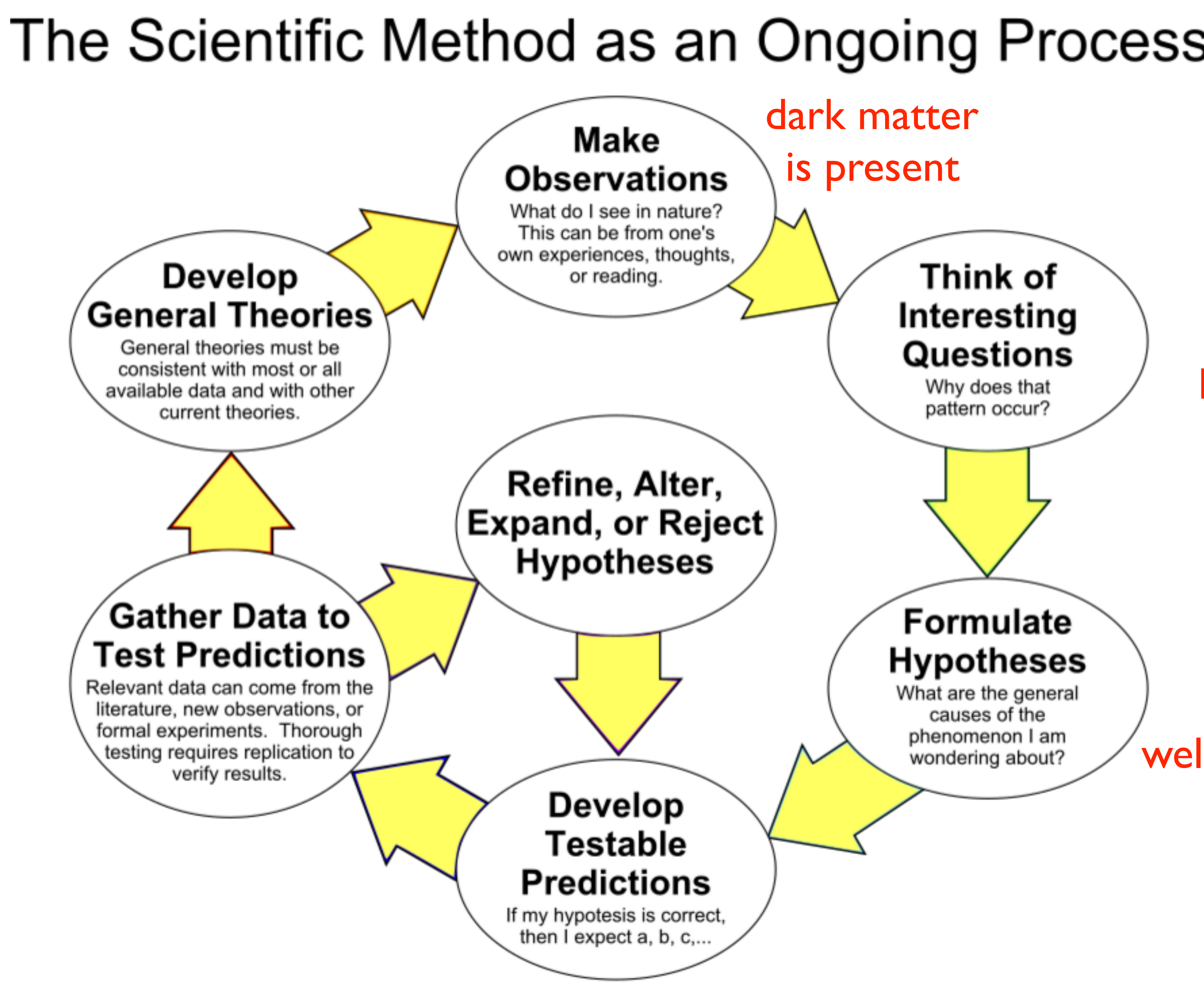

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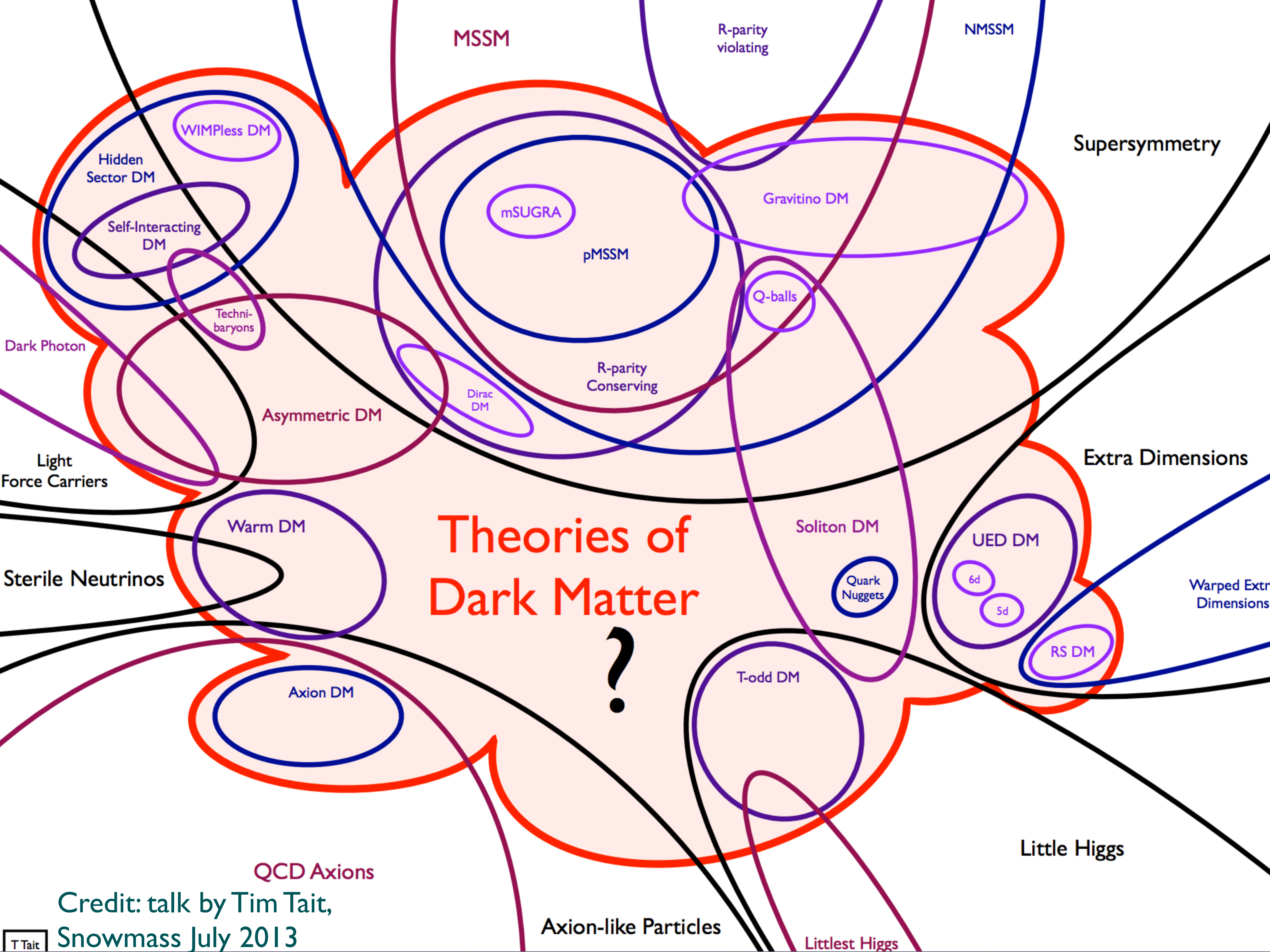


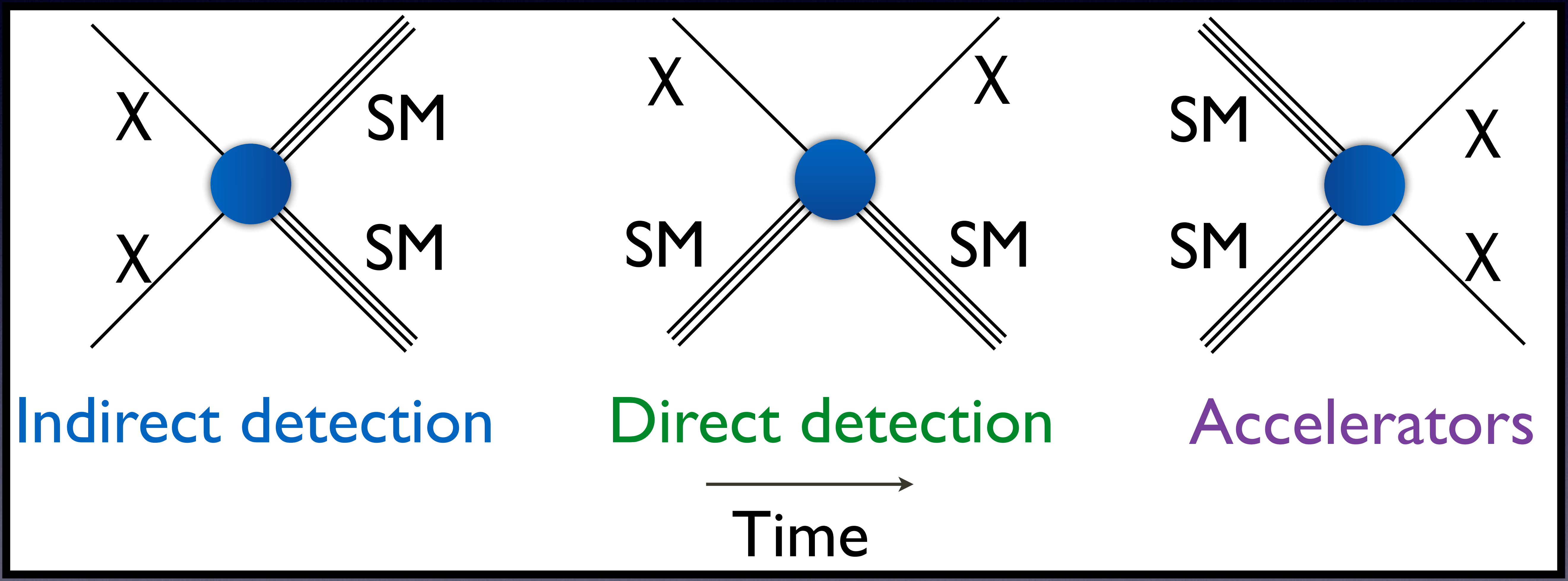
Credit: talk by Tim Tait,
Snowmass July 2013

What about non-gravitational interactions?

- Huge range of scenarios (including enormous range of particle masses, interaction strengths, etc) that are perfectly consistent with current data!
- But they predict very different interactions between dark matter and ordinary particles (and sometimes between dark matter particles).
- Detecting such interactions would let us distinguish between such models - or prove them all wrong!

Searches for DM interactions

- There is a large multi-faceted search program for signatures of dark matter
- Many complementary search strategies



- Not an exhaustive list - in recent years also a great deal of attention to scenarios where dark matter can be absorbed by visible matter, or oscillate to/from visible matter, etc
- Everything we currently know about dark matter has come from cosmological/astrophysical observables - they can also shed light on such interactions

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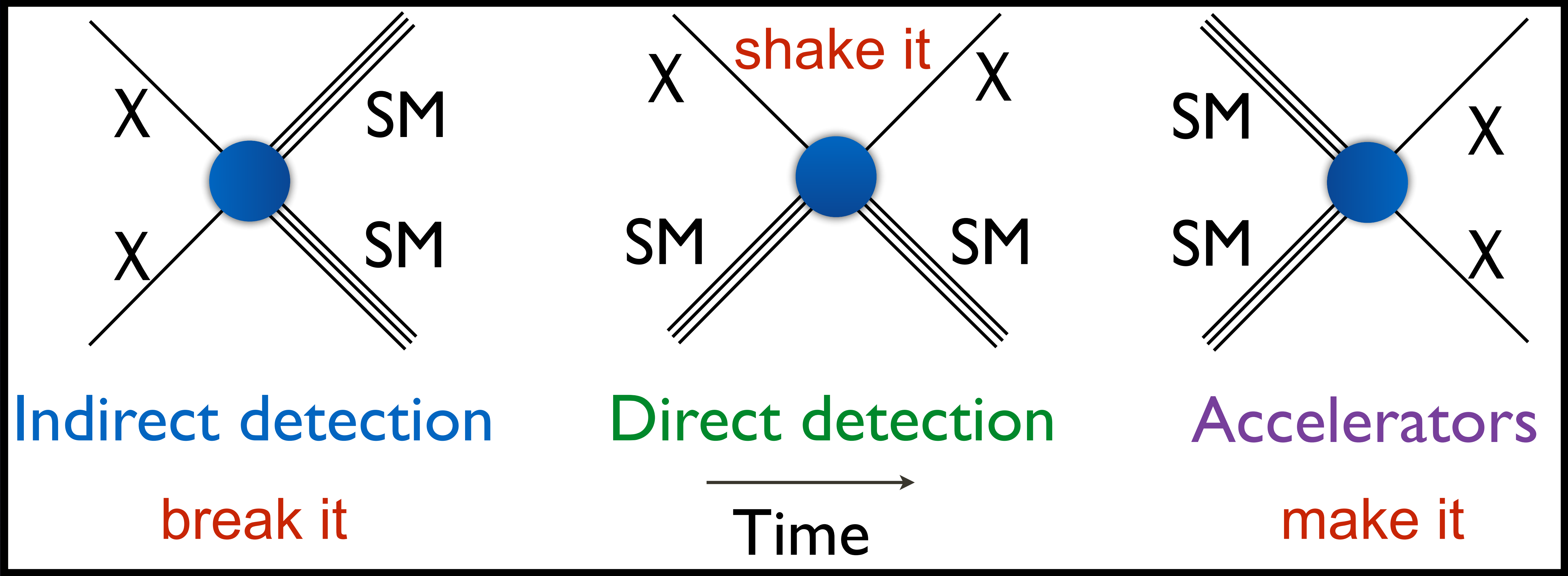

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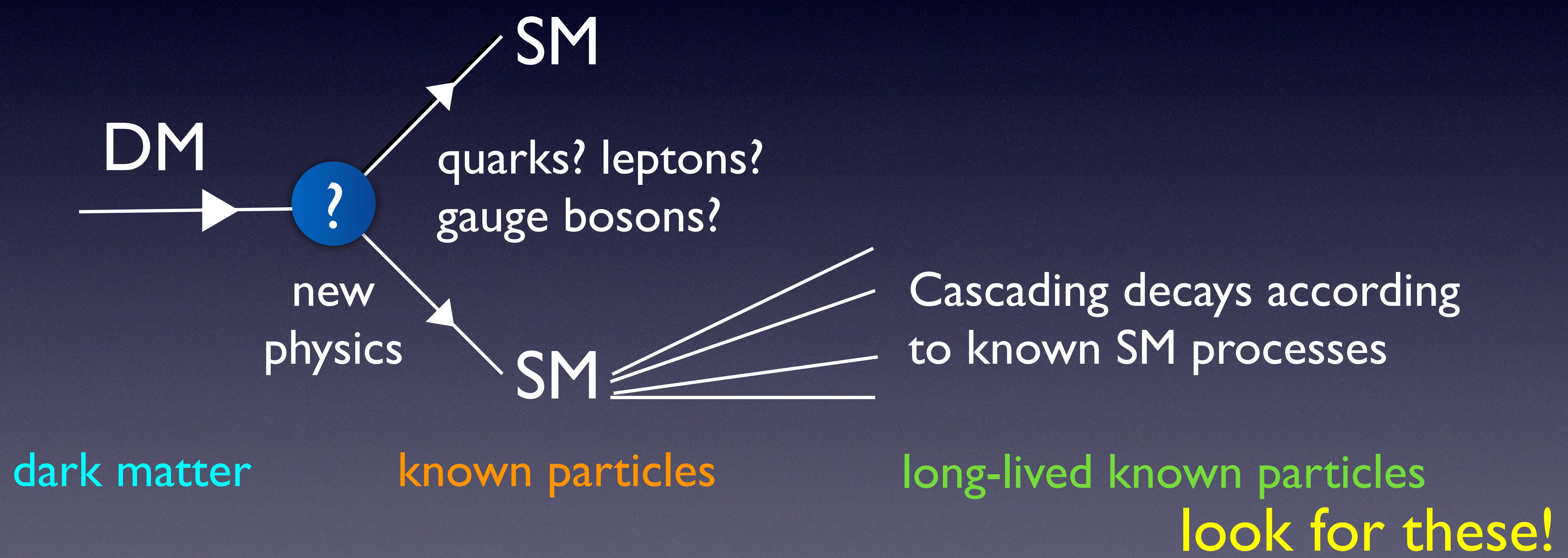
New particles from the invisible cosmos

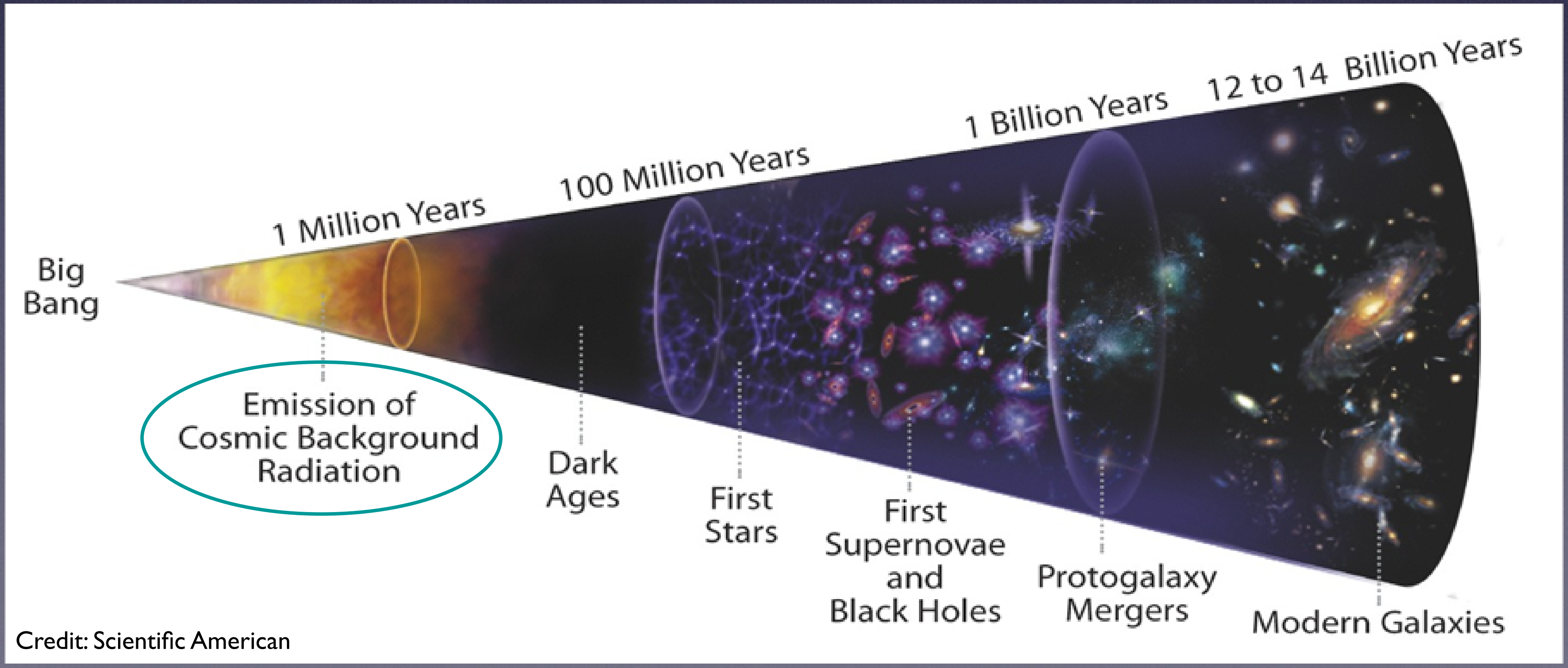
- In many (but not all) scenarios, dark matter particles can produce visible particles when they collide with each other or just decay away.



- Other possibilities: photons could convert to dark matter particles and escape from regions where they would otherwise be trapped; dark matter particles could emit photons as an "echo" of light from supernovae; dark matter could form bound states around colliding black holes; and many more…

One example: changing cosmic history

- Even a tiny fraction of dark matter interacting through these non-gravitational channels could cause a slow and steady trickle of energy between the dark and visible particles - modifying the history of our universe in striking ways
- This could leave particularly visible fingerprints on the cosmic dark ages - epoch after the cosmic microwave background was released, but before stars formed
- During this period the universe was quiet, dark, just hydrogen + helium



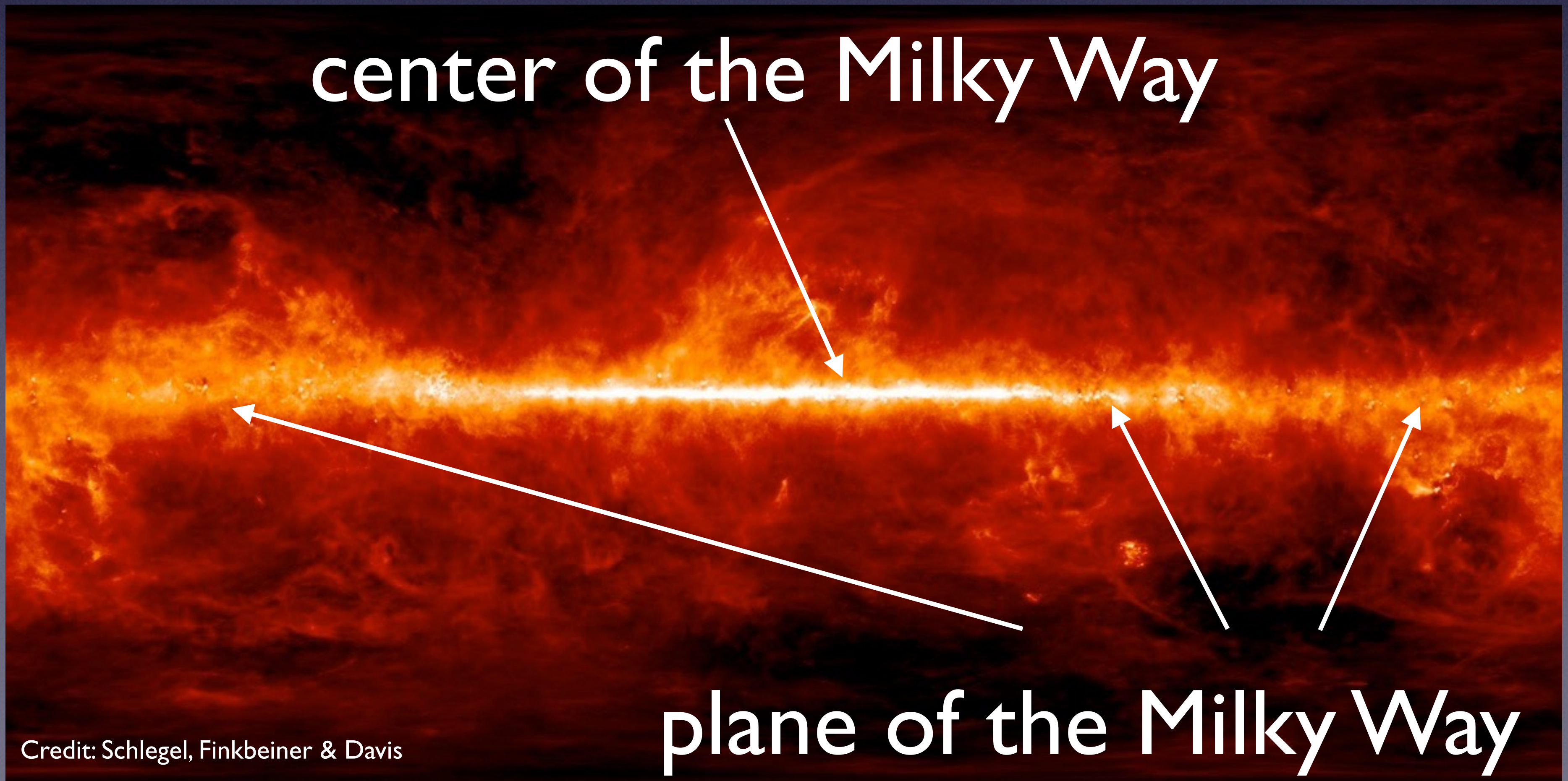
Ionizing and heating the early cosmos

- $E=mc^2$, and there is a great deal of energy stored in the dark matter mass (roughly 10^{-9} joules, or 5 GeV, per hydrogen atom)
- This may seem like a small number, but converting just one-billionth of that energy into visible radiation (via annihilation or decay) would provide enough power to:
  - heat up every hydrogen atom in the universe by roughly 50,000 degrees Kelvin (or Celsius)
  - split apart (into an electron and proton) half the hydrogen atoms in the universe
- We would have noticed if this had happened! We can actually test scenarios where only around one-trillionth of the dark matter is converted into visible signals in this epoch
- This corresponds to dark matter lifetimes around 10^8x longer than the current age of the cosmos, which can be probed for particle masses from the keV scale to the Planck scale (more than 20 orders of magnitude)

Another example: could dark matter be shining in our Galaxy?

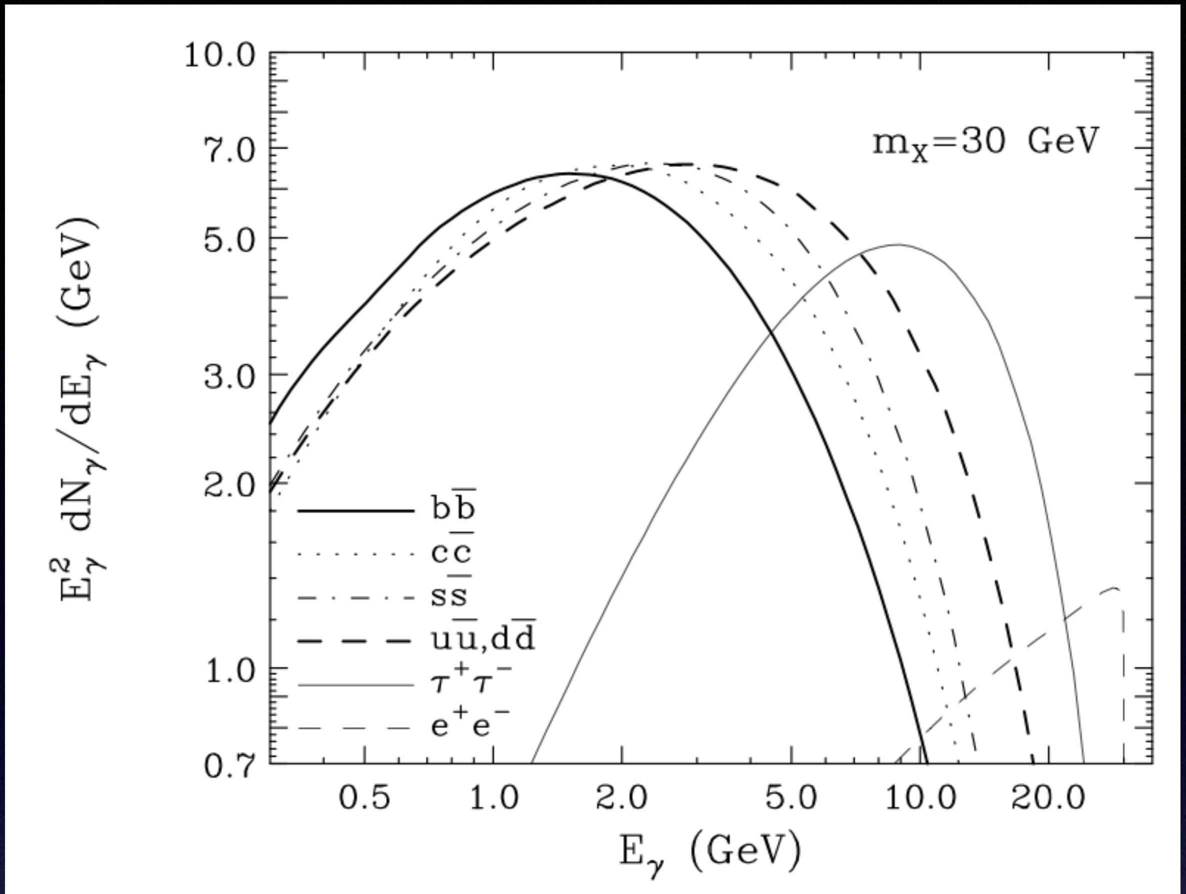
- Suppose dark matter was annihilating to make high-energy visible particles - these will typically radiate high-energy photons
- We can look for these photons with gamma-ray telescopes - however, there are other sources of high-energy photons, such as cosmic rays striking gas clouds

gas in the Milky Way

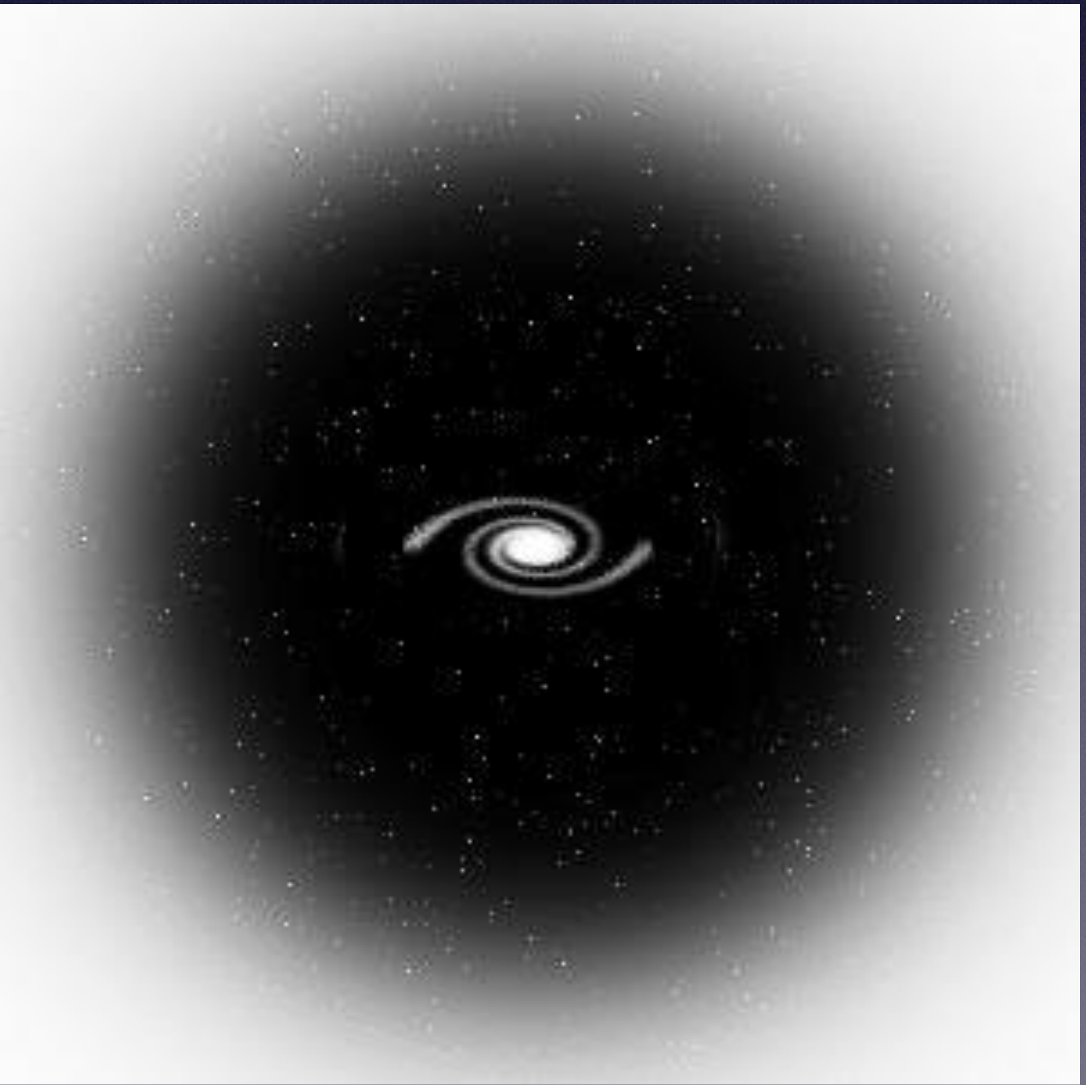


Features of a signal

- Spectral information: study how signal changes as a function of energy. A dark matter signal often has a peak at a particular energy, determined by the dark matter particle mass.

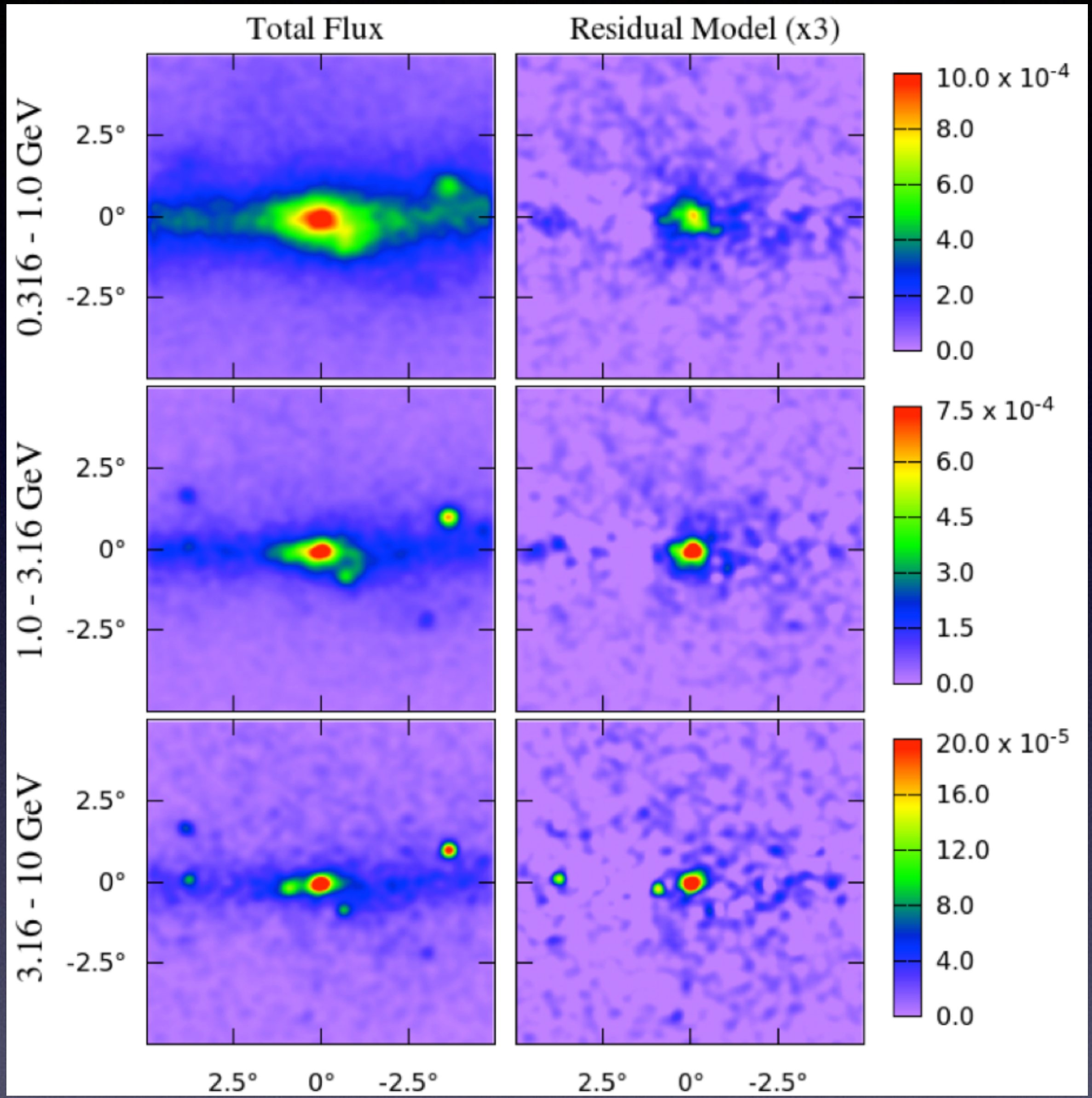


- Spatial information: dark matter should have a roughly spherical distribution, following the halo rather than the Galactic disk.



What we see

original data



after removing background

- "Blob" of gamma ray emission that does not seem to trace the disk of the Galaxy.
- Broad peak-like spectrum, as expected from dark matter
- Steeply peaked at the center of the Galaxy, but extends out to ~10 degrees (nearly 5000 light years) from the center, and looks roughly spherical.
- Brightness just what you would expect from standard dark matter models.

Hypotheses

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Particle theorist: 😀

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> Particle theorist: 😀

- "Conventional" astrophysics (i.e. not requiring physics beyond the Standard Model):
  - A new population of stars or other point sources - most discussed candidate is millisecond pulsars.
  - A new diffuse background - most discussed candidate is an outflow or burst from the Galactic Center.

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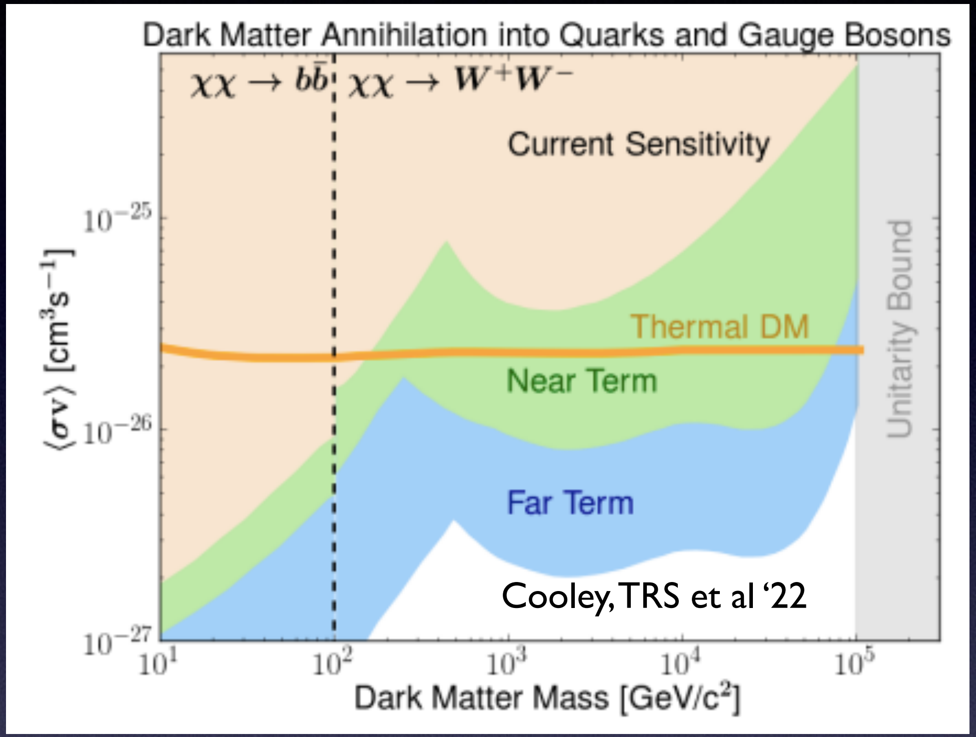
- The challenge: distinguishing the two! Understanding astrophysics is an essential ingredient for learning about dark matter (and many new statistical and computational tools are being applied, including artificial-intelligence approaches)

Plans for the next decade

- Arrays of telescopes can see when high-energy light or particles strike our atmosphere, producing a flash of Cherenkov radiation - new large arrays are under construction or proposed
- If we build them, these arrays will have sensitivity to general classes of dark models where annihilation determines the present-day abundance, over almost all their natural mass range
- Space-based telescopes are needed to look for lower-energy gamma-rays and X-rays - many ideas for new technologies
- One exciting new direction: searching for antideuterons and antihelium, which are thought to be background-free



But what if there are no interactions to find?

- It is possible dark matter doesn't interact with known particles (except through gravity)
- In this case, our best tool is to study the pattern of how dark matter is distributed through the cosmos

  - Dark matter that is too light can be ruled out because it has a wavelength larger than the smallest galaxies!
  - Primordial black holes much heavier than asteroids can be ruled out as 100% of the dark matter, via searches with gravitational lensing
  - Dark matter that is too fast-moving doesn't form the cosmic web
  - Dark matter particles could interact with each other, leaving characteristic signatures in the dark matter distribution

Summary

- Dark matter (DM) is more than 80% of the matter in the universe, and we don't know what it is.
  - Although we know it is collisionless or only weakly interacting, relatively slow-moving, and forms large halos around galaxies.
- There are a huge number of ideas for what DM could be, spanning an enormous range of masses - we hope to narrow down the possibilities by searching for its non-gravitational interactions with other particles.
- One promising route for isolating such signals is to look for visible particles produced by DM interactions, and their effects, in our Galaxy and beyond.
- We probably haven't found DM interactions so far, although there are some hints of possible signals that are telling us about something we need to understand (likely new and exciting astrophysics)
- There is an ambitious program to search for DM signals in the sky (both by testing for visible particles from DM interactions, and by improved measurements of the DM distribution) over the next decade

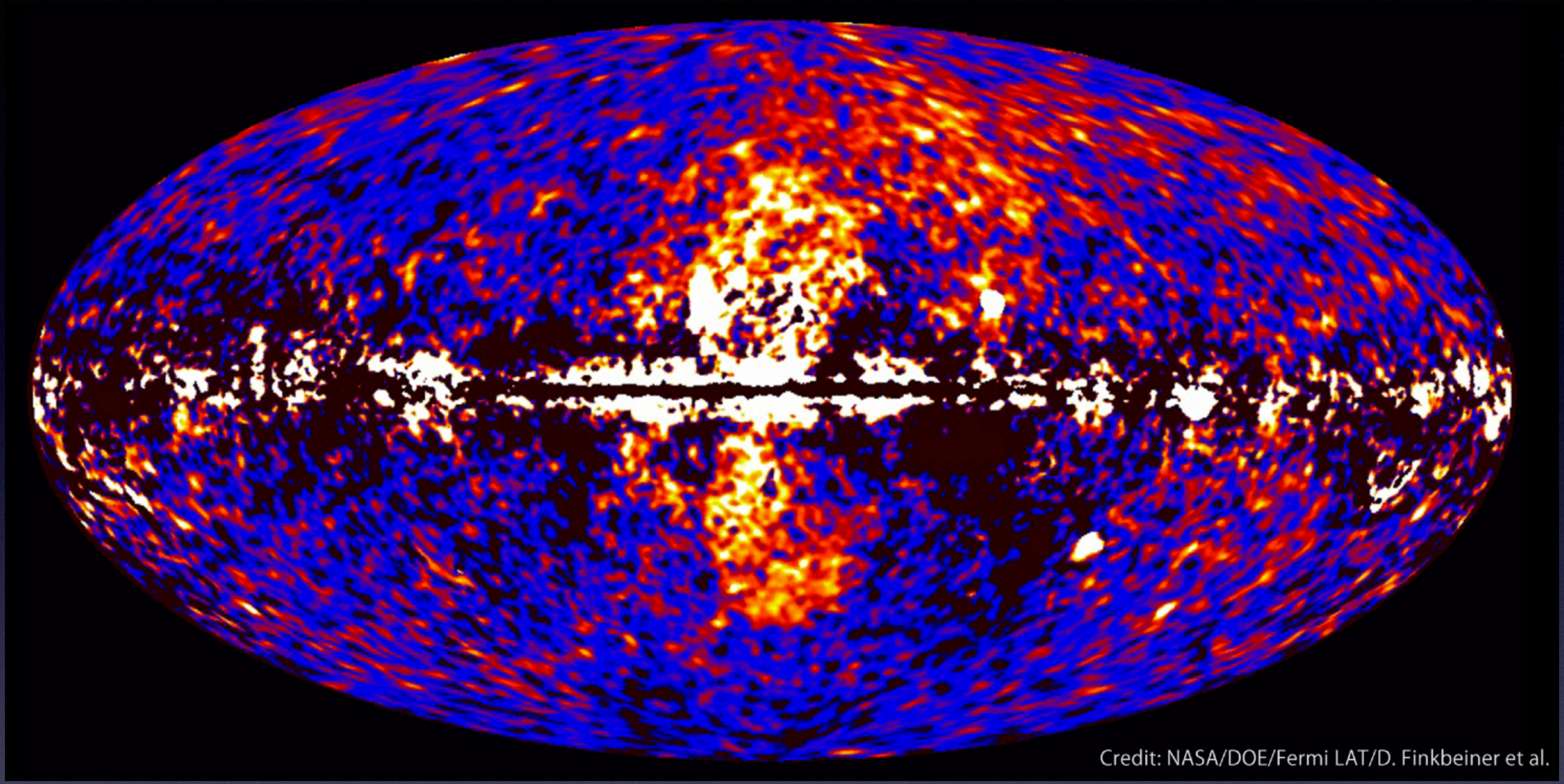
BONUS SLIDES

The Fermi Gamma-Ray Space Telescope

- Launched successfully from Cape Canaveral on 11 June 2008.
- Now in low-Earth orbit, 340 mile altitude.
- Scans the entire sky every two orbits (~3 hours).
- Sensitive to gamma-rays from 300 MeV up to several TeV.
- All data is public.

Credit: NASA

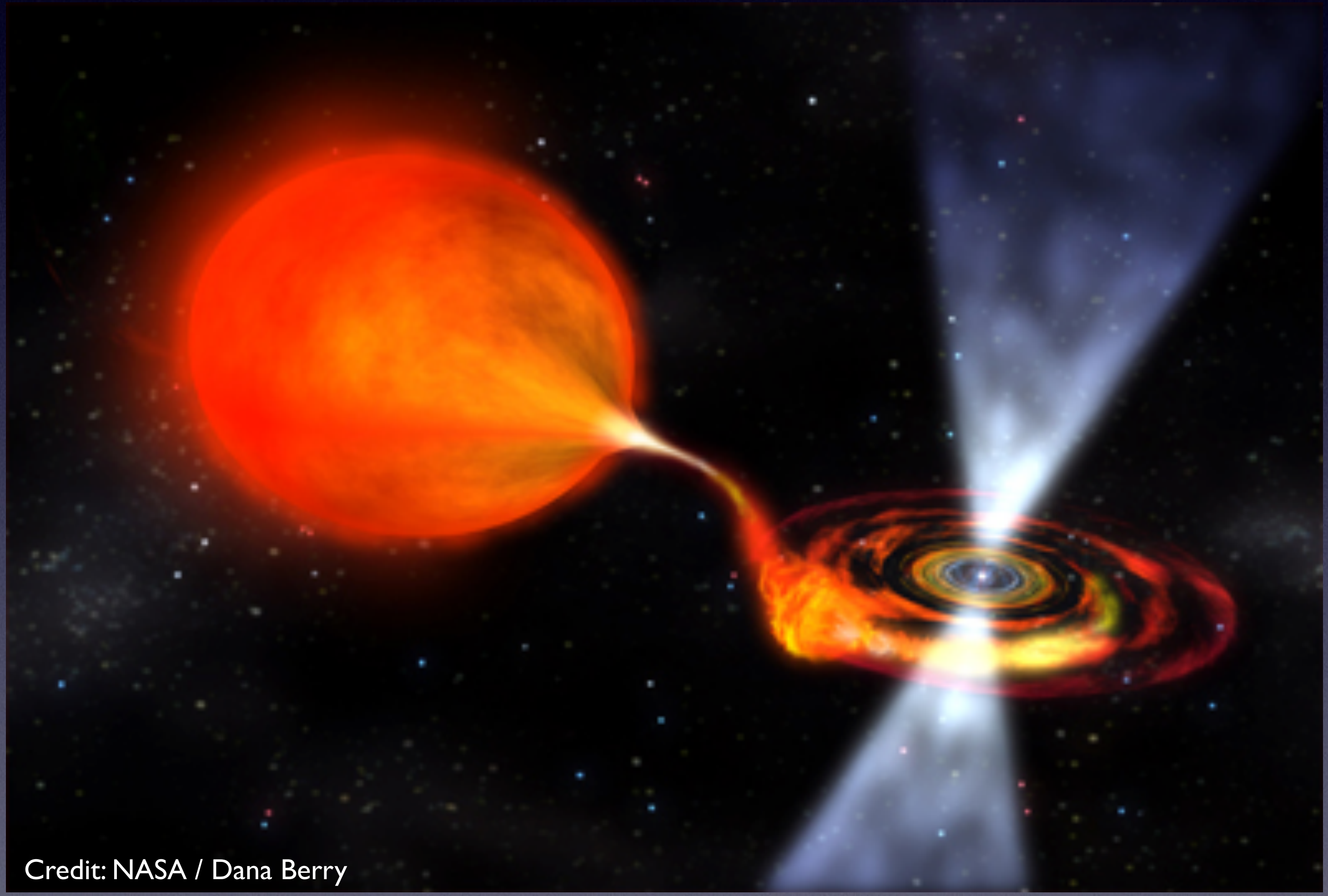
The "Fermi Bubbles"



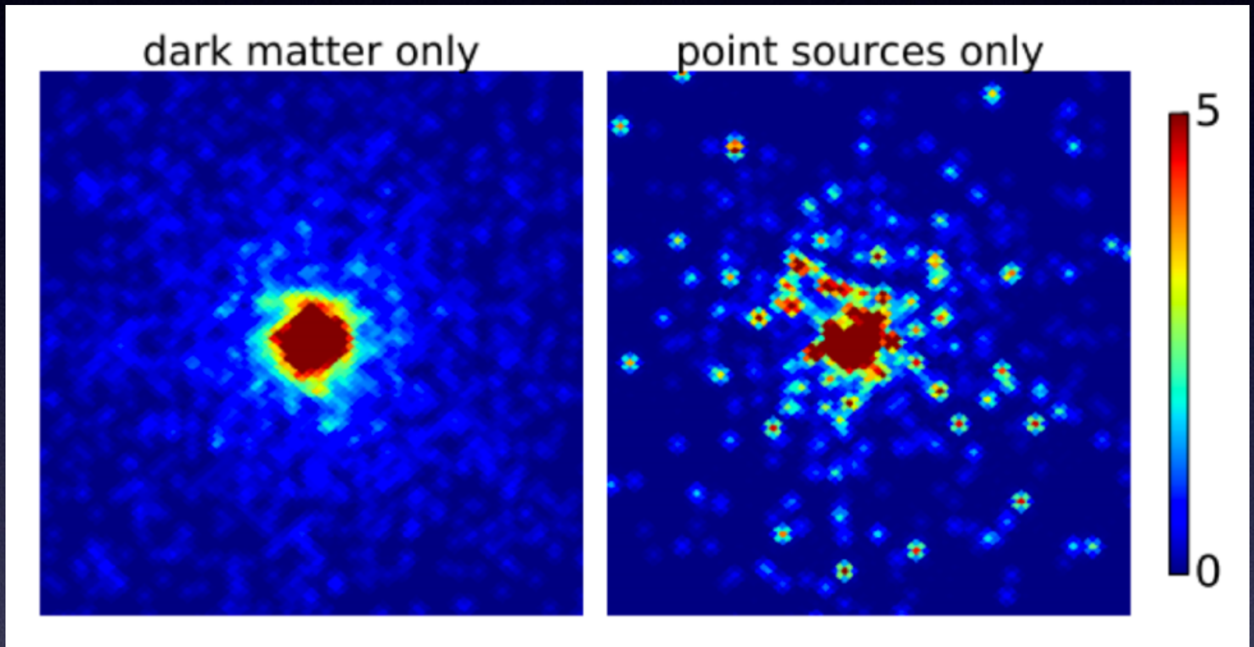
- Giant, double-lobed structure centered at the Galactic Center, extending ~50 degrees to the north and south - about 50,000 light years from top to bottom.
- Bright in 1-100 GeV gamma rays. Now also observed in X-ray and microwaves.
- May be a relic of activity of the black hole at the Galactic Center, or supernovae in the inner Galaxy, over the last several million years.
- Many puzzling features and their origin is still an open question.

What is a pulsar?

- Rapidly rotating star, composed of ultradense neutrons, that emits a beam of radiation as it spins
- Can emit in radio, X-ray and gamma-ray wavelengths
- Expected to have a “bump” spectrum in gamma rays



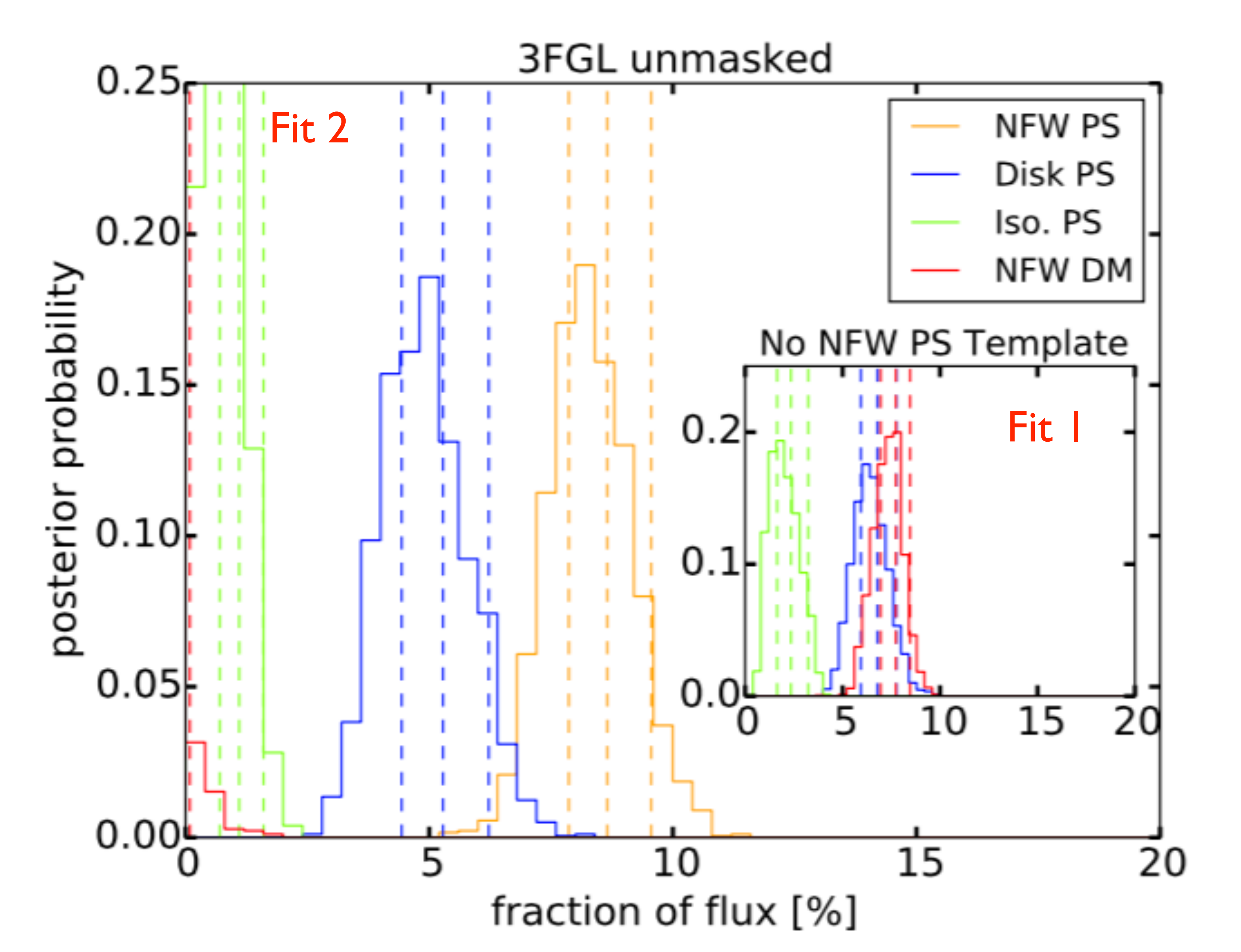
Pulsars or dark matter: how can we tell?



- We may be able to distinguish between these hypotheses by looking at <u>clumpiness</u> of the photons.
- If we are looking at dark matter (or an outflow/burst), we expect a fairly <u>smooth</u> distribution.
- In the pulsar case, we might instead see many "hot spots" scattered over a fainter background.

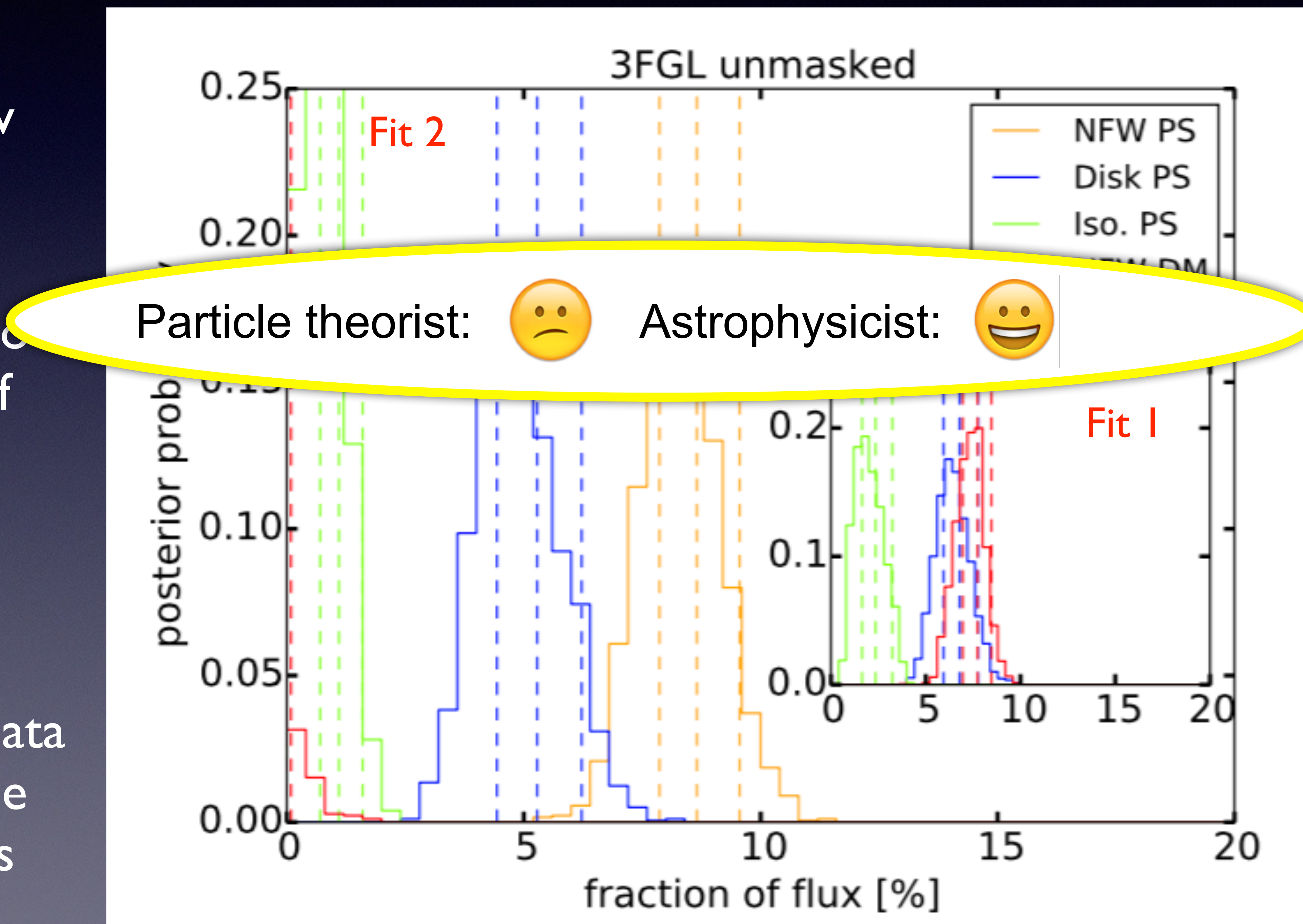
Evidence for point sources

- Analyses from 2015 seem to favor a new source population - probably pulsars.
- If given the option to have a population of point sources, most dense toward the Galactic center…
- Then the best description of the data is obtained when the entire excess comes from point sources.



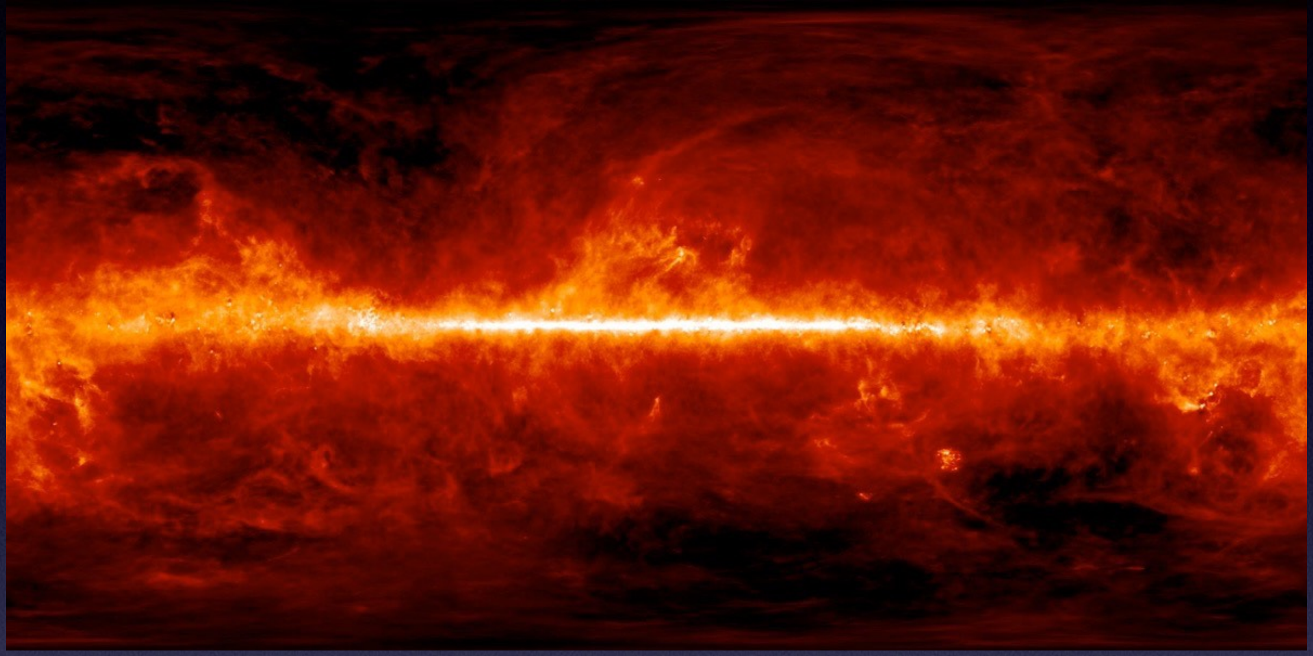
Evidence for point sources

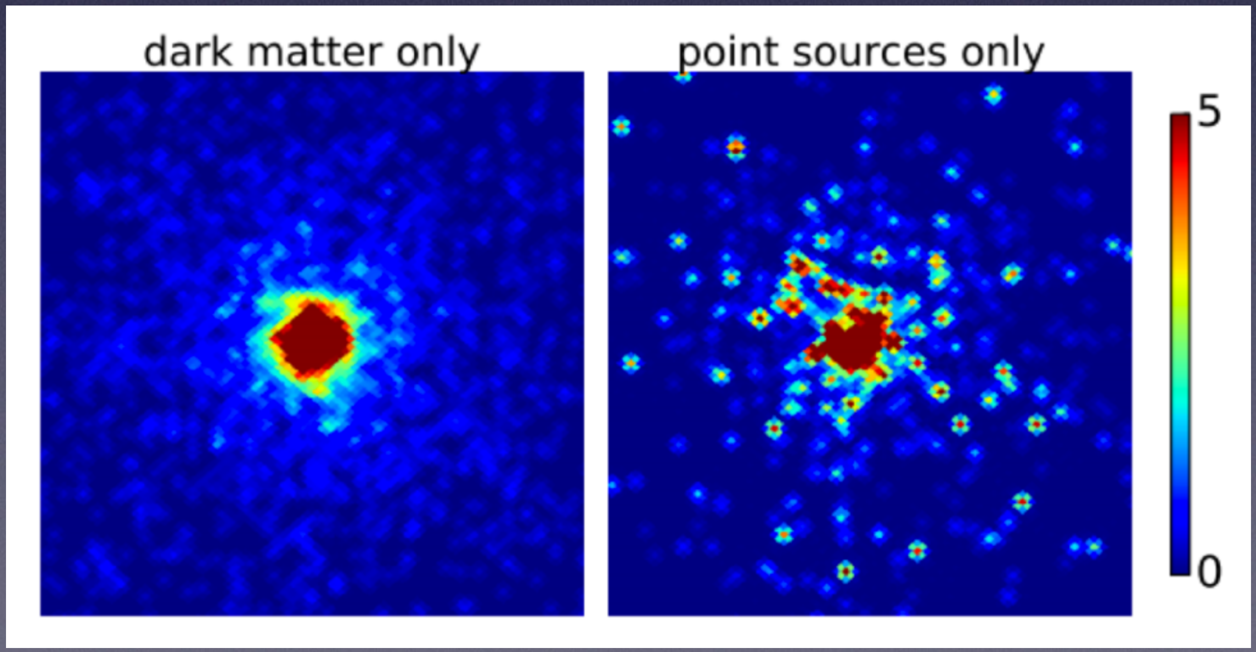
- Analyses from 2015 seem to favor a new source population - probably pulsars.
- If given the option to have a population of point sources, most dense toward the Galactic center…
- Then the best description of the data is obtained when the entire excess comes from point sources.



Dark matter strikes back?

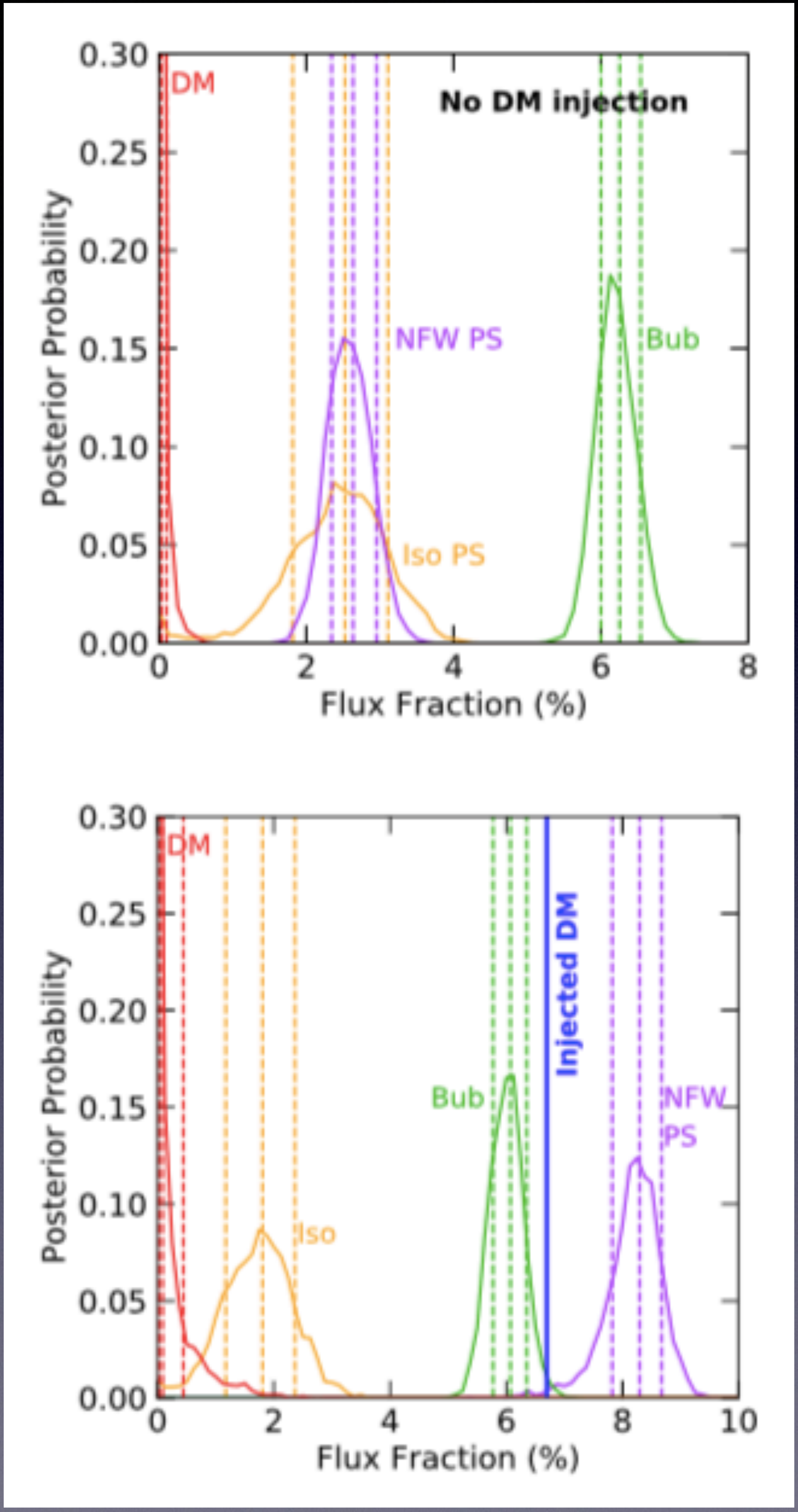
- The statistical method we developed relies on a good model of the background gamma rays
- If this model isn't good enough, a dark matter signal could get misidentified as pulsars
- Hot/cold spots would come from mistakes in background





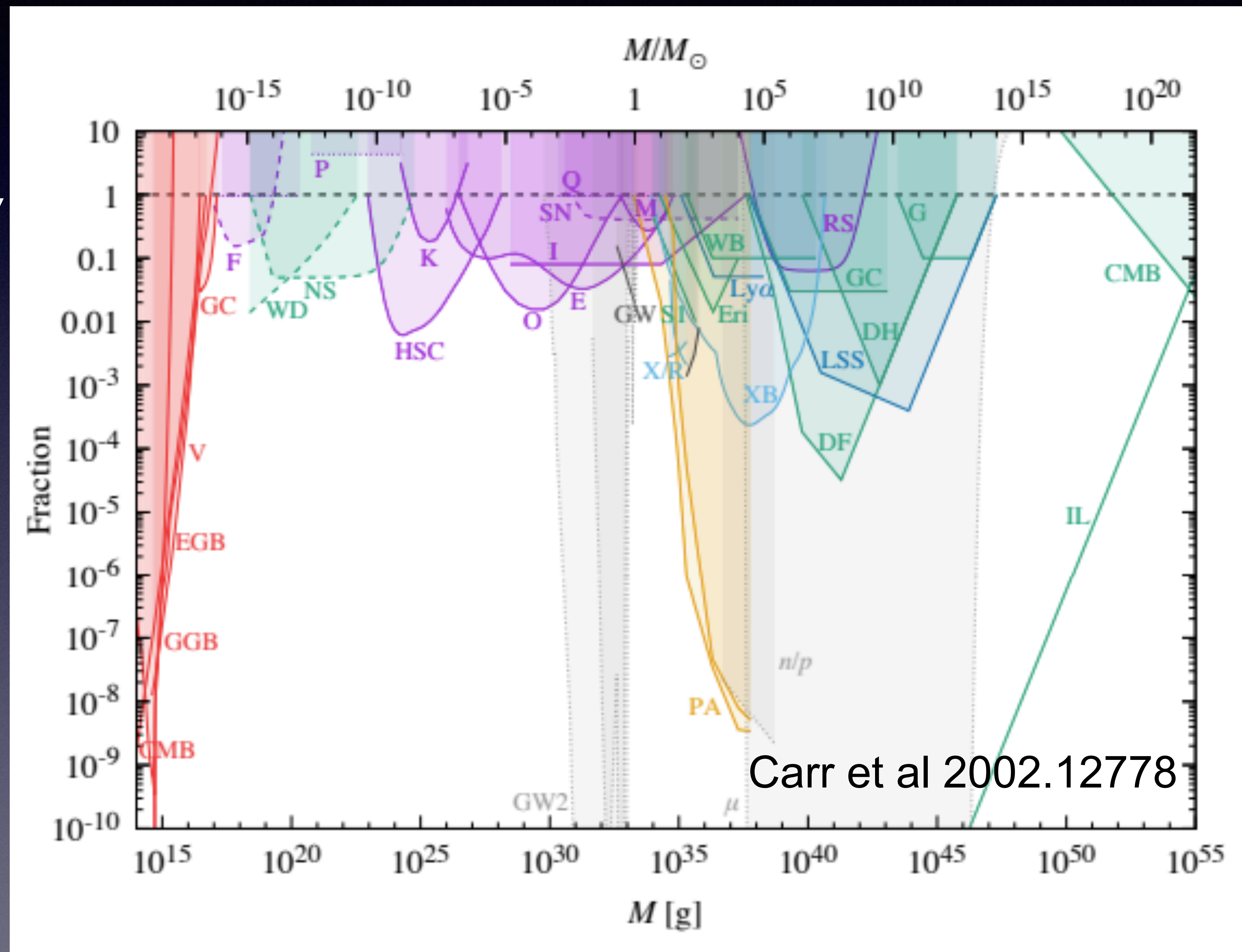
A new test

- Add a model of a dark matter signal to the real data
- Analyze the modified data
- Check that you get back original results + extra dark matter signal
- Bad news - the analysis thinks the injected dark matter signal is 100% point sources too!
- Signals a problem with the background model
- So maybe the DM explanation is not quite dead yet?



Primordial black holes (PBHs) as dark matter

- Primordial black holes are a viable DM candidate if they can be produced copiously during the universe's first instants
- There is an open window for all DM to be PBHs for PBH masses M~10^{17}-10^{23}g
- At the low end of this window, PBHs slowly evaporate via Hawking radiation



Dashed lines = constraints have been proposed, but are not reliable or have been refuted

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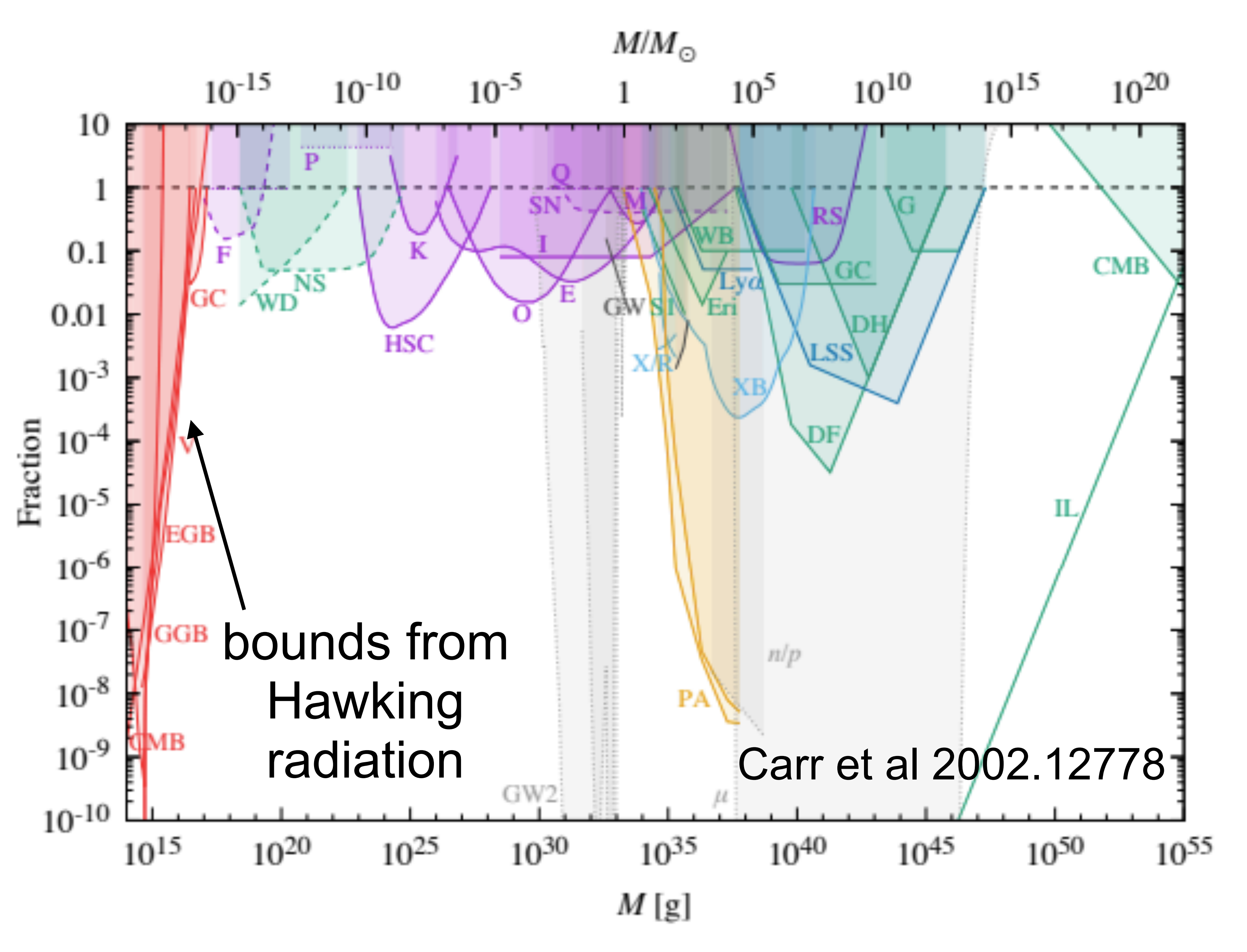

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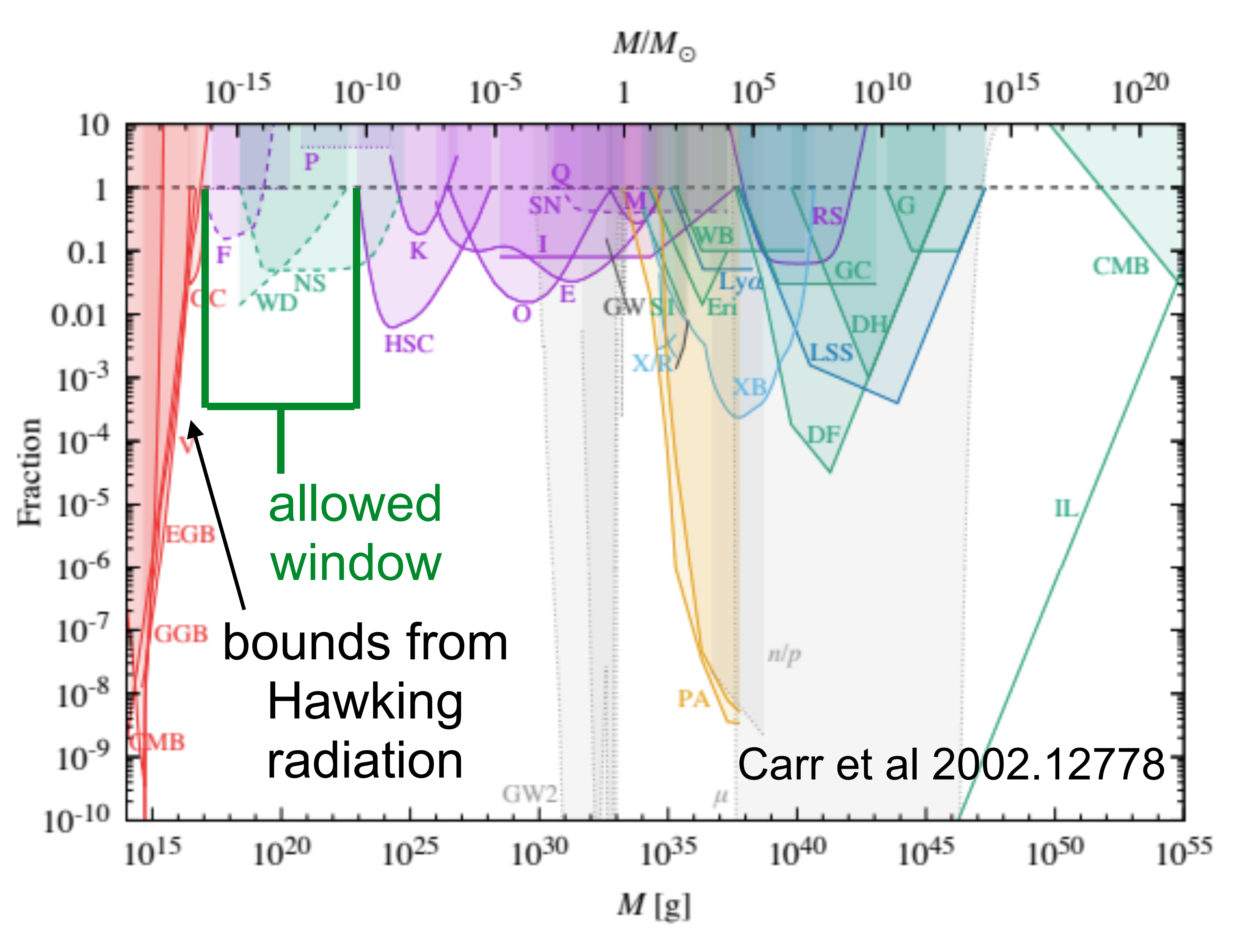

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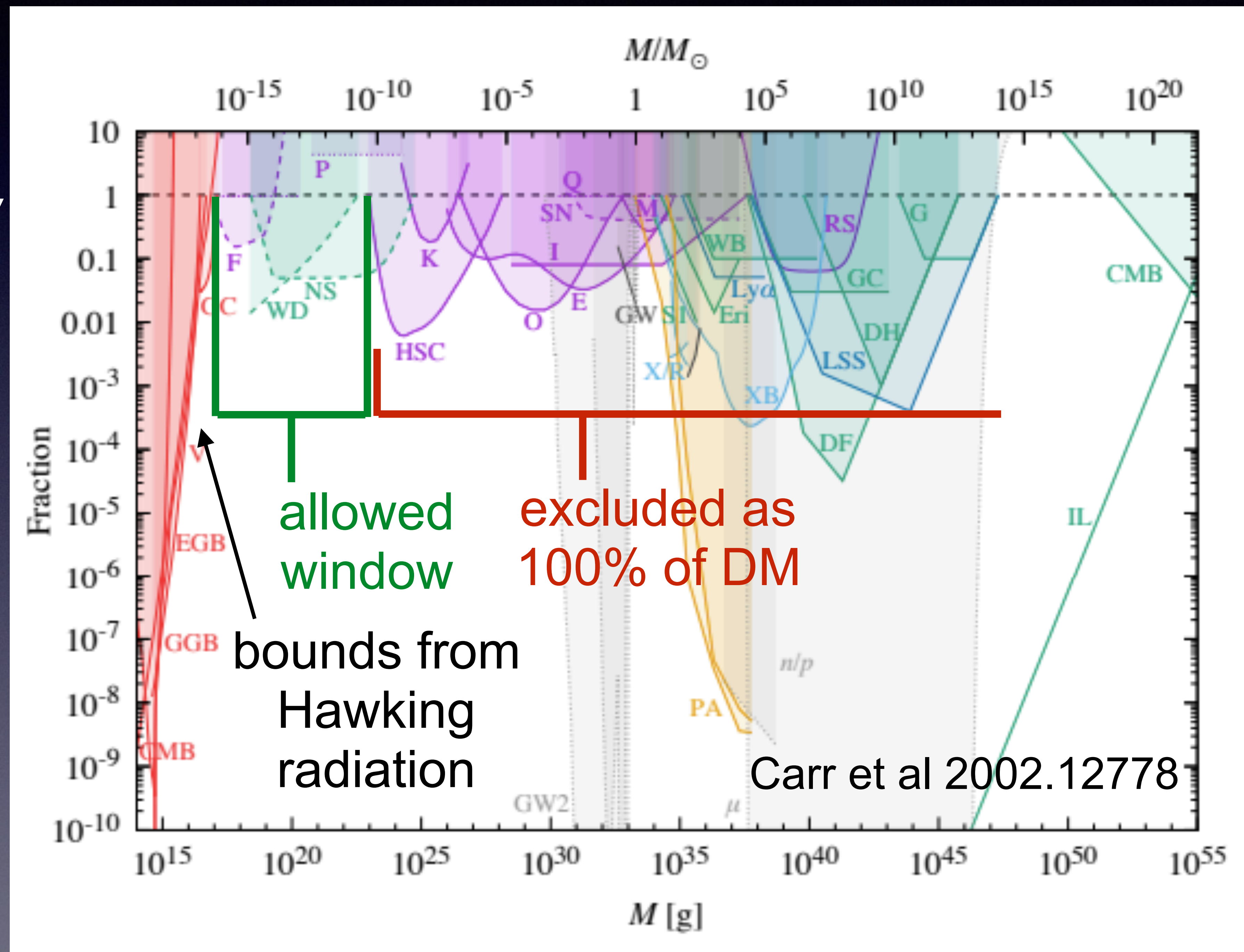

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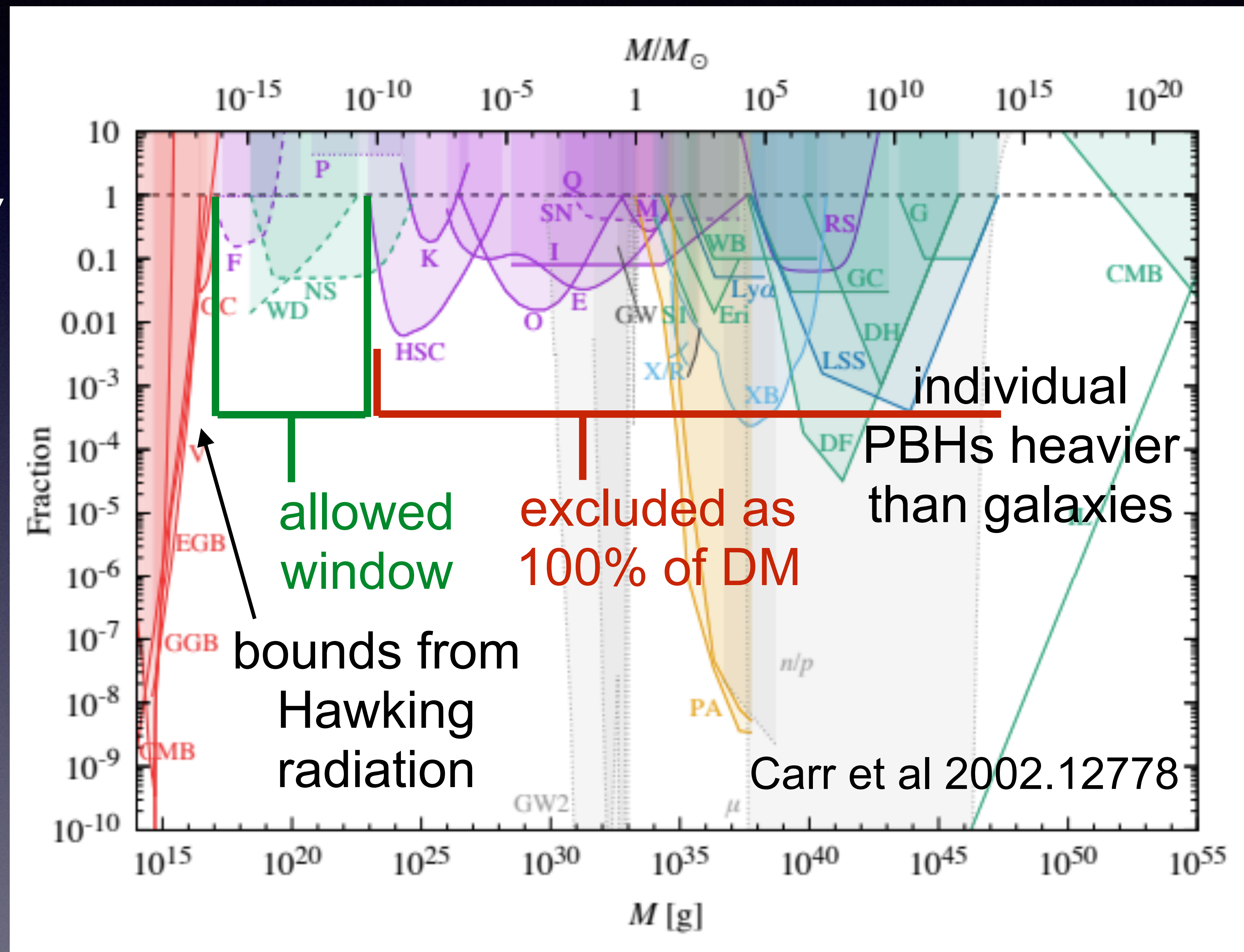

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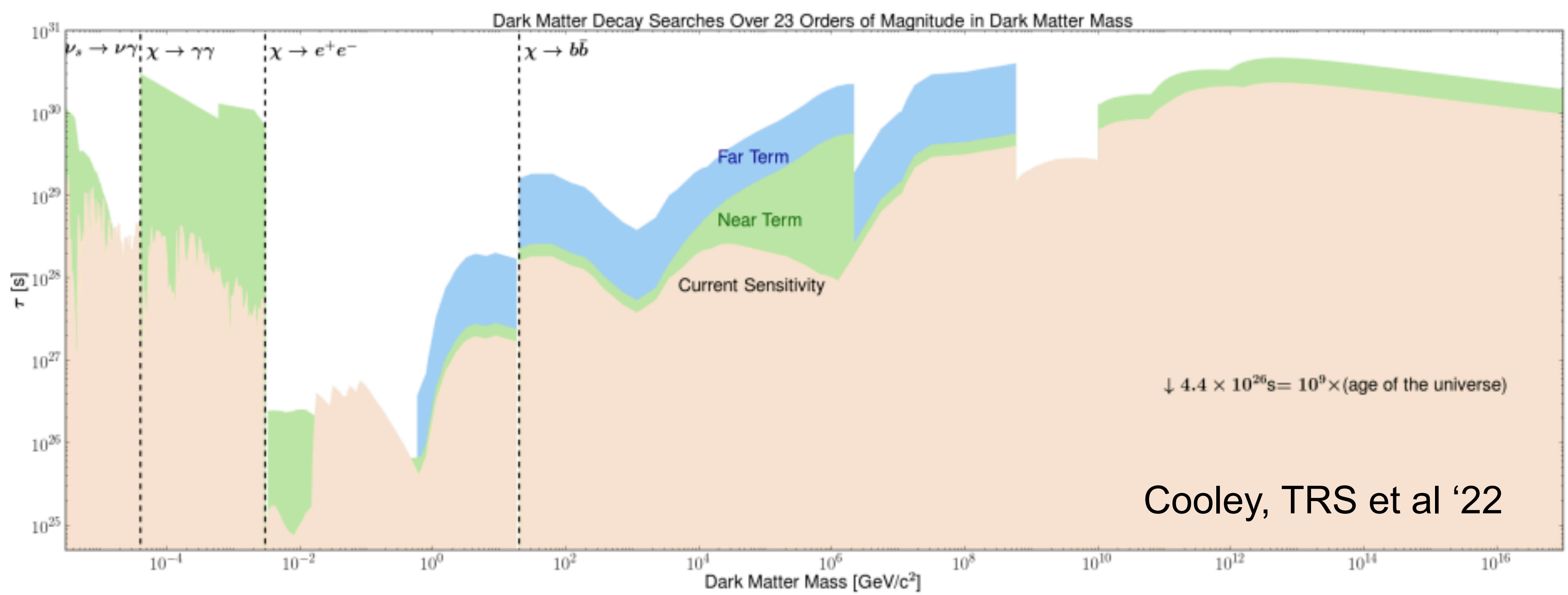
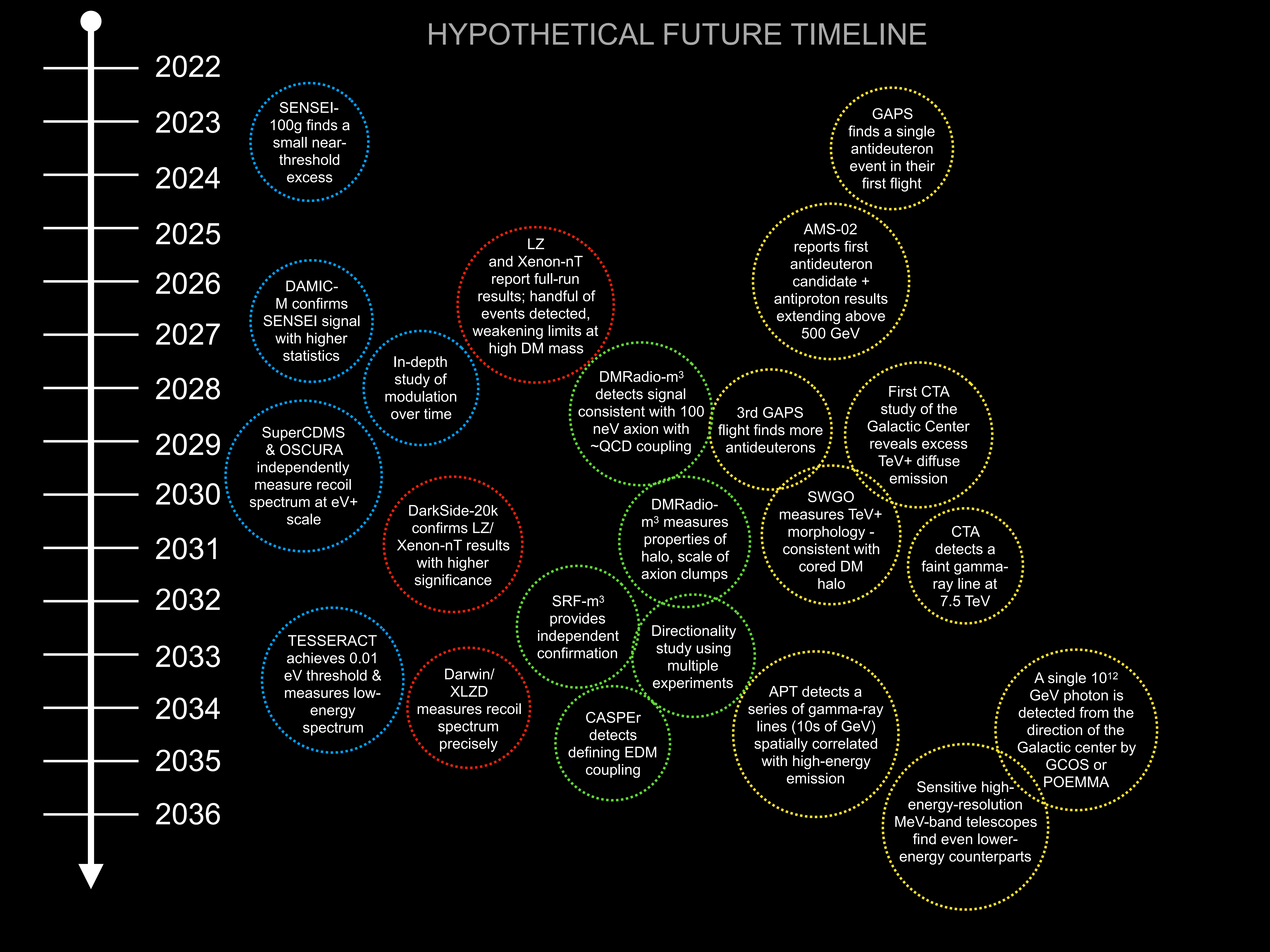
What about non-thermal DM?

- Not all DM candidates are relics of thermal freezeout, and those that are can have present-day cross sections that are enhanced or suppressed relative to the freezeout cross section.

- At low masses, DM annihilation rates far below the thermal cross-section can be constrained, especially if proposed future balloon- and space-based gamma-ray telescopes are realized.

- With similar searches, we can also set limits on DM decay over a huge range of masses.





HYPOTHETICAL FUTURE TIMELINE
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2036
SENSEI-100g finds a small near-threshold excess
DAMIC-M confirms SENSEI signal with higher statistics
In-depth study of modulation over time
SuperCDMS & OSCURA independently measure recoil spectrum at eV+ scale
TESSERACT achieves 0.01 eV threshold & measures low-energy spectrum
LZ and Xenon-nT report full-run results; handful of events detected, weakening limits at high DM mass
DarkSide-20k confirms LZ/ Xenon-nT results with higher significance
Darwin/ XLZD measures recoil spectrum precisely
DMRadio-m^3 detects signal consistent with 100 neV axion with ~QCD coupling
DMRadio-m^3 measures properties of halo, scale of axion clumps
SRF-m^3 provides independent confirmation
Directionality study using multiple experiments
CASPEr detects defining EDM coupling
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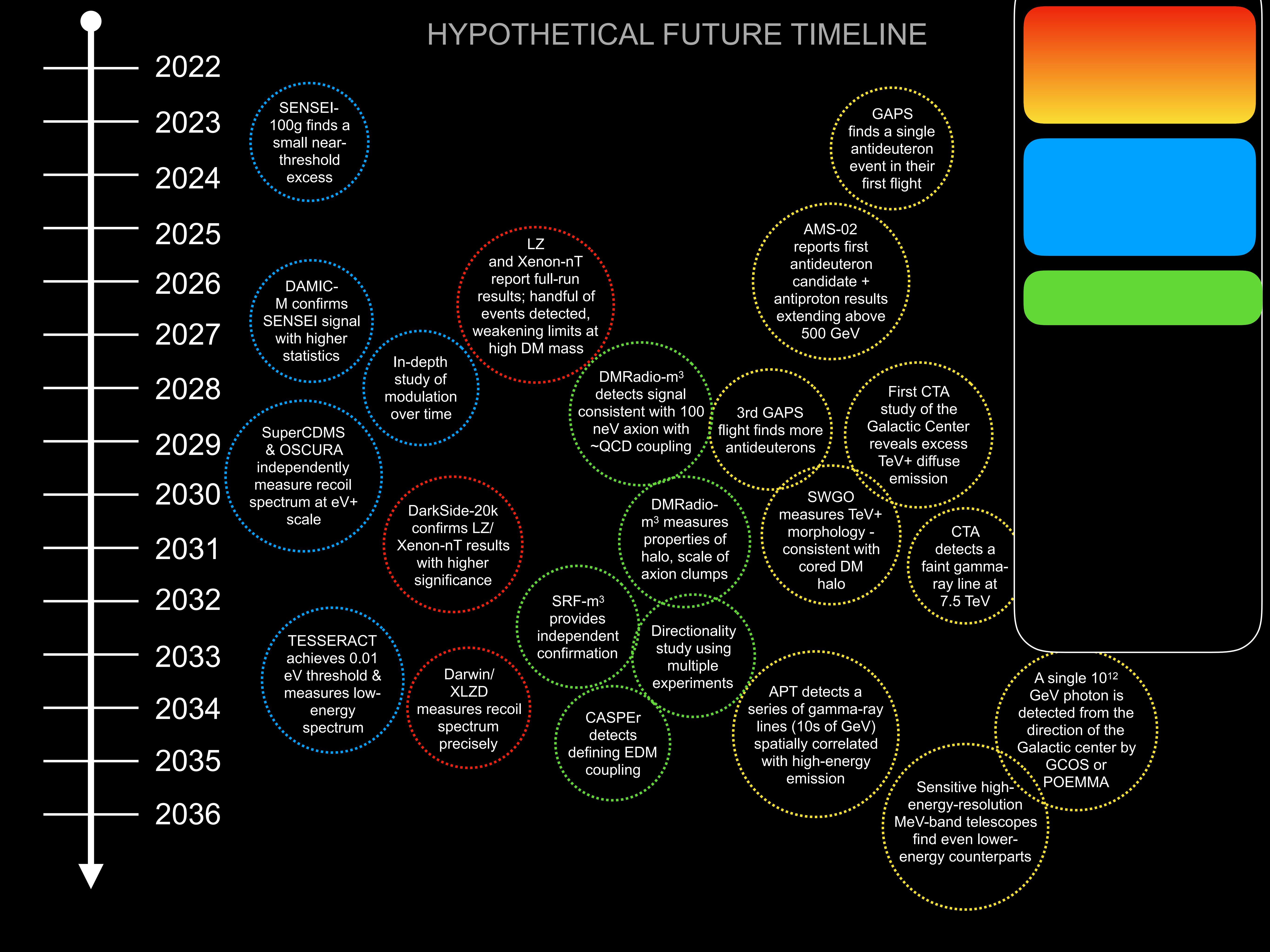
AMS-02 reports first antideuteron candidate + antiproton results extending above 500 GeV
3rd GAPS flight finds more antideuterons
First CTA study of the Galactic Center reveals excess TeV+ diffuse emission
SWGO measures TeV+ morphology - consistent with cored DM halo
CTA detects a faint gamma-ray line at 7.5 TeV
APT detects a series of gamma-ray lines (10s of GeV) spatially correlated with high-energy emission
A single 10^{12} GeV photon is detected from the direction of the Galactic center by GCOS or POEMMA
Sensitive high-energy-resolution MeV-band telescopes find even lower-energy counterparts



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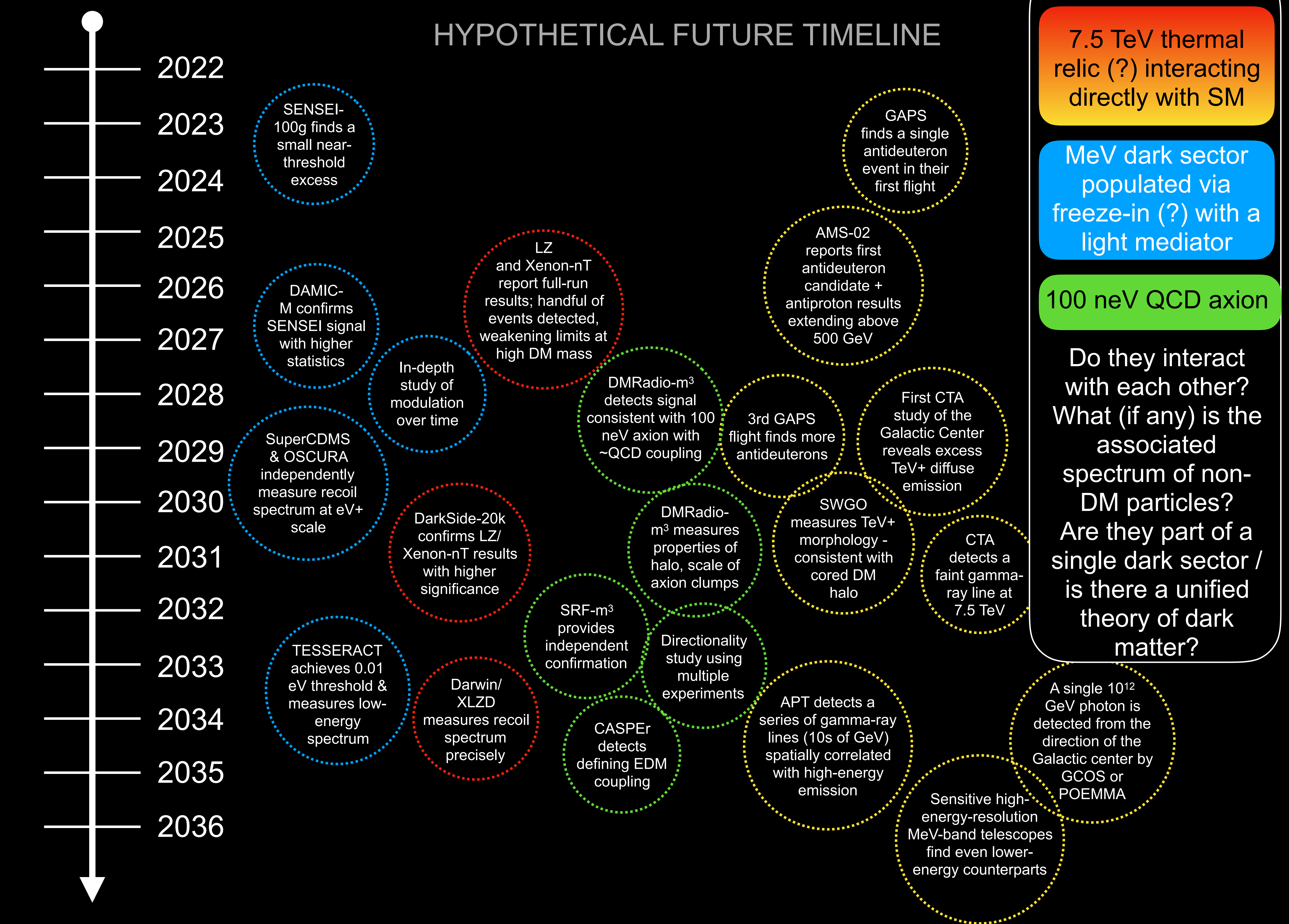
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7.5 TeV thermal relic (?) interacting directly with SM
MeV dark sector populated via freeze-in (?) with a light mediator
100 neV QCD axion
Do they interact with each other? What (if any) is the associated spectrum of non-DM particles? Are they part of a single dark sector / is there a unified theory of dark matter?