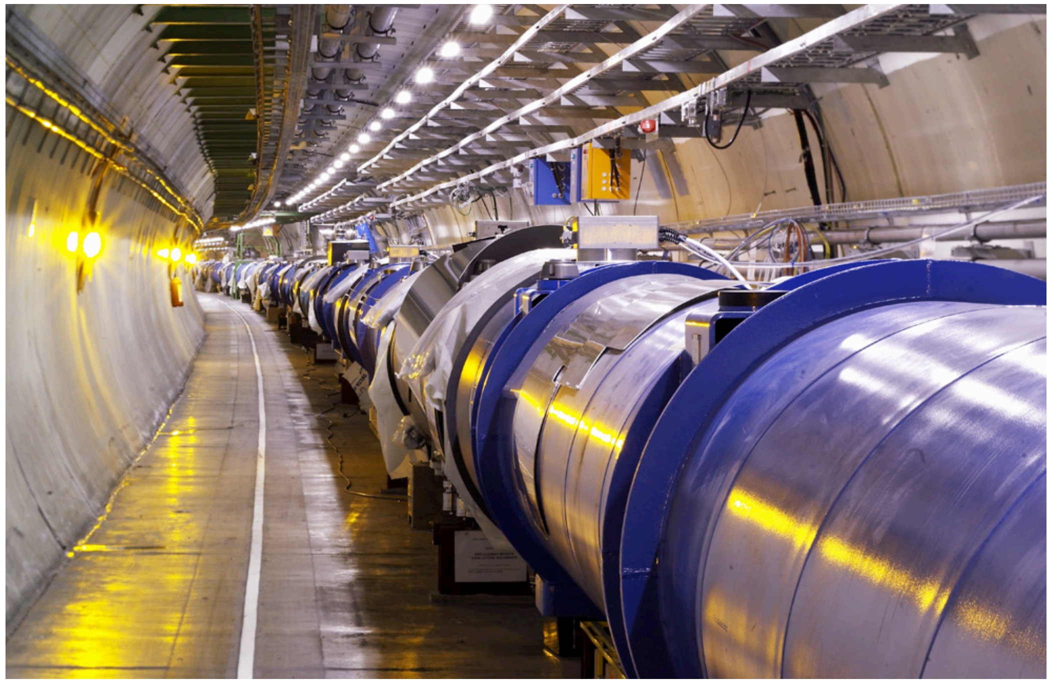
Connections of Colliders to Astrophysics

and Cosmology



Roni Harnik, Fermilab

Before we begin

* Who am I?
* Who are you?
* User instructions for students who've gone thru 10 days (!) of lectures: ask questions!

The Goal

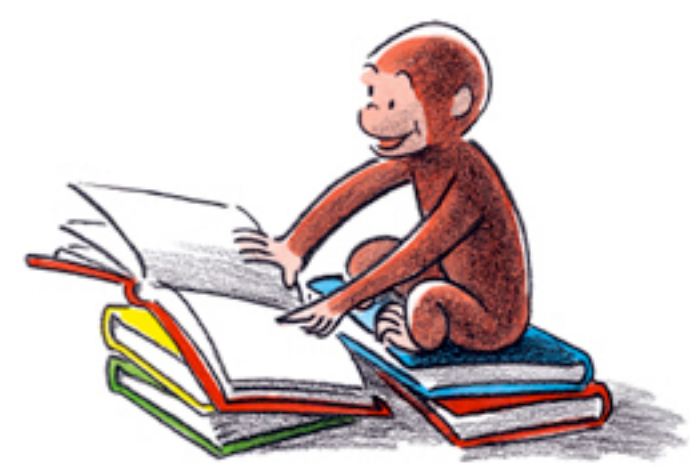
* The big questions our field tries to answer can be summarized as

$$\mathcal{L} = ?$$

What are the degrees of freedom?

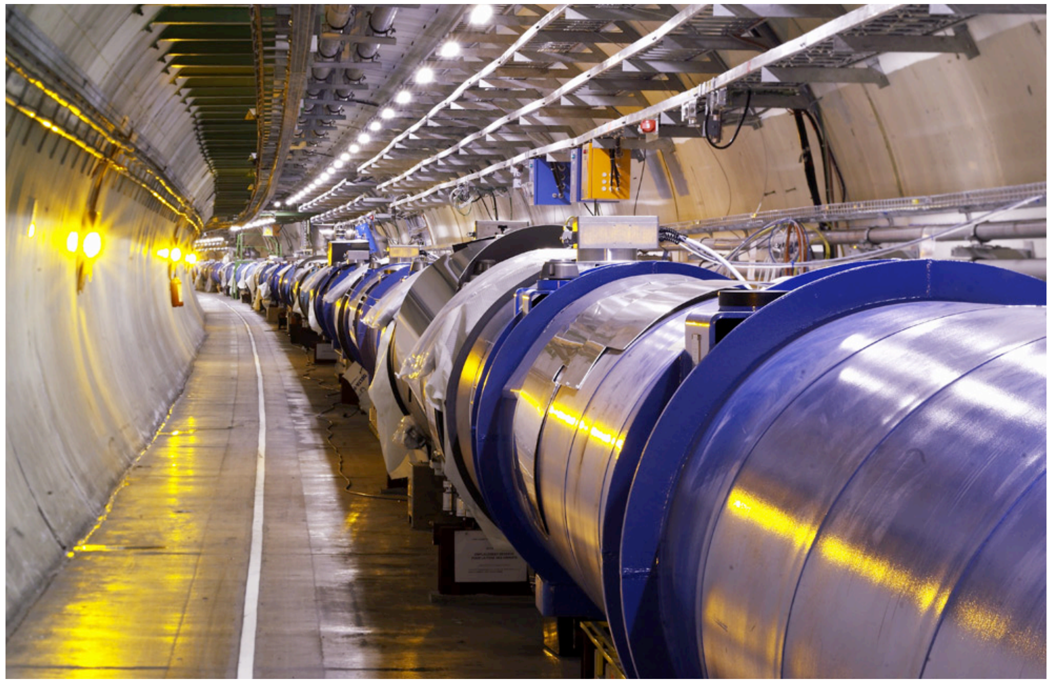
What are their interactions? symmetries?

What are the rules?!



The Tools

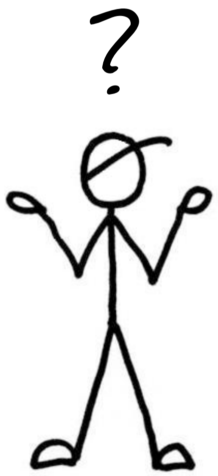
* Colliding Stuff:



* Looking Around Us:

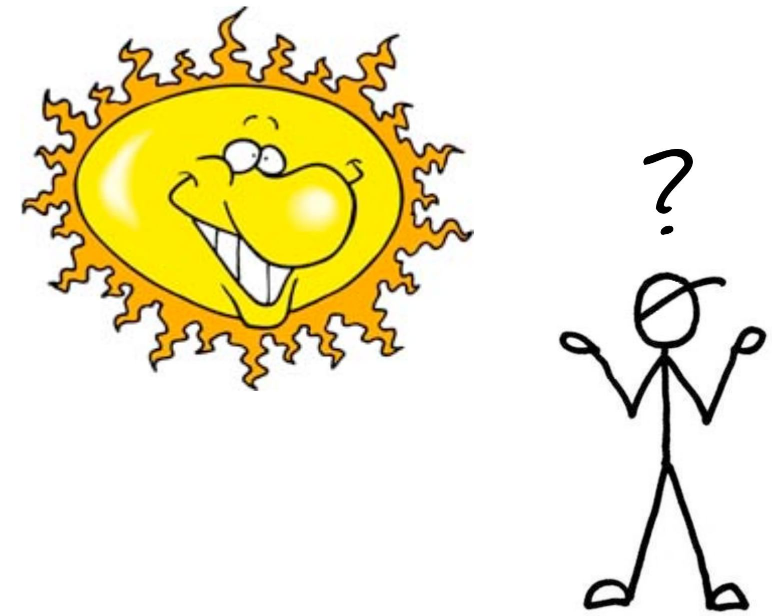
We have a whole Universe to look through for clues!

Example:



* What Power's the sun?
  - 1860's - Kelvin and Helmholtz:
    "SM" physics of those days - gravitational contraction.
    Age estimate : 20 million years.
  - 1904 - Rutherford:
    An internal source of heat.
  - 1920's (post relativity)-
    Eddington proposed nuclear fusion.
  - 1930's -
    Bethe calculated main nuclear reactions.
  - ...

Example:



The observation of the Sun's
energy problem could lead people
to new forces of nature (and relativity).

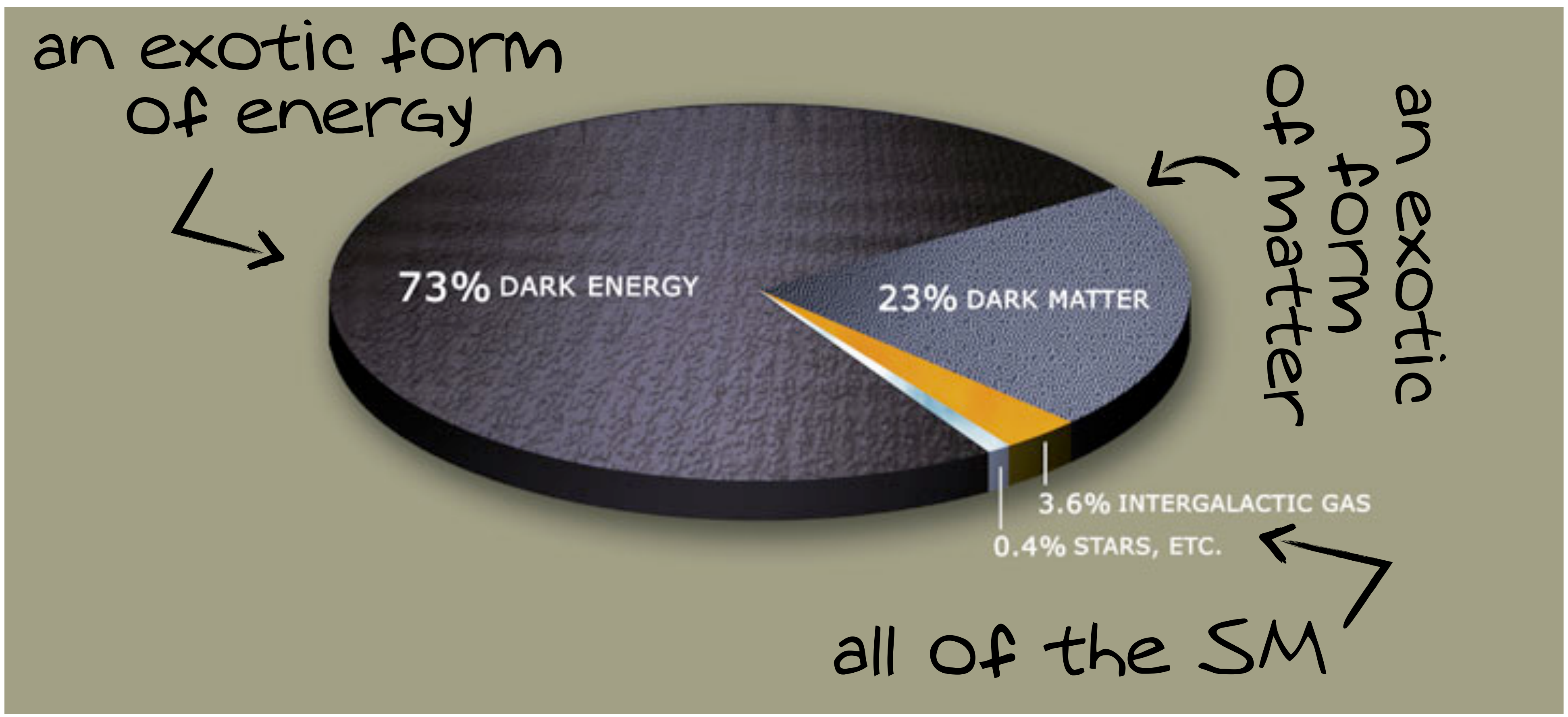
$$\mathcal{L} = ?$$

$E=mc^2$

nuclear reactions

Our Universe

* Our Universe is big, homogeneous, isotropic. Contains the following (by mass/energy):

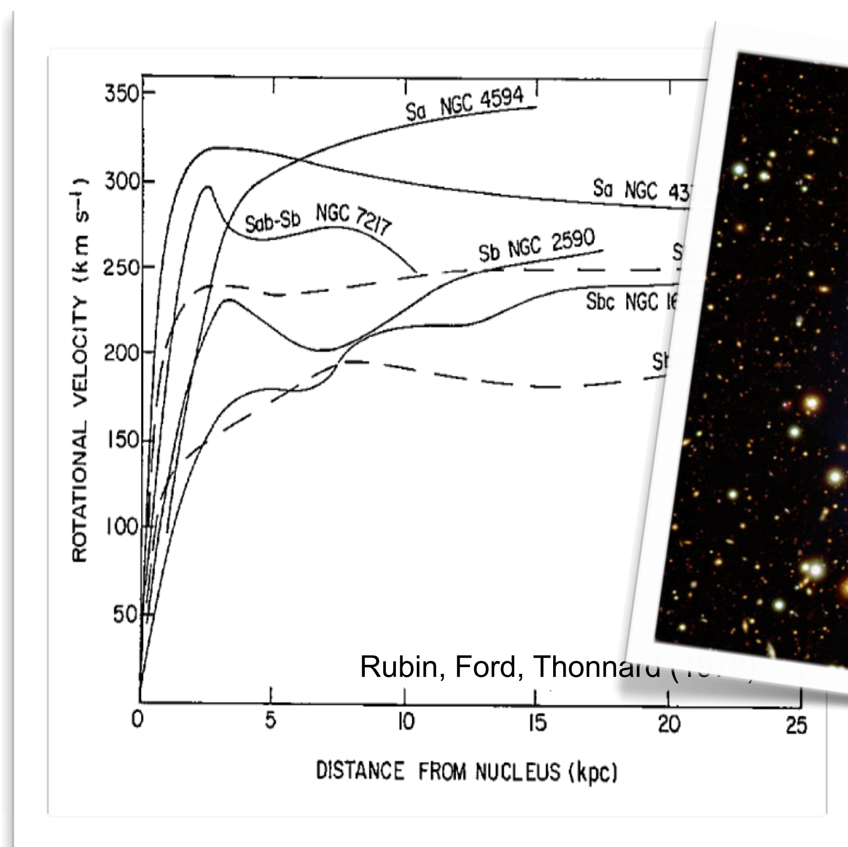


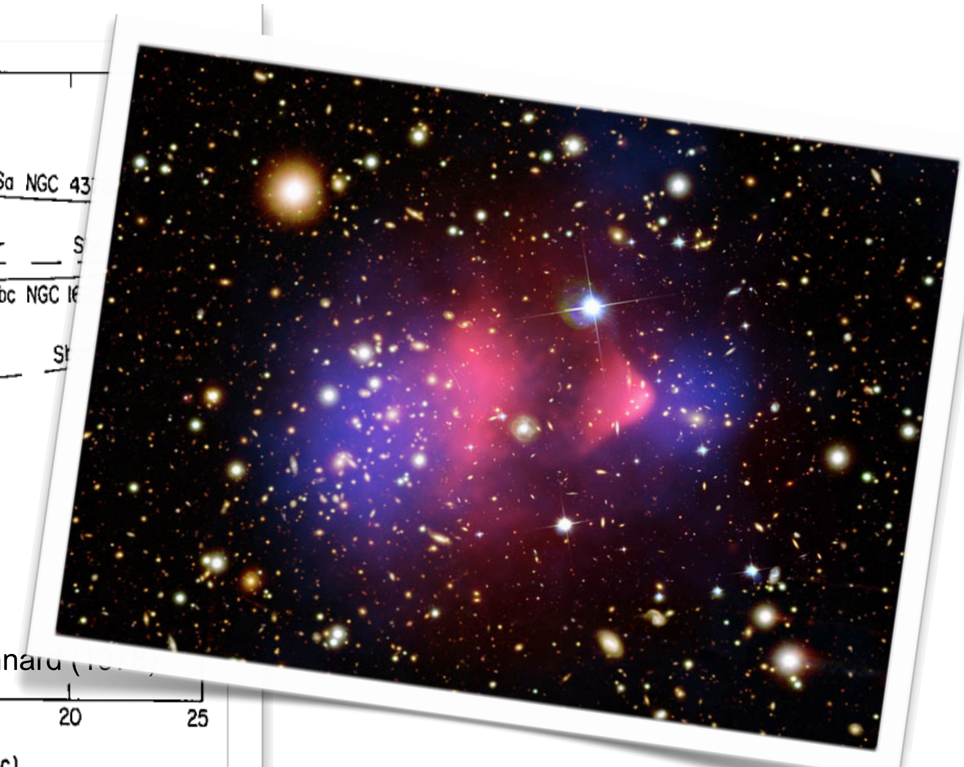
We have a Universal energy problem:
"whats all this stuff?"

Outline

* Evidence for Dark Matter (Dark Energy too, if we have time):
  - Rotation curves, CMB, BBN, lensing, supernovae.
* Properties of Dark Matter:
  - Lifetime, hot/cold,
  - **Abundance & interaction w/ matter**.
* Candidates for Dark Matter:
  - SUSY, WIMPs, axions,..................
* Searches for Dark Matter:
  - Direct
  - Indirect
  - **Colliders**

Evidence for Dark Matter





Take Home massage will be:
dark matter exists!

Coma Cluster (1932)

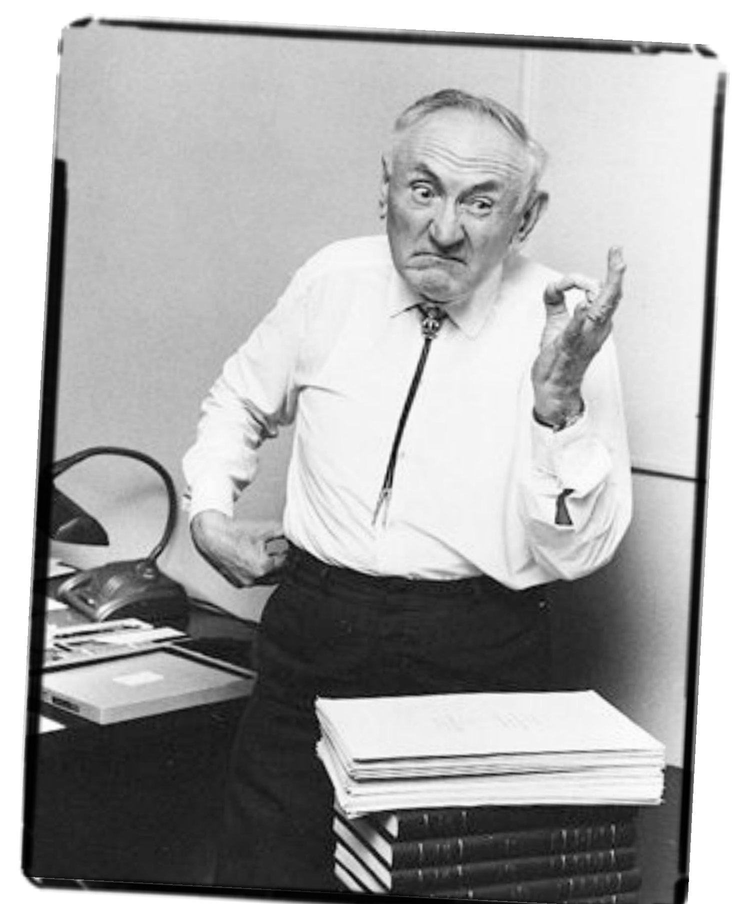
* Zwicky "measured" the mass of the coma cluster using velocities of individual galaxies:

$$2\langle K\rangle = -\langle V\rangle \qquad \text{(virial theorem)}$$

$$mv^2 = G_N \frac{mM}{R}$$

$$\boxed{M = \frac{v^2 R}{G_N}}$$

This yielded a factor of 400
b/w the luminous and "gravitational" mass.



Called the missing stuff "dark matter".

Rotation Curves

* Vera Rubin measured galactic rotation curves (60's):

$$\frac{mv^2}{r} = G_N \frac{mM}{r^2}$$

outside luminous bulk

$$v \propto r^{-1/2}$$

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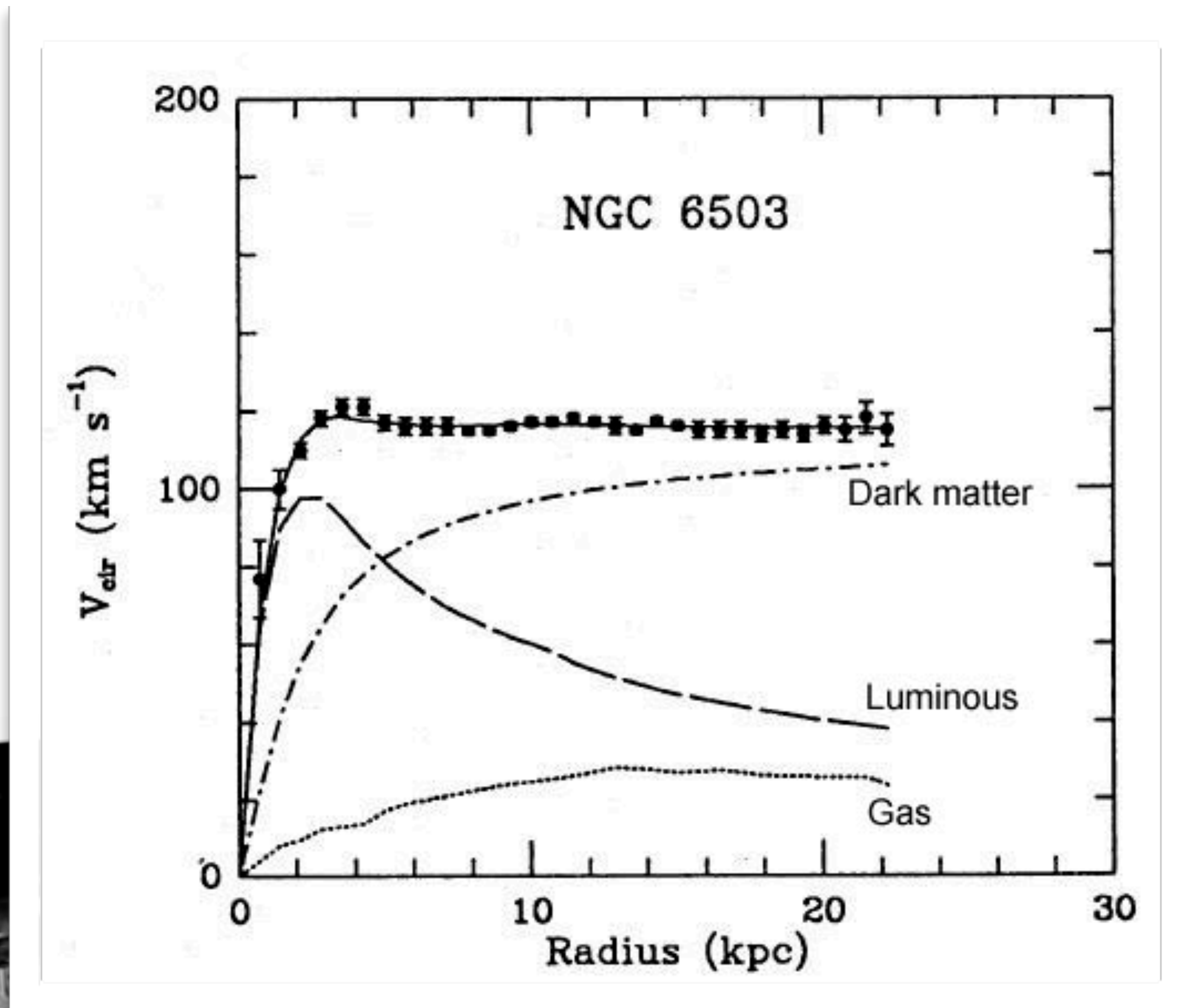


$$\frac{mv^2}{r} = G_N \frac{mM}{r^2}$$

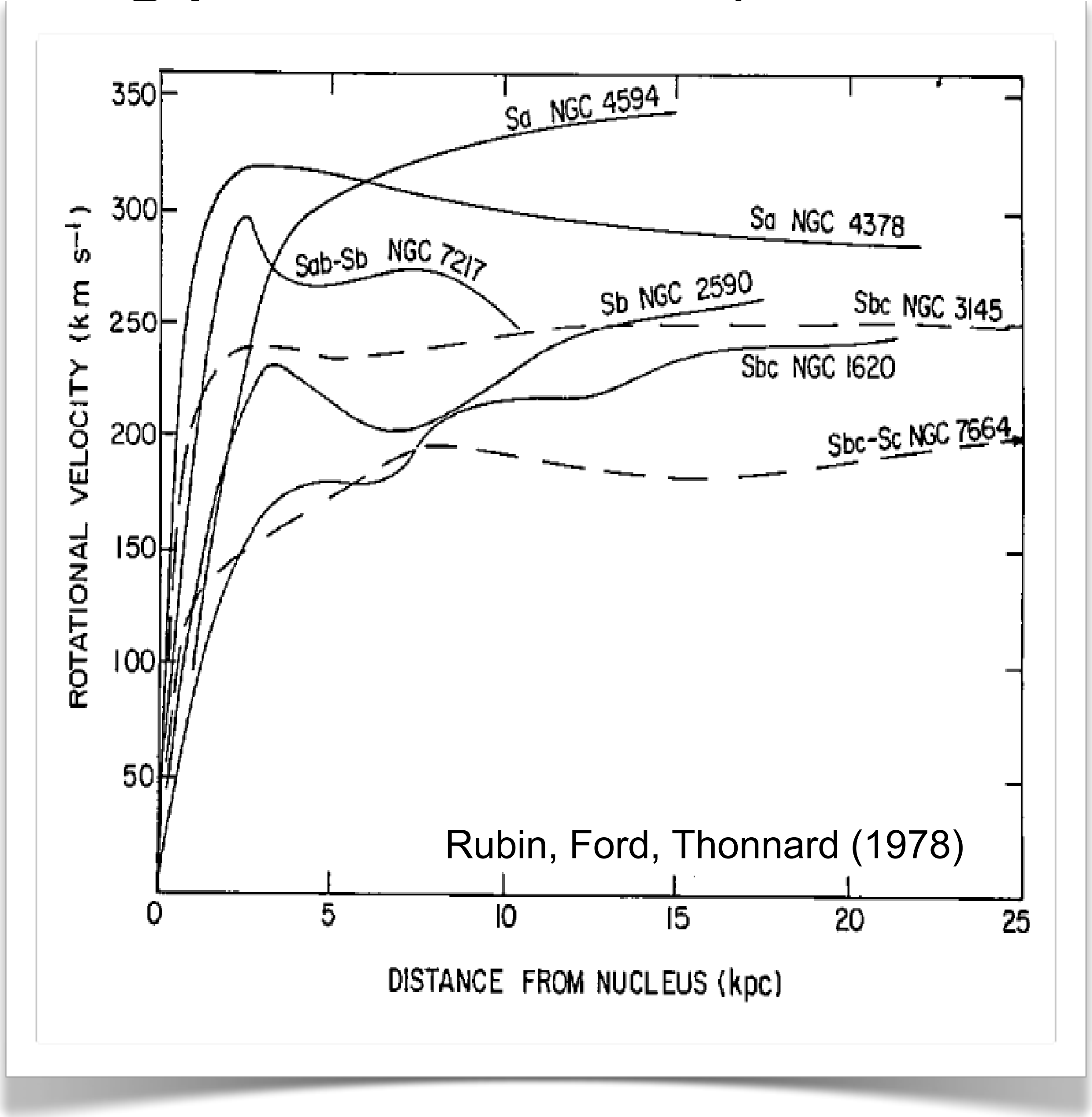
outside luminous bulk

$$v \propto r^{-1/2}$$

Instead, she finds a flat curve!

Rotation Curves

- This has been done many times, with ever increasing precision for object of various sizes:



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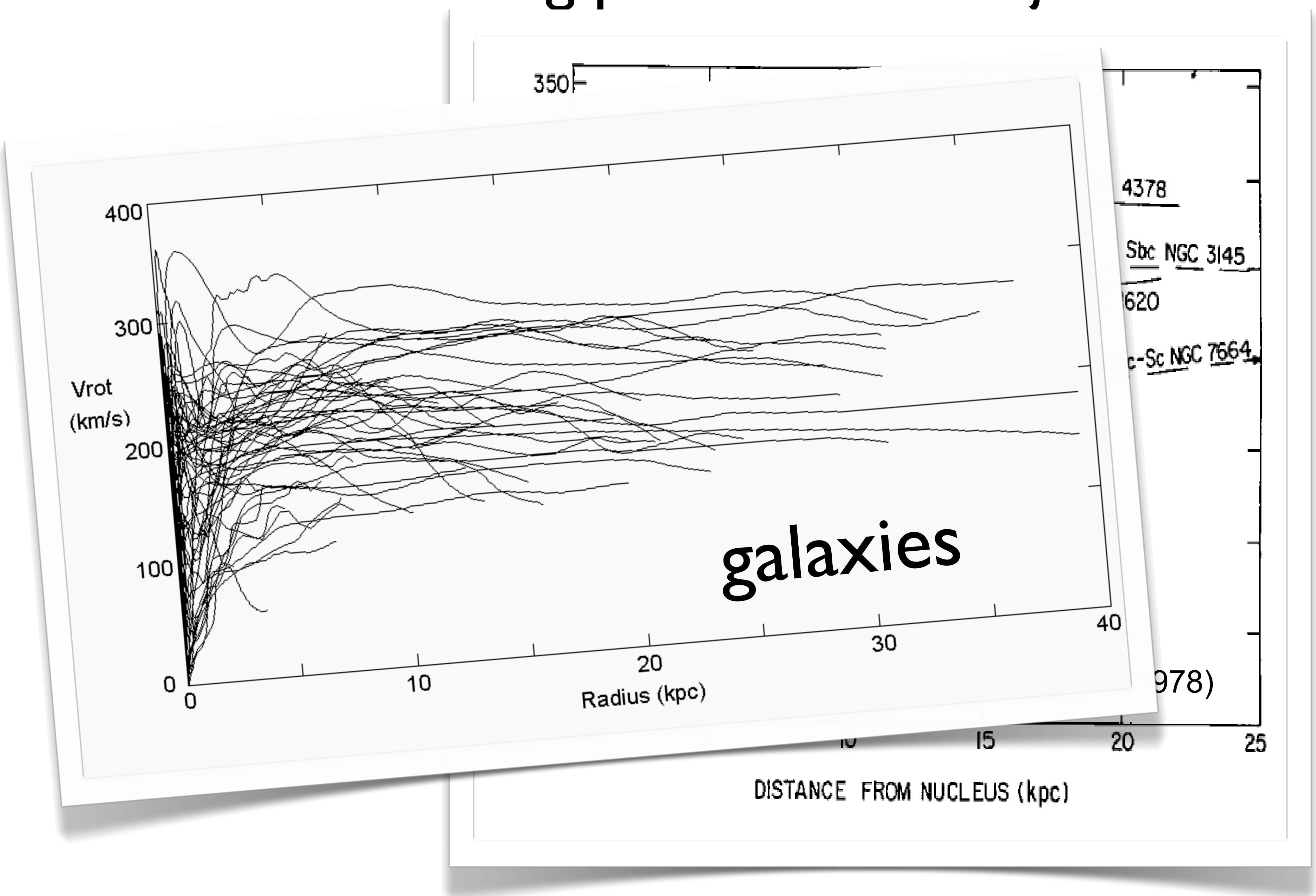

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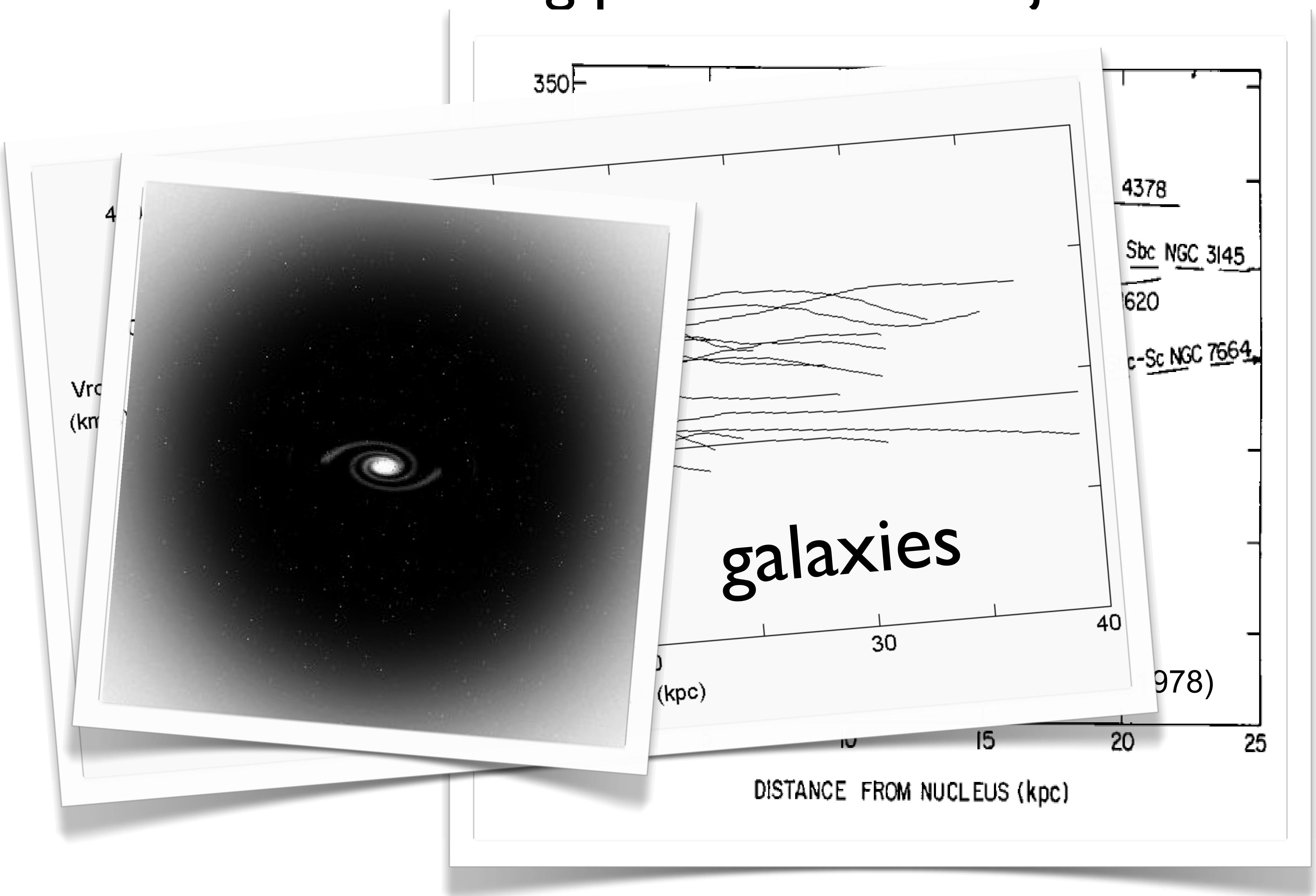

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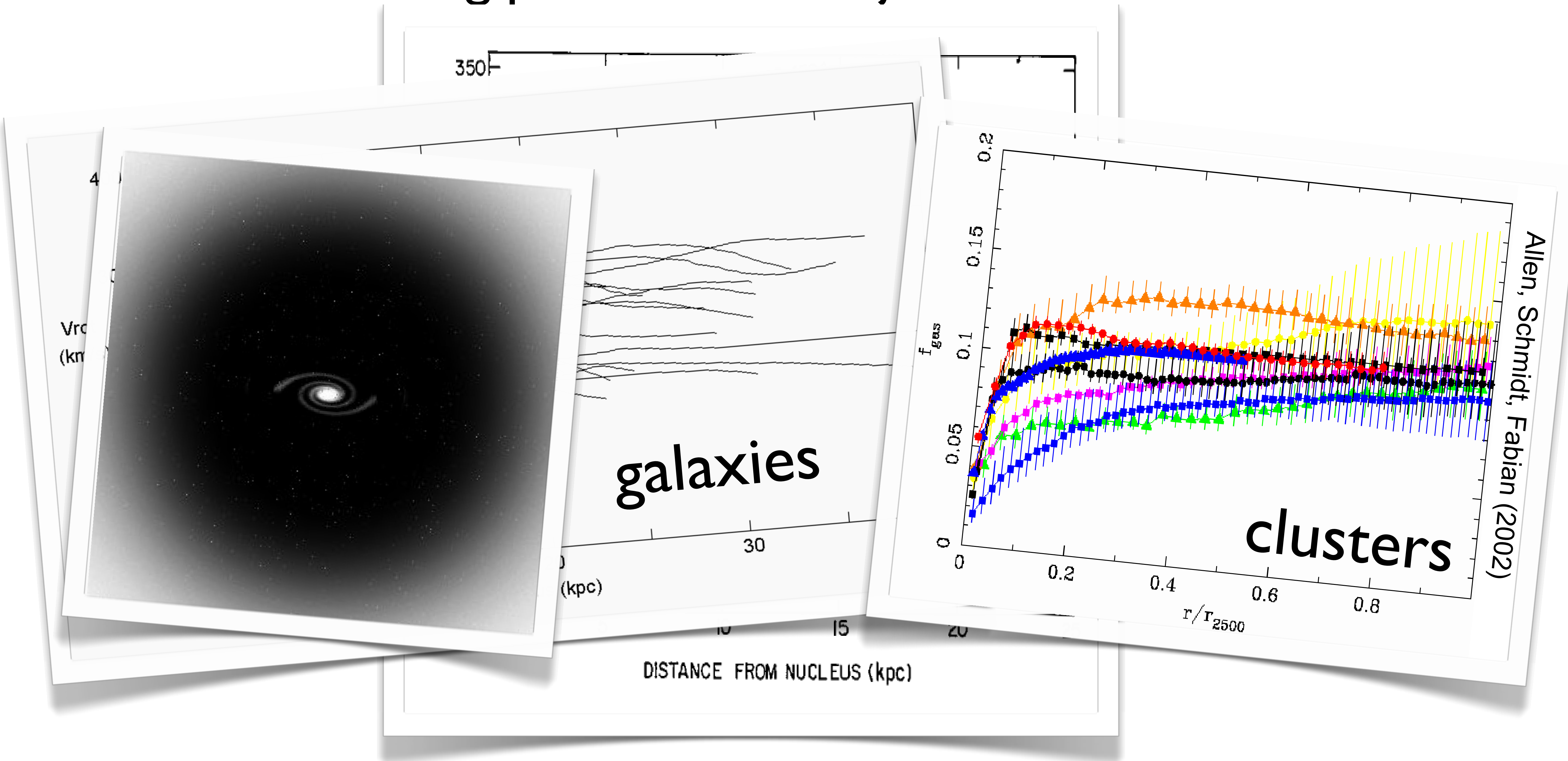

Dark Baryons...?

* At this point you might argue:

So a bunch of baryons
are unaccounted for.
Not all Baryons shine light.
(Hey, maybe this "dark matter" is a bunch
of used sneakers floating in space.)
What's the big deal?!

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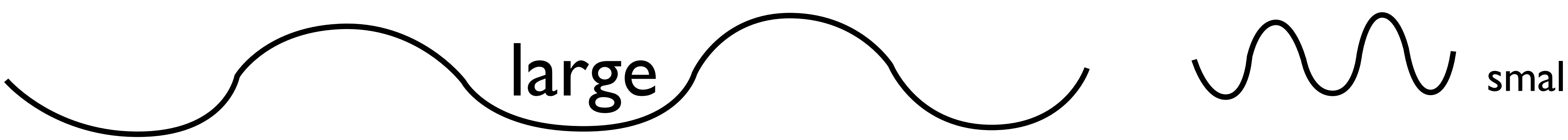
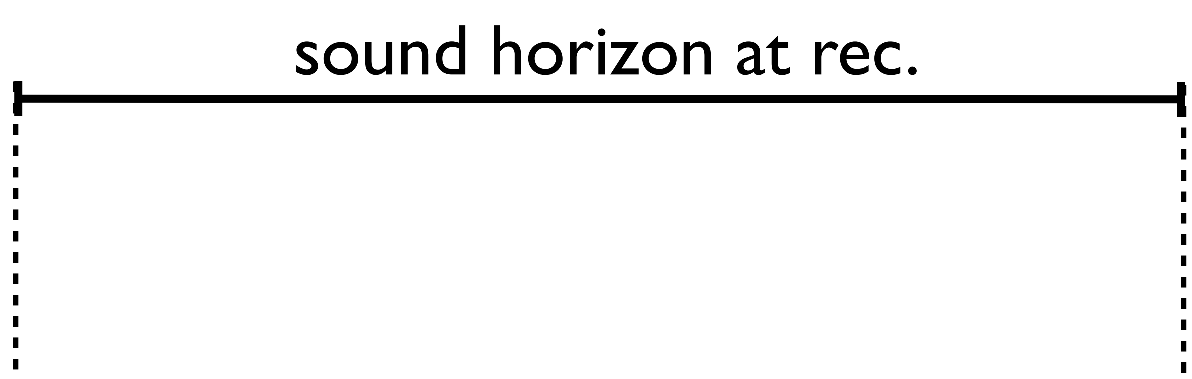
CMB (Disney version)

- The CMB is a relic of the hot early Universe.
- Emitted when atoms (re)combined and the Universe became transparent.
- In the era before recombination the density of the plasma was oscillating on all scales.



- Some of these modes will “resonate” with the size of the sound horizon at recombination.



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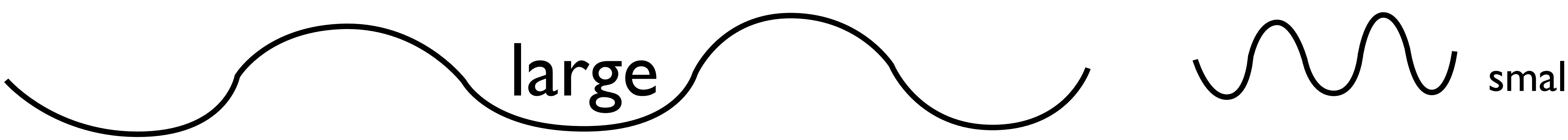

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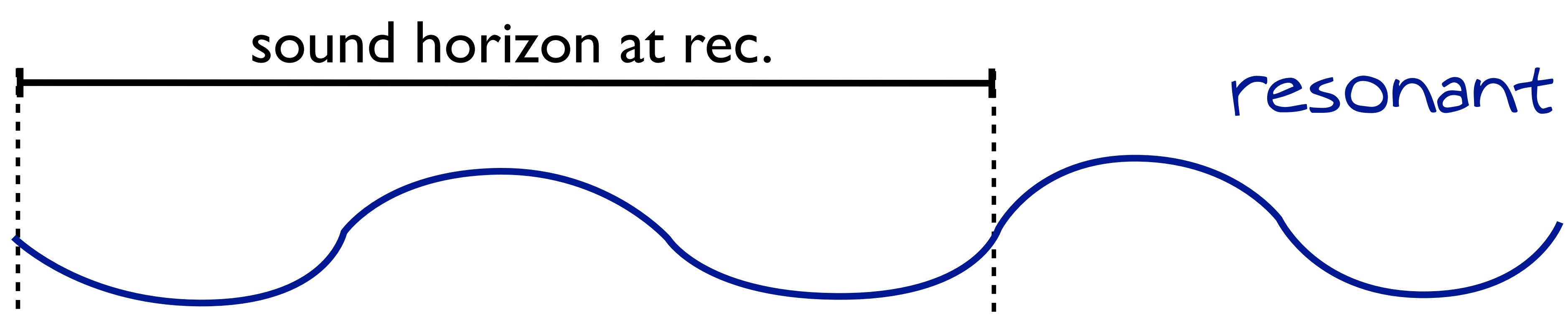

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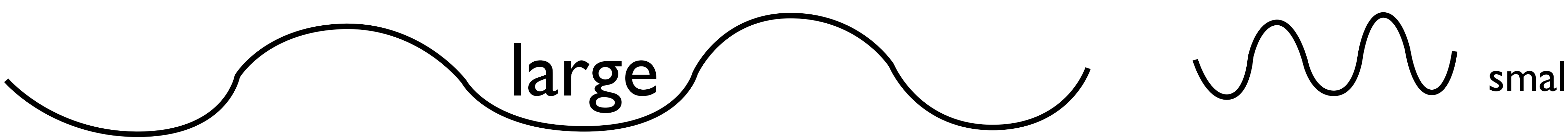

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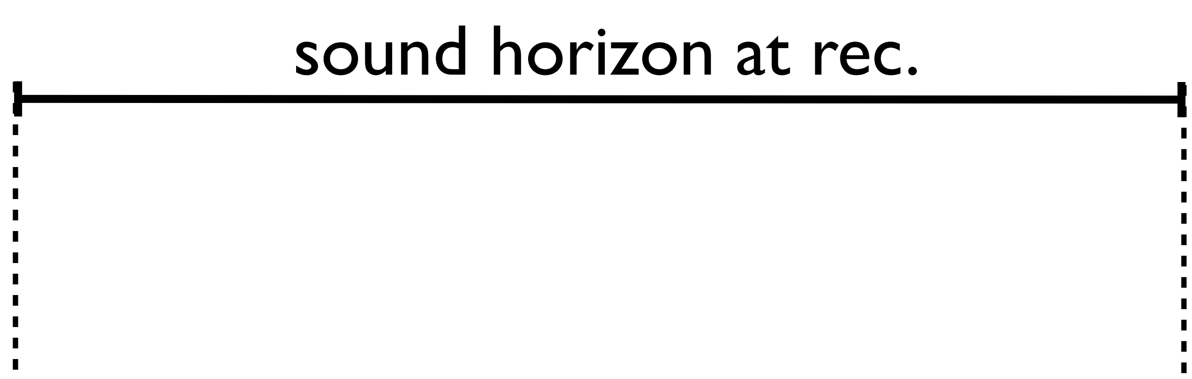

resonant

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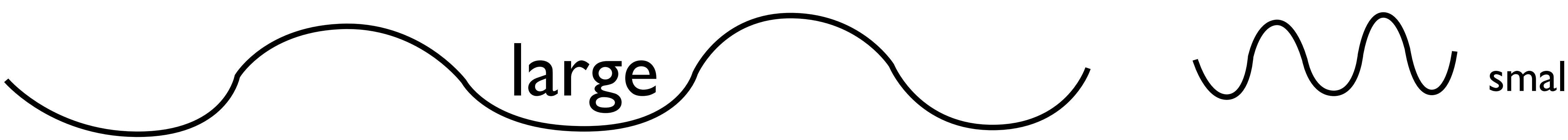

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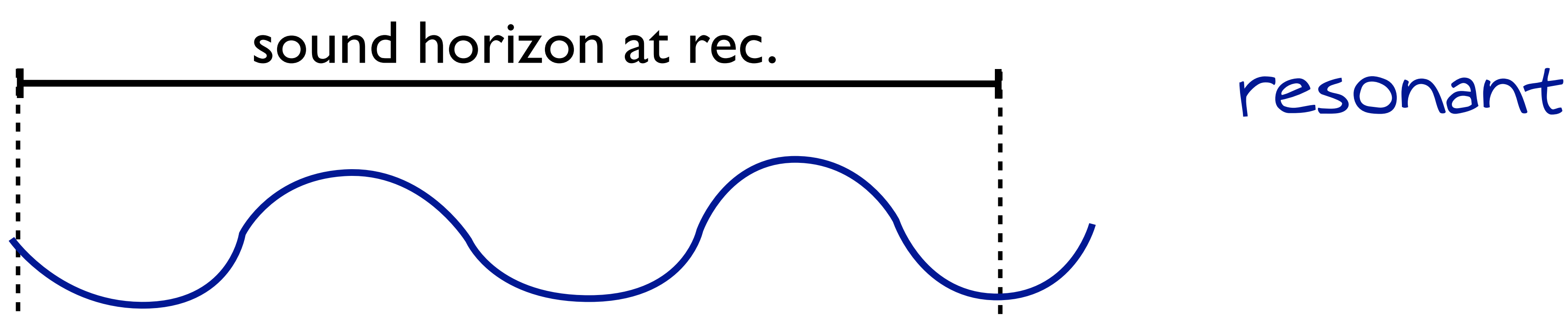

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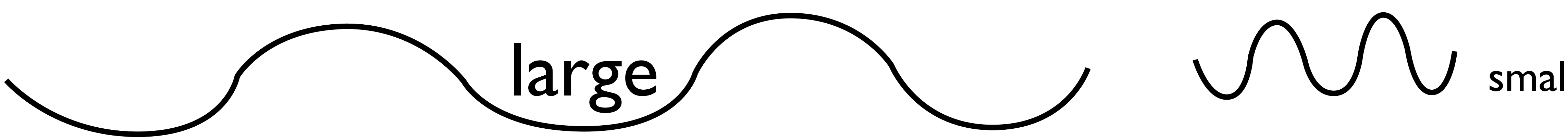

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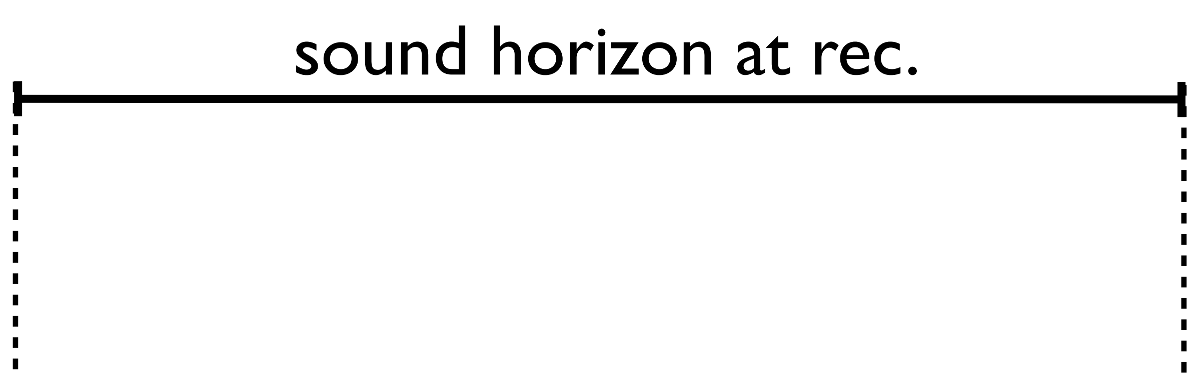

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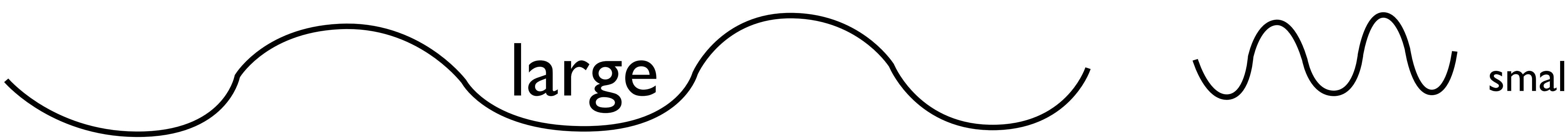

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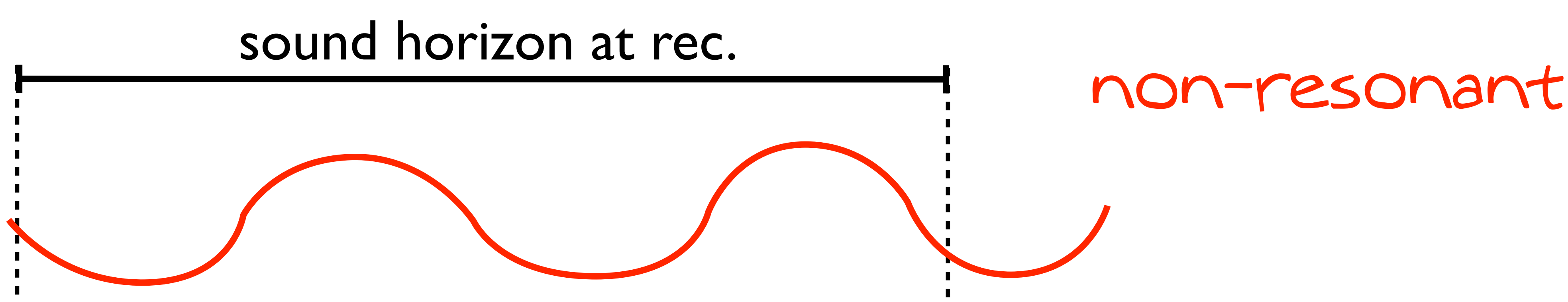
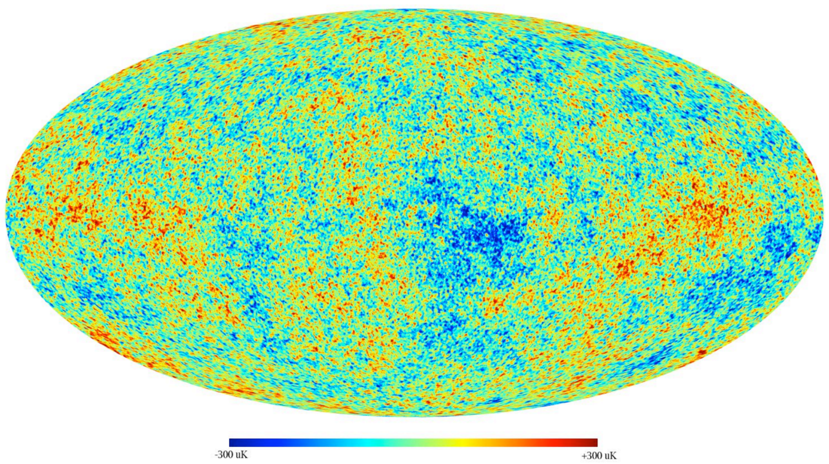
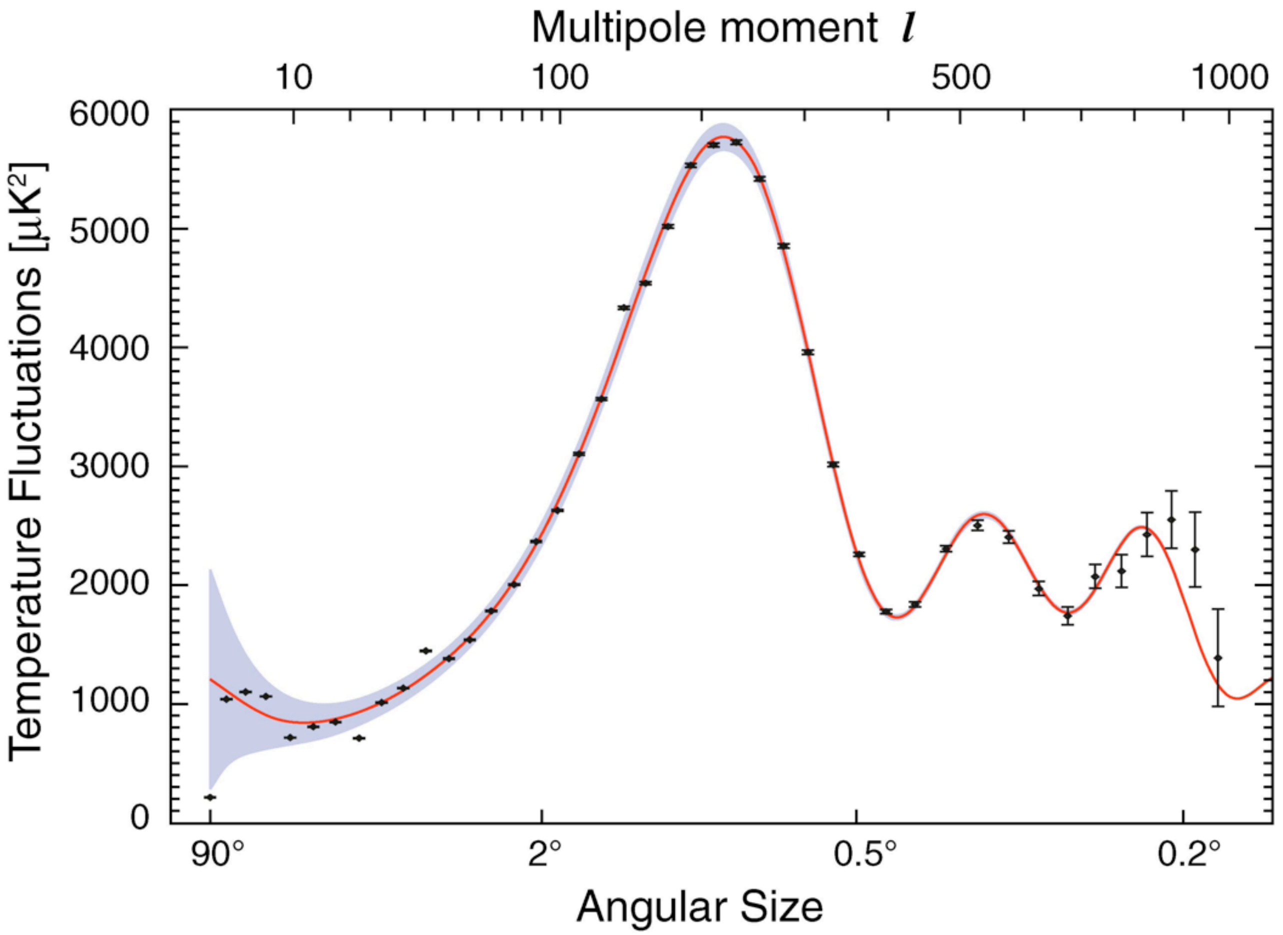


CMB

Hu 0802.3688

* Modes that reonate with the Universe at recombination have more power.





* The precise dynamics depends, among many things, on the ***matter density*** and ***baryon density***.

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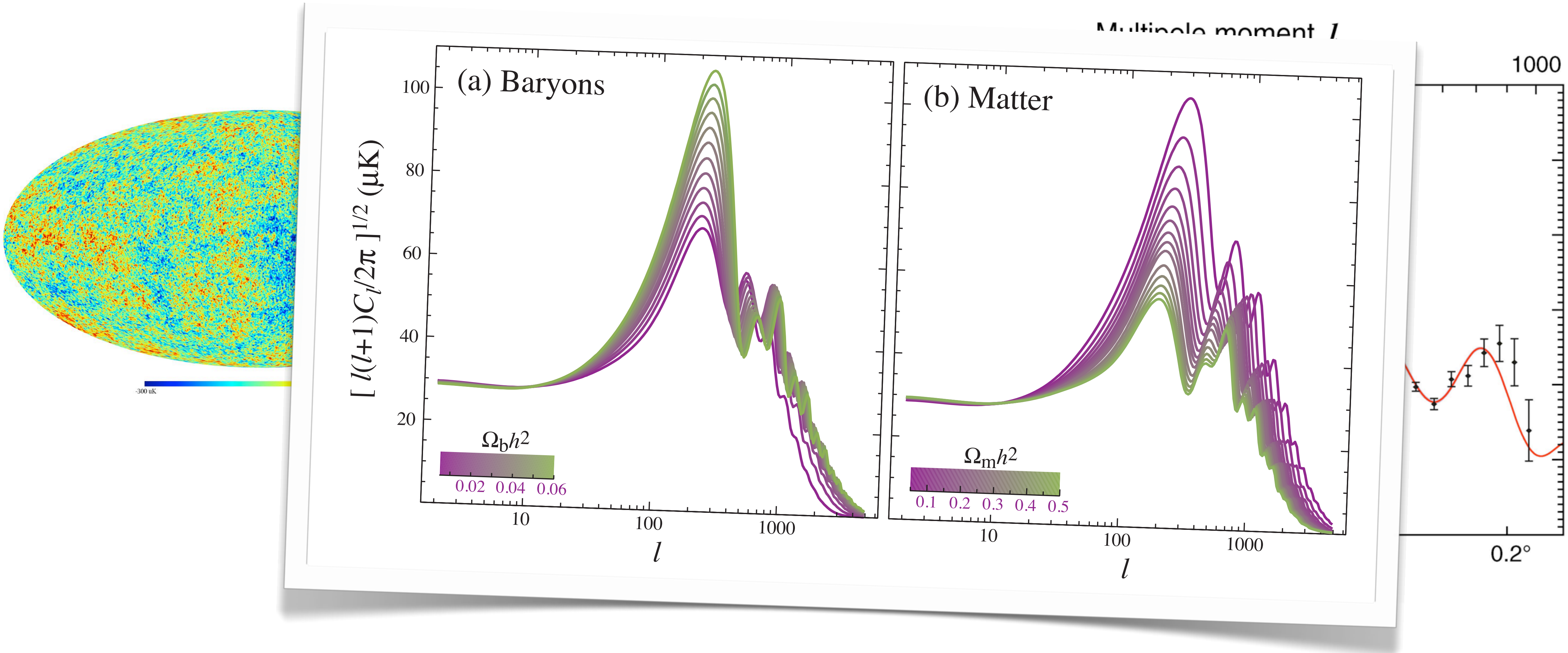

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Big Bang Nucleosynthesis

* The theory of BBN describes how D, He, Li, were fused during the early universe.
* Disney version:
  - Put a bunch of protons and neutrons into a hot soup.
  - Let the soup cool and expand.
  - Include nuclear reactions and apply thermodynamics.

nuclear abundances for H, D, He, Li

* One of the key parameters that will determine the outcome is the ***density of baryons***.

Big Bang Nucleosynthesis

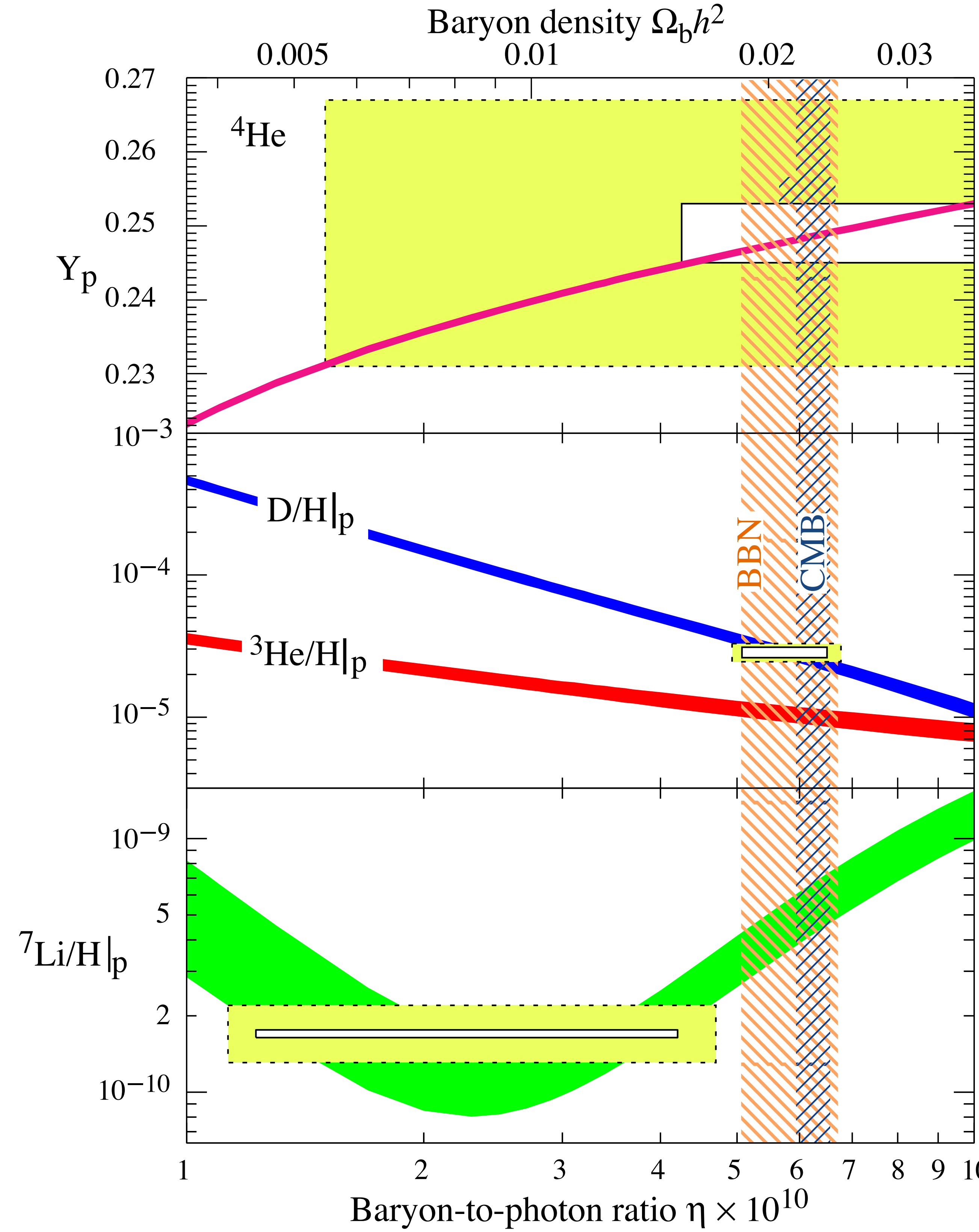
Baryons amount to 4% of the Universe.

From other sources: Total matter is 22%.

↓

DM is non-baryonic.

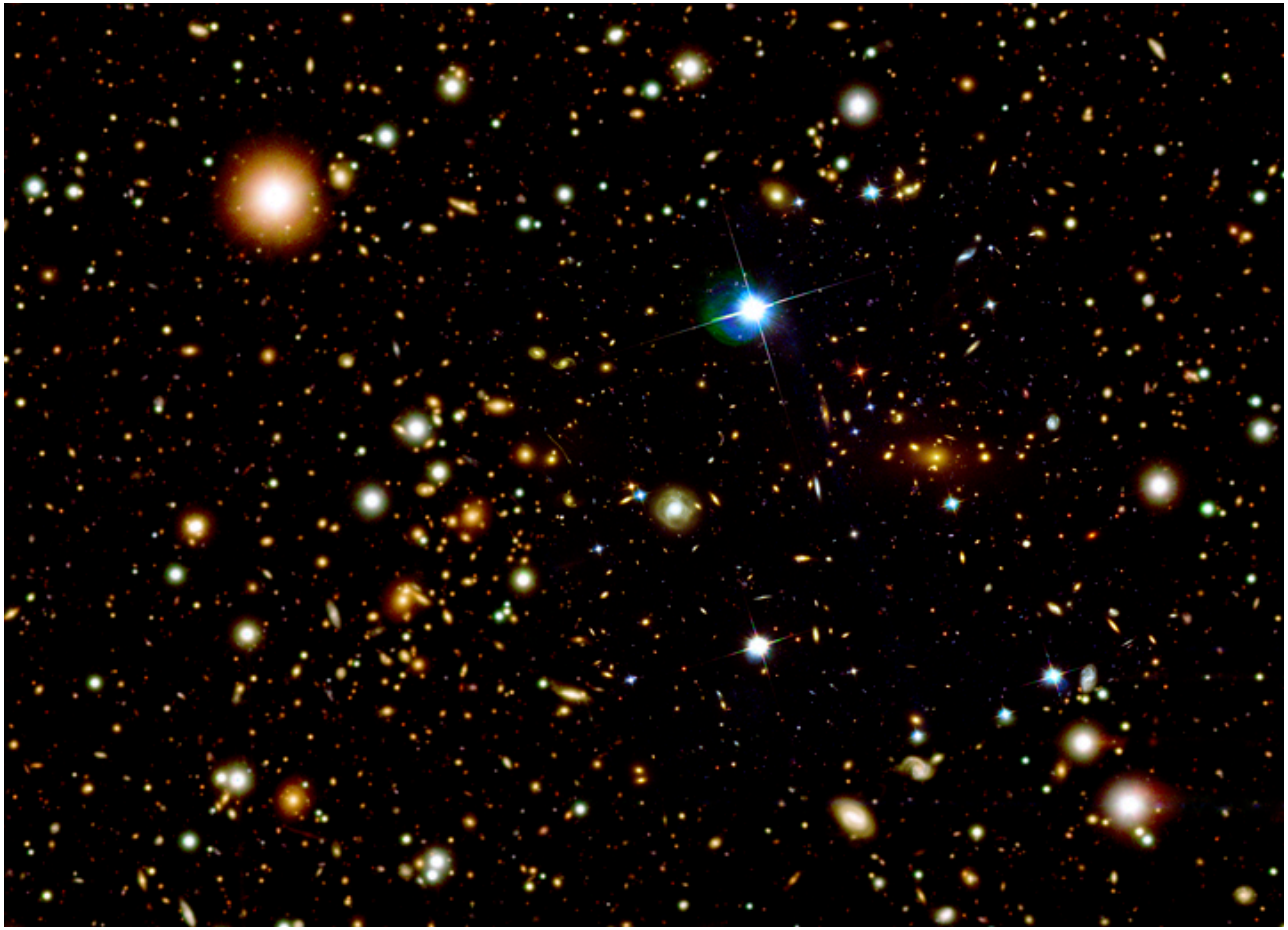
(there went my theory of "sneaker dark matter")



(PDG review on BBN)

Bullet Cluster

* Two galaxy clusters collided (Hubble):



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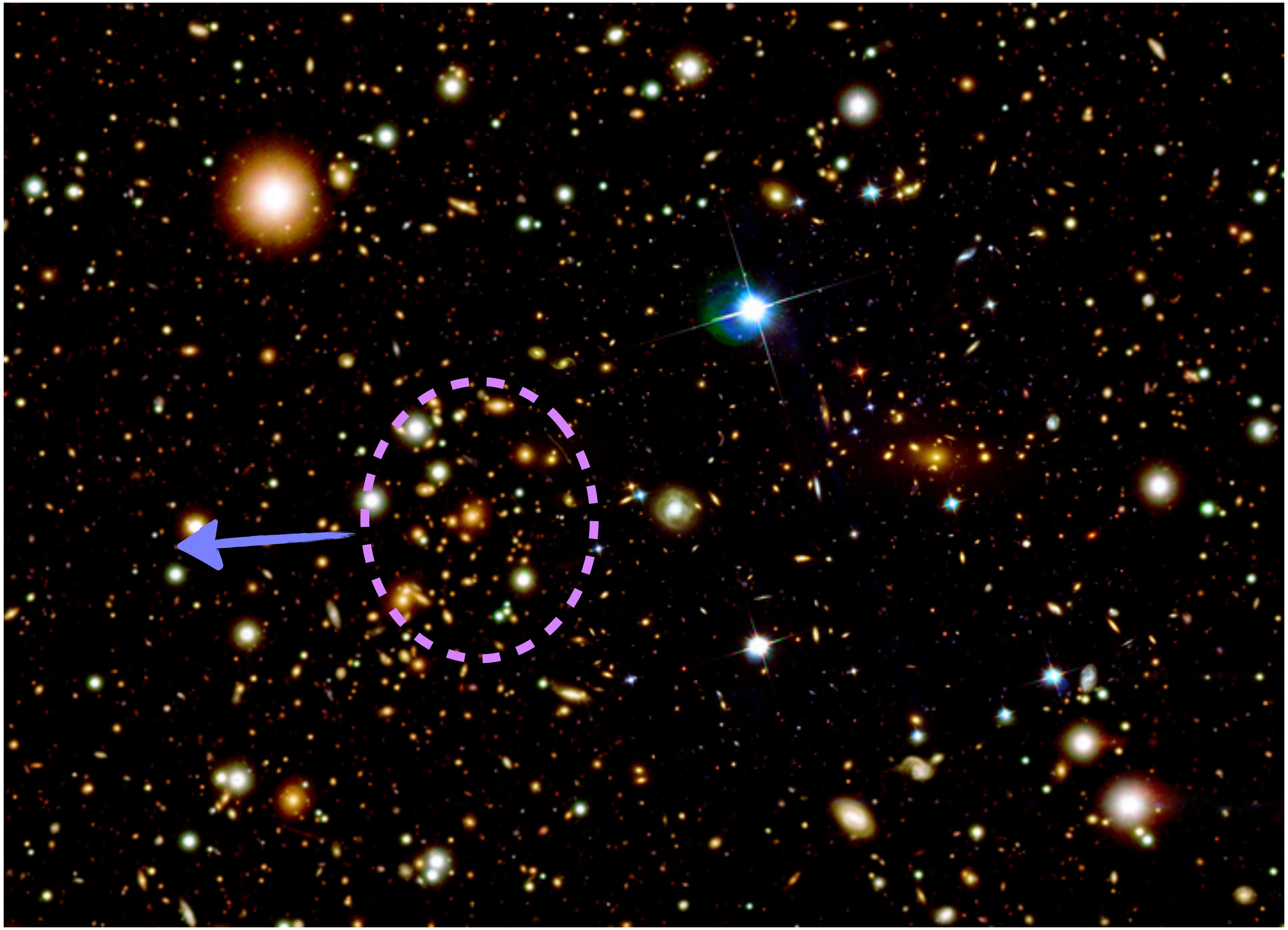

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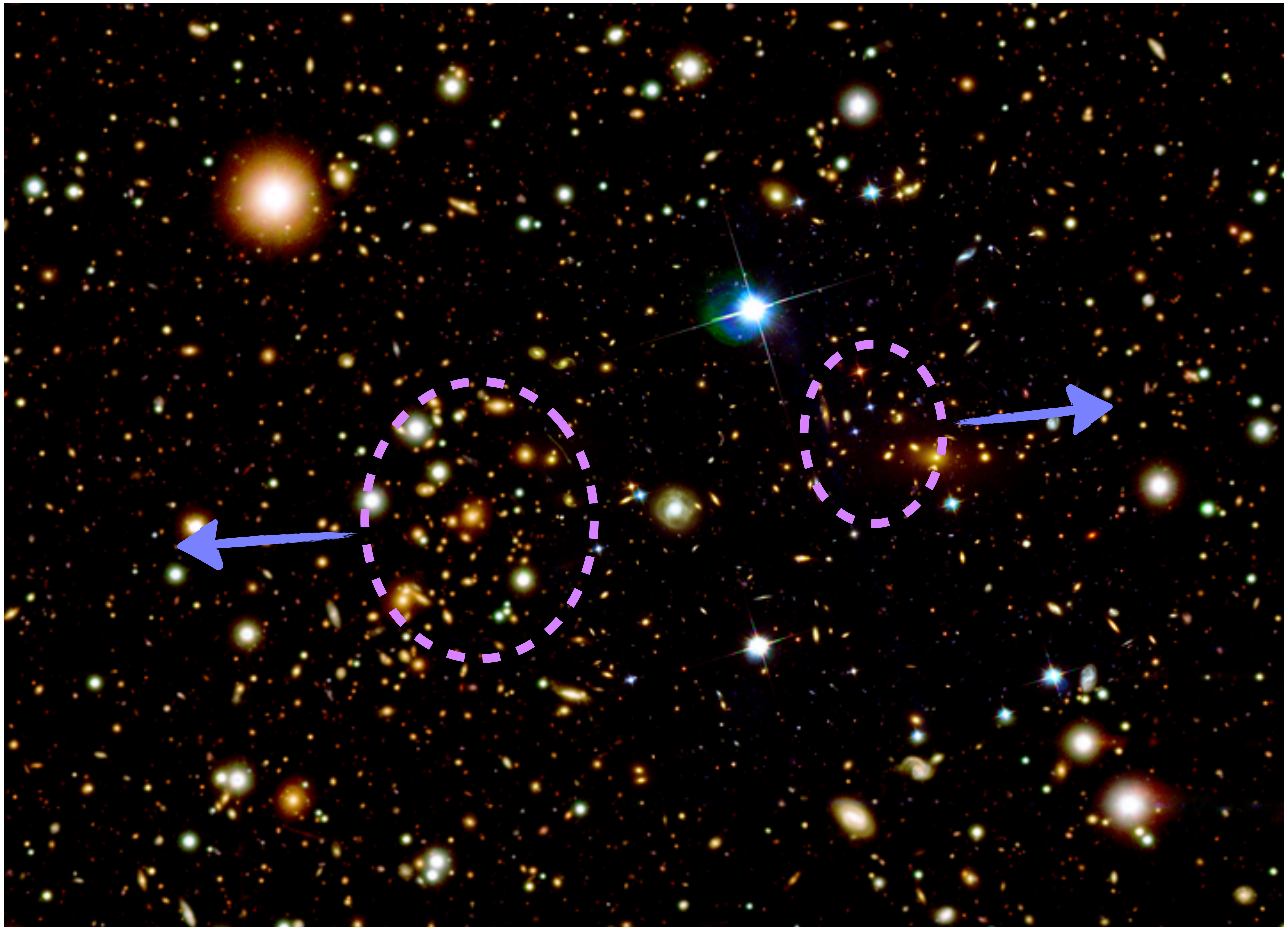

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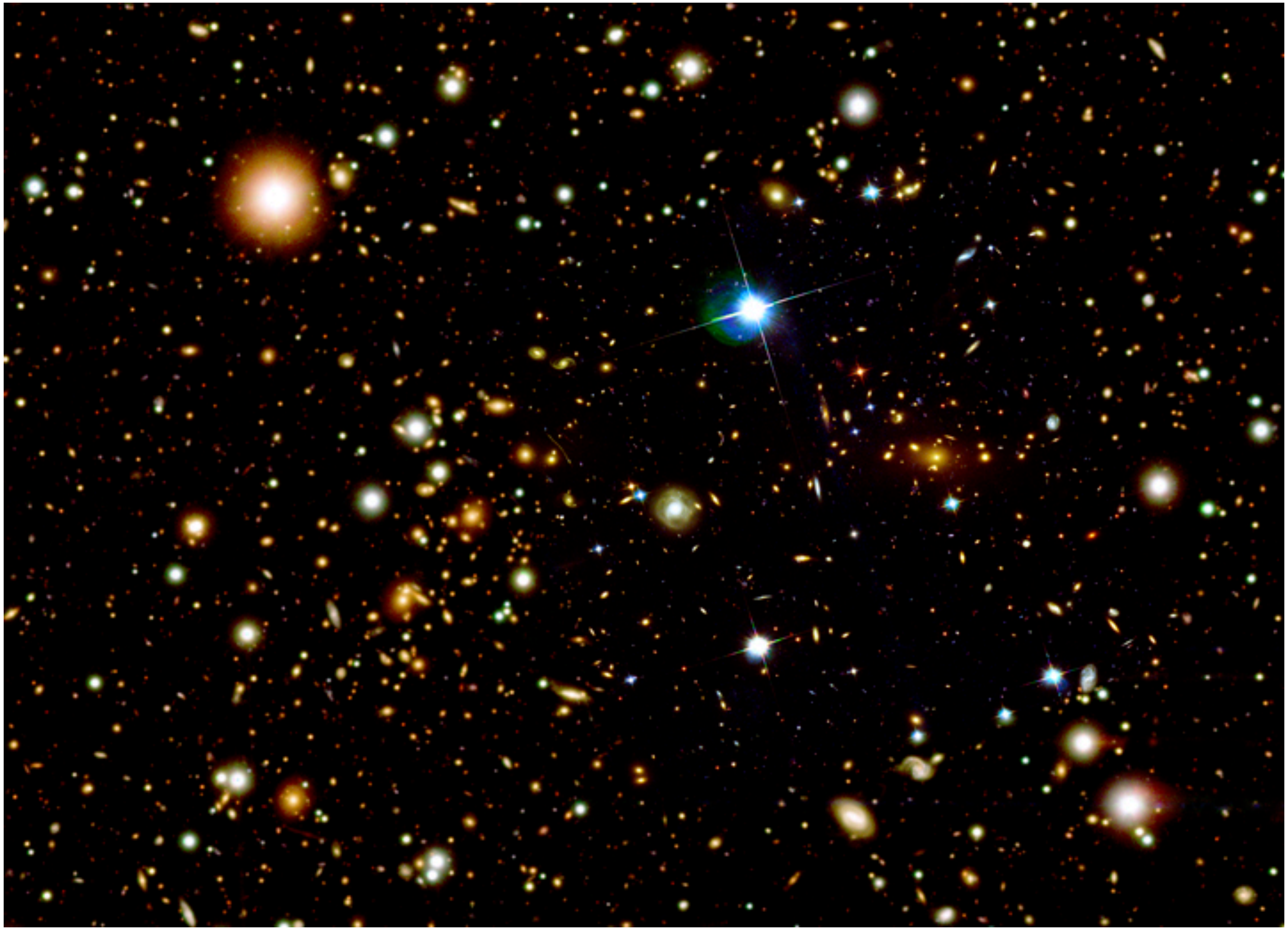
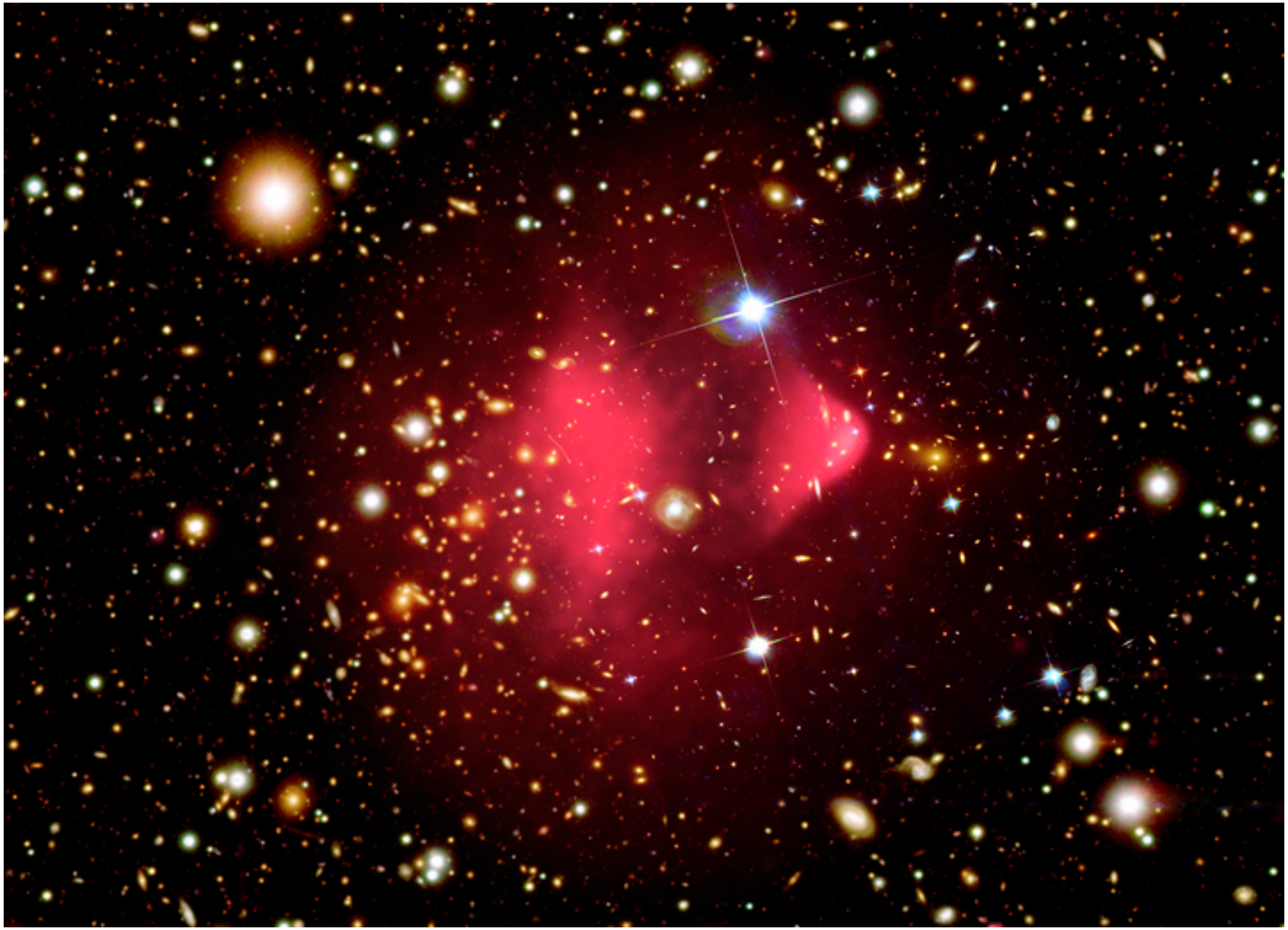


Bullet Cluster

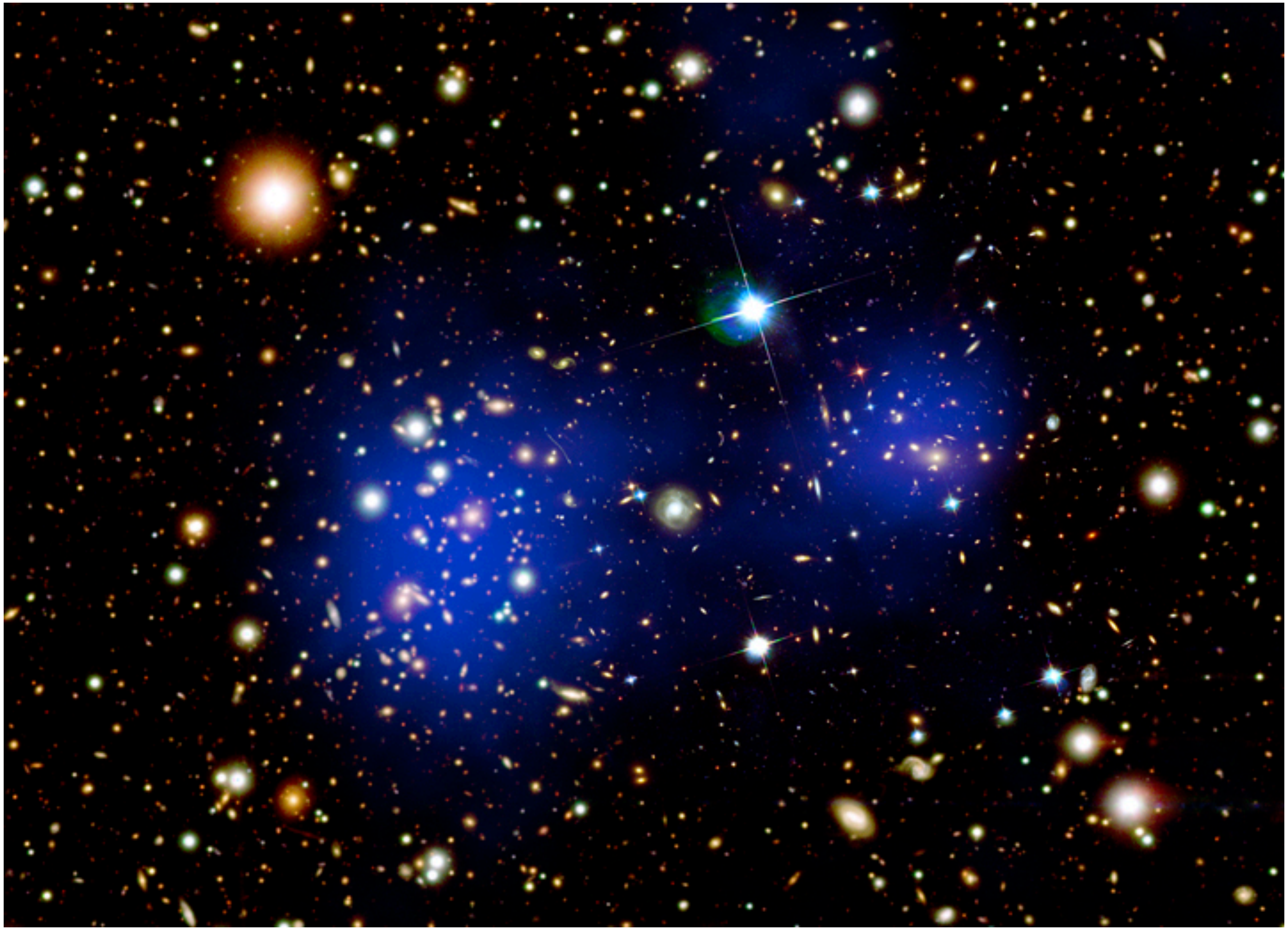
* The baryonic mass is mostly gas.
  Gas is hot due to the collision. Emits x-rays (red):



Note: the gas was stripped away from the clusters

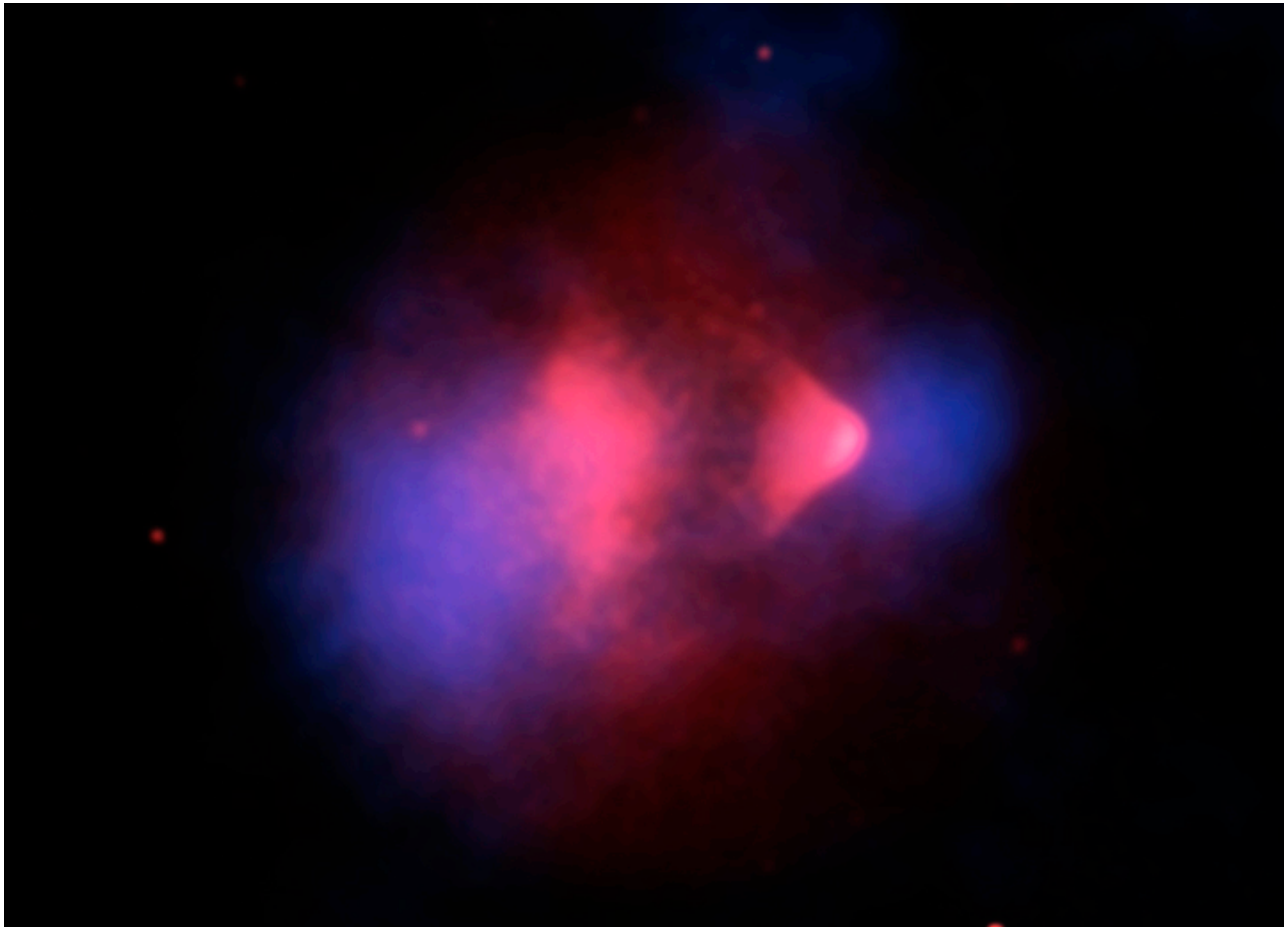
Bullet Cluster

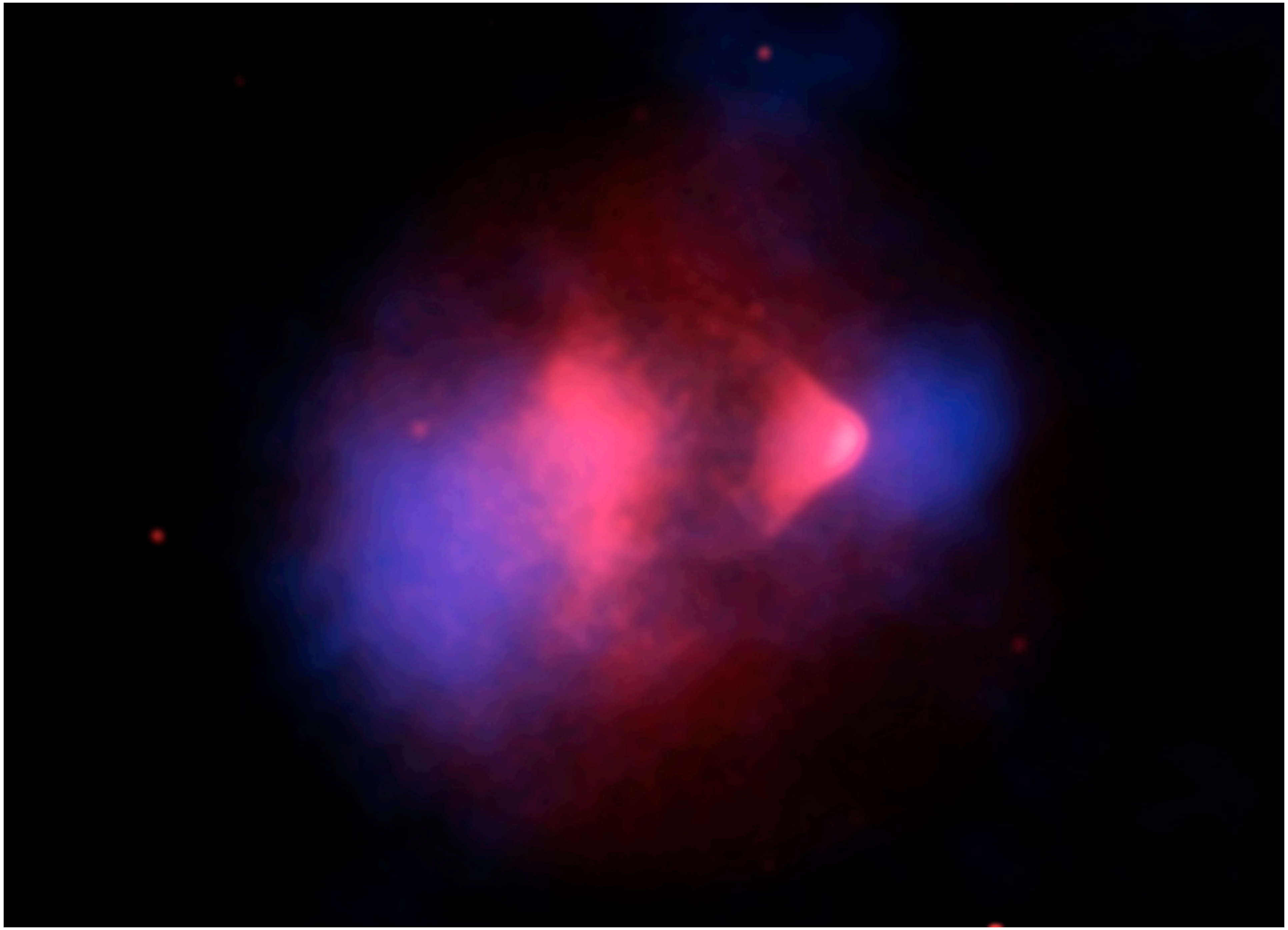
* The distribution of the total mass is determined by gravitational lensing (blue):



Bullet Cluster

* The total mass and the dominant baryonic mass are not in the same place:





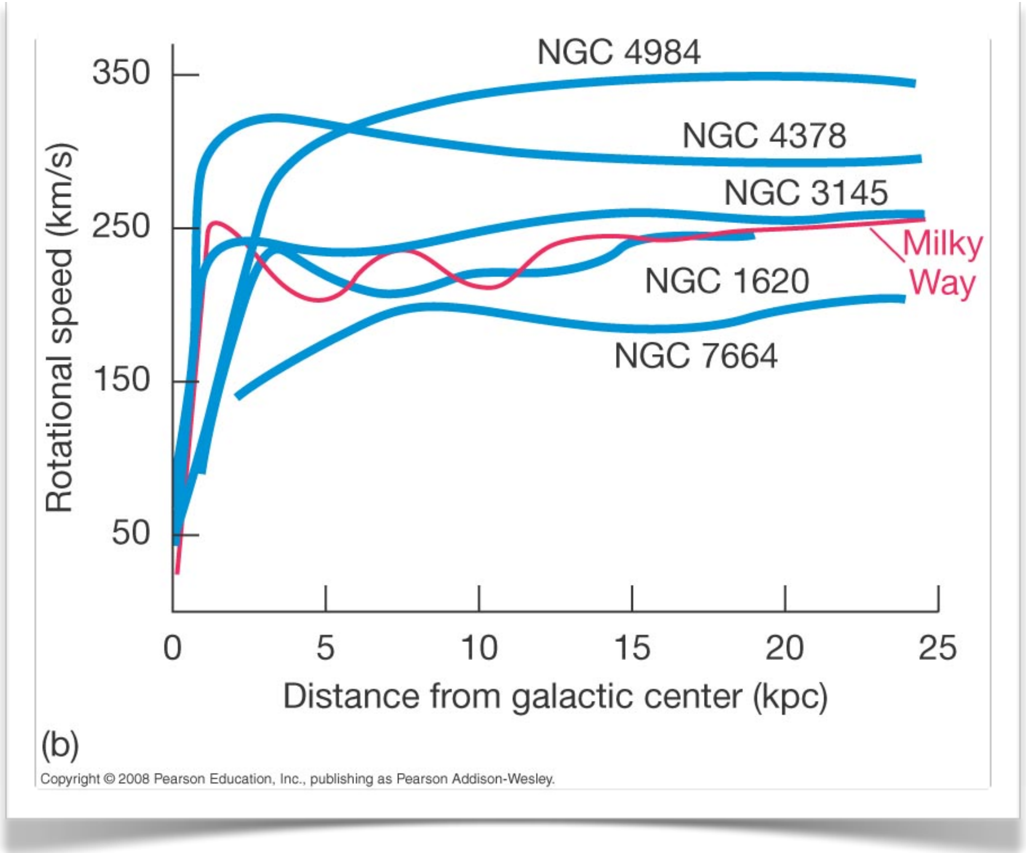
But is there DM ***here***?

* A recent analysis of the velocities of near by stars supports the hypothesis that there is DM in our neighborhood of the milky way (1205.4033).

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

(give or take a factor of two).

This is the canonical value that was used before.



dark matter exists!

Food for thought for this evening:

Every pint of beer comes with a single dark matter particle.

(assuming it's mass is ~150 GeV)

So, what the @*$^# is it ???

In Parenthesis: Dark Energy

<u>note</u>: the reason I'm note discussing much of DE is not because its not interesting or mysterious.
Its because the connections to colliders is weak.

Supernovae:

* Hubble's discovery of the expanding Universe.

* Version 2.0:
  Done to higher precision and to earlier times with type 1A supernovae.

* The expansion of the Universe is ***accelerating***!

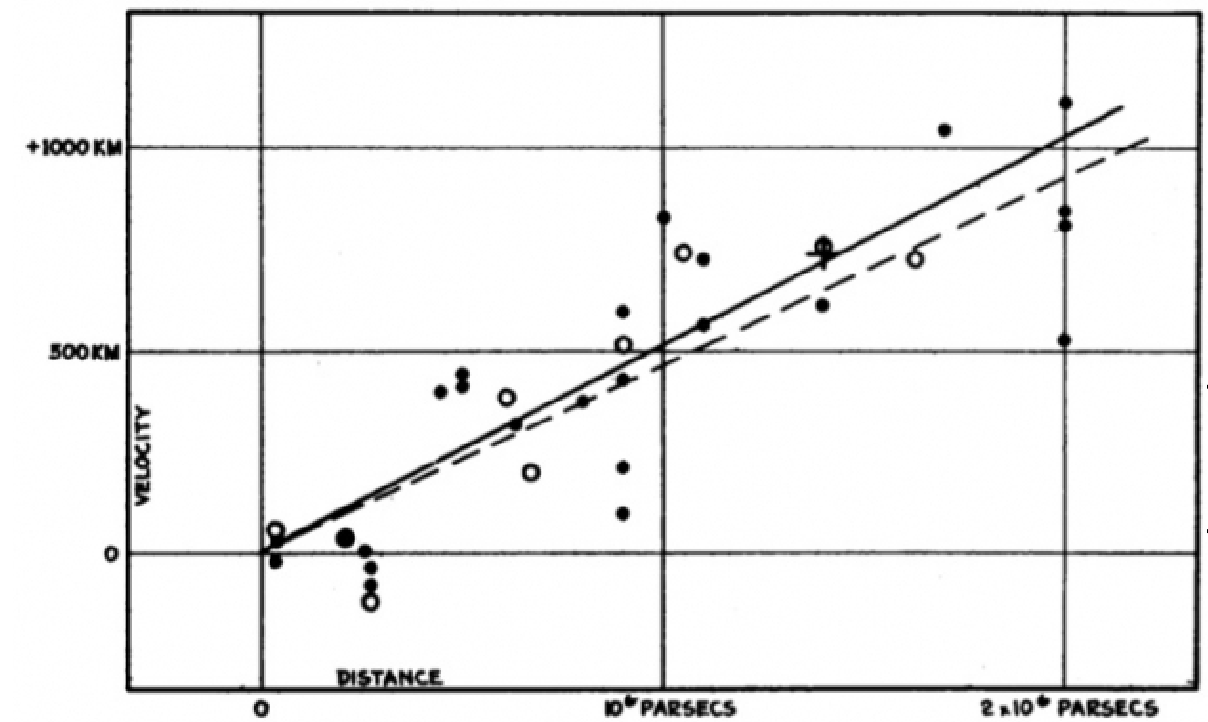
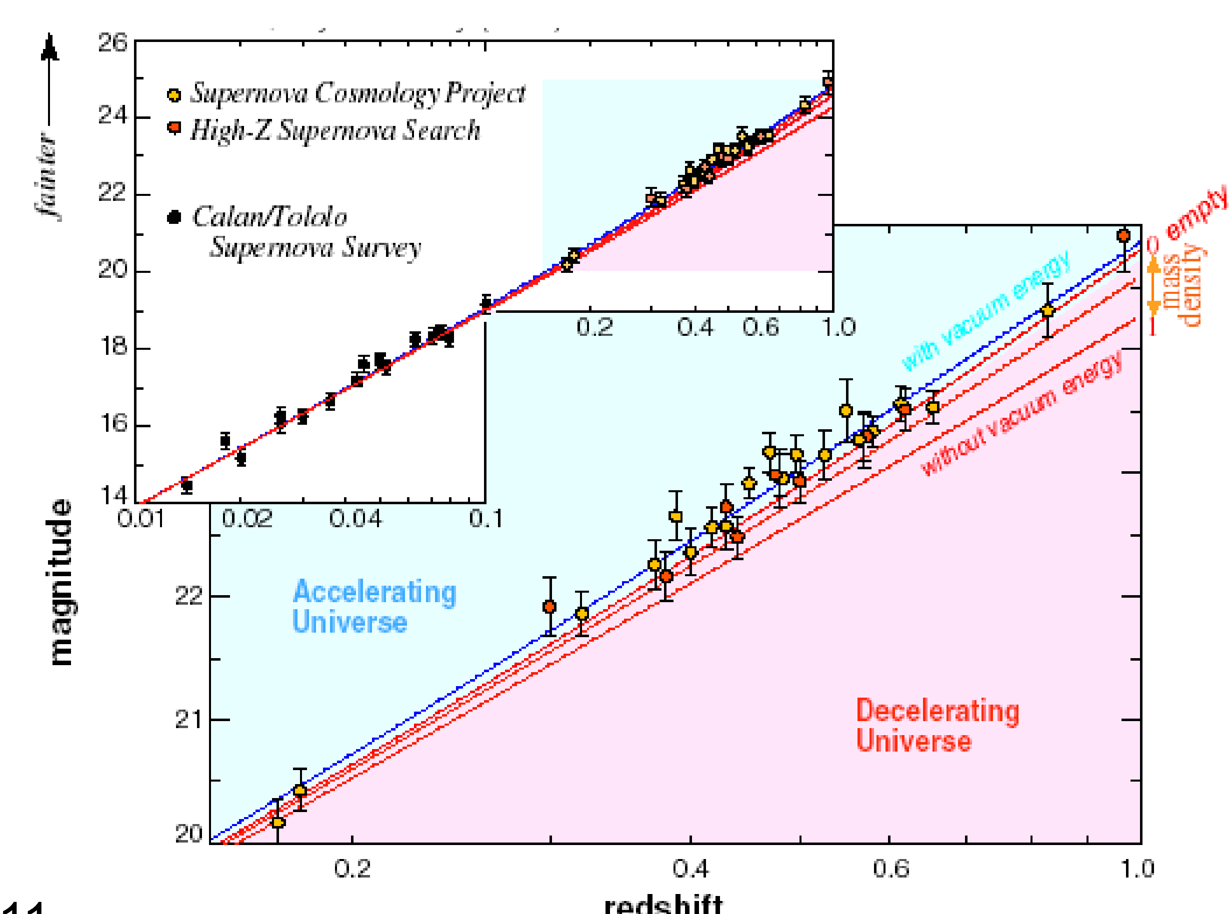


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble (1929)



This is most simply explained with
a cosmological constant.
(Einstein's biggest blunder, remember?)

This is a ***huge*** theoretical problem...
but thats for another time.

DM Properties

* ***cold***:
  Simulations of the formation of large scale structure seems to favors cold (a.k.a non-relativistic) DM.

* ***long lived***:
  DM is still around today. It should not decay faster than the age of the Universe. If it decays to SM particles the limits are *much* stronger:

Decay Channel	τ Lower Limit	Experiment
$q\bar{q}$	10^{27} s	PAMELA antiprotons
e^+e^- or $\mu^+\mu^-$	2×10^{25} s $\left(\frac{\text{TeV}}{m_{\text{DM}}}\right)$	PAMELA positrons
$\tau^+\tau^-$	10^{25} s $\left(1 + \frac{\text{TeV}}{m_{\text{DM}}}\right)$	EGRET + PAMELA
WW	3×10^{26} s	PAMELA antiprotons
$\gamma\gamma$	2×10^{25} s	PAMELA antiprotons
$\nu\bar{\nu}$	10^{25} s $\left(\frac{m_{\text{DM}}}{\text{TeV}}\right)$	AMANDA, Super-K

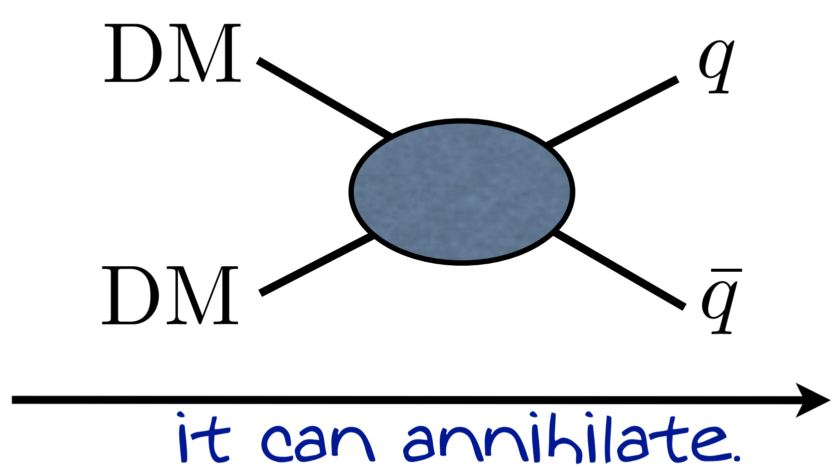
DM Properties

* ***does not interact much**:*
  Obviously. Its dark.
  But due to halo shapes we know-
  - it does not interact strongly with itself, otherwise halos would be too spherical (e.g. Fox and Buckley 2009).
  - it does not interact with massless particles, otherwise those could be radiated, and the halo would collapse to a disk.

Does it have any non-gravitational interactions?

Relic abundance: WIMPS

* What sets the amount of DM?
* Lets assume that DM has a weak interaction with matter:



* What happens if we add such a particle to the primordial hot soup?

Relic abundance: WIMPS

Disney Version:

- Initially DM is in thermal equilibrium.

$$\chi\chi \leftrightarrow \bar{f} f$$

- As the T drops below the mass it is "energetically favorable" for DM pair to convert to SM particles.

  → DM abundance begins to drop.

- At some point, DM particles will not find friend to annihilate with. The abundance is set. ***Freeze-out*****.**

Relic abundance: WIMPS

* When is it that two WIMPs can't find each other?

annihilation rate ~ Expansion rate of the Universe

or

Particle Physics $$n_{\rm DM}\langle\sigma v\rangle \sim \frac{\dot{a}}{a} \sim \frac{T^2}{M_{\rm pl}}$$ Cosmology

(in practice we solve a Boltzman equation)

This gives an intriguing result...

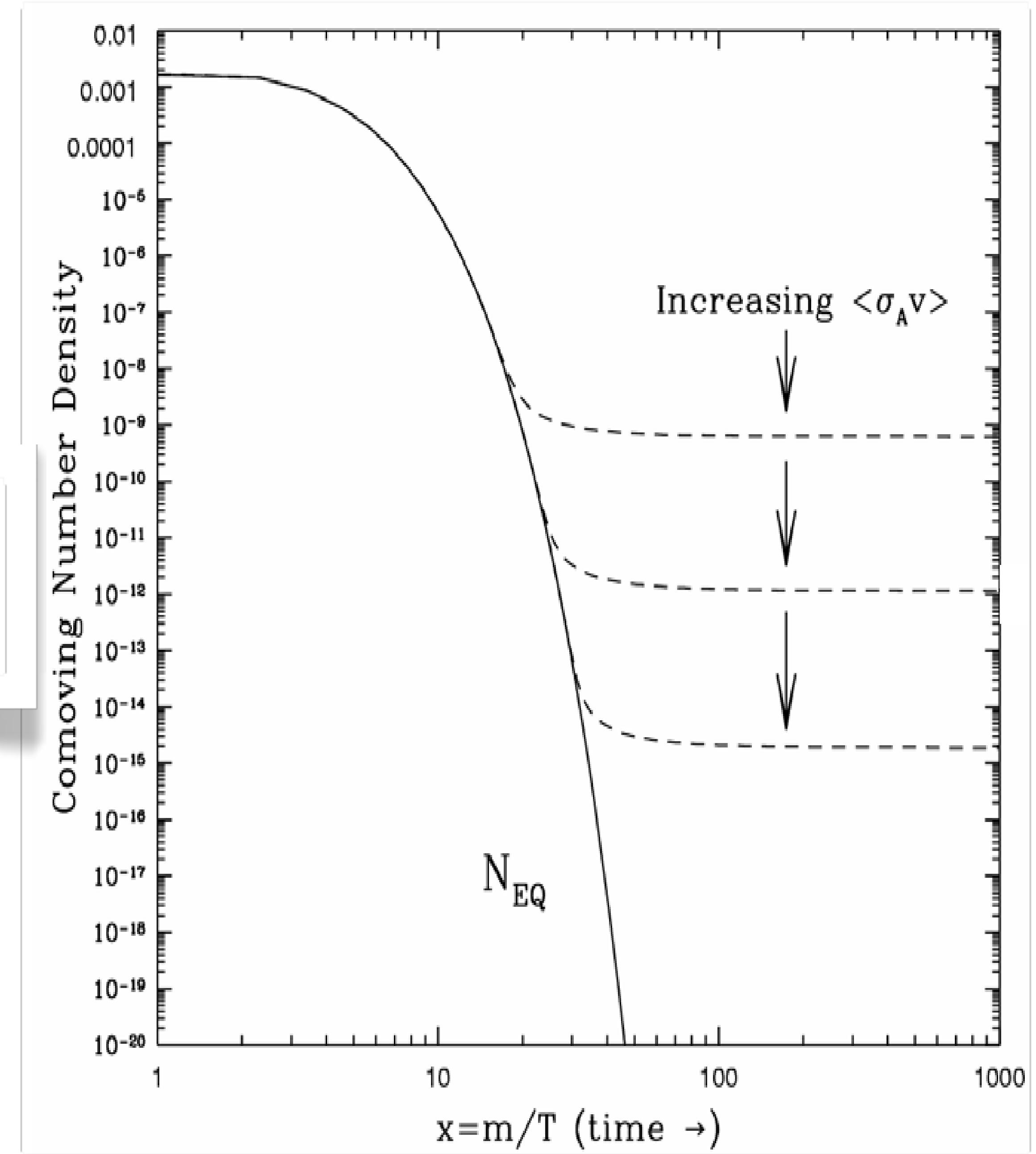
Relic abundance: WIMPS

* Abundance is *independent* of initial conditions. :-)
* Set by annihilation cross-section:

$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right) \left(\frac{g_*}{80}\right)^{-1} \left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

or

$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}$$

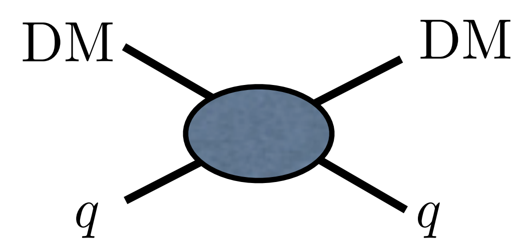


EW cross-sections! what a coincidence!

WIMPs :-)

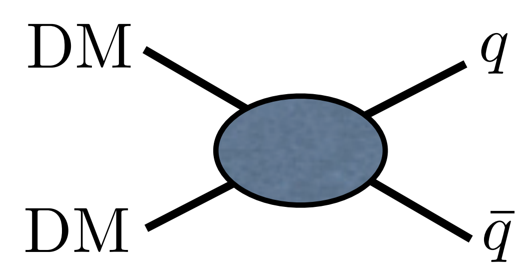
* ***Experiment***:
  A new particle with weak scale mass and cross section around 1 pb. sounds good! Could lead to:

  - Scattering off a nucleus.



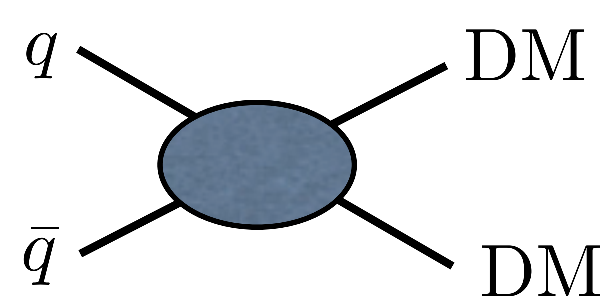
direct detection

  - Annihilation in our galaxy.



indirect detection

  - Production at a collider.



Production. (though we'd better find another diagram)

Just keep turning the diagram on its side.... (more later)

WIMPs :-)

* ***Theory***:
  Dark matter needs to annihilate with ***weak-scale*** cross-sections.

New physics at the weak or TeV scale .

We have plenty of those lying around!

For examples, see Lian Tao's Talk:
SUSY, Extra dimensions, compsiteness...

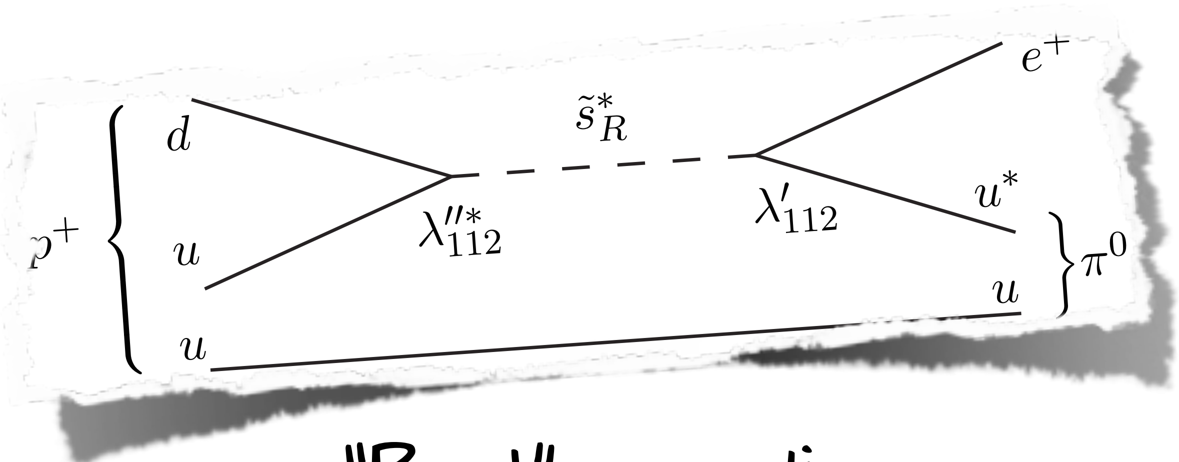
* ***Experiment (again)***:
  Many of these theories have new colored particles.
  Produced strongly. Decay to DM.

High rates for NP signals with MET !!!

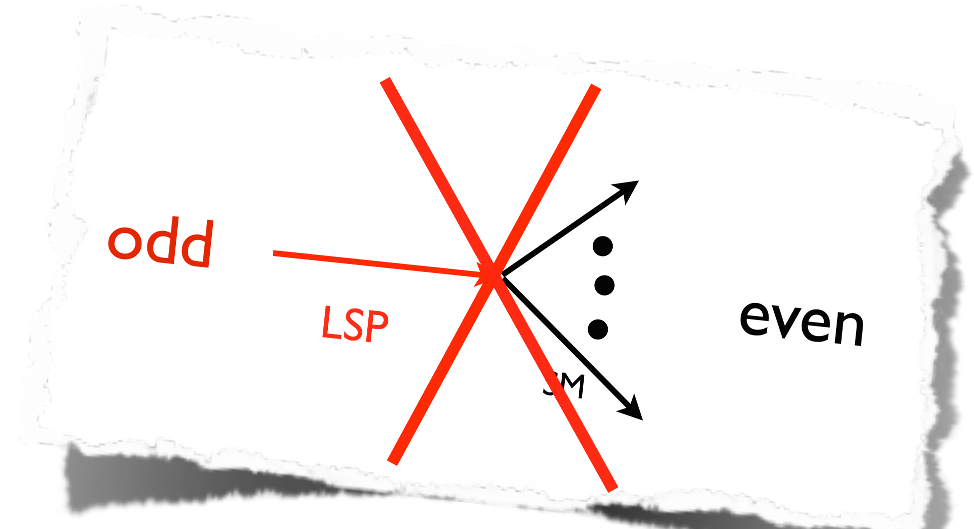
WIMPs in BSM e.g. SUSY

- In many theories a new parity was needed to, say, prevent proton decay (in SUSY):

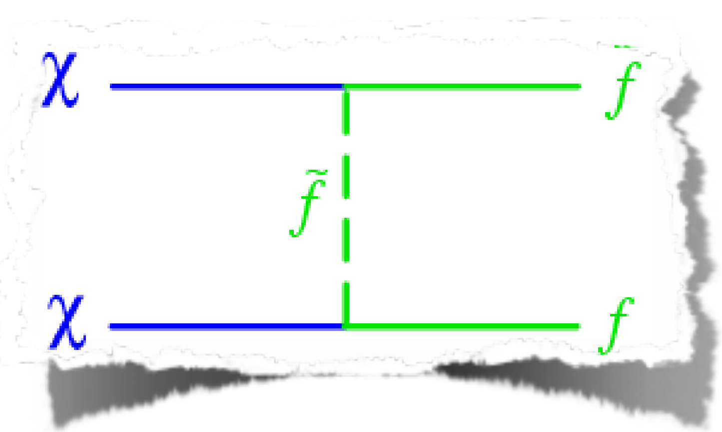
(ripped from Lian Tao's talk)



"Bad" coupling forbidden.



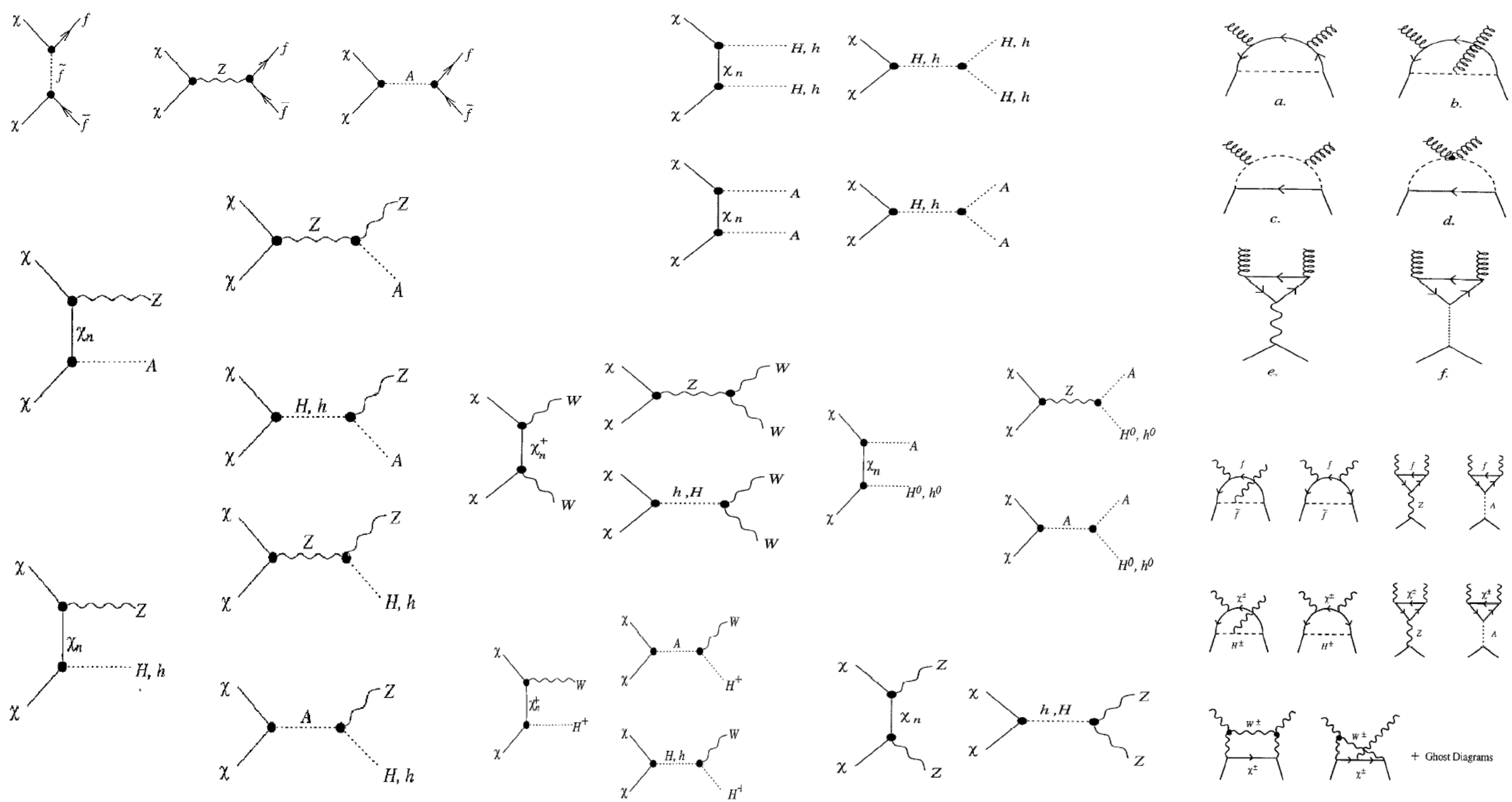
Lightest odd particle is stable (for "free"? No).



But it can annihilate via sparticle exchange. sparticle mass is set to solve other problems!

SUSY WIMPs

* In fact, neutralinos can annihilate in many many ways:



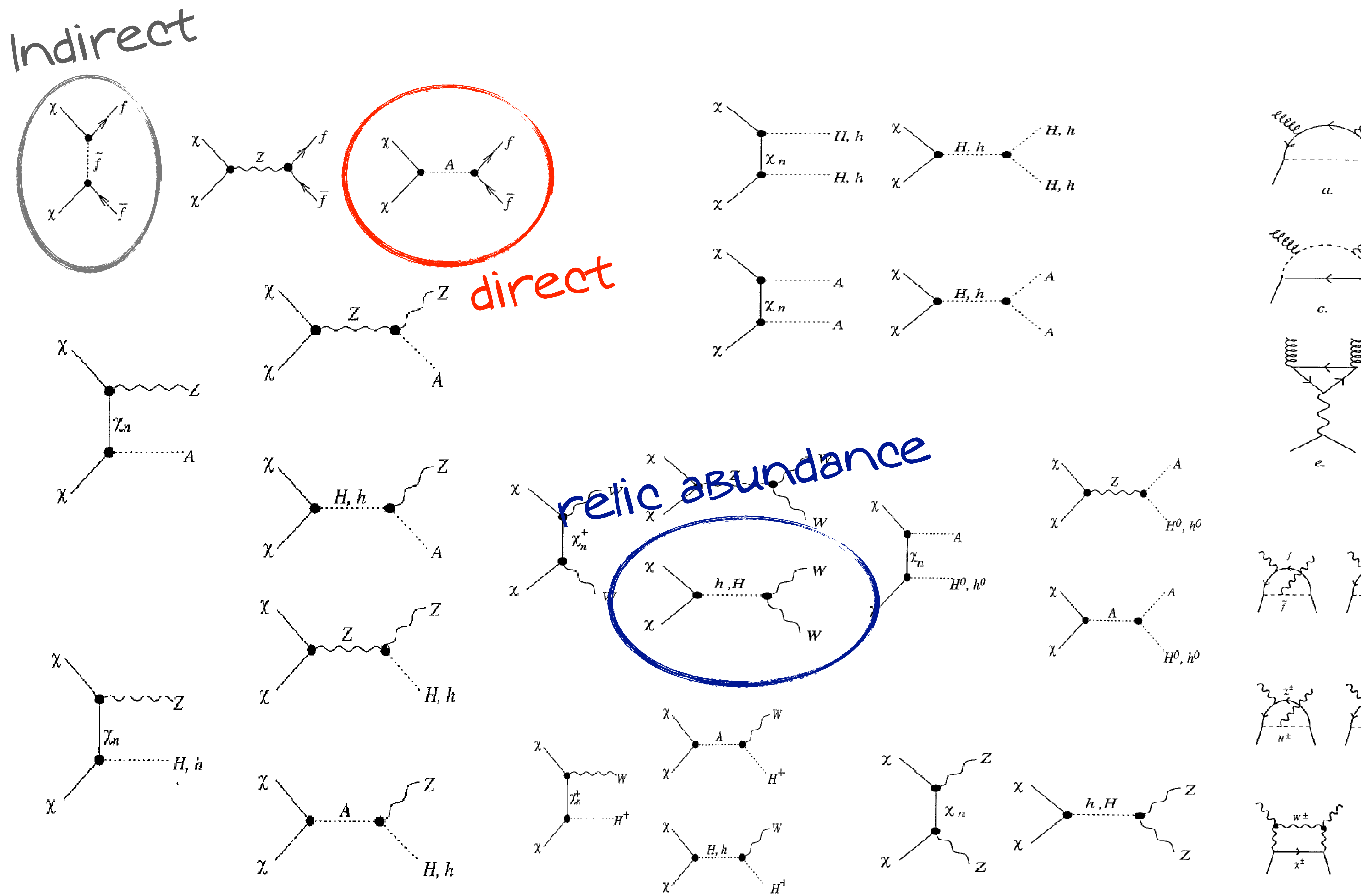
Jungman, Kamionkowski, Griest (1995)

SUSY WIMPs

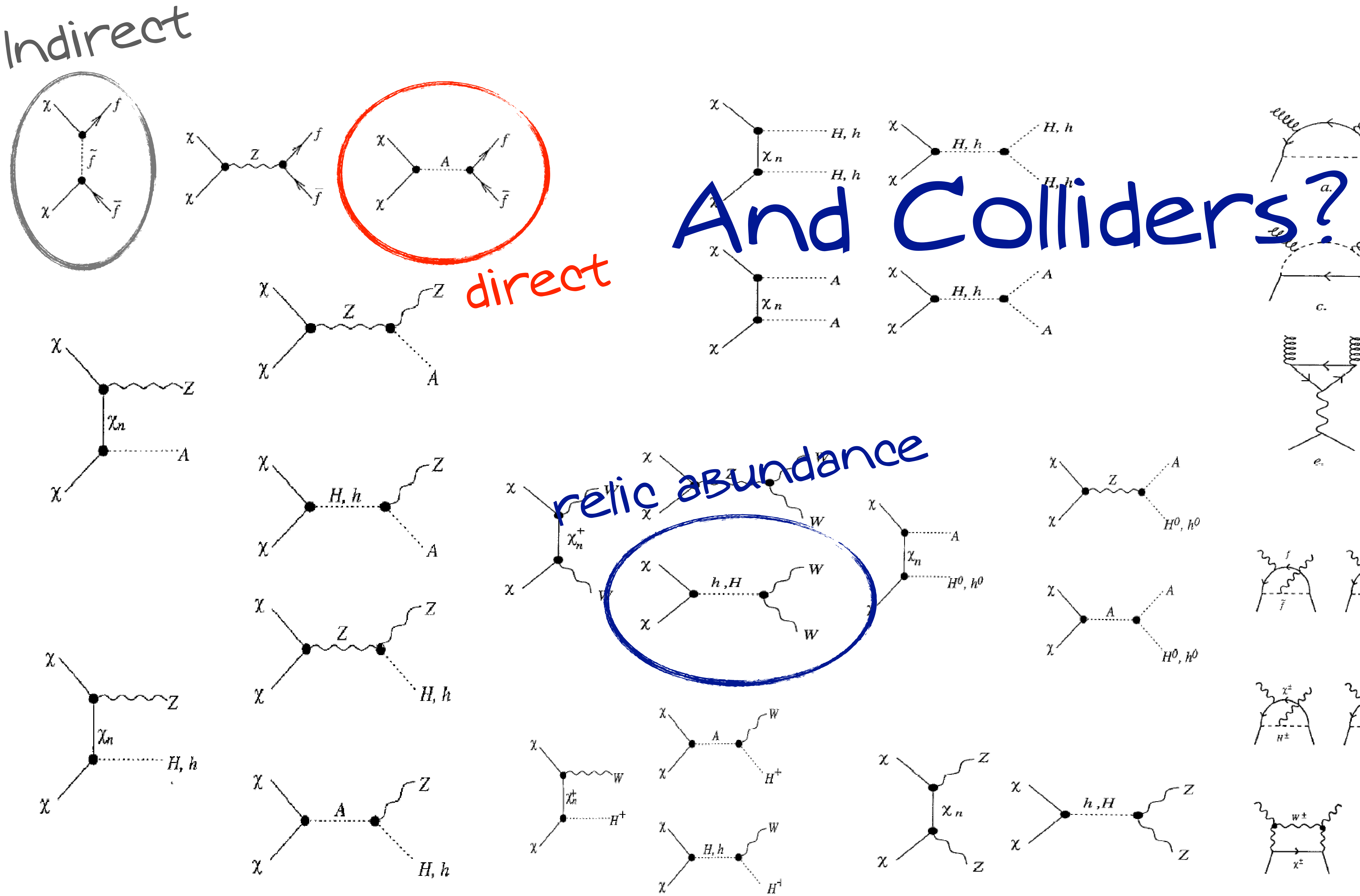
* A variety of possibilities: interesting phenomenology, but also...
* Connections between experiments are highly model dependent.

No longer turning a single diagram on its side...

For example:



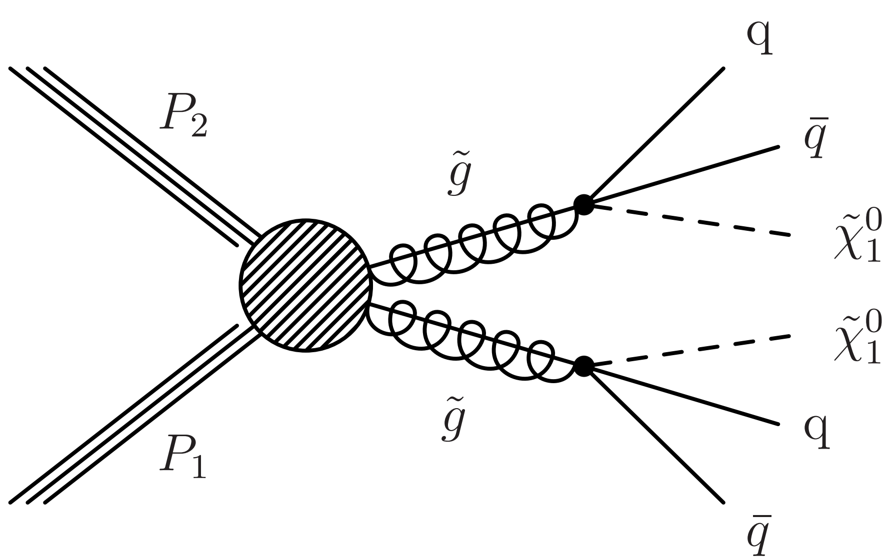
Jungman, Kamionkowski, Griest (1995)

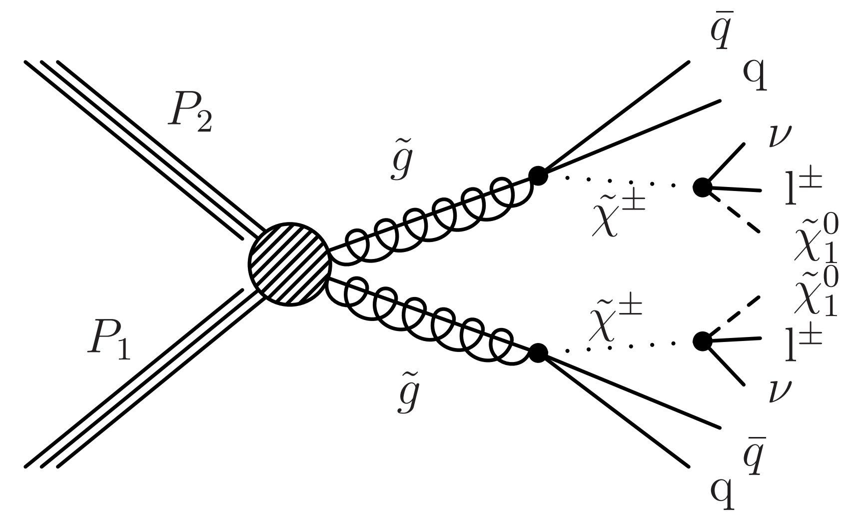


Jungman, Kamionkowski, Griest (1995)

SUSY & Colliders

* SUSY particles are produced via colored squarks or gluinos.



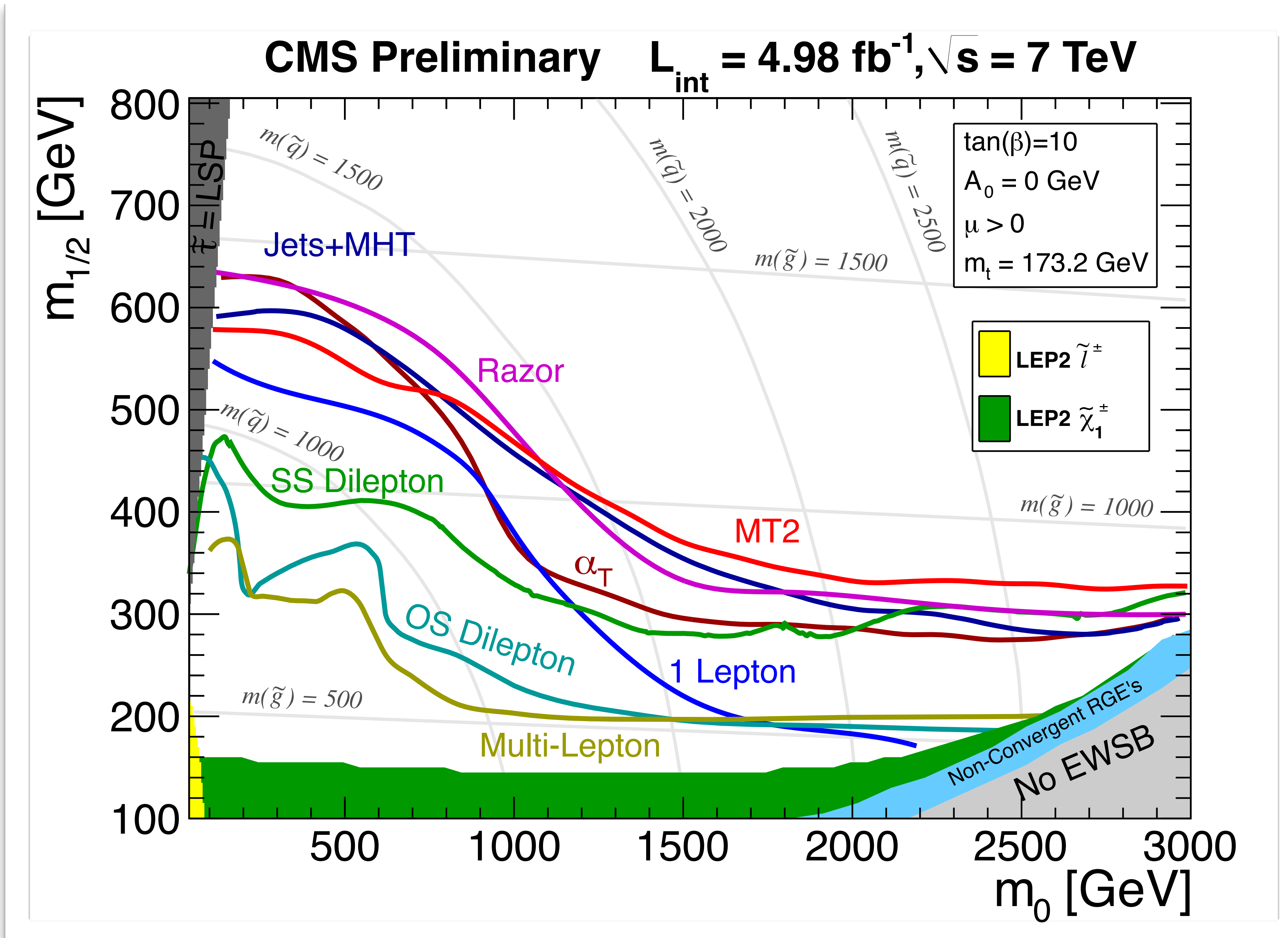


* This is great for discovering New Physics, but hard to make the connections to dark matter. (nature can certainly be this way).

Indeed, I wish we had this problem....

SUSY Limits

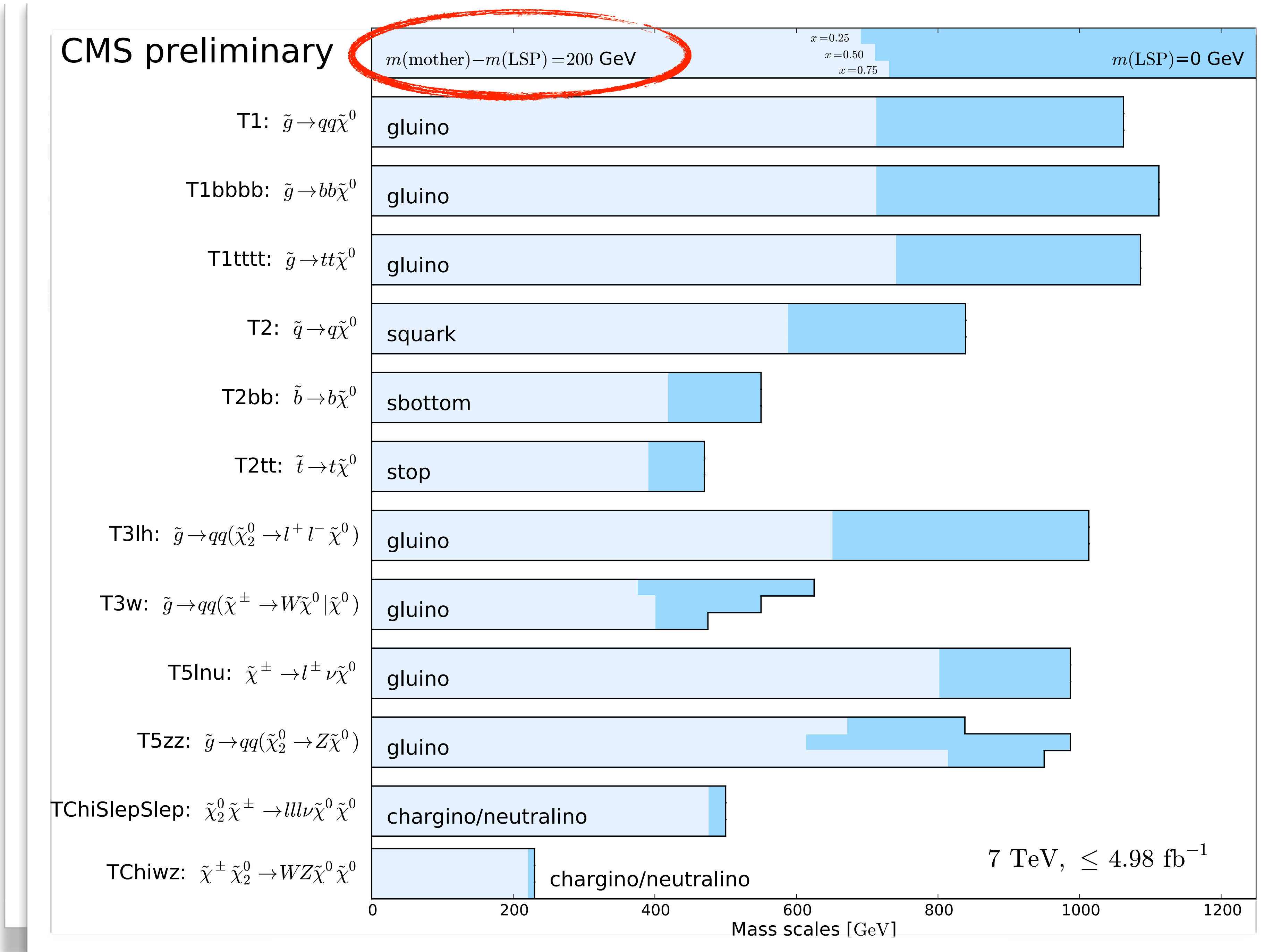
* Limits on SUSY also are model dependent:



Which means there are ways to evade them! :-)

SUSY Limits

* Limits on SUSY also are model dependent:

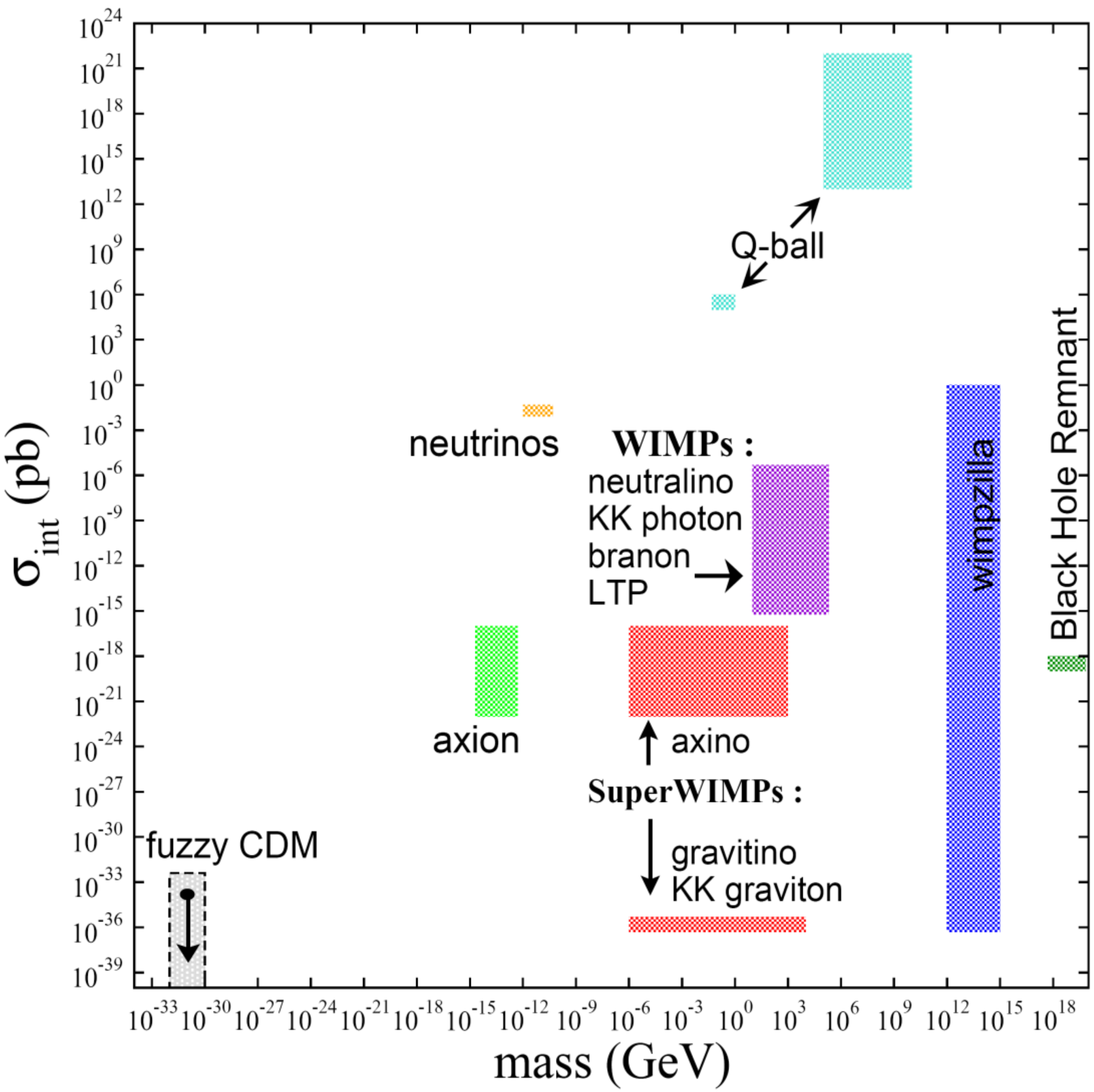


Which means there are ways to evade them! :-)

Other DM Candidates

* ***Other Wimps-***
  - KK-photons (extra dimensions), LTP (little Higgs), Inert doublet,
* ***Axions- (not a WIMP!)***
  - Originally proposed to for the strong CP problem.
  - it is a *very* weakly coupled and very light particle.
  - Searches are far fewer (opportunity!), and non-collider.
* ***Asymmetric DM- (also not a WIMP)***
  - Exploit the fact that $\rho_{\rm DM} \sim \text{few} \times \rho_{\rm matter}$.
  - Invoked an asymmetry b/w DM and anti-DM (like us).
  - Signals are model dependent, but possible everywhere.

Many More...



Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
σ_{int} (pb)
mass (GeV)

Enjoy

- Interim summary: today was about getting you curious about what's in your pint. ***Dark Matter***!
- ***Tomorrow***:
  More on how to detect it.

Cheers.

Direct, indirect, collider

Direct detection

Current Anomalies

Indirect

Colliders