Dark matter under our feet and in the sky

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- dark matter searches are well-motivated
  - the field is changing rapidly and experiments capable of "seeing" WIMP dark matter are finally operational
- *however*, there are indications that we may have to extend the cold dark matter model
  - if so, then dark matter is not a WIMP

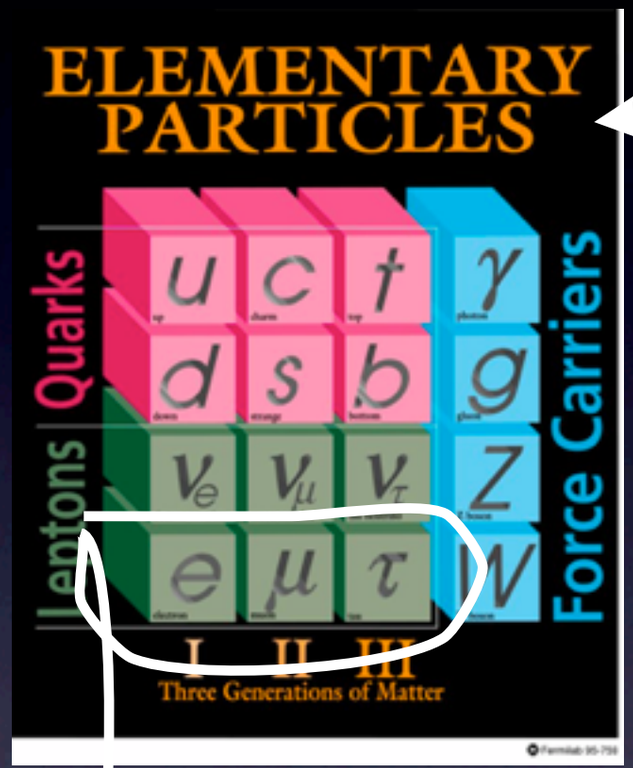
what is the universe made of?

- Normal matter (makes bacteria, comets, etc)
- Dark matter (behaves gravitationally like normal matter but so far we no concrete evidence that it interacts with anything else)
- More dark stuff (seriously!) dubbed dark energy (that does not behave gravitationally like normal matter)

Background:
The Hubble Ultra Deep Field

is dark matter weird?

- Doesn't have to be. In fact, we would have been wondering why there isn't any dark matter if all of matter was "normal"!
- Neutrinos are good dark matter candidates. Just not heavy enough to make up all of the dark matter we see.

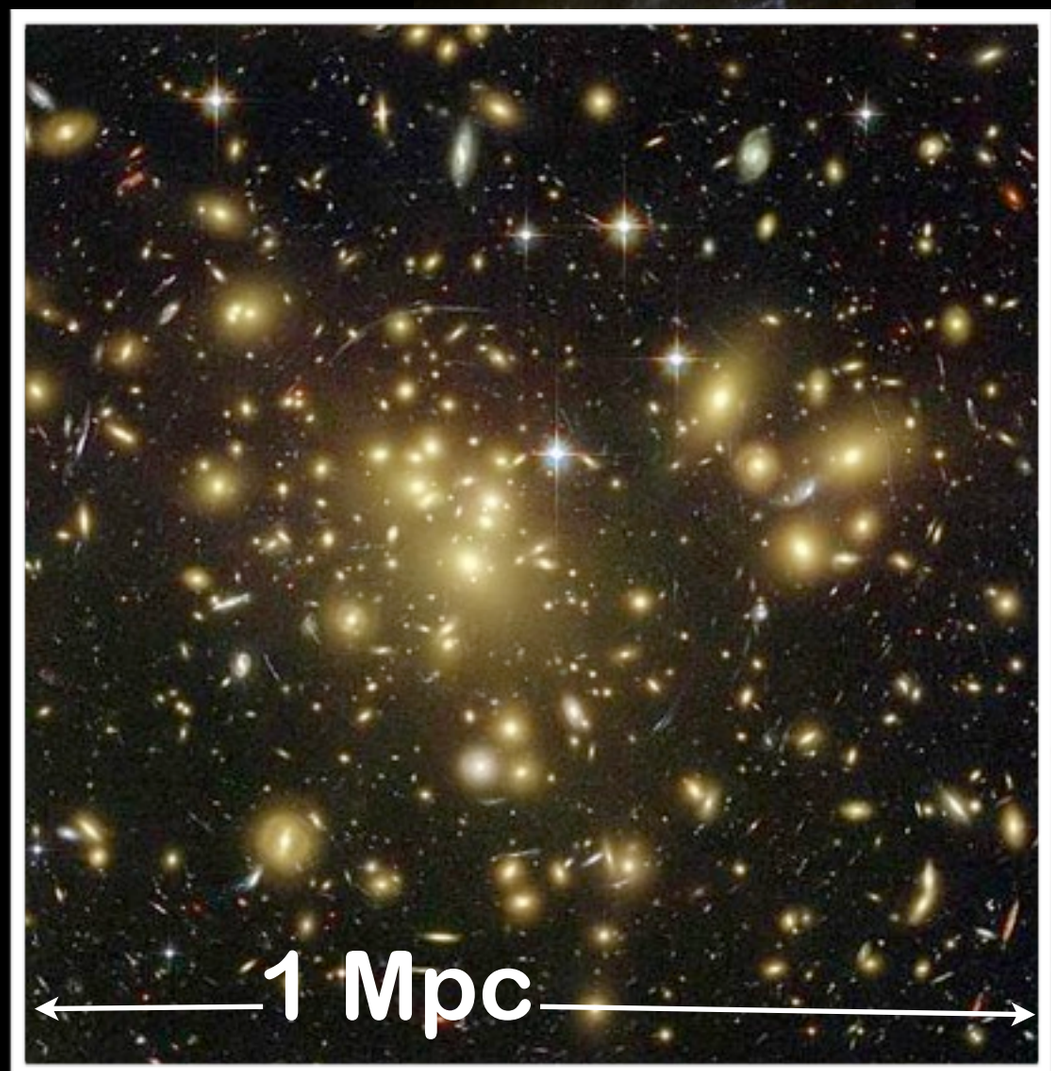


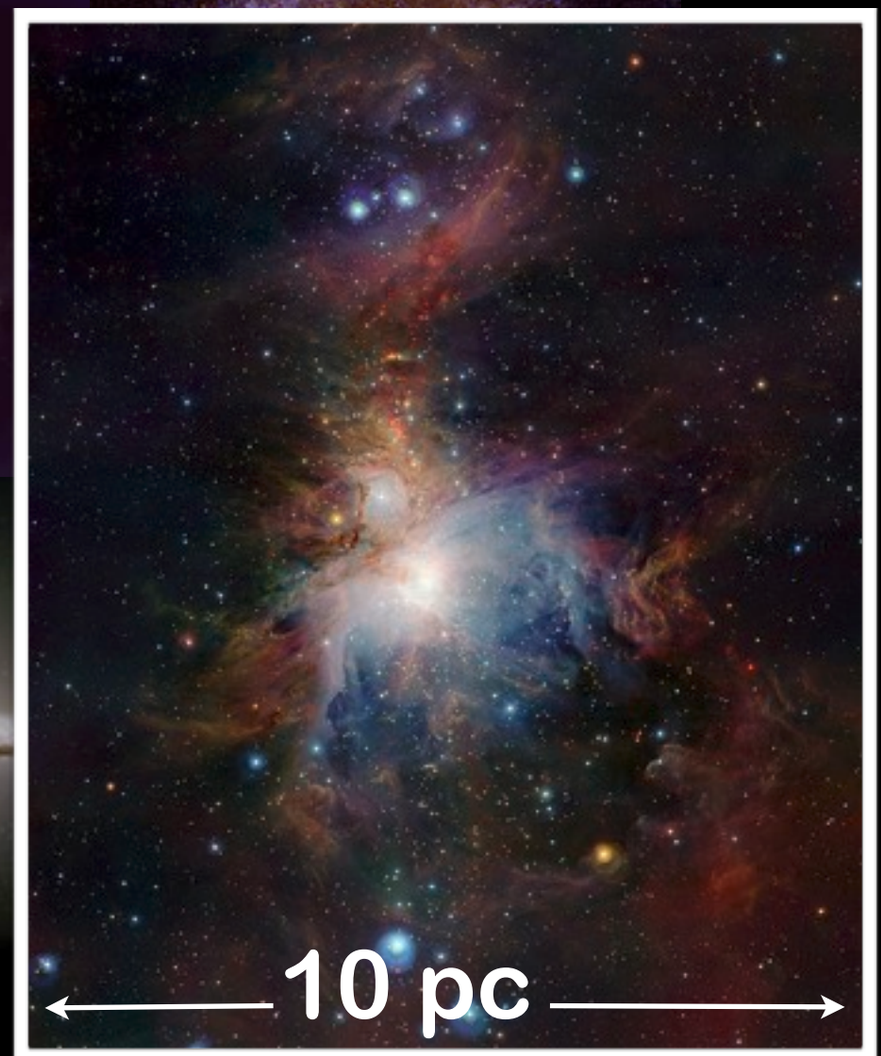
Particles of the standard model of particle physics that have been seen in the laboratory

what we see: some length scales

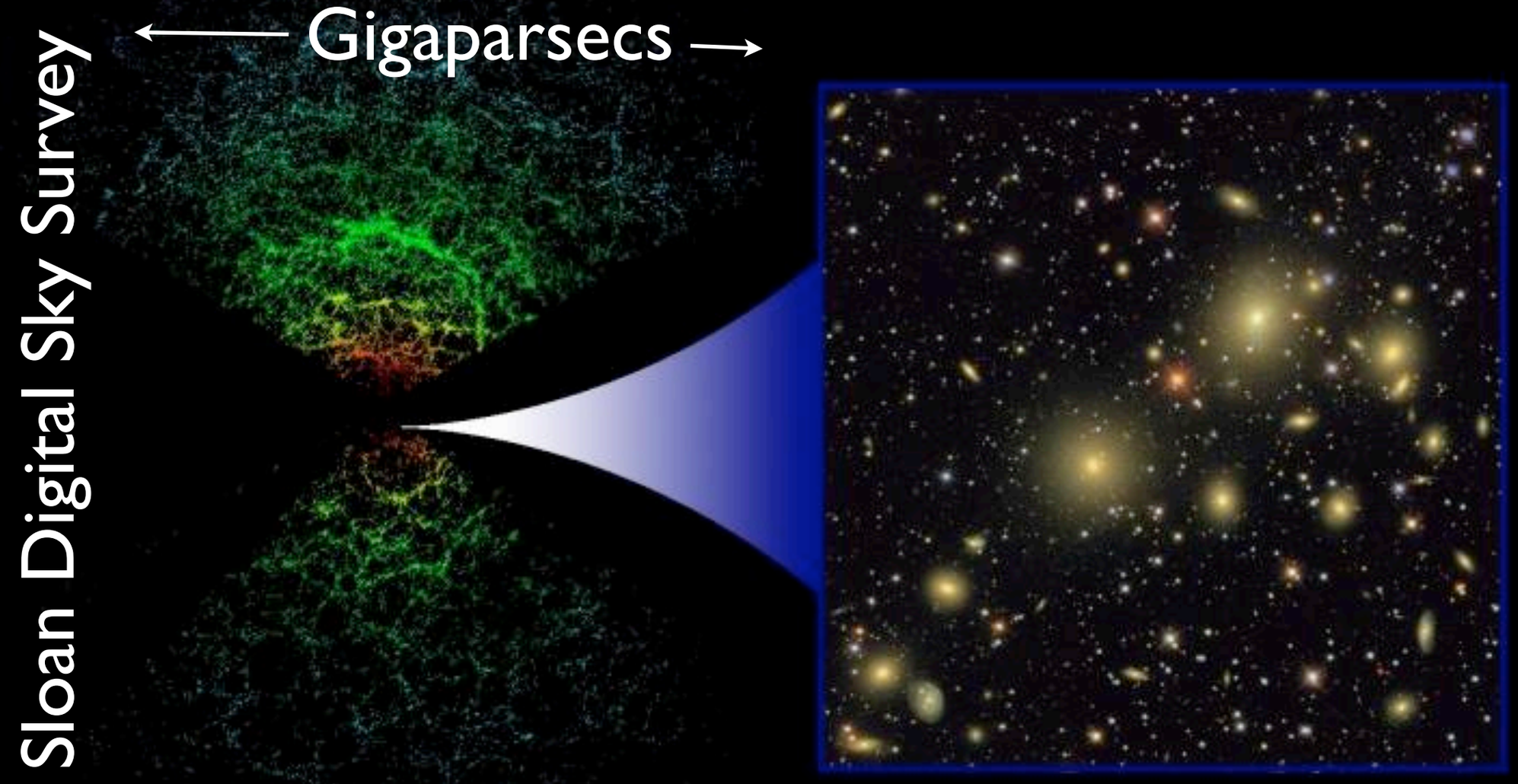
Stellar nurseries
Galaxies
Clusters of galaxies

pc (parsec) is 3 light-years or 30 trillion km or 200,000 AU





what we see: some length scales

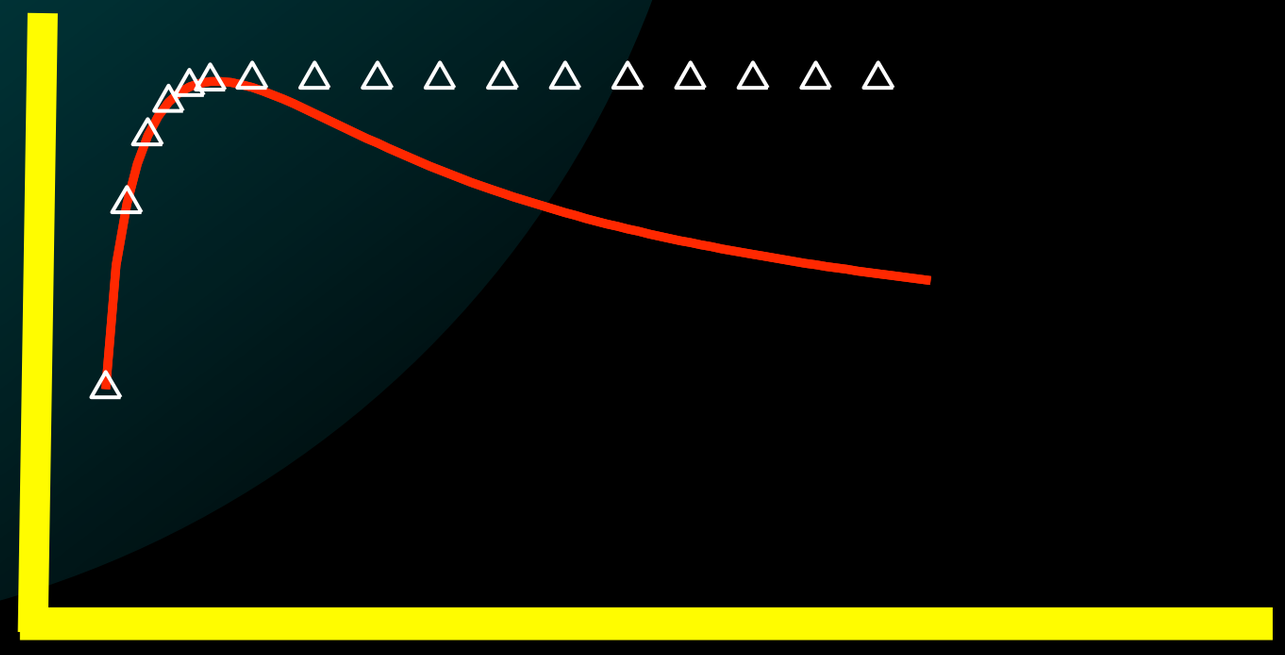


Filaments of structure -- the “cosmic web”

dark matter in galaxies

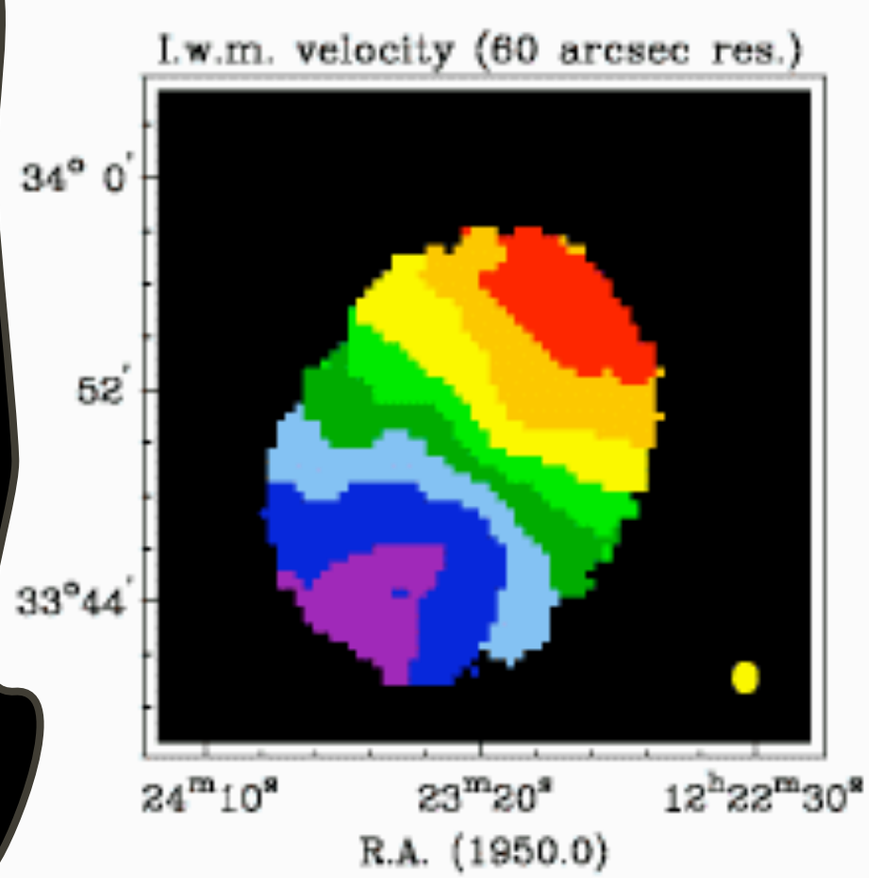
About half gram of dark matter in a cube with side 1000 km in the solar neighborhood

Typical speed of dark matter particles is about 200 km/s near the solar neighborhood.



dark matter in galaxies

UGC 7524/NGC 4395



Galaxy:	UGC 7524
Distance:	4.3 Mpc
Type:	.SAS9*.
B^0_T:	10.55
Inclination:	34°
Optical size:	13.′2 x 10.′8
Total HI mass:	14.4×10^8 $M_\odot$

© WHISP, Mon May 26 15:57:00 1997

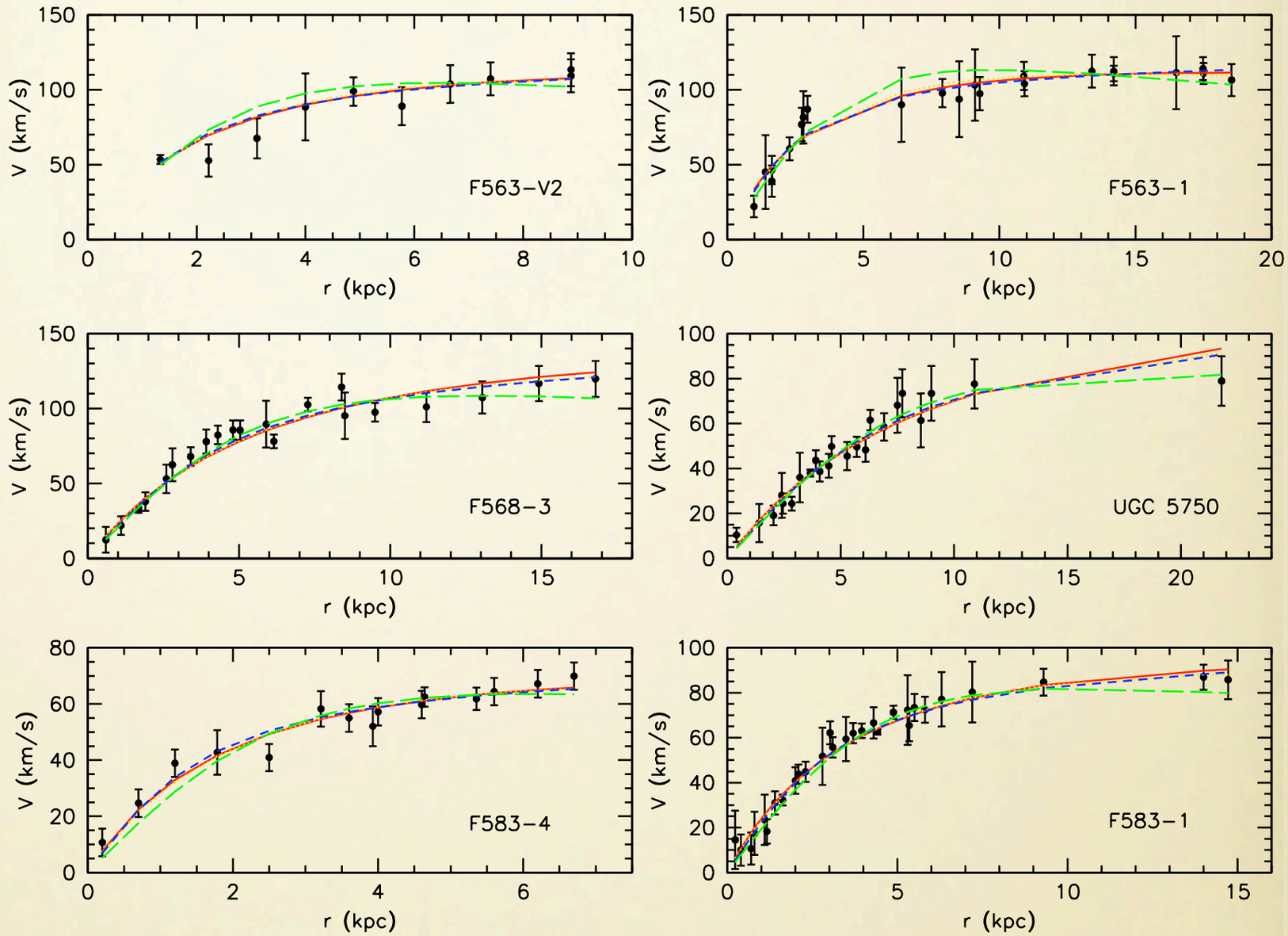
Close-by and faint

Rotation supported by dark matter

dark matter in galaxies: rotation speeds

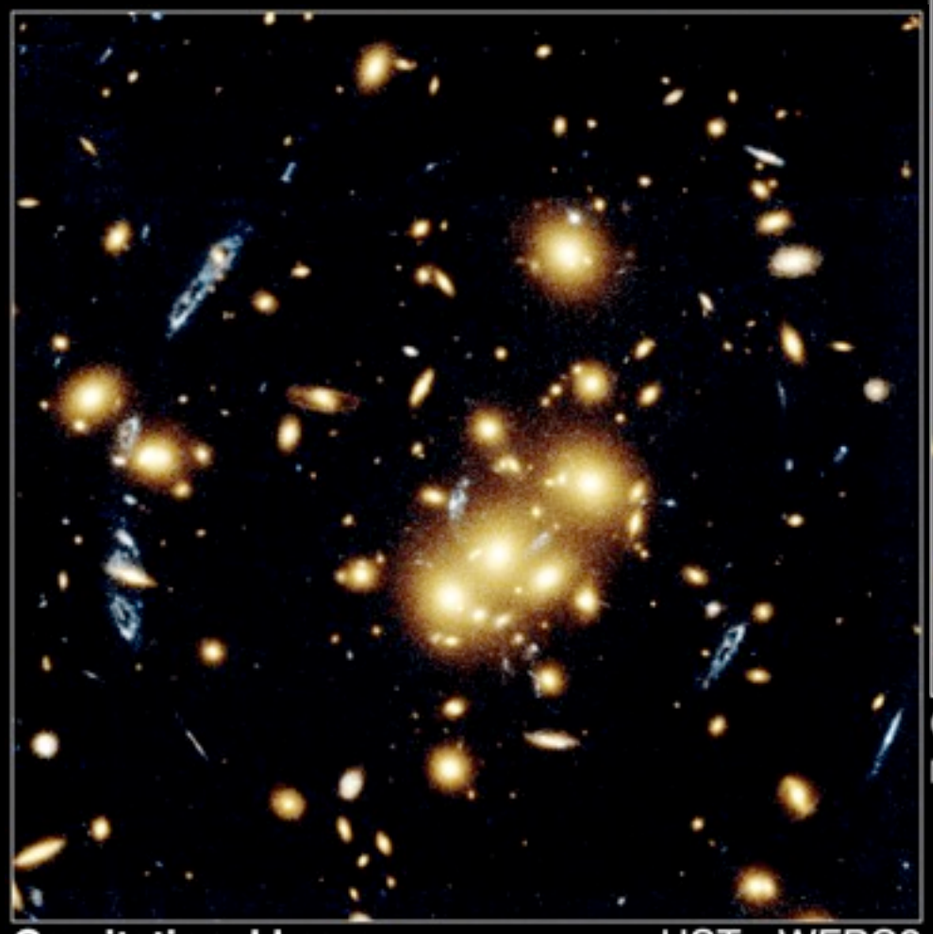
Note the plateau in speed as the distance from the center increases.

This universal feature is the primary case for dark matter in galaxies.



Note the linear rise in rotation speed close to the center.

dark matter in clusters of galaxies: gravitational lensing



Gravitational Lens Galaxy Cluster 0024+1654 HST • WFPC2

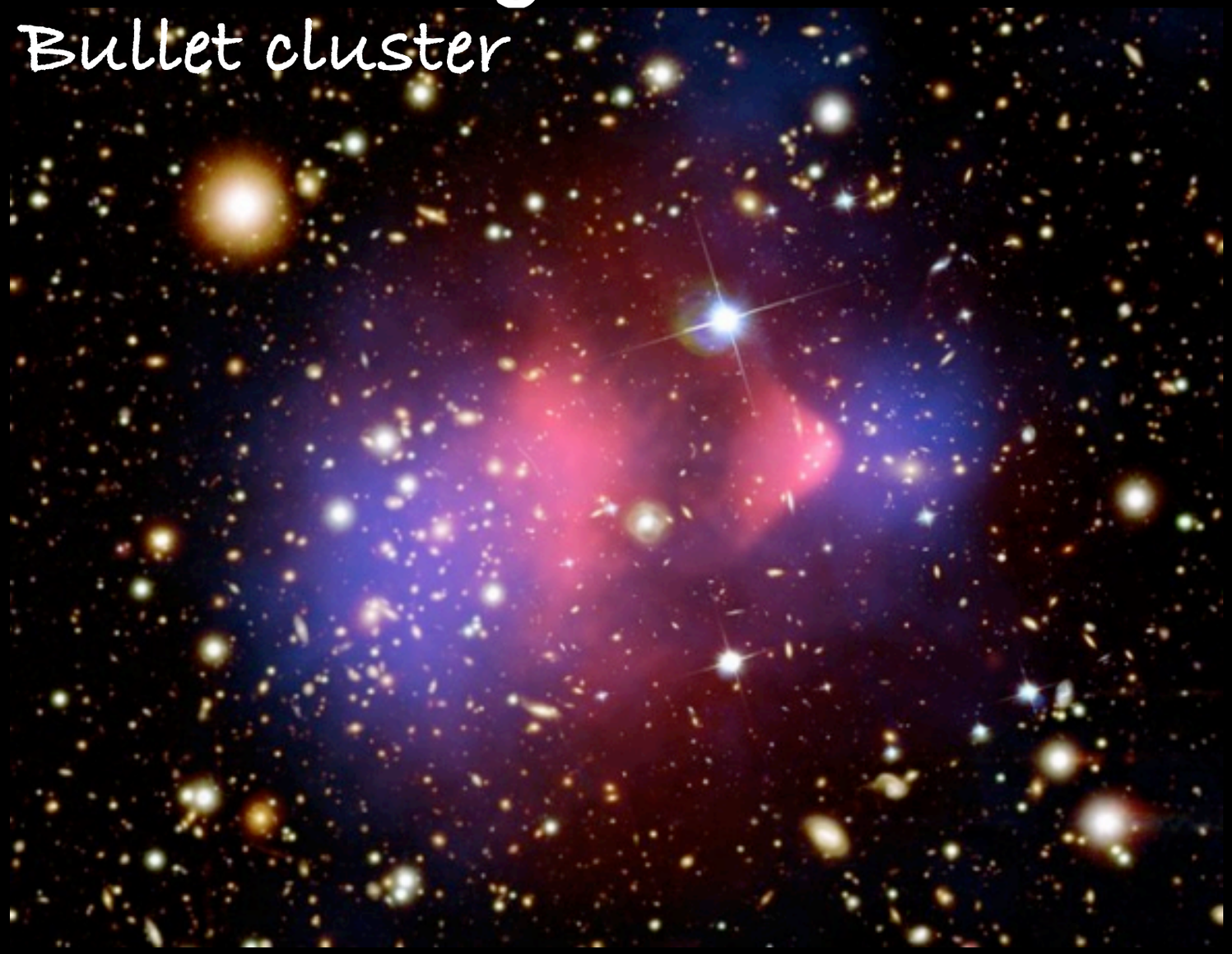
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

Galaxy Cluster Abell 2218 HST • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Arcs are distorted images of background galaxies: “strong gravitational lensing”

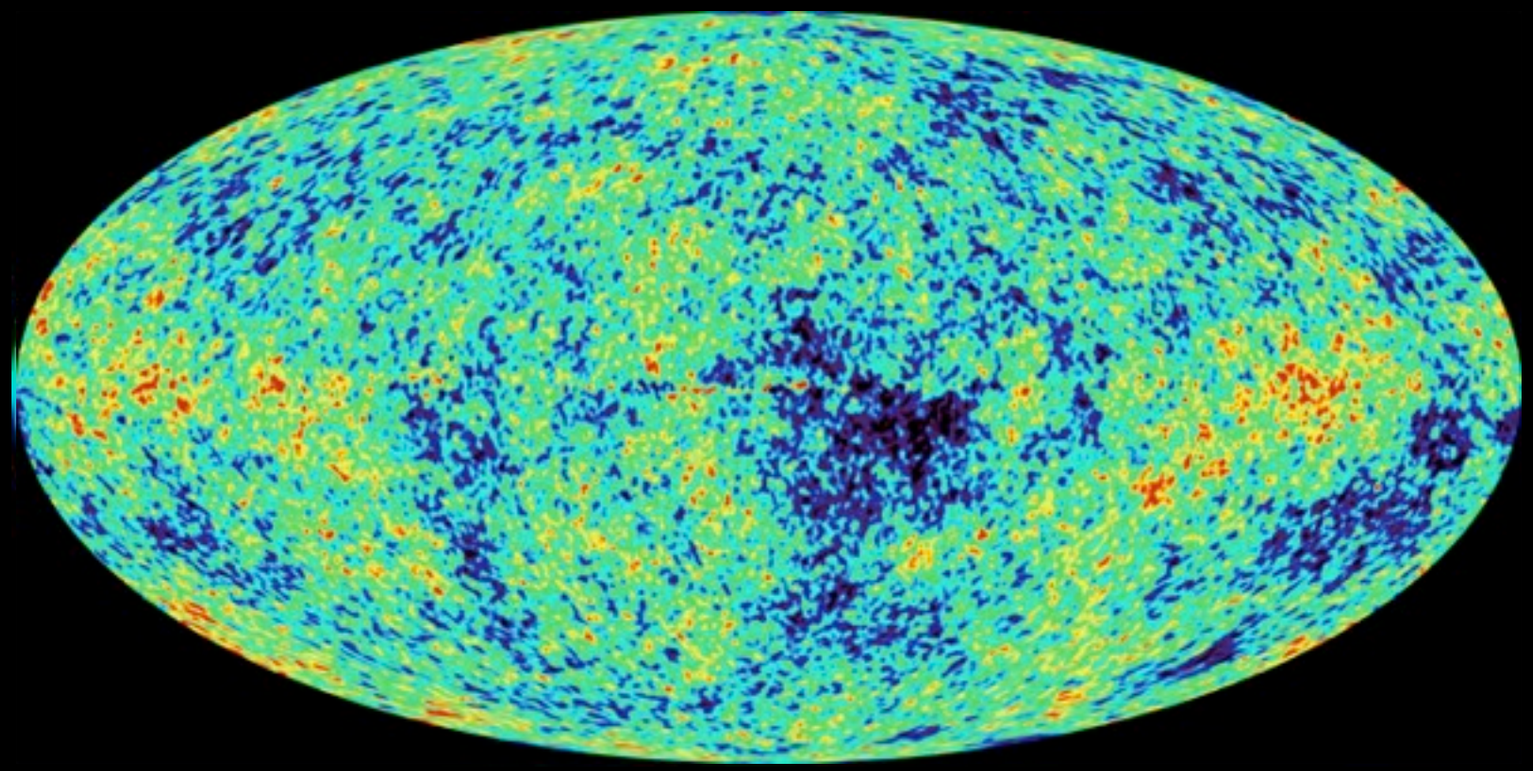
dark matter in clusters of galaxies: gravitational lensing



Blue: matter from "weak" gravitational lensing
red: gas in x-rays

Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

dark matter on horizon scales



WMAP (2003)

The Universe is not perfectly smooth -- very small variations are needed to make galaxies.

WMAP : (a) universe is close to flat, and (b) about 5 times more dark matter than normal matter

Discovered in 1990s with the COBE satellite

story so far

We have looked at some of strongest lines of evidence for dark matter.

The next section is about the basic questions we may ask about dark matter *particles*.

Dark matter: Cold and Warm

Cold/Warm: main distinction is (of course) temperature

Temperature: <u>measure of random (thermal) motion</u> *before* dark matter particles are bound into halos (galaxies)

As the universe cools, this thermal motion decreases

Operational definitions

<u>Cold dark matter</u>: thermal motions irrelevant for galaxy formation

<u>Warm dark matter</u>: thermal motions (a) cut-off formation of small-galaxies or (b) reduce the amount of dark matter in the central parts of galaxies

dark matter interactions (other than gravitation)

Does it interact with other particles?

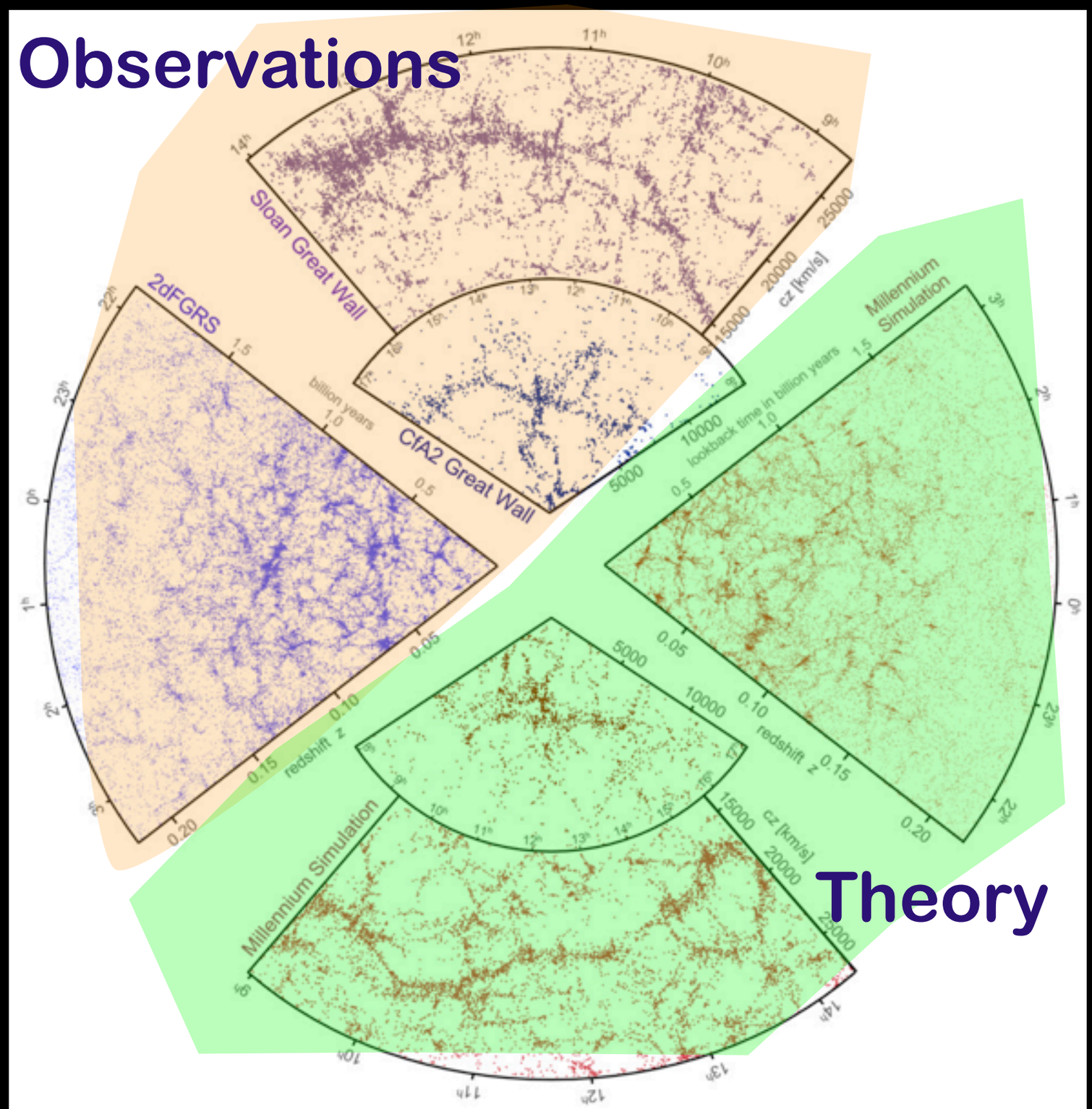
Does it interact with itself?

Is it stable?

COLD dark matter on "large" scales

Matches data on cosmological scales (CMB) down to scales of order Mega-parsec (Galaxies)

Zero-parameter fit (not counting the cosmological parameters) from the astrophysical point of view



extending cold dark matter model?

Should we really expect dark sector to be so simple (so much simpler than the visible sector)?

Cold dark matter model is clearly right (on large scales) but will it need modification as we probe smaller scales?

If yes, what are the motivations? What sort of modifications? How may we test them? How does computing play into this?

extending cold dark matter model

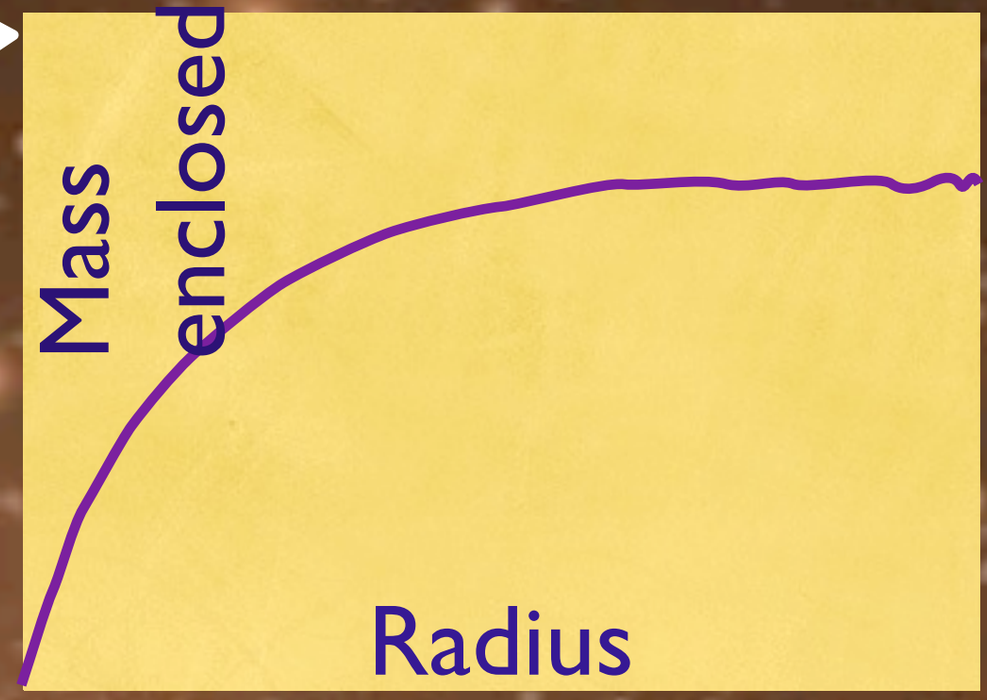
(i) Warmer
or
(ii) Stronger self-interaction

Actually...
(i) much much ... warmer
or
(ii) much much ... stronger self-interaction

How does warmness or strong self-interaction manifest itself in astrophysics?
Next ...

Milky Way halo simulated (almost...)

Milky Way halo simulated (almost...)



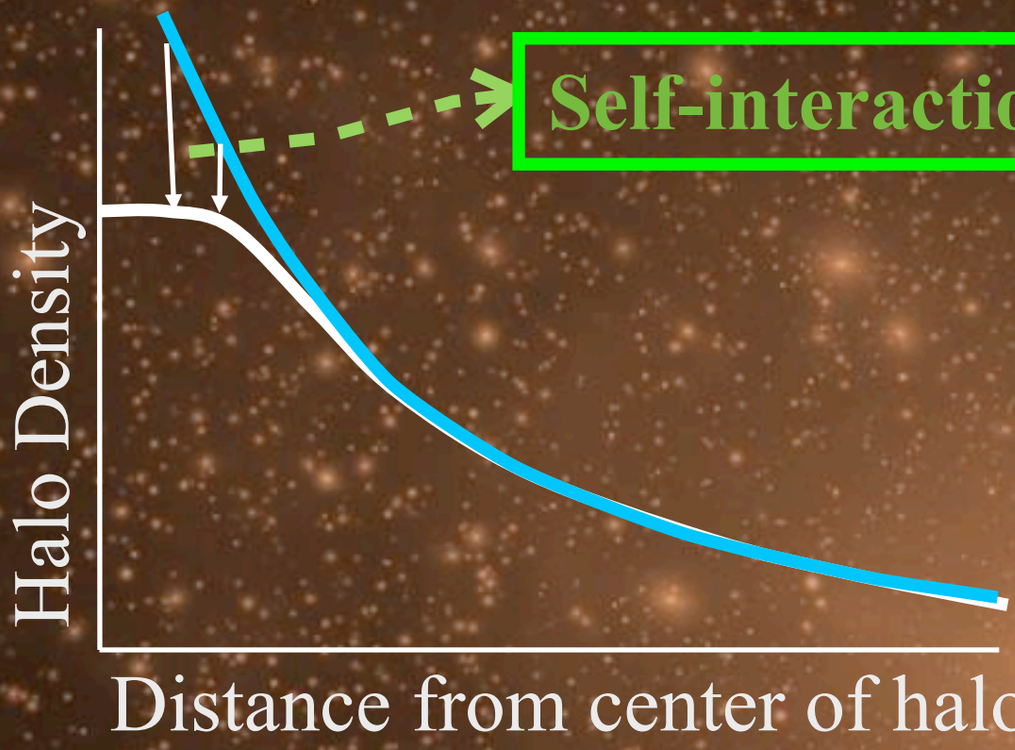
(distance from center of clump or "subhalo")

Via Lactea

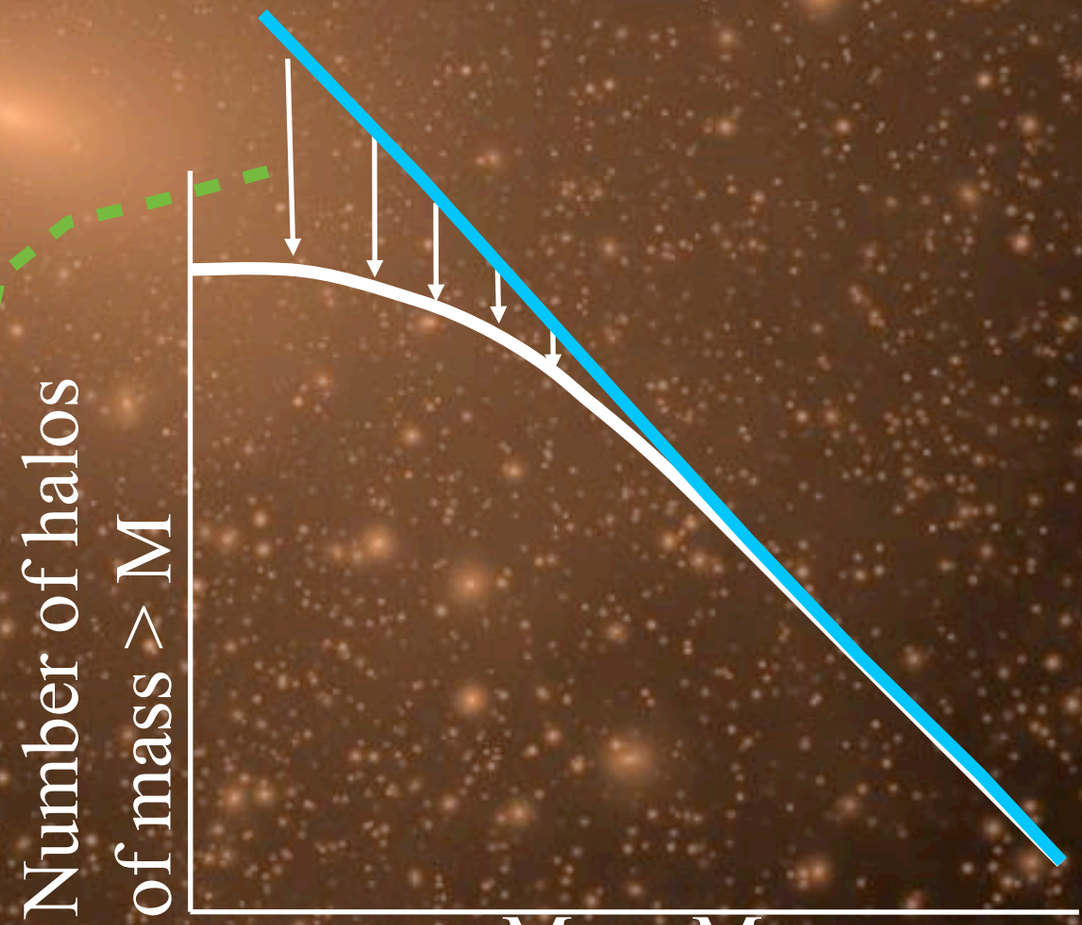
z=0.0

Warmness and Self-interactions

Self-interaction strength is dialed up



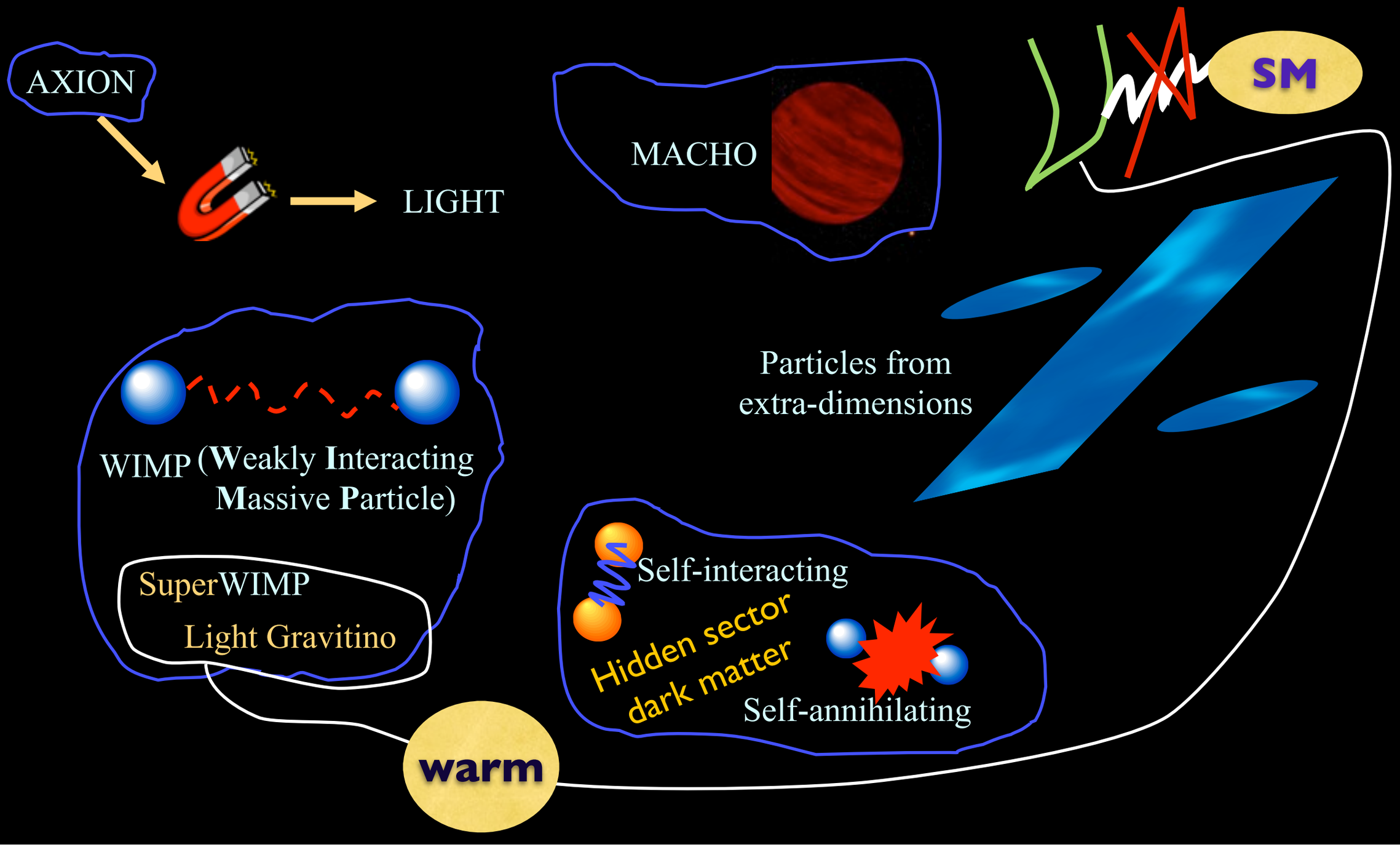
Warmer



80 kpc

some models of dark matter

- Behaves like normal matter except it does not shine.
- Interacts very weakly with normal matter.



Central density of halos is lowered

Warmness

WIMP

Sterile ν

SuperWIMP

Hidden sector DM

Damping

Mass of smallest halos

Self interaction

Halos more spherical and bigger cores

Hidden Sector

if our sector is supersymmetric

imagine proton and neutron-like particles here

~~**SUSY**~~

SM

Connector

Hidden

How is dark matter produced?

- By freeze-out process : stronger the self-annihilation smaller the present abundance (e.g., WIMP, x-dim)
- Through decay process where the parent particle's abundance is set via the freeze-out mechanism (e.g., SuperWIMP)
- By non-thermal process (e.g., axions, sterile neutrino)
- Directly during reheating : fine tuned (e.g., WIMPZILLA)

Weak scale dark matter

Right abundance!

Successful cosmological predictions on large scales

Hints for new physics at the weak scale (~1000 proton masses)

STORY SO FAR

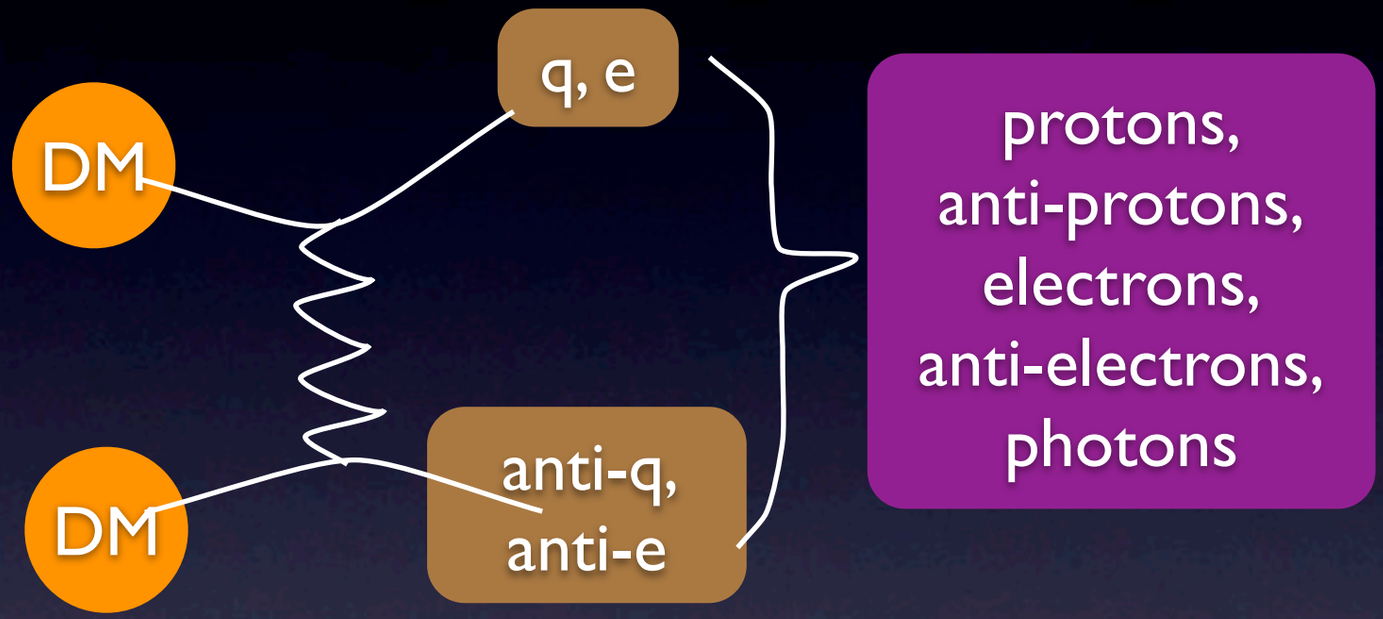
- We have seen that well-motivated dark matter models are varied and they make differing predictions for:
  - formation of small galaxies
  - for density of dark matter in the central parts of the galaxy
- WIMPs are the favored candidates
  - well-motivated
  - provide the most dramatic avenues for seeing dark matter **-- Direct detection, Indirect detection, Direct production.** ***Coming up next…***

dark matter is all around us: how do we “see it”?

the WIMP casebook

- Weakly Interacting Massive Particle
- Weakly interacting: this is what makes dark matter effectively "dark". The weak interactions also endow the dark matter with the right cosmological abundance.
- "Massive": has to be or we would have seen it in the lab despite the weak interactions
- These particles fall out of theories designed to complete the standard model of particle physics

Indirect detection



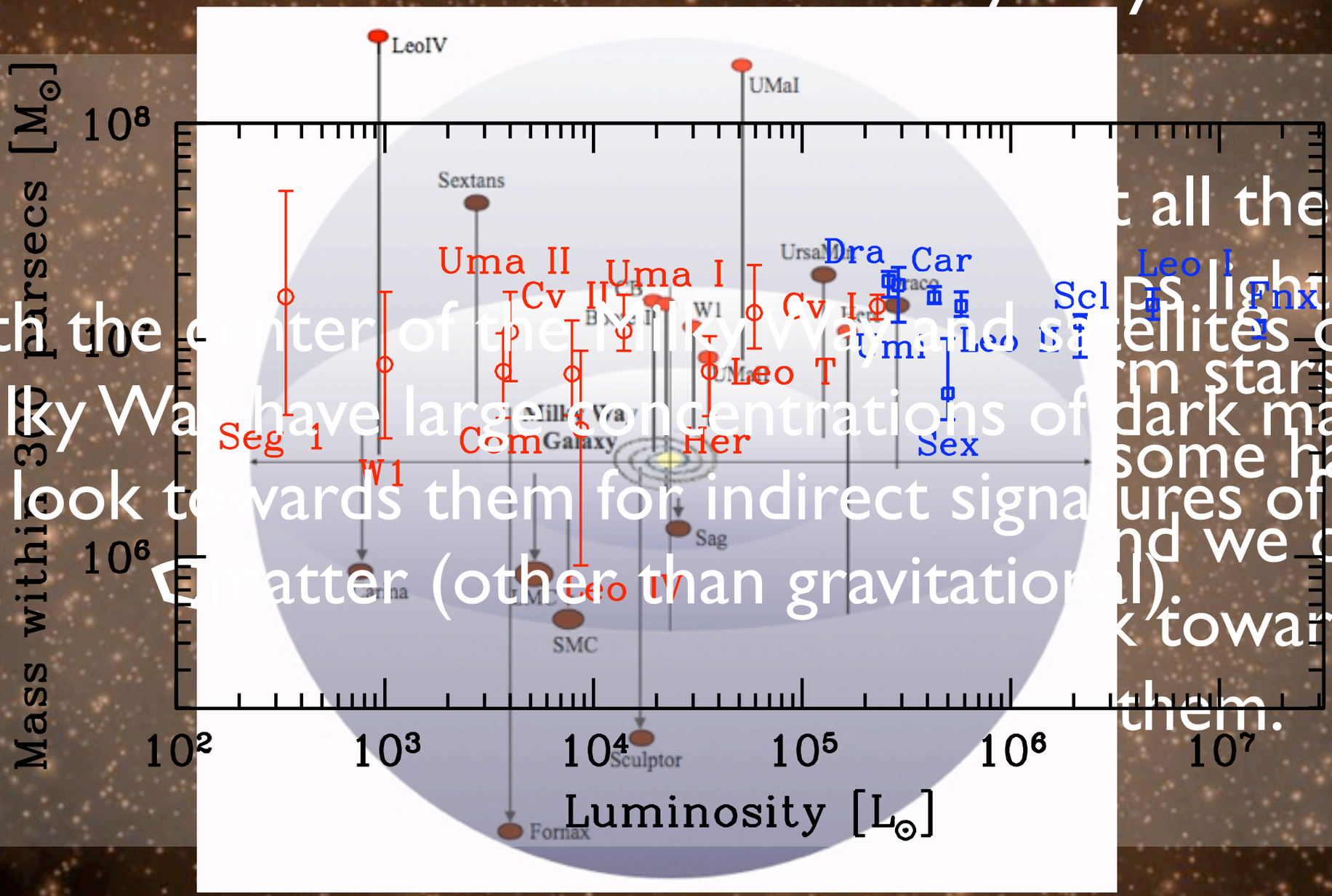

Fermi (gamma-rays)

Stay tuned for results from AMS-02


PAMELA (antimatter)

Sources for indirect detection

Satellites of the Milky Way



Both the center of the Milky Way and satellites of the Milky Way have large concentrations of dark matter.

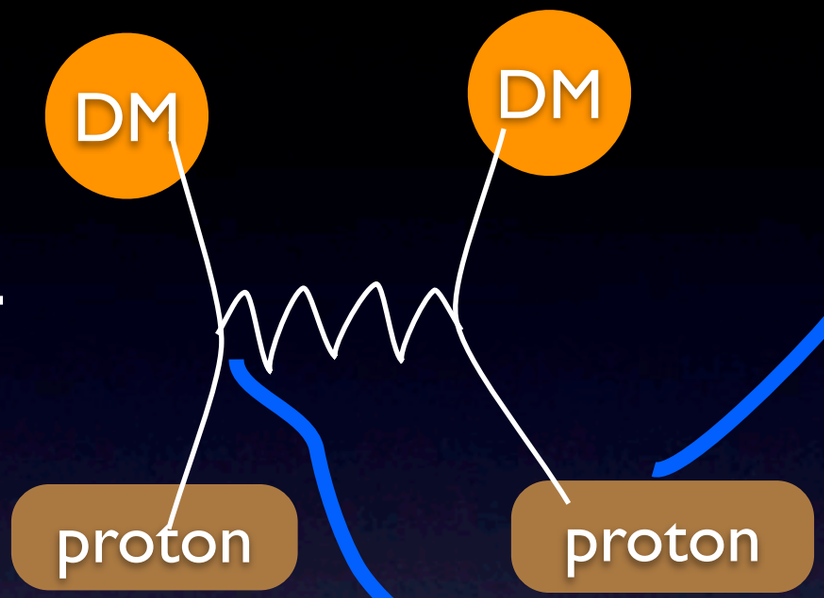
So look towards them for indirect signatures of dark matter (other than gravitational).

t all these
DS light up
m stars)!
some have
ures of dark
nd we can
k towards
them.

80 kpc

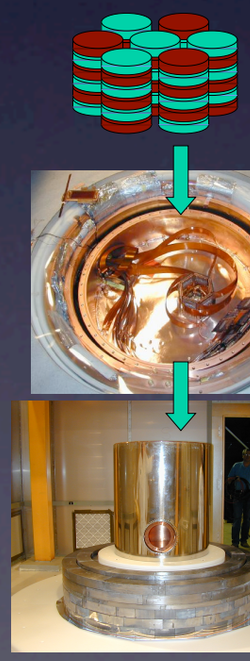
Direct detection

DAMA
COGENT
CRESST



recoils with energy of order (DMP mass)(200 km/s)^2

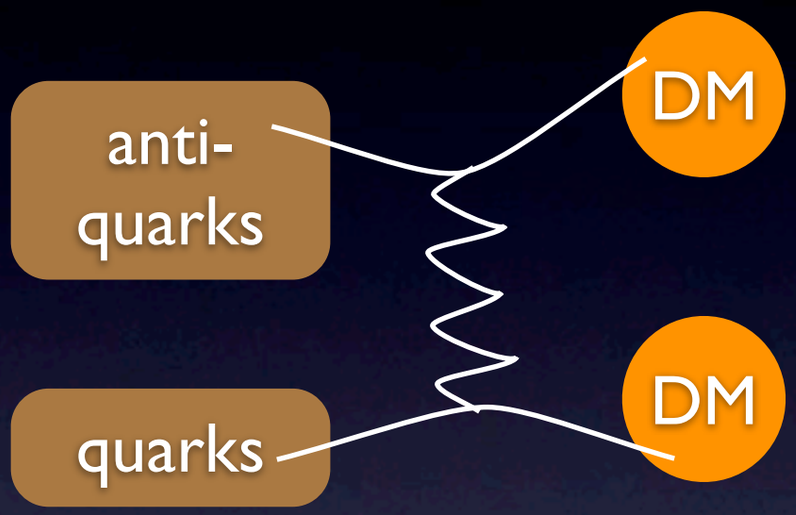
number of events depends on: **(a)** how strongly DMP couples to protons and neutrons, and **(b)** how many DMPs per meter^3 in the solar neighborhood

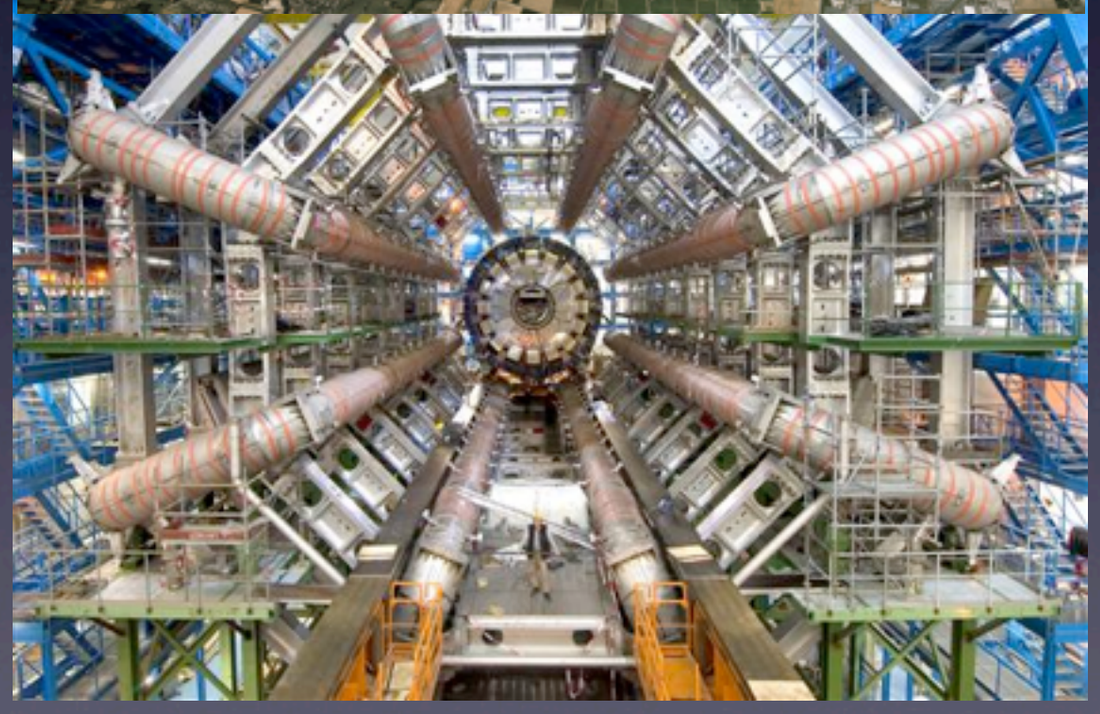


Cryogenic Dark Matter Search (Soudan)

Direct production

Make dark matter!

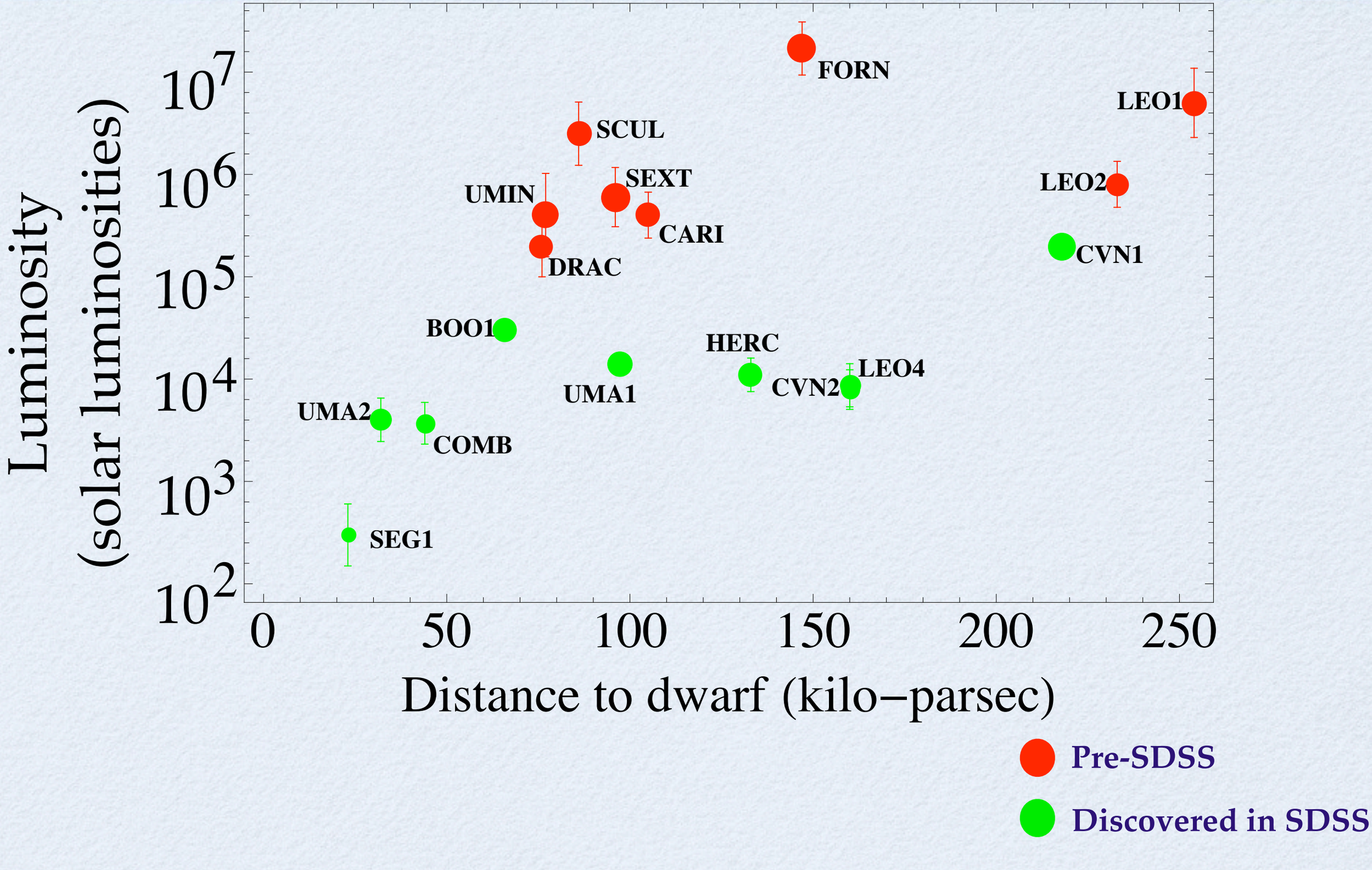




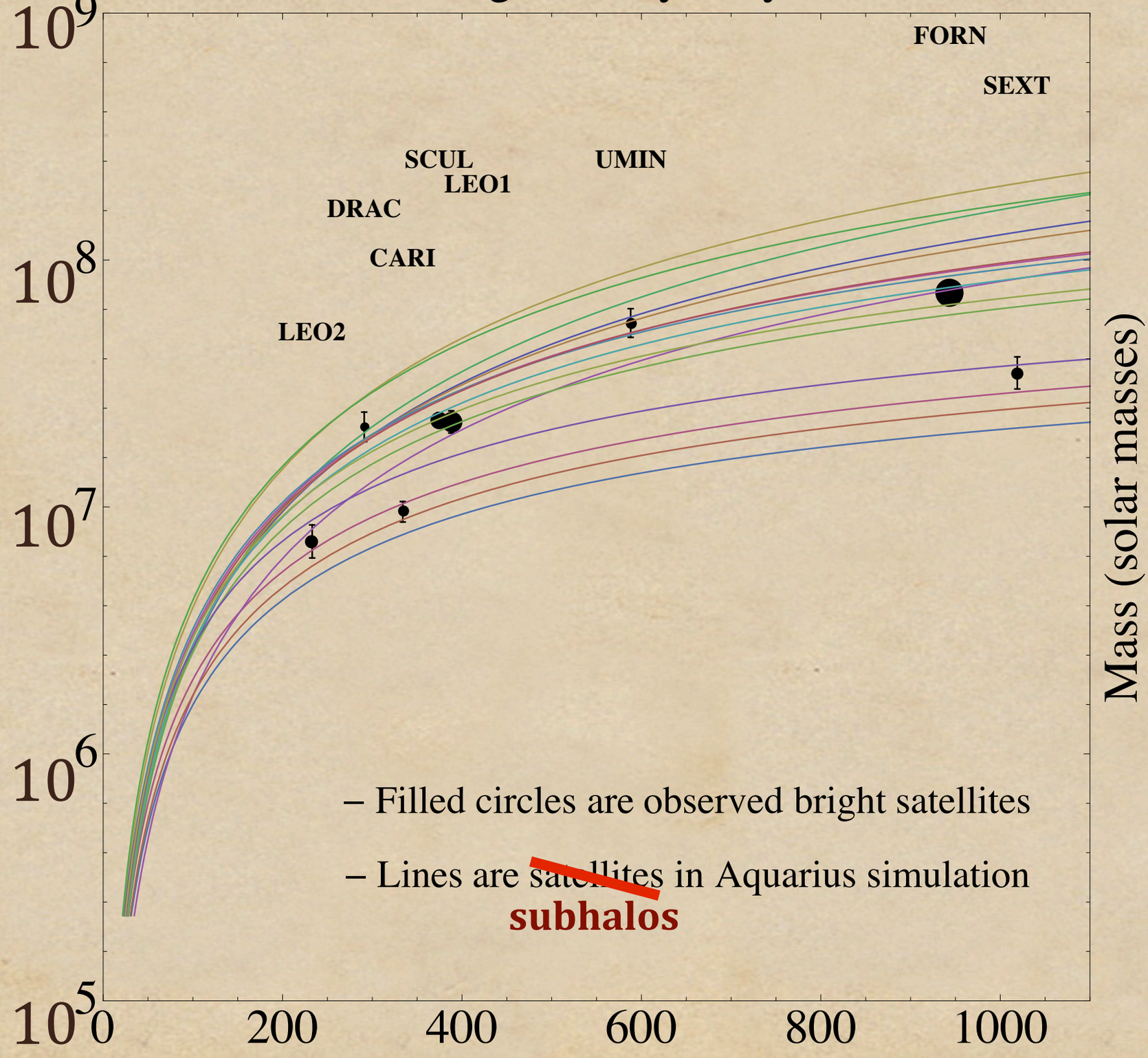
last part of talk now...

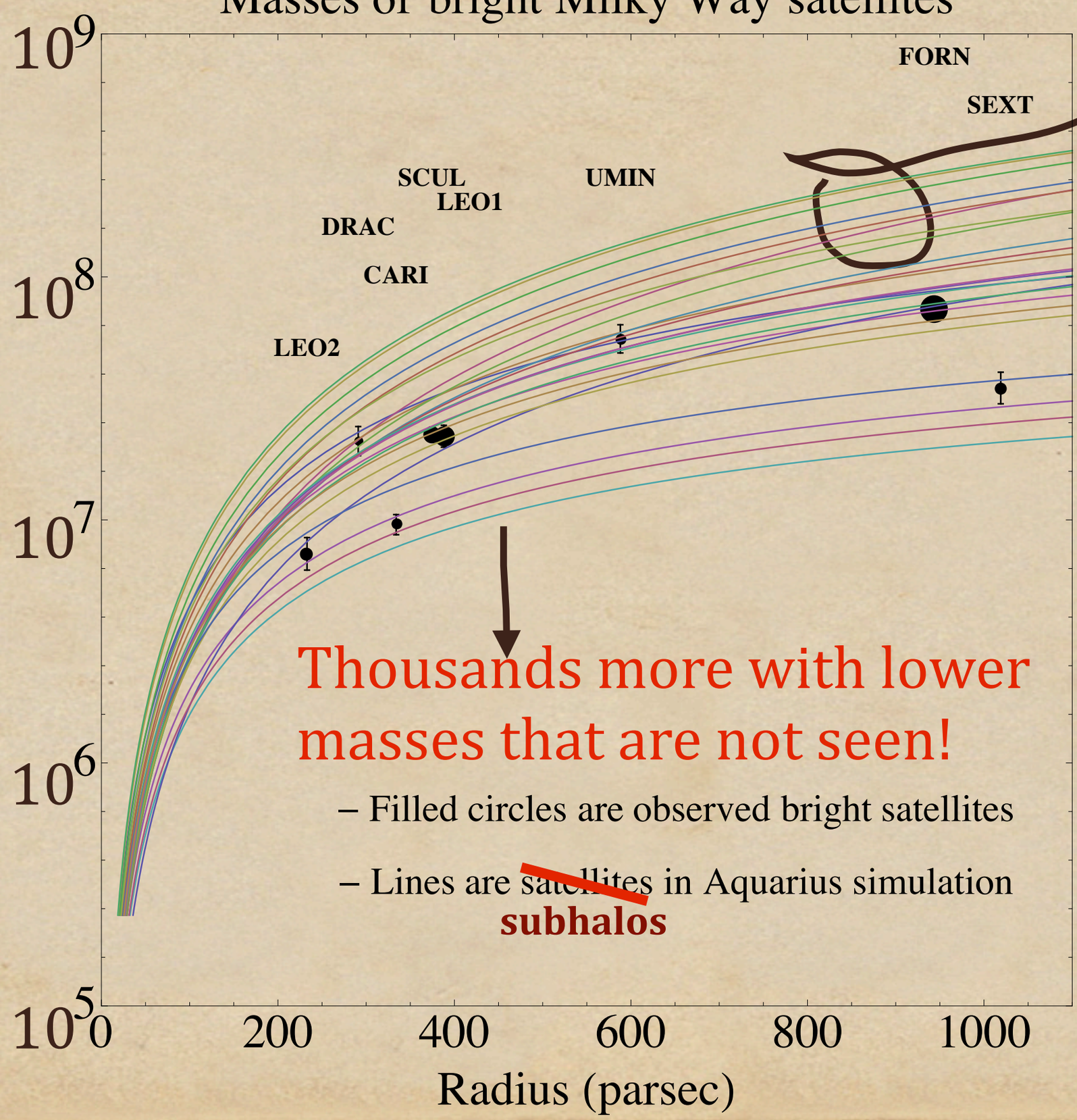
- We have seen various ways to "see" WIMPs and we have seen why they are (deservingly) the most favored candidates
- Next we look at two issues for a *perfectly* Cold Dark Matter model
  - Density of dark matter in satellites of the Milky Way
  - Density of dark matter in small spiral galaxies

Satellites of the Milky Way



Masses of bright Milky Way satellites

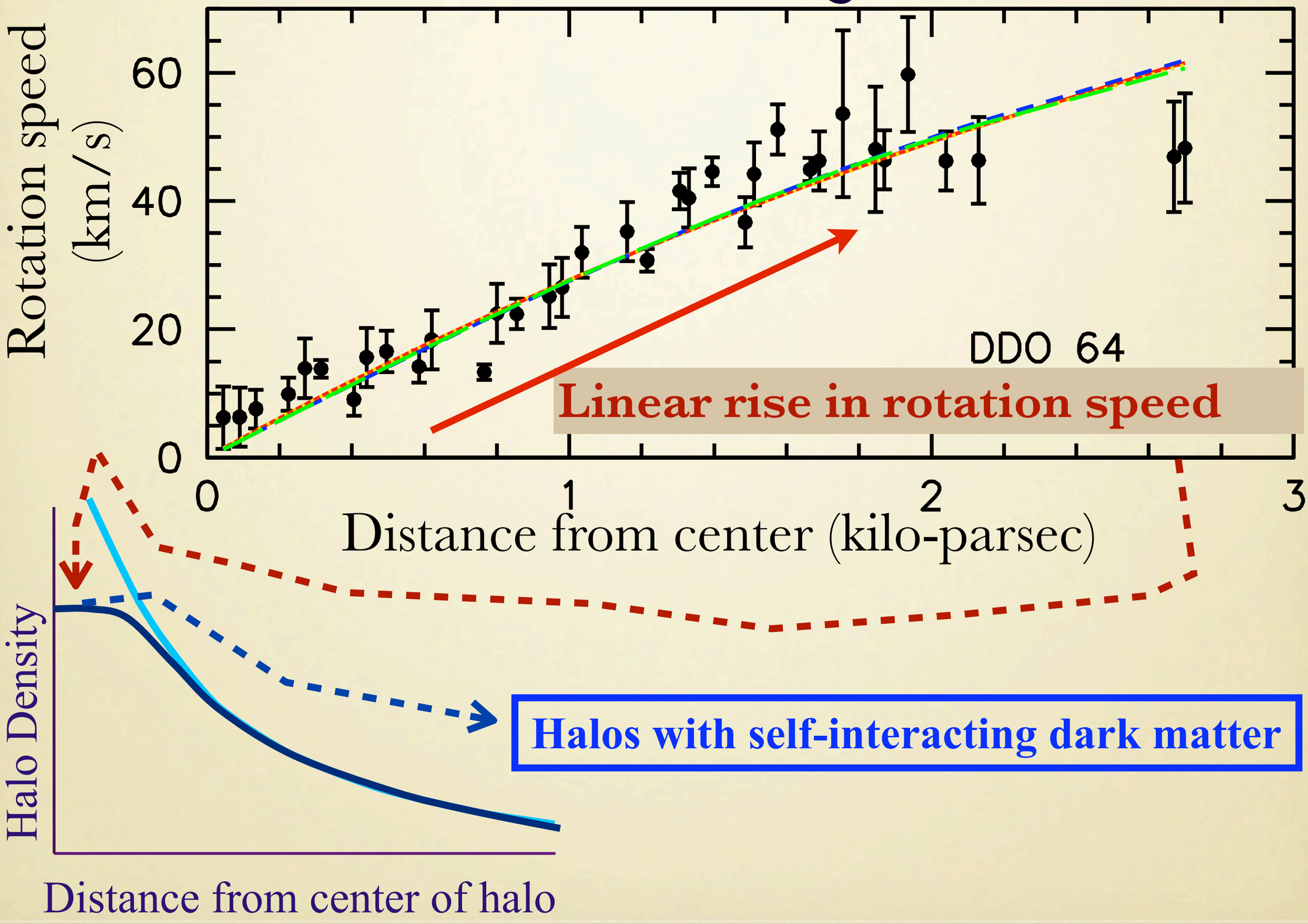




Massive satellites missing!

Could be solved by self-interacting or warm dark matter

dark matter in other galaxies



- dark matter searches are well motivated
  - the field is changing rapidly and experiments capable of "seeing" WIMP dark matter are finally operational
- however, there are strong hints that we may have to extend the cold dark matter model
  - if so, then dark matter is not a WIMP
  - requires investment in supercomputing for **(a)** understanding feedback from star formation and **(b)** simulating alternative dark matter cosmologies