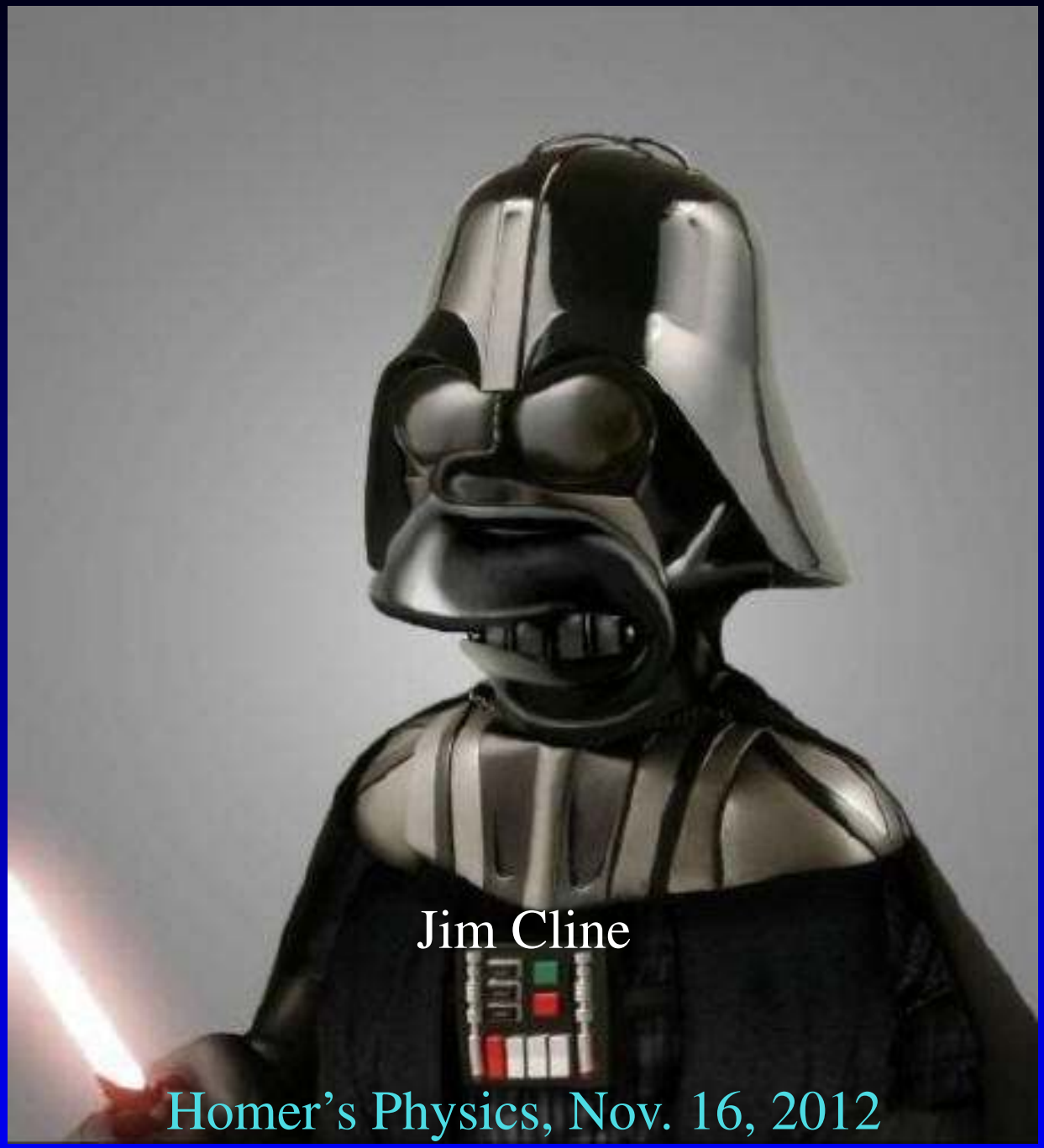
The Dark Side of the Universe



Jim Cline

Homer's Physics, Nov. 16, 2012

WARNING:

Viewer Discretion is Advised.

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This talk contains disturbing adult content,
coarse language, nudity, and scenes of violence

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Sensitive viewers are advised to finish their pizza quickly

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Have a second beer ready

Some theories depicted here are speculative.

Any resemblance to physical reality is purely coincidental.

A dark fact: people like people like themselves

Ours is a tribalistic species:

- Nationalism
- Sectarianism
- Racism
- Sexism
- Ageism
- Homerism
  (discrimination against cerebrally challenged individuals)

As educated people we try to avoid these tendencies,
but there is one which is ubiquitous . . .

Baryo-leptocentrism

Humans are baryo-leptocentric.

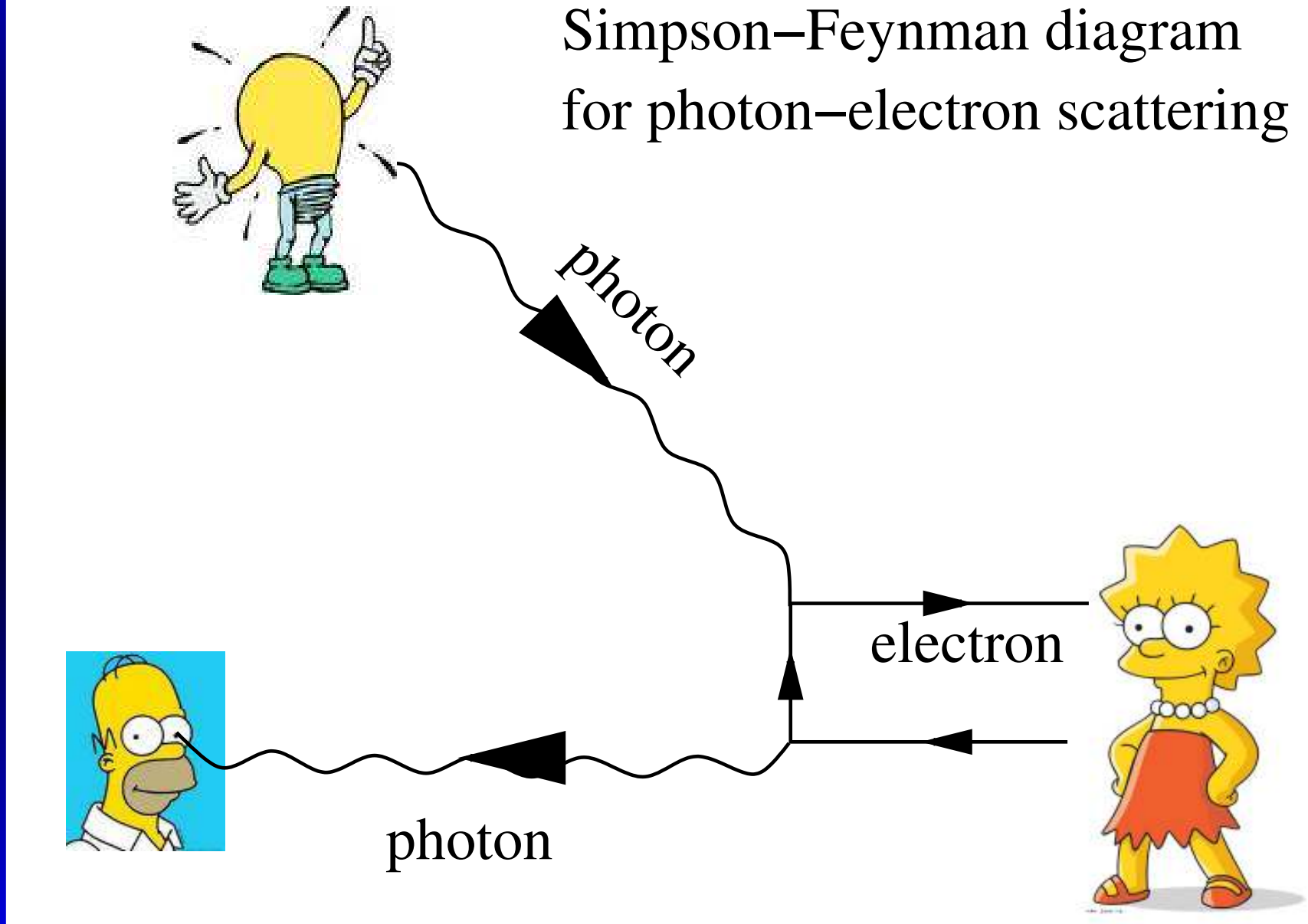
Baryons: neutrons + protons, the constituents of atomic nuclei

Leptons: electrons (+ neutrinos), the other constituents of atoms

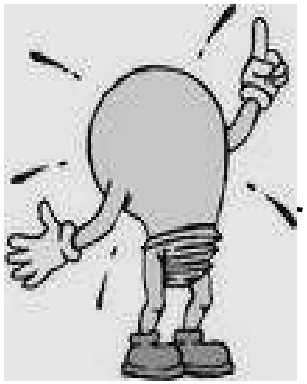
Humans are 99.98% baryonic (0.02% leptonic) by mass, 74% baryonic (26% leptonic) by number of particles. 100% baryo-leptonic.

Humans are baryo-leptocentric to the point that nonbaryo-leptonic people are *invisible* to them!

How we see baryonic people



Invisibility of nonbaryonic people



darkbulb

Everything is similar, but
Homer can't see the dark photon!

dark photon

dark
Lisa

dark
electron

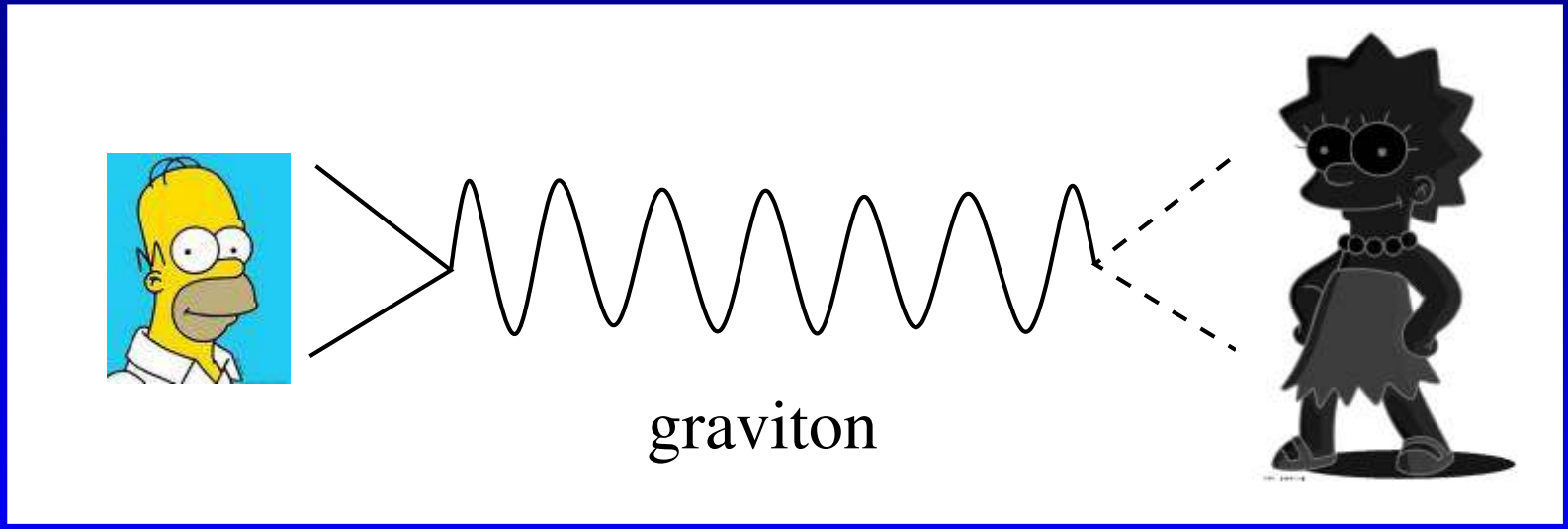
dark photon

Nonbaryonic people: the true untouchables

If Homer tried to touch Dark Lisa, his hand would pass right through her.

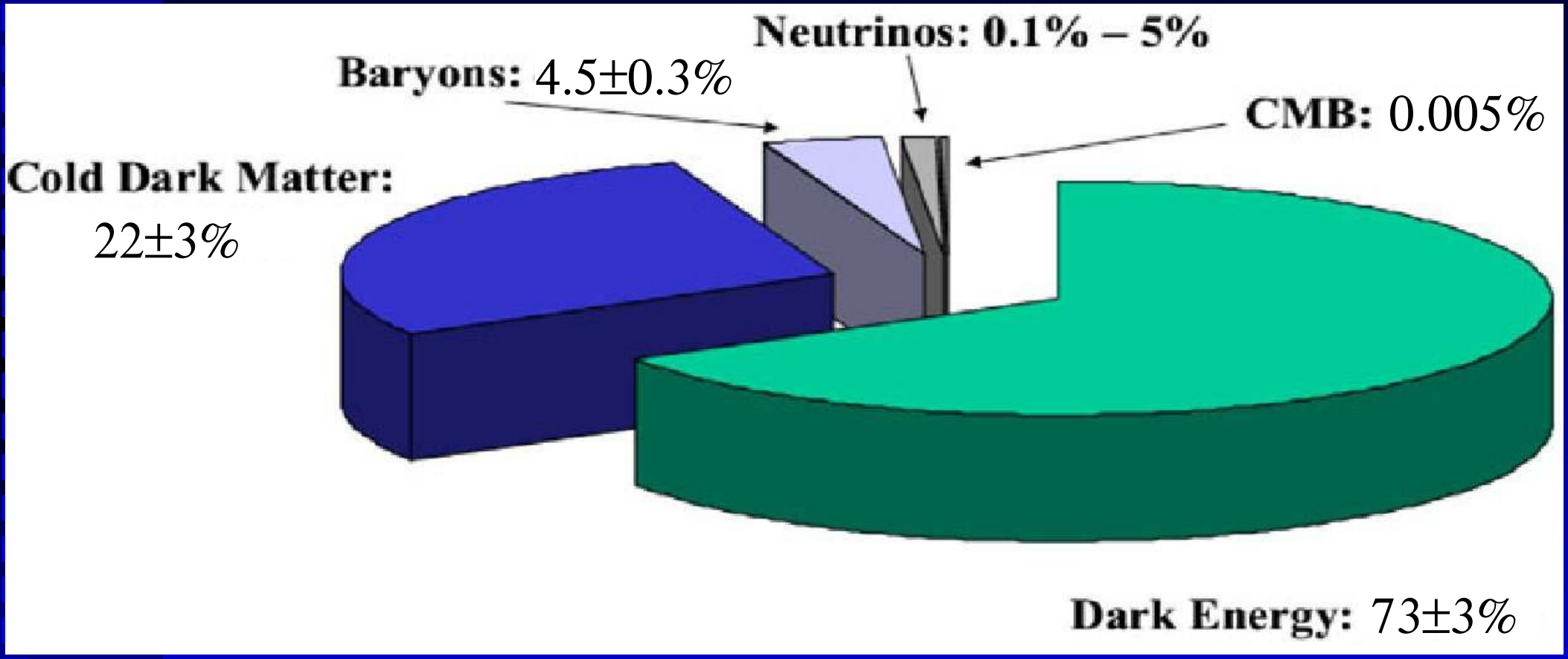
Electromagnetic interactions keep you from falling through your chair.

Homer would feel the gravitational attraction to Dark Lisa, but this is extremely weak! There is only one graviton, no "dark graviton."



The dark side dominates our universe

The mass-energy of the universe is mostly in the dark sector!



The dark person population should be ~ 6 times heavier than its baryonic counterpart (us).

Part I:

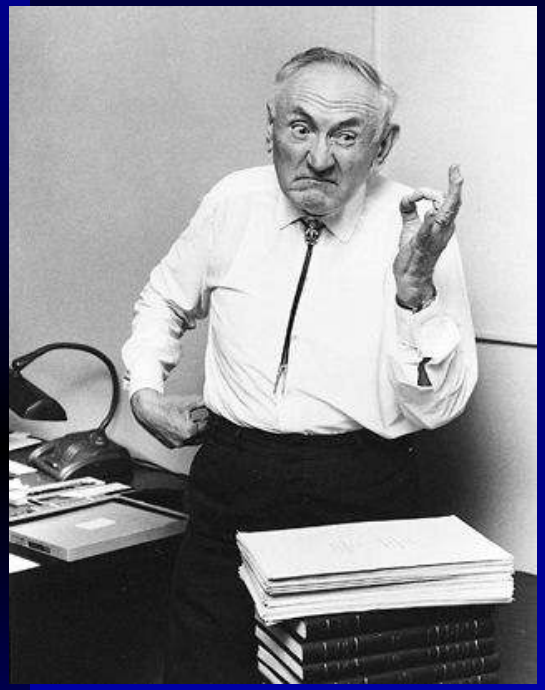
Dark Matter

How do we know it's there if it's dark?

Dark matter and luminous matter interact via gravity.
We see the effect of the dark matter on baryons.

Fritz Zwicky, father of dark matter

Gravitational pull is how he inferred existence of dark matter



Fritz Zwicky, 1898-1974
Astrophysicist
Caltech, Pasadena

Called astronomers “spherical bastards,” explaining “You’re a bastard every way I look at you."

1933, studied motions of galaxies around each other in Coma cluster. They were moving too fast!

Zwicky's 1933 paper

appeared in Helvetica Physica Acta, vol 6, 1933, p.110-127

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

"The redshifts of extragalactic nebulae"

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Dark matter

400 times more prevalent than visible matter

400 was an overestimate (error in distance to Coma cluster), but the conclusion was correct

Impact of Zwicky's 1933 paper

Did it cause a sudden revolution?

Table 1: Citations of Zwicky (1933)

from S. van den Bergh
astro–ph/0005314

Year	No. citations
1955-59	2
1960-64	6
1965-69	5
1970-74	2
1975-89	63[a]
1990-99	71

[a] There is a clustering of eight references that cite the wrong page number for Zwicky's article. Apparently seven of these authors copied the reference from Bahcall (1977), which contains a typographical error, without actually reading the original paper.

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Maybe this is why Zwicky thought his colleagues were bastards.

I sympathize with him deeply.

Too much mass in galaxies

Most astronomers became convinced of dark matter around 1973-74, by measurements of speeds of stars orbiting in galaxies.

Stars move too fast for only the visible matter to be pulling on them.

So, the first evidence of this kind must have come in the mid-1970's, right?

Babcock's 1939 measurement

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ASTRONOMY

LICK OBSERVATORY BULLETIN

NUMBER 498

THE ROTATION OF THE ANDROMEDA NEBULA*

BY

HORACE W. BABCOCK

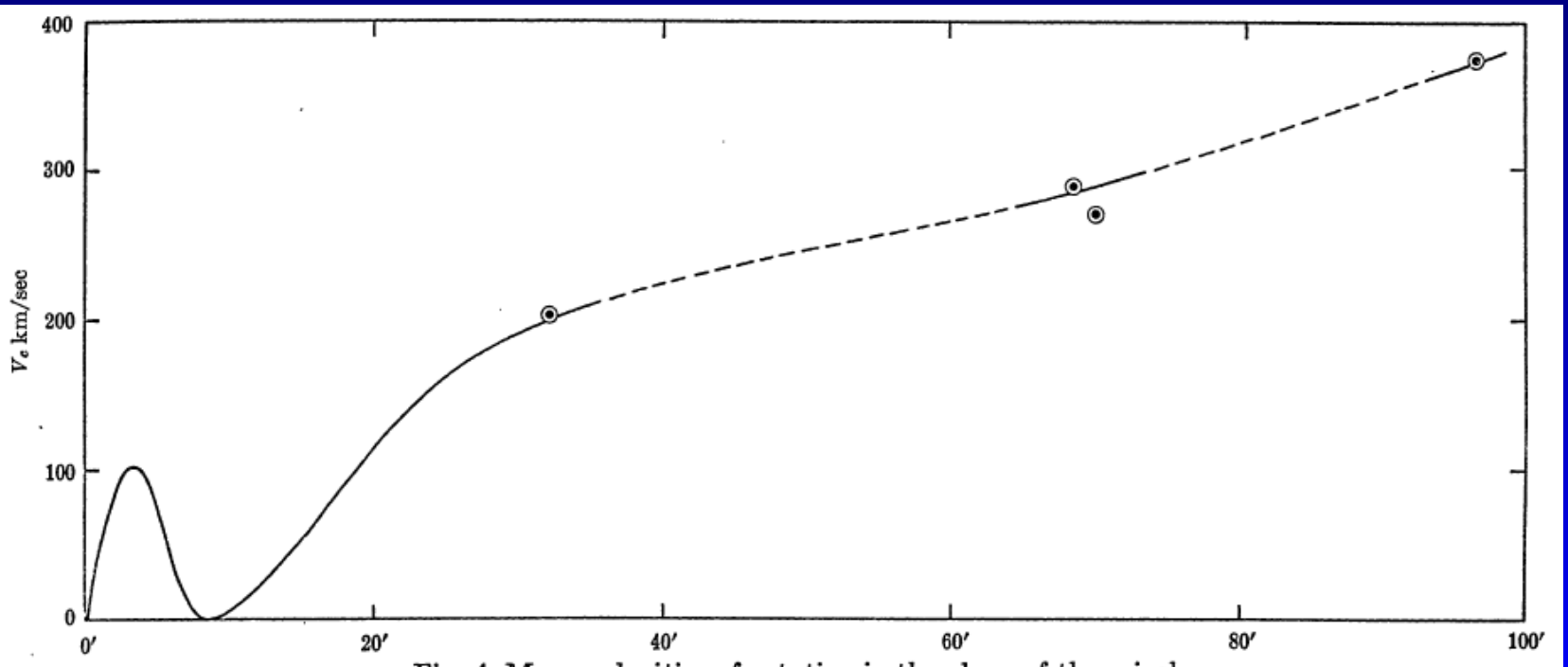

Fig. 4. Mean velocities of rotation in the plane of the spiral.

Rotation speed stays too high

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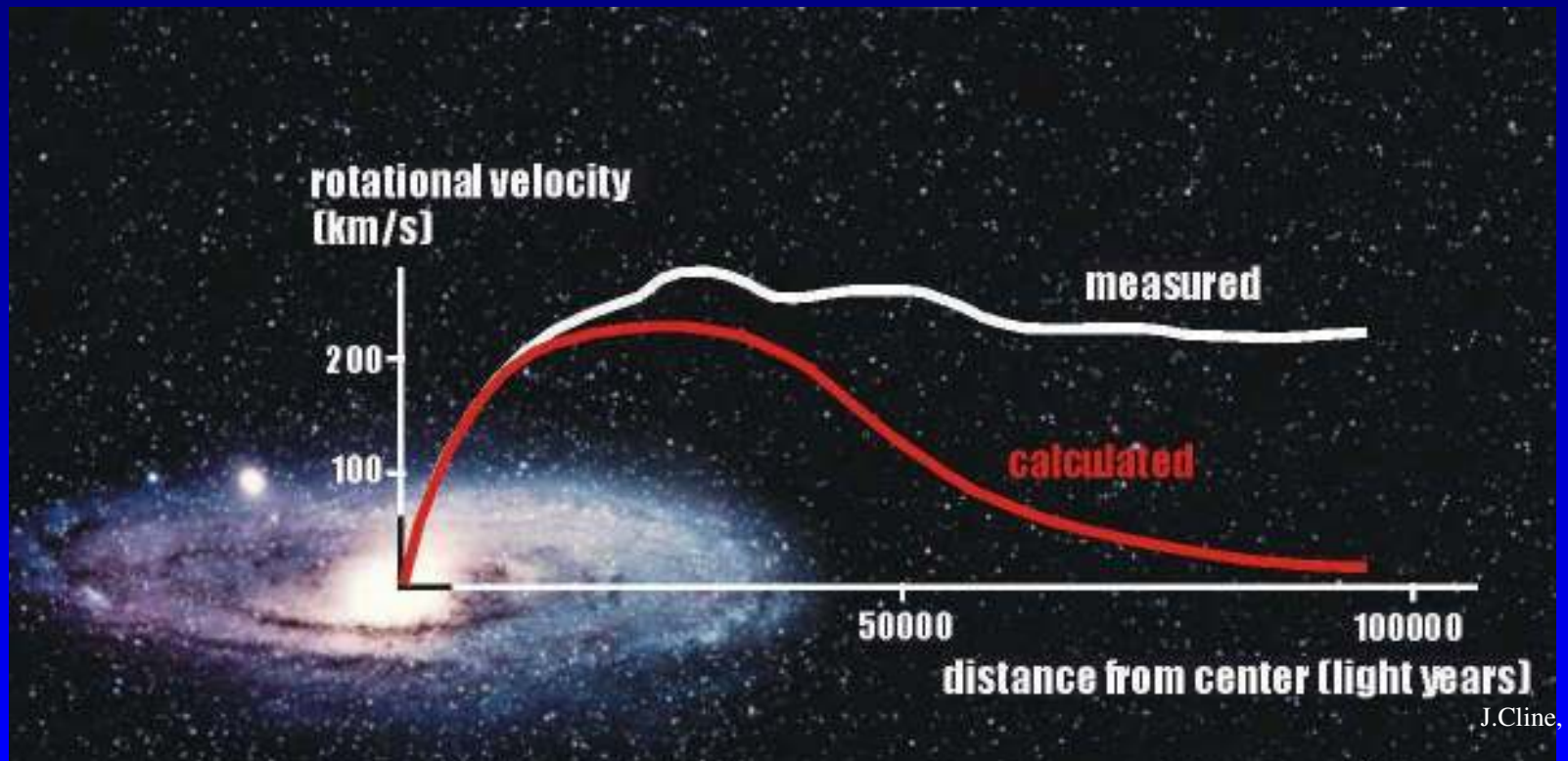


Babcock's inferences

model used in the preceding section, is 1.04×10^{11} cubic parsecs, and the calculated mass is 1.02×10^{11} ⊙. It follows that the mean luminosity density, in absolute visual magnitudes, is 8.85 per cubic parsec, and that the average mass per cubic parsec is 0.98⊙. The total luminosity of M31 is found to be 2.1×10^{9} times the luminosity of the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun. The difference can be attributed mainly to the very great mass calculated in the preceding section for the outer parts of the spiral on the basis of the unexpectedly large circular velocities of these parts.

He computes mass of Andromeda

Then mass-to-light ratio

Notes that it is surprisingly large due to surprisingly high velocities at large radii

Now there are similar measurements for hundreds of galaxies indicating the same flat curves at large radii

What took them so long?

Astronomers are skeptical. They are paid to discover things they can see, not things they can't see.

According to van den Bergh, they were influenced by M. Schwarzschild's 1954 paper:

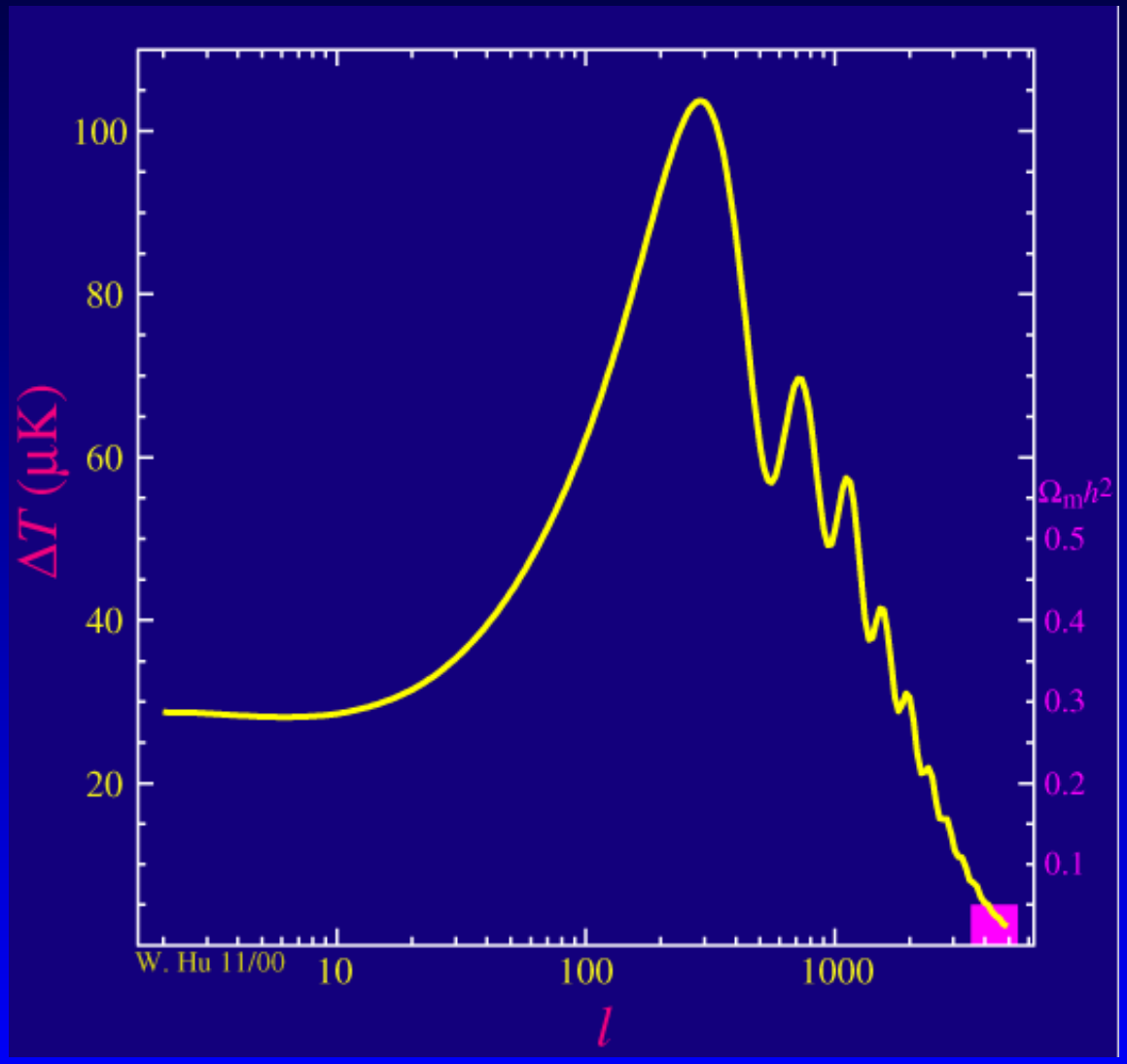
> In retrospect it appears that the acceptance of a dark matter component to the universe was delayed by a decade or so as a result of the enormously influential paper of Schwarzschild (1954). Taking direct aim at Oort (1940), he concluded that "The observations now available permit the assumption that in any one galaxy the mass distribution and the luminosity distribution are identical. On the other hand the present observations are not accurate enough to prove this assumption." What led Schwarzschild to

> to 30′ (7 kpc), Schwarzschild concluded that "the present velocity observations in M 33 do not disagree with the assumption of identical mass and light distribution." Finally Schwarzschild stated that "This bewilderingly high value for the mass-luminosity ratio [in Coma] must be considered as very uncertain since the mass and particularly the luminosity of the Coma cluster are still poorly determined." In this connection it is of interest to recall

(M. Schwarzschild was the son of K. Schwarzschild, who discovered the black hole solution of Einstein's general relativity.)

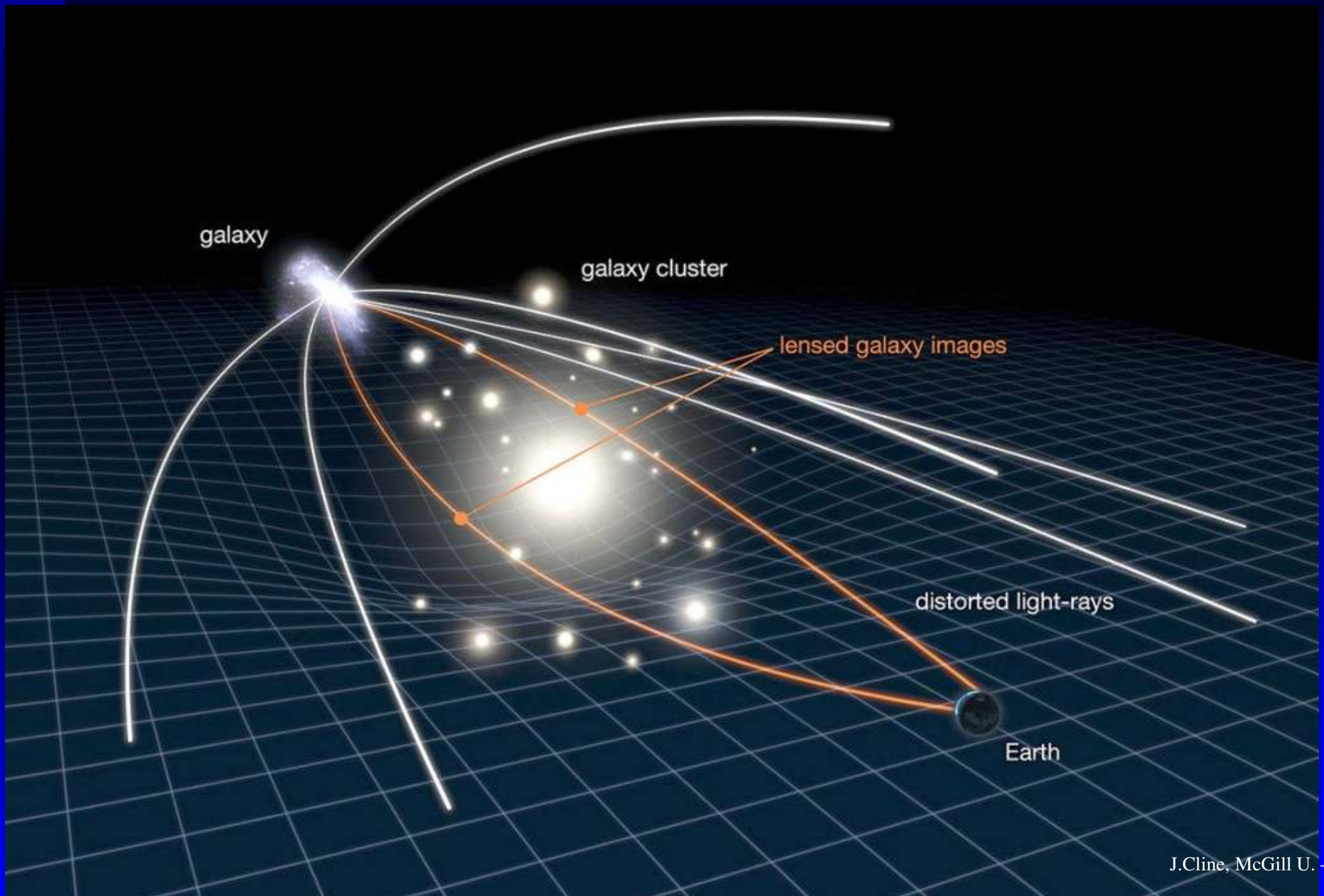
Other evidence: the CMB

Fluctuations of the Cosmic Microwave Background are very sensitive to the amount of dark matter in the early universe. Measurements prove DM must be 22% of mass density of universe!



Other evidence: gravitational lensing

Gravity of dark matter bends the light of objects from behind it

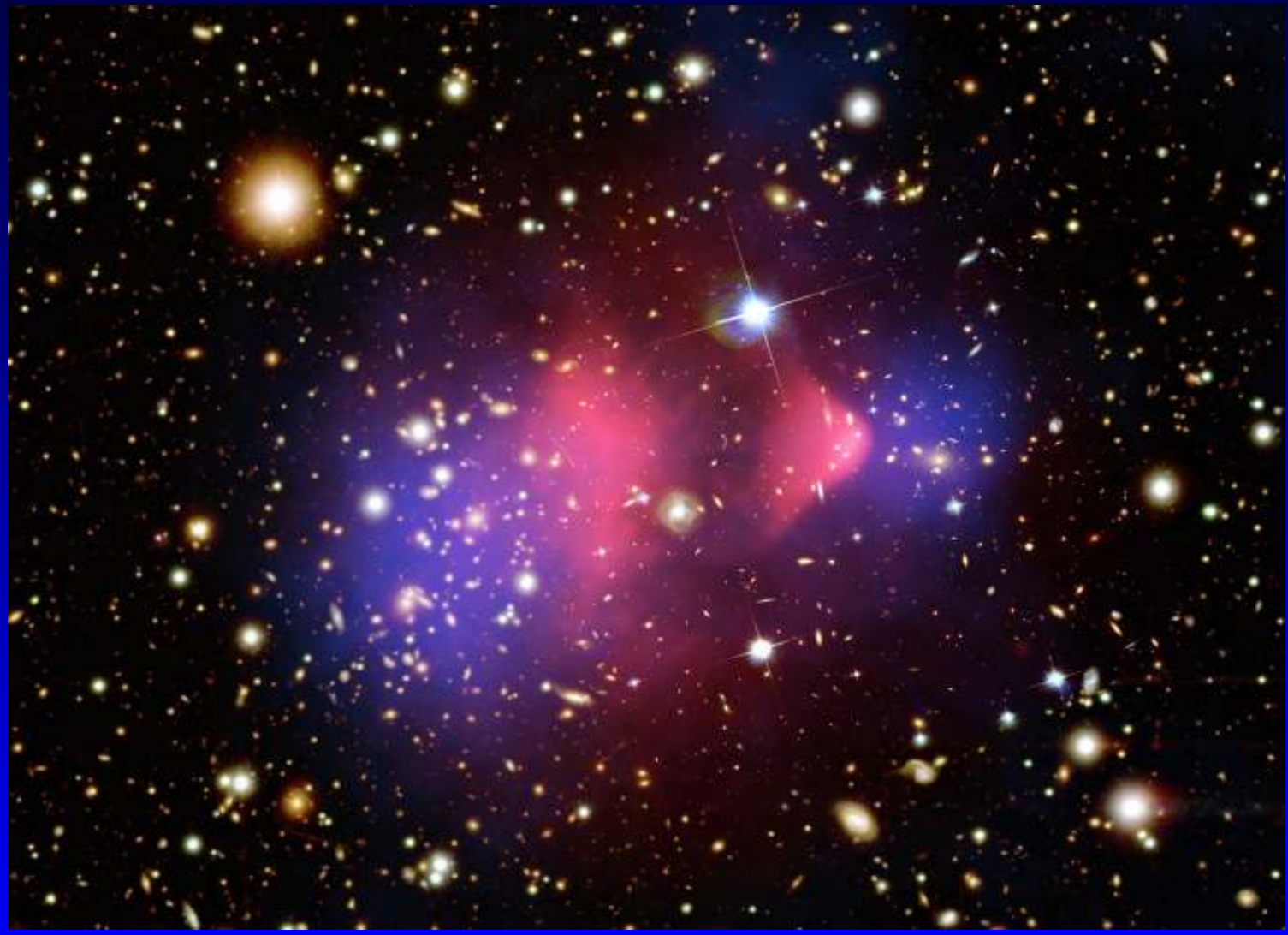


Other evidence: gravitational lensing

Lensed galaxy looks like this (Hubble Space Telescope):

Other evidence: gravitational lensing

Lensed image allows estimate of mass in the middle.
Bullet Cluster is a famous example:



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Dark Matter Exists

Zwicky suggested use of gravitational lensing to "see" dark matter in a 1937 paper continuing his earlier work!

IV. NEBULAE AS GRAVITATIONAL LENSES

As I have shown previously,[6] the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect the light coming to us from certain background nebulae. The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses. No

Yet there are still dark-matter deniers in the astronomical community

What would Zwicky have to say about them?

Role-playing exercise

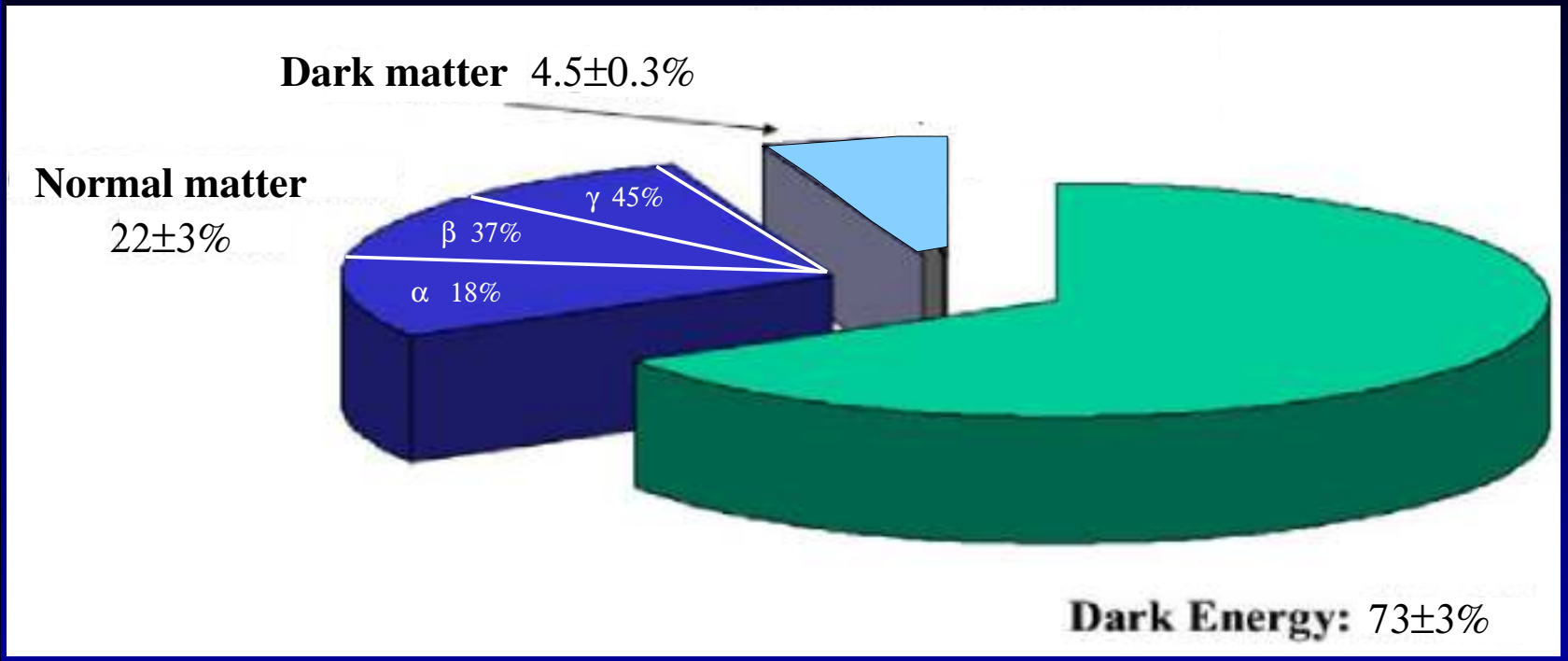
Let's pretend we are dark matter people come to hear a talk about baryo-leptonic matter.

When I say "normal matter" I will mean dark matter (us in the dark matter world)

When I say "dark matter" I will mean baryo-leptonic matter (us in the normal matter world)

Confused?

Energy budget of universe

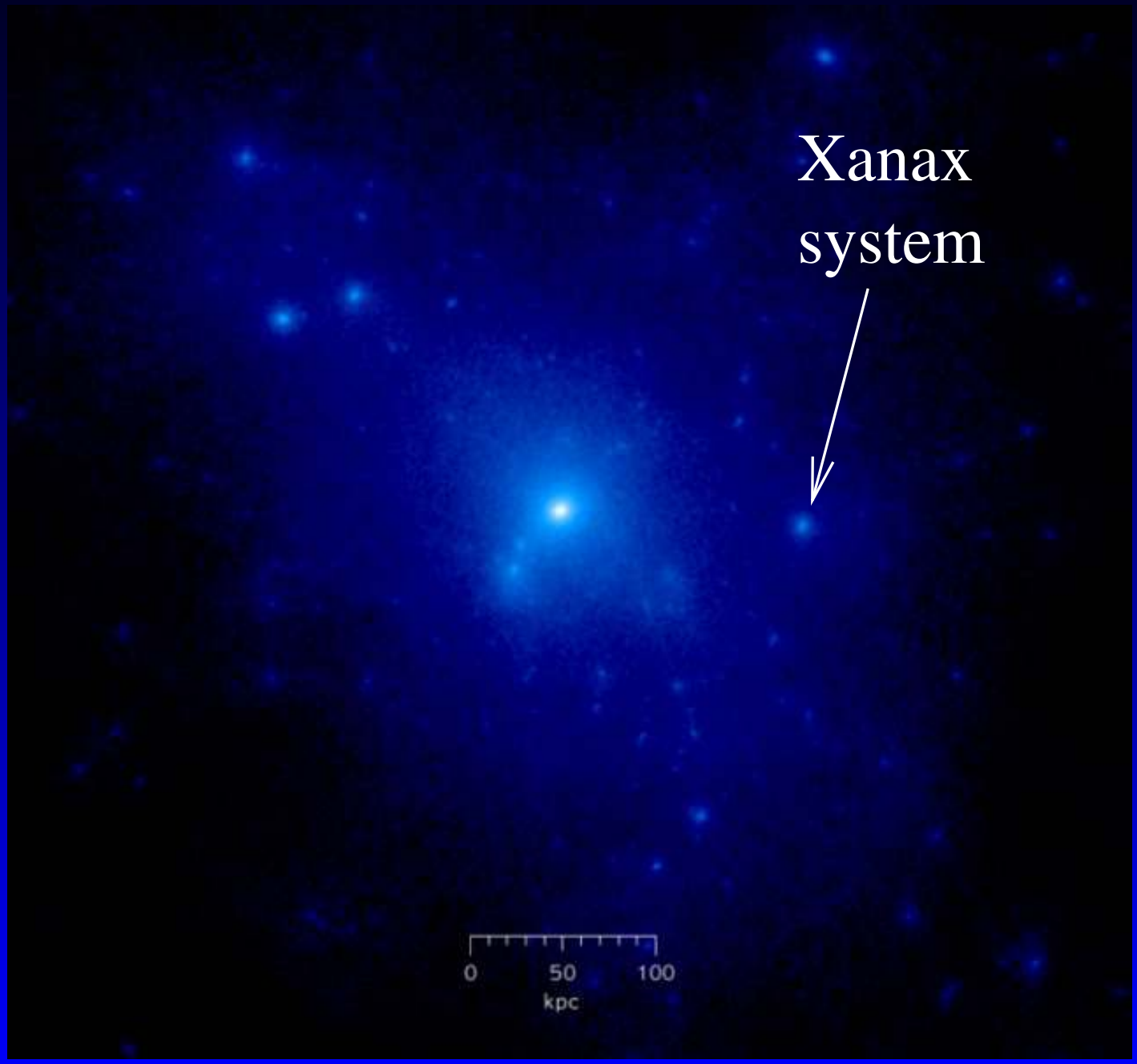


For many years astronomers doubted existence of 4.5% dark matter

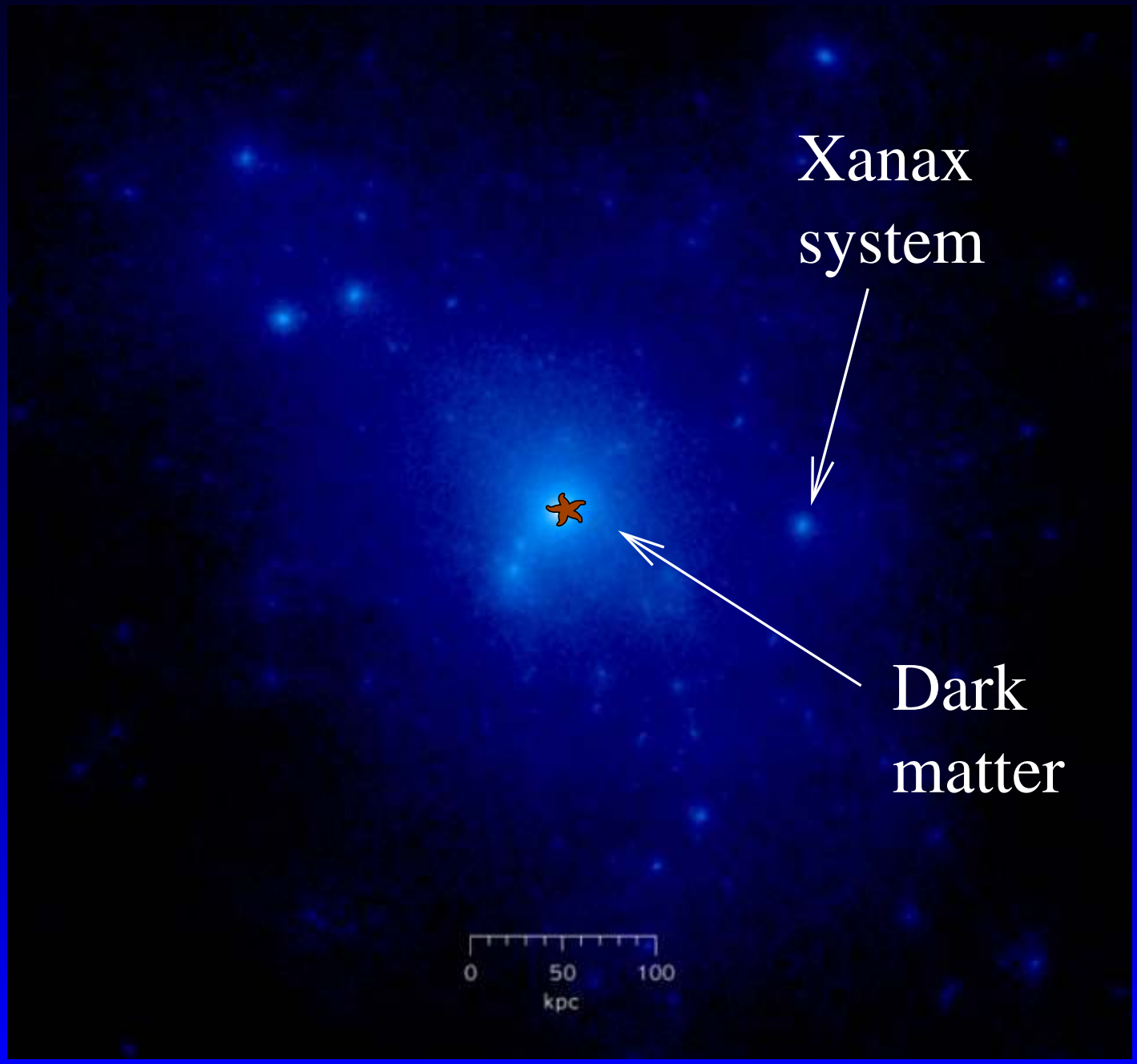
Now precision measurements of cosmic normal photon background and rotational curves of galaxies prove it

(To all except the small but indefatigable minority of unbelievers)

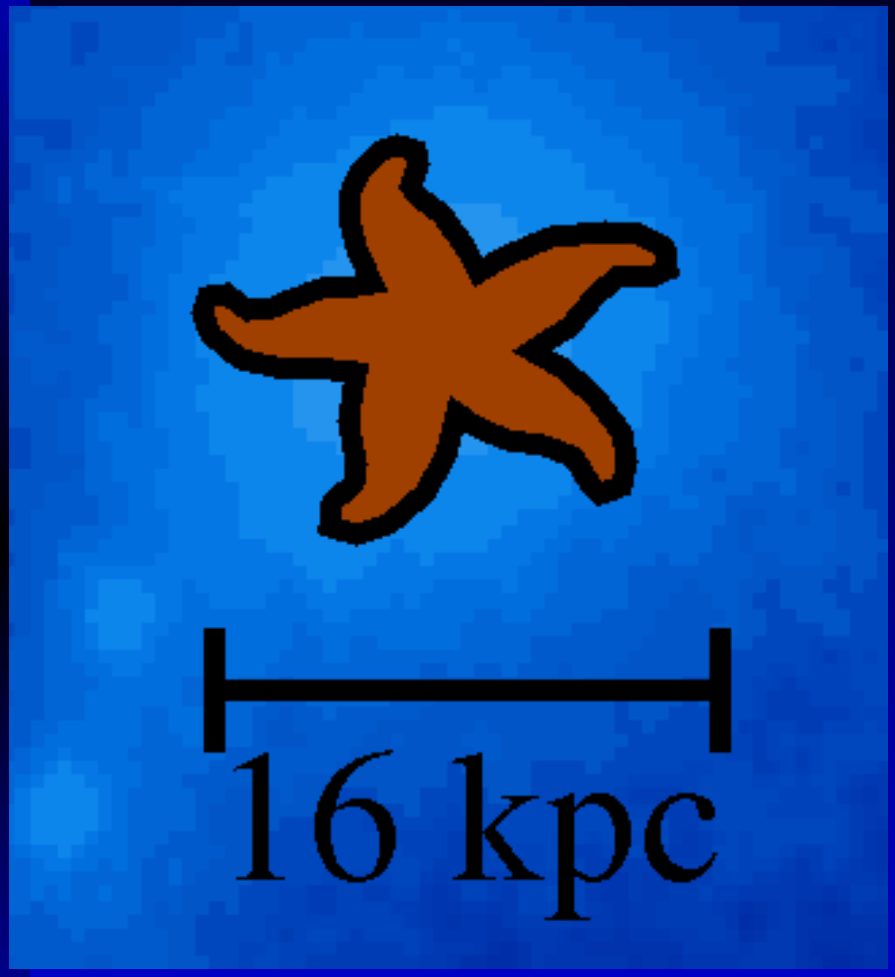
The matter in our galaxy



The matter in our galaxy



The dark matter in our galaxy



Dark matter occupies tiny region in center of galaxy.

It likes to clump together much more than does normal matter.

Its properties are well-described by the "sticky-goo" model

Sticky goo initially distributed like normal matter.

Inelastically self-interacts, sticks together, falls to center of galaxy.

Angular momentum leads to spiral arm structure.

Discussion

Discussion

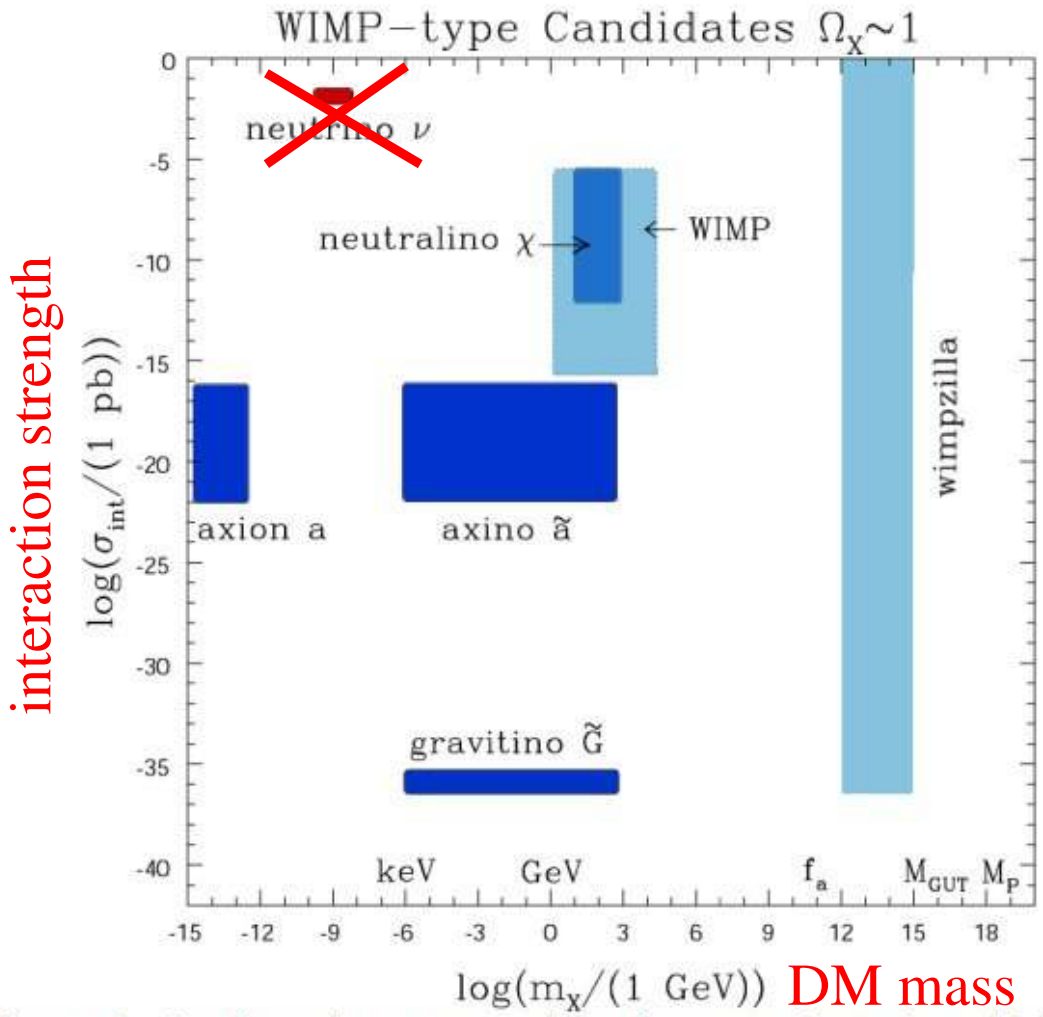
Which of your preconceptions about dark matter people were challenged?

Discussion

Which of your preconceptions about dark matter people were challenged?

What can we learn from their perceptions about us?

What else do we believe about DM?

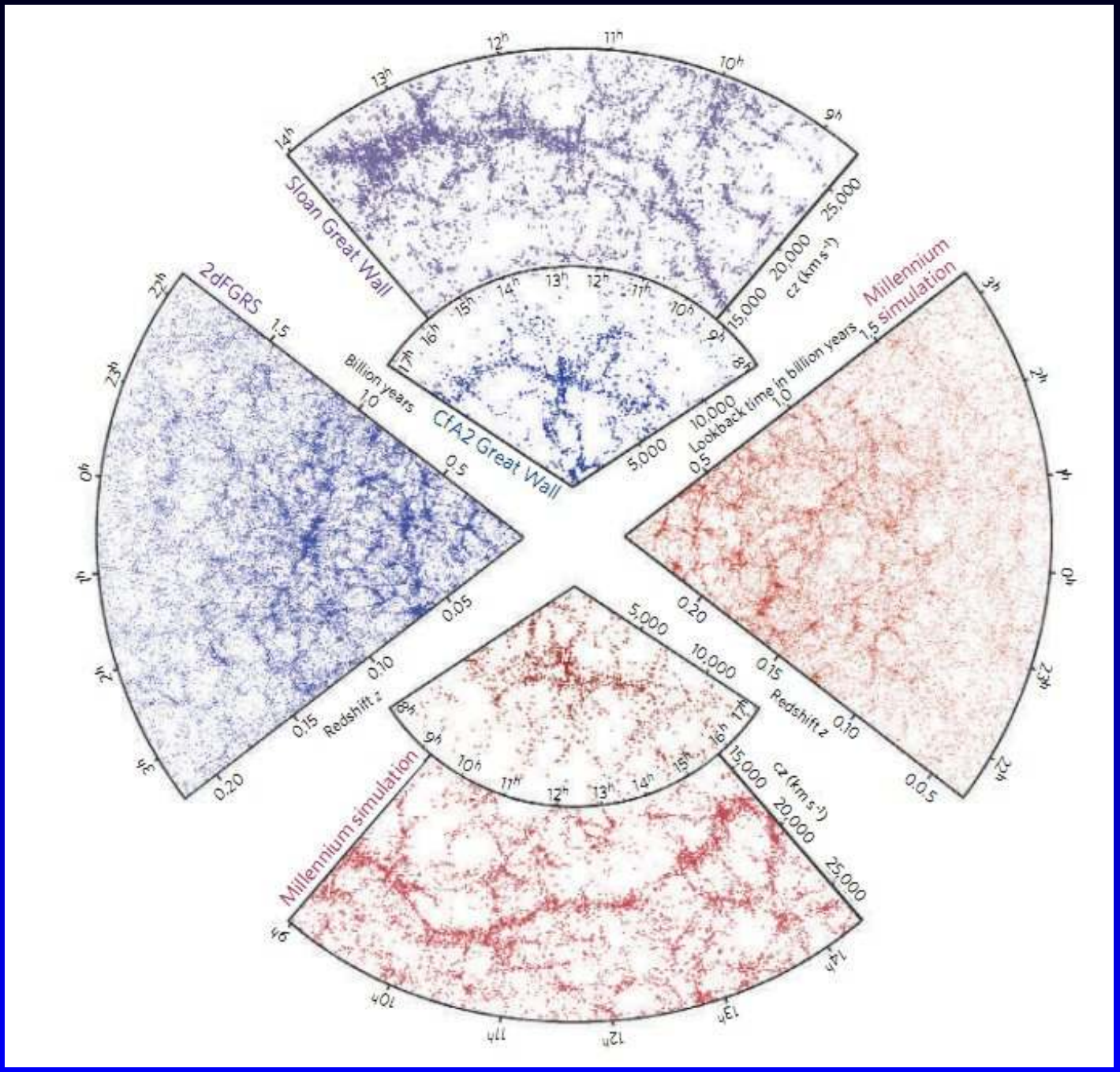


L. Roszkowski
hep−ph/0404052

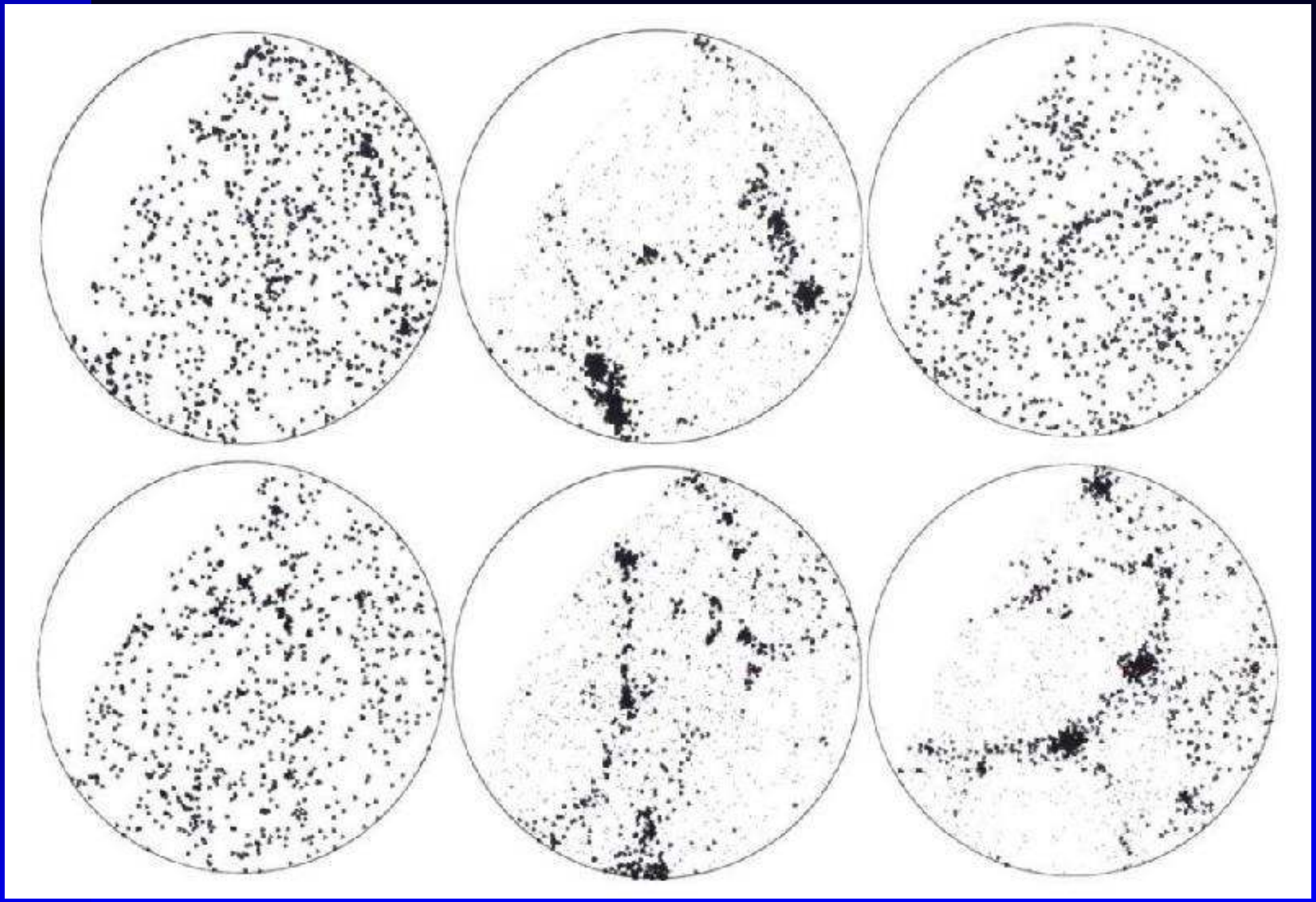
(WIMP = weakly interacting massive particle)

Figure 1. A schematic representation of some well–motivated WIMP–type particles for which a priori one can have $\omega \sim 1$. $\sigma_{\rm int}$ represents a typical order of magnitude of interaction strength with ordinary matter. The neutrino provides hot DM which is disfavored. The box marked "WIMP' stands for several possible candidates, *e.g.*, from Kaluza–Klein scenarios.

Cold DM agrees with observations



Hot DM doesn't



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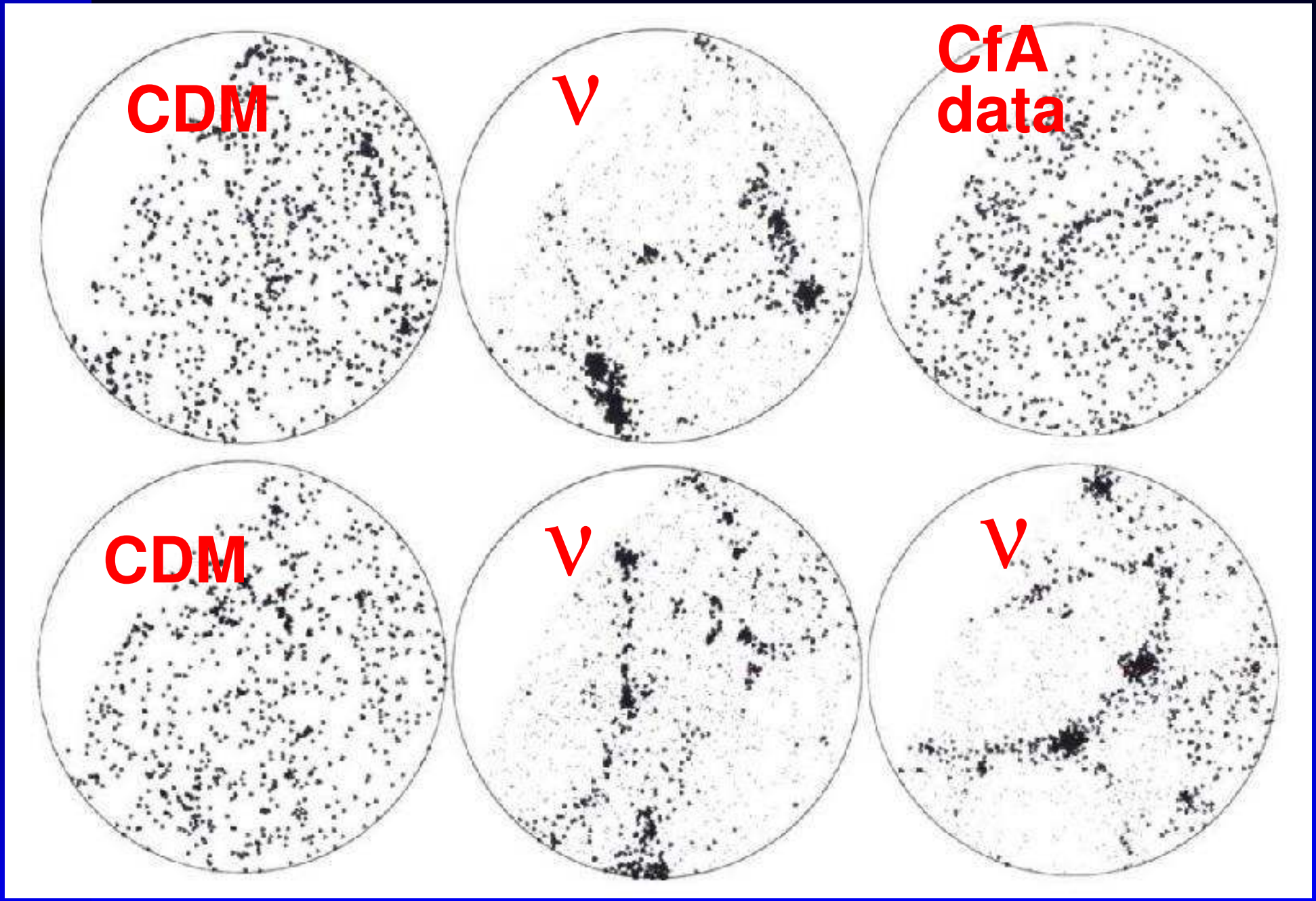
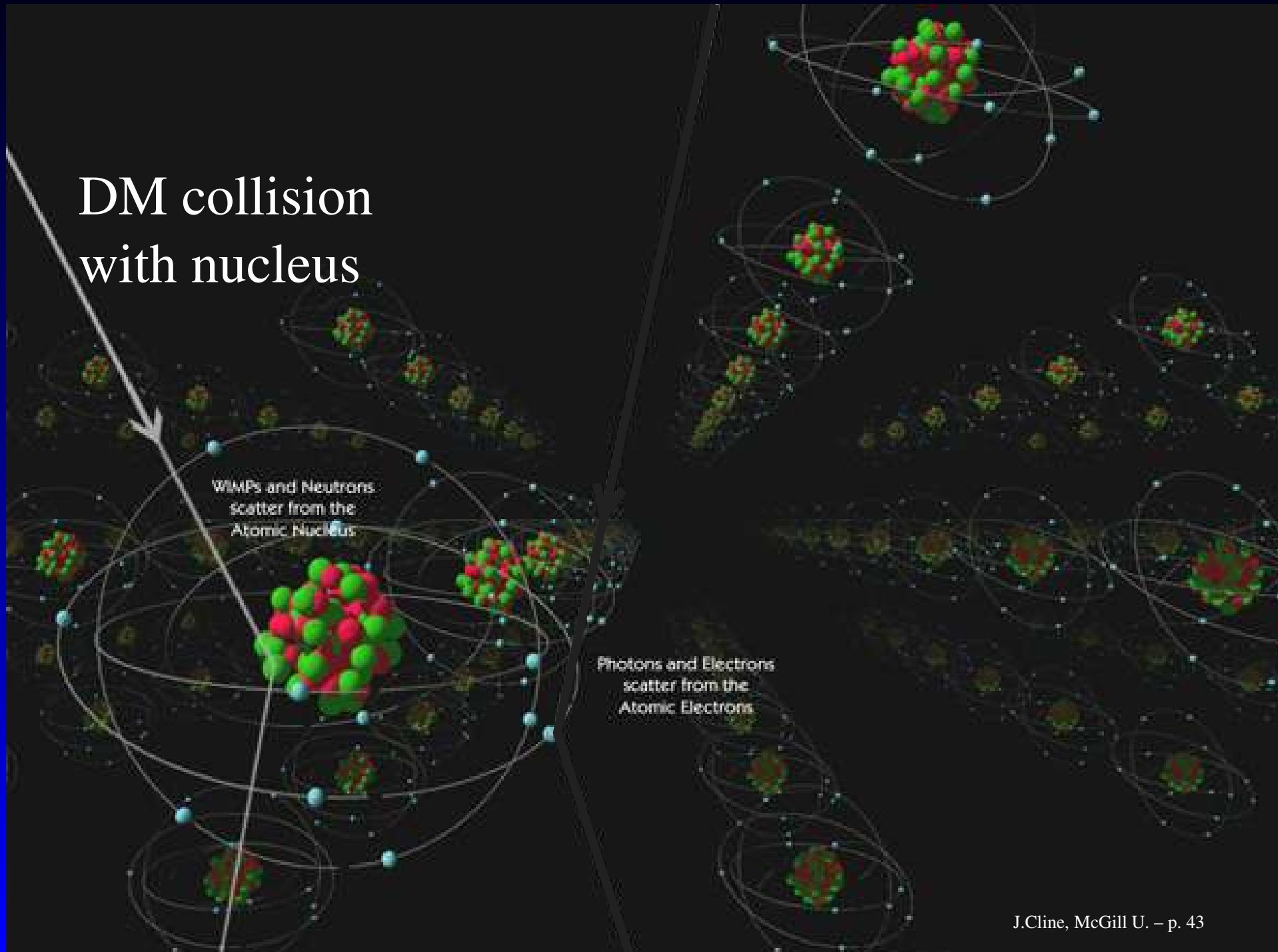


Frenk & White, arXiv:1210.0544

Can we directly detect DM?

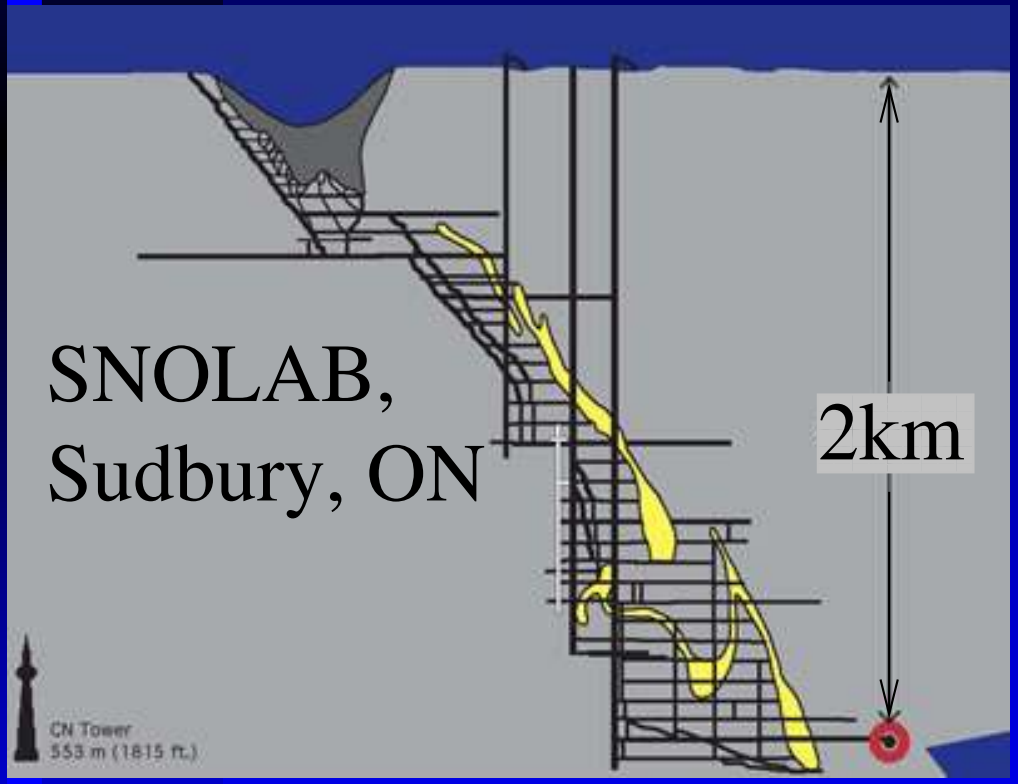


Can we directly detect DM?

DM interacts with normal matter very weakly, if at all

Like trying to stop a bullet with spider webs—

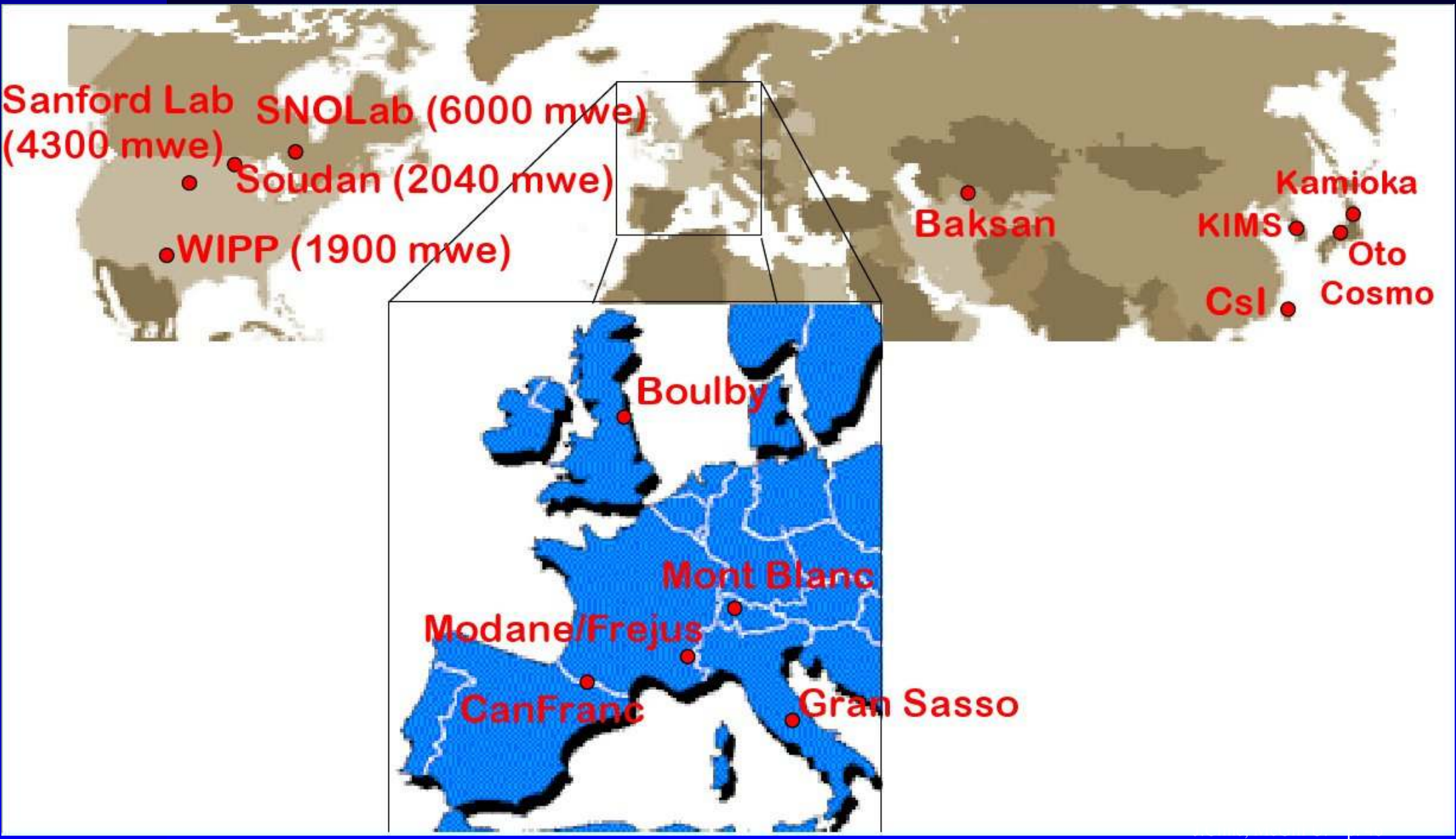
Need big and well-shielded targets



A world-wide effort

Underground laboratories

Several in mines or highway tunnels



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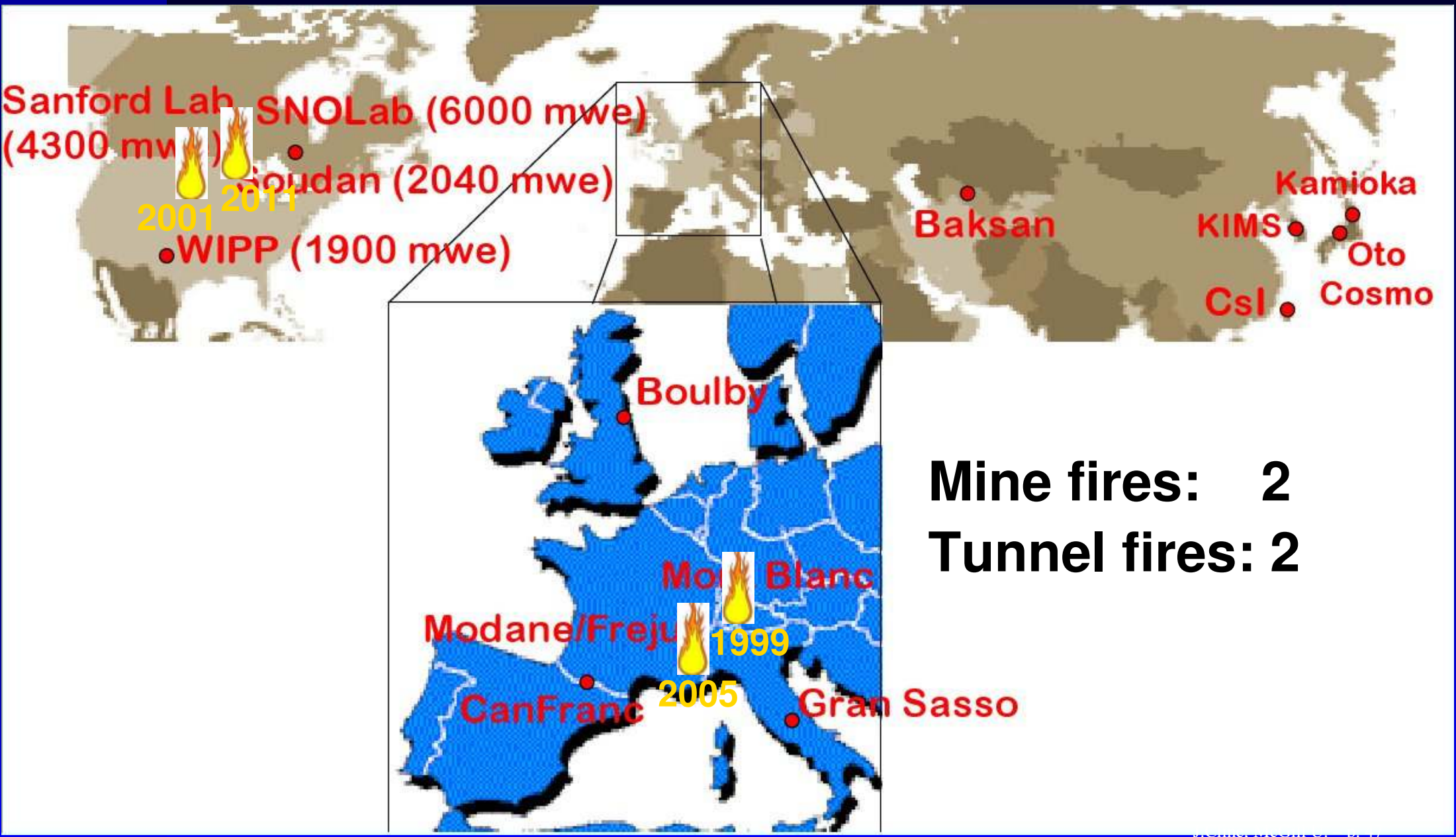


Mine fires: 2

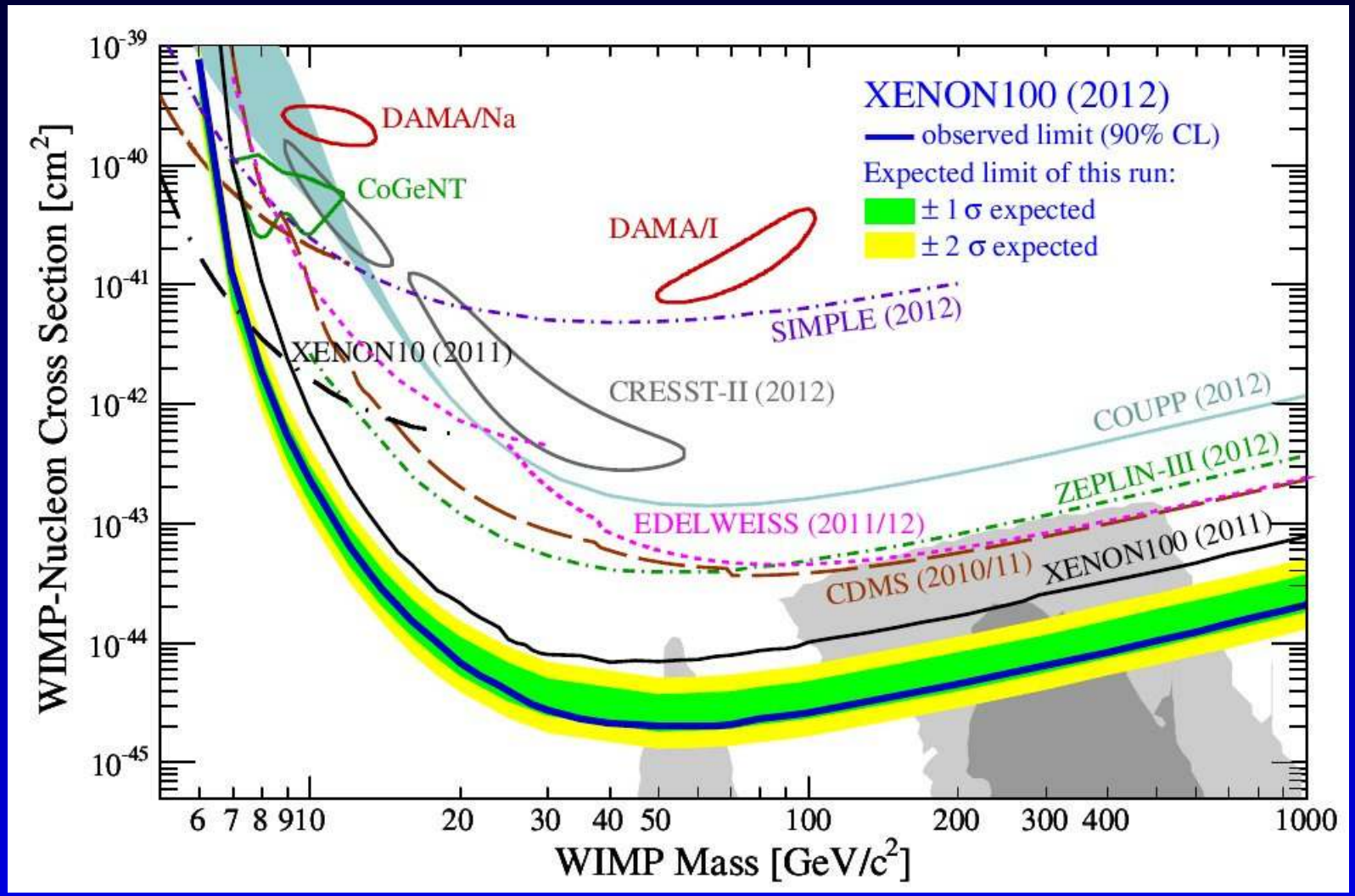
Tunnel fires: 2

Going deep to shield from cosmic rays

The Cube Hall of SNOLAB houses the DEAP/CLEAN experiments

How strong are DM interactions?

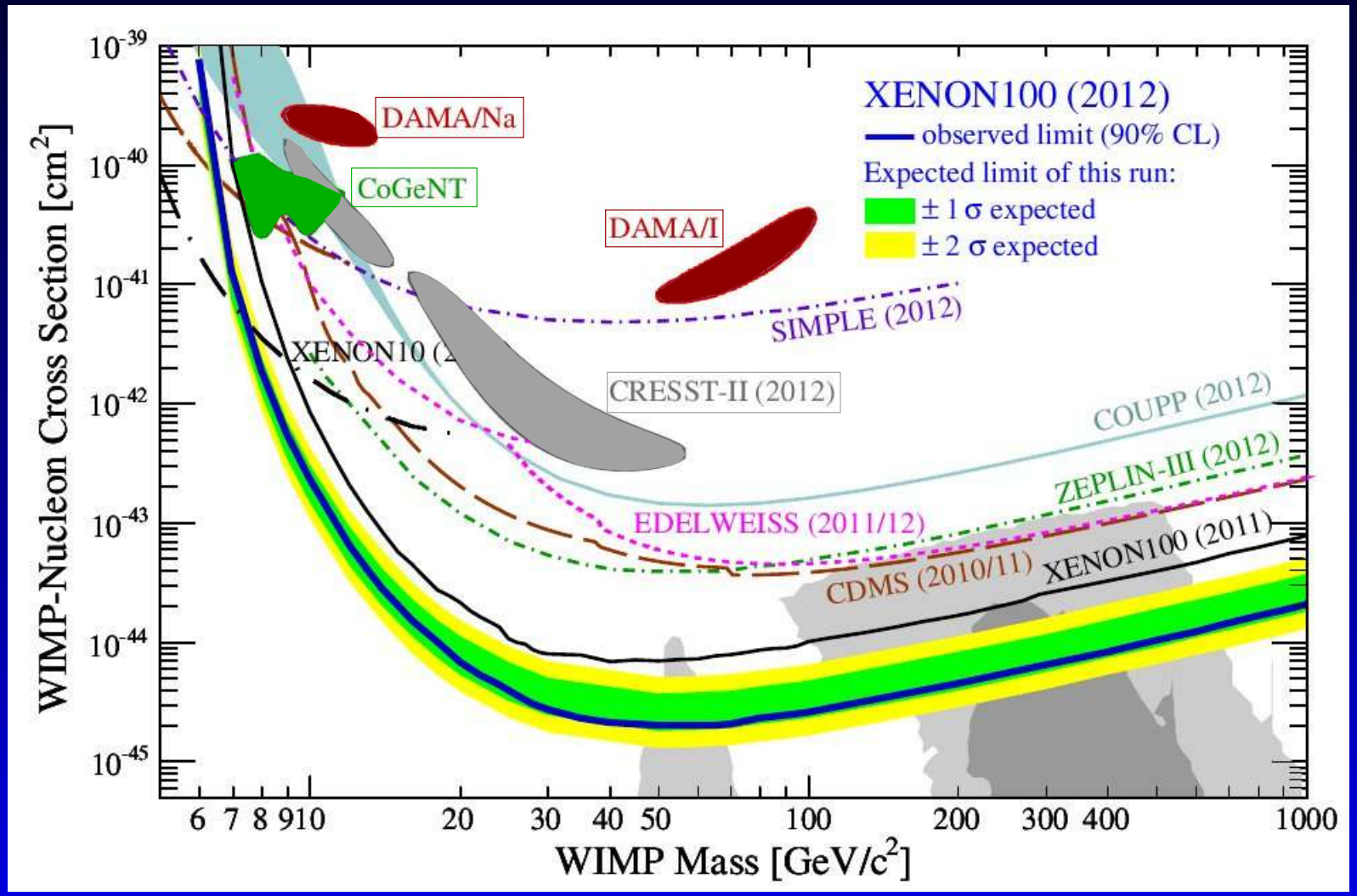
Physicists define effective area (cross section, σ) for likelihood of interaction. Upper limit from XENON100 experiment:



Compare to the size of a proton: 10^{-26} cm^2!

Do some experiments see DM?

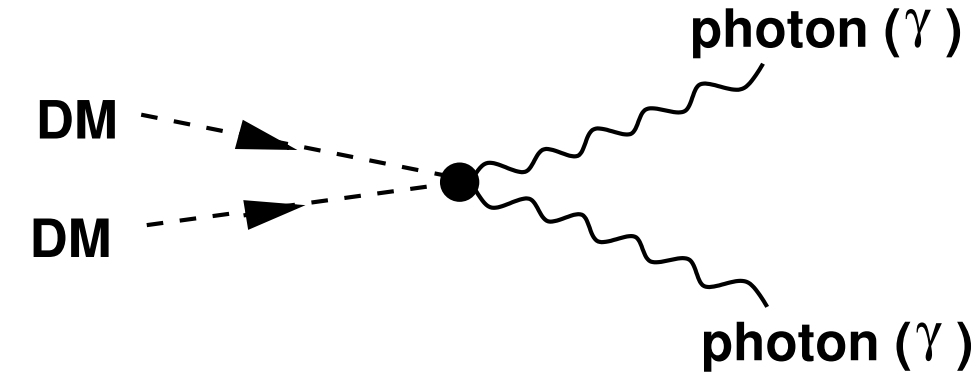
DAMA, CoGeNT, and CRESST think they may be seeing DM interactions:

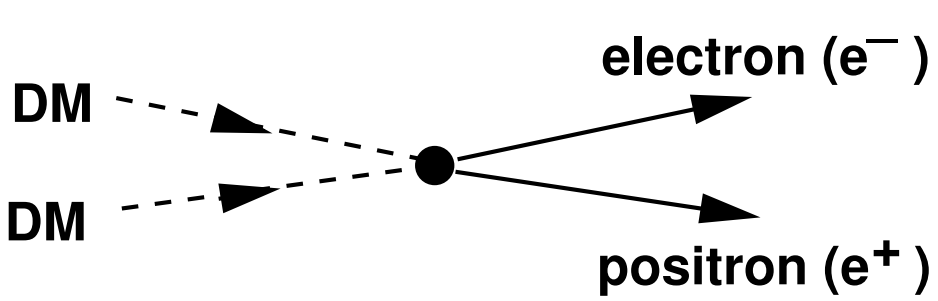


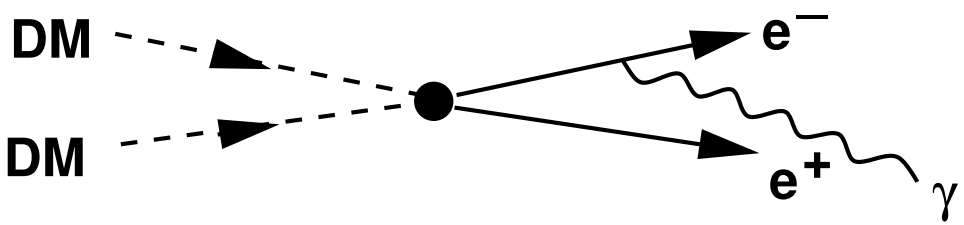
How to reconcile with XENON100's null result?
Theorists are having fun.

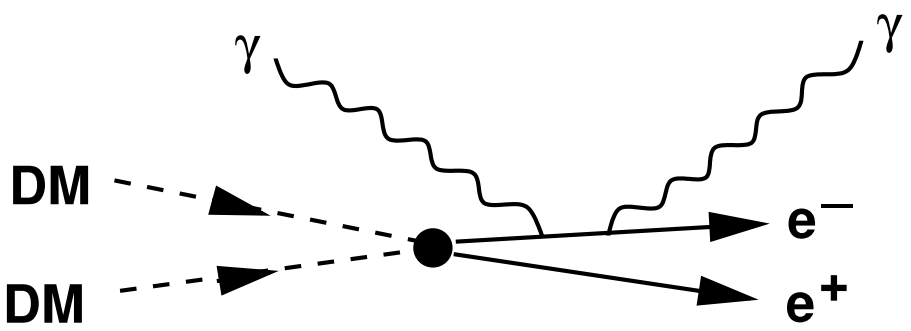
Indirect detection of DM

DM annihilation in galaxy or early universe could create cosmic rays (e^+, e^- or photons)



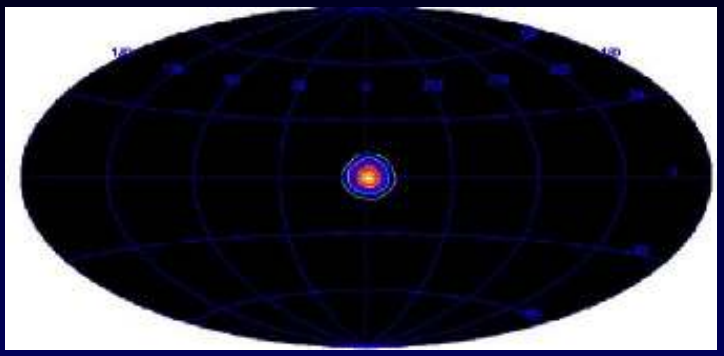




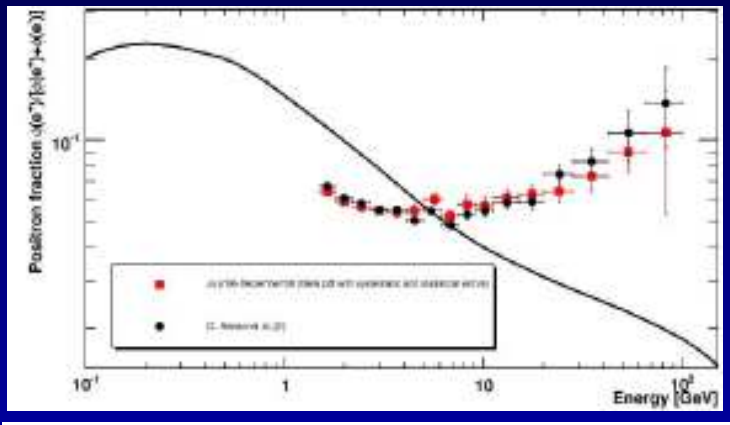


Some cosmic ray anomalies . . .

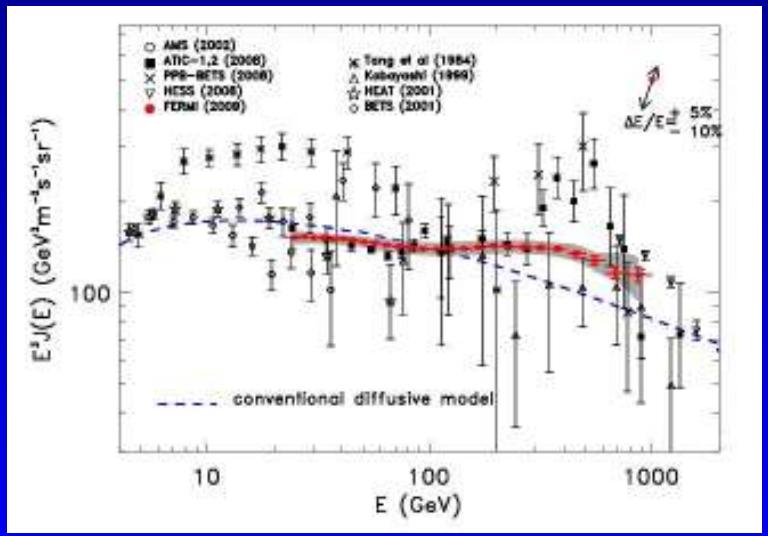
- Excess 511 keV γ's from galactic center, observed by INTEGRAL/SPI



- PAMELA positron excess at 10−100 GeV

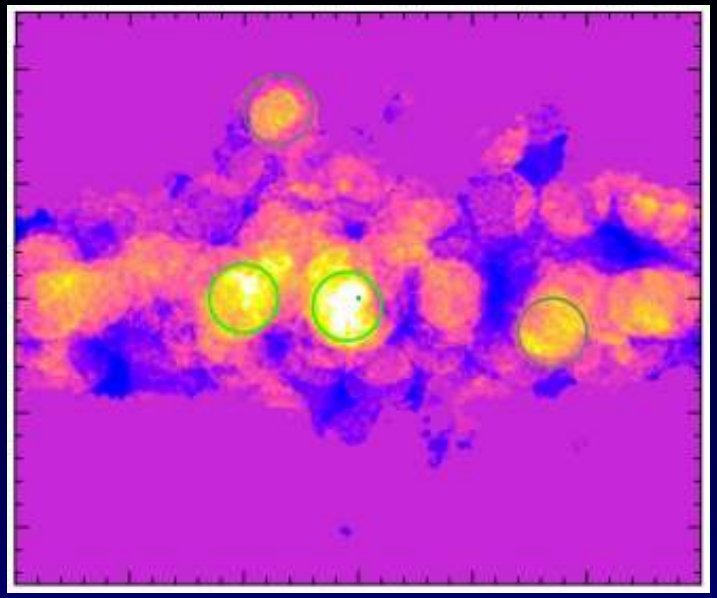


- Fermi/LAT (Large Area Telescope) $e^{\pm}$ excess at 100−1000 GeV

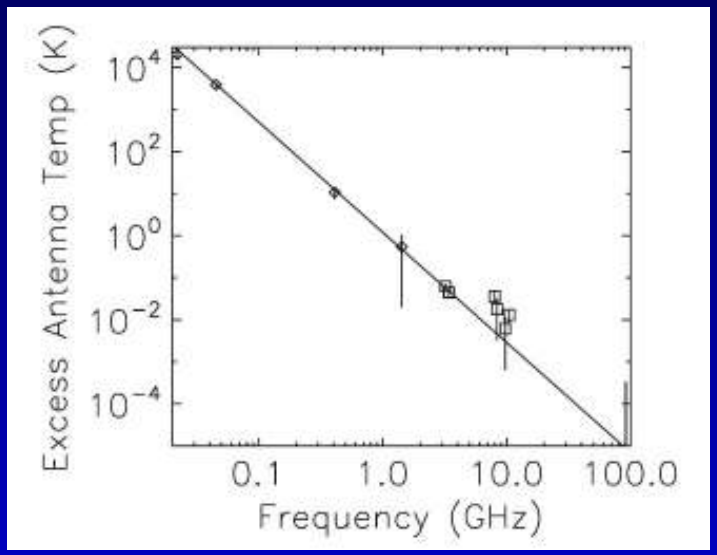


. . . and some more

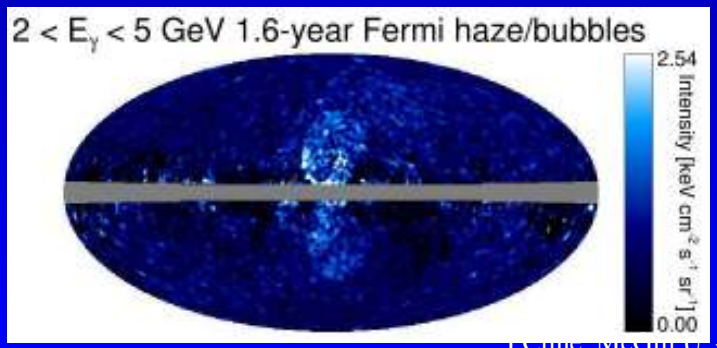
- 130 GeV γ-rays from galactic center, observed by Fermi/LAT



- Excess cosmological radio background photons, observed by ARCADE and other experiments



- WMAP and Fermi/LAT "haze"



DM explanations of anomalies

Particle physicists proposed models of DM annihilation to explain all of these

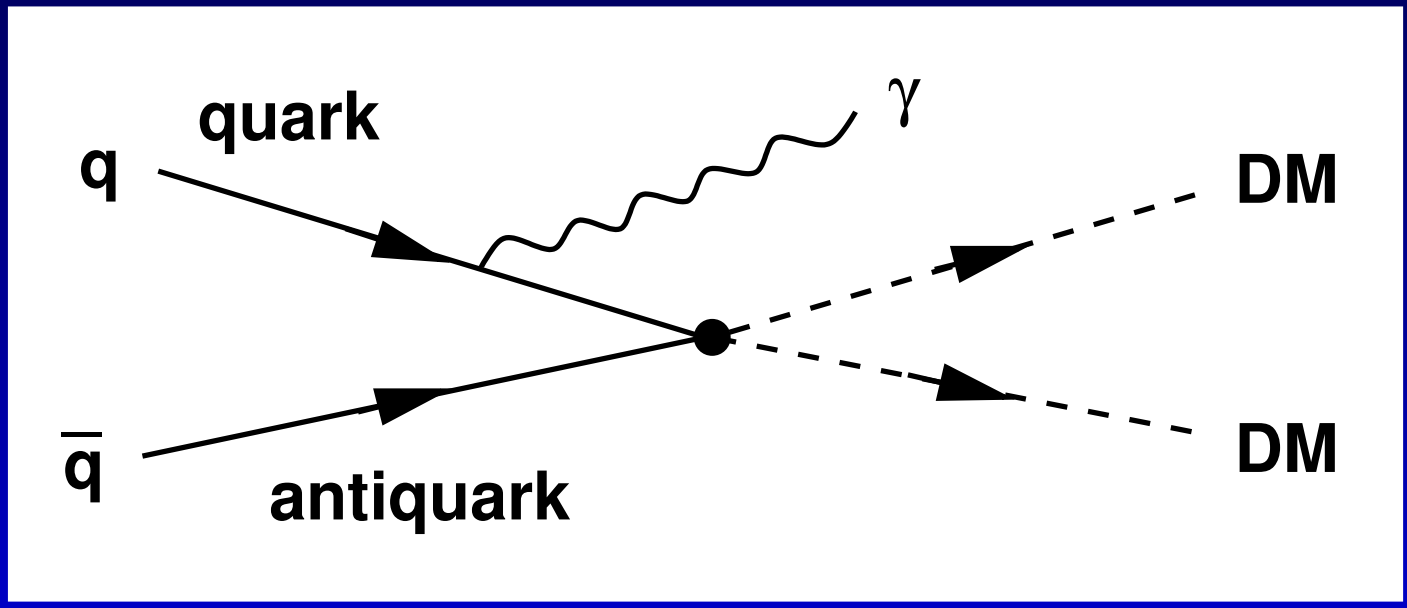
Alternative explanations exist for some

Need complementary evidence to be convinced it's DM

Creation of DM on earth

Dark matter would look like *missing energy* in a high-energy collision

Particle experimentalists are used to looking for that

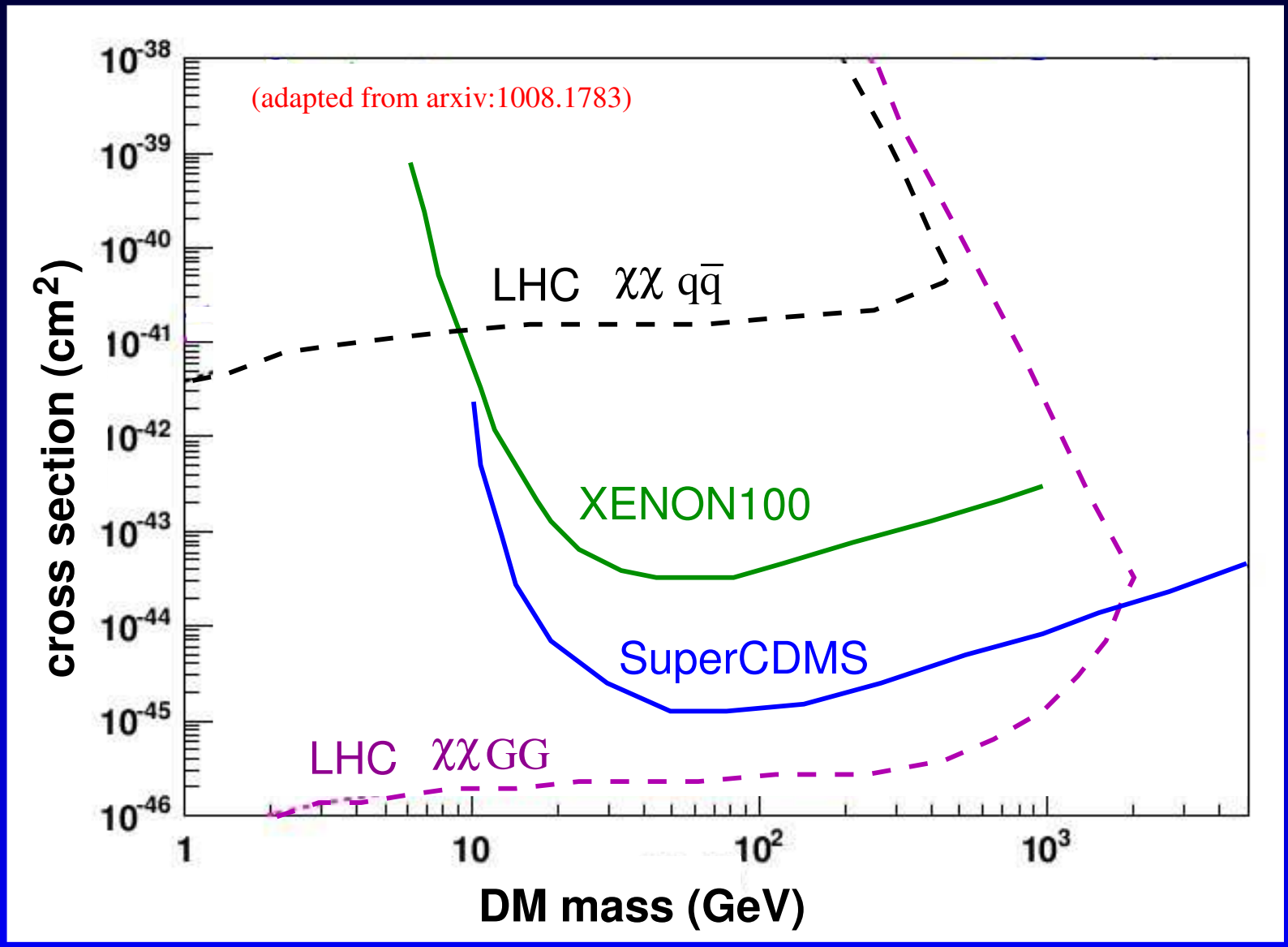


Momentum of photon must be balanced by *something*

Would be evidence for DM in the lab

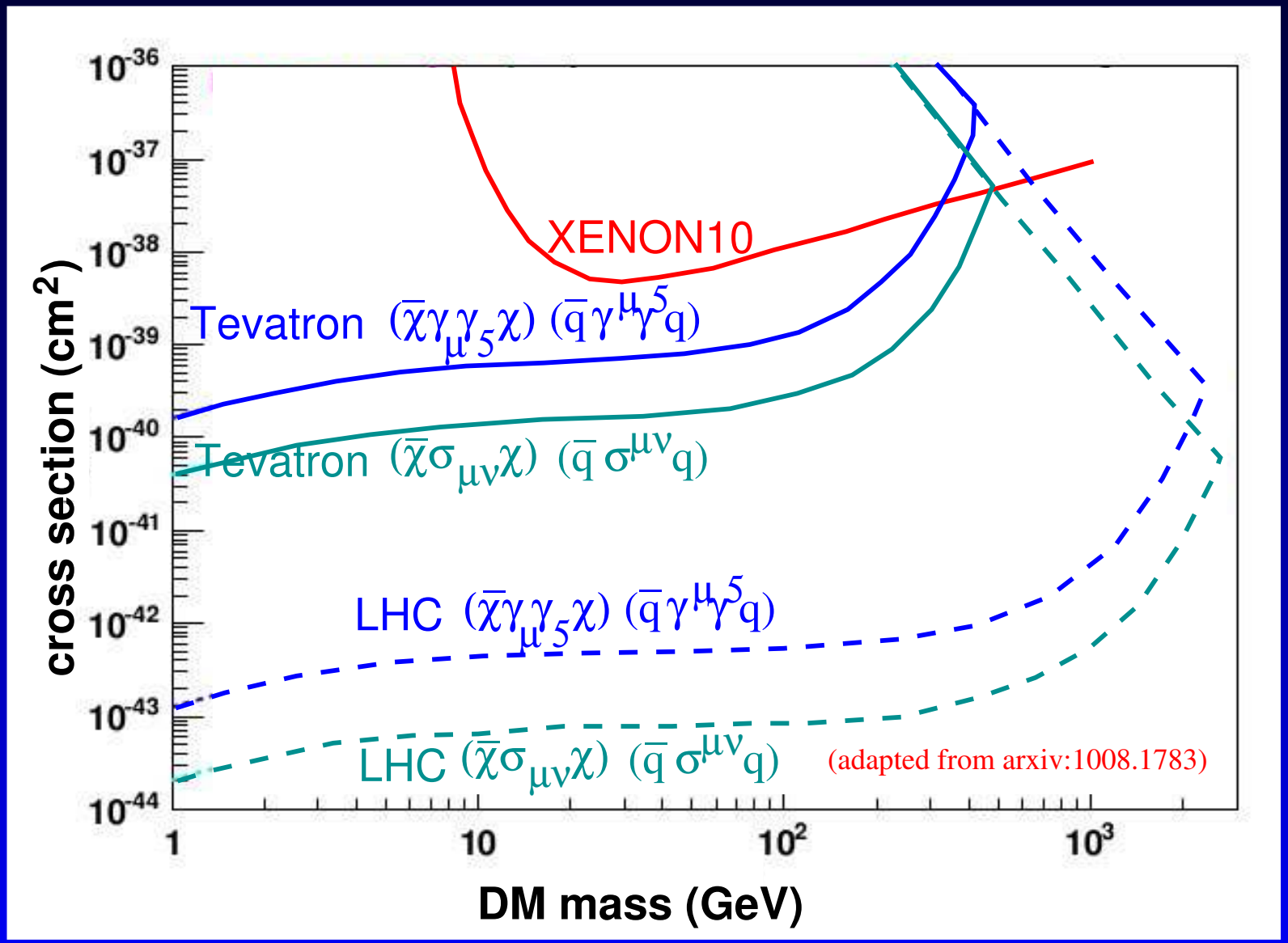
LHC sensitivity to DM

LHC could be more sensitive or less so than direct searches, depending on exactly how DM interacts with quarks.



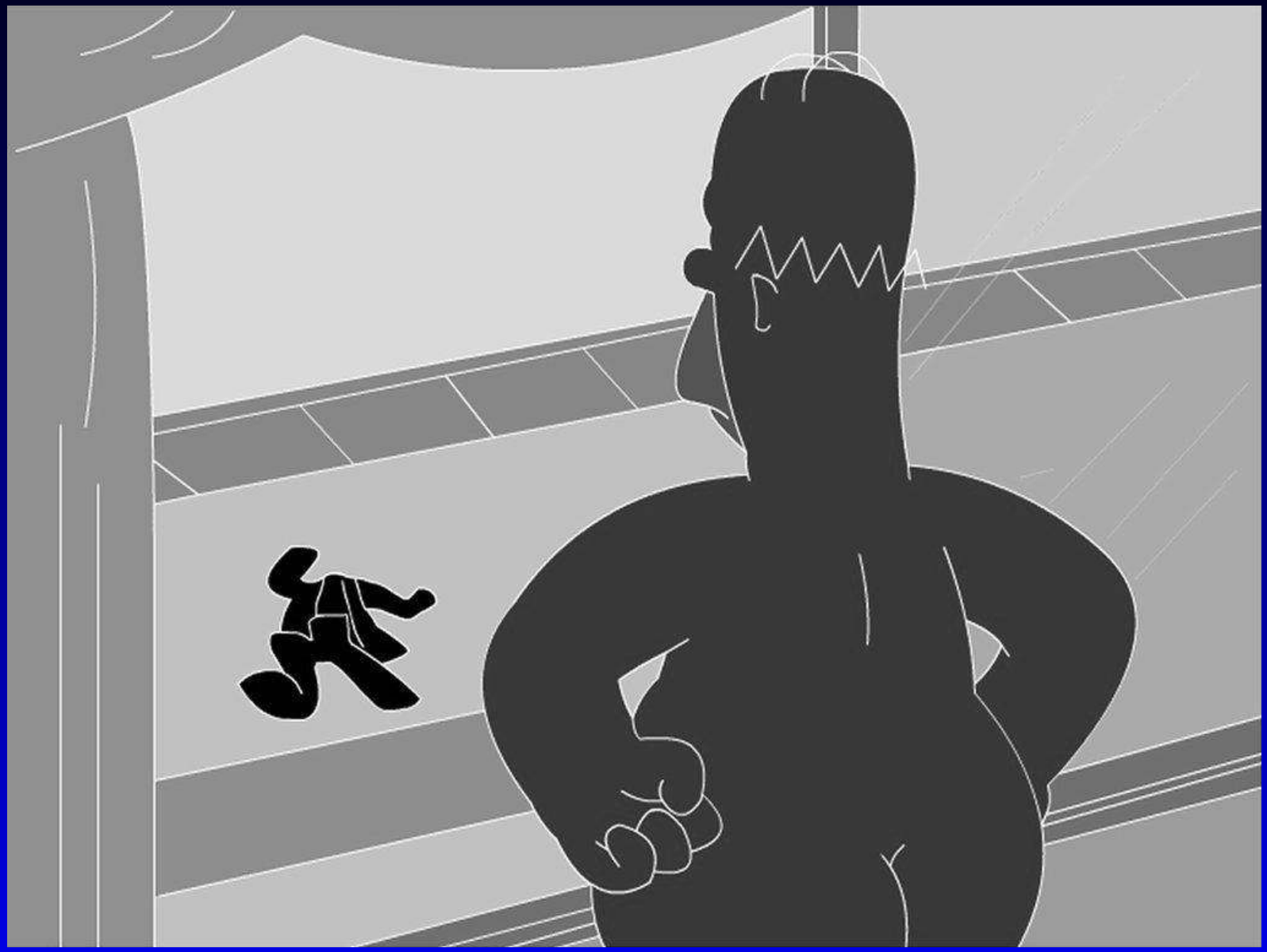
LHC sensitivity to DM

If DM couples to nucleon spin instead of nucleon number, LHC and Tevatron are more sensitive than direct detectors

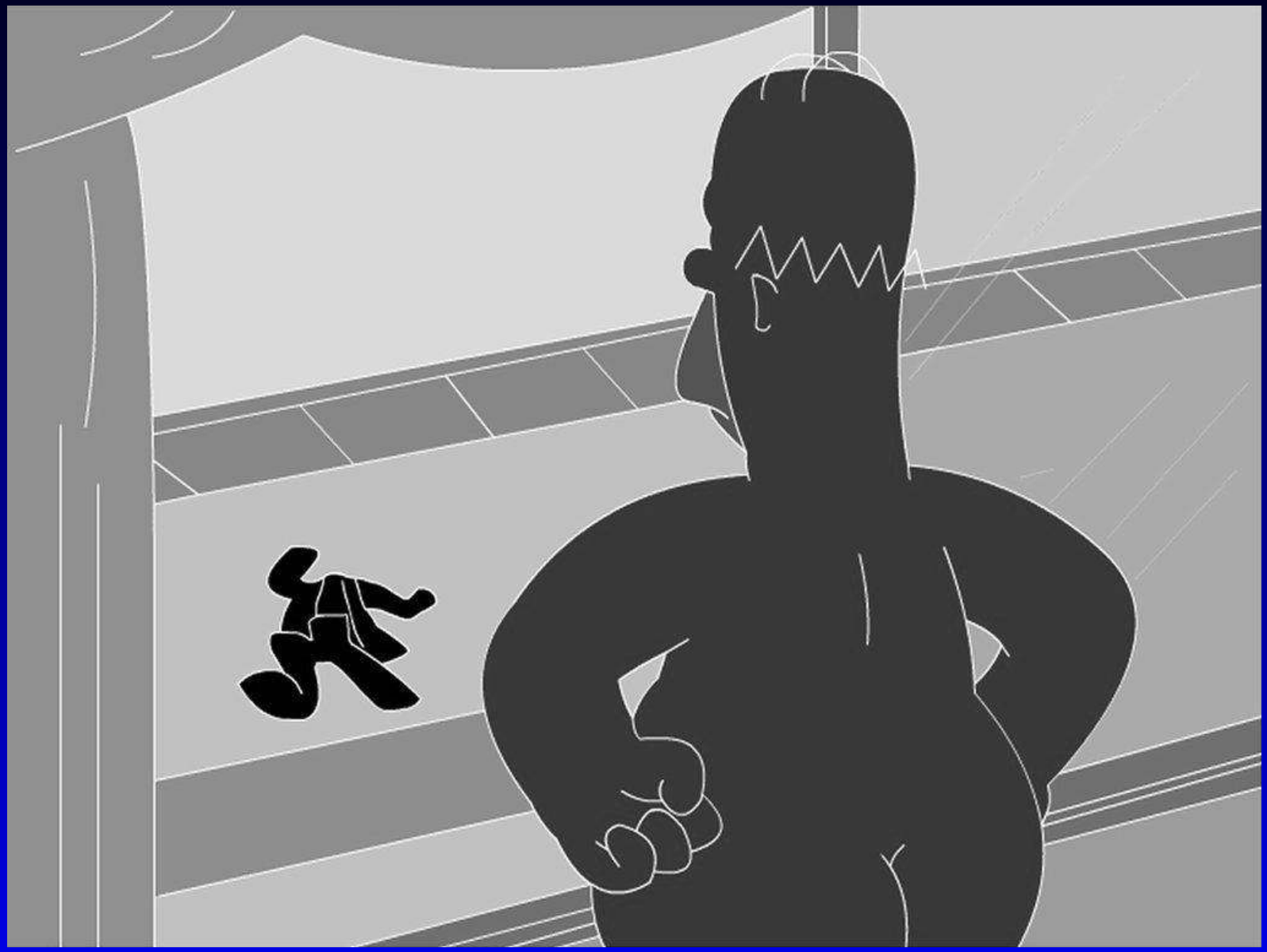


Part Ia: The more speculative part

DM people probably don't wear clothes



DM people probably don't wear clothes



Dark manufacturing sector hampered by lack of chemistry

Do dark atoms exist?

Possibly, but with different properties from normal atoms

Normal atoms interact strongly with each other

Dark matter can interact only weakly with itself

($\sigma \lesssim 10^{-25}$ cm^2 for dark atoms of 10 GeV mass)

Compare to normal matter: $\sigma \sim 10^{-16}$ cm^2

Possible if dark atom is 10^5 times smaller than normal atoms;

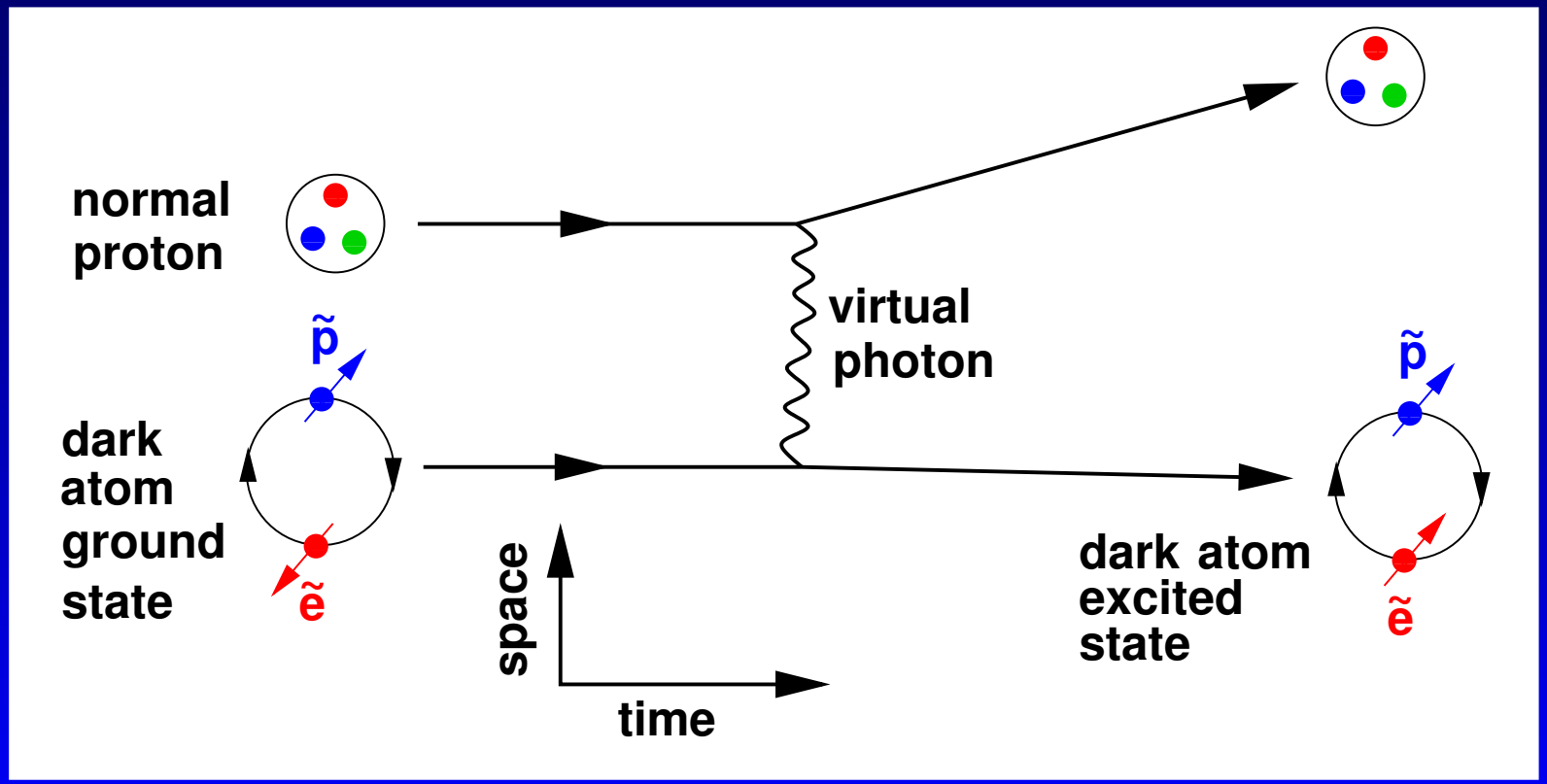
e.g., dark electron mass $= 10^4$ times normal electron mass;
dark electric force $= 10$ times normal electric force

Could be!

What are dark atoms good for?

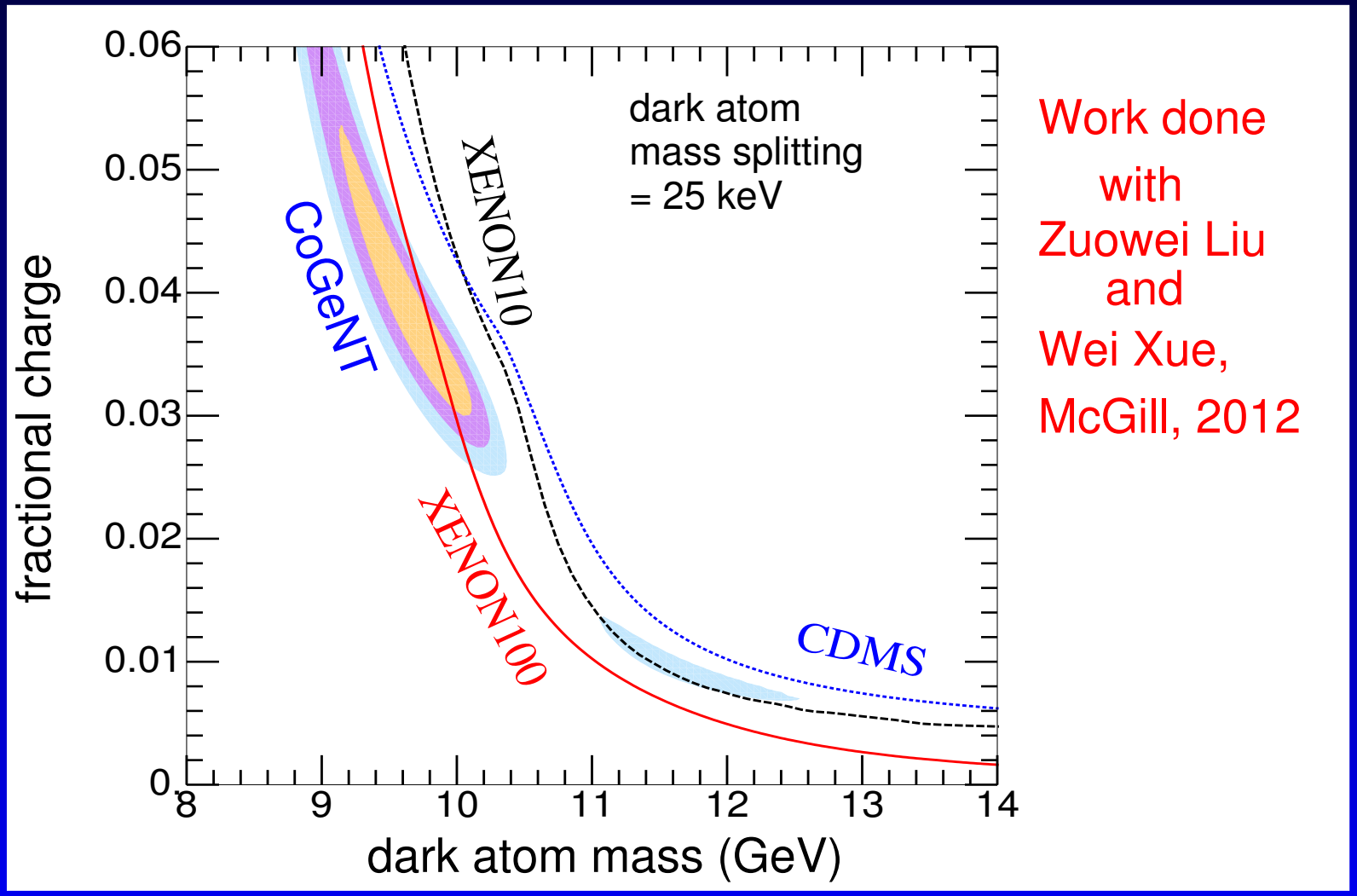
- Clothing and housing for dark matter people.
- Reconciling CoGeNT DM observation with XENON100 nonobservation?

  Dark atoms could behave differently in XENON100 detector than simple DM particles.



Sneaking CoGeNT under XENON limit

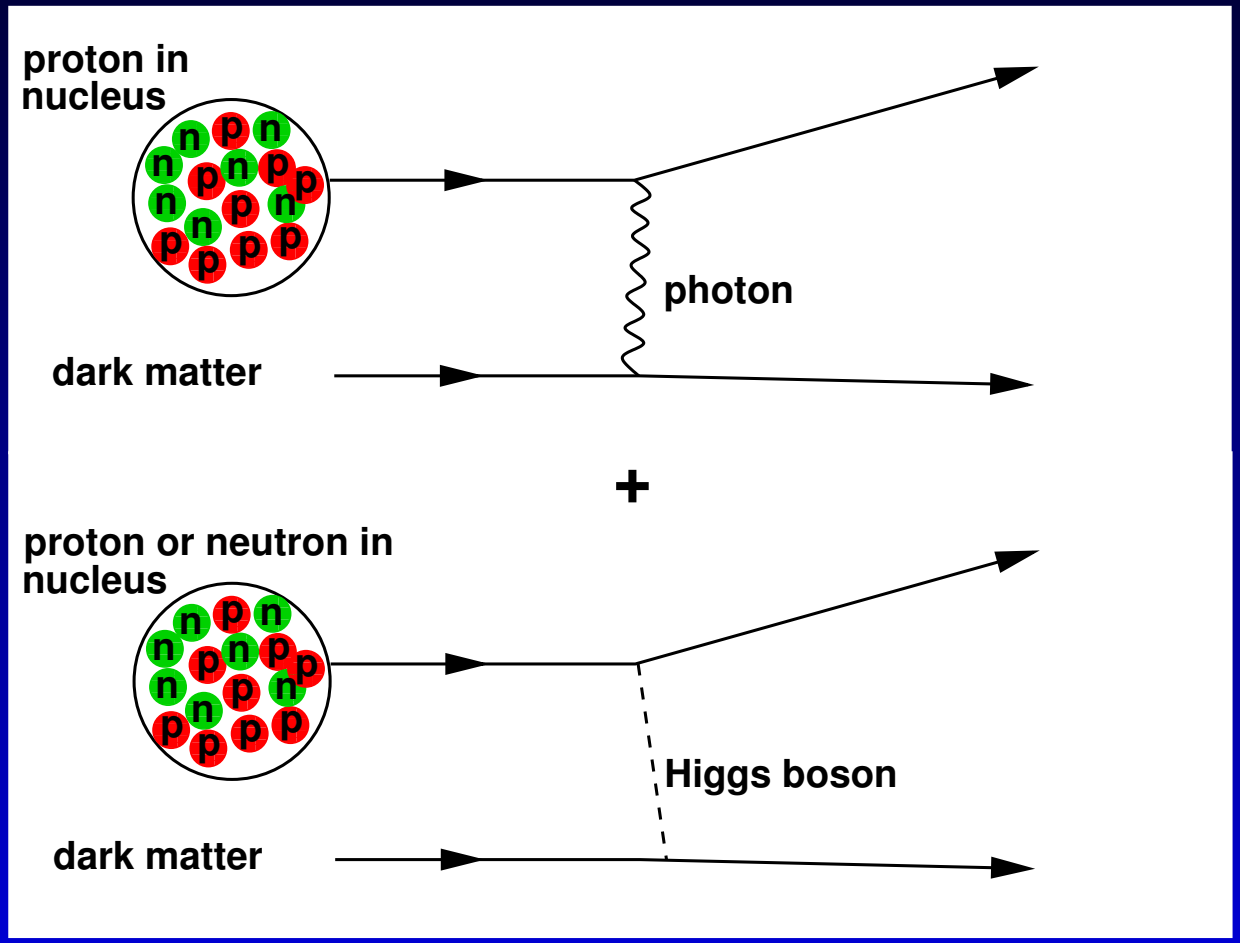
If dark proton and electron have equal mass ~ 4.7 GeV,
mass splitting ~ 25 keV and electric charge ~ 0.04,
can sneak CoGeNT region under the XENON100 constraint



Work done with Zuowei Liu and Wei Xue, McGill, 2012

Other theorist tricks

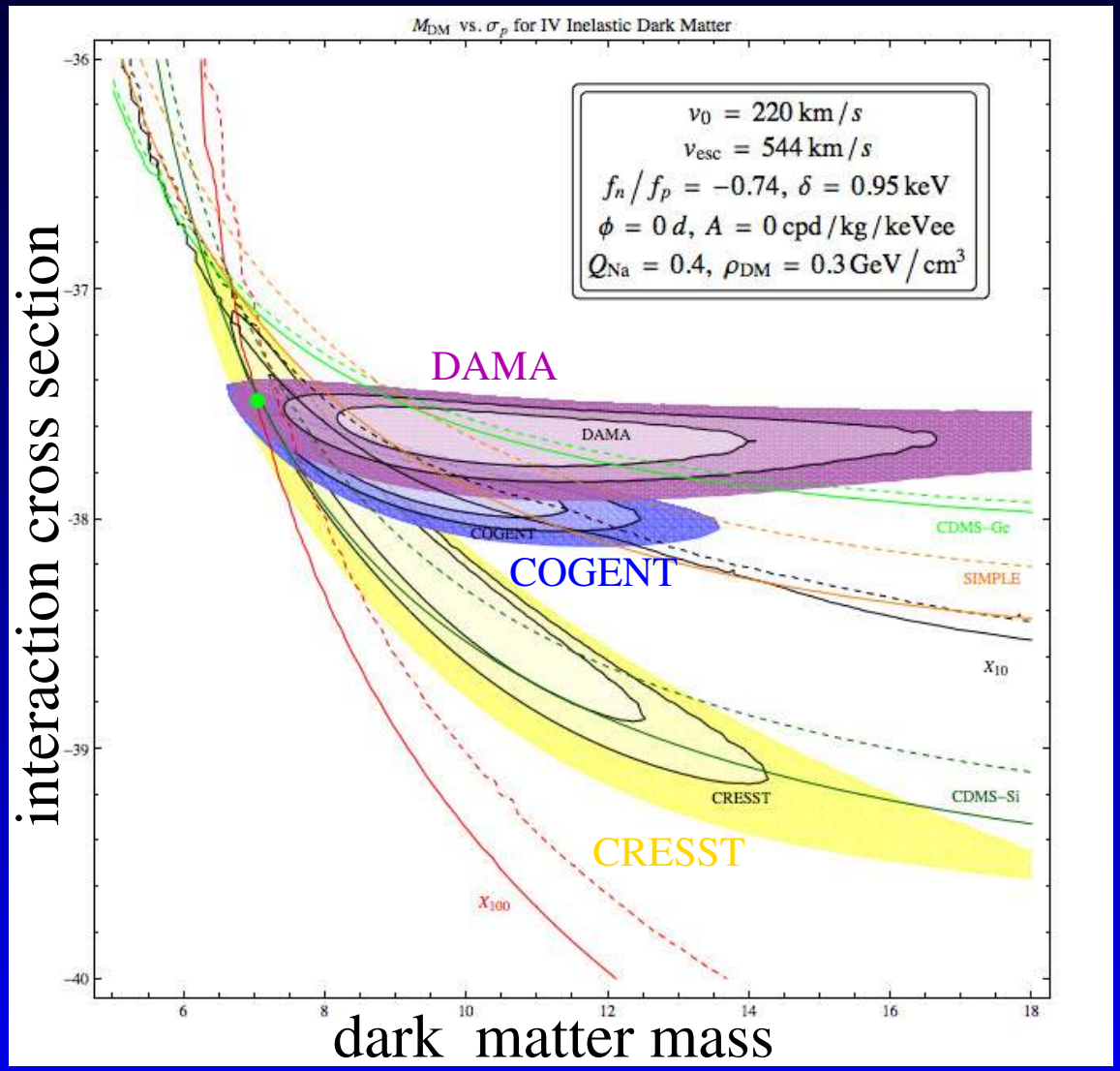
Protons and neutrons could interact differently with dark matter



Could explain why different experiments get seemingly incompatible results

Reconciling the observations

By adjusting relative strength of interactions between dark matter and protons/neutrons, can get conflicting data to agree better



Result from Zak Whittamore, current M.Sc. student

Part II:

Dark Energy

Everything you need to know about DE:

It’s all bullshit