

Dark Matter: A Journey To The Dark Side

Precursor for the MadDM tutorial

Gopolang Mohlabeng



WELCOME TO THE DARK SIDE

Ice Breaker

Let me introduce myself

I come from South Africa



What got me interested in Physics?

Hold onto your seat, this is going to blow you away...

Has anyone seen this movie

“Honey I blew up the Kid?”

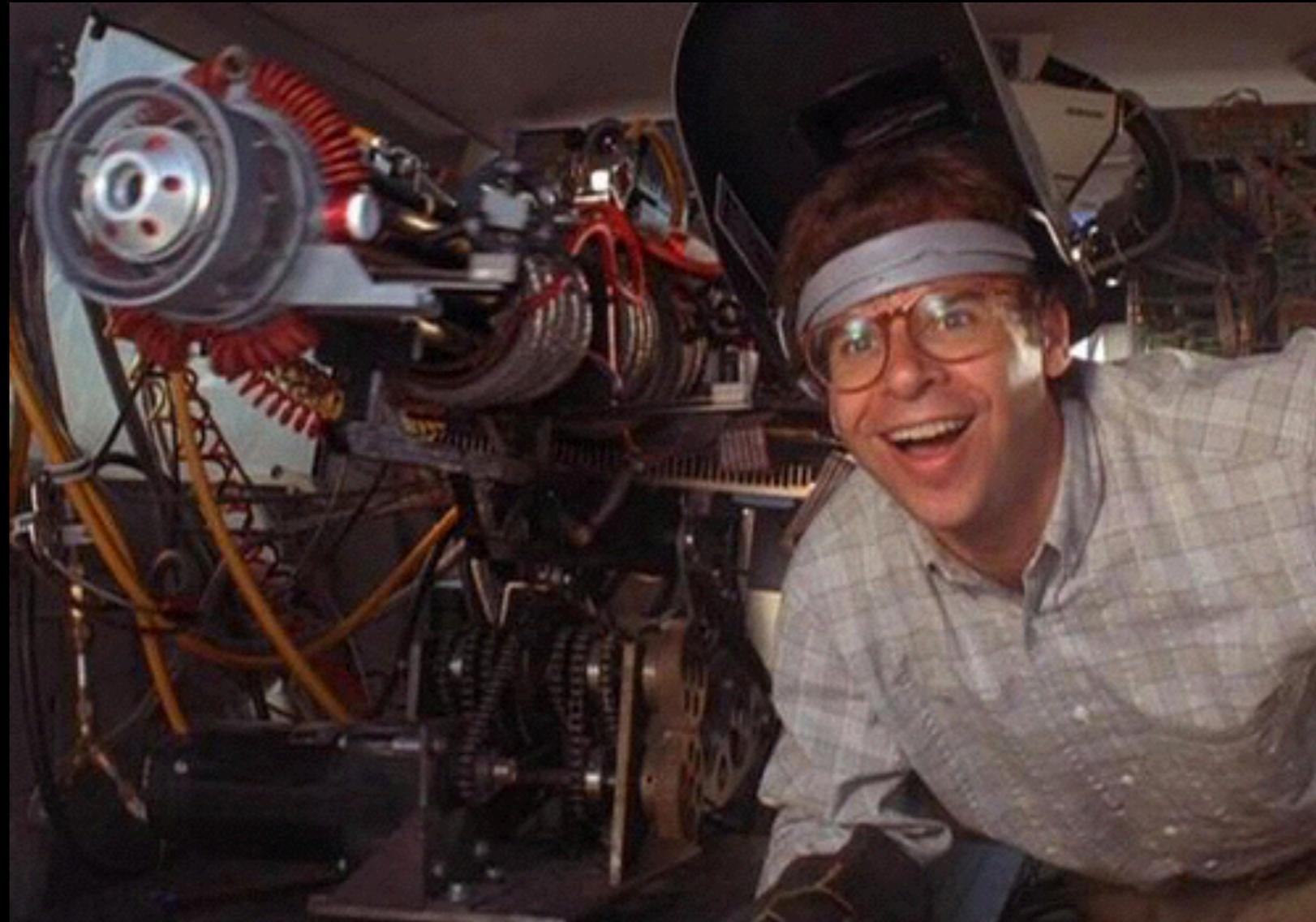
Do you remember now?

**HONEY, I
BLEW UP
THE KID**

HD



I wanted to be an inventor



In high School I had to do a research Project
on physicists in the 1800's and 1900's

In high School I had to do a research Project
on physicists in the 1800's and 1900's



John Dalton

One of first people to
work on atomic theory

In high School I had to do a research Project
on physicists in the 1800's and 1900's



John Dalton



JJ Thompson

Discovered
the Electron

In high School I had to do a research Project
on physicists in the 1800's and 1900's



John Dalton



JJ Thompson



Niels Bohr

One of the early
pioneers of
Quantum Mechanics

In high School I had to do a research Project on physicists in the 1800's and 1900's



John Dalton

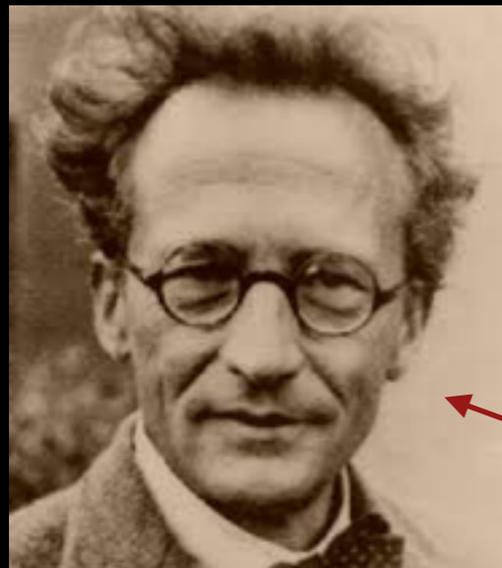


JJ Thompson



Niels Bohr

Also, you've heard
of Schrodinger's Cat



Erwin Schrodinger

One of the
pioneers of
Quantum Mechanics



In high School I did a research project
on physicists and chemists in the 1800's and 1900's



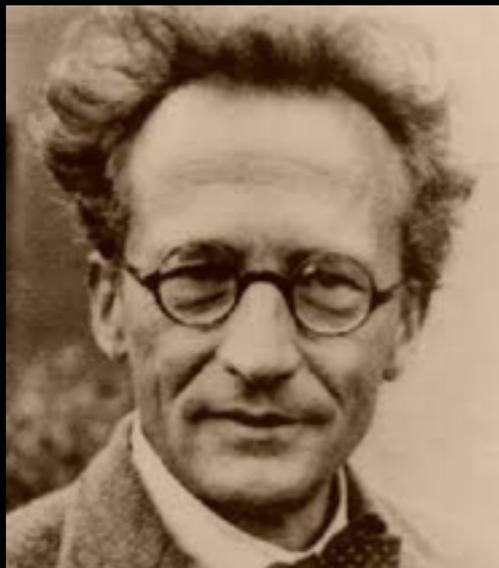
John Dalton



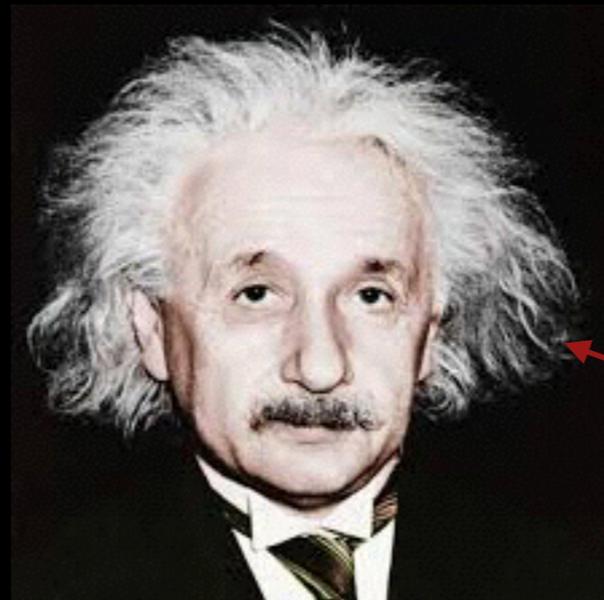
JJ Thompson



Niels Bohr



Erwin Schrodinger



Albert Einstein

Needs no
introduction

In high School I did a research project
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John Dalton

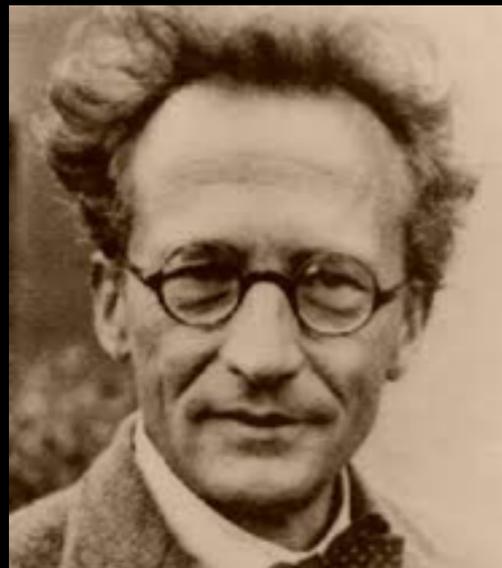


JJ Thompson

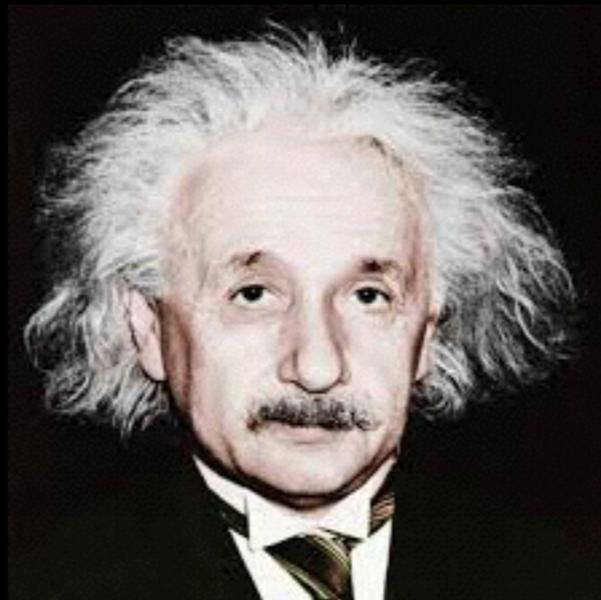


Niels Bohr

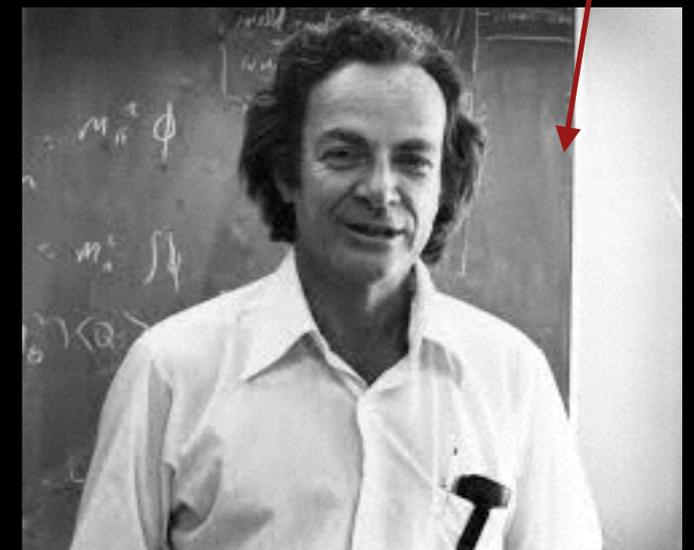
Father
of Quantum
Field
Theory



Erwin Schrodinger



Albert Einstein



Richard Feynman

I wanted to be a Physicist

Studied Material Physics first 3 years of Undergraduate

Last Year I went to different University and
studied Astrophysics

I got interested in Cosmology and eventually
Dark Matter

The detection of Dark Matter using the
MeerKAT telescope.

Author: Gopolang Mohlabeng

Supervisor: Dr Marco Regis

November 2010

Super Short CV

- Undergraduate in Physics, University of Pretoria, SA(2009)
- Honors degree, astrophysics and space science with the NASSP program, University of Cape Town, SA (2010)
- Masters M.Sc. in Physics, University of Kansas, USA (2013)
- Ph.D in Physics, University of Kansas, USA, (2017)
- Postdoctoral Research Associate, Brookhaven National Lab (current)

Field of Research

- Theoretical Particle Physics

High Energy Colliders physics

Low Energy precision physics

- Astro-Particle Physics

Dark Matter Physics:

Direct Detection

Low mass dark matter searches

Now that we are well acquainted....

Lets talk about Dark Matter

What do we know about our Universe?

What is our Universe made of?

What is our Universe made of ?

When we look up at the night sky....



What is our Universe made of ?

When we look up at the night sky....



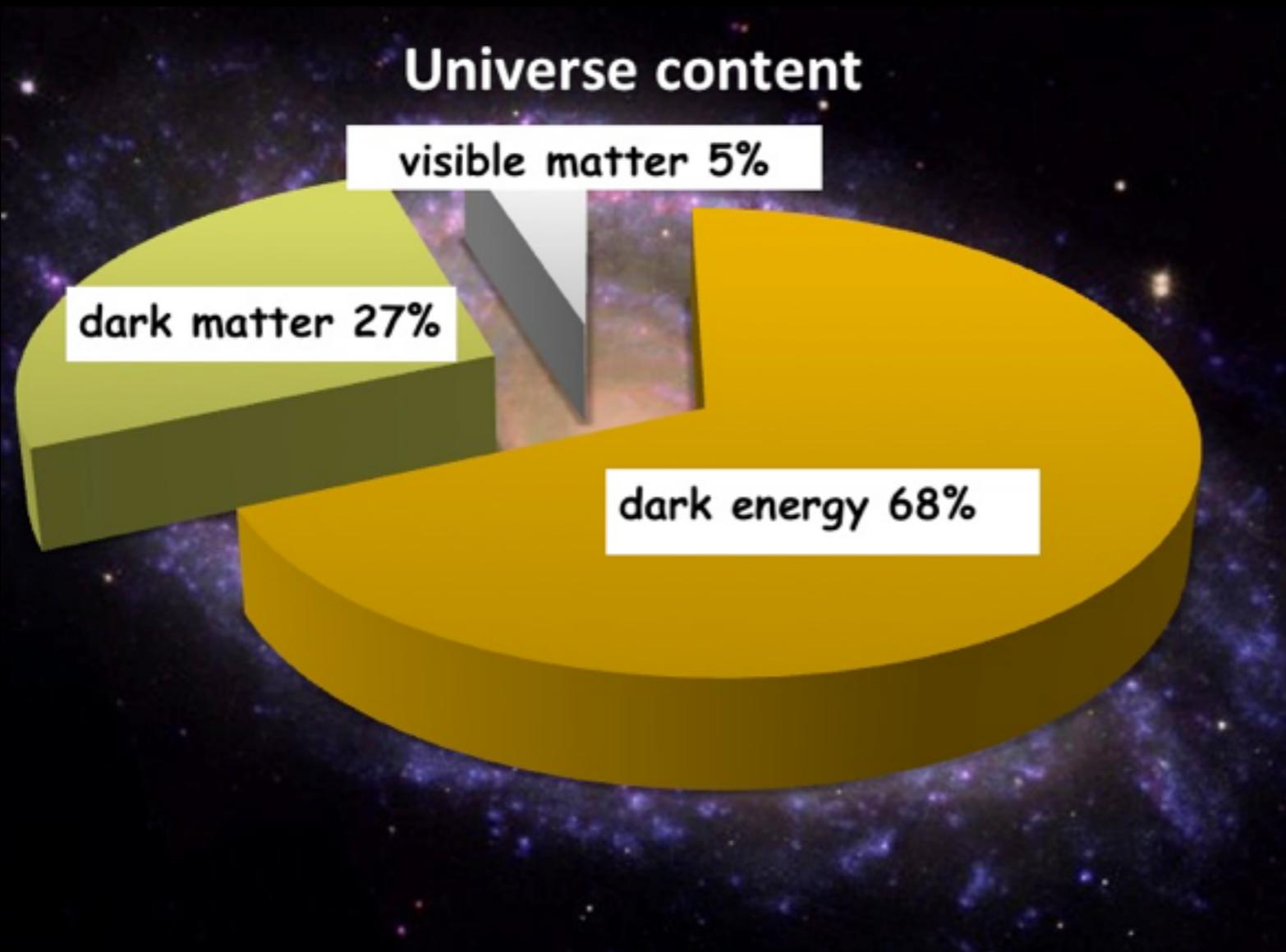
more stars in universe than grains of sand on every beach on earth

Would expect stars, gas, galaxies to be
100% of Universe

On the contrary....

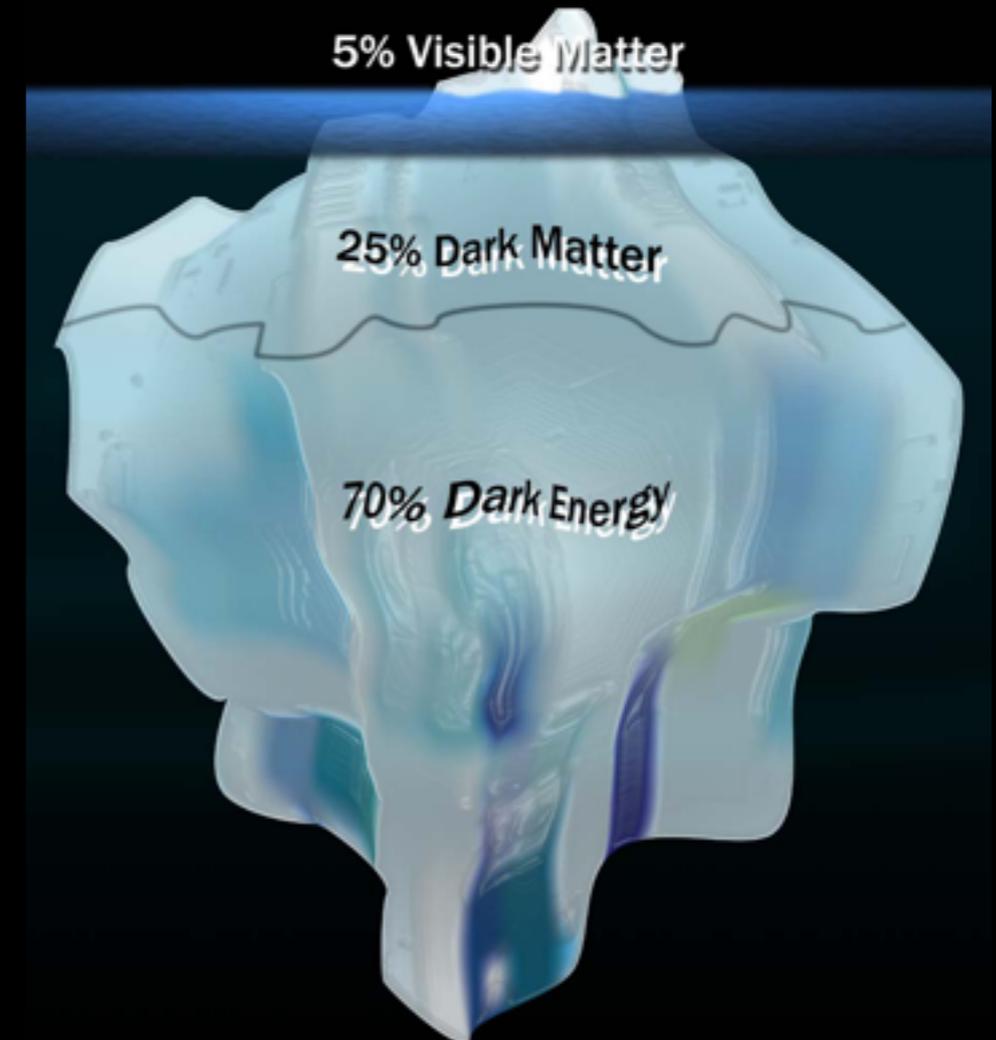
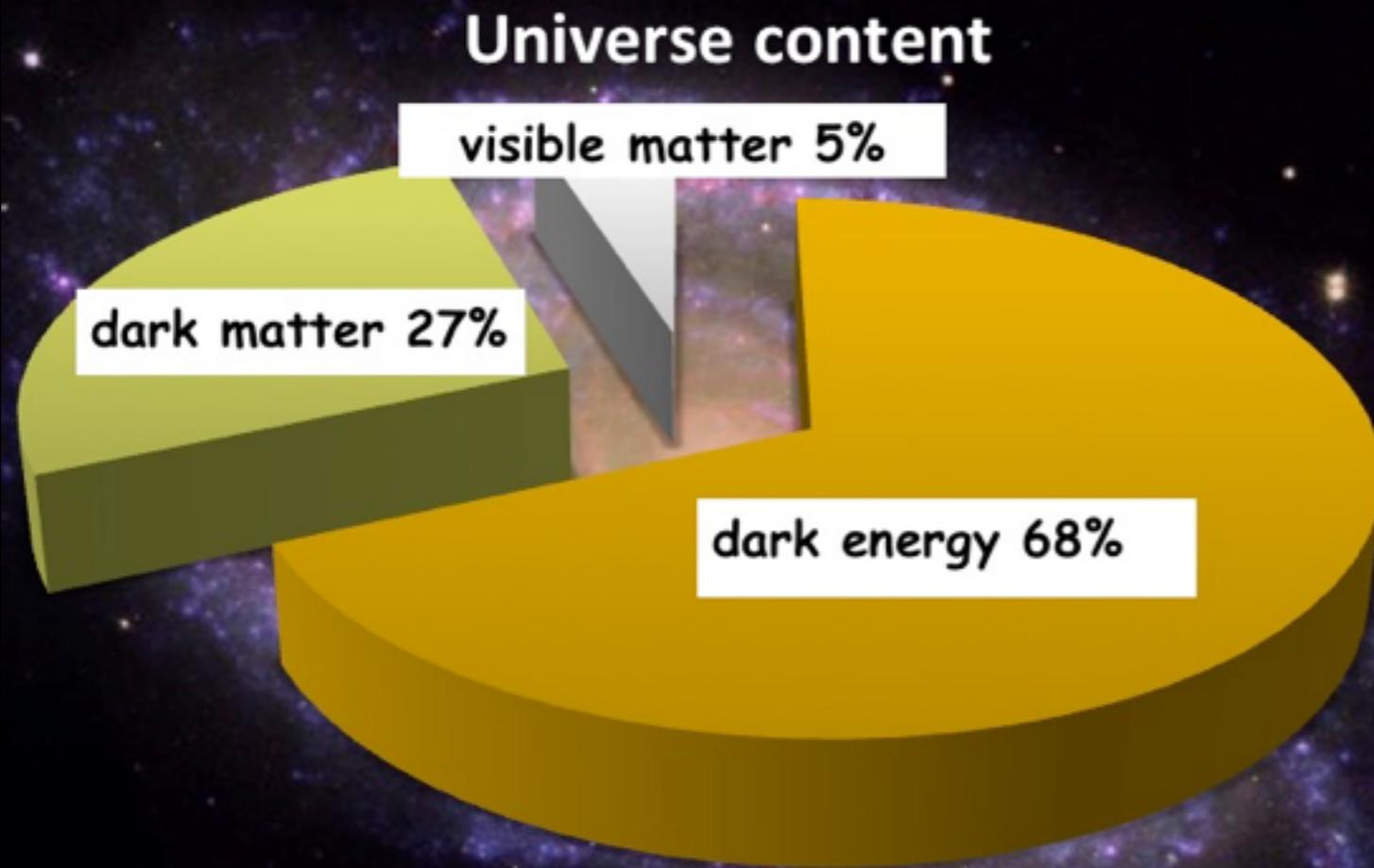
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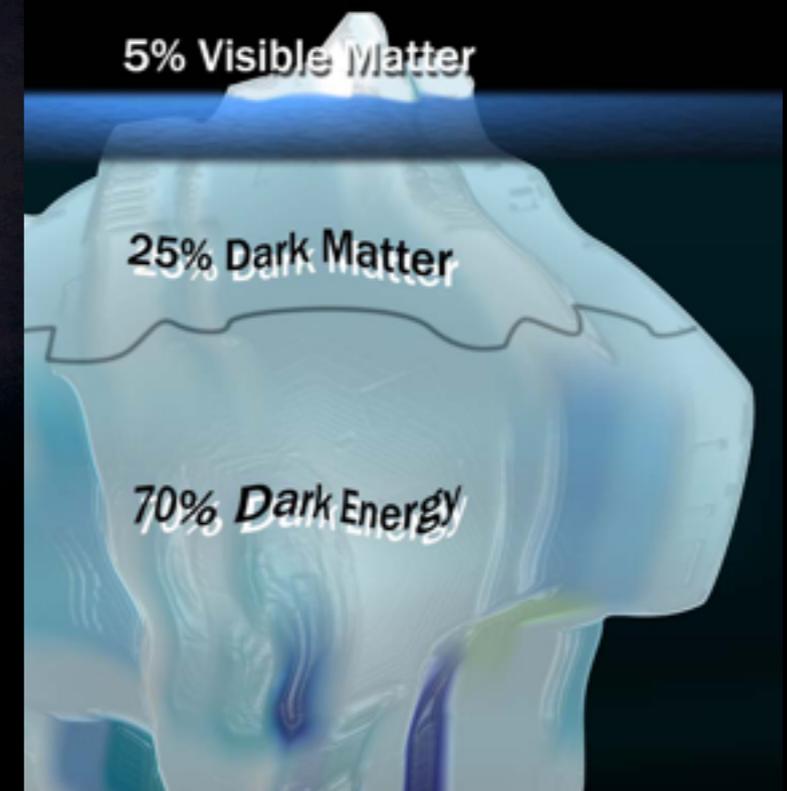
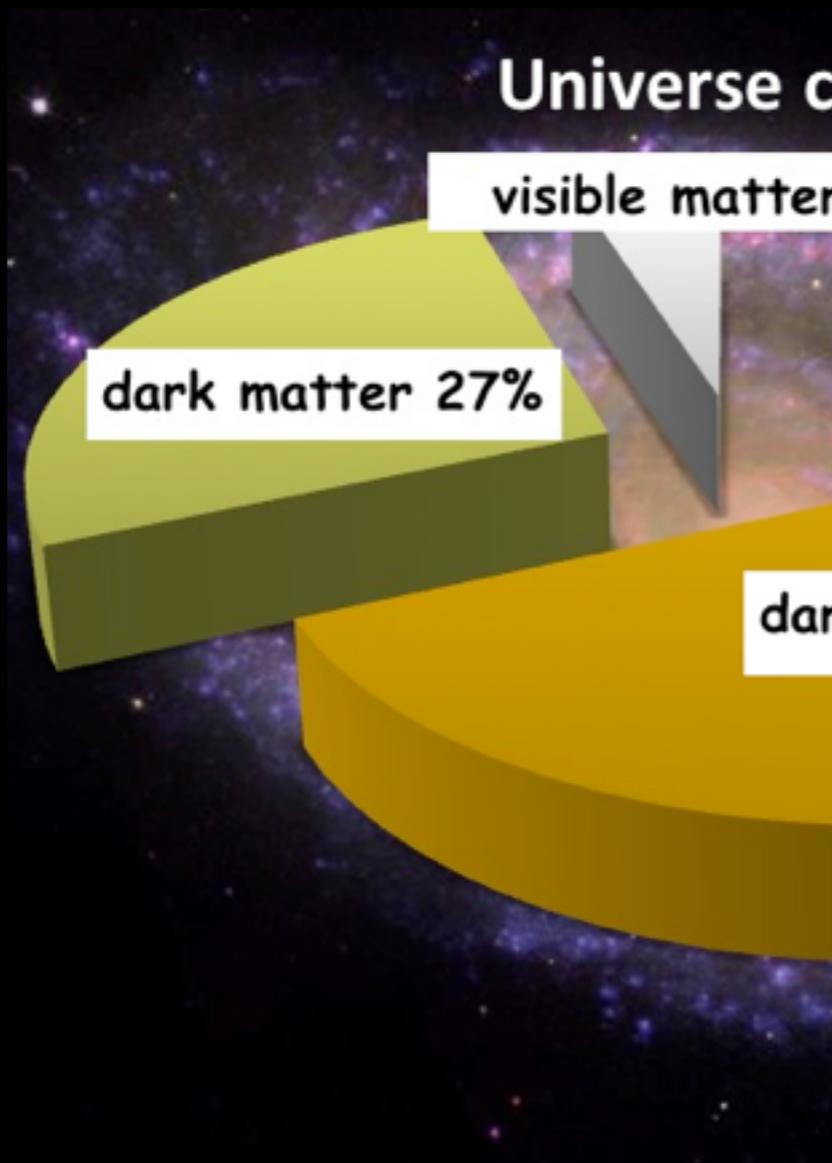
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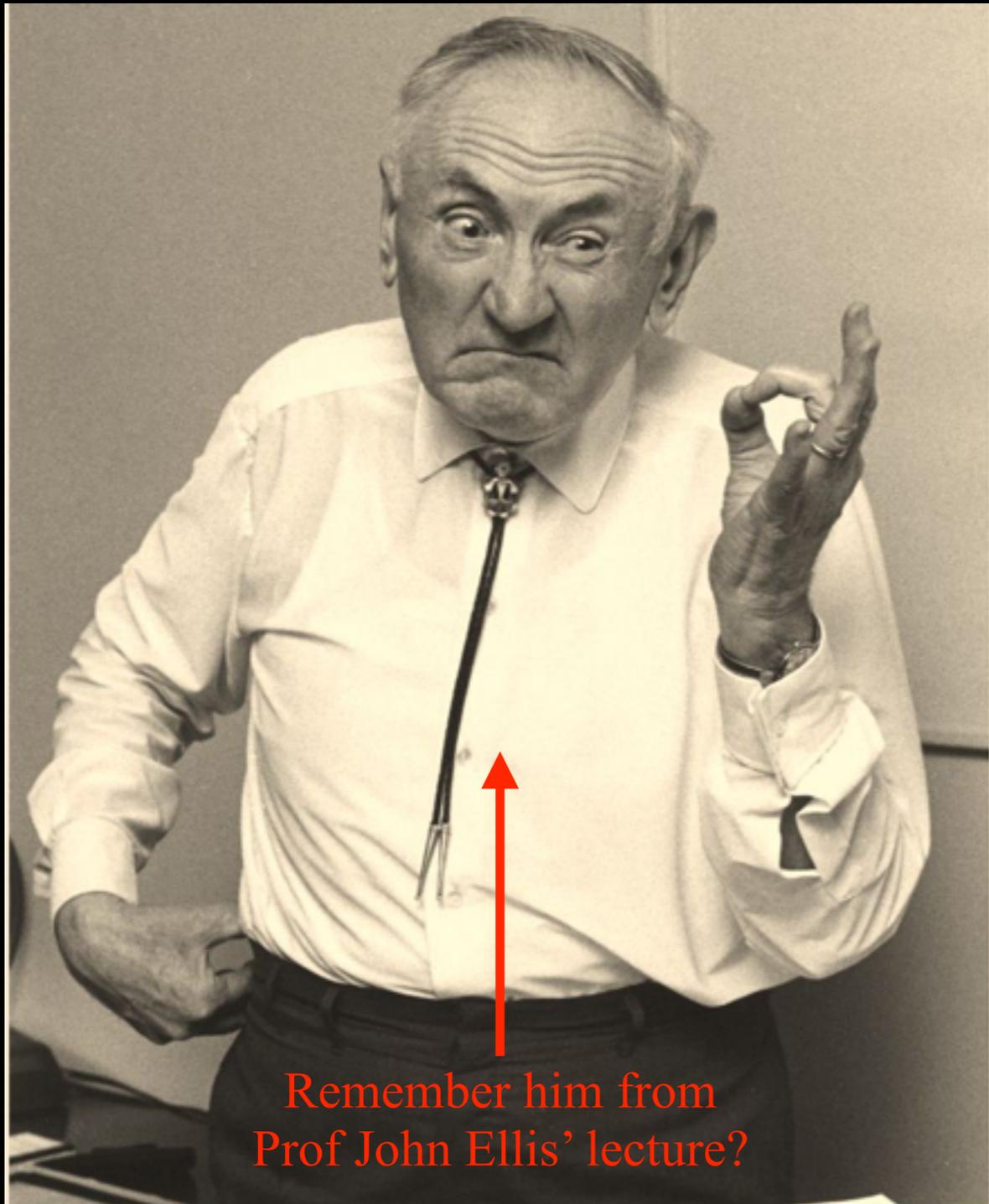
On the contrary.....



Dark Matter
Dark Energy

So how do we know DM exists?

In 1933, Swiss Astrophysicist, Fritz Zwicky



Remember him from
Prof John Ellis' lecture?

Found evidence for unseen matter
when studying Coma galaxy cluster

Calculated 400x more mass than
seen

Coined it Black Matter

For years no one believed him

Roughly 40 years later...

American astronomer Vera Rubin

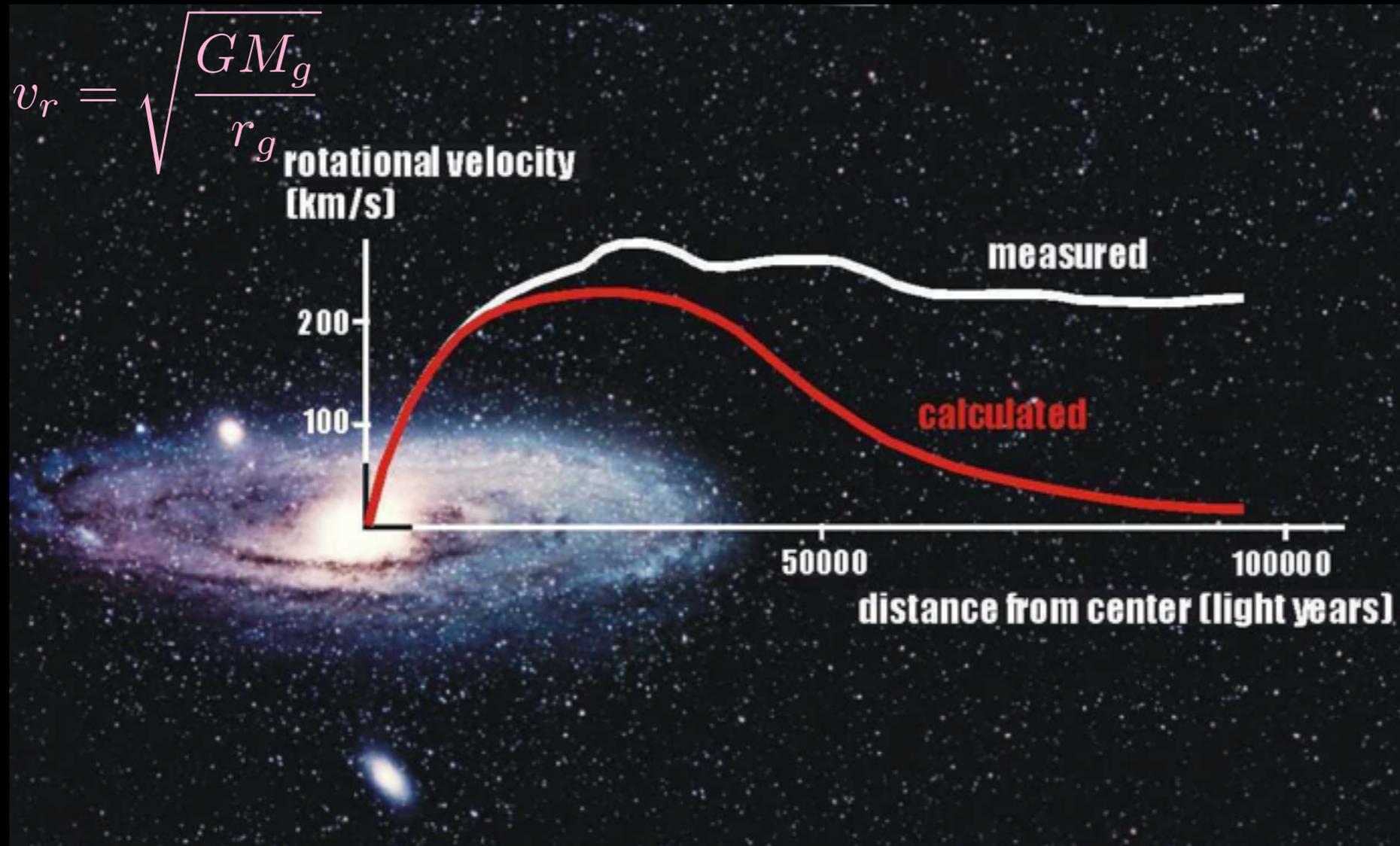
Studied velocity curves of
spiral galaxies

Found evidence of unobservable
matter



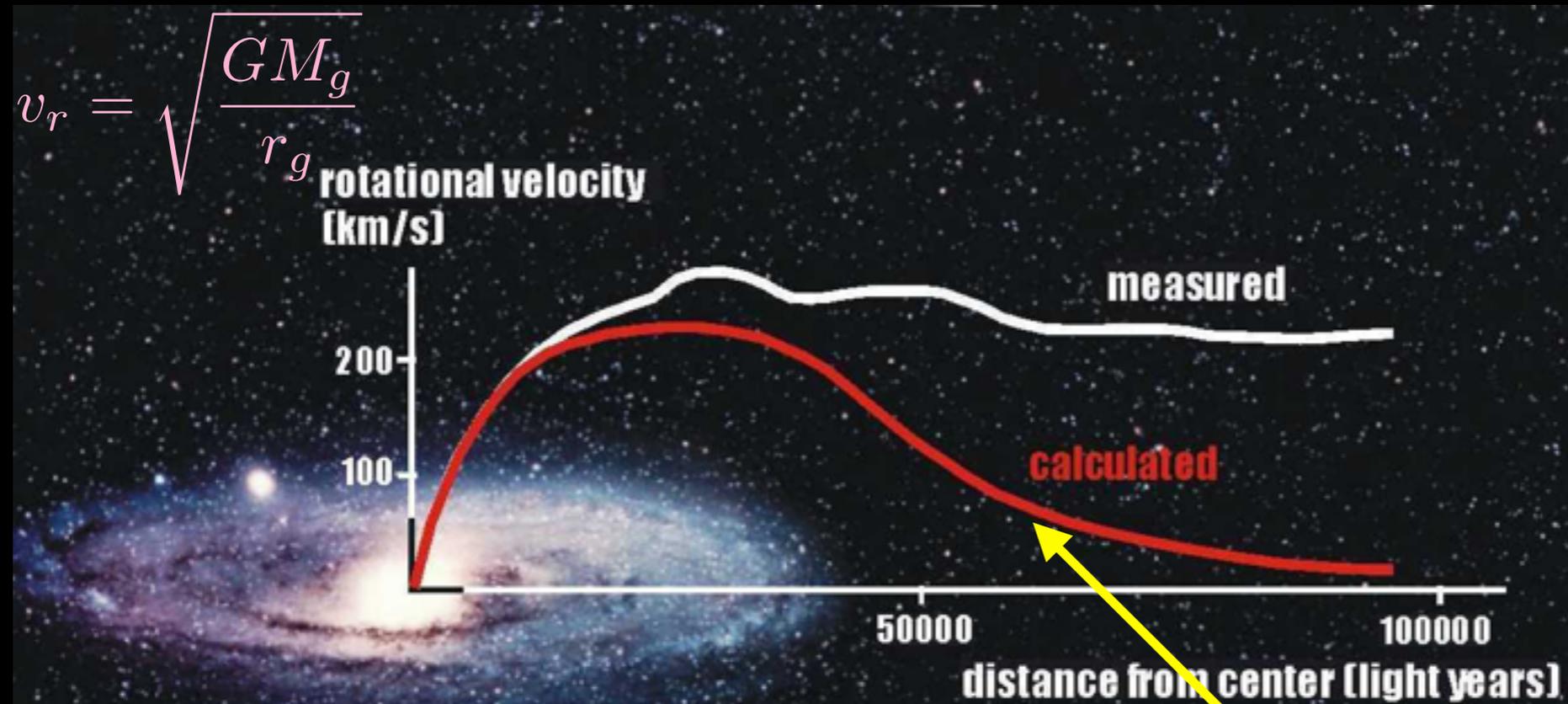
Velocity curves should follow Newtonian dynamics

Measurements did not match calculations



Velocity curves should follow Newtonian dynamics

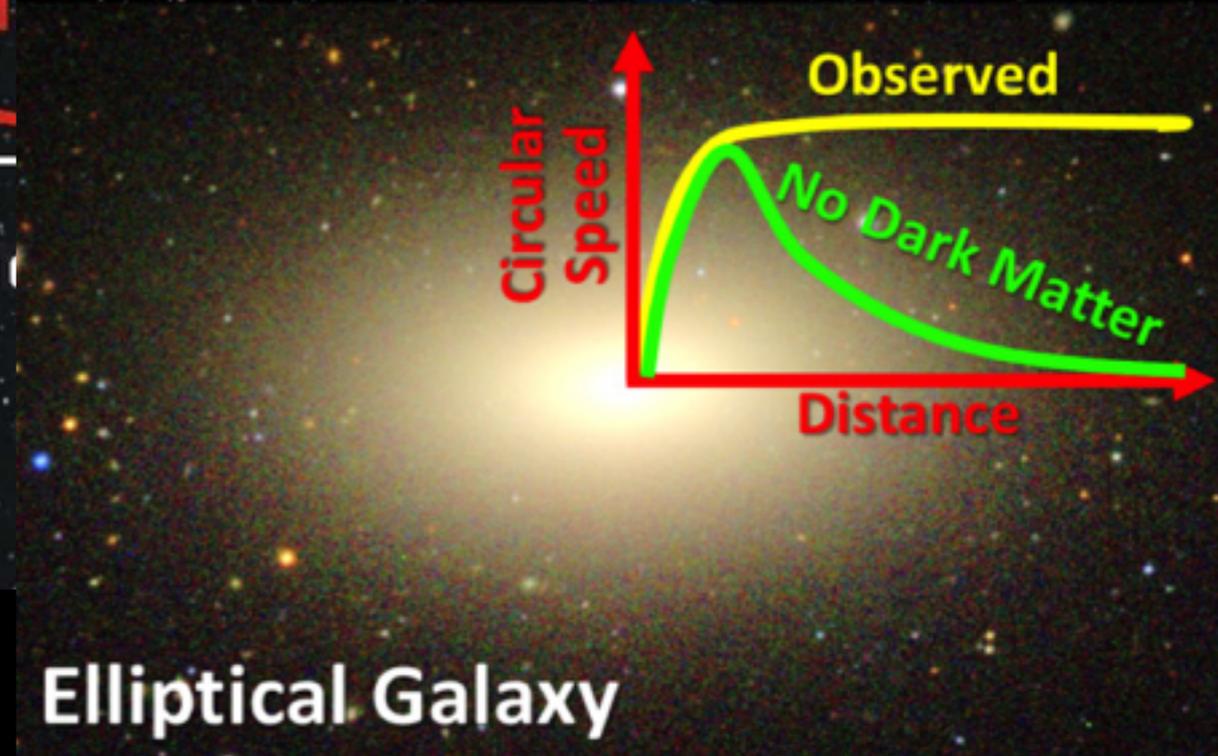
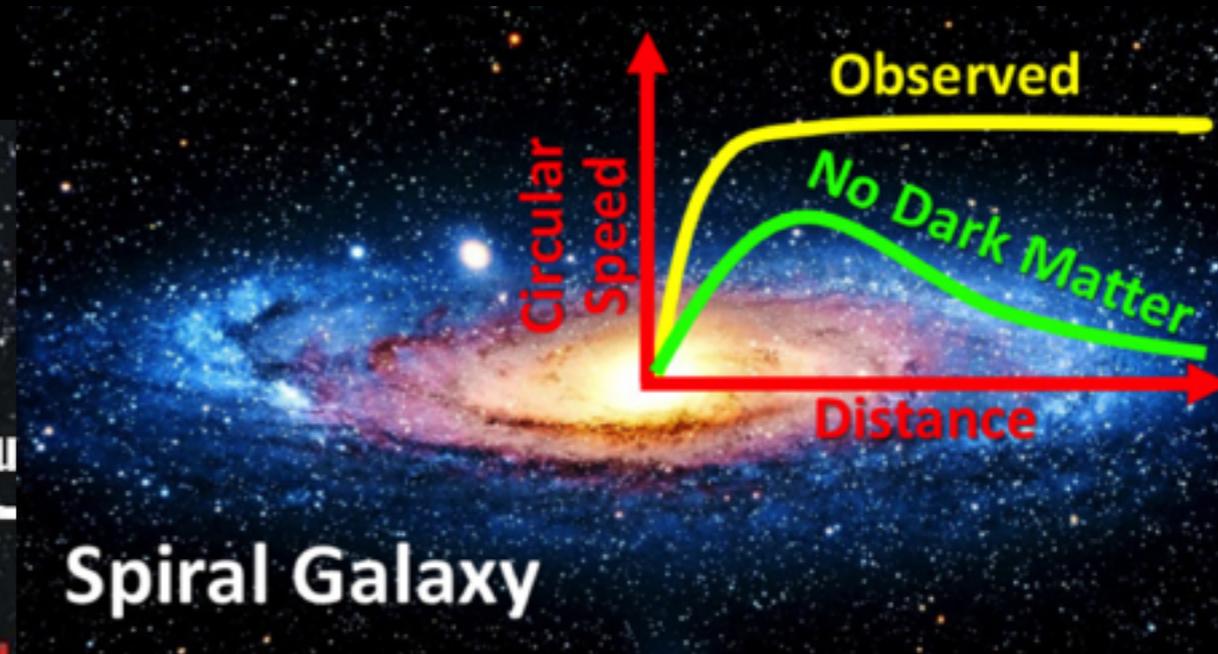
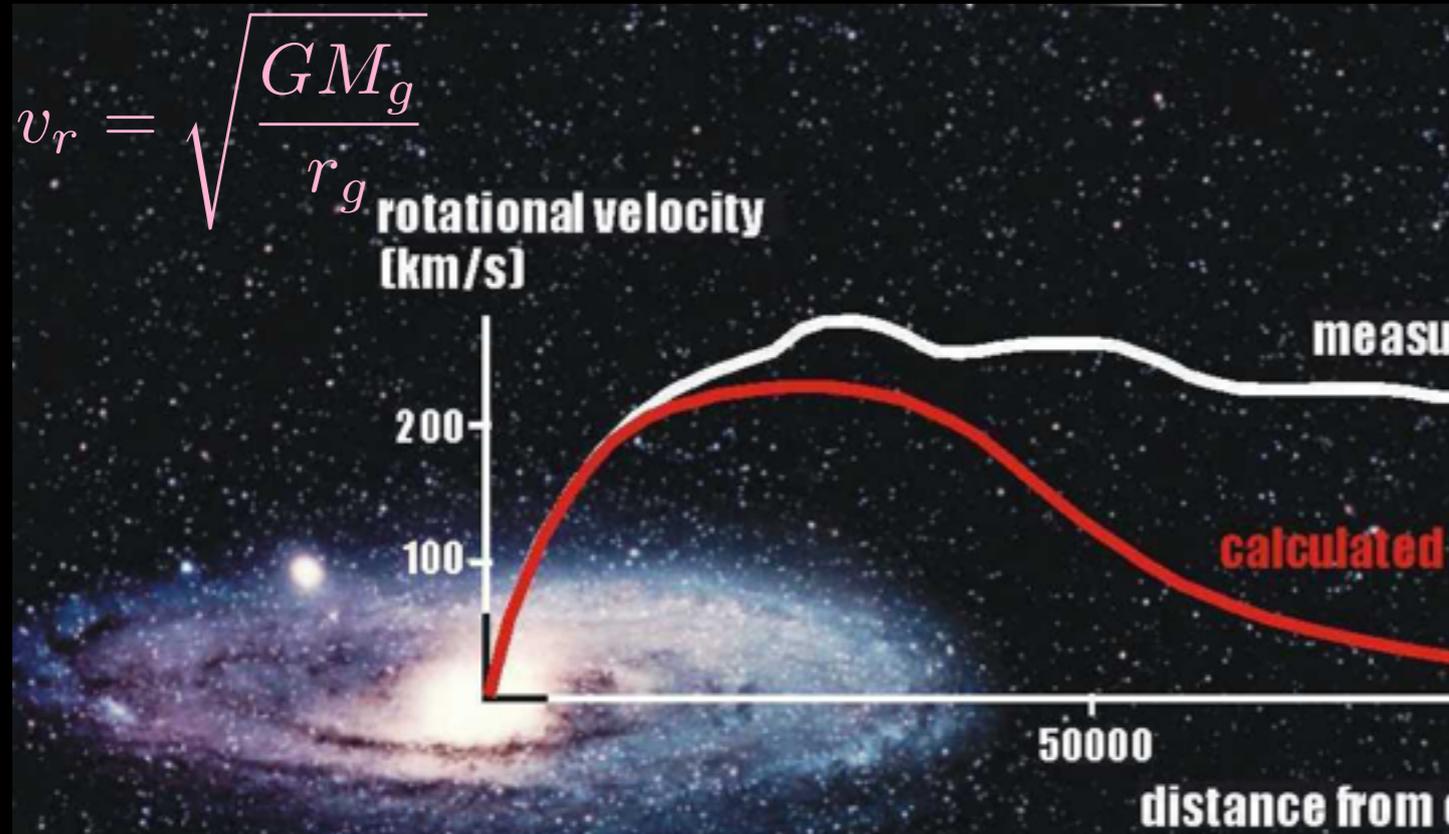
Measurements did not match calculations



Question:
why do we expect
the red curve to have this shape?

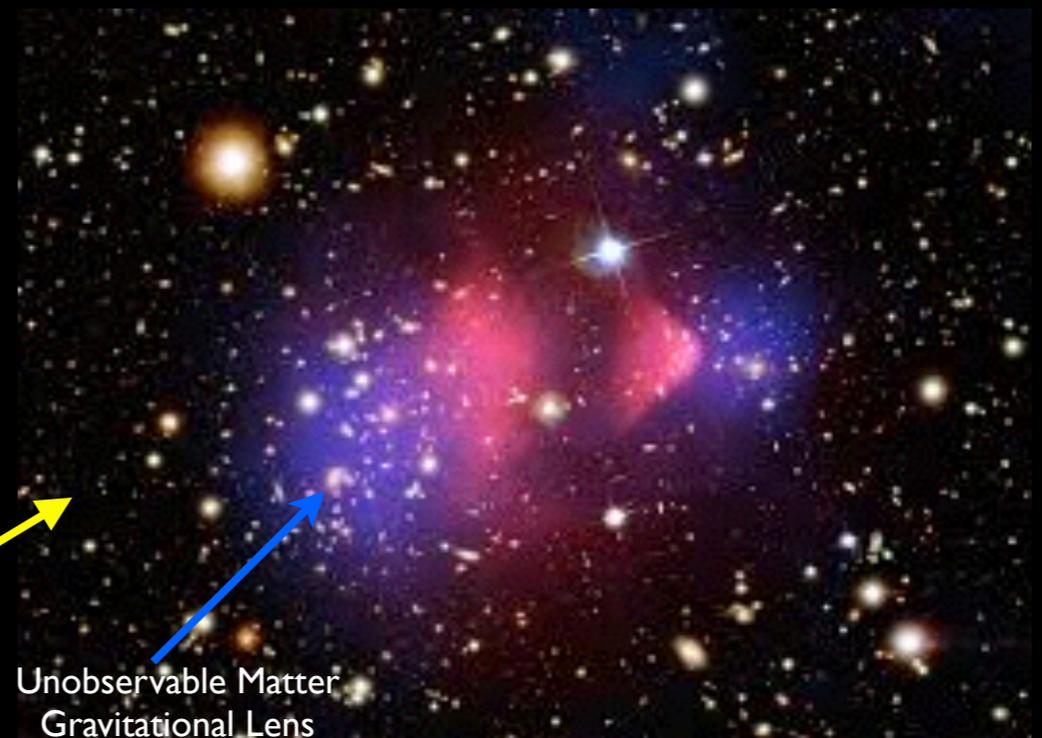
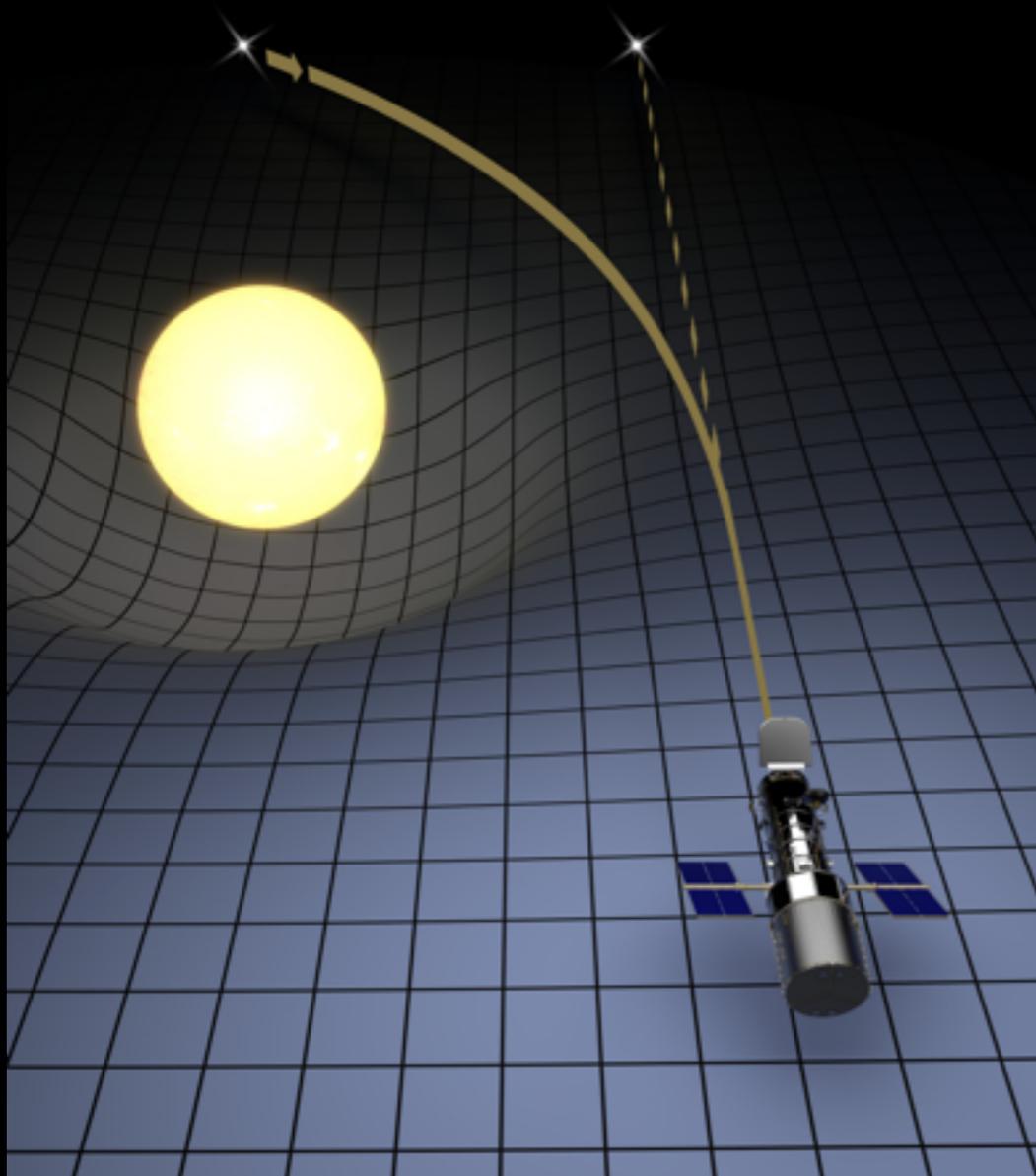
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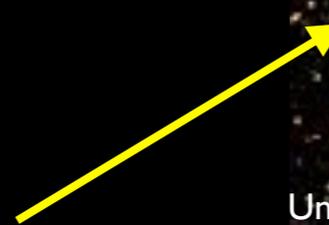


Much more evidence

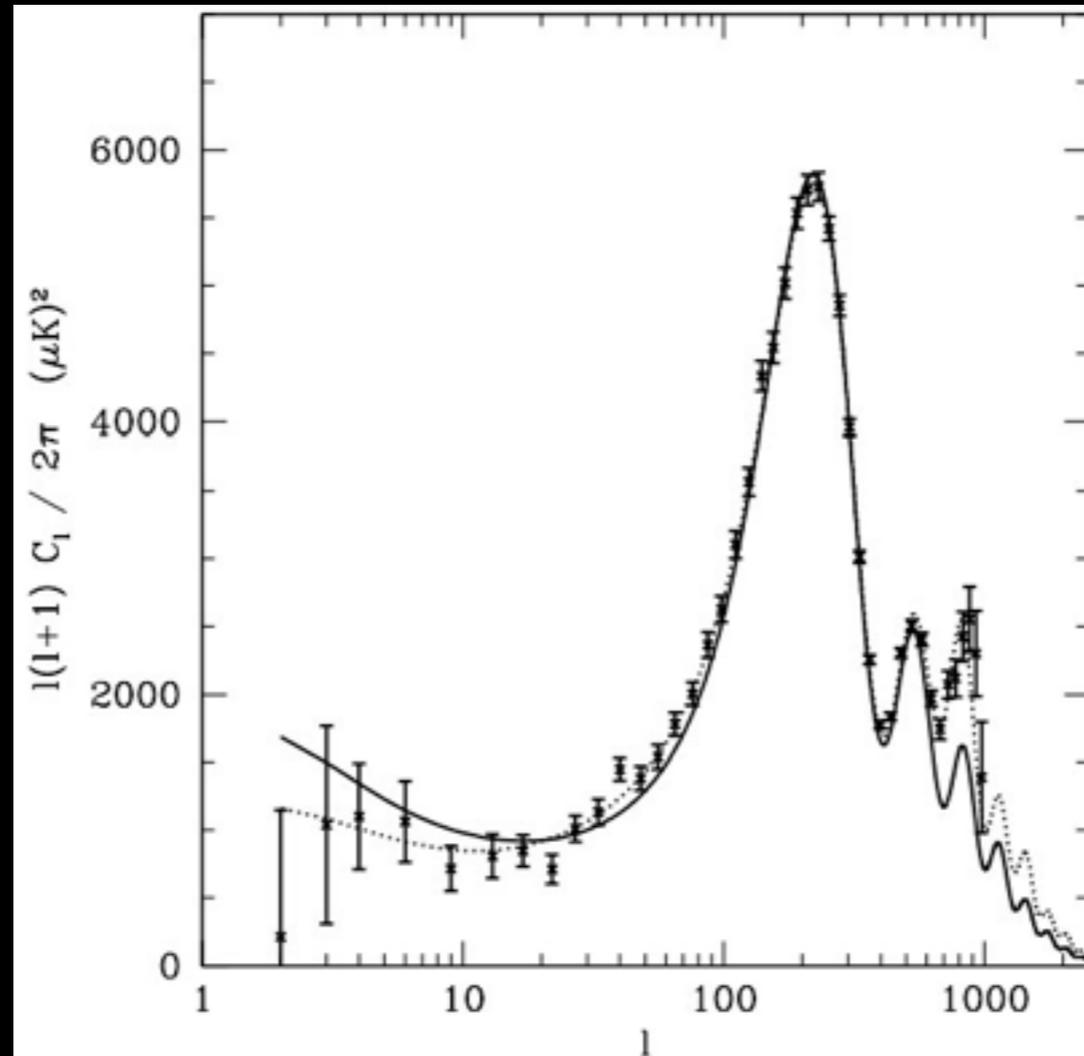
Gravitational lensing - light from distant objects bent by unobserved matter



Bullet Cluster

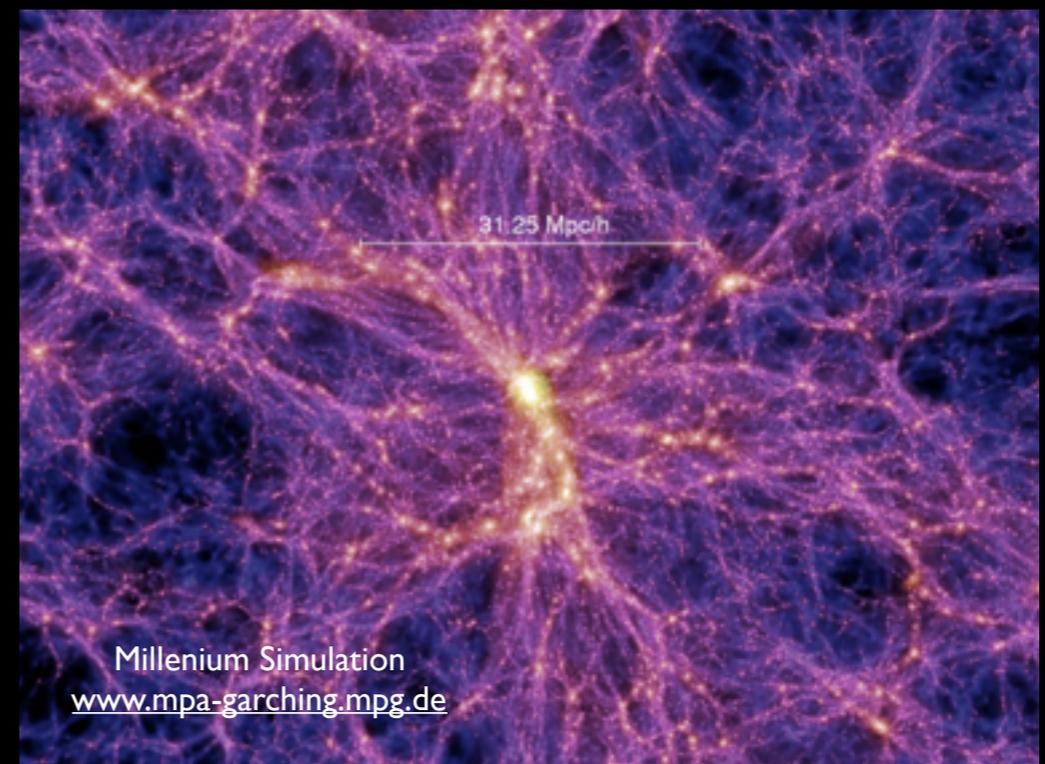
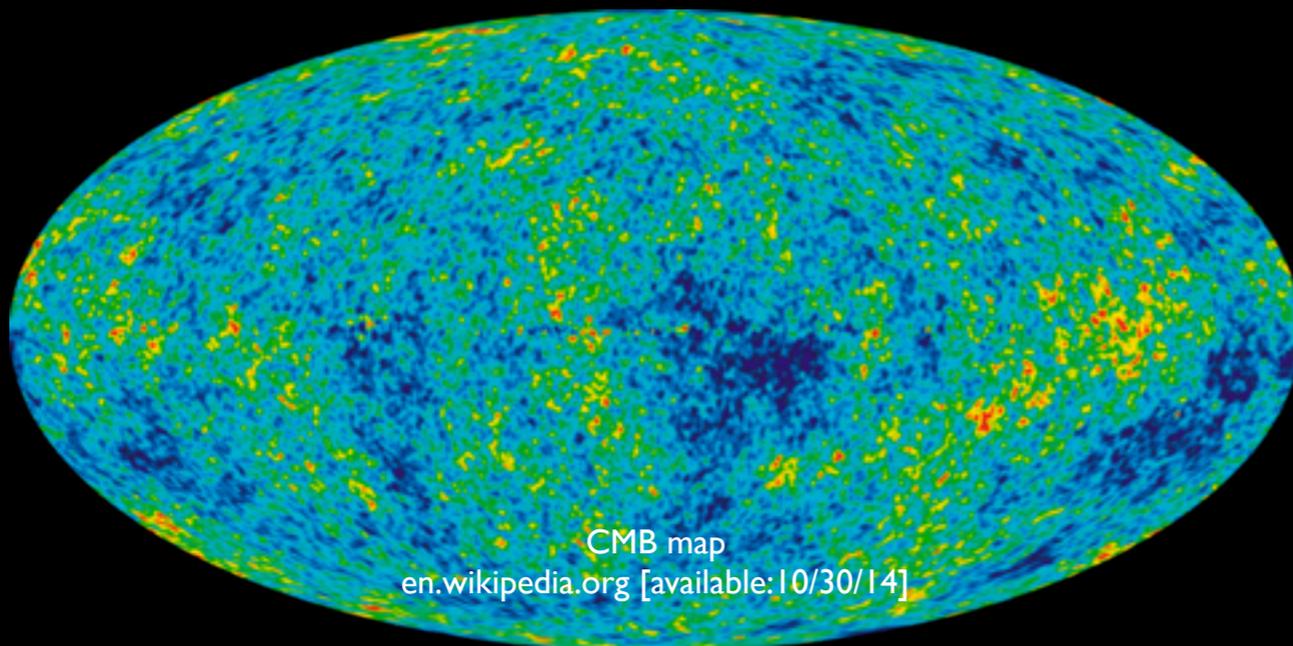


Primordial Fluctuations



Sean Carroll
www.preposterousuniverse.com
[Available:09/13/16]

Velocity dispersions, CMB maps, N-body simulations



Well What is DM?

Who can tell me?

Well What is DM?

Simple Answer?

or

Complicated Answer?

Well What is DM?

Simple Answer?

We don't know!!!!

Complicated Answer?

We don't know!!!!

Well What is DM?

We don't know!!!!

But we think we do

We have some ideas

Simple characteristics....

- Type of unobservable matter that interacts very weakly with ordinary matter
- Does not emit nor does it absorb light
- Only interacts through gravity
- Is responsible for structure formation

Cosmic Glue

So how is DM responsible for structure formation?

DM mostly interacts gravitationally

It clumps up and forms “wells”

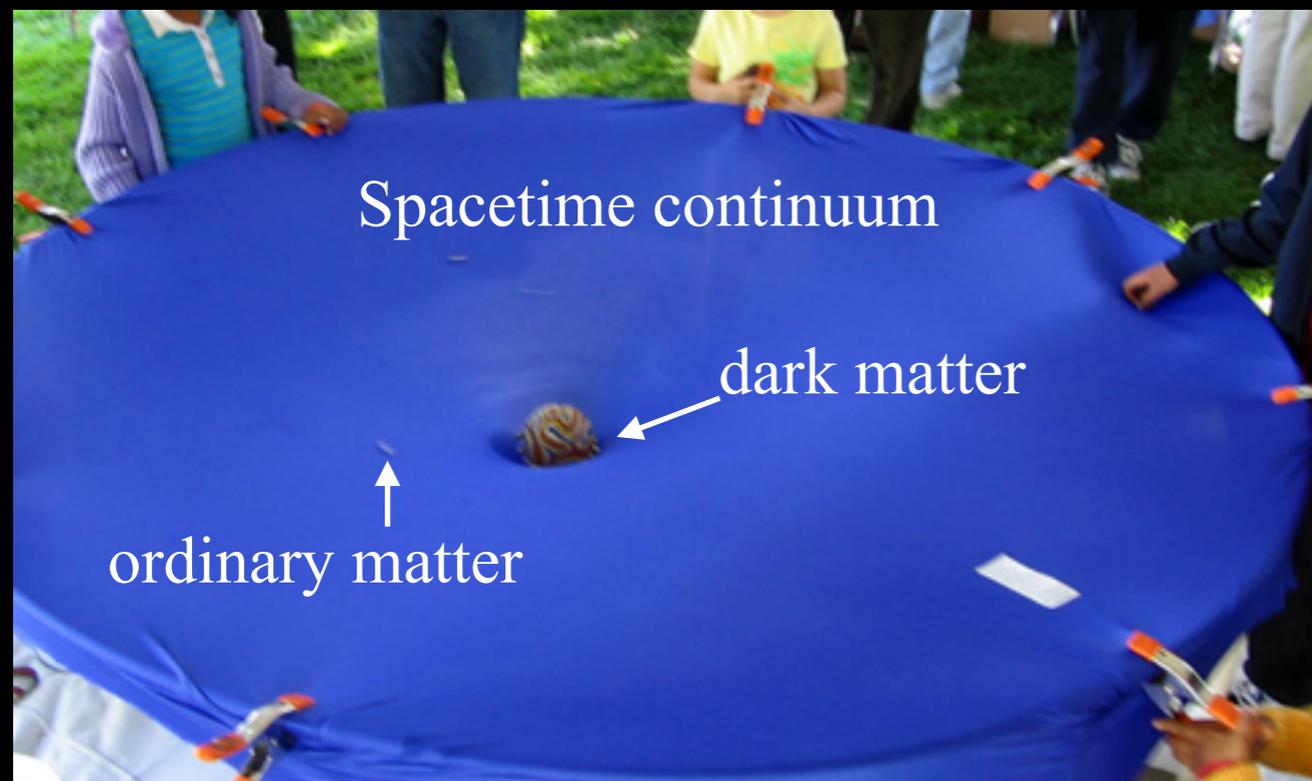
Ordinary matter falls in these “wells”

So how is DM responsible for structure formation?

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Rubber sheet with bowling ball and marbles

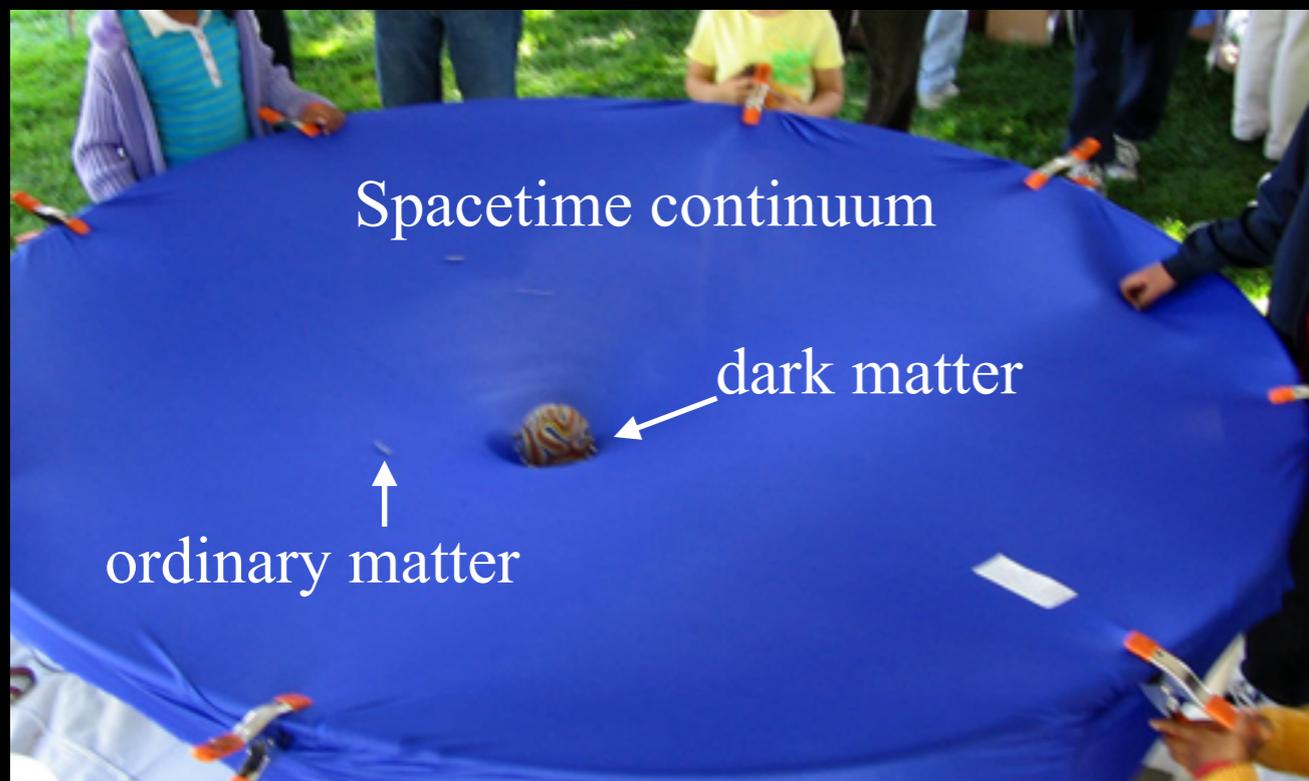
So how is DM responsible for structure formation?

DM mostly interacts gravitationally

It clumps up and forms “wells”

Ordinary matter falls in these “wells”

Well known example



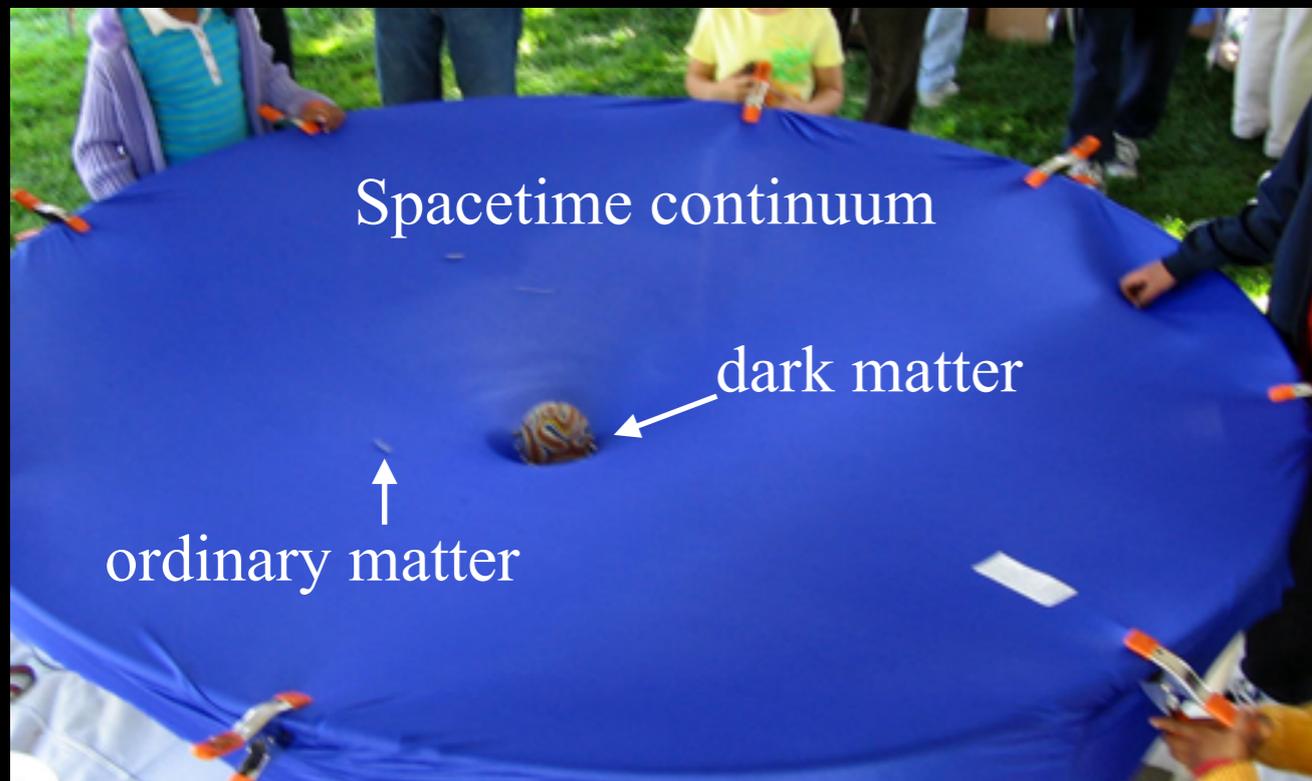
Rubber sheet with bowling ball and marbles

So how is DM responsible for structure formation?

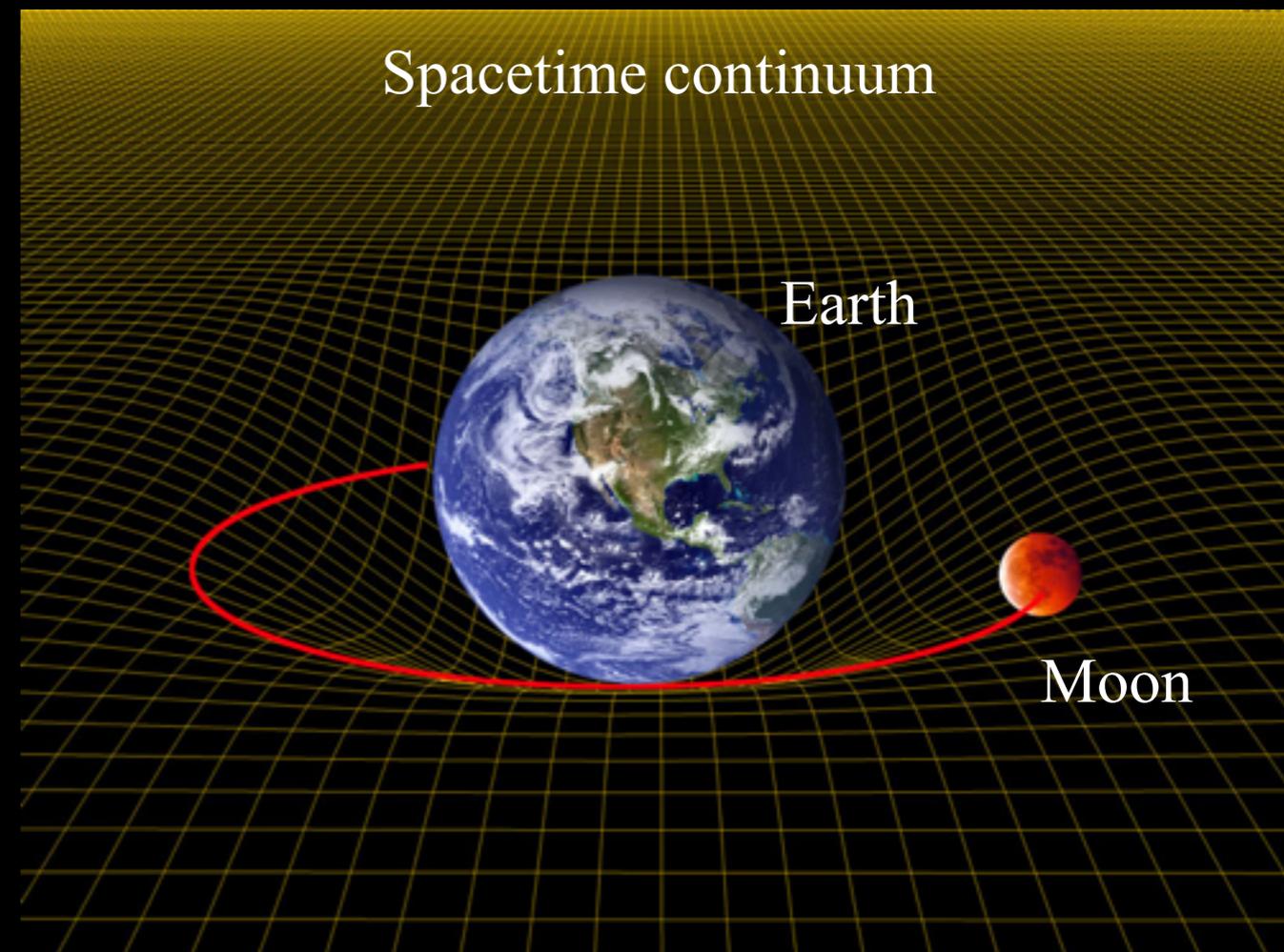
DM mostly interacts gravitationally

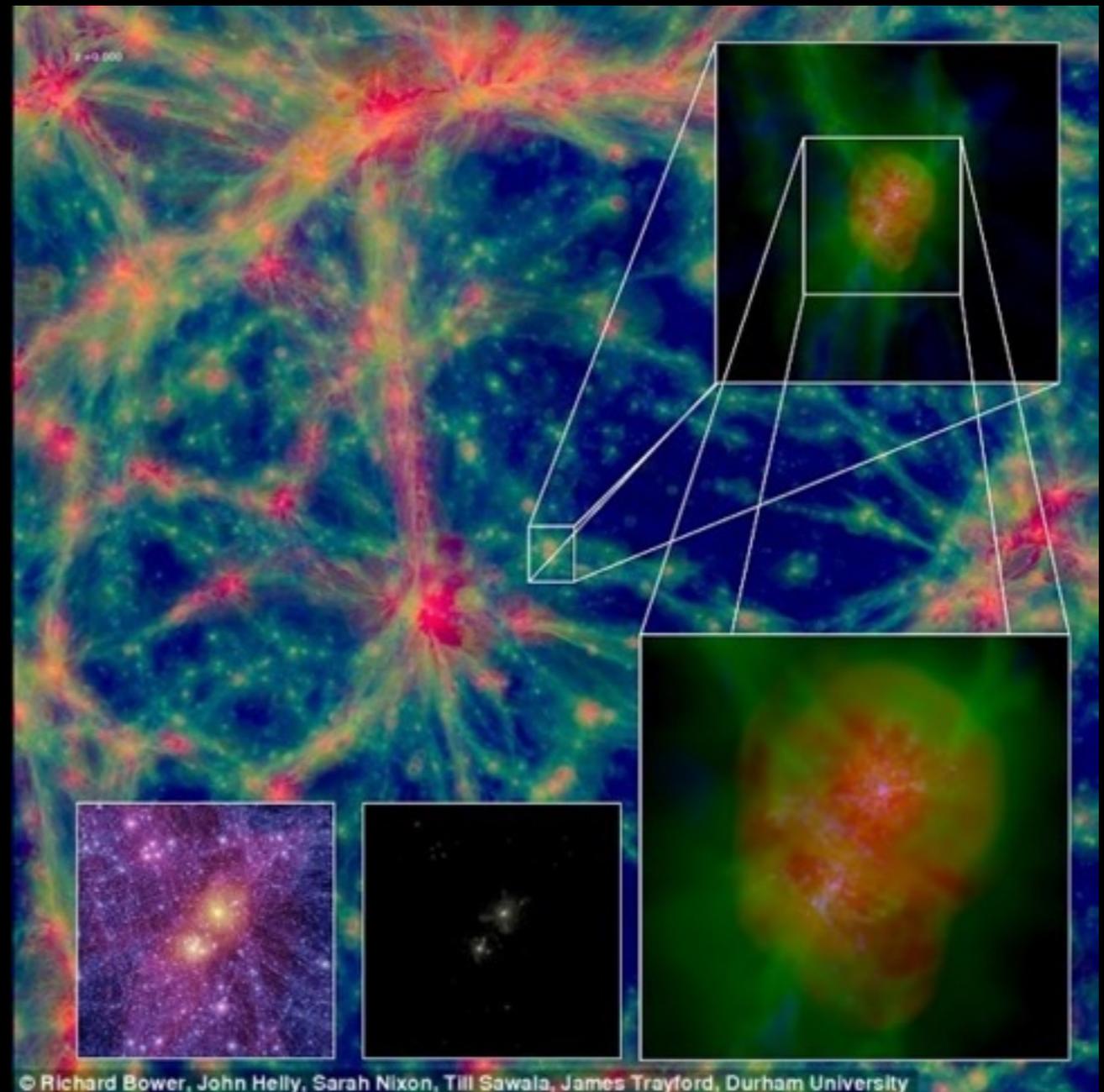
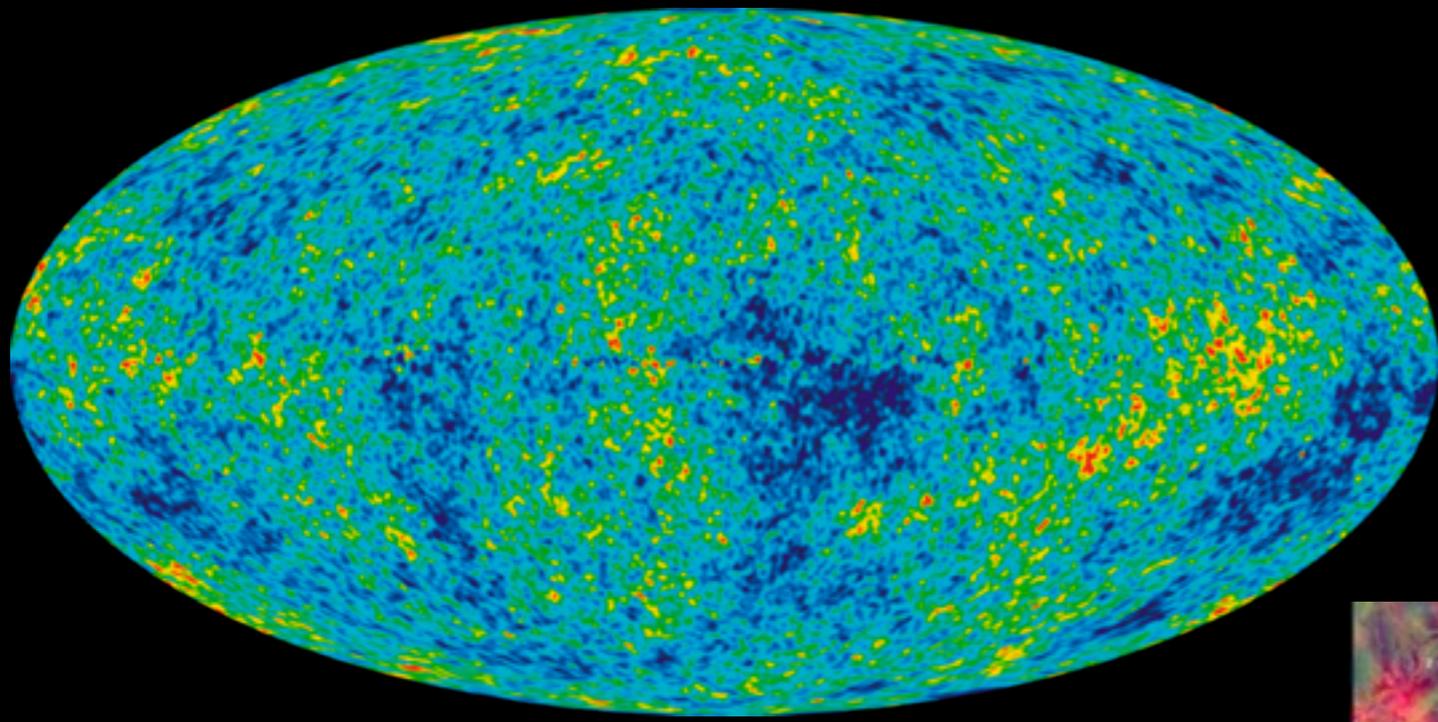
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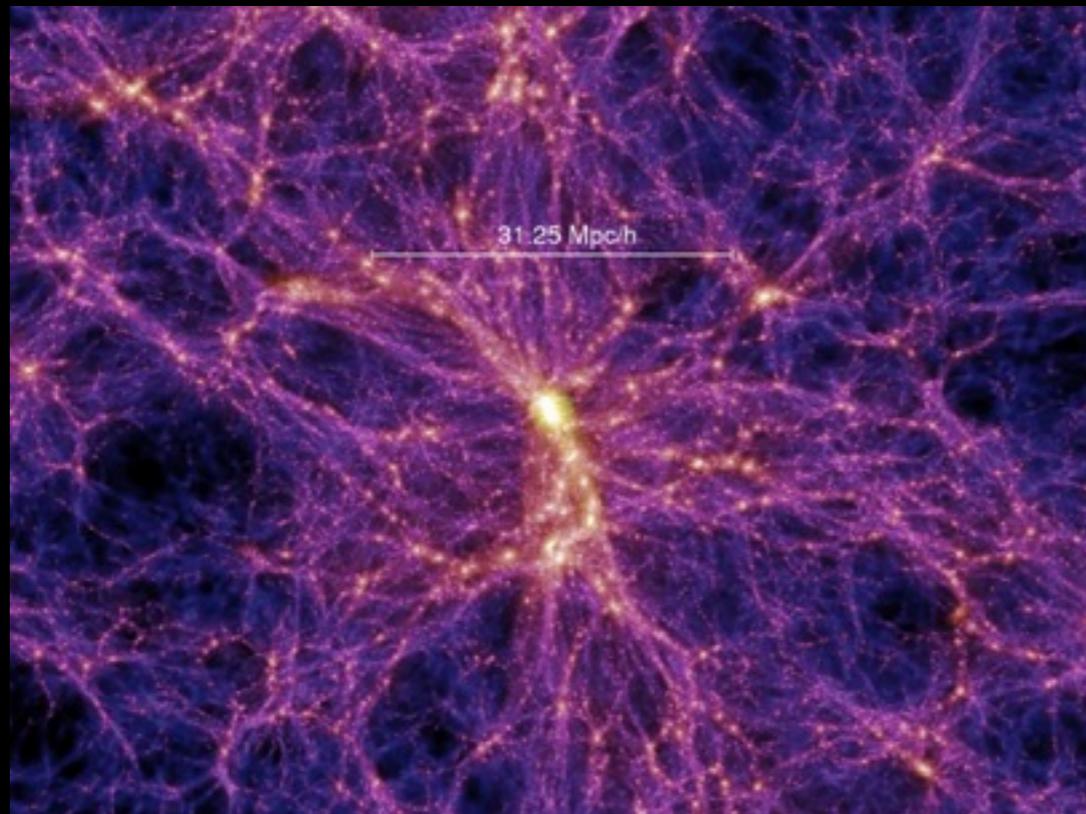


Rubber sheet with bowling ball and marbles





© Richard Bower, John Helly, Sarah Nixon, Till Sawala, James Trayford, Durham University



Ok but Fundamentally, what is DM?

Microscopic properties?

From Astrophysics and Cosmology we infer:

- DM most likely elementary particle

Ok but Fundamentally, what is DM?

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- It must be cold i.e. non-relativistic

Ok but Fundamentally, what is DM?

Microscopic properties?

From Astrophysics and Cosmology we infer:

- DM most likely elementary particle
- It must be cold i.e. non-relativistic
- It must be stable i.e. long-lived, not decay

Ok but Fundamentally, what is DM?

Microscopic properties?

From Astrophysics and Cosmology we infer:

- DM most likely elementary particle
- It must be cold i.e. non-relativistic
- It must be stable i.e. long-lived, not decay
- It must interact very weakly

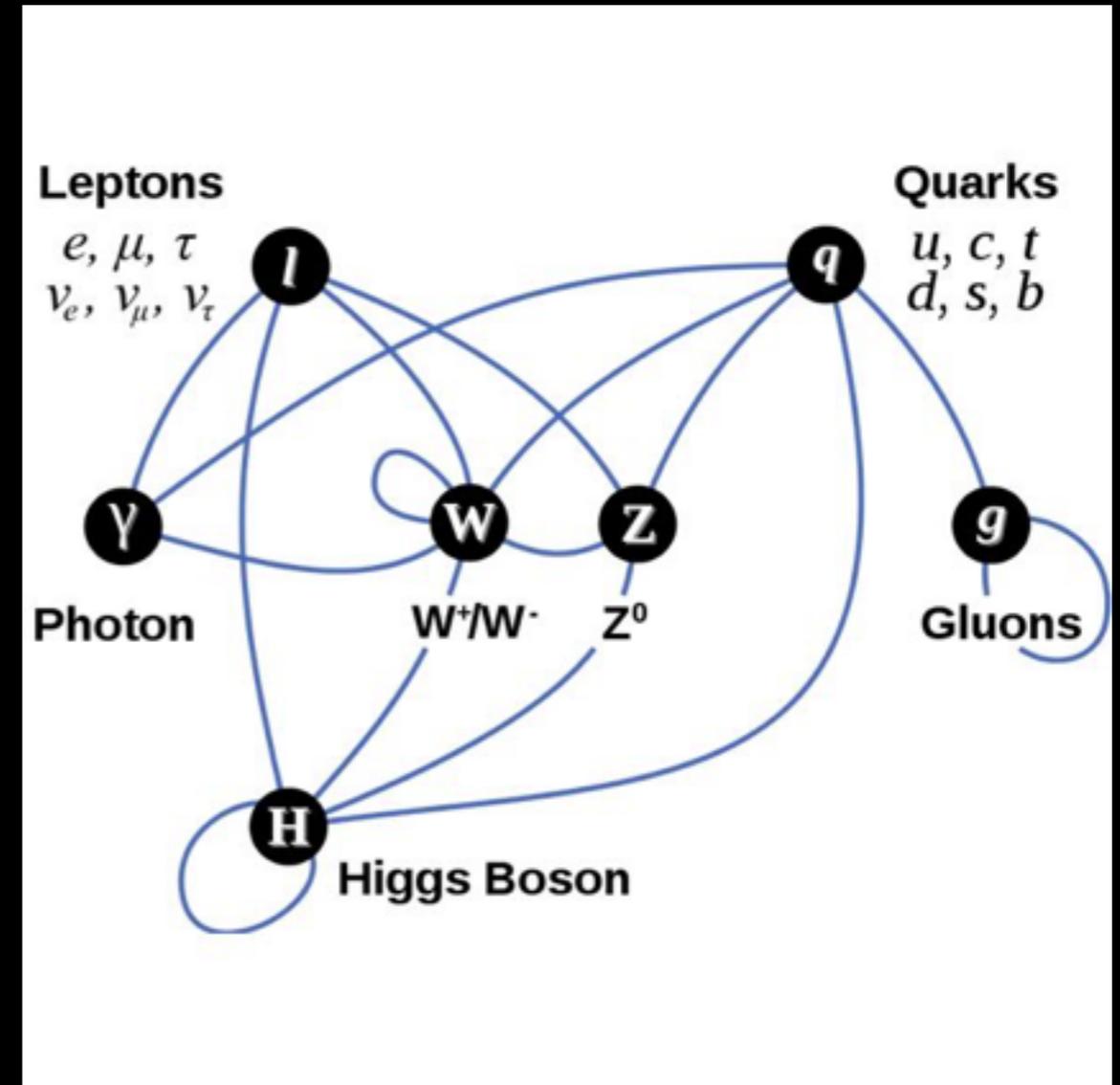
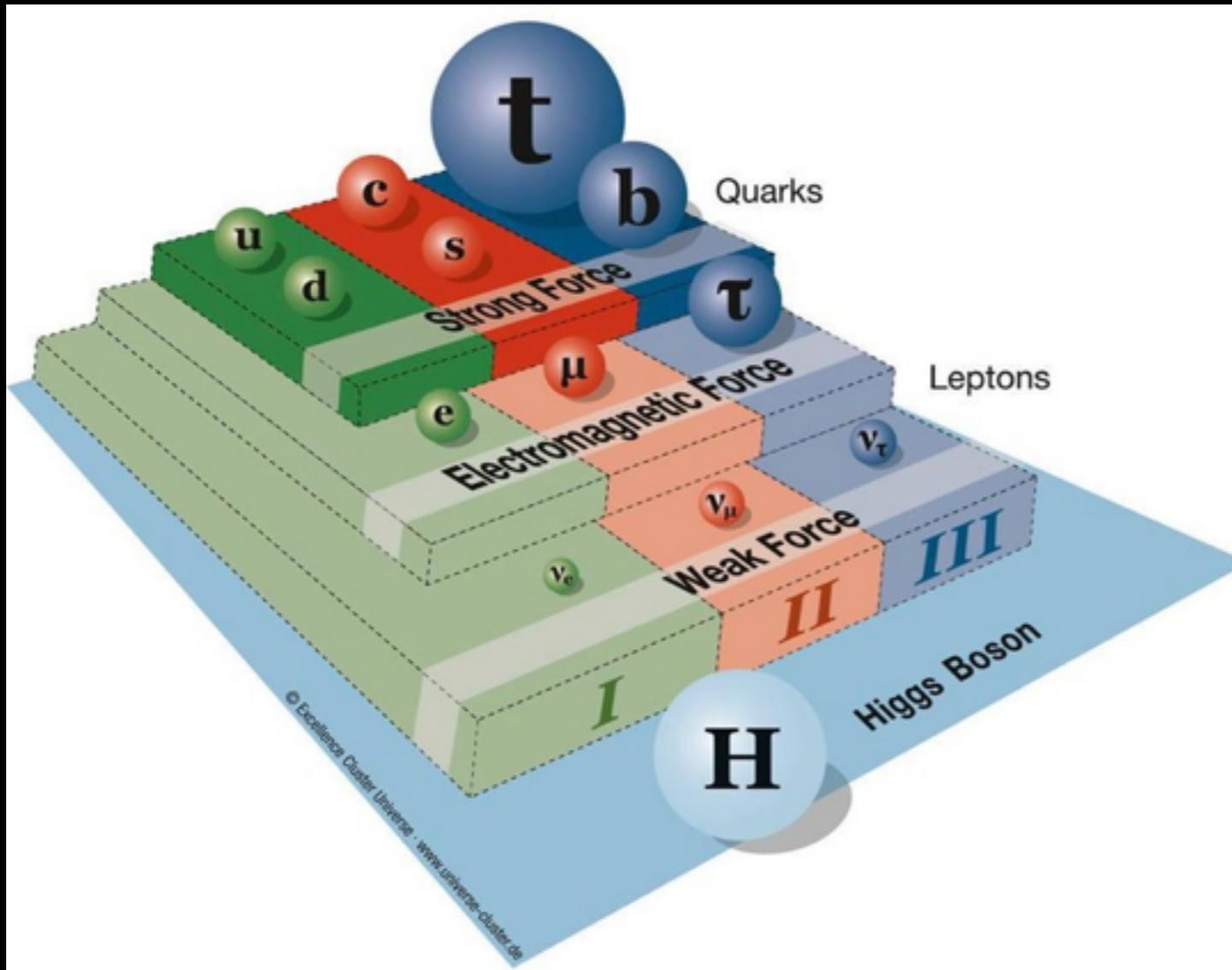
What could possibly fit these criteria?

Where can we start to look?

We can start with the theory we know the most.

What Theory is this?

Standard Model of Particle Physics



Elementary particle theory been successful at explaining current data

Standard Model of Particle Physics

Standard Model of Particle Physics

Can someone name a dark matter
Candidate in the SM?

Standard Model of Particle Physics

It cannot explain some of recently observed data

Both from particle physics and astrophysics



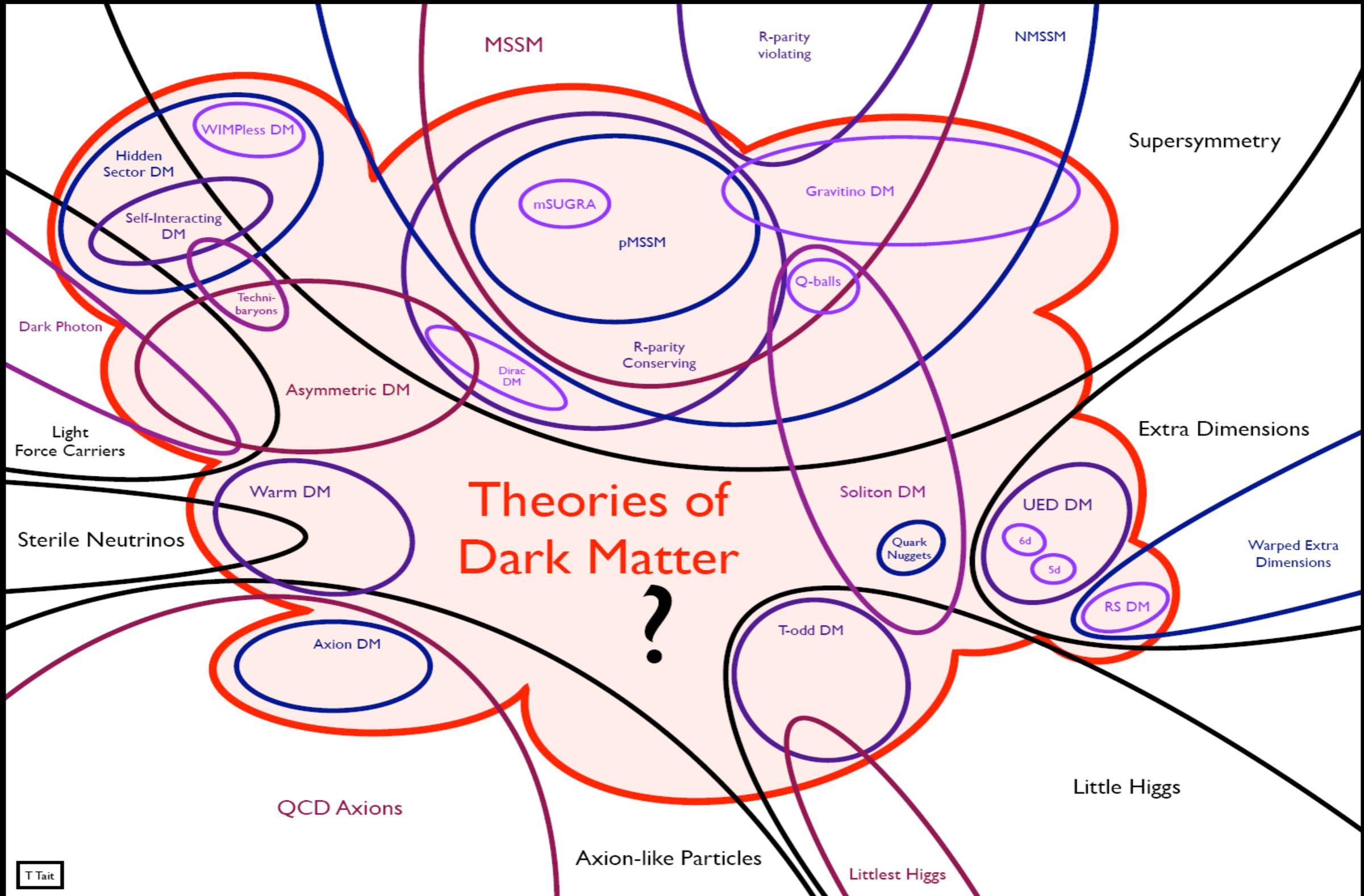
Does not have microscopic description
of Dark Matter

So then what can it be?

Look for elementary particles beyond the SM

So then what can it be?

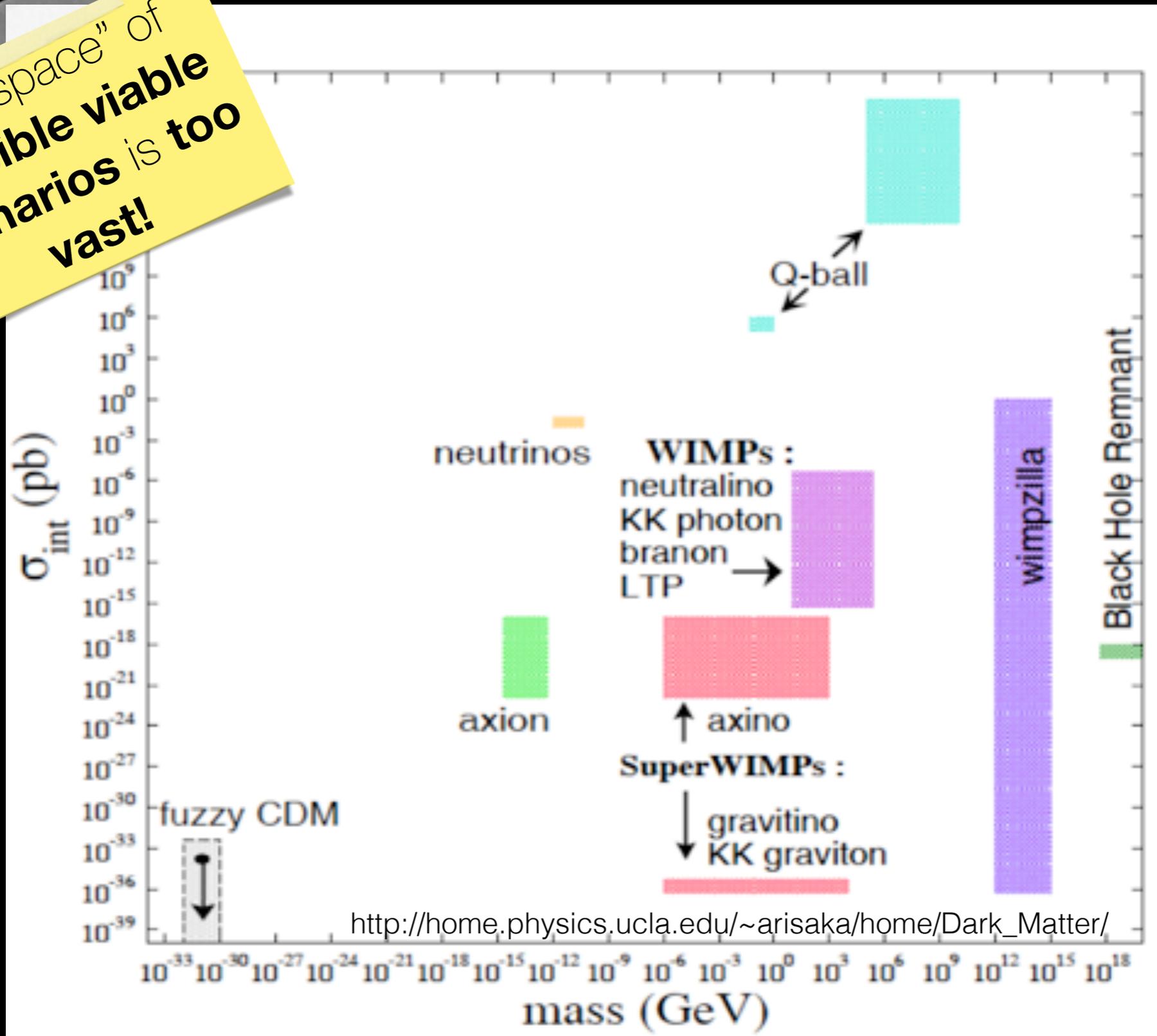
Look for elementary particles beyond the SM



Dark Matter Complementarity

- We have no sense of where new physics is hiding

The "space" of possible viable scenarios is too vast!



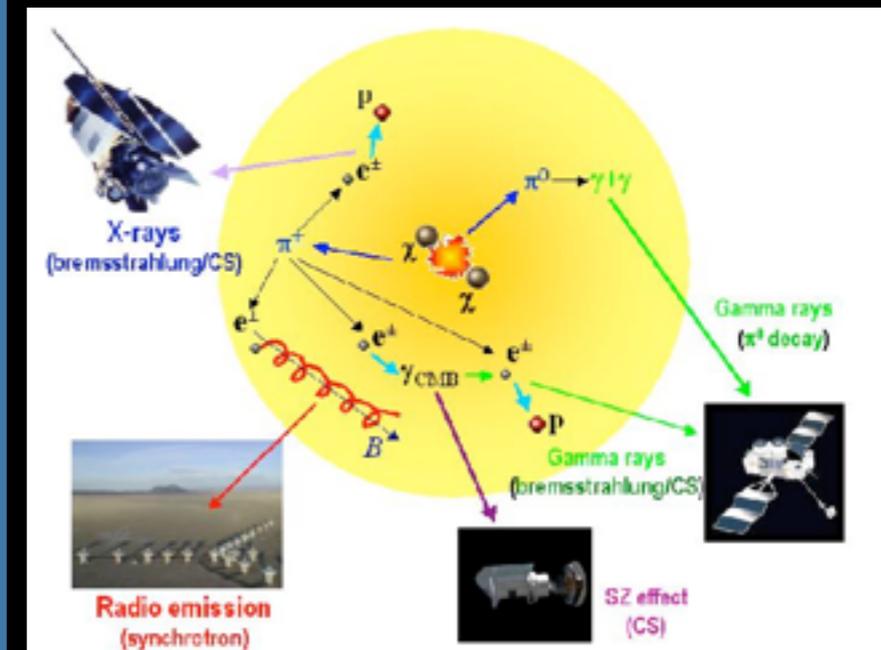
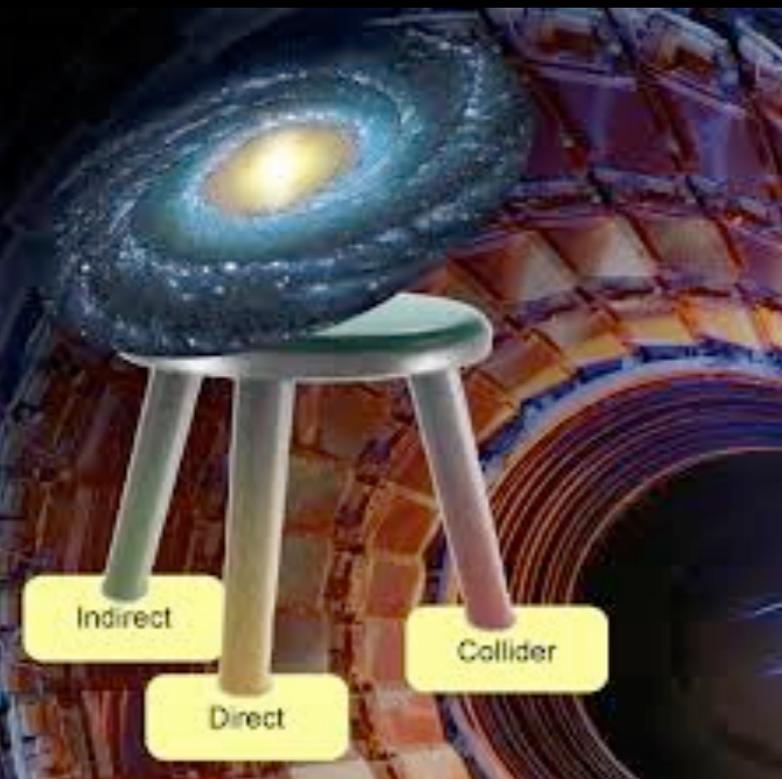
How can we possibly look for
something we don't know?

How do we know what we are looking for?

How can we find DM?

- Four strategies of detection
 - Astrophysical Evidence
 - Direct Detection
 - production at Colliders
 - Indirect Detection

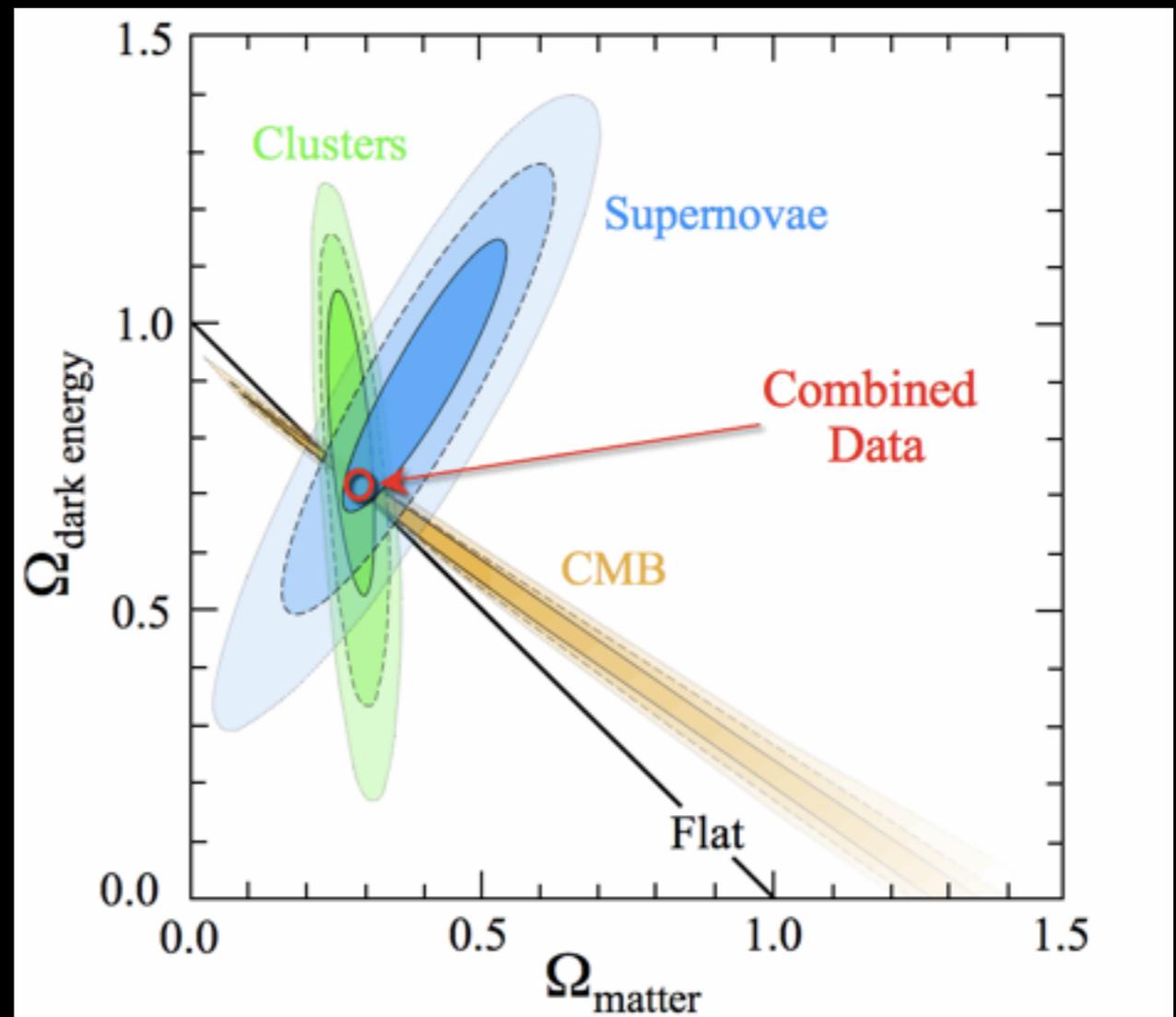
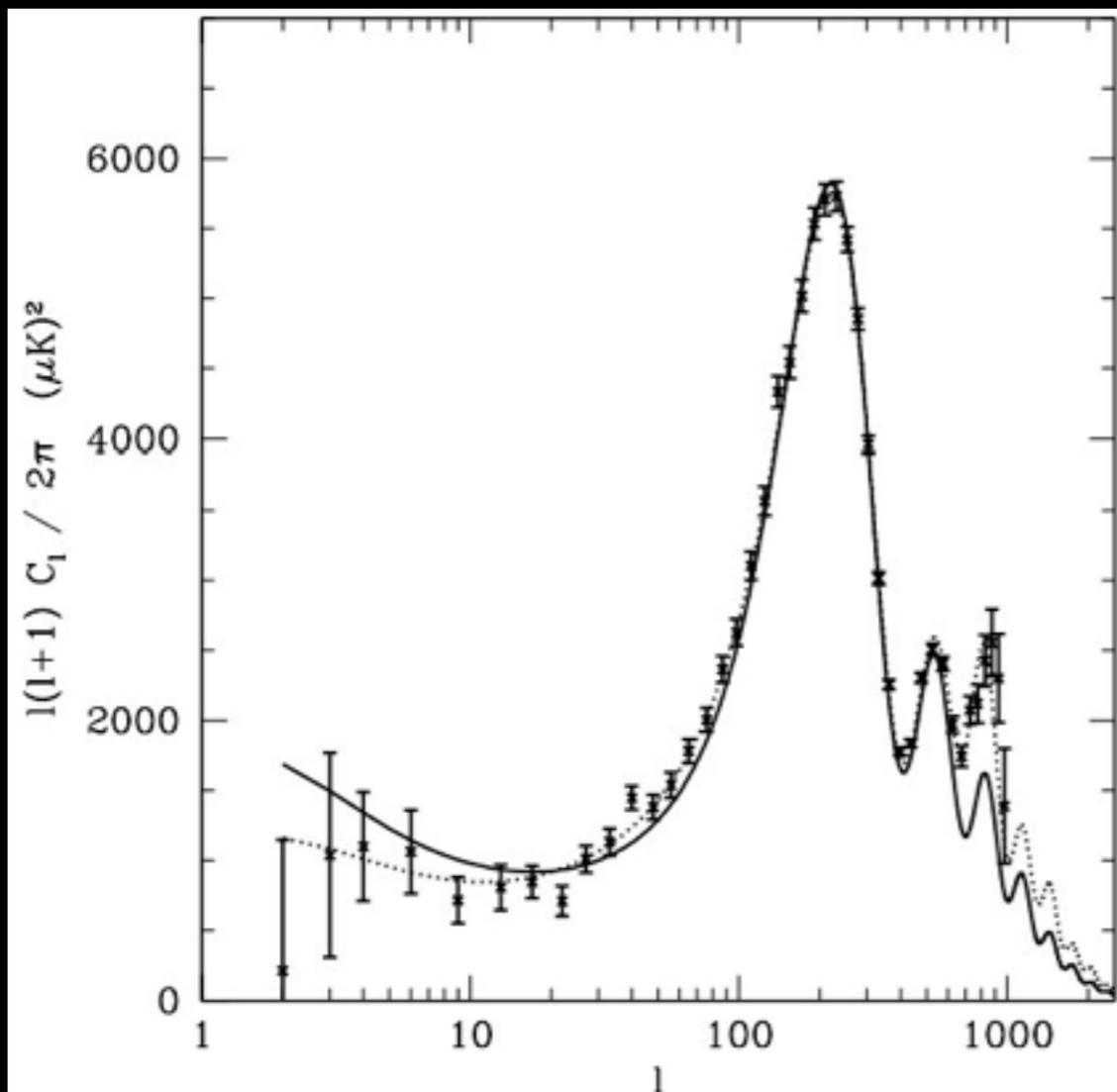
All complementary and important



inspirehep.net[available:10/31/14]

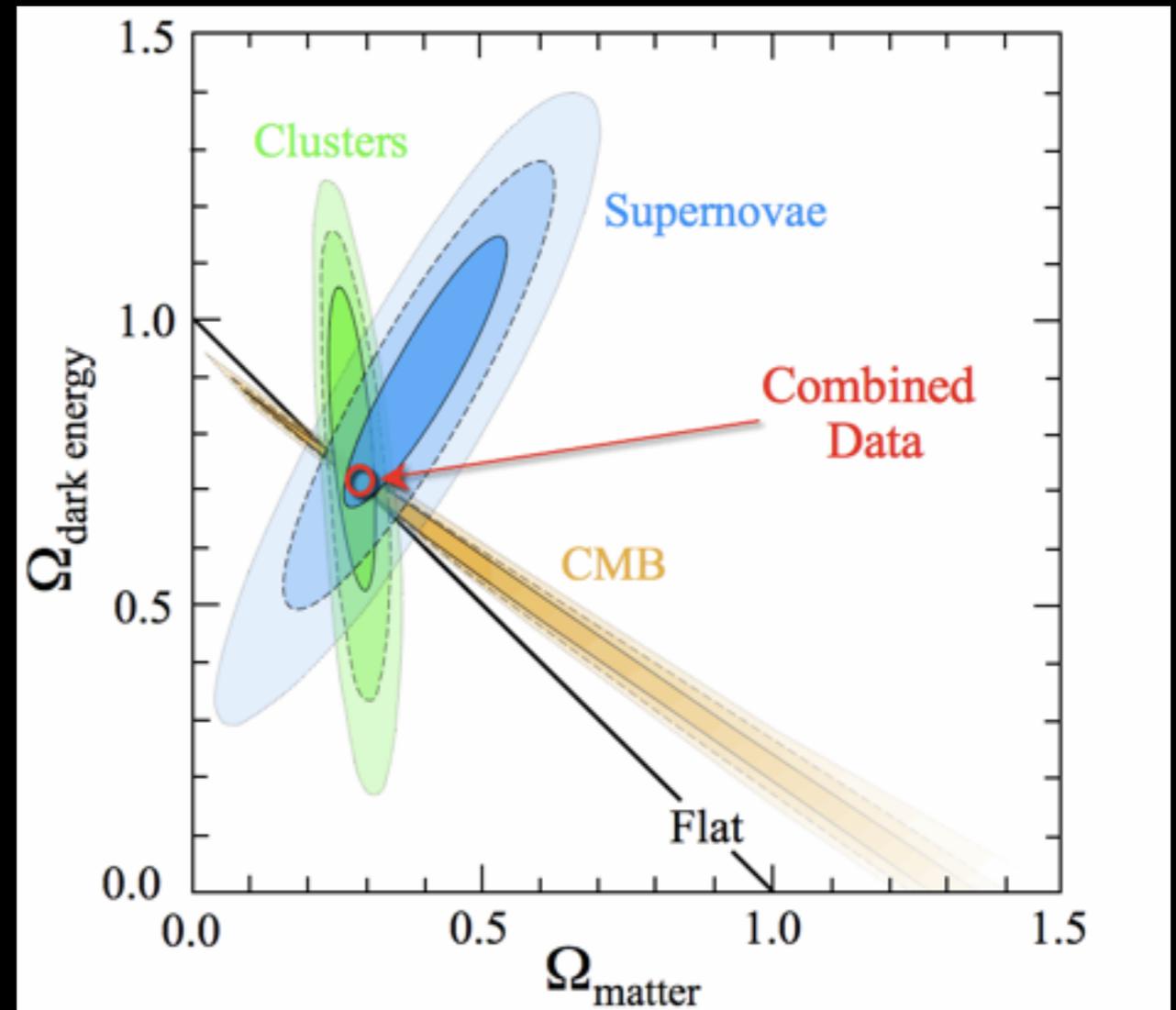
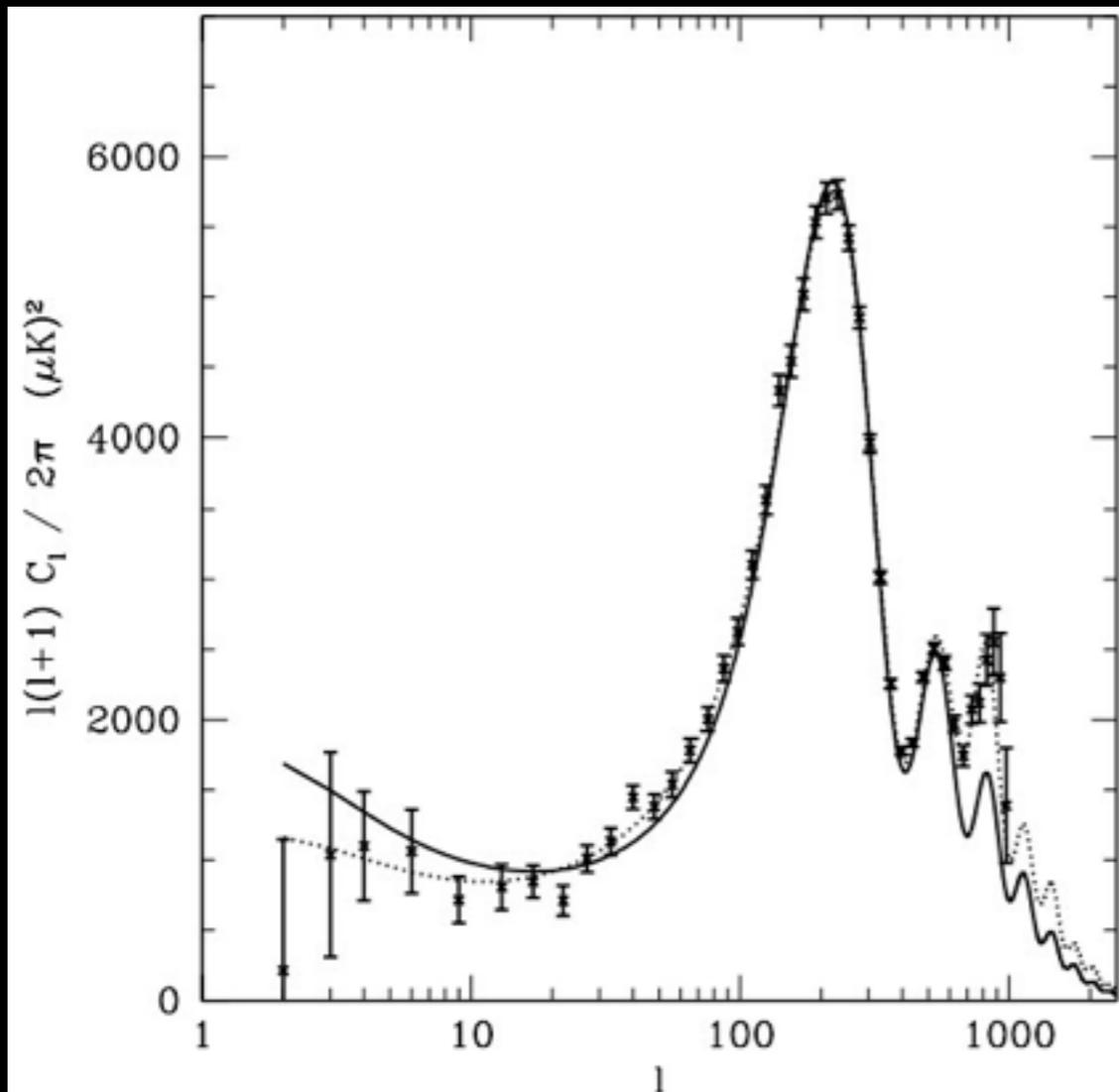
1. Astrophysical & Cosmological Evidence

- Use the gravitational interactions of DM to infer its energy density, i.e. how much DM there is in the Universe.
- Amount of DM in Universe is extracted from:



Astrophysical & Cosmological Evidence

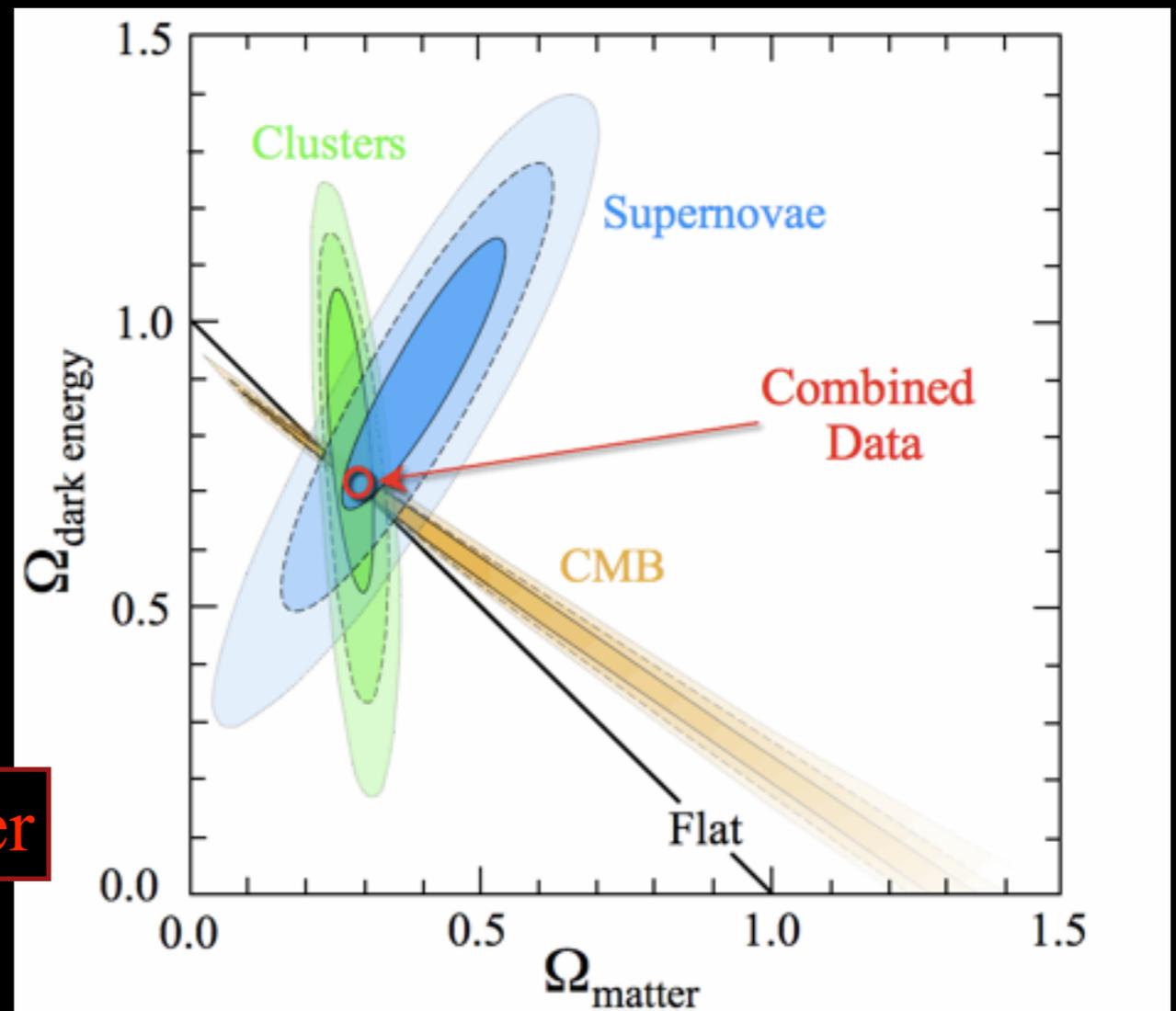
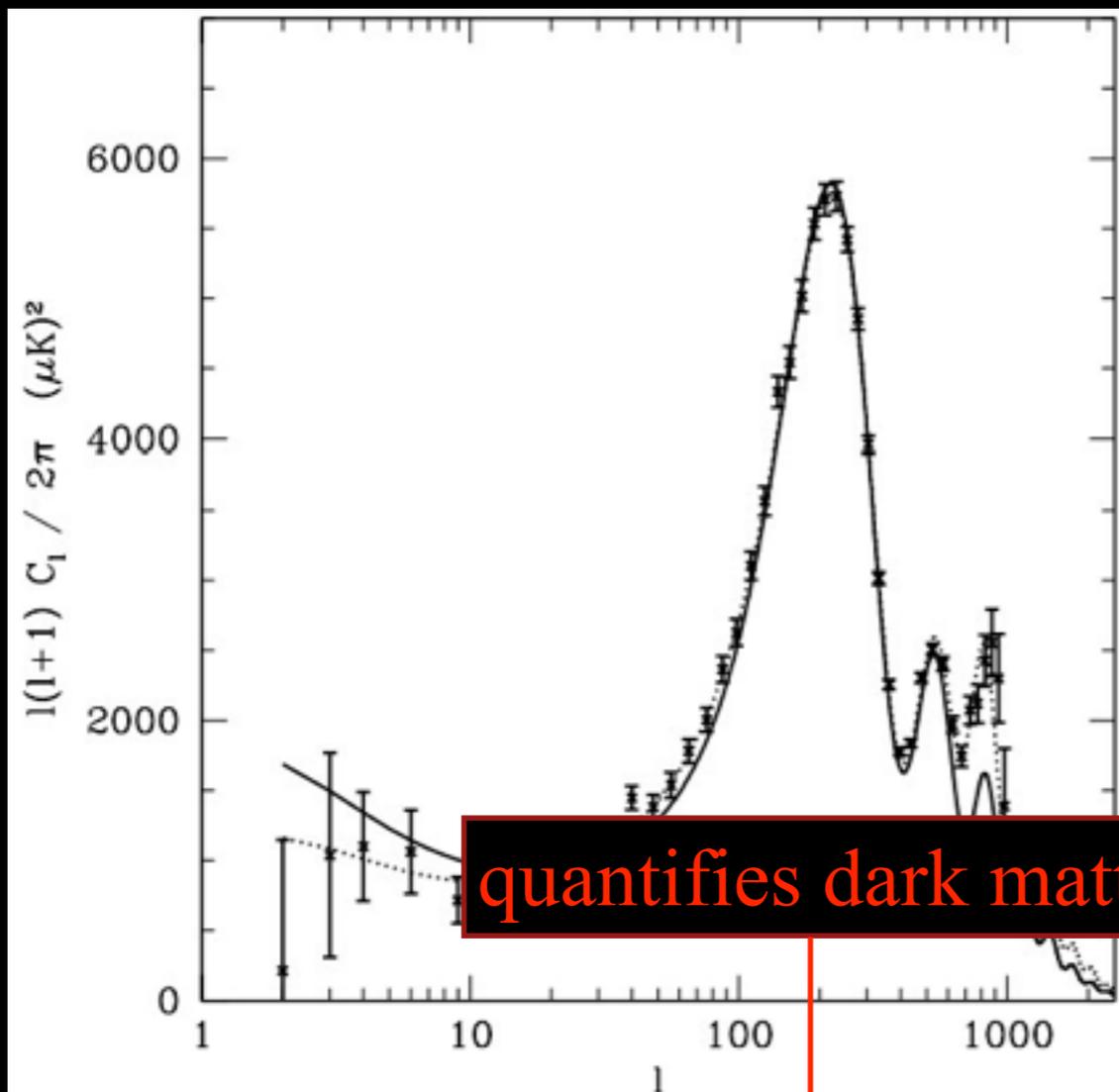
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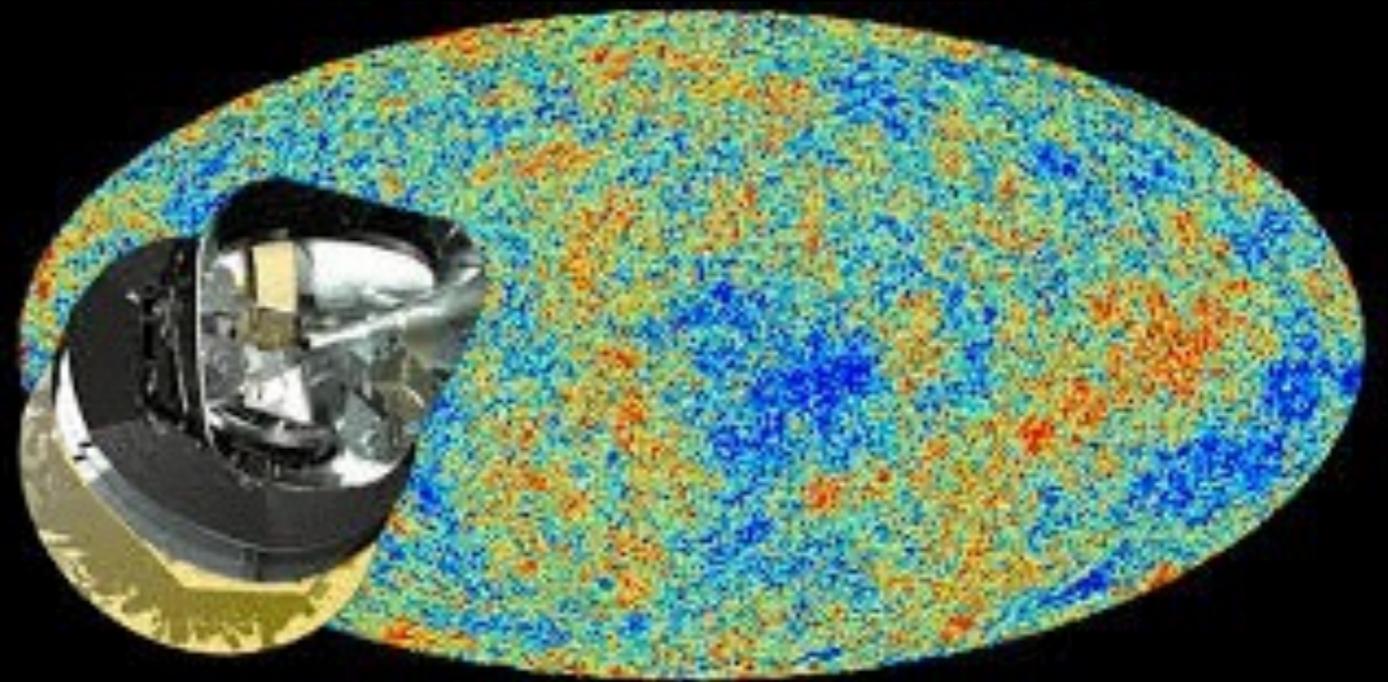
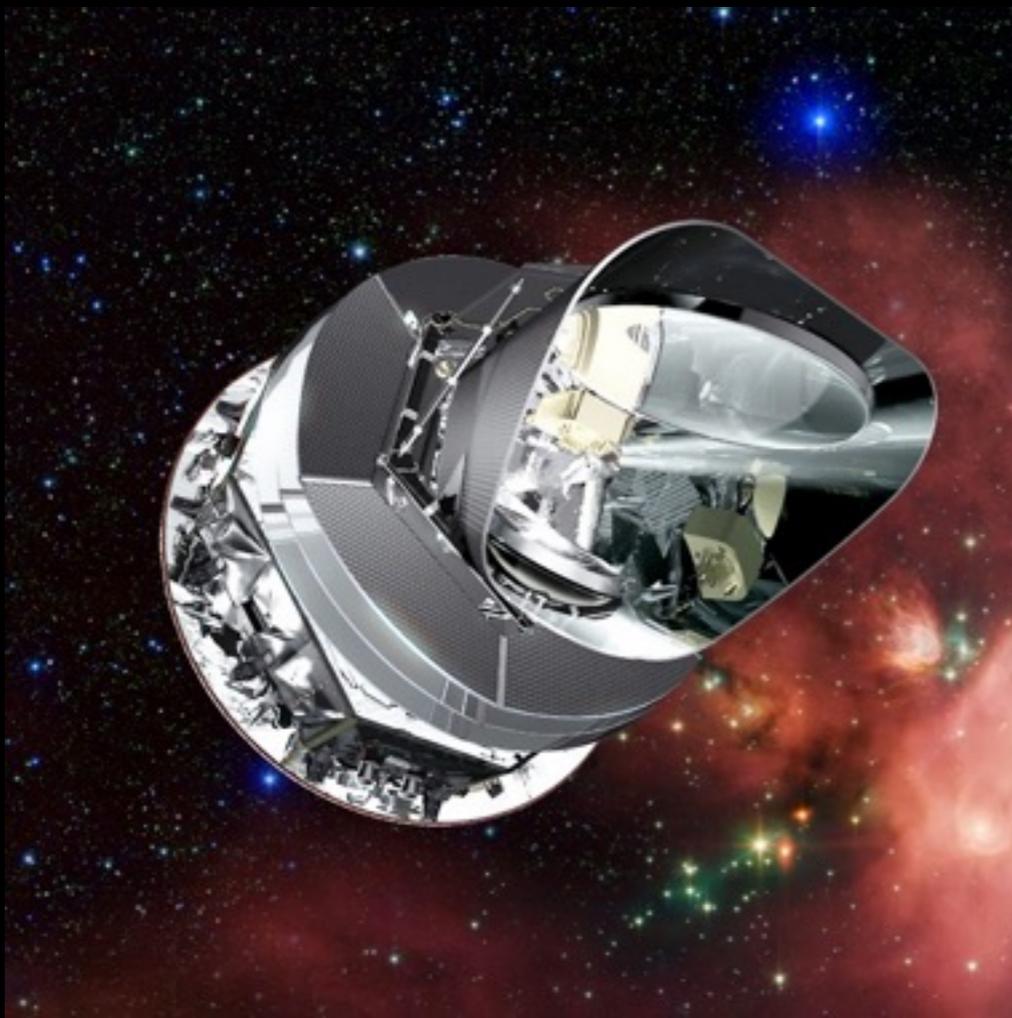
$$H(a) \equiv \frac{\dot{a}}{a} = H_0 \sqrt{(\Omega_c + \Omega_b)a^{-3} + \Omega_{rad}a^{-4} + \Omega_k a^{-2} + \Omega_\Lambda a^{-3(1+w)}}$$

Astrophysical & Cosmological Evidence

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$$H(a) \equiv \frac{\dot{a}}{a} = H_0 \sqrt{(\Omega_c + \Omega_b)a^{-3} + \Omega_{rad}a^{-4} + \Omega_k a^{-2} + \Omega_\Lambda a^{-3(1+w)}}$$



Planck Collaboration: Cosmological parameters

Table 3. Parameters of the base Λ CDM cosmology computed from the 2015 baseline *Planck* likelihoods, illustrating the consistency of parameters determined from the temperature and polarization spectra at high multipoles. Column [1] uses the *TT* spectra at low and high multipoles and is the same as column [6] of Table 1. Columns [2] and [3] use only the *TE* and *EE* spectra at high multipoles, and only polarization at low multipoles. Column [4] uses the full likelihood. The last column lists the deviations of the cosmological parameters determined from the *Planck* TT+lowP and *Planck* TT,TE,EE+lowP likelihoods.

Parameter	[1] <i>Planck</i> TT+lowP	[2] <i>Planck</i> TE+lowP	[3] <i>Planck</i> EE+lowP	[4] <i>Planck</i> TT,TE,EE+lowP	([1] - [4])/ $\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

The Planck Satellite tells us that the amount of
DM in the Universe is:

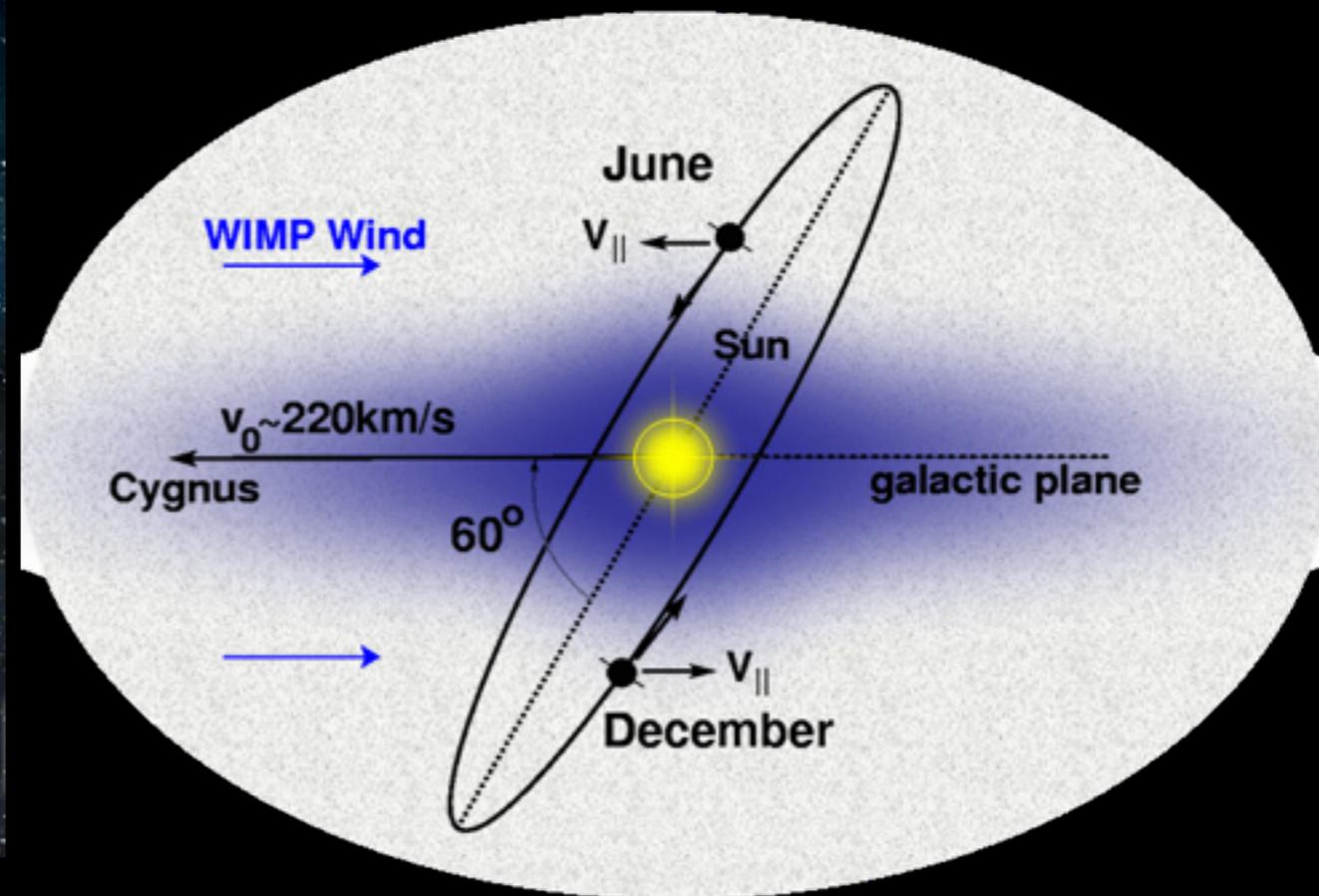
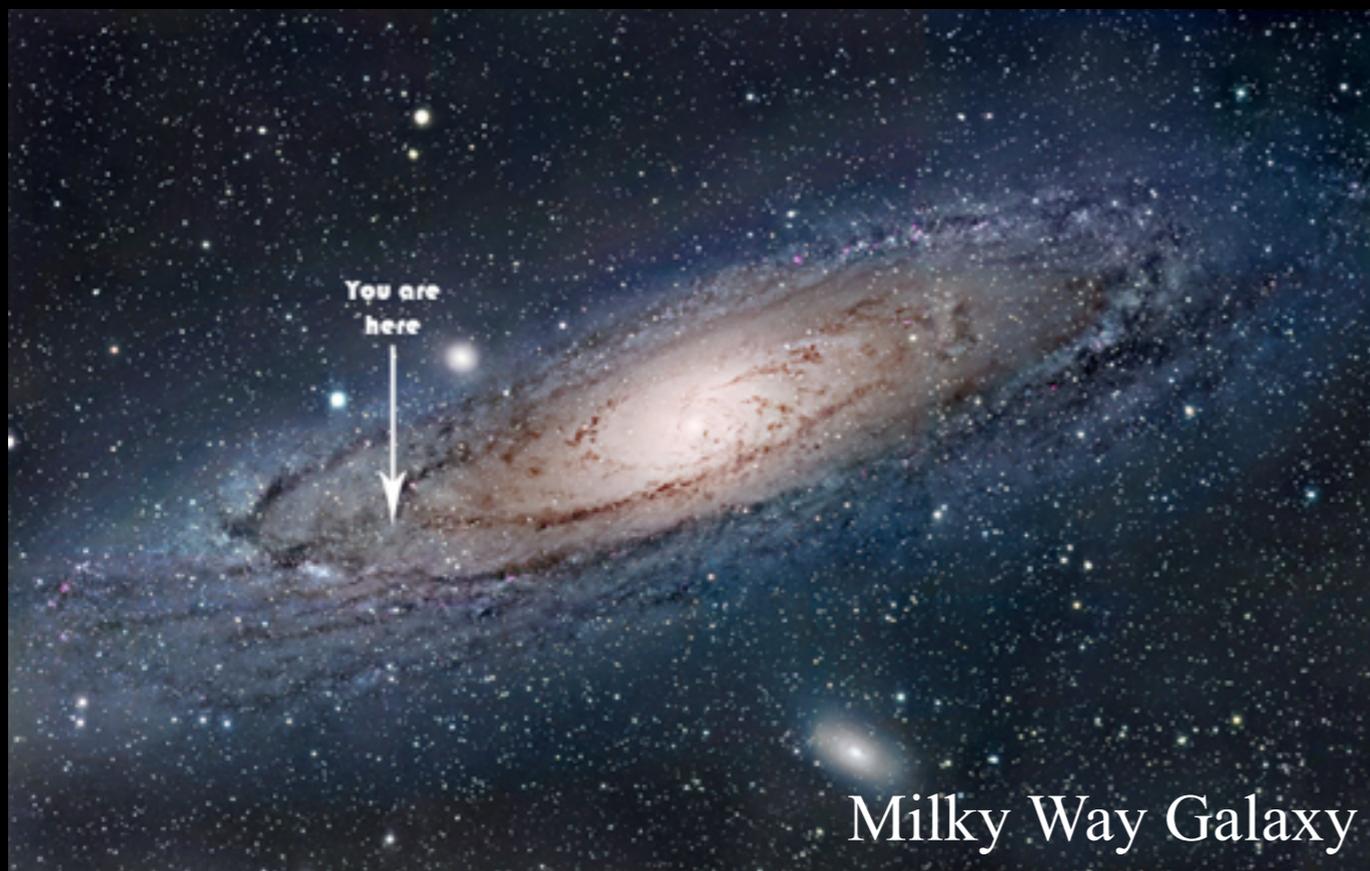
$$\Omega h^2 \sim 0.12$$

We call this the
Relic Density/Relic Abundance

Any DM model you come up with has to satisfy this value

2. Direct Detection

Consider the following:



As sun moves around galactic plane Earth gets hit by DM wind

DM wind moves through Earth so put detectors on the Earth and see what you see

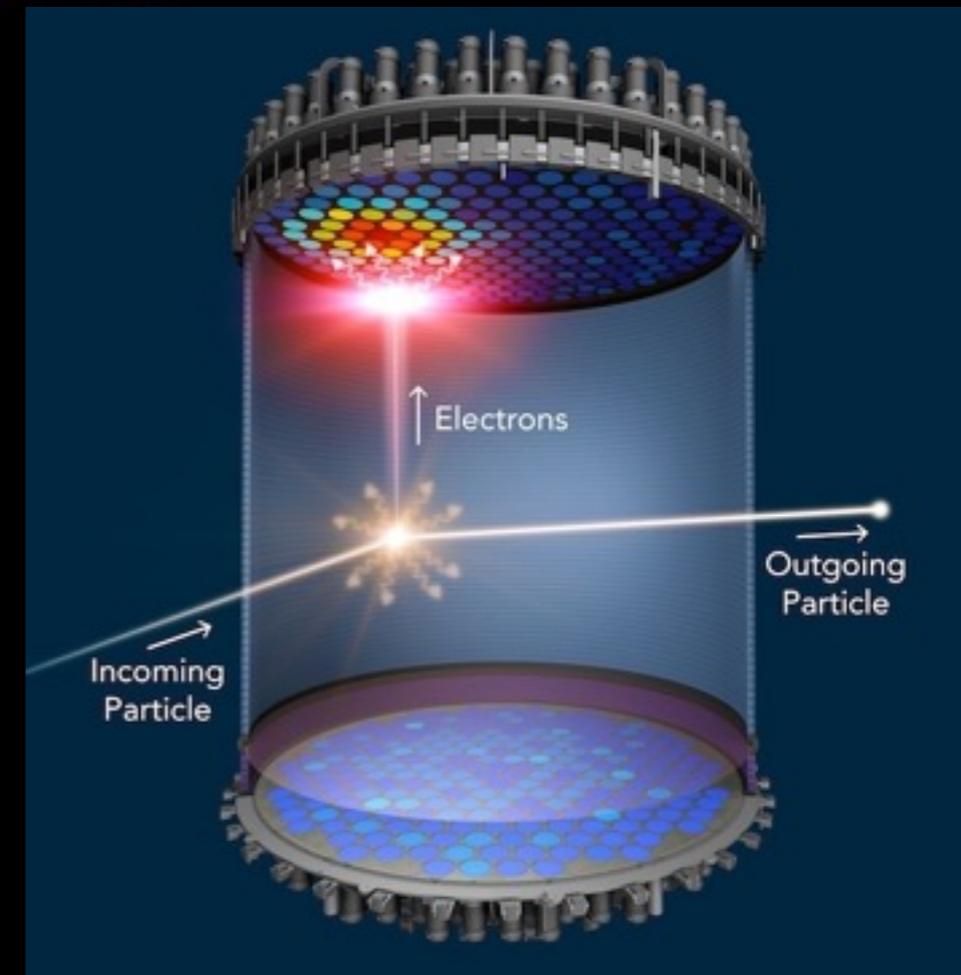
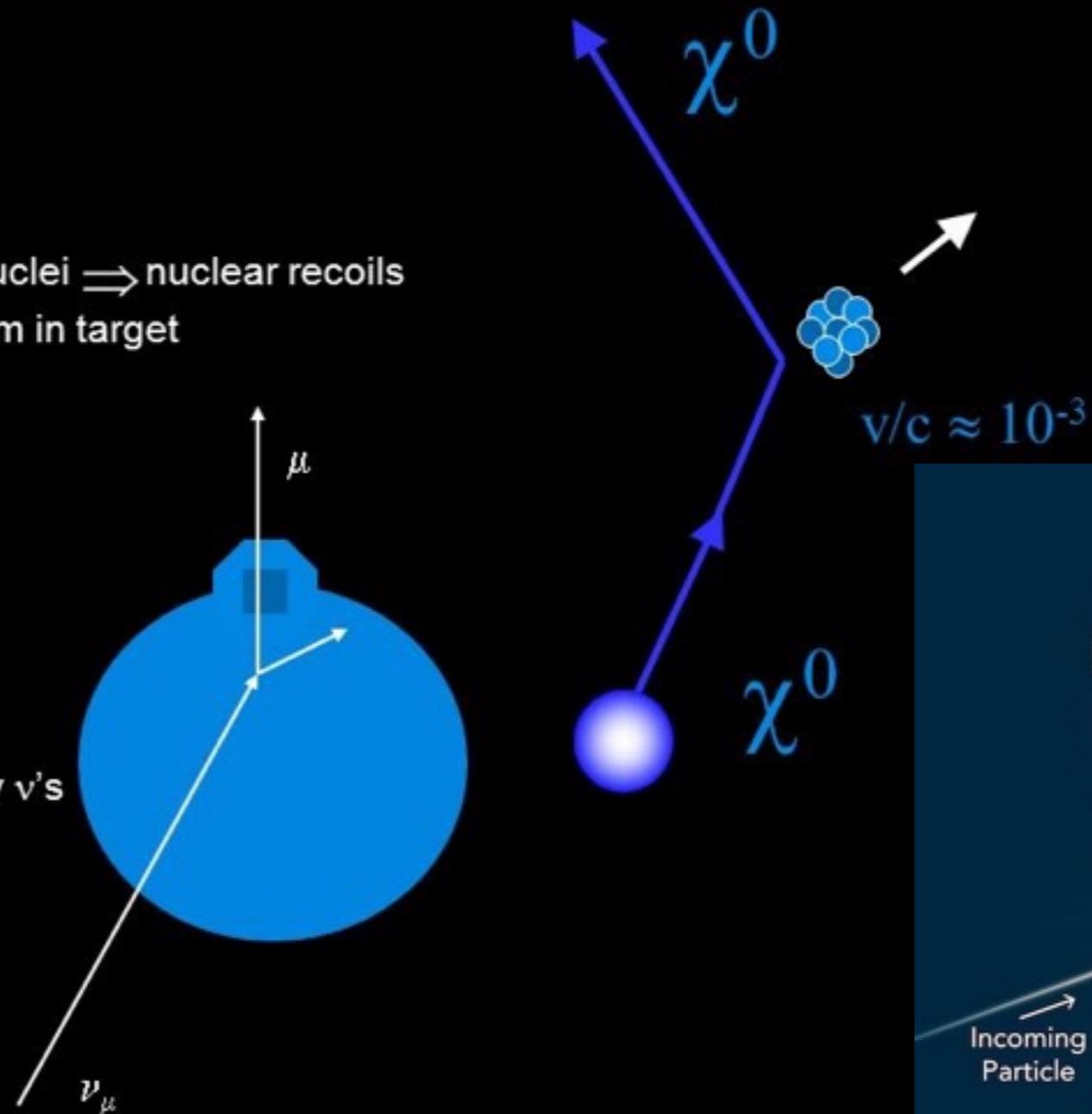
Detecting WIMPs

Direct detection:

WIMPs elastically scatter off nuclei \Rightarrow nuclear recoils
Measure recoil energy spectrum in target

Indirect detection:

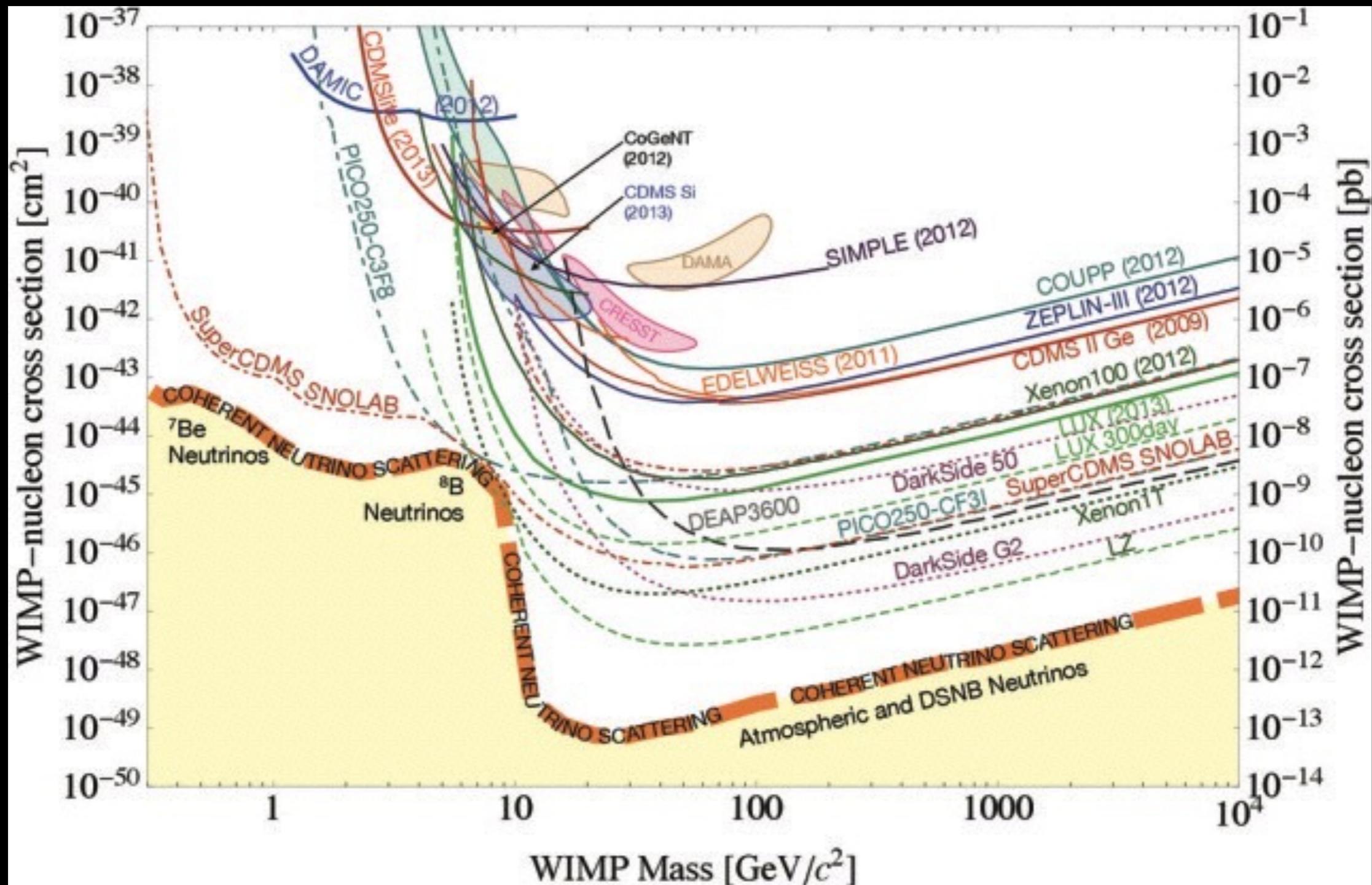
WIMPs annihilate
in halo: e^+ , \bar{p} , γ
in Sun, Earth core: high energy ν 's



Remember the lecture by Prof. Ellis

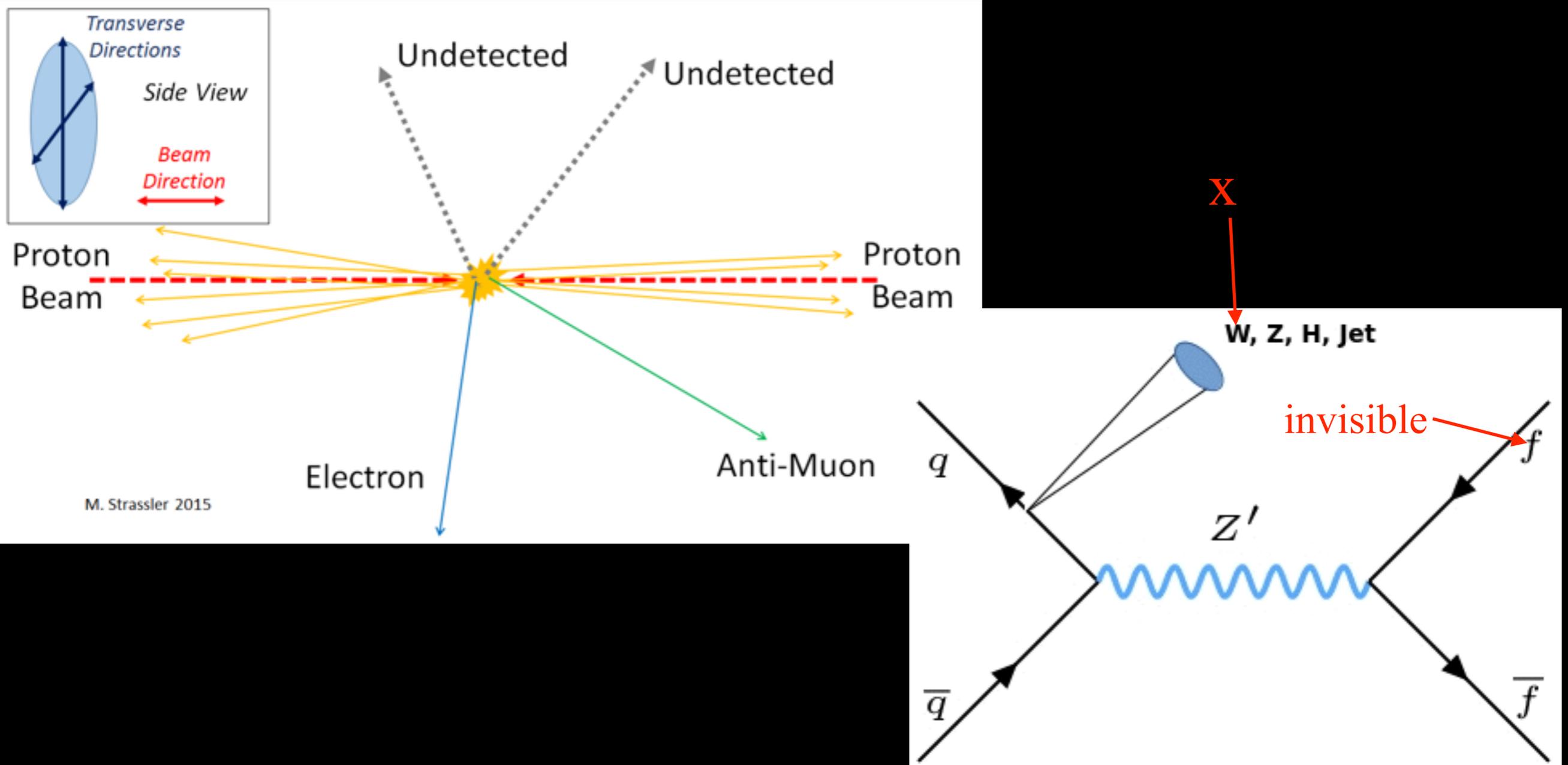
Experiments usually represent results in scattering cross-section vs DM mass space

scattering cross-section = probability of DM scattering off nucleus



3. Production at particle Colliders

Colliders are controlled environments in which we may produce DM particles



Can be detected through Mono-X signatures

Experiments include:



BaBar Experiment SLAC

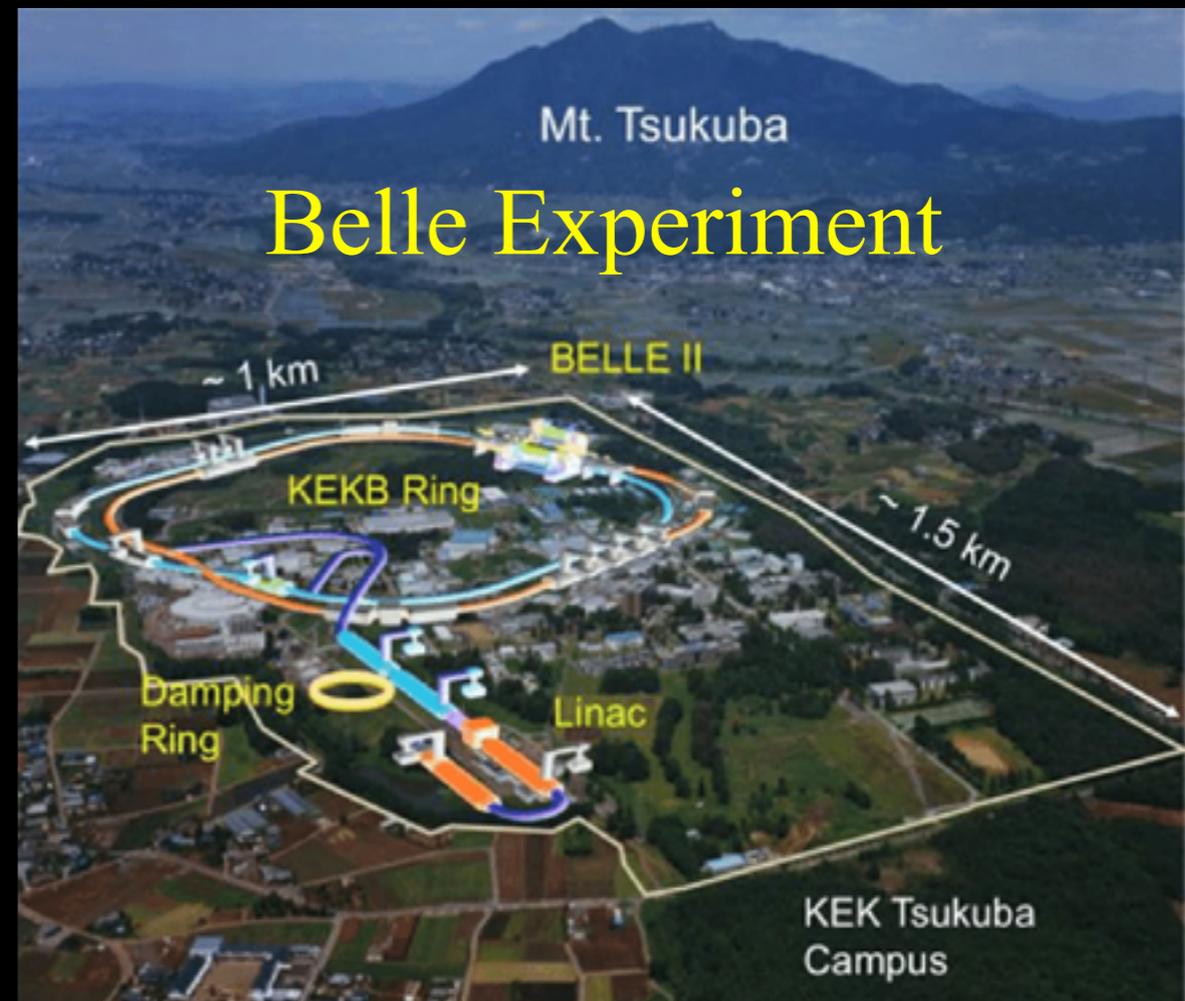
SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BABAR



Both Rings Housed in Current PEP Tunnel

5-95
6355461

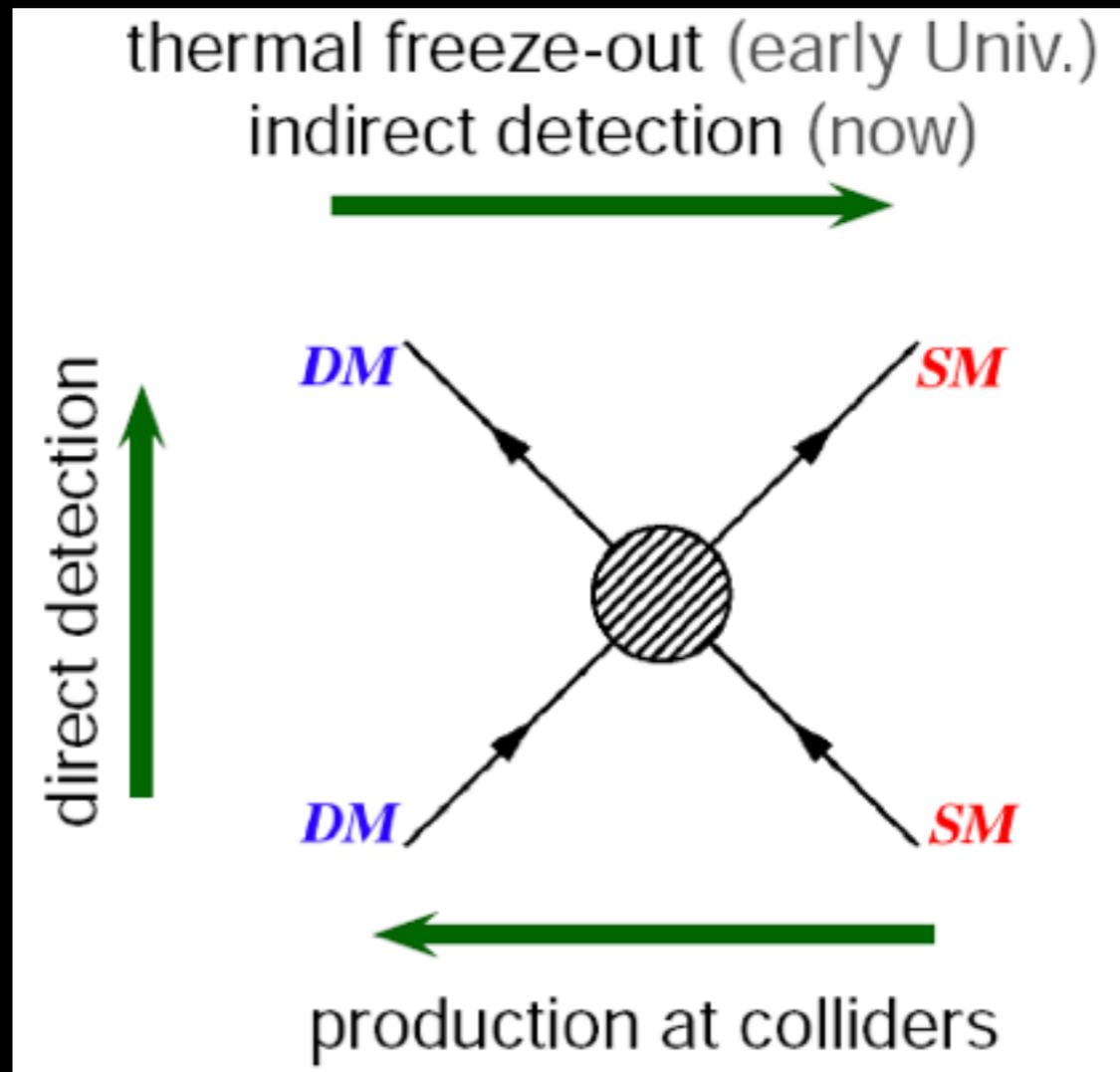
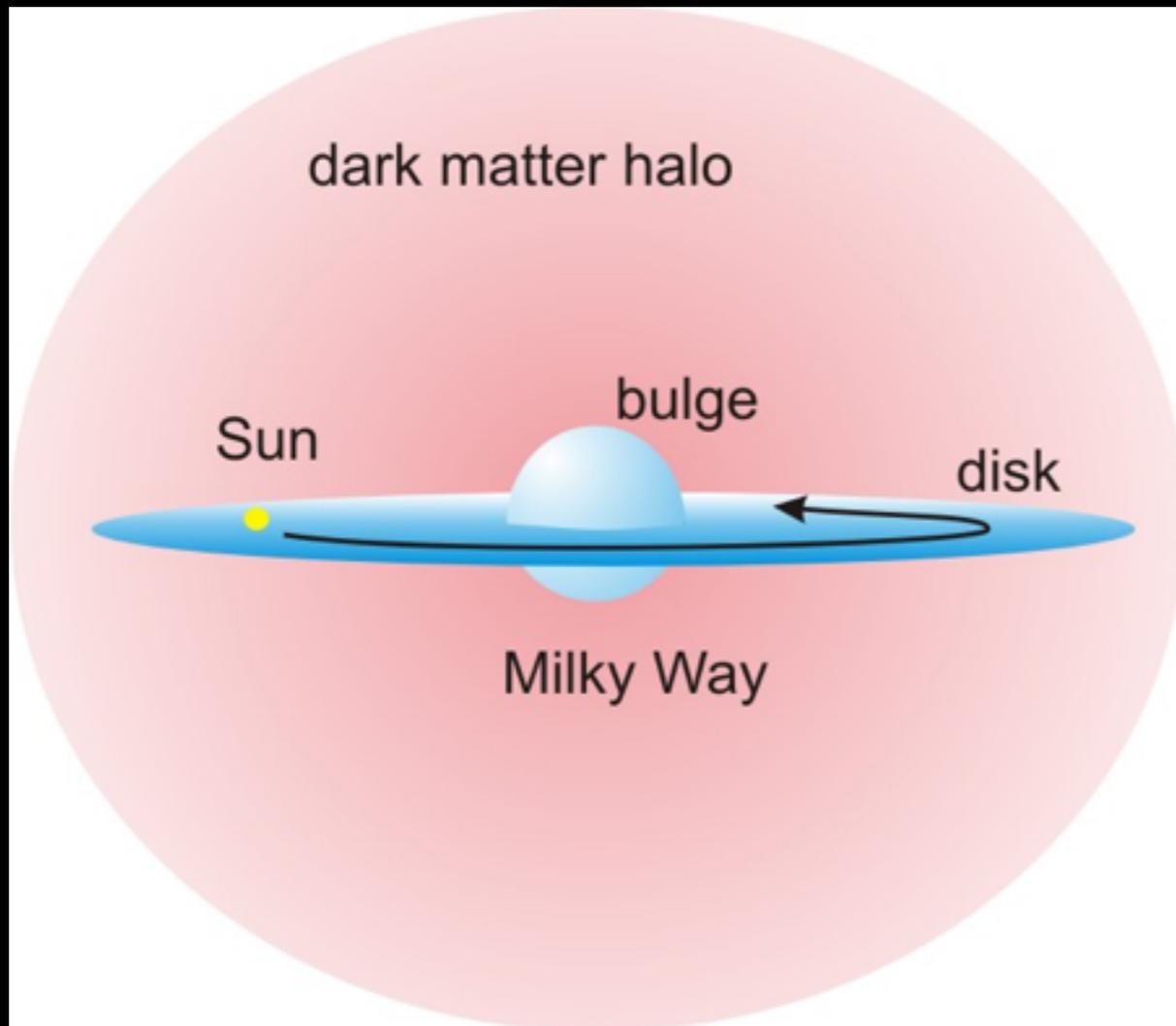
Belle Experiment

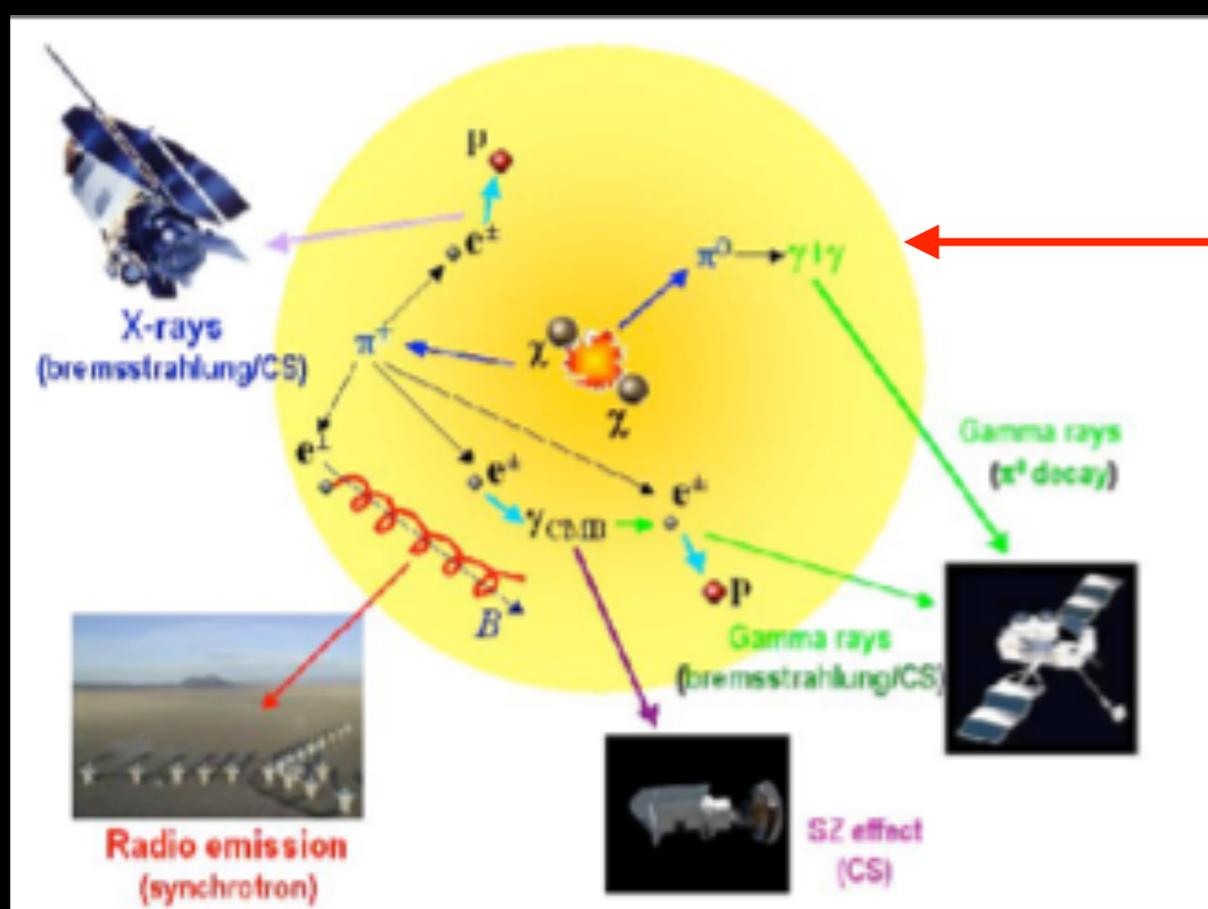


4. Indirect Detection

Think of DM collider in sky, only we have no control

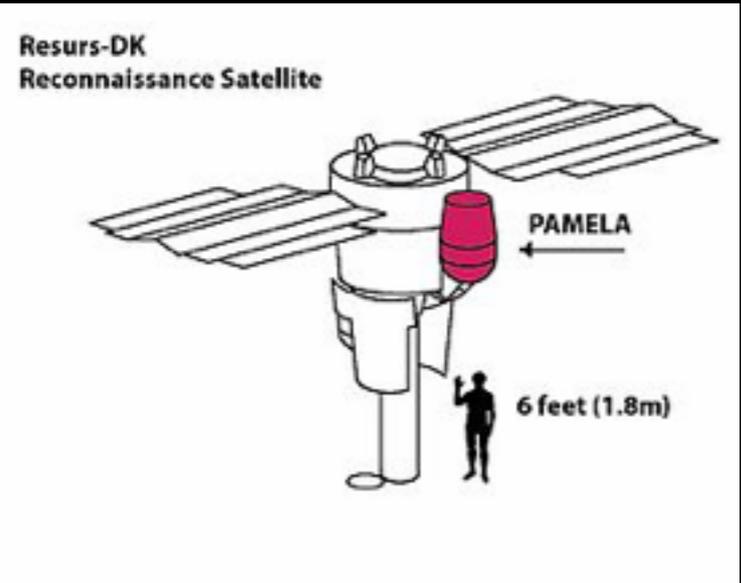
DM collides and converts into SM particles we can see in telescopes





Different spectra that DM can annihilate into

Some telescopes include:



Pamela telescope



H.E.S.S



SKA

There are other types of DM

Non-elementary particle dark matter

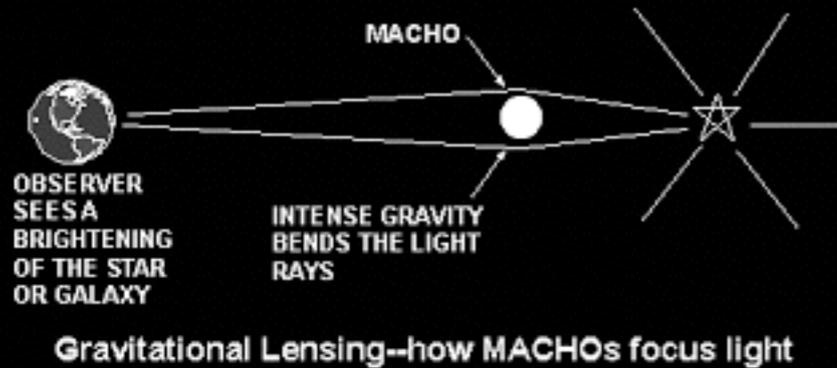
MACHOs

Macro Dark Matter

Black Holes

Brown dwarf stars

Dark Neutron Stars



Brown Dwarf star



Black Holes



Neutron stars

Now that you are Dark Matter experts

Next session we will talk about how we calculate:

- Relic Density
- Direct Detection cross-section

We will discuss what MadDM is

In the tutorial we will calculate:

Relic Density

Direct Detection

In a specific DM model