Cold Dark Matter
Is it cold, dark, or matter?

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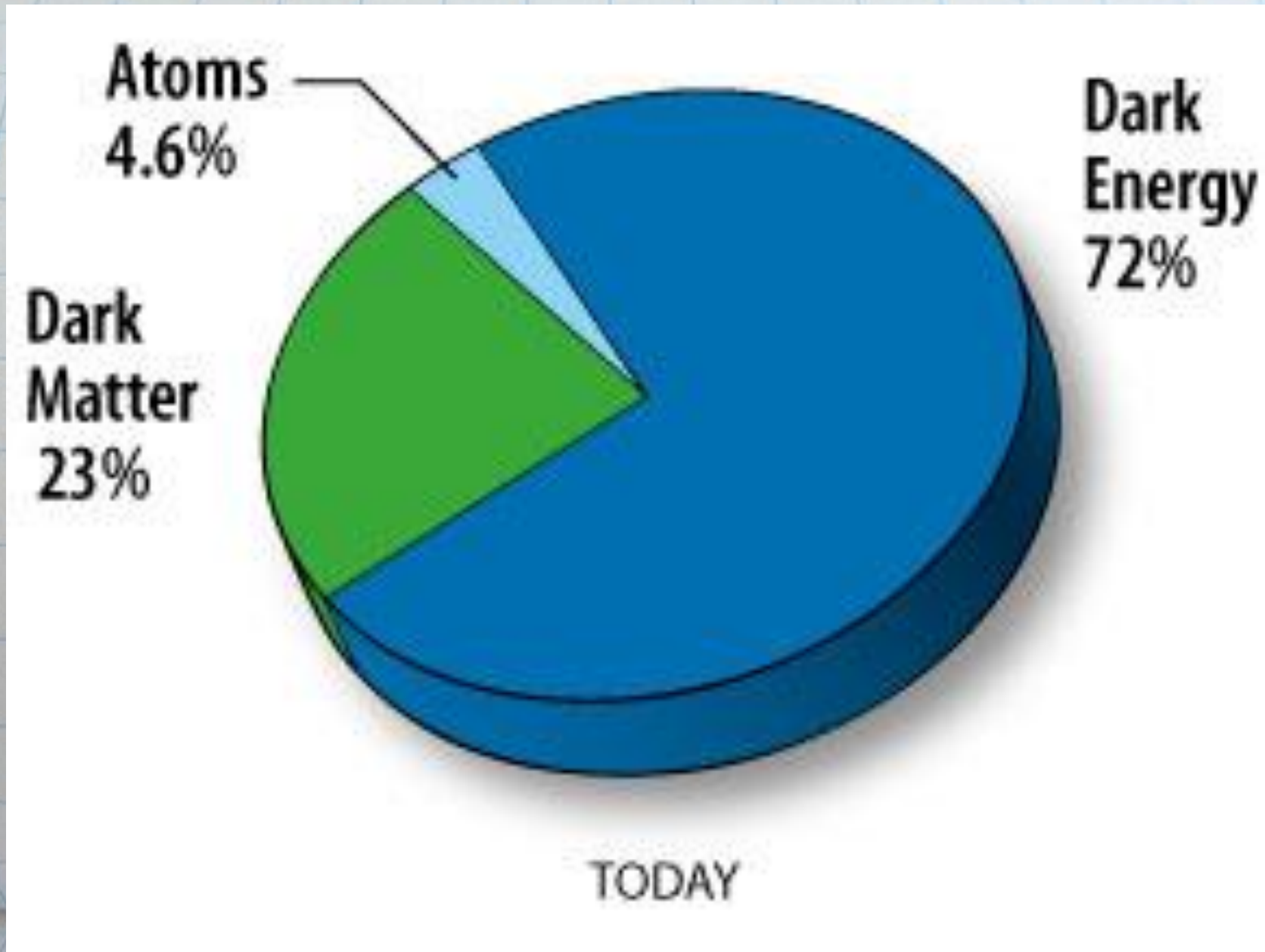
The Plan
Why do we believe it exists?
What could it be?
How can we find it?
1.5 ‘

What is the universe made of?

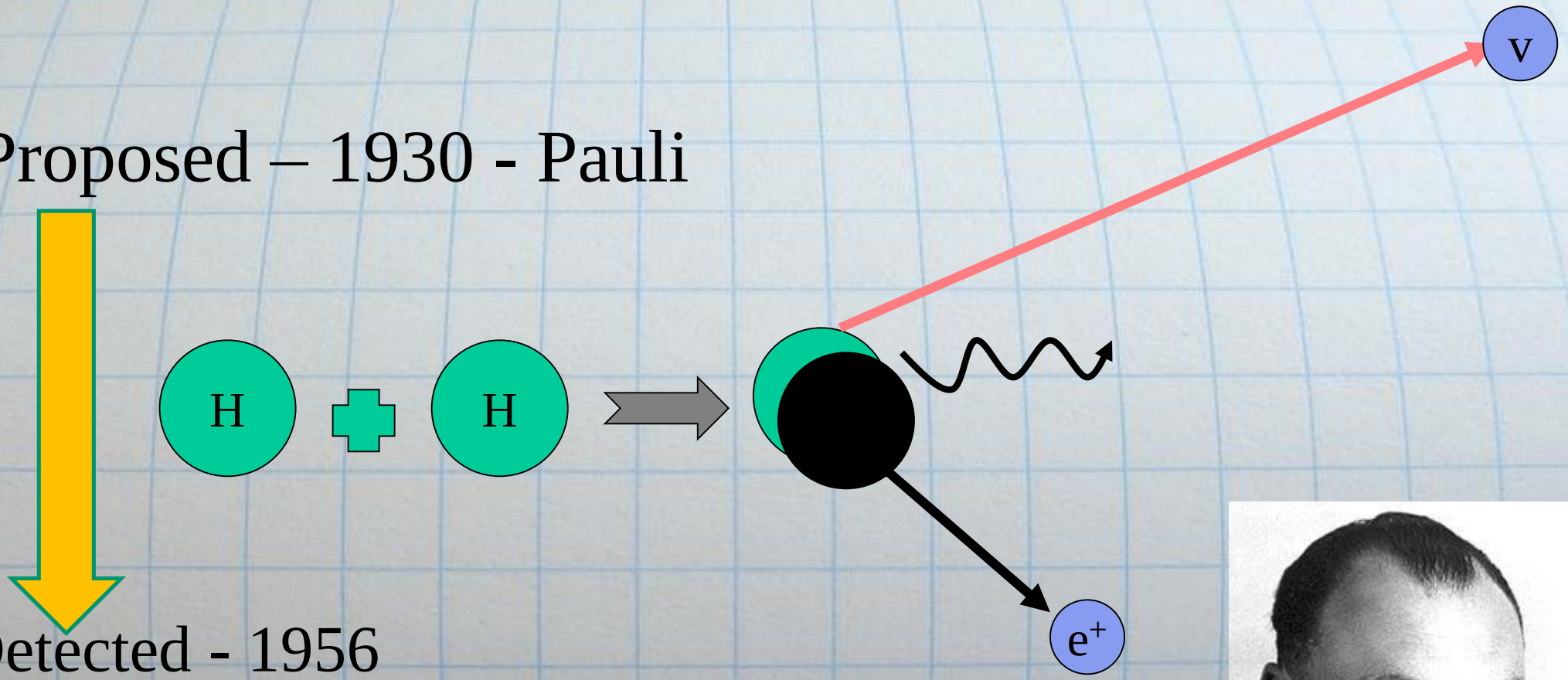



REALLY ?
MemGenerator.pl

WE HAVE BEEN HERE BEFORE THOUGH!

Neutrino déjà-vu?

Proposed – 1930 - Pauli

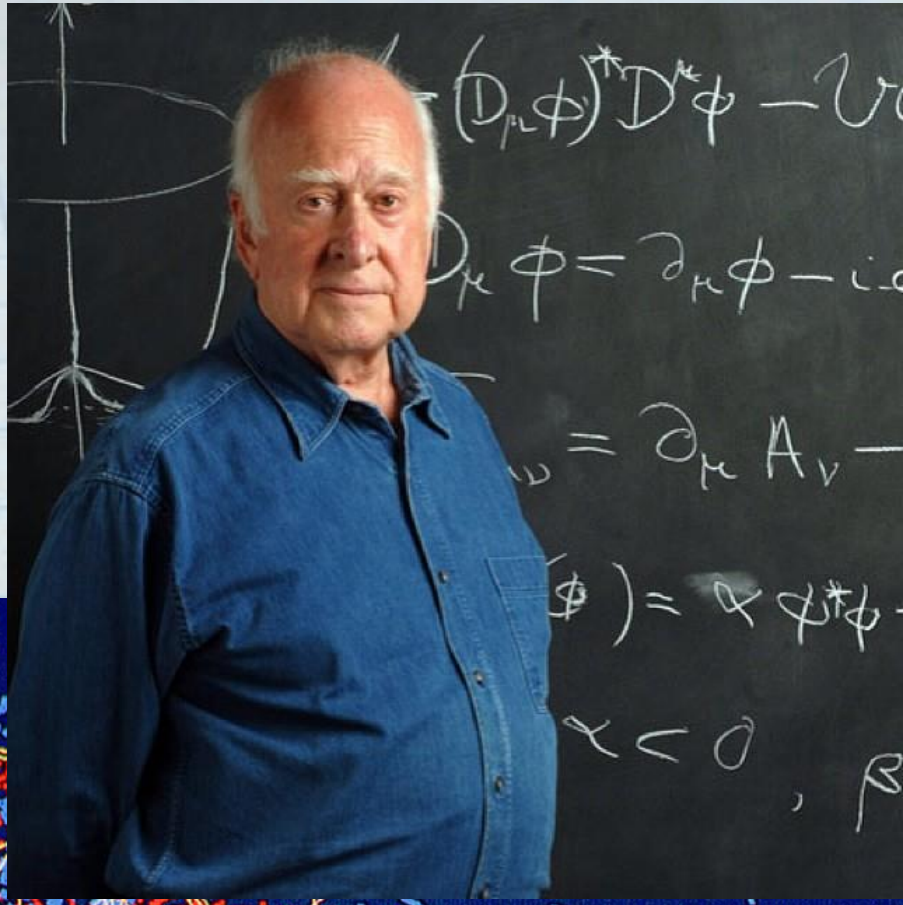


Detected - 1956

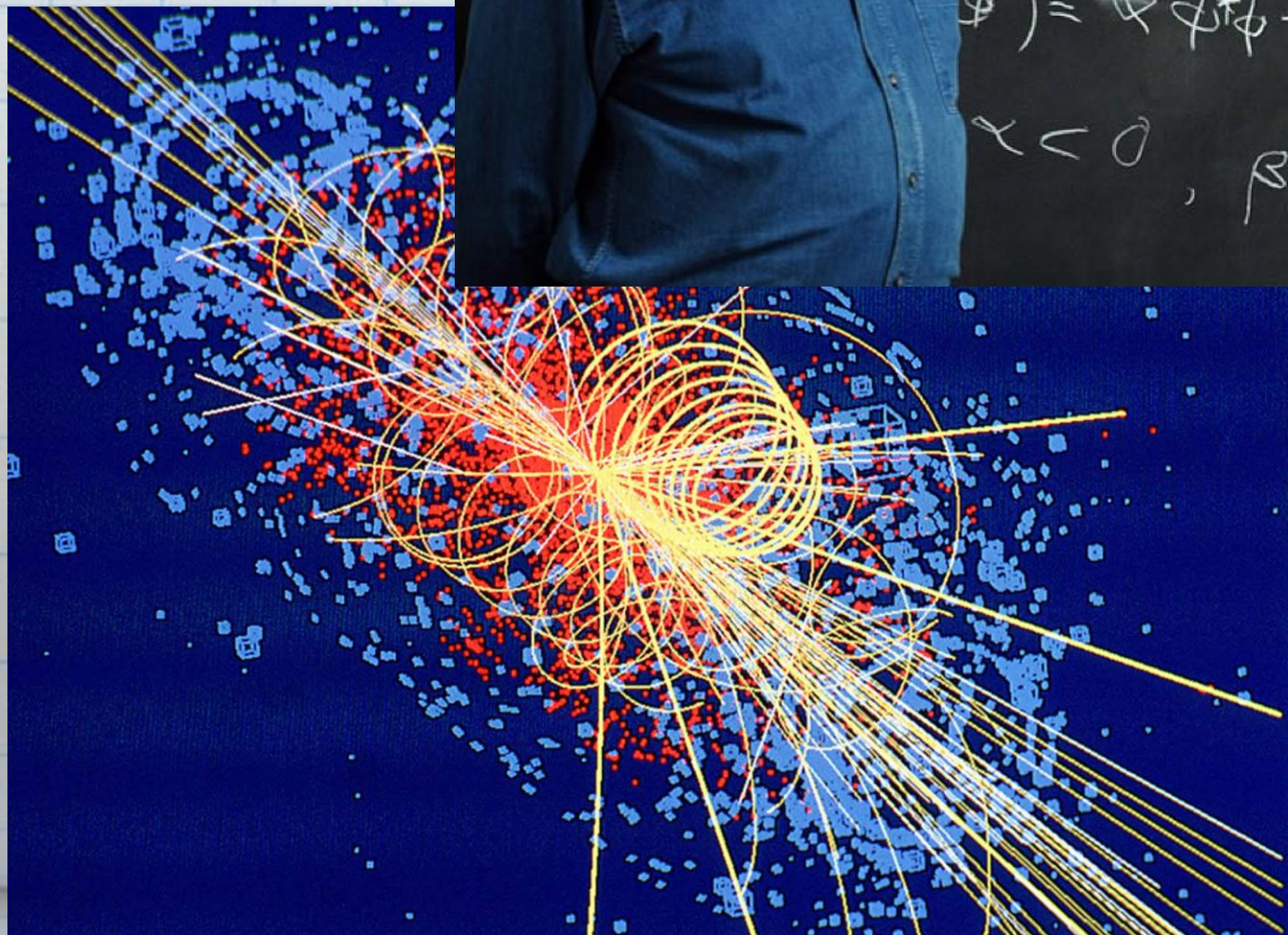
I have done a terrible thing, I have postulated a particle that cannot be detected. -Wolfgang Pauli

Higgs déjà-vu?

Proposed: 1964 Peter Higgs

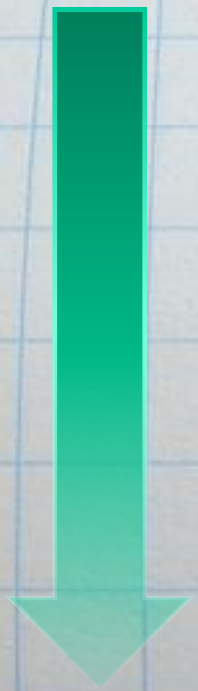


Detected: 2012



Dark Matter…

Proposed: 1932ish



Still waiting…

Cosmology

Λ-CDM

Current model of the universe

ΛCDM

Lambda

Cold Dark Matter

Non-comoving Cosmology

Authors: J. A. R. Cembranos, A. L. Maroto, H. Villarrubia-Rojo

Abstract: One of the fundamental assumptions of the star components of the Universe share a common rest frame. ... contact and tightly coupled in the primeval Universe. The dark se...

Submitted 26 March, 2019; originally announced March 2019.

Cosmological parameter inferen... ...e scales, all the matter-energy ... has been in thermal

Authors: Luis E. Padilla, Luis O. Tell...

Abstract: ...MCMC algorithms... general description of th... current datasets co...

Submitted 26 M...

Observational constraints on sign-changeable interaction models and alleviation of the H_0 tension

Authors: Supriya Pan, Weiqiang Yang, Chiranjeeb Singha, Emmanuel N. Saridakis

Abstract: ...CL. Examining the effect of the interaction on the CMB TT and matter power spectra we show that while from the simple spectra it is hard to distinguish the interacting case from ΛCDM scenario, in the residual graphs the interaction is indeed traceable. Finally, we find that sign-changeable interaction models can reco... ▽ More

Submitted 26 March, 2019; originally announced March 2019.

...an statistics

...to Vazquez

...orm the parameter inference procedure. We also provide a ... the ΛCDM model, along with several alternatives to it; and ...bservations. Finally, with... ▽ More

...osmology

...CDM cosmic history change the large scale transfer function and can pr...

...ple, the best fit seven parameter model for our Periodic Time Co...

...of state, is only disfavoured relative to a power-law power ...

...2019; originally announced March 2019.

The life and death of cosmic voids

Authors: P. M. Sutter, Pascal Elahi, Bridget Falck, Julian Onions, Nico Hamaus, Alexander Knebe, Chaichalit Srisawat, Aurel Schneider

Abstract: We investigate the formation, growth, merger history, movement, and destruction of cosmic voids detected via the watershed transform code VIDE in a cosmological N-body dark matter ΛCDM simulation. By adapting a method used to construct halo merger trees, we are able to trace individual voids back to their initial appearance and record the merging and evolution of their progenitors at high redshift... ▽ More

Submitted 20 September, 2014; **v1** submitted 28 March, 2014; **originally announced** March 2014.

...ond ΛCDM

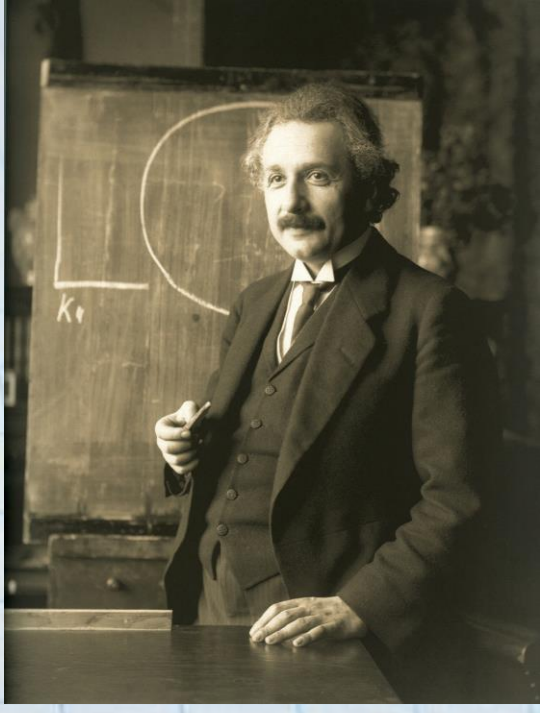
...galaxy clustering surveys. We propose a computationally cheap method to create an emulator for ...gravity models by utilizing existing emulators for ΛCDM. Using a suite of N-body simulations we construct a fitting function for the enhancement of both the linear and non-linear matter power spe... ▽ More

...Kazuya Koyama, Baojiu Li, Lucas Lombriser, Gong-Bo Zhao

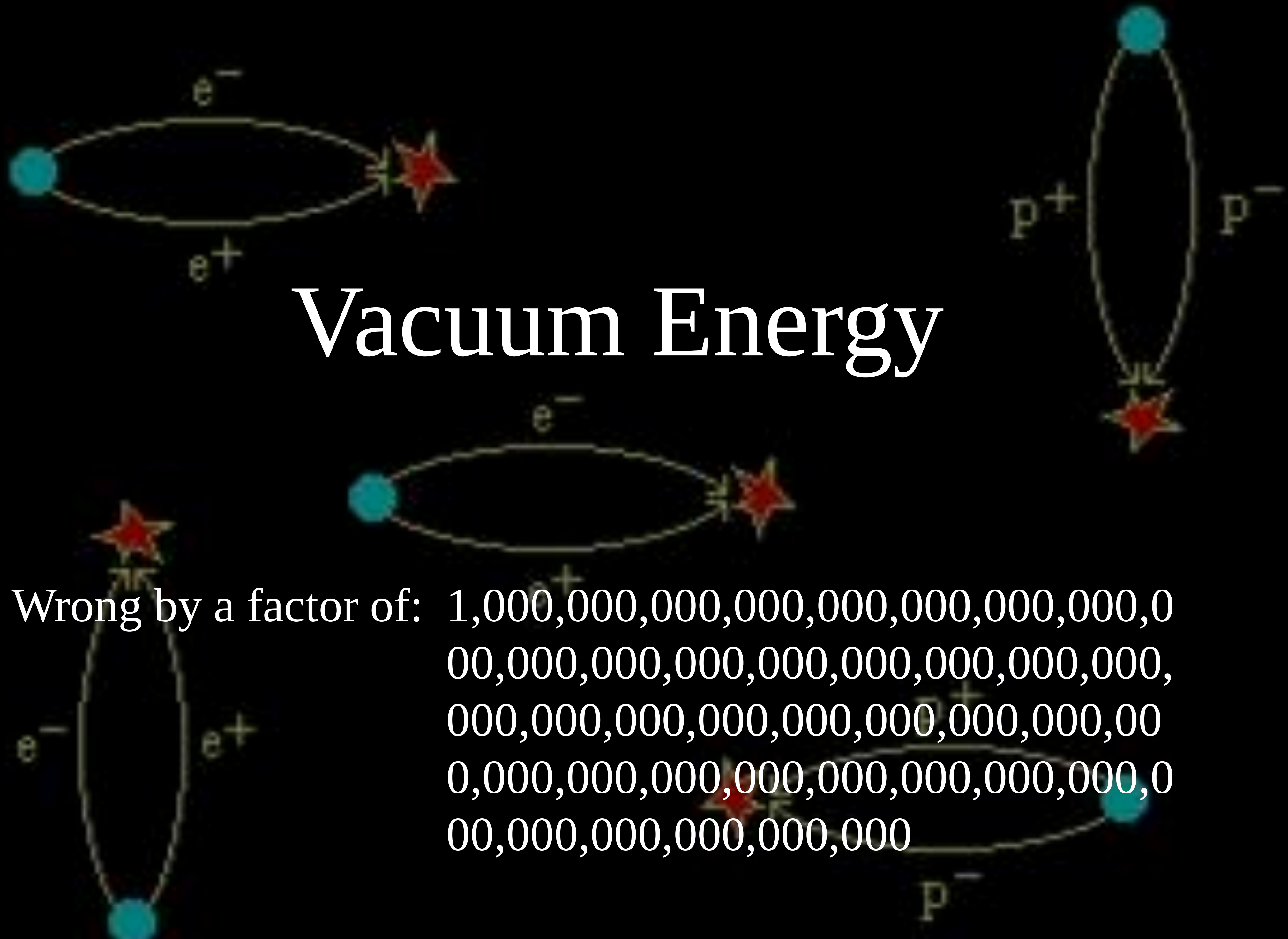
Submitted 20 March, 2019; originally announced March 2019.

Lambda

ΛCDM



$$\underbrace{G_{\mu\nu} + g_{\mu\nu}\Lambda}_{\text{How space curves}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{How matter behaves}}$$

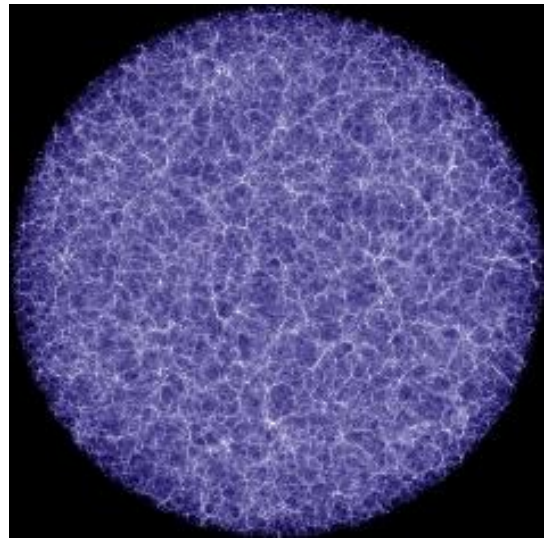


Vacuum Energy

Wrong by a factor of: 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000

Quintessence

- A fifth force
  - Earth, Wind, Fire & Water
  - OR Strong, Weak, Electromagnetic, Gravity
  - OR normal matter, radiation (photons), cold dark matter, and neutrinos
- A scalar field theory?
- Chameleon field?
- Static or varying?



CDM

ΛCDM

Cold

– relatively slow moving

CDM

ΛCDM

Dark

– can’t be seen

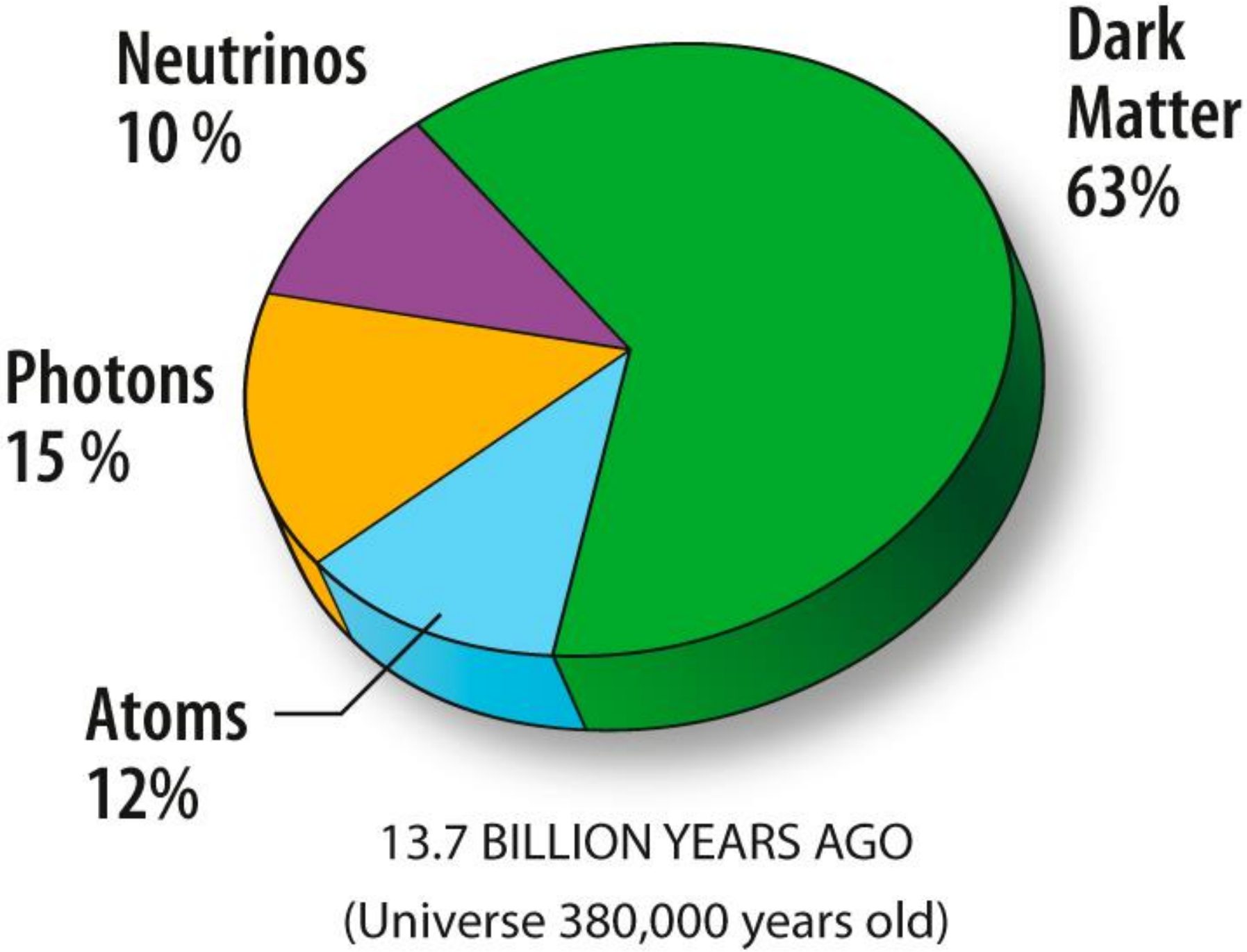
At least not by light

CDM

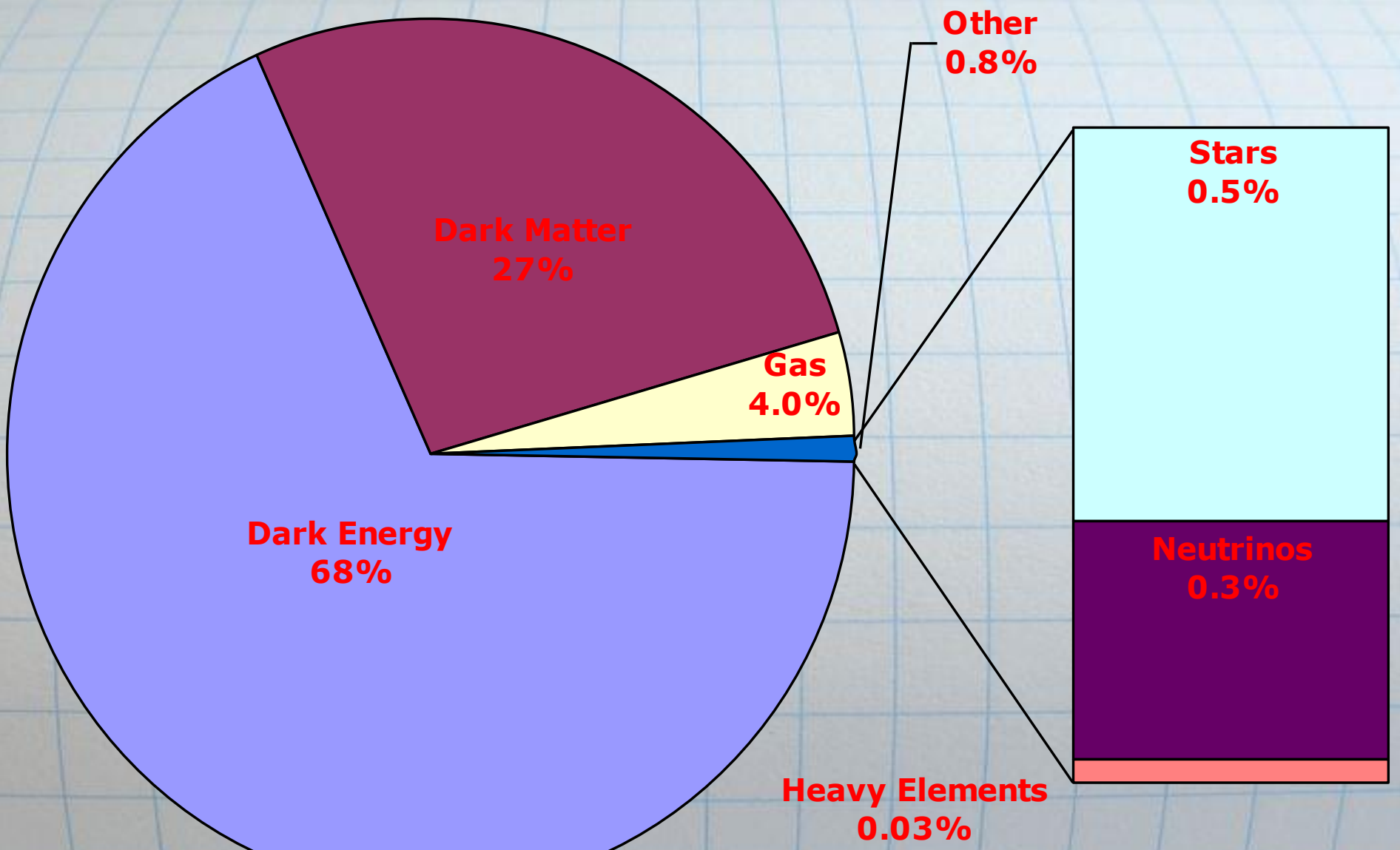
ΛCDM

Matter

– as opposed to radiation


Neutrinos
10 %
Dark
Matter
63%
Photons
15 %
Atoms
12%
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Now

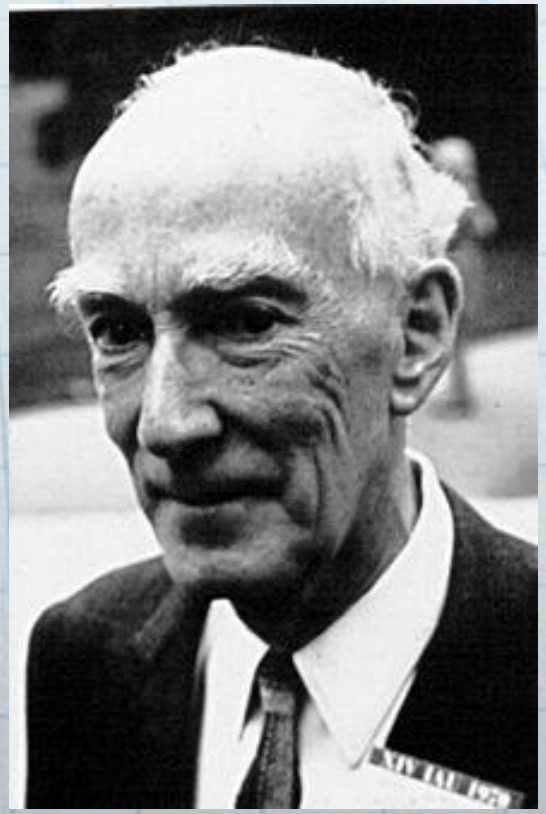

Other
0.8%
Dark Matter
27%
Gas
4.0%
Dark Energy
68%
Stars
0.5%
Neutrinos
0.3%
Heavy Elements
0.03%

A brief history
why we think it exists?

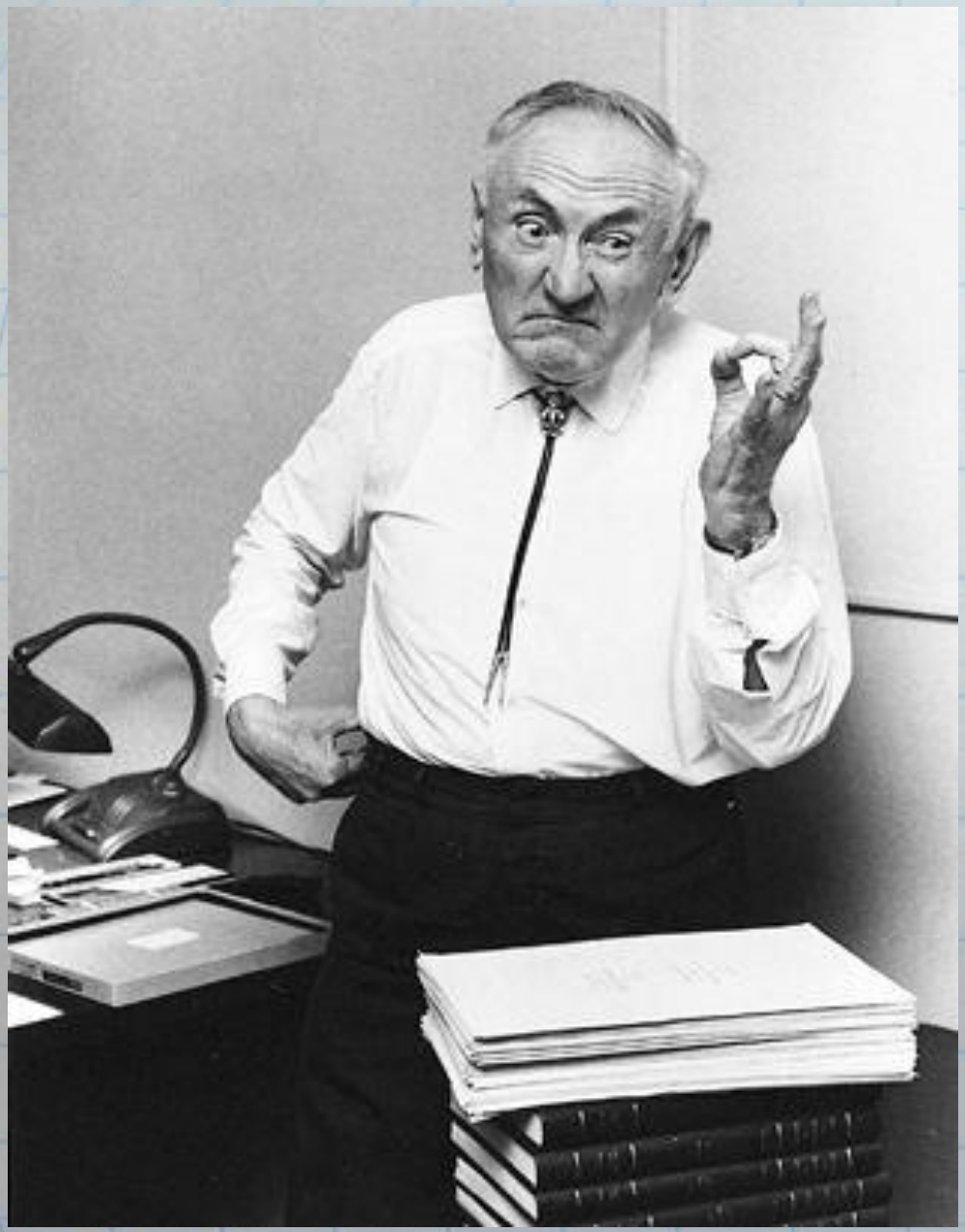
What's past is prologue

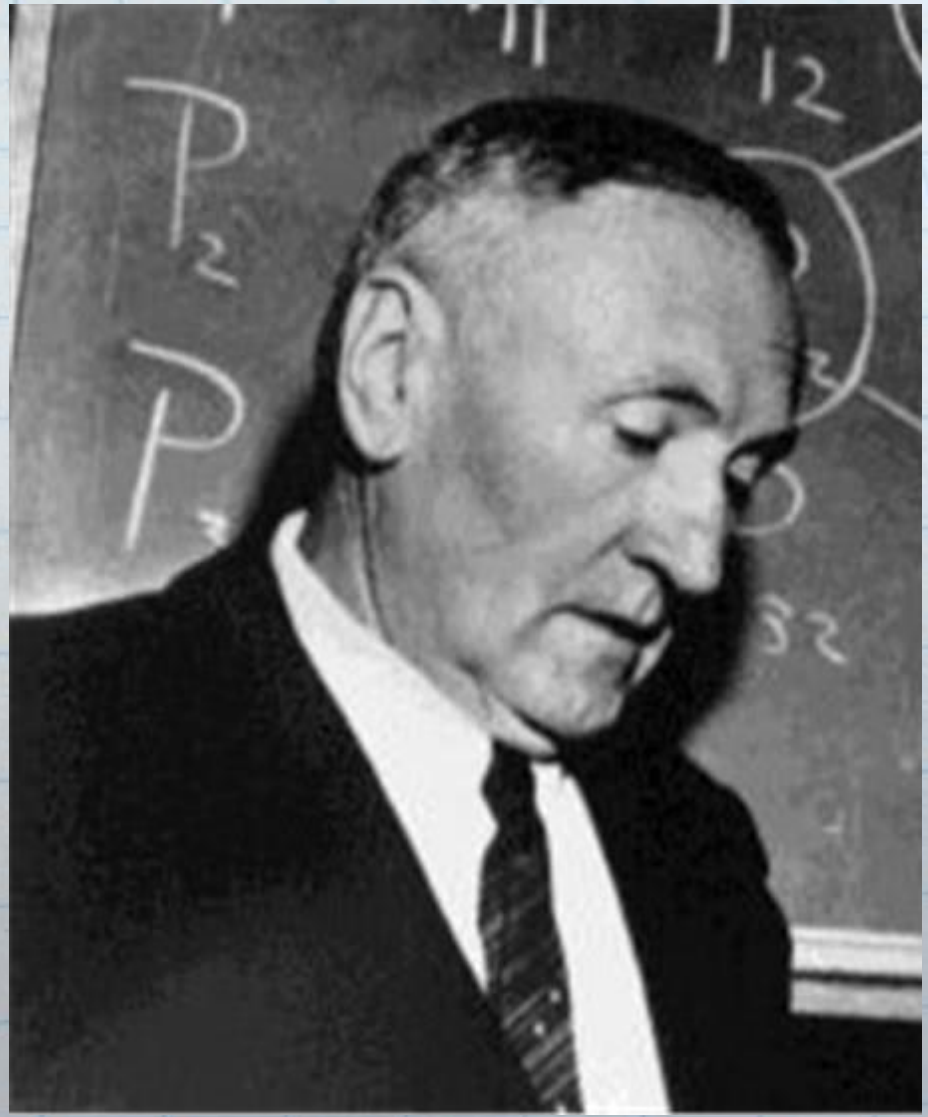
History

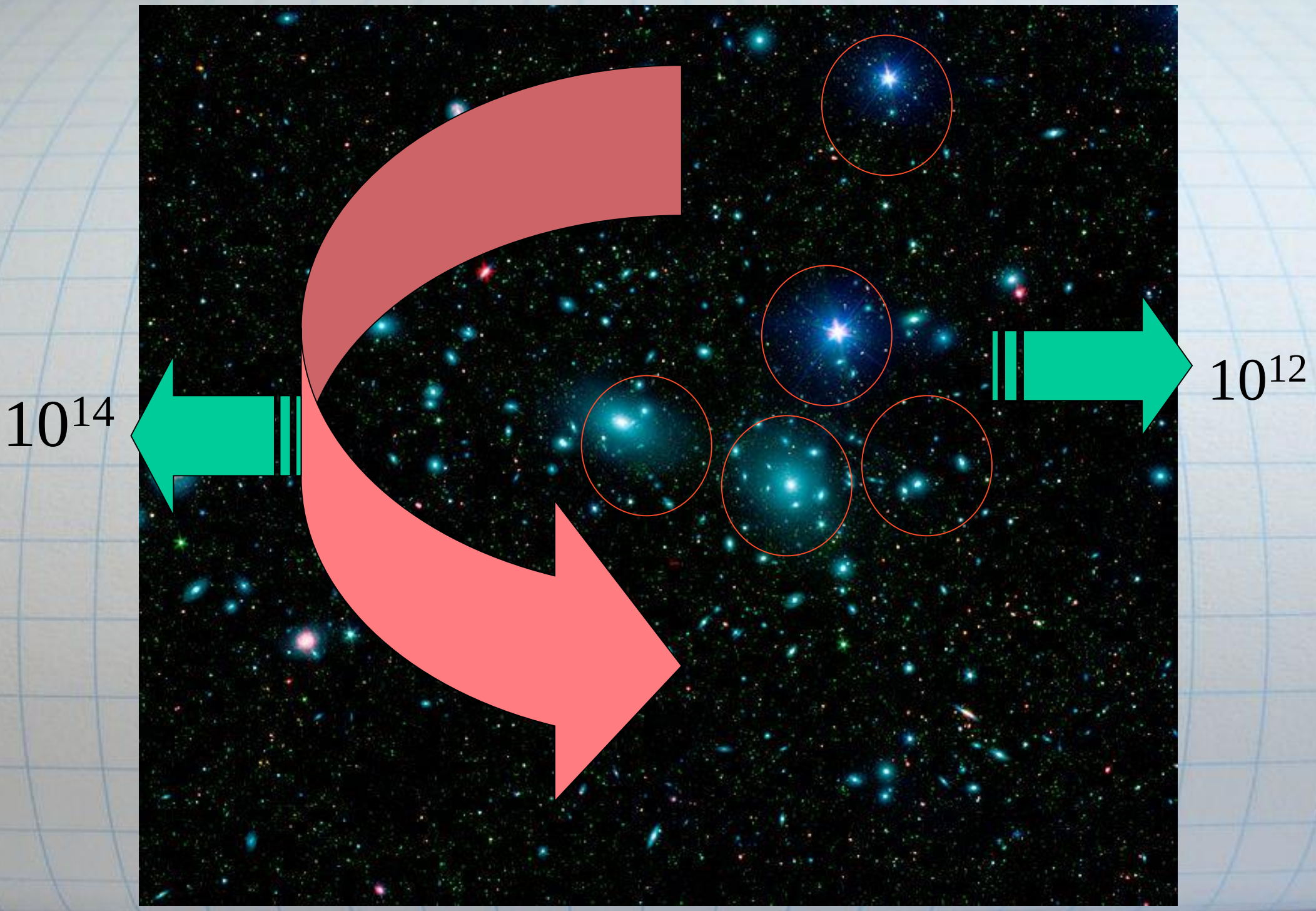
- Jan Oort – 1932 looked at proper motion of stars in the galactic plane
  - Only 1/3 of the bright stars needed.
  - Missing mass assumed to be dim stars, dust and gas.



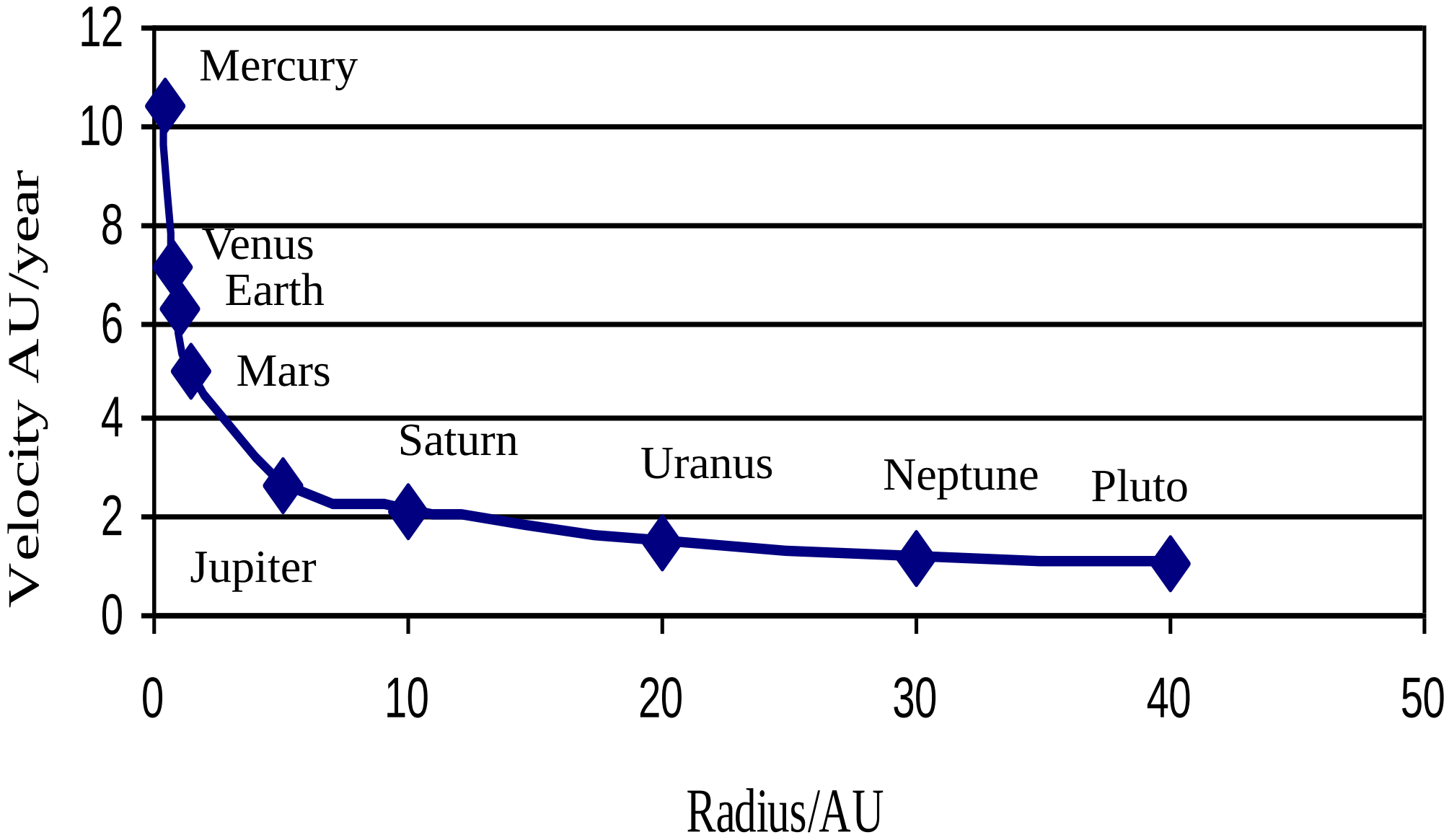
Fritz Zwicky

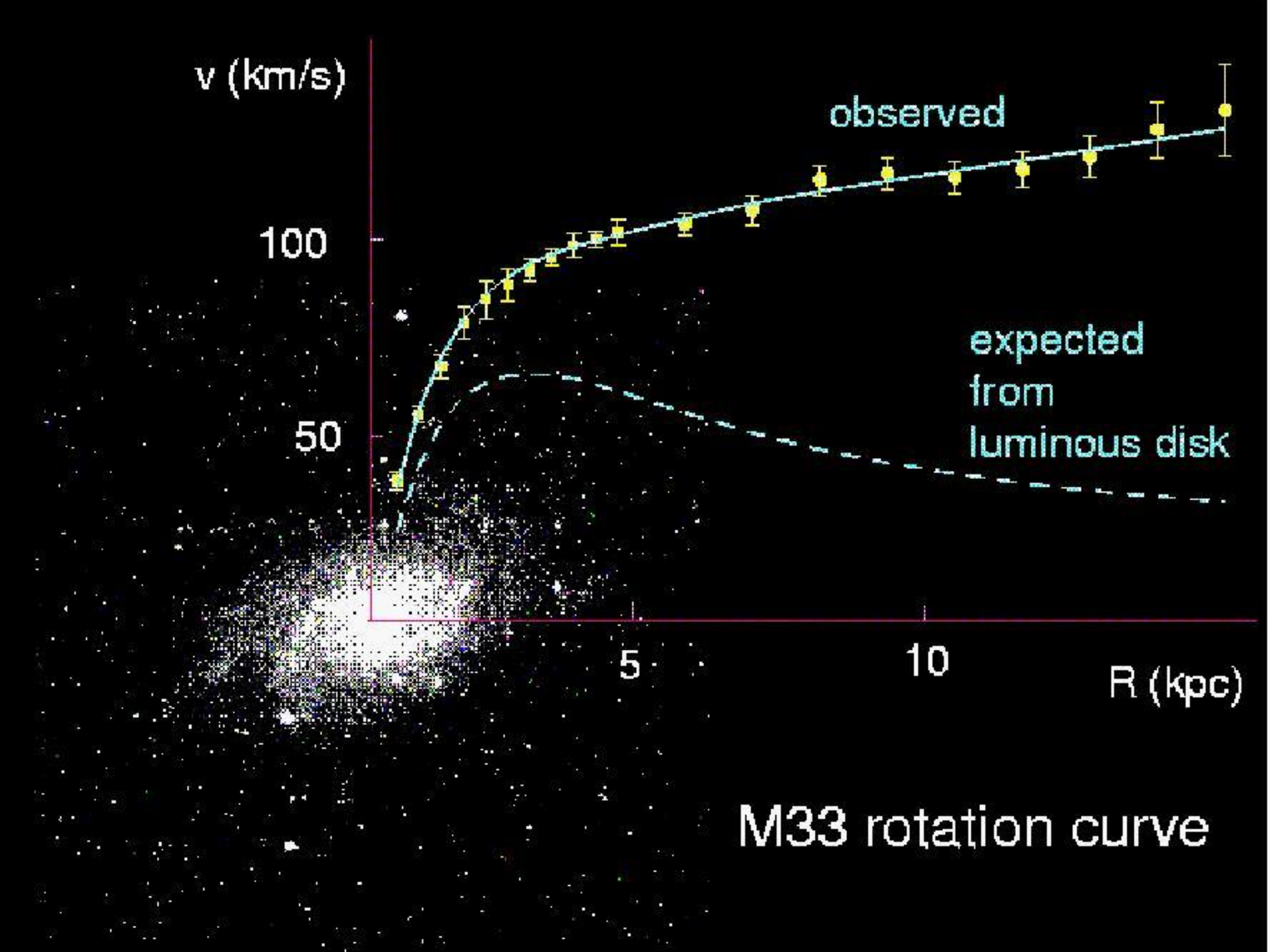





10^{14}
10^{12}

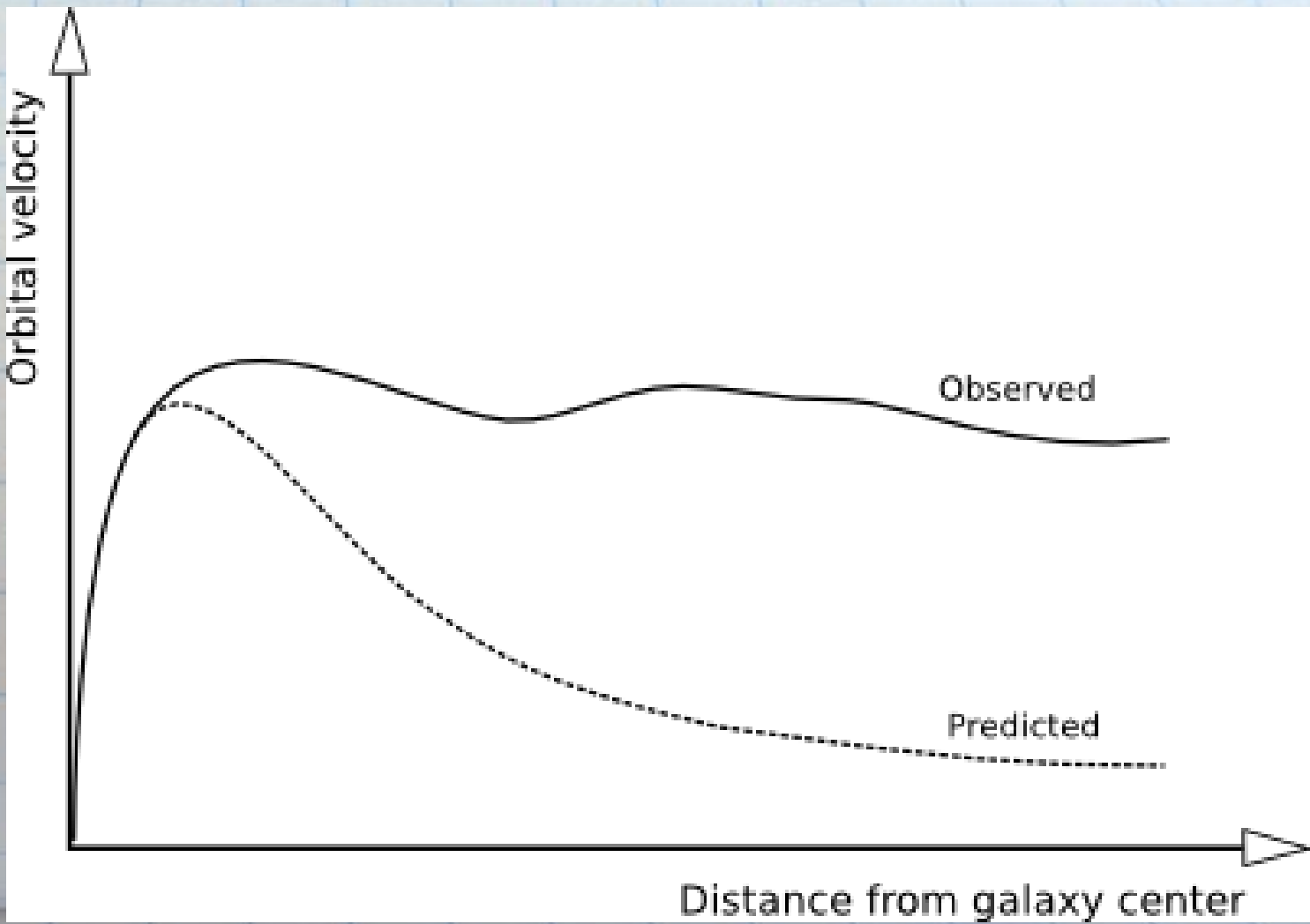
Keplerian Orbits




v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

More recent

- Radio Astronomy allows mapping of gas
- Much further out for Andromeda



Big Bang Nucleosynthesis

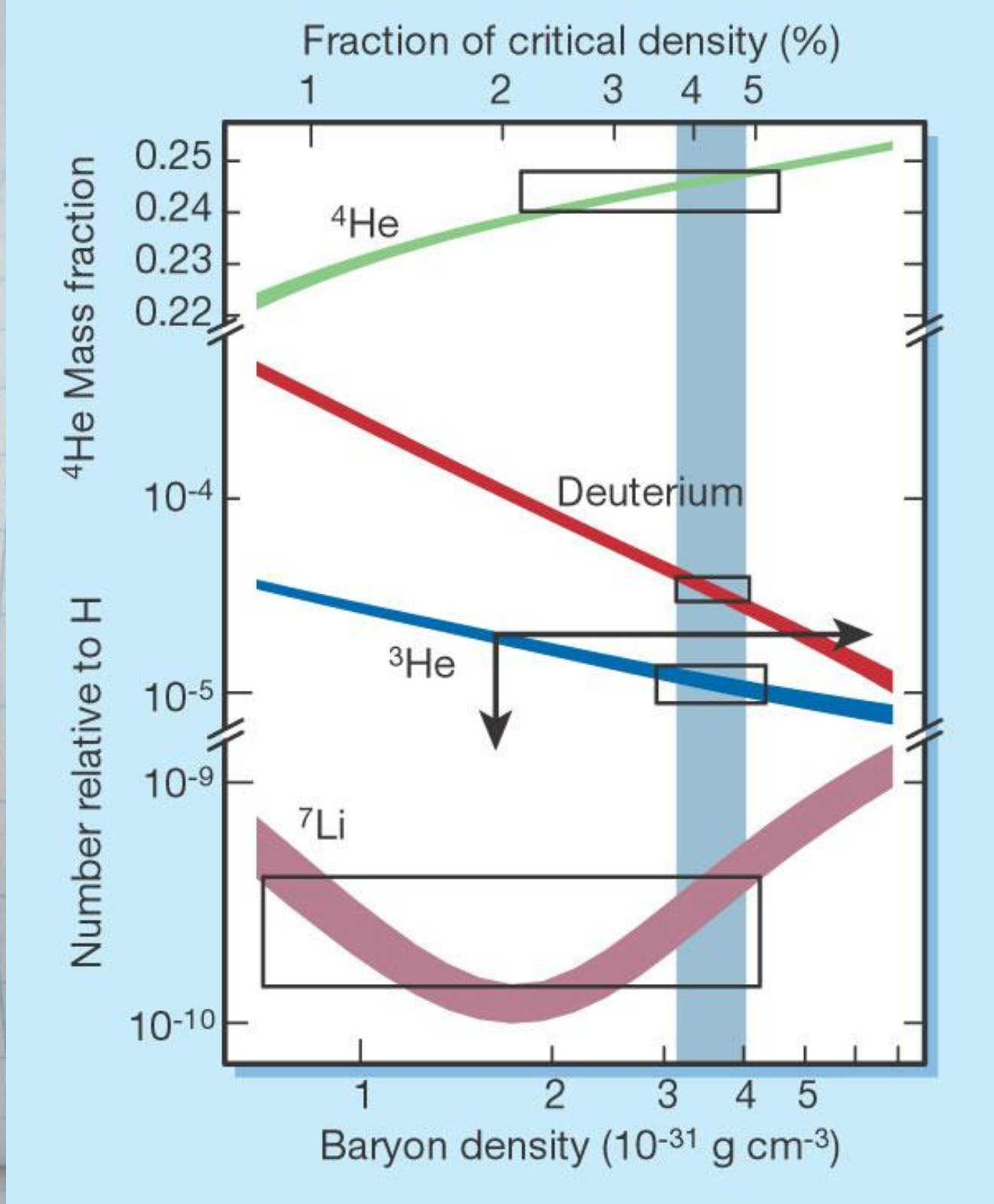
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

Big Bang

3 minutes
Fusion starts

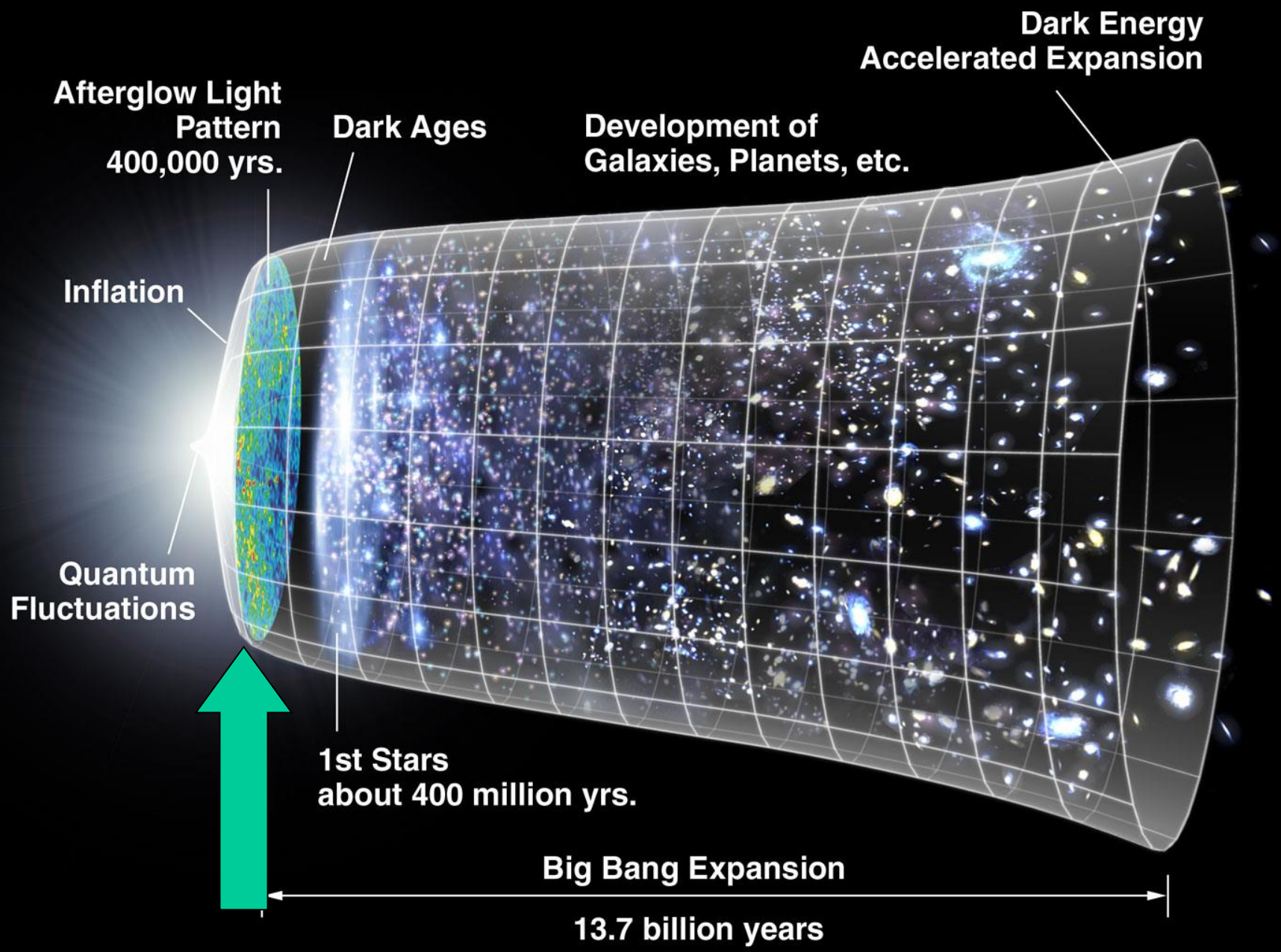
1second
Nuclei form

20 minutes
Fusion stops

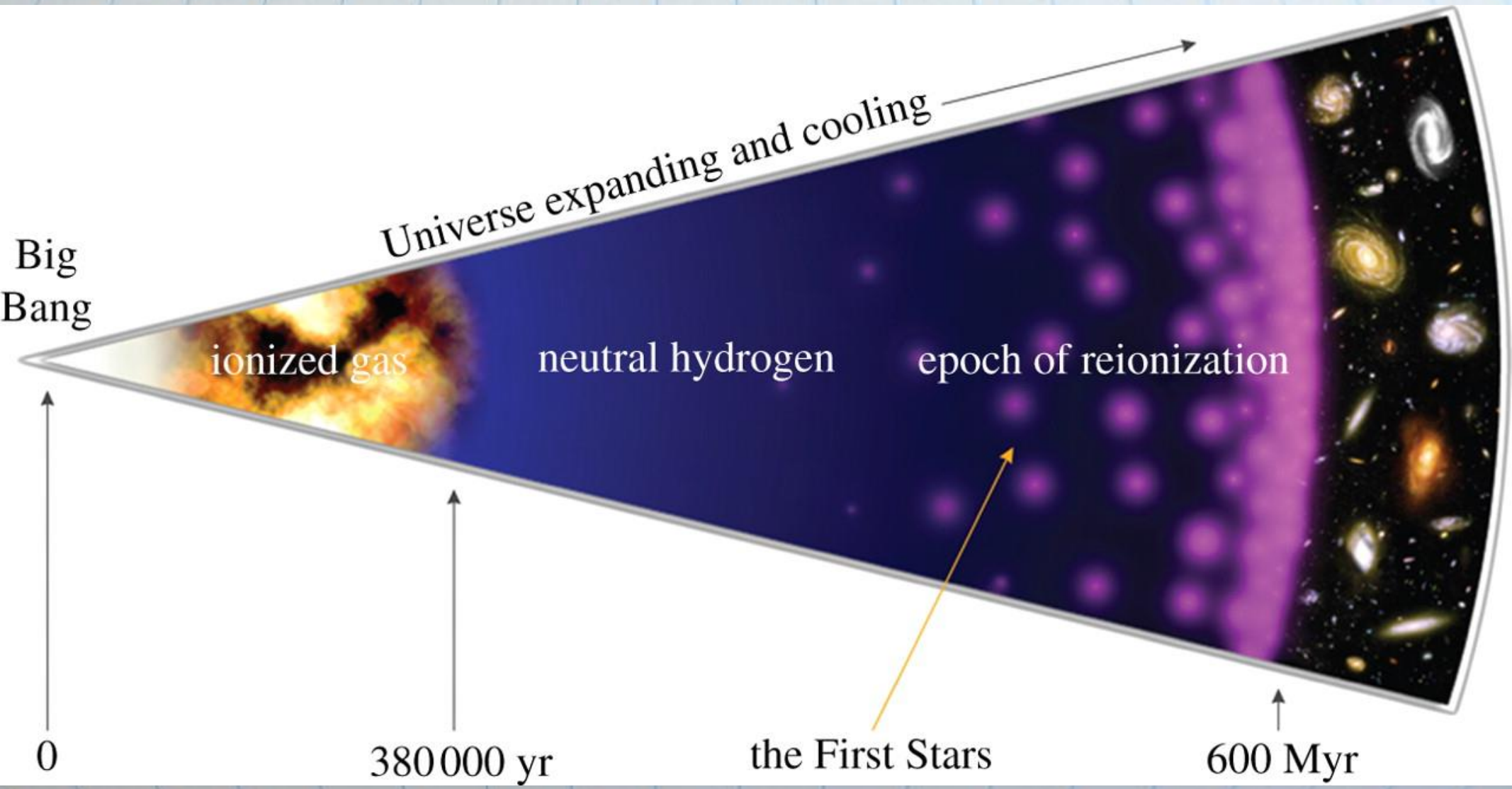

Fraction of critical density (%)
1
2
3
4
5
0.25
0.24
0.23
0.22
^{4}He Mass fraction
^{4}He
Deuterium
^{3}He
^{7}Li
10^{-4}
10^{-5}
10^{-9}
10^{-10}
Number relative to H
1
2
3
4
5
Baryon density (10^{-31} g cm^{-3})

Nature 2002

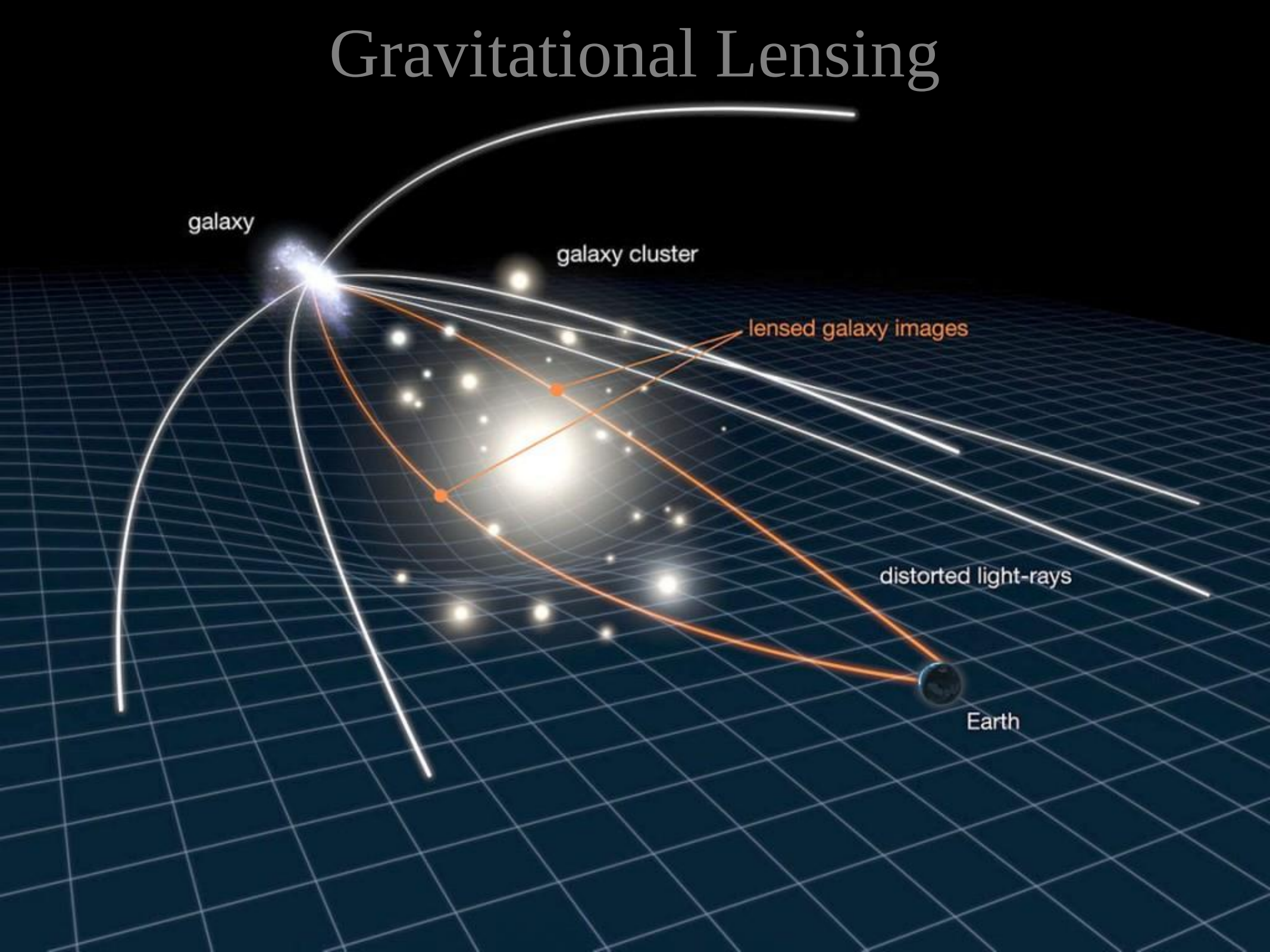
Formation of galaxies



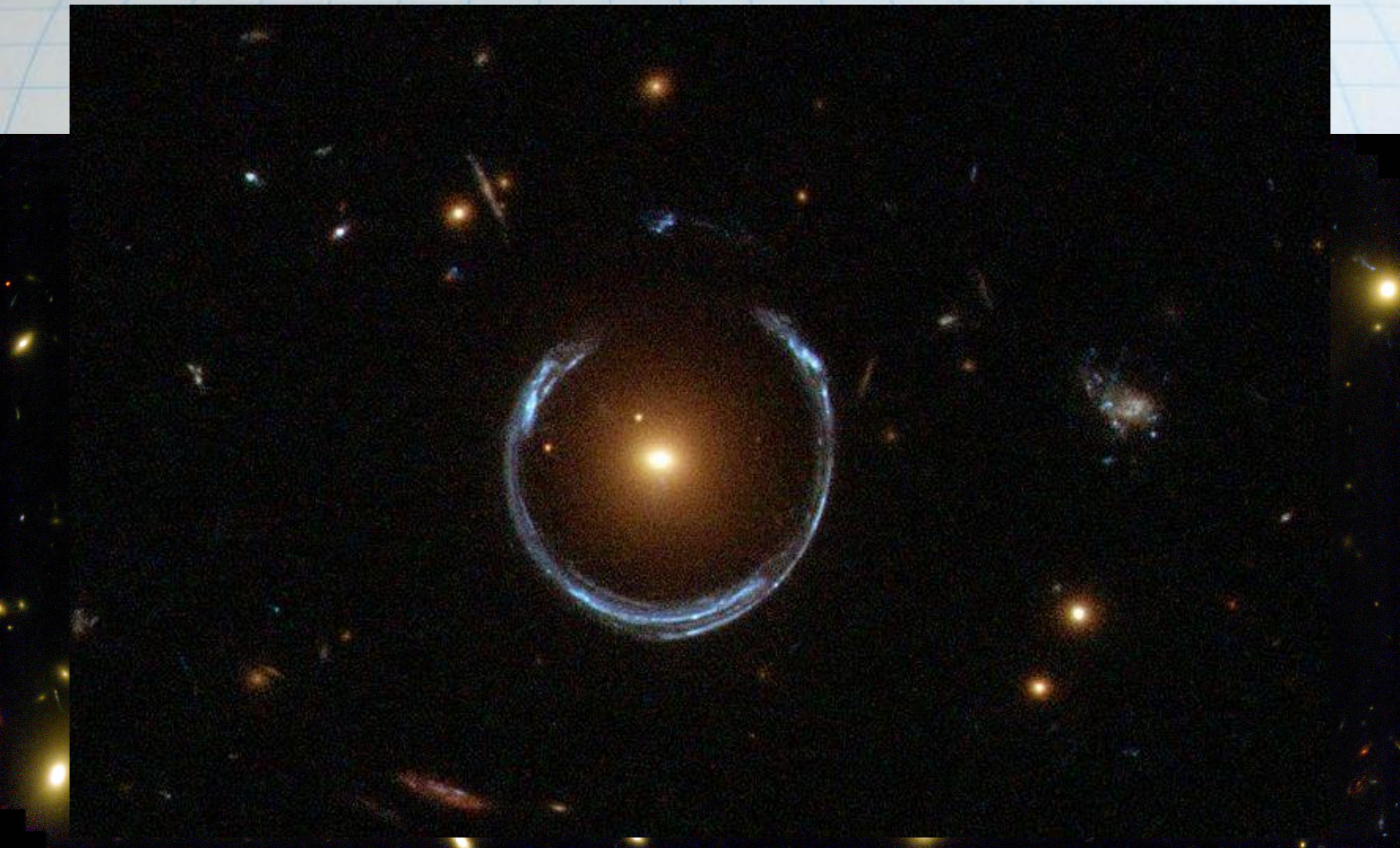
Time for galaxies to form



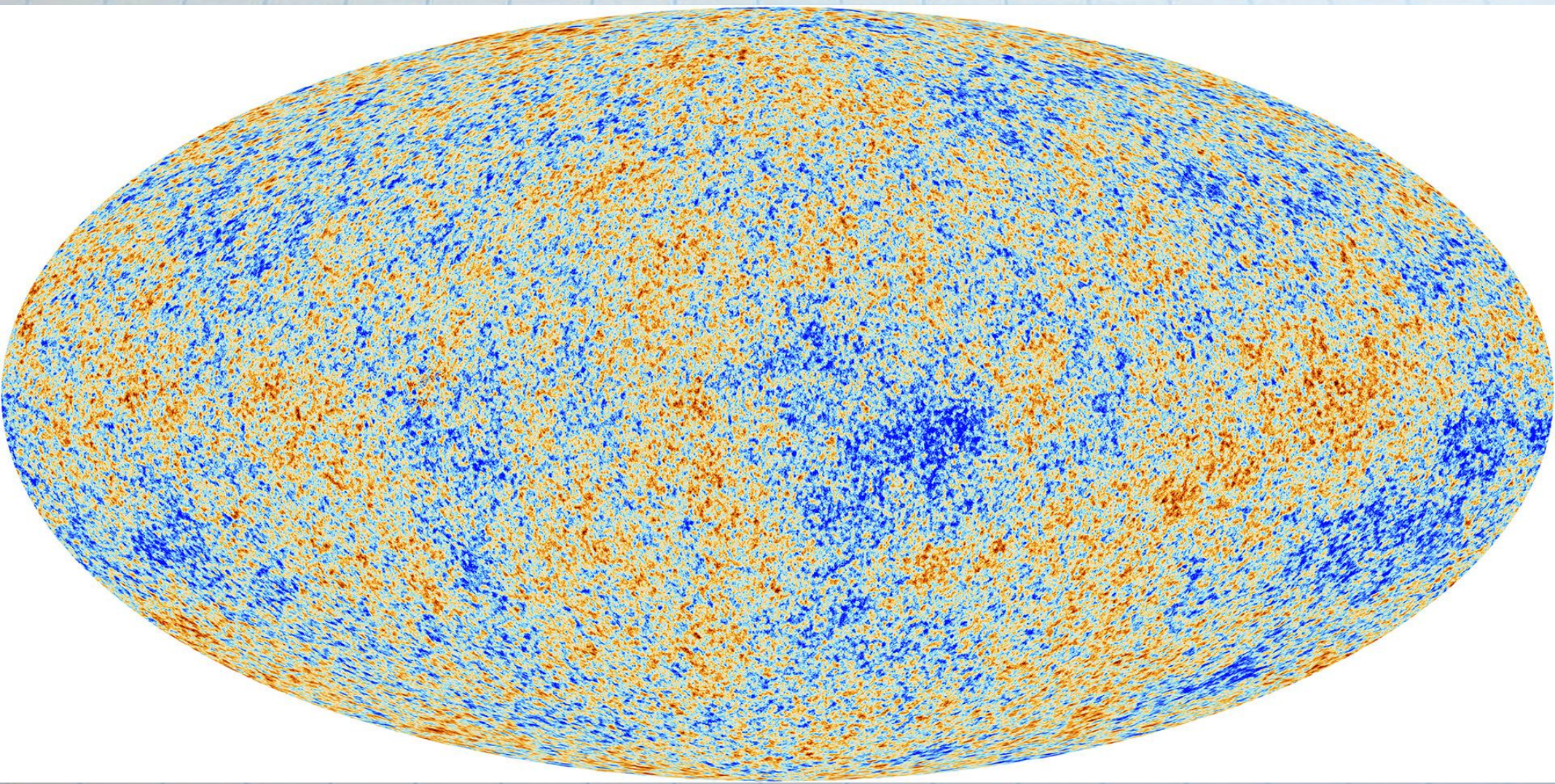
Gravitational Lensing

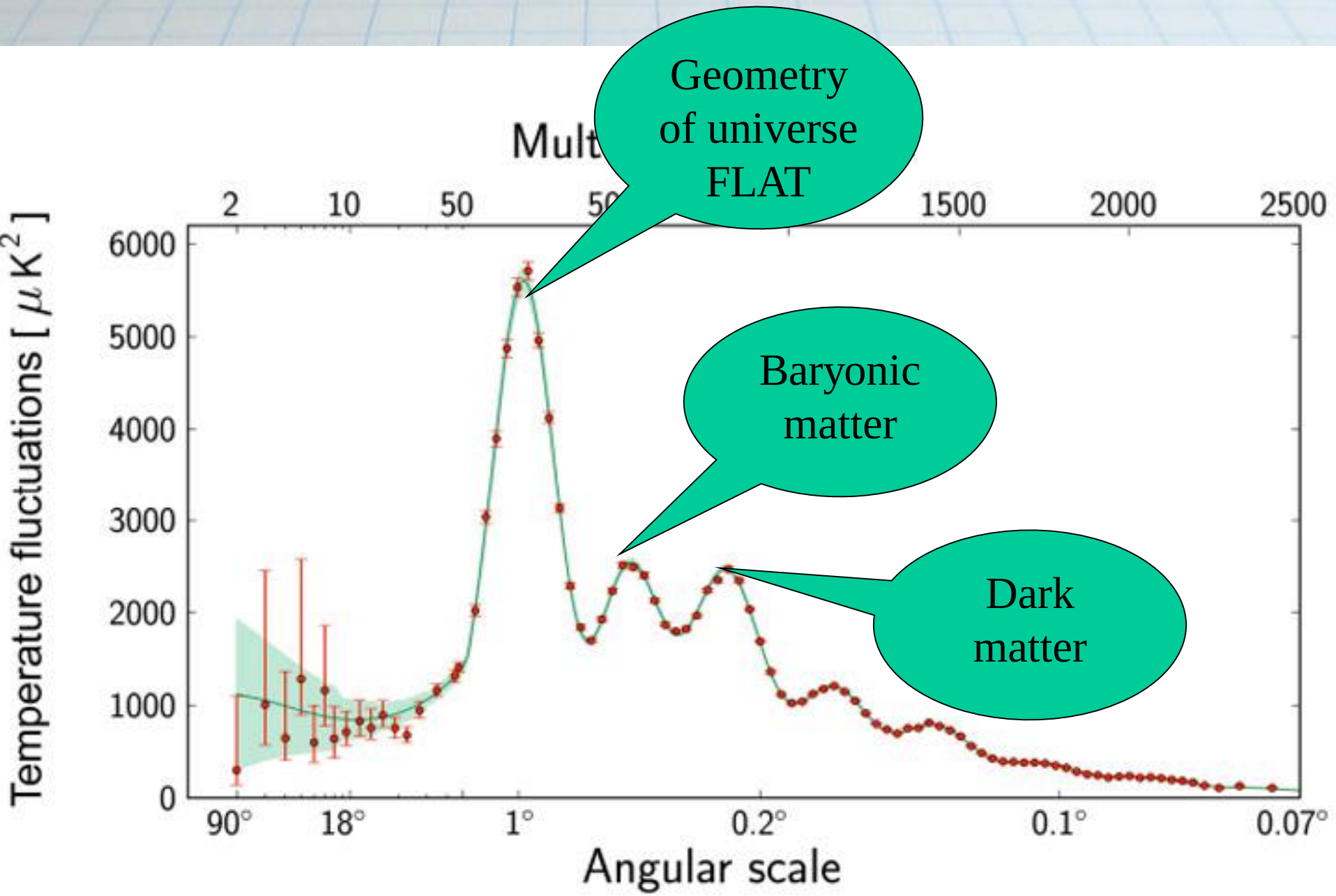


Horseshoe ring / Abell 2218



Evidence from the CMB

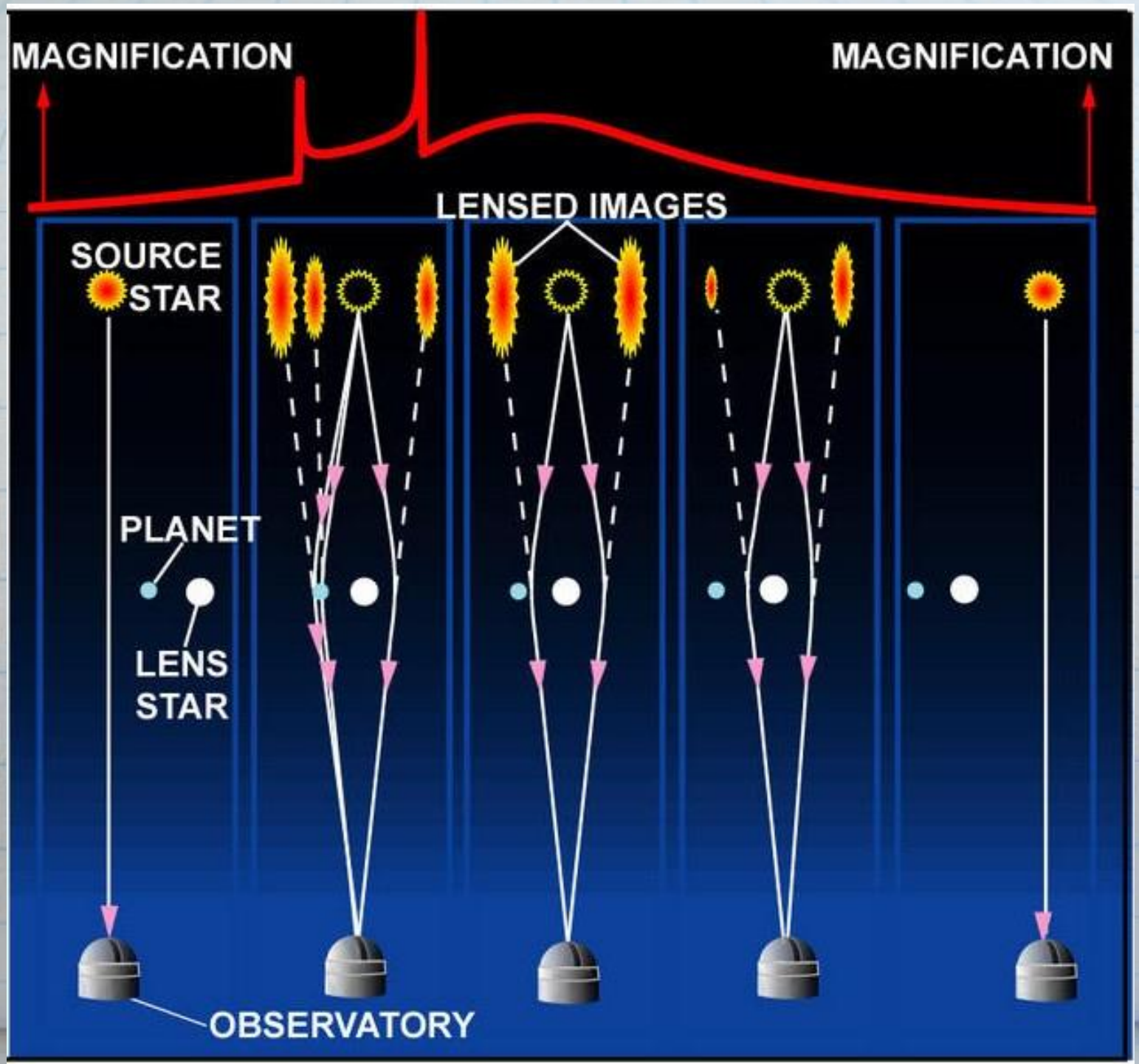



Geometry
of universe
FLAT
Baryonic
matter
Dark
matter
Mult
2
10
50
1500
2000
2500
6000
5000
4000
3000
2000
1000
0
Temperature fluctuations [μK^2]
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

So how to fix it?

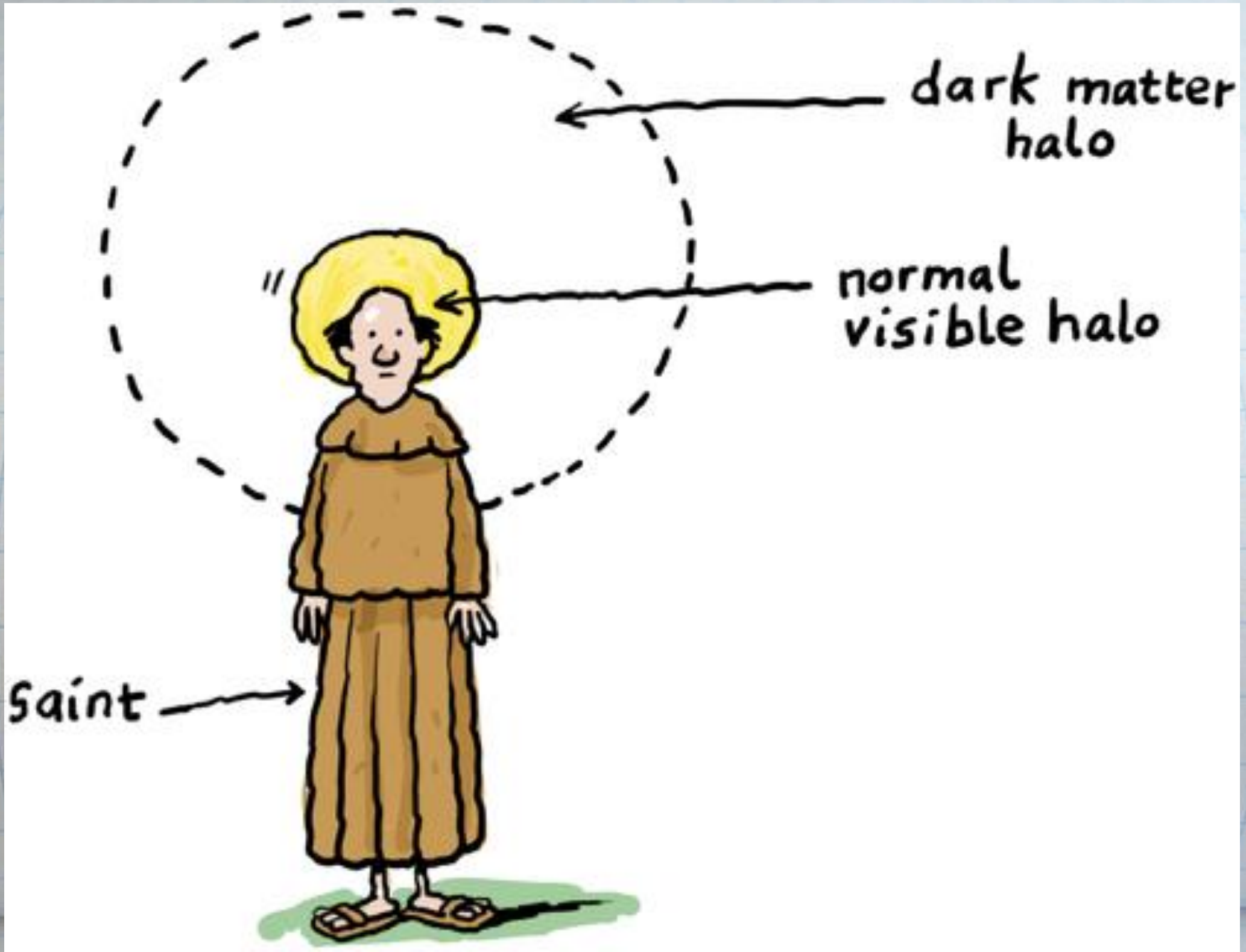
- Either gravity doesn’t work like we think it does
- Or, there is a whole lot of missing mass.
- Which might be explained by:
  - MACHOs.
  - Neutron stars
  - Black holes.
  - Extra gas.
  - Brown dwarfs

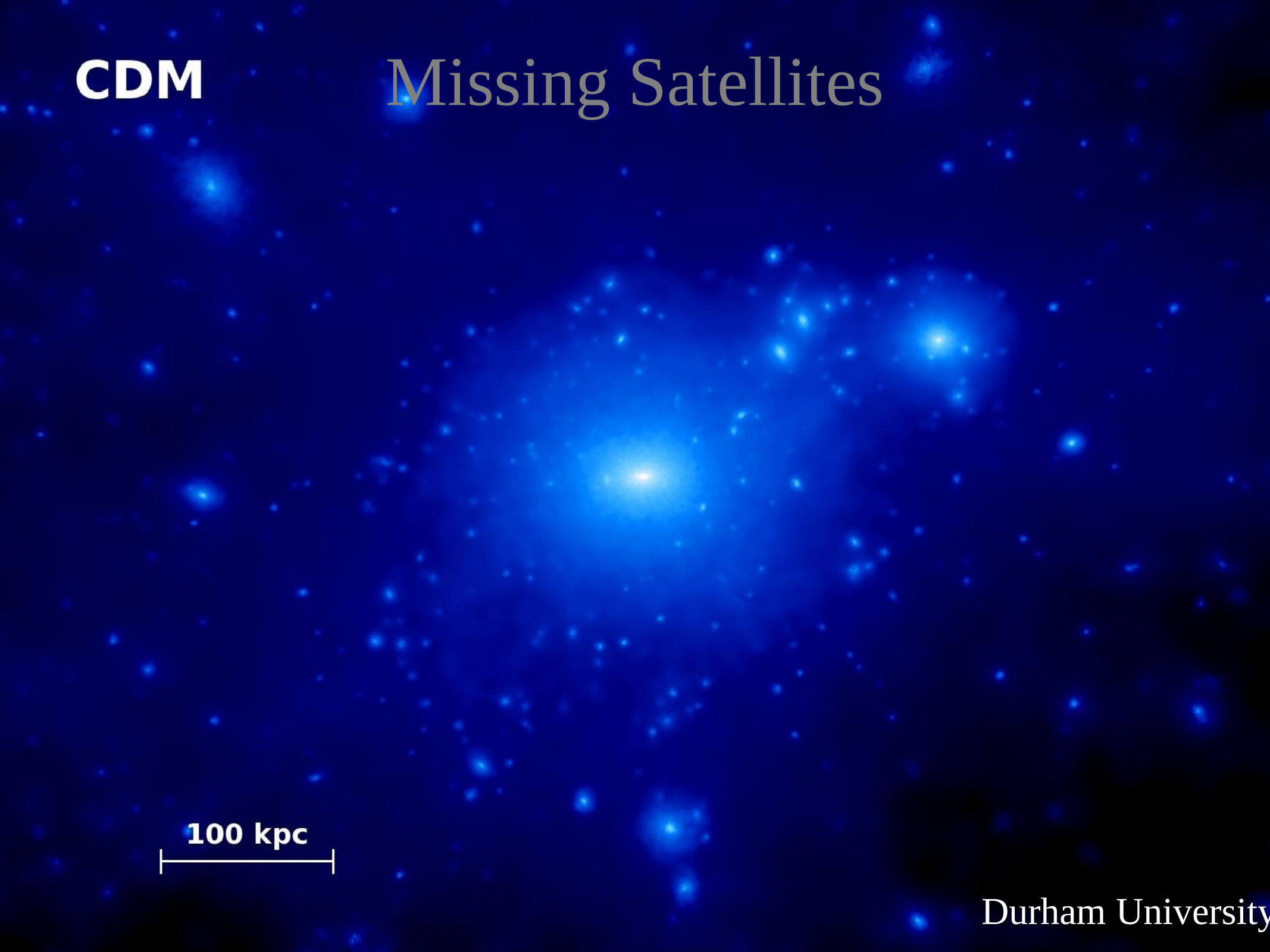
Microlensing




Stephen Rand

Tom Buckley-Houston


dark matter
halo
normal
visible halo
Saint


CDM
Missing Satellites
100 kpc
Durham University


WDM

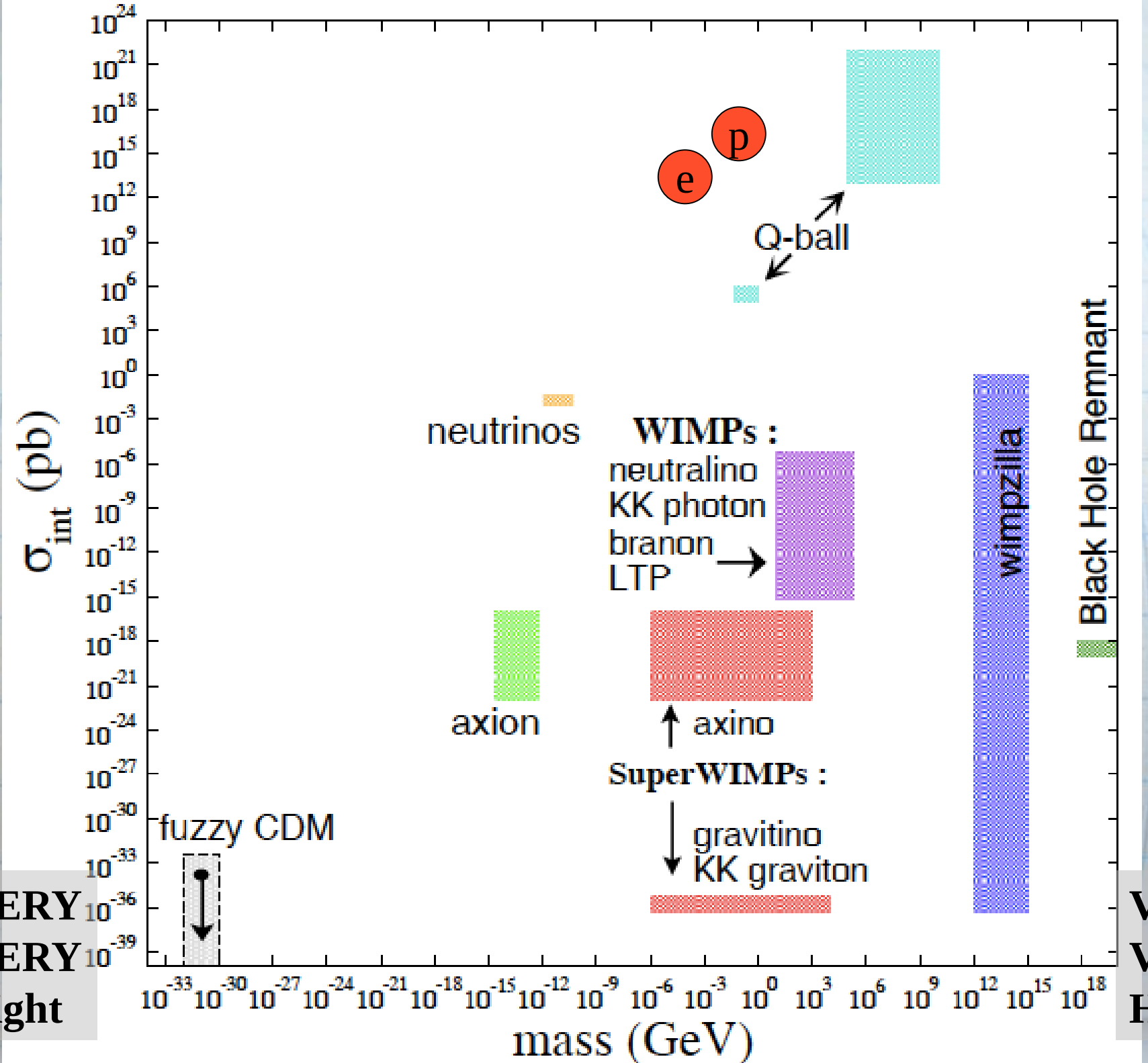
What could it be?

Is this a dagger I see before me?

What could it be?

- Possibilities
  - WIMP
  - Neutralino
  - Sterile neutrino
  - Axion
  - Graviton
  - Dark sector (woooooo!)
  - MAQRO (Macroscopic quantum resonator) – *no really!*
  - Q-ball, fuzzy-dark-matter, wimpzilla, … *they're just making stuff up now!*

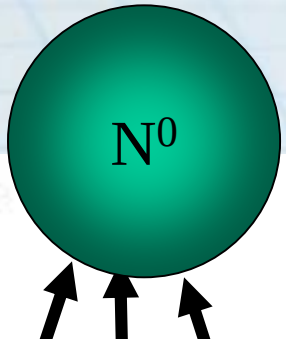
How wide it is/easy to hit



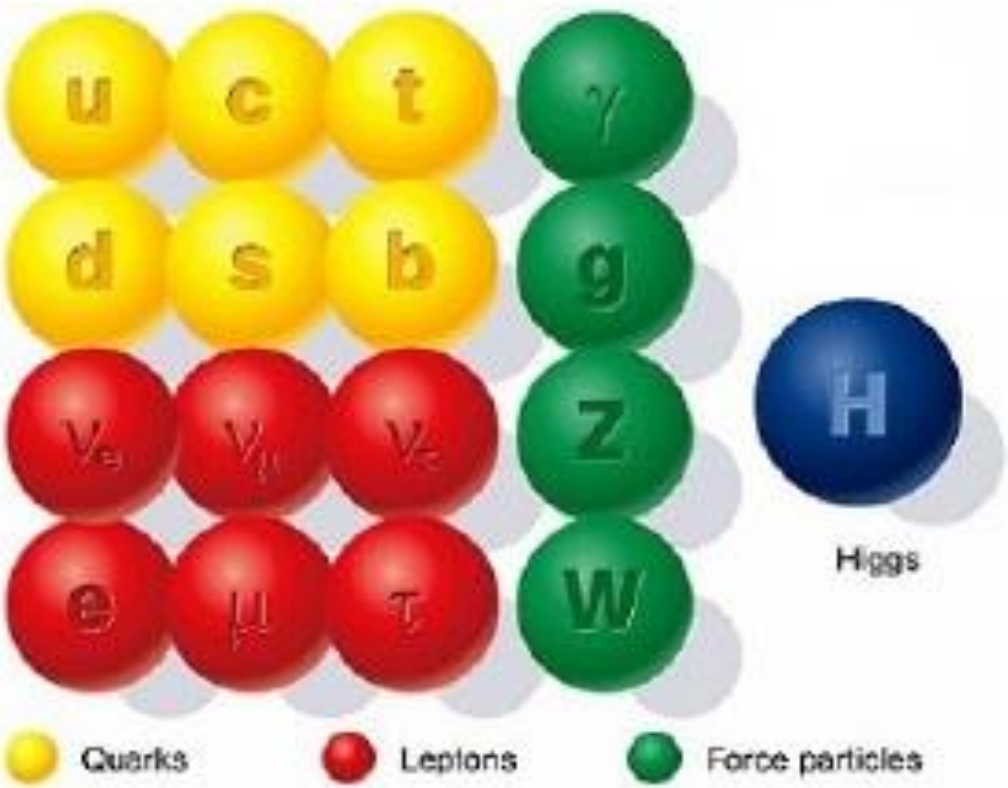
VERY VERY Light

VERY VERY Heavy

Supersymmetry and the Neutralino



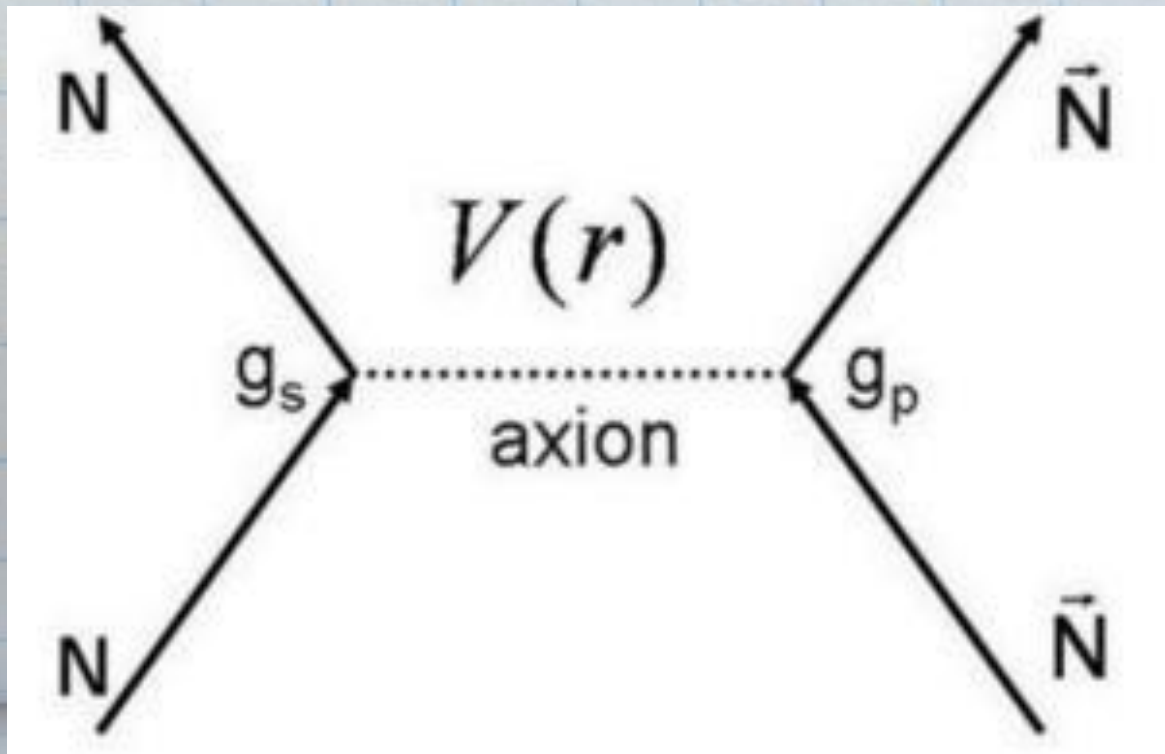
SUPERSYMMETRY



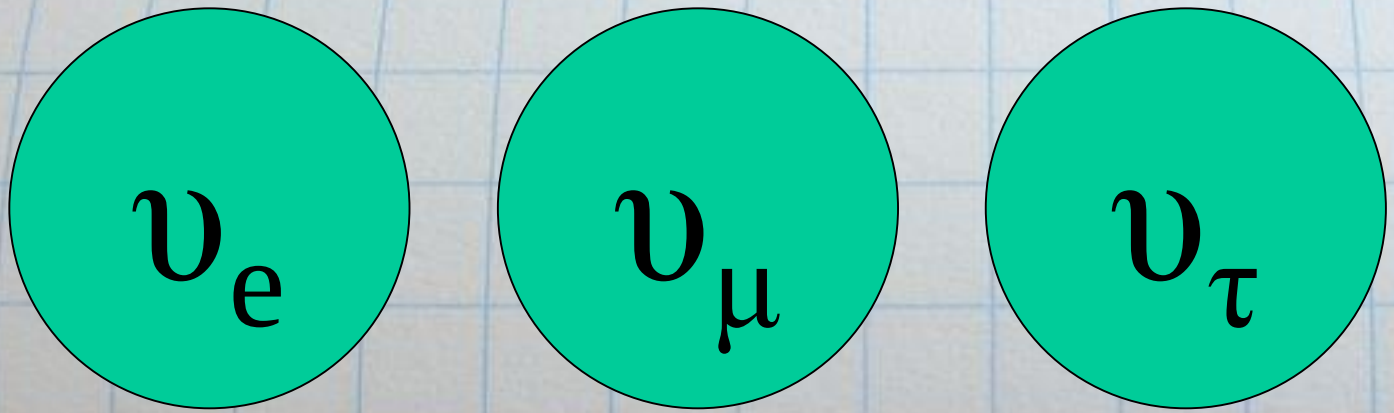
Standard particles

Axion/Axino

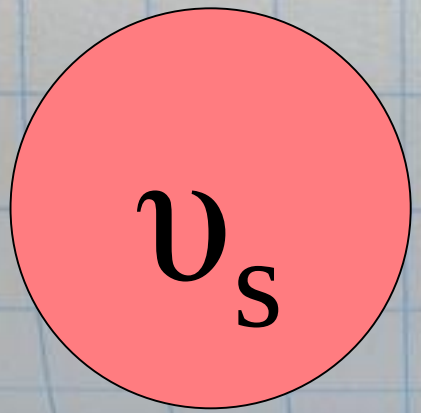
- Quantum Chromo Dynamics (QCD)
- Roberto Peccei and Helen Quinn (1977)
- A bit like a Higgs for quarks.



Sterile Neutrino



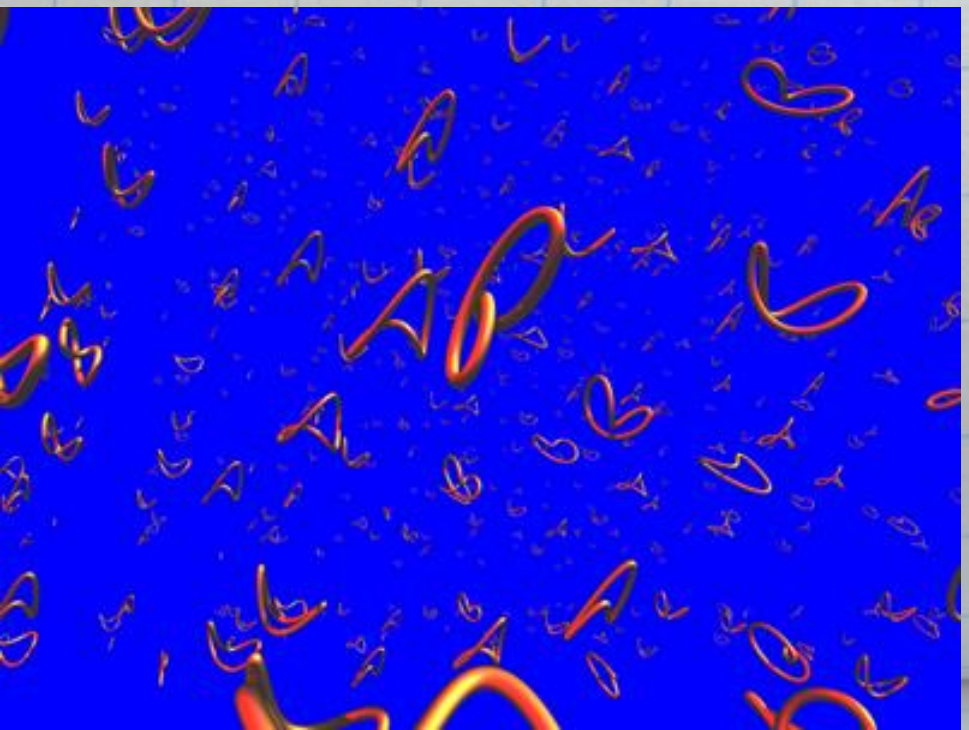
Left handed
Minute mass

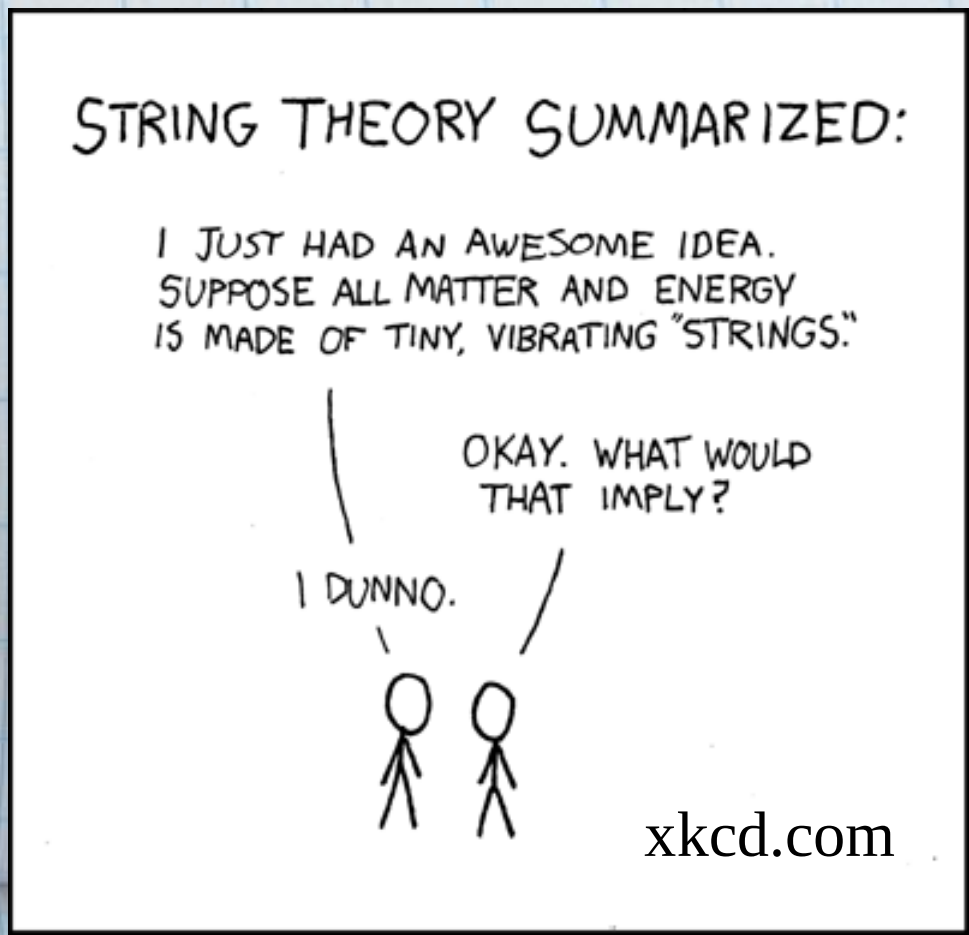


Right handed
Small mass

LKK

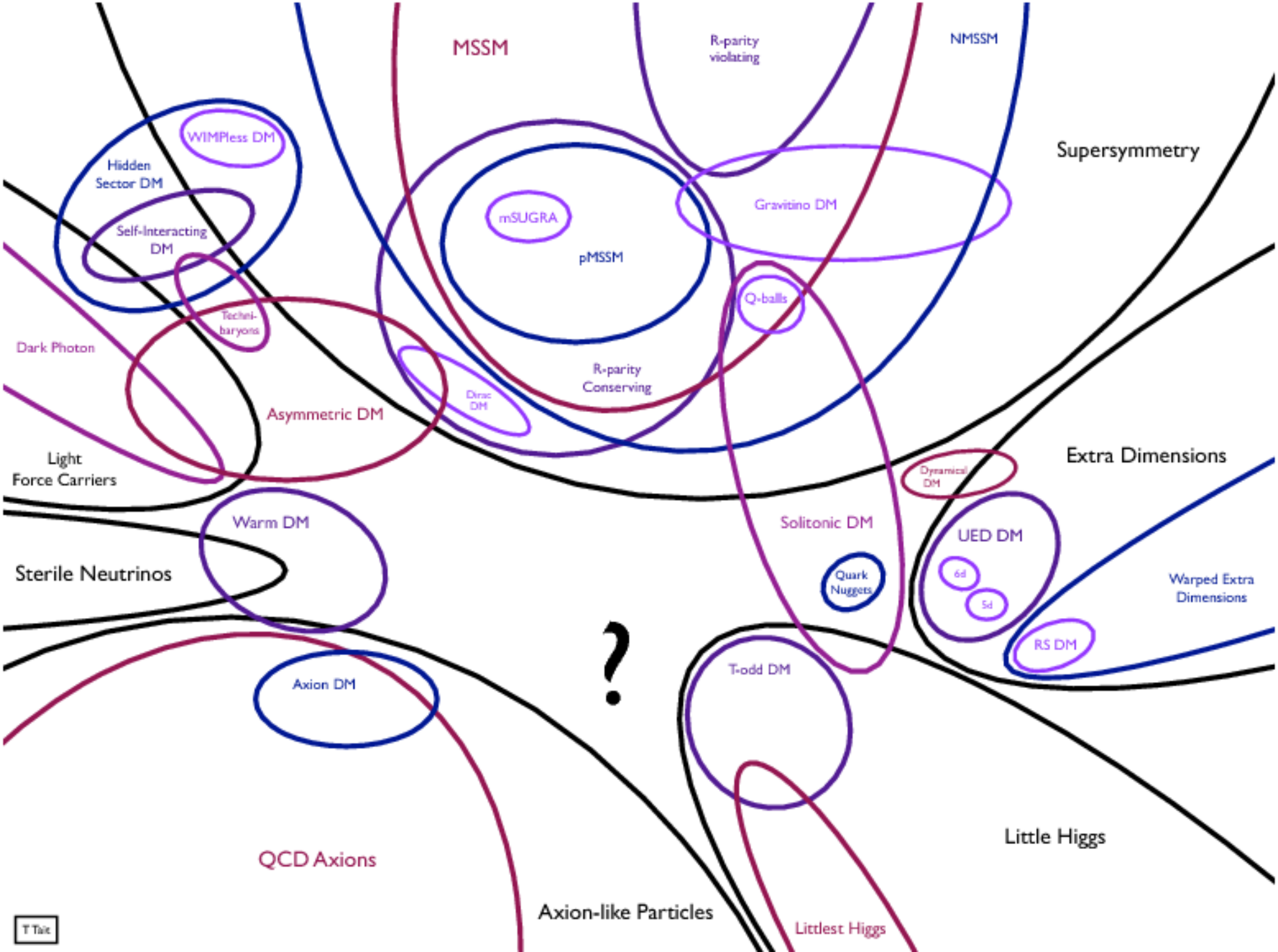
- Theory of extra dimensions from string theory
- Lightest Kaluza-Klein particle.
- KK photon
- KK neutrino





Others

- WIMPzilla
- Q-ball
- Scalar graviton
- Magic unicorn dust
- …

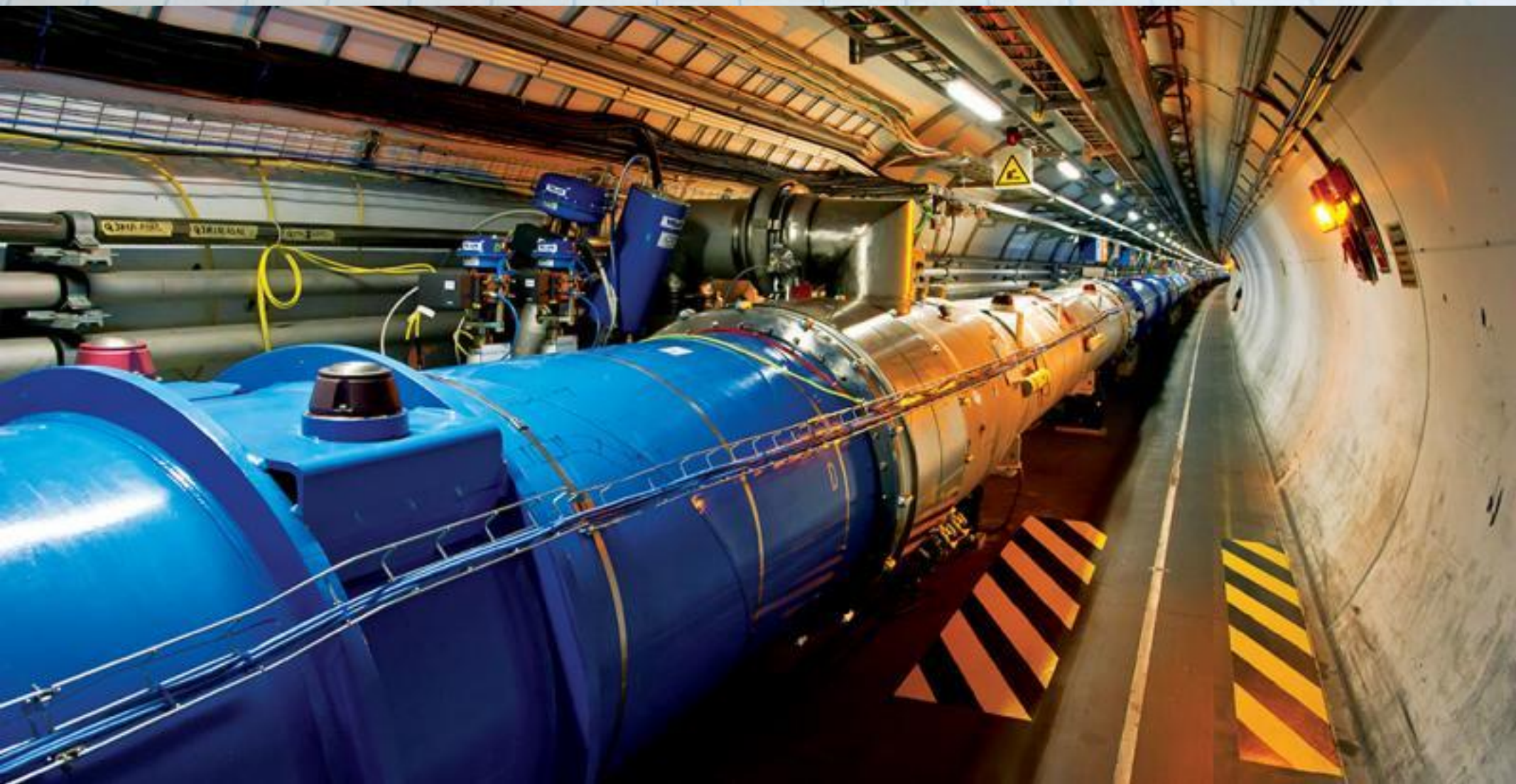

MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Finding dark matter
Make it, Shake it, Break it!

How do I detect thee?
Let me count the ways…

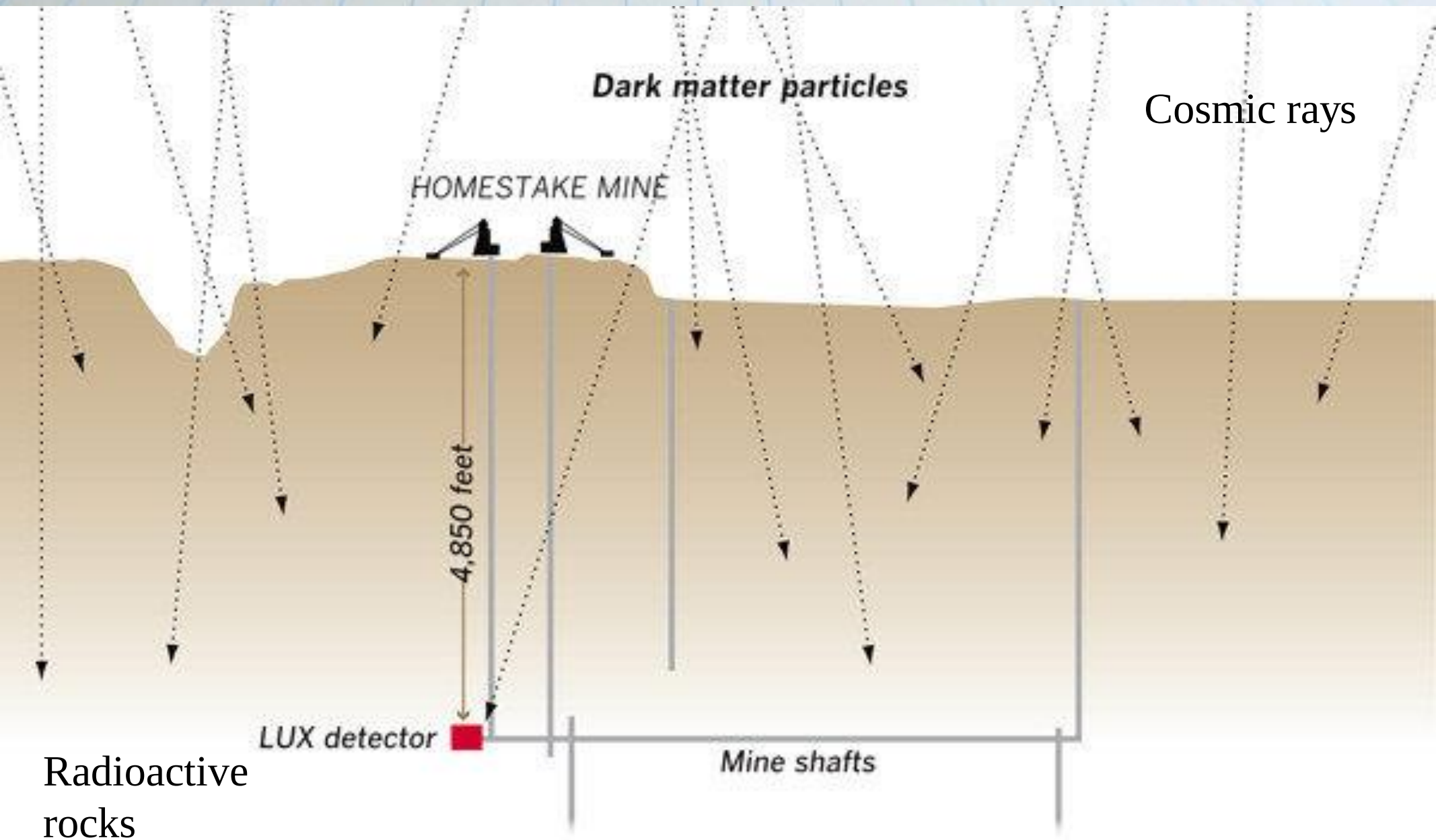
3

Making it

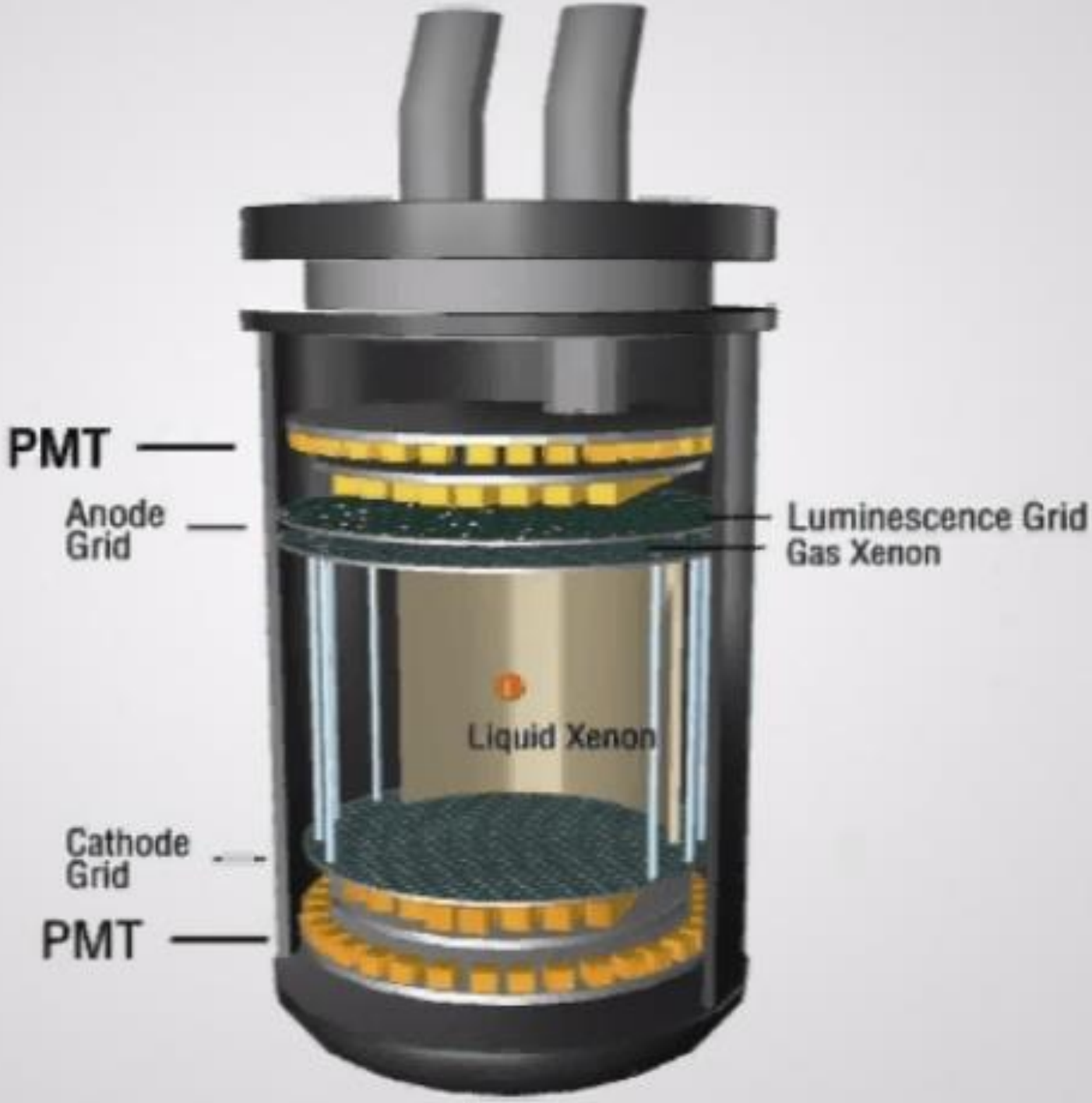



LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Detecting it directly



Detection


PMT
Anode Grid
Luminescence Grid
Gas Xenon
Liquid Xenon
Cathode Grid
PMT

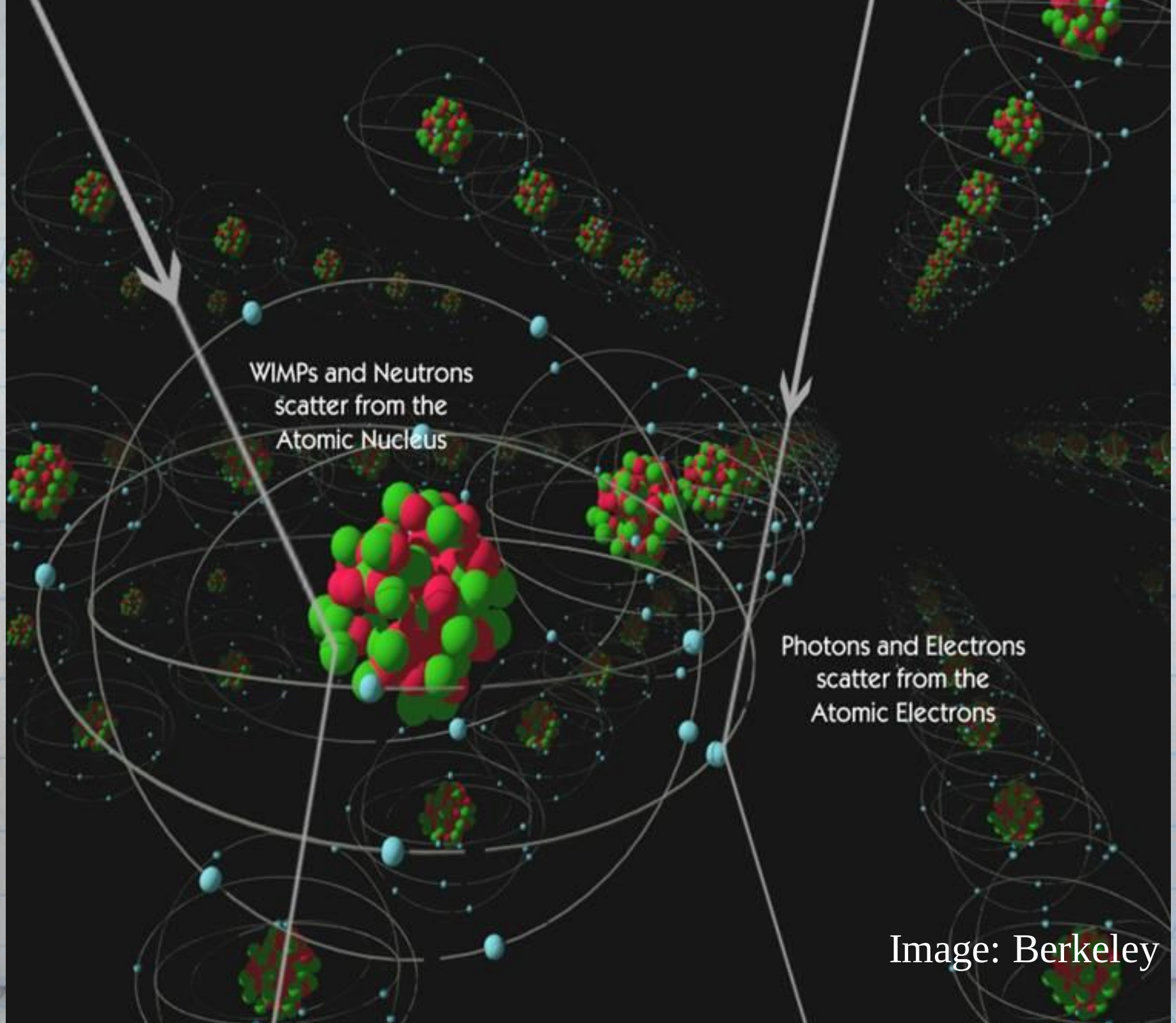
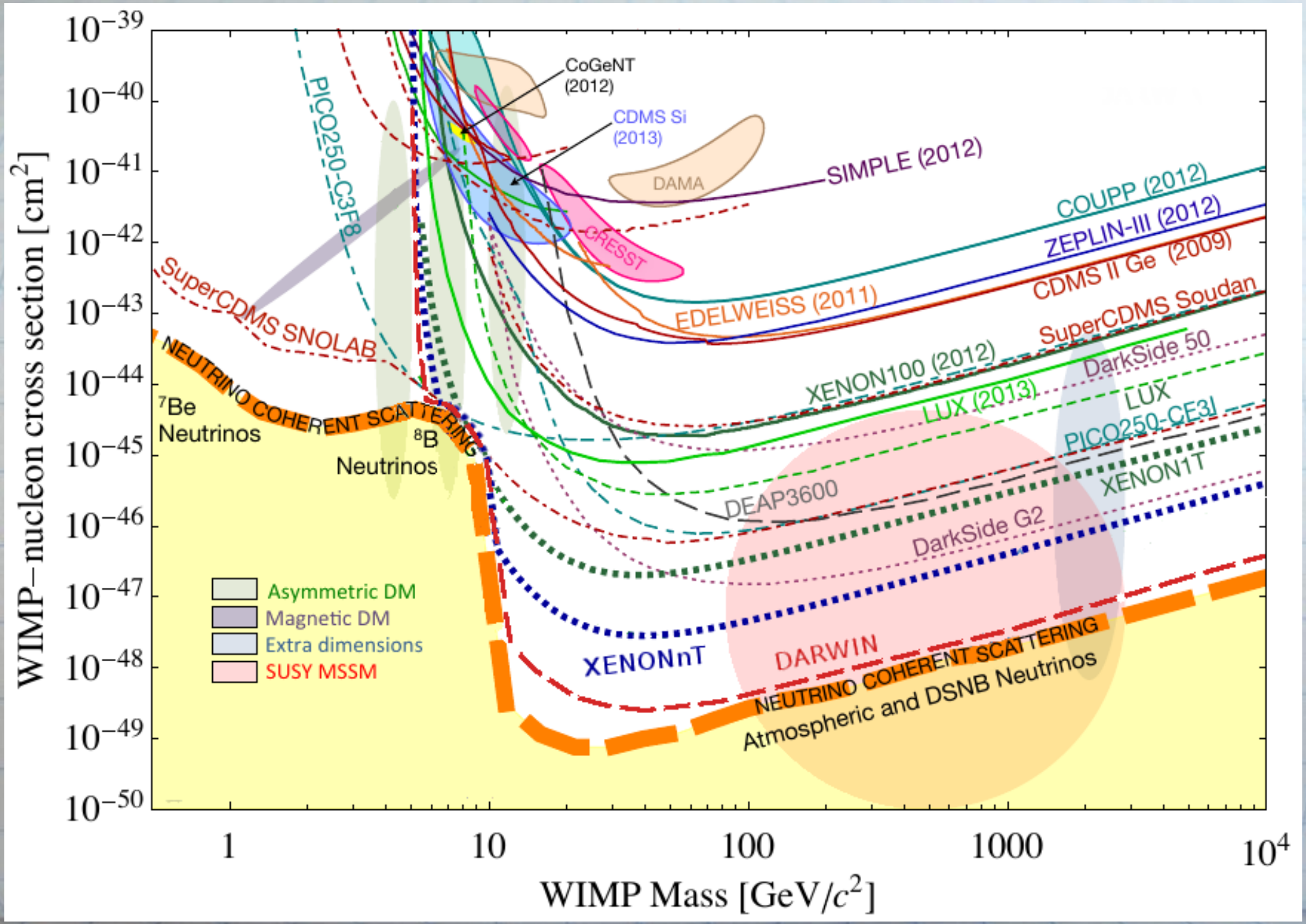
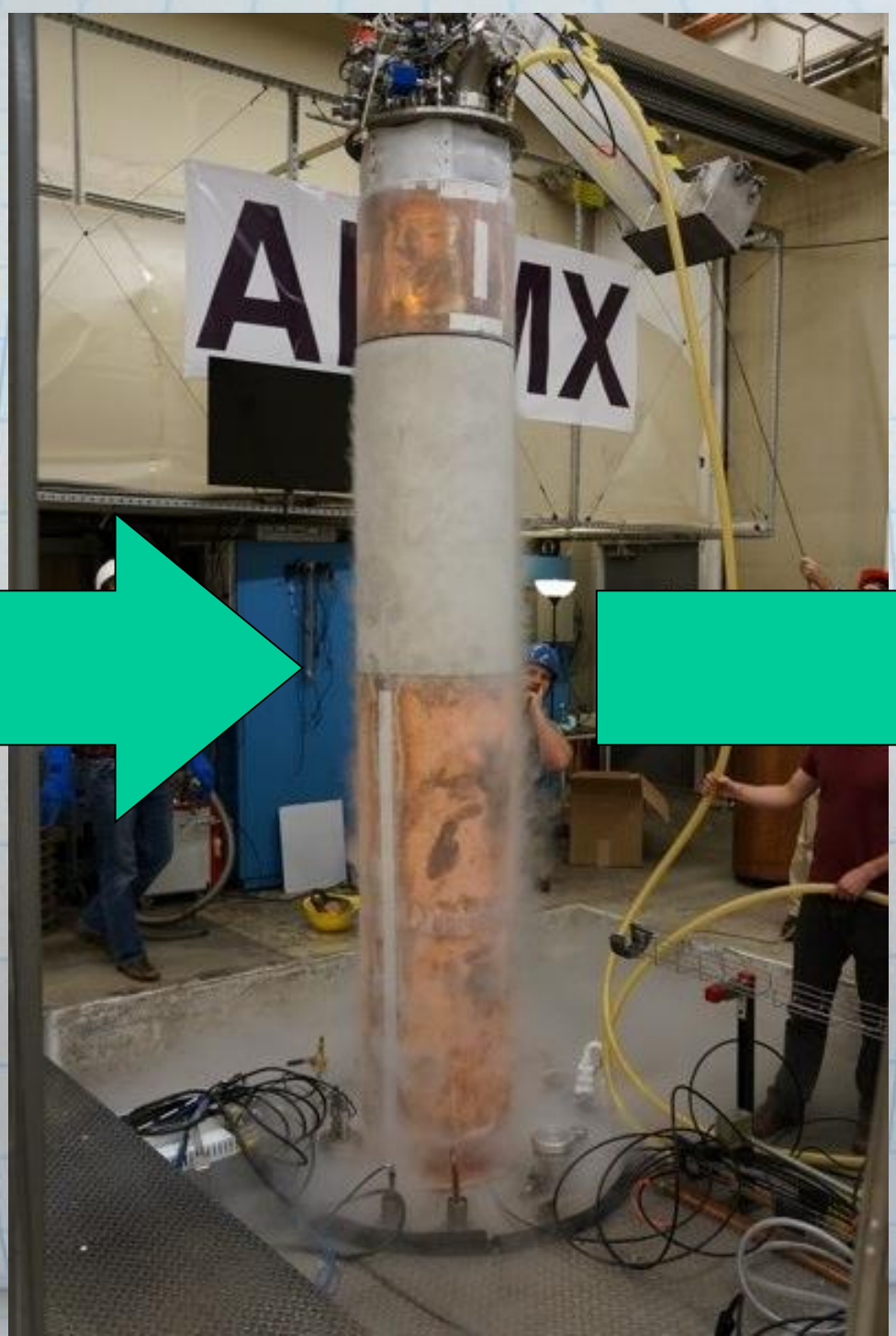


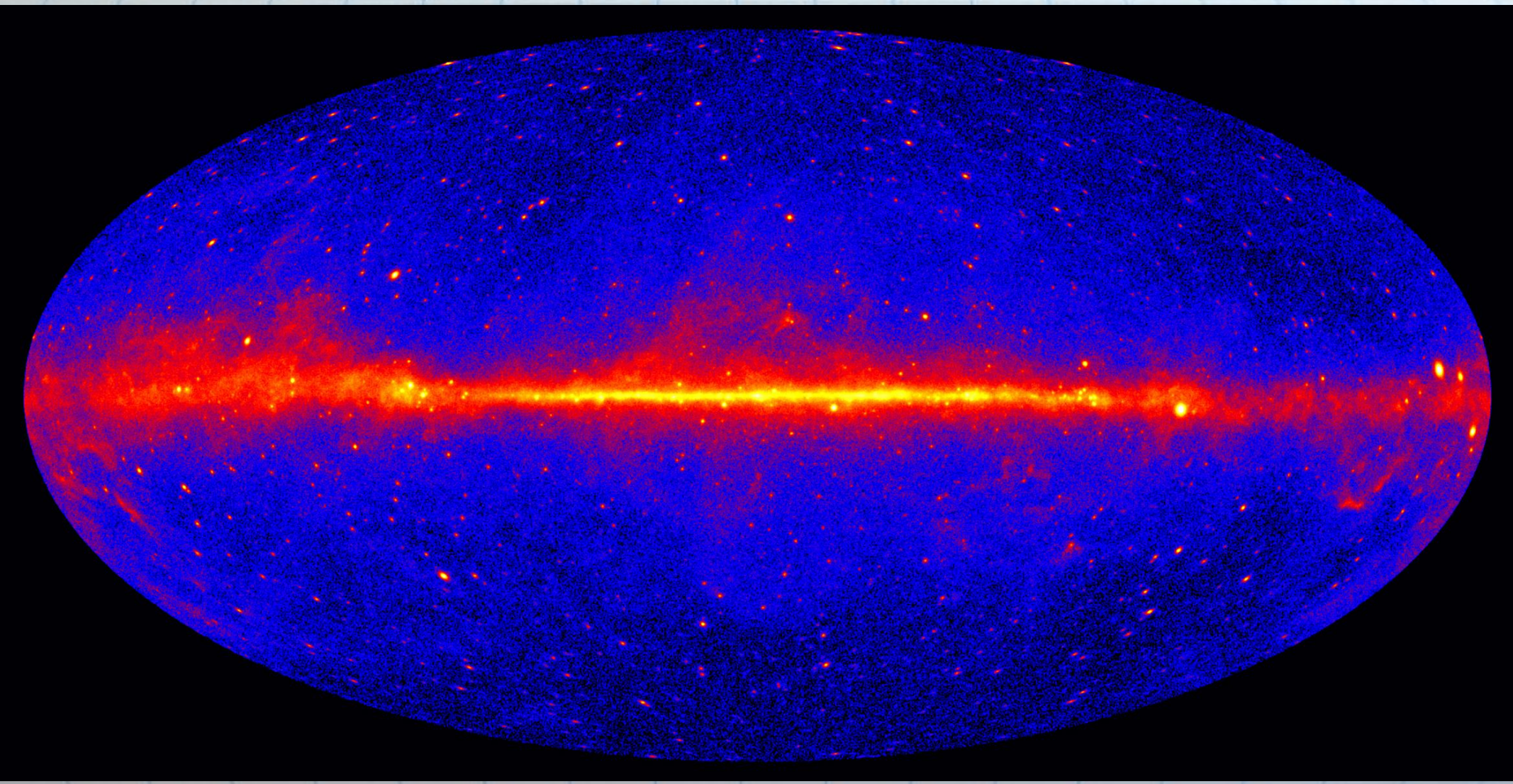
Image: Berkeley


WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10^4
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
PICO250-C3F8
SuperCDMS SNOLAB
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
XENON100 (2012)
DarkSide 50
LUX (2013)
LUX
PICO250-CF3I
DEAP3600
XENON1T
DarkSide G2
XENONnT
DARWIN
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM

ADMX – Univ of Washington



Detecting it indirectly



Alternatives

To be or not to be…

Milgrom and MOND

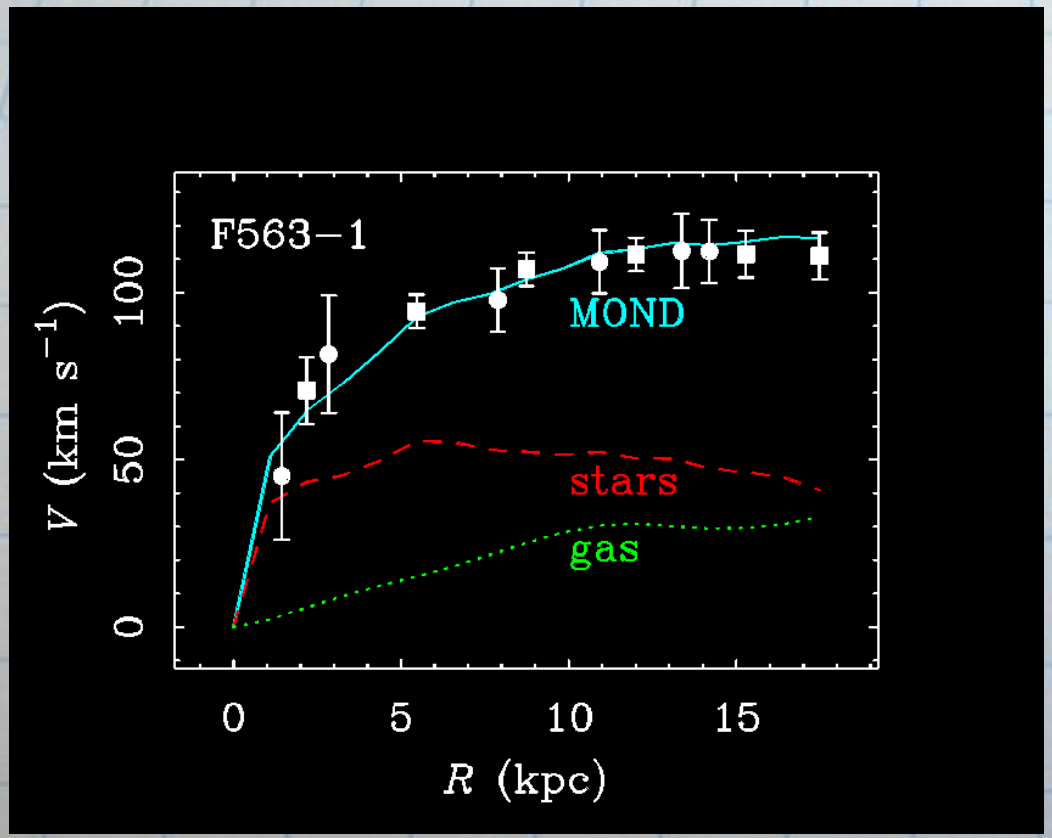
$$F = ma \quad \Rightarrow \quad F = m\mu\left(\frac{a}{a_0}\right)a$$

When $a >> a_0$ $\quad F = ma$

When $a << a_0$ $\quad F = \dfrac{ma^2}{a_0}$

- Makes galaxies behave perfectly
- But then it is designed to!
- Has some success.

MOND



- However
  - Doesn't satisfy conservation laws such as momentum.
  - Doesn't handle relativistic cases.
  - Other issues

TeVeS and others

- Tensor-Vector-Scalar gravity (Berkenstein 2004)
- Relativistic generalisation of MOND
- Stars may be unstable under TeVeS
- Also
  - Scalar-Tensor-vector gravity (MOG)
  - Bi-scalar-tensor-vector gravity
  - f(R) theories – modified Einstein equations

Conclusions

Cold Dark Matter

- Cold – probably – but could be warm
- Dark – not really, more transparent
- Matter – not really

Thank you for listening