SCALAR FIELD DARK MATTER WITH TWO COMPONENTS: A COMBINED COSMOLOGY AND PARTICLE PHYSICS APPROACH

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PRD 2022

DARK MATTER: FELT BUT NOT SEEN

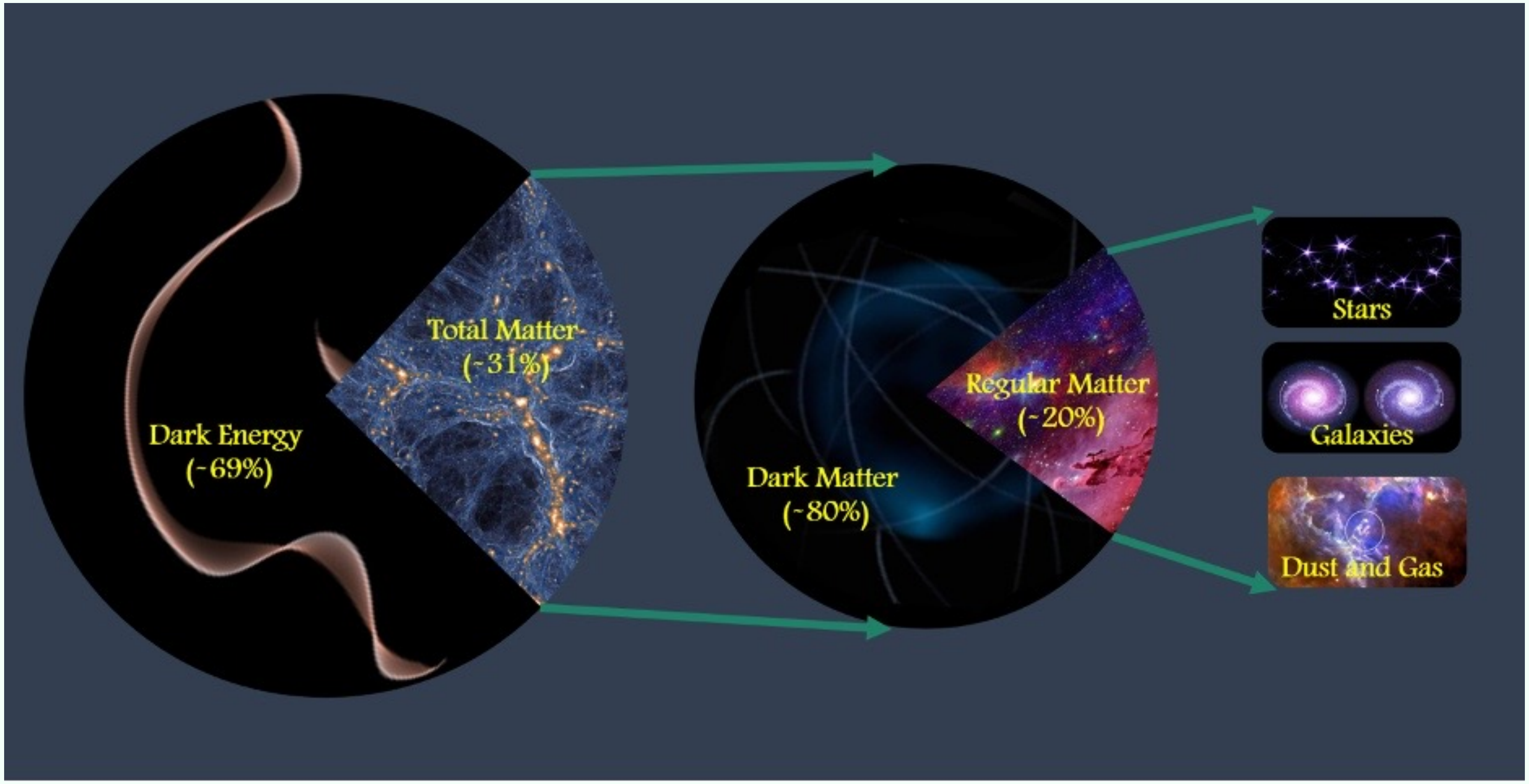
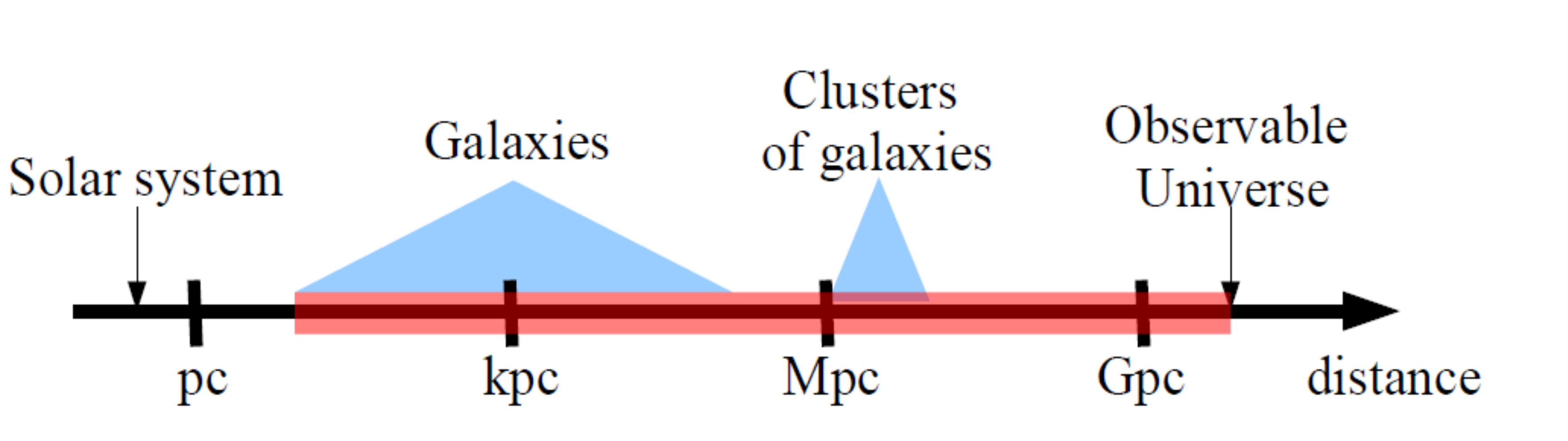
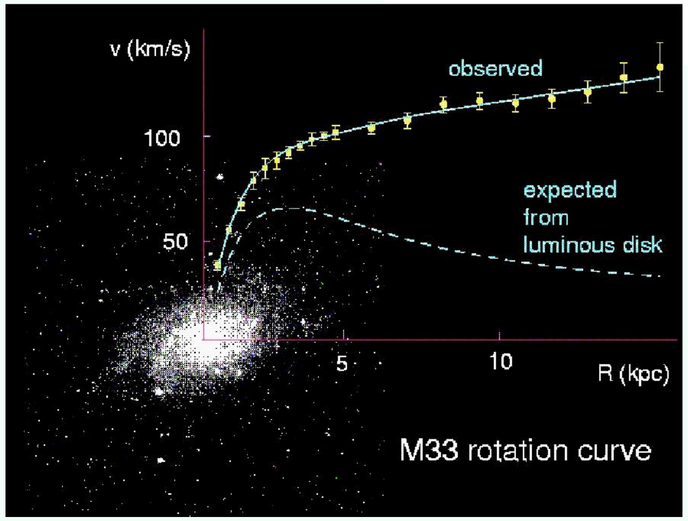


Image credit: UCR/Mohamed Abdullah

- ➤ Particle Physics → BSM
- ➤ Cosmology → ΛCDM +??

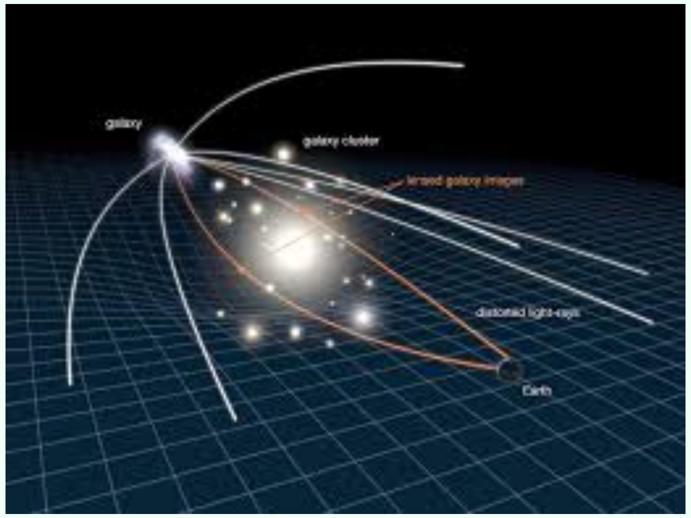
EVIDENCE OF DARK MATTER AT DIFFERENT SCALES IN THE UNIVERSE

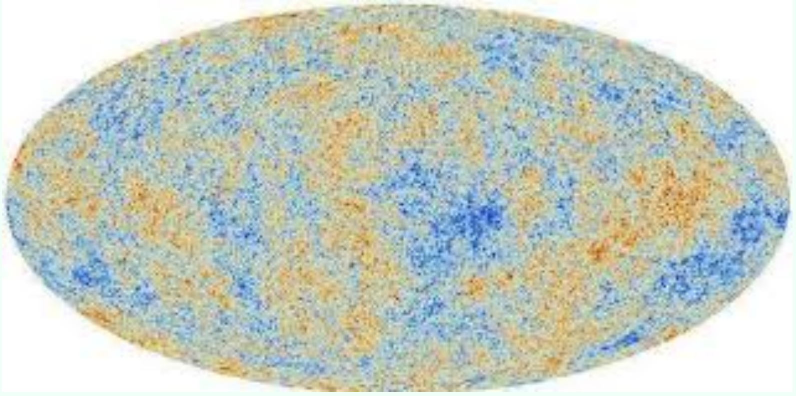




F. Zwicky, 1933
galaxy clusters

V. Rubin y K. Ford, 1960
galaxies

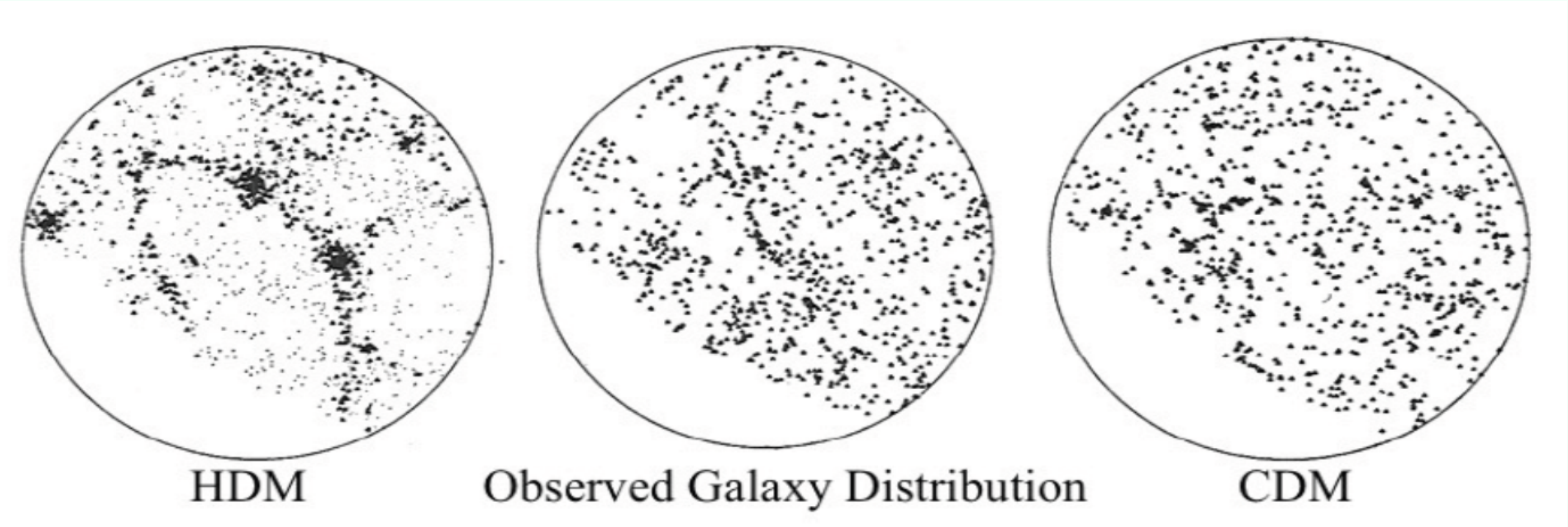




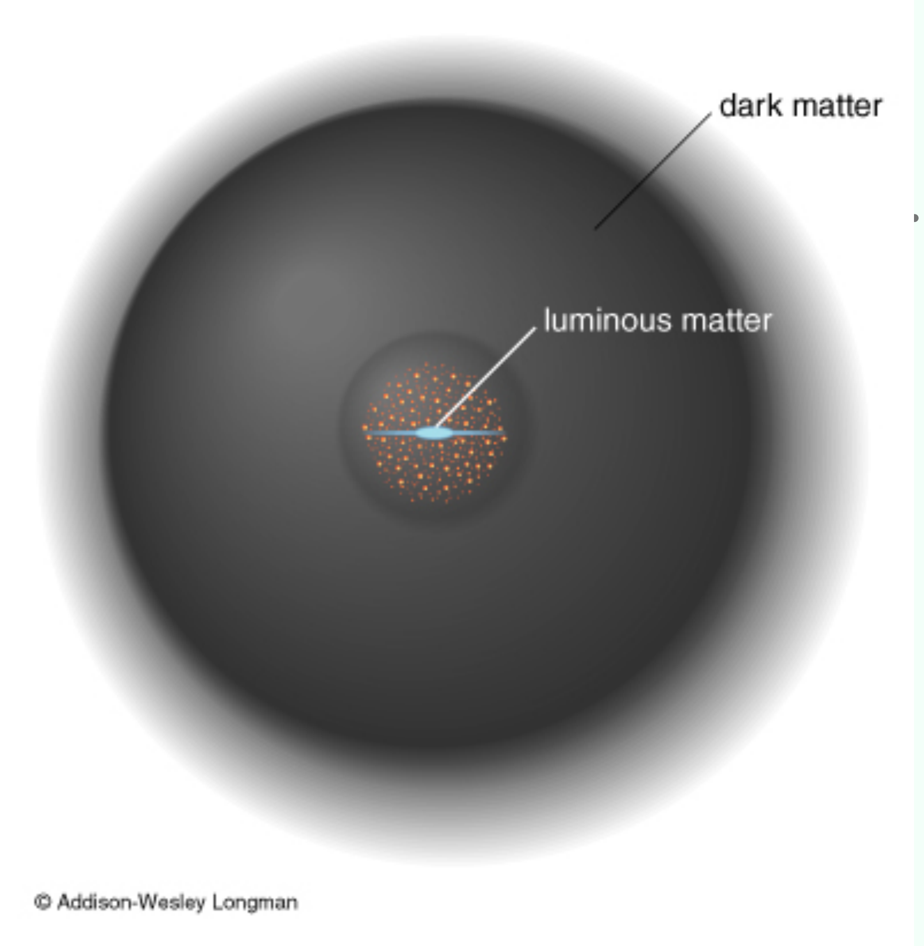
Temperature anisotropies
CMB ~2012

WHAT DO WE KNOW ABOUT DM?

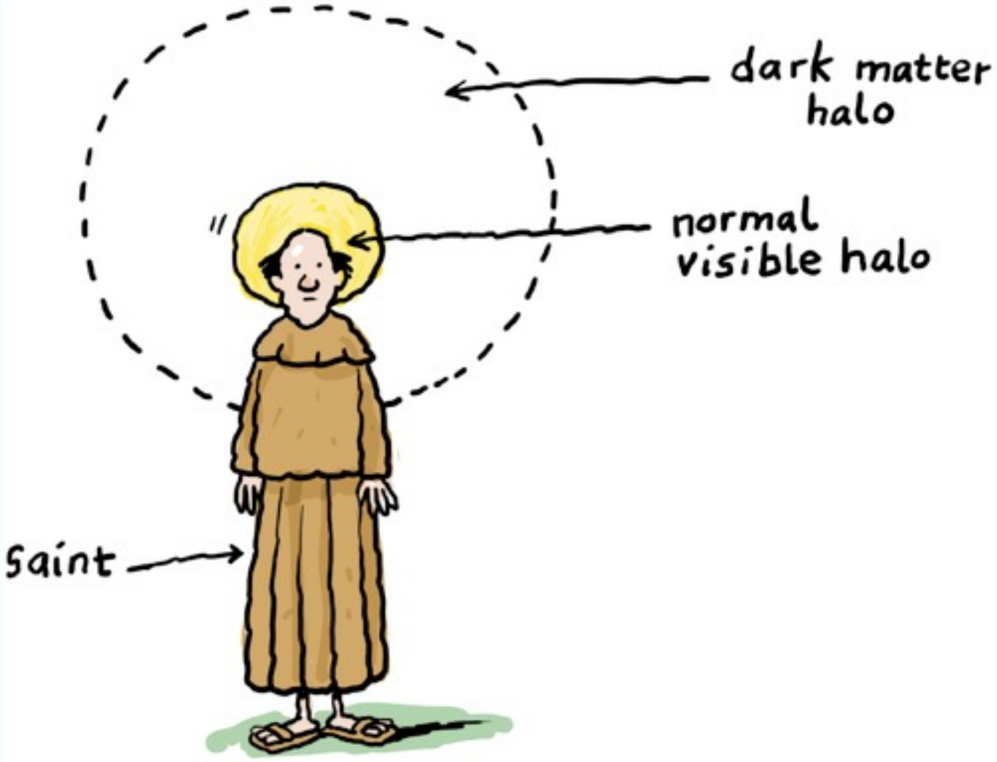
- Electrically neutral
- Non-baryonic (not made of protons or neutrons)
- Moved very slowly during formation of first structures
- Has mean lifetime longer that the age of the Universe



DARK MATTER: PARTICLE PHYSICS

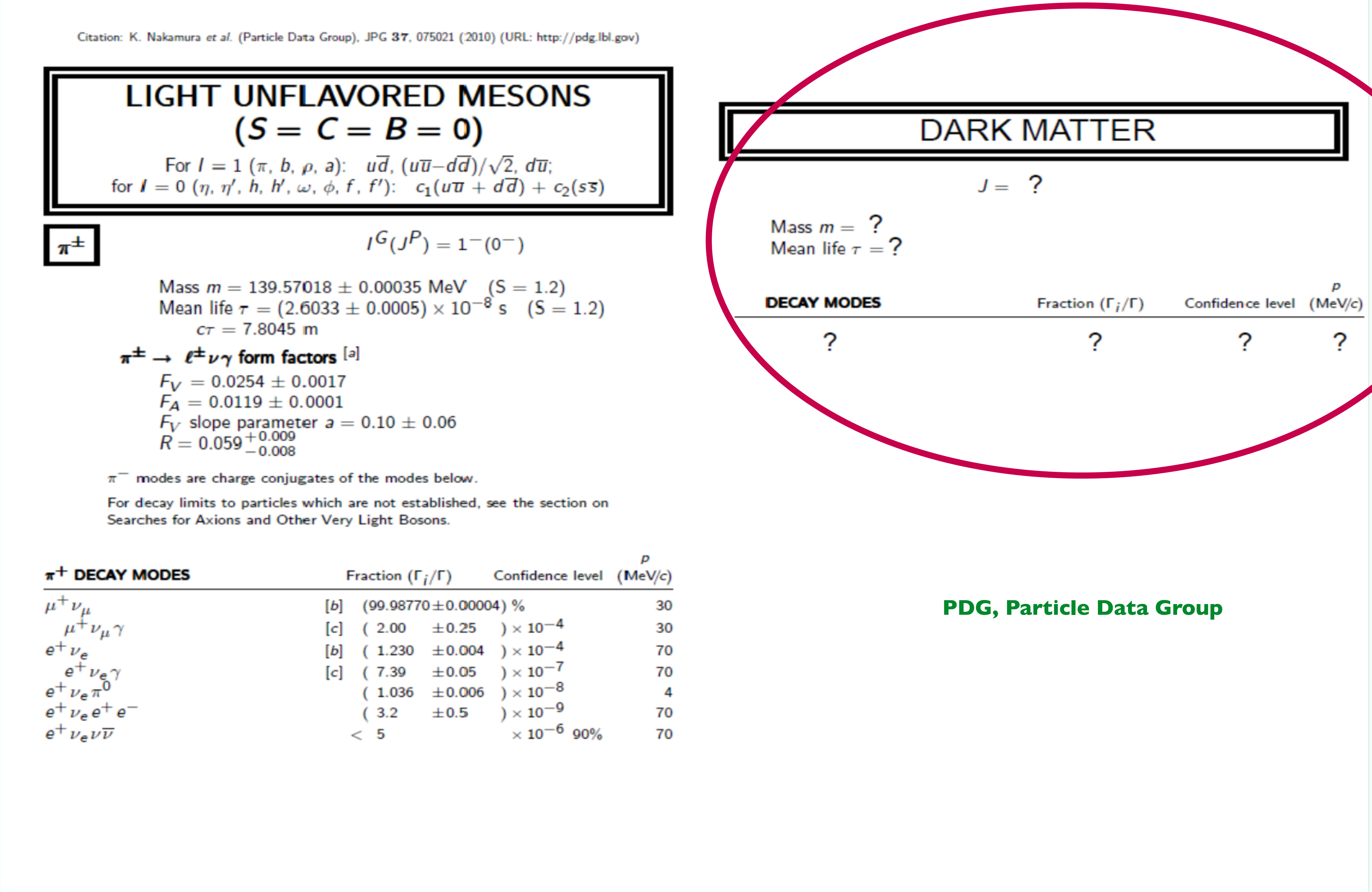


© Addison-Wesley Longman



- First proof that there is new physics
- None of the SM particles can account for 100% of DM
- Better explanation requires new particles

WHAT DO WE KNOW OF DM FROM PARTICLE POINT OF VIEW?



Citation: K. Nakamura *et al.* (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

$\pi^\pm$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^\pm \rightarrow \ell^\pm \nu \gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	(2.00 ± 0.25) × 10^{-4}		30
$e^+\nu_e$	[b]	(1.230 ± 0.004) × 10^{-4}		70
$e^+\nu_e\gamma$	[c]	(7.39 ± 0.05) × 10^{-7}		70
$e^+\nu_e\pi^0$		(1.036 ± 0.006) × 10^{-8}		4
$e^+\nu_e e^+ e^-$		(3.2 ± 0.5) × 10^{-9}		70
$e^+\nu_e\nu\bar{\nu}$		< 5 × 10^{-6}	90%	70

DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

PDG, Particle Data Group

WHY GO BEYOND?

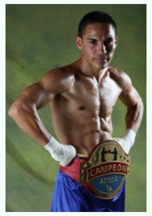
- The hierarchy problem
- Neutrino masses
- Origin of gauge interactions
- Dark matter
- Matter over anti-matter abundance
- Cosmological constant
- Inflation

- Higgs sector not natural
- Fermion masses vastly different
- Origin of electroweak symmetry breaking unknown
- Dirac or Majorana neutrinos
- Strong CP problem
- Number of generations

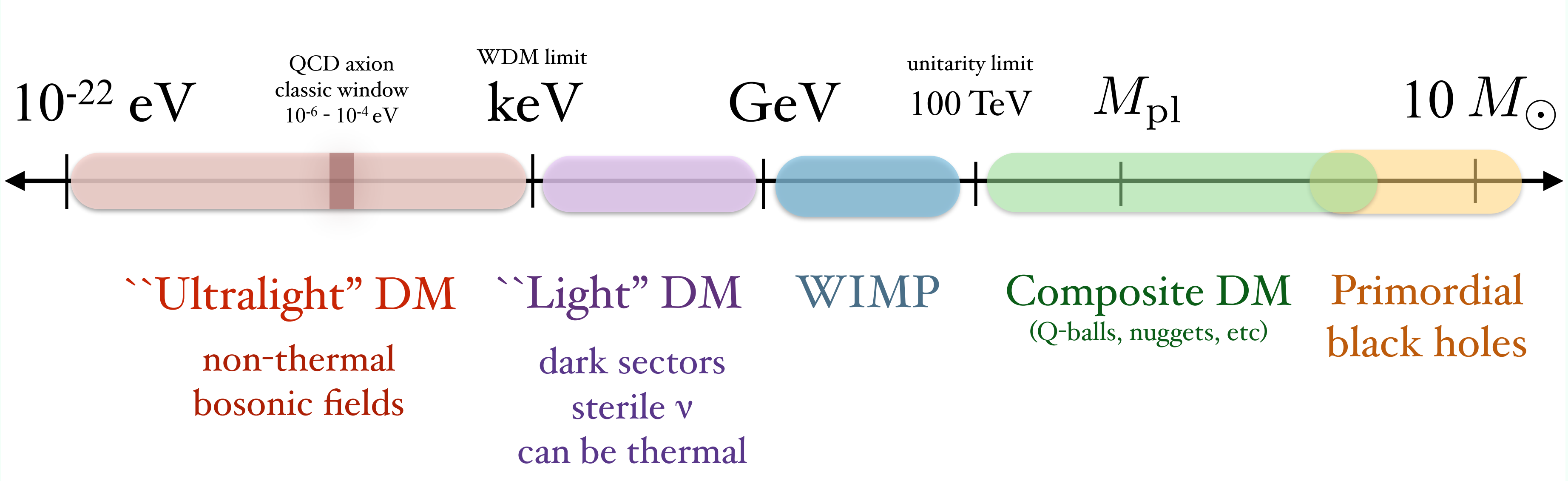
⇅

- Not enough CP in SM for Baryogengesis
- Value of cosmological constant
- Inflation inconsistent with non-zero baryon number
- If DM a particle, then which, is it only one?

SOME CANDIDATES



Juan Francisco Estrada



10^{-22} eV

QCD axion
classic window
10^{-6} - 10^{-4} eV

WDM limit
keV

GeV

unitarity limit
100 TeV

$M_{\rm pl}$

10 $M_\odot$

``Ultralight” DM
non-thermal
bosonic fields

``Light” DM
dark sectors
sterile ν
can be thermal

WIMP

Composite DM
(Q-balls, nuggets, etc)

Primordial
black holes

Audley Harrison

- Axions and “axion-like”: From ultra-light to light
  10^{-22} eV to keV
- WIMPS Weakly Interacting Massive Particles:
  Neutralinos, Kaluza-Klein particles, Higgses, sterile neutrinos
  few GeV - 100 TeV
- Superheavy: primordial black holes,WIMPzillas
  super-heavy particles or compact objects

SCALAR DM IN PARTICLE PHYSICS

They can come all the way
from strings
or
just above SM energy scale

- Multi-Higgs models
- Kaluza-Klein models
- Axion and axion-like models
- Usually stabilized by a discrete symmetry
  - Put by hand or
  - Residual symmetry

Many of these

- Check DM relic density
- Decaying DM also studied
  - lately advocated to relieve H_0 tension

e.g. Ibarra et al 2013, Lester et al 2021; Anchordoqui 2021; etc

FROM PARTICLES

- one or more candidates
- WIMPS, non-WIMPS, standard, exotic
- decaying DM
- combination of all the above
- Direct searches: nothing
- Indirect searches: nothing
    - Astrophysical gamma rays, cosmic rays, etc
- Production: LHC nothing
- But we are all convinced it is there

SCALAR FIELD FROM COSMOLOGY/GRAL RELATIVITY

- Modelling DM as a scalar field with corresponding potential
- Can describe galactic halo

  Matos,Guzmán, Class.Quantum.Grav.17, 2000

  Hui, Ostriker, Tremaine, Witten, PRD95, 2017

  Ureña-López, Front.Astron.Space Sci 6, 2019

- Different approaches: from GR or from strings
- Avoid overabundance of satellites (halos)from WIMPS
- Reproduce large scale fibre structure
- Harmonic structure of perturbations
- Ultra-light (very ultra), fuzzy dark matter

ULTRA-LIGHT DM

- Very light bosons, axions

$$m \sim 10^{-22} - 10^{-21}\ eV$$

- Large de Broglie wavelength surpasses small-scale structure
- Early work potential considered Matos,Guzmán, Class.Quantum.Grav.17 (2000)

$$V(|\phi|) = \mu^2 |\phi|^2 + \sigma^2 |\phi|^4$$

μ related to the mass, very small parameter and self-interaction $\sigma = 0$

- Possible also to model it with complex scalar field (better)

B. Li, T. Rindler-Daller, and P. R. Shapiro, Phys. Rev.D 89(2014);A. Suarez and P.-H. Chavanis, Phys. Rev. D 95(2017)

- Allow for $\sigma \neq 0$, which is the gravitational length scale (ultra-long), strongly constrained by σ^2/μ^4

$$m_\phi > 10^{-21}\,\mathrm{eV}/c^2$$

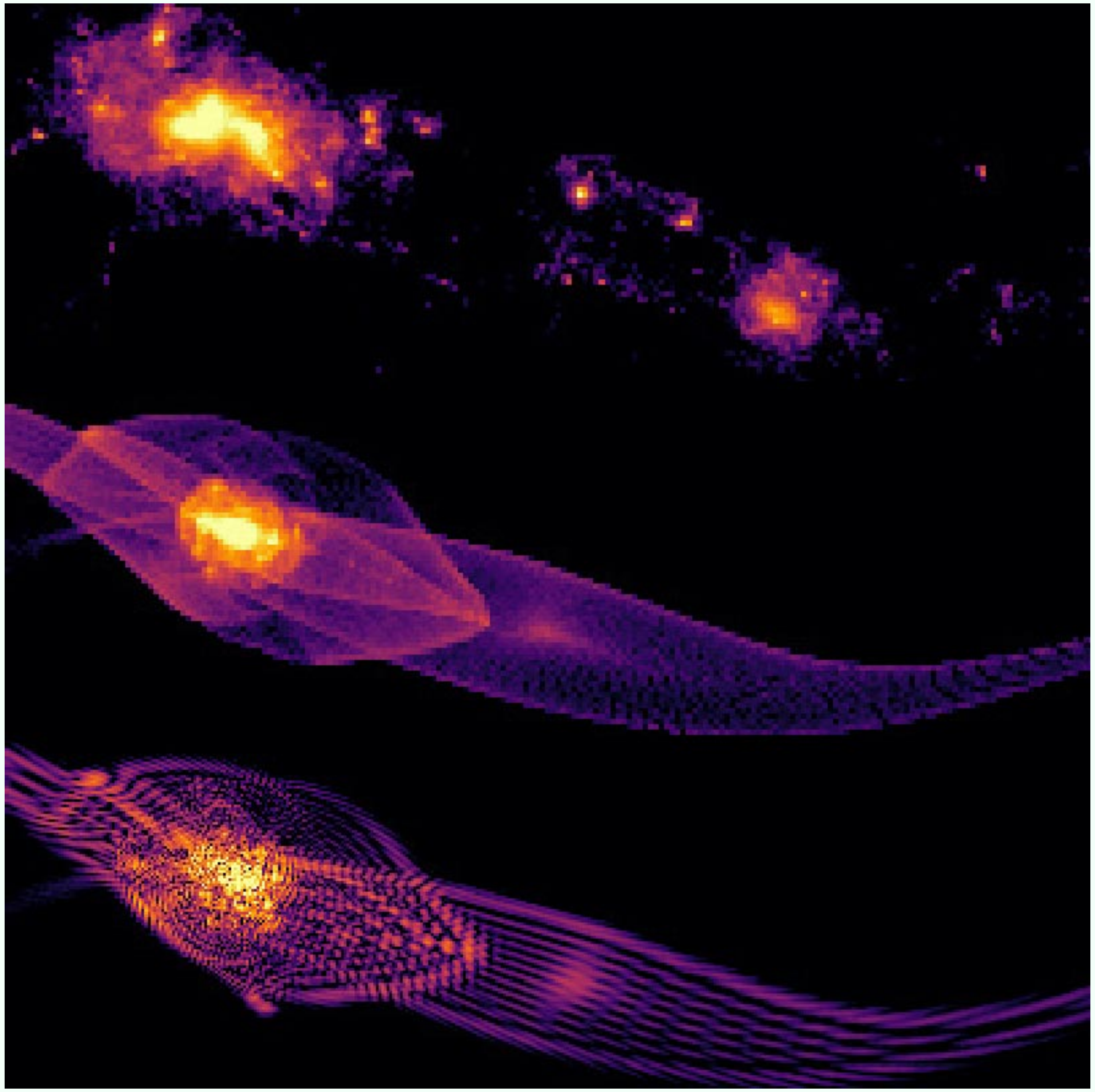
- This is a classical approach → classical field

STRINGS — FUZZY DARK MATTER

- Ultra-light scalar axion-like particles $m \sim 10^{-22}$ eV

- Bosons, form condensates

- Leave footprint in structure formation



Early galaxy formation:
CDM (top), warm DM (middle), fuzzy (bottom)

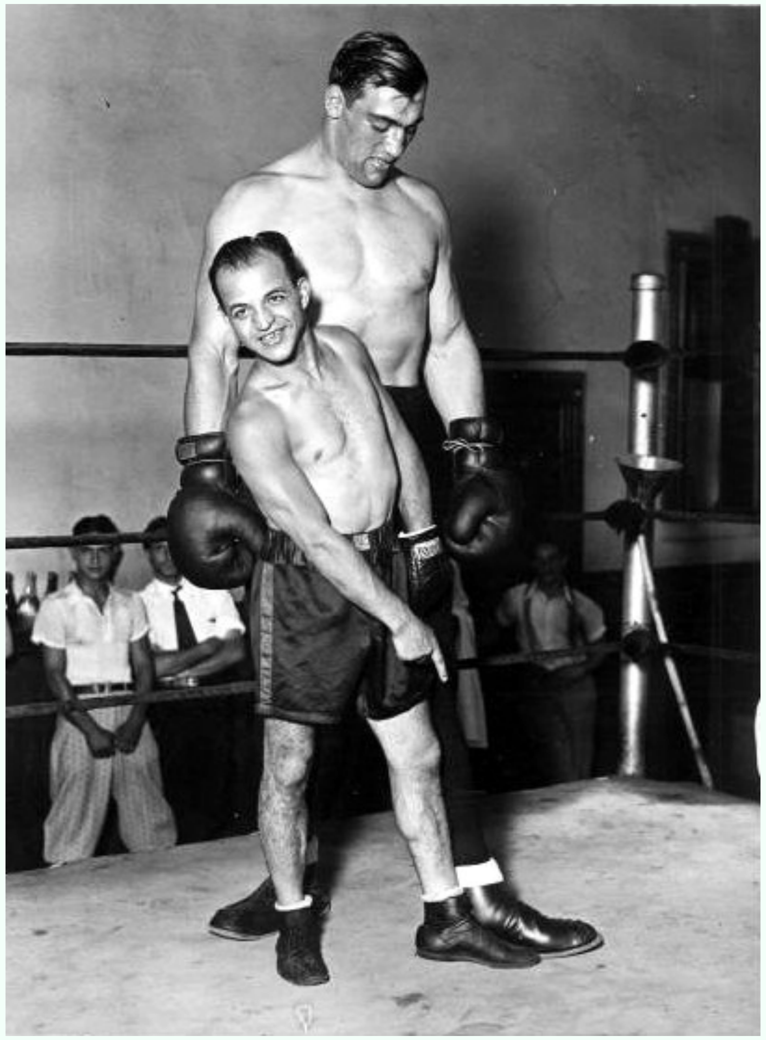
Philip Mocz, Anastasia Fialkov, Mark Vogelsberger, Fernando Becerra, Mustafa A. Amin, Sownak Bose, Michael Boylan-Kolchin, Pierre-Henri Chavanis, Lars Hernquist, Lachlan Lancaster, Federico Marinacci, Victor H. Robles, and Jesús Zavala, Physical Review Letters ***123****, 141301 (2019)*

ULTRA-LIGHT AND PARTICLE DM

- Ultra-light or fuzzy DM
  - Gravitational models with scalar field
  - We will refer to it as "classical"
  - Stringy models with ultra-light axion-like particle lots of possible candidates come out
  - Modeled like a fluid
- Scalar particle, "normal" particle physics
  - Higgs-like
  - Axion-like
- Different descriptions

OUR FIRST ATTEMPT: COMBINE BOTH APPROACHES (SOMEHOW)

- We will assume that DM can be a combination of two different scalar fields:
  one classical
  one scalar from particle physics
- We take some classical limit for the particle candidate
- We model it like a fluid, using particle type scalar potential
- We put some cosmological constraints
- We see what comes out



https://boxrec.com/media/index.php/Weight_divisions

Heavyweight Primo Carnera & Flyweight Frankie Genaro

FIRST PP CANDIDATE: AN AXION

- Axion/axion-like candidate, from particle physics (KSVZ, DFSZ).

  No specific model considered, "axion-like"

  Chadhan-Day, Ellis & March, Sci.Adv.8 (2022)

- We take as potential:

$$V_a(\Phi_a) = \frac{1}{2}\left(m_a^2\Phi_a^2 - \frac{1}{12}\frac{m_a^2}{f_a^2}\Phi_a^4\right)$$

  f_a scale of U(1) breaking, which is first two terms in Taylor expansion around the minimum of the potential generated by instantons

- Mass protected, self interactions and interactions with SM suppressed

- Light (less than meV), weakly interacting, long lived

AXION AND AXION-LIKE

- Usually $f_a \lesssim M_{pl} \sim 10^{19}$

  Graham & Rajendran, PRD88 (2013); Marsh, Phys.Rept.643 (2016); Chadhan-Day, Ellis & March, Sci.Adv.8 (2022)

- Production:
  - Decay of parent particle
  - Decay of topological defect
  - Thermal population from radiation
  - Vacuum misalignment

axion photon conversion

$$\mathcal{L}_{A\gamma\gamma} = g_{A\gamma\gamma}\Phi_a \vec{E}\cdot\vec{B}$$

- Possible explanation to
  - Anomalous excessive cooling of stars
  - Anomalous transparency of Universe to UHE cosmic rays

HIGGS-LIKE CANDIDATE

- Ubiquitous in BSM in multi-Higgs models
- Usually one inert Higgs plus discrete symmetry(ies) can be dark matter
- Can be SU(2) doublet or singlet
- WIMP electroweak interactions with SM particles, null vev

$$\Phi_h = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix}$$

$$V_h(\Phi_h) = m_h^2(\Phi_h^\dagger \Phi_h) + \frac{\lambda_h}{2}(\Phi_h^\dagger \Phi_h)^2$$

DM INERT HIGGS MODELS

- Acquire mass through the breaking of some symmetry
- DM is the lightest neutral scalar or pseudoscalar
- Protected from decaying to SM by some discrete symmetry
- WIMPS: only eW interactions with SM
- e.g. inert 2HDM, one complex doublet is the SM field, the other one is inert, no vev, no coupling to gauge bosons

$$M_{H_0}^2 = \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2/2$$
$$M_{A_0}^2 = \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2/2$$

Scalar and pseudoscalar masses differ through their interaction terms λ_i in V after eW symmetry breaking *Lopez-Honorez et al, JCAP 02 (2007)*

THE CLASSICAL LIMIT

- We make use of the effective action approach

$$G(x_1, x_2, \dots x_n) = (-i)^n \frac{\delta}{\delta J(x_1)} \frac{\delta}{\delta J(x_2)} \cdots \frac{\delta}{\delta J(x_n)} \; Z[J] \Big|_{J=0}$$

G is n-point Green function, Z is the generating funcional, J is an external source

Z[J] generates all diagrams

- The connected generating functional W[J] is related to Z by

$$Z[J] = e^{\frac{i}{\hbar} W[J]}$$

- The effective action Gamma from W is

$$\Gamma[\bar{\phi}] = W[J] - \int d^4x \frac{\delta W[J]}{\delta J(x)} J(x)$$

Where $\frac{\delta W[J]}{\delta J(x)} \equiv \bar{\phi}$ *and* $\bar{\phi}$ *is called the average or classical field*

EFFECTIVE ACTION

- The effective action can be expressed as a series expansion in loops

$$\Gamma[\bar{\phi}] = I[\bar{\phi}] + \frac{1}{2} i\hbar \ln \det(i\mathcal{D}^{-1}) + \mathcal{O}(\hbar^2)$$

- where I is the tree level action, and $\mathcal{D}$ is the propagator for a modified action: the original action expanded around $\boldsymbol{\phi}$ and keeping only terms of second and higher order $\boldsymbol{\phi}$ *Jackiw,PRD9 (1984)*
- In the limit $\hbar \rightarrow 0$ we recover the classical action

TWO SCALAR FIELD COSMOLOGICAL MODEL

- We combine our two complex fields, assuming both obey classical field equations
- Gravitate via minimal coupling, action

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{c^4}{16\pi G}R + \mathcal{L}_{\Phi_1,\Phi_2}\right)$$

$$2\mathcal{L}_{\Phi_1,\Phi_2} = -\nabla^\mu\Phi_1^*\nabla_\mu\Phi_1 - \nabla^\mu\Phi_2^*\nabla_\mu\Phi_2 - V(\Phi_1,\Phi_2)$$

- We minimize the action, assume separate potentials (no interaction among fields) and add a pressure term for each field

AFTER MINIMIZATION OF THE ACTION

- We are left with a system of coupled complex differential equations
- The variation with respect to the fields gives

$$\Box\Phi_1 - \frac{dV}{d|\Phi_1|^2}\Phi_1 = 0,$$
$$\Box\Phi_2 - \frac{dV}{d|\Phi_2|^2}\Phi_2 = 0.$$

- And the tt component of the variation respect to the metric is

$$H^2 = \frac{8\pi G}{3c^2}[\rho_r(t) + \rho_b(t) + \rho_\Lambda(t) + \rho_{\Phi_1,\Phi_2}]$$

where H, Hubble parameter, rho_i are the densities of radiation, baryonic matter, dark energy, and the fields

- The solution to the Einstein eqs. is the Friedman-Lemaître-Robertson-Walker metric

EQUATIONS OF STATE FOR SCALARS

- In

$$H^2 = \frac{8\pi G}{3c^2}\left[\rho_r(t) + \rho_b(t) + \rho_\Lambda(t) + \rho_{\Phi_1,\Phi_2}\right]$$

- Density and pressure

$$\begin{aligned}\rho_{\Phi_1,\Phi_2} &= \frac{1}{2c^2}|\partial_t\Phi_1|^2 + \frac{1}{2c^2}|\partial_t\Phi_2|^2 + \frac{1}{2}V(\Phi_1,\Phi_2)\\ p_{\Phi_1,\Phi_2} &= \frac{1}{2c^2}|\partial_t\Phi_1|^2 + \frac{1}{2c^2}|\partial_t\Phi_2|^2 - \frac{1}{2}V(\Phi_1,\Phi_2)\end{aligned}$$

- Define eq.state w as ratio of density to pressure $w = p/\rho$

- $V = V1 + V2$, similarly for ρ and p.

  Eqs of motion imply

$$\begin{aligned}\partial_t\rho_1 + 3H(\rho_1 + p_1) &= 0\\ \partial_t\rho_2 + 3H(\rho_2 + p_2) &= 0\end{aligned}$$

SOLVE SYSTEM OF DIFF EQUATIONS

- The domain is split in 3: both fast oscillating, one field fast other slow, both slow oscillating
- 2 complex Klein-Gordon eqs plus Friedman eq

$$\dot{a} = aH_0\sqrt{\frac{\Omega_r}{a^4} + \frac{\Omega_b}{a^3} + \Omega_\Lambda + \frac{\rho_1}{\rho_{\rm crit}} + \frac{\rho_2}{\rho_{\rm crit}}}$$

$$\frac{d\rho_1}{da} = -3\frac{2\rho_1 - A_1}{a},$$

$$\frac{dA_1}{da} = \pm\frac{B_1}{\dot{a}}\sqrt{1 + \frac{2\lambda_1}{m_1^4}A_1},$$

If $\lambda>0$, take the upper sign. If $\lambda<0$ both signs are possible.

$$\frac{dB_1}{da} = -3\frac{B_1}{a} + 2m_1^2\frac{1}{\dot{a}}\left[2(\rho_1 - A_1) - \frac{m_1^4}{2\lambda_1}\left(\sqrt{1 + \frac{2\lambda_1}{m_1^4}A_1} \mp 1\right)^2\right]$$

$$A_1 = \rho_1 - p_1, \quad A_2 = \rho_2 - p_2, \quad B_1 = m_1^2\partial_t|\Phi_1|^2, \quad B_2 = m_2^2\partial_t|\Phi_2|^2$$

EVOLUTION

- A characteristic of the scalar field is its oscillating behaviour
  Turner, Pays.Rev.D18 (1983)
- Models with complex scalar as DM give a consistent description of the Friedman homogeneous Universe.
  Angular oscillation frequency $w/\mathrm{H} >> 1$
  Rapid oscillation regime → CDM fluid
  Li, Rindler-Daller, Shapiro, Phys.Rev.D89 (2014); Suárez, Chavanis, Phys.Rev.D.95 (2017)
- We evolve from the present time $z=0$ to the past
- At $z=0$ we use as initial condition the observed abundance of DM Ω_{DM}
  In the past
  - Effective number of neutrinos N_{eff} at BBN,
    $$N_{eff} = 3.56 \pm 0.23, \quad \Delta N_{\nu} = 0.5 \pm 0.23$$
    taking $\Delta N_{\nu}(a)$ places constraints on m, λ and f_a
  - Scalar field solutions reach a matter like behavior at $z_{\mathrm{eq}} \approx 3365$,
    $w(z_{\mathrm{eq}}) \leq 0.001$, measured by CMB *Li, Rindler-Daller, Shapiro, Phys.Rev.D89 (2014)*

OUR CANDIDATES — THE CLASSICAL APPROX FOR PP

- Our Higgs field acquires mass through the breaking of some symmetry. In the classical limit A_0 and H_0 are degenerate.
  Describe it as one complex scalar field.
  Behaves like CDM fluid, oscillates rapidly
  A. Suarez and P.-H. Chavanis, Phys. Rev. D 95 (2017)
- In QFT axions described by real scalar field.
  Low-energies, classical, non-relativistic effective field theory described by a complex scalar field *H. Zhang, Symmetry 12, 25 (2019)*
- In this limit we do not take into account:
    - Decay of heavy Higgs into lighter ones
    - Interaction with SM particles
    - Interaction among the PP candidates

SCALAR POTENTIALS V

- For the λ axion-like we take:

$$V_a(\Phi_a) = m_a^2|\Phi_a|^2 - \frac{m_a^2}{12f_a^2}|\Phi_a|^4$$

f_a scale of symmetry breaking

- For the Higgs-like:

$$V_h(\Phi_h) = m_h^2(\Phi_h^\dagger\Phi_h) + \frac{\lambda_h}{2}(\Phi_h^\dagger\Phi_h)^2$$

λ is self-interaction, $-4\pi < \lambda < 4\pi$, m_h in GeV region

- For the classical one

$$V(|\phi|) = \mu^2\,|\phi|^2 + \sigma^2\,|\phi|^4$$

σ is self-interaction

MODELS

SINGLE MODEL	Free parameters	m	λ	Representative cases $(m,\, \lambda)$	**Viability**	
					(i)	(ii)
Axion (Φ_a)	f_a	$5.69\left(\frac{10^9\,\text{GeV}}{f_a}\right)$ meV	$-m_a^2/(6f_a^2)$	$(5.7\times10^{-13}\,\text{eV},\, -5.4\times10^{-82})$	×	✓[37]
Higgs (Φ_h)	$m_h,\, \lambda_h$	$\sim 100\,\text{GeV}$	$(-4\pi, 4\pi)$	$(100\,\text{GeV}, 1)$	×	✓[30]
Classical (Φ_c)	$m_c,\, \lambda_c$	$\lesssim 1\,\text{eV}$	> 0	$(3\times10^{-21}\,\text{eV}, 4.2\times10^{-86})$	✓	NA

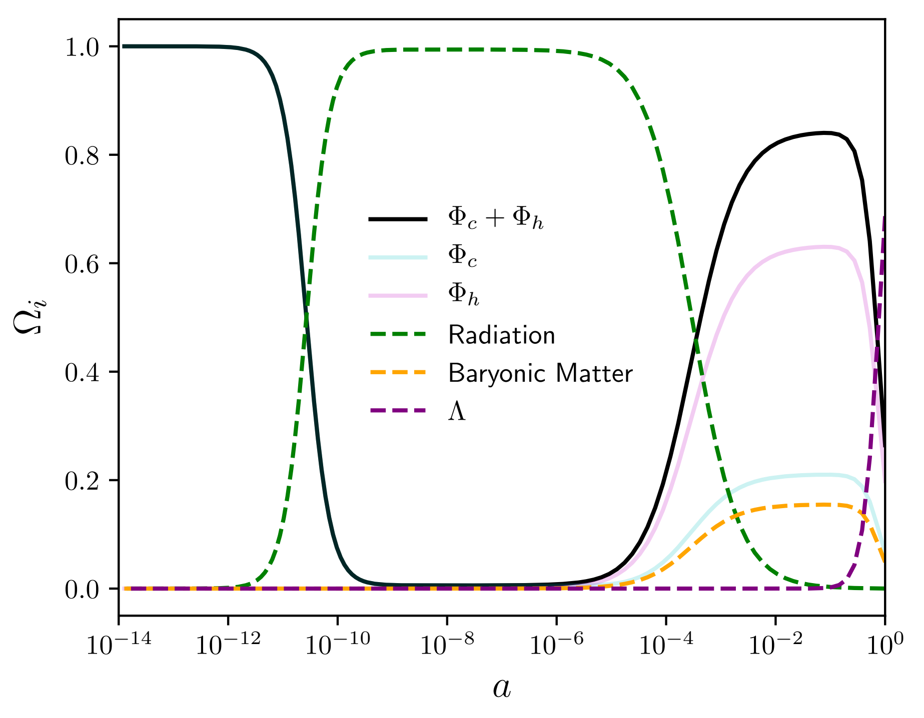
DOUBLE MODEL	Description
I	Classical + Higgs
II	Axion + Higgs
III	Classical + Axion

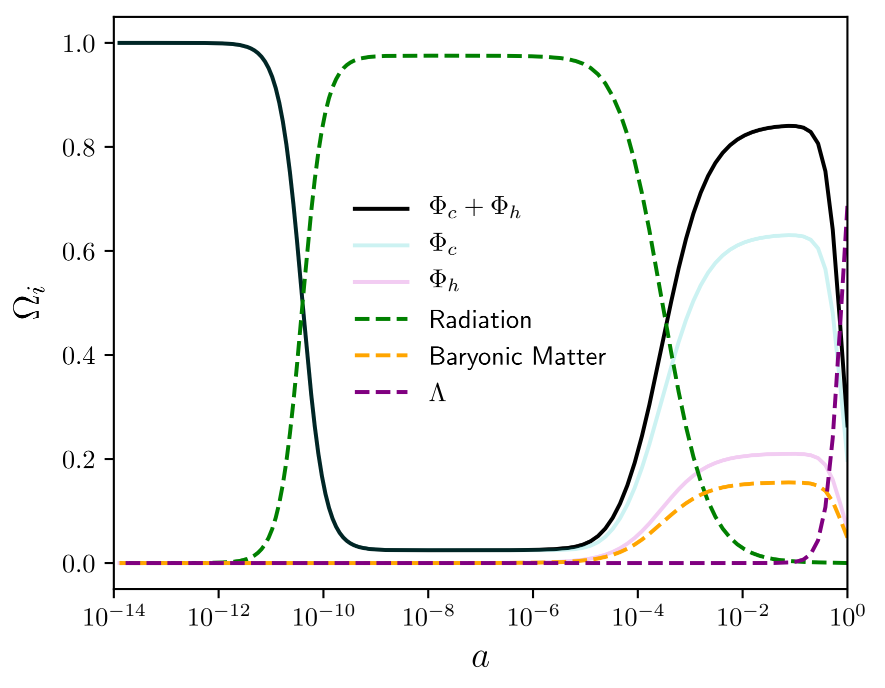
- Viability in single models:
  - (i) Complies with N_{eff} at BBN and z_{eq} constraint Marsh, Phys.Rept.643 (2016)
  - (ii) Consistent with DM relic density Abe et al (LHC DM working group),Phys. Dark Univ. 27 (2020)
- Double models: same range of parameters
- Viability in double models: $N_{\text{eff}} + z_{\text{eq}},\ \Omega_{\text{DM}}$
- η is the fraction of the lightest field at present time with respect to total DM density

RESULTS: DENSITY FRACTIONS

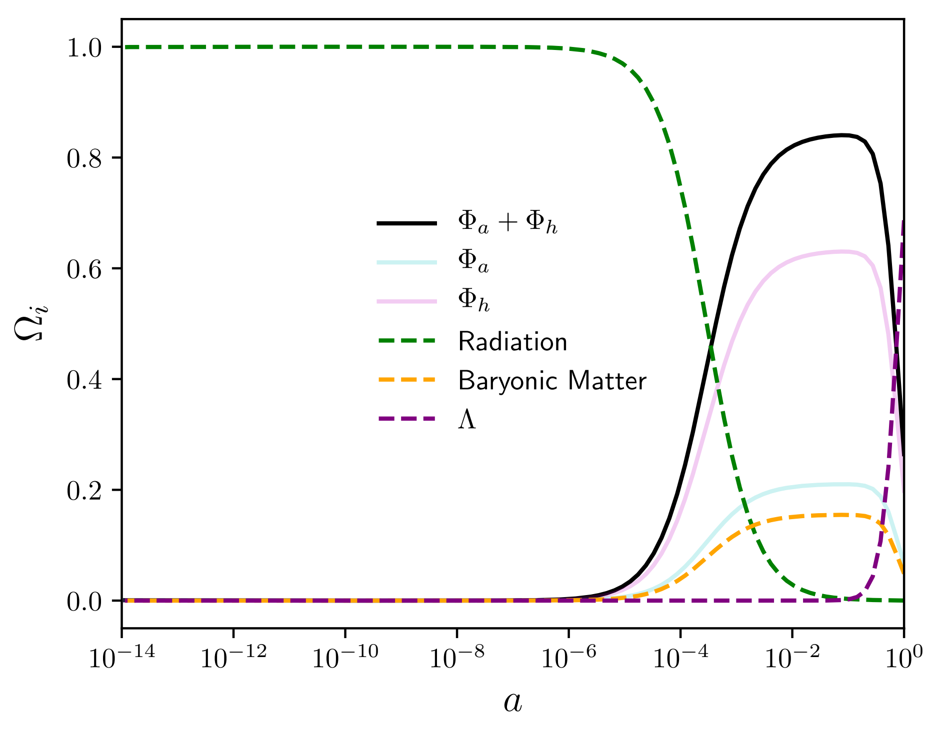
η = 0.25 **η= 0.75**

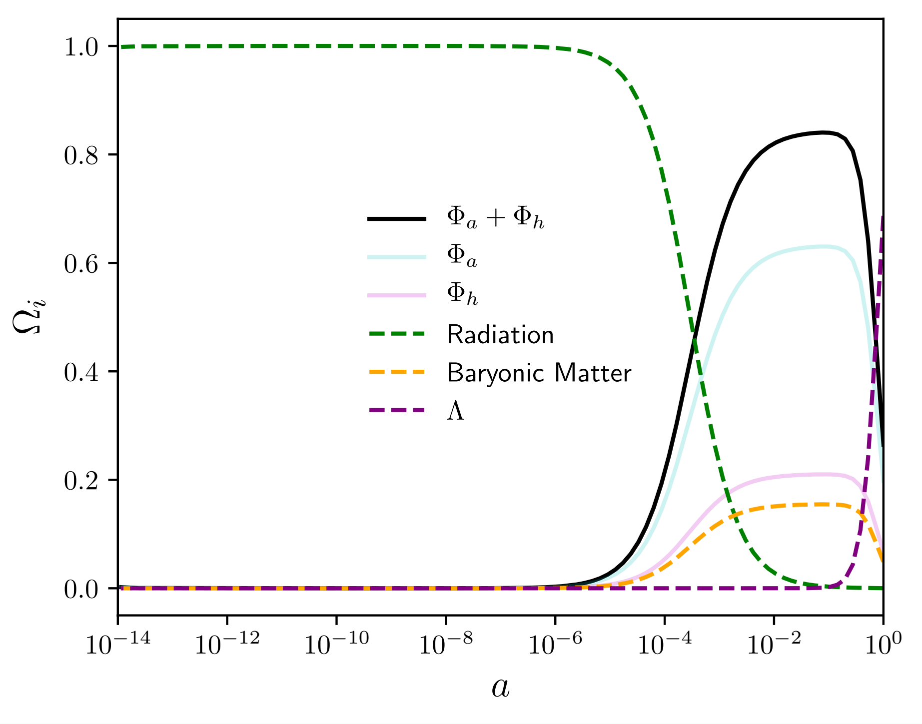
Model I
Classical + Higgs





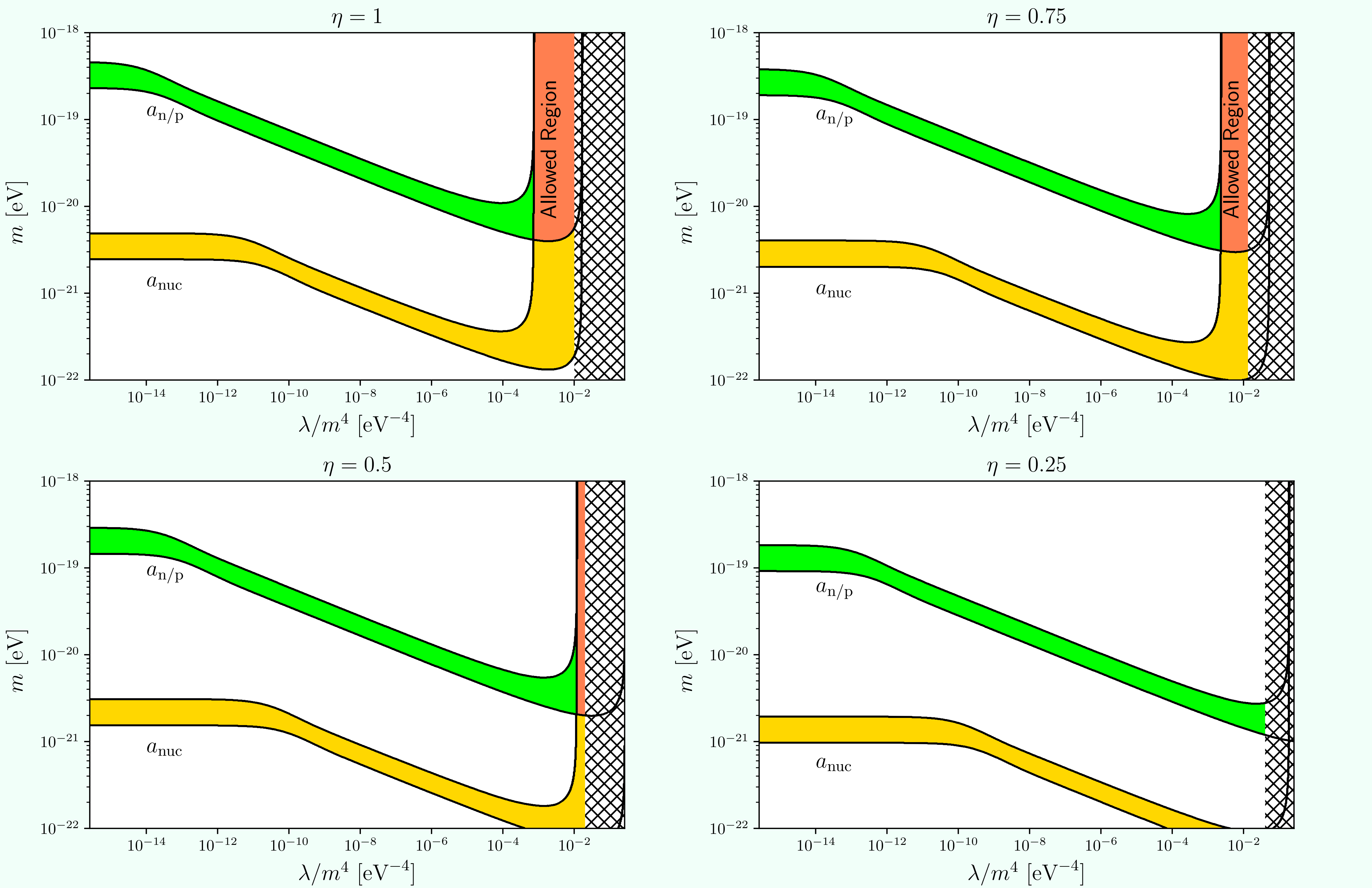
Model II
Classical + axion





a = scale factor, today a=1

CONSTRAINTS FROM Z_{EQ} AND N_{EFF} AT 1 SIGMA MODEL 1



Yellow and green bands comply with N_{eff} at

n/p = neutron to proton freeze out, nuc = first nuclei production

Crosshatched not allowed by z_{eq}

Orange region allowed

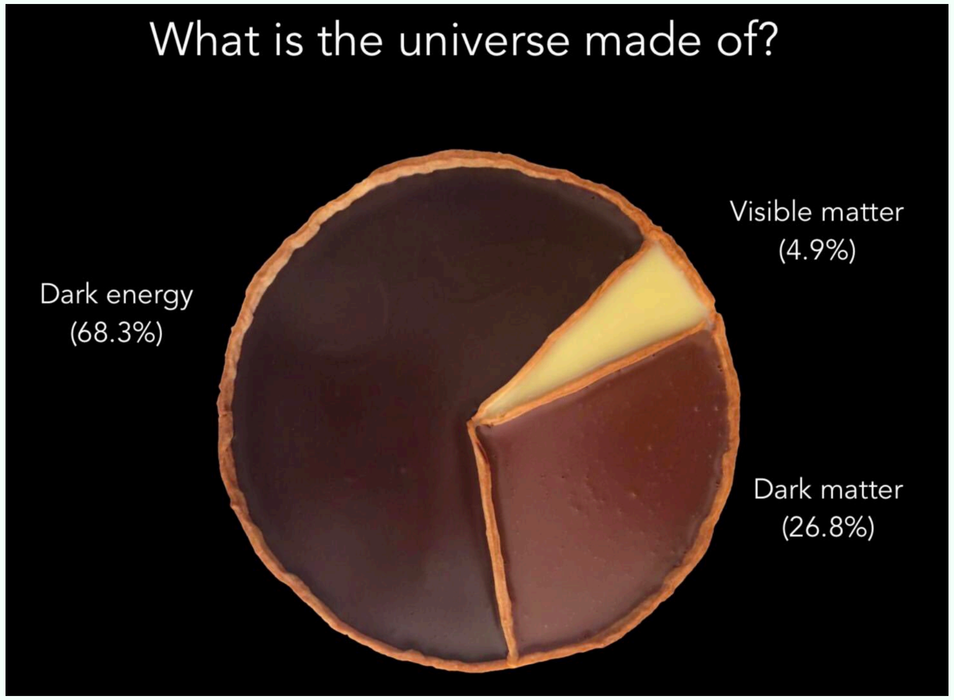
RESULTS

DOUBLE MODEL	Description	η constraint	Viability
I	Classical + Higgs	$\gtrsim 0.423$	✓
II	Axion + Higgs	×	×
III	Classical + Axion	NA[a]	✓

- Model I — Classical + Higgs
  - $\eta > 0{,}423$ to satisfy the constraints
  - Higgs always stays in the fast oscillating regime, behavior indistinguishable for CDM
- Model II — Axion + Higgs
  - No set of parameters satisfy the constraint on N_{eff} Not at 1or 2σ
  - Similar to the single axion case
- Model III — Classical + Axion
  - 4 free parameters, complete analysis no ready yet
  - Same restrictions as I apply for viability, N_{eff}, z_{eq}

CONCLUSIONS

- DM is probably a lot more complicated than we think
- Halo composition may be a combination of seemingly different objects
- In different proportions…
- This will impact analysis in direct and indirect searches
- Expected flux might be smaller than expected
- Combination of classical+axion or
  classical+Higgs a possibility



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