Dark Matter Models

Debasish Majumdar

Astroparticle Physics and Cosmology Division
Saha Institute of Nuclear Physics, Kolkata

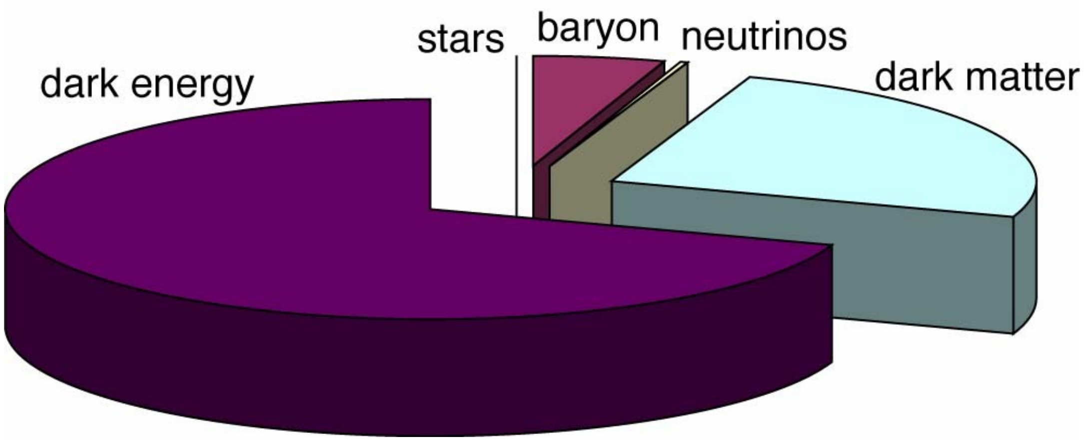
What is *Dark Matter* ?

- An Unknown, non-luminous matter with almost no interactions with other particles except gravity
- Contains more than 80% of the matter content of the universe
- All pervading across the galaxies, clusters, super-clusters

Energy Budget of Universe

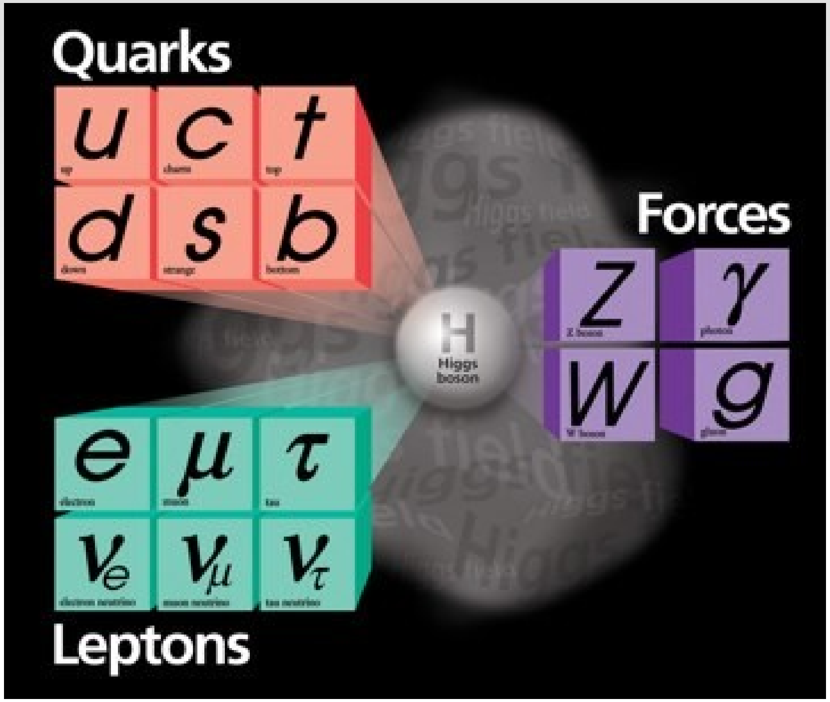
PLANCK 2013 RESULTS !!!
(March 21, 2013)

- Baryonic Matter are ~ 4.9%
- Dark Matter ~ 26.8%
- Dark Energy ~ 68.3%



General Properties of Dark Matter

- Should be neutral
- Gravitationally interacting
- Stable
- Very weak interaction with other particles



➔Major constituent is perhaps heavy (massive) particles (non-relativistic while decoupling)

➔Mainly non-baryonic in nature

DARK MATTER

- Dark matter has **already been discovered** through
  - Galaxy clusters
  - Galactic rotation curves
  - Weak lensing
  - Strong lensing
  - Hot gas in clusters
  - Bullet Cluster
  - Supernovae
  - CMB

- **era of dark matter identification**

źCDM Model

Λ	Cosmological Constant
CDM	Cold Dark Matter

Concordance Model (The Standard Model of Cosmology) describes the evolution of the Universe from Big Bang.

Describes the important cosmological observations:

- CMB Fluctuation
- Large Scale Structures
- Accelerated Expansion (SN observations)
- Distribution of H, D, He, Li

Baryonic Dark Matter

MACHOs – Massive Astrophysical Compact Halo Objects

Brown Dwarfs: with m < 0.08 M⊙
(no H-burning)

Jupiters: with m < 0.001 M⊙

Black Holes with m ~ 100 M⊙
(not sufficient to close the universe)

Quark Nuggets (?) with m ~ 0.1 M⊙ (MNRAS 340 (2003) 284)

clouds of molecular hydrogen (?)

Particle dark matter

Hot dark matter
- relativistic at kinetic decoupling
- large free streaming length
- cannot cluster on galaxy scales

e.g. light neutrinos

Cold dark matter
- non-relativistic at kinetic decoupling
- possible to cluster in small scales

Cold (v < 10^{-8} c)

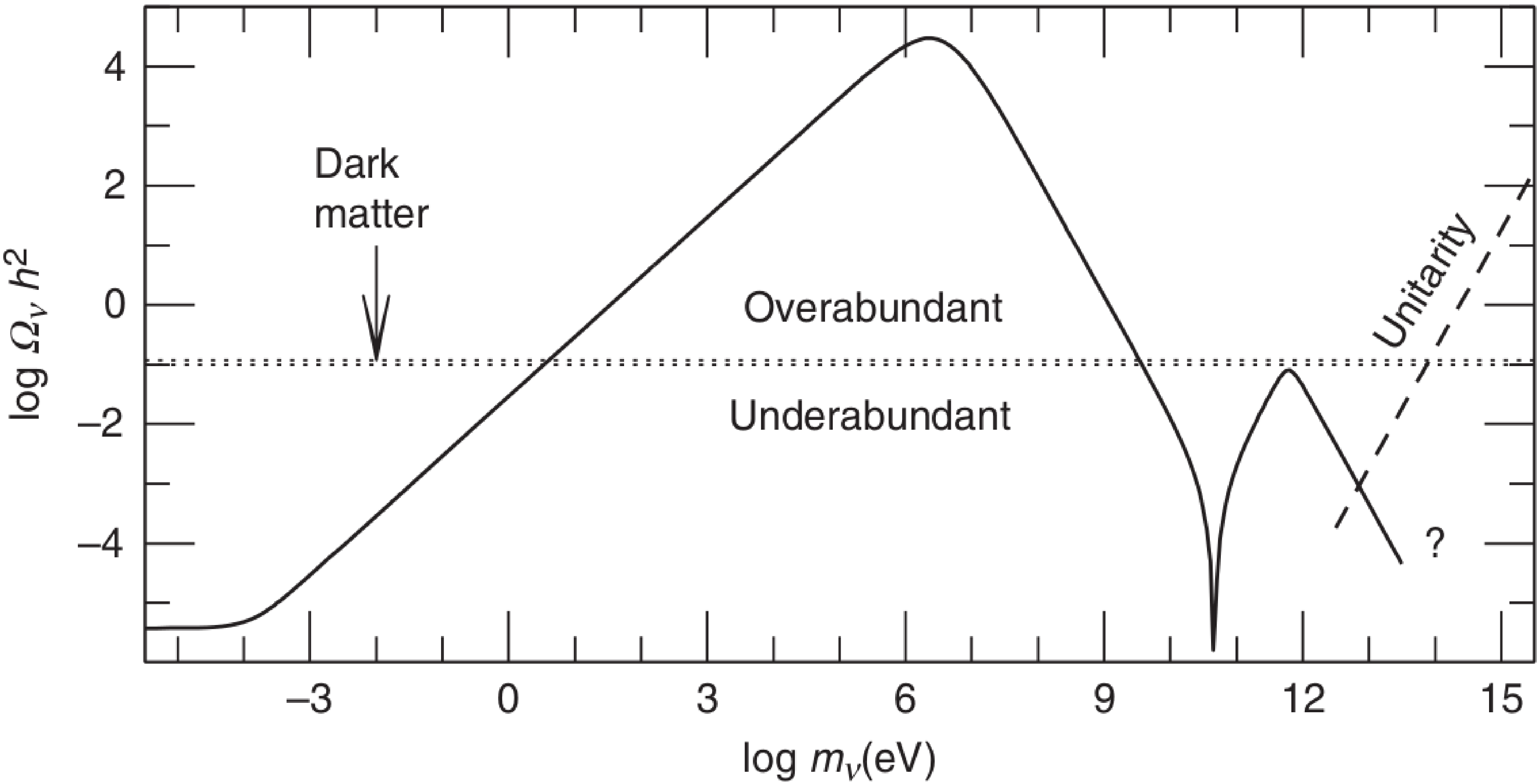
e.g. neutralinos, axions, KK particles

Warm dark matter
- semi-relativistic at kinetic decoupling

e.g. sterile neutrinos, gravitinos

Neutrino Dark Matter

$$\Omega_\nu h^2 \simeq \frac{m_\nu}{100eV}$$



Cannot close the universe

Neutrino Dark Matter

Structure formation

There is a lower limit on particle mass for smallest scale structure

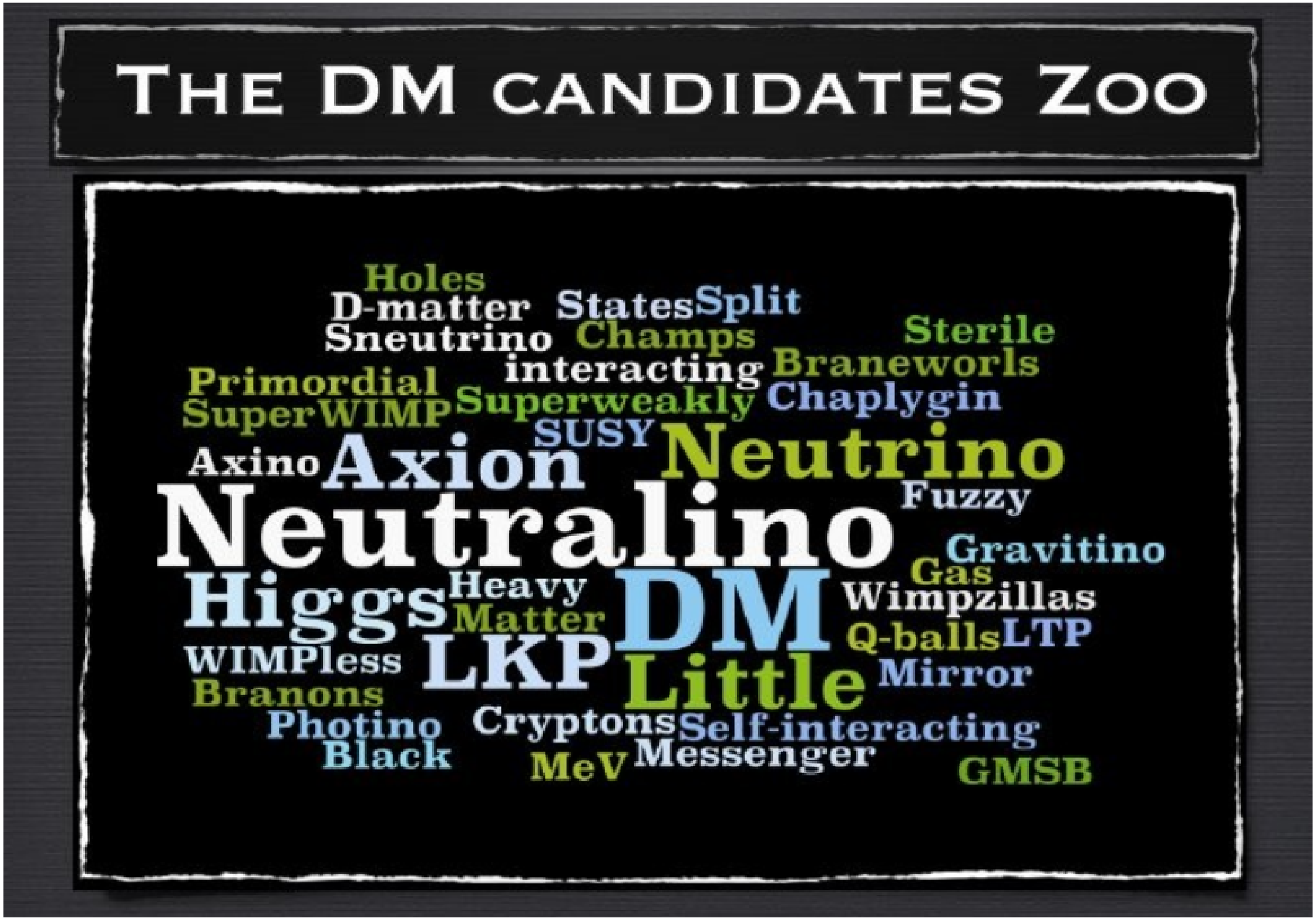
For small scale structures at z~3: mass of dark matterŒ2 keV

Neutrinos being low mass and high speed

travels large distances
density perturbations may be washed out

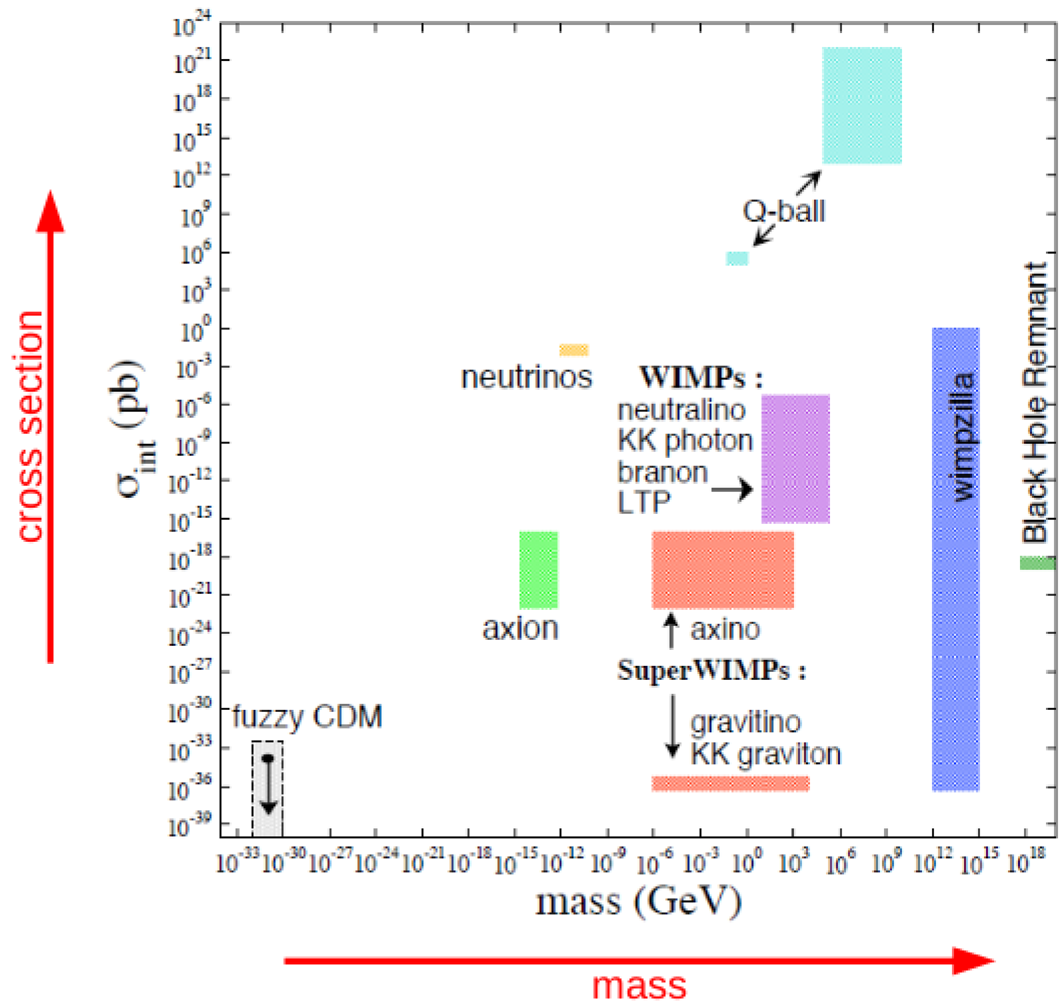
Non baryonic Dark Matter

Explore beyond Standard Model



from Gianfranco Bertone

(Some) Dark Matter Candidates



- Axion
- WIMPs
  - Neutralino
  - (LKP)
- sterile neutrinos

from Marc Schumann

Particle dark matter

Thermal relics

- in thermal equilibrium with the plasma in the early universe
- produced in collision of plasma particles
- insensitive to initial conditions

e.g. neutralinos, other WIMPs, ...

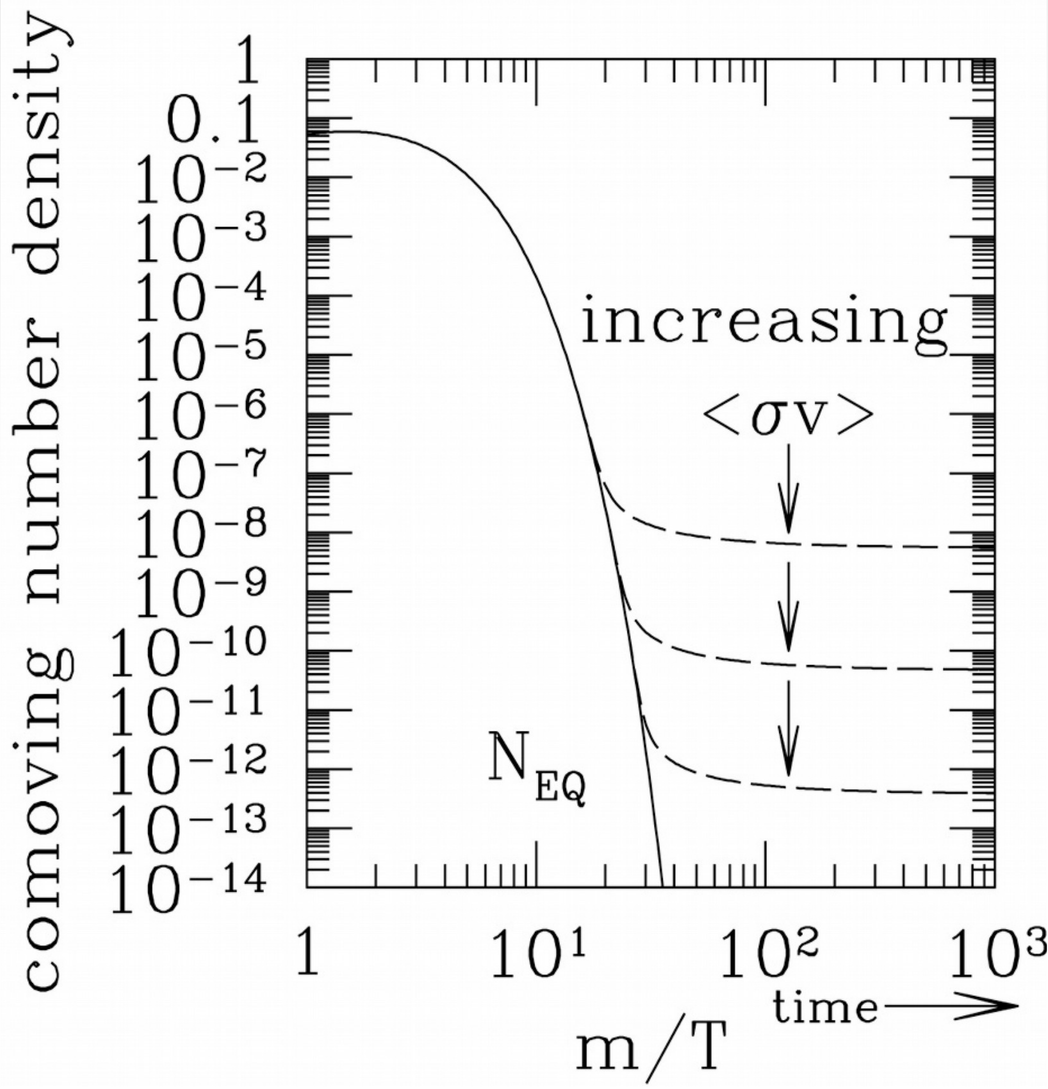
Non-thermal relics

- not in thermal equilibrium with the plasma in the early universe
- produced in decays or out-of-equilibrium decays of heavier particles

e.g. Axions ....

Thermal WIMP Paradigm

- In the early universe, WIMPs and the SM particles were in thermal and chemical equilibrium with each other
- So, at very high temperature $(T \gg m_\chi)$, the equilibrium number density (n_χ^{eq}) behaved like photons, $n_\chi^{eq} \propto T^3$



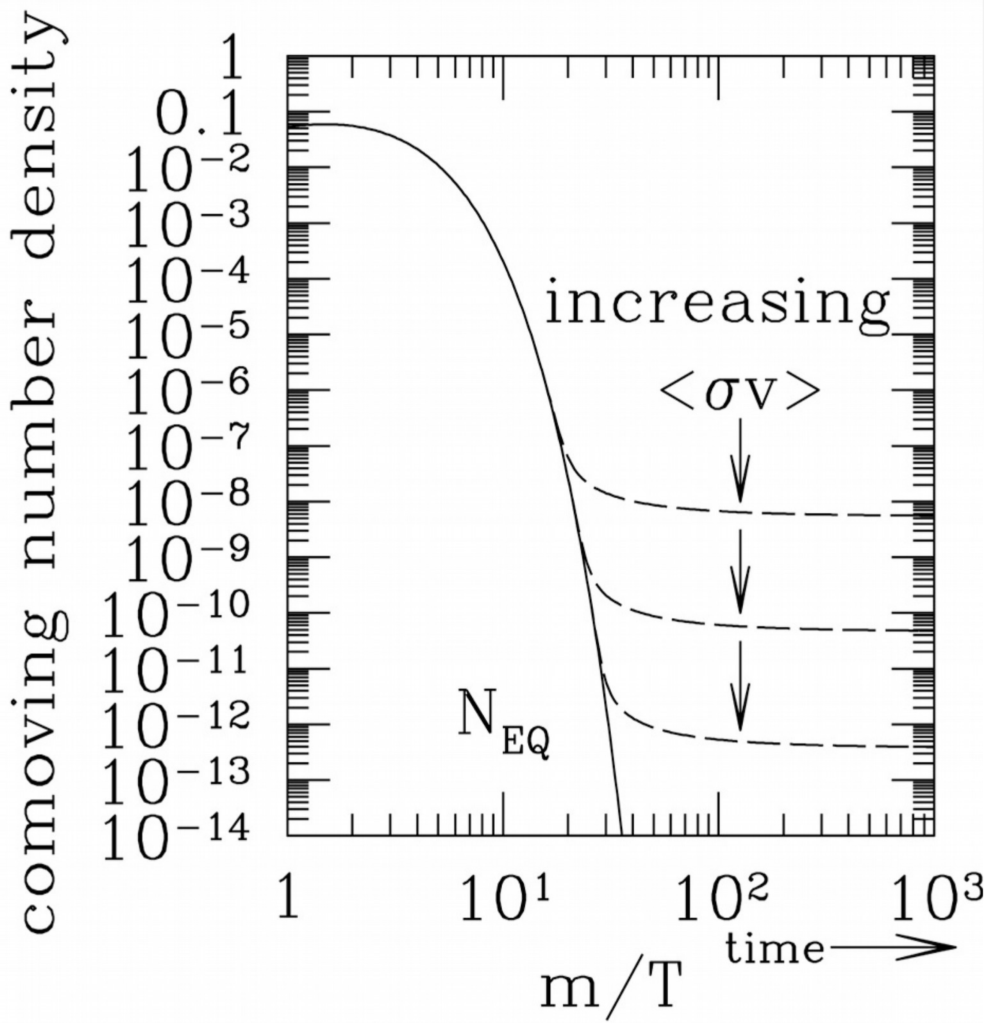
Thermal WIMP Paradigm

- As the universe expands, the temperature falls below WIMP mass($T \ll m_\chi$) and then behaves like MB distribution

$$n_\chi^{eq} \sim (m_\chi T)^{\frac{3}{2}} exp(-\frac{m_\chi}{T})$$

- When the universe expansion rate (H) surpasses the decay rate

  ($H > \Gamma$) of WIMPs, i.e., when, then chemical decoupling happens and WIMPs per comoving distance are fixed. (out of equilibrium condition)



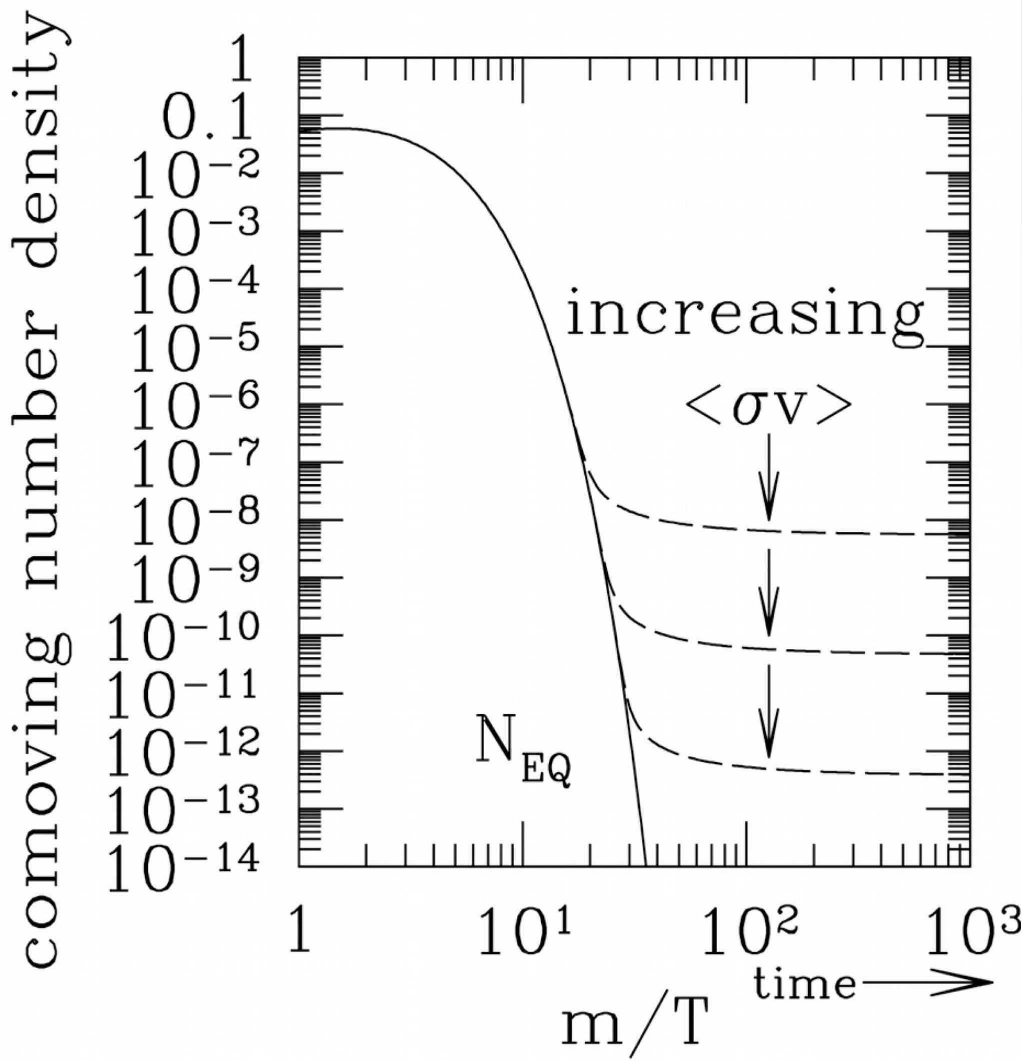
Thermal WIMP Paradigm

- So, the evolution of number density, n(t) is quantitatively given by,

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle[(n_\chi)^2 - (n_\chi^{eq})^2]$$

- Thus, the relic density (DM) is set by,

$$\Omega_{DM} \sim \frac{1}{\langle\sigma v\rangle}$$



Some factors important for the particle dark matter

— Production from interaction with thermal plasma of the Universe:
- reaches reaction equilibrium and going away from equilibrium at freeze-out (WIMP)
- does not reach reaction equilibrium (but approaching towards equilibrium – freeze-in) (FIMP)
- coannihilating with similar mass particles (neutralinos)

—Production via out-of-equilibrium decay of massive particles
(non-thermal)

— Production from decays of non-thermal particles (gravitinos, ...)

— Dark matter-antimatter asymmetry:
• self-conjugate (Majorana fermions, neutralinos, axions, gravitinos, ...)
• not self-conjugate (Dirac fermions, asymmetric dark matter, ...)

— Hubble expansion rate before nucleosynthesis:
• standard vs nonstandard cosmology (low temperature reheating, ...)

Axion Dark Matter

There are CP violating terms in the QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \Theta\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \overline{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

since no strong CP violation is observed, ű must be very small or zero
but in general ű can take any value

Strong CP Problem

introduce the global U(1) symmetry (Peccei-Quinn Symmetry)

this symmetry is spontaneously broken at some large scale

dynamical interpretation of the angle ű

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \overline{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi + \left(\Theta - \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \frac{1}{2}\partial_\mu a\partial^\mu a$$

for $a = \Theta f_a$ CP symmetry is restored

a is the axion field

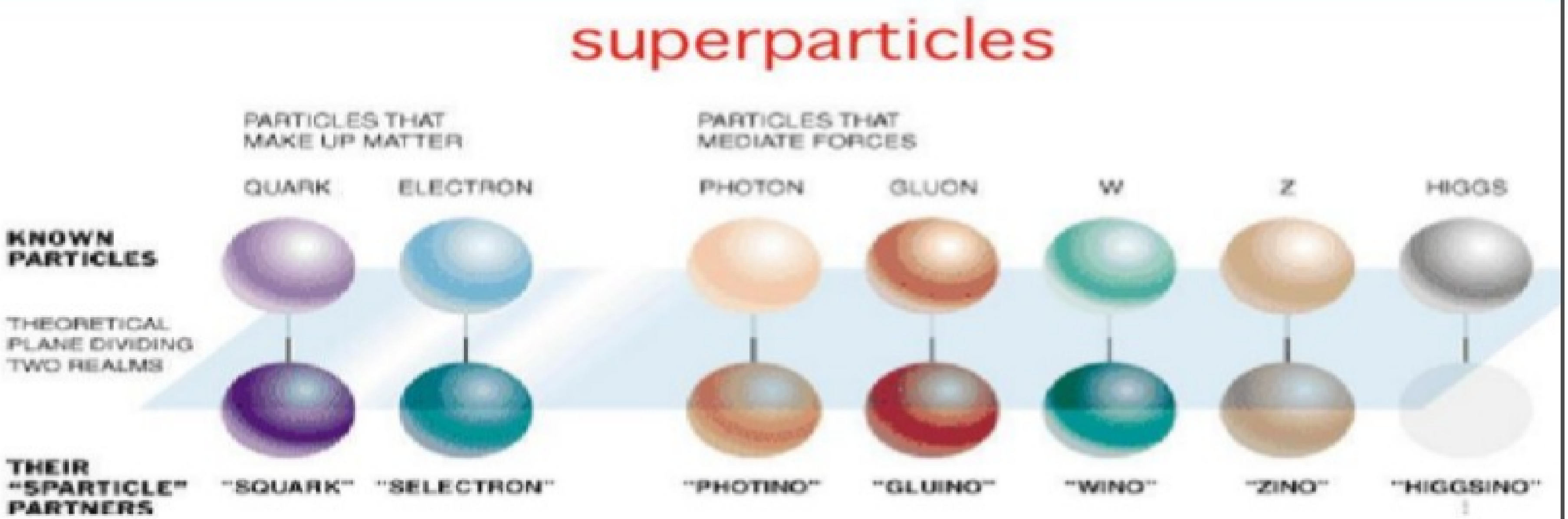
this theory has a pseudo-scalar boson (the axion) of the spontaneously broken PQ symmetry

SUSY Dark Matter

- Q_α is a fermionic charge that relates particles of different spins

$$Q_\alpha \left| \begin{matrix} \text{Fermion} \\ \text{Boson} \end{matrix} \right\rangle = \left| \begin{matrix} \text{Boson} \\ \text{Fermion} \end{matrix} \right\rangle$$

- Every SM particle has a SUSY partner (of equal mass), identical quantum #'s except for spin



Where is SUSY?

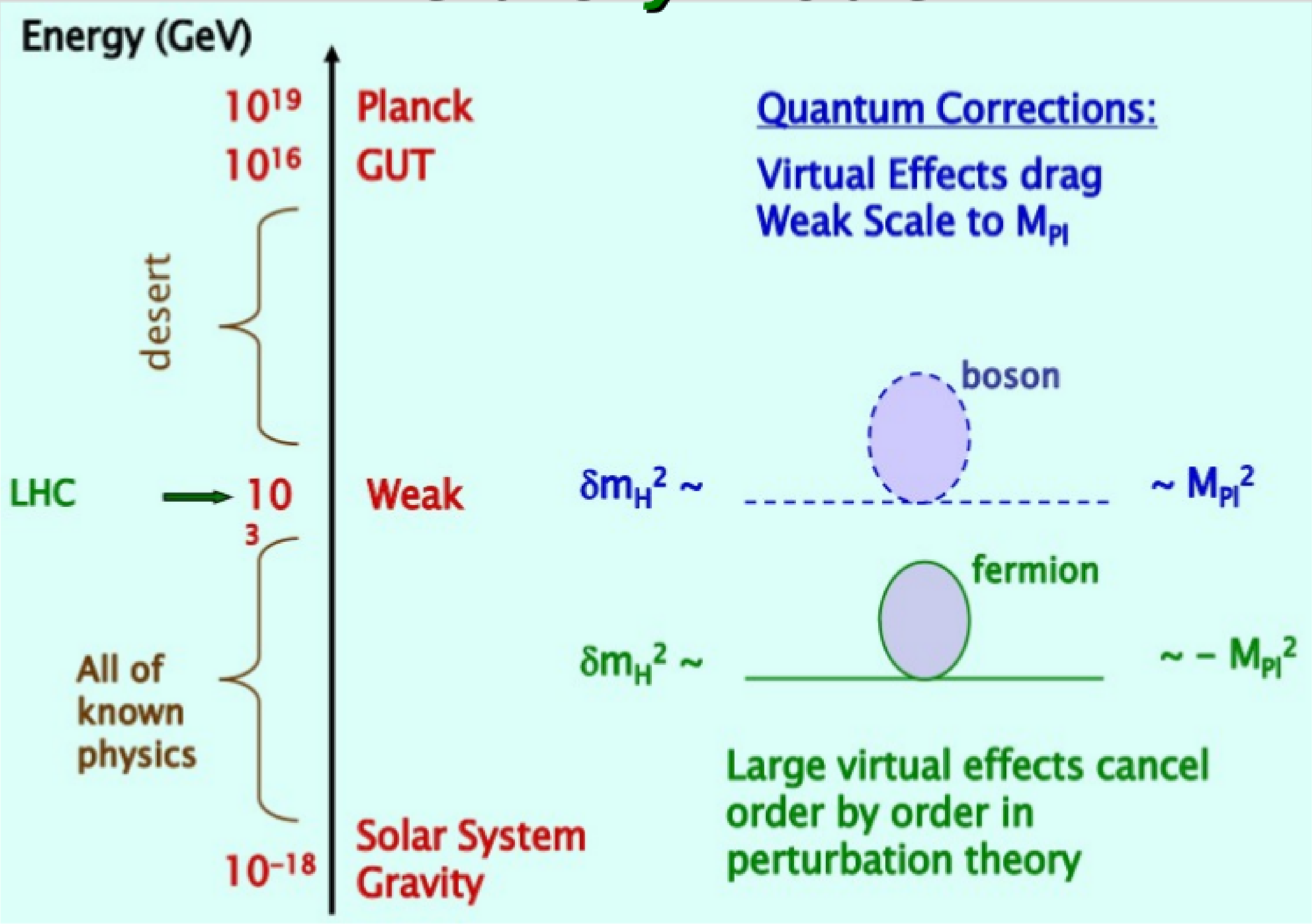
- We know 3 fundamental constants
  - Special Relativity: speed of light, c
  - General Relativity: Newton's constant G
  - Quantum Mechanics: Planck's constant, h

- Together, they form the Planck scale

$$M_{\rm Pl} = \sqrt{\frac{hc}{G}} \approx 10^{19}\ \text{GeV}$$

- SUSY scale can be anywhere, from 0 up to M_{Pl} !

Why SUSY? solves Hierarchy Problem



- A BIG problem: proton decay occurs very rapidly!

- Introduce R-parity: $R_p = (-1)^{3(B-L)+2S}$
- New multiplicative, conserved quantum number
  - P has $R_p = +1$; $\tilde{P}$ has $R_p = -1$
  - Requires 2 superpartners in each interaction
- Consequence: the Lightest Supersymmetric Particle (LSP) is stable and cosmologically significant

Neutral SUSY Particles: LSP Candidates

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2			Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$			$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Dark Matter Candidates in the MSSM

1. sneutrino (spin 0)
would have relatively large coherent scattering with nuclei direct DM expts exclude sneutrinos between a few GeV and several TeV

2. neutralino (spin 1⁄2) → the favourite

3. gravitino (spin 3/2)

Dark Matter candidate from extra dimension

Let us consider only one extra spatial dimension (y, say)

The Lagrangian density for a massless scalar field can be written as

$$\Phi \equiv \Phi(x_\mu, y), \quad \mu = 0,1,2,3; \; y \text{ is the extra spatial coordinate}$$

$$\mathcal{L} = -\frac{1}{2}\partial_A \Phi \partial^A \Phi, \; A = 0,1,2,3,4 .$$

Kaluza- Klein DM

$$\Phi \equiv \Phi(x_\mu, y), \quad \mu = 0,1,2,3\,; \; y \text{ is the extra spatial coordinate,}$$

$$\mathcal{L} = -\frac{1}{2}\partial_A \Phi \partial^A \Phi, \; A = 0,1,2,3,4\,. \tag{8.10}$$

The extra fifth dimension is to be compactified over a circle of radius R, where R is called the compactification radius. At a scale $\gg R$, the effect of this extra dimension is not manifested. Since the compactification is over a circle, y is periodic such that $y \to y + 2\pi R$ ($\Phi(x,y) = \Phi(x, y + 2\pi R)$). Therefore, we have [49]

$$\Phi(x,y) = \sum_{n=-\infty}^{\infty} \phi_n(x) e^{iny/R}\,, \tag{8.11}$$

(with $\phi_n^*(x) = \phi_{-n}(x)$). From Eqs. 8.10 and 8.11,

Kaluza- Klein DM

$$\mathcal{L} = -\frac{1}{2} \sum_{n,m=-\infty}^{\infty} \left(\partial_\mu \phi_n \partial^\mu \phi_m - \frac{nm}{R^2} \phi_n \phi_m \right) e^{i(n+m)y/R} \,. \qquad (8.12)$$

The action S is given by

$$S = \int d^4x \int_0^{2\pi R} dy \; \mathcal{L} \,. \qquad (8.13)$$

Integrating out the extra space dimension, Eq. 8.13 takes the form (substituting for $\mathcal{L}$)

$$S = \int d^4x \left(-\frac{1}{2} \partial_\mu \psi_0 \partial^\mu \psi_0 \right) - \int d^4x \sum_{k=1}^{\infty} \left(\partial_\mu \psi_k \partial^\mu \psi_k^* + \frac{k^2}{R^2} \psi_k \psi_k^* \right) , \qquad (8.14)$$

Kaluza- Klein DM

where $\psi_n = \sqrt{2\pi R}\phi_n$. From Eq. 8.14, we obtain, for a 5D massless scalar field (after compactification of the extra space dimension over a circle), a zero mode (ψ_0) as real scalar field and an infinite number or tower of massive complex scalar fields. The mass of each mode is given by $m_k = k/R$. These modes are known as Kaluza–Klein modes (or Kaluza–Klein tower). The quantum number k is called the Kaluza–Klein (KK) number. This corresponds to the quantized momentum p_5 in the compactified dimension. From Lorentz invariance in 5D, we have the relation

$$E^2 = \mathbf{p}^2 + p_5^2 = \mathbf{p}^2 + m_k^2 \qquad (8.15)$$

All Standard Model fields can propagate into an extra dimension and every SM particle has a KK tower. The proposed candidate for dark matter in the UED model can be the particle B1 (LKP), which is the first KK partner of the hypercharge gauge boson.

Kaluza- Klein DM

Since the SM fermions are chiral, one should obtain chiral fermions for this UED model in equivalent 4D theory. In order to satisfy this, the compactification of the extra dimension has to be made over an orbifold S^1/Z_2 [53] where S^1 denotes the circle of compactification with compactification radius R and Z_2 is the reflection symmetry under which the fifth coordinate $y \to -y$. Under this Z_2 symmetry, the fields are even or odd. With this reflection symmetry, the orbifold is now reduced to a line segment of length πR such that $0 \leq y \leq \pi R$. The orbifold fixed points or boundary points are at $0, \pi R$. The two boundry conditions (Neumann and Dirichlet) for even and odd fields are given by

$$\begin{aligned} \partial_5 \phi &= 0 \;\; (\text{even fields}) \,, \\ \phi &= 0 \;\; (\text{odd fields}) \,. \end{aligned} \tag{8.16}$$

Kaluza- Klein DM

Now one can make a consistent assignment for chiral fermion ψ. We can thus have ψ_L even, ψ_R odd, or vice versa. From Eq. 8.11 and with the above orbifold compactification we have for even or odd fields,

$$\Phi_+(x,y) = \sqrt{\frac{1}{\pi R}}\phi_+^0 + \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\cos\frac{ny}{R}\phi_+^n(x)\,,$$

$$\Phi_-(x,y) = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\sin\frac{ny}{R}\phi_-^n(x)\,. \qquad (8.17)$$

In Eq. 8.17, one readily sees that Φ_- (odd field) has no zero mode. Eq. 8.17 also satisfies the boundary conditions in Eq. 8.16. Thus assigning one of the Φ_+ (or Φ_-) as left chiral or (right chiral) field, one can identify the chiral fields in equivalent 4D theory.

Kaluza- Klein DM

But notice that the boundary points $(0, \pi R)$ break the translational symmetry along the y direction. This means that the momentum p_5 is no longer conserved and subsequently the KK number is also not conserved. Hence the LKP appears to be not stable. But for LKP to be a dark matter candidate, this must be stable. From Eq. 8.17, notice that under a transformation πR in the y direction, the KK modes remain invariant for the transformation $y \to y + \pi R$ for even KK number n. But for odd n, the KK modes change sign. This situation gives us a quantity $(-1)^{\mathrm{KK}}$ (known as KK parity), which is conserved (good symmetry for this transformation). The LKP will be stable due to the conservation of this KK parity. Therefore, the LKP in the UED model may be a possible candidate for dark matter.

Sterile Neutrinos

Motivation:

- We know that neutrinos exits, and that they have a mass
  → the only solid lab evidence for beyond SM physics
- Maybe this is a sign for existence of a new *E* scale (GUT?)
- Assume
  - ν masses come from existence of new unseen particles
  - complete theory is a renormalizable extension of the SM
- Introduce sterile neutrinos or heavy neutral leptons N_I
  (=singlet [w. respect to the SM gauge group] Majorana fermions → no weak i/a)
- Number of singlet fermions unknown → choose 3 in SM analogy

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\overline{L}_\alpha N_I\tilde{\Phi} - \frac{M_I}{2}\overline{N}^c_I N_I + h.c.$$

Kinematics

Couplings (F) to leptons L
And the Higgs field Φ

Majorana mass term:
N_I is SU(3)xSU(2)xU(1) inv.
→ consistent with the SM symmetry

- νMSM: neutrino minimal SM

Taken from Marc Schumann

Dark Matter models in simple extension of SM

Scalar Higgs-portal dark matter
Fermionic dark matter
....

➔ *Scalar Singlet Dark Matter*
(SM+extra scalar singlet)

The most general form of the potential

$$V(H,S) = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2}H^\dagger H S + \frac{\delta_2}{2}H^\dagger H S^2 + \left(\frac{\delta_1 m^2}{2\lambda}\right)S + \frac{\kappa_2}{2}S^2 + \frac{\kappa_3}{3}S^3 + \frac{\kappa_4}{4}S^4$$

➔ Apply Z_2 symmetry ($S \to -S$) ensures stability of DM

$$\langle H \rangle = V/\sqrt{2}$$

$$m_S^2 = k_2 + \delta_2 V^2/2$$

$$m_h^2 = -m^2 = \lambda V^2/2$$

Barger et al., Phys. Rev. D 77 (2008) 035005
A. B., S. C., A. G., D. Majumdar, JHEP 1011 (2010) 065
A. Biswas, D. Majumdar, 1102.3024

Inert Higgs Doublet Model

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + iG^0\right) \end{pmatrix}, \qquad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix};$$

$$H = (0, v) \qquad \Phi = -\Phi \qquad \Phi = (0, 0)$$

$$V_0 = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \text{h.c.}\right]$$

$$M_{h^0}^2 = -2\mu_1^2 = 2\lambda_1 v^2 ,$$

$$M_{H^0}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 = \mu_2^2 + \lambda_L v^2 , \qquad \lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5),$$

$$M_{A^0}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 = \mu_2^2 + \lambda_S v^2 , \qquad \lambda_S = \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5).$$

$$M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2 .$$

Six independent parameters in this model

$$\{M_{h^0}, \ M_{H^0}, \ M_{A^0}, \ M_{H^\pm}, \ \lambda_L, \ \lambda_2\}$$

Constraints

Perturbative calculations $|\lambda_i| < 8\pi$

Vacuum stability conditions

$$\lambda_{1,2} > 0 \quad \text{and} \quad \lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1 \lambda_2} > 0 \quad \text{and} \quad \lambda_3 + 2\sqrt{\lambda_1 \lambda_2} > 0$$

Unitarity Conditions

$$\lambda_3 \pm \lambda_4 < 8\pi \quad , \quad \lambda_3 \pm \lambda_5 < 8\pi \quad ,$$
$$\lambda_3 + 2\lambda_4 \pm 3\lambda_5 < 8\pi \quad , \quad -\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2} < 8\pi \quad ,$$
$$-3\lambda_1 - 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2} < 8\pi \quad ,$$
$$-\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_5^2} < 8\pi \quad .$$

Constraints (contd.)

LEP measurements of Z decay width

$$M_{H^0} + M_{A^0} \geq M_Z \text{ and } 2M_{H^\pm} \geq M_Z$$

ALTAS and CMS bounds on diphoton signal strengths (LHC Constraints)

$$R_{\gamma\gamma} \equiv \frac{\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)}{\sigma(gg \to h)^{\mathrm{SM}} \times \mathrm{BR}(h \to \gamma\gamma)^{\mathrm{SM}}}$$

$1.55^{+0.33}_{-0.28}$ (ATLAS) 0.78 ± 0.28 (CMS)

PLANCK bound on CDM relic density

$$\Omega_{\mathrm{DM}} = 0.1199 \pm 0.0027$$

Two Component Dark Matter Model with Two Scalar Singlets

We Propose SM with additional 2 SM gauge singlets $S_1\,, S_2$

Stability ensured by $\mathbb{Z}_2 \times \mathbb{Z}_2$ or $\mathbb{Z}_2 \times \mathbb{Z}_2'$

$$\begin{pmatrix} S \\ S' \end{pmatrix} \xrightarrow{\mathbb{Z}_2 \times \mathbb{Z}_2} \begin{pmatrix} -S \\ -S' \end{pmatrix} \qquad S \xrightarrow{\mathbb{Z}_2} -S \;\; \text{and} \;\; S' \xrightarrow{\mathbb{Z}_2'} -S'$$

K. P. Modak, D. Majumdar, S. Rakshit,
JCAP 1503 (2015) 011

The Scalar Potential

$$V(H,S,S') = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$

$$+\frac{\delta_1}{2}H^\dagger H S + \frac{\delta_2}{2}H^\dagger H S^2 + \frac{\delta_1 m}{2\lambda}S + \frac{k_2}{2}S^2 + \frac{k_3}{3}S^3 + \frac{k_4}{4}S^4$$

$$+\frac{\delta_1'}{2}H^\dagger H S' + \frac{\delta_2'}{2}H^\dagger H S'^2 + \frac{\delta_1' m}{2\lambda}S' + \frac{k_2'}{2}S'^2 + \frac{k_3'}{3}S'^3 + \frac{k_4'}{4}S'^4$$

$$+\frac{\delta_2''}{2}H^\dagger H S' S + \frac{k_2''}{2}SS' + \frac{1}{3}(k_3^a SSS' + k_3^b SS'S')$$

$$+\frac{1}{4}(k_4^a SSS'S' + k_4^b SSSS' + k_4^c SS'S'S')$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \longrightarrow \delta_1 = k_3 = \delta_1' = k_3' = k_3^a = k_3^b = 0$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2' \longrightarrow \delta_2'' = k_2'' = k_4^b = k_4^c = 0 \quad \text{(in addition)}$$

A fermionic DM Model in hidden sector

Dark Matter candidate belongs to a dark sector

Proposed: The existence of a `hidden' dark sector

The Lagrangian of this hidden sector remains invariant under local $\mathrm{SU(2)_H}$

The Lagrangian is also invariant under a global $\mathrm{U(1)_H}$

Two fermion generations

$$\chi_{1\mathrm{L}} = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}_{\mathrm{L}} , \quad \chi_{2\mathrm{L}} = \begin{pmatrix} f_3 \\ f_4 \end{pmatrix}_{\mathrm{L}}$$

$f_{i\mathrm{L}}$ transforms like a part of a doublet under $\mathrm{SU(2)_H}$

$f_{i\mathrm{R}}$ singlet under $\mathrm{SU(2)_H}$

Both $f_{i\mathrm{L}}$ and $f_{i\mathrm{R}}$ are charged under $\mathrm{U(1)_H}$

$\mathrm{SU(2)_H}$ Scalar doublet Φ Does not have global $\mathrm{U(1)_H}$ charge

The dark sector is connected to the visible sector through the gauge invariant Interaction term, $\lambda_3 H^\dagger H \Phi^\dagger \Phi$

$$\rightarrow \mathrm{mixing\,between}\ \Phi\ \mathrm{and\,SM\,Higgs}\ H$$

Global $\mathrm{U(1)_H}$ does not break spontaneously

Local $\mathrm{SU(2)_H}$ breaks spontaneously when neutral component of Φ gets a VEV

Three dark gauge bosons $A'_{i\mu}(i=1,2,3)$ get mass

Φ Also possesses a custodial SO(3) symmetry

$\rightarrow A'_{i\mu}(i=1,2,3)$ become degenerate in mass

No mixing between $\mathrm{SU(2)_H}$ gauge bosons and SM gauge bosons

Dark Sector fermions $f_i, i = 1, 4$ are charged under global $\mathrm{U(1)_H}$

Invariance of dark sector Lagrangian under $\mathrm{U(1)_H}$ requires equal and opposite $\mathrm{U(1)_H}$ charges between each fermion and its antiparticle.

Dark sector fermions are Dirac type (not Majorana).

Dark sector fermions can interact by exchanging dark gauge bosons $A'_{i\mu} (i = 1, 2, 3)$

Heavier fermions decays into the lightest fermion f_1

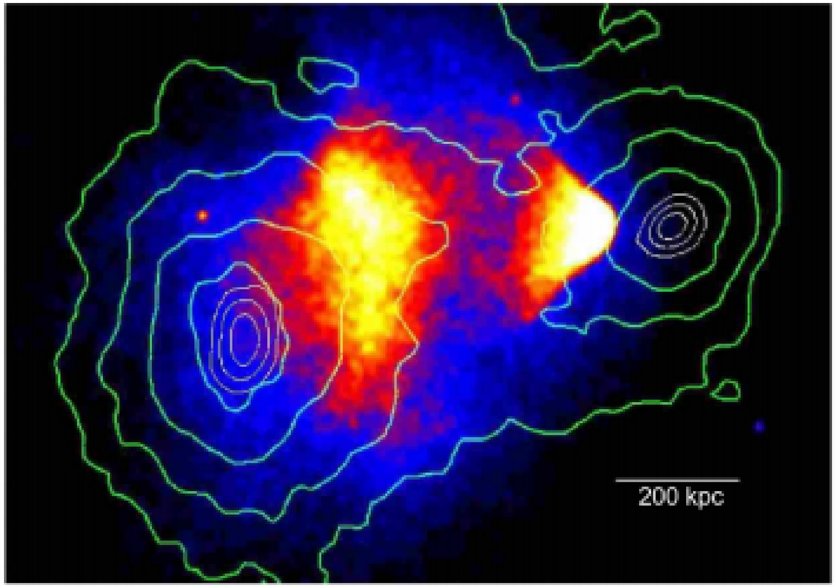
f_1 gets mass by the VEV of Φ when $\mathrm{SU(2)_H}$ of hidden sector breaks spontaneously

$$m_{f_1} = \frac{y'_1 v_s}{\sqrt{2}}.$$

Self Interacting Dark Matter

Does it interact with itself (collisions)?

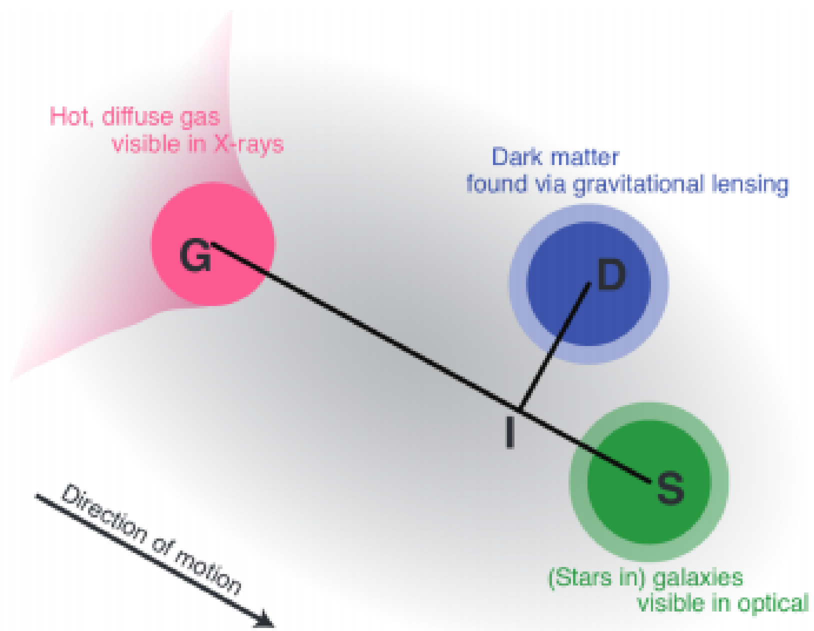
Bullet Cluster (Clowe+ 2006)



$\sigma/m < 0.7\ \mathrm{cm^2/g}$ mass loss in Bullet Cluster *Randall et al 2008*

$\sigma/m < 0.47\ \mathrm{cm^2/g}$ 72 cluster collisions *Harvey et al 2015*

$\sigma/m = (1.7 \pm 0.7) \times 10^{-4}\ \mathrm{cm^2/g}$ in Abell 3827 (?) *Massey et al 2015*



Non-thermal dark matter?

A. Biswas, DM, P. Roy, Europhys.Lett. 113 (2016) no.2, 29001

Asymmetric dark matter

- Dark matter in a hidden mirror sector (“dark sector”)
- Dark matter asymmetry similar to baryon asymmetry, generated by similar mechanisms

$$n_\chi \approx n_\mathrm{p}$$

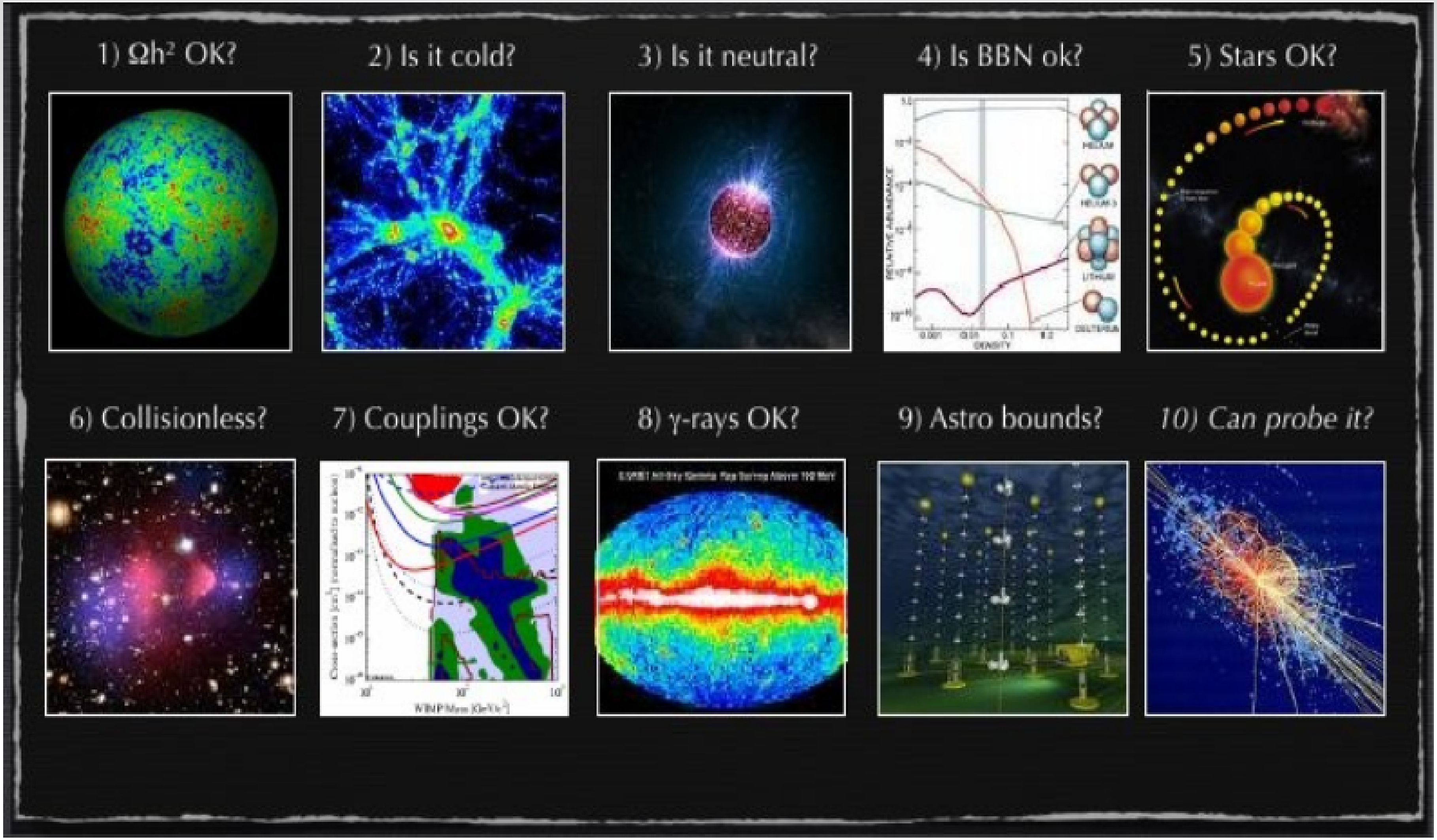
- Dark matter mass is a few times the proton mass

$$\Omega_\chi \approx \frac{m_\chi}{m_p} \Omega_\mathrm{p} \approx (\mathrm{a\ few})\, \Omega_\mathrm{p}$$

Nussinov 1985; Gelmini, Hall, Lin 1986; Hooper, March-Russell, West 2008; Kouvaris 2008; Kaplan, Luty, Zurek 2009; Hall, March-Russell, West 2010; Buckley, Randall 2010; Dutta, Kumar 2011; Cohen, Phalen, Pierce, Zurek 2010; Falkowski, Ruderman, Volansky 2011; Frandsen, Sarkar, Schmidt-Hoberg 2011; etc.

Courtesy: Paolo Gondolo

Tests for DM Particles



Taken from Gianfranco Bertone, arXiv:0711.4996

THANK YOU