Minimal Dark Matter

Why the proton is so stable?

(a) No low-energy coupling allows its decay. [SM]

(b) Thanks to ad hoc engineering.

[SUSY, split SUSY, extra-dims,...]

MDM keeps and extends (a) to DM stability

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talk at CERN 2006/02/07 — Pisa, 2006/02/02

Gran Sasso, 2006/01/11 — Madrid, 2005/12/16

From a work with Marco Cirelli, Nicolao Fornengo.

www.cern.ch/astrumia/MDM.pdf

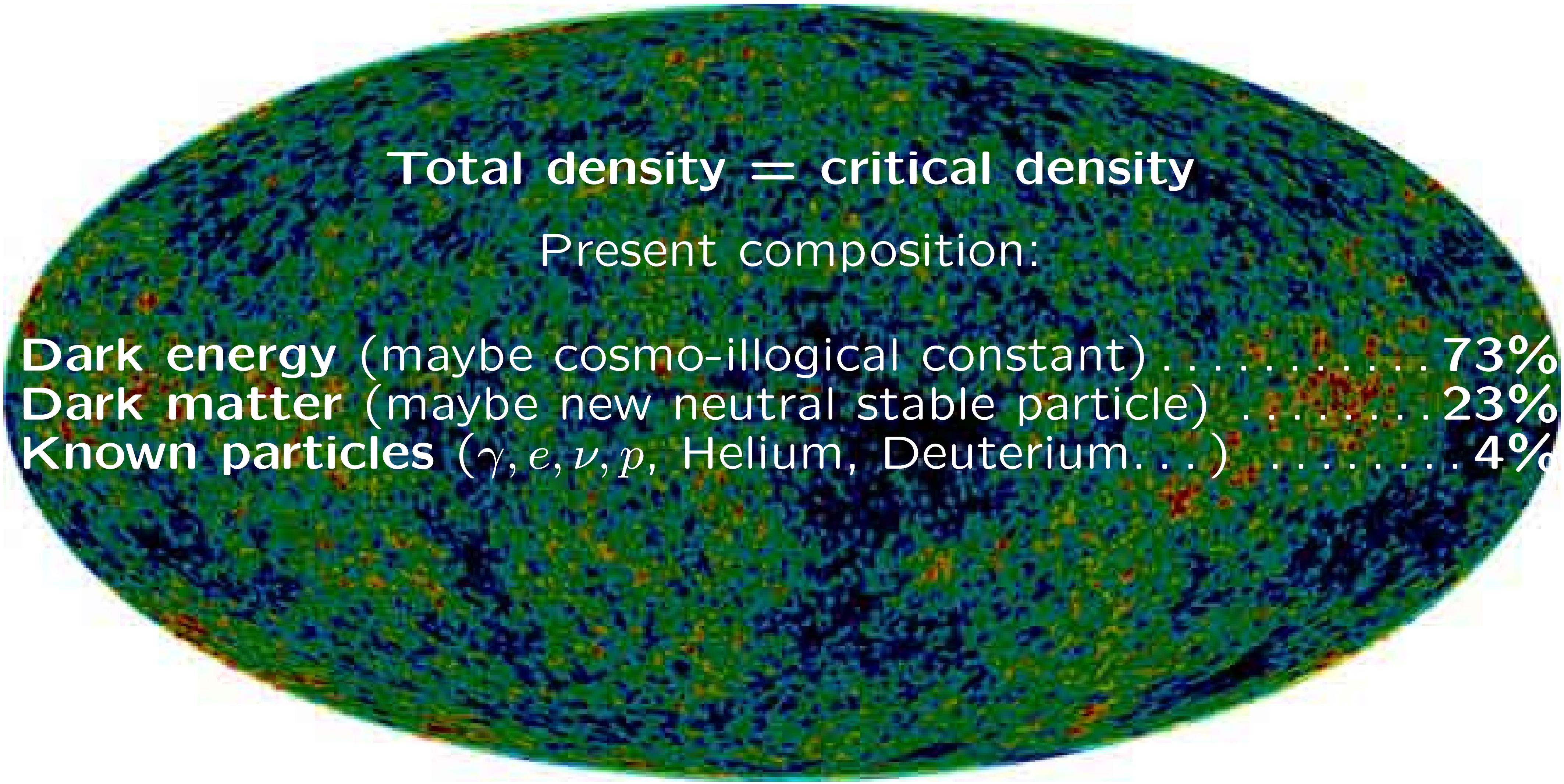
Why one more DM candidate?

“Dark matter” paper number 4231 in SPIRES.

Neutrino (excluded), sterile neutrino, right-handed neutrino, neutralino, higgsino, bino, photino, wino, gravitino, sneutrino, possibly split or anthropic, right-handed sneutrino, scalar singlet, singlino, Kaluza Klein LKP: graviton$_1$, photon$_1$, neutrino$_1$, Z_1, Z', axion, axino, B-balls, Q-balls, odd-balls, inflatino, quintissencino, scalar condensate, Pseudo-Goldstone, ultra light PG, radion, radino, modulus, modulinos, Planck relicts, quark nugget, encapsulated atoms, top bound state, shadow matter, mirror matter, branon, branino, normal matter on folded brane or on another brane or membrane or D-brane or p-brane, cosmic string, cosmic necklace, mini black hole, soliton, monopole, techni-baryon, techni-meson, Chaplygin gas, fuzzy DM, WIMPzilla, familion, familin CP pseudoscalar, preon, dilaton, doubly-charged lepton, degenerate fermion, kination, H dibaryon, crypton, hiddenon, heterotic, d-quark from Wilson lines, 4th generation, ...

Minimal Dark Matter: simple & predictive

Cosmic inventory



Total density = critical density

Present composition:

Dark energy (maybe cosmo-illogical constant) **73%**
Dark matter (maybe new neutral stable particle) **23%**
Known particles (γ, e, ν, p, Helium, Deuterium. . .) **4%**

Inflation explains $\rho = \rho_{\rm cr}$. Big-bang explains $n_e = n_p$, $n_{^4{\rm He}}/n_p \approx 0.25/4$, $n_{\rm D}/n_p \approx 3\ 10^{-5}/2$, $n_{\nu_i} \stackrel{?}{=} n_{\bar\nu_i} \stackrel{?}{=} 3n_\gamma/22, \ldots$, Could also explain DM and n_B/n_γ.

Dark matter as thermal relic

What happens to a stable particle at $T < m$?

Scatterings try to give thermal equilibrium

$$n_{\rm DM} \propto \exp(-m/T).$$

But at $T \lesssim m$ they become too slow:

$$\Gamma \sim \langle n_{\rm DM}\sigma\rangle \lesssim H \sim T^2/M_{\rm Pl}$$

Out-of-equilibrium relic abundancy:

$$\frac{n_{\rm DM}}{n_\gamma} \sim \frac{T^2/M_{\rm Pl}\sigma}{T^3} \sim \frac{1}{M_{\rm Pl}\sigma m}$$

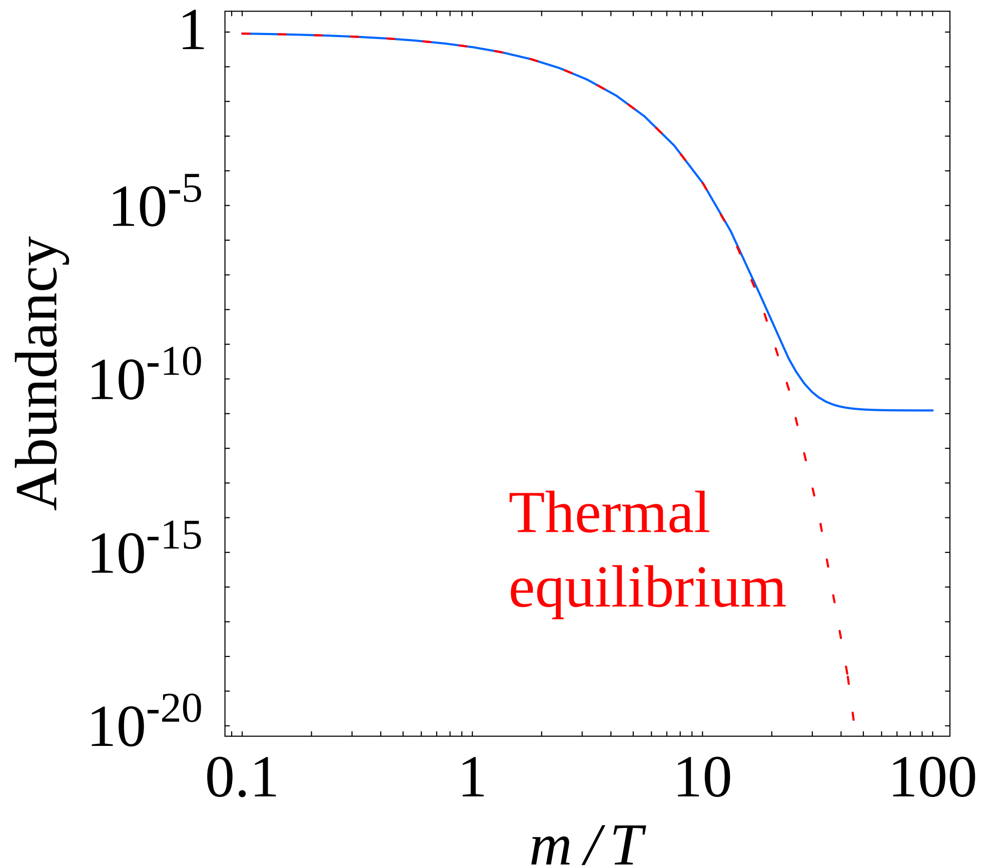
$$\frac{\rho_{\rm DM}}{\rho_\gamma} \sim \frac{m}{T_{\rm now}}\frac{n_{\rm DM}}{n_\gamma} \sim \frac{1}{M_{\rm Pl}\sigma T_{\rm now}}$$

Inserting $\rho_{\rm DM} \sim \rho_\gamma$ and $\sigma \sim g^2/m^2$ fixes

$$m/g \sim \sqrt{T_{\rm now}M_{\rm Pl}} \sim \text{ TeV}$$

Directly seen at LHC 2008? Fully precise:

$$16\pi\langle\sigma v\rangle = 0.21/\text{ TeV}^2$$



DM candidates from EWSB theories...

Need: neutral, stable

Solutions to the hierarchy problem employ new physics at the electroweak scale.
DM usually studied as a byproduct

- ✷ Bino/wino/higgsino or sneutrino from SUSY.
  Stable thanks to R or matter parity.

- ✸ Z' in little-Higgs.
  Stable thanks to T-parity.

- ✹ KK of photon or neutrino from would-be-universal extra dimensions.
  Stable thanks to KK parity.

...and their unsatisfactory aspects

- Needed DM properties can be imposed adding ad-hoc ingredients. Known stable particles (ν, e, p) are stable for better reasons.

- These solutions employ embarrassingly rich phenomenology; and nothing seen so far: simplest models **survive by fine-tuning** their free parameters.

- DM **phenomenology obscured** by many unknown parameters.
  All signals can be realized in some corner of parameter space (scatter plots).

Minimal approach to DM

Add to the SM extra particles $\mathcal{X}$ + h.c. Search for assignement of quantum numbers (gauge charges, spin) that give a as-perfect-as-possible DM candidate:

1. Cosmologically stable
2. Only one parameter: M
3. Lightest component is neutral.
4. Allowed

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{when } \mathcal{X} \text{ is a spin 1/2 fermionic multiplet} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{when } \mathcal{X} \text{ is a spin 0 bosonic multiplet} \end{cases}$$

Simple because no other term is compatible with gauge/Lorentz invariance

EWSB induces a well-defined and non-trivial phenomenology. M fixed by Ω_{DM}.

Neutral?

n-tuplets of $\mathrm{SU}(2)_L$ containing a neutral components: $Q = T_3 + Y = 0$ for

❷ $n = 2$: $|Y| = 1/2$: $\mathcal{X} = (\mathcal{X}^+, \mathcal{X}^0)$ (e.g. Higgsino, lepton or Higgs doublet).
All $\mathcal{X}$ components are complex (Dirac) fermions or complex scalars.

❸ $n = 3$:
- $|Y| = 0$: $\mathcal{X} = (\mathcal{X}^+, \mathcal{X}^0, \mathcal{X}^-)$ (e.g. wino, fermion triplet of see-saw)
  $\mathcal{X}^0$ is real (Majorana) fermion or a real scalar.
- $|Y| = 1$: $\mathcal{X} = (\mathcal{X}^{++}, \mathcal{X}^+, \mathcal{X}^0)$ (scalar triplet of see-saw or little-Higgs)
  All $\mathcal{X}$ components are complex (Dirac) fermions or complex scalars.

❹ $n = 4$:
- $|Y| = 1/2$: $\mathcal{X} = (\mathcal{X}^{++}, \mathcal{X}^+, \mathcal{X}^0, \mathcal{X}^-)$
- $|Y| = 3/2$: $\mathcal{X} = (\mathcal{X}^{+++}, \mathcal{X}^{++}, \mathcal{X}^+, \mathcal{X}^0)$

❺ $n = 5$: $|Y| = 0$: $\mathcal{X} = (\mathcal{X}^{++}, \mathcal{X}^+, \mathcal{X}^0, \mathcal{X}^-, \mathcal{X}^{--})$ or $|Y| = \{1, 2\}$.

etc.

Stable?

A coupling with coefficient $1/\Lambda^p$ produces $\tau \sim (\Lambda\,\text{TeV})^{2p}/\,\text{TeV}$:
renormalizable and dimension-5 couplings with $\Lambda \lesssim M_{\rm Pl}$ are dangerous.

E.g. a scalar 5-plet can couple as $\mathcal{X}HHH^*H^*/\Lambda$: bad.
The first automatically stable MDM candidates are:

fermion 5-plets and scalar 7-plets

These also are the last MDM candidates.
Upper limit $n \le 8$ for scalars and $n \le 5$ for fermions by demanding

$$\alpha_2^{-1}(E) = \alpha_2^{-1}(M) + \frac{19/6 - \mathcal{O}(n^3)}{2\pi} \ln \frac{E}{M} > 0$$

Dependence on n is much stronger than dependence on $E \sim M_{\rm Pl}$.
(p, π looked composite, while composite q, ℓ complicates physics).

MDM candidates

Quantum numbers SU(2)$_L$	U(1)$_Y$	Spin	DM can decay into	DM mass in TeV	$m_{\text{DM}^\pm} - m_{\text{DM}}$ in MeV	Events at LHC $\int \mathcal{L}\,dt = 100$/fb	σ_{SI} in $10^{-45}\,\text{cm}^2$	Rating
2	1/2	0	EL	0.54 ± 0.01	350	$340 \div 550$	0.3	$\times\times$
2	1/2	1/2	EH	1.2 ± 0.03	341	$160 \div 320$	0.3	$\times\times$
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3	$\surd\times$
3	0	1/2	LH	2.5 ± 0.06	166	$0.7 \div 3.7$	1.3	$\surd\times$
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	2.5	$\times\times$
3	1	1/2	LH	1.9 ± 0.05	526	$25 \div 80$	2.5	$\times\times$
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.1 \div 0.6$	1.9	$\times\times$
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$4.8 \div 23$	1.9	$\times\times$
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.09$	10	$\times\times$
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.5 \div 8.5$	10	$\times\times$
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12	$\surd\times$
5	0	1/2	$-$	4.4 ± 0.1	166	$\ll 1$	12	$\surd\surd$
7	0	0	$-$	8.5 ± 0.2	166	$\ll 1$	46	$\surd\surd$

Rating = { allowed without tricks , stable without tricks }

The intra-multiplet mass splitting

Scalar MDM can have non-minimal renomalizable couplings

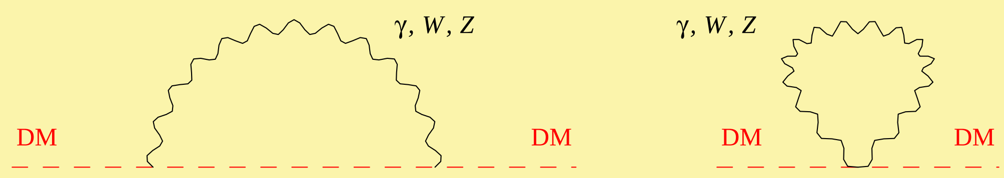
$$\mathscr{L}_{\text{non minimal}} = \mathscr{L} - \lambda_H (\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})\,(H^* T^a_H H) - \lambda'_H |\mathcal{X}|^2 |H|^2$$

producing a mass splitting **suppressed by M**

$$\Delta M = \frac{\lambda_H v^2 |\Delta T^3_{\mathcal{X}}|}{4M} = \lambda_H \cdot 7.6\,\text{GeV}\frac{\text{TeV}}{M}$$

One loop corrections generate:

$$M_Q - M_0 = \frac{\alpha_2 M}{4\pi}\left\{Q^2 s^2_{\rm W} f(\frac{M_Z}{M}) + Q(Q-2Y)\left[f(\frac{M_W}{M}) - f(\frac{M_Z}{M})\right]\right\}$$



$f(r) \overset{r\to 0}{\simeq} -2\pi r$ for both fermionic and scalar multiplets if $M \gg M_Z$:

$$M_Q - M_0 \overset{M\gg M_Z}{\simeq} Q(Q + \frac{2Y}{\cos\theta_{\rm W}})\Delta M$$

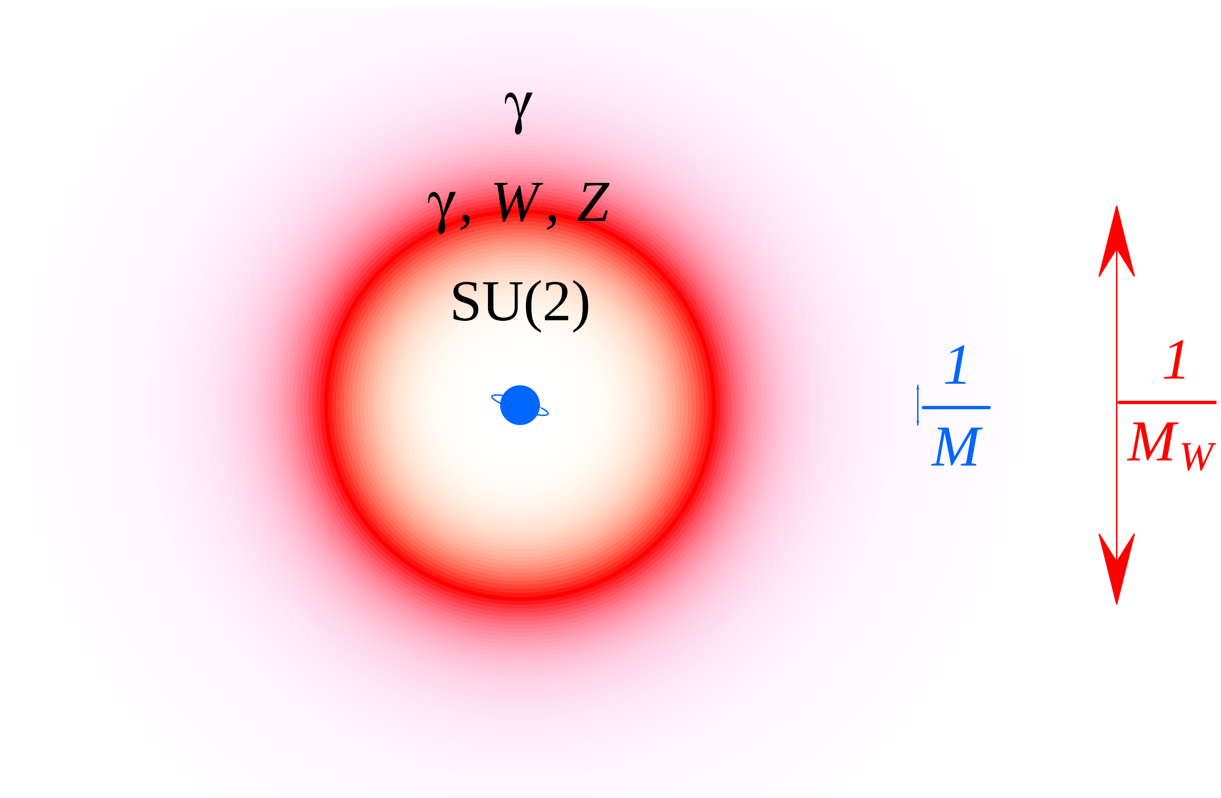
$$\Delta M = \alpha_2 M_W \sin^2\frac{\theta_{\rm W}}{2} = (166 \pm 1)\,\text{MeV}$$

The lightest component is neutral

Intuitive explanation

The mass difference corresponds to the *classical* non-abelian Coulomb energy

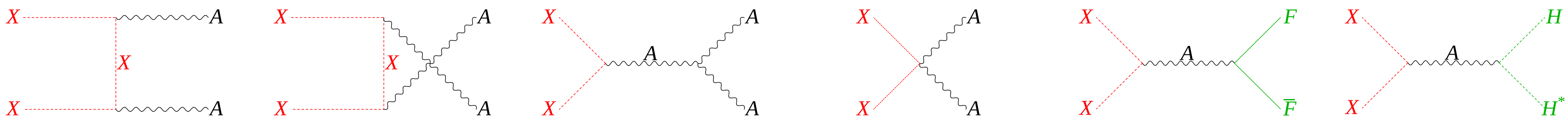
$$\delta M = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi)^2 + \frac{M_V}{2}\varphi^2\right] = \frac{\alpha}{2}M_V + \infty \qquad \varphi(r) = \frac{g e^{-M_V r/\hbar}}{4\pi r}$$



Same physics responsible for very-low-energy scatterings: $\sigma \sim 1/M_W^2$.

The DM abundancy

$$\frac{n_{\rm DM}}{s} \approx \frac{1}{M_{\rm Pl}\ T_f \langle \sigma_A v\rangle} \qquad T_f \sim \frac{M}{26}$$



Assume $\sqrt{s} \simeq 2M \gg M_Z$: compute in SU(2)$_L$-symmetric non-relativistic limit:

$$\mathrm{Tr}\, T^a T^b T^a T^b = \frac{n}{16}(n^2-5)(n^2-1)$$

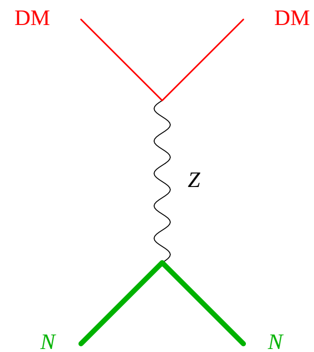
automatically sums over all co-annihilations. Scalar and fermion DM annihilates into AA with the same σ. Fermions also annihilate in quarks, leptons, higgses.

$$\langle \sigma_A v\rangle \simeq \begin{cases} \dfrac{g_2^4\ (3-4n^2+n^4) + \mathcal{O}(g_2^2 g_Y^2, g_Y^4)}{64\pi\ M^2\ g_\mathcal{X}} & \text{if } \mathcal{X} \text{ is a scalar} \\ \dfrac{g_2^4\ (n^4+9n^2-10) + \mathcal{O}(g_2^2 g_Y^2, g_Y^4)}{64\pi\ M^2\ g_\mathcal{X}} & \text{if } \mathcal{X} \text{ is a fermion.} \end{cases}$$

($\Omega_{\rm DM} \propto M^2$: smaller M if multiple multiplets).

Allowed?

MDM candidates with $Y \neq 0$ are already excluded by Z-exchange scattering:

$\sigma(\text{DM}\,\mathcal{N} \to \text{DM}\,\mathcal{N}) =$ 

$\sim\ (G_{\text{F}} M_{\mathcal{N}} N Y)^2\ \sim\ 10^3 \times (\text{exp. bound})$

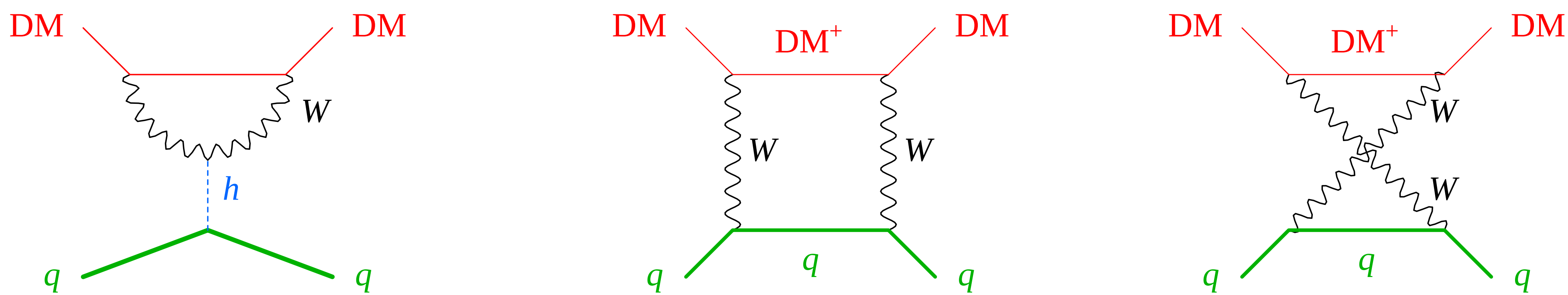
Ill Higgsino-like candidates can be resurrected by mixing with a Singlet:

$$\mathscr{L}_{\text{non minimal}} = \mathscr{L} + \mathcal{X} H^n S + m S^2$$

This splits the neutral components into two real eigenstates that couple to the Z as $\mathcal{X}_0 \mathcal{X}_0' Z$. NC scattering kinematically forbidden if $M_{\mathcal{X}_0'} - M_{\mathcal{X}_0} > M\beta^2/2 \lesssim$ MeV.

Direct DM searches

The usual NC signal arises at one loop:



$$\mathscr{L}_{\rm eff}^{W} = (n^2-1)\frac{\pi\alpha_2^2}{16M_W}\sum_q \left[(\frac{1}{M_W^2}+\frac{1}{m_h^2})[\bar{\mathcal{X}}\mathcal{X}]m_q[\bar{q}q] - \frac{2}{3M}[\bar{\mathcal{X}}\gamma_\mu\gamma_5\mathcal{X}][\bar{q}\gamma_\mu\gamma_5 q]\right]$$

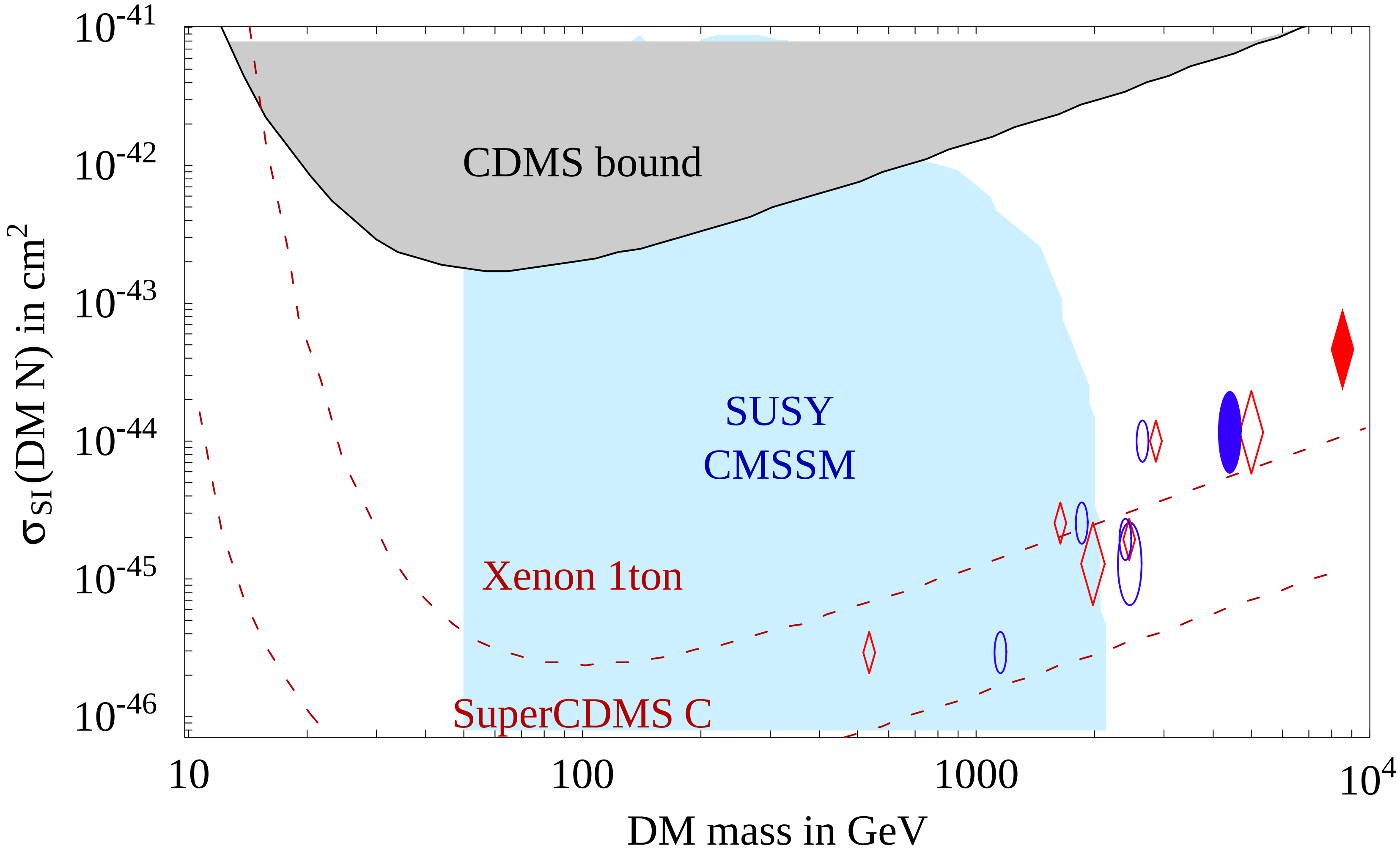
The SI-contribution is not suppressed by M and does not depend on DM spin.

(Disagreement with analogous computations for higgsinos and winos)

Actually, to compute nuclear matrix elements one should leave quarks off-shell obtaining different operators. But $\bar{q}i\partial\!\!\!/ q$ not yet studied, so for simplicity:

$$\langle N|\sum_q m_q\bar{q}q|N\rangle \equiv f m_N \qquad f=\{0.4, 1.2, ?\} \rightsquigarrow 1/3$$

Predictions for $\sigma_{\rm SI}(\text{DM } N)$



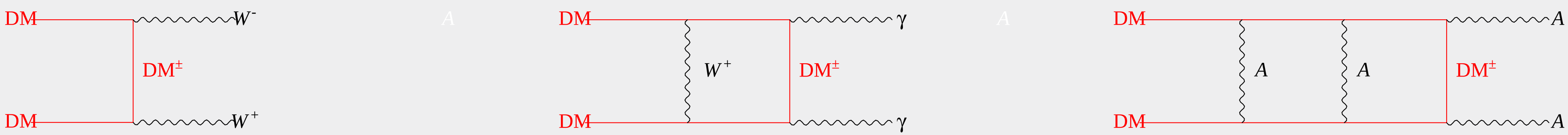
Indirect DM searches

DM DM annihilations in the Sun, Earth ($\to \nu$) or in the Galaxy ($\to \bar{e}, \gamma, \bar{p}, \bar{d}$)

Too small NR cross sections at apparently-dominant order

$$\sigma(\text{DM DM} \to W^+W^-) \cdot v \;=\; (n^2-1)^2 \frac{\pi\alpha_2^2}{32M^2} \;\sim 10^{-26}\,\frac{\text{cm}^3}{\text{sec}}$$

$$\sigma(\text{DM DM} \to \gamma\gamma) \cdot v \;=\; (n^2-1)^2 \frac{\pi\alpha_{\text{em}}^2\alpha_2^2}{16M_W^2} \sim 10^{-26}\,\frac{\text{cm}^3}{\text{sec}}$$



Resonant non-relativistic enhancement if the binding energy of the DM$^+$DM$^-$ two-body state $\Delta E_{\text{bind}} \sim \alpha^2 M$ compensates the mass difference $\Delta M \sim \alpha M_W$. This happens for $M = M_* \sim M_W/\alpha$ enhancing σ by $\mathcal{O}(1 - M/M_*)^{-2}$

n	M_* in TeV				
3	2.5	9.8	...		
5	1.8	3.3	6.6	...	
7	.74	1.6	2.9	3.7	...

Signal possible if $M \sim M_*$ [Hisano et al.]. This is predicted for $n = 3$.

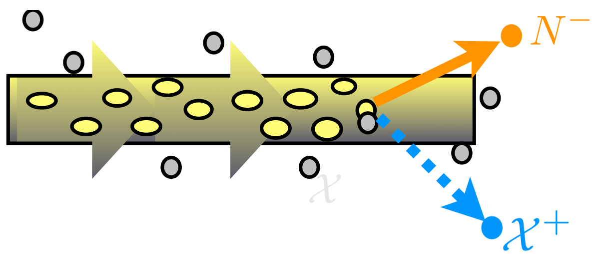
Astrophysical uncertainties and $M - M_*$ make rates significantly uncertain.

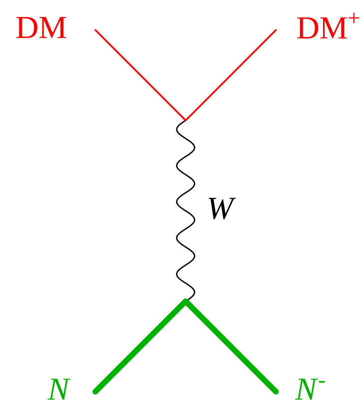
CC DM searches?

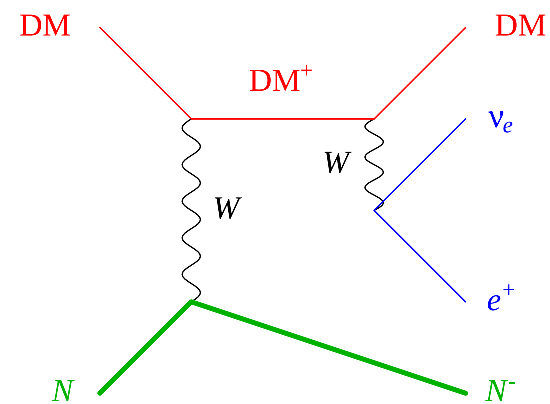
The quasi elastic $\hat{\sigma}(\mathrm{DM}q \to q'\mathrm{DM}^+)$ is 10 orders of magnitude higher:

$$\hat{\sigma} = \sigma_0 \frac{n^2-1}{4}\left[1 - \frac{\ln(1+4E^2/M_W^2)}{4E^2/M_W^2}\right], \qquad \sigma_0 = \frac{G_\mathrm{F}^2 M_W^2}{\pi} = 1.1\,10^{-34}\,\mathrm{cm}^2$$

but in our Galaxy is kinematically forbidden, and off-shell becomes negligible.







Can one accelerate and store a unfocused intense p or nuclear beam?

$$\frac{dN}{dt} = \varepsilon N_p \sigma \frac{\rho_\mathrm{DM}}{M} = \varepsilon \frac{10}{\mathrm{year}} \frac{N_p}{10^{20}} \frac{\rho_\mathrm{DM}}{0.3\,\mathrm{GeV/cm}^3} \frac{\mathrm{TeV}}{M} \frac{\sigma}{3\sigma_0}$$

The problem is the beam-related backgrounds. If DM^+ had a clean signature...

DM$^\pm$ phenomenology

Since $166 > 139$ the life-time is not enough macroscopic: $\tau = 44\,\mathrm{cm}/(n^2-1)$

$$\mathrm{DM}^\pm \to \mathrm{DM}^0\pi^\pm \quad : \quad \Gamma_\pi = (n^2-1)\frac{G_\mathrm{F}^2 V_{ud}^2\,\Delta M^3 f_\pi^2}{4\pi}\sqrt{1-\frac{m_\pi^2}{\Delta M^2}}, \qquad \mathrm{BR}_\pi = 97.7\%$$

$$\mathrm{DM}^\pm \to \mathrm{DM}^0 e^\pm \overset{(-)}{\nu}_e \quad : \quad \Gamma_e = (n^2-1)\frac{G_\mathrm{F}^2\,\Delta M^5}{60\pi^3} \qquad \mathrm{BR}_e = 2.05\%$$

$$\mathrm{DM}^\pm \to \mathrm{DM}^0 \mu^\pm \overset{(-)}{\nu}_\mu \quad : \quad \Gamma_\mu = 0.12\ \Gamma_e \qquad \mathrm{BR}_\mu = 0.25\%$$

Experimentally DM$^+$ behaves like a ‘lepton’ or an ‘hadron’? $\tau \sim (\tau_\mu \tau_\tau)^{1/2}$.

High energy signals

Corrections to precision data: negligible constraints and signals ($c = 1/4 \div 1$)

$$\hat{S} = \hat{T} = 0, \qquad W = c\, g_\chi \frac{\alpha_2}{60\pi}\frac{M_W^2}{M^2}\frac{n^2-1}{12}, \qquad Y = c\, g_\chi Y^2 \frac{\alpha_Y}{60\pi}\frac{M_W^2}{M^2}$$

LHC phenomenology

MDM production for $Y = 0$ (heavy scalars are p-wave suppressed)

$$\hat{\sigma}_{u\bar{d}} = \hat{\sigma}_{d\bar{u}} = 2\hat{\sigma}_{u\bar{u}} = 2\hat{\sigma}_{d\bar{d}} = \frac{g_\chi g_2^4(n^2-1)}{13824\ \pi\hat{s}}\beta \cdot \begin{cases} \beta^2 & \text{if } \mathcal{X} \text{ is a scalar} \\ 3-\beta^2 & \text{if } \mathcal{X} \text{ is a fermion} \end{cases}$$

MDM signal: charged DM$^\pm$ tracks (detectors blind to first 5 cm).

$E_{\rm beam} = 2(4) \times E_{\rm LHC}$ needed to test all fermionic (scalar) MDM candidates.

SUSY. Production: dominantly from gluino decays. Signal: $\not{E}_T +$ jets, μ.

Conclusions

A fermion 5-plet with $Y = 0$ gives a stable, allowed, predictive DM candidate.

Other imperfect MDM candidates need to be stabilized (e.g. wino) or allowed-ized ($Y \neq 0$) or both (e.g. higgsino) or predictivized (scalars).

Broken gauge interactions induce a well-defined non trivial phenomenology.
Fixing $\mathcal{O}(2)$ factors was hard and crucial: e.g. $166 > 139 > 166/2$.

Direct DM searches under planning can probe MDM candidates with higher n (and, if multiple multiplets are present, those that dominate $\Omega_{\rm DM}$).
LHC can probe those with lower n (and sub-dominant contributions to $\Omega_{\rm DM}$).

(Nicodemitic thanks to phil-anthropist).

X

Anthropic selection

The Big Question

1789

Which family will dominate Europe:

Habsburg or Lothringen?

1990

Which origin for sparticle masses:

supergravity or gauge interactions?

2000

Which solution to the hierarchy problem:

SUSY or extra dimensions or...?

2010

The hierarchy problem has a

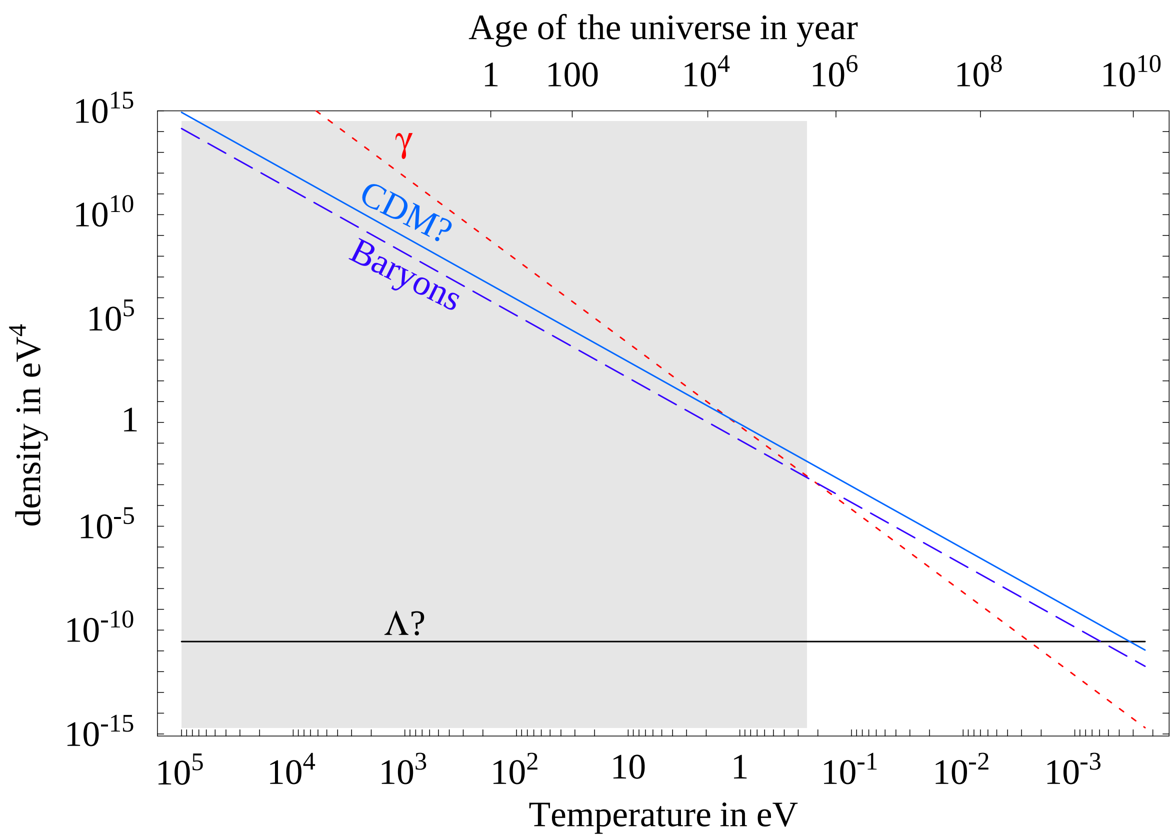
natural solution or anthropic selection?

3 results transformed many theorists into anthropists:

❶ $V \sim (10^{-3}\,\text{eV})^4 \neq 0$

Dark Energy seems to be just a cosmological constant Λ

Another hierarchy problem, with no known solution.



In any case: why $V \sim \rho$ now? Structure form when $\rho_{\text{matter}} \gtrsim V, \rho_{\text{radiation}}$

A Λ $10 \div 100$ times bigger will have prevented formation of (our) galaxy.

Caution: really a success?

❷ The problem of the hierarchy problem

$\delta m_h^2 \lesssim m_h^2$ now calls for new physics below a TeV. **But nothing found.**

Typical SUSY models no longer in healthy state. Other solutions that affect precision data (technicolor, little Higgs, extra dimensions) in worse state. Furthermore data confirm SM flavour structure (p stable, almost no EDMs...).

Unelegant solutions to an æstetical problem or...

... the weak scale v is anthropically selected?

$\uparrow$ Increasing v by a few makes $m_n - m_p > E_B$: nuclei decay to H.
$\downarrow$ Reducing v by a few makes $m_p > m_n$ so that H decays.

Caution: not yet clearly a problem. **LHC will tell?**

❸ The string demographic explosion

Quantum gravity (possibly experimentally irrelevant) was attached hoping that it leads to a unique 'theory of everything' that predicts something at low energy.

String theory was promising and gained a **strong** influence on theorists.

1 M-theory in 11d $\to$ 5 string theories in 10d $\to$ $10^{\mathcal{O}(500)}$ string models in 4d

Predictivity is lost when inventing ways of getting rid of the extra dimensions. Dirty physics mostly comes from higher dimensional geography, not from theory. (Maybe not so bad: the number of realistic string models is 0 so far)

Maybe strings gave no results for 30yrs because it provides the **right** anthropic theory: V(many Higgs) has 2^{many} vacua: we can only live in one of them that accidentally has small v and V. Other anthropic models can be more testable.

Caution: alternative?

What Is to Be Done?

Anthropic selection is plausible, but real progress could be impossible.

String approach:

exploit the string predictive power in a statistical way?

E.g. possibly so many vacua have high scale SUSY, that it becomes ‘likely’.

Result: SUSY maybe at weak or Planck or any scale [JHEP 05!]

Philantropic approach:

Hope that physics is better than anthropic.

Explore predictive unnatural models for:

DM. Unification. ν masses. Inflation.

(Often done avoiding the word ‘anthropic’)

Neutrino masses from $h/\tilde{L}$ unification?

Super-Split-Super-Symmetry can be a new source of neutrino masses: suppose that at low energy there is only SM, but we 'know' that high-energy is SUSY.

L, B violation suppressed by $1/m_{\rm SUSY}$.

Neutrino masses open a (little) window on high-energy; maybe we can build a predictive enough high-energy model. Most Minimal SUSY SM:

$\boldsymbol{\lambda_{ijk} L_i L_j E_k}$ **with** $\boldsymbol{\tilde{L}_i = v_i}$.

- If $m_{\rm SUSY} \sim 10^{12}\,$GeV slepton can be higgs and R-parity not needed.
- v fine-tuned to be small

$$m_{e,\mu,\tau} \sim \lambda v, \qquad m_{\nu_{1,2,3}} \sim \frac{v^2 A_0}{m^2_{\rm SUSY}} \frac{\lambda^4}{(4\pi)^2}$$

Neutrino masses unified with charged lepton masses.

Large mixing angles from ij antisymmetry.

5 parameters $\to$ many **predictions** $\to$ **excluded** after 2002 + hours.

Non-minimal models do not make testable predictions.

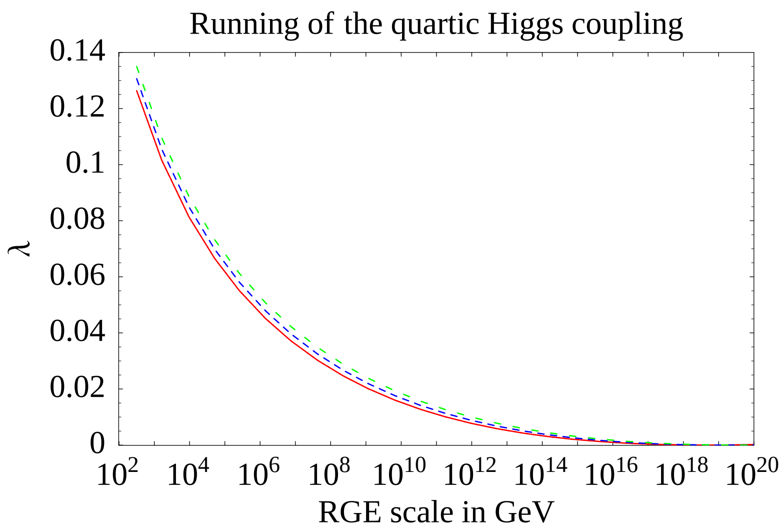
(One can write a paper about typical phenomena, $\langle \tilde{\nu}_R \rangle \sim M_{\rm GUT} \gg m_{\rm SUSY}$).

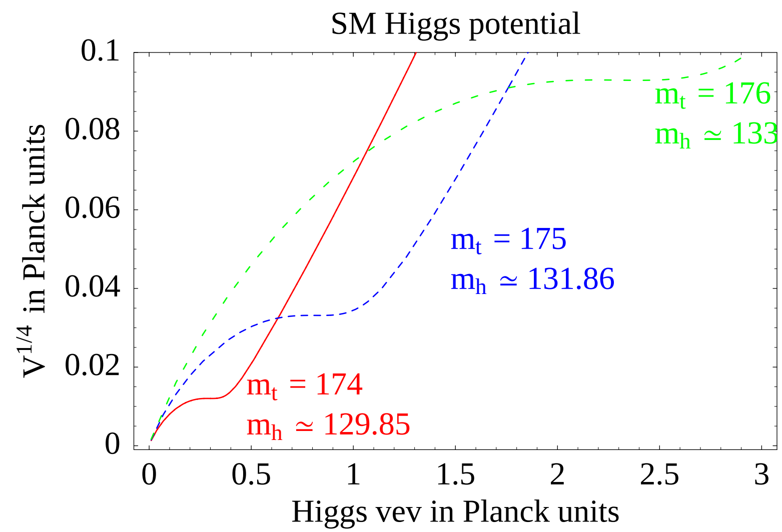
Higgs inflation?

Many attempts of building models of inflation. No compelling model emerges. No connection with particle physics. Maybe inflation is not natural.

Try with the SM higgs.

For m_t around its measured value and fine-tuning $m_h \approx m_t - 43\,\text{GeV}$ such that $\min_h \lambda(h) \simeq 1/4096\pi^4$ makes the SM potential $V_{\text{SM}} \simeq \lambda(h)h^4$ unnaturally flat:





Slow-roll inflation is possible, but $\delta(N \approx 60)$ is larger than the observed value.

Connection with particle physics is so strong that one cannot hammer V!

(One can try again with extensions of the SM)