3. Particle Dark Matter
toward “more exotic” lands

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Plan

- We have seen the “vanilla” mechanism to obtain DM. Today we’ll try to go beyond that:
- Decays (Superwimps, from inflaton...)
- Asymmetry (link with baryogenesis)
- Misalignment (application to axions)
- Gravitational Production

Slightly changed my mind about strategy: I’ll try to go a quick but broad overview as opposed to indulge in detailed derivation, so that DM “experts” can hopefully find something new, too...

Do not hesitate to stop me and ask questions, though!

Production from decay

Super-WIMPs (from WIMP decay)

The freeze-out computation works almost unchanged also for a class of non-thermal candidates which are less-than-weakly interacting, but arise as by-product of wimps, e.g. by the decay of next-to-lightest new particle. In this case:

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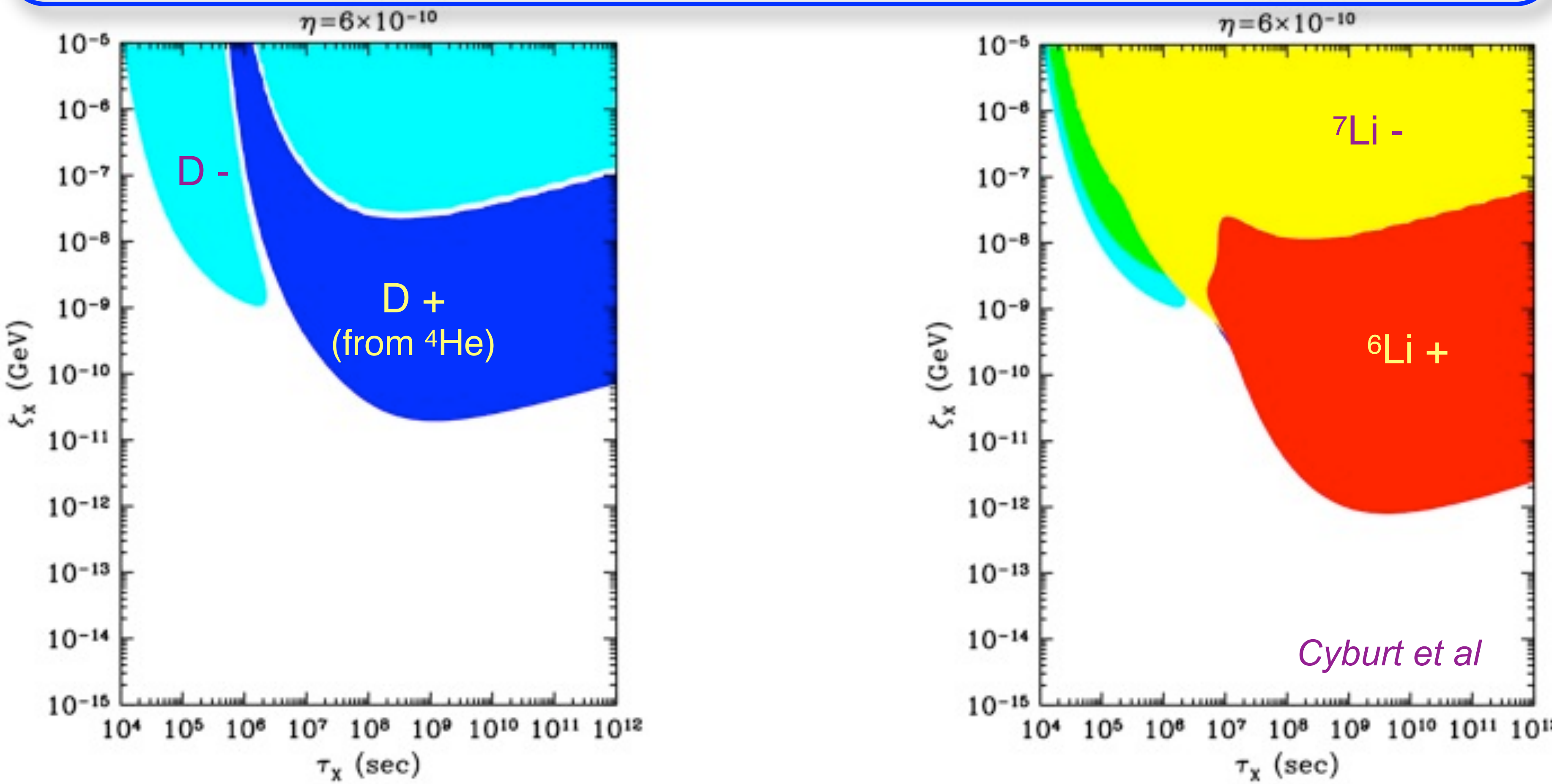
- The particles produced in the decay have larger velocity dispersion, possibly leaving signatures in astrophysical structures. *Check the free-streaming length!*
- Paradigm is the *gravitino* in SUGRA, but can be also applied to *axinos, RH sneutrinos, Kaluza-Klein gravitons, Kaluza-Klein Right-Handed neutrinos*...
- There are also other, non-thermal production mechanisms (by definition, all the rest!) like end-of inflation production, oscillations... check if they are dominant!
- If lifetime of metastable state is longer than ~0.1 s, might alter BBN (e.g. by injecting hadrons altering n/p ratio, or at later time photo-dissociating elements)
- Displaced vertices detectable at colliders?

BBN bounds: Electromagnetic cascades

- Develop rapidly: results depend mostly on injection time τ_X (large enough for γ's with E_γ> Binding to avoid damping via $\gamma\gamma_{CMB} \to e^\pm$) & overall injected energy, e.g. via $\zeta = m_X n_X / n_\gamma$
- At small τ_X Li not formed yet, constraints from D. At large τ_X large ζ yields also too much depletion of the fragile ^{7}Li; but even small ζ sufficient to overproduce ^{6}Li (thanks to late injection of energetic ^{3}He & ^{3}H from tiny fraction of ^{4}He dissociation)
- If DM is produced from X in the process, $\zeta > 2\times10^{-9}$ GeV $\Rightarrow \tau_X < 3\times10^5$ s



Hadronic Cascades

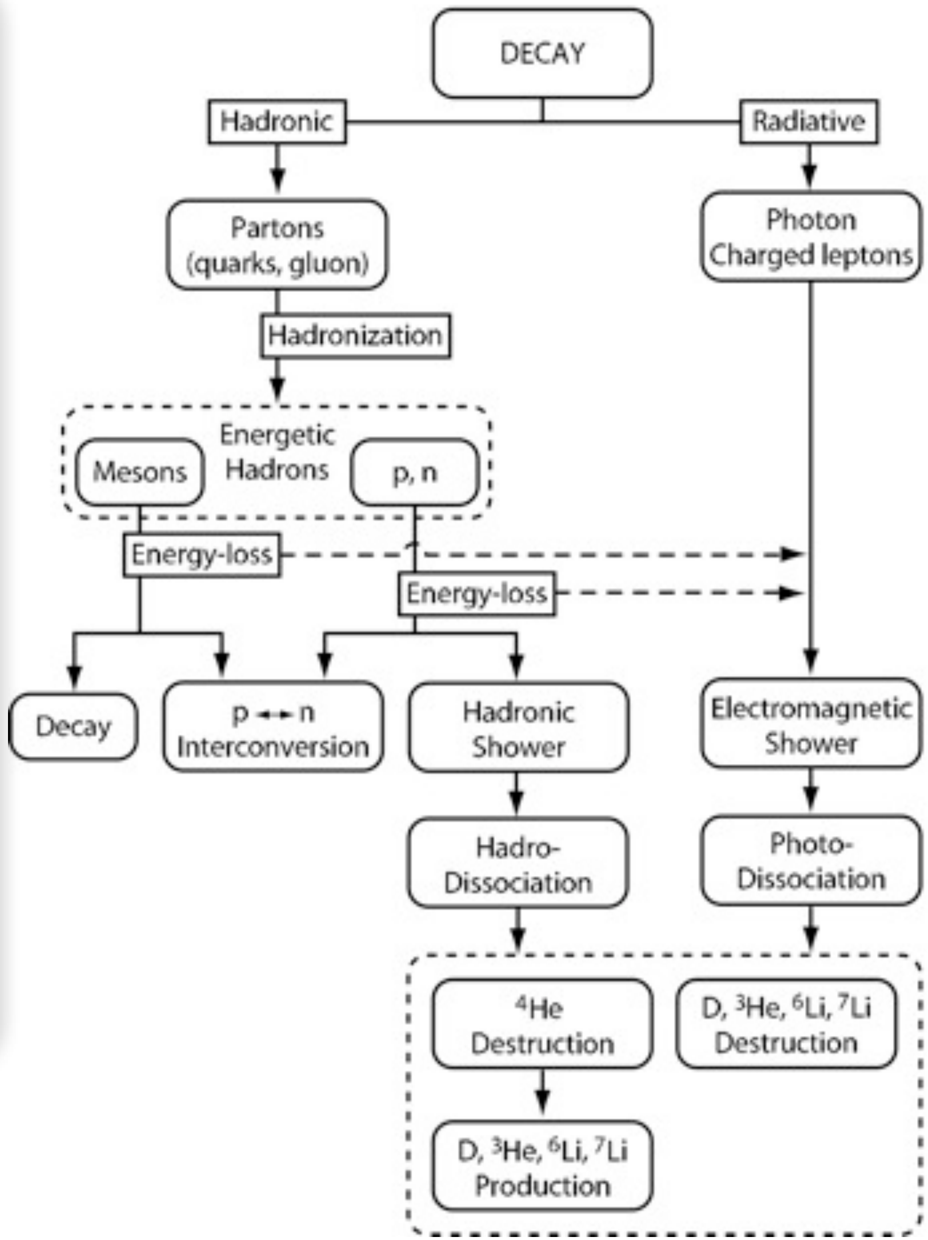
- Much more complicated process, since "factorization" Standard BBN →non-thermal Nucleos. is not possible at early times. Many secondary processes are induced!

- Depends on many particle physics parameters, e.g. b.r.'s. More model dependent!

- At late τ_X e.m. effects dominate.

- At early times, the n/p ratio can be directly altered by the presence of antinucleons and mesons.

- At intermediate times, novelty is introduced via the possibility of ^{4}He dissociation by (anti)nucleons.

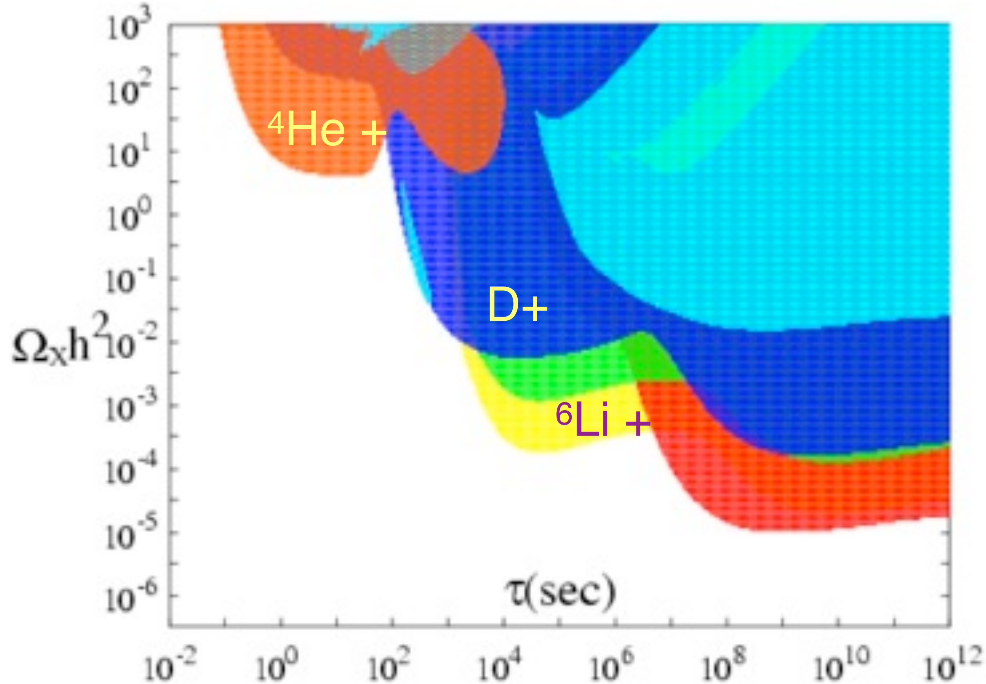


Studied via MC, e.g. PITHYA based

Hadronic Cascades - Constraints

1 TeV particle,
Hadronic B.r.=3.3%
(relic abundance it would have today…)

note that if this is responsible for DM,
$\tau_X > 2\times10^2$ is excluded.



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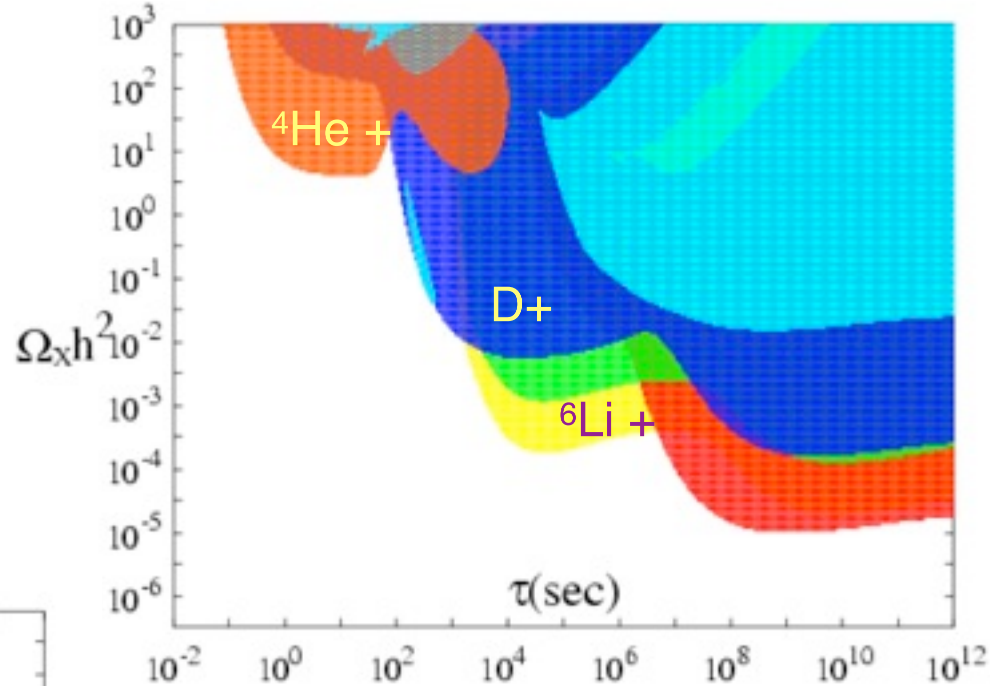
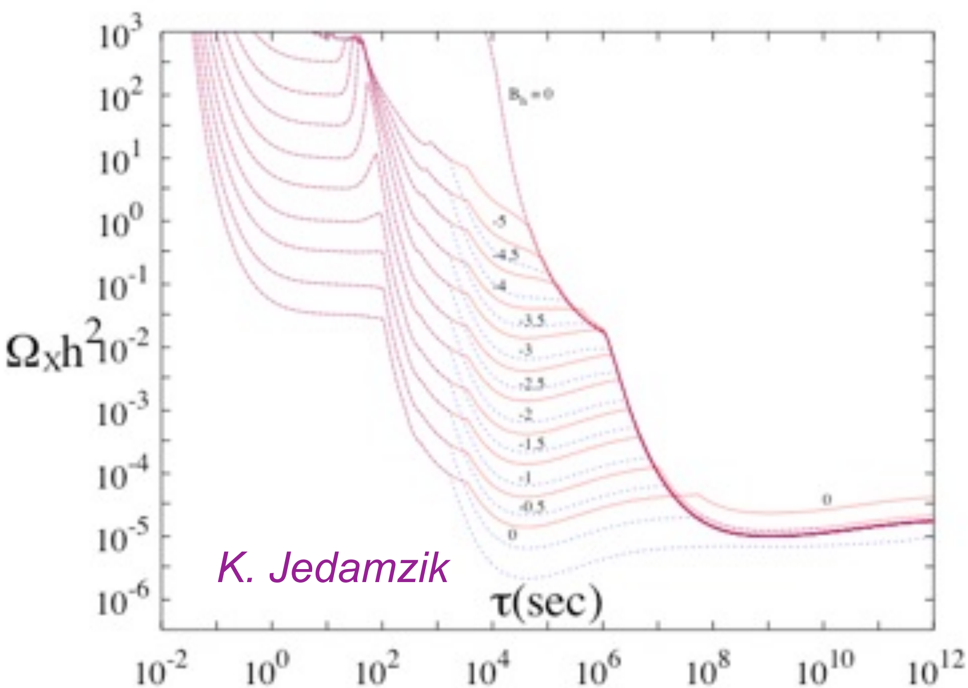


In the vanishing B_h limit,
one recovers e.m. constraints
for the convolution of the bounds



Who ordered these particles decaying @ BBN?

- One possibility is to play with phase-space and/or gravitationally suppressed interactions

Alternatively,

- The long lifetime of particles in the “dark sector” might be due to very tiny breaking of some symmetry, just like the proton is stable due to “accidental” baryon number conservation.

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What if same GUT operators mediating "rare" p-decays are involved in the decays of dark sector particles? Naïve estimate for the lifetime:

$$\tau_{DM} \approx 8\pi \frac{M_{GUT}^2}{m_{DM}^3} \approx 7\ s \left(\frac{TeV}{m_{DM}}\right)^3 \left(\frac{M_{GUT}}{2\times 10^{16}\,GeV}\right)^2$$

From Dim 5 Operator
Related to metastable particles decaying at BBN epoch & solution to "Lithium problems"?

$$\tau_{DM} \approx 8\pi \frac{M_{GUT}^4}{m_{DM}^5} \approx 3\times 10^{27}\, s \left(\frac{TeV}{m_{DM}}\right)^5 \left(\frac{M_{GUT}}{2\times 10^{16}\,GeV}\right)^4$$

From Dim 6 Operator
Observable consequences in cosmic rays in the halo?

Further considerations along these lines e.g. in: *Arvanitaki, Dimopoulos, Dubovsky, et al. arXiv:0812.2075*

Decay from inflation: an opportunity for heavier DM

From inflaton decay, into DM or into particles cascading and decaying into DM (and typically for low reheating)

$$n_X|_{T_{\rm RH}} = {\rm Br}(\phi \to X)\, n_\phi|_{T_{\rm RH}}$$

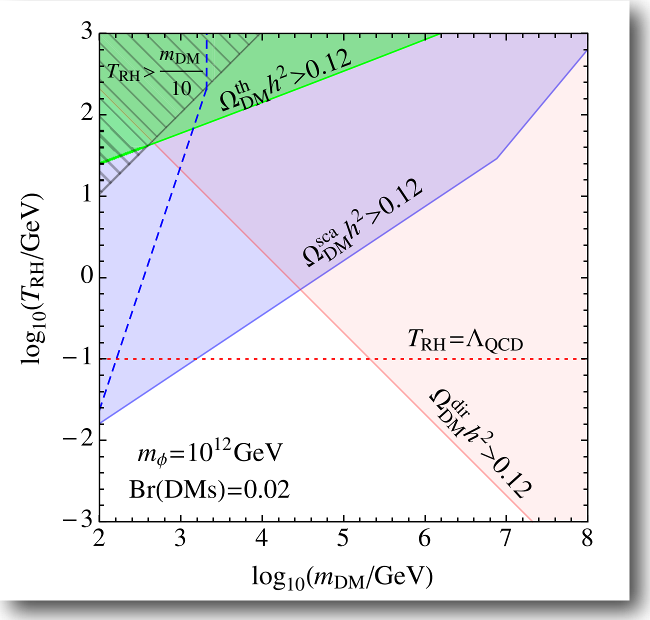
$$\left.\frac{n_X}{s}\right|_{\rm now} = T_{\rm RH}\left.\frac{3\,n_X}{4\,\rho_\phi}\right|_{T_{\rm RH}} \simeq \frac{3\,T_{\rm RH}}{4\,m_\phi}{\rm Br}(\phi\to X)$$

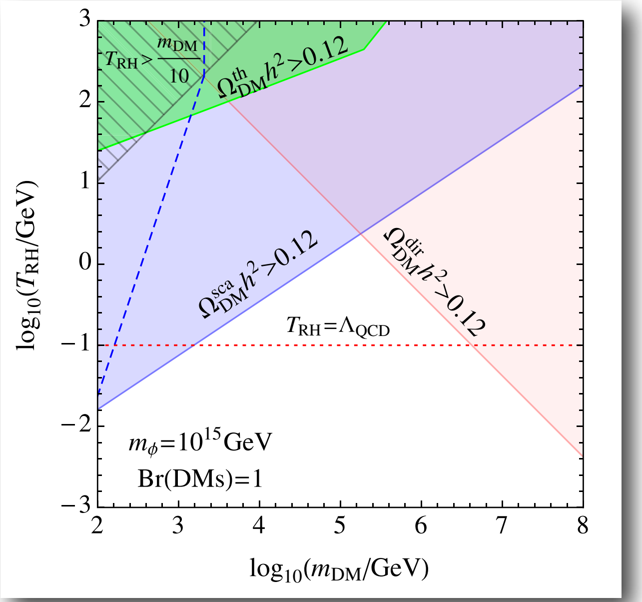
or, accounting from indirect production (via cascade and decay products of inflaton decays)

$$\left.\frac{n_X}{s}\right|_{\rm now} \simeq \frac{3\,T_{\rm RH}}{4\,m_\phi}\sum_i {\rm Br}(\phi \to i)\mu_i$$

One viable way, for instance, to achieve “heavy” (e.g. PeV) DM candidates, with very suppressed interactions

K. Harigaya, M. Kawasaki, K. Mukaida and M.Yamada, “Dark Matter Production in Late Time Reheating," PRD 89, 083532 (2014) [1402.2846]



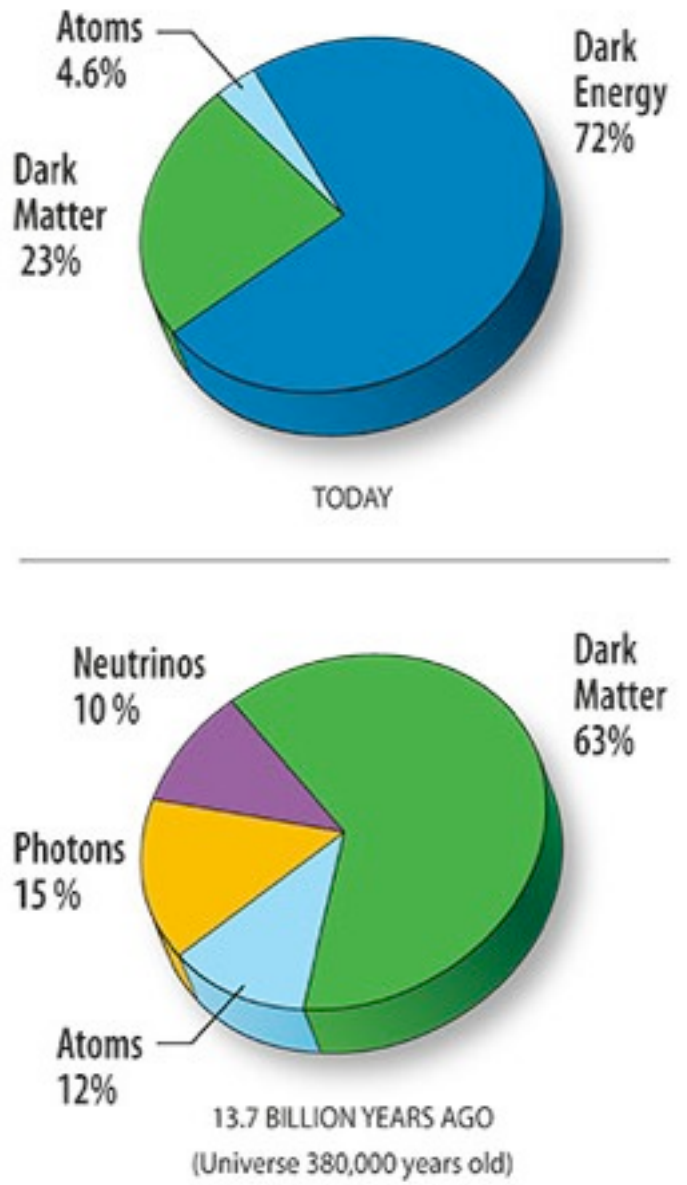


Asymmetric Dark Matter

The “Pie Chart” problems

You have perhaps heard saying that we do not know what 95% of the Universe is made of (because of DM and DE)

The situation is much worse than that: if you did the exercise I suggested yesterday, even baryons we do not know where they come from (Neutrinos we know better, but we do not know their mass/ exact contribution)



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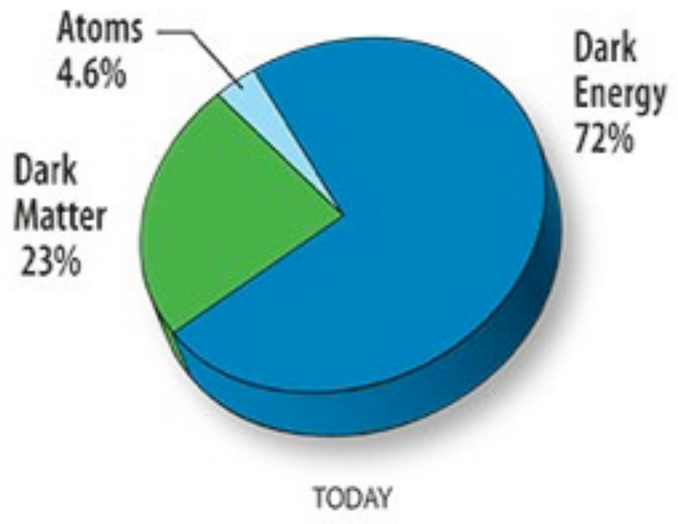
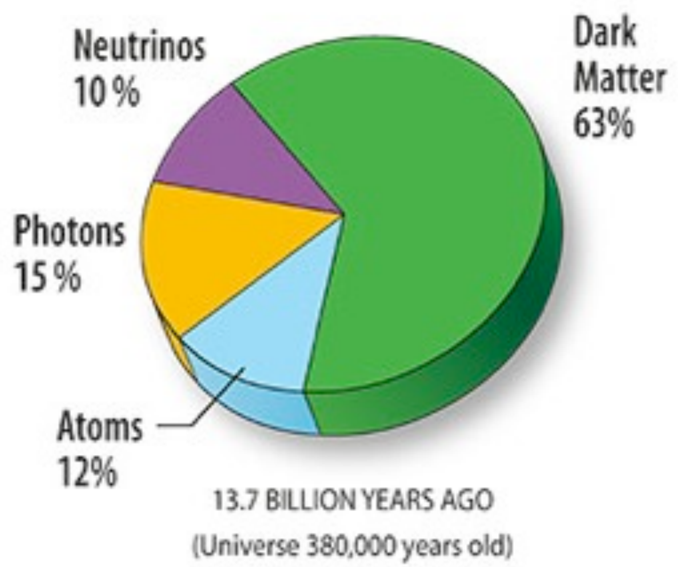


The (yet unknown) physical mechanism behind the observed abundance of protons (and the matter-antimatter asymmetry) is called **Baryogenesis**

Apart for "theoretical elegance", it seems plausible that this is dynamically generated, not some initial condition (should have been diluted away via inflation)



Sakharov conditions

It was realized that one can generate baryon asymmetry dynamically, provided that

- B should be violated
- C & CP should be violated
- departure from thermal equilibrium is needed

Remarkably, these conditions are met in the SM as well... but (to cut a long story short) the EW transition provides a too weak violation of 3rd condition (second order!) to be useful.

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The two main classes are:

- **EW baryogenesis:** in extended models of TeV scale physics (SUSY or not), the problem mentioned with the SM could be overcome. <u>Appeal:</u> could be tested at colliders. <u>Disadvantage:</u> at the moment, they're somewhat "ad hoc"

- **Leptogenesis:** B is in fact produced starting from L asymmetry, then reshuffled via sphalerons (violating B+L but conserving B-L in the SM at T~100 GeV). <u>Appeal</u>: L asymmetry could be linked to neutrino mass generation (e.g. heavy neutrino mass term violates L by 2 units!). <u>Disadvantage:</u> usually happens at high-scales, involving parameters that are in large part not accessible to measurements

Could something similar happen for DM?

Of course! A few remarks

1) Basically, all classes of models considered for baryogenesis can be considered (actually more, since more freedom in DM sector...): ADM

2) Technically, one needs to use a generalization of the Boltzmann equations we wrote (both particles and antiparticles should be followed, care with Matrix elements since C, CP symmetries are violated...), but no major difference.

3) Should make sure that the symmetric part of relic abundance, if relevant, is annihilated away: this typically requires large couplings and/or with light "dark" particles, hence the characteristic link of these models with **"strongly interacting"** DM and/or **"dark radiation/dark forces"**. Usually these ones (or decay via effective operators, like for p-decay) are the handles that can lead to constraints.

No time for in-depth review, see

K. M. Zurek, "Asymmetric Dark Matter: Theories, Signatures, and Constraints," Phys. Rept. 537, 91 (2014) [arXiv:1308.0338 [hep-ph]].

However, one point worth noting about 1):

would be theoretically nice to invoke a "co-genesis" of DM and baryon asymmetry. Not only for theoretical elegance, also to explain a "coincidence"...

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- The relation $\dfrac{\Omega_{dm}}{\Omega_b} \simeq 5$ perhaps suggestive of a common origin?

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- Introduce asymmetry in DM number density (must not coincide with its antiparticle)

$$n_{dm} - \bar{n}_{dm} \neq 0$$

- Use dynamics to relate it to the baryon asymmetry

$$n_{dm} - \bar{n}_{dm} \propto n_b - \bar{n}_b$$

- Which generically allows one to write (κ is model dependent!)

$$\frac{\Omega_{dm}}{\Omega_b} = \frac{|n_{dm} - \bar{n}_{dm}|\, m_{dm}}{n_b\, m_b} \simeq \kappa \frac{m_{dm}}{m_N}$$

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Caveat: should find a link between QCD and whatever new physics is responsible for DM mass... it's not only about similar number densities!

Scalar fields in the early universe

Scalar Field in arbitrary (curved) spacetime

Generically, we have for a scalar field in a generic background (if no other coupling but with gravity or self-coupling is present)

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{1}{2} g^{\alpha\beta} \partial_\alpha X \partial_\beta X - V(X) - \frac{\xi}{2} R\, X^2 \right] \right\}$$

where ξ is a dimensionless parameter generically needed for consistency in QFT in curved spacetime, with *ξ=0* corresponding to *minimal coupling* and *ξ=1/6* to the *conformal one*. ***R*** is the Ricci scalar associated to the metric $g_{\mu\nu}$ (*g* being its determinant).

The expression in curly brackets is the Lagrangian density. The corresponding EOM write

$$\frac{\partial \mathcal{L}}{\partial X} - \partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu X)} = \partial_\alpha (\sqrt{-g}\, g^{\alpha\beta} \partial_\beta X) + \frac{\partial V}{\partial X} + \sqrt{-g}\, \xi\, R\, X = 0$$

Ener.-mom. tensor in arbitrary (curved) spacetime

It can be shown that for consistency one needs

$$T_{\alpha\beta} = \frac{2}{\sqrt{-g}} \frac{\delta S}{\delta g^{\alpha\beta}}$$

which for our scalar field writes

$$T_{\alpha\beta} = \partial_\alpha X \partial_\beta X - g_{\alpha\beta} \left[\frac{g^{\mu\nu}}{2} \partial_\mu X \partial_\nu X - V(X) \right]$$

whose energy density is for instance given by T_{00}
(note the “kinetic plus potential energy” structure)

Scalar Field in FLRW

$$ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2$$

(flat FLRW for simplicity)

The action writes

$$S = \int dt \int d^3\mathbf{x} \frac{a^3}{2} \left[\dot{X}^2 - \frac{(\nabla X)^2}{a^2} - 2V(X) - \xi R X^2 \right]$$

In the so-called *conformal coordinates*:

$$ds^2 = a(t)^2 [d\eta^2 - d\mathbf{x}^2]$$

which, apart for the rescaling, is equivalent to the Minkowski one, where we introduced the conformal time

$$\eta = \int_{t_0}^{t} \frac{dt'}{a(t')}$$

$$g_{\alpha\beta} = a^2 \eta_{\alpha\beta} \qquad g^{\alpha\beta} = a^{-2} \eta^{\alpha\beta} \qquad \sqrt{-g} = a^4$$

EOM in conformal coordinates

For simplicity, consider
free massive particle potential

$$V = M_X^2 X^2/2$$

and introduce the auxiliary field

$$\chi \equiv a\, X$$

The EOM write

$$\chi'' - \nabla^2\chi + \left[M_X^2 a^2 + (6\xi - 1)\frac{a''}{a}\right]\chi = 0$$

This is a “Klein-Gordon" like equation, with a “time-dependent” mass (also contributed in general by the curvature, but for the case where ξ=*1/6*). This equation is at the basis of a couple of “paradigmatic” examples of dark matter production mechanisms.

Misalignment mechanism

DM from field “misalignement”: classical solution

A long story short

- **(Pseudo)scalar field with a random initial value in the early universe**

- **At a timescale set by its mass, the fields starts oscillations around the minimum of its potential (amplitude given by the initial value)**

- **Provided that the damping (i.e. via decays) is negligible, the field energy density evolves as dark matter**

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To see that, let us rewrite the previous equation in proper coordinates

$$a\,X'' + 2a'\,X' - a^2\nabla^2 X + \left[M_X^2 a^3 + 6\xi a''\right] X = 0$$

taking into account

$$a' = a\,\dot{a} \qquad X' = a\,\dot{X} \qquad X'' = a\,\dot{a}\dot{X} + a^2\,\ddot{X}$$

yields

$$a^3[\ddot{X} + 3H\,\dot{X} + M_X^2 X] = 0$$

ξ=0 for simplicity

Heuristic solutions: Early times

$$a^3[\ddot{X} + 3H\,\dot{X} + M_X^2 X] = 0$$

if mass term negligible wrt expansion rate (i.e. at sufficiently high temperatures)

$$H^2 \gg M_X^2$$

by setting $\dot{X} = W$ the equation reduces approximately to

$$\dot{W} + 3H\,W \simeq 0$$

whose solution is

$$X(t) = X_1 + W_1 \int_{t_1}^{t} \left(\frac{a_1}{a}\right)^3 dt$$

in general dominated by the constant term (barring fine tuning). The field “gets frozen” due to the high expansion rate, which acts like friction (overdamping).

Heuristic solutions: Late time

$$a^3[\ddot{X} + 3H\,\dot{X} + M_X^2 X] = 0$$

If mass term large wrt expansion rate
(i.e. at sufficiently low temperatures) $H^2 \ll M_X^2$

the above EOM suggest that the field starts to oscillate (harmonic oscillation EOM), on the top of which there's a "slow" evolution driven by *H*

In fact, consider the energy density $$\rho = \frac{1}{2}(\dot{X}^2 + M_X^2 X^2)$$

Its evolution given by $$\dot{\rho} = \dot{X}(\ddot{X} + M_X^2 X) = -3\,H\,\dot{X}^2$$

Averaging over times much longer than M_X^{-1} but shorter than H^{-1} $$\langle\dot{\rho}\rangle = -3\,H\,\langle\dot{X}^2\rangle$$

$$\langle\dot{X}^2\rangle = 2\langle K\rangle = \langle K\rangle + \langle V\rangle$$

valid for harmonic oscillator

Heuristic solutions: Late time, cont'd

$$\langle\dot\rho\rangle = -3\,H\,\langle\rho\rangle \Rightarrow \langle\rho\rangle = \langle\rho\rangle_1 \left(\frac{a_1}{a}\right)^3$$

The average energy density evolves as the one for cold dark matter!

This heuristic derivation can be comforted by a more accurate solution which can be obtained in the so-called WBK approximation. Let us seek a solution of type

$$X = A\exp\left(i\phi\right)$$

Φ much faster variations than A

$$\dot X \simeq X\,i\dot\phi\,, \quad \ddot X \simeq X\left(i\ddot\phi - \dot\phi^2\right)$$

$$i\ddot\phi + 3Hi\dot\phi - \dot\phi^2 + M_X^2 = 0$$

Leading term is $-\dot\phi^2 + M_X^2 = 0 \Rightarrow \phi = M_X t + \mathrm{const.}$

Consistent, since $\ddot\phi \simeq= -3Hi\dot\phi \simeq -3H\,M_X\,, \quad \Rightarrow \dfrac{\ddot\phi}{\dot\phi^2} \sim \mathcal{O}\left(\dfrac{H}{M_X}\right)$

WKB solution at late time

Armed with the solution we just found, we now look for a solution $$X = A \exp\left(iM_X\, t\right)$$

$$\dot{X} \simeq X\left(\frac{\dot{A}}{A} + iM_X\right)X\,, \quad \ddot{X} \simeq X\left[\frac{\ddot{A}}{A} - \frac{\dot{A}^2}{A^2} + \left(\frac{\dot{A}}{A} + iM_X\right)^2\right].$$

$$\frac{\ddot{A}}{A} + 2iM_X\frac{\dot{A}}{A} + 3H\left(\frac{\dot{A}}{A} + iM_X\right) = 0 \Rightarrow \frac{\dot{A}}{A} \simeq -\frac{3}{2}\frac{\dot{a}}{a}$$

where the last step made use of the fact that by consistency, we know that *A'/A*<< M_X since the evolution of *A* is slow, hence we can drop the second derivative term and neglect the terms not containing M_X.

$$A \simeq A_*\left(\frac{a_*}{a}\right)^{3/2}$$

$$\boxed{X \simeq A_*\left(\frac{a_*}{a}\right)^{3/2} e^{iM_X\, t}}$$

DM from misalignment

$$\rho_0 = M_X\, n_X^* \left(\frac{a_*}{a}\right)^3 \simeq M_X \frac{\rho_*}{M_X} \left(\frac{a_*}{a}\right)^3 \simeq M_X^2 A_*^2 \left(\frac{a_*}{a_0}\right)^3$$

$$\downarrow$$

$$\rho_0 \simeq M_X^2 A_*^2 \frac{g_S(T_0) T_0^3}{g_S(T_*) T_*^3}$$

$$\downarrow$$

where T* is given roughly by the condition 3H(T*)=M_X, which clearly yields (in the radiation era) T*~$(M_{Pl}\, M_X)^{1/2}$. The scaling is thus

$$\rho_0 \propto M_X^{1/2} A_*^2\,,$$

$$\rho_0 \sim 10^{-5} \mathrm{GeV\, cm^{-3}} \sqrt{\frac{M_X}{\mathrm{eV}}} \left(\frac{A_*}{10^{12}\,\mathrm{GeV}}\right)^2 , \Leftrightarrow \Omega_X h^2 \sim 0.1 \sqrt{\frac{M_X}{100\,\mathrm{meV}}} \left(\frac{A_*}{10^{12}\,\mathrm{GeV}}\right)^2$$

Note: light particles + large values for the initial field displacement needed

Caveats for the axion case: i) mass “time dependent” ii) competing mechanisms exist

More possibilities from GUT & symmetry breaking

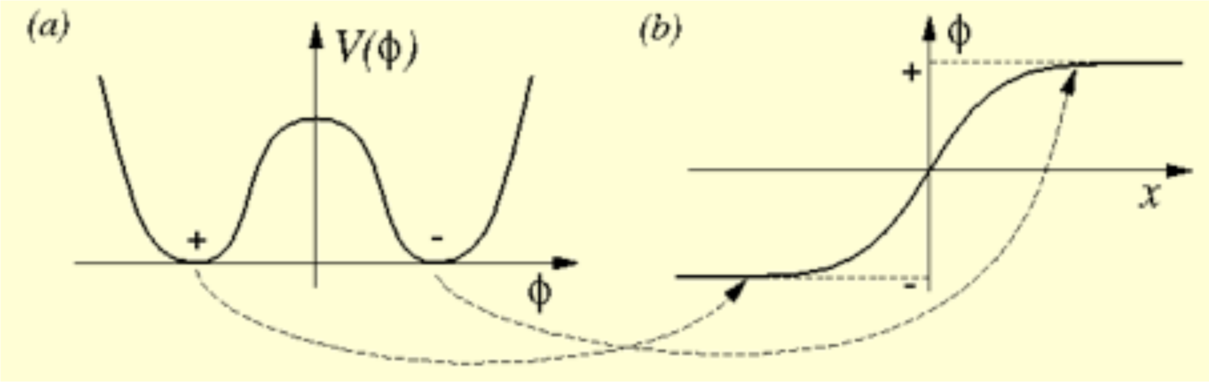
A long story short

1. As a consequence of phase transitions in the Early Universe, some energy can get "stored" into ***topological defects***. In most models where this happens it' is a lethal blow

2. When the defects in question are cosmic strings, it can be beneficial, turning into a potential (complementary) seed of structure or at the origin of DM, via e.g. string decay byproduct

Example 1:
take a real scalar field which in the broken phase has potential

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - \eta^2)^2$$



By settling at either

$$\langle\phi\rangle = +\sigma$$

$$\langle\phi\rangle = -\sigma$$

the vacuum spontaneously breaks the Z_2 symmetry (in general, DW arise when disconnected vacua are possible). Since the fields picks up one or another value in causally disconnected regions of space, 2-D "domain walls" separate them.

Hitting the Domain Wall problem

Gradient of the field across the wall (ξ=coherence length) associated to the energy density per unit area, Σ.

Since $\rho = \frac{1}{2}(\partial\phi_i)^2 + V$ the sum of kinetic and potential energy write

$$\Sigma \sim \rho\xi \sim \left(\frac{\eta}{\xi}\right)^2 \xi + \lambda\eta^4\xi$$ minimized for $$\xi \sim \lambda^{-1/2}\eta^{-1}$$

i.e. $$\Sigma \sim \lambda^{1/2}\eta^3$$

On a purely dimensional ground, Σ appears intolerably high (e.g. for the isotropy of the CMB). Even with an average of 1 domain wall per Hubble length, the mass due to this is

$$M_W \sim \Sigma H_0^{-2} \ll \rho_c H_0^{-3} \sim M_{\rm Pl} H_0^{-1}$$

i.e. $$\eta \lesssim 10\,\lambda^{-1/6}\mathrm{MeV}$$ Ridiculously small compared to typical expectations in BSM extensions!

Similar problems arise for most of the other kinds of topological defects, with one notable exception: strings.

Cosmic Strings

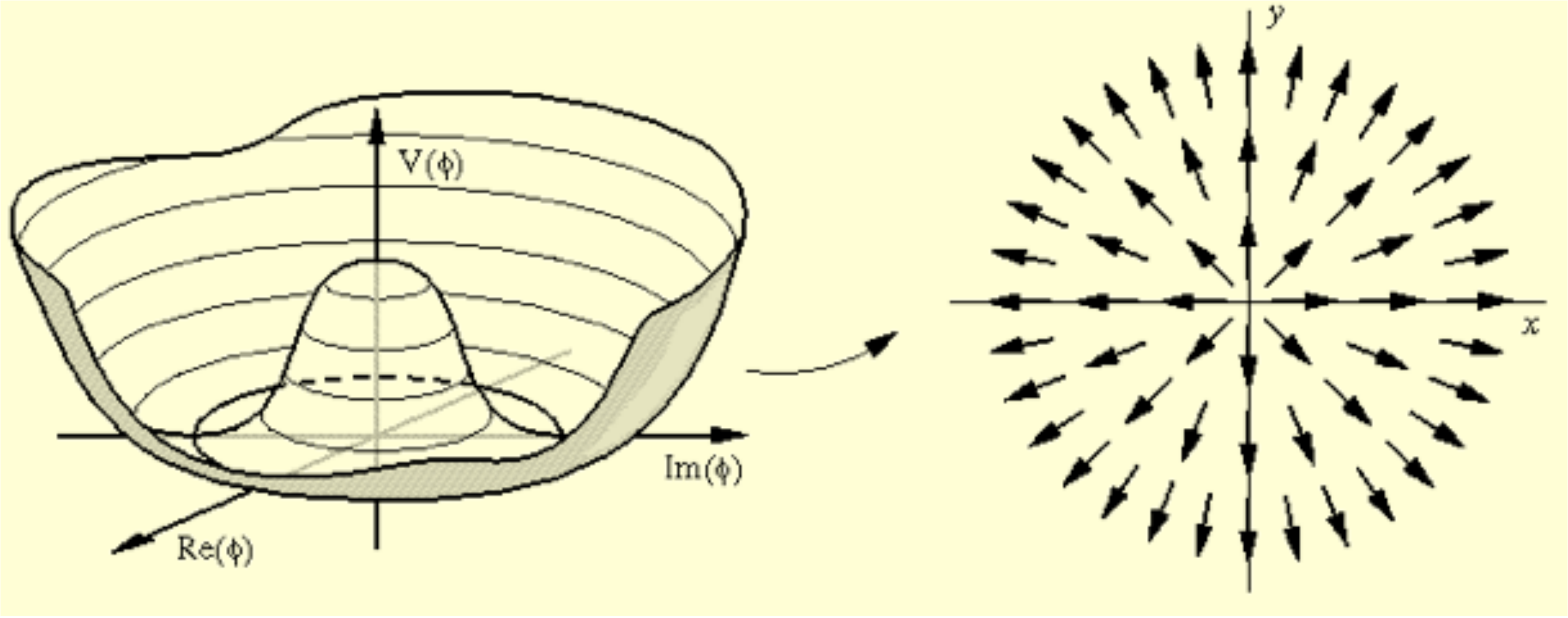
Example 2: Take now the complex field

$$V(\phi) = \frac{\lambda}{4}(\phi^* \phi - \eta^2)$$

Invariant under $\phi \to e^{i\chi}\phi$

In the vacuum $|\phi| = \eta$

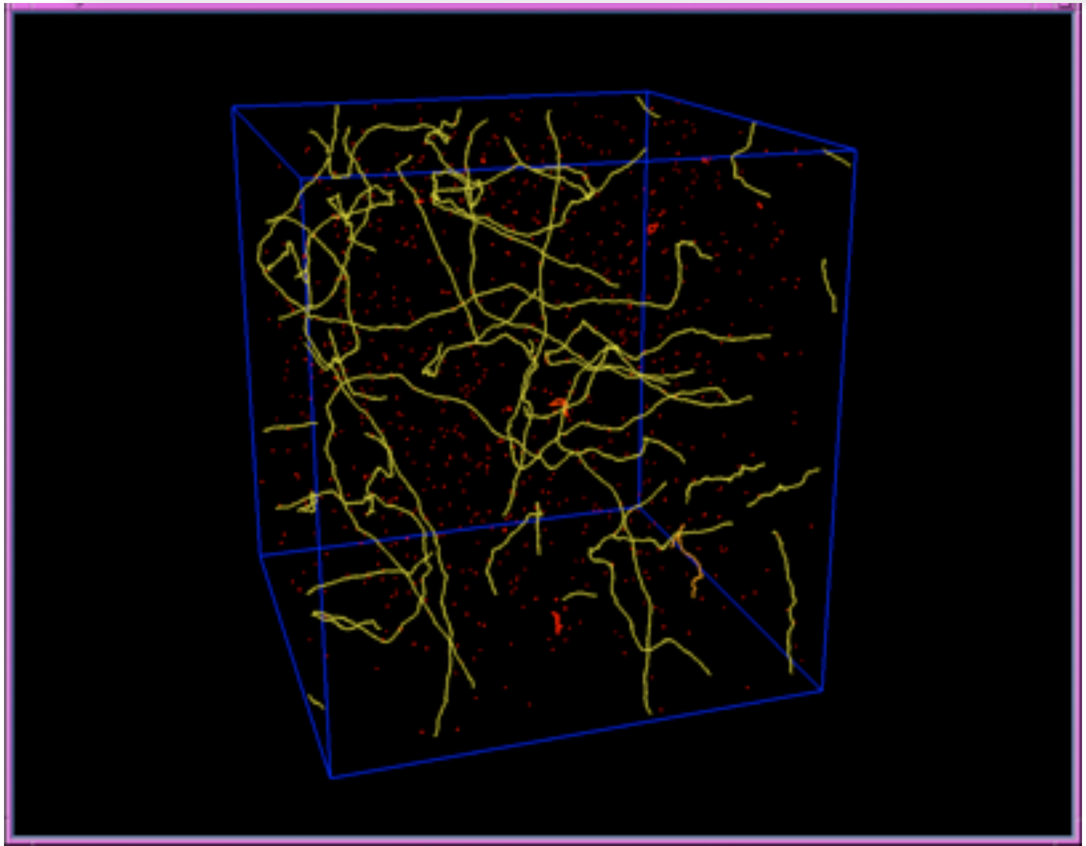
but it spontaneously breaks the invariance, by picking one phase. Now, inhomogeneous phases "cost" energy because of the gradient. Generically, there will be circuits around which the phases changes by 2π, which corresponds to a defect (|Φ| goes to zero over a range ξ)



Cosmic Strings

one finds again $\xi \sim \lambda^{-1/2}\eta^{-1}$

The resulting network of infinite and closed loop strings would be a similar catastrophe as the DW, were not for two effects:
i) intercommutation of intersecting string segment, that get chopped into smaller loops
ii) string loops decay away by emission of GW (at least), maybe something else...
"cosmologically acceptable" scaling behaviours are found.



- Can contribute to source GW
- contribute to seed structures (specific CMB signatures)
- contribute to generate DM
- have peculiar lensing features

The Strong CP problem

$$L_{CP} = \theta \frac{N_f g^2}{32\pi^2} Tr(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Standard QCD Lagrangian contains a CP, P & T violating term*

$$\theta \rightarrow \bar{\theta} = \theta - Arg(\det M_q)$$

Due to non-trivial topological structure of QCD vacuum, $0<\theta_{QCD}<2\pi$

Phase "rotated away" from quark mass matrix (complex couplings in Higgs sector)

$\bar{\theta}$ induces a neutron EDM violating experimental limits unless $\bar{\theta}<10^{-10}$

*despite being a total derivative, there are topologically inequivalent gauge configuration at infinity that make this term physical

The Strong CP problem

$$L_{CP} = \theta \frac{N_f g^2}{32\pi^2} Tr(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Standard QCD Lagrangian contains a CP, P & T violating term*

$$\theta \rightarrow \bar{\theta} = \theta - Arg(\det M_q)$$

Due to non-trivial topological structure of QCD vacuum, $0<\theta_{QCD}<2\pi$

Phase "rotated away" from quark mass matrix (complex couplings in Higgs sector)

$\bar{\theta}$ induces a neutron EDM violating experimental limits unless $\bar{\theta}<10^{-10}$

One way to see this is to "remove" the θ–term and replace it via the "mass-term"

$$i\bar{\theta} \frac{m_u m_d}{m_u + m_d}(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d) \quad (2 \ \ flavours)$$

Again, one of the nasty "fine-tuning" problems of the SM asking for an explanation (like hierarchy, cosmological constant?…)

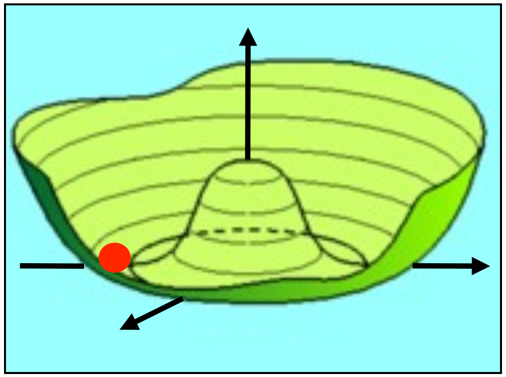
***despite being a total derivative, there are topologically inequivalent gauge configuration at infinity that make this term physical**

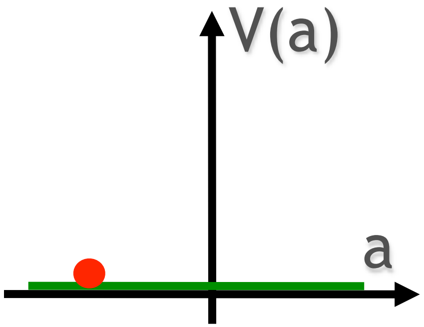
Axions: $\theta \rightarrow a/f_a$

- One cannot solve the problem with known symmetries. Peccei, Quinn ‘77 proposed to solve it by a new global, axial $U(1)_{PQ}$ symmetry (1977), requiring a second Higgs doublet. This symmetry is spontaneously broken at a scale f_a
- Axions are the corresponding Nambu-Goldstone mode (Weinberg,Wilczek ‘78)

At $E \approx f_a$

- $U_{PQ}(1)$ spontaneously broken
- The axion is the m=0 (Goldstone) mode settling at some value “θ” in the “Mexican hat”





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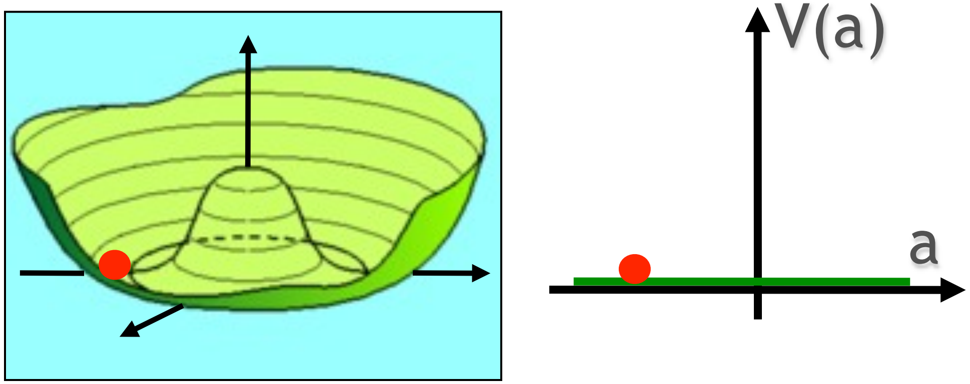
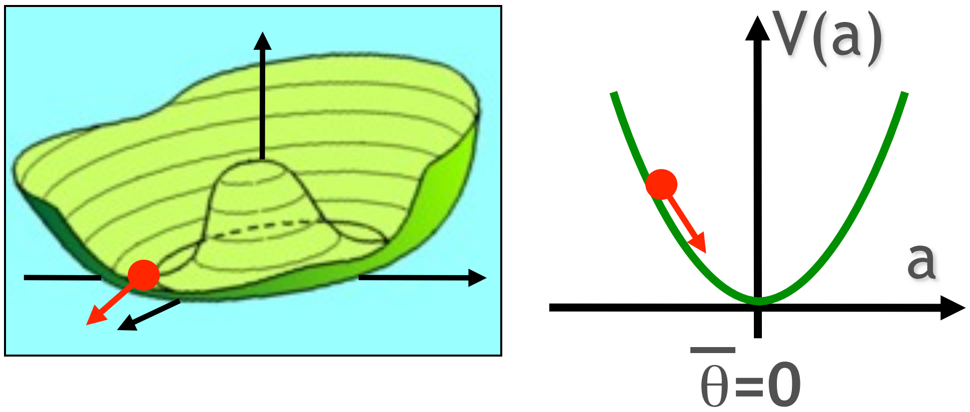


At $E \approx \Lambda_{QCD} \ll f_a$

- $U_{PQ}(1)$ explicitly broken by chiral SSB & the Mexican hat tilts
- In the potential induced by L_{CP} the (now-massive) $a(x)$ dynamically restores the CP-conserving minimum



Axions as cold dark matter

- To bypass possible problems from topological defects, one possibility is to require that inflation takes place after $U(1)_{PQ}$ breaking (but alternatives exist)

- When $T \lesssim \Lambda_{QCD}$ axions the potential tilts, and the energy stored in the "offset" position of θ_i converts into "coherent oscillations of the a field" → behaves as non-relativistic, cold gas of axions. Abundance given by

$$\Omega_{a,\mathrm{mis}}\, h^2 \simeq 0.1\,\bar{\theta}^2 \left(\frac{\Lambda_{\mathrm{QCD}}}{200\,\mathrm{MeV}}\right)^{-0.7} \left(\frac{m_a}{10\,\mu\mathrm{eV}}\right)^{-1.18}$$

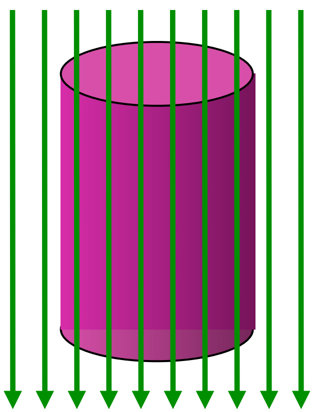
- *Note*: Dark matter fraction not calculable from first principles: random number chosen by process of spontaneous symmetry breaking (→ anthropic arguments?)

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation. Strong CMBR bounds on isocurvature fluctuations. Scale of inflation required to be $\lesssim 10^{13}$ GeV *Beltrán, García-Bellido & Lesgourgues hep-ph/0606107*

Haloscopes: searches for Cold Dark Matter Axions

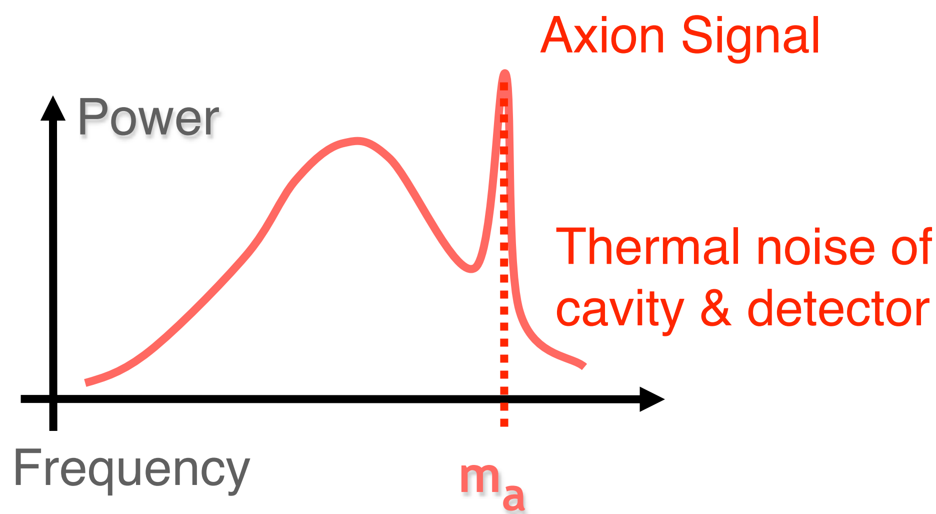
m_a = 1-1000 μeV → Resonance at Microwave Energies (1 GHz ≈ 4 μeV)

$v_a \approx 10^{-3}$ c → $E_a \approx (1 \pm 10^{-6})\, m_a$ → very, very narrow!



$B_{ext} \approx 8$ Tesla

μwave Resonator
$Q \approx 10^5$, overcomes
momentum mismatch



Currently pursued by ADMX in the US

Gravitational production

Basic Idea

A long story short

- Spontaneous particle creation generically takes place in time-dependent gravitational backgrounds!

- We saw that a massive scalar field in FLRW metric is equivalent to an auxiliary scalar field in Minkowski with a “time-dependent mass”. Loosely speaking, this allows for particle production at the expense of gravity.

Let’s start from the EOM we derived earlier on

$$\chi'' - \nabla^2 \chi + \left[M_X^2 a^2 + (6\xi - 1)\frac{a''}{a} \right] \chi = 0$$

Its spatial dependence can be handled simply via the usual Fourier expansion, while time dependence requires some care...

Mode expansion

$$\chi'' - \nabla^2\chi + \left[M_X^2 a^2 + (6\xi - 1)\frac{a''}{a}\right]\chi = 0$$

$$\chi(\vec{x},\eta) = \int \frac{d^3k}{(2\pi)^{3/2}} \left[a_k h_k(\eta) e^{i\vec{k}\cdot\vec{x}} + a_k^\dagger h_k^*(\eta) e^{-i\vec{k}\cdot\vec{x}}\right].$$

where a_k and $a_k^\dagger$ are creation and annihilation operators, and $h_k(\eta)$ are mode functions that satisfy:

- the normalization condition $h_k h_k'^* - h_k' h_k^* = i$,
- the mode equation

$$h_k''(\eta) + \omega_k^2(\eta)\, h_k(\eta) = 0,$$

where

$$\omega_k^2(\eta) = k^2 + M_X^2 a^2 + (6\xi - 1)\frac{a''}{a}.$$

Mode equation & interpretation

Mode equation = formally the same as EOM of harmonic oscillator with time-varying frequency $\omega_k(\eta)$.

For a given complete set of positive-frequency solutions $h_k(\eta)$, the vacuum $|0_h\rangle$ of the field X , i.e. the state with no X (or χ) particles, is defined as the state that satisfies $a_k|0_h\rangle = 0$ for all k.

For the constant frequency (ω_0) case you may be used to

$$h_k^0(\eta) = e^{-i\omega_0\eta}/(2\omega_0)^{1/2}$$

For the second order mode equation with frequency depending on time, the normalization condition is in general not sufficient to specify the positive frequency modes uniquely!

Different Vacua...

Different boundary conditions for the solutions $h_k(\eta)$ define in general different creation and annihilation operators a_k and $a_k^\dagger$, and thus in general different vacua.

For example, solutions which satisfy the condition of having only positive-frequencies in the distant past,

$$h(\eta) \sim e^{-i\omega_k^- \eta} \quad \text{for } \eta \to -\infty, \tag{1}$$

contain both positive and negative frequencies in the distant future,

$$h(\eta) \sim \alpha_k e^{-i\omega_k^+ \eta} + \beta_k e^{+i\omega_k^+ \eta} \quad \text{for } \eta \to +\infty. \tag{2}$$

where

$$\omega_k^\pm = \lim_{\eta \to \pm\infty} \omega_k(\eta)$$

Gravitational particle creation

an initial vacuum state is no longer a vacuum state at later times, i.e. "particles" are created, with a number density of particles given in terms of the Bogolubov coefficient β_k

$$n_X = \frac{1}{(2\pi a)^3} \int d^3k |\beta_k|^2 .$$

Beware: Some ambiguities in the boundary conditions/vacuum definition not dealt with here!

$\sim$15 years ago, it was shown that particles with mass comparable with the inflaton one-or better with the Hubble parameter at the end of inflation,

$$H_I \approx 10^{-6} M_{\rm Pl} \approx 10^{13}\ {\rm GeV}$$

can be produce this way and account for the DM in the Universe!

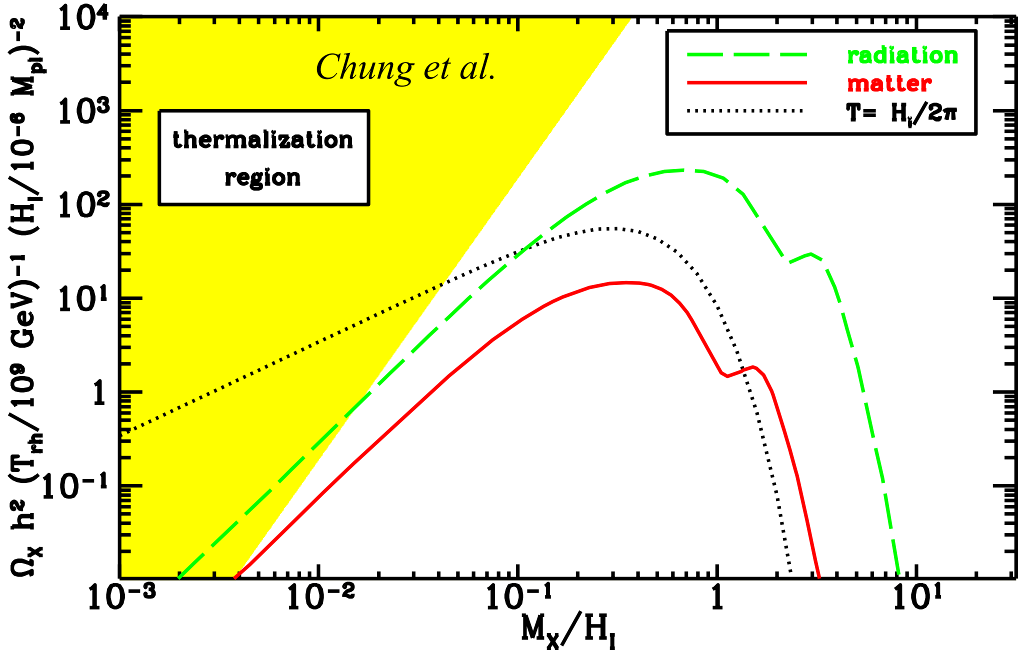
D. J. H. Chung, E. W. Kolb and A. Riotto,
``Nonthermal supermassive dark matter,'' PRL 81, 4048 (1998)
"Superheavy dark matter," PRD 59, 023501 (1999)

V. Kuzmin and I. Tkachev,
"Matter creation via vacuum fluctuations in the early universe and observed UHECR events,"
PRD 59, 123006 (1999)

Results: WIMPZILLAS!

Numerical results yield

$$\Omega_X h^2 \approx \frac{T_R}{10^8\,\mathrm{GeV}} \begin{cases} (m_X/H_I)^2\,, & m_X \ll H_I \\ \exp(-m_X/H_I)\,, & m_X \gg H_I \end{cases}$$



To be DM, must be stable or to have a lifetime of the order of the age of the universe (should avoid sizable couplings to ordinary matter or anything heavier than SM but lighter than them). Their decay products may contribute to the highest energy cosmic rays, to which they contribute with a higher-than-standard fraction of photon and neutrino events, as well as a peculiar angular pattern (e.g. enhanced towards the Galactic Center). For a mini-review see e.g.

M. Kachelriess, "The rise and fall of top-down models as main UHECR sources," arXiv:0810.3017

Conclusions

✤ We have summarized the main evidences for the existence of dark matter emphasizing the conceptually important ones of cosmological origin.

✤ We have listed the basic properties nature tells us DM has to fulfill

✤ Exciting part: **we need new physics**! Which one? Focus on mechanisms

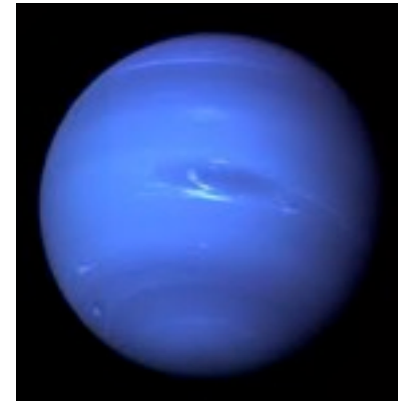
✤ We detailed the most commonly invoked mechanism to provide DM in right amount: freeze-out of a non-relativistic thermal relic & made the link with collider searches of new physics.

✤ Then we moved to more and more “exotics”: freeze-in, non-thermal production via oscillations (sterile neutrinos), production from decay (Superwimps, inflaton...), asymmetry, misalignment, gravitational production.

✤ Plenty of possibilities, but we lack till now any indication about the **right scale** of DM mass and interactions: From micro-eV axions to keV sterile neutrinos to 100 GeV WIMP neutralinos, to 10^{13} GeV WIMPzillas: ***We need experimental guidance!*** Good news: plenty of experiments ongoing...

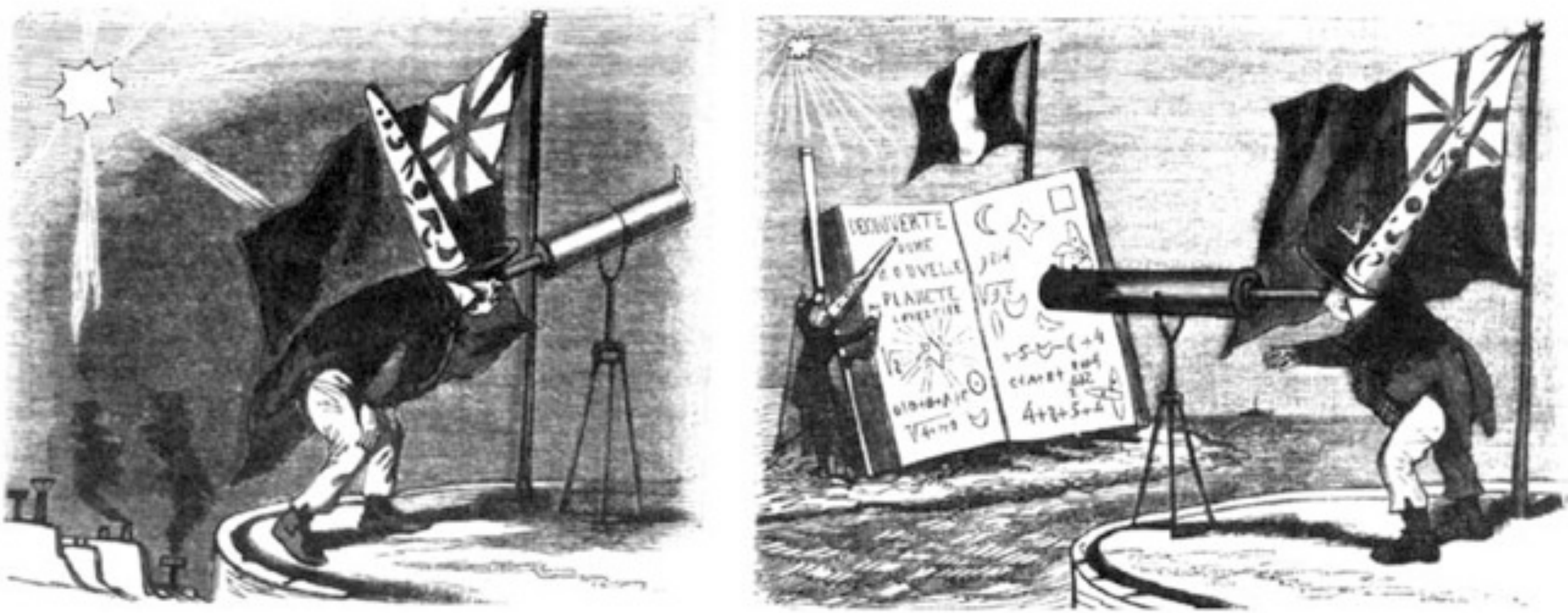
If you're pessimist... remember:

An additional "species" inferred from gravitational effects has been already identified (*electromagnetically detected*) once!



Adams (1844-45) and independently Le Verrier (1845-46) interpreted irregularities in Uranus's orbit as due to perturbation by a yet unknown planet, calculating its orbital elements "by inversion"

On September 24, 1846 Galle found that "the planet whose place you [Le Verrier] have [computed] *really exists*"

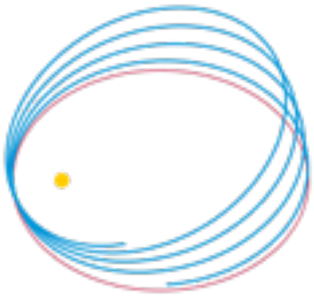


A cartoon published in France at the time of the controversy over the discovery of Neptune Adams is shown looking for it in vain and then finding it in the pages of Leverrier's book.

but ... sometimes one does not find what looked for!

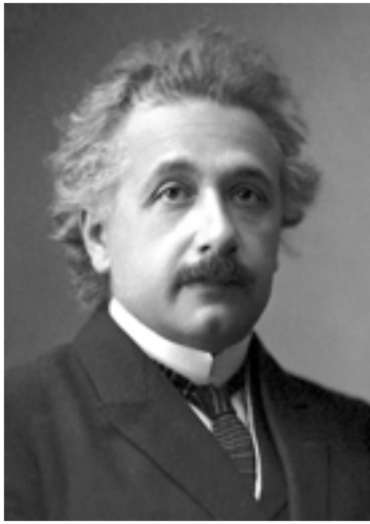
In 1859, Le Verrier analyzed the effect of gravitational perturbations of other planets on the perihelion shift of Mercury, finding a residual "anomalous" shift of 38 arcsec/century.

He re-used his "old" trick, hypothesizing that this was the result of another planet, which he named *Vulcan* whose orbital elements he inferred.



This planet was claimed to be found *several times*...

... but its existence was eventually disproved and Mercury's anomaly (re-evaluated in 43 arcsec/century) was finally explained thanks to GR effects (first major prediction that convinced A. Einstein that GR was right)



hence, so far both "Dark Matter" and "Modified Gravity" have been already discovered...
... but only after several trials & errors, hard work... and fake claims of discoveries!

Questions? Comments? If not...