Theoretical Perspectives & Frontiers of Particle Astrophysics

(Talk at 10th ICFA Seminar on Future Perspectives in High-Energy Physics)

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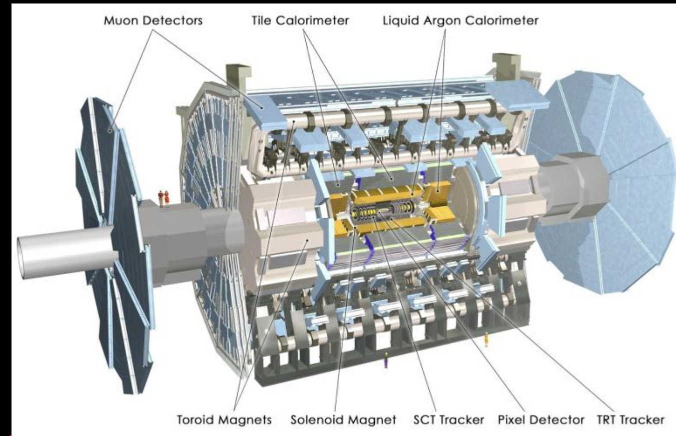
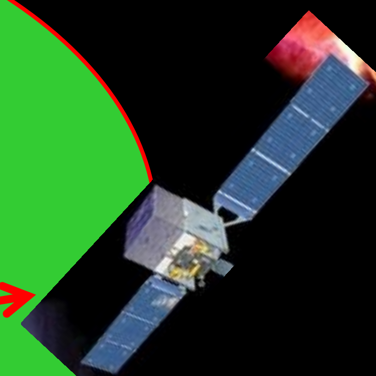
CERN, 4 October 2011



Direct production

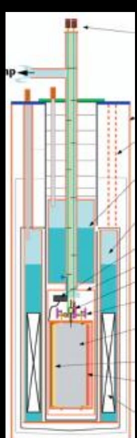
Direct detection

1. Complementarity with the assumption $\rho_{\rm WIMP}/\rho_{\rm a}$
2. Identification of dark matter
3. Interplay with astrophysics

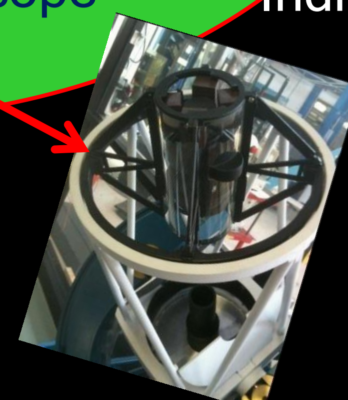


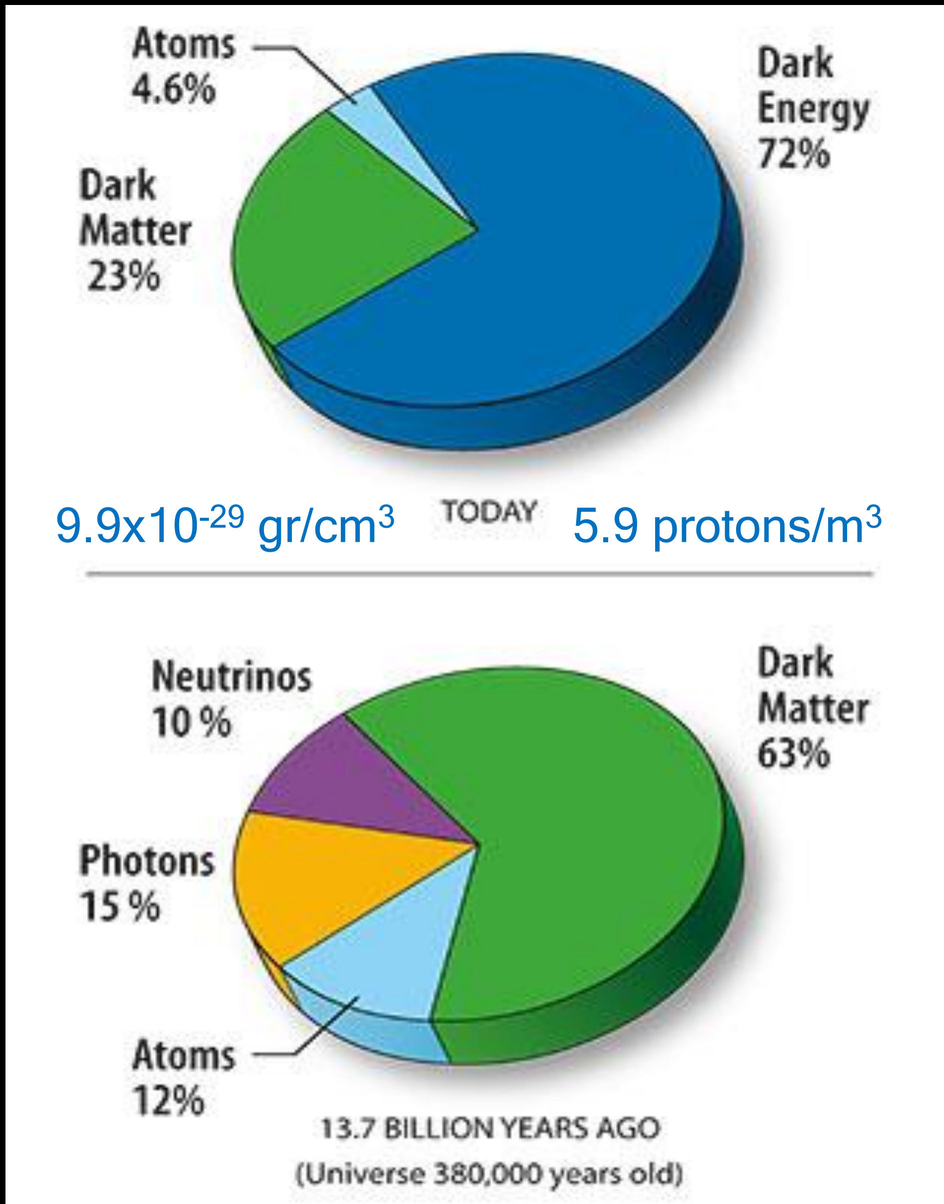
4. Dark energy telescope

Indirect detection



Axion detection



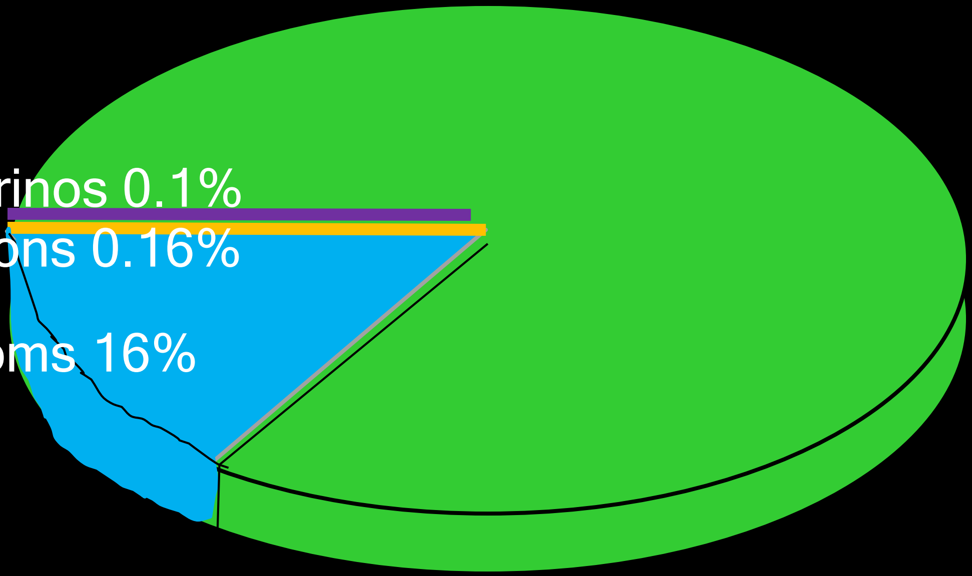


DE important now

WMAP pies

DE insignificant right after recombination. DM was the key for galaxy formation.

40 years after the Bang



DM was the key for galaxy formation. Even though atoms were significant, they were homogeniously distributed until the epoch of recombination

The effectiveness of DM in the galaxy formation is more conspicuous than this pie.

What are the candidates of DM?

1. Brown dwarfs (MACHOS)

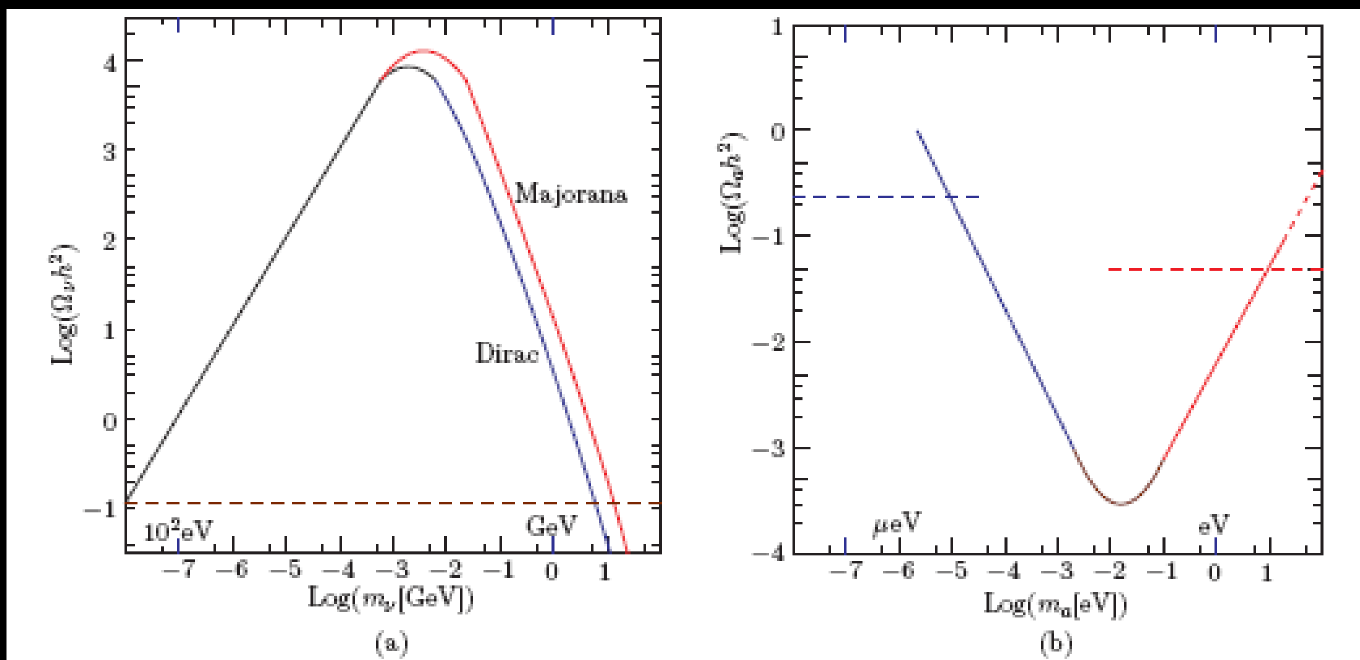
2. Supermassive black holes

3. New particles:
   WIMPS, axions, ……

Dark matter in the universe is the most looked-for particle(s) in cosmology and at LHC, and also at low temperature labs. The 100 GeV scale DM and the10-1000 micro eV axion are the most promising candidates.

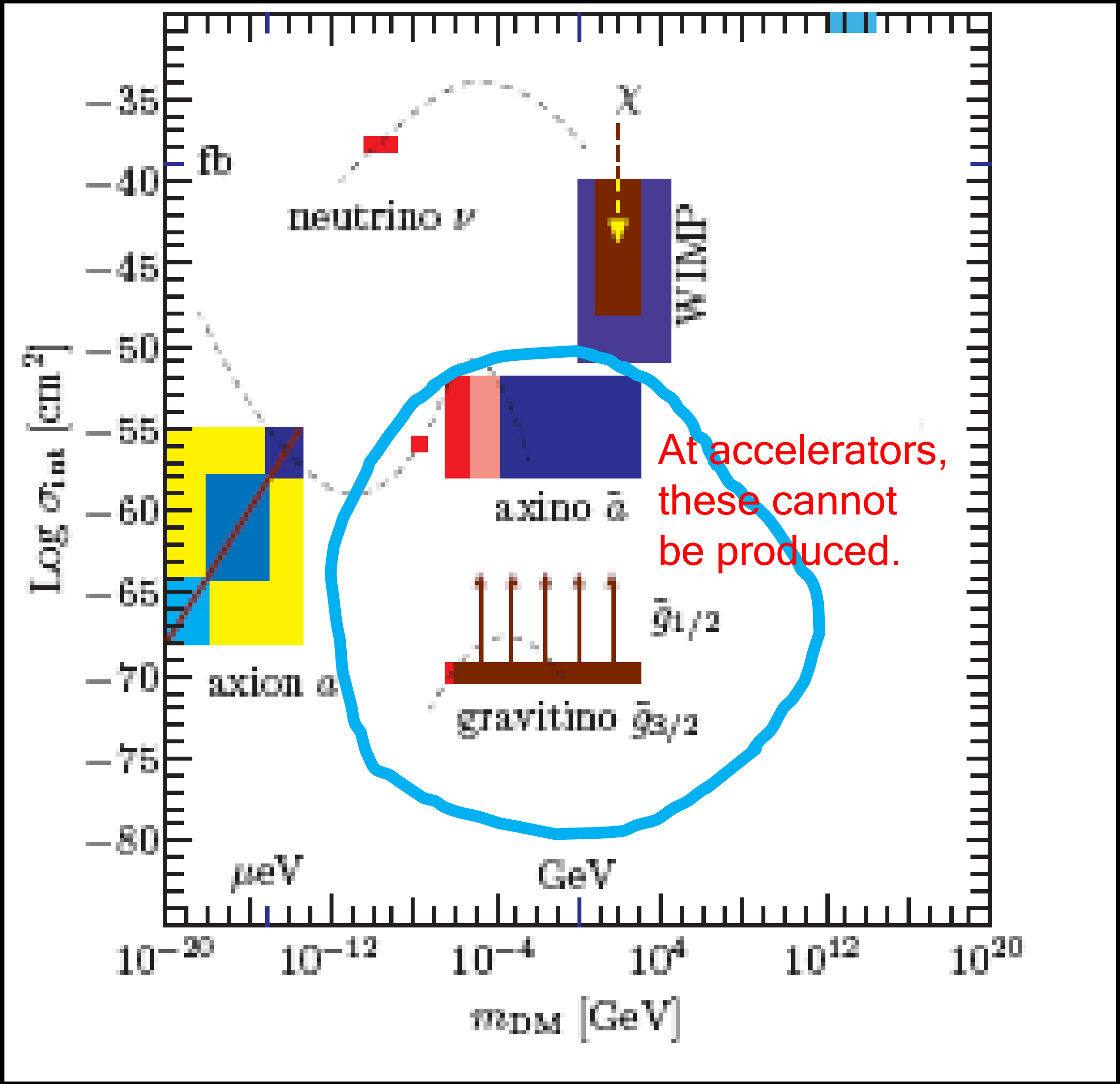
Neutrinos

Light bosons



Low E ⟷ High E

Energy frontier for new particle searches



A rough sketch of masses and cross sections. Bosonic DM with collective motion is always CDM.

Stars lose energy created by nuclear fusion (MeV order)

The energy created at the core is seen by electromagnetic waves on Earth.

If there is additional energy loss mechanisms, they can contribute to the evolution of stars. The hypothetical particles of these additional mechanisms must be very light in particle physics standard, since mostly considered process is like the Primakoff process. This gives the usual astrophysical lower bound of the axion decay constant of 10^9 GeV.

Supernova study: SN1987A

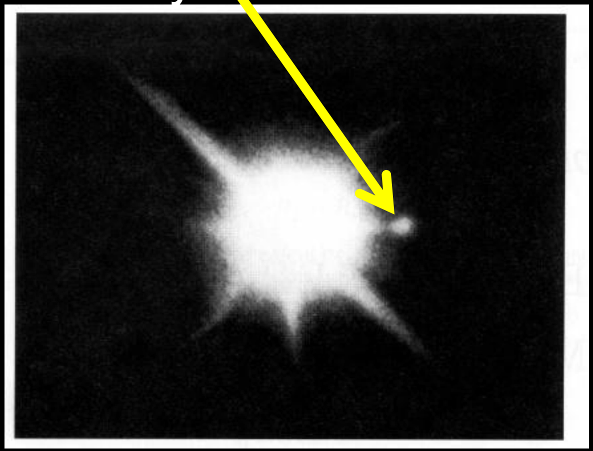
White dwarf lose energy by processes of condensed matter physics (eV order)

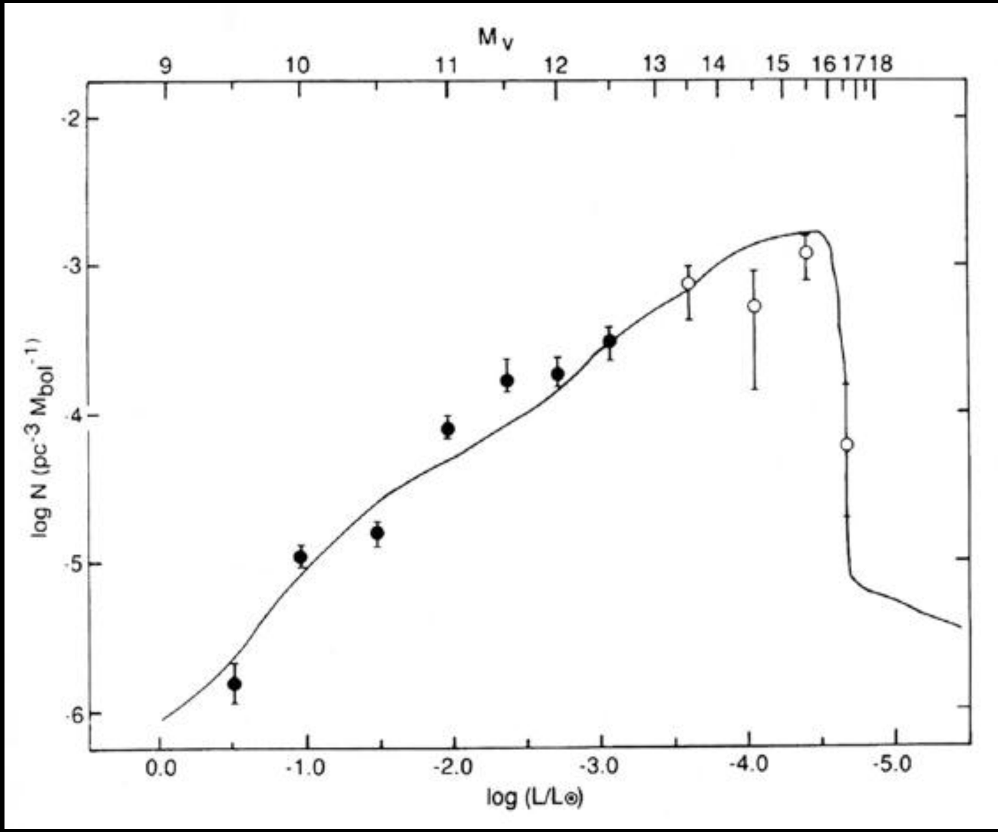
White dwarfs can give us useful information about their last stage evolution. Main sequence stars will evolve after consuming all their nuclear fuel to WDs if their mass is less than 1.08 $M_{\odot}$. WDs of Sun's mass have the size of Earth, and DA WDs are studied most.

If any new mechanism is affecting the WD evolution, its mass must be less than eV.

The exceptionally strong pull of WD's gravity is the reason for the thin hydrogen surface of DA white dwarfs.
In fact, the core of WDs follows simple physics, the degenerate fermion gas.

Sirius B, $1.05 M_\odot$
8.65 ly





Winget et al., Ap. J. Lett. 315 (1987) L77.

Baryon asymmetry of the universe

$$Y_{\Delta B} = (7.2\text{-}9.2)\times 10^{-11}$$

GUT baryogenesis
Electroweak baryogenesis
Leptogenesis

Leptogenesis seems most attractive since the CP phase of leptogenesis can be related to the phase of the PMNS matrix in some models.

1. Axions

2. WIMPs, etc.

3. Dark energy

1. Axions

Theory: the strong CP invariance

Experiments:

Cavity for photon ⟷ axion conversion

Theory: the strong CP invariance

The existence of instanton solution in nonabelian gauge theories needs θ. It introduces the θ term,

$$\frac{\bar{\theta}}{32\pi^2}\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \bar{\theta}\{F\tilde{F}\}$$

$$\bar{\theta} = \theta_{\rm QCD} + \theta_{\rm weak}, \qquad \theta_{\rm weak} = \arg.{\rm Det}M_q$$

This CP violation must be sufficiently suppressed.

Kim-Carosi, arXiv:0807.3125 “Axions and the strong CP problem” (Rev. Mod. Phys. 82, 511 (2010))

$$|\bar{\theta}| < 0.7 \times 10^{-11}.$$

We used C A Baker et al, PRL 97, 131801 (06), to obtain $\rightarrow|\Theta|< 0.7\times10^{-11}$

Why is this so small? : Strong CP problem.

1. Calculable Θ, 2. Massless up quark (X)
3. Axion

Massless up quark

Suppose that we chiral-transform a quark,

$$q \rightarrow e^{i\gamma_5\alpha} q \quad : \quad \int(-m\bar{q}q + \frac{\theta}{32\pi^2}F\tilde{F})$$

$$\rightarrow \int(-m\bar{q}e^{2i\gamma_5\alpha}q + \frac{\theta-2\alpha}{32\pi^2}F\tilde{F})$$

If m=0, it is equivalent to changing $\theta \rightarrow \theta - 2\alpha$. Thus, there exists a shift symmetry $\theta \rightarrow \theta - 2\alpha$.

Here, θ is not physical, and there is no strong CP problem. The problem is, “Is massless up quark phenomenologically viable?”

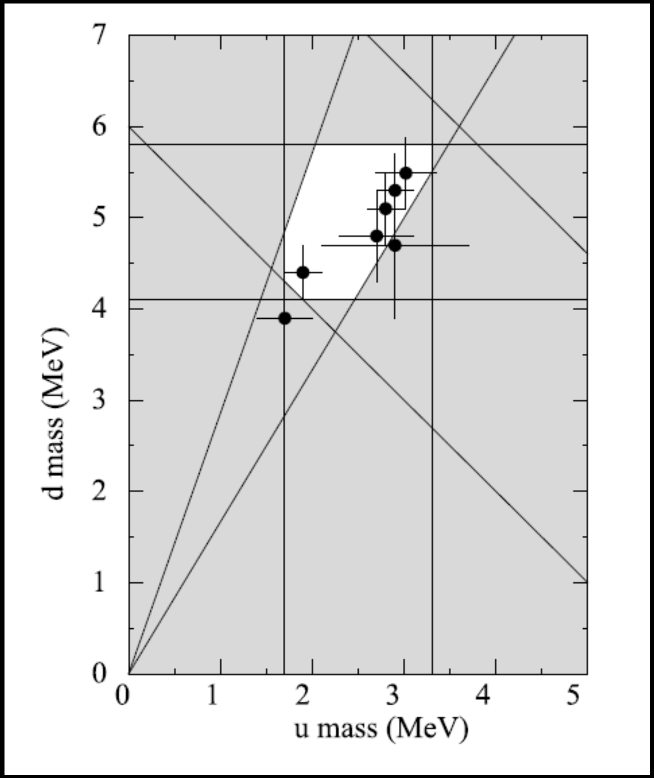
$$\frac{m_u}{m_d} = 0.5,$$

$$m_u = 2.5 \mp 1 MeV,$$

$$m_d = 5.1 \pm 1.5 MeV$$

(Manohar-Sachrajda)

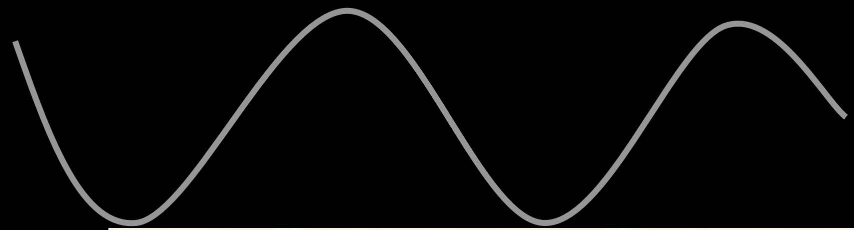
This is convincing that m_u=0 is not a solution now.



Particle Data (2010)

The axion models interpret $\theta=a/F_a$ as a pseudoscalar field with the vacuum value

$$\bar{\theta}=0$$



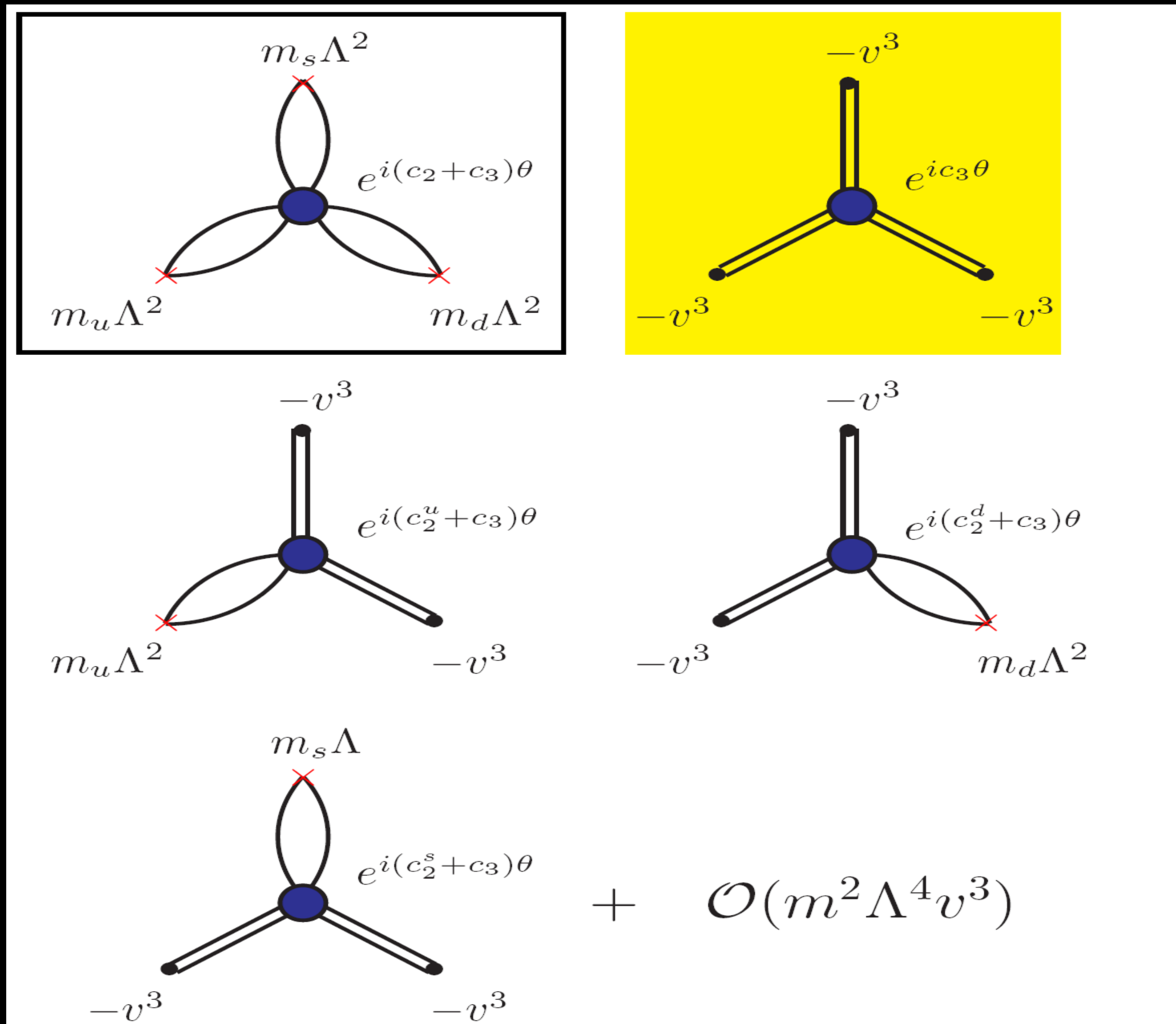
$\uparrow$

$\bar{\theta} = 0$ $\qquad m_u m_d \Lambda^2 \longleftarrow \Lambda^4$

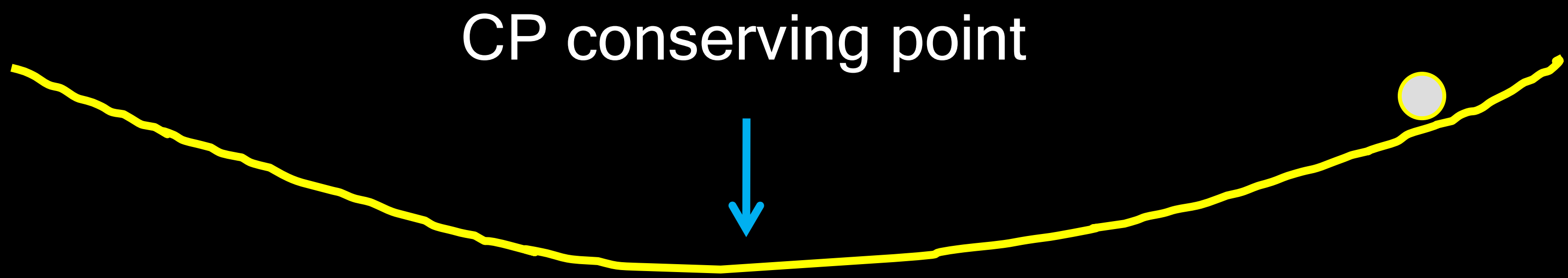
$$V[a] = \frac{Z}{(1+Z)^2} f_\pi^2 m_\pi^2 \left(1 - \cos\frac{a}{F_a}\right)$$

The interaction $\qquad \frac{1}{32\pi^2}\frac{a}{F_a}\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \frac{a}{F_a}\{F\tilde{F}\}$

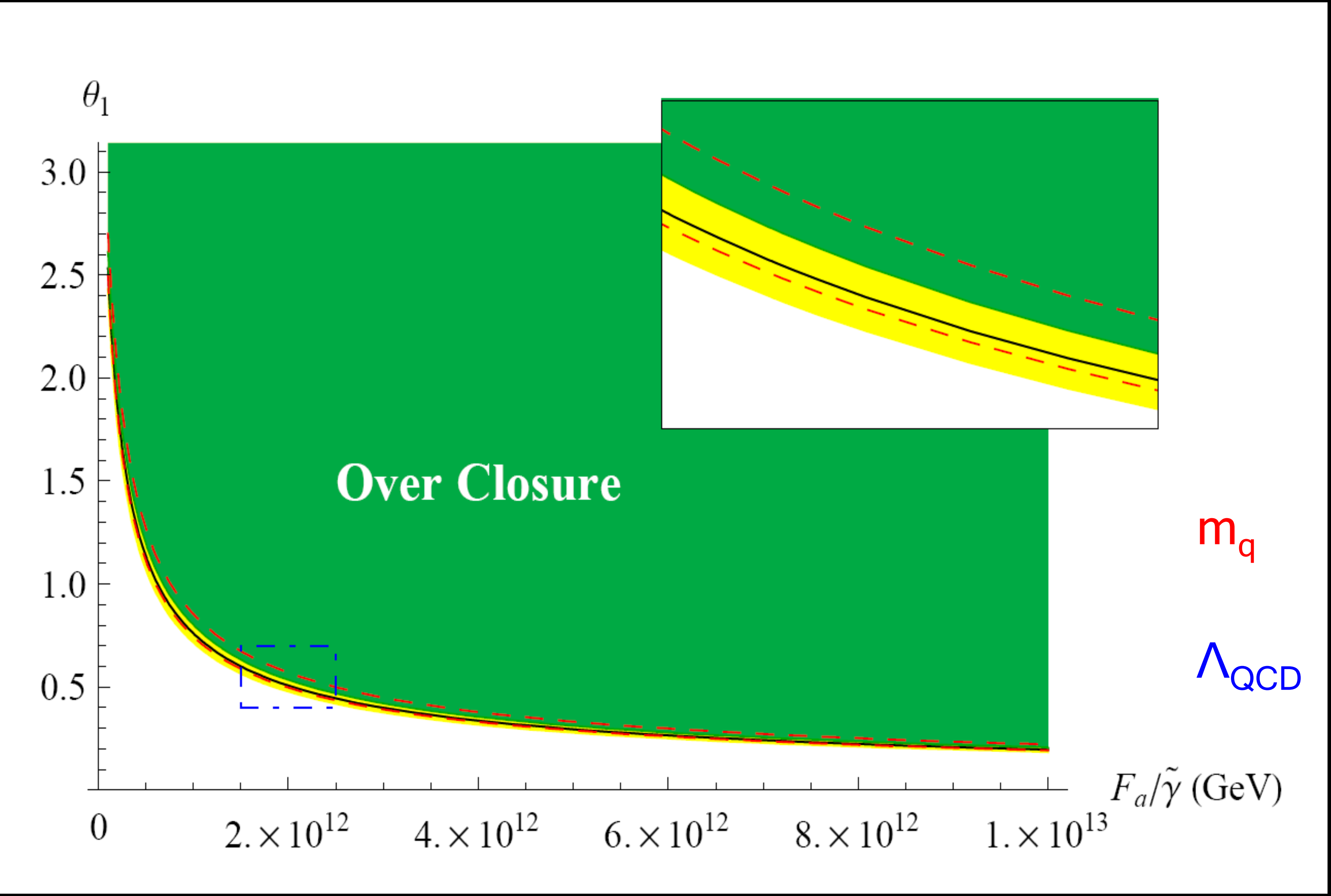
$$-m_u \Lambda^3 \cos\frac{a}{F_a} \Rightarrow m_a = \frac{\sqrt{Z}}{1+Z}\frac{f_\pi m_\pi}{F_a} = 0.6[eV]\frac{10^7 GeV}{F_a}$$


$m_s\Lambda^2$
$e^{i(c_2+c_3)\theta}$
$m_u\Lambda^2$
$m_d\Lambda^2$
$-v^3$
$e^{ic_3\theta}$
$-v^3$
$-v^3$
$-v^3$
$e^{i(c_2^u+c_3)\theta}$
$m_u\Lambda^2$
$-v^3$
$-v^3$
$e^{i(c_2^d+c_3)\theta}$
$-v^3$
$m_d\Lambda^2$
$m_s\Lambda$
$e^{i(c_2^s+c_3)\theta}$
$-v^3$
$-v^3$
$+ \quad \mathcal{O}(m^2\Lambda^4 v^3)$

It is very flat if the axion decay constant is large,



In the evolving universe, at some temperature, say T_1, *a* starts to roll down to end at the CP conserving point sufficiently closely. This analysis constrains the axion decay constant (upper bound) and the initial VEV of *a* at T_1.



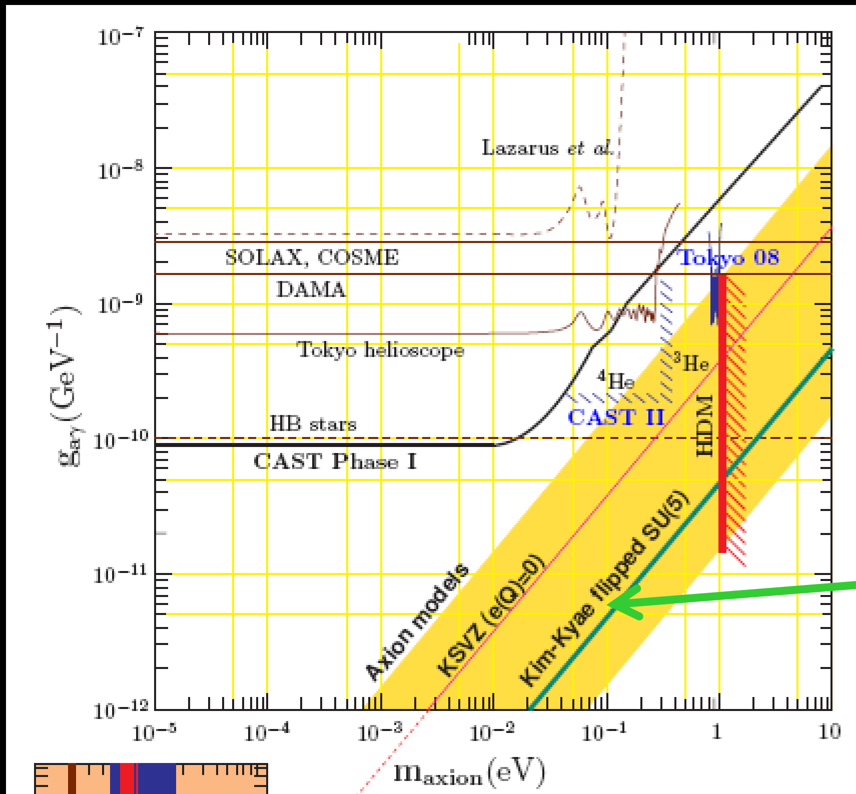
Bae-Huh-Kim, JCAP0809, 005

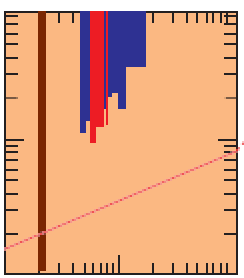
Above the electroweak scale, we integrate out heavy fields. If colored quarks are integrated out, its effect is appearing as the coefficient of the gluon anomaly. If only bosons are integrated out, there is no anomaly term. Thus, we have (c_1=derivative term, c_2=mass term , c_3=anomaly term)

KSVZ: $c_1=0$, $c_2=0$, c_3=nonzero

DFSZ: $c_1=0$, c_2=nonzero, $c_3=0$

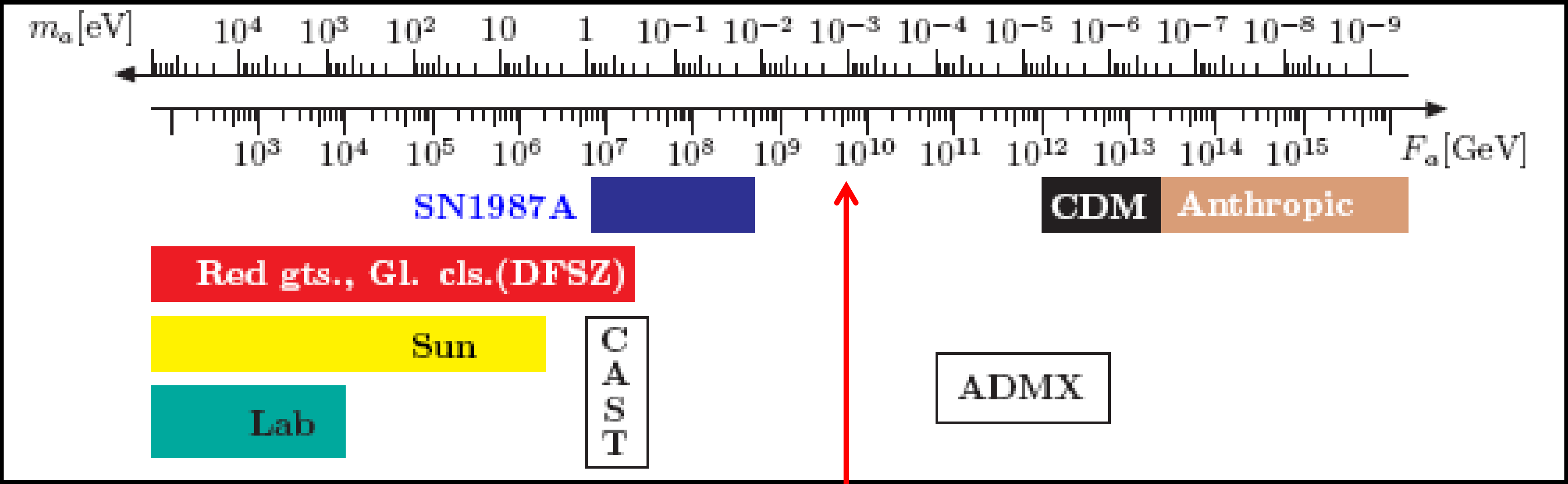
PQWW: similar to DFSZ



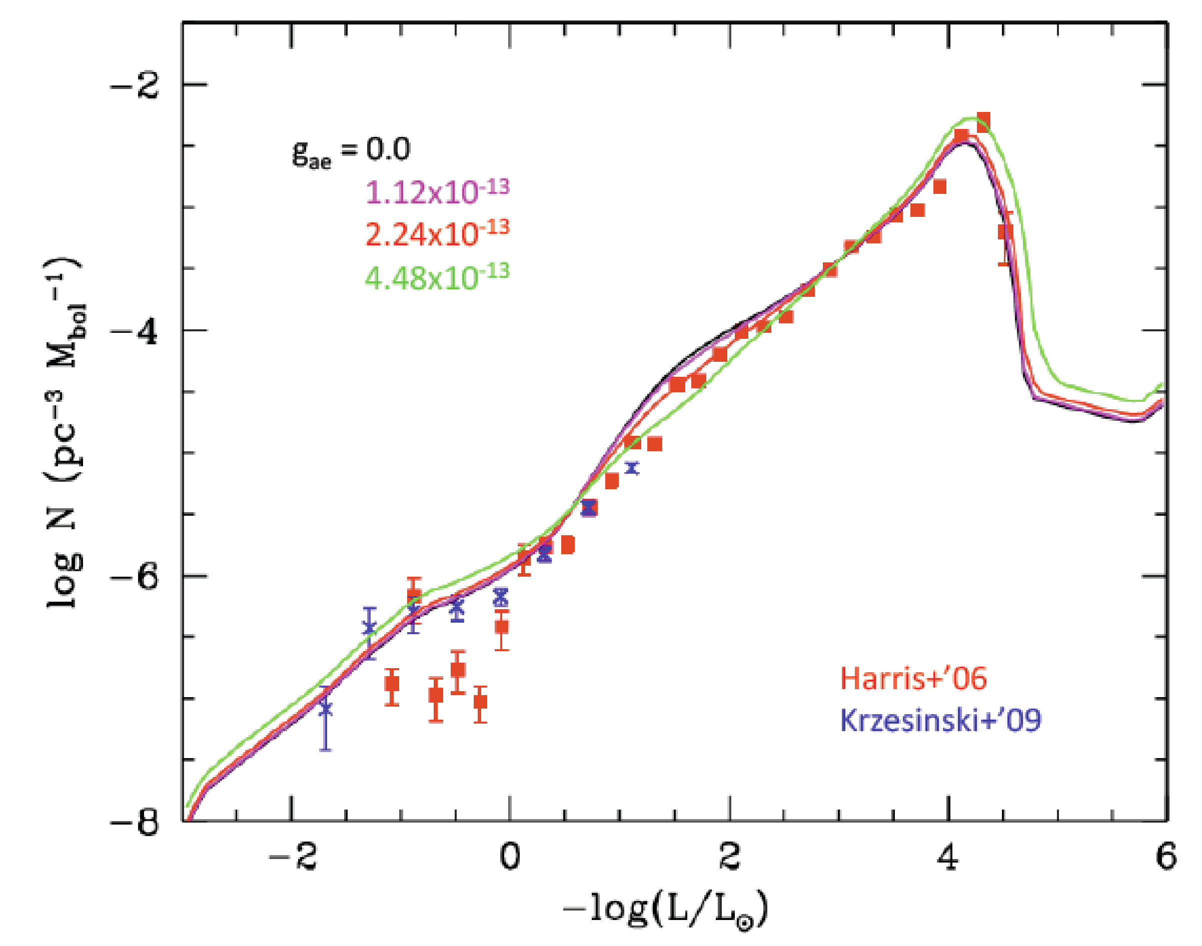


It depends on models.
There are not many calculations in string models.
Many many quarks' PQ charges seem cancelling.

KSVZ		DFSZ		
$Q_{\rm em}$	$c_{a\gamma\gamma}$	$x=\tan\beta=v_u/v_d$,	same Higgs for (q^c,e) masses,	$c_{a\gamma\gamma}$
0	-1.95	any x,	(d^c,e)	0.72
$\pm\frac{1}{3}$	-1.28	any x,	(u^c,e)	-1.28
$\pm\frac{2}{3}$	0.72			
±1	4.05			
(m,m)	-0.28			



White dwarf bound
(1st hint at the center of the axion window)



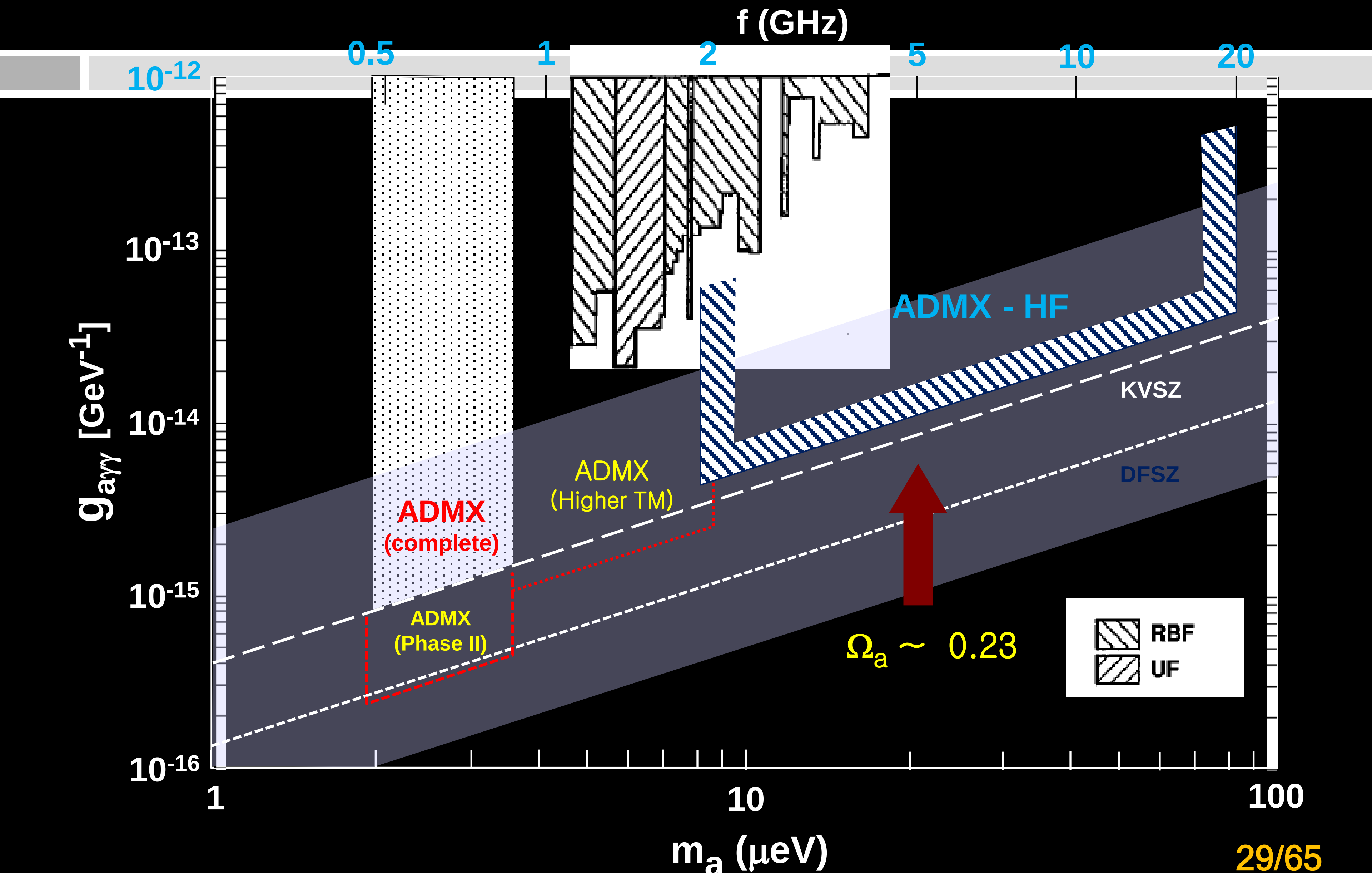
Isern,
7th PATRAS
2011

$$2.24\times10^{-13} \quad \rightarrow \quad F_a = 0.5\times10^{10}\ \text{GeV for } N_{DW} = \frac{1}{2}$$

Bae, Huh, JEK, Kyae, Viollier, NPB 817, 58 (2009)

ADMX Phase II & ADMX-HF Coverage

van Bibber at ASK 2011



2. WIMPs

Theory: new Z2 or a kind of parity.

The lightest Z2 odd particle constitutes the DM in the universe. These are called WIMP

Experiment: Direct detections are

- Cosmological scenario: detect the flux of WIMP DM
- LHC: produce them by collisions of pp.

Indirect detections look for its effect in the universe

- N-body simulation
- e and positron spectrum in our galaxy

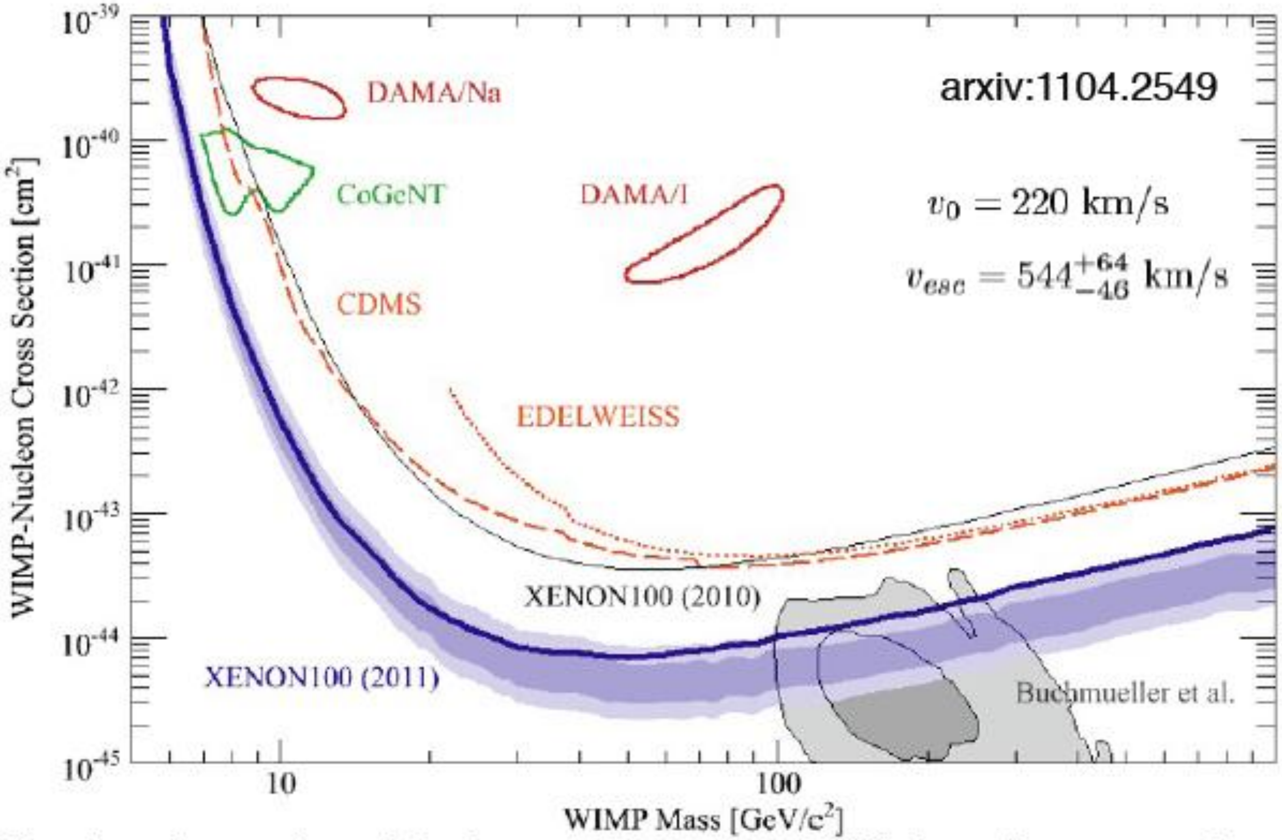
The most widely discussed WIMP is the LSP in SUSY. If DM is dominated by WIMP, the WIMP density is inversely proportional to the cross section,

Generally,

$$\Omega h^2 \cong \frac{0.1\text{pb}\cdot c}{\langle \sigma(\chi\chi \to \text{SM}) v \rangle}$$

Larger WIMP mass $\rightarrow$ larger Ω
Smaller WIMP mass $\rightarrow$ smaller Ω

XENON100 Dark Matter Limit (90% CL)



Blue bands are 1 and 2 sigma expectations (PL) based on zero signal

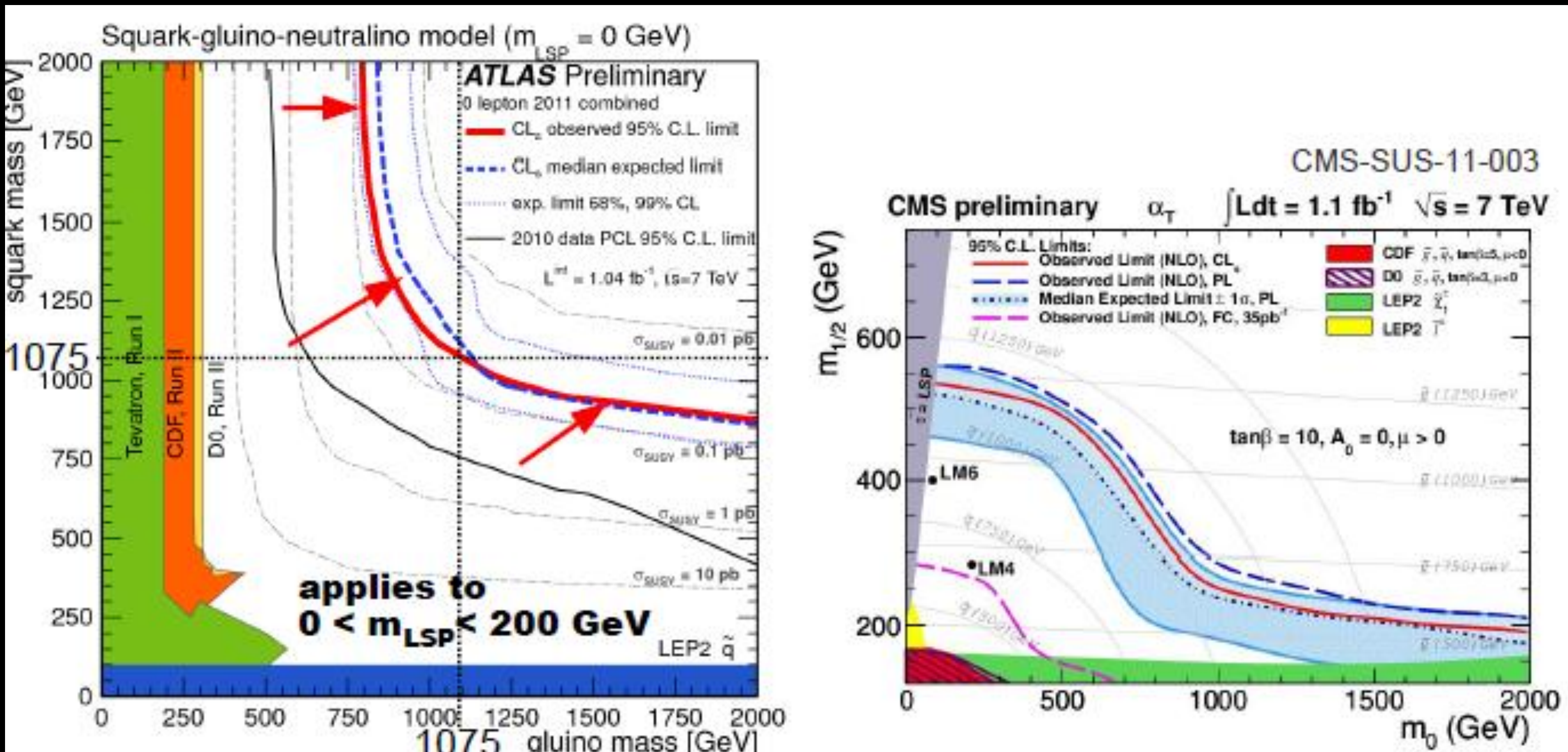
Minimum at 7 x 10 $^{-45}$ cm^2 @ 50 GeV

Now, two motivated DM candidates exist: axion and WIMP.
These will have very different astrophysical sources.

(1) High energy electron/positrons → WIMP
(2) White dwarf energy loss → sub-eV particles

Why not parametrize DM (23% of cosmic pie) by ?

$$\Omega_{DM} = \xi\,\Omega_{axion} + (1-\xi)\,\Omega_{WIMP}$$



squark to jets, or gluinos to jets

[H. Bachacou, LP 2011]

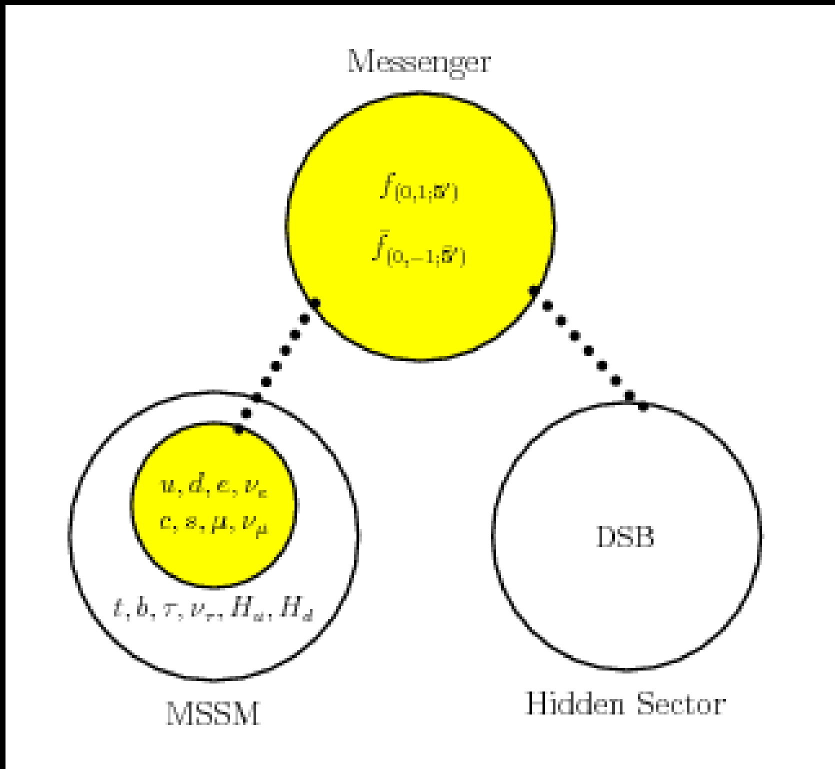
SUSY is attractive, and there can be a SUSY way.

It is an effSUSY [Cohen-Kaplan-Nelson (1996)] .

1. One Higgs doublet pair. The 3rd families sparticles are light. [Georg Weiglein's talk]

3. Quantum numbers of extra U(1)' charges as needed in the U(1)' mediation.

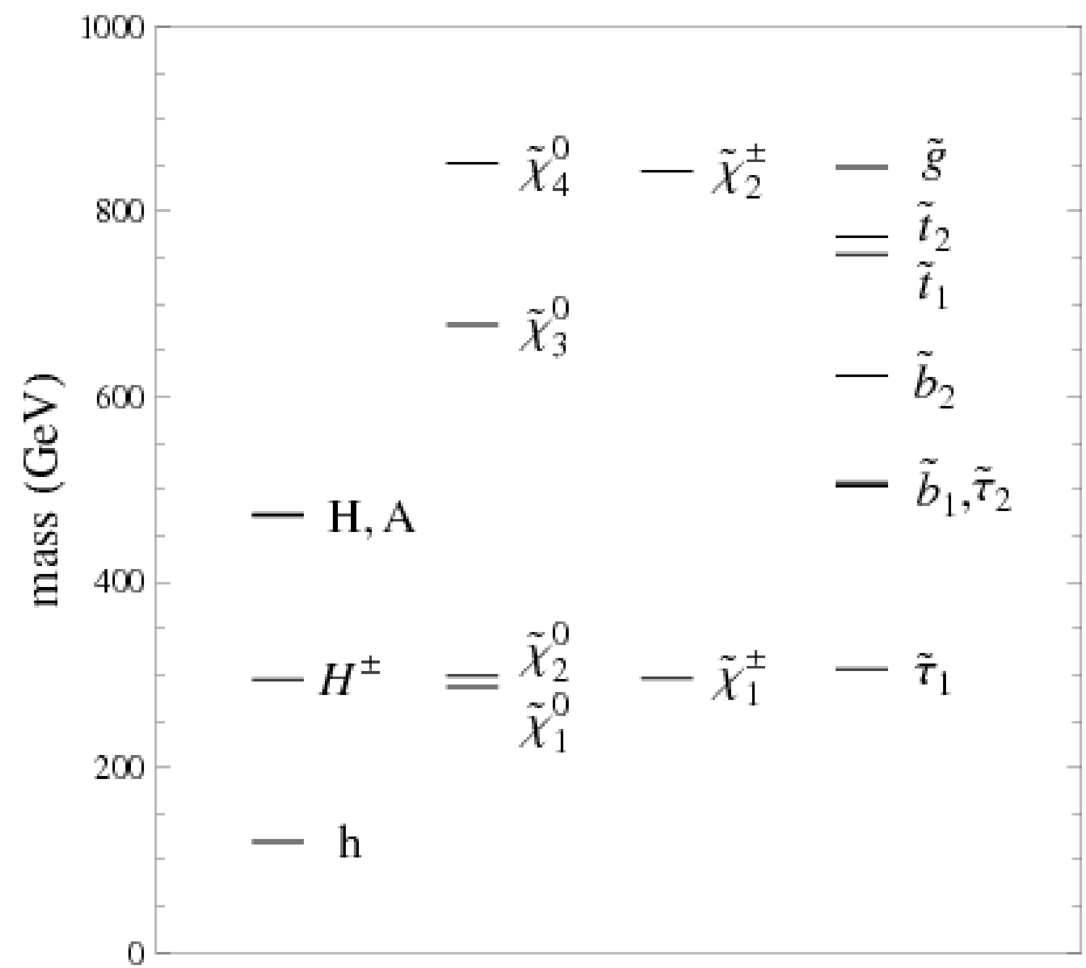
Z' mediation (Langacker et al(2009)) to effSUSY



It is only possible in flavor unification models. For example, string compactification is a possibility since E8 is a kind of flavor unification.

Naïve GUTs such as SU(5), SO(10), E6 do not succeed.

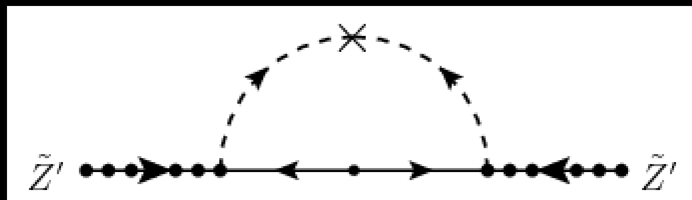
[JEK, plb 656, 207 (2007) [arXiv:0707.3292]] ← from string
[K. S. Jeong, JEK, Seo, [arXiv:1107.5613 [hep-ph]]



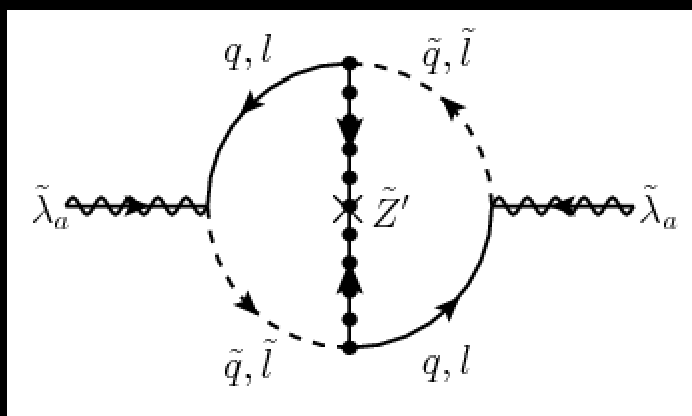
LSP=gravitino

[K. S. Jeong, JEK, Seo, [arXiv:1107.5613 [hep-ph]]

The hierarchy of SUSY partner masses are



$$M_{\tilde{Z}'} \cong \frac{g_{Y'}^2}{16\pi^2} Y'^2 \frac{F_{\rm mess}}{M_{\rm mess}}$$



$$M_{\lambda_a}(\mu) \cong \frac{g_{Y'}^2 g_a^2}{(16\pi^2)^2} M_{Z'} \log\left(\mu \big/ M_{Z'}\right)$$

$$M_{\tilde{q}_{1,2},\tilde{l}_{1,2}}(\mu) \cong \frac{g_{Y'} Y'_{\tilde{q},\tilde{l}}}{4\pi} M_{Z'} \left(\log\left(\mu \big/ M_{Z'}\right)\right)^{3/2}$$

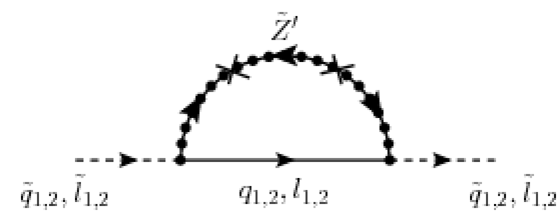


FIG. 4: The first two family sfermion($\tilde{q}_{1,2}, \tilde{l}_{1,2}$) mass diagrams. The SUSY breaking from Zprimino sector is shown as ×.

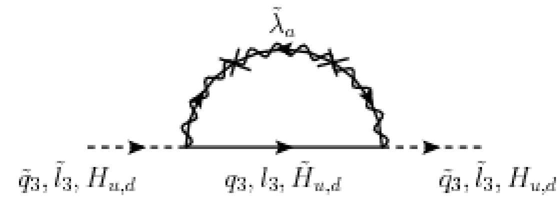


FIG. 5: The mass diagrams for the third family sfermion(q_3, l_3) and Higgs bosons. The SUSY breaking from the SM gauginos are shown as ×.

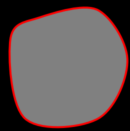
Dark matter candidates

		axion	WIMP	sterile ν
mass	m	$10^{-5}\,\mathrm{eV}$	$100\,\mathrm{GeV}$	$10\,\mathrm{keV}$
vel. disper.	δv	$10^{-17}c$	$10^{-12}c$	$10^{-8}c$
coh.length	$\ell = \dfrac{\hbar}{m\delta v}$	$10^{17}\,\mathrm{cm}$	$10^{-5}\,\mathrm{cm}$	$10^{-1}\,\mathrm{cm}$

The axion and WIMP both behave as CDM at the time of forming galaxies. They differ in spin and coherence lengths. Sikivie and Yang pointed out that for axions there is a possibility of BEC. [PRL 103 (2009) 111301]
Sikivie comments that axion is better in explaining the inner caustics and angluar momentum of galaxies.

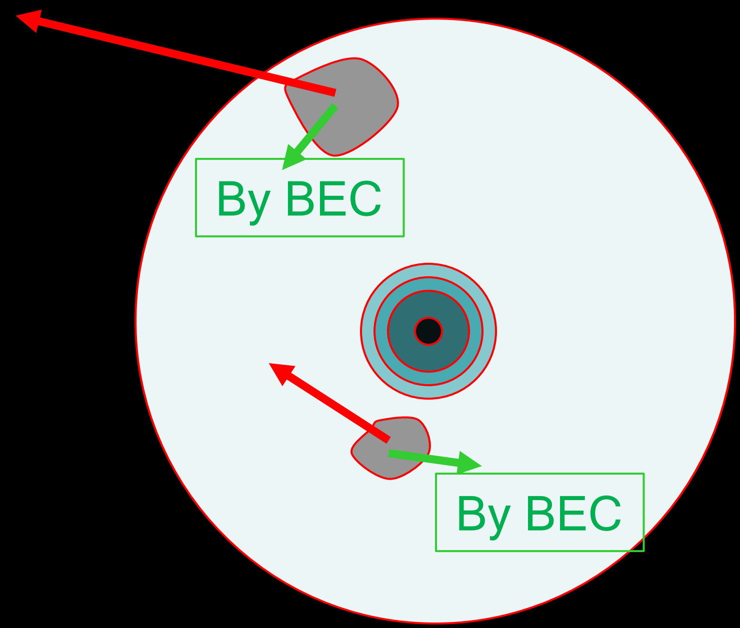
Tidal torque theory with axion BEC

Sikivie: Talk at 7th PATRAS, 2011



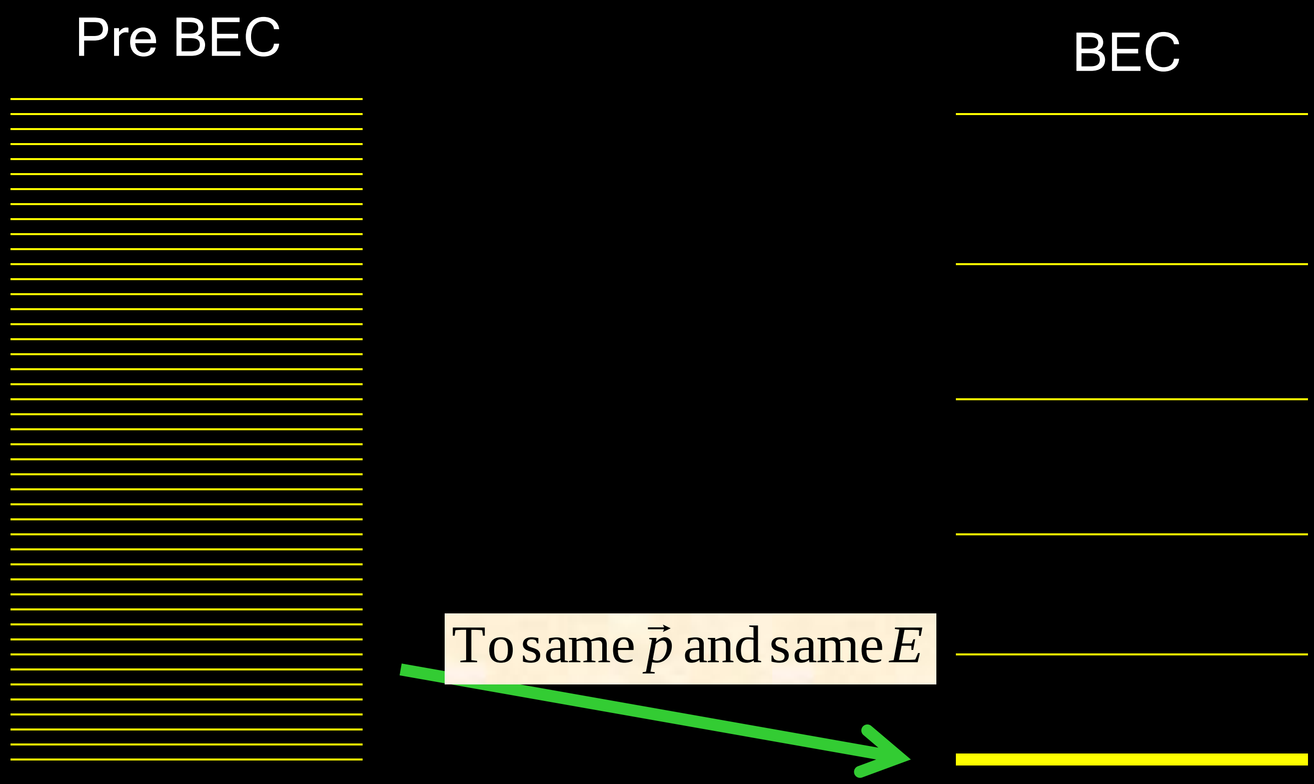
Not irrotational:
net overall rotation

$$\vec{\nabla} \times \vec{v} \neq 0$$

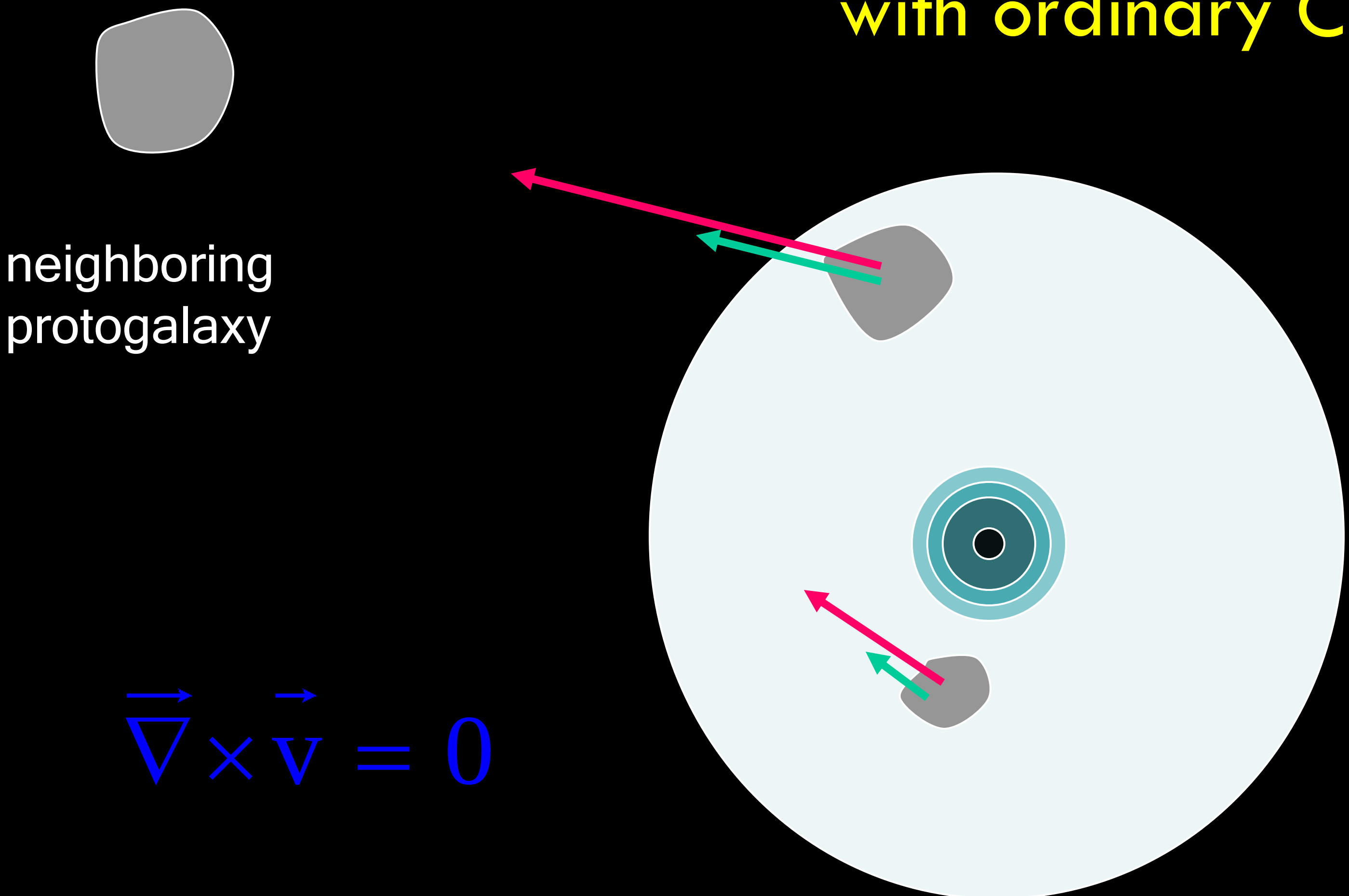


Net overall rotation is obtained because, in the lowest energy state, all axions fall with the same angular momentum. Two distinctive behaviors before the dark matter falls into galactic halos. WIMPs have an irrotational velocity field whereas axions fall in with net overall rotation. Axions do this because they go to the lowest energy state for given angular momentum BEFORE FORMING GALAXIES. That state has net overall rotation.

Why BEC ? by yielding their energy to the non-condensed particles, the total entropy is increased.



Tidal torque theory with ordinary CDM



$$\vec{\nabla} \times \vec{v} = 0$$

the velocity field remains irrotational

Sikivie: the caustics are different in the two cases:

Caustic rings for axions and `tent-like' caustics for WIMPs.

The evidence my collaborators and I found for caustic rings is only consistent with axions.

So the bulk of dark matter must be axions.

3. Dark Energy

The most frequently talked word in connection with DE is

Cosmological Constant.

There are three important epochs related to the CC.

1. Inflation

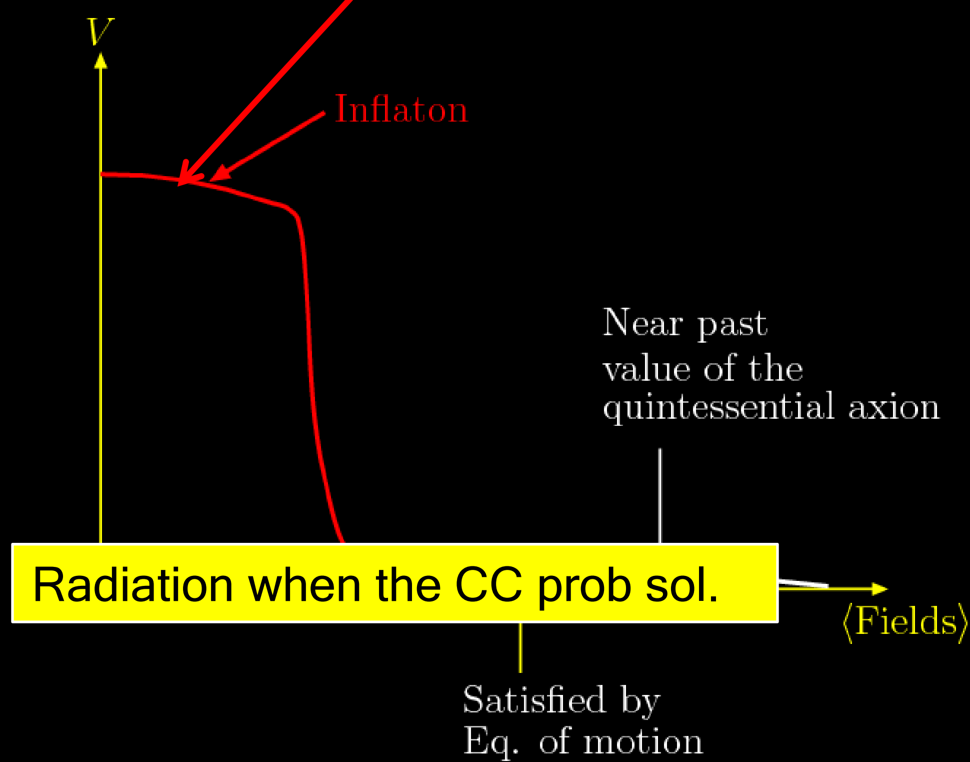
2. Theoretically appealing
   vanishing cosmological constant

3. Current dark energy $(0.003\ \mathrm{eV})^4$

Based on papers: Kim-Kyae-Lee, PRL 46 (2001) 4223,
Kim, PRD 81 (2010)123018; and
[arXiv:1009.5071 [hep-th]]

The picture is the following.

Usually, the inflation is taking place at the brane by the slow roll along the inflaton direction: chaotic, hybrid, etc.

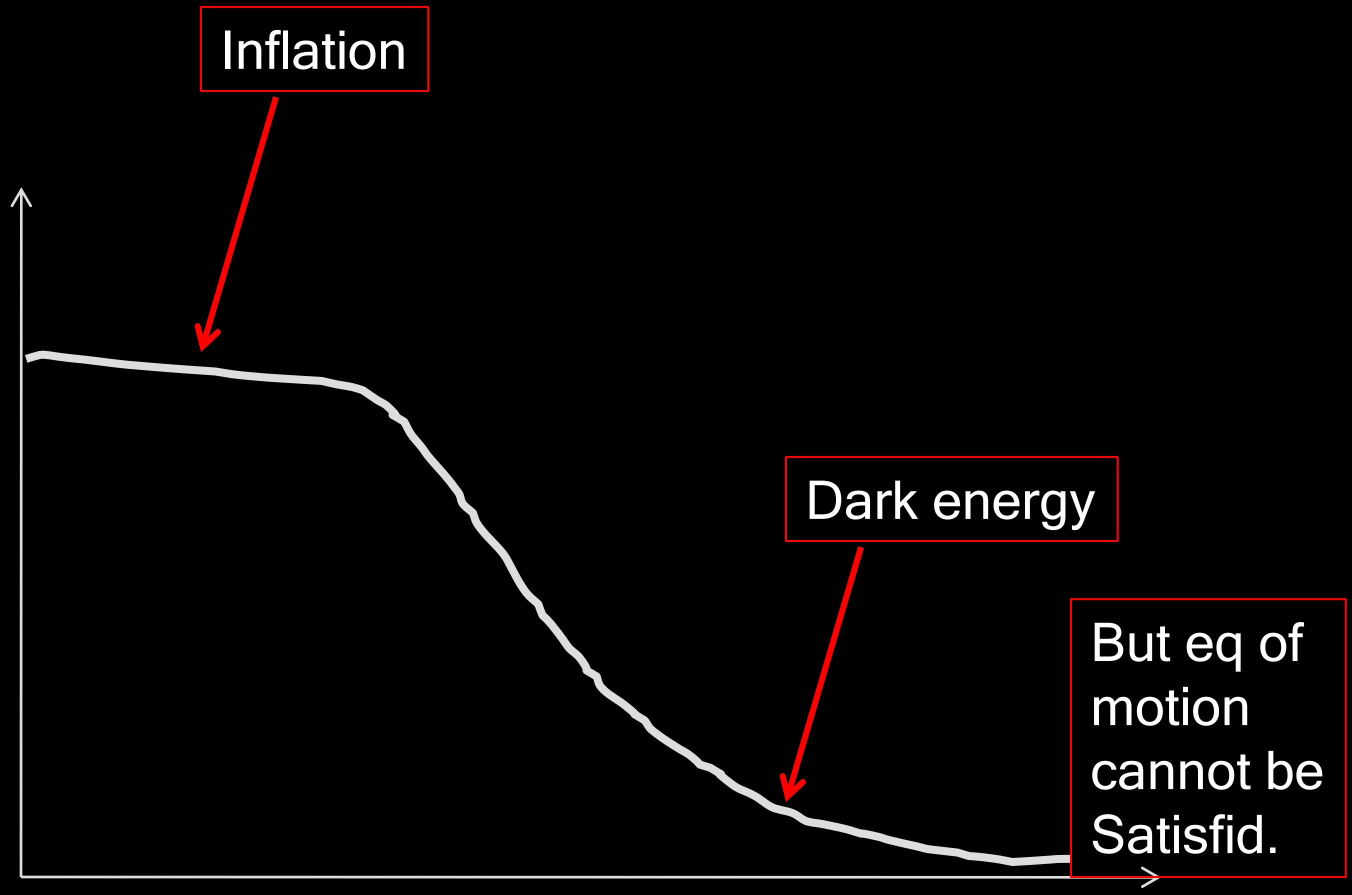


And we need a quintessential axion [K-Nilles(2003,2009)].

$$\frac{p}{\rho}=w, \quad -1\le w\le -\frac{1}{3}$$

This is the place where we must solve the c.c. problem. But, …….

Some quintessence picture is the following.



This model should solve the CC problem also.

H. Nicoli (June 28, 2010) says that the Einstein Eq. is inconsistent at the outset.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

LHS is exactly determined by the continuous space-time geometry. It is classical.

RHS is probabilistic. Determined by QM.

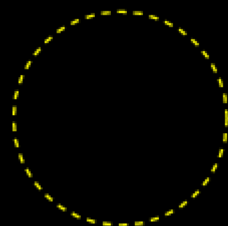
Mutually inconsistent

At present, any discussion in the Planck era is speculative and not yet well formulated [Kolb-Turner].
So, I must admit that any solution of the CC may be incomplete, and we present here the CC solution idea just by replacing the RHS $\Lambda g_{\mu\nu}$.

Even before considering the tree level c.c., the loop correction to the vacuum energy was a problem since the early days of quantum mechanics.

Here, we do not rely on some anthropic solution [Weinberg, PRL 59 (1988) 2607; V. Agrawal, S. M. Barr, J. Donoghue, PRD 57 (1998) 5480].

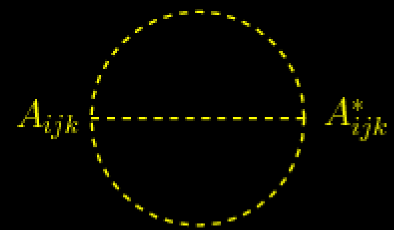
So, we must consider the cosmological constant generically, at tree level, and also at loop levels unless the following type of diagrams are forbidden:



$$\frac{1}{2}\hbar\omega$$

$$\downarrow$$

$$\simeq N\frac{m_B^2\Lambda^2}{8\pi^2}$$

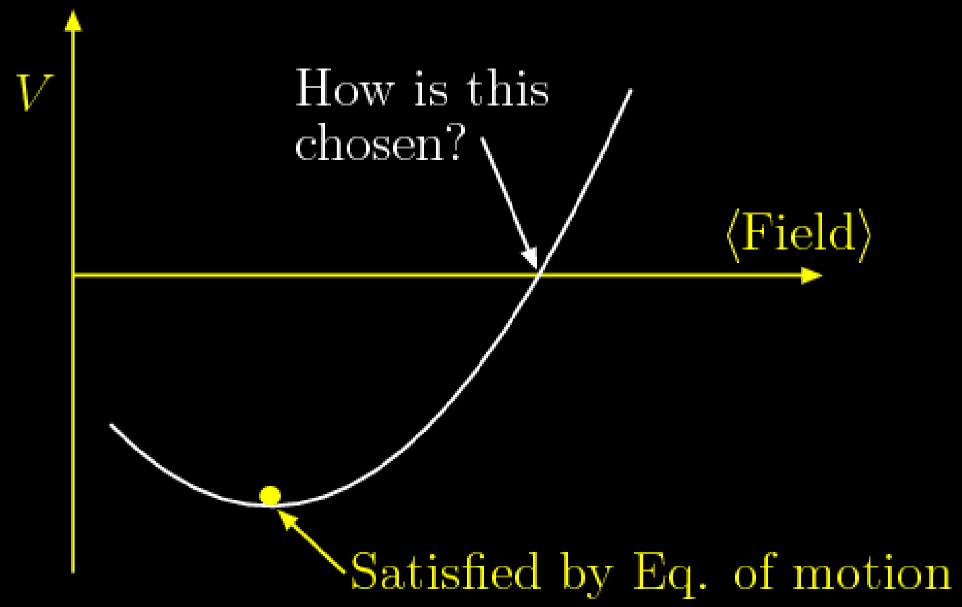


$$N\int\frac{d^3k}{(2\pi)^3}\left(\sqrt{\mathbf{k}^2+m_B^2}-\sqrt{\mathbf{k}^2+m_F^2}\right)$$

$$\simeq\frac{1}{(4\pi^2)^2}\sum_{ijk}A_{ijk}A^*_{ijk}\Lambda^2$$

The c.c. is a serious fine-tuning problem. In 4D, we do not find any symmetry such that the c.c. is forbidden.

If a symmetry is present in changing Λ, one may try a scalar potential:



So, a solution is not easily realizable in 4D.

Probability amplitude

When we consider QM, we talk in terms of the probability amplitude: The initial state |i> to transform to a final state |f>. So, E. Baum[PLB 133 (1983) 185] and S. Hawking[PLB 134 (1984) 403] considered the Euclidian action with the

R and Λ terms only.

The Euclidian action integral has the form

$$\exp(-\tilde{I}) = \exp\left(\frac{3\pi M_P^2}{\Lambda}\right)$$

So, $\Lambda=0^+$ is has a very large value, the probability for it is close to 1. But, there are questions regarding to this solution.

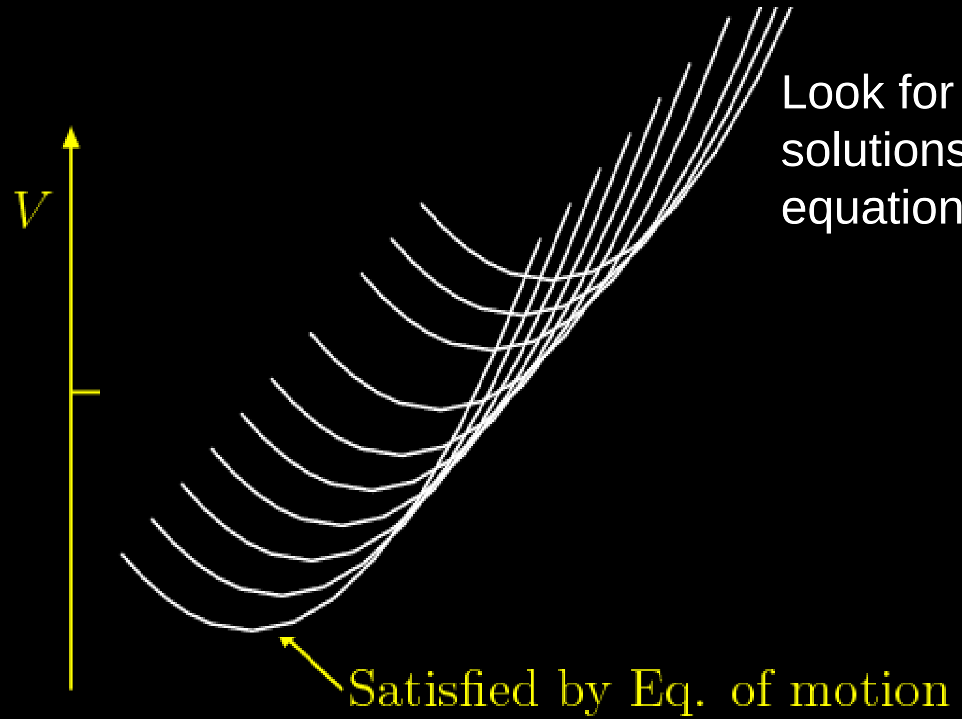
It is the action integral. Another question is

"How do we assign the initial state?"
"How does the needed primary inflation come about in this scenario?"
"How does it fit to the current dark energy?"

So the c.c. solution needs to explain other two c.c. related questions also.

S. Hawking [PLB 134 (1984) 403] introduced a scalar field without the kinetic energy term :
$A_{\mu\nu\rho}$ ($F_{\mu\nu\rho\sigma}$ field strength),
or ϕ.

Then, we consider the following type



Look for the solutions of equations of motion

$H_{\mu\nu\rho\sigma}$ field is constant in 4D, and does not contain the KE term. If we want to use $H_{\mu\nu\rho\sigma}$ field, we must work beyond 4D.

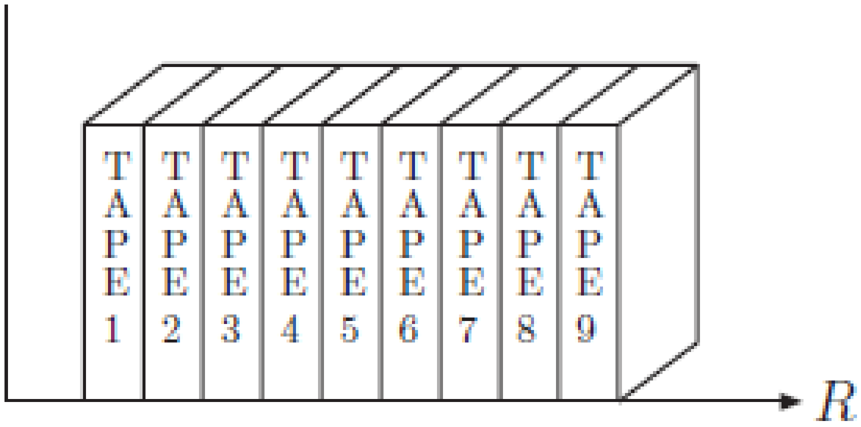


Figure 4. A stack of tapes in the video room. The picked tape is run with the classical Einstein equation. Different tapes contain different fundamental constants.

The wave function obtained from WD Eq. is independent of time.

According to the prob. amplitude from wave function of U, a video tape is chosen.

When we consider QM, we talk in terms of the probability amplitude: The initial state |I> transforming to a final state |F>. Baum and Hawking considered the Euclidian action, only with the Ricci scalar R and the CC. However, there arises vacuum energy from particle physics Lagrangian also.

This method touches upon the quantum gravity. Hawking states, "My proposal requires that a variable effective CC be generated in some manner." For this purpose, Hawking explicitly considered in terms of $A_{\mu\nu\rho}$ (or the field strength $H_{\mu\nu\rho\sigma}$). Even if we understand the CC in this way, there exists another questions such as

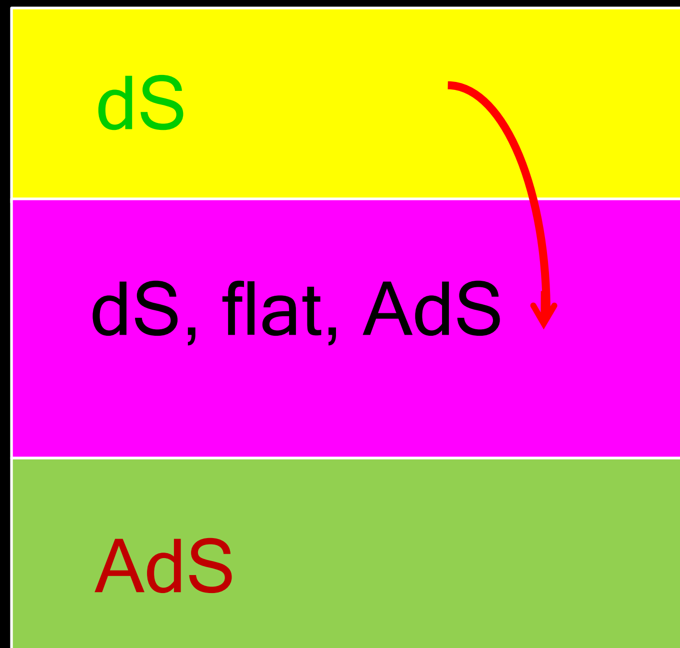
- How do we assign the initial state?
- How does the needed primary inflation come about in this scenario?

Hawking calculated the probability amplitude from and the volume integral is the largest for $\Lambda=0^+$. It is not satisfactory, since it is not clear how the primordial inflation is taken into account.

There also arises vacuum energy from particle physics Lagrangian also. This may change his view completely.

The initial state and the probability amplitude. How did the universe begin?

This situation is shown below, from the initial $\Lambda_1 : \Lambda_1 > (6\Lambda_b)^{1/2}$



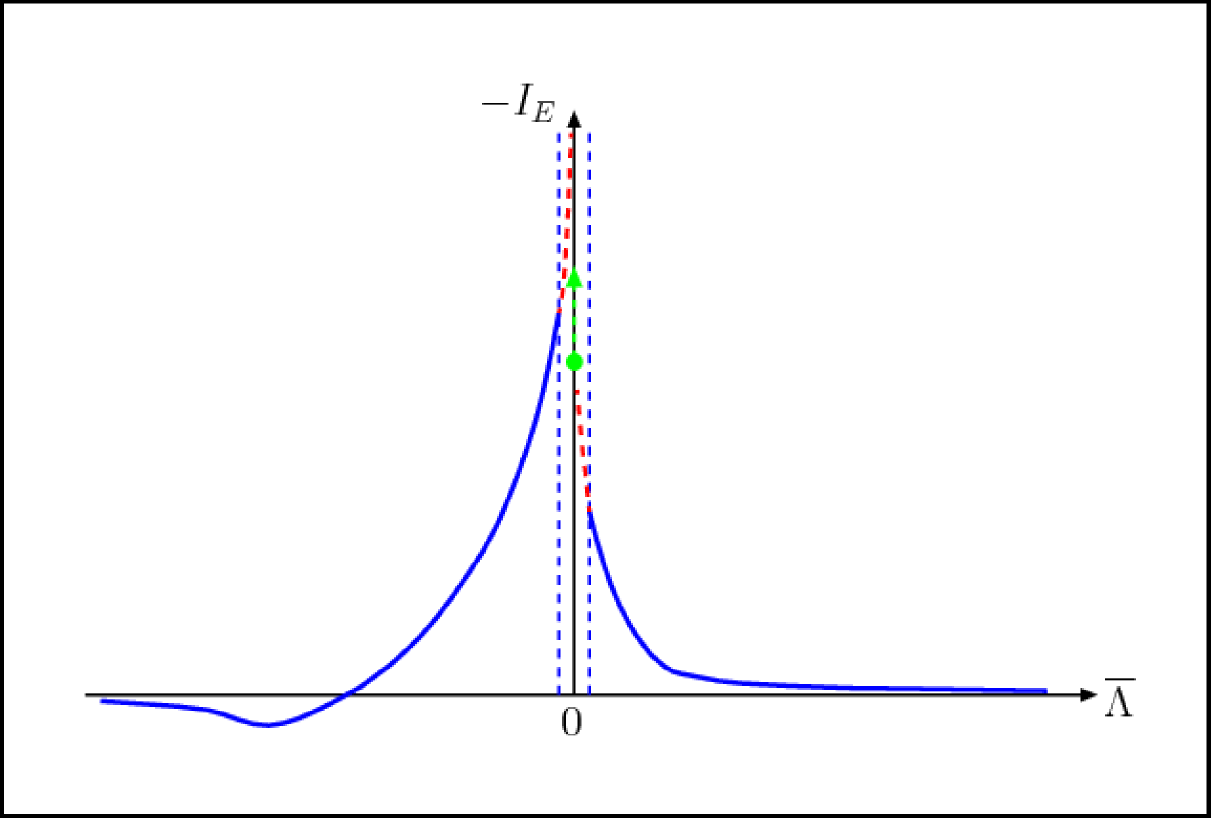
To the final Λ_1 :
$|\Lambda_1| < (6\Lambda_b)^{1/2}$

The roll over to the (flat, dS, AdS) region is like choosing the initial condition |I>. It is an eigenstate of Hamiltonian.

It is a kind of filtering in QM.

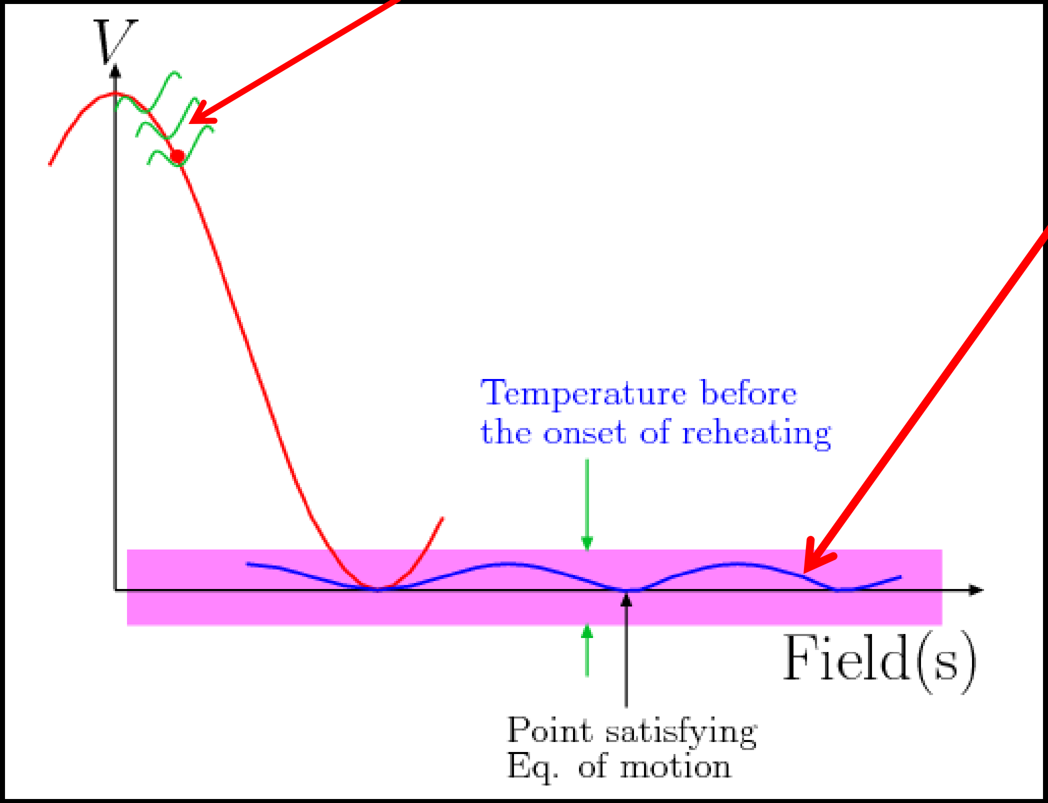
We start the universe from this state, after finishing inflation at dS.

It is our initial condition, not the Hartle-Hawking, or Vilenkin.


$-I_E$
0
$\overline{\Lambda}$

The picture is the following.

When inflation ends at the brane along the inflaton direction, wave function of U is maximum for CC=0 when the universe is supercooled.



And we need a quintessential axion [K-Nilles(2003,2009)].

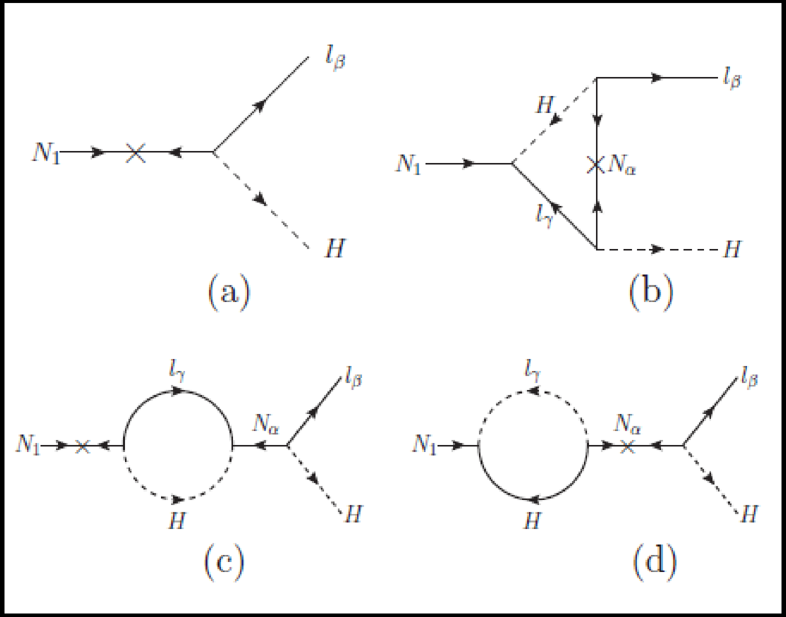
$$\frac{p}{\rho} = w, \quad -1 \le w \le -\frac{1}{3}$$

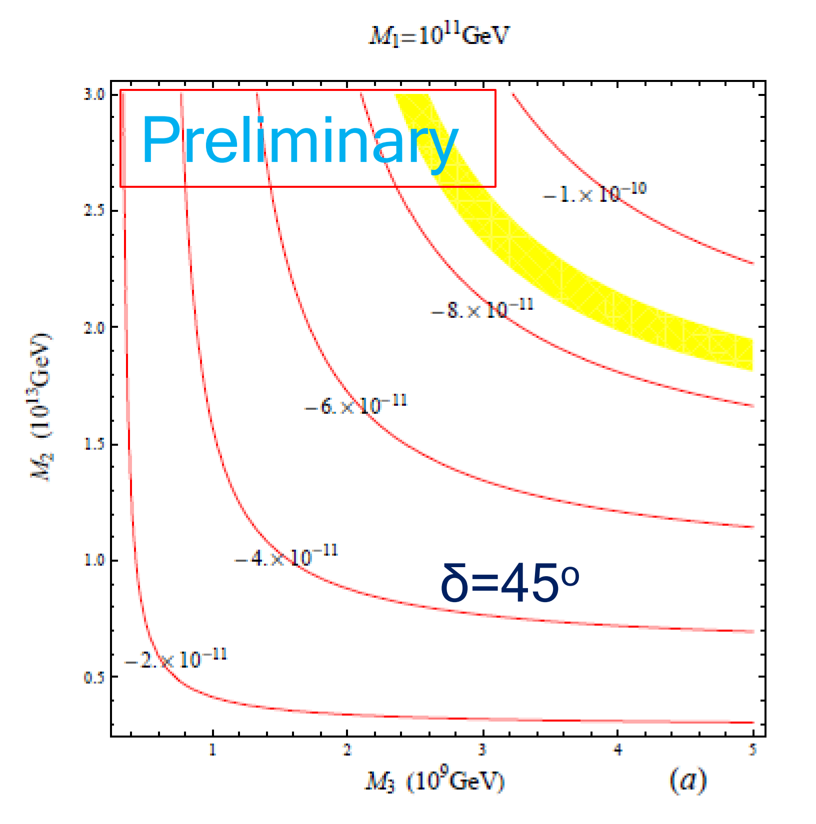
These parameters are chosen when the wave function of universe is collapsed. Galaxy formation by DM happenned at much later cosmic time.

One more: BAU

Leptogenesis is most attractive for generating BAU.
In this framework, one may relate the CP phase of leptogenesis to the KM CP phase 90^0 : probably 45^0?
The best merit testable experimentally.

$$Y_{\Delta B} \cong 10^{-3} \sum_a \varepsilon_{\ell_a}{}^{N_{\rm light}} \eta_a$$





Inverted hierarchy
for large Majorana neutrino
masses

It is difficult to make M_{light} below 10^9 GeV, with Type I seesaw with O(1) Dirac Yukawas. [Buchmuller-Plumacher(1998)]

↕

Conflict with gravity mediation with Tera mass gravitino

Conclusion

1. There exist a few reliable astrophysical data:
   DM, Star evolution, DE, BAU.
   We better explain these, probably from symmetry principles the basis of QM.

2. Axions and WIMPs are probable DM candidates, suggested from symmetries.

3. For DE, three CC related issues must be answered theoretically. No accepted solution yet except for the anthropic scenario. The initial state of the universe in quantum cosmology?

4. Theoretical perspectives prefer to provide examples from the top-down approach also. Otherwise, explanation seems ad hoc.