Axion and Dark Matter Studies in IBS

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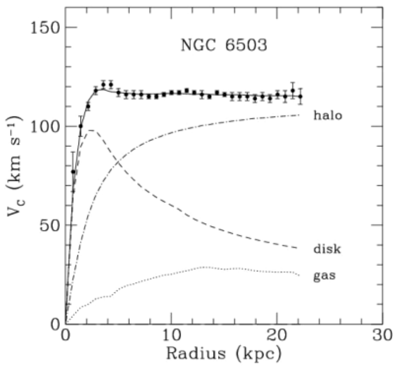
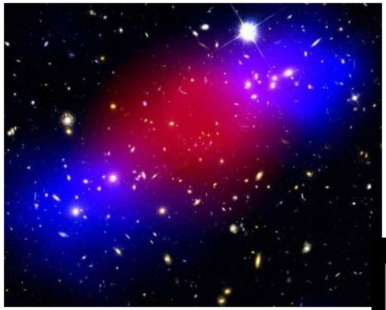
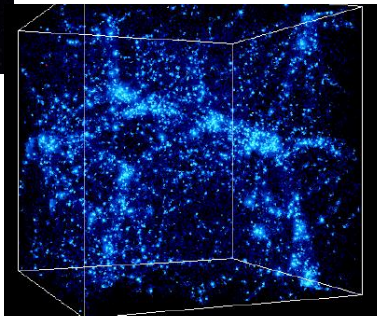
The IBS Center for Theoretical Physics of the Universe

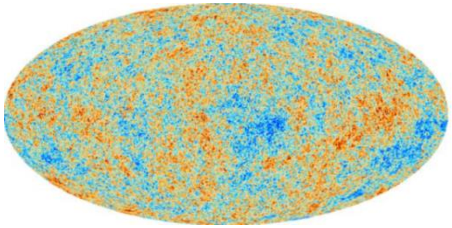
ibs 기초과학연구원 Institute for Basic Science

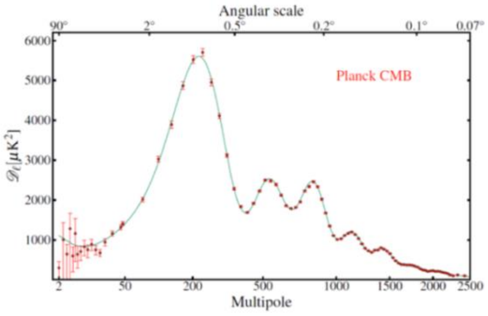
There are plenty of evidences for dark matter (DM) in the universe.











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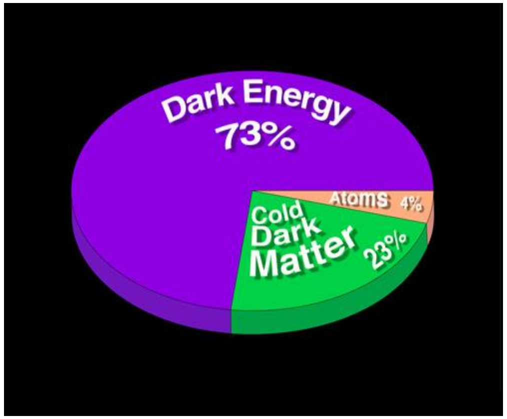
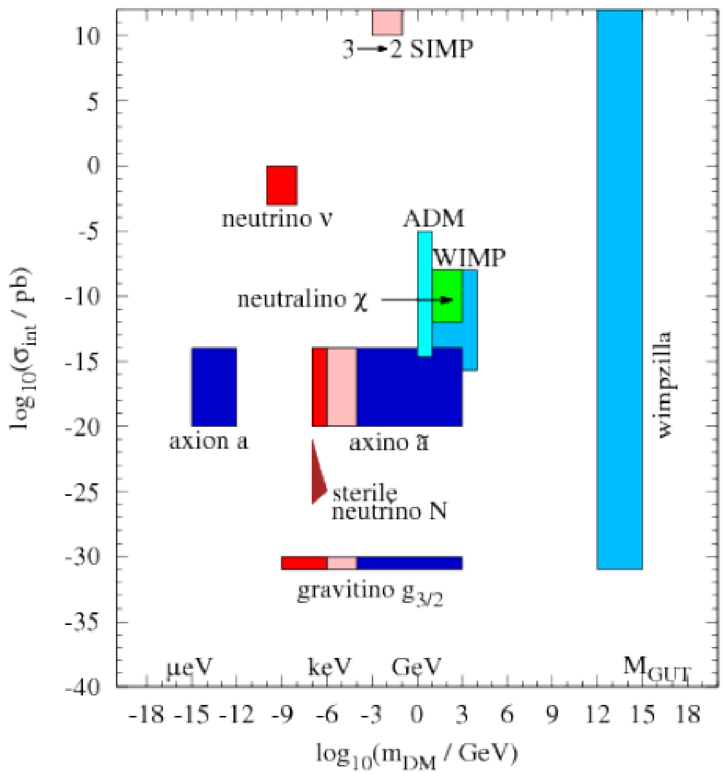


We know too little about DM, so theoretically there are so many possible candidates for DM.



Baer et al '14

Which one would be the more likely candidate?

Axion and **WIMP** (Weakly Interacting Massive Particle) are the leading candidates as they appear as a natural consequence of an attempt to solve the naturalness problems in the Standard Model (SM) of particle physics.

Standard Model + General Relativity:

* Three so different mass scales

Dark energy (= Cosmological constant): $\Lambda_{\rm DE} \sim 10^{-12}\ {\rm GeV}$

Higgs boson mass: $m_{\rm higgs} \sim 10^{2}\ {\rm GeV}$

Planck scale: $M_{\rm Planck} = \dfrac{1}{\sqrt{8\pi G_N}} \sim 10^{18}\ {\rm GeV}$

* Two so different CP-odd angle

Kobayashi-Maskawa phase for the weak CP violation:

$$\delta_{\rm KM} \sim 1$$

QCD vacuum angle which can cause strong CP violation:

$$|\theta_{\rm QCD}| < 10^{-10}$$

Naturalness problems

If something is so small compared to its cousin, putting big and small together requires a fine tuning.

A. Weiler

3 fine-tuning problems associated with the 3 scales and 2 angles:

* Cosmological constant problem:

Why $\Lambda_{DE}/M_{Planck} \sim 10^{-30}$ is so small?

* Gauge hierarchy problem:

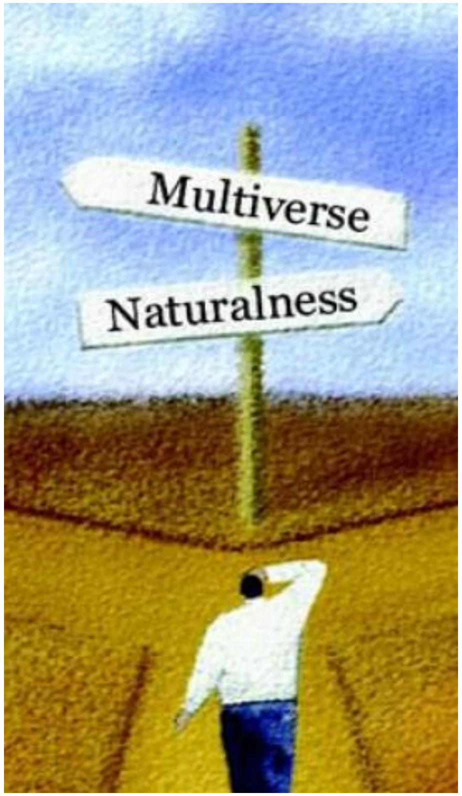
Why $m_{higgs}/M_{Planck} \sim 10^{-16}$ is so small?

* Strong CP problem:

Why $\theta_{QCD} / \delta_{KM} < 10^{-10}$ is so small?

Possible explanations for fine tuning

Anthropic selection in multiverse?



Physical mechanism to make the fine tuning natural?

Peccei-Quinn symmetry with axion DM, …?

↑

Strong CP problem

Cosmological constant problem

SUSY with WIMP DM, …?

Illustration by Villadoro

Gauge hierarchy problem

As the strong CP problem does not find a solution in multiverse, it is more likely that there is some physical mechanism to make θ_{QCD} small, and the most appealing solution is the axion solution.

Axion solution to the strong CP problem

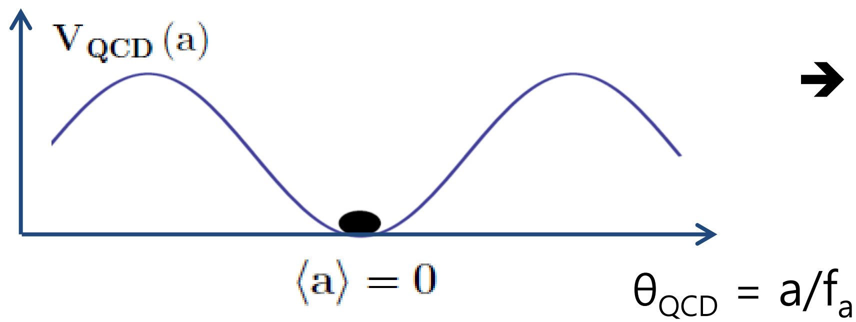
Introduce a spontaneously broken global U(1) symmetry, which is explicitly broken mostly by the QCD anomaly (Peccei-Quinn symmetry '77)

➔ θ_{QCD} becomes a dynamical field "axion" being the Nambu-Goldstone boson of the spontaneously broken PQ symmetry:

$$\frac{1}{32\pi^2}\theta_{\rm QCD}\, F^{a\mu\nu}\tilde{F}^a_{\mu\nu} = \frac{1}{32\pi^2}\frac{\langle a\rangle}{f_a} F^{a\mu\nu}\tilde{F}^a_{\mu\nu}$$

f_a = Axion scale = Mass scale of the spontaneous breaking of $U(1)_{PQ}$

Low energy QCD dynamics develops an axion potential minimized at $\langle a \rangle = 0$:



➔ QCD becomes CP conserving after the axion is settled down at its VEV.

Most of axion physics is determined by the axion scale f_a

* axion mass: $m_a \sim 5 \times 10^{-6} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right) \mathrm{eV}$

* axion-photon couplings

$$\frac{g_{a\gamma\gamma}}{2} a\vec{E}\cdot\vec{B} \;:\; g_{a\gamma\gamma} \sim 10^{-15} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right) \mathrm{GeV}^{-1}$$

* axion-nucleon couplings

$$g_{aNN} a\bar{N}\gamma_5 N \;:\; g_{aNN} \sim 10^{-12} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

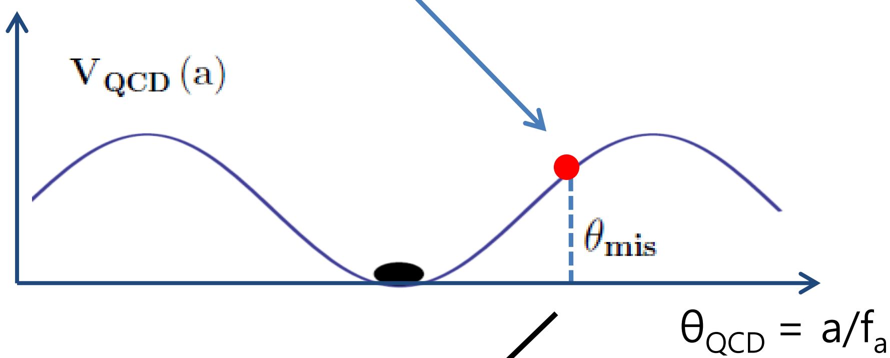
Star cooling by axion emission: $f_a > 4 \times 10^8$ GeV

➔ $\tau_a \gg 10^{17}$ sec, so once axions were produced in the early universe, they constitute (part of) the DM in the present universe.

Cosmological production of the QCD axion dark matter

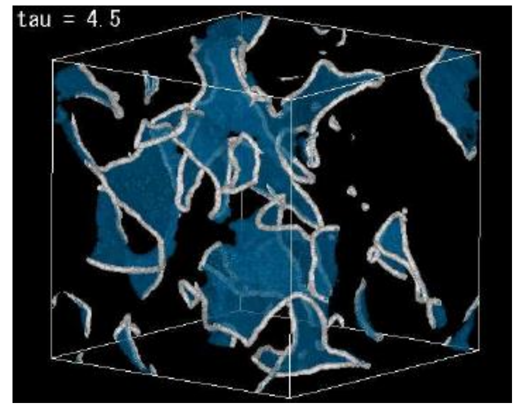
Misalignment

Initial axion field misaligned
from the minimum of the axion potential



Topological defects

axionic string attached by domain wall



Kawasaki et al '14

$$\Omega_a \sim 0.2\,\left(\,\langle\theta^2_{mis}\rangle + (10-20)\,\right)\left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6}$$

(if exists, the defect contribution dominates over the misalignment contribution!)

Axions from both misalignment and topological defects are produced when $m_a(t) \sim H(t)$, and subsequently evolve like non-relativistic matter, so their relic densities have a common dependence on f_a.

QCD axion has a good potential to be experimentally tested!

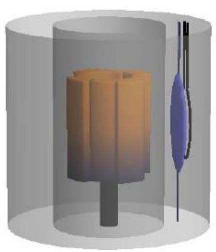
Axion dark matter

Astrophysical bound

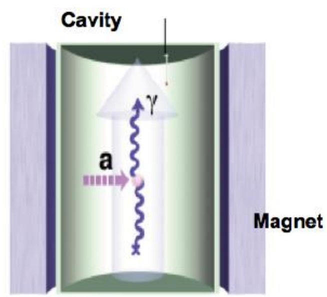
f_a 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{15} 10^{16} 10^{17} 10^{18} (GeV)

Axion mediated force

(Arvanitaki & Geraci '14)



Resonant cavity:



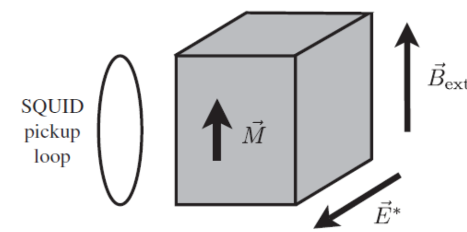
(Sikivie '83)

IAXO:

Next generation of axion helioscope

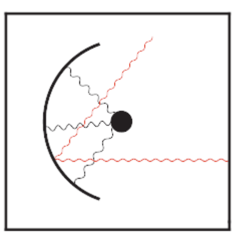
Oscillating EDM induced by oscillating DM axions

(Graham & Rajendran '13)



Dish antenna

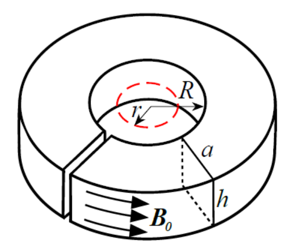
(Horns et al '12)



ABRACADABRA:

Effective current induced by oscillating DM axions

(Kahn, Safdi & Thaler '16)



Axion cosmology

Axion cosmology depends crucially on how the PQ symmetry is realized during the early universe inflation.

Pre-inflation scenario:

PQ symmetry is spontaneously broken during the inflation epoch, and the spontaneously broken phase is kept until today.

Post-inflation scenario:

There has been a phase of restored PQ symmetry after inflation, so the last PQ phase transition from the restored phase to the spontaneously broken phase took place after the inflation is over.

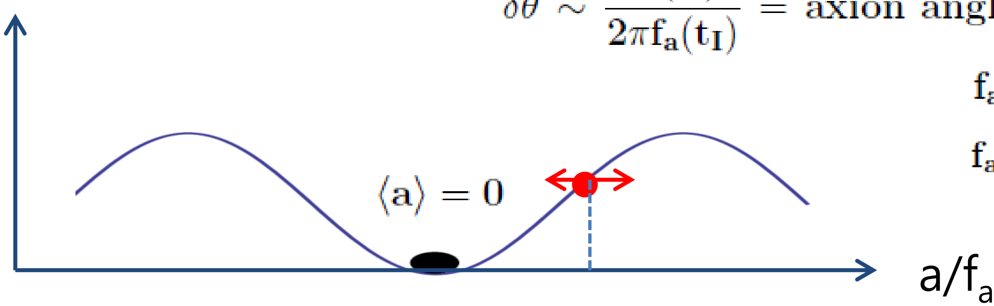
Pre-inflation scenario:

No axionic strings or domain walls, but the axion field could have a nonzero misalignment together with a fluctuation generated during the inflation period:

$$\delta\theta \sim \frac{\mathrm{H}(\mathrm{t_I})}{2\pi \mathrm{f_a}(\mathrm{t_I})} = \text{axion angle fluctuation generated during inflation}$$

$\mathrm{f_a}(\mathrm{t_0}) = \text{axion scale today}$

$\mathrm{f_a}(\mathrm{t_I}) = \text{axion scale during inflation}$



$$\theta_0 = \langle\theta_{\rm mis}\rangle = \text{Averaged axion misalignment angle}$$

Relic axion dark matter: Preskill, Wise, Wilczek '83; Abbott , Sikivie '83; Dine, Fischler '83; ...

$$\Omega_{\rm a} \sim 0.2\,(\theta_0^2 + \delta\theta^2)\left(\frac{\mathrm{f_a}}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \qquad \left(\,\langle\theta_{\rm mis}^2\rangle = \theta_0^2 + \delta\theta^2\,\right)$$

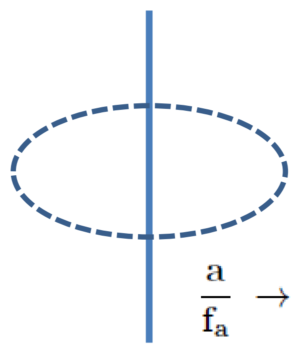
Axion isocurvature perturbation: Axenides, Brandenberger, Turner '83; Fox, Pierce, Thomas '04; ...

$$\left(\frac{\delta \mathrm{T}}{\mathrm{T}}\right)_{\rm iso} \sim \frac{\Omega_{\rm a}}{\Omega_{\rm DM}}\frac{\delta\theta}{\theta_0} \sim \left(\frac{\Omega_{\rm a}}{\Omega_{\rm DM}}\right)^{1/2}\left(\frac{\mathrm{f_a}(\mathrm{t_0})}{10^{12}\,\mathrm{GeV}}\right)^{7/12}\left(\frac{\mathrm{H}(\mathrm{t_I})}{\pi \mathrm{f_a}(\mathrm{t_I})}\right) < 10^{-5}$$

Post-inflation scenario:

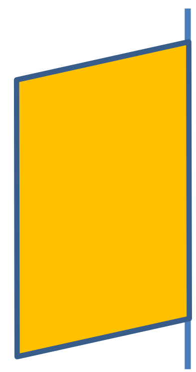
There are axionic strings attached by N_{DW} domain walls, which would cause cosmological domain wall problem unless $N_{DW} = 1$:

Axionic string produced during the PQ phase transition



$$\frac{a}{f_a} \to \frac{a}{f_a} + 2\pi$$

Domain walls attached to strings, which are formed during the QCD phase transition



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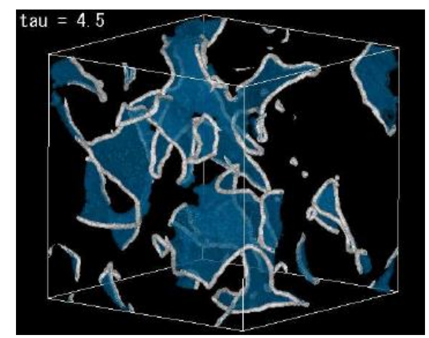


To avoid the overclosure due to stable string-wall networks (=domain wall problem), we need

$$N_{DW} = \sum_i q_i \mathrm{Tr}(T_c^2(\psi_i)) = 1$$

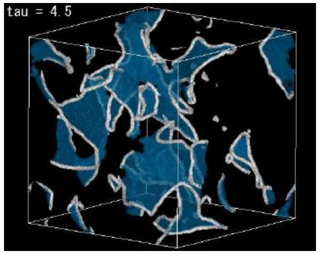
Then the axion DM is mostly from the collapsing string-wall system, yielding

$$\Omega_a \sim 0.2 \left(\frac{f_a}{10^{11}\mathrm{GeV}} \right)^{7/6}$$

Davis '86; Davis, Harari, Sikivie '87; Davis, Shellard '89; ...

Axion dark matter

Post-inflation

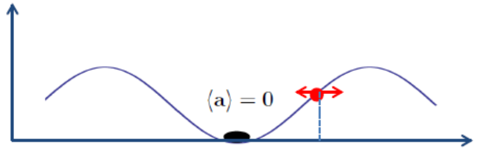


$$\Omega_a \sim 0.2 \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^{7/6}$$

$$N_{DW} = \sum_i q_i \mathrm{Tr}(T_c^2(\psi_i)) = 1$$

Pre-inflation:

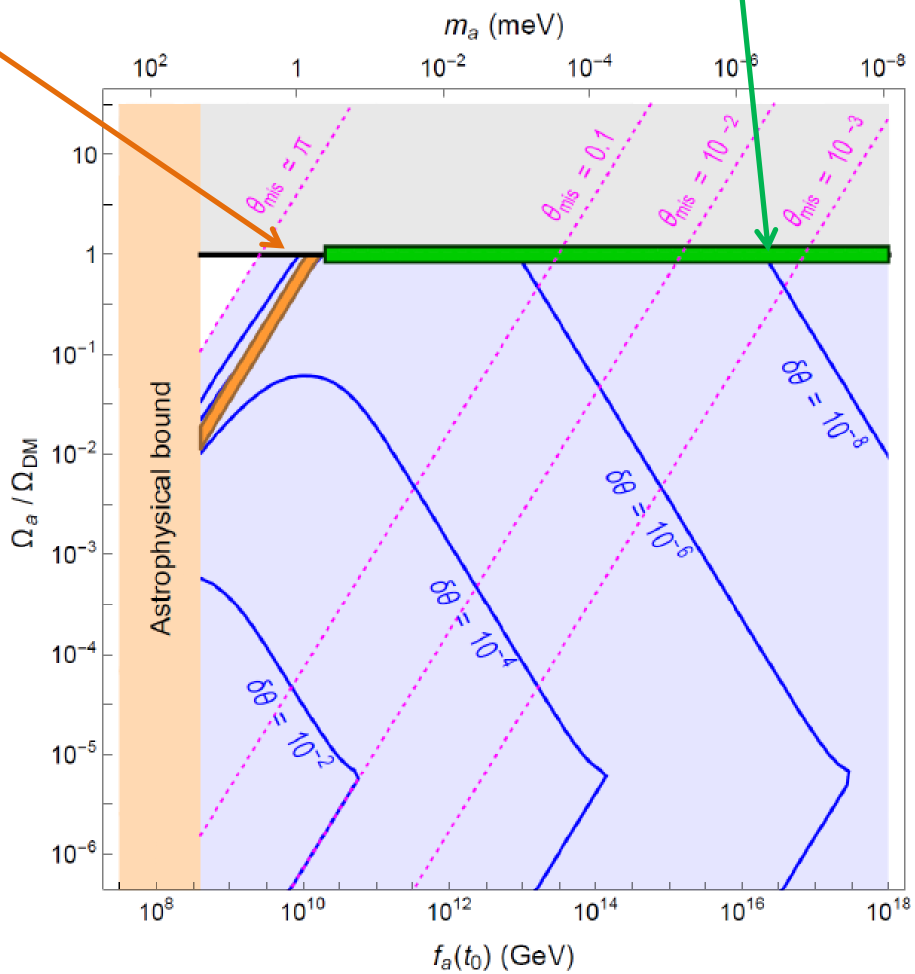
$$\Omega_a \sim 0.2 \langle \theta_{mis}^2 \rangle \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$



$$\langle \theta_{mis}^2 \rangle = \theta_0^2 + \delta\theta^2$$

$$\delta\theta \sim \frac{H(t_I)}{2\pi f_a(t_I)}$$

$$\left(\frac{\delta T}{T}\right)_{iso} \sim \frac{\Omega_a}{\Omega_{DM}} \frac{\delta\theta}{\theta_0} < 10^{-5}$$



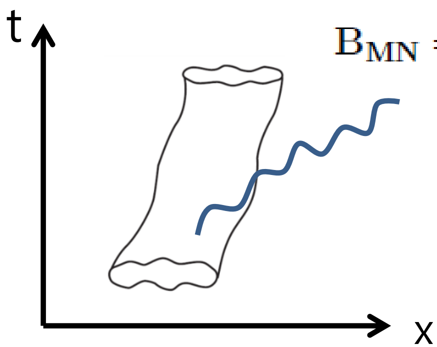
anthropic axion DM

KC, Jeong, Seo '14

Any hint on axion scale from theory?

Axions in string theory

Extended objects in string theory predict antisymmetric tensor gauge fields which couple to their world-volume:



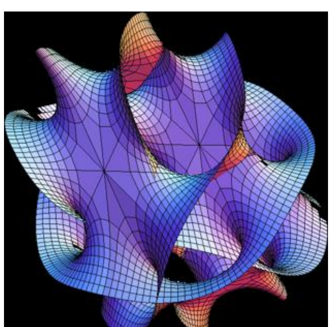
$$\mathrm{B_{MN}} = -\mathrm{B_{NM}}$$

$$\mathrm{S_{WS}} = \int \mathrm{d}^2\sigma \left(\mathrm{g_{MN}} \partial_\alpha \mathrm{X^M} \partial^\alpha \mathrm{X^N} + \mathrm{B_{MN}} \epsilon_{\alpha\beta} \partial^\alpha \mathrm{X^M} \partial^\beta \mathrm{X^N} \right)$$

with higher-dimensional gauge symmetry:

$$\delta \mathrm{B_{MN}} = \partial_{[\mathrm{M}} \Lambda_{\mathrm{N}]} \qquad (\mathrm{M}, \mathrm{N} = 0, 1, ..., 9)$$

Upon compactification, antisymmetric tensor field in extra-dimensional directions can be identified as 4-dimensional pseudo-scalar axions:

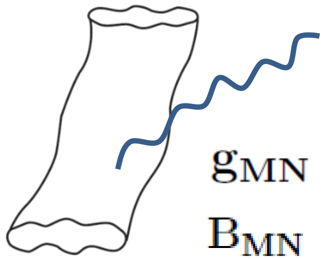


6D internal space

$$\mathrm{B_{mn}} = \sum_{\mathrm{2-cycles}} \mathrm{a_i(x)}\, \omega^{\mathrm{i}}_{\mathrm{mn}}(\mathrm{y})$$

$$\left(\mathrm{x^M} = (\mathrm{x}^\mu, \mathrm{y^m}) = (\text{4D Minkowski}, \ \text{6D internal}) \right)$$

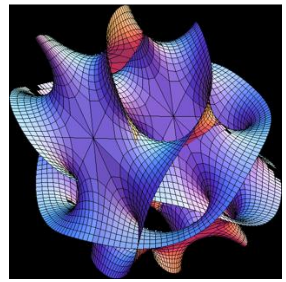
* Axion scales determined by compactification



g_{MN}

B_{MN}

Compactification



$g_{\mu\nu}$

$$B_{mn}(x, y) = a(x)\,\omega_{mn}(y)$$

gravity–axion unification

$$\rightarrow \quad f_a \sim \frac{g_{GUT}^2}{8\pi^2} M_{Planck} \sim 10^{16}\,\mathrm{GeV}$$

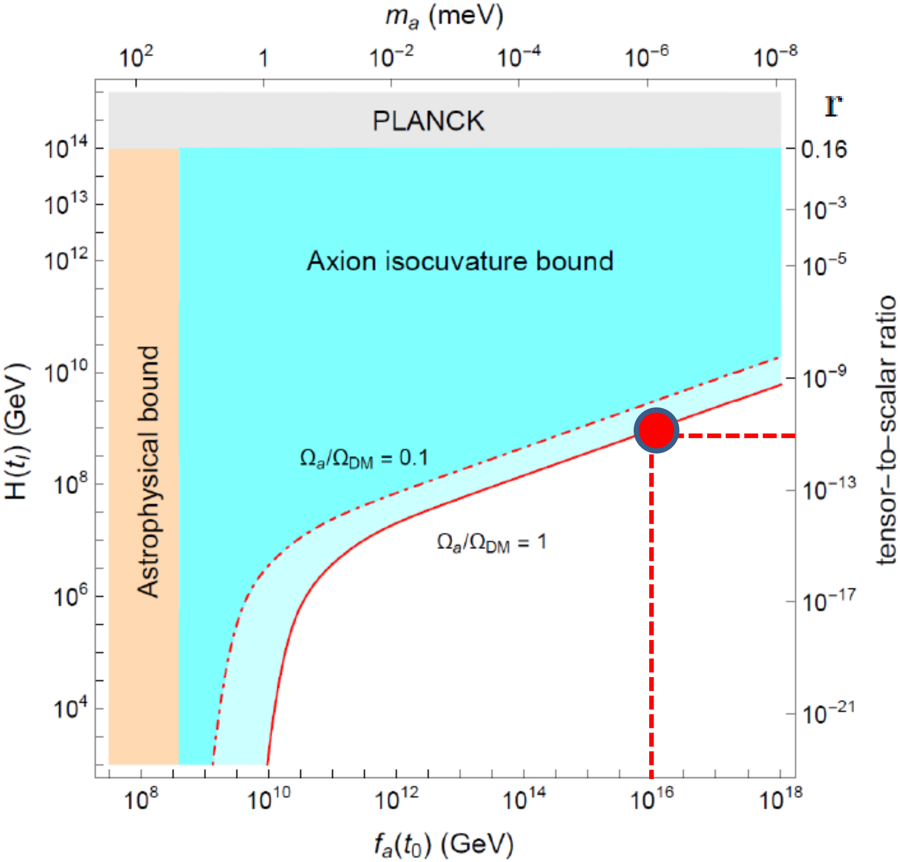
KC, Kim '85; Svrcek, Witten '06

Compactification should occur before the end of inflation, then the axion cosmology follows the pre-inflation scenario with

$$f_a(t_I) \sim f_a(t_0) \sim 10^{16}\,\mathrm{GeV}$$

Stringy axion DM with $f_a(t_I) \sim f_a(t_0) \sim 10^{16}\,\mathrm{GeV}$ is severely constrained by the axion isocurvature perturbation:

$$\left(\frac{\delta T}{T}\right)_{\rm iso} \sim \frac{\Omega_a}{\Omega_{\rm DM}}\frac{\delta\theta}{\theta_0} < 10^{-5} \quad \text{with} \quad \delta\theta \sim \frac{H(t_I)}{2\pi f_a(t_I)}$$



Stringy inflation scenario

String Scenario	n_s	r
D3/$\overline{\rm D3}$ Inflation	$0.966 \le n_s \le 0.972$	$r \le 10^{-5}$
Inflection Point Inflation	$0.92 \le n_s \le 0.93$	$r \le 10^{-6}$
DBI Inflation	$0.93 \le n_s \le 0.93$	$r \le 10^{-7}$
Wilson Line Inflation	$0.96 \le n_s \le 0.97$	$r \le 10^{-10}$
D3/D7 Inflation	$0.95 \le n_s \le 0.97$	$10^{-12} \le r \le 10^{-5}$
Racetrack Inflation	$0.95 \le n_s \le 0.96$	$r \le 10^{-8}$
N − flation	$0.93 \le n_s \le 0.95$	$r \le 10^{-3}$
Axion Monodromy	$0.97 \le n_s \le 0.98$	$0.04 \le r \le 0.07$
Kahler Moduli Inflation	$0.96 \le n_s \le 0.967$	$r \le 10^{-10}$
Fibre Inflation	$0.965 \le n_s \le 0.97$	$0.0057 \le r \le 0.007$
Poly − instanton Inflation	$0.95 \le n_s \le 0.97$	$r \le 10^{-5}$

Burgess, Cicoli, Quevedo '13

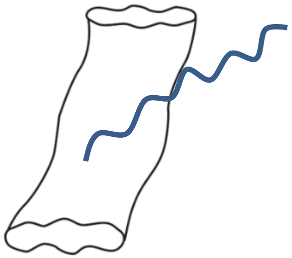
r = tensor to scalar ratio in CMB
= $0.16\,(H/10^{14}\,\mathrm{GeV})^2$

➔ $r <$ few x 10^{-11} which is difficult to be compatible with most of the known stringy inflation scenario

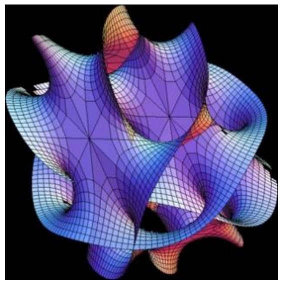
* Axion scale determined by SUSY breaking

KC, Jeong, Okumura, Yamaguchi '11

Compactification



$\mathbf{B_{MN}}$



$$\mathbf{B_{mn}(x,y) = a(x)\,\omega_{mn}(y)}$$

Stuckelberg mixing with an anomalous $U(1)_A$ gauge boson:

$$\mathcal{L}_{\mathbf{Stuckelberg}} = \frac{\mathbf{1}}{\mathbf{2}}(\partial_\mu \mathbf{a} + \mathbf{M_A A_\mu})^{\mathbf{2}} + |(\partial_\mu + \mathbf{igA_\mu})\phi|^{\mathbf{2}}$$

$$\left(\mathbf{M_A} \sim \frac{\mathbf{g^2}}{\mathbf{8\pi^2}}\mathbf{M_{Planck}}\right)$$

The stringy axion "a" from antisymmetric tensor field is eaten by the $U(1)_A$ gauge boson, while leaving instead another axion which originates from the phase of $U(1)_A$-charge complex scalar field ϕ :

$$\mathbf{f_a} = \langle \phi \rangle$$

Typically $\mathbf{N_{DW}} = \sum \mathbf{q_i Tr(T_c^2(\psi_i))} > \mathbf{1}$ in this scenario, so one should follow again the pre-inflation scenario to avoid the domain wall problem.

Axion scale determined by SUSY breaking

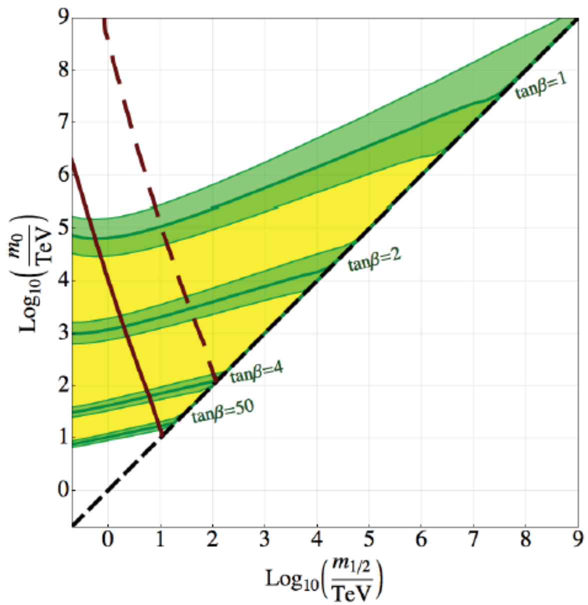
KC, Jeong, Seo '14

$$V(\phi) = m_\phi^2|\phi|^2 + \frac{|\lambda|^2}{M_{Planck}^2}|\phi|^6 \quad \text{with} \quad m_\phi^2 = q_\phi D_A + \ldots < 0$$

$$(D_A = \text{SUSY-breaking D-term of } U(1)_A,\ q_\phi = U(1)_A \text{ charge of } \phi)$$

$$D_A(t_0) \sim m_{SUSY}^2, \quad D_A(t_I) \sim \frac{8\pi^2}{g^2}H^2(t_I)$$

➔ $f_a(t_0) \sim \sqrt{m_{SUSY}M_{Planck}}$, $f_a(t_I) \sim \sqrt{\frac{8\pi^2}{g^2}H(t_I)M_{Planck}}$



Arvanitaki et al' 12

* LHC SUSY search: $m_{SUSY} > 1$ TeV

* m_{higgs} = 125 GeV: $m_{SUSY} < 10^4 - 10^7$ TeV

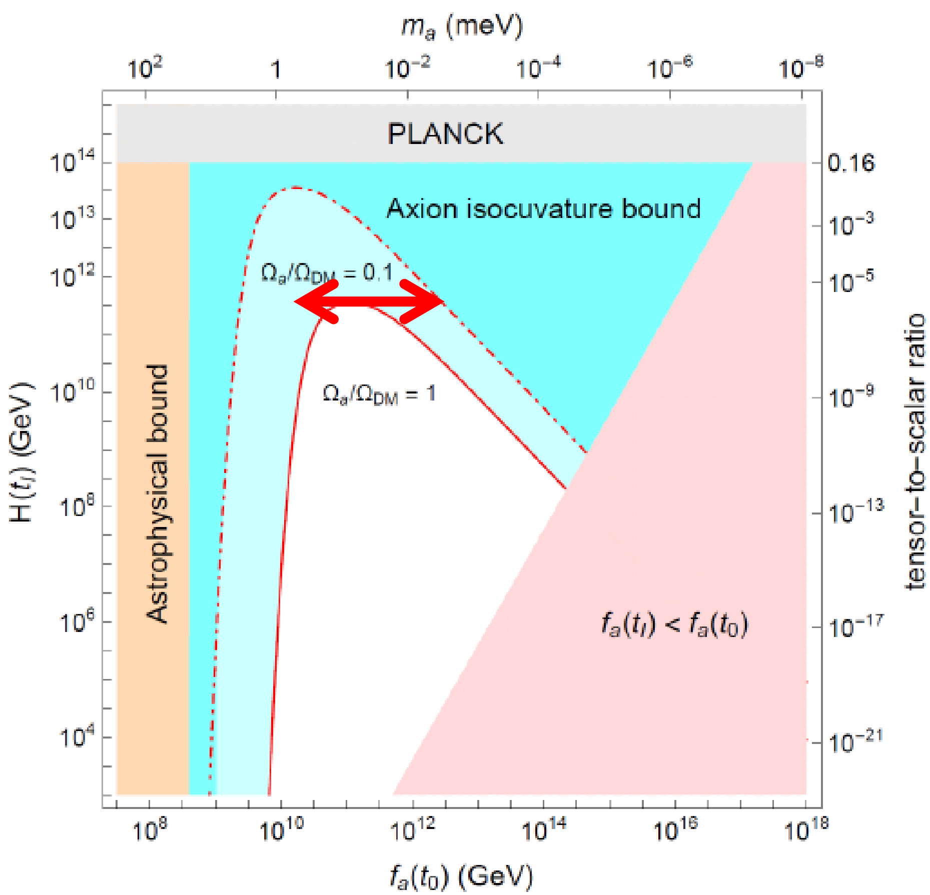
* Gauge coupling unification: $m_{SUSY} < 10^3$ TeV

➔ $f_a(t_0) \sim 10^{10} - 10^{12}$ GeV

$$f_a(t_I) \sim \sqrt{\frac{8\pi^2}{g^2}H(t_I)M_{Planck}}$$

* Isocurvature constraint on axion scale determined by SUSY breaking

$$f_a(t_0) \sim \sqrt{m_{SUSY} M_{Planck}} \sim 10^{10} - 10^{12}\,\text{GeV}\ , \quad f_a(t_I) \sim \sqrt{\frac{8\pi^2}{g^2} H(t_I) M_{Planck}}$$



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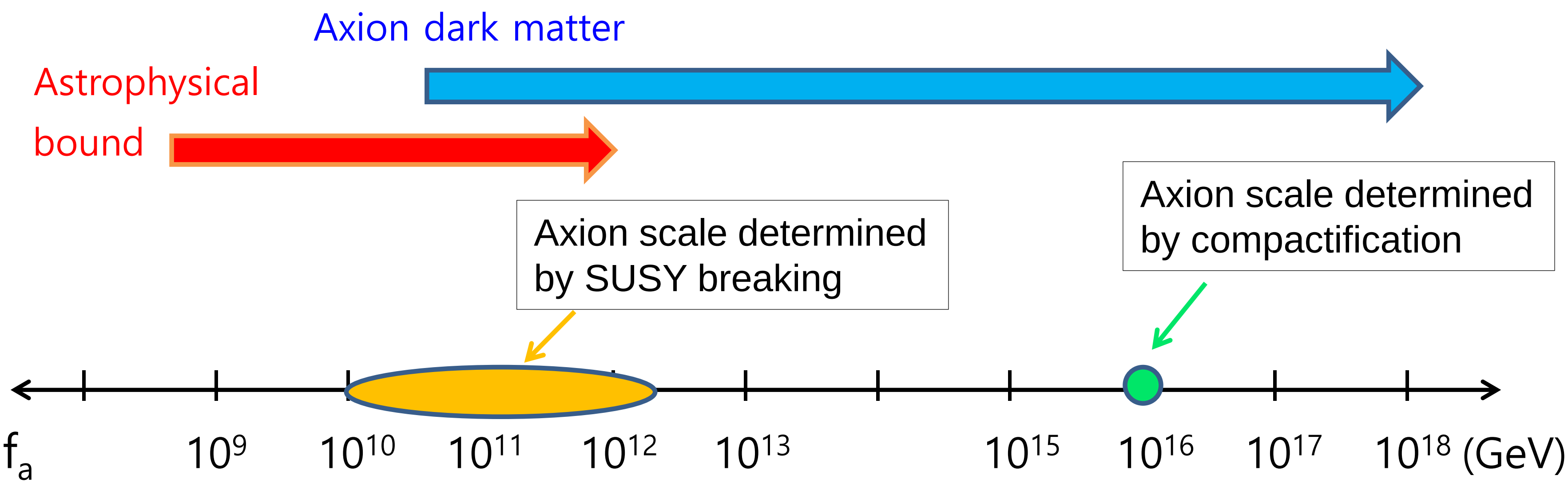
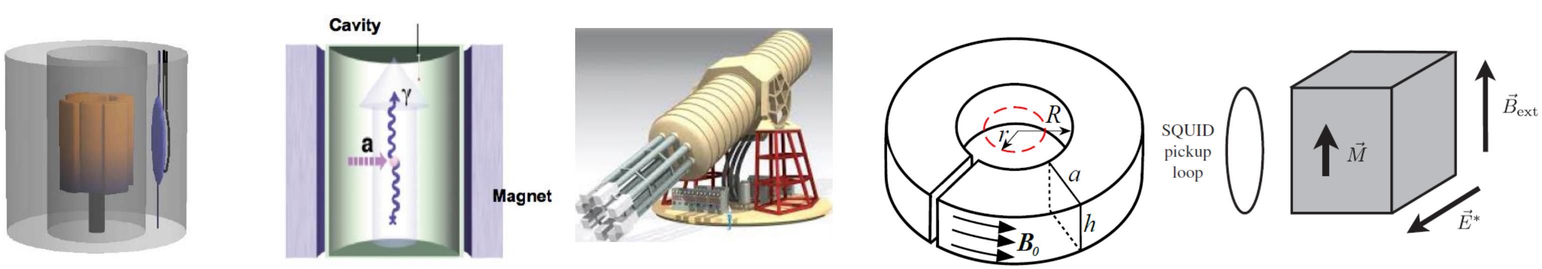
Kahler Moduli Inflation	$0.96 \le n_s \le 0.967$	$r \le 10^{-10}$
Fibre Inflation	$0.965 \le n_s \le 0.97$	$0.0057 \le r \le 0.007$
Poly − instanton Inflation	$0.95 \le n_s \le 0.97$	$r \le 10^{-5}$

This scenario can be consistent with most of the known string inflation model.

Where is axion?





DM studies in IBS

IBS includes 28 research centers for basic science (math, physics, chemistry, life science), and there are three research centers related to DM physics:

* Center for Theoretical Physics of the Universe (CTPU)
* Center for Axions and Precision Physics (CAPP)
* Center for Underground Physics (CUP)

Center for Axion and Precision Physics (CAPP)

Projects : Search for axion dark matter, Detection of axion-mediated long range forces, R&D for storage ring proton EDM experiment

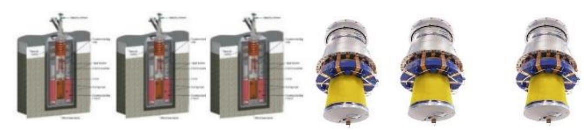
Members :

- 1 Director
- 1 Group Leader
- ~25 Research Fellows
- 2 Engineers
- 6 Administrators
- ~15 Graduate Students

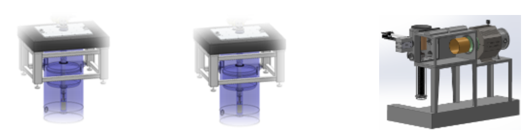
Refurbishing a state of the art lab in an existing bldg.

State of the art infra-structure:

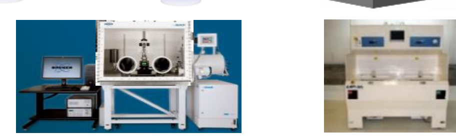
*** 7 low vibration pits for parallel experiments**



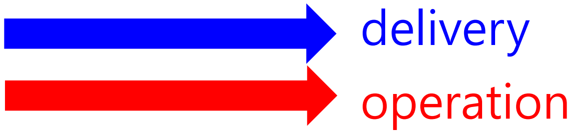
*** 6 high power dilution refrigerators**

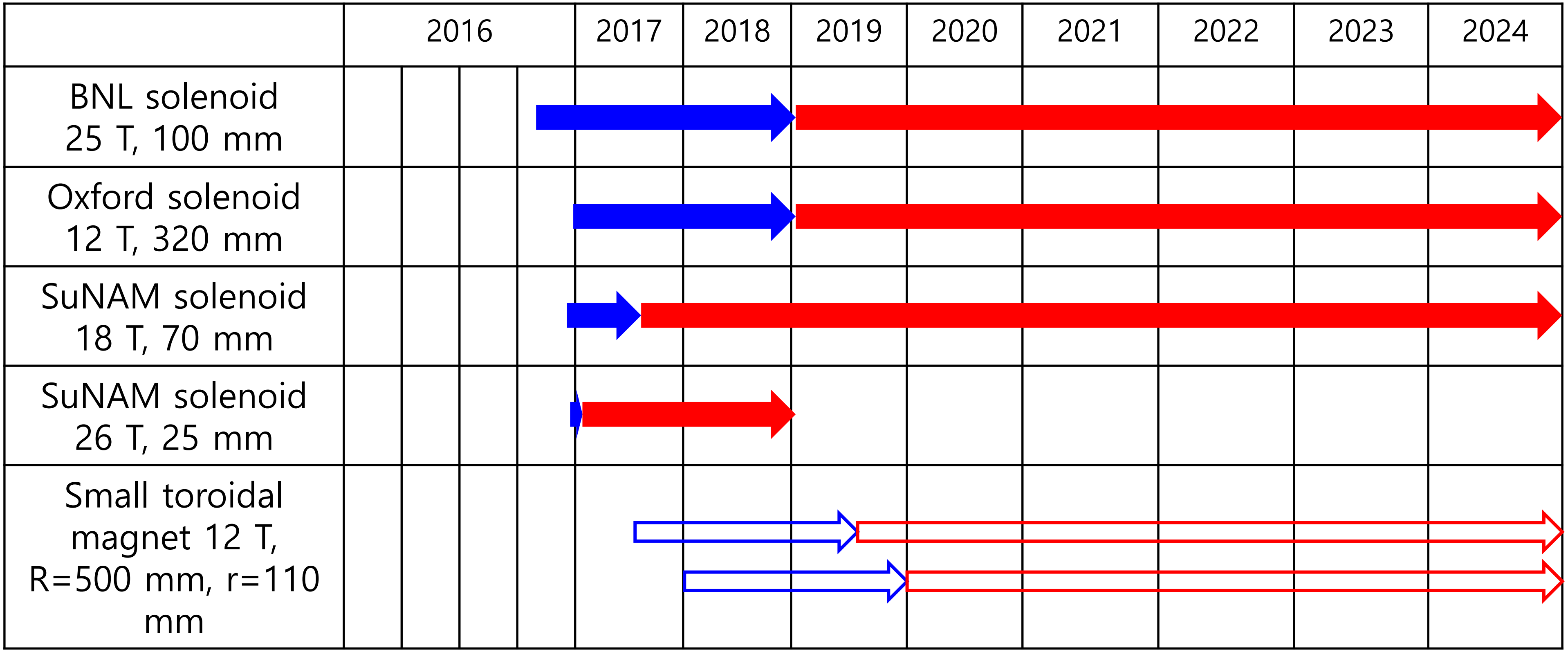


*** high B-field magnets: 25T, 18T, 12T**



Magnet schedule

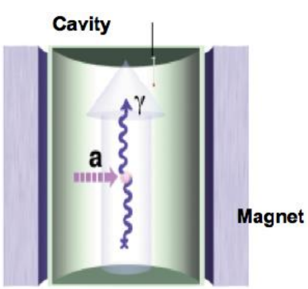




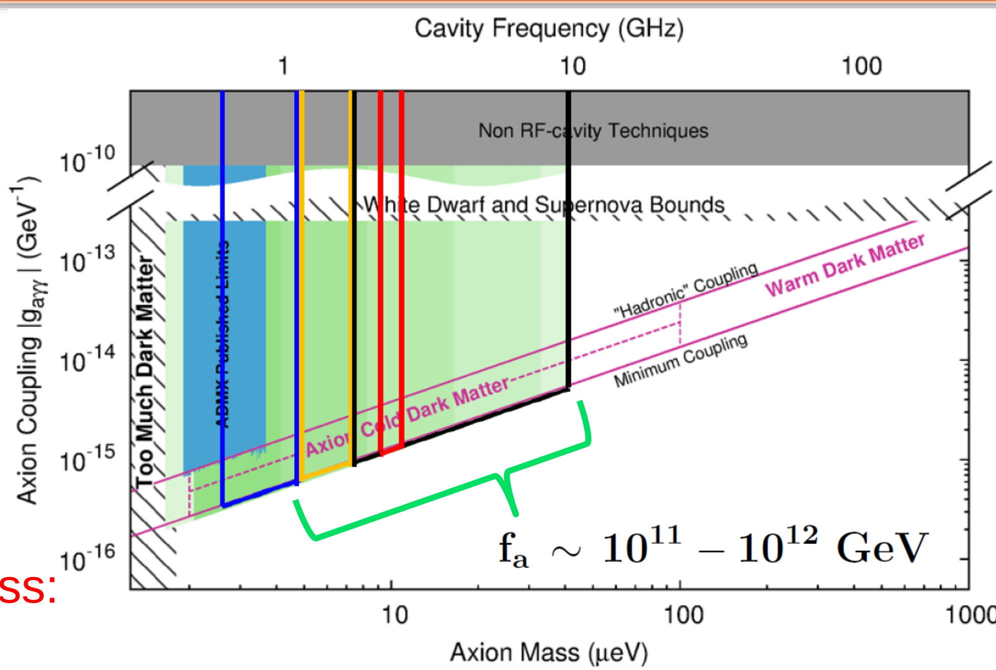
- 26 T/25 mm solenoid : operation schedule?
- small toroidal magnet : depends on the starting point

Expected axion mass range per magnet

location	magnet	Fridge	Search range
C105	dry 8T/110mm	dry DF	
C105	dry 8T/155mm	dry DF	
Pit3	wet 12T/180mm toroid	wet DF (need ~50 liters ^{3}He)	1~2 GHz
Pit4	wet 9T/5inches	wet ^{3}He	
Pit5	wet 12T/320mm	wet DF (need ~50 liters ^{3}He)	0.5~1.3 GHz
Pit6	wet 20T/65mm	dry DF	3~4 GHz
Pit7	wet 25T/100mm	dry DF	2~10 GHz



In few years, CAPP will override the ADMX sensitivity, and explore new territory with heavier axion mass:



Axions with ARIADNE:
Axion Resonant InterAction DetectioN Experiment

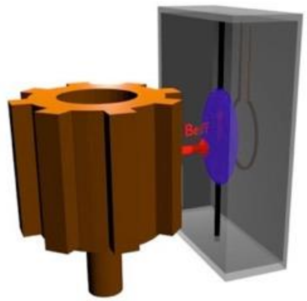
PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

New macroscopic forces?

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 17 January 1984)

The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the *T*-violating axion monopole-dipole forces are proposed.

Detection of
axion-mediated
long range force



Center for Underground Physics (CUP)

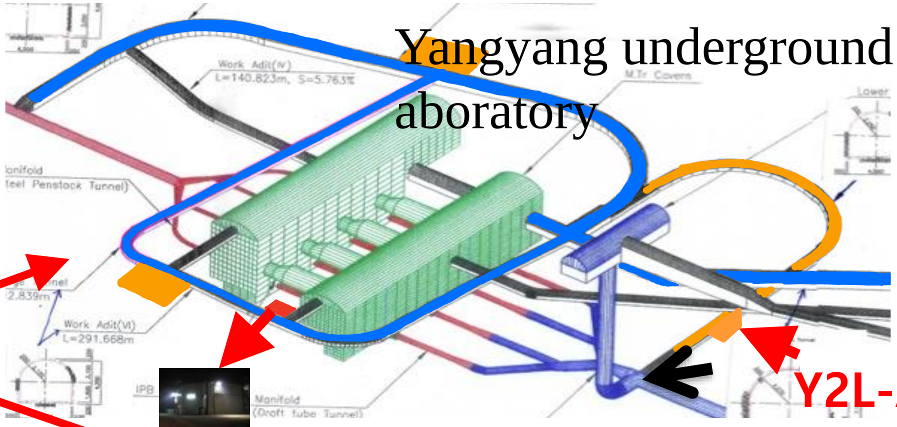
Projects : Search for WIMP-like dark matter (KIMS+),
Double Beta Decay (AMoRE), Low temperature Detectors.

Members :

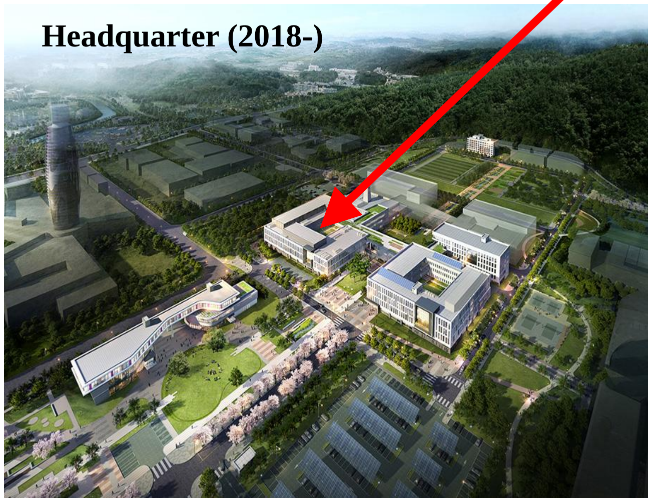
- 1 Director
- 2 Group Leaders
- ~25 Research Fellows
- 6 Technicians
- 3 Administrators
- ~25 Adjunct Students.

Labs.

Yangyang underground laboratory

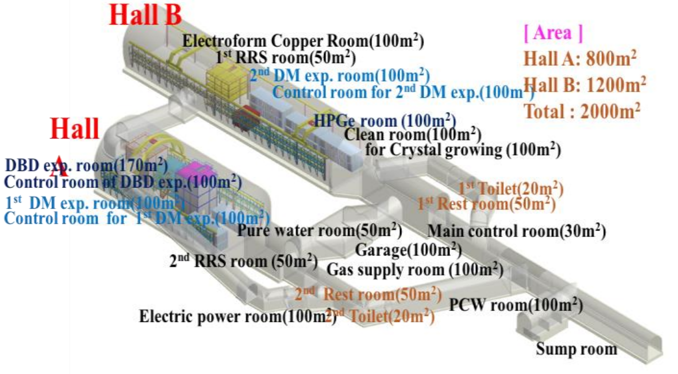


Y2L-A6



Current Daejeon Lab.

New underground lab. (2019-)

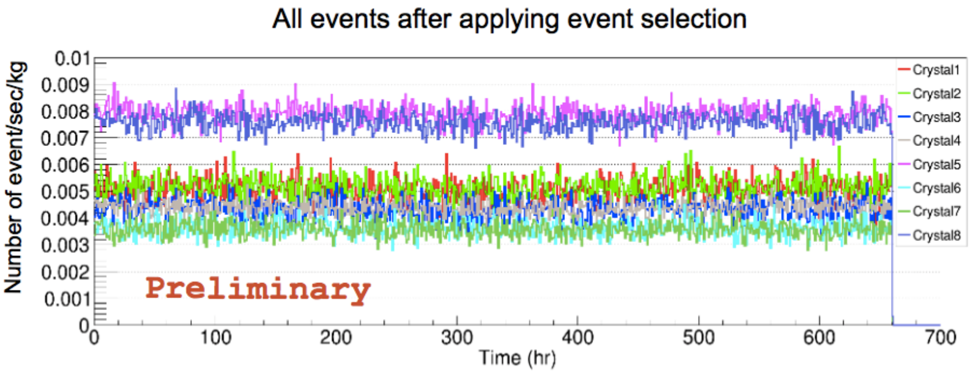


Projects at CUP

1. COSINE-100 (Collaboration Of Sodium IodiNe Experiments)

- DM-ICE group + KIMS-NaI group → COSINE at Y2L.
- 200 kg NaI(Tl) crystals inside liquid scintillator active veto.
- Phase I (100 kg) commissioned in Oct, 2016. → running stable.
- Develop purer crystals → Phase II exp. (2018-2019)

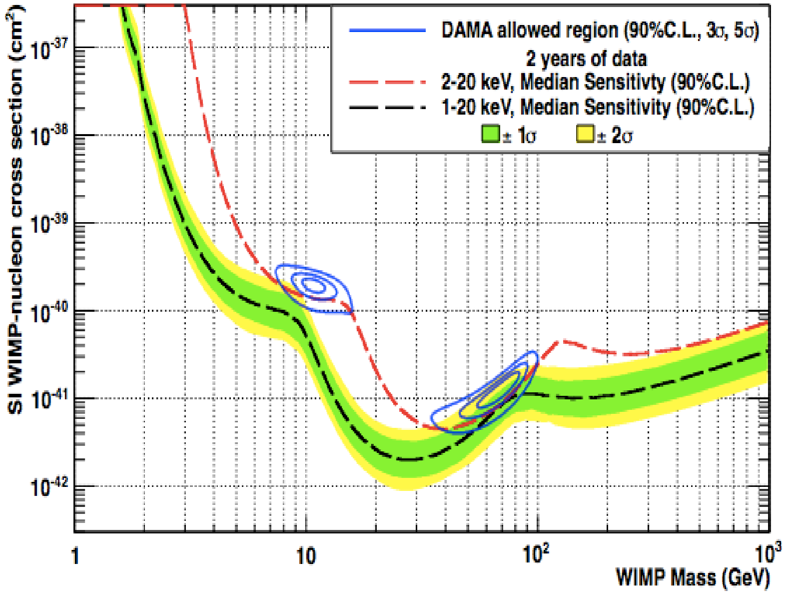
Event rate



One month data - 100% DAQ time.

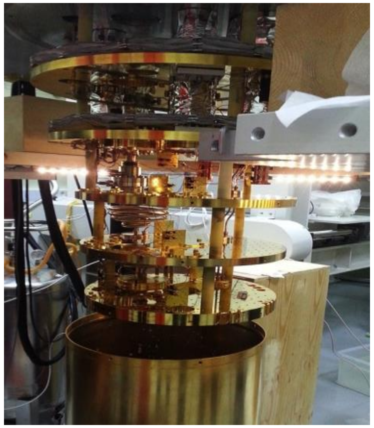
Current set of event selection applied (not final!).

Expected Sensitivity for COSINE-100



**Assumed 2 dru or 4 dru flat backgrounds depending on crystals.*

2. AMoRE ββ experiment



^{100}Mo double beta decay experiment.

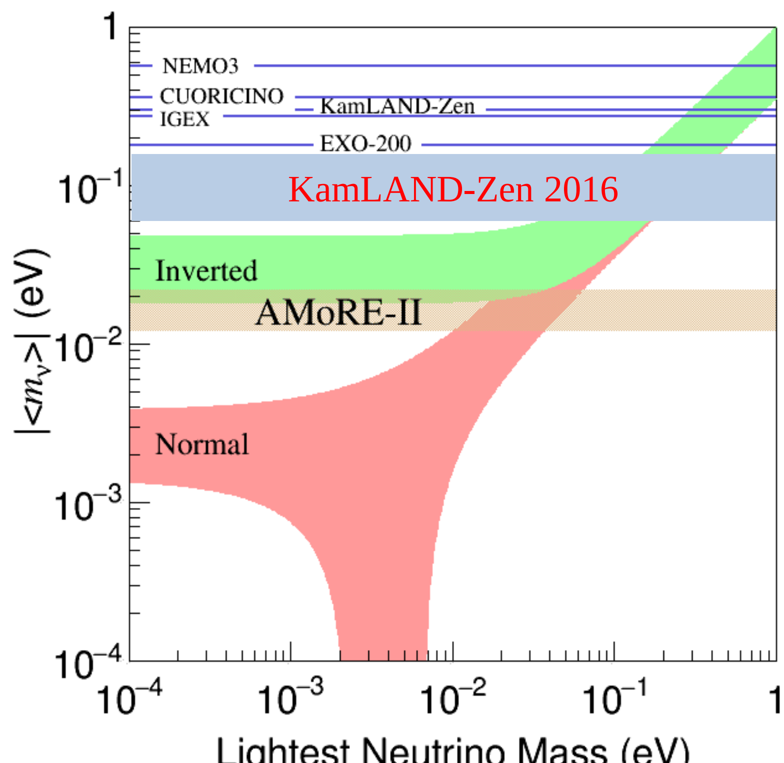
- **Scintillating crystals at 10mK temperature.**
- **R&D for $CaMoO_4$, Li_2MoO_4, $Na_2Mo_2O_7$**
- **AMoRE-I : 5kg crystals (2017-2018)**
- **AMoRE-II : 200 kg of (X)$^{100}MoO_4$ crystals. (2020-2022)**
- **Ultra-low background crystals are grown at CUP.**

$CaMoO_4$

CZ01_1502 annealing

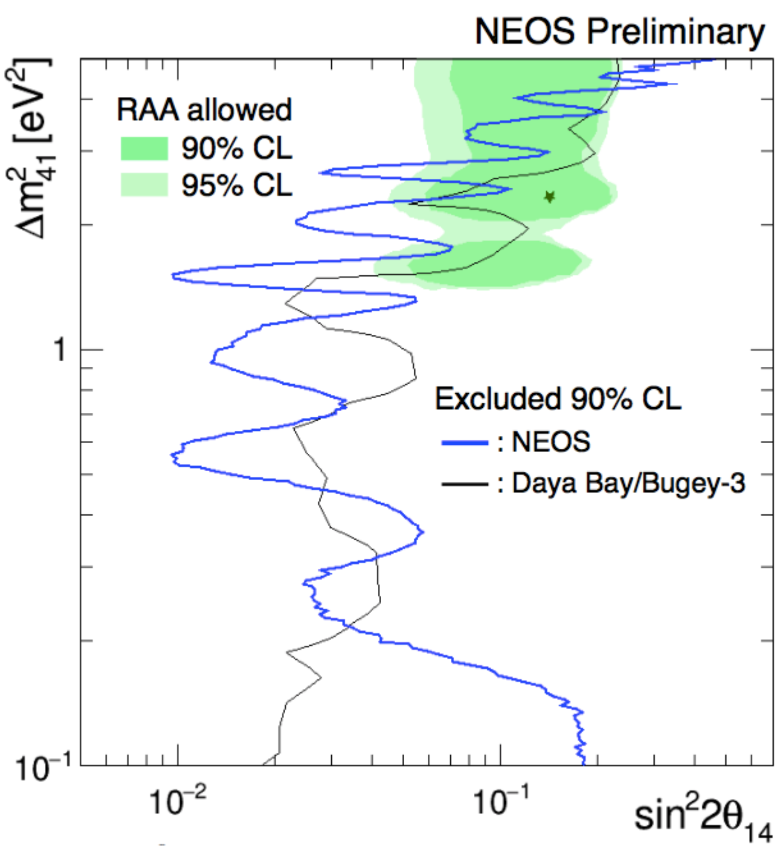
CZ01_1604 annealing

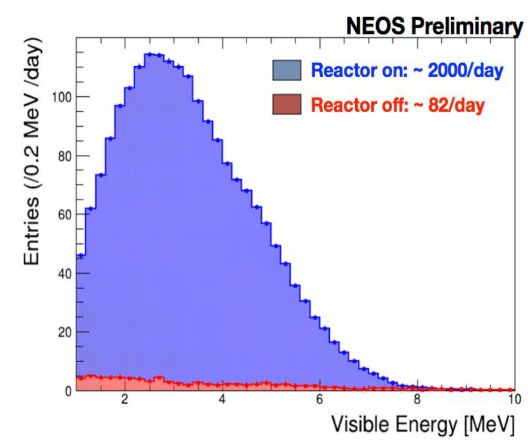
$Na_2Mo_2O_7$



3. NEOS (Neutrino Experiment for Oscillation at Short baseline)

- **Short baseline reactor neutrino experiment for sterile neutrino.**
- **Data taken for 6 months, with best signal to background ratio.**
- **Disfavored the best parameters from reactor anomaly with best limits for theta 14 around ~ eV mass region.**
- **NEOS-II can be set at closer position at Russian reactor.**





Conclusion

- The QCD axion, which was introduced originally to solve the strong CP problem, is one of the most compelling candidate for dark matter, and may have a good chance to be discovered in near future.

- String theory provides the best theoretical framework to realize the axion solution to the strong CP problem, and then there are two particularly interesting range of the axion scale suggested by string theory:

$$f_a \sim 10^{10} - 10^{12}\ \mathrm{GeV} \quad \text{and} \quad f_a \sim 10^{16}\ \mathrm{GeV}$$

- The IBS Center for Axion and Precision Physics (CAPP) has an ambitious plan to search for axion dark matter, which will have an enough sensitivity to detect the axion dark matter with

$$f_a \sim 10^{11} - 10^{12}\ \mathrm{GeV}$$

even when the axions constitute only 10% of the observed DM.