INR, Russia
August 21, 2019

AXION DARK MATTER SEARCH: THE FINAL FRONTIER

YANNIS K. SEMERTZIDIS, IBS/CAPP & KAIST

- Weighing the vacuum using magnets and quantum-noise limited RF amplifiers!
- The technology is here to make decisive axion experiments
- Superconducting devices make all the difference!

CAPP and axion searches

- CAPP: Center for Axion and Precision Physics Research
- CAPP has developed the expertise and the systems needed to search for axions in the 1-10GHz frequency range with high sensitivity
- High-field/high-volume magnets are essential in this regard. Our LTS-12T/320mm, based on Nb_3Sn cable (inner coil) and NbTi (outer coil) has a large B^2V and it is going to be our flagship experiment
- It will be delivered within 2019 or early next year.

IBS/CAPP-Physics
(Established October 2013)

Strong CP problem (Symmetry crisis in strong forces: hadronic EDM exp. Limits too small!)

- Cosmic Frontier (Dark Matter axions): Improve in all possible fronts: B-field, Volume, Resonator Quality factor, Physical and Electronic noise.
- Storage ring proton EDM (most sensitive hadronic EDM experiment). Improve theta_QCD sensitivity by three to four orders of magnitude!
- Together with long-range monopole-dipole (axion mediated) forces probe axion Physics!

Quantum-noise limited RF-amplifiers

- Frequency of interest: 1-10 GHz first phase; 10-20 GHz second phase
- Immediate need: 1.5-2 GHz, 2-3 GHz, 3-7 GHz
- Longer term: 0.7-1.5 GHz, 7-10 GHz, and finally up to 20 GHz

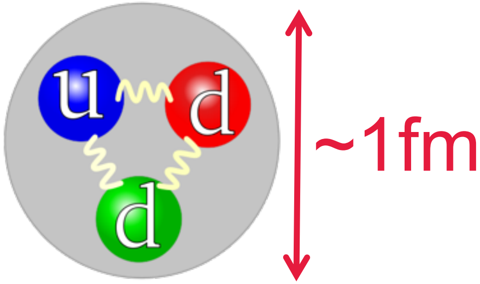
Importance of QNL RF-amplifiers:

- With them, we can reach theoretically interesting sensitivities.

The Strong CP-problem, Axion parameters, Dark Matter

Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\,\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times 10^{-17}\right)\mathrm{e\cdot cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times 10^{-16}\,\bar{\theta}\ \mathrm{e\cdot cm}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

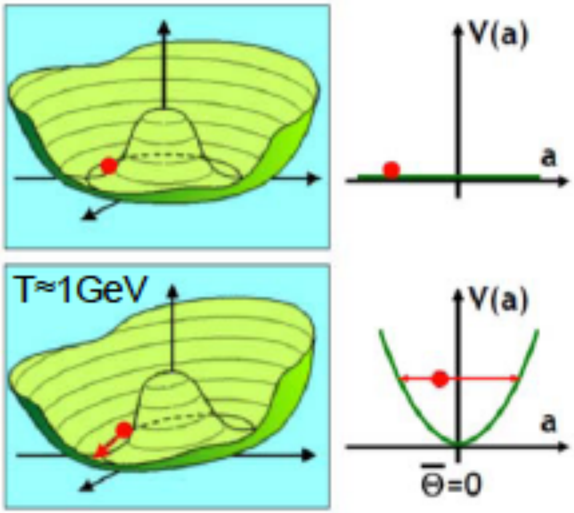
$$\text{Exp.:}\ d_n < 3\times 10^{-26} e\cdot\mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

Strong CP-problem

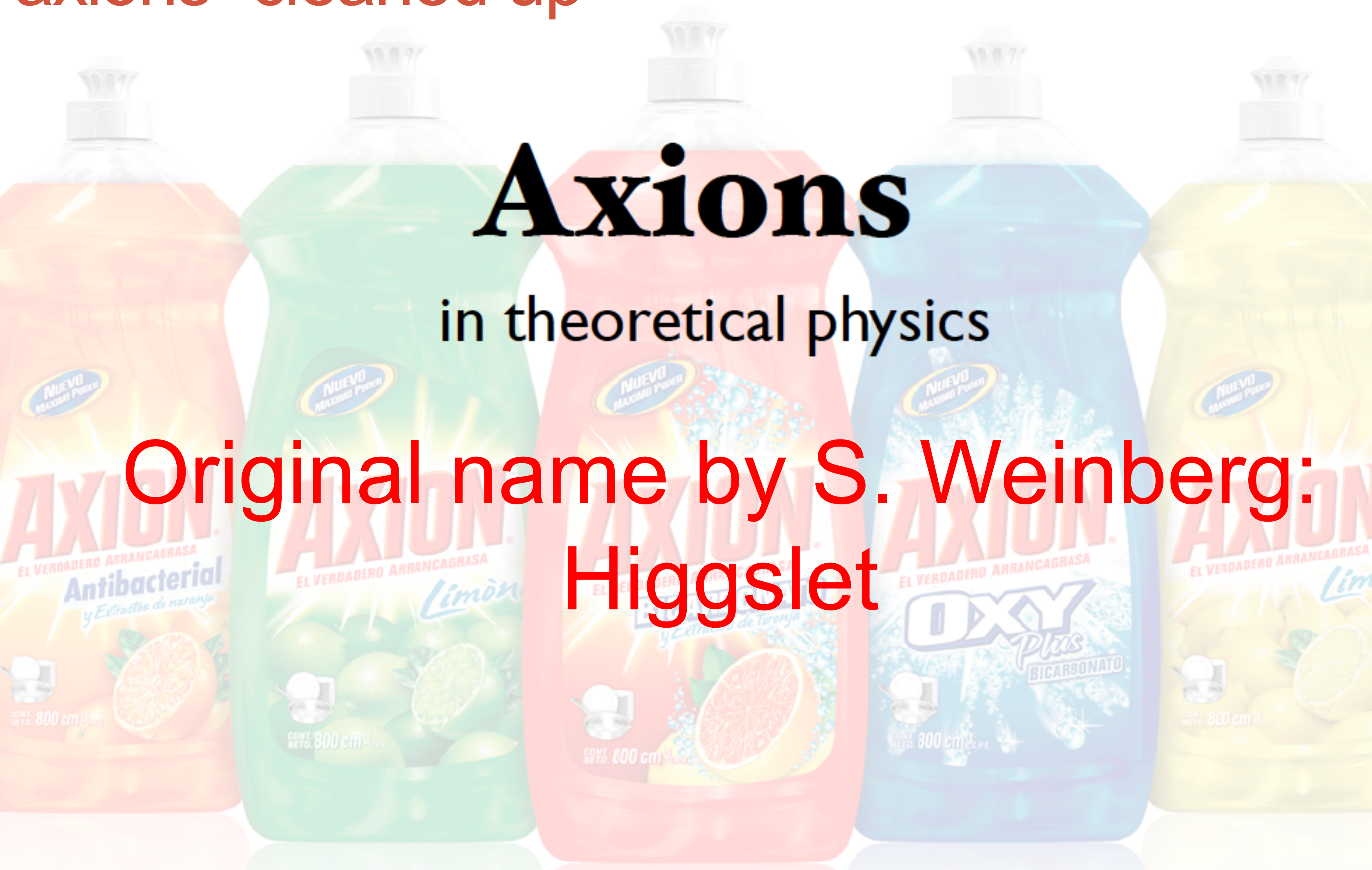
- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally
- Wilczek and Weinberg: axion particle (1977)
- J.E. Kim: Hadronic axions (1979)

- Axions: pseudoscalars, light cousins of neutral pions



$$m_a \approx 6 \times 10^{-6}\ \mathrm{eV}\ \frac{10^{12}\ \mathrm{GeV}}{f_a}$$

Named by Frank Wilczek (Nobel Prize) as axions “cleaned up”



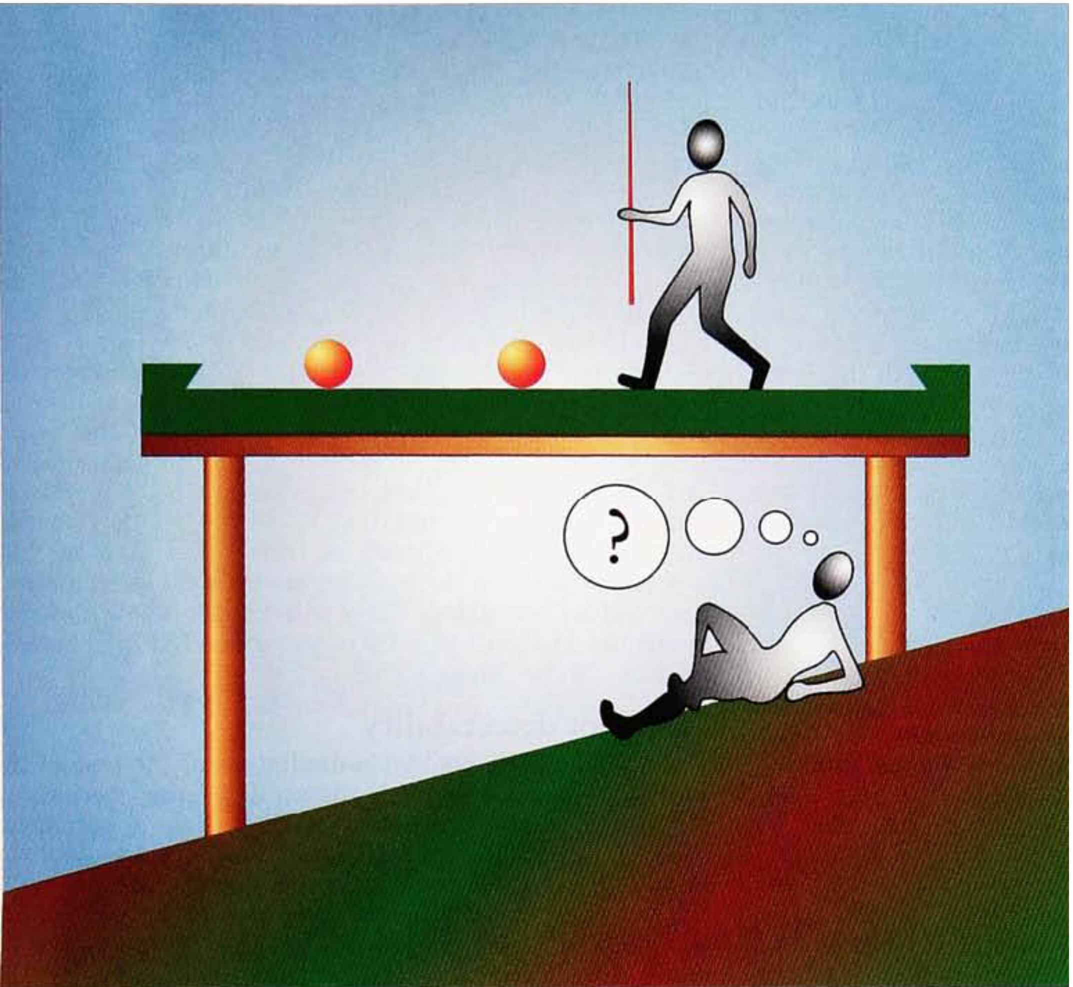
Axions

in theoretical physics

Original name by S. Weinberg: Higgslet

Strong CP-problem: level of pool table to <1 nrad!

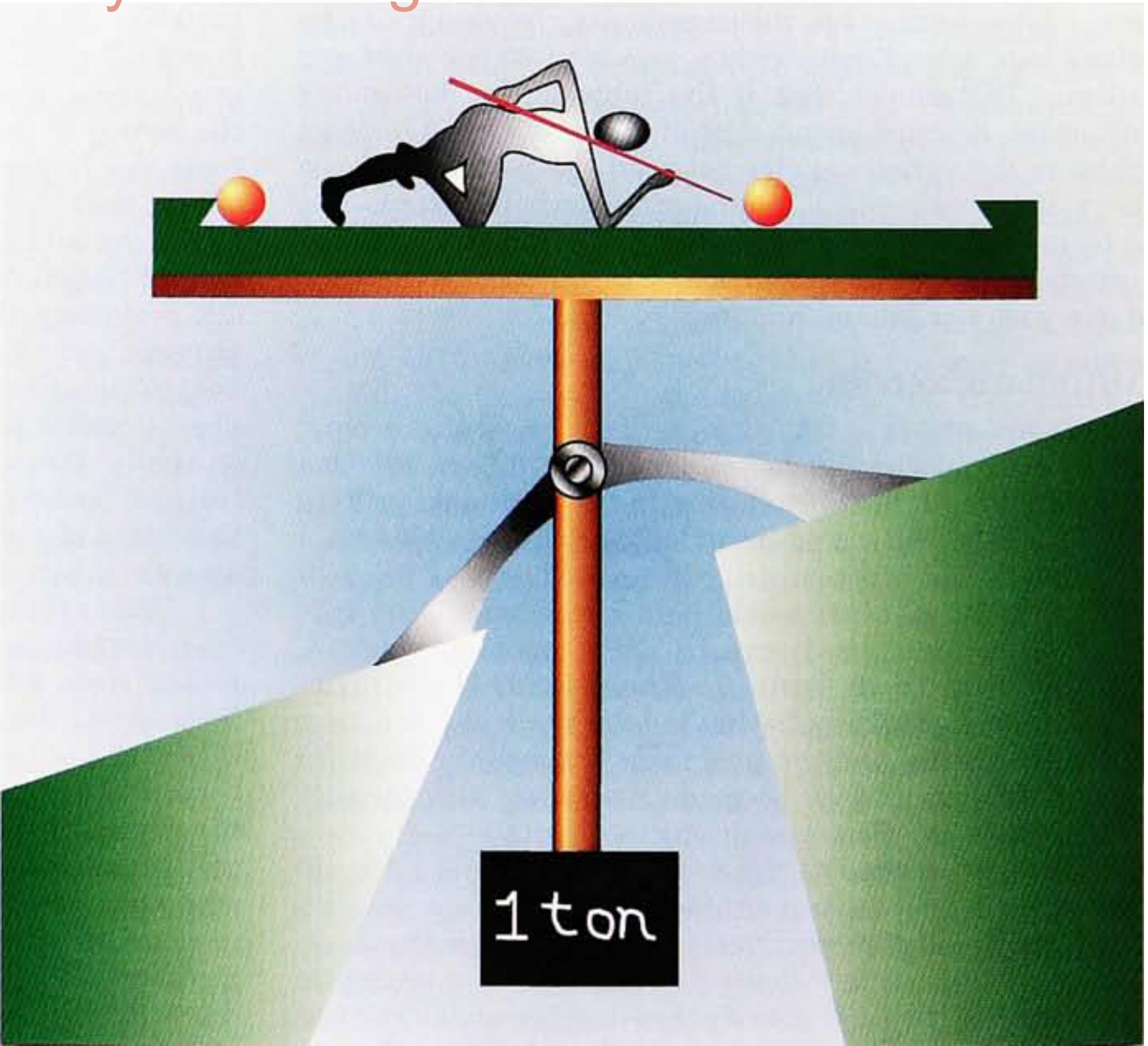
- Pool table is too carefully aligned!



The Pool-Table Analogy with Axion Physics, Pierre Sikivie
Physics Today **49**(12), 22 (1996);
http://dx.doi.org/10.1063/1.881573

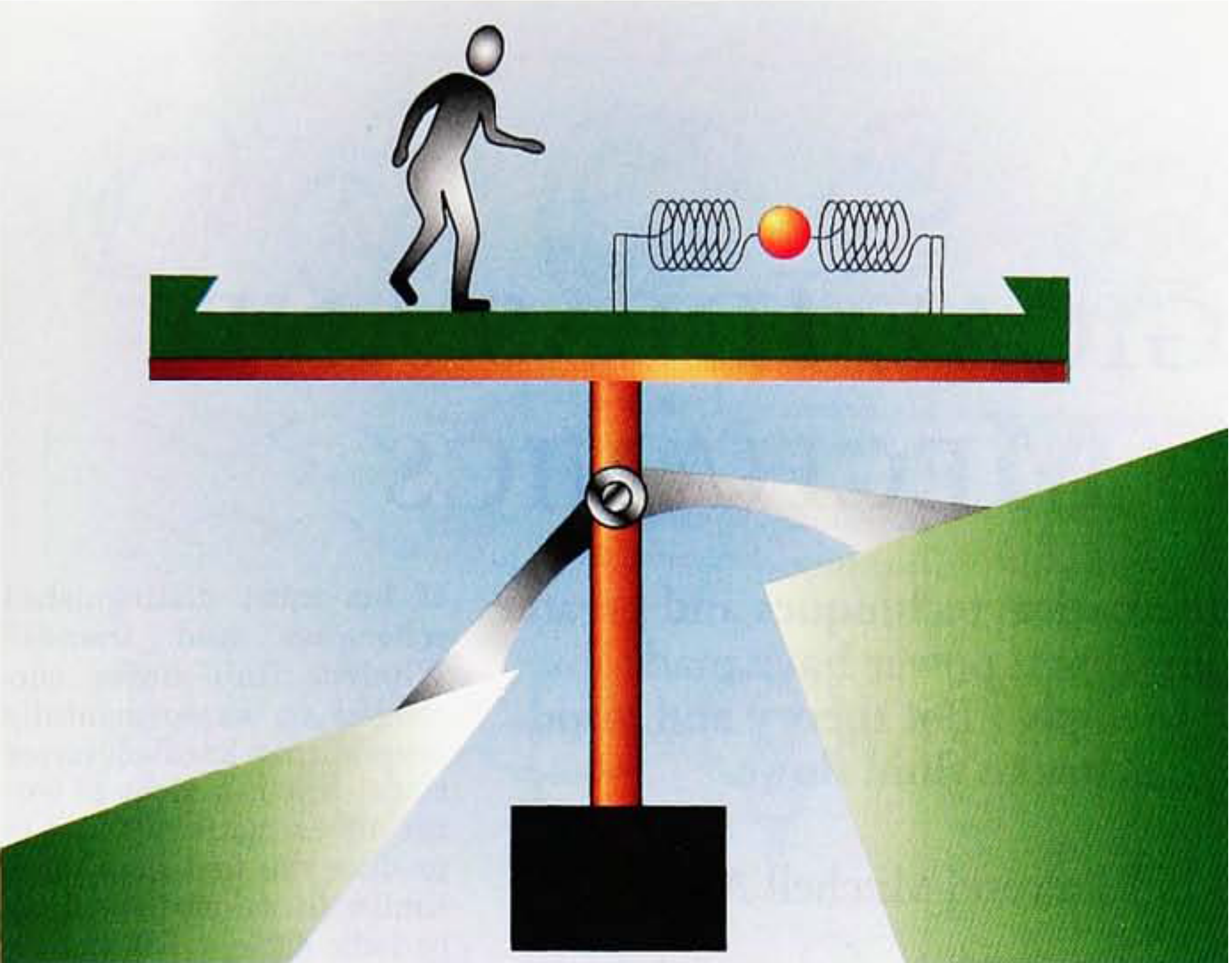
Peccei-Quinn solution of Strong CP-problem

- Dynamic alignment mechanism!



Peccei-Quinn solution of Strong CP-problem

- Axions: oscillation of the system. Frequency of oscillation = axion mass.

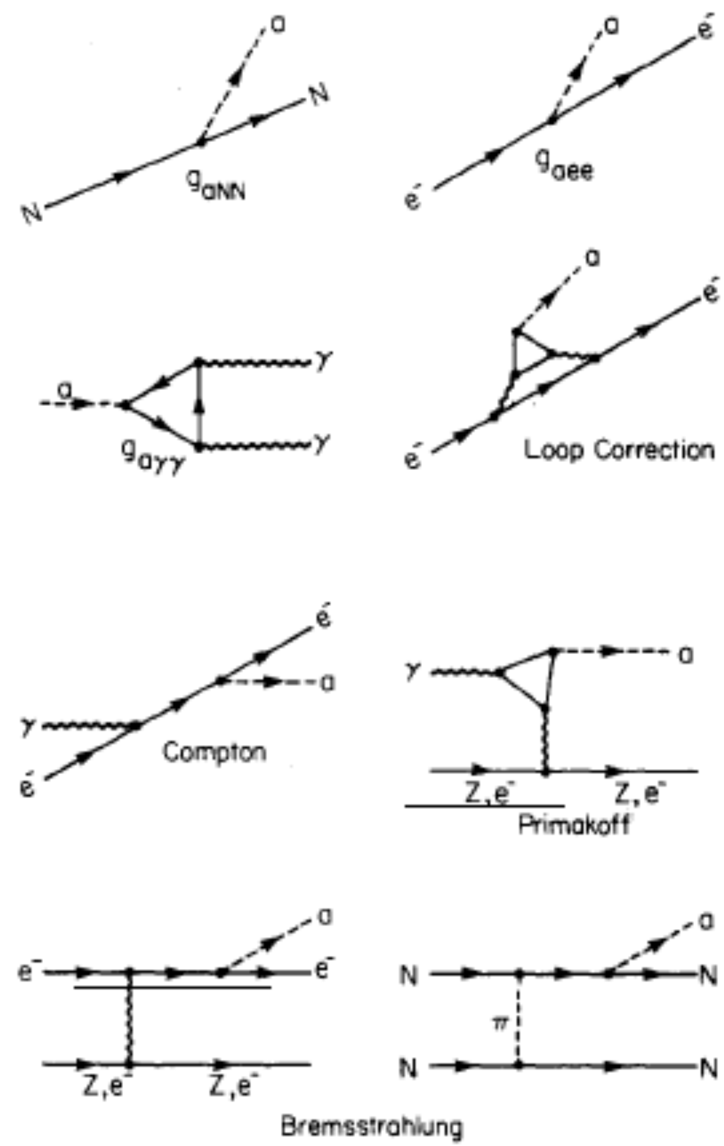


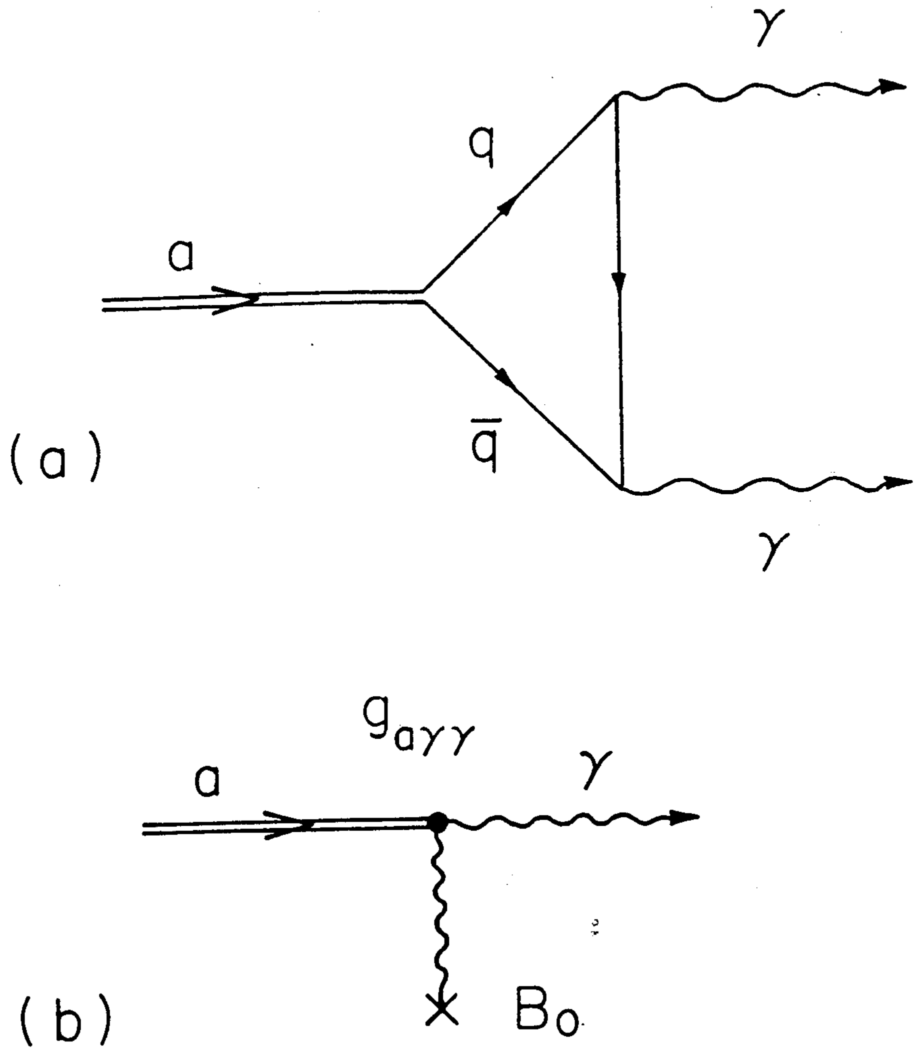
Axion coupling to ordinary matter

- Couple to hadrons (hadronic axions)
- Electrons (leptonic)

$$\tau(a \rightarrow \gamma\gamma) = 10^{49}\,\mathrm{s}\left[\frac{f_a}{10^{12}\,\mathrm{GeV}}\right]^5$$

$$g_{a\gamma\gamma} = \left(1.3\times 10^{-15}\ \mathrm{GeV}^{-1}\right)\frac{m_a}{10^{-5}\ \mathrm{eV}}$$





Axions decay to two photons with very long lifetime. In a strong Electric or Magnetic field they can convert to one photon.

Two photons can also produce AXIONS, which can escape the sun easier than photons.

The sun shines! Photons take:

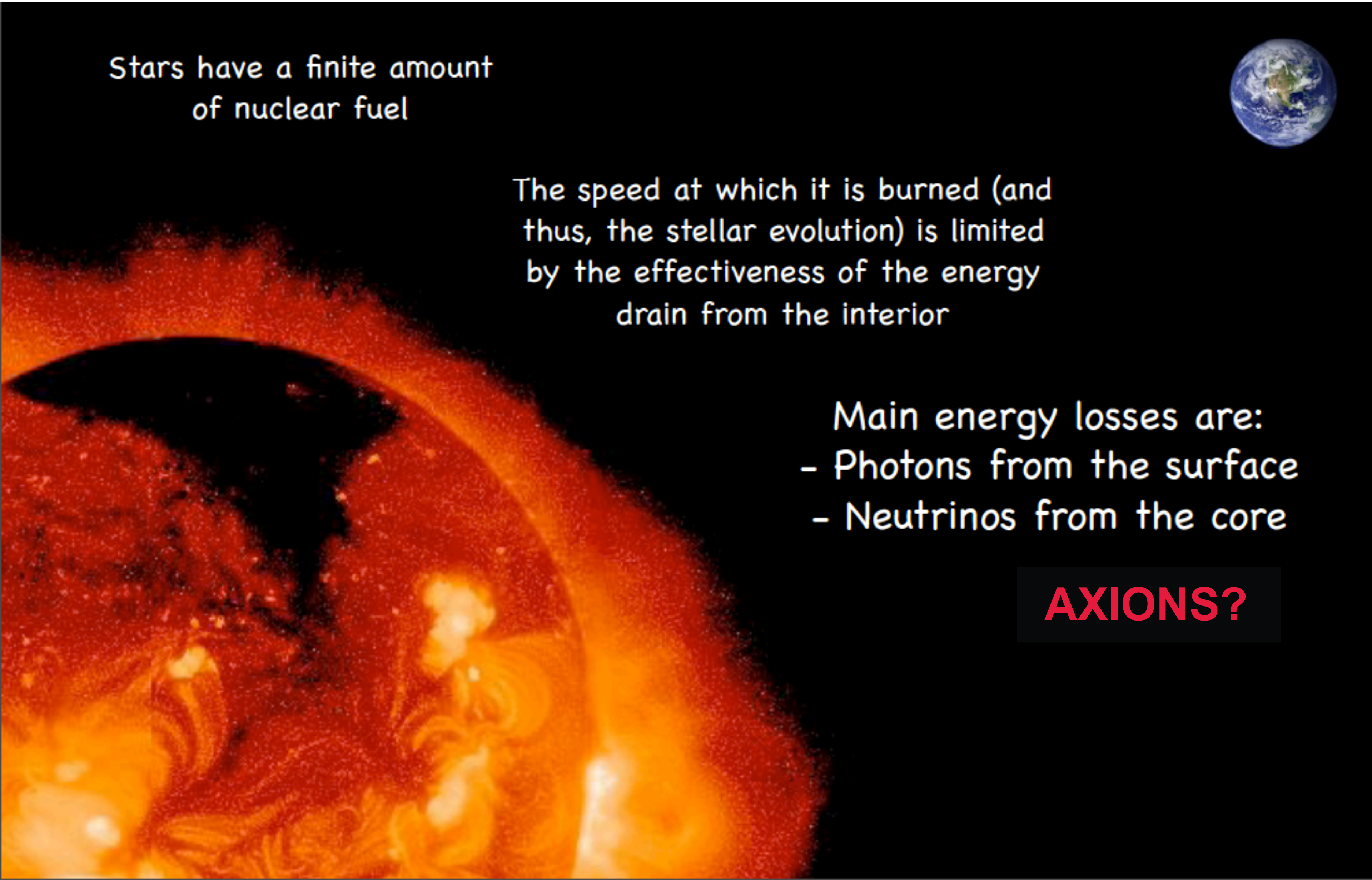
Sun → earth (150 million km): 8 minutes

Sun's center → sun's surface (0.7 million km):
10 million years! Radiation pressure…

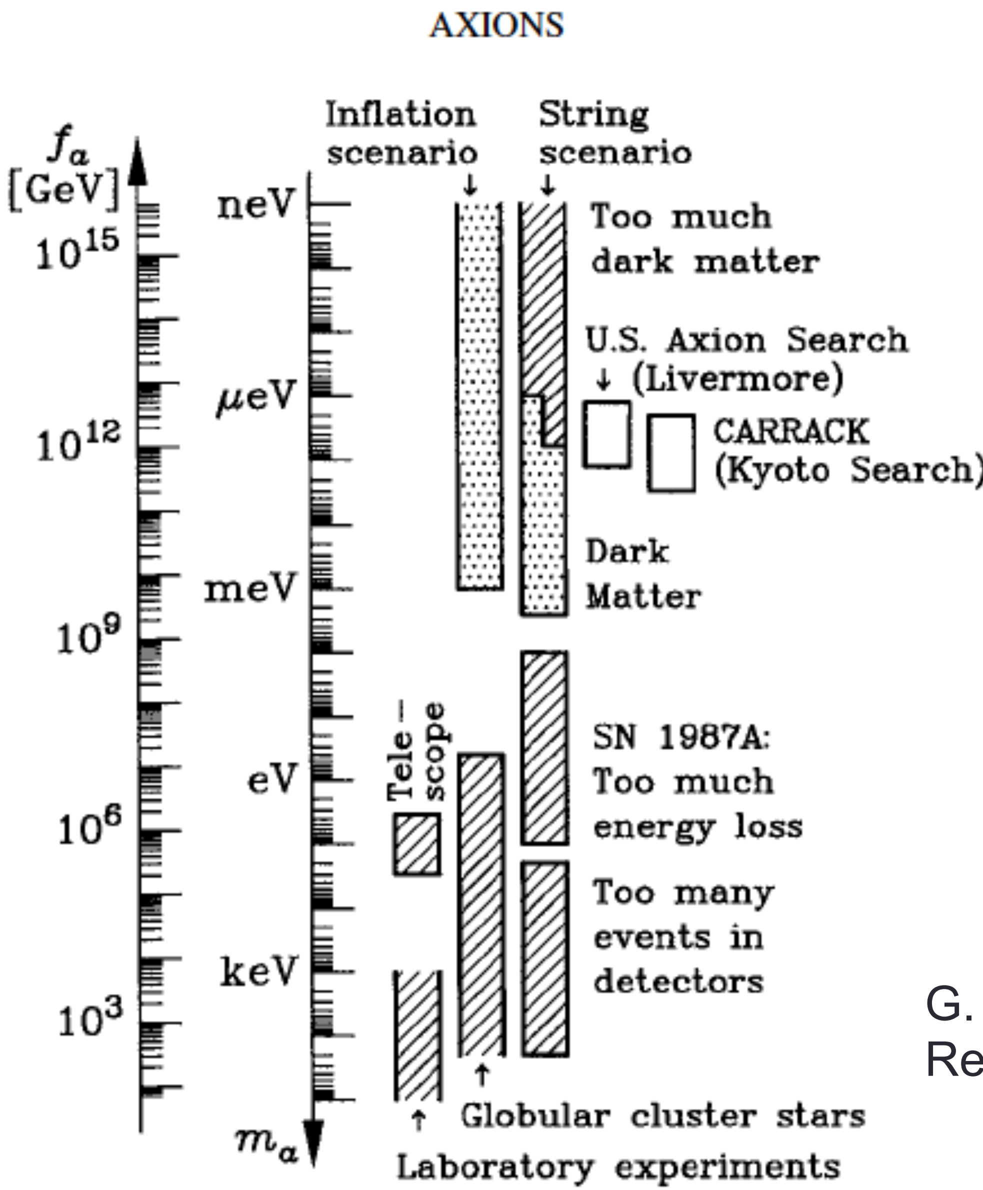
Hence: the photons keep the sun alive!!
Otherwise it would crash on its own weight fast

Dynamic equilibrium, lasts ~10 billion years, unless too many axions are produced and stream out…

Energy loss from stars

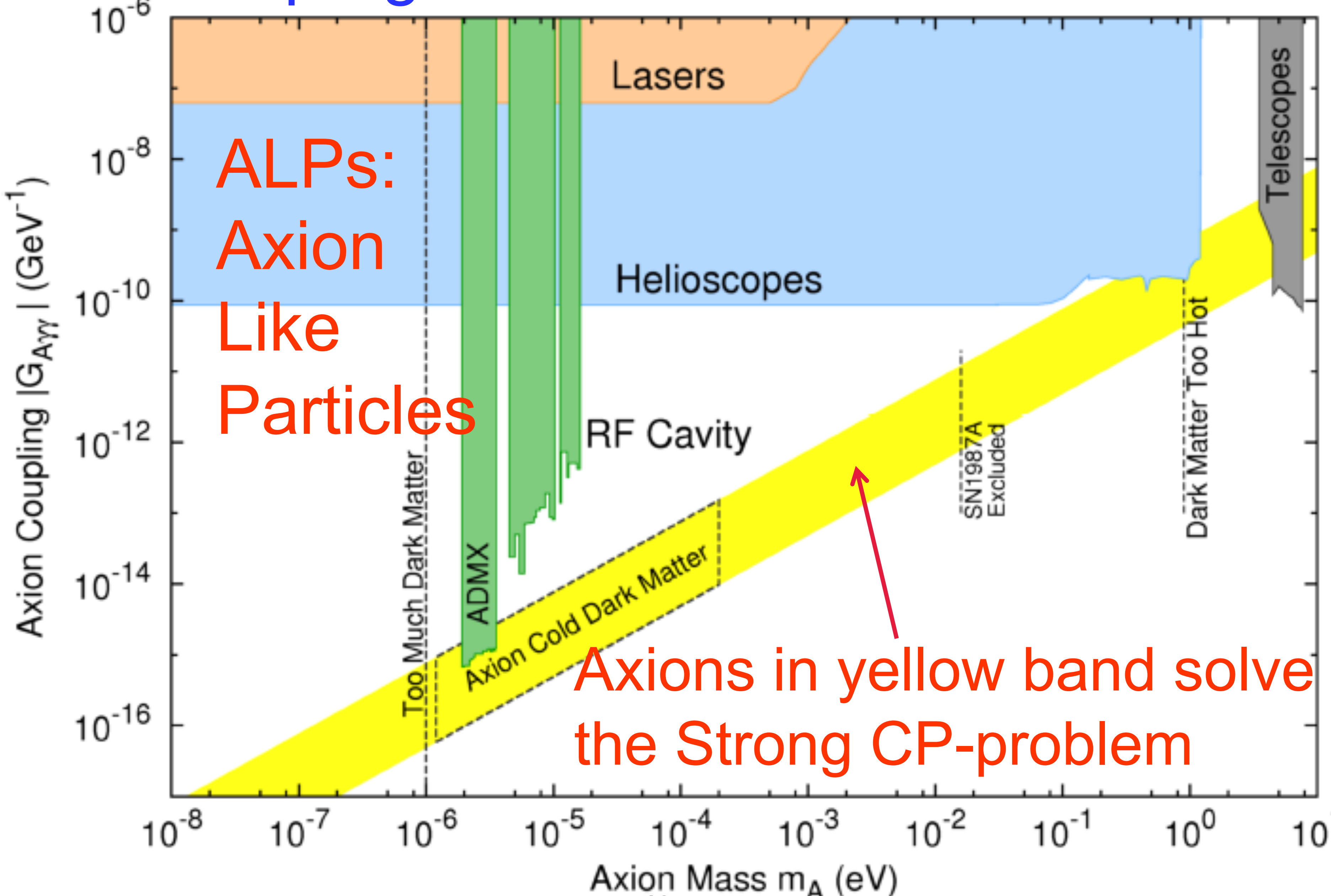


Axion parameters range



G. Raffelt, Space Science Reviews **100**: 153-158, 2002

Axion coupling vs. axion mass



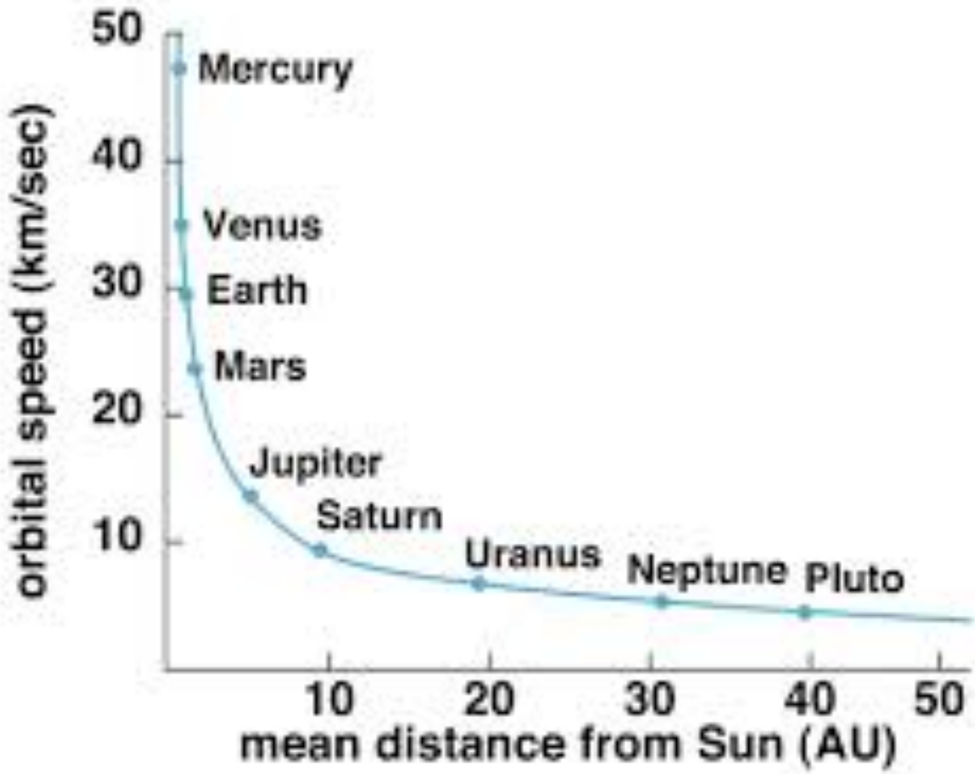
Dark Matter

Dark Matter

- Gravitational law applied to the planets:

$$F = \frac{GM_\odot m}{r^2} = \frac{mv^2}{r}$$

$$v = \sqrt{\left(\frac{GM_\odot}{r}\right)}$$



Origins of dark-matter: Zwicky (Coma cluster) & Smith (Virgo cluster)

Coma Cluster

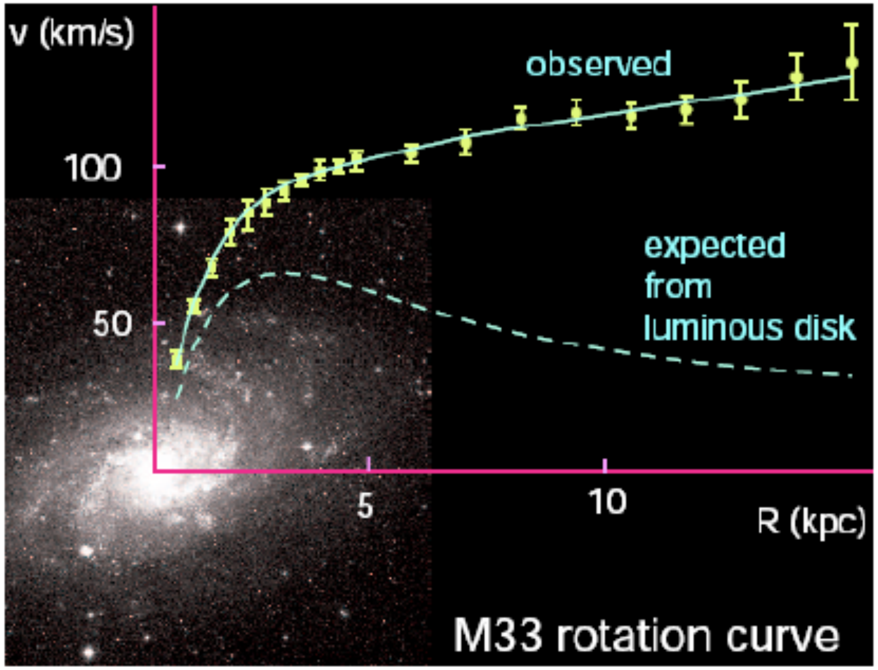
Virial motions within galaxy clusters:

"The difference between this result and Hubble's value for the average mass of a nebula must remain unexplained until further information becomes available."

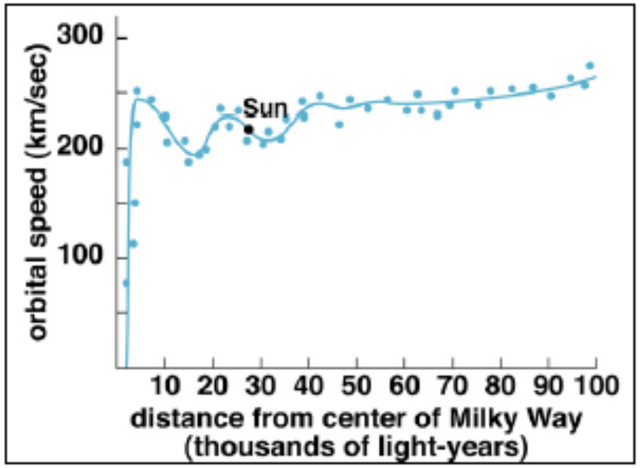
The "dunkelmaterie" of Zwicky 1936

Origins of dark matter: Rubin, Gallagher, Faber et al.

Flat galactic rotation curves
Rubin, "1970's: The decade of seeing is believing."



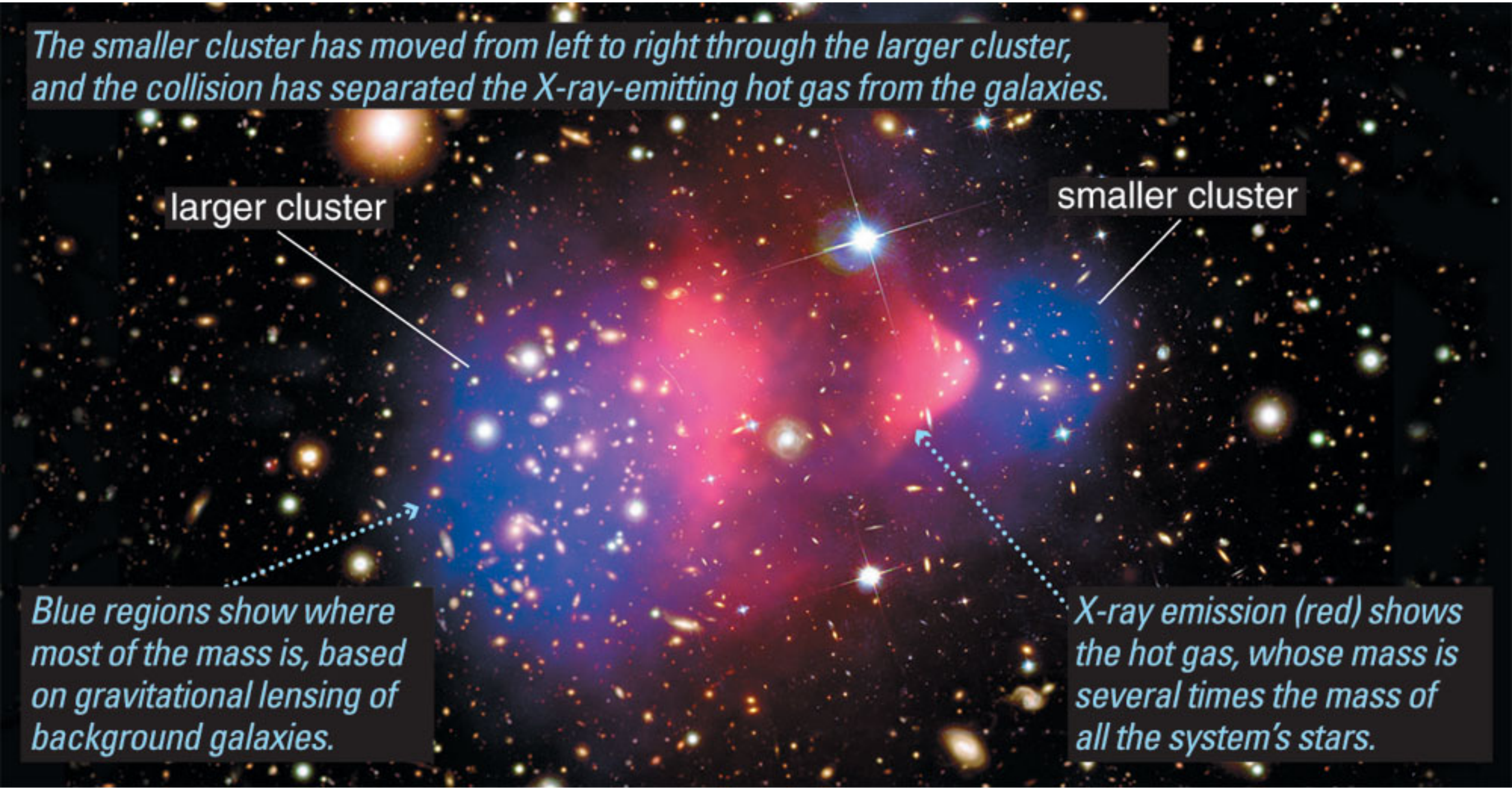
Paolo Saluchi



Dark Matter smoking gun

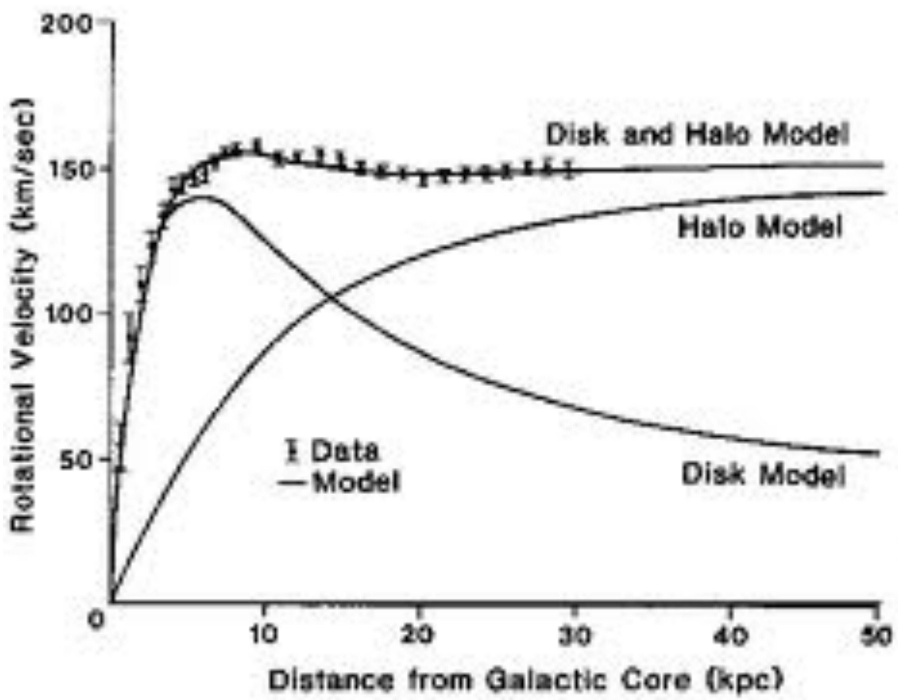
- Two cluster galaxies colliding
- The regular matter (red) interacts, i.e., collides (friction) with each other
- The dark matter (blue) moves unaffected…

Dark matter: the Bullet Cluster



- Comments by J.O. Bennett (U. of Colorado, Boulder), M.O. Donahue (Michigan State U.), N. Schneider (U. of Colorado, Boulder), and M. Voit (Space Telescope Science Institute)

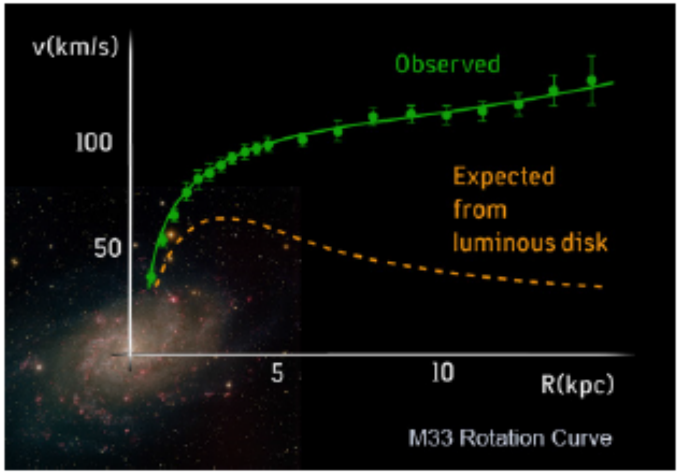
Dark matter halo



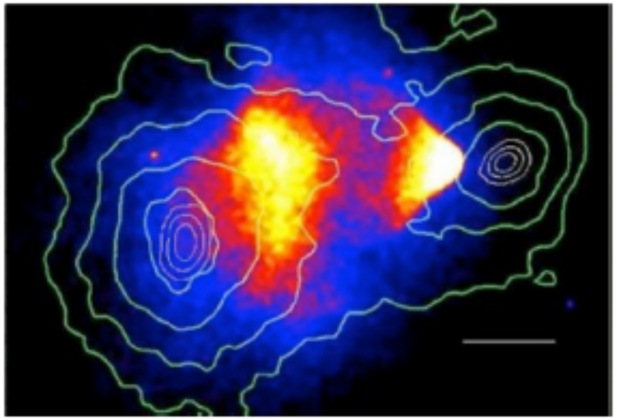
Eric Charles, Fermi-LAT collaboration

Evidence for / Salient Features of Dark Matter

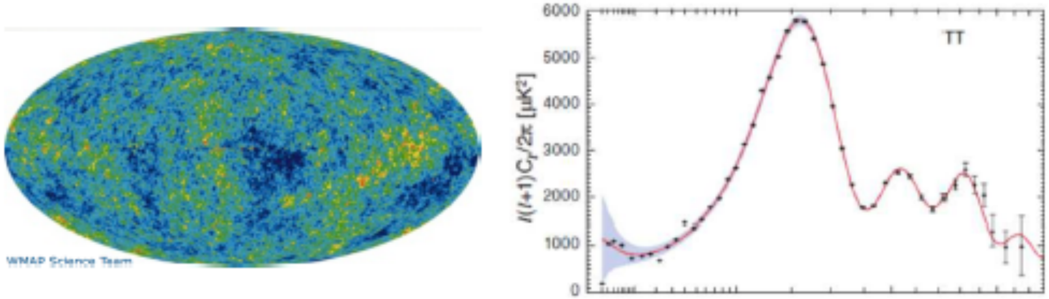
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)



*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)

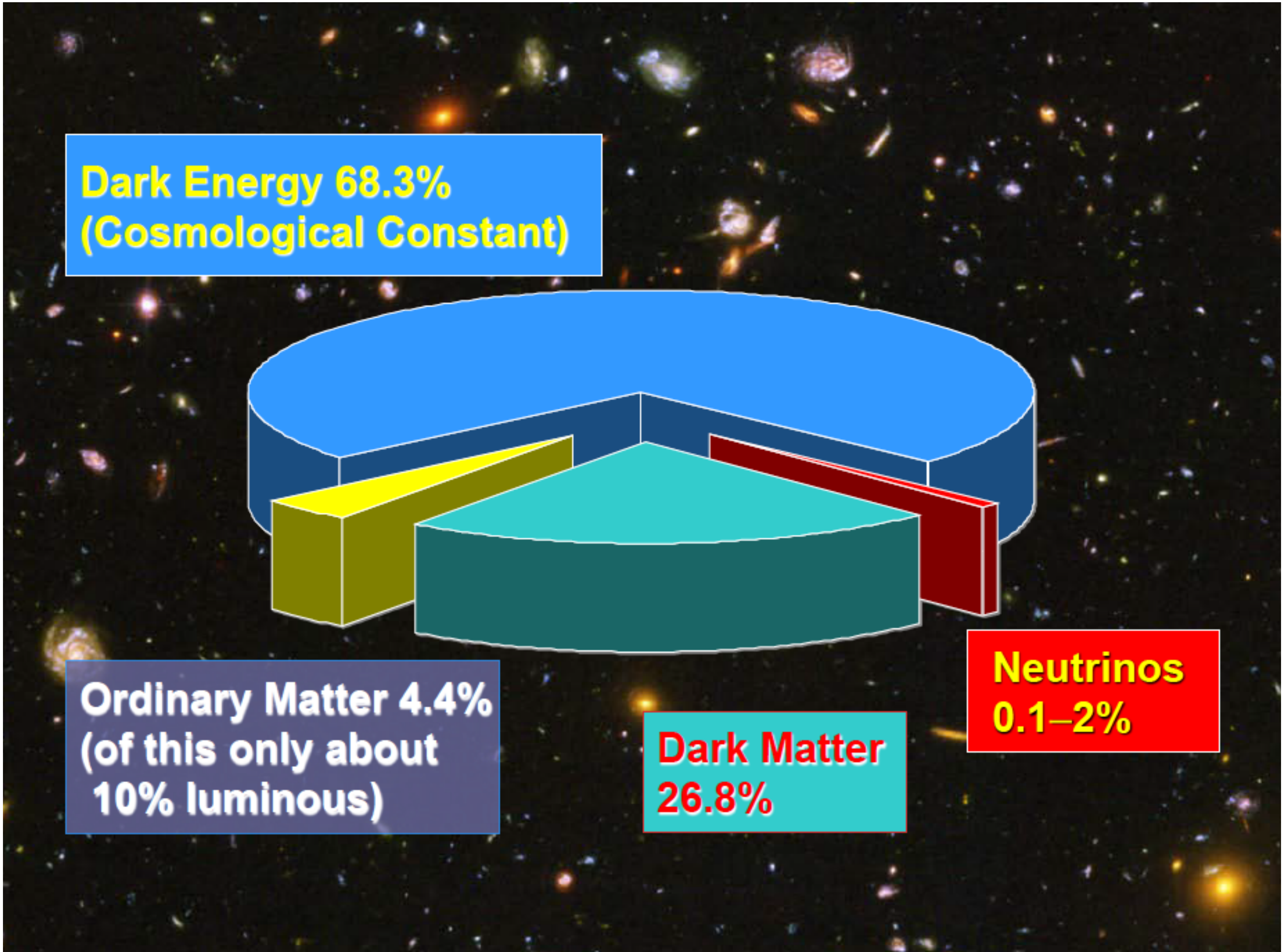


*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

Cosmological inventory

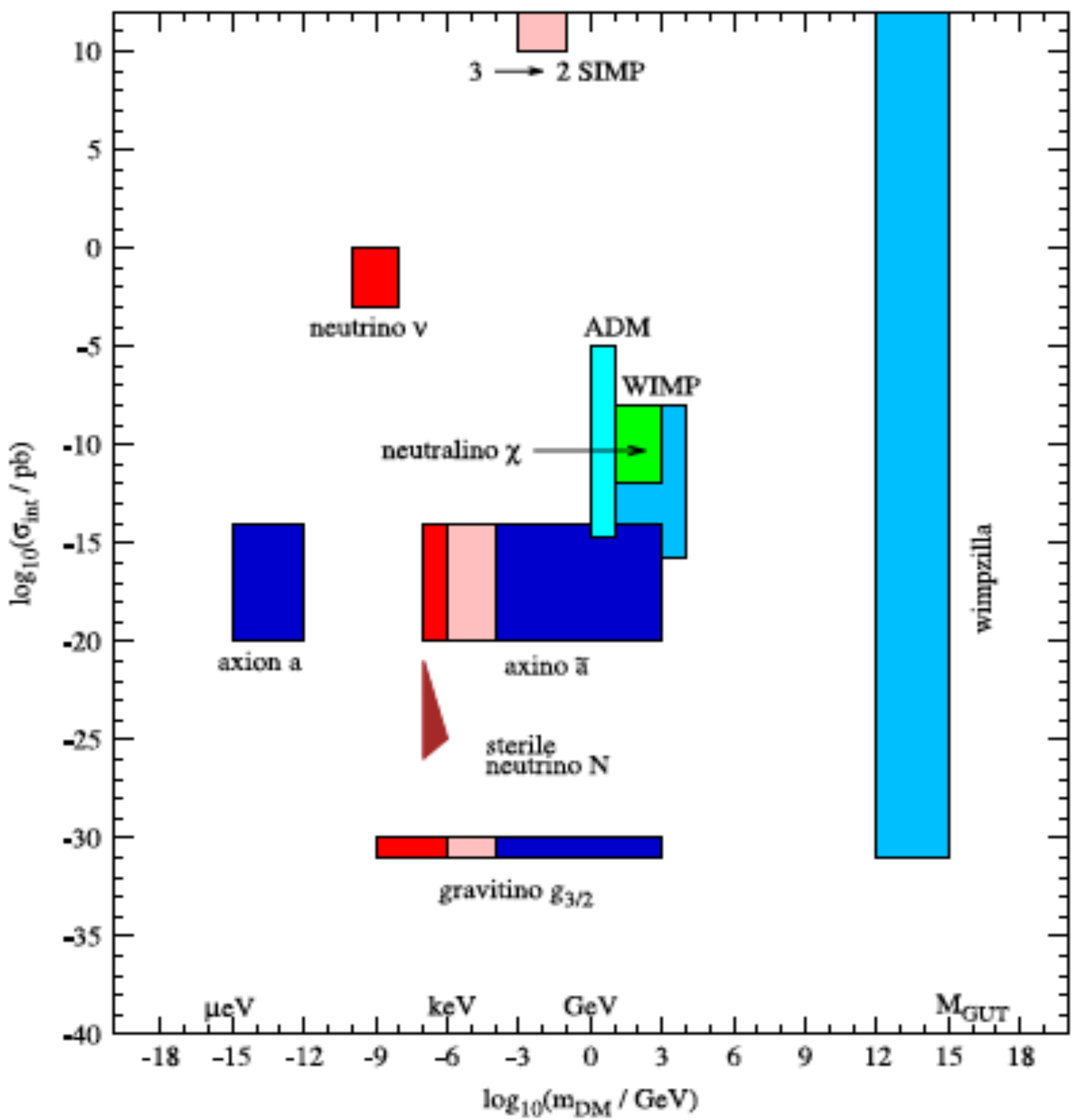


We Have Discovered Dark Matter

…but what is it?

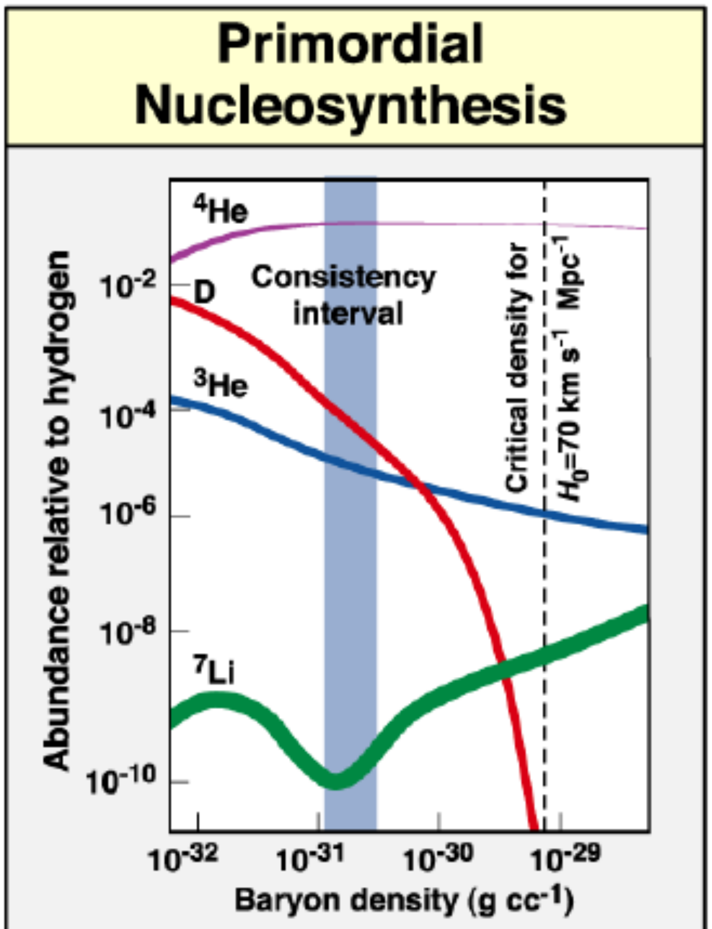
Dark matter candidates

H. Baer et al. / Physics Reports 555 (2015) 1–60



What do we know about the nature of dark matter? Its not normal matter or radiation and it's "cold"

(1) From light element abundance:
Dark matter probably isn't bowling balls or anything else made of baryons.



(2) Is dark matter made of, e.g., light neutrinos?
Probably not: fast moving neutrinos would have washed-out structure.
Dark matter is substantially "cold".

(3) "Dark matter: I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist…"

Frank Wilczek in Physics Today

Frank's referring to WIMPS and Axions

Dark Matter Candidates

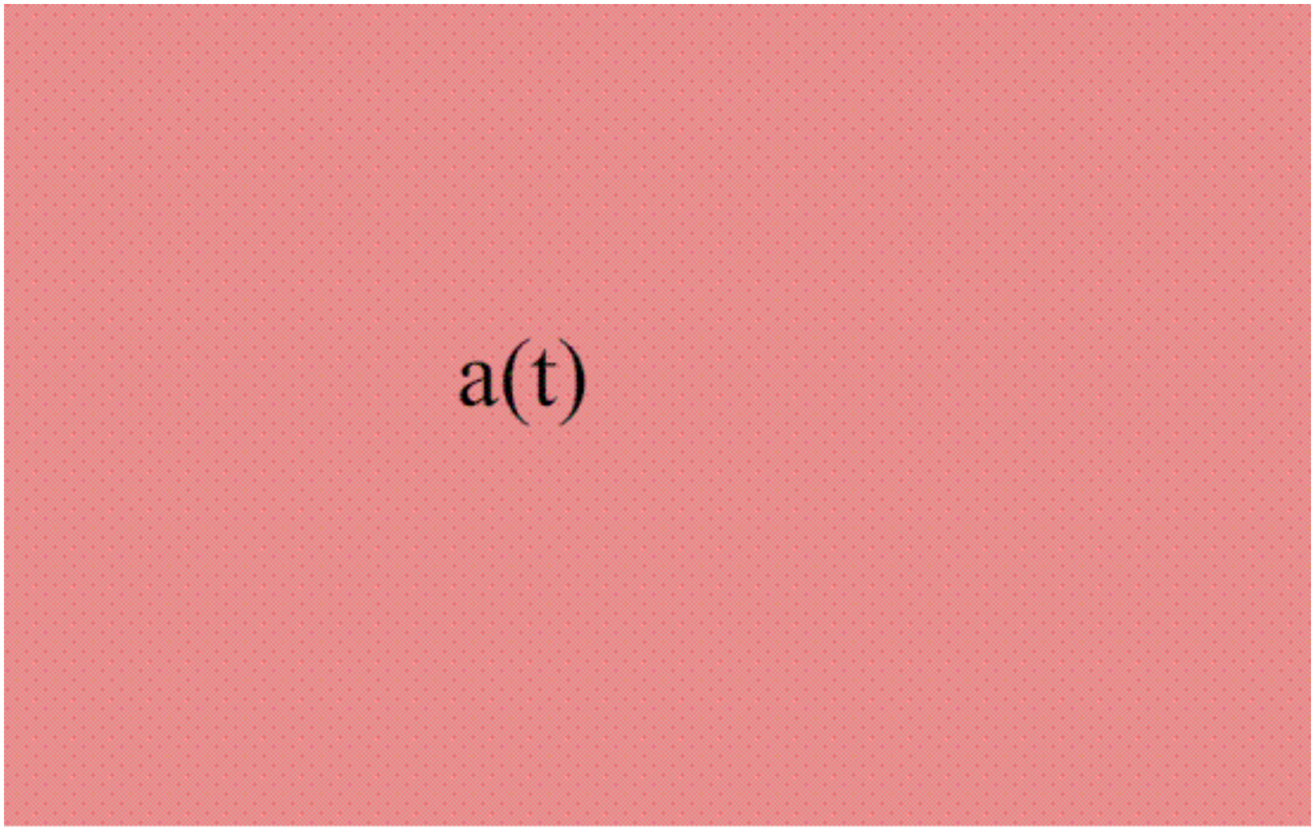
	Axions	WIMPs
Year invented	1977	1985
Original purpose	Solve technical problem in theory of strong nuclear force	Explain dark matter
Detectable because they	Turn into photons in strong magnetic fields	Bounce off atomic nuclei
Pros	Solve more than one problem; allow for decisive test	Flow naturally from supersymmetry; provide many models and multiple avenues of detection
Cons	Provide few models and one means of detection	Resist decisive testing; haven't shown up in decades of looking

Science, Vol 342, 1 Nov. 2013

Axion Dark matter

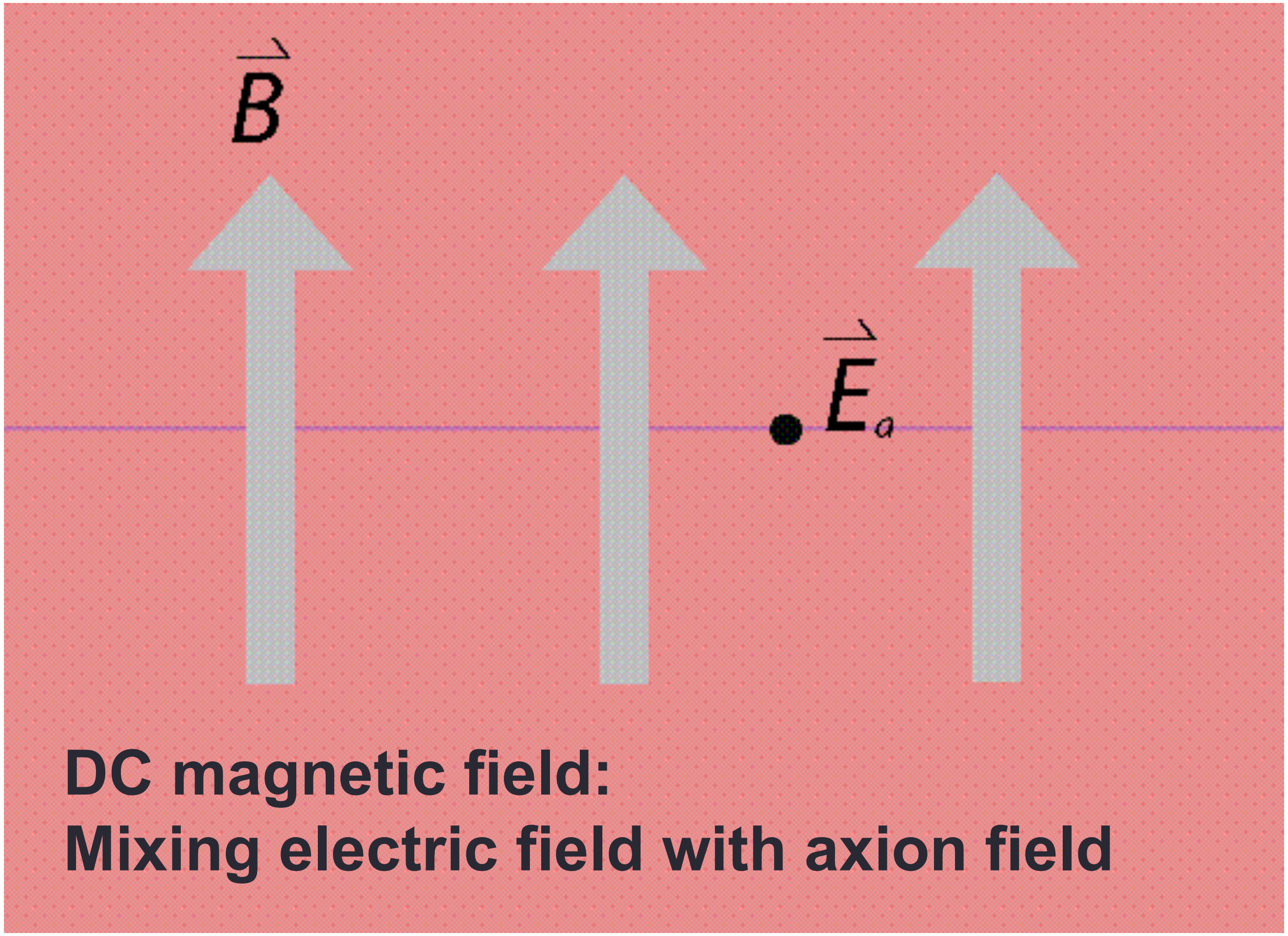
- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3, classical system.
- Lifetime ~7×10^{44}s (100μeV / m_a)^5
- Kinetic energy ~$10^{-6}m_a$, very narrow line in spectrum.

Axion (Higgslet) dark matter: Imprint on the vacuum since soon after the Big-Bang!



Animation by Kristian Themann

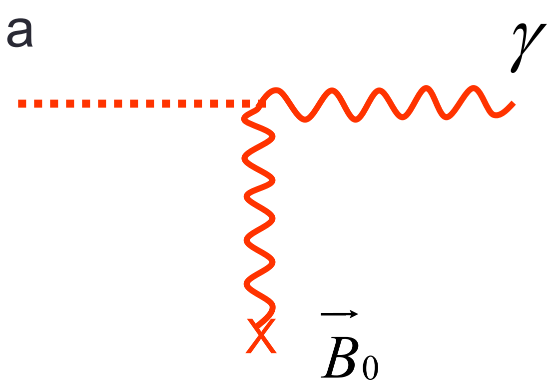
Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



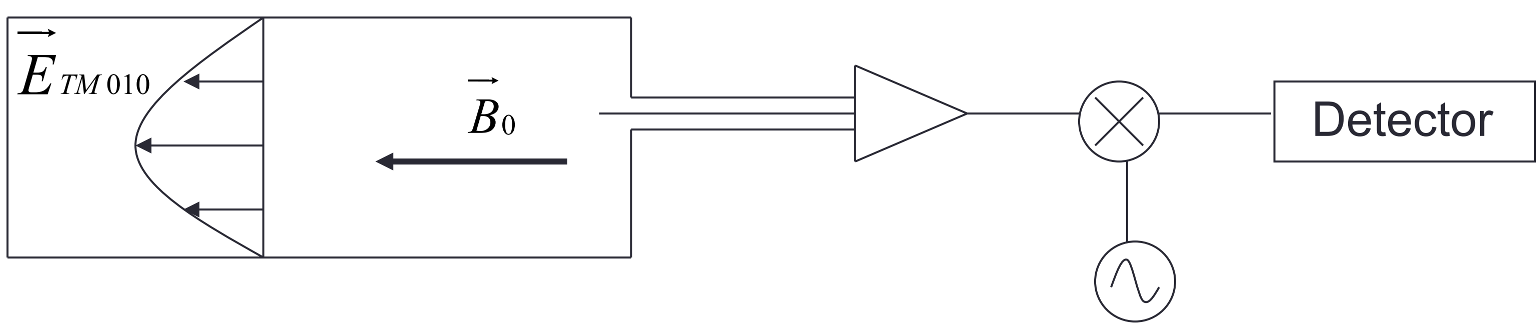
Animation by Kristian Themann

J. Hong, J.E. Kim, S. Nam, YkS
hep-ph: 1403.1576

P. Sikivie's method: Axions convert into microwave photons in the presence of a DC magnetic field (Primakov effect)



$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



Need to tune the cavity over a vast frequency range

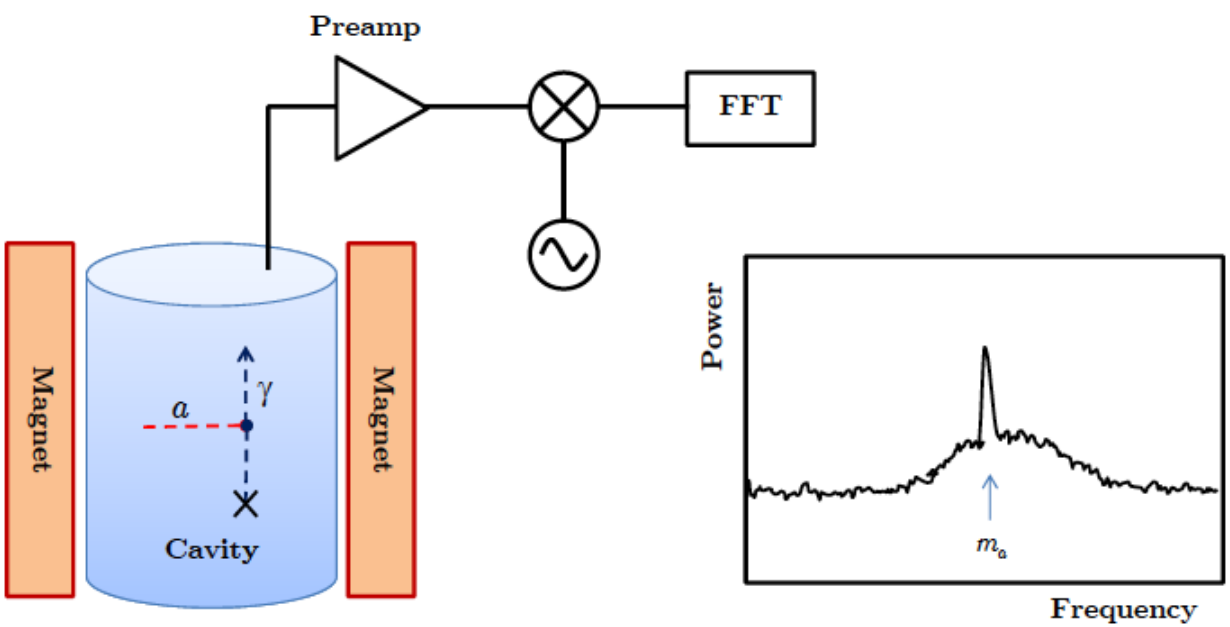


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

$$a \rightarrow \gamma$$

The conversion power on resonance

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V\, B_0^{\;2}\, \rho_a\, C\, m_a^{\;-1}\, Q_L$$

$$= \;2\cdot 10^{-22}\ \text{Watt}\left(\frac{V}{500\ \text{liter}}\right)\left(\frac{B_0}{7\ \text{Tesla}}\right)^2\left(\frac{C}{0.4}\right)$$

$$\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{5\cdot 10^{-25}\ \text{gr/cm}^3}\right)\left(\frac{m_a c^2}{h\ \text{GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

The axion to photon conversion power is very small.

If you don't know the axion mass need to tune

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \mathrm{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\mathrm{GeV}\right)^4\left(\frac{5\ \mathrm{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \mathrm{K}}{T}\right)^2$$

$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

$$T = T_{\mathrm{N}} + T_{\mathrm{ph}}$$

How CAPP is making a difference

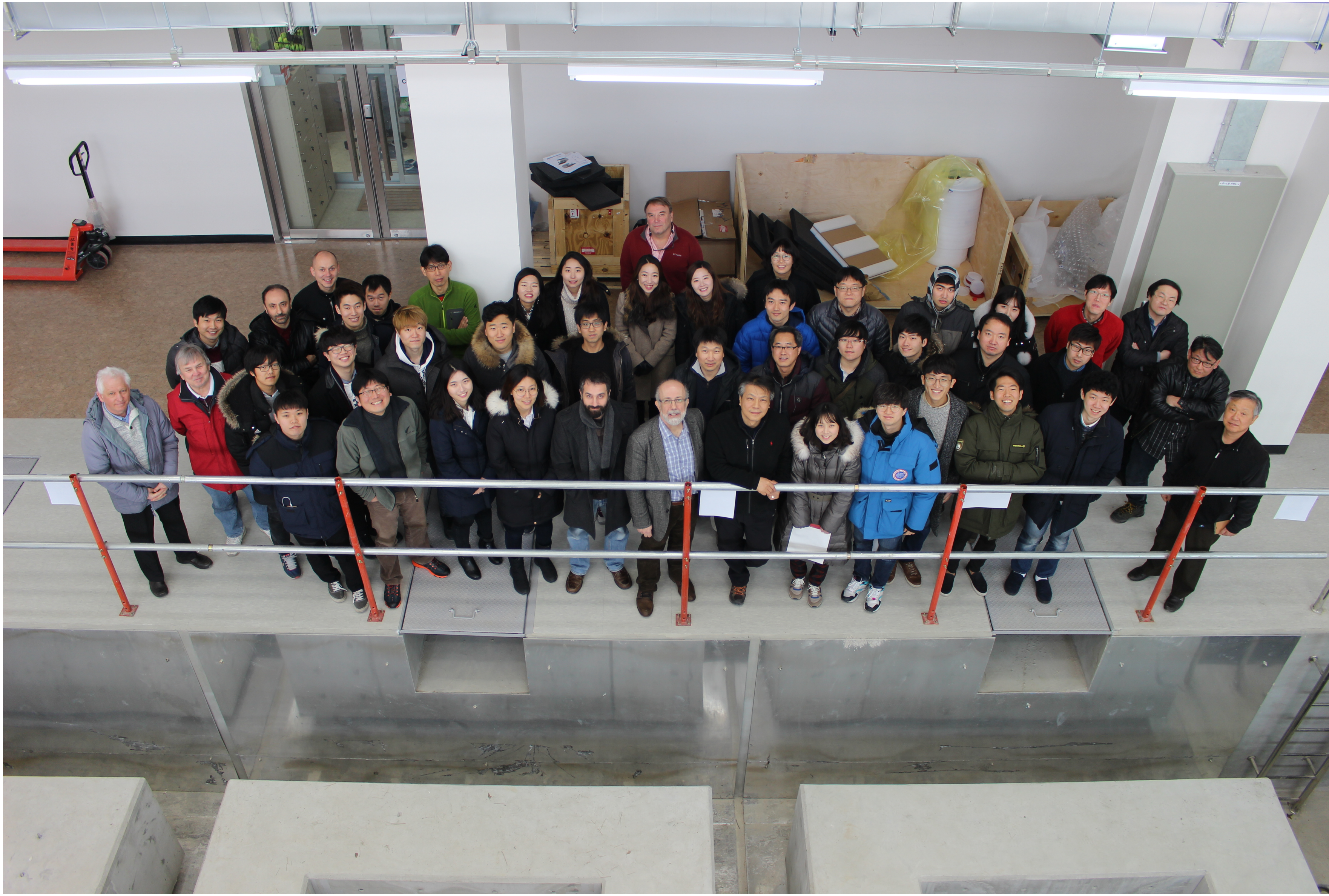
- Establish a facility to be able to run several axion dark matter experiments in parallel
- Take immediate advantage of currently available technology
  - HTS and
  - LTS (NbTi, and Nb_3Sn) magnets

- NI-HTS, 18T, 70mm diam. Delivered Summer 2017
- NI-HTS, 25T, 100mm diam. (funding limited) delivery in 2020?
- LTS (Nb_3Sn), 12T, 320mm diam. From Oxford Instr. to be delivered in late 2019 or early 2020

CAPP's plan

- Low temperature, high quality resonators (near or SC?)
- Quantum-noise limited RF-detectors (SQUIDs, JPAs)
- Single photon RF-detectors (>10GHz). (First appl. of qubits?)

IBS/CAPP at Munji Campus, KAIST, January 2017.

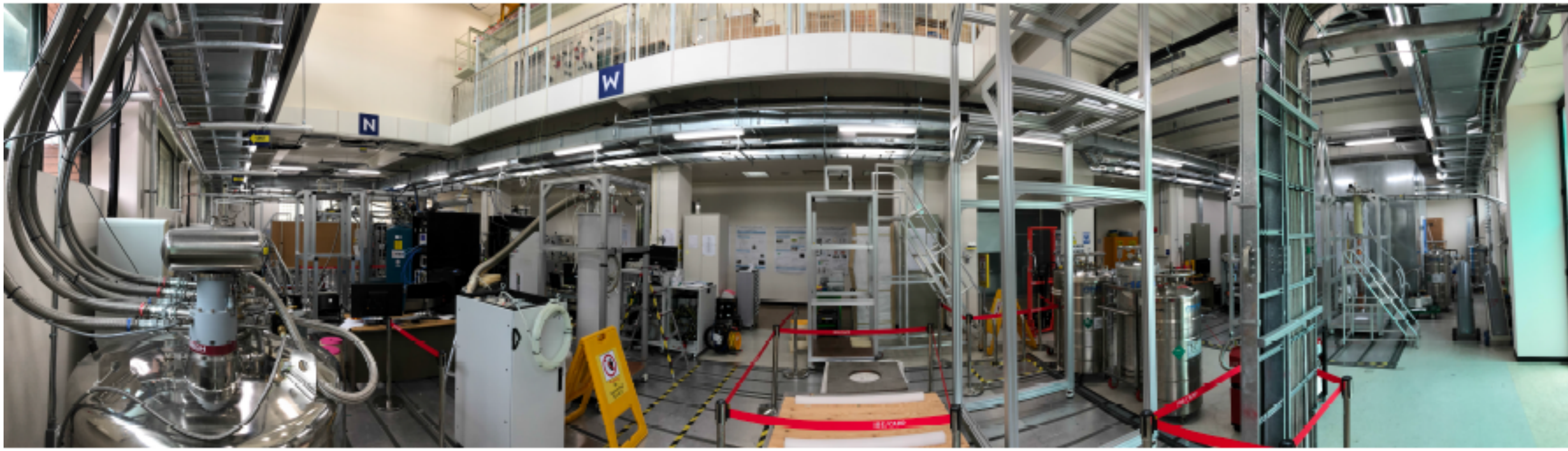


Dil. Refr. installed

The experimental hall is getting very busy

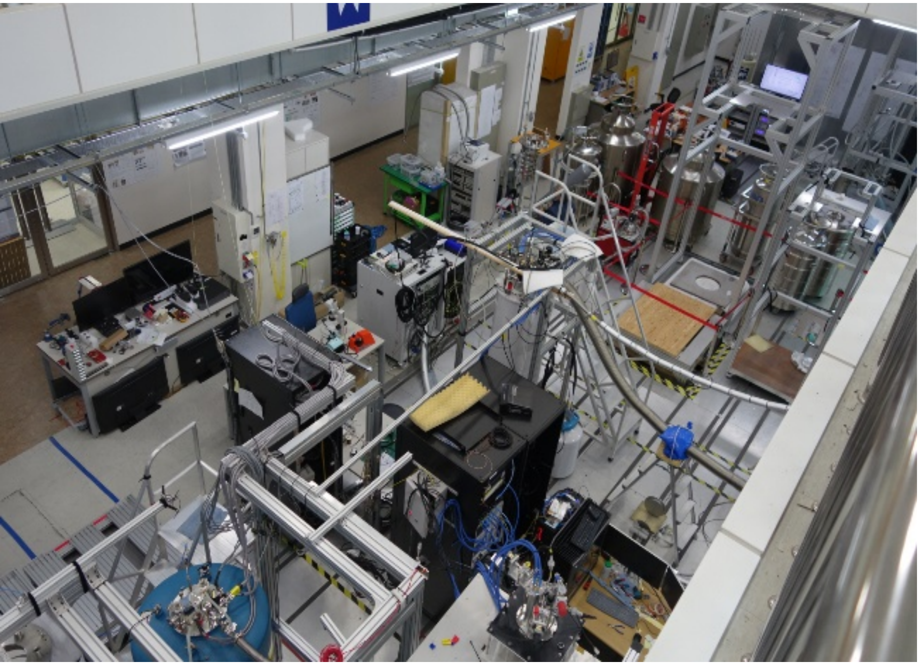
Several high power dilution refrigerators have been procured, installed and are running at mK temps.

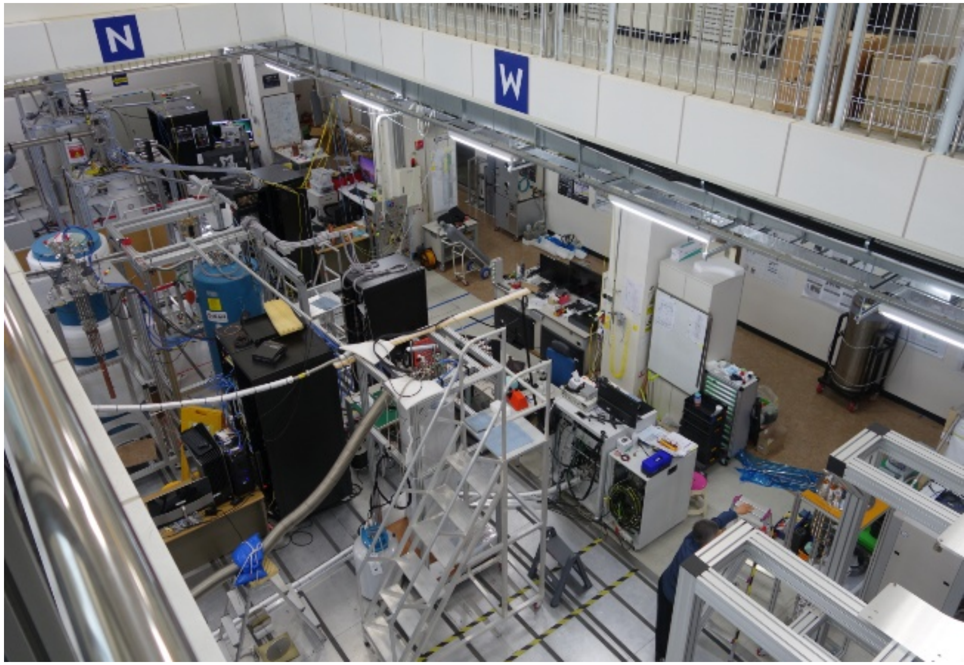
CAPP Experimental Hall (LVP)



Woohyun Chung's slide

CAPP experimental hall, top view





CULTASK Refrigerators and Magnets

Refrigerators

Vendor	Model	T_B (mK)	Cooling power	Installation
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016
BlueFors (BF4)	LD400	10	18μW@20 580μW@100	2016
Janis	HE3	300	25μW@300mK	2017
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100K	**2017**
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100K	2017
Leiden	DRS1000	100	1mW @100mK	2018
Oxford	Kelvinox	<30	400 @120mK	2017

Magnets

B field	Bore (cm)	Material	Vendor	Delivery
26T	3.5	HTS	SUNAM	2016
18T	7	HTS	SUNAM	2017
9T	12	NbTi	Cryo-Magnetics	2017
8T	**12**	**NbTi**	**AMI**	**2016**
8T	16.5	NbTi	AMI	2017
25T	10	HTS	BNL/CAPP	2020
12T	32	Nb_3Sn	Oxford	2020

Woohyun Chung's slide

CAPP’s base plan

- Delivery of 12T/32cm magnet in 2020 and 25T/10cm (funding limited).

- In the meantime, we are getting ready for it:
  - Quantum noise limited SQUID-amplifiers
  - Superconducting cavity in large B-fields
  - Cryo-expertise, reach lowest physical temperature (down to <50mK)
  - Demonstrate efficient high-frequency, high-volume resonators
  - Efficient DAQ
  - Prepare systems for large magnets

Superconducting cavity in large B-field!

arXiv:1904.05111v1 [physics.ins-det] 10 Apr 2019

Maintaining high Q-factor of superconducting $YBa_2Cu_3O_{7-x}$ microwave cavity in a high magnetic field

Danho Ahn,[1,2] Ohjoon Kwon,[1] Woohyun Chung,[1,*] Wonjun Jang,[3] Doyu Lee,[1,2] Jhinhwan Lee,[4] Sung Woo Youn,[1] Dojun Youm,[2] and Yannis K. Semertzidis[1,2]

[1] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*

[2] *Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*

[3] *Center for Quantum Nanoscience, Institute for Basic Science, Seoul 33760, Republic of Korea*

[4] *Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science, Pohang 37673, Republic of Korea*

(Dated: April 11, 2019)

A high Q-factor microwave resonator in a high magnetic field could be of great use in a wide range of fields, from accelerator design to axion dark matter search. The natural choice of material for the superconducting cavity to be placed in a high field is a high temperature superconductor (HTS) with a high critical field. The deposition, however, of a high-quality, grain-aligned HTS film on a three-dimensional surface is technically challenging. We have fabricated a polygon-shaped resonant cavity with commercial $YBa_2Cu_3O_{7-x}$ (YBCO) tapes covering the entire inner wall and measured the Q-factor at 4 K at 6.93 GHz as a function of an external DC magnetic field. We demonstrated that the high Q-factor of the superconducting YBCO cavity showed no significant degradation from 1 T up to 8 T. This is the first indication of the possible applications of HTS technology to the research areas requiring a strong magnetic field at high radio frequencies.

Superconducting cavity in large B-field!

arXiv:1904.05111v1 [physics.ins-det] 10 Apr 2019

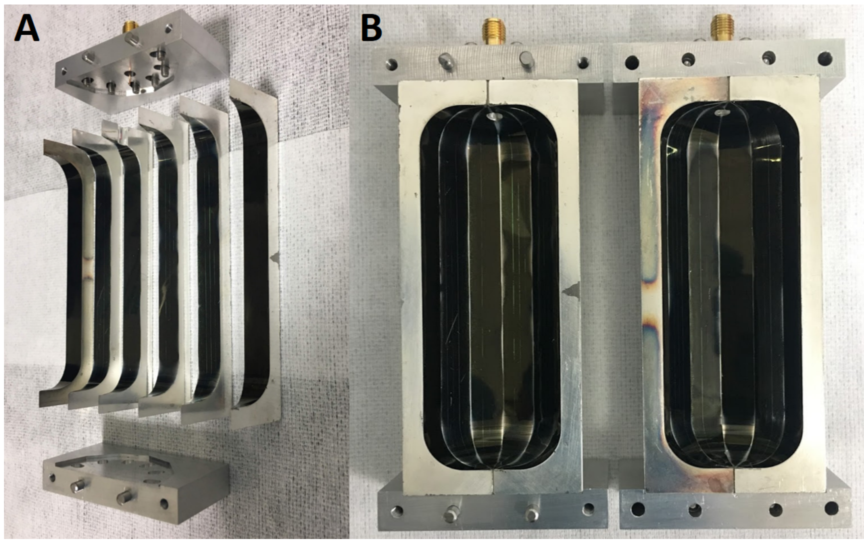
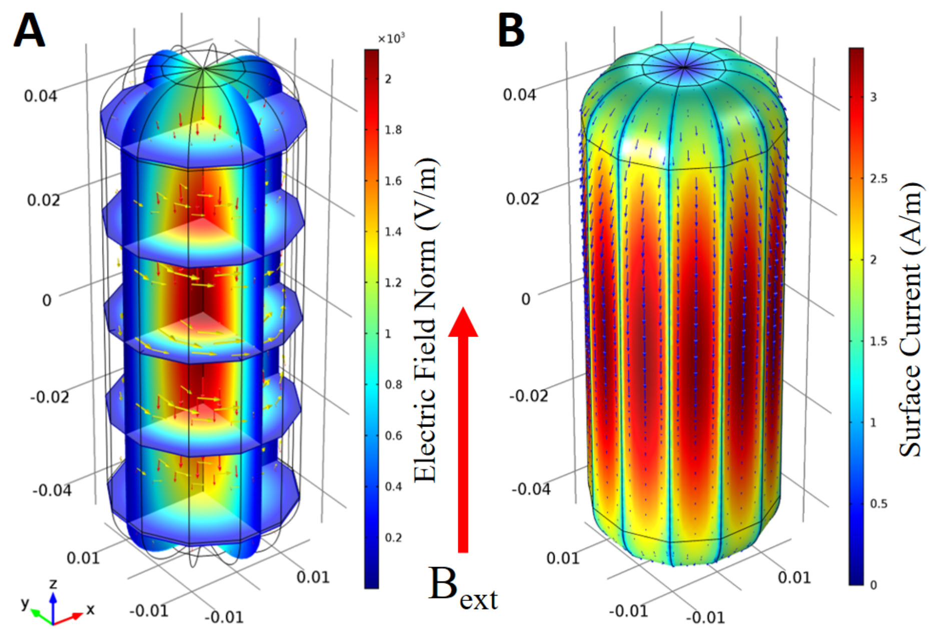


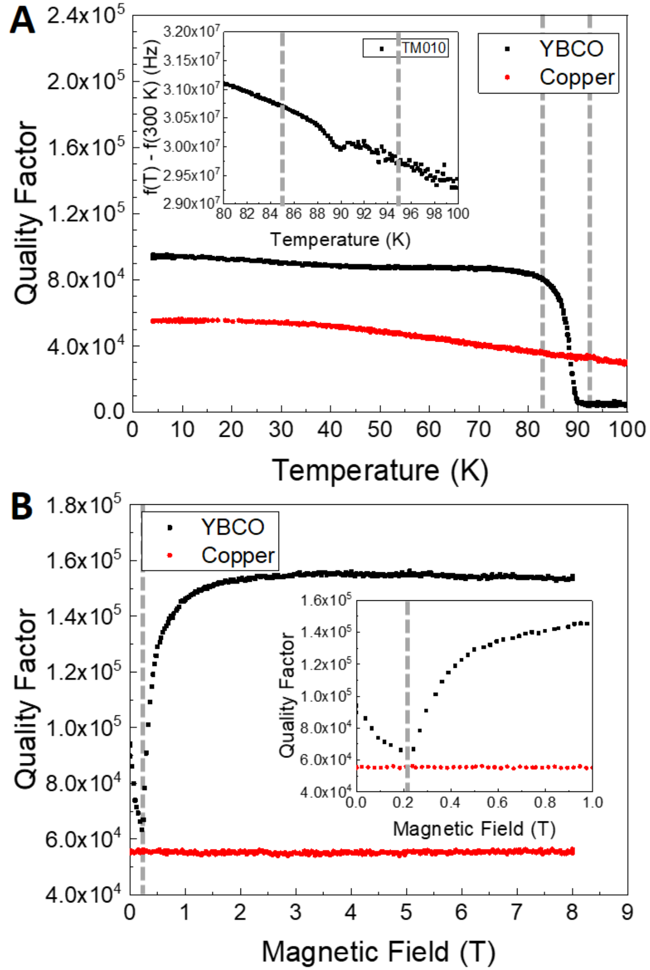
FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

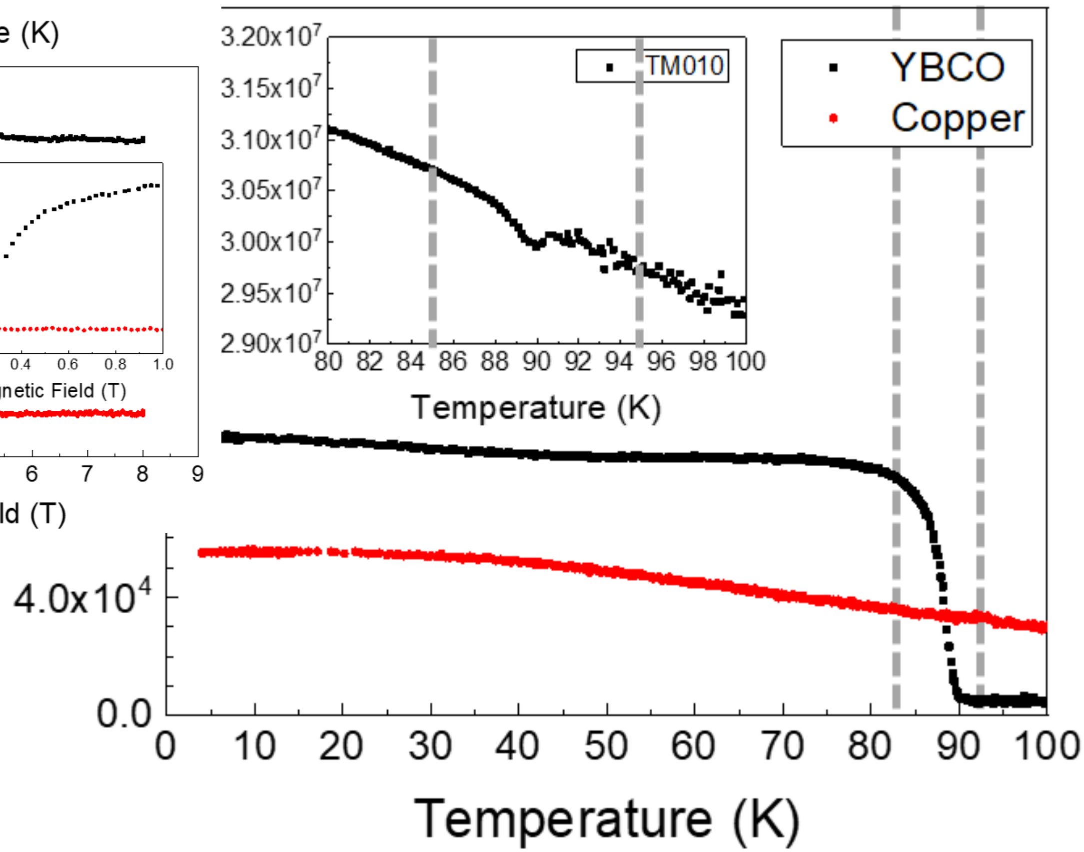


YBCO stripes (tape) placed on cavity slices!

ting cavity in large B-field!

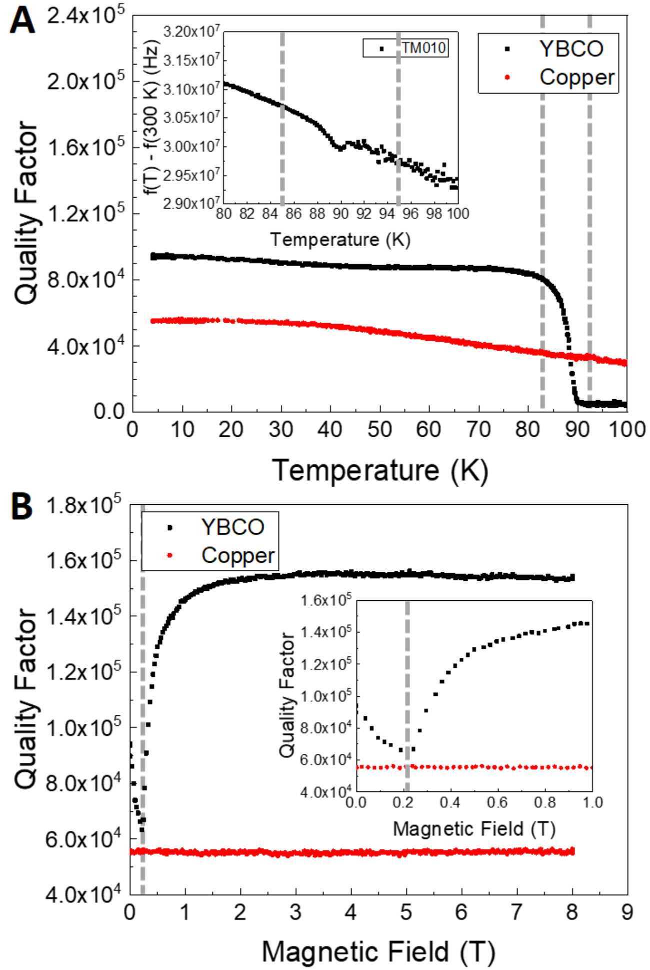
hysics.ins-det] 10 Apr 2019

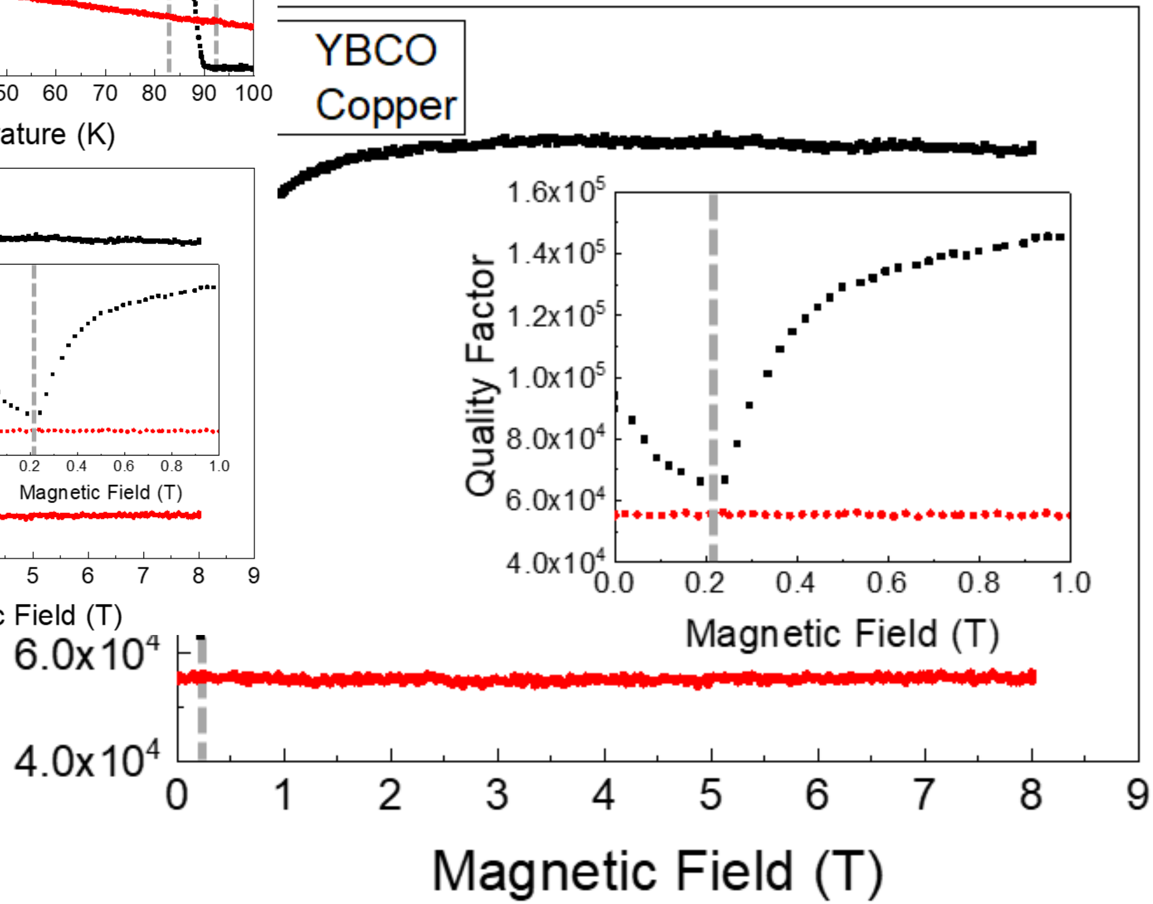




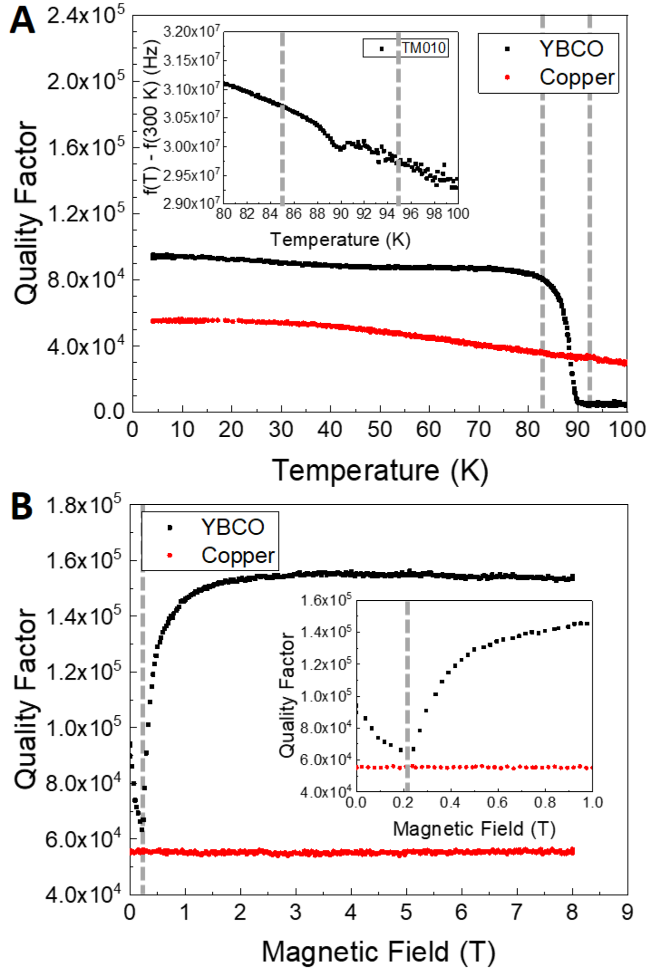
ting cavity in large B-field!

hysics.ins-det] 10 Apr 2019





Our first YBCO cavity results. The second cavity showed much improved results



se-limited RF amplifiers

SQUID Amplifiers for Axion Search Experiments

ov, Doyu Lee,
nnis Semertzidis
sics Research
a
T

Vyacheslav Zakosarenko
Supracon AG
Jena
Germany

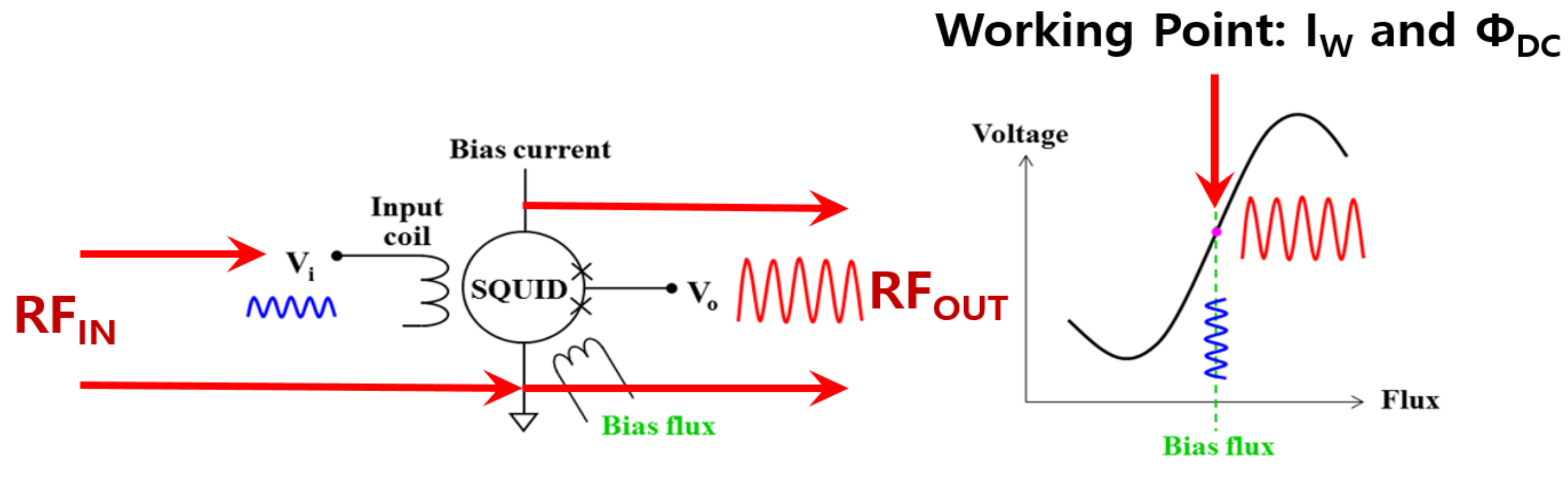
Arjan van Loo, Yoshiro Urade, Shingo Kono
RIKEN
Saitama, Japan

Matthias Schmelz, Ronny Stolz
IPHT
Jena, Germany

Yasunobu Nakamura
University of Tokyo
Japan

International collaboration for applications in axion research

Microstrip SQUID Amplifiers

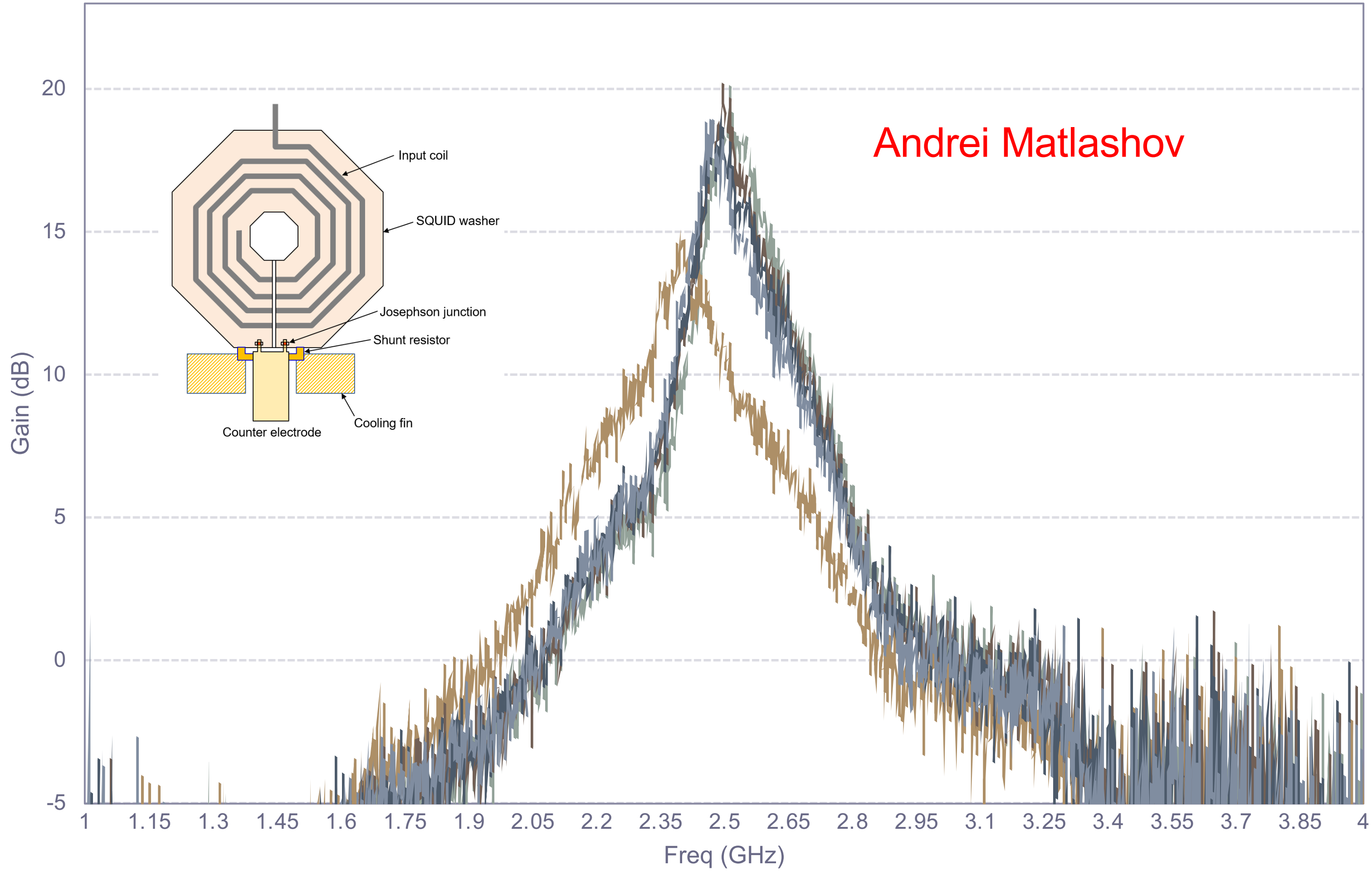


(a) (b)

Principe of operation: (a) schematics, (b) $dV/d\Phi$ transfer coefficient

Andrei Matlashov

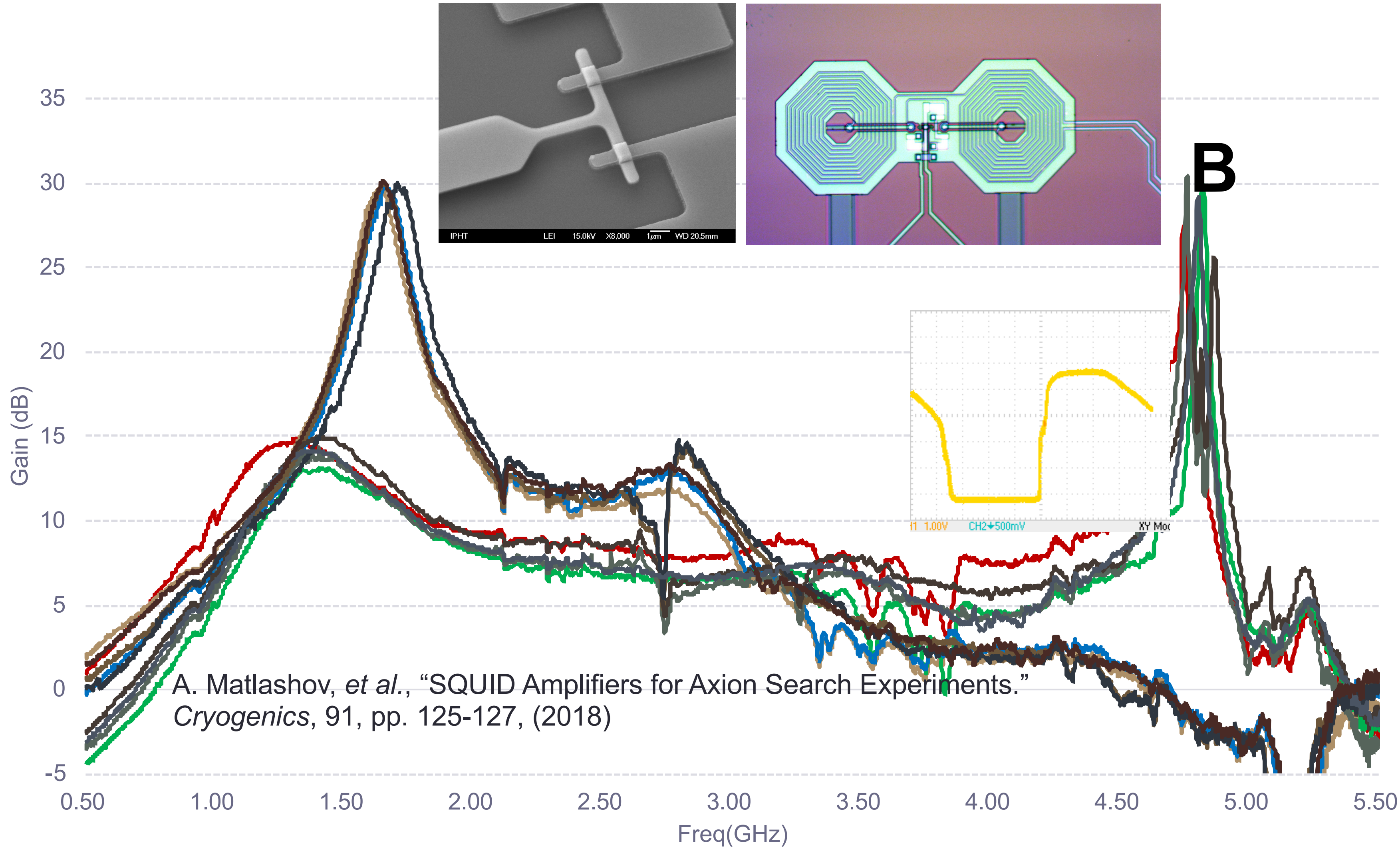
MSAs from Yong-Ho Lee, KRISS: World's first at 2.2-2.5GHz, 2016



RF-amplifiers and CAPP

- KRISS delivered first functional MSA at >1GHz, 2016
- Private companies sprung up producing MSAs, JPAs
- Quantum computing is fueling the development. Single photon detection is possible on the bench!
- “She/he who controls this technology rules!”

Broadband MSAs:
CAPP collaboration with IPHT, Germany



A. Matlashov, *et al.*, “SQUID Amplifiers for Axion Search Experiments.” *Cryogenics*, 91, pp. 125-127, (2018)

Josephson Parametric Amplifier at 2.3 GHz JPA were provided by RIKEN/Univ. of Tokyo

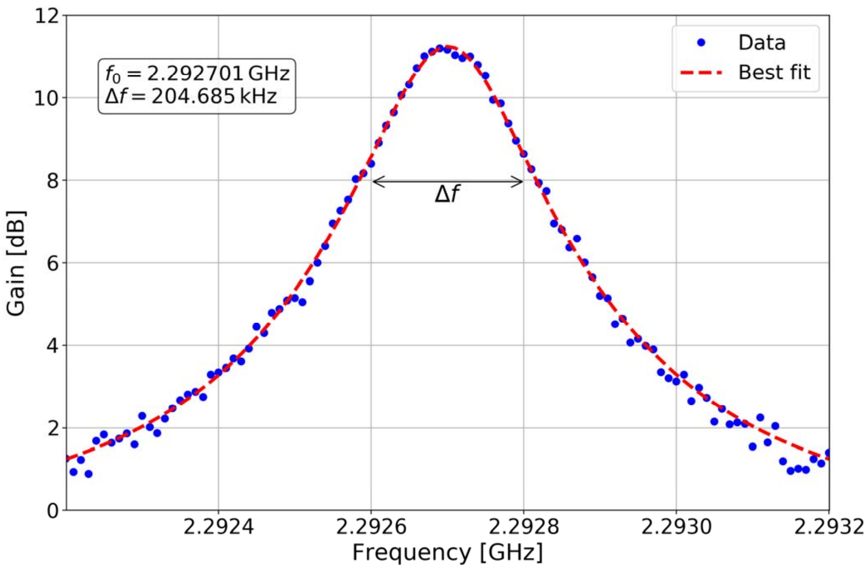


Fig. 3. Lorentzian gain band with a resonance frequency of about 2.3 GHz. The bandwidth is about 205 kHz.

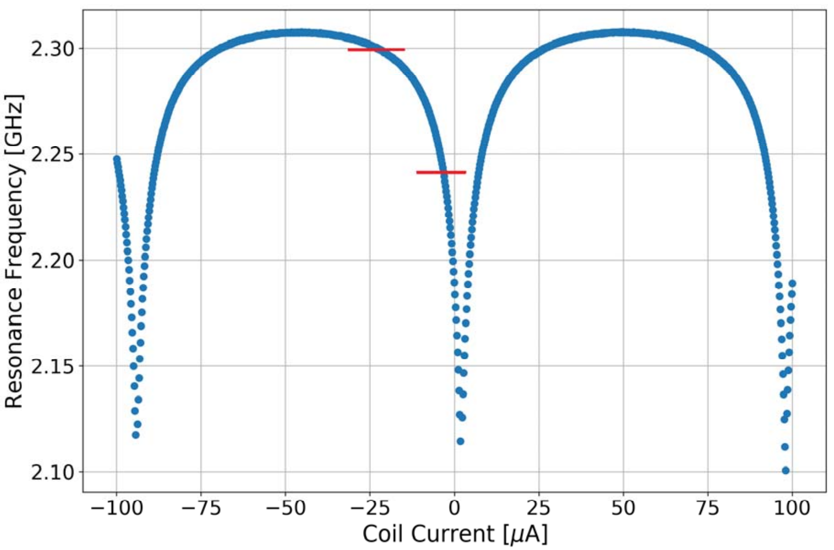


Fig. 4. Dependence of the JPA resonance frequency on dc flux bias. Red lines show that the operating frequency range is about 30 MHz.

- Reasonable gain and tunability to about 50 MHz

JPA results at 2.3 GHz

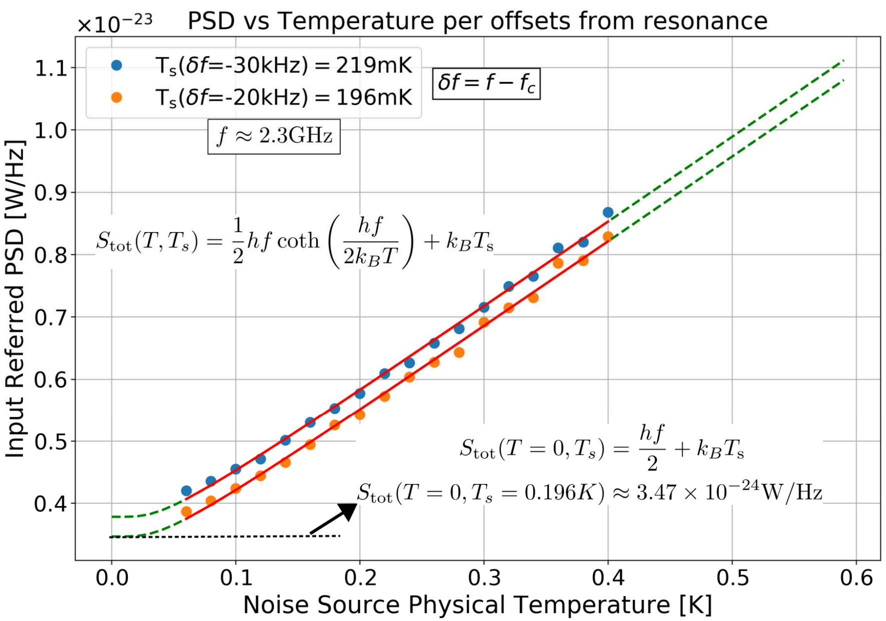


Fig. 5. PSD dependence on the temperature of 50Ω noise source for a 2.3 GHz JPA. The green line corresponds to the resistance noise PSD including quantum fluctuation corrections.

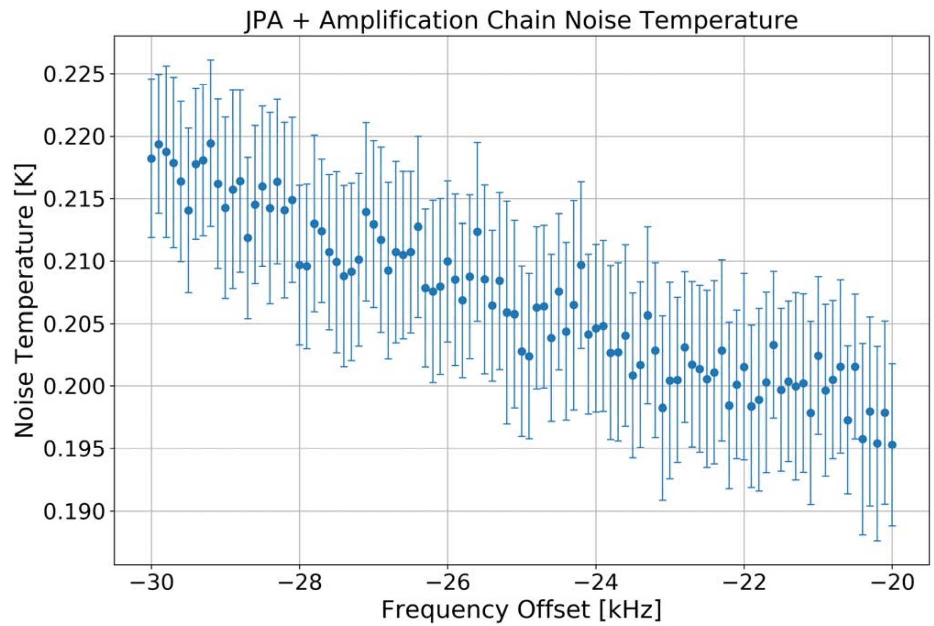
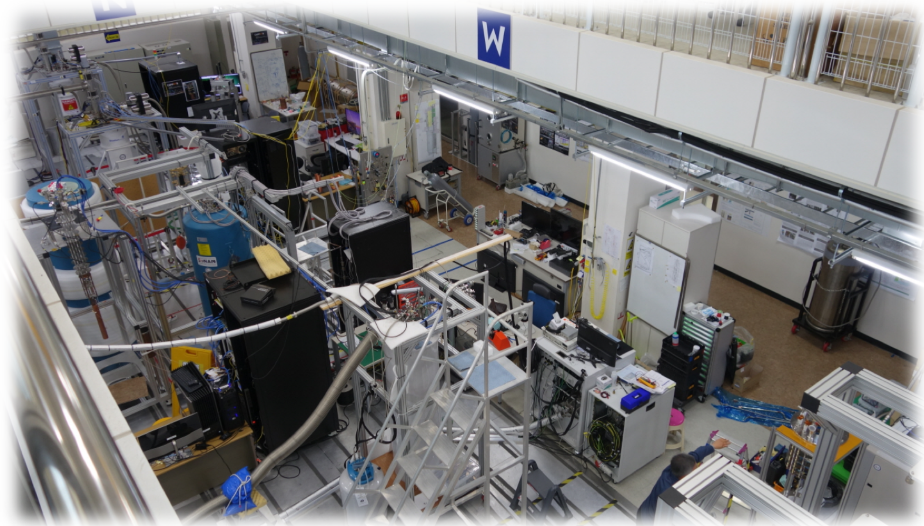


Fig. 6. Frequency dependence of the system noise temperature for 2.3 GHz JPA.

- Quantum noise limit (QNL): 50mK for every GHz
- Noise level of this JPA a little over the quantum limit
- Next JPA at 2.3 GHz was measured to be at QNL

Axion Dark Matter Search at IBS/CAPP

- *Center for Axion and Precision Physics Research (CAPP)*
  - *Established in Oct. 2013*
- *Completion of infrastructure*
  - *7 low vibration pads for parallel experiments*
  - *Several refrigerators and SC magnets*
- *Constructing experiments*
  - *Accomplished all technical challenges*
    - *Described in numerous publications in literature*
  - *Three experiments in DAQ mode in 2019*



Refrigerator			Magnet			Experiment
Manufacturer	**Model**	**T_B [mK]**	**Manufacturer**	**B_{max} [T]**	**Bore [mm]**	**Name**
BlueFors (BF3)	LD400	10				
BlueFors (BF4)	LD400	10				
Janis	HE-3-SSV	300	Cryo Magnetics	9	125	CAPP-9T MC
BlueFors (BF5)	LD400	10	AMI	8	125	CAPP-8T (PACE)
BlueFors (BF6)	LD400	10	AMI	8	165	CAPP-8TB
Oxford	Kelvinox*	30	SuNAM	18	70	CAPP-18T
Leiden	DRS1000	100	Oxford	12	320	CAPP-12TB
Oxford Instr.	Kelvinox	30	BNL Magnet Div.	25	100	CAPP-25T

Operating several experiments targeting different axion mass ranges in parallel.

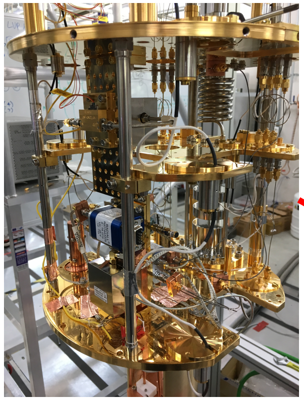
* The Kelvinox refrigerator will be reused for CAPP-25T

Axion Activities at IBS/CAPP

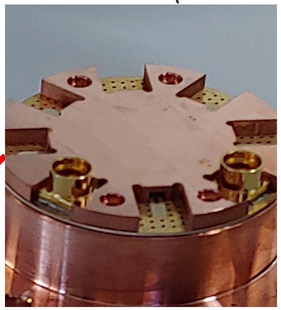
Enhancing the scanning rate

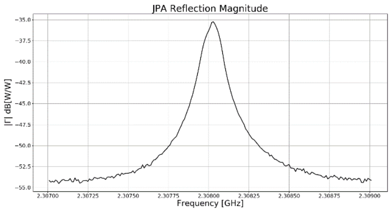
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics (T)
Lowering thermal noise



Quantum noise limited amplifier (T)
Amplification w/ noise squeezing
(U. of Tokyo & RIKEN)

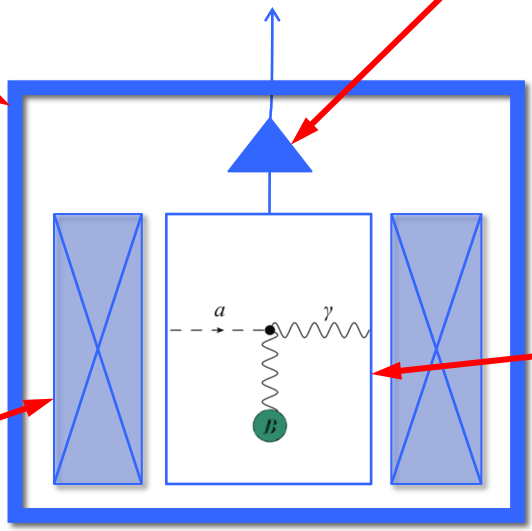




JPA gain measurement:
20 dB @ 2.3 GHz

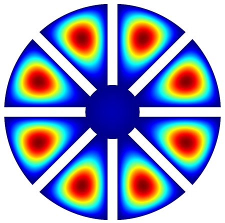
Functional JPA w/ in-house expertise

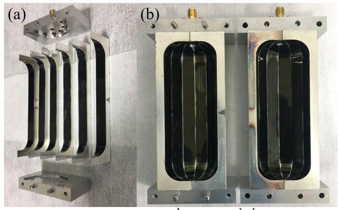
RF readout chain



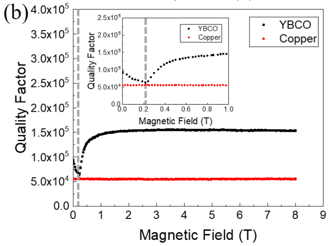
Axion-photon conversion
(Sikivie's method)

Microwave resonator (V,C,Q)
High frequency / high Q factor



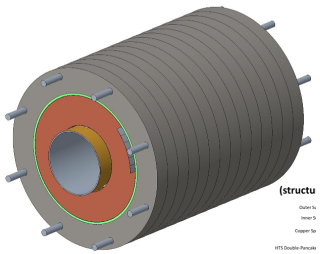


Pizza cavity
for high frequency
*Phys. Lett. B **777** 412 2018*



SC (YBCO) cavity
under high B field
Arxiv: 1904.05111

High field HTS Magnet (B)
Boosting a→γγ conversion rate

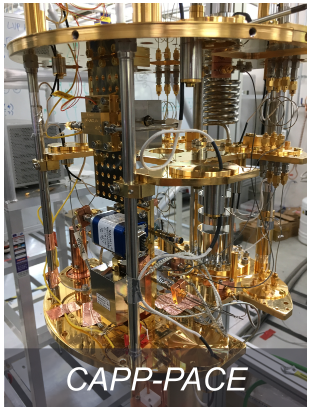


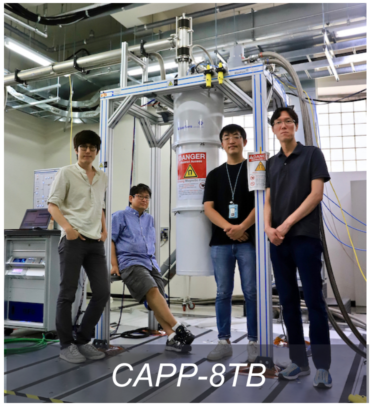
HTS 25T/100mm
w/ BNL
(funding limited)
*IEEE T. Appl. Supercon. **29**, 5 (2019)*

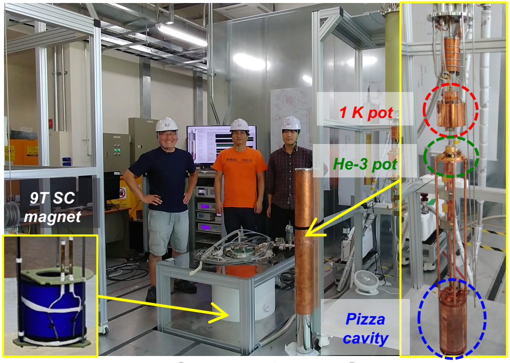
LTS 12T/320mm
(Oxford Instr., 2020)

IBS/CAPP Prospects

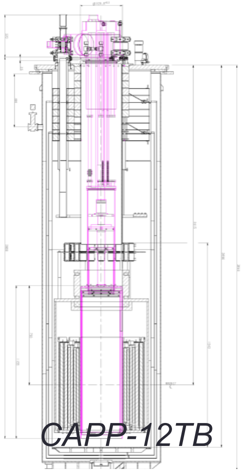
- *All the ingredients together, we will reach the DFSZ sensitivity even for 10% axion content in the local dark matter halo.*

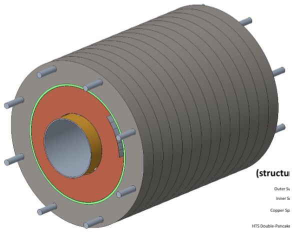


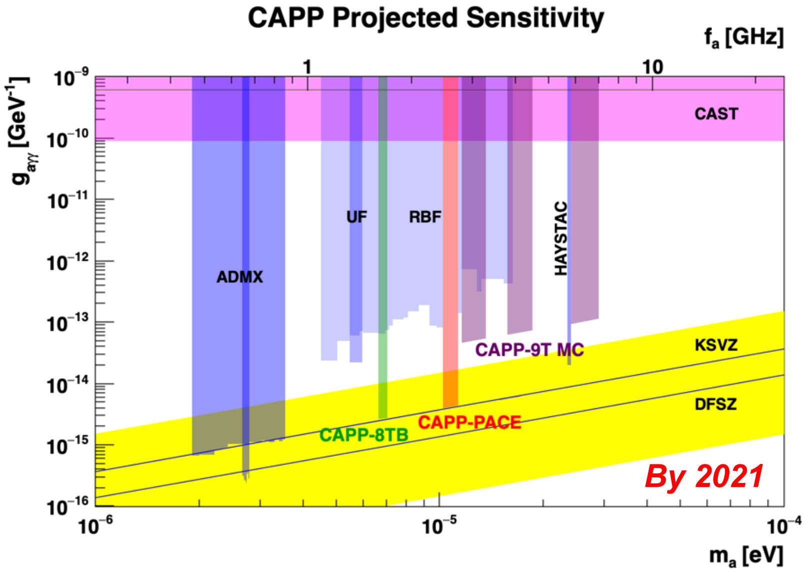


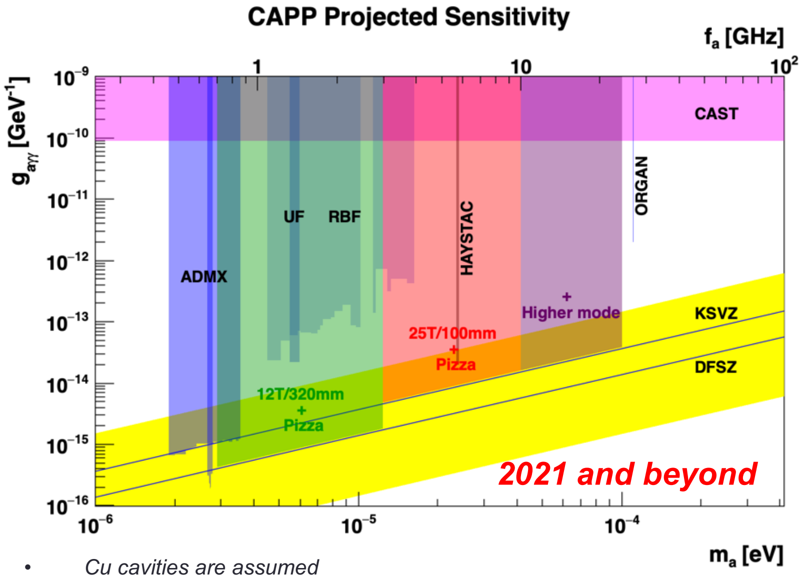


CAPP-9T MC


CAPP-12TB


CAPP-25T





- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

CAPP
Center for Axion and Precision Physics Research

Summary

- Axions are part of the Strong CP-problem. They are also excellent dark matter candidates.
- IBS/CAPP: multiple exps. in parallel, QNL amplifiers, High-frequency/High-efficiency resonators, SC cavities
- IBS/CAPP will probe 1-10 GHz within the next five years down to DFSZ hadronic axion models. Next 10-20 GHz.
- When all is put together we will probe axions down to 10% of local dark matter halo.