Dark Universe

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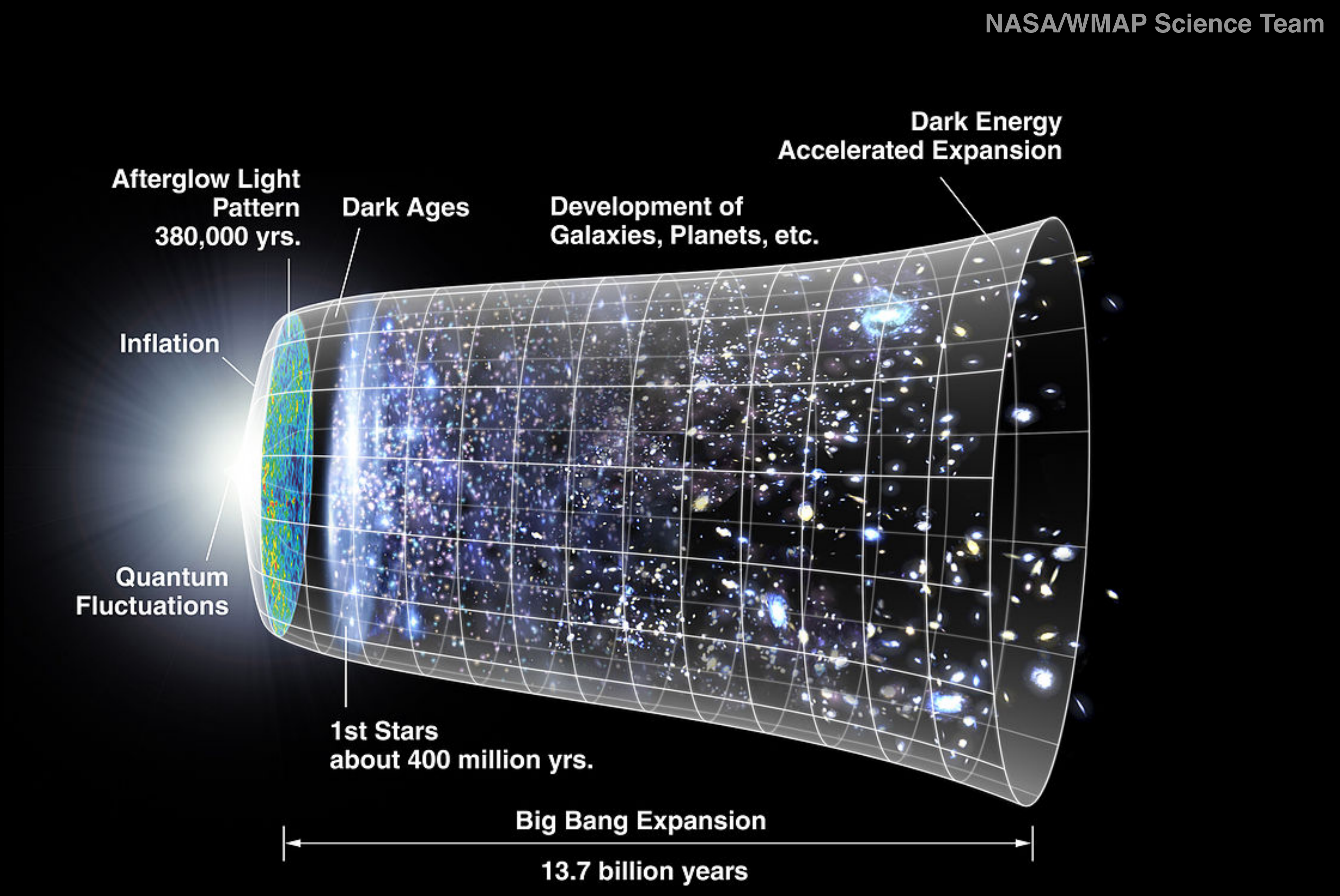
TGSW2018: Evolution of the Universe

Tsukuba

The Bright Side of the Universe

B.Nord (Fermilab)
Cerro Pachón, Chille

Evolution of the Universe



Hubble Constant

Velocity-Distance Relation among Extra-Galactic Nebulae (Hubble 1929)

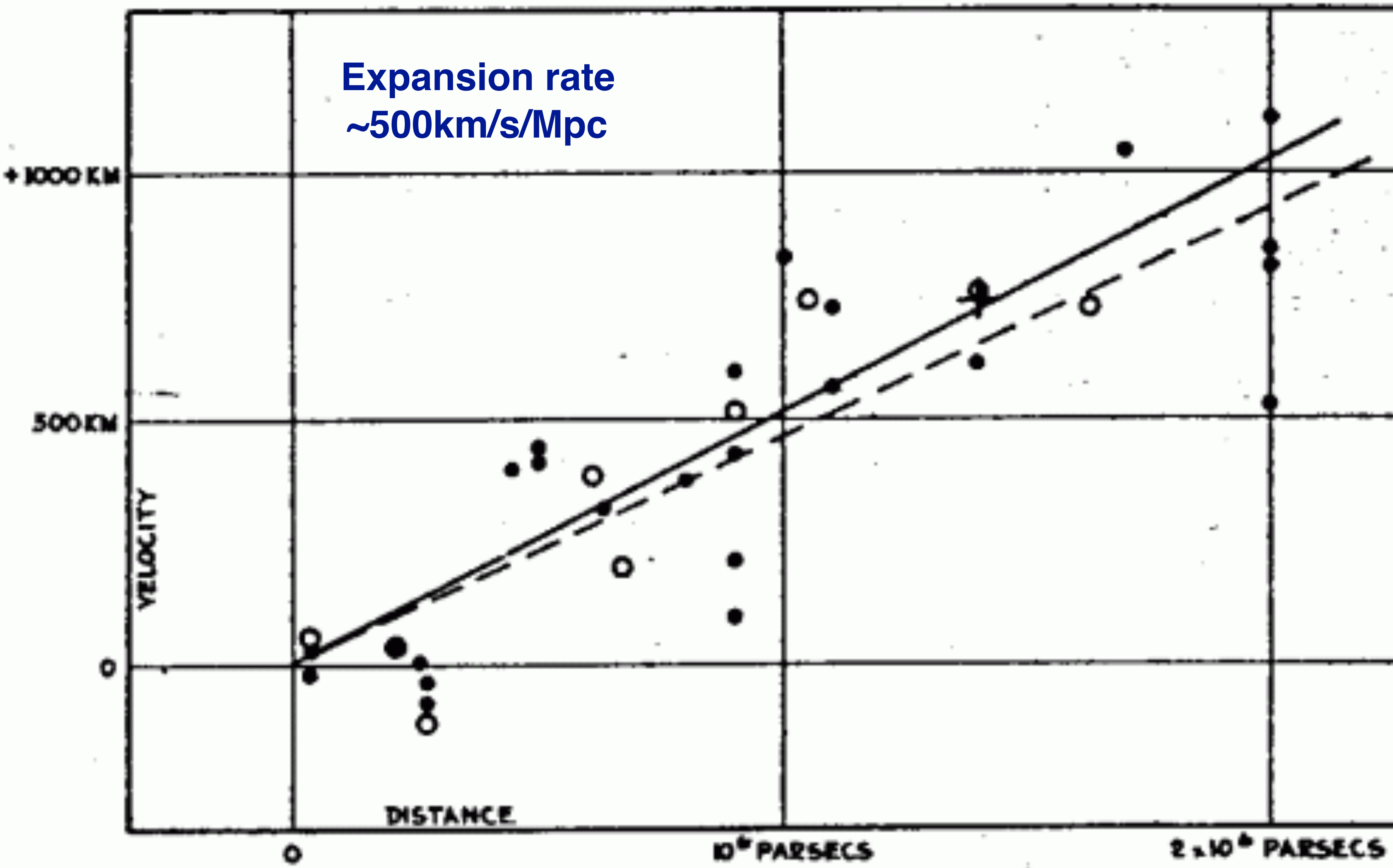
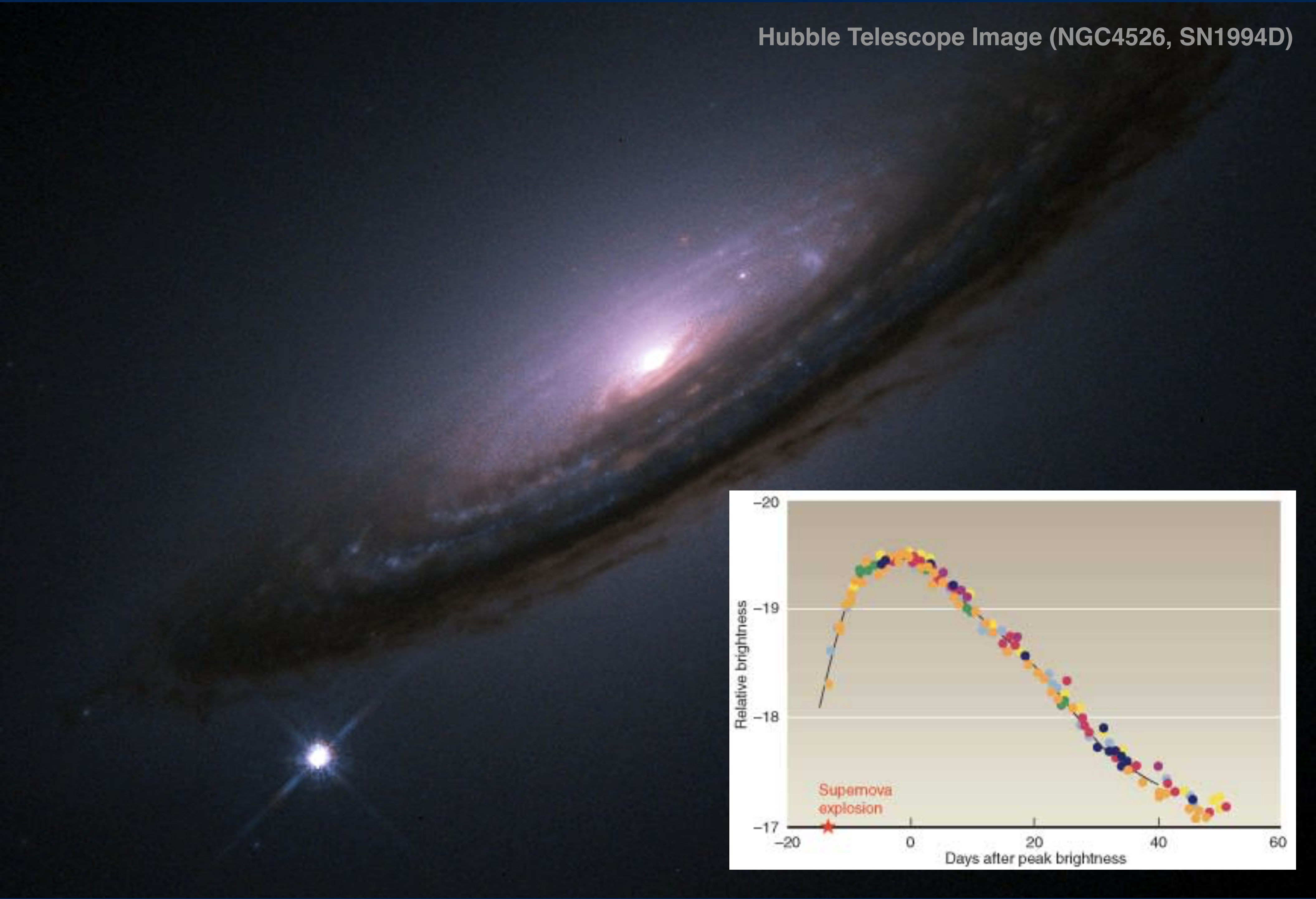


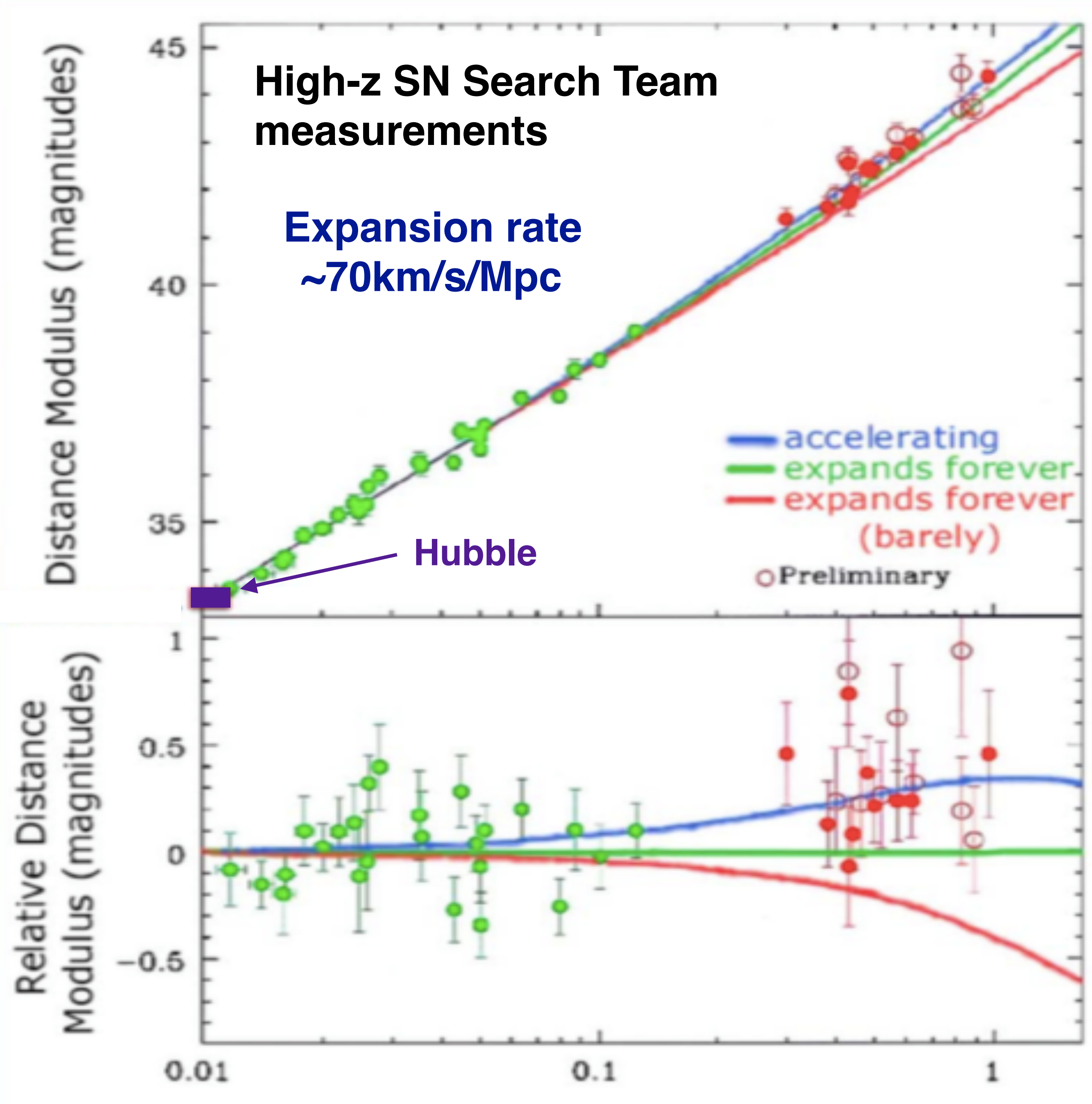
FIGURE 1

Type Ia Supernova: Standard Candle



Hubble Telescope Image (NGC4526, SN1994D)

Modern Hubble Diagram: Accelerating Universe



$$\left(z = \frac{\lambda_o - \lambda_e}{\lambda_e} = \frac{a_{\mathrm{now}}}{a_{\mathrm{then}}} - 1\right)$$

Totally unexpected discovery in 1998 by two independent observatory teams

(1) High-z SN Search Team
(2) Supernova Cosmology Project

Accelerating Universe!

Nobel Prize in Physics 2011
Saul Perimutter
Brian P. Schmidt
Adam G. Riess
for the discovery of the accelerating expansion of the Universe

Recall a Friedmann equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) \quad > 0\ (?)$$

Acceleration?
Negative pressure?

Cosmological Constant: Dark Energy(?)

- **ΛCDM Model**

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

gravity (matter) **dark energy**

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

slows down expansion

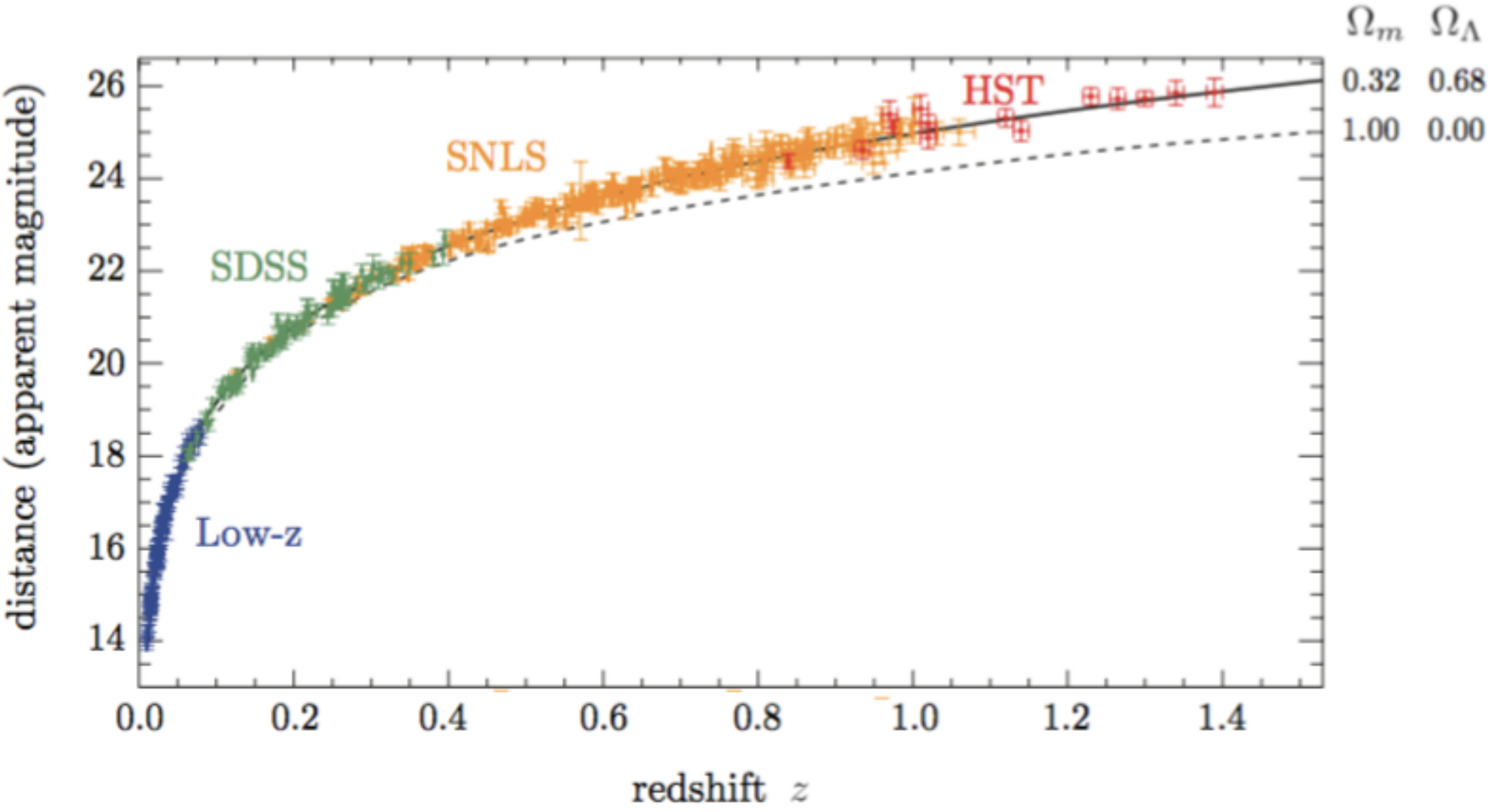
speeds up expansion

$$\frac{H^2}{H_0^2} = \underset{\substack{\uparrow \\ 9.4\times10^{-5}}}{\Omega_r a^{-4}} + \underset{\substack{\uparrow \\ \sim 0.32}}{\Omega_m a^{-3}} + \underset{\substack{\uparrow \\ <0.01}}{\Omega_k a^{-2}} + \underset{\substack{\uparrow \\ 0.68}}{\Omega_\Lambda}$$

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$$

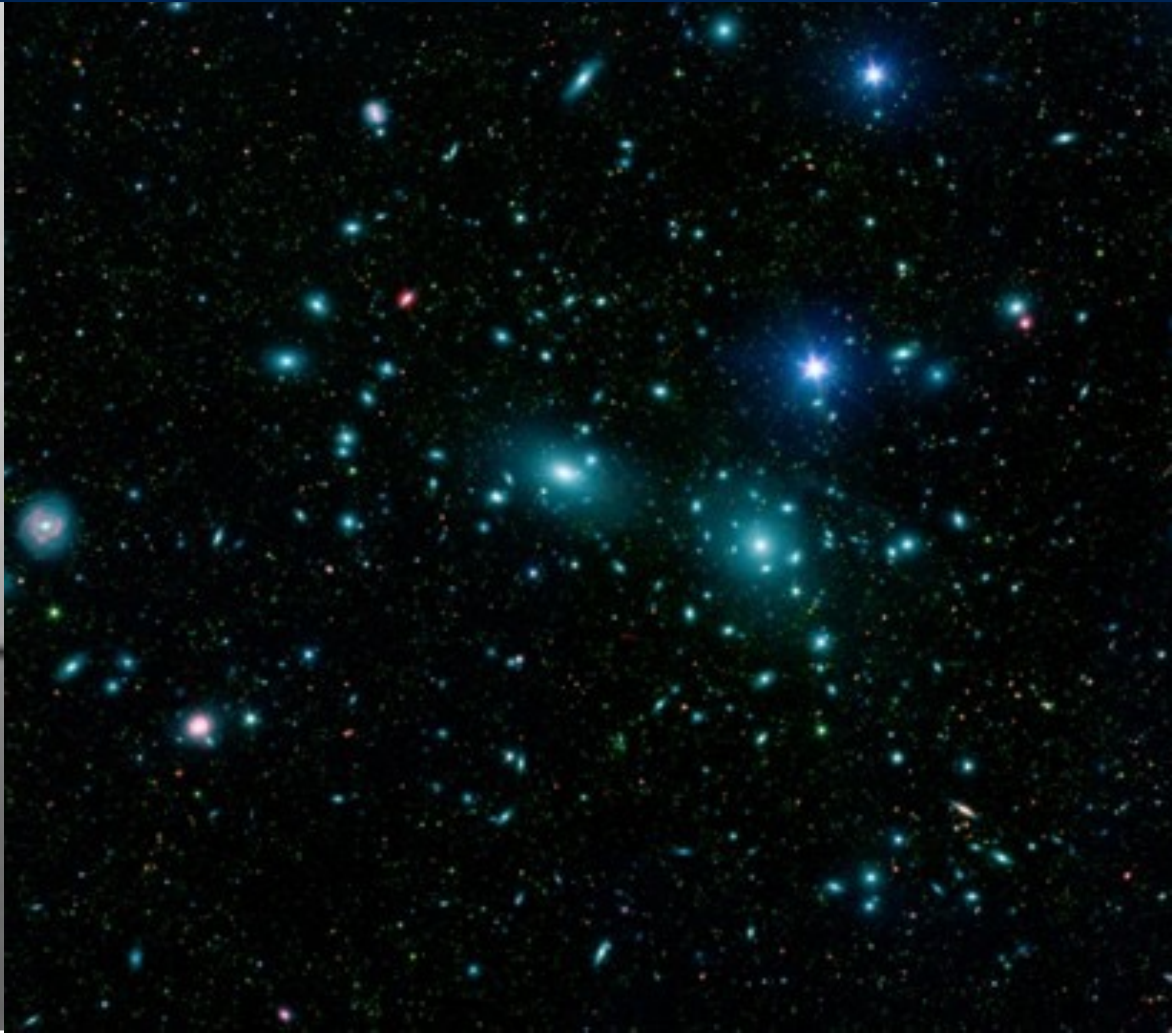
$$1 = \Omega_r + \Omega_m + \Omega_k + \Omega_\Lambda$$

Dark Energy



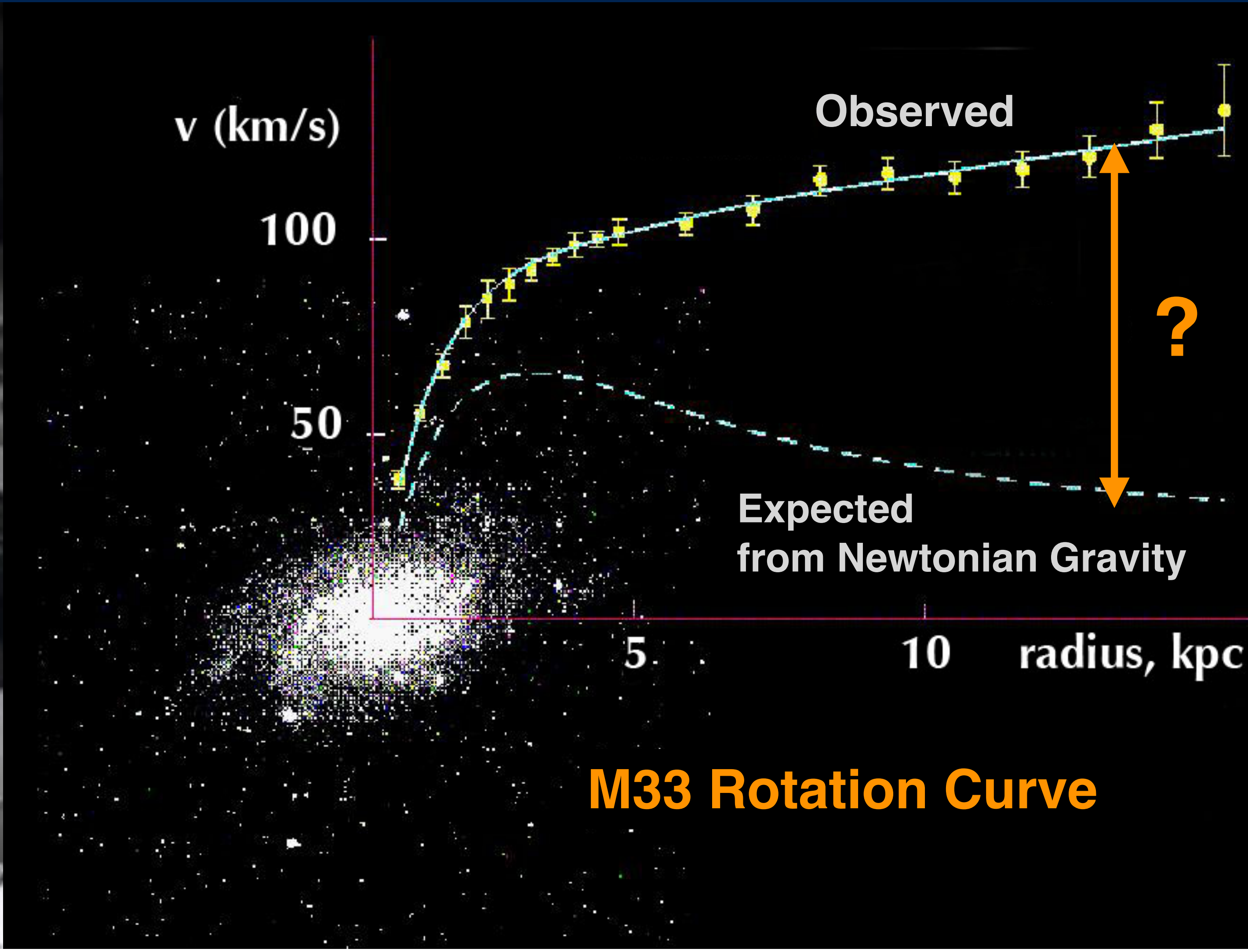
70% of the energy budget of the universe is Dark Energy!
30% is matter component…

Fritz Zwicky (1933): Coma Galaxy Cluster



1933 Fritz Zwicky found evidences for **dark matter** in the Coma galaxy cluster (consisted of approximately 1,000 galaxies.) by studying the velocity of the galaxies in the cluster. He found the light output per unit mass from the cluster fell short of that from gravitational mass of the cluster.

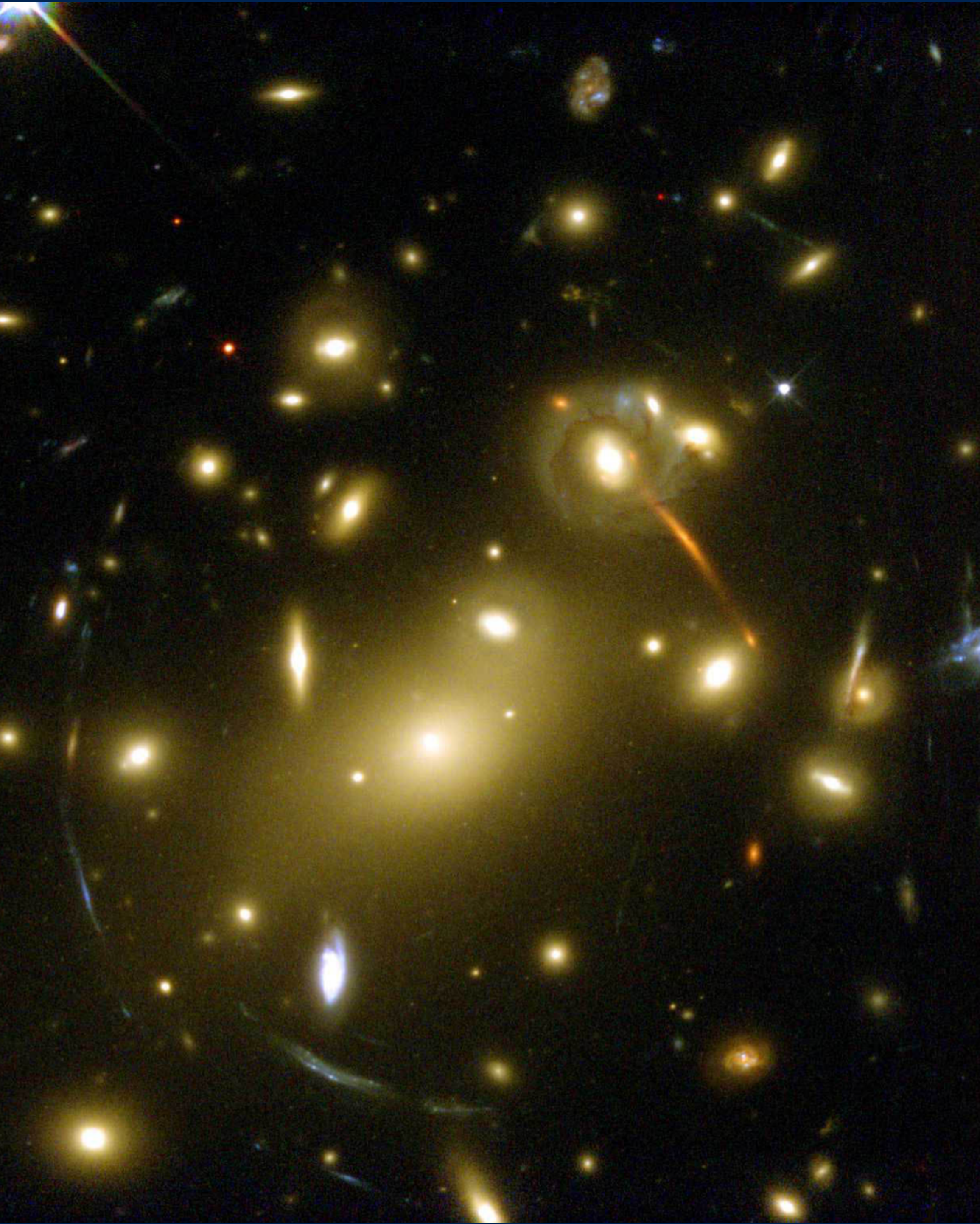
Rotation Curve of Galaxy

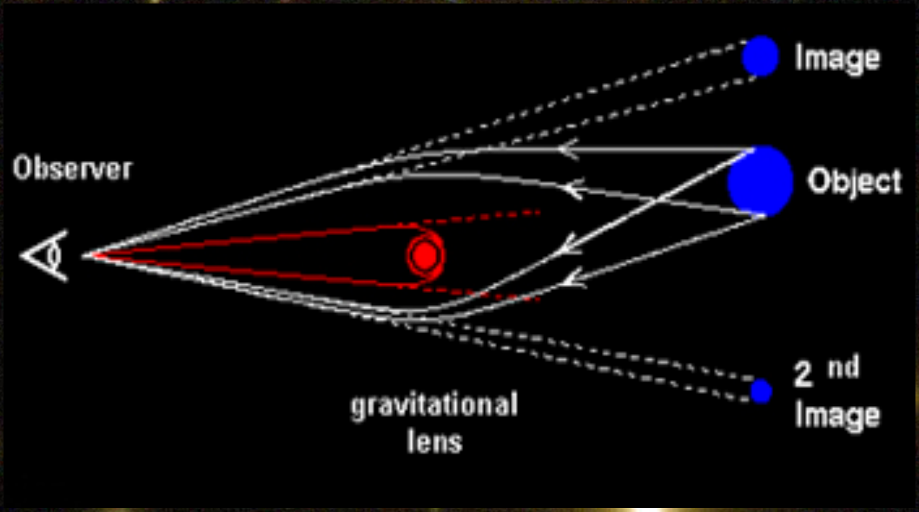


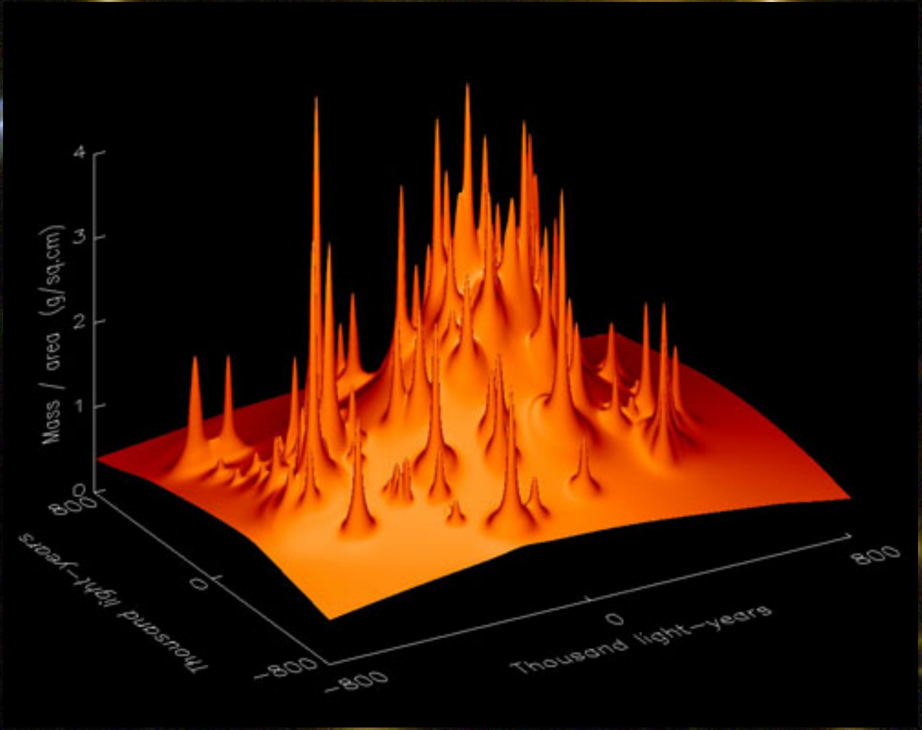
M33 Rotation Curve

1970s Vera Rubin studied the rotation curve of galaxies (speed of stars) and found inconsistency between the velocity distributions predicted by Newton’s gravitational law and the velocity distribution of stars.

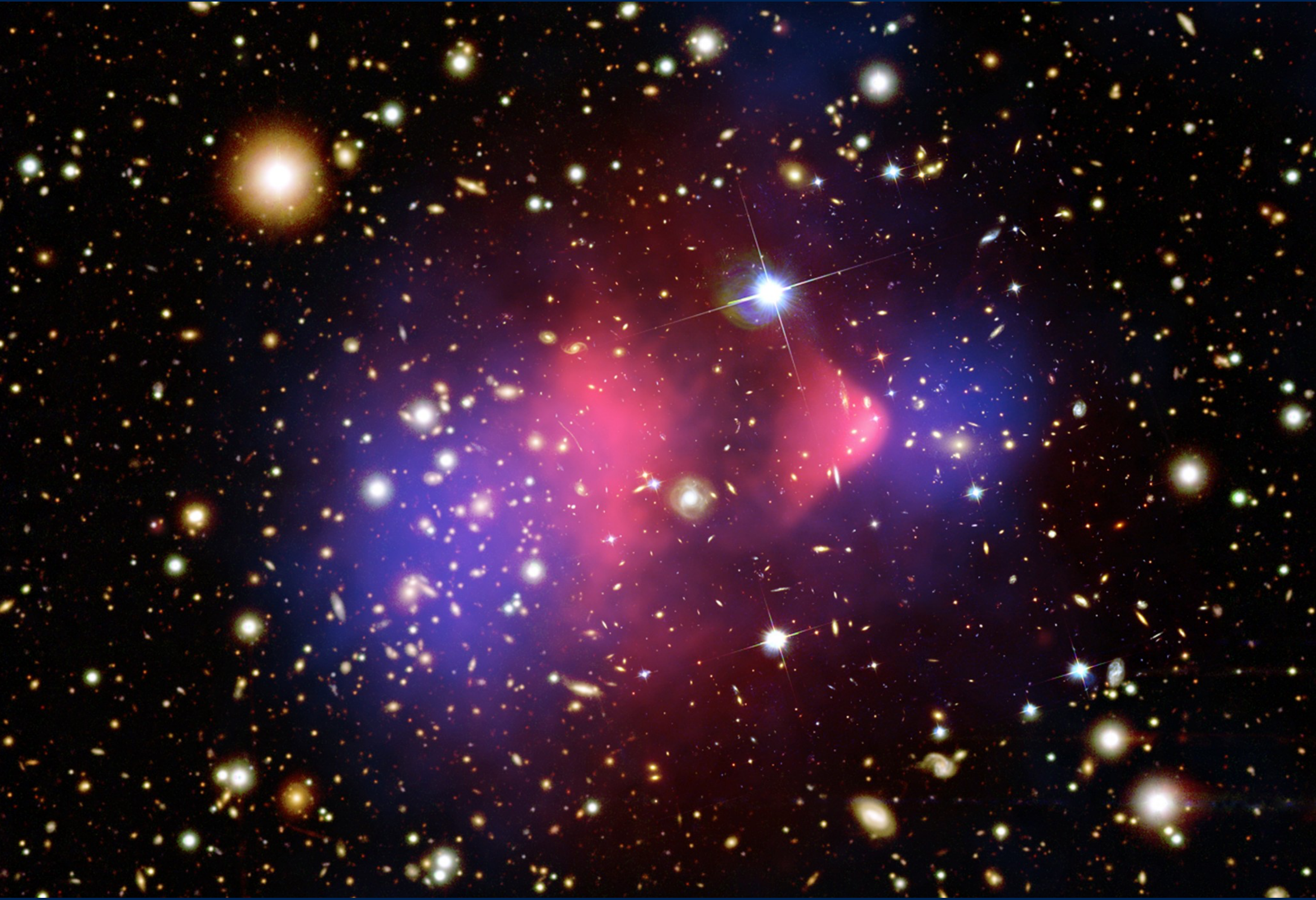
Dark Matter: Galaxy Clusters



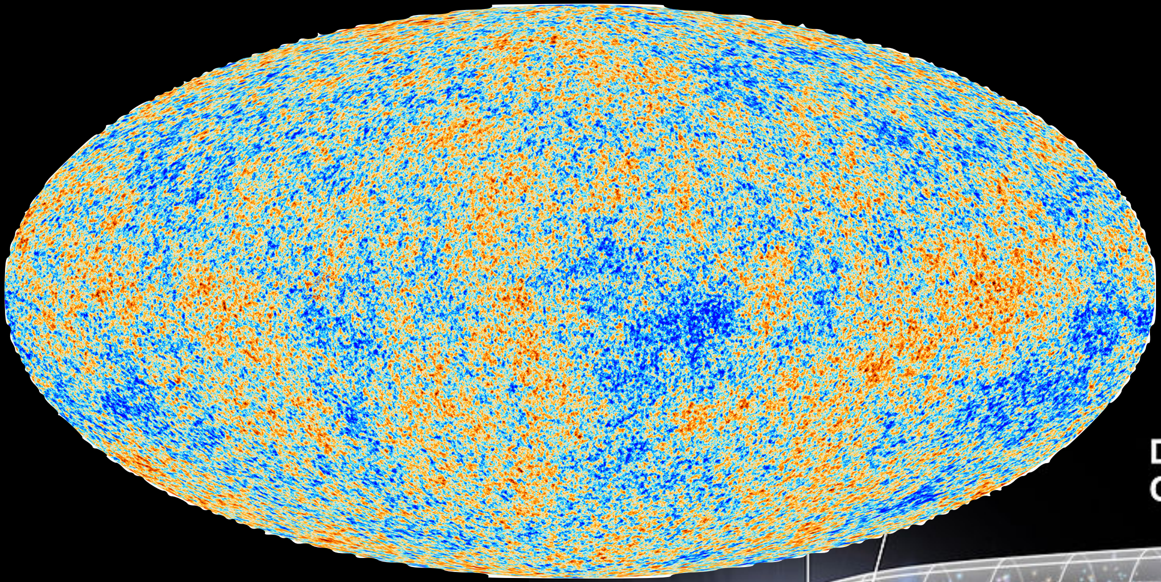


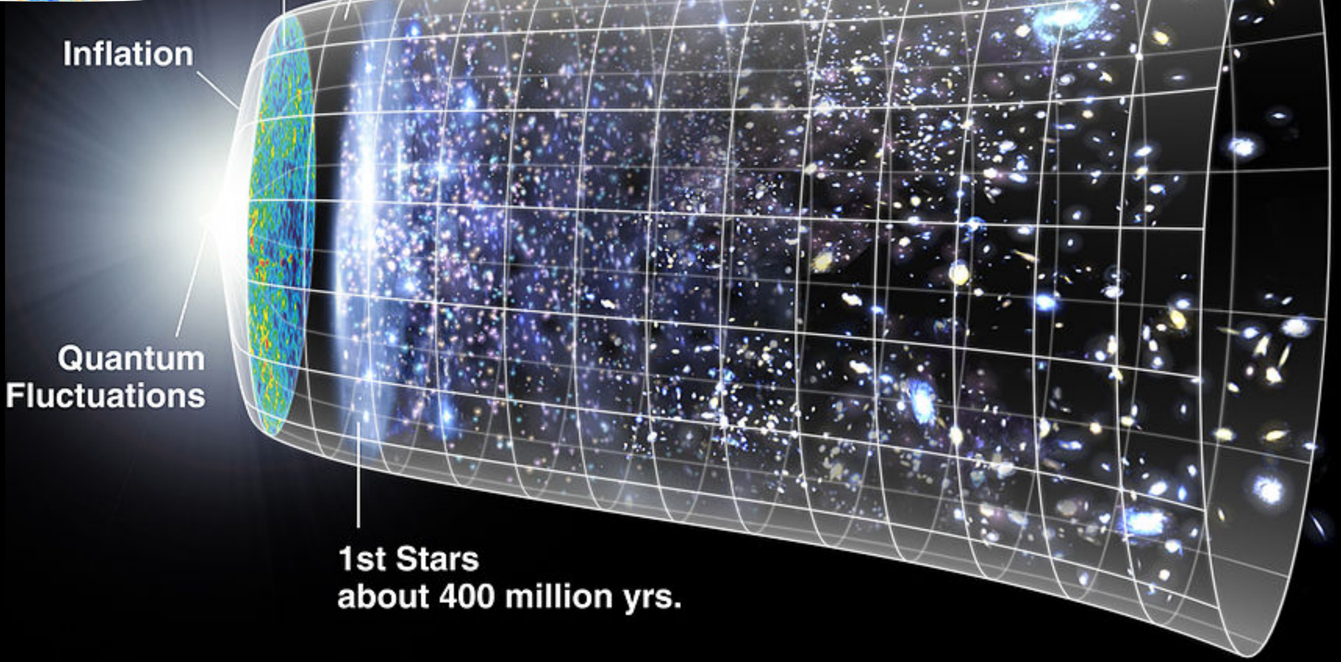


Dark Matter: Bullet Cluster Collision



Cosmic Microwave Background (CMB)

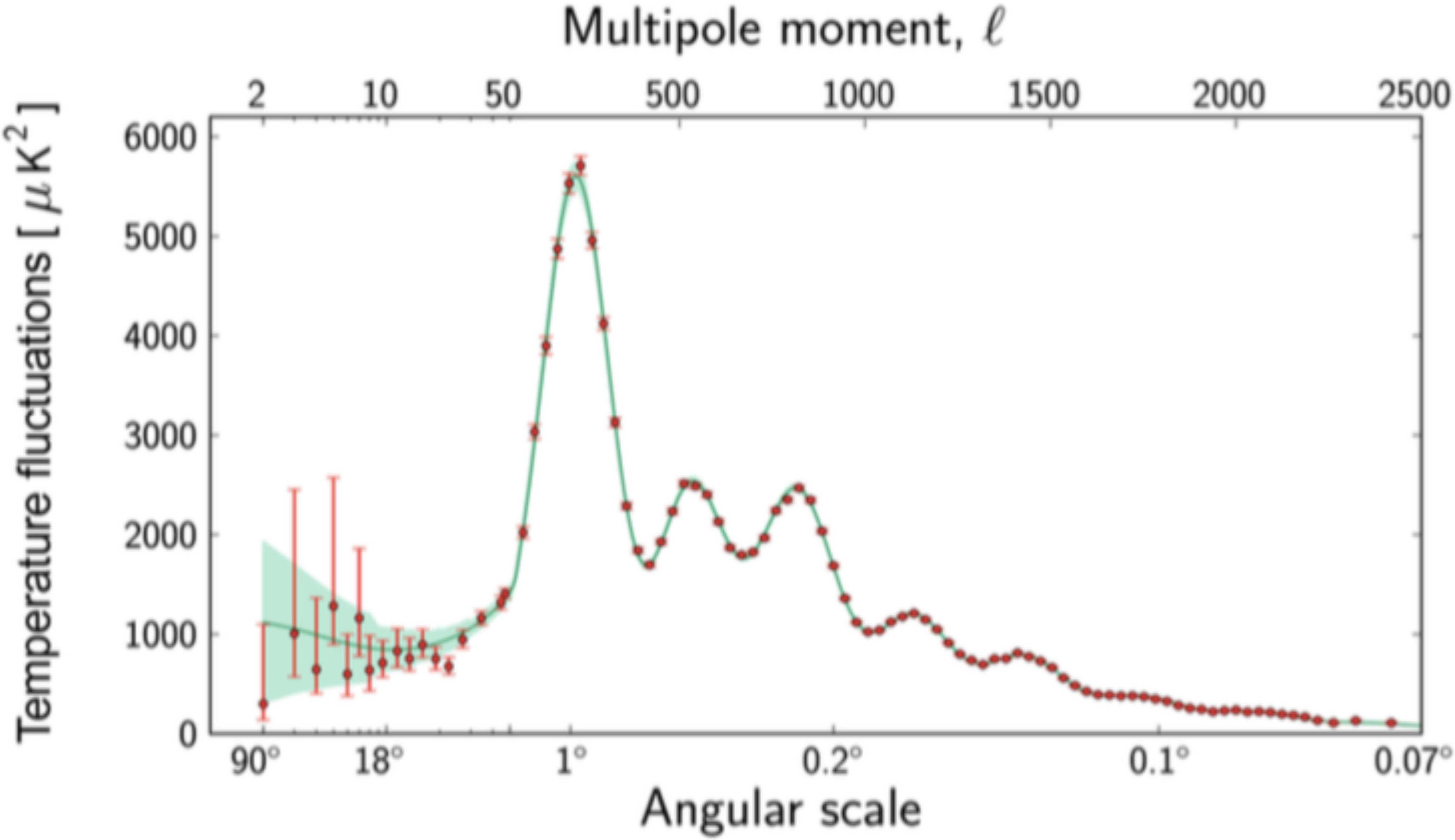




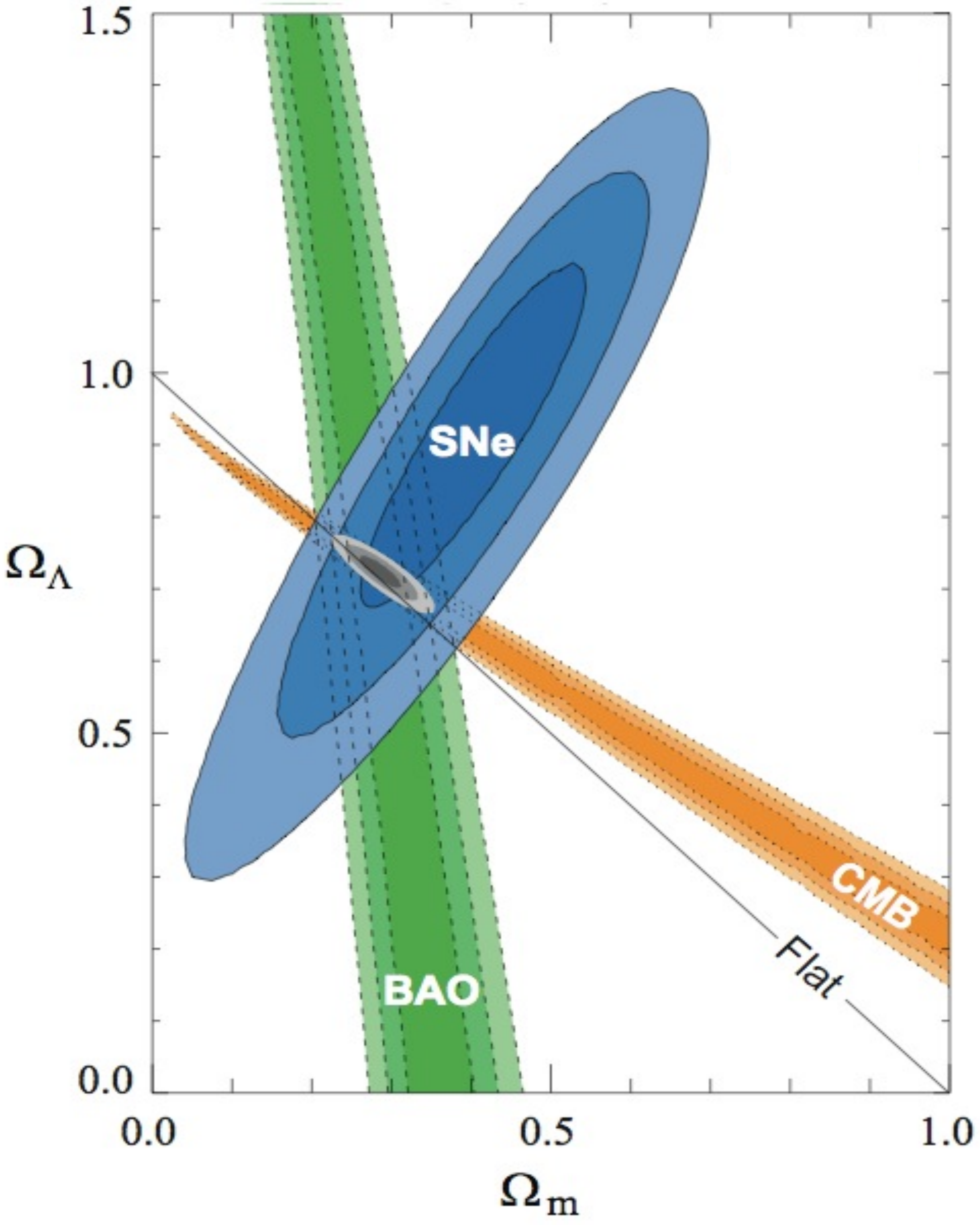
Snapshot of the Universe 380,000 years after the Big-Bang

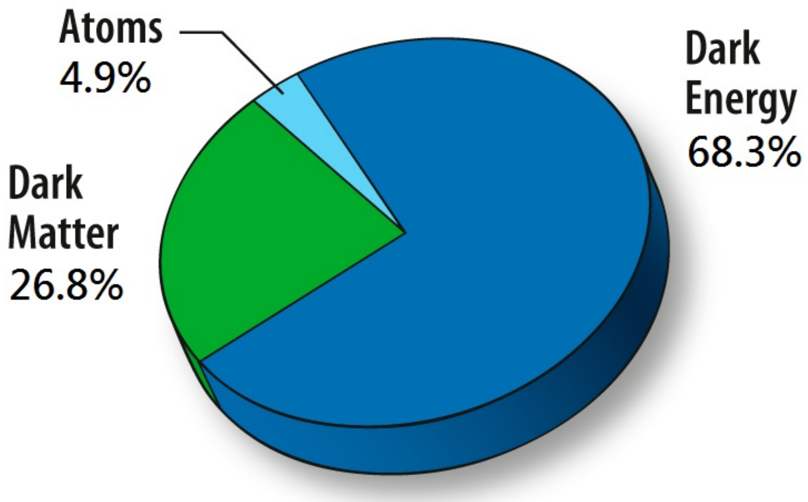
13,700,000,000 years

CMB Anisotropy



Universe is Dark





- We know that Dark Matter is
  - stable
  - non-baryonic
  - non-relativistic
  - interacts gravitationally

- We don't know what it actually is:
  - mass ?
  - coupling ?
  - spin ?
  - composition ?
  - distribution in the Universe …

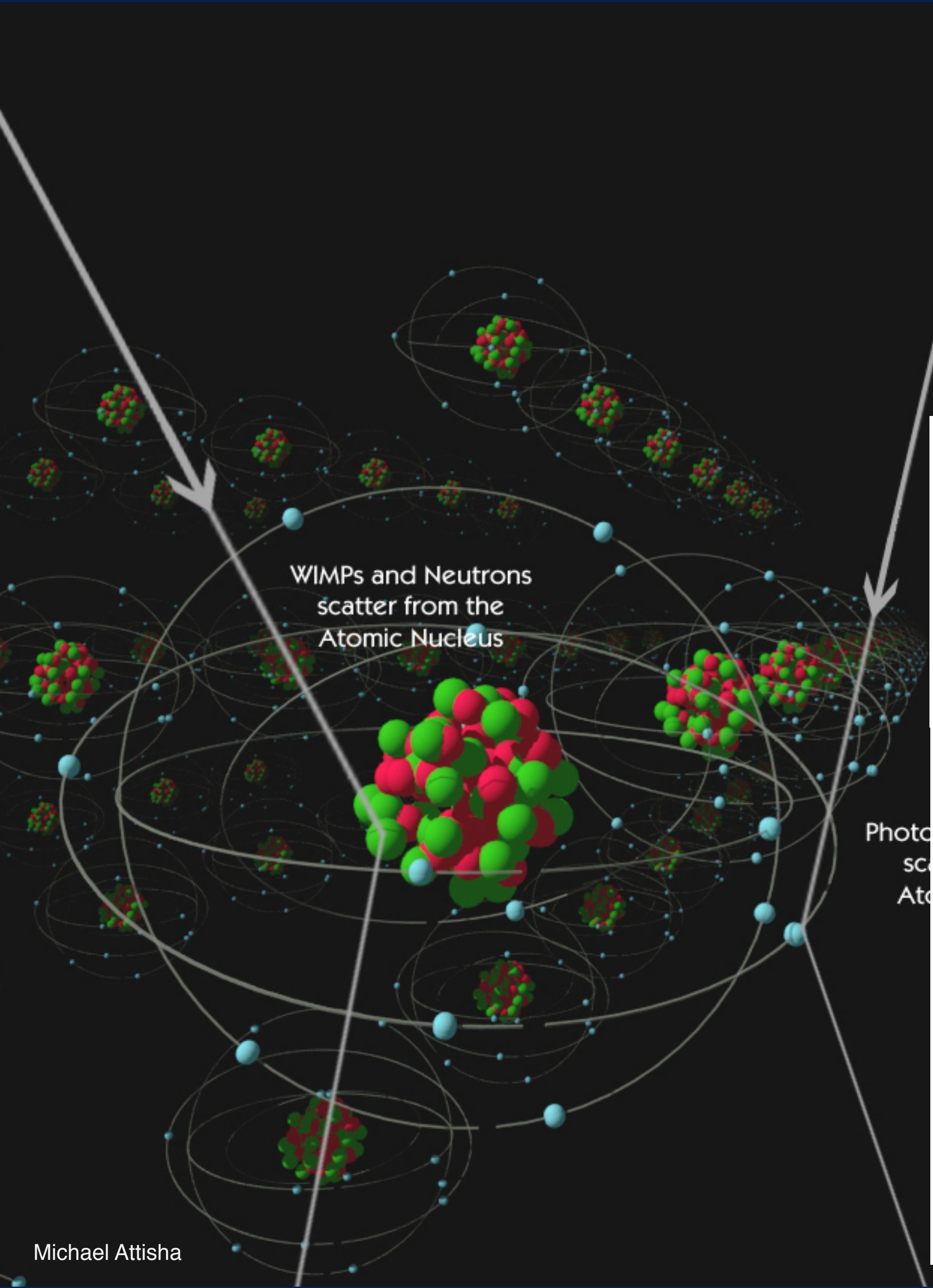
Dark Matter Distribution

Invisible Component of Matter Halo

We are here

200 kpc

Direct Detection of WIMP



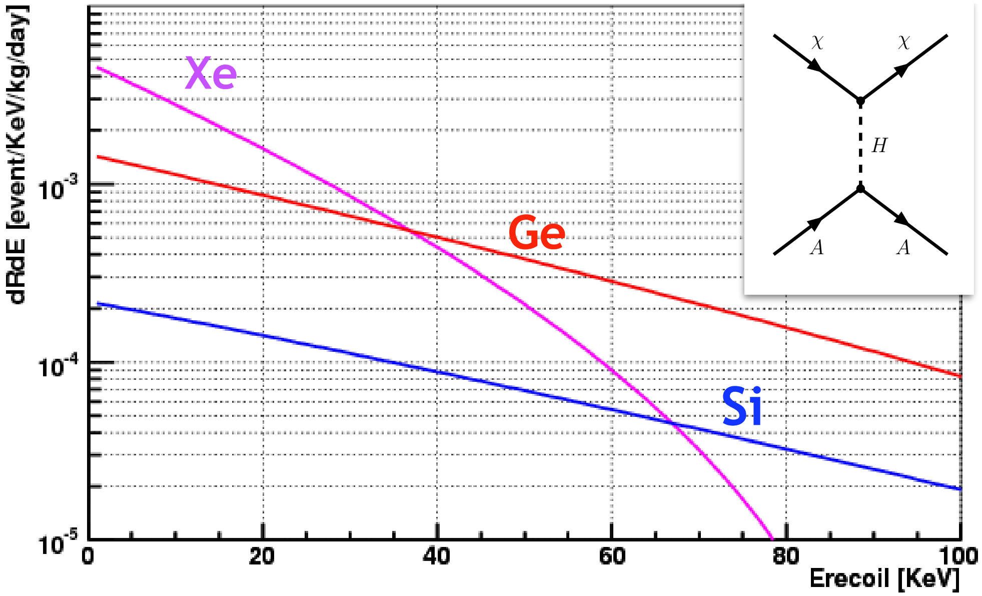
Michael Attisha

WIMPs (Weakly Interacting Massive Particles) coherently scatter from the entire nucleus

$$\sigma_{\chi N} \simeq \frac{4}{\pi}\mu^2[Zf_p + (A-Z)f_n]^2$$

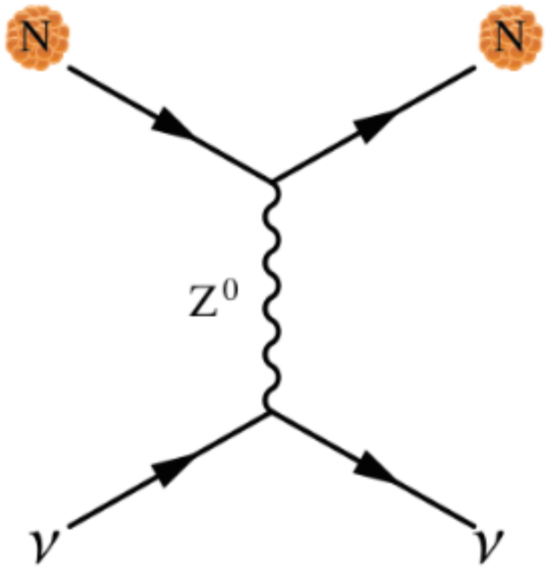
$$\frac{dR}{dE} = \frac{\sigma_0}{m_\chi}\frac{A^2}{2\mu_n^2}F_A^2(E) \times \rho_0 \int_{v_m} \frac{f(v)}{v}dv$$

Differential Event Rate in Recoil Energy @mD=60 GeV



CEvNS

$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu$$



Cross section for zero-momentum transfer limit

$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[Z\omega_p + (A-Z)\omega_n\right]^2$$

$$g(Z_0 u) = \frac{1}{4} - \frac{2}{3}\sin^2\theta_W, \qquad g(Z_0 d) = -\frac{1}{4} + \frac{1}{3}\sin^2\theta_W$$

$$\omega_p = \frac{G_F}{4}(4\sin^2\theta_W - 1), \qquad \omega_n = \frac{G_F}{4}$$

Differential cross section for finite momentum transfer

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1-4\sin^2\theta_w)Z - (A-Z)\right]^2 M \left(1 - \frac{ME}{2E_\nu^2}\right) F(Q^2)^2$$

Coherent Elastic Neutrino-Nucleus Scattering

Coherent scattering observed in Lepton sector (ORNL, by COHERENT Collaboration)

Dinosaur heretic looks for redemption p. 1088

Increase inclusion to increase STEM diversity p. 1101

Fluorescent or magnetic cotton fibers p. 1118

Science

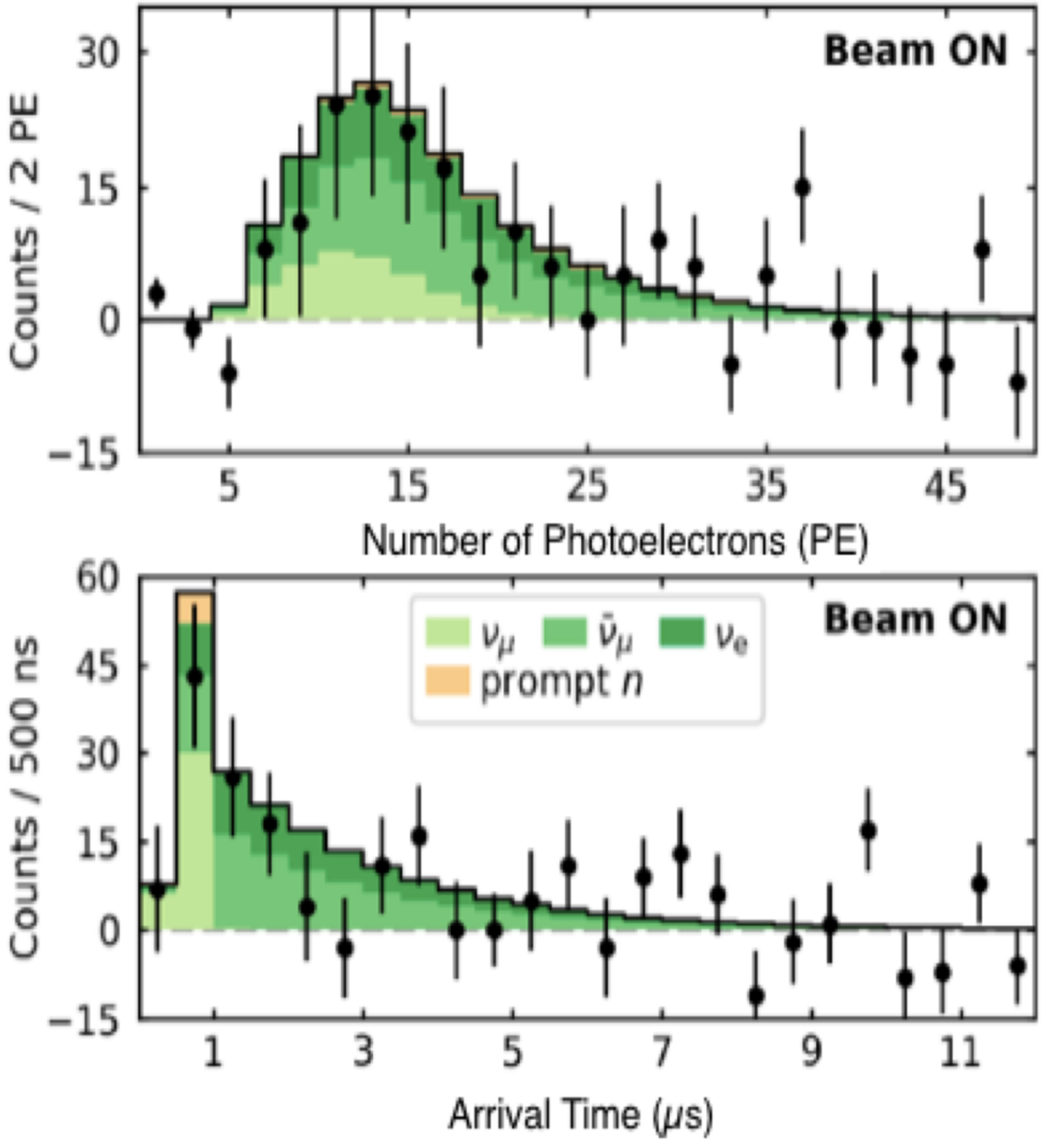
$15
15 SEPTEMBER 2017
sciencemag.org

AAAS

SPOTTING A GHOST

A compact detector spies neutrinos scattering from nuclei
pp. 1098 & 1123

2017 September 15



XENON 1T Experiment

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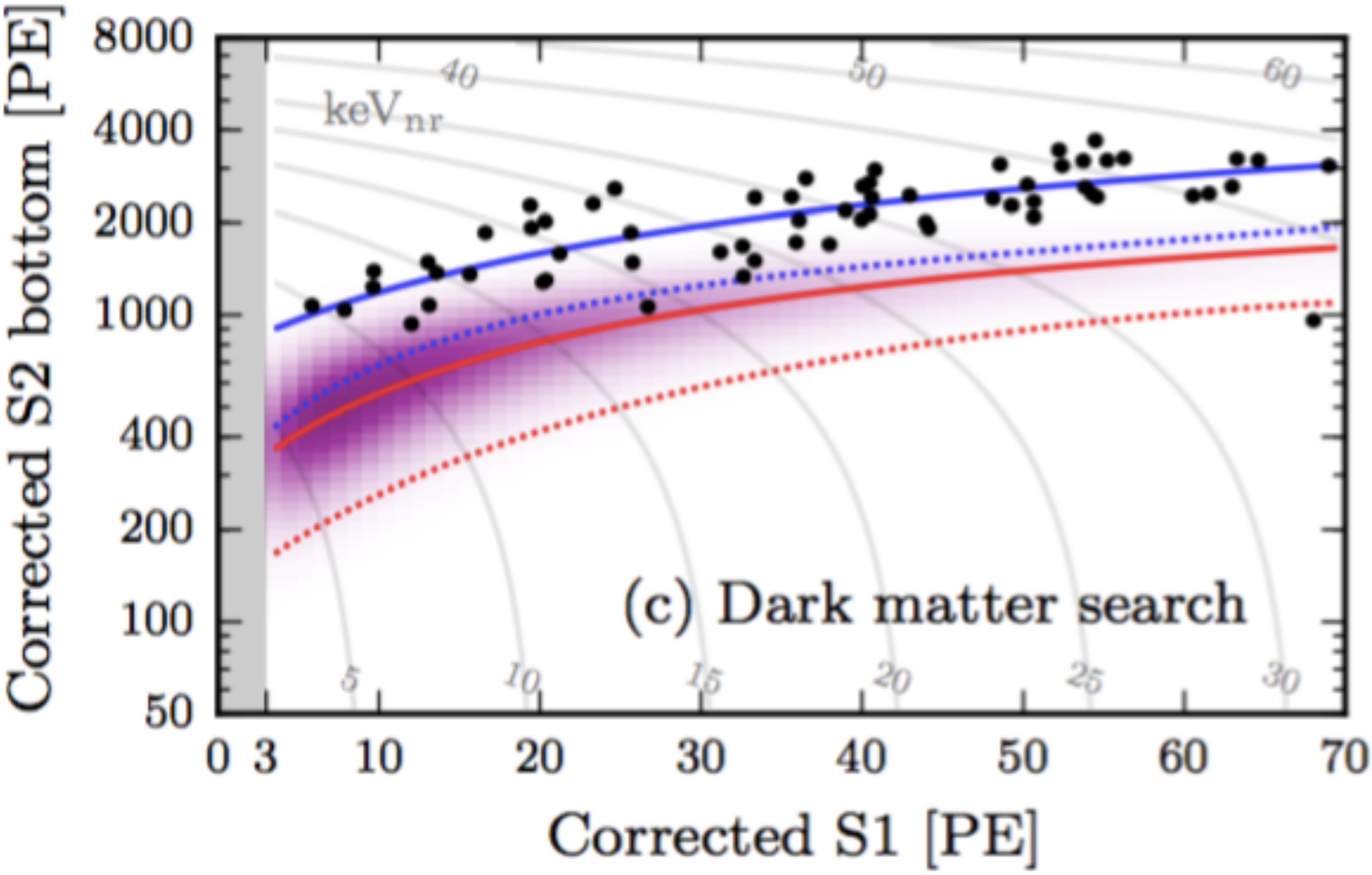
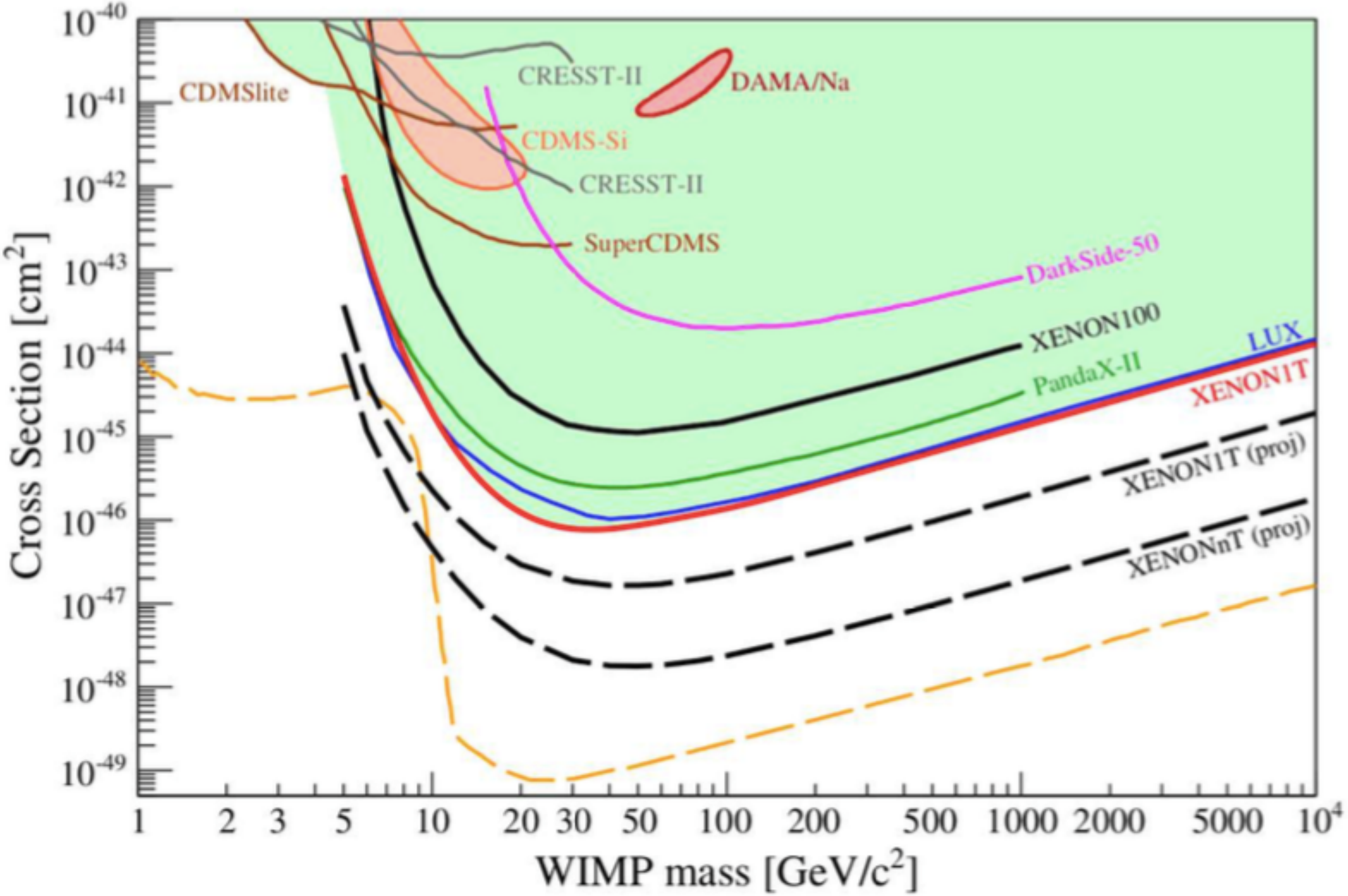
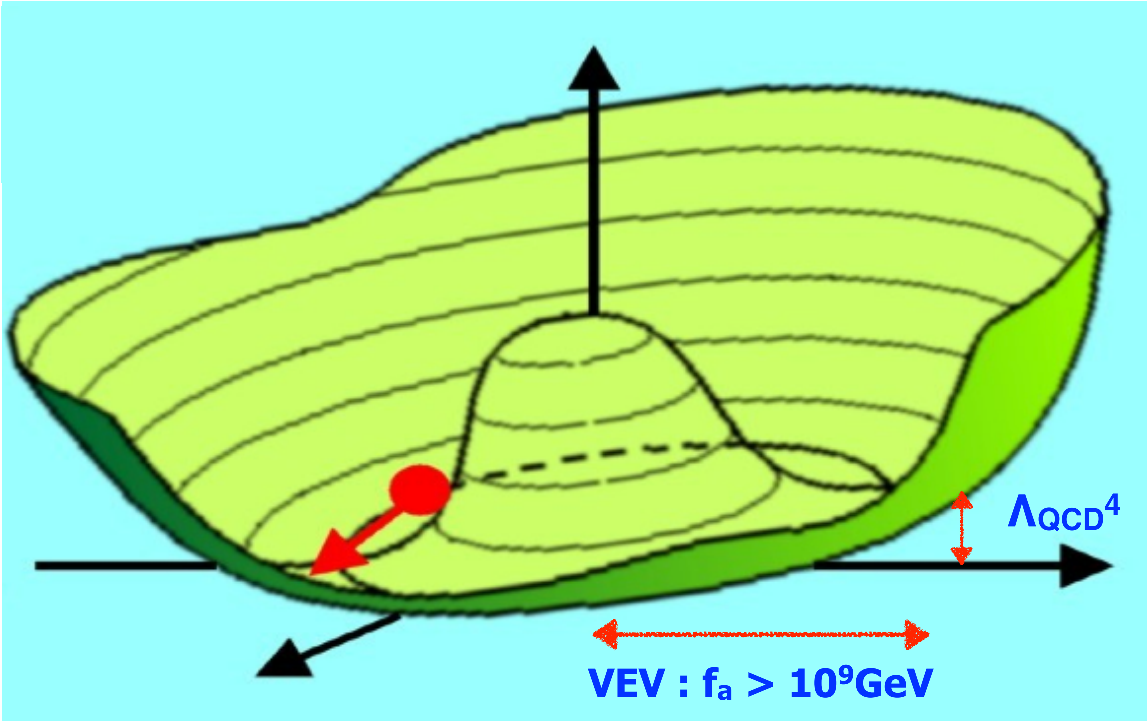


XENON 1T Experiment



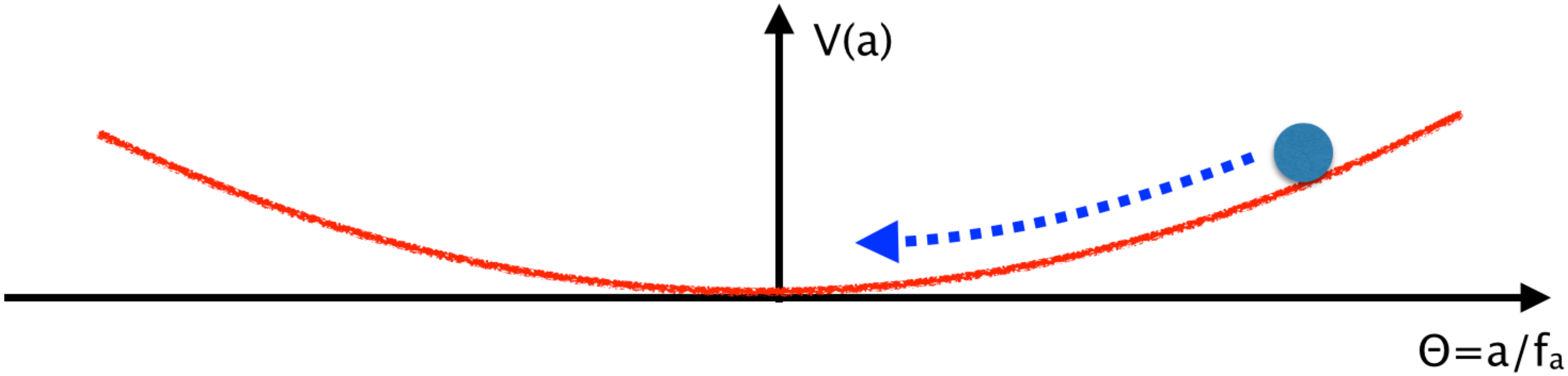
Axion as a Dark Matter

Invented to solve the strong-CP problem in QCD

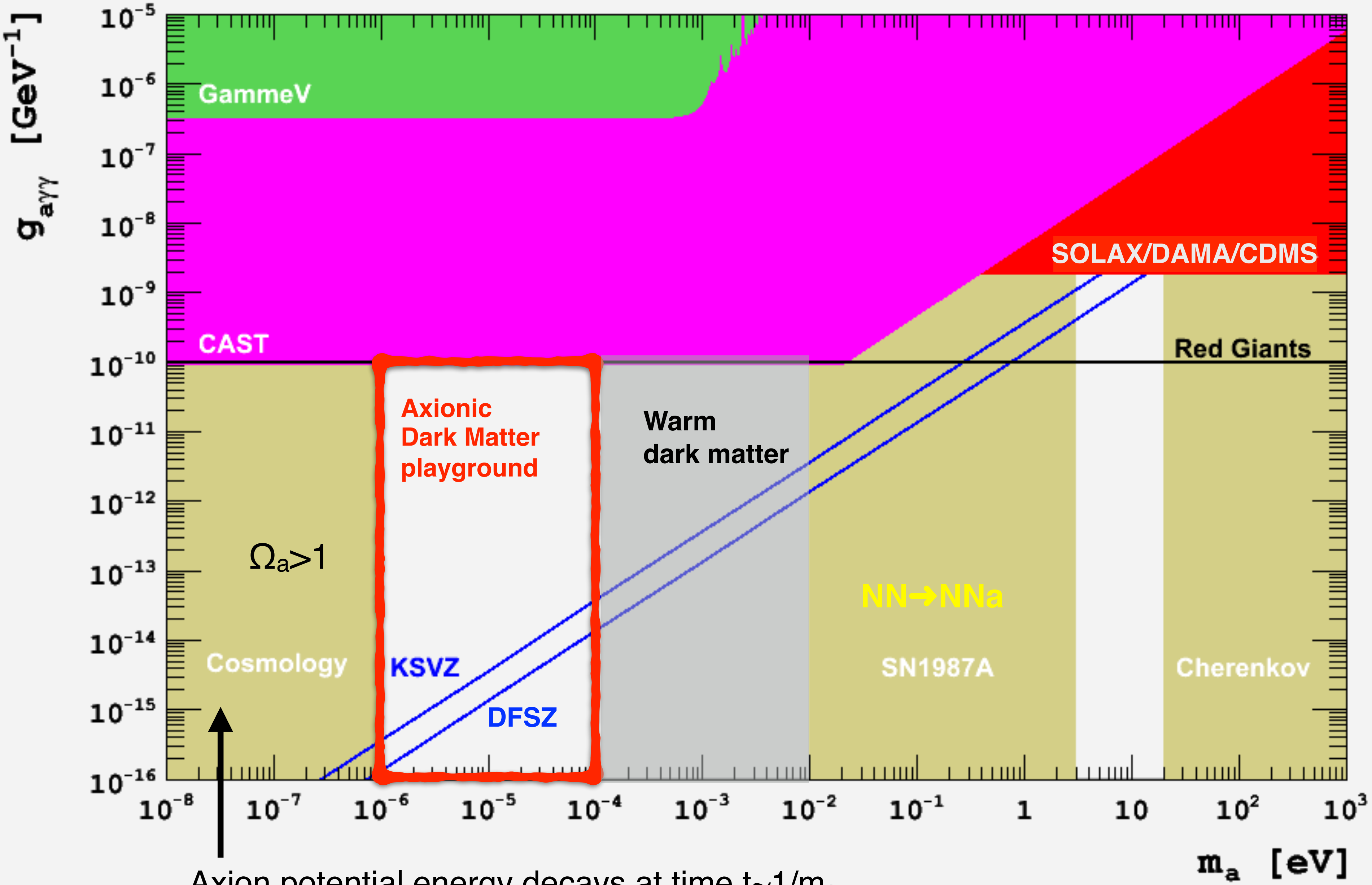


- Non-thermal mechanism of producing axion dark matter in the early Universe
- The initial axial angle Θ determines the potential energy to be released.
- The potential energy density (order of $\Lambda_{QCD}{}^4$) is converted into **cold dark matter**
- Axion dark matter mass is determined by the harmonic oscillator frequency

$m_a \simeq \Lambda_{QCD}{}^2/f_a < 10^{-3}$ eV !



Axion Dark Matter Search



Axion potential energy decays at time t~1/m_a.
If this is too late (too small m_a) in cosmological time
the dark matter can be overproduced relative to the photons

Axion Dark Matter Search in A Nutshell

Assume: $\mathrm{m}_a \simeq \mu\mathrm{eV}$

$$\rho_{\mathrm{DM}} = 3 \times 10^8\, \mathrm{eV/cc} = 2.4 \times 10^{-6} \mathrm{eV}^4$$

$$\beta = 10^{-3} \text{ or } < v_a >= 10^{-3} c$$

$$L_{coh} = \frac{1}{p} \simeq 10^9 \mathrm{eV}^{-1} \simeq \boxed{200\,\mathrm{m}}$$

$$t_{coh} = \frac{1}{E} \simeq 10^{12} \mathrm{eV}^{-1} \simeq \boxed{\mathrm{msec}}$$

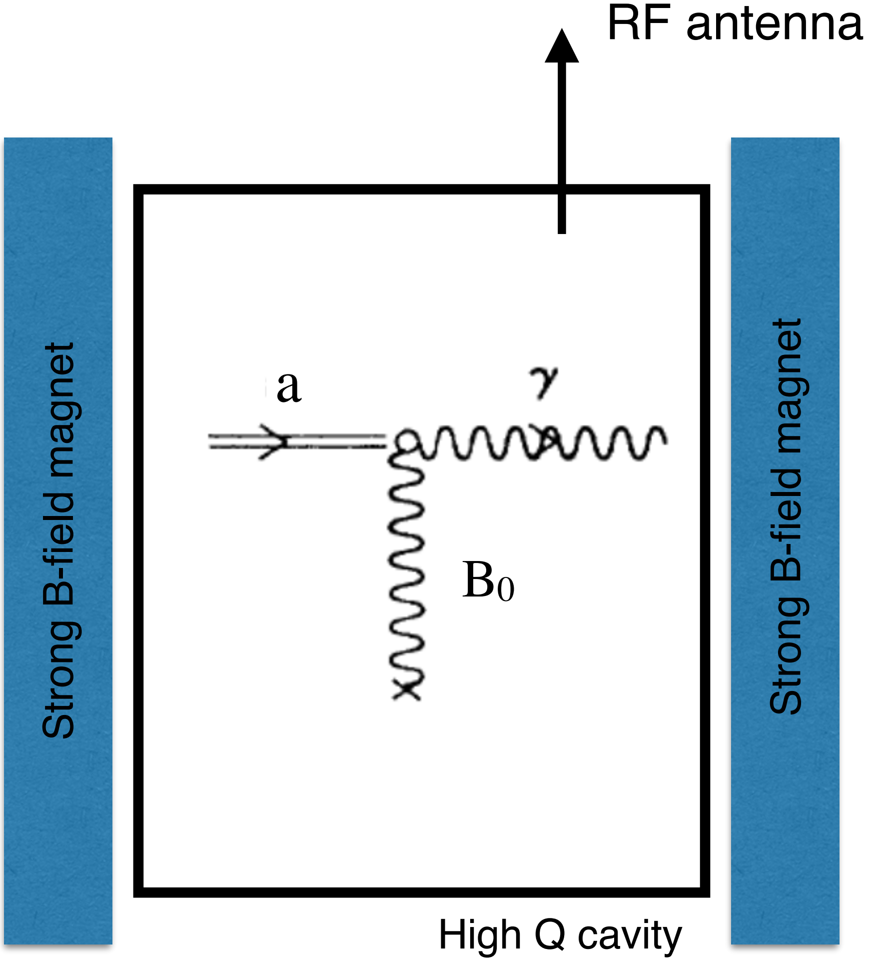
$$\mathcal{L} \equiv -\frac{1}{4} g a F \tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F \tilde{F}$$

$$= g a \vec{E} \cdot \vec{B}$$

$$\frac{\partial\left(\mathbf{E}^2/2\right)}{\partial t} - \mathbf{E} \cdot (\nabla \times \mathbf{B}) = g_{a\gamma} \dot{a} (\mathbf{E} \cdot \mathbf{B})$$

Oscillating source current ➜ RF photons

RF photon frequency = axion mass



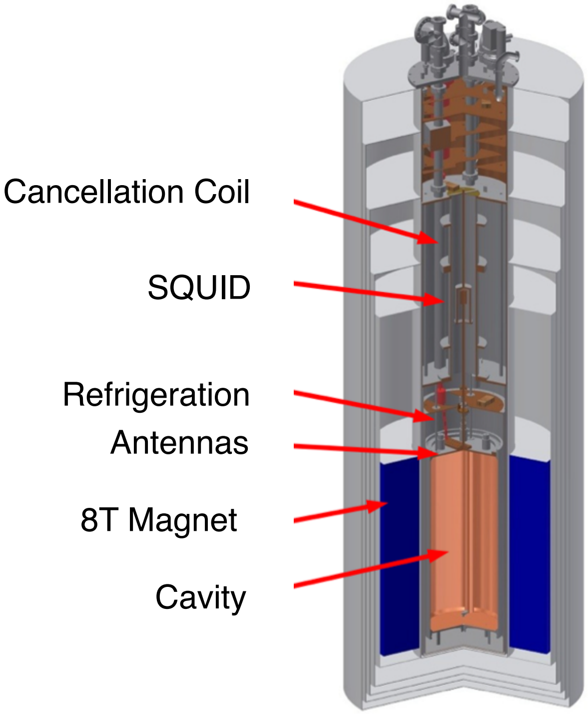
$$P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{\mathrm{cav}}, Q_a)$$

~ 10^{-21}W at $\mathrm{m_a}$=μeV

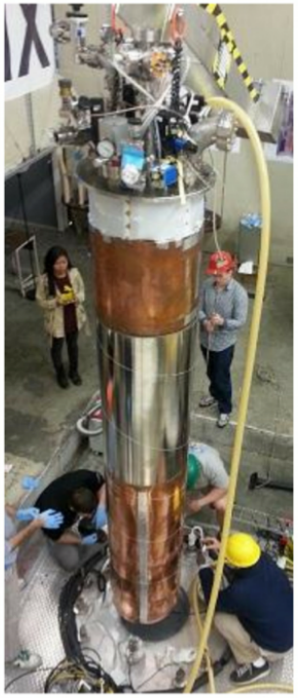
(assuming B=8T, V=0.2 m^3 magnet and cavity Q =10^5)

Axion Dark Matter eXperiment (ADMX)

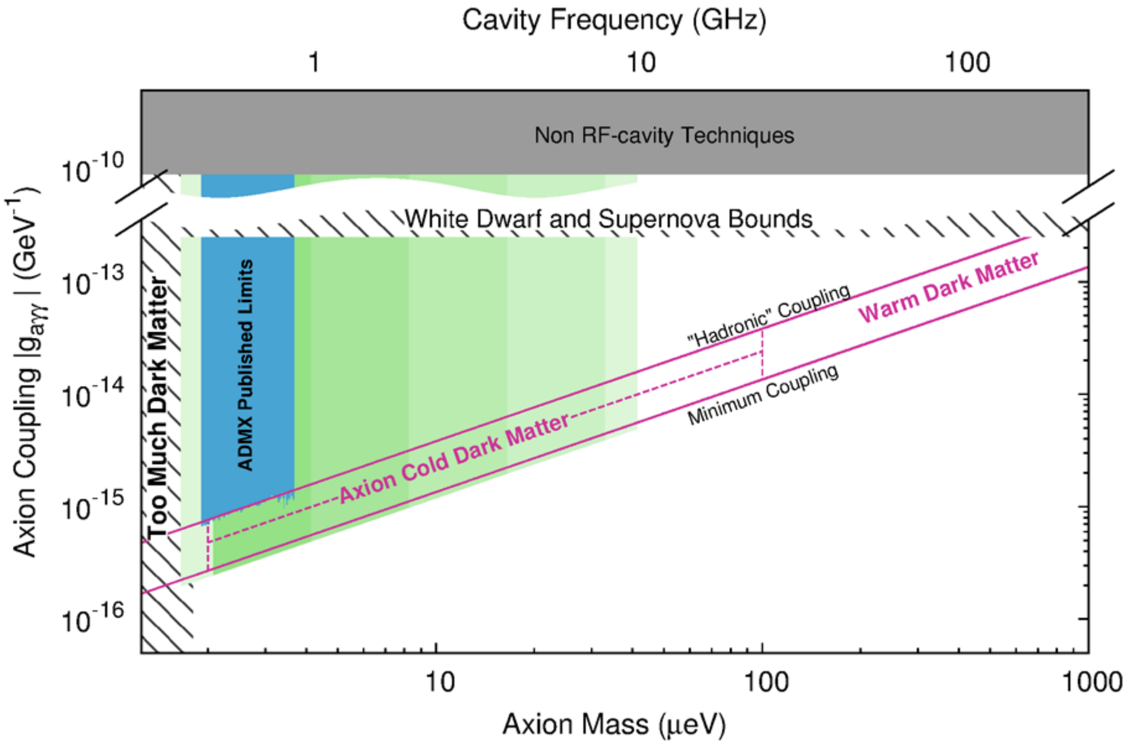
- **ADMX collaboration (hosted at the University of Washington)**
- "Currently (2017)" the world most sensitive dark matter axion search experiment
- The experiment started in 1995 — **more than 20 years of efforts**
- Relatively **low magnetic field (8 Tesla)** but large volume (140 liter, Q~60,000)
- Probing low mass (~μeV) axions



Insert + Magnet Schematic



Insert extraction from magnet



Linear Amplifier: Quantum Noise Limit

Time to scan axion DM mass range using 2010 technology ➜ **100-years!**

Improve scan speed

$$\frac{dm_a}{dt} \propto \left(\frac{B_0^2 V}{T_N}\right)^2$$

$T_N = T_{amplifier} + T_{physics}$

$$kT_N = h\nu\left(\frac{1}{e^{h\nu/kT}-1} + \frac{1}{2}\right) + kT_A$$

Run colder to reduce thermal noise!

➜ Use dilution refrigerator (~50mK)

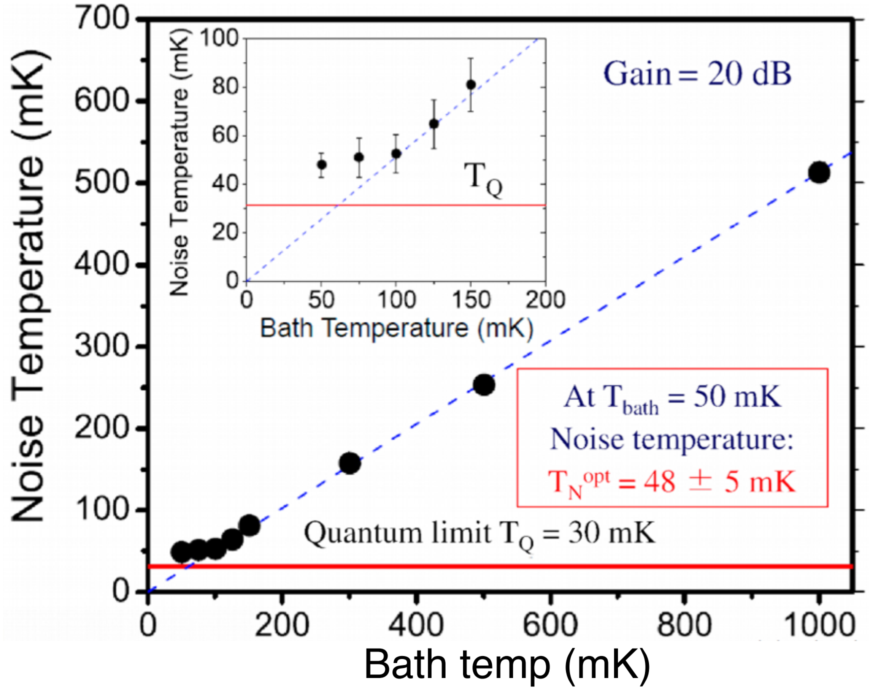
➜ Quantum limited amplifiers

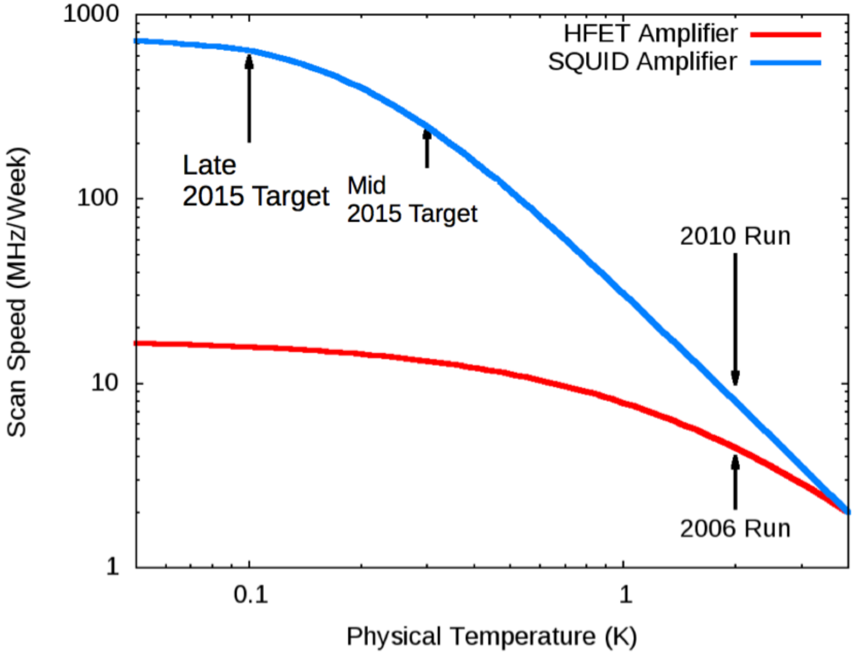
  - Microstrip SQUID Amplifier (<1GHz)

  - Josephson Parametric Amplifier (>1GHz)

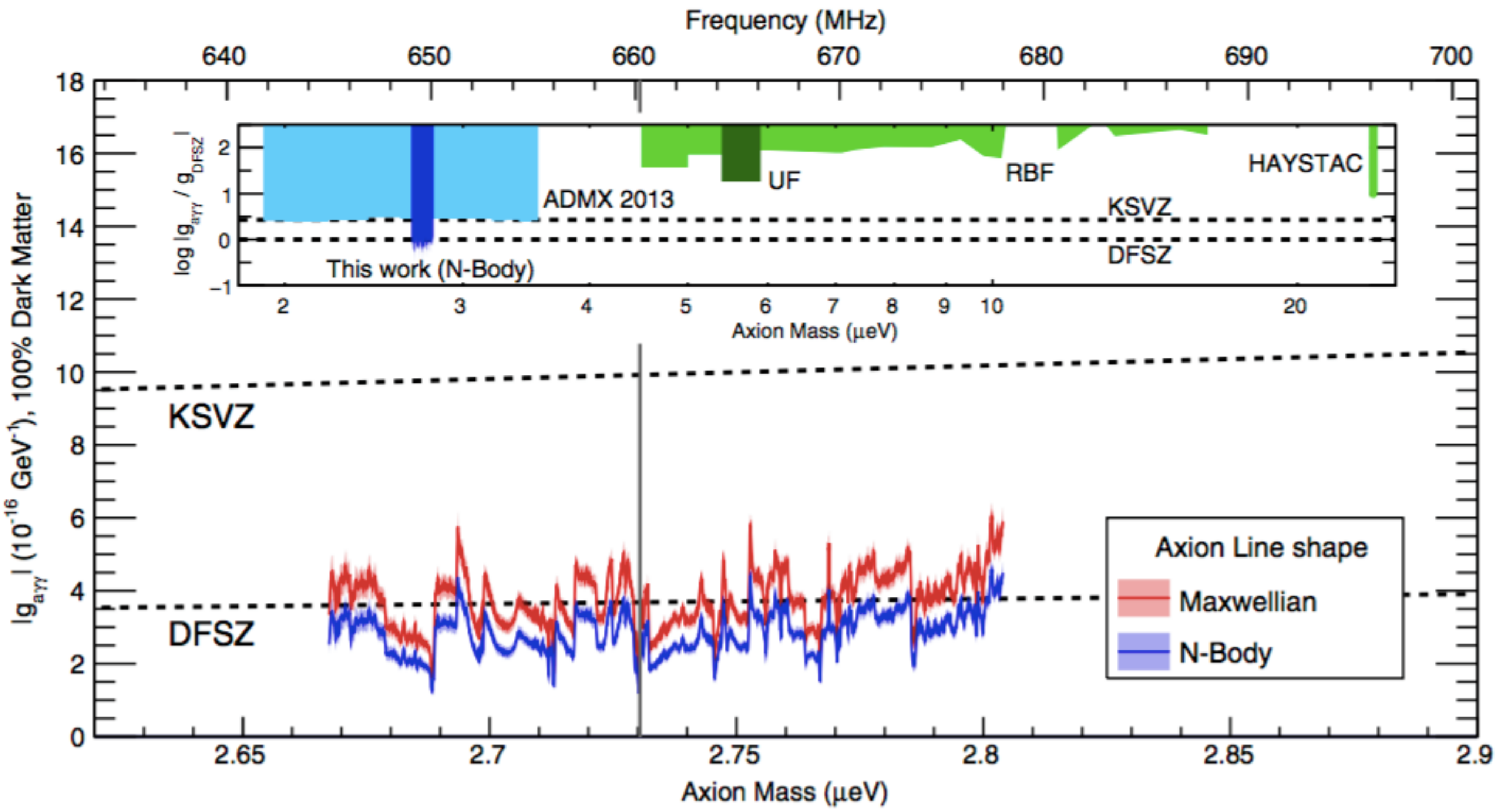
The scan speed can be improved by factor >100

J. Clarke

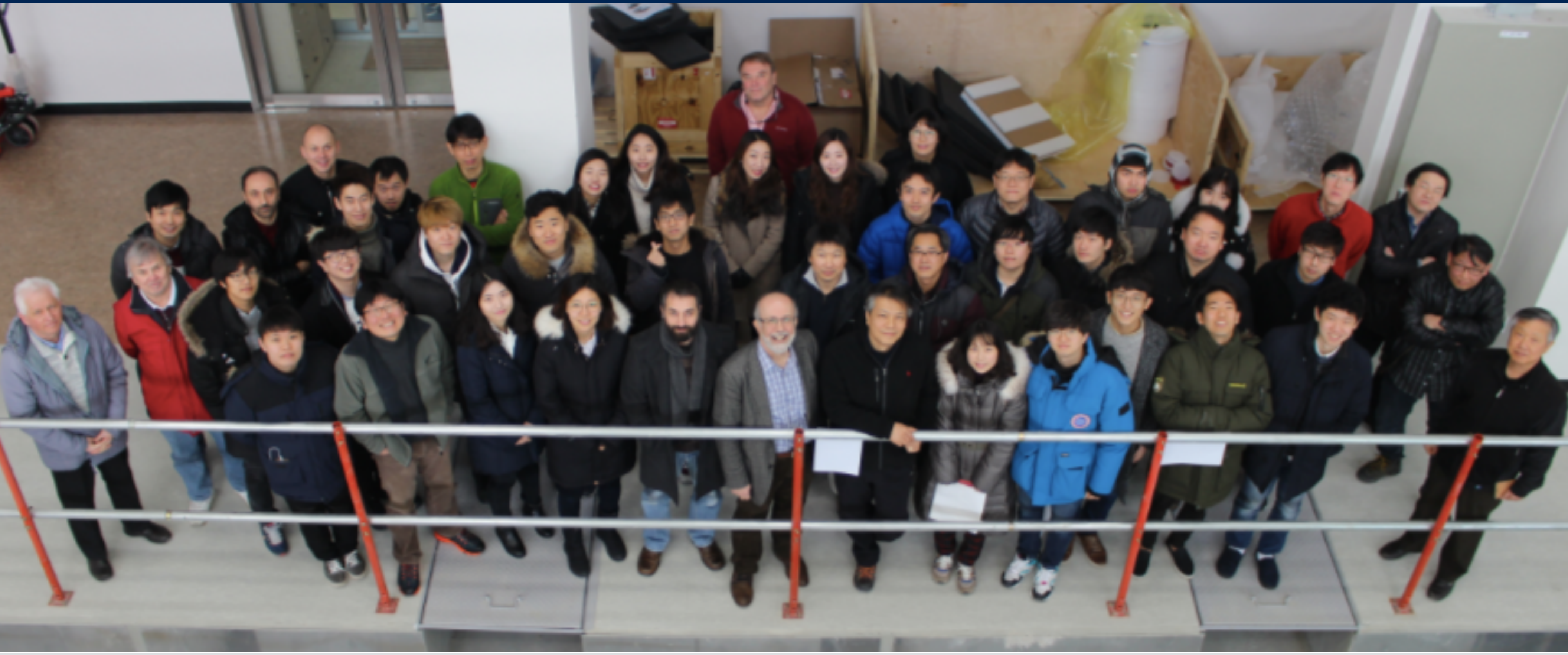




ADMX 2G Results (2018)



Center for Axion and Precision Physics Research (CAPP)



CAPP/IBS at KAIST University launched in October 2013

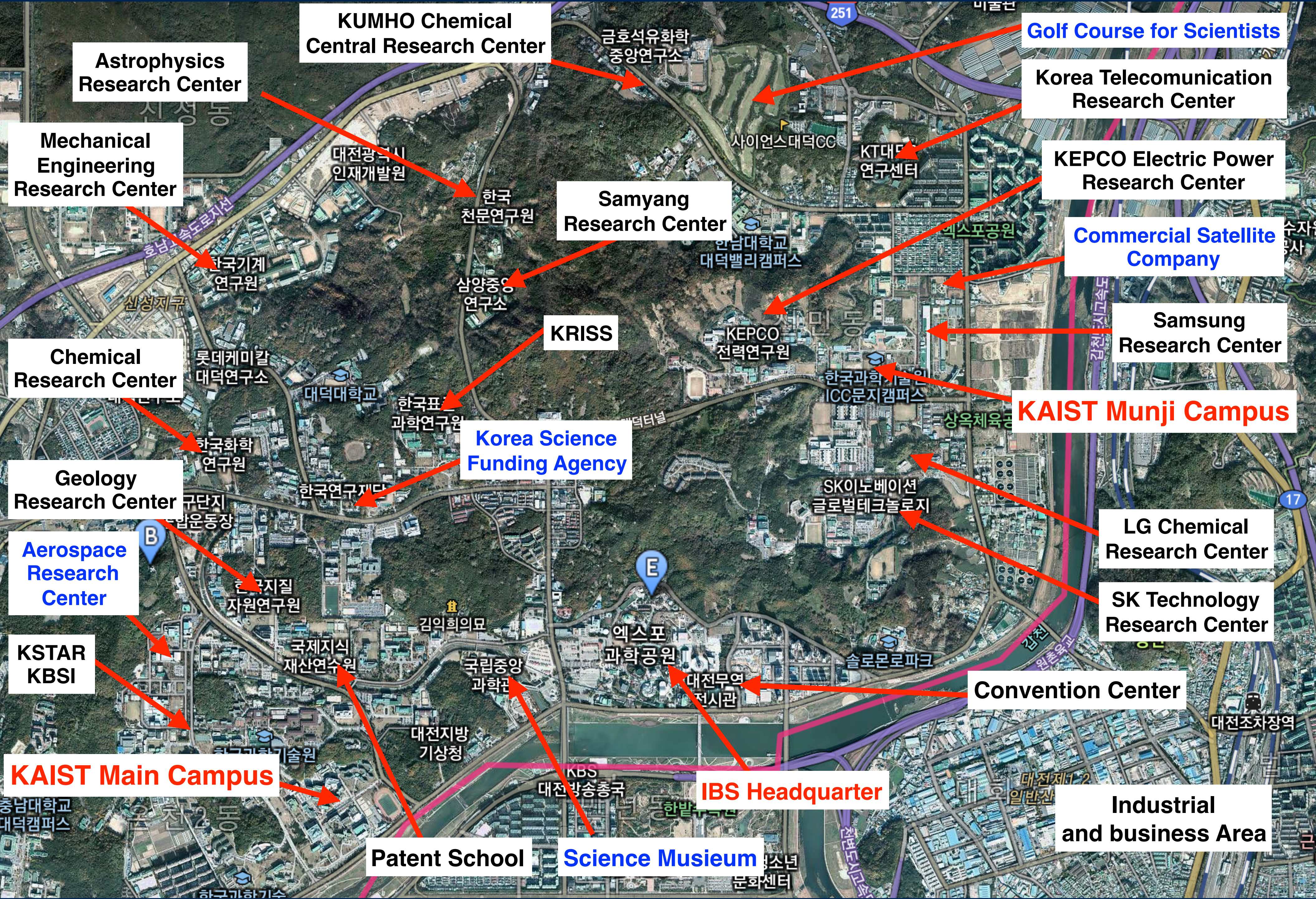
Physics
- Axion Search
- Proton EDM
- Muon g-2 / mu2e

Host Institution
- KAIST University
- IBS (Institute for Basic Science)

Human Resource
- 25 researchers
- 20 graduate students
- 7 staffs (admins/techs)
- Visiting scholars

Daejeon: A City of Science in Korea

Daejeon: A City of Science in Korea



KUMHO Chemical Central Research Center

Astrophysics Research Center

Mechanical Engineering Research Center

Samyang Research Center

KRISS

Chemical Research Center

Korea Science Funding Agency

Geology Research Center

Aerospace Research Center

KSTAR
KBSI

KAIST Main Campus

Patent School

Science Musieum

IBS Headquarter

Golf Course for Scientists

Korea Telecomunication Research Center

KEPCO Electric Power Research Center

Commercial Satellite Company

Samsung Research Center

KAIST Munji Campus

LG Chemical Research Center

SK Technology Research Center

Convention Center

Industrial and business Area

CAPP's Dark Matter Axion Search Strategy

Strong magnetic field (18T → 25T → 35T)

$$\frac{df}{dt} = \frac{70\,\mathrm{MHz}}{\mathrm{year}}\left(\frac{4}{[s/n]}\right)^2\left(\frac{\mathrm{V}}{10\ l}\right)^2\left(\frac{\mathrm{B}_0}{10\ \mathrm{T}}\right)^4 \times C^4\left(\frac{g_a}{0.36}\right)^4\left(\frac{\rho_a}{0.3\,\mathrm{GeV/cc}}\right)\left(\frac{1\,\mathrm{K}}{\mathrm{T}_n}\right)^2\left(\frac{f}{\mathrm{GHz}}\right)^2\left(\frac{\mathrm{Q}}{\mathrm{Q}_a}\right)$$

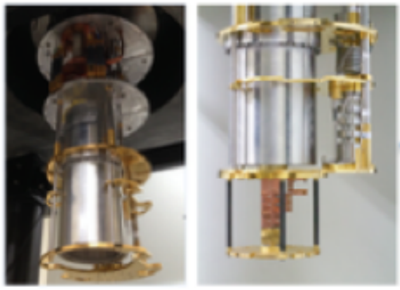
Lower the thermal noise temperature (cryogenics & low noise amplifier)

High Q cavity (Q~10^6)

Cryogenics

<100mK

Prof. Hyoungsoon Choi of KAIST

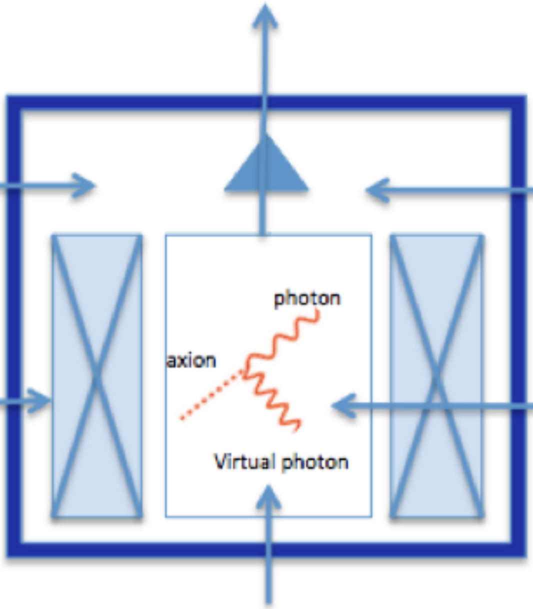


High Field SC Magnet

25T and then 35T or 40T

BNL (HTS Technology) Design

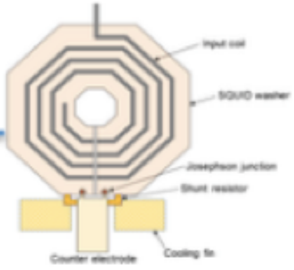
To RF Receiver



(Reverse) Primakoff Effect

SQUID Amplifier

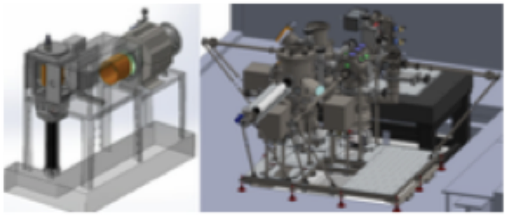
Outsourced Research from KRISS



High Q Tunable Cavity

Superconducting Coating

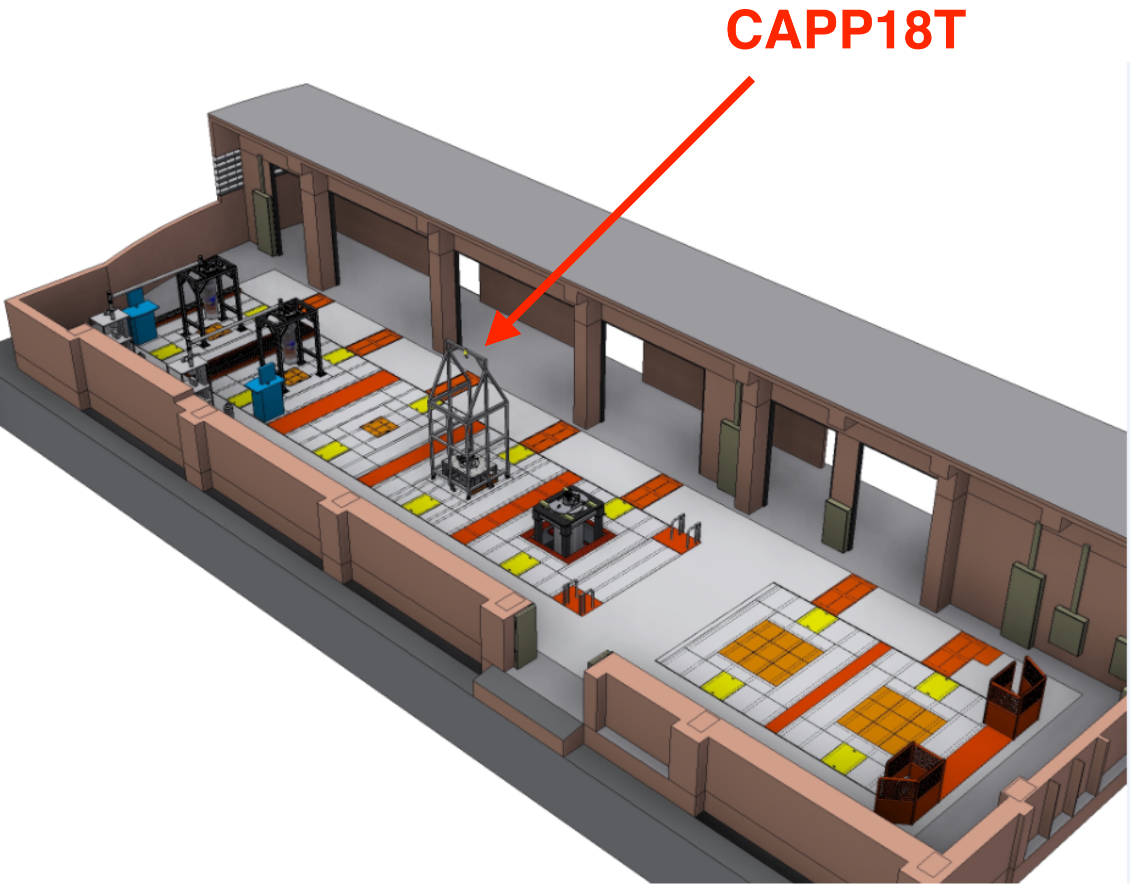
Prof. Jhinhwan Lee of KAIST

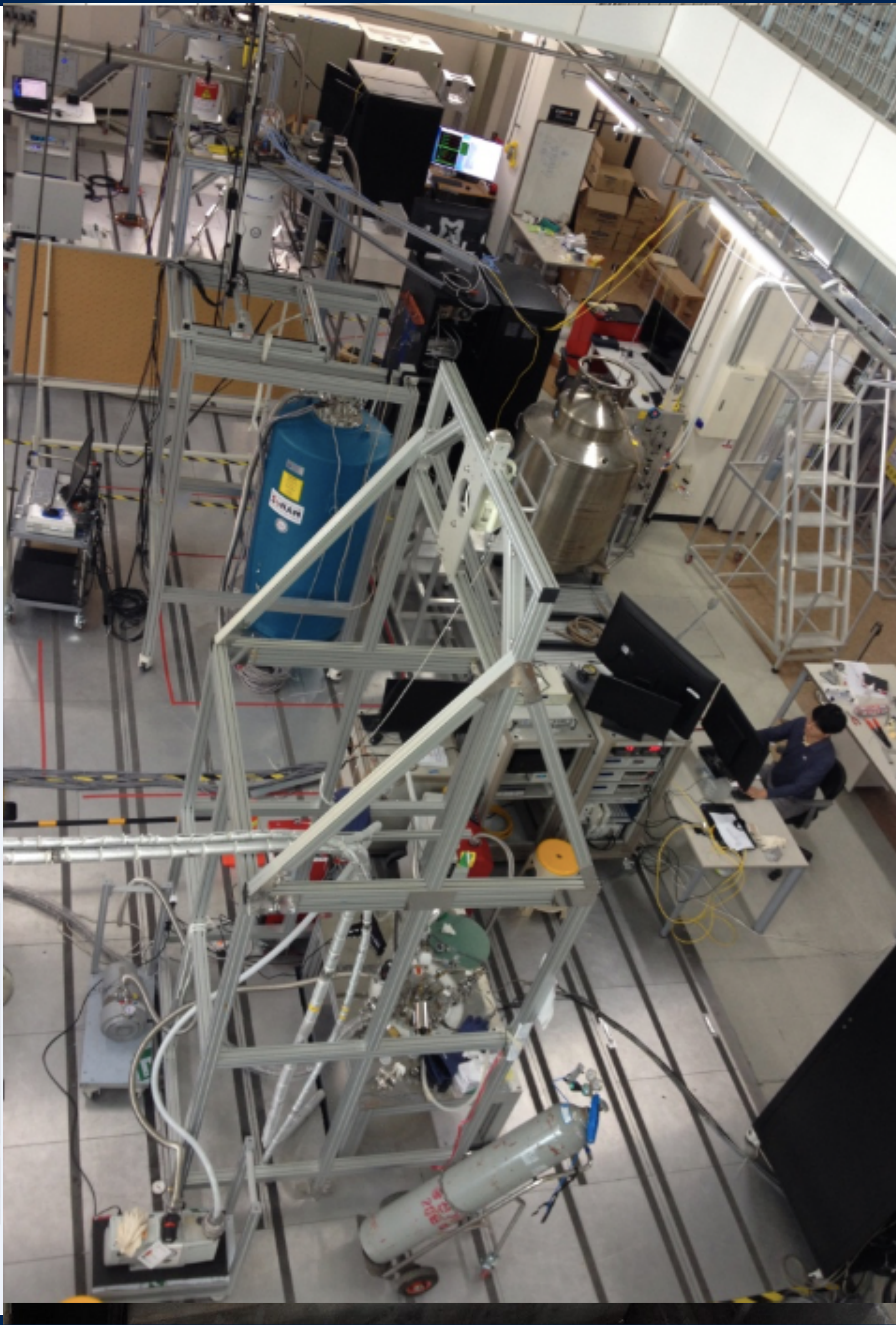


Experiment Hall

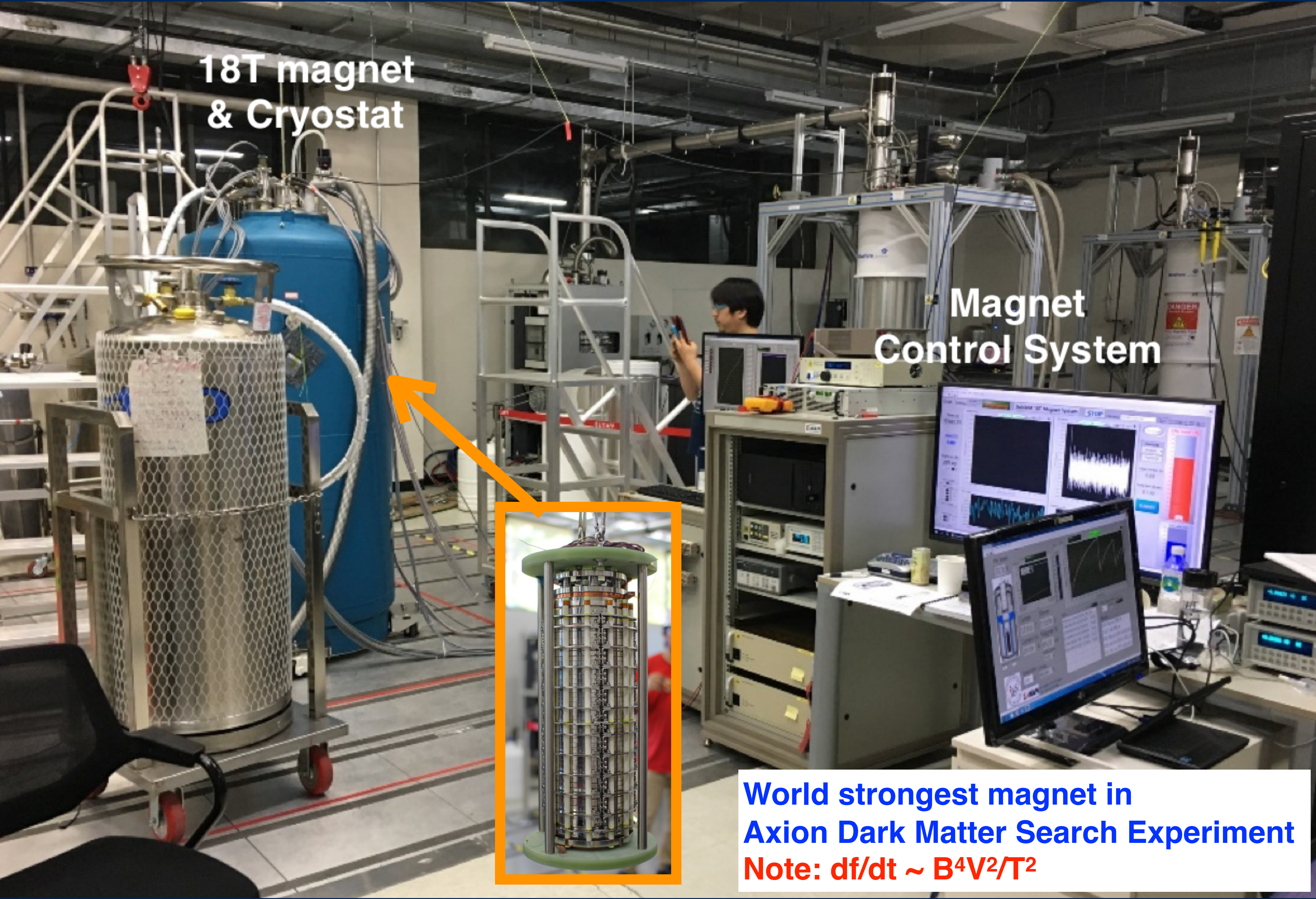
Low vibration facility

More than five large scale axion search experiments can be hosted





18T HTS Magnet @ KAIST

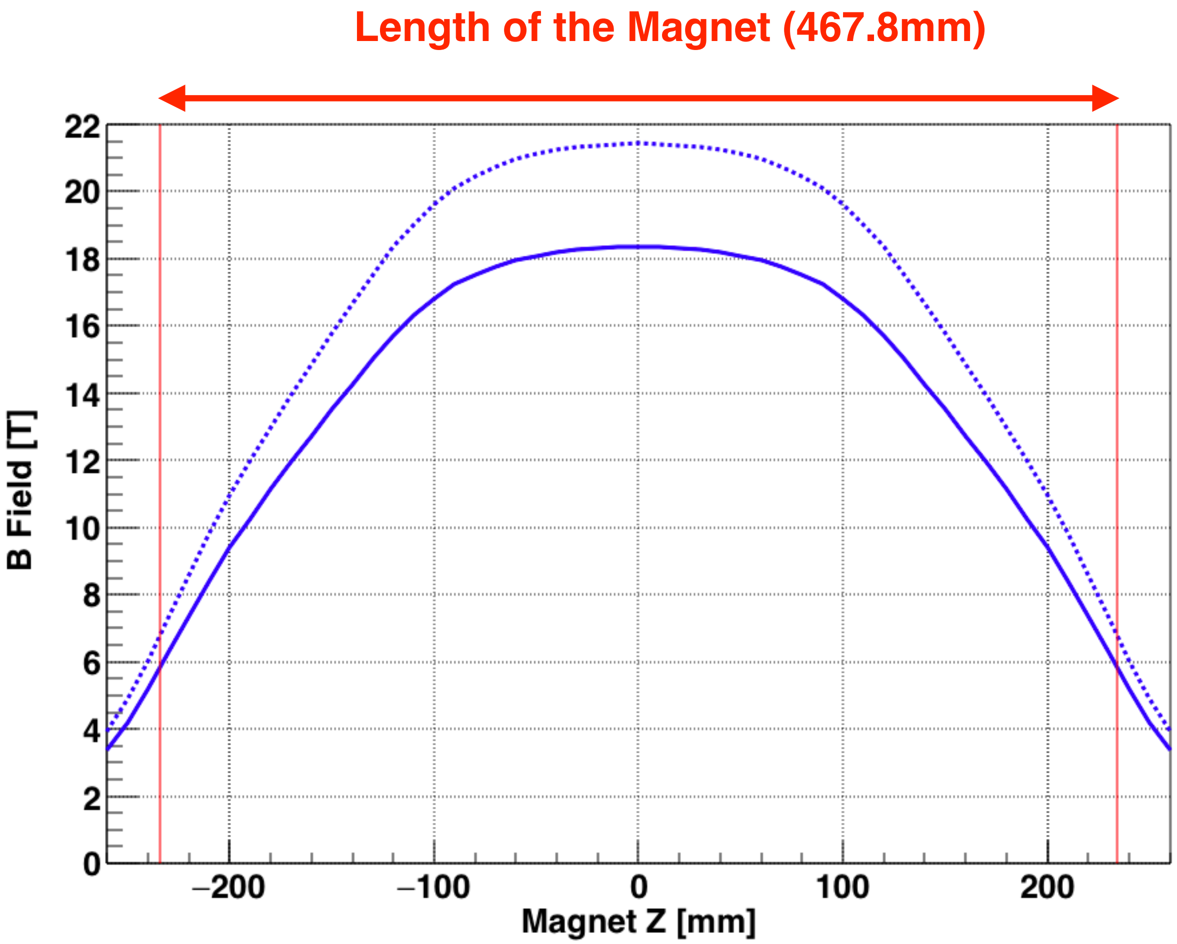


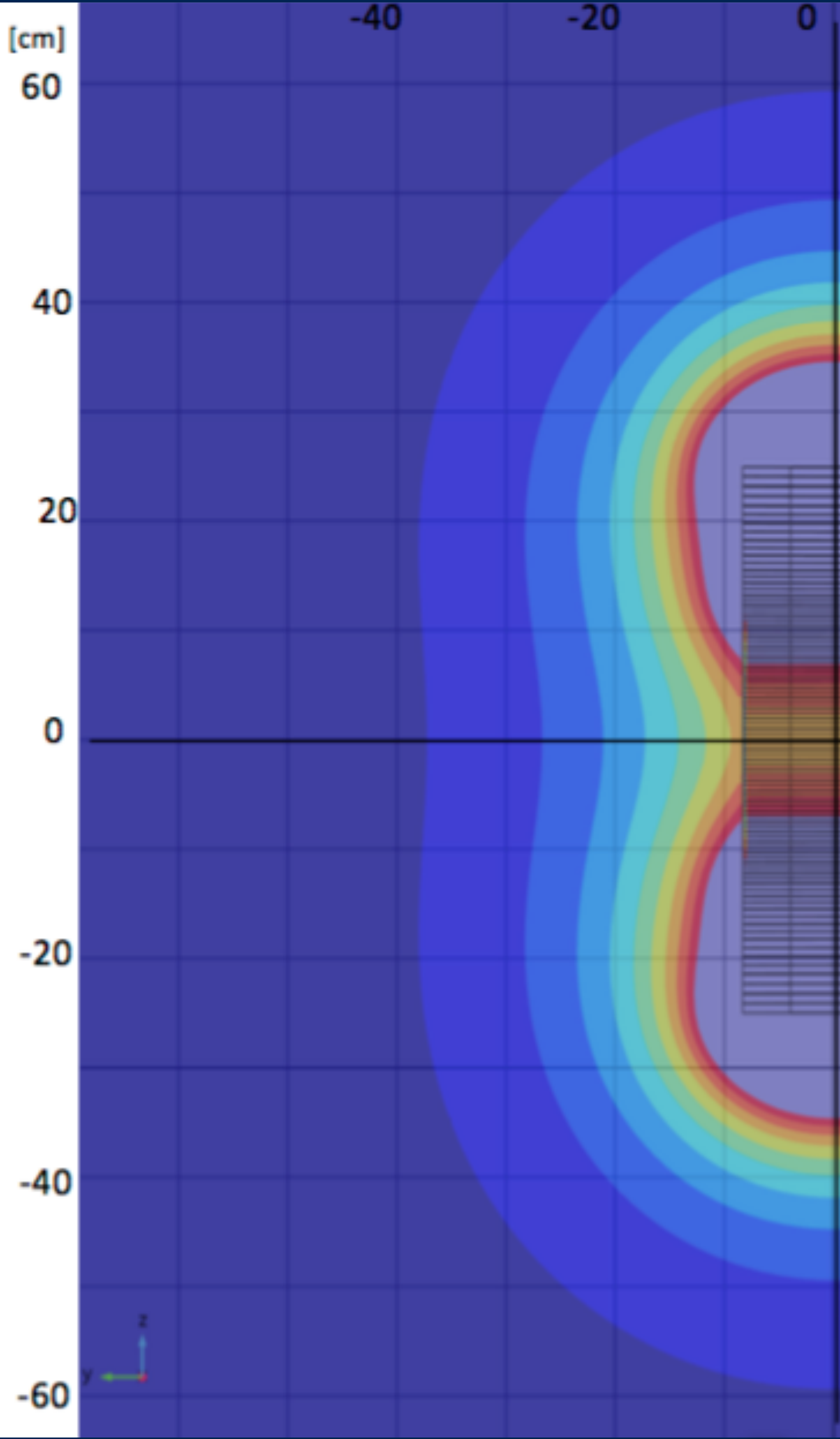
World strongest magnet in
Axion Dark Matter Search Experiment

Note: df/dt ~ B^4V^2/T^2

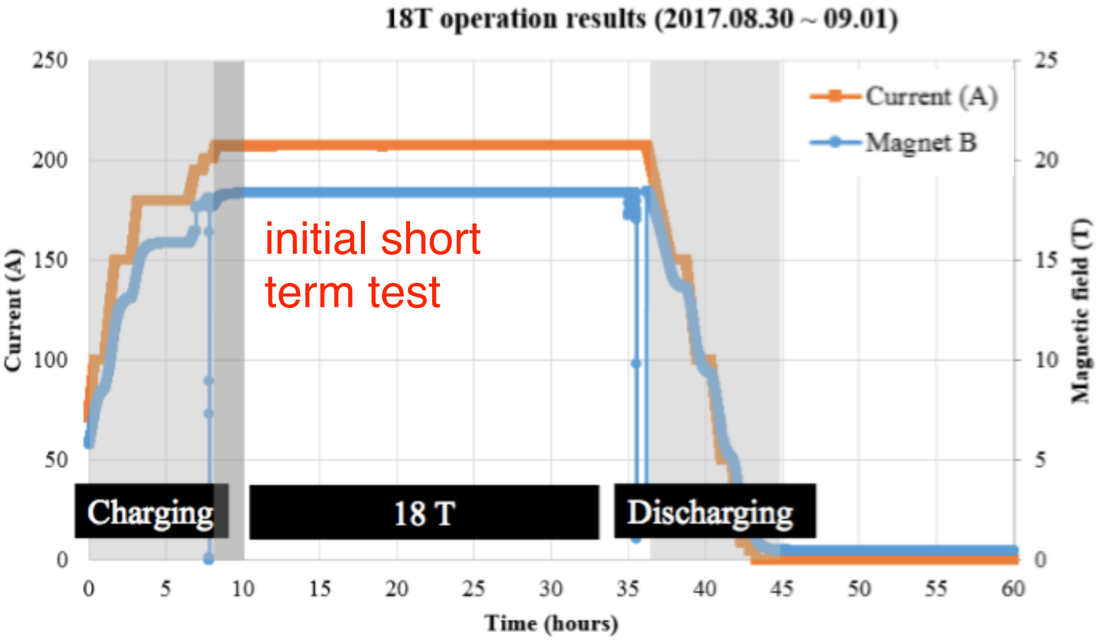
18T HTS Magnet Field Map

- 18T magnet field map simulation
  - → Shielding magnet design
  - → Safety margin

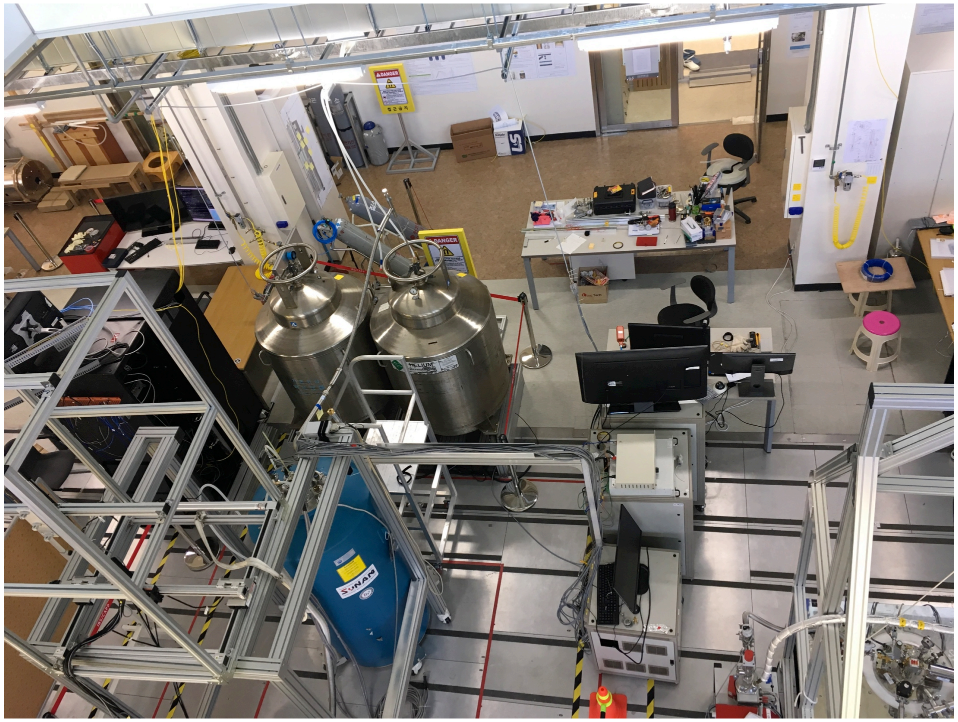


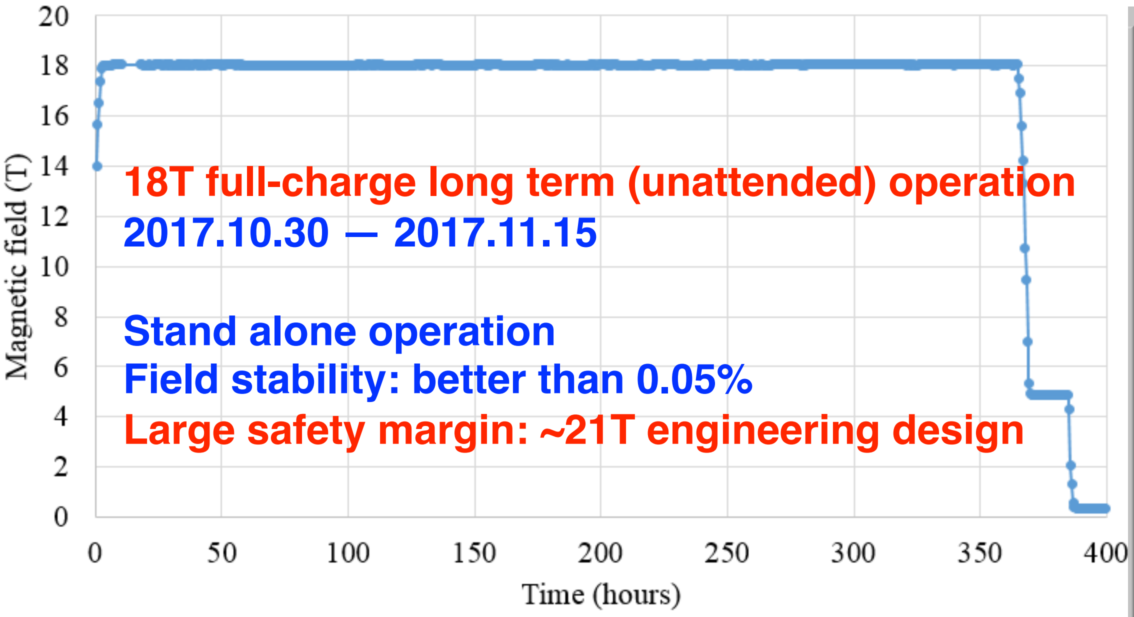


18T HTS Magnet Performance



initial short term test





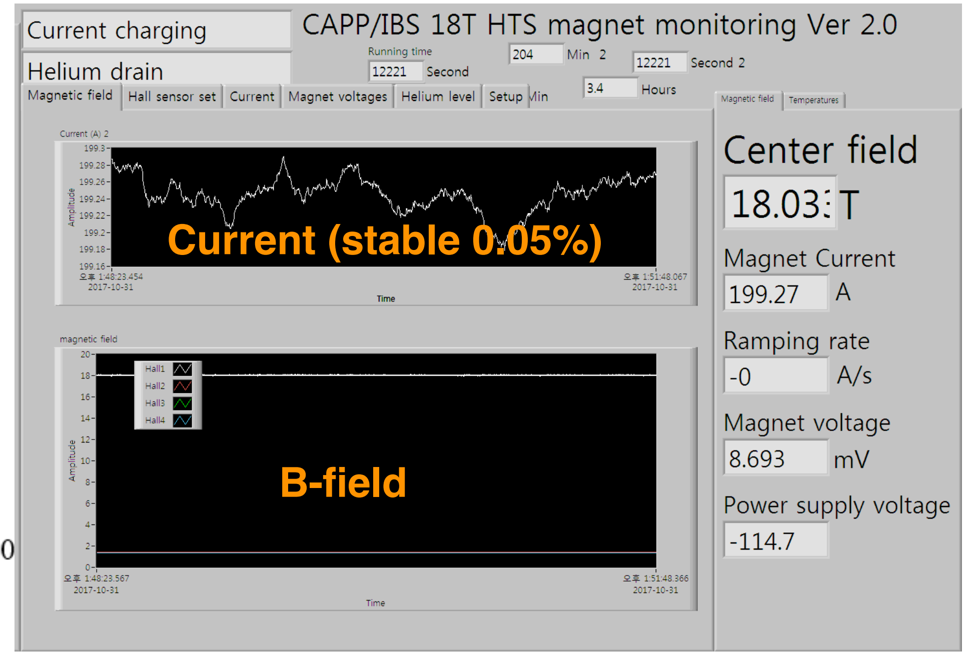
18T full-charge long term (unattended) operation

2017.10.30 — 2017.11.15

Stand alone operation

Field stability: better than 0.05%

Large safety margin: ~21T engineering design



CAPP/IBS 18T HTS magnet monitoring Ver 2.0

Running time 12221 Second

204 Min 2

12221 Second 2

3.4 Hours

Center field 18.03: T

Magnet Current 199.27 A

Ramping rate -0 A/s

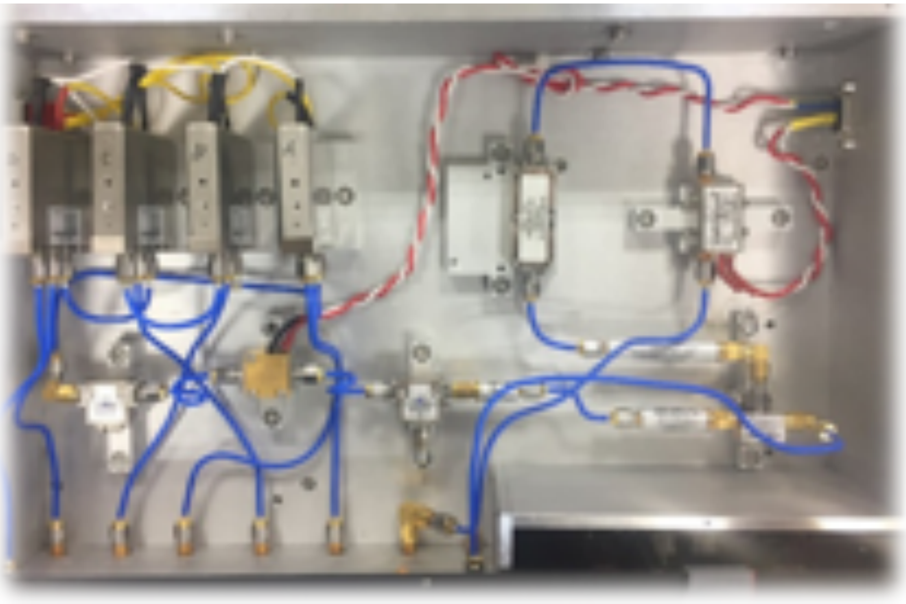
Magnet voltage 8.693 mV

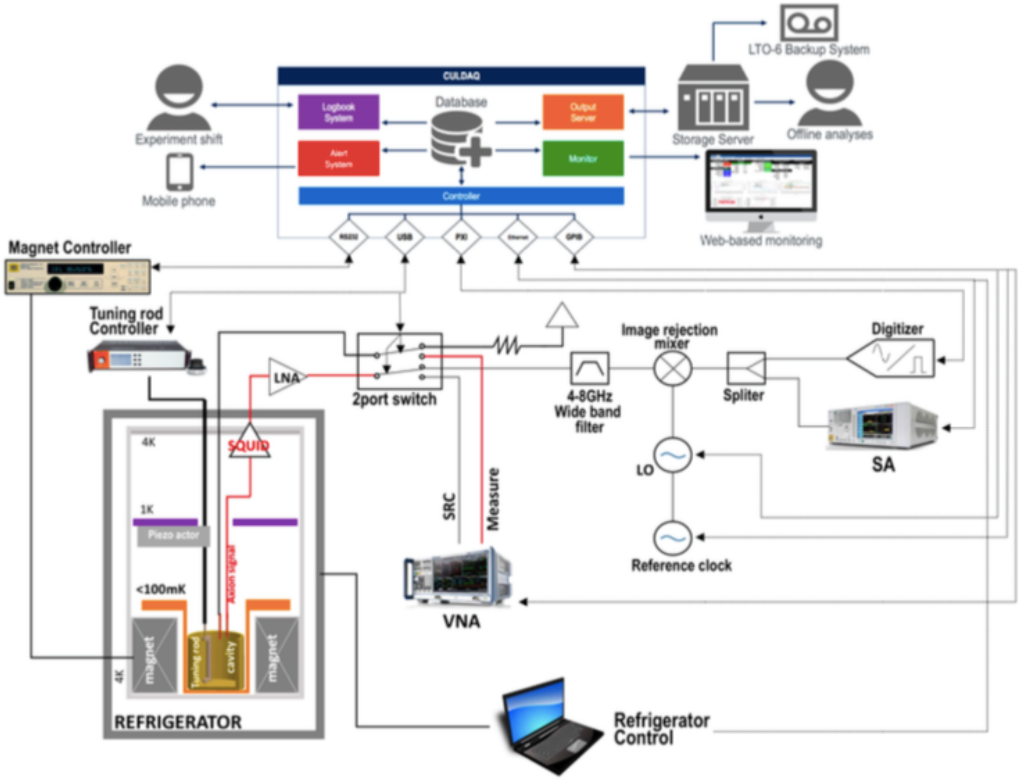
Power supply voltage -114.7

Current (stable 0.05%)

B-field

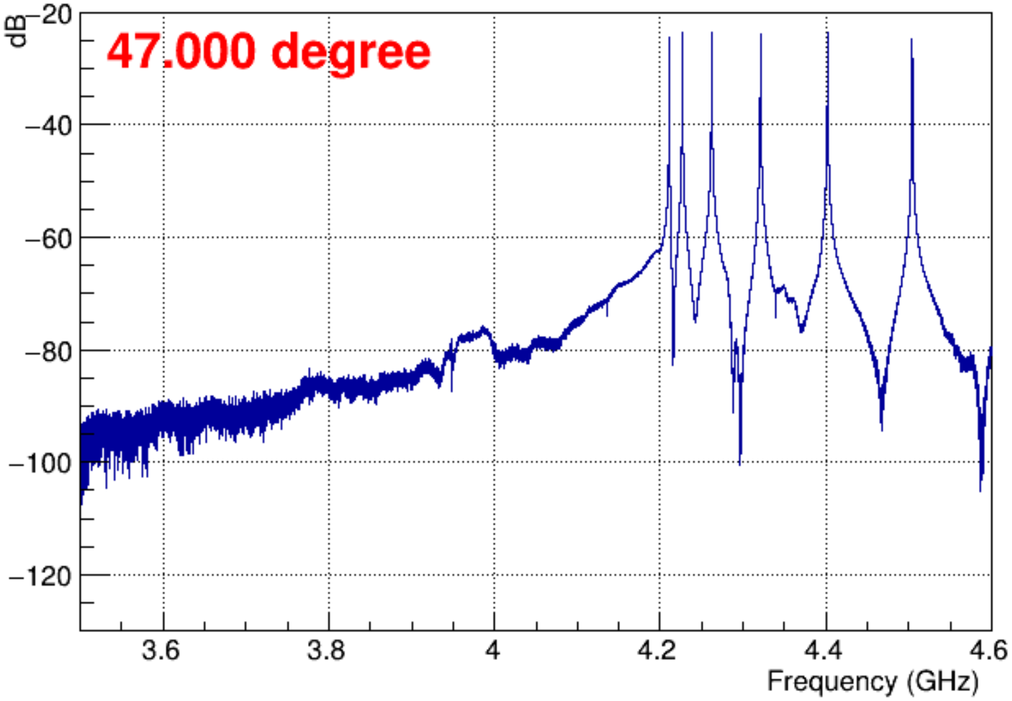
DAQ

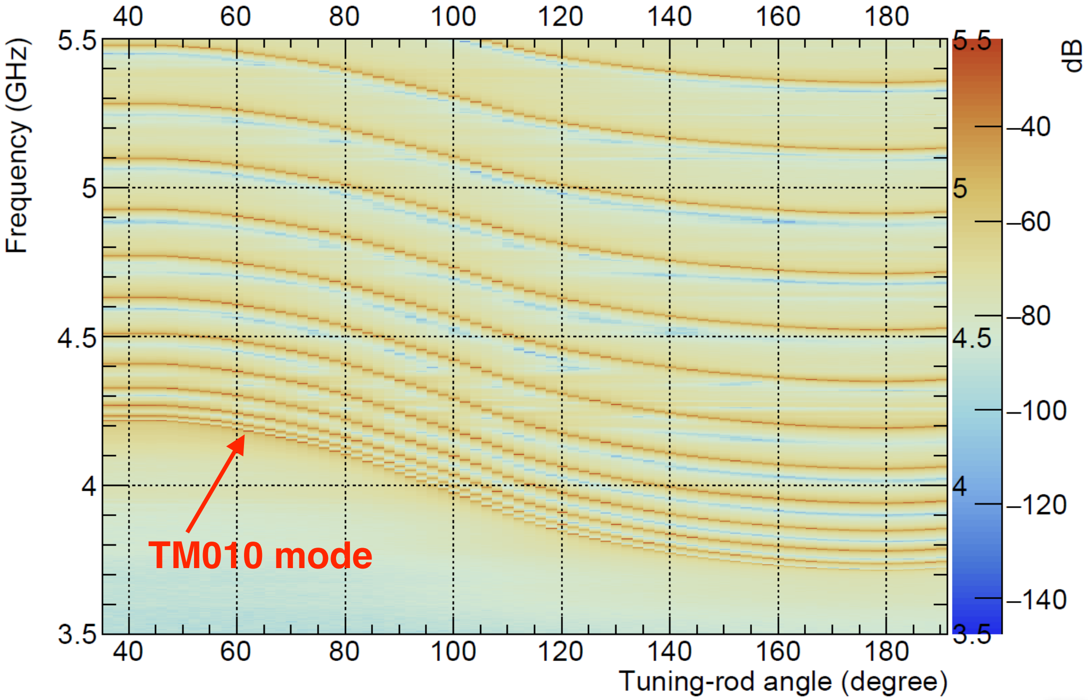



LTO-6 Backup System
CULDAQ
Experiment shift
Logbook System
Database
Output Server
Storage Server
Offline analyses
Alert System
Monitor
Mobile phone
Controller
RS232
USB
PXI
Ethernet
GPIB
Web-based monitoring
Magnet Controller
Tuning rod Controller
LNA
2port switch
Image rejection mixer
Digitizer
4-8GHz Wide band filter
Spliter
SA
4K
SQUID
LO
1K
Piezo actor
SRC
Measure
Reference clock
<100mK
Axion signal
VNA
4K
magnet
Tuning rod
cavity
magnet
REFRIGERATOR
Refrigerator Control

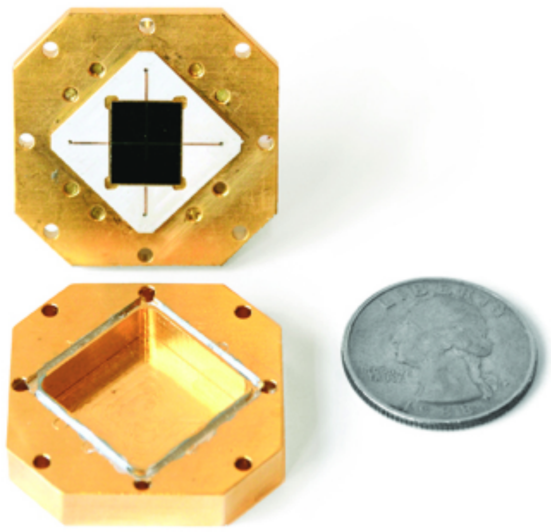

CAPP 10T

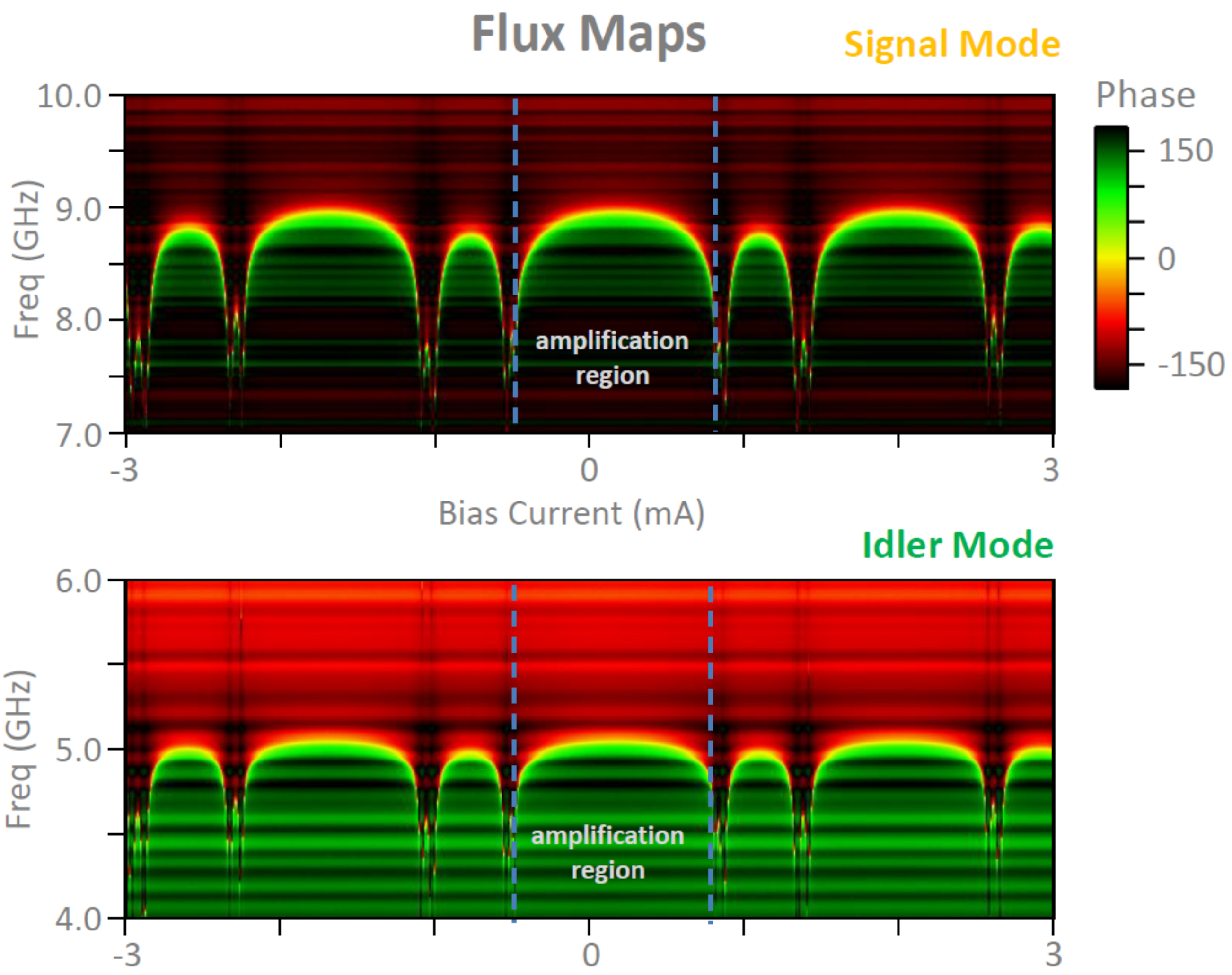
Cavity and Tuning-Rod Performance (4K Test)





Josephson Parametric Amplifier (JPA/JPC)





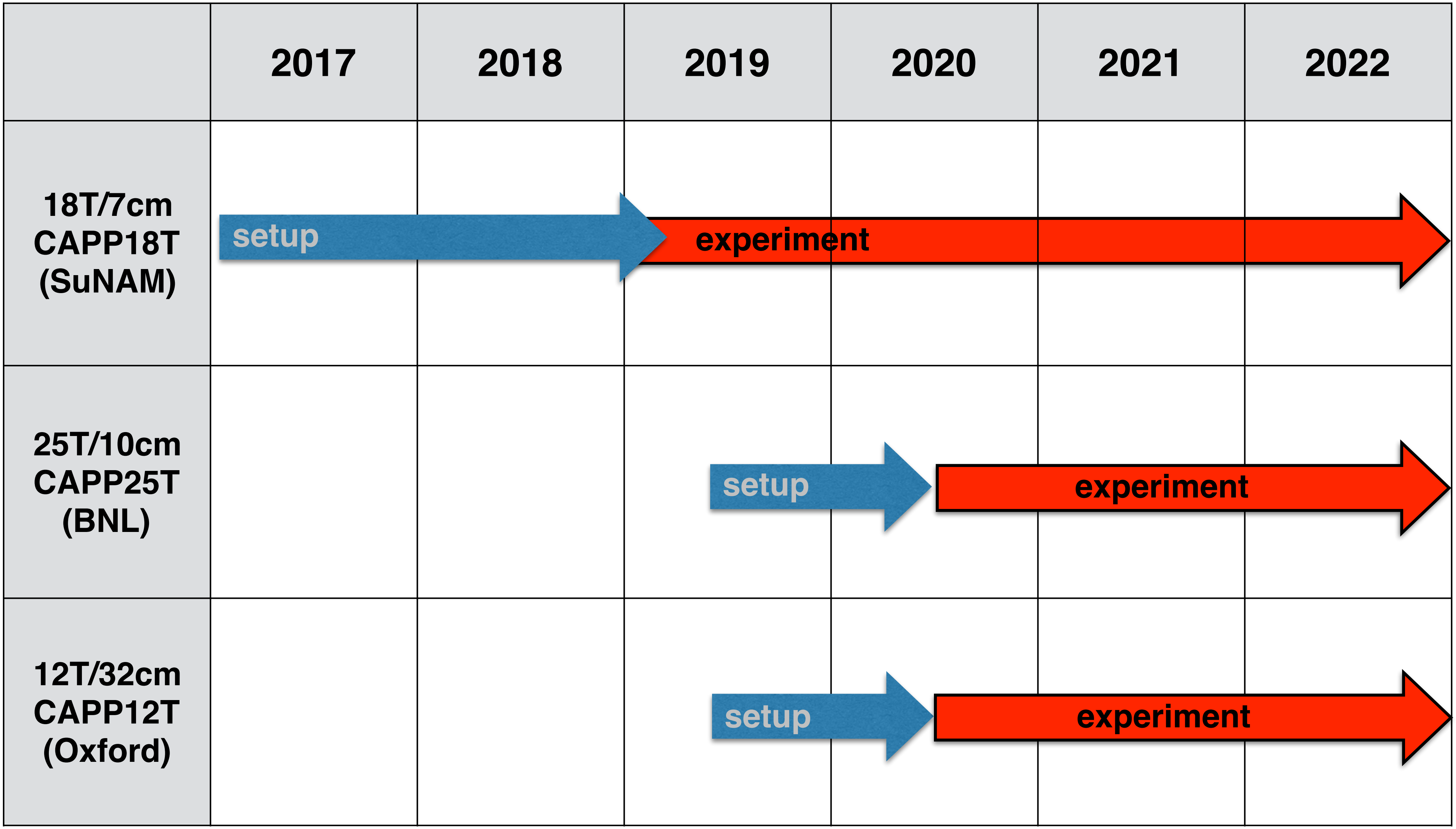
Gain(20 dB min)	F_{min} (GHz)	f_{max} (GHz)
High frequency	7.72	8.802
Low frequency	4.757	5.01

Dilution Refrigerator

< ~30mK physical base temperature achieved (2018 March)

Note: $df/dt \sim B^4V^2/T^2$

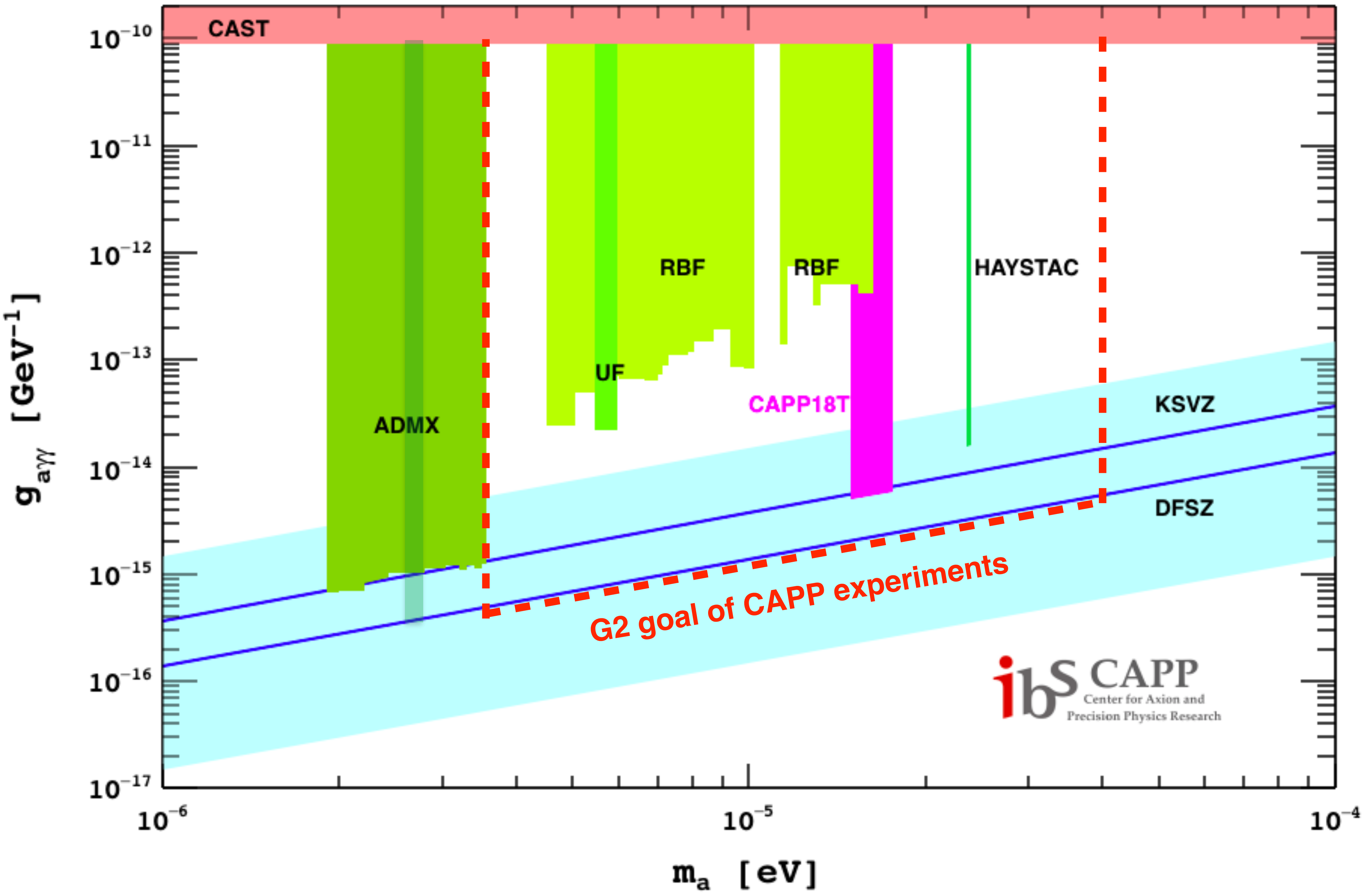
CAPP Dark Matter Axion Search Schedule



	2017	2018	2019	2020	2021	2022
18T/7cm CAPP18T (SuNAM)	setup		experiment			
25T/10cm CAPP25T (BNL)			setup		experiment	
12T/32cm CAPP12T (Oxford)			setup		experiment	

There are R&D efforts for higher mass dark matter axion search (>40μeV)

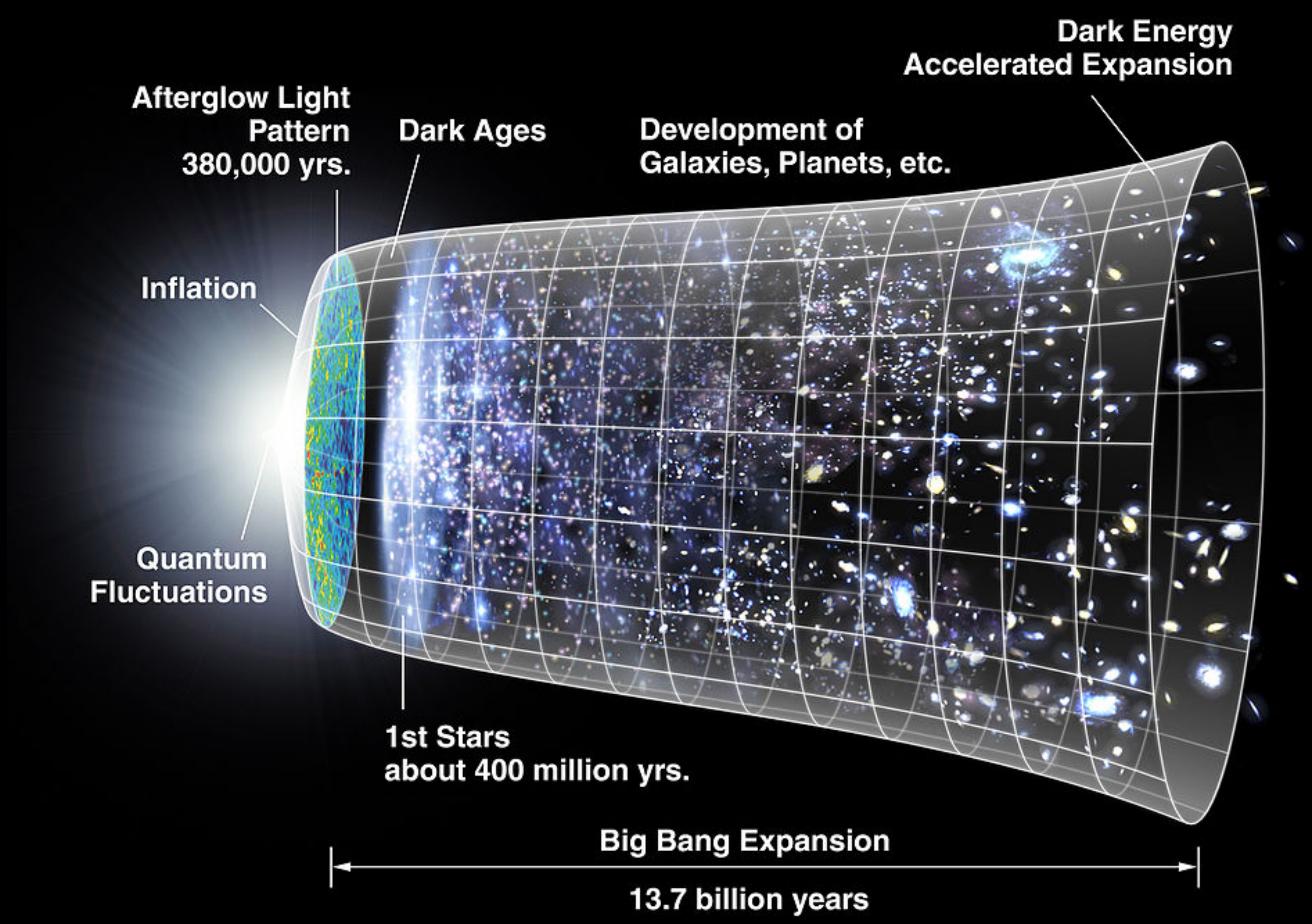
Prospect of Axion Dark Matter Search at CAPP



Stay tuned! Discovery of the dark matter axions maybe around the corner!

Evolution of the Universe

NASA/WMAP Science Team



The Universe

- **It’s big** $\sim 10^{24}$ km
- **It’s old** $\sim 10^{10}$ years
- **It’s dark** ~95%