A Physicist Walks on the Dark Side

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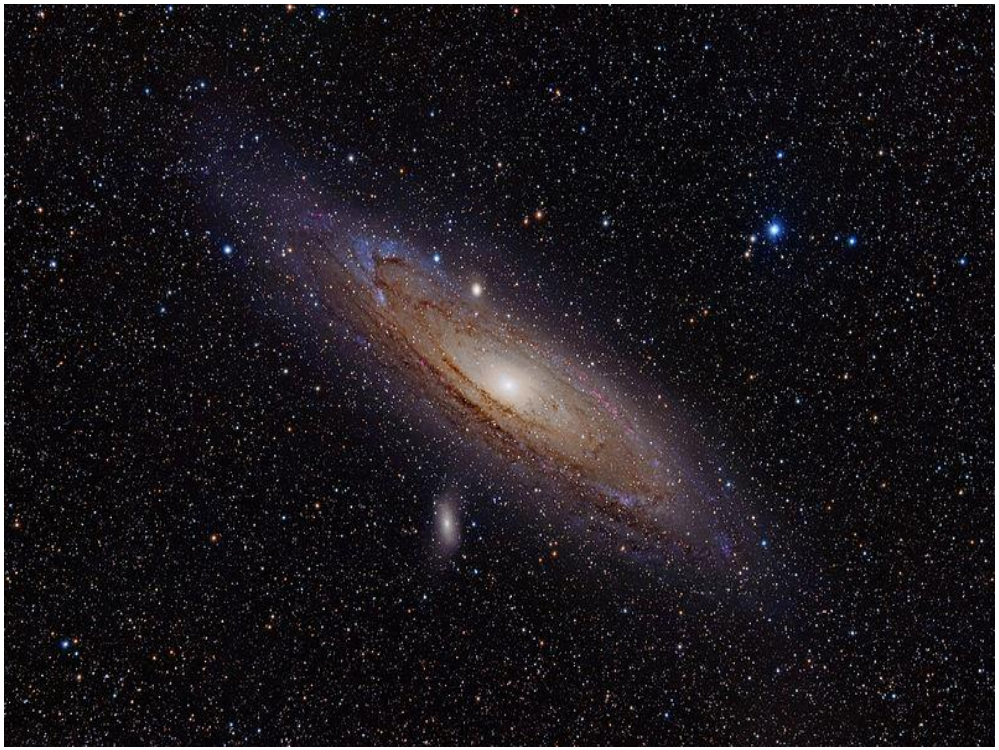
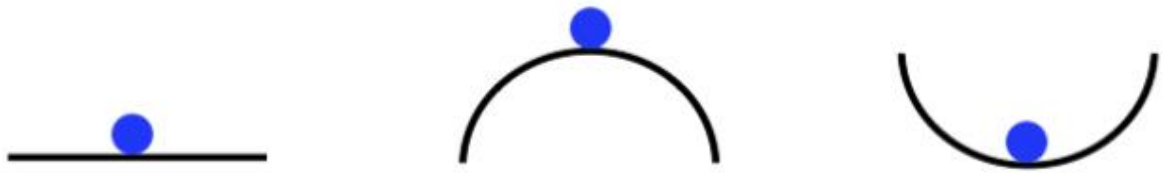
Outline

- A lightning tour of Cosmology since Newton
- A (hopefully) soluble problem – the Dark Matter
- The microwave cavity search for axionic dark matter
- What next?

From the Big Bang to the Big Game in 60 Minutes



Notion of Stability

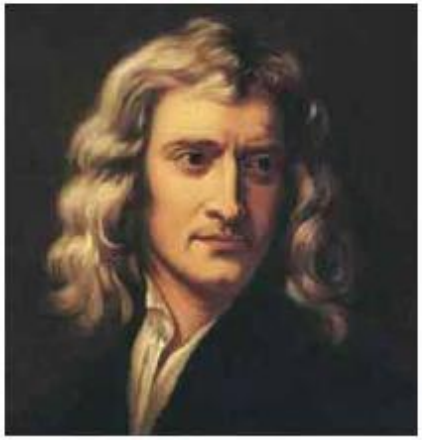


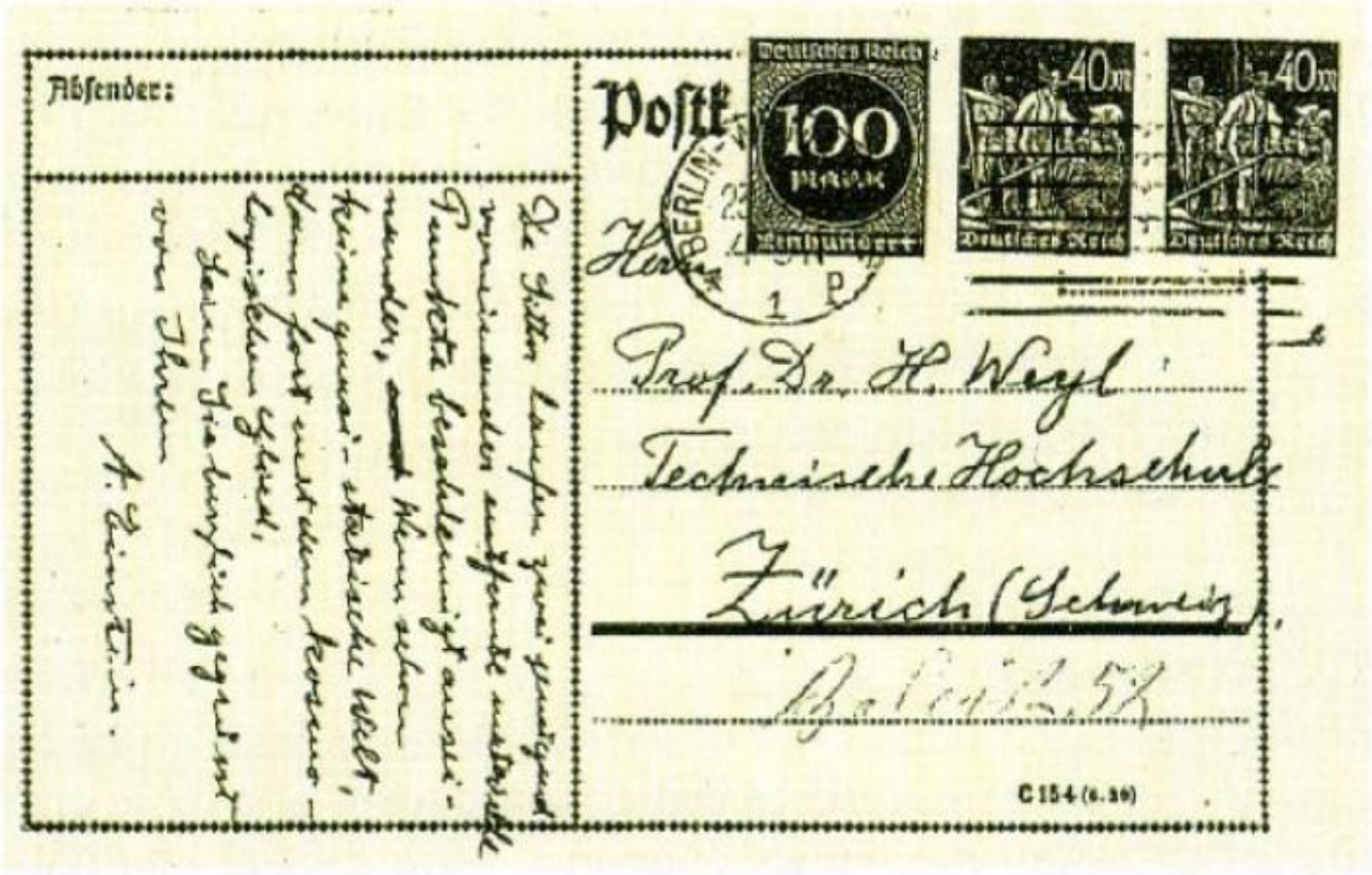
Neutral equilibrium *Unstable equilibrium* *Stable equilibrium*

Newton (December 10, 1692):

"…if the matter of our Sun & Planets and the matter of the Universe was evenly scattered throughout all the heavens, & every particle had an innate gravity towards all the rest & the whole space through which this matter was scattered was but finite: the matter on the outside of this space would by its gravity tend toward all the matter on the inside & by consequence fall down to the middle of the whole space & there compose one great spherical mass."

The scheme might work if a "divine power" intervened to ensure that the stars "would continue in that posture [spaced at equal distances] without motion forever."

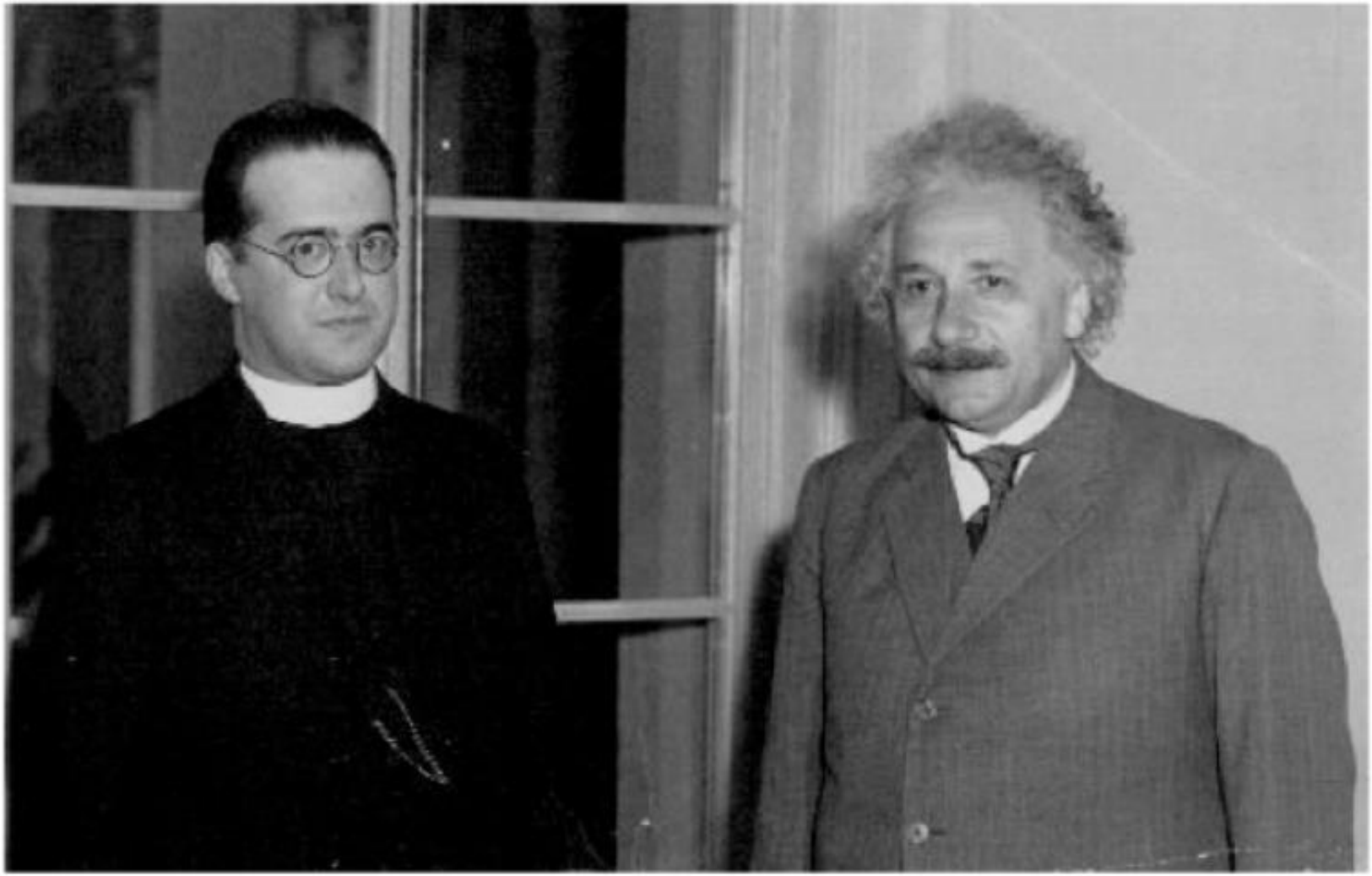




Einstein postcard (c. 1921-1923 from the cost of postage):

"....De Sitter runs two sufficiently separated material points accelerating apart.

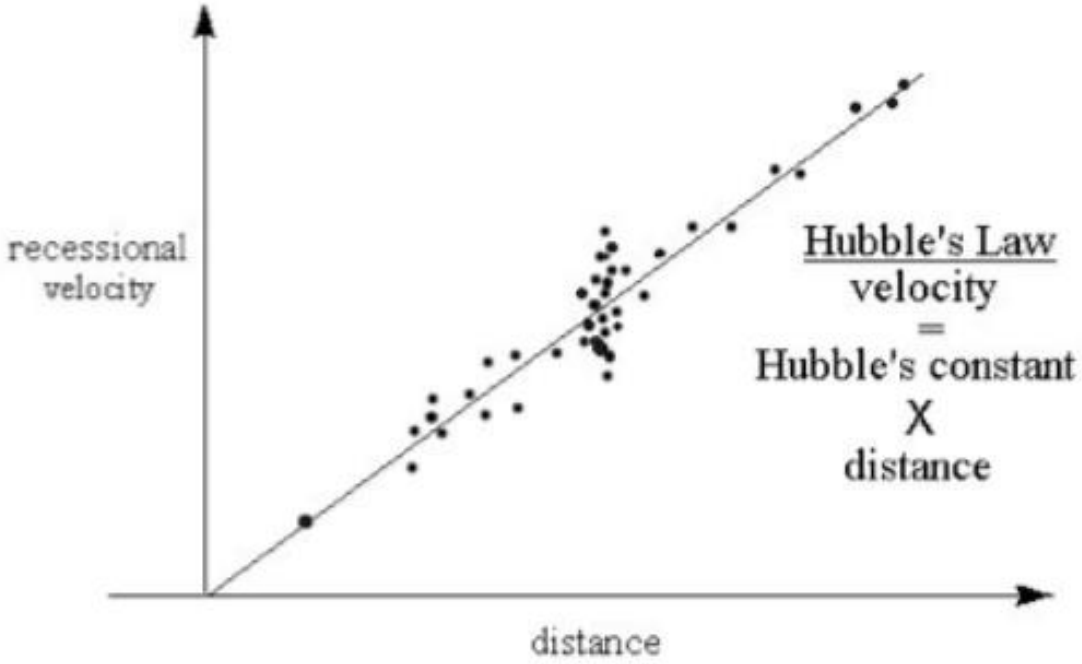
If not a quasi-static world, then away with the Cosmological term."



"Your calculations are impeccable, but your physical intuition is abominable"
(Einstein to Lemaitre, Solvay Conference 1927)

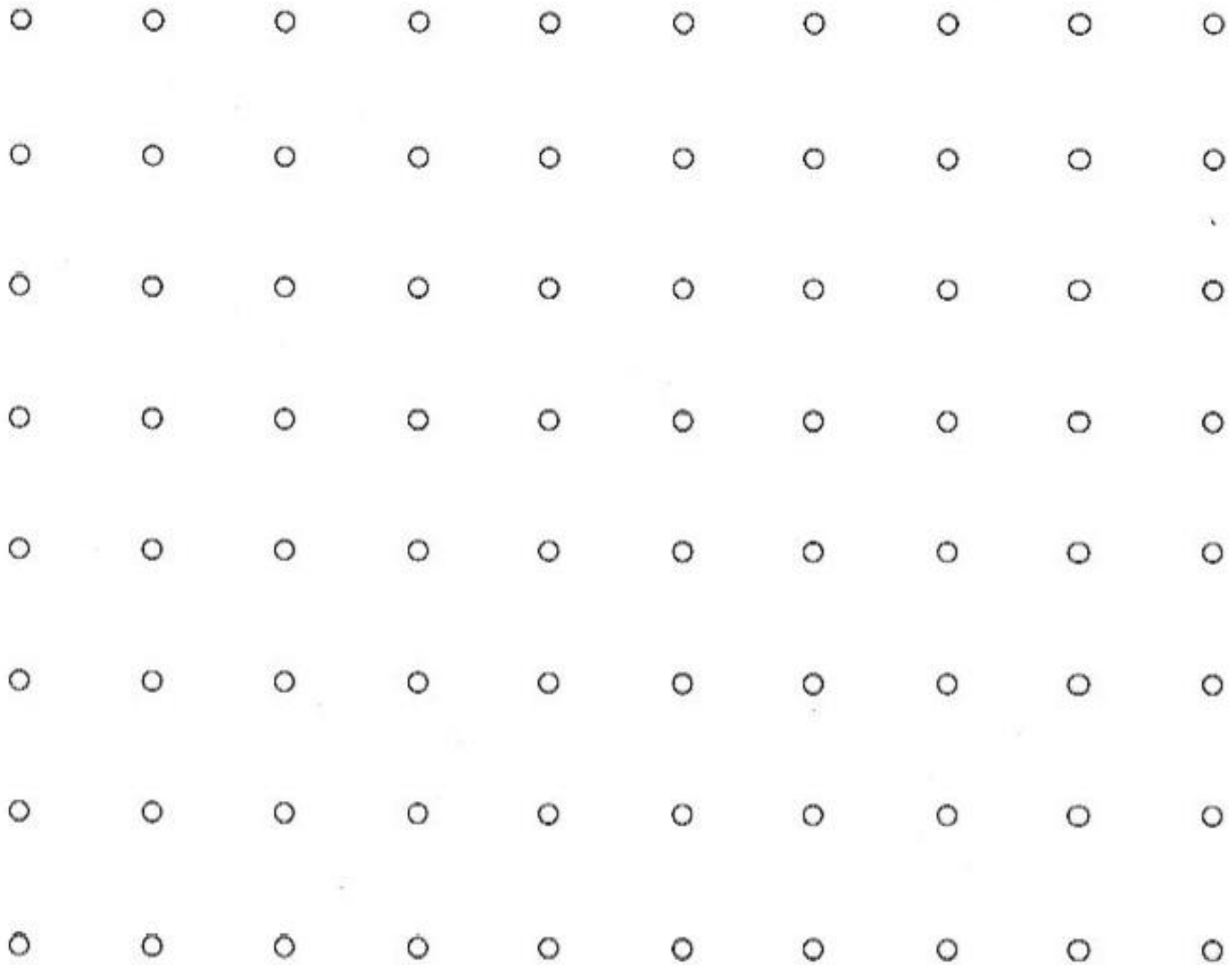
"It would seem that the most satisfactory theory would be one which made the beginning not to unaesthetically abrupt" (Sir Arthur Eddington to Lemaitre)

Edwin Hubble



Einstein's recantation on the Cosmological Constant (Λ) :

"My greatest blunder!" (c. 1929)



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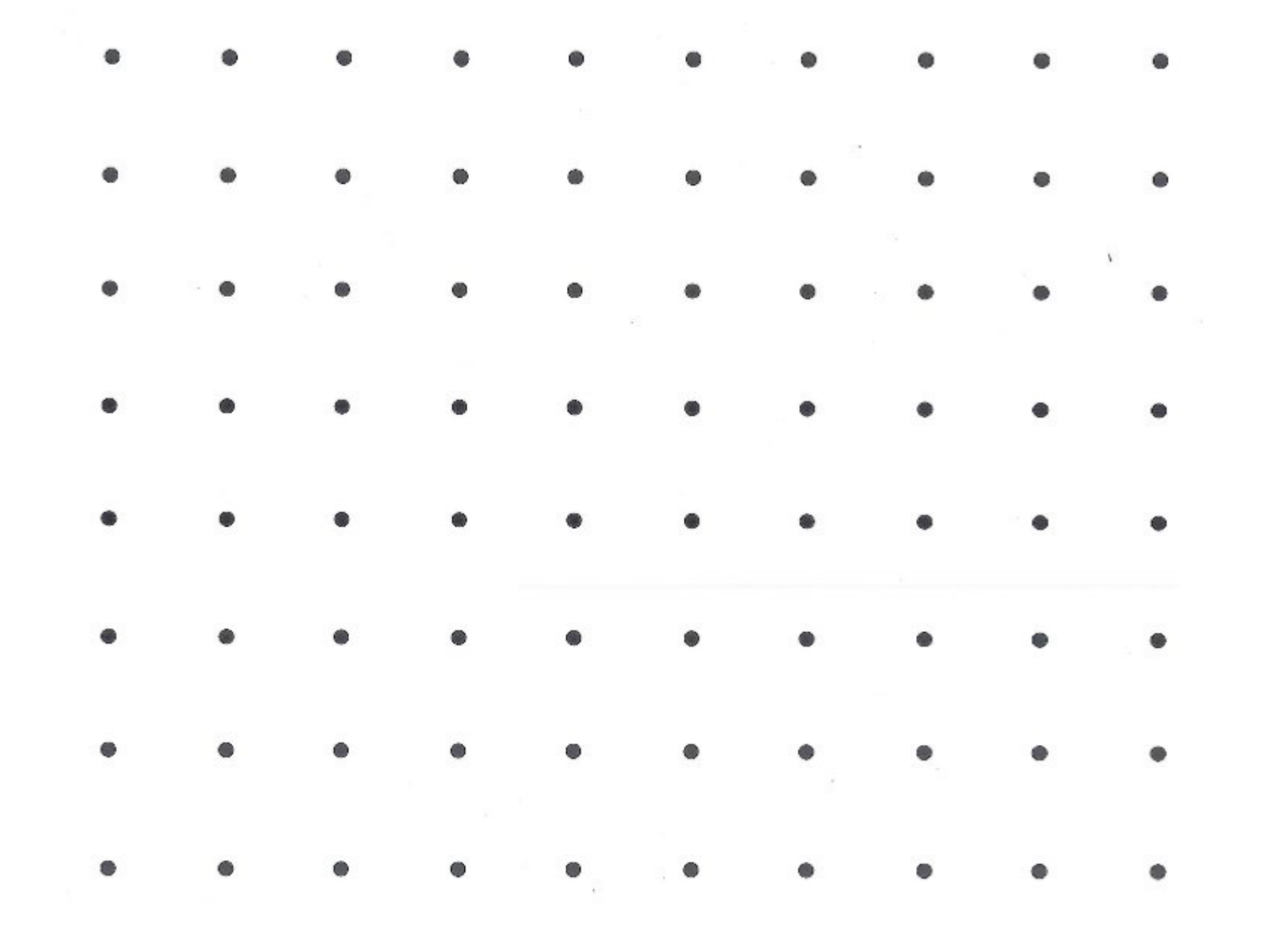

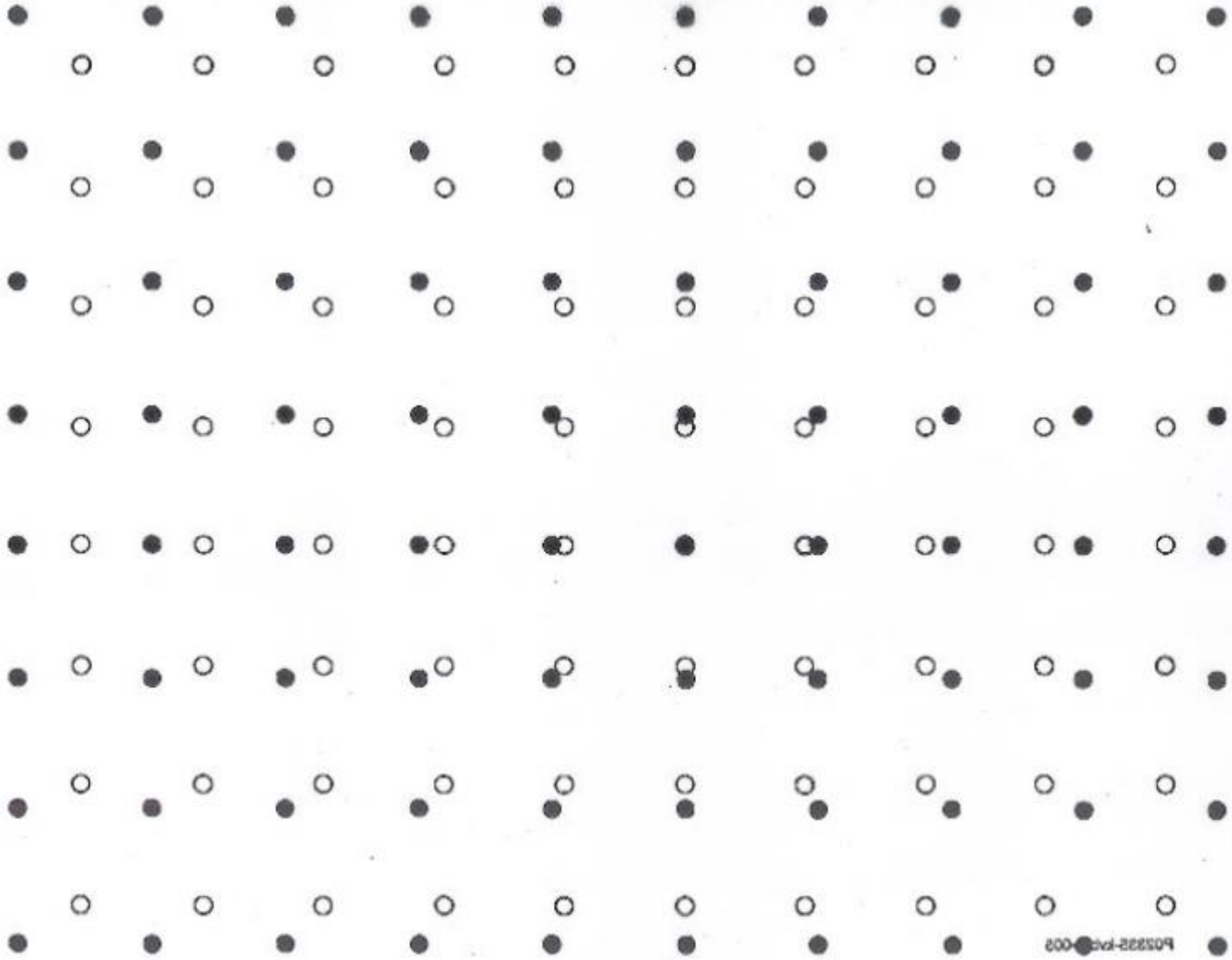

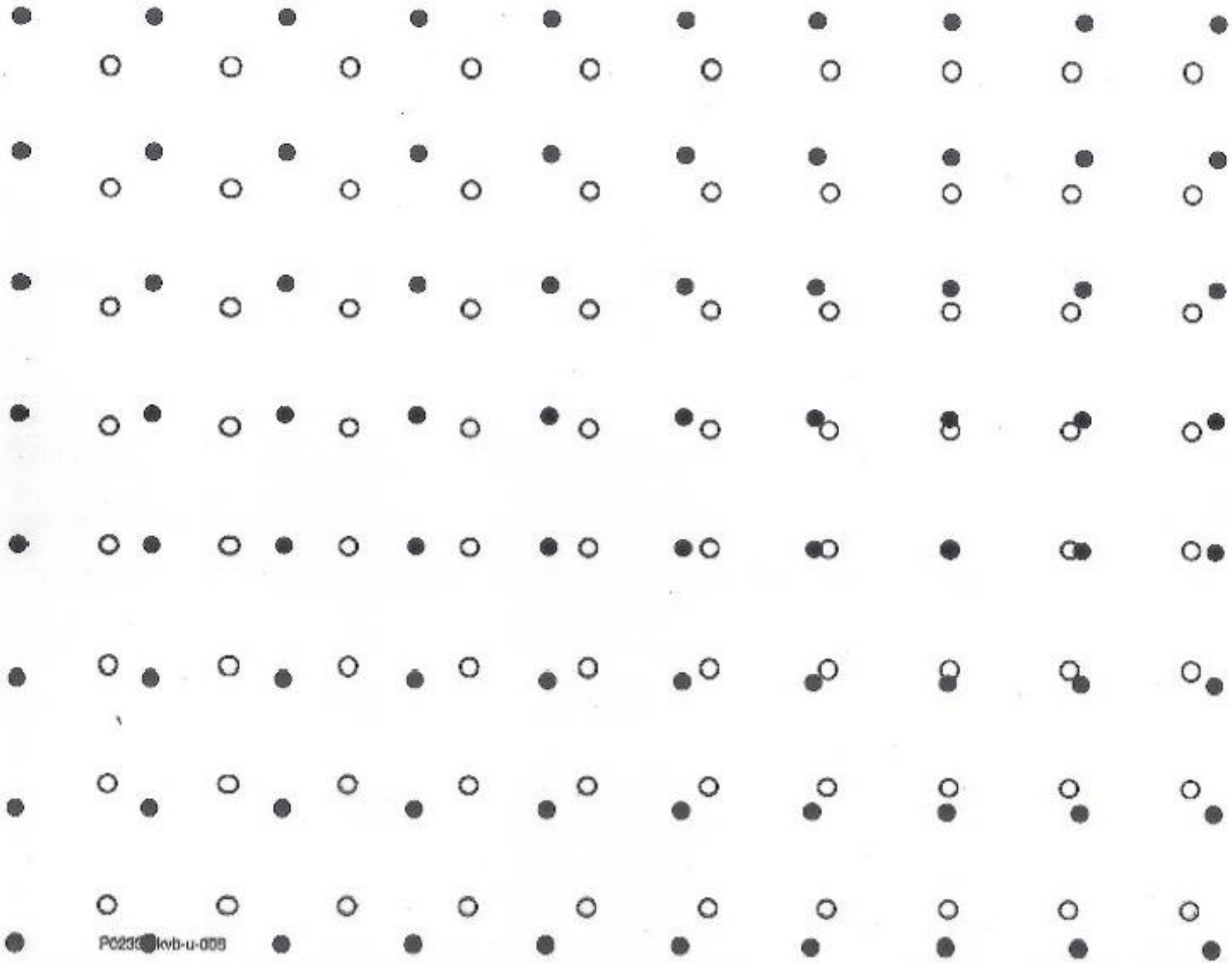
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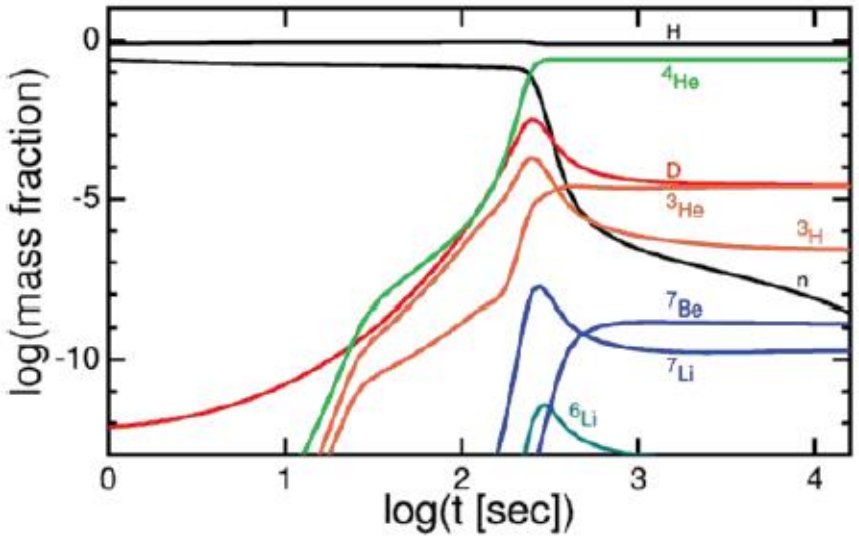
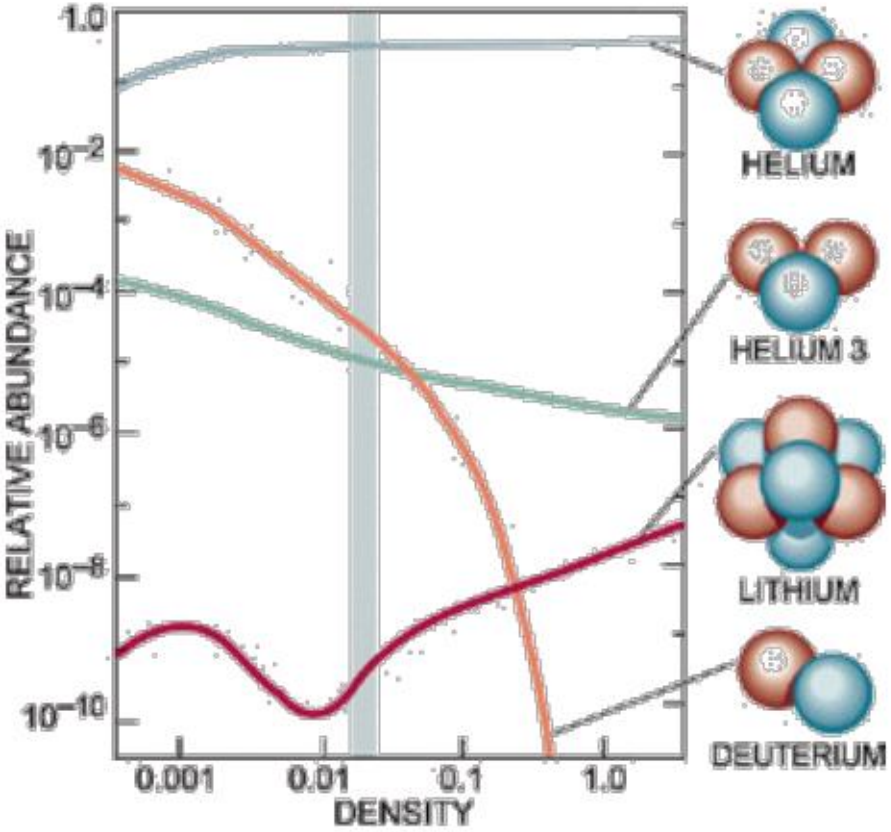
First experimental validation of the Big Bang Hypothesis: Primordial Nucleosynthesis ("The first 15 minutes")

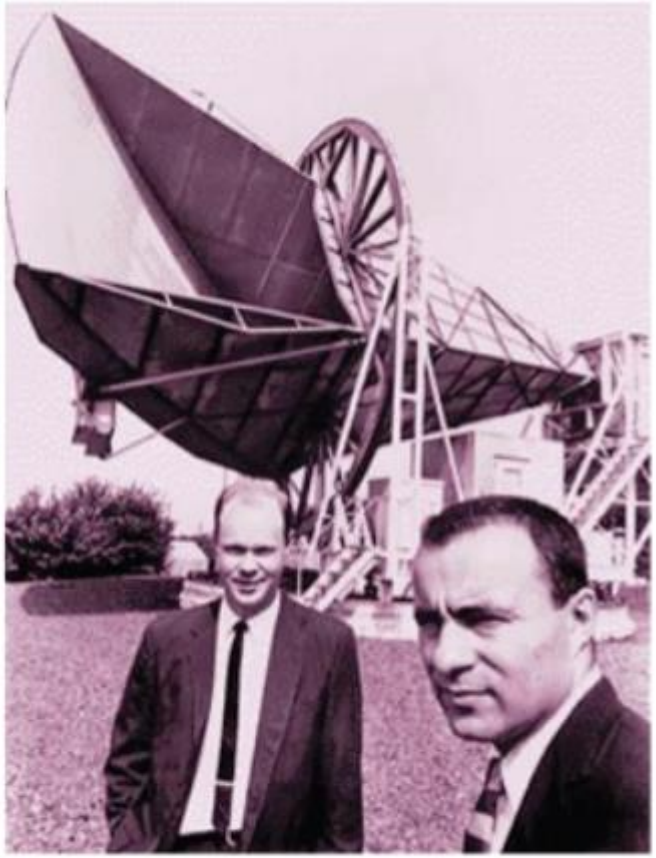
Robert Alpher, Ralph Herman, George Gamow (late 1940's)



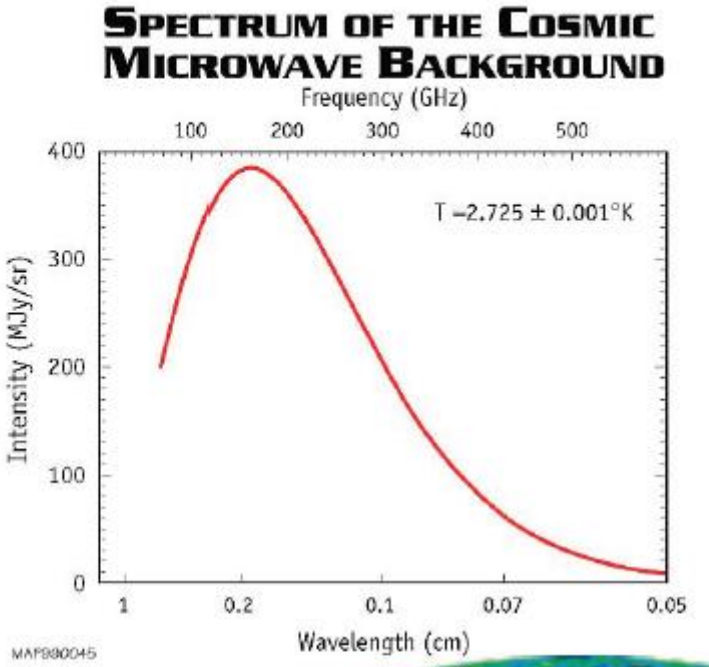


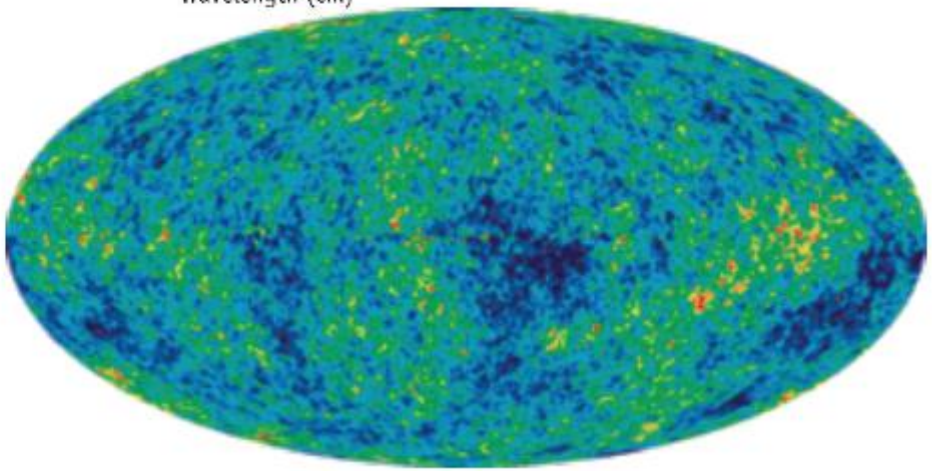
The Silver Bullet – Cosmic Microwave Background: The relic radiation from the Big Bang

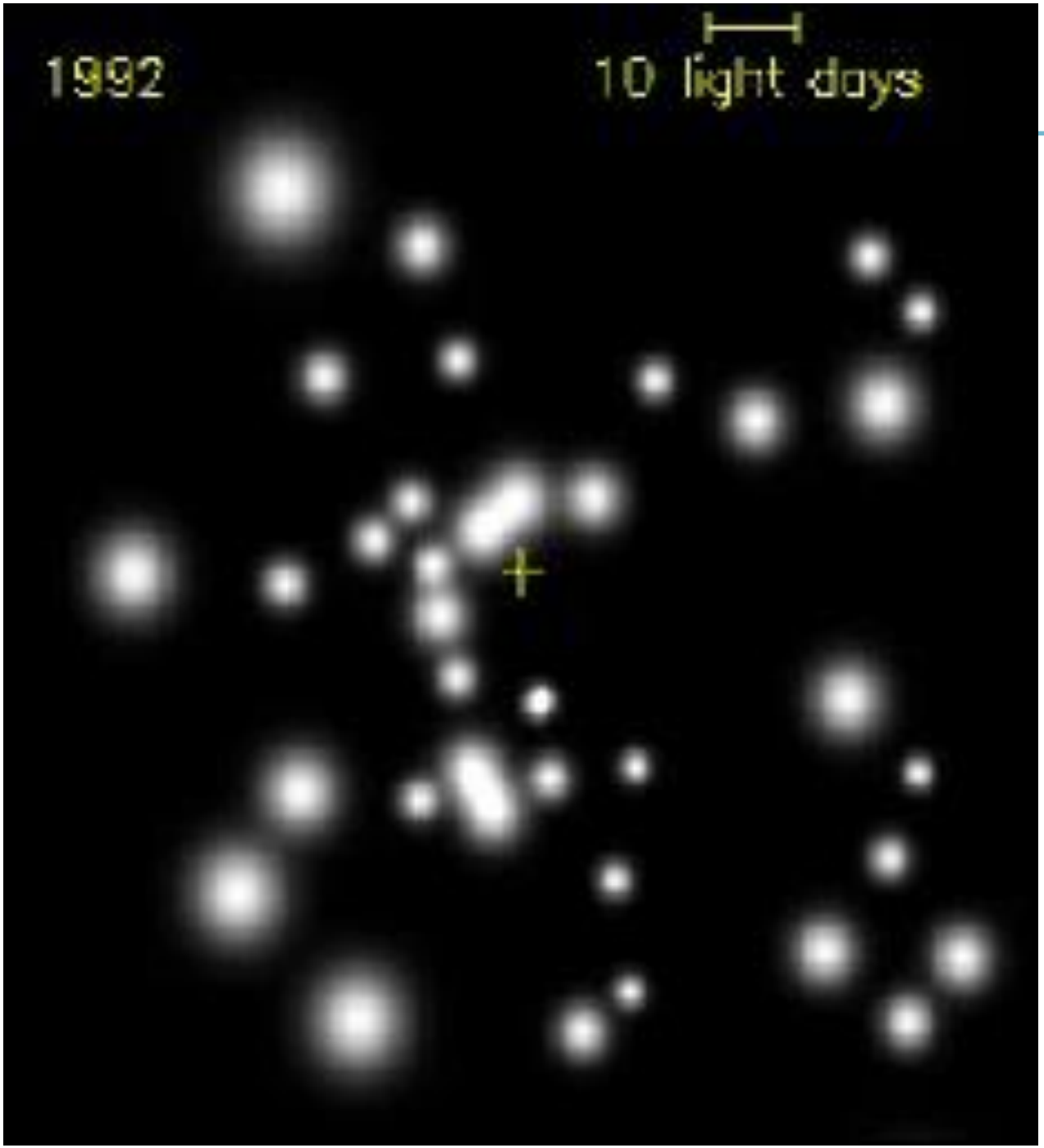
Arno Penzias & Robert Wilson (1964)



The discovery of the Cosmic Microwave Background (3K)







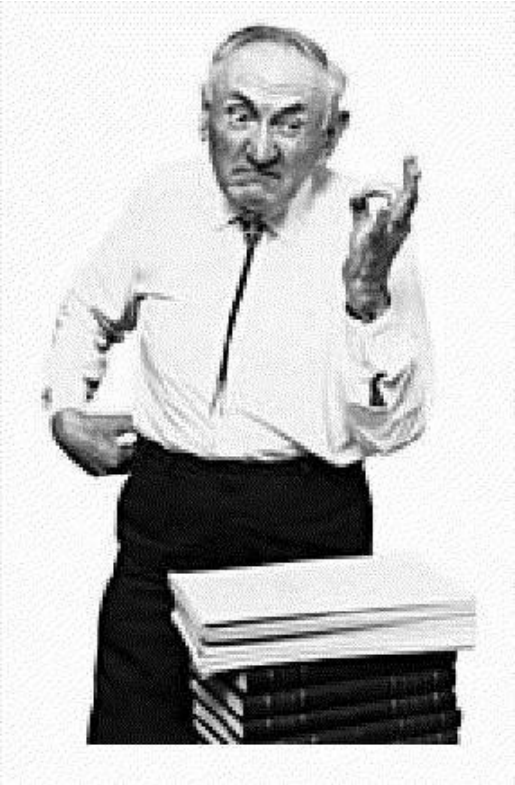
Click the box to the left to launch the video in Youtube.

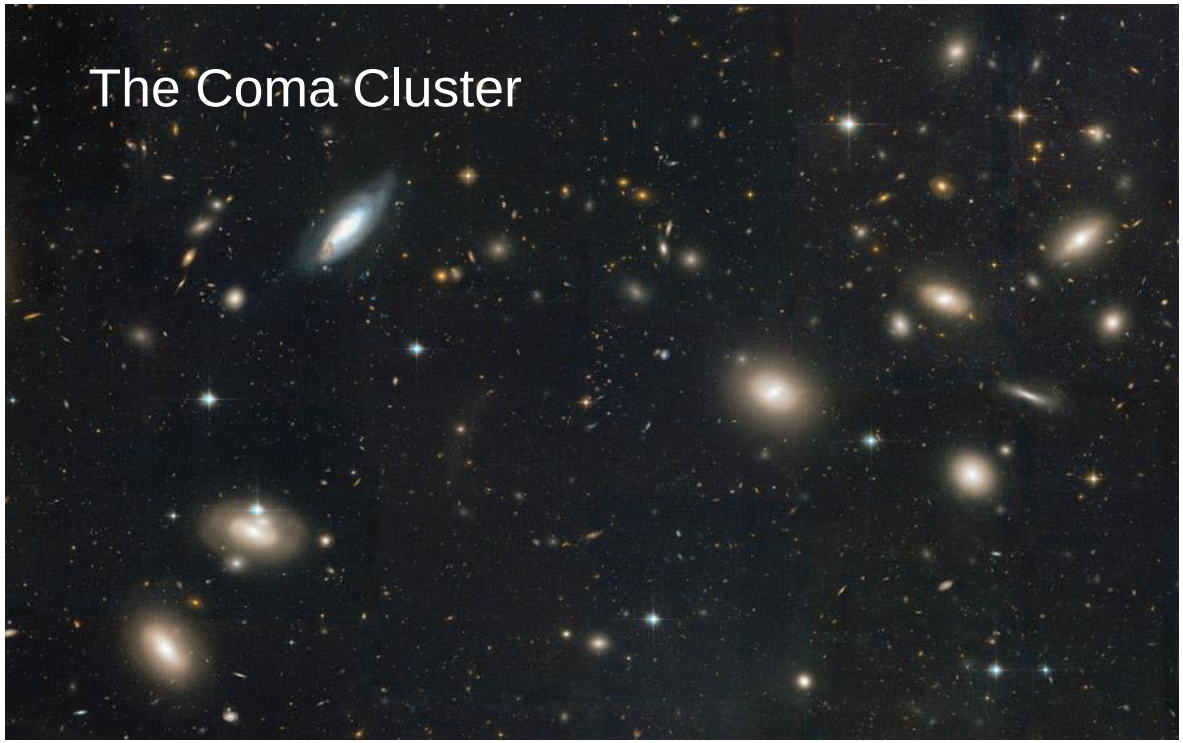
What does it mean to "see" Dark Matter?

Let's peer into the center of the galaxy for an example . . .

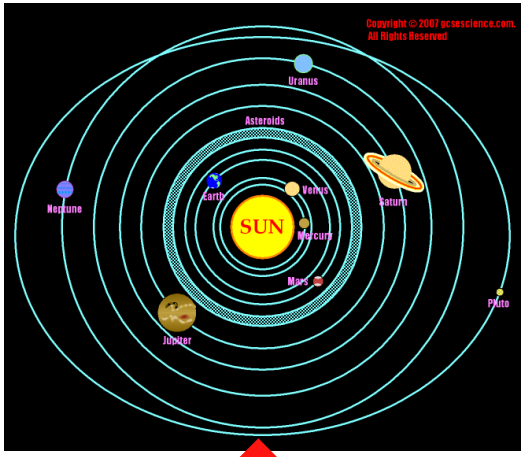
…of a very tiny component of DM

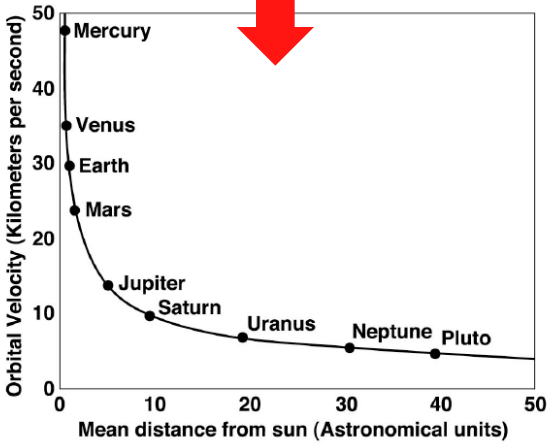
Fritz Zwicky first confronts evidence for DM in 1930's



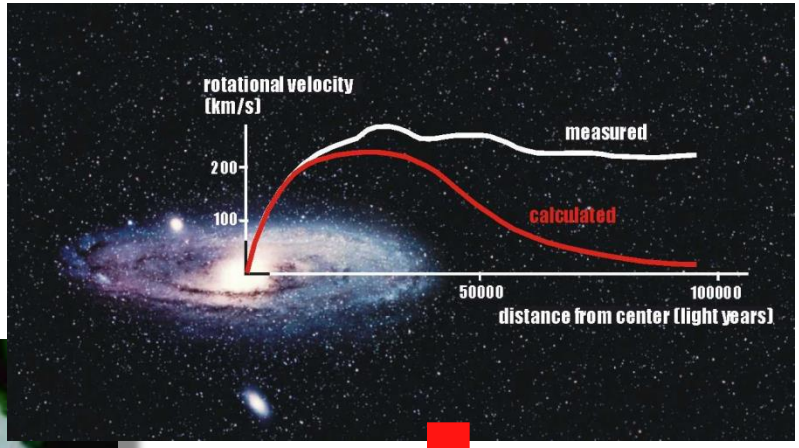


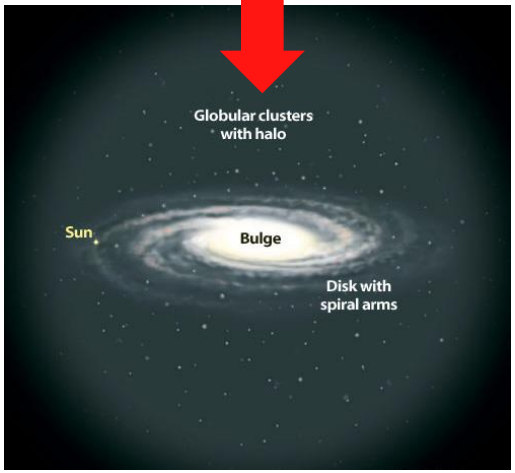
Rotation curves of spiral galaxies (Rubin & Ford, 1960's)





Vera Rubin
Carnegie Institute



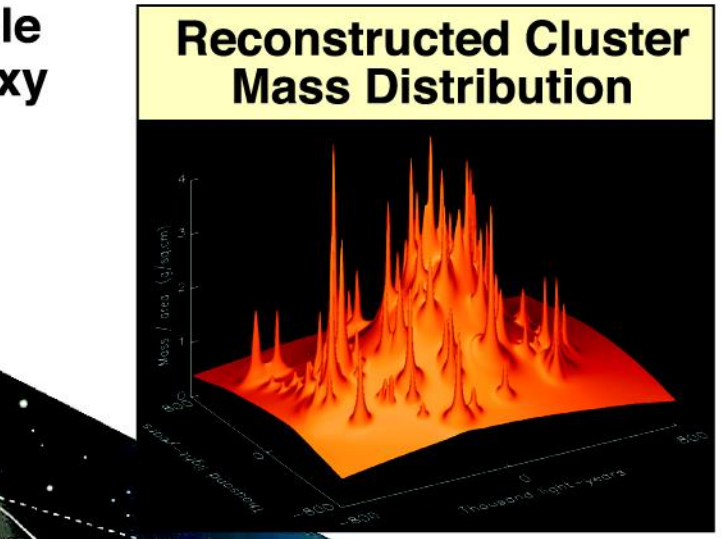


Our solar system:
What you see = What you got

Spiral galaxies:
What you see << What you got

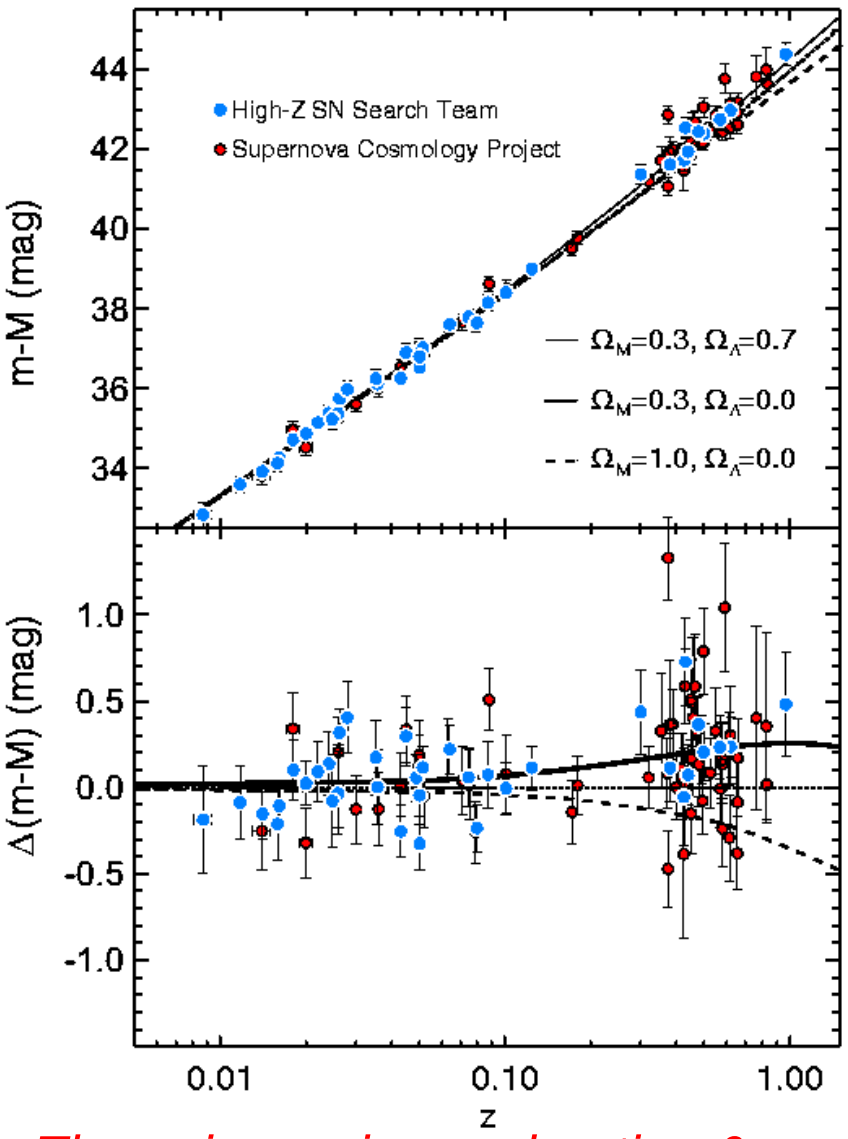
Evidence for dark matter on larger scales: Gravitational lensing by clusters of galaxies

- **Cluster mass reconstruction from multiple gravitational lensing of background galaxy**



Consistent with dynamical estimates; $\Omega_M/\Omega_B \sim 7$

Two teams of physicists & astronomers tried to ‘weigh’ the total matter in the Universe by measuring the curvature of the Hubble diagram at large red-shift (= long time ago)



Curvature of Hubble diagram at high-z points to existence of Dark Energy

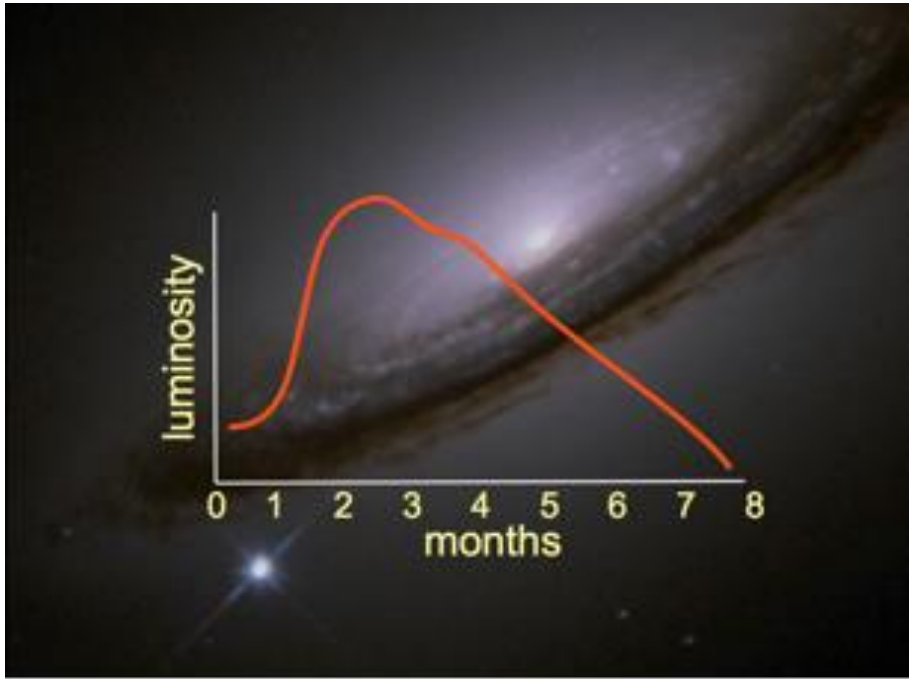
Λ (or something) is back!

Riess, Schmidt & Perlmutter

The universe is accelerating & never coming back? (Who ordered this?)

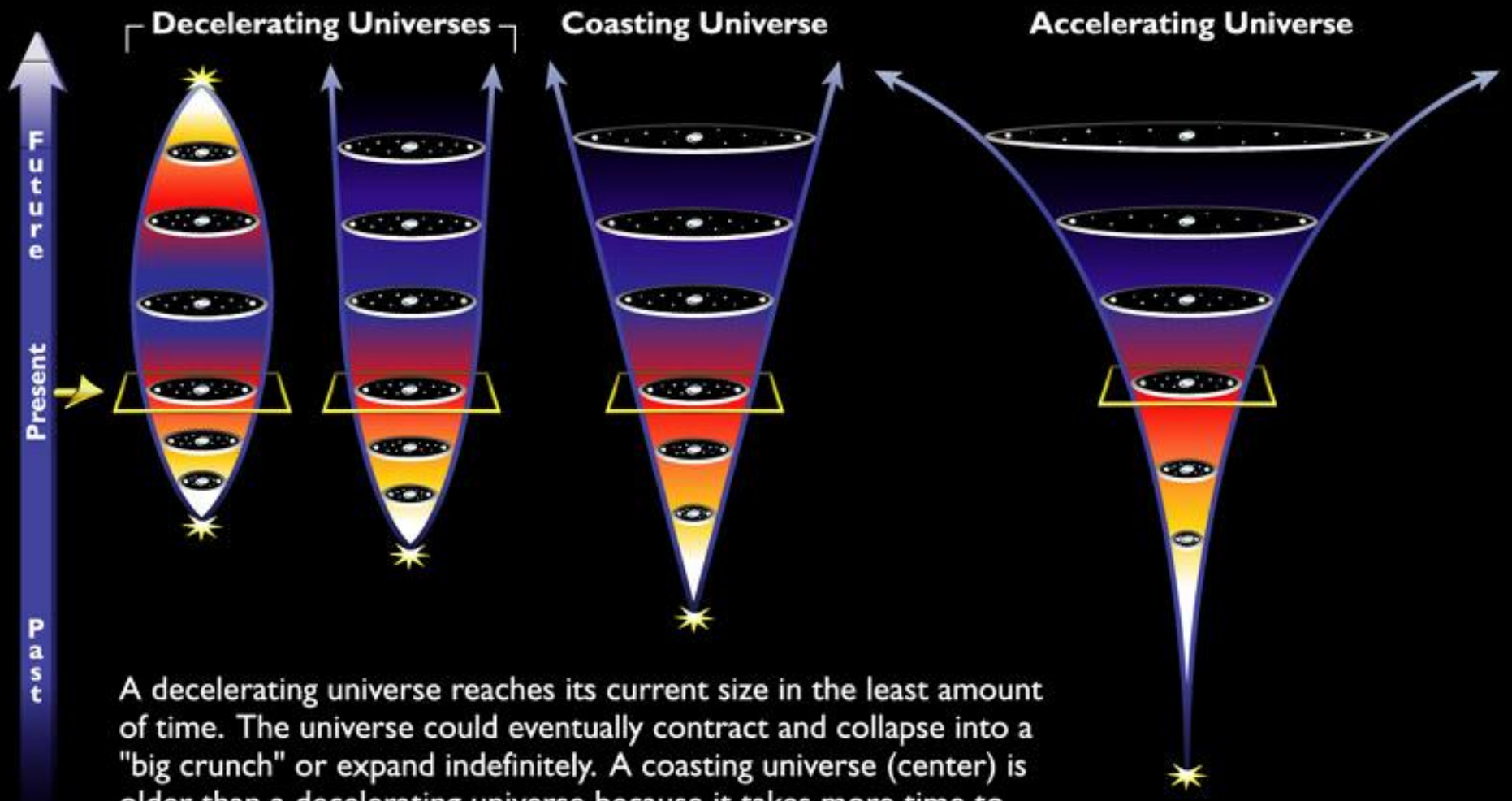
Type 1a Supernovae as “Standard Candles”

“For any idea that at first does not seem completely crazy, there is no hope” – A. Einstein



Supernovae Cosmology Project & High-Z Redshift Survey

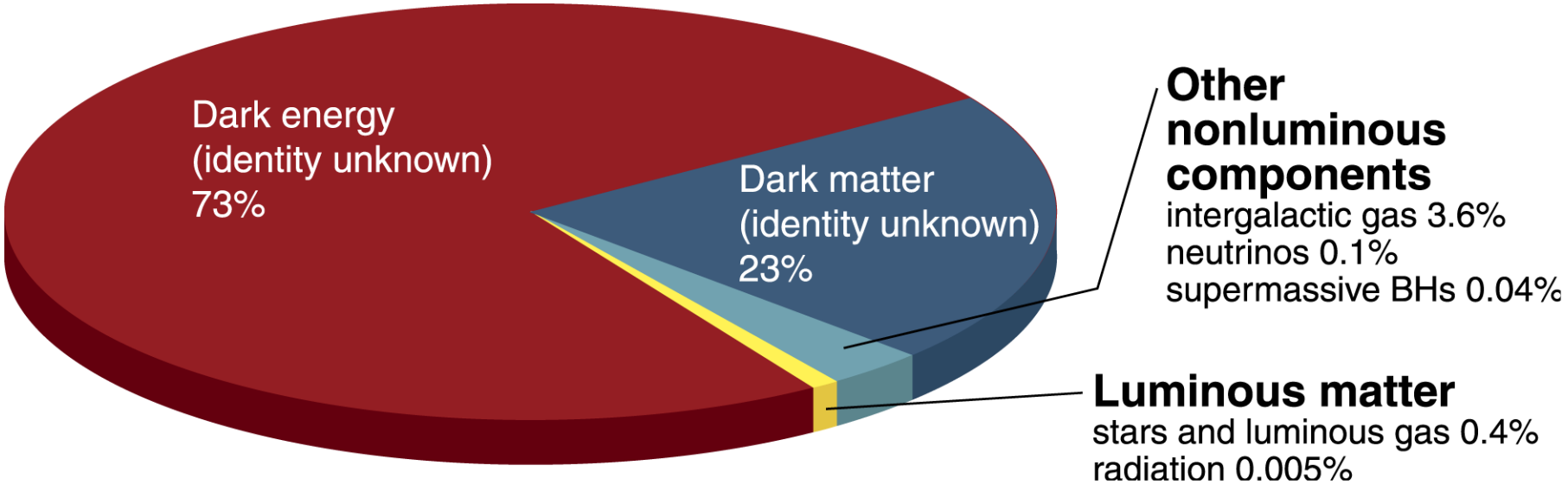
Possible Models of the Expanding Universe



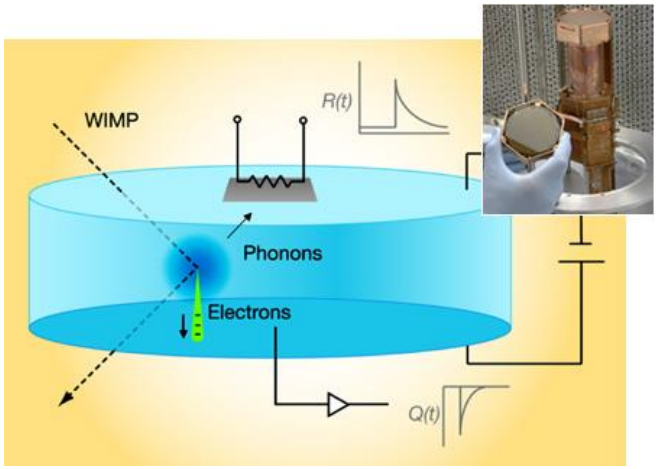
A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

The cosmological budget is fairly well determined now

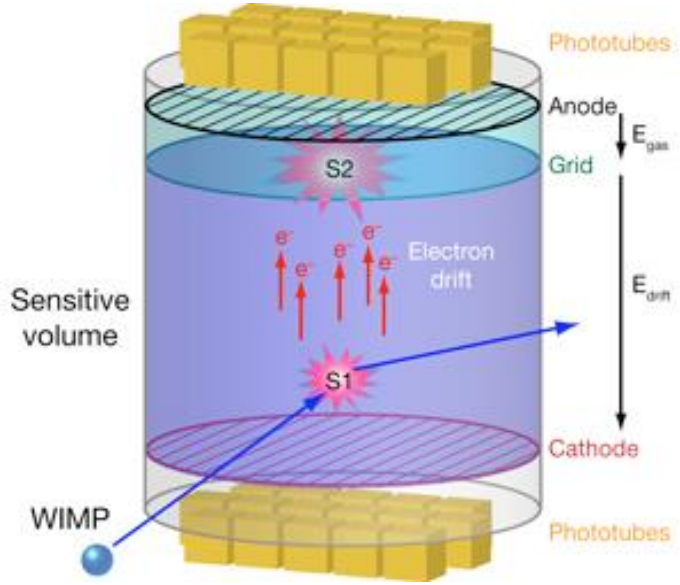
- But we don't know what either the dark energy or the dark matter is !
- A particle relic from the Big Bang is our best guess for the dark matter
  - —WIMPs ?
  - —Axions ?



How we look for WIMPS *(Thousand times the proton mass)*



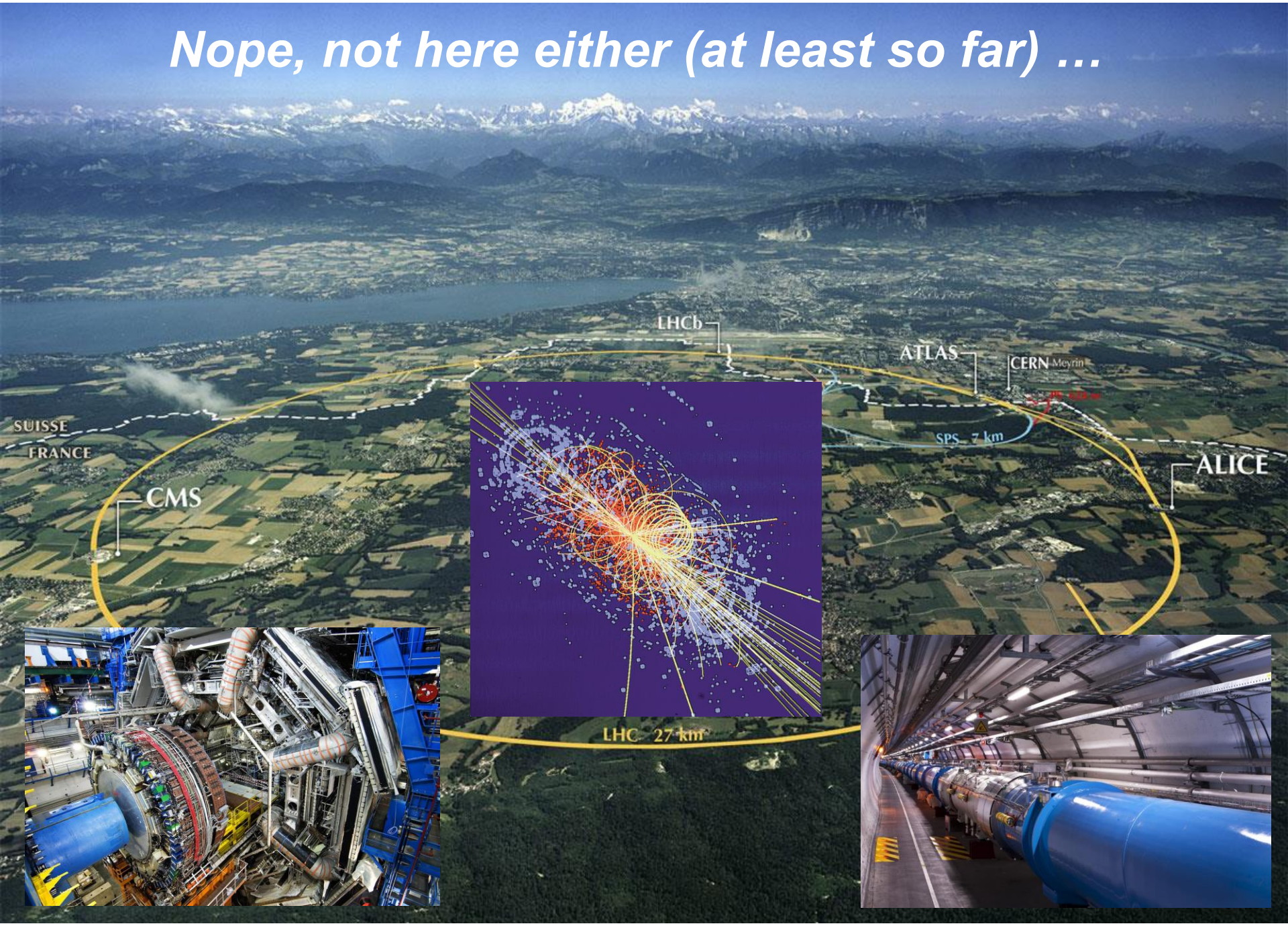
Cryogenic solid state detectors
e.g. SuperCDMS



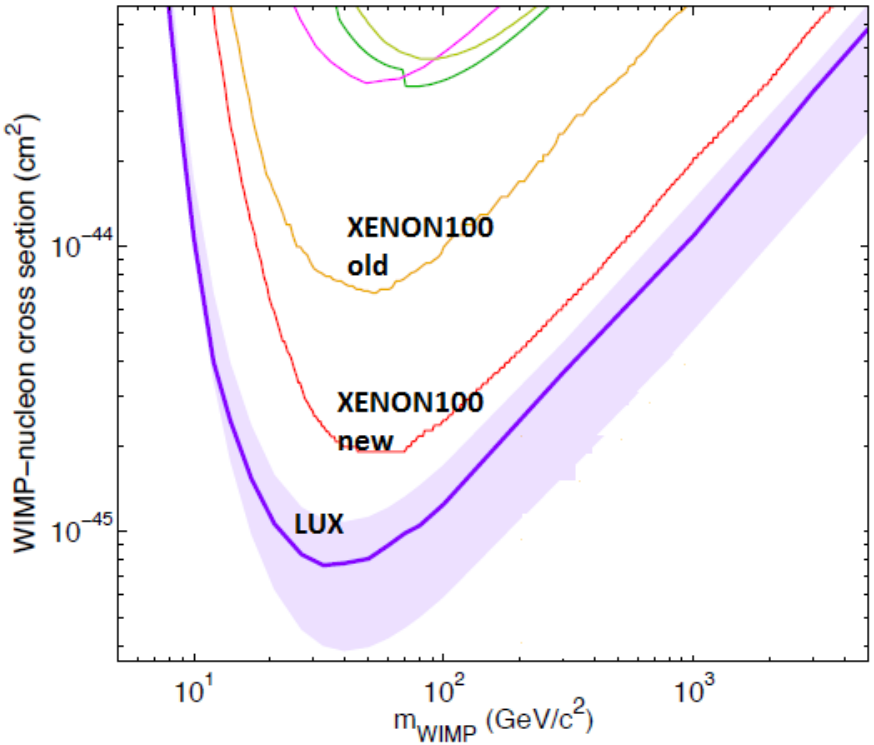
Liquid noble detectors
e.g. XENON100, LUX

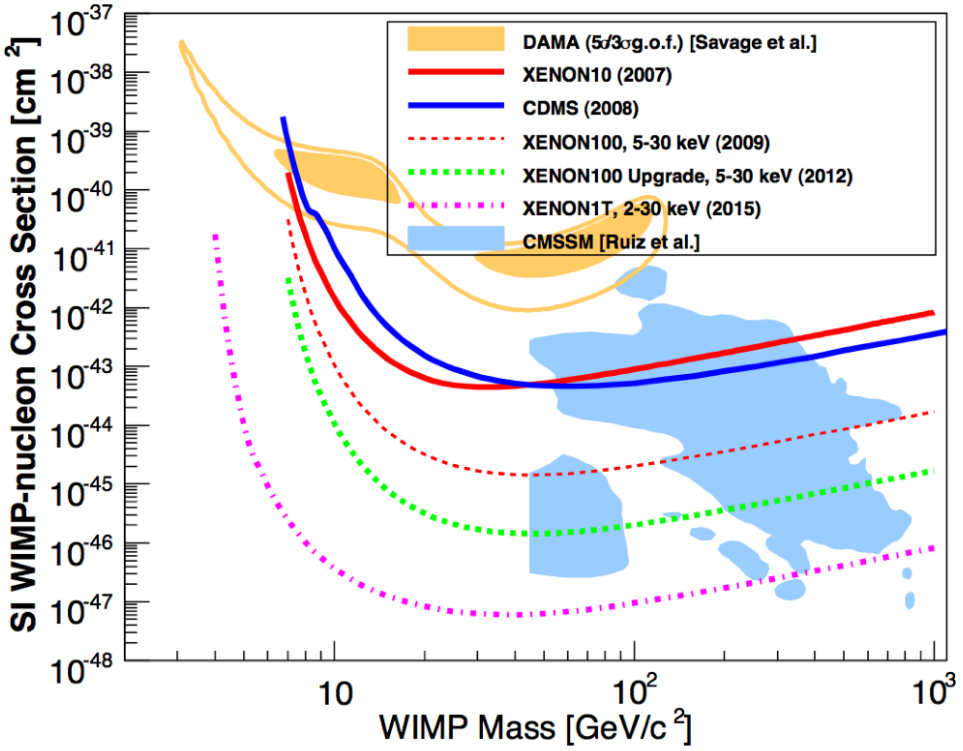
So far, no sign of such particles in detectors of several 100 kg

Nope, not here either (at least so far) …



WIMP exclusion region - now & projected





So what is the axion?

Where does it come from?

Why do we need it?

How do we understand it?

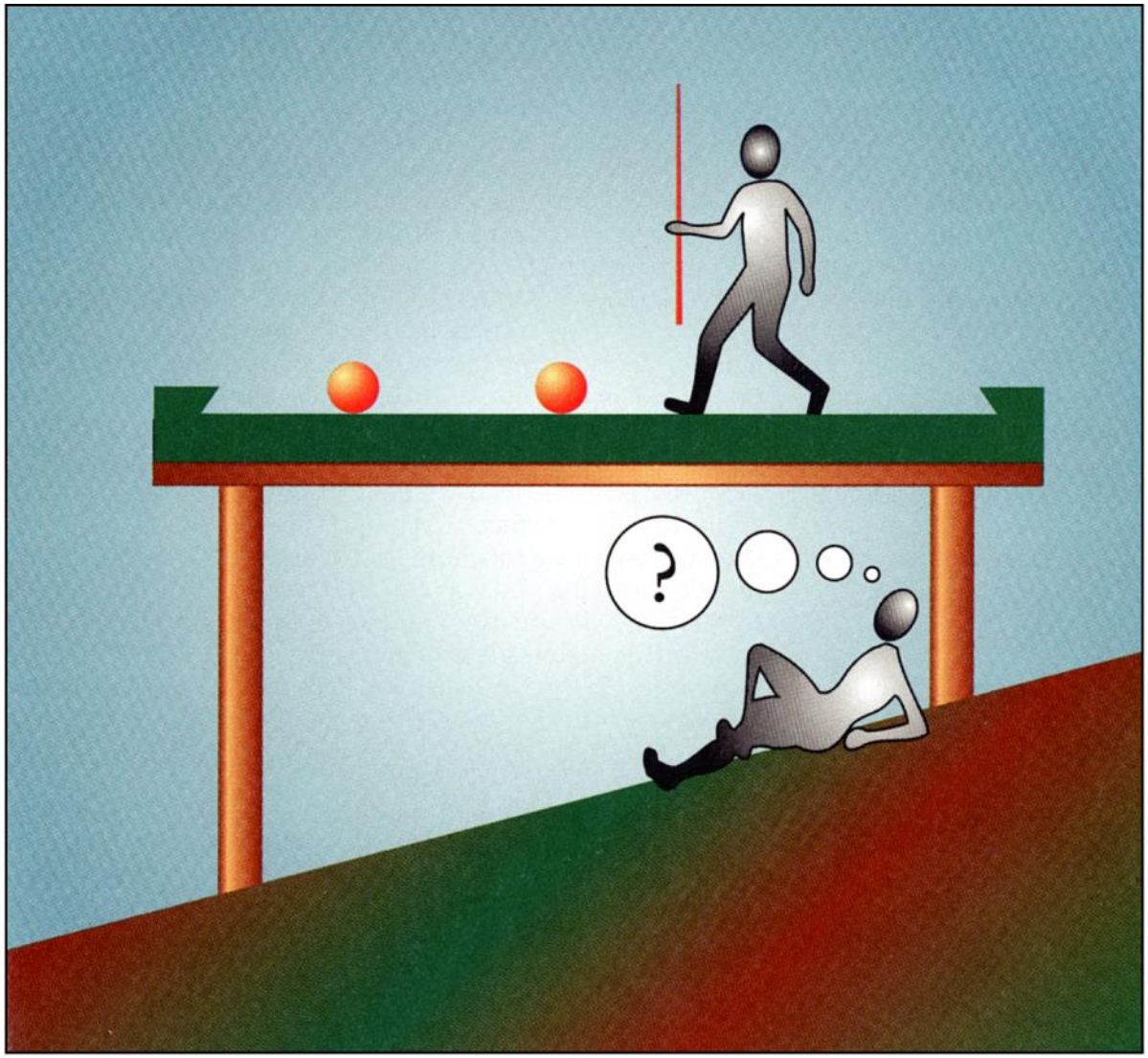
Where and how might we find it?

(Then what?)

The axion.

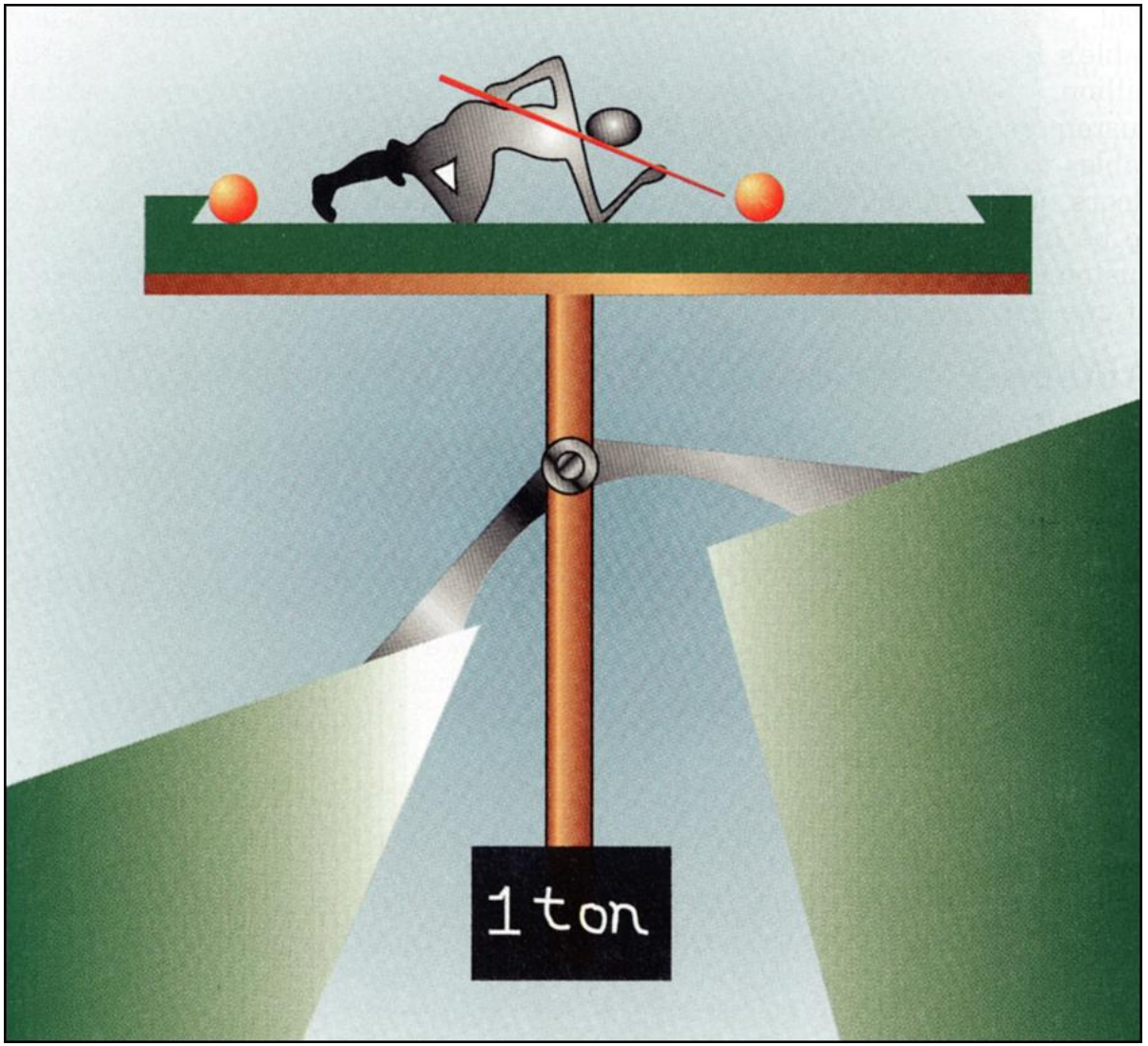
A very small particle accompanying a very Big Bang…

TSP's* fine-tuning problem

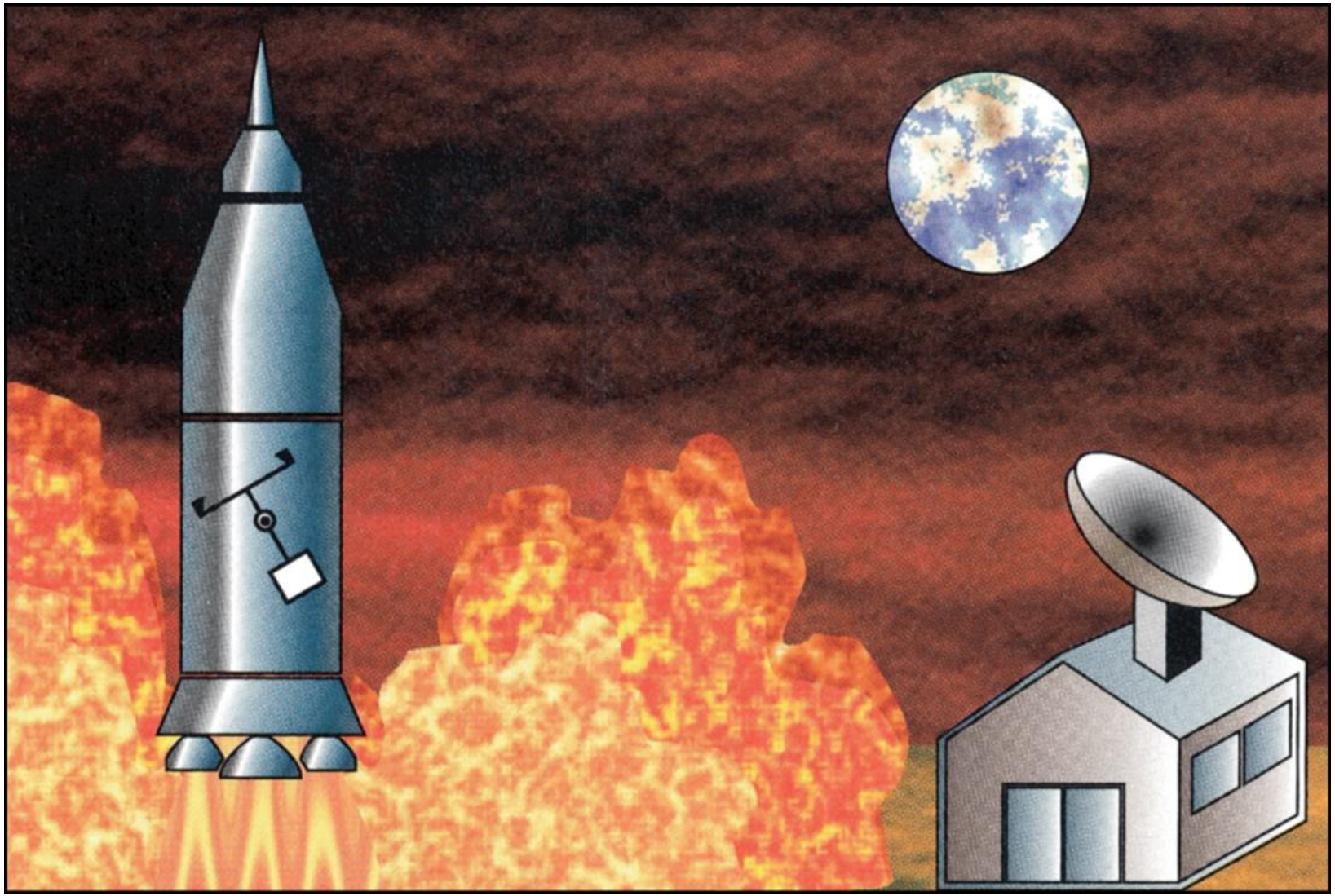


*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)

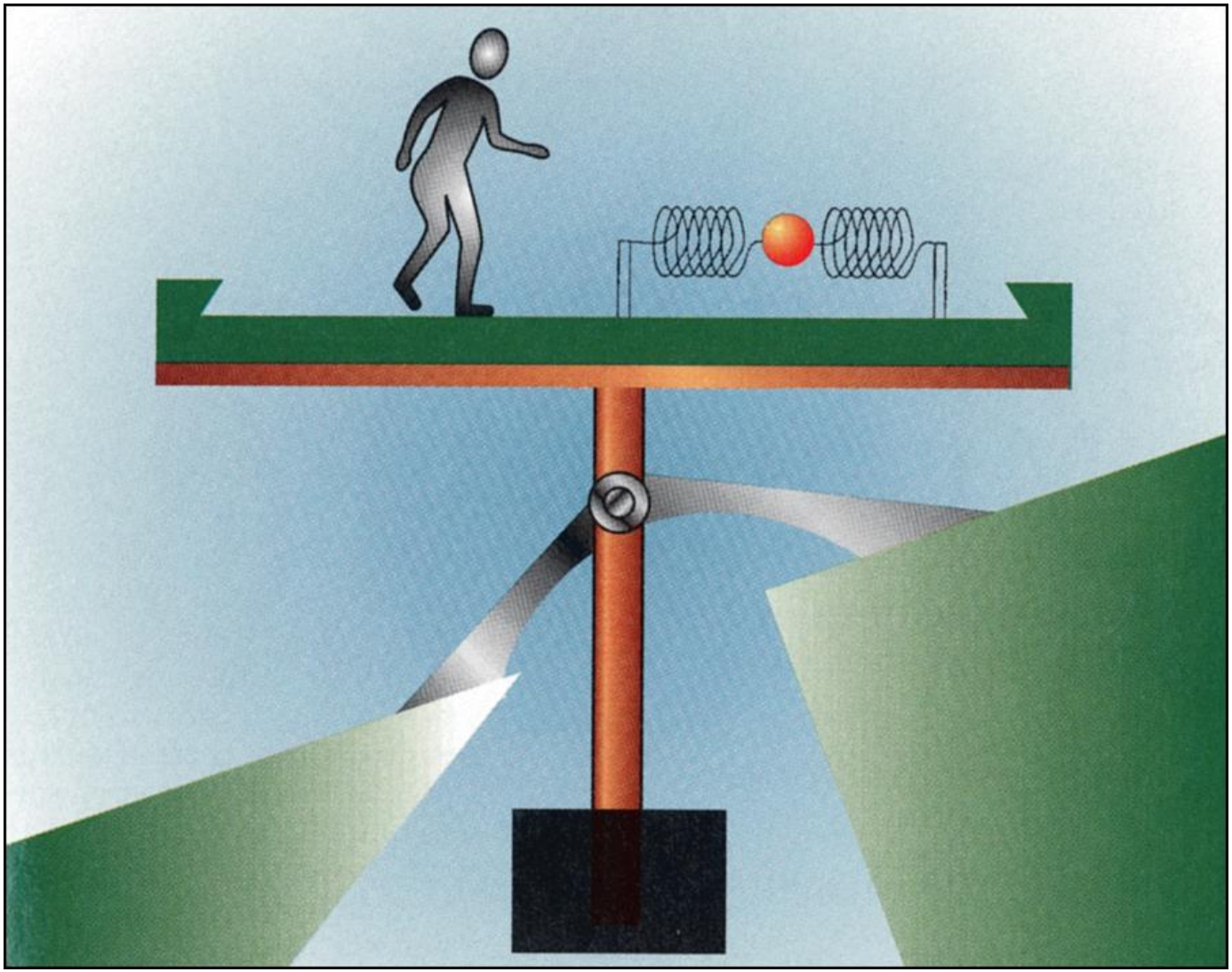
TSP's hypothesis, and first unsuccessful experiment



The key insight



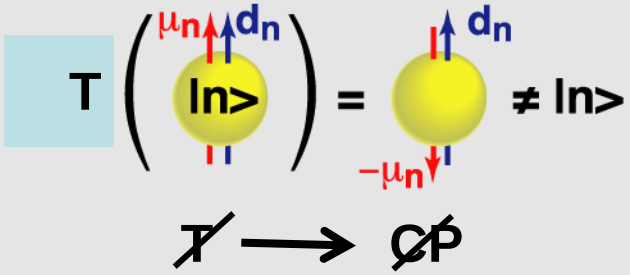
A high-Q search for relic oscillations



The Axion

The Strong-CP Problem

- $\mathcal{L}_{QCD} = ... + \frac{\theta}{32\pi^2} G\tilde{G}$
  - — Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - — $\bar{\theta} < 10^{-10}$
  - — Strong-CP preserving



~~T~~ ⟶ ~~CP~~

- Why?

The Axion

The Strong-CP Problem

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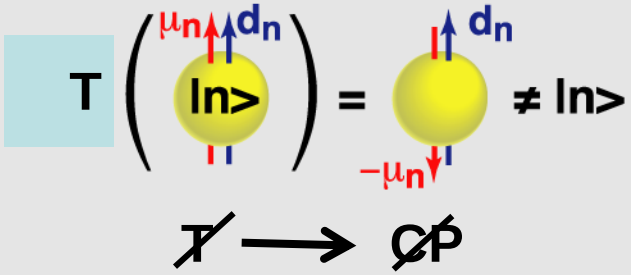
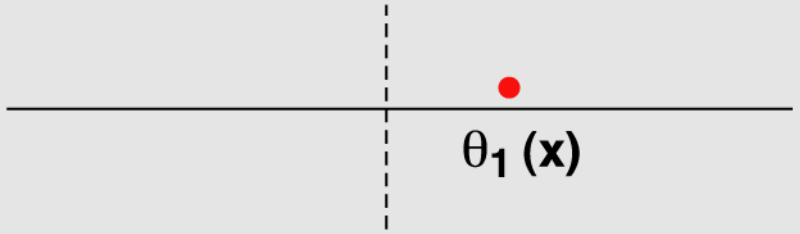


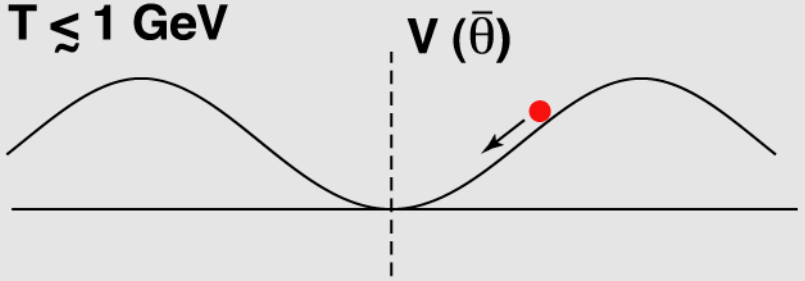
- Why?

Peccei-Quinn / Weinberg-Wilczek

- θ a dynamical variable
- T = f_a spontaneous symmetry breaking

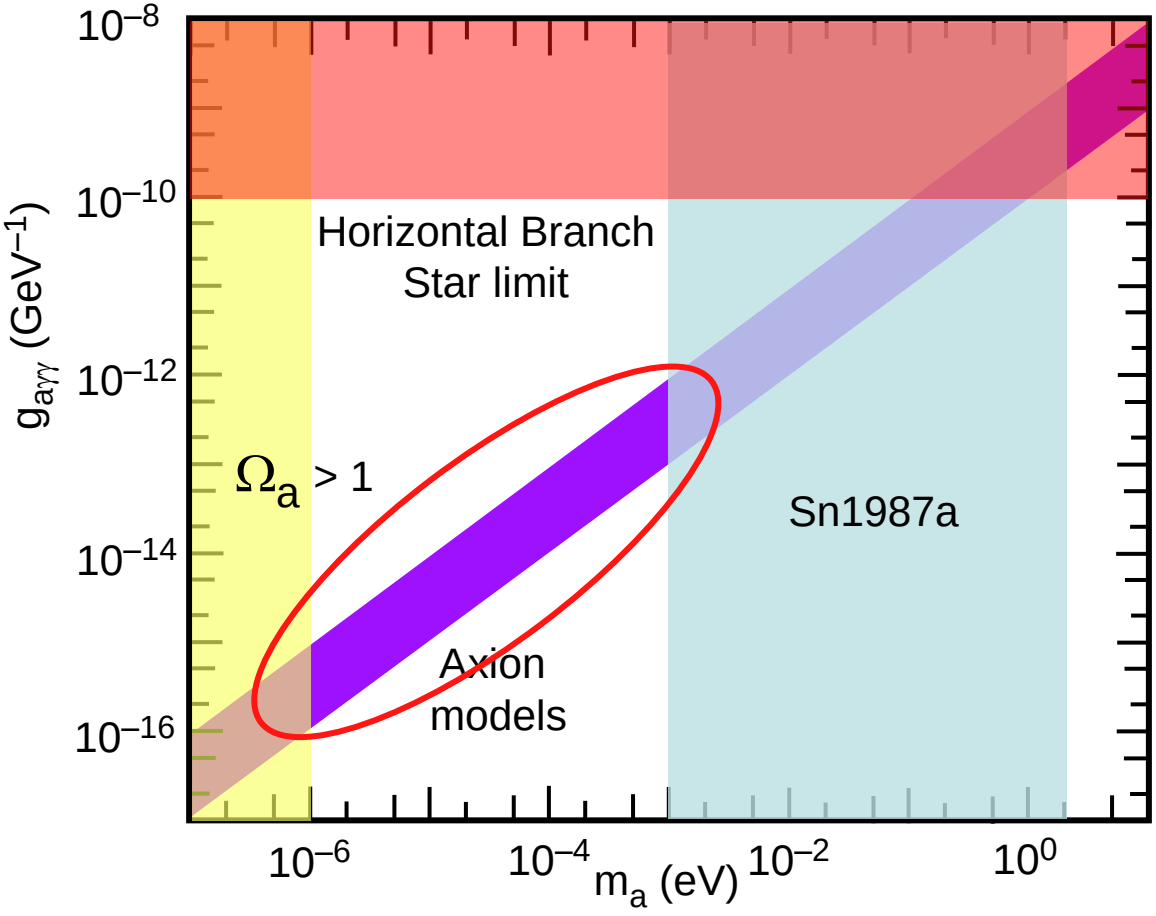


- T $\lesssim$ 1 GeV

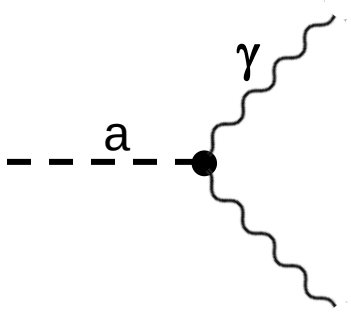


  - — $\bar{\theta}$ dynamically → 0
  - — Remnant oscillation = Axion

Axion basics *(arm-chair science – what you learn for free)*



Light cousin of π^0: $J^{\pi} = 0^-$



Couplings ∝ Axion mass

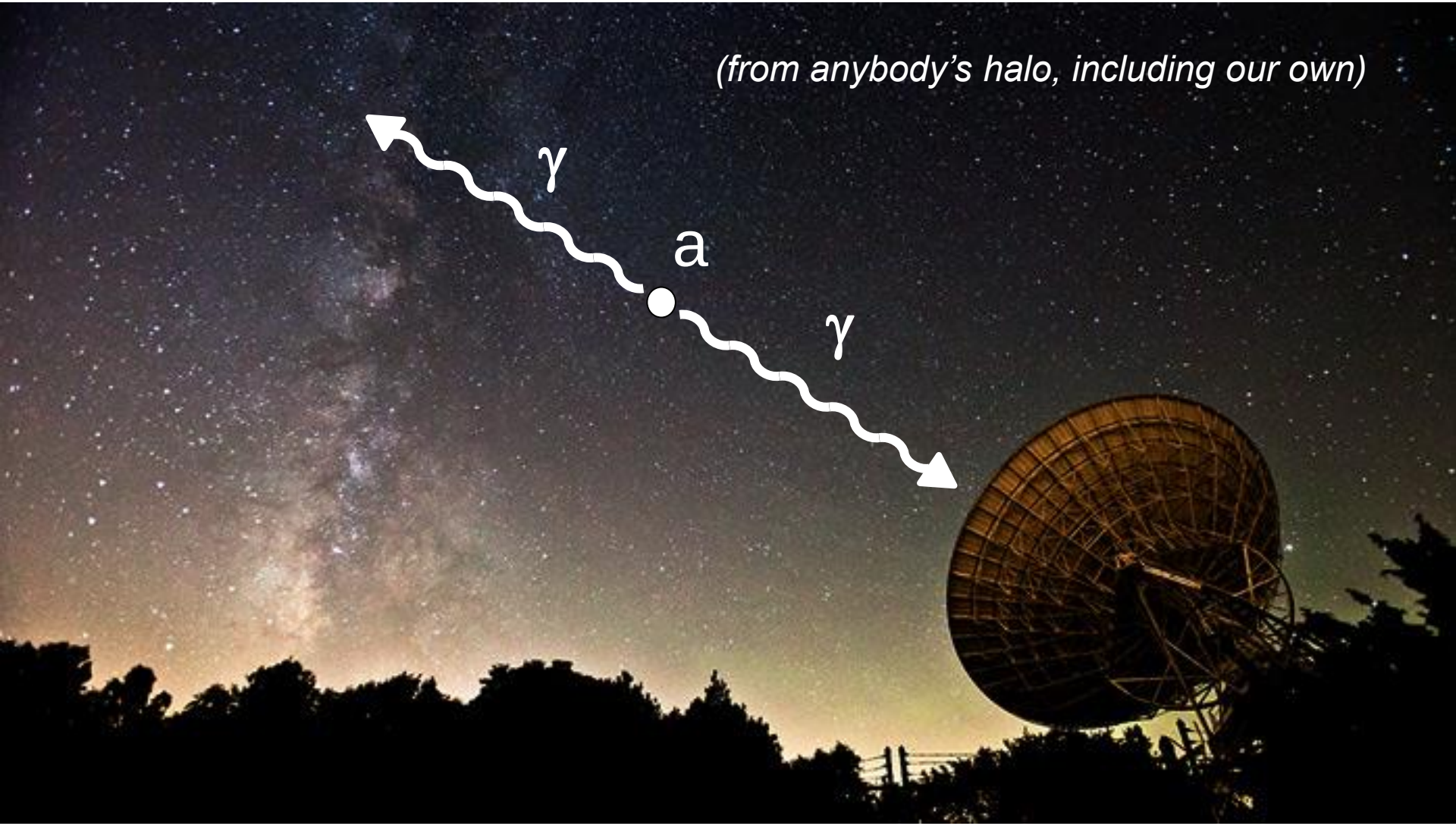
Total density ∝ (mass)$^{-7/6}$

Axion production quenches neutrino pulse from SN1987a if mass too big (~ meV)

Ordinary stellar burning rules out axions if coupling too big

Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

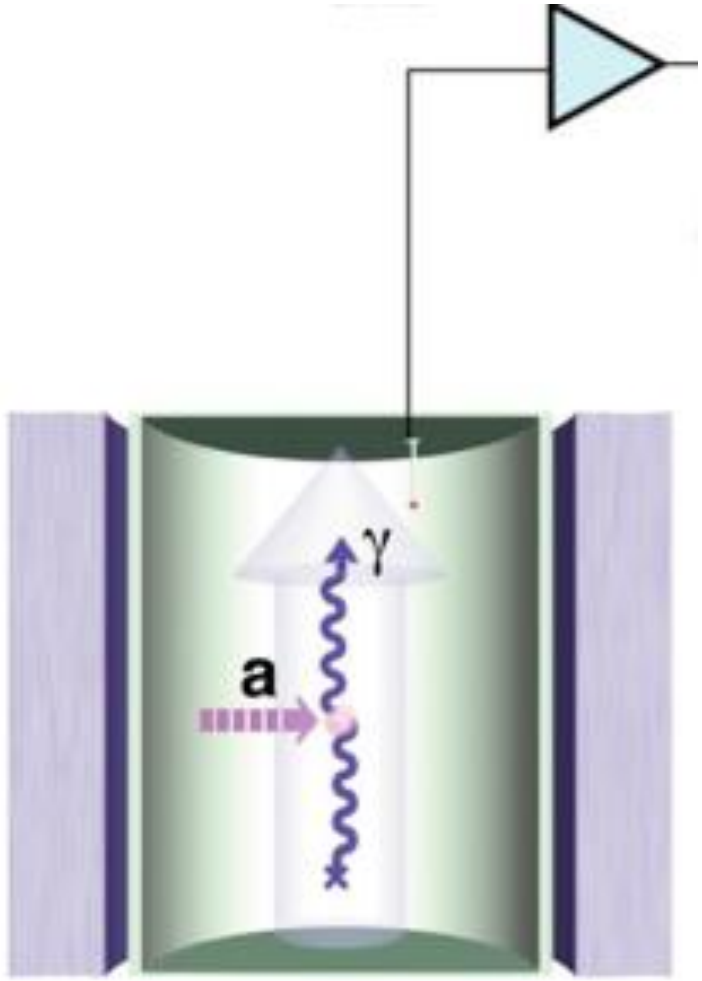
Why is this hard? Why not just look for an unidentified radio line at which $E_\gamma = m_a / 2$?

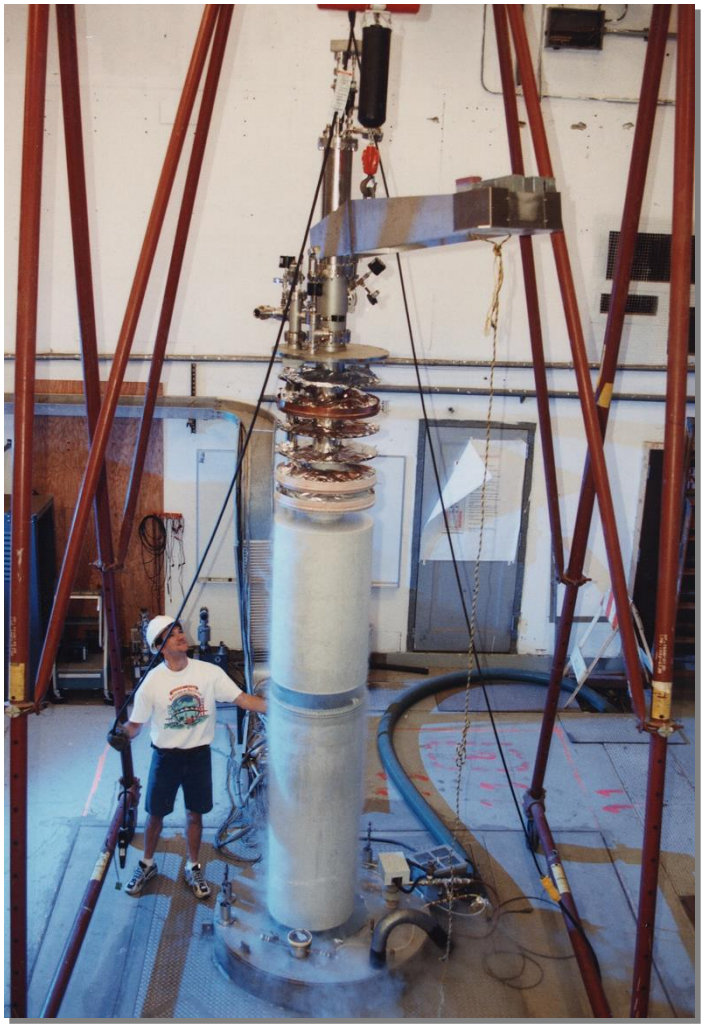


The difficulty is that the spontaneous decay lifetime ~ 10^{60} sec for m_a ~ μeV

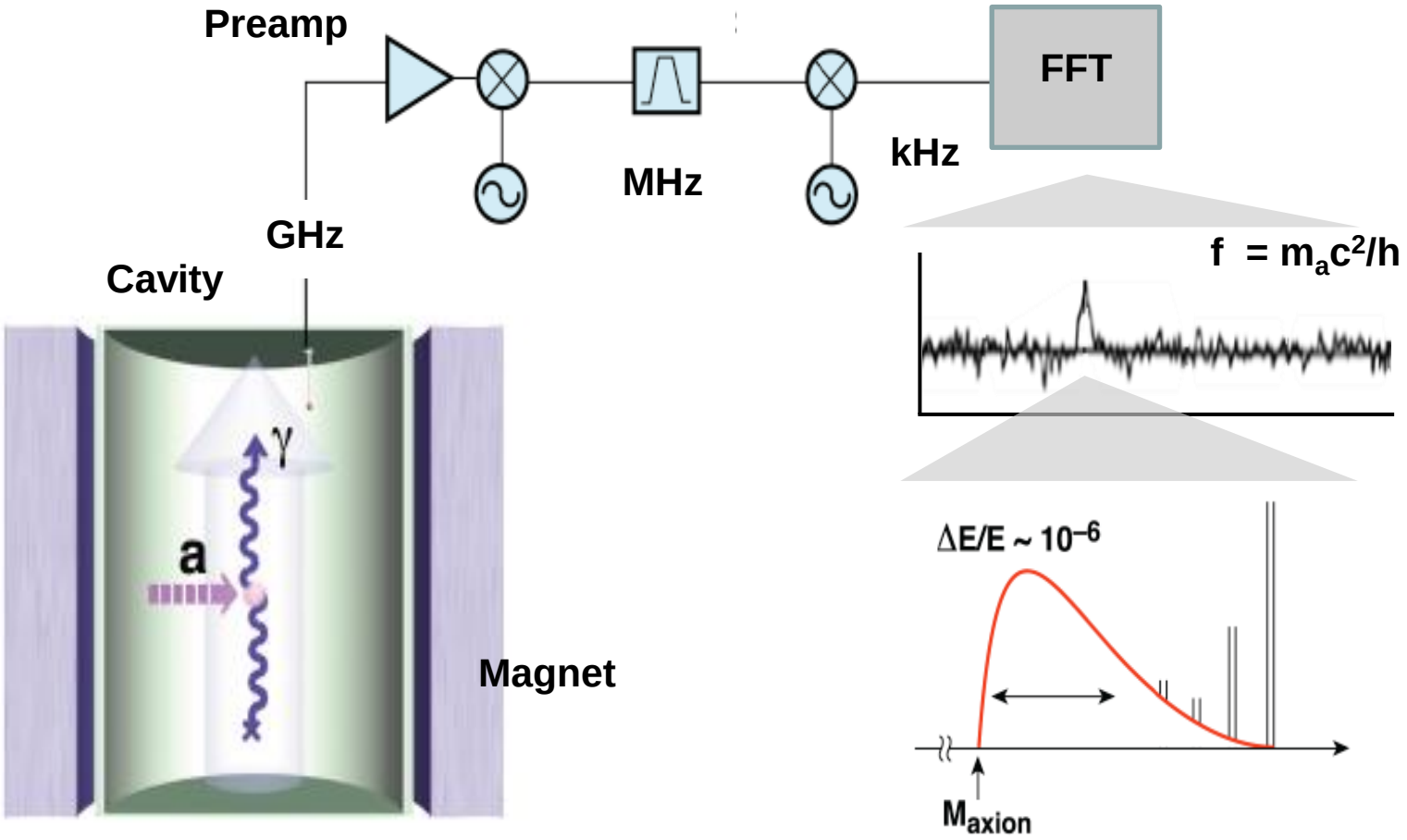
(Remember, that's why it's called "dark matter" !)

But we have a trick up our sleeve …





The microwave cavity axion search – Your car radio on steroids



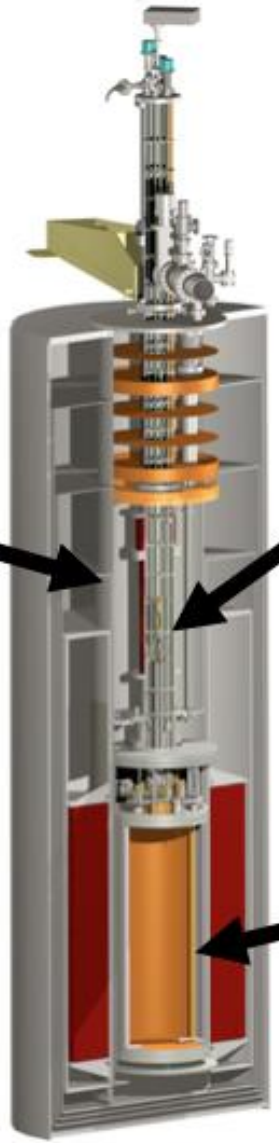
$$P_{sig} \propto (B^2 V Q_{cav})(g^2 m_a \rho_a) \sim 10^{-23}\,W \qquad s/n = \frac{P_{sig}}{kT_{sys}}\sqrt{\frac{t}{\Delta\nu}}$$

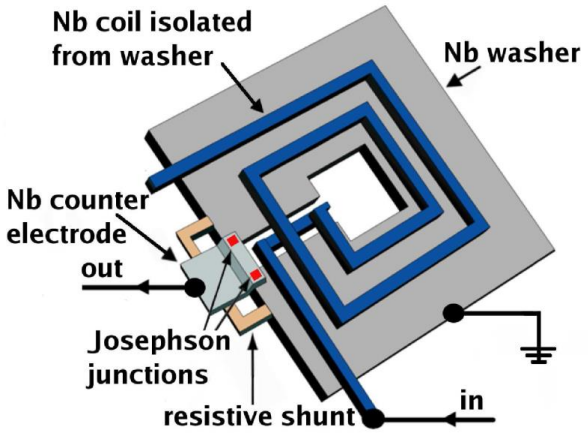
ADMX *UW-LLNL-UCB-UF-NRAO*

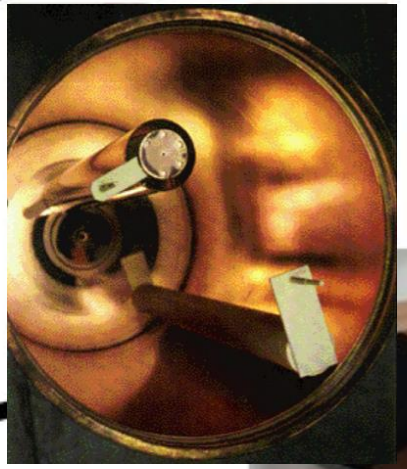
Quantum limited SQUID amplifiers

Field compensation magnet for SQUIDs

Cryogenics

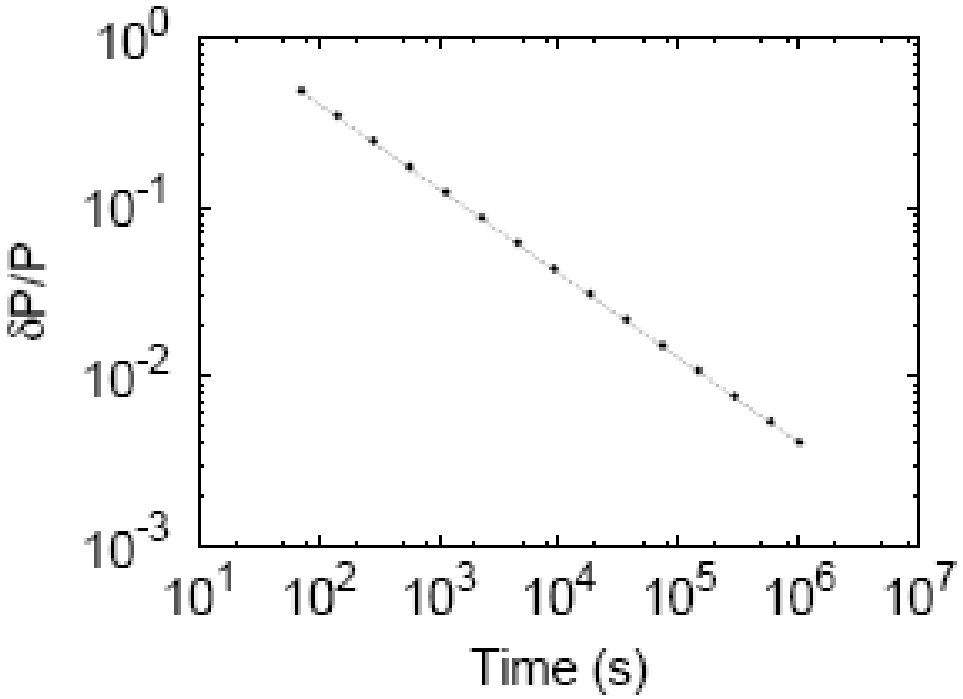






Microwave Cavity

ADMX is the world's quietest spectral receiver

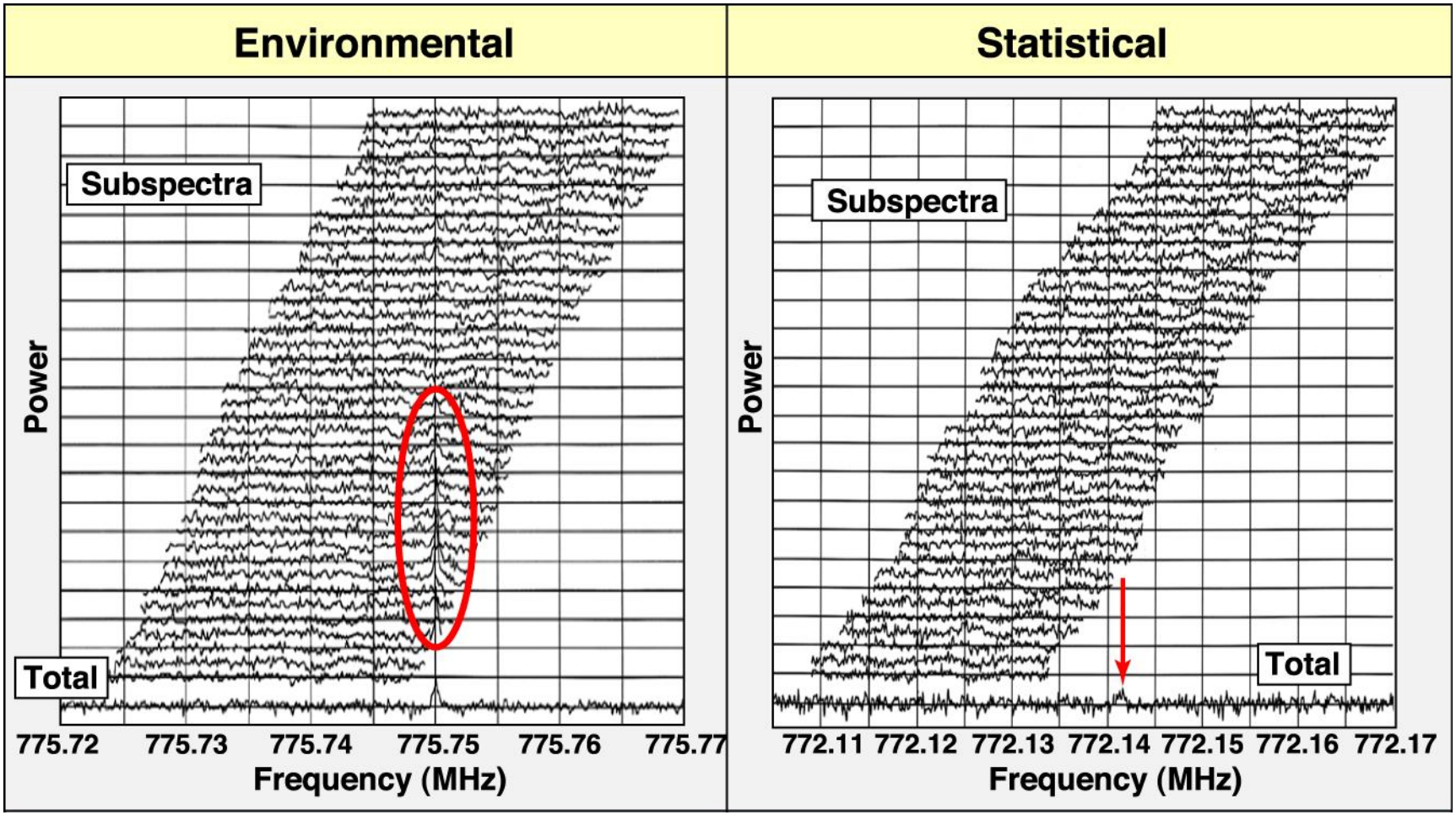


Dicke Radiometer equation:

$$\frac{s}{n} = \frac{P_s}{kT_n}\sqrt{\frac{t}{\Delta\nu}}$$

Systematics-limited for signals of 10^{-26} W – 10^{-3} of DFSZ axion power.
Last signal received from Pioneer 10 (6 billion miles away) ~ 10^{-21} W.

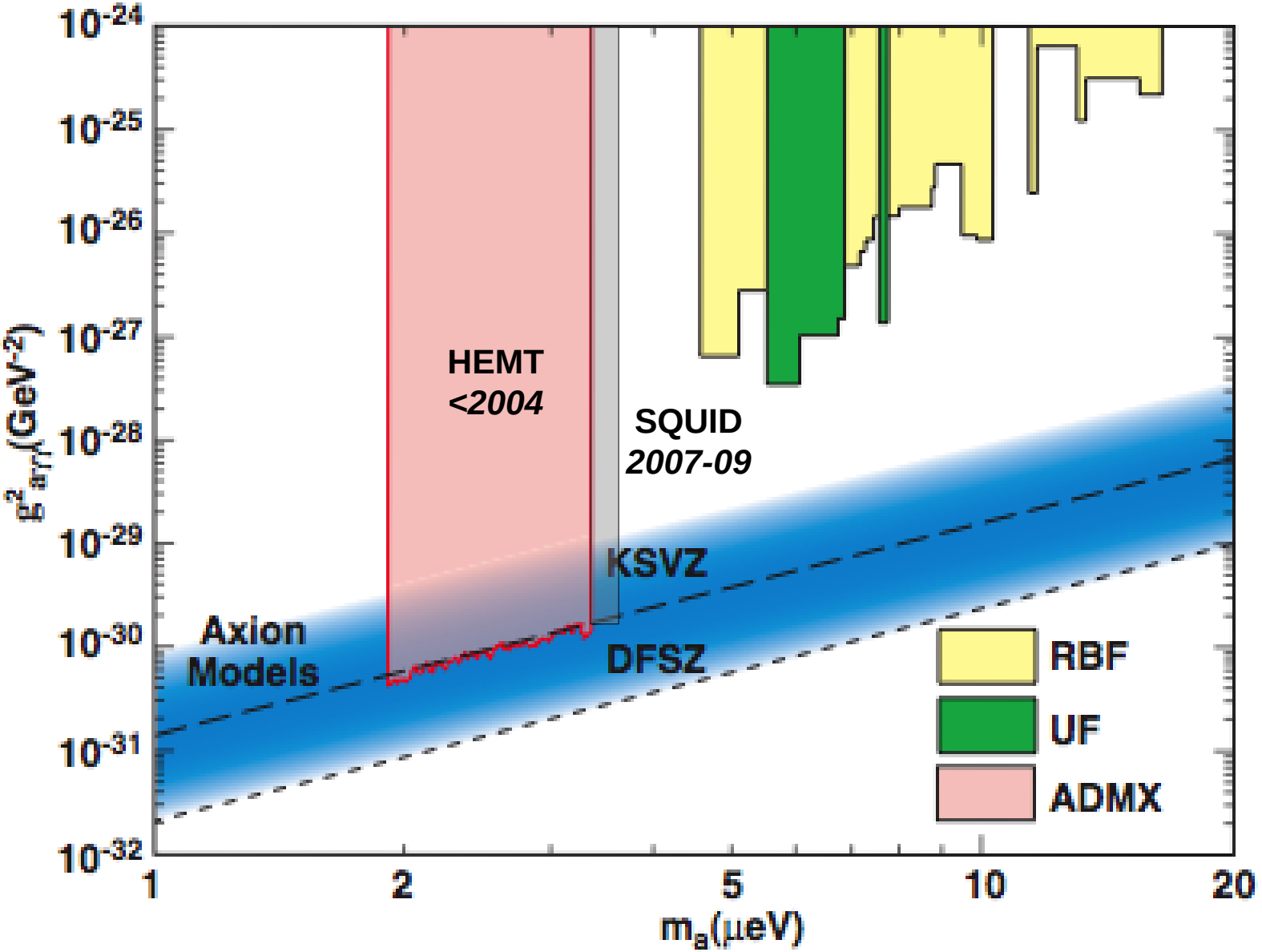
Sample data and candidates



Signal maximizes in the wings, and furthermore is episodic → Radio peak

Distributed over many subspectra (good), but didn't repeat → Statistical peak

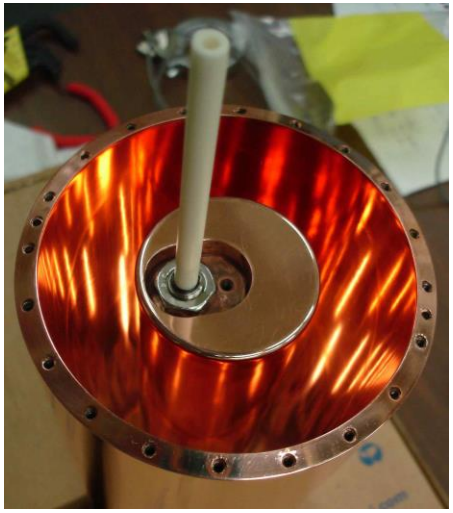
Limits on the axion after twenty years

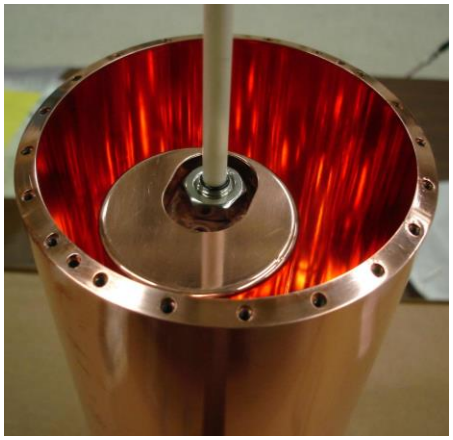


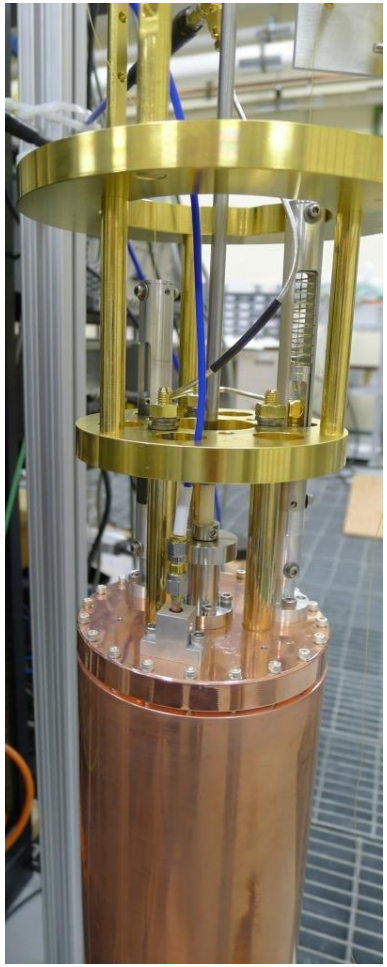

IT DOESN'T MATTER IF THE GLASS
IS HALF FULL OR HALF EMPTY
THERE IS CLEARLY ROOM
FOR MORE ALCOHOL

AXIONS!

ADMX-HF (High Frequency) *Yale-Berkeley-Colorado-LLNL*



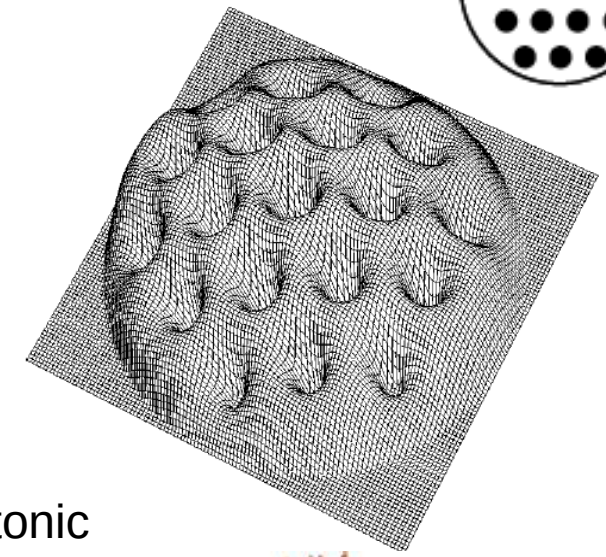


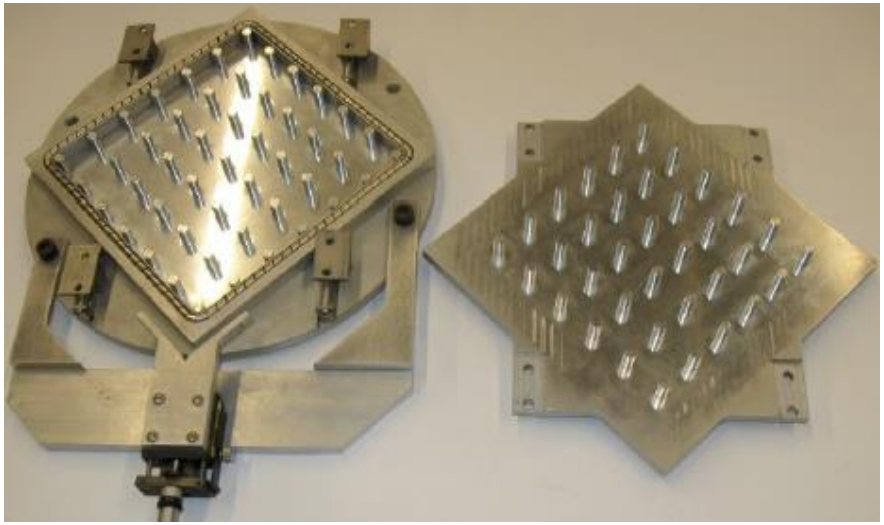


Smaller, Higher-Field, Colder – Aimed at finding the path to higher masses

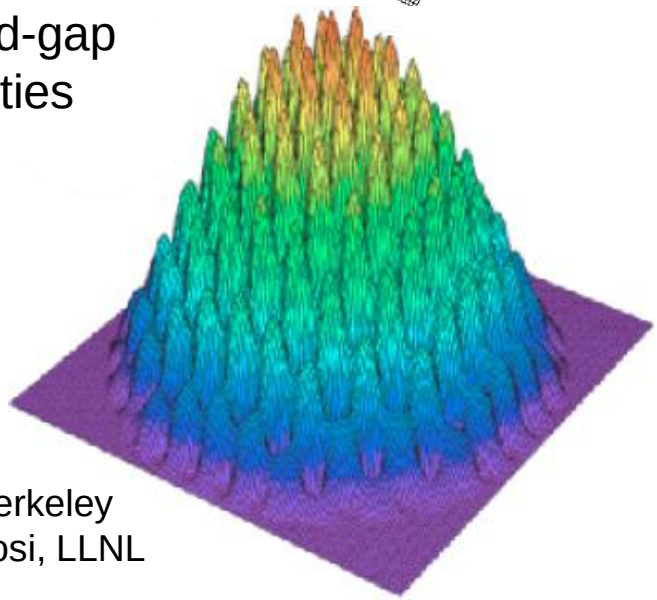
R&D on cavity resonators but which reach much higher frequencies

Ganging multiple cavities together





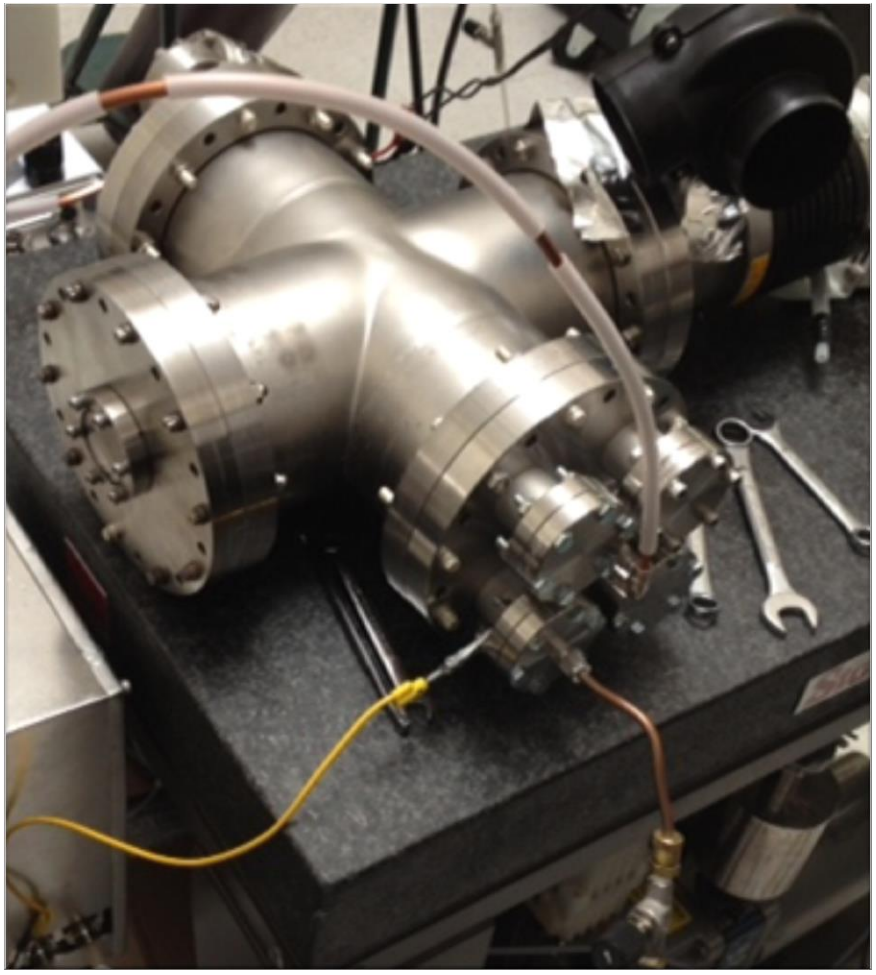
Photonic band-gap cavities

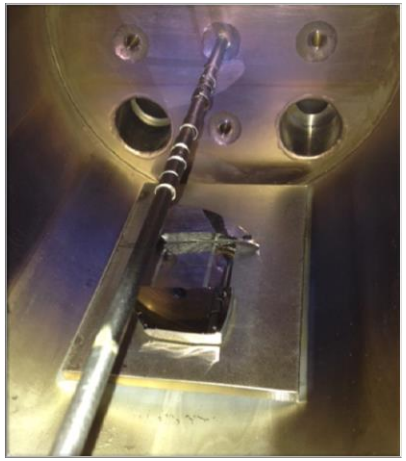


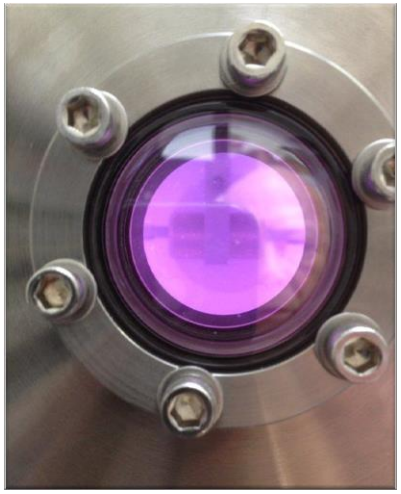
KvB, Berkeley
G. Carosi, LLNL

Can we make microwave cavities of dramatically higher Q?

We are developing cavities with thin film coatings of Type-II superconductors, e.g. $Nb_xTi_{1-x}N$ by RF plasma deposition

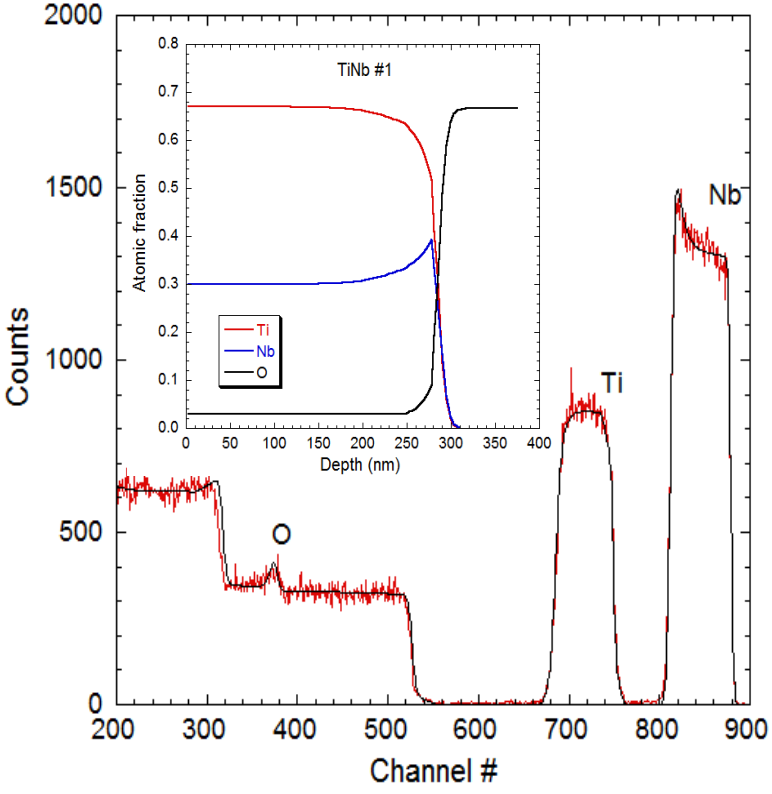


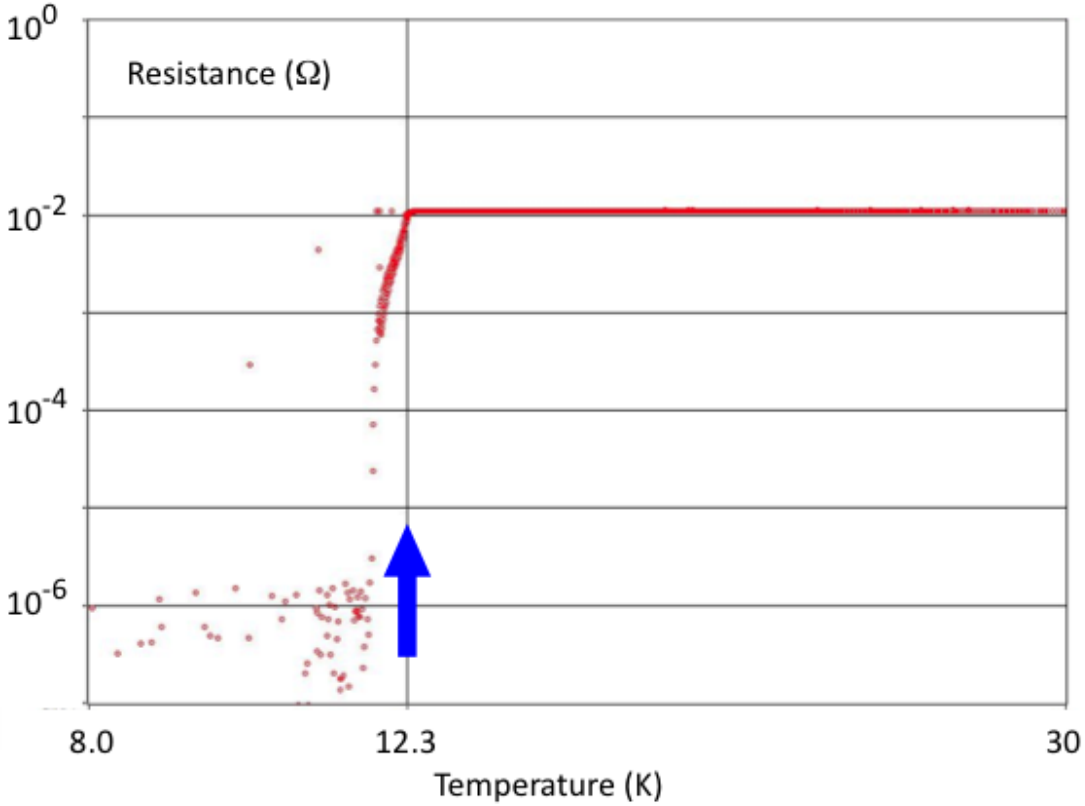




Thin films of the desired stoichiometry, thickness and transition temperature have been successfully made – RF cavity prototype is next

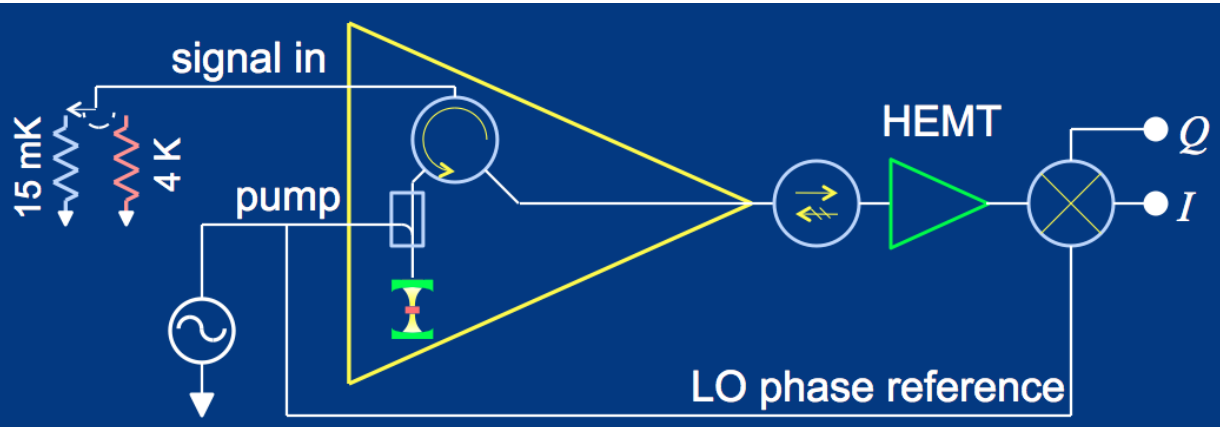
$Nb_{0.30}Ti_{0.67}O_{0.03}$: 280 nm

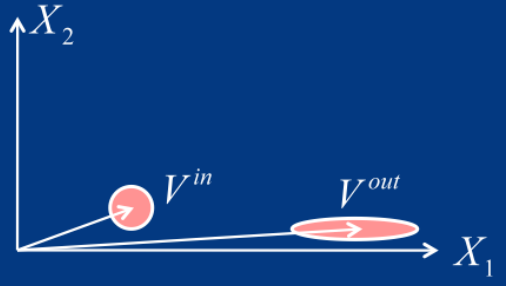




Josephson Parametric Amplifiers (JPA)

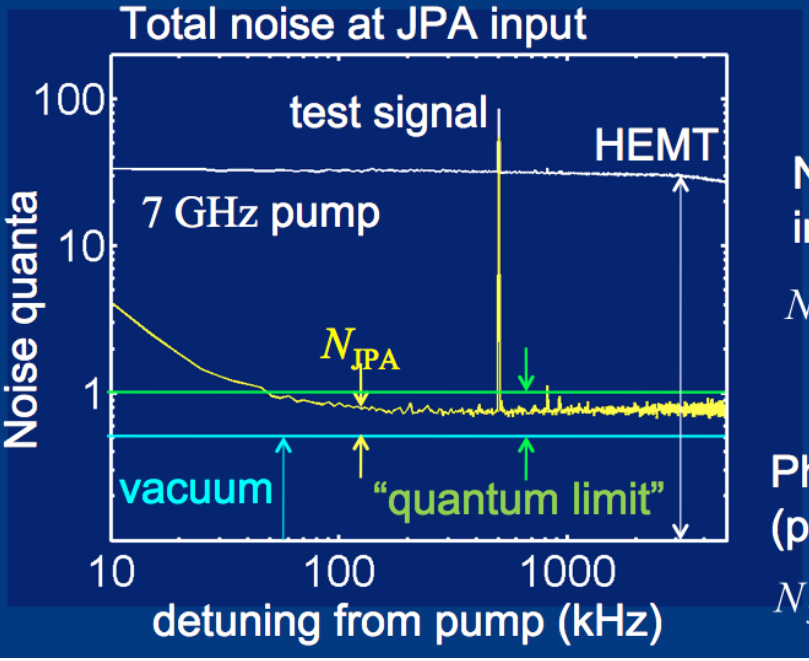
Konrad Lehnert, JILA/CU





$$I \propto X_1 + \text{noise}$$

$$Q \propto X_2 + \text{noise}$$



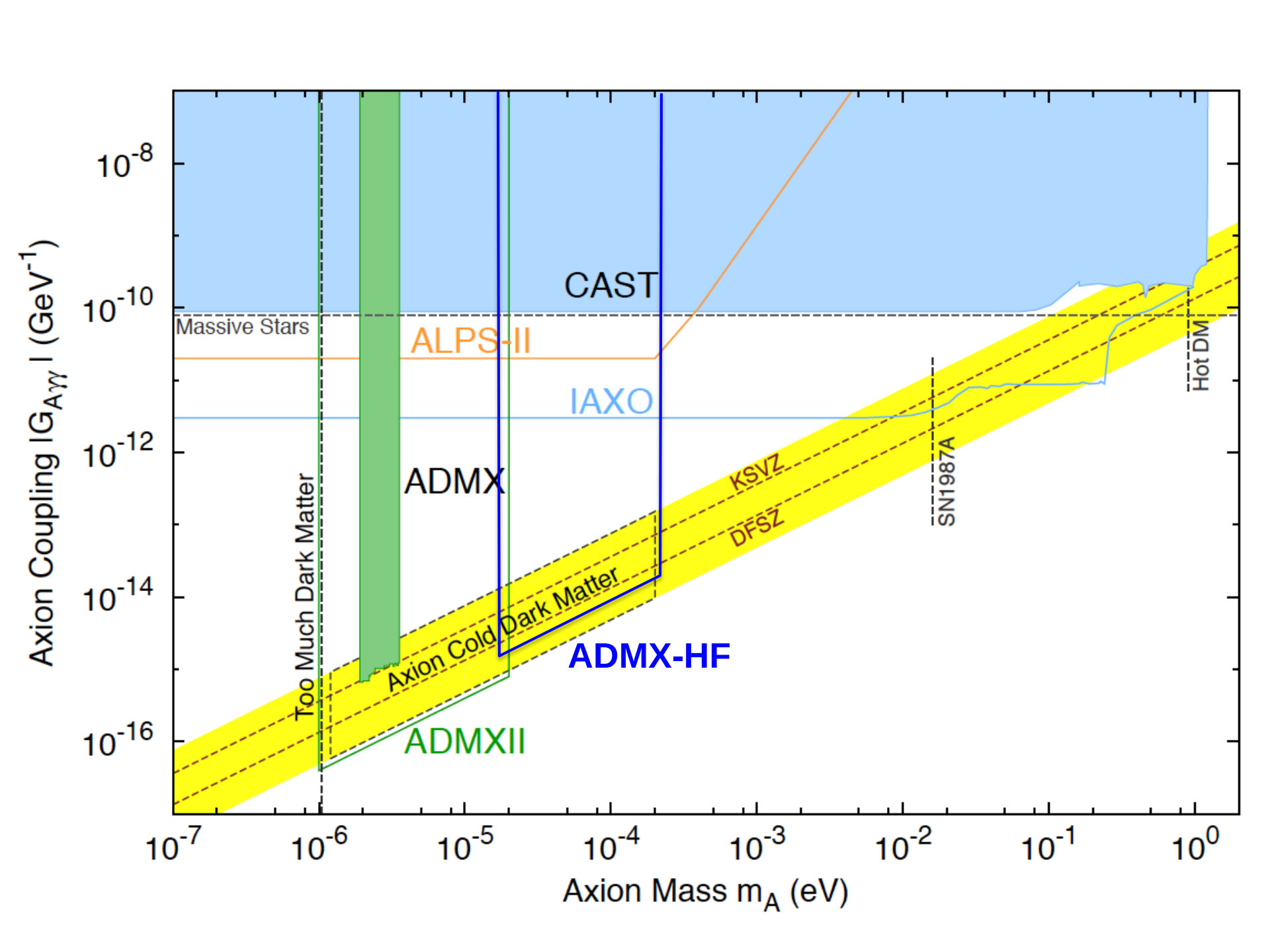
Noise referred to JPA input

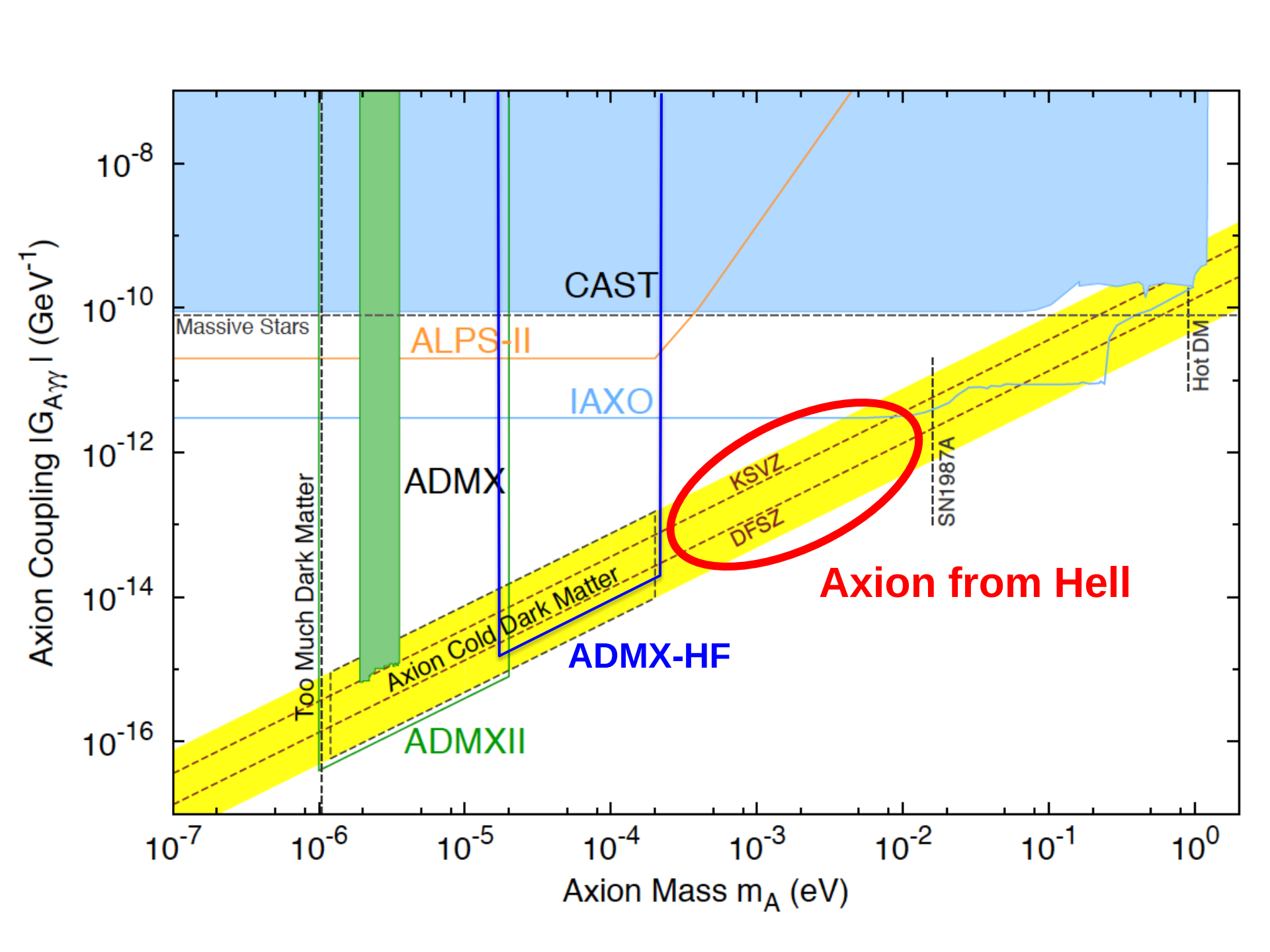
$$N_{\text{tot}} = \frac{1}{2} + N_{\text{JPA}}$$

Phase insensitive amp (phase preserving)

$$N_{\text{JPA}} \geq \frac{1}{2}$$

- Natural for higher frequencies
- Broadly & easily tunable
- Operates at the SQL or below (squeezing)
- ADMX-HF will initially utilize an existing and proven system design
  - 4-8 GHz
  - Quantum-limited T

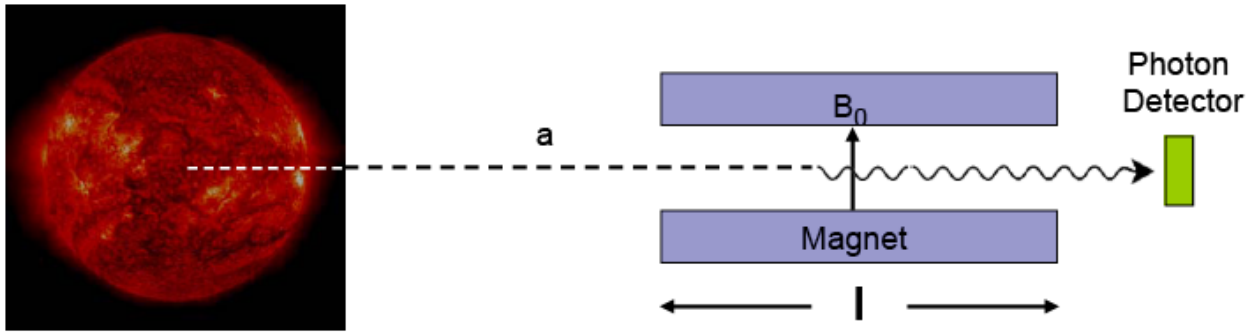

CAST
Massive Stars
ALPS-II
IAXO
ADMX
Too Much Dark Matter
KSVZ
DFSZ
Axion Cold Dark Matter
ADMX-HF
ADMXII
SN1987A
Hot DM
Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass m_A (eV)
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

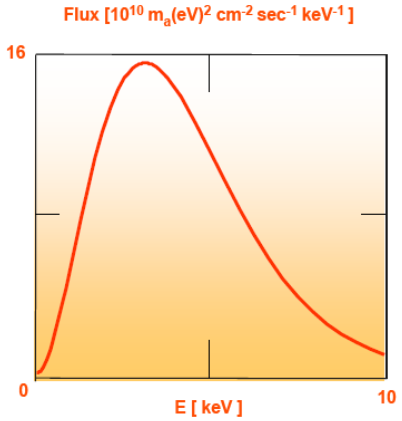

Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
CAST
Massive Stars
ALPS-II
IAXO
ADMX
Too Much Dark Matter
Axion Cold Dark Matter
KSVZ
DFSZ
SN1987A
Hot DM
ADMX-HF
ADMXII
Axion from Hell
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Axion Mass m_A (eV)

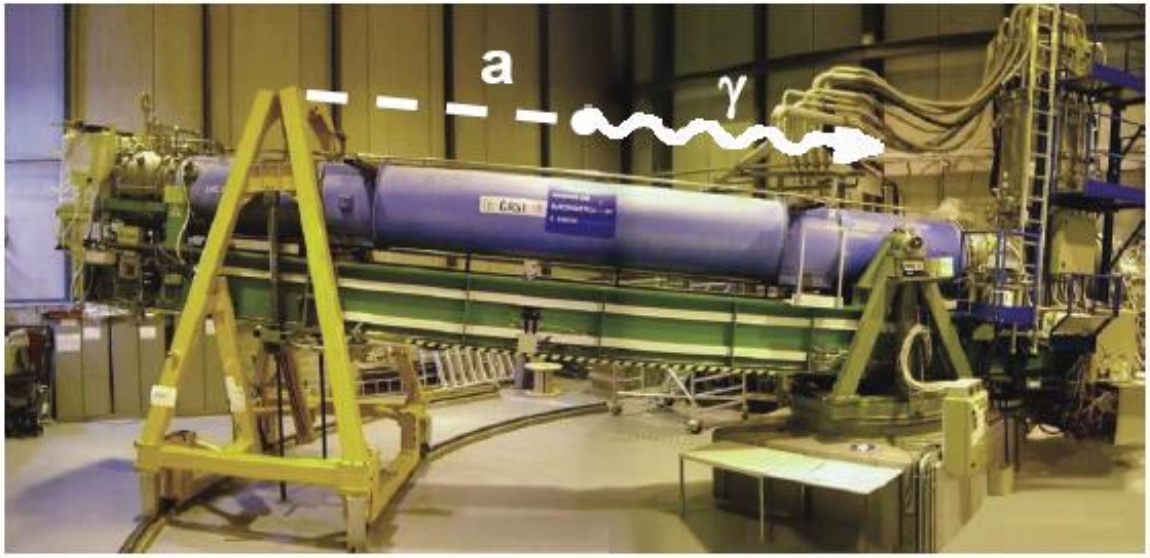
Are there other ways of searching for the axion?

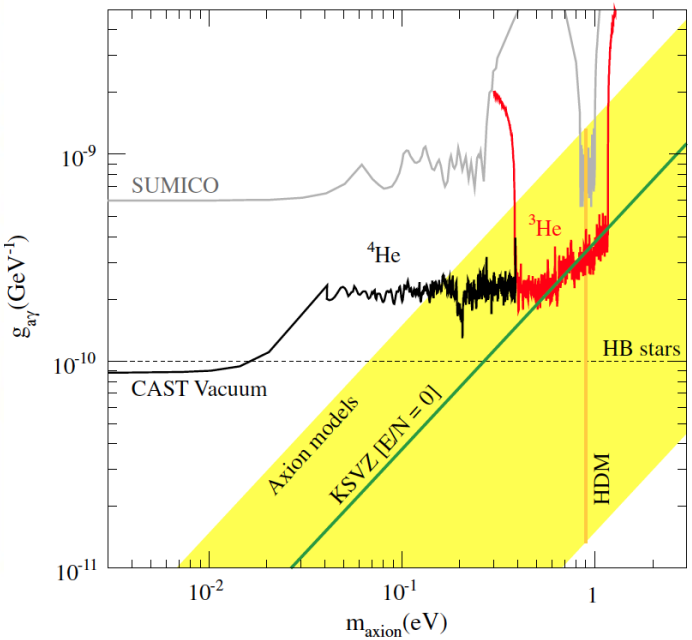
(Yes, but not very good)

Axion Helioscope: The CERN Axion Solar Telescope (CAST)



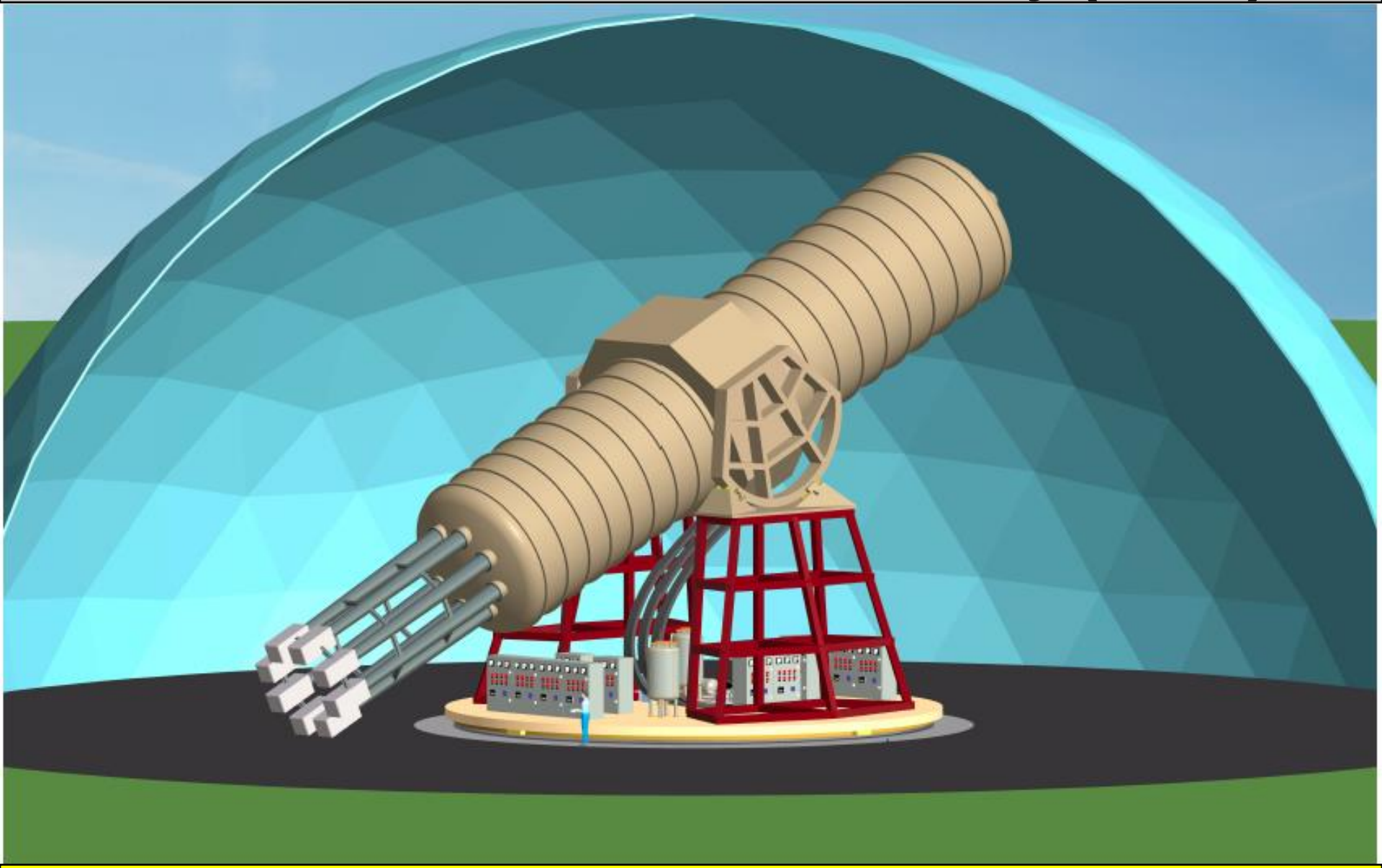






M. Arik et al., PRL 112 (2013) 091302

The International Axion Observatory (IAXO)



E. Armengaud *et al.*, Letter of Intent to the CERN SPC, August 7, 2013

So when are we going to find the axion?

Final remarks

- The discovery of the identity of Dark Matter within a decade is plausible, even probable
- I will (cautiously) predict that ADMX/ADMX-HF will find evidence for a predominantly axionic dark matter halo
- Should the axionic DM be found, it would open up a unique Bose quantum system for study (& axion astronomy?)
- We are always looking for a few wild & crazy students who will follow us
- But *caveat emptor* …

"Problems worthy of attack
Prove their worth by hitting back"
– Piet Hein

The 4% Universe

Dark Matter, Dark Energy & the Race to Discover the Rest of Reality

Harcourt, Houghton & Mifflin, 2010

Richard Panek

(See the chapter "The Curse of the Bambino", about ADMX)