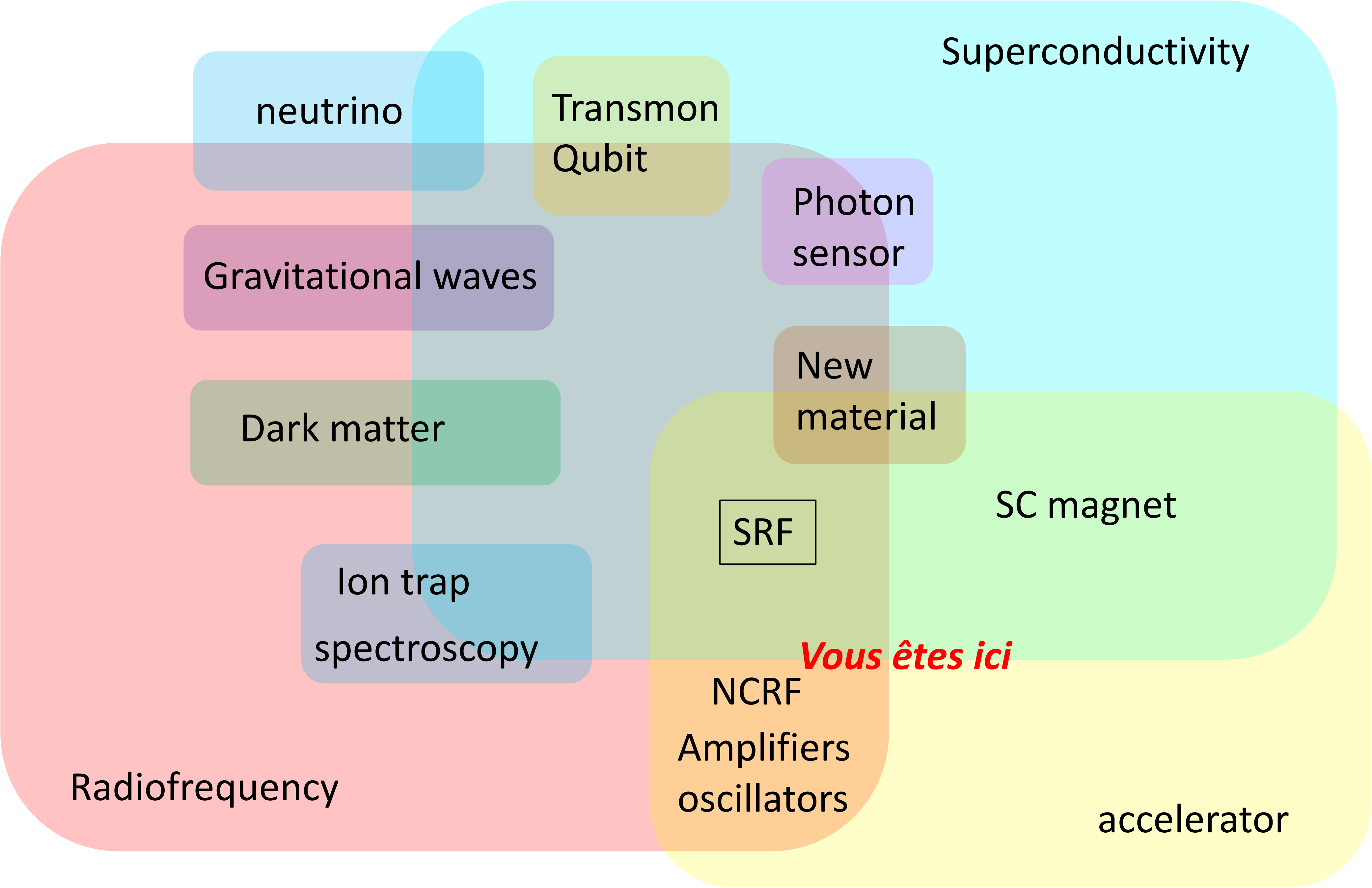
New applications of SRF technology, recent progresses and future capabilities

Akira Miyazaki & David Longuevergne
Séminaire Pôle accélérateurs

Cross the border from accelerators



Superconductivity

neutrino

Transmon Qubit

Photon sensor

Gravitational waves

New material

Dark matter

SC magnet

SRF

Ion trap spectroscopy

Vous êtes ici

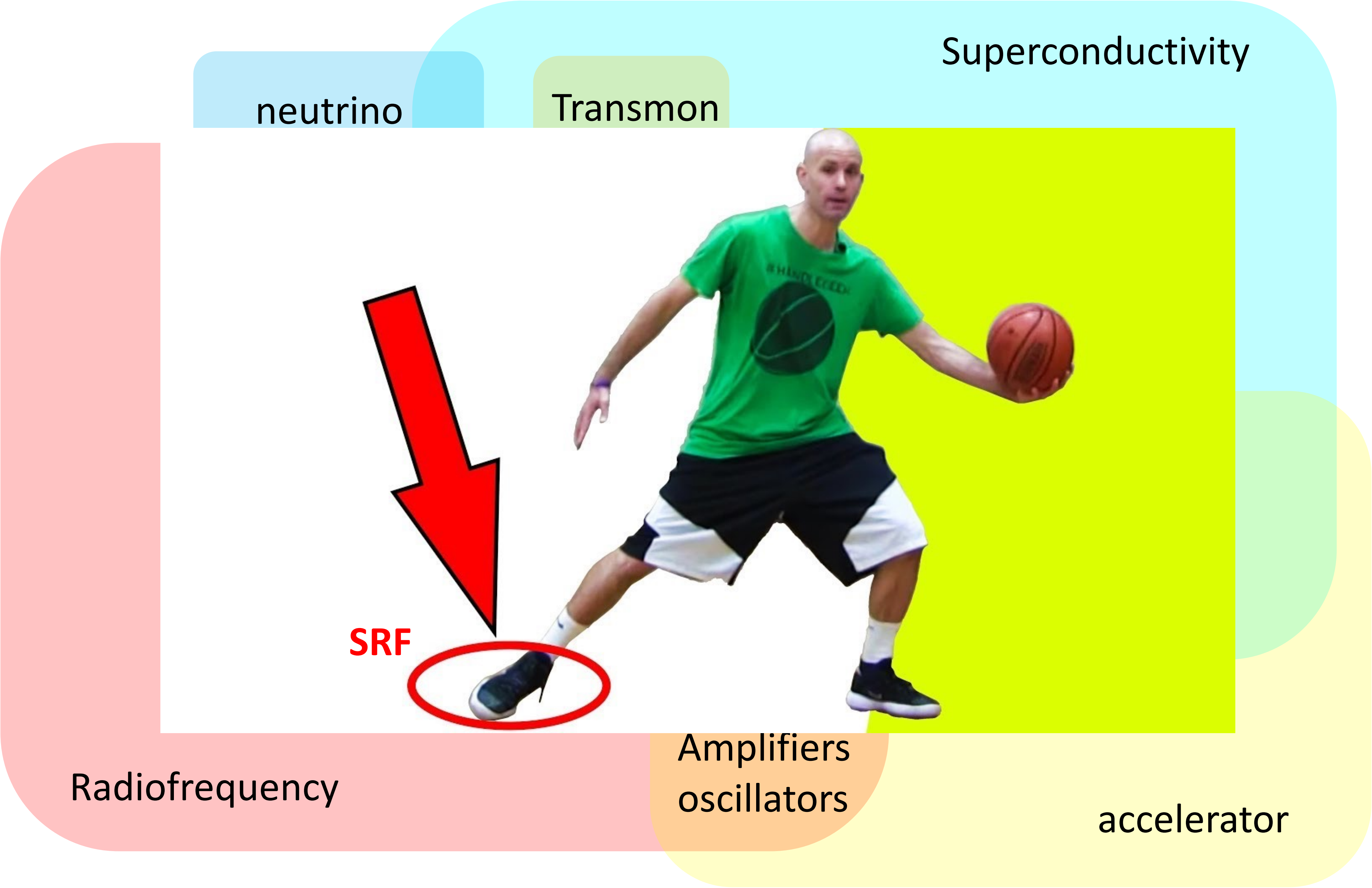
NCRF

Amplifiers

oscillators

Radiofrequency

accelerator



neutrino

Transmon

Superconductivity

SRF

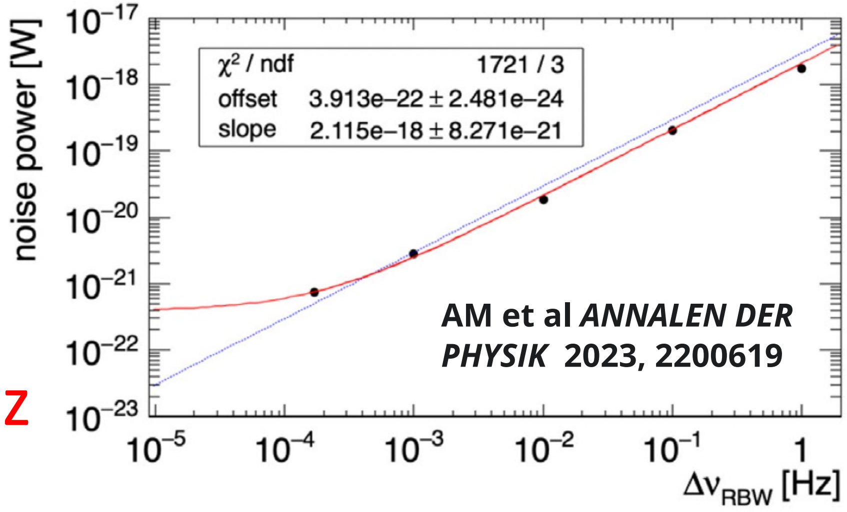
Radiofrequency

Amplifiers
oscillators

accelerator

Outline

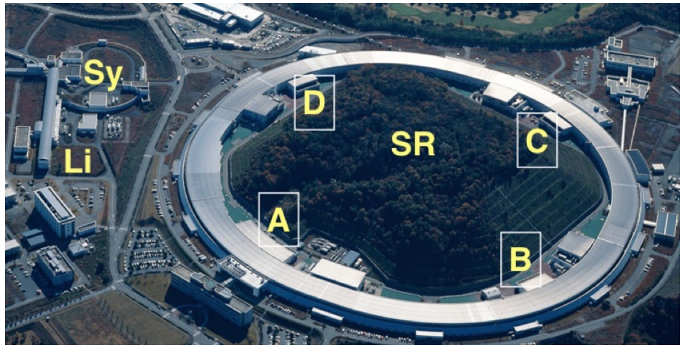
Almost all are my own original studies…only partly published

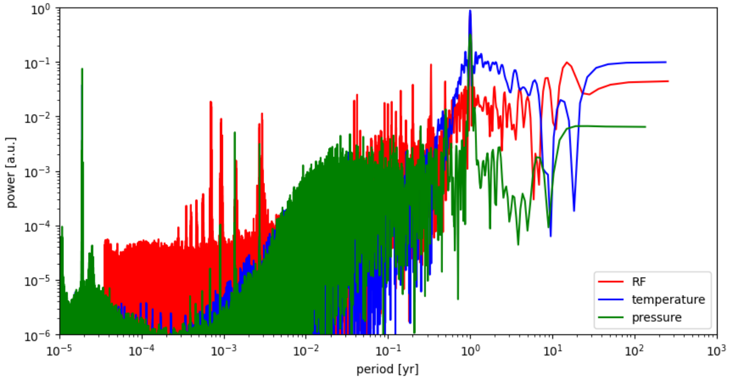


AM et al *ANNALEN DER PHYSIK* 2023, 2200619

- New superconductors for SRF accelerators 1 GHz
- Axion dark matter and dark photons 20-30 GHz
- Gravitational waves: storage ring 500 MHz
- Paul trap (35 MHz) for anti-hydrogen
- Relic neutrino via 28 GHz

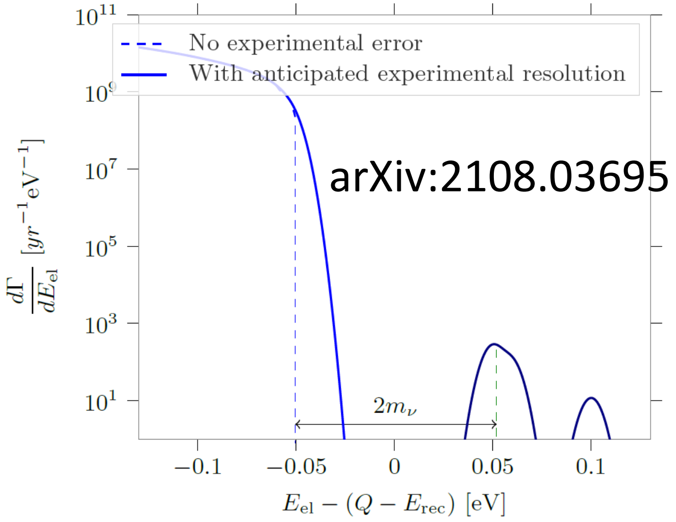
Not covered by this talk





With SPring-8

With Max Planck & CERN



arXiv:2108.03695

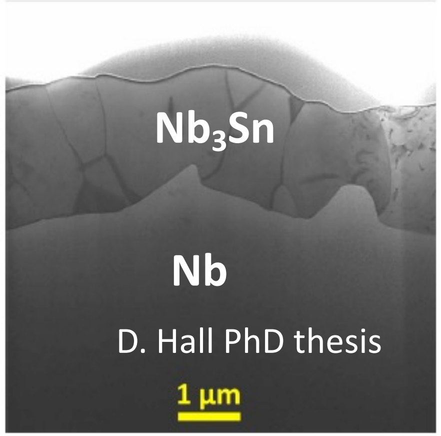
With KIT

Outline

- New superconductors for SRF accelerators
- Axion dark matter
- Gravitational waves

Beyond Nb for sustainability and higher performance

- Niobium material (RRR=300) is getting more and more expensive
  - Over 20 times more expensive than copper
- Nb cavities are typical operated in 2K Liquid helium
  - Crisis in He supply
  - Very expensive cryogenic infrastructure
- On-going researches
  - Nb-coating on copper substrates
  - Nb_3Sn on Nb to be operated at 4K
    - Cryocooler
    - Nb_3Sn on Cu
  - NbTiN, MgB_2, multi-layer, etc…
- Another point: HTS market is growing
  - Magnet, cavity, detector communities
  - Does HTS have any potential for the particle accelerator application?

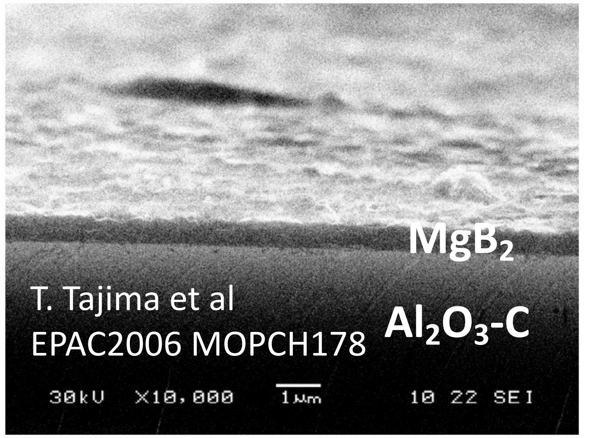


D. Hall PhD thesis

A.-M. Valente-Feliciano et al SRF2013 TUP088

Material	$\lambda(T=0)$ [nm]	$\xi(T=0)$ [nm]	$\mu_0 H_{sh}$ [mT]	T_c [K]	$\Delta/k_B T_c$
Nb	50	22	219	9.2	1.8
Nb_3Sn	111	4.2	425	18	2.2
MgB_2	185	4.9	170	37	0.6-2.1
NbN	375	2.9	214	16	2.2

S. Posen PhD thesis



T. Tajima et al EPAC2006 MOPCH178

Beyond Nb for sustainability and higher performance

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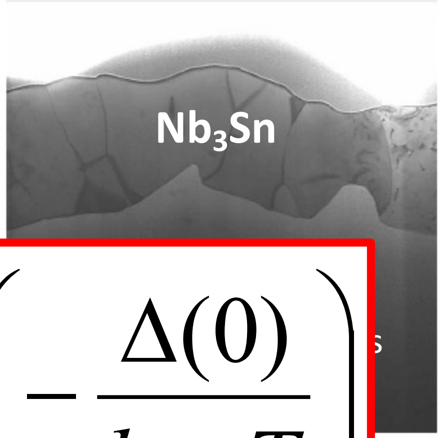
Go beyond

$$R_{BCS} = A(\lambda, \xi, l, v_F) \cdot \frac{\omega^2}{T} \cdot \exp\left(-\frac{\Delta(0)}{k_B \cdot T}\right)$$



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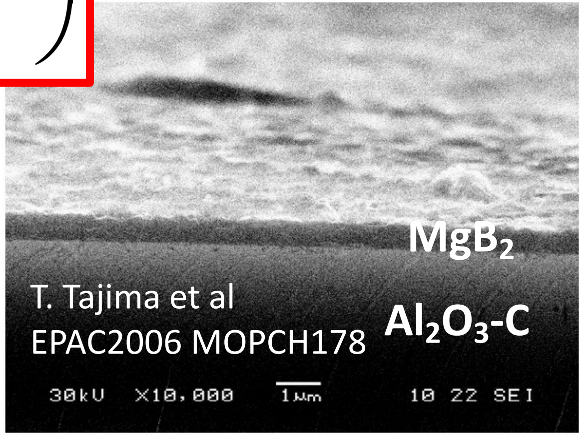
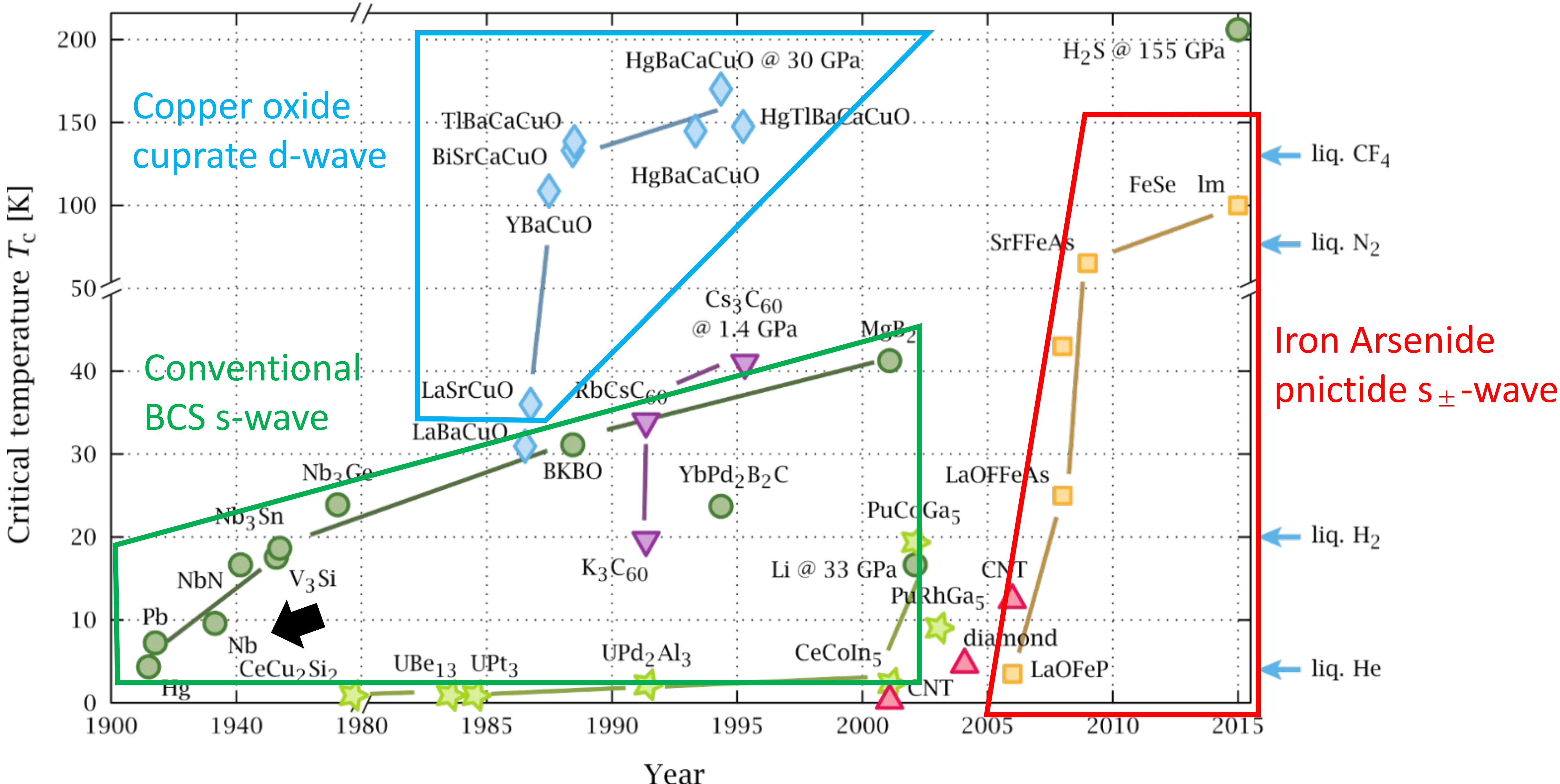


T. Tajima et al EPAC2006 MOPCH178

Three different families of superconductors



Copper oxide
cuprate d-wave

Conventional
BCS s-wave

Iron Arsenide
pnictide $s_{\pm}$-wave

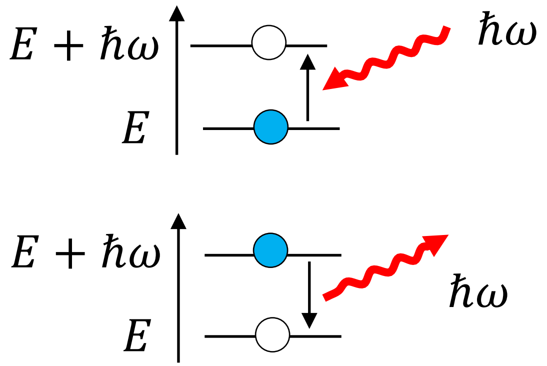
Optical conductivity in the Meissner state

$$\sigma_1 = \frac{2\sigma_n}{\hbar\omega}\int_0^\infty [f(\epsilon) - f(\epsilon+\hbar\omega)][\mathrm{Re}G^R(\epsilon)\mathrm{Re}G^R(\epsilon+\omega) + \mathrm{Re}F^R(\epsilon)\mathrm{Re}F^R(\epsilon+\omega)]d\epsilon$$

S. N. Nam, Phys Rev 156 470 (1967)

$$\sim \frac{2\sigma_n}{\hbar\omega}(1-e^{-\omega/T})\int_0^\infty e^{-\epsilon/kT}N(\epsilon)N(\epsilon+\hbar\omega)d\epsilon$$

J. Halbritter Z. Physik 266 p.209 (1974)



Conventional s-wave (Dynes)

$$\frac{N(\epsilon)}{N_0} = \mathrm{Re}\left(\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta_0^2}}\right)$$

$$\Delta_0(T) = \Delta_0[\cos(\pi T^2/2T_c^2)]^{1/2}$$

Cuprate d-wave

$$\frac{N(\epsilon)}{N_0} = \mathrm{Re}\left(\left\langle\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta^2(\theta)}}\right\rangle\right)$$

$$\Delta(\theta) = \Delta_0\cos 2\theta$$

P. Coleman ”Introduction to Many-Body Physics”

Pnictide s$_\pm$-wave

$$\frac{N(\epsilon)}{N_0} = \mathrm{Re}\left(\left\langle\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta^2_{\alpha_{1,2},\beta_{1,2}}(\phi_{1,2})}}\right\rangle\right)$$

$$\Delta_{\alpha_{1,2},\beta_{1,2}}(\phi_{1,2}) = \Delta_0\Phi_{\alpha_{1,2},\beta_{1,2}}$$

$$\Phi_{\alpha_{1,2}} = -\Phi_a$$

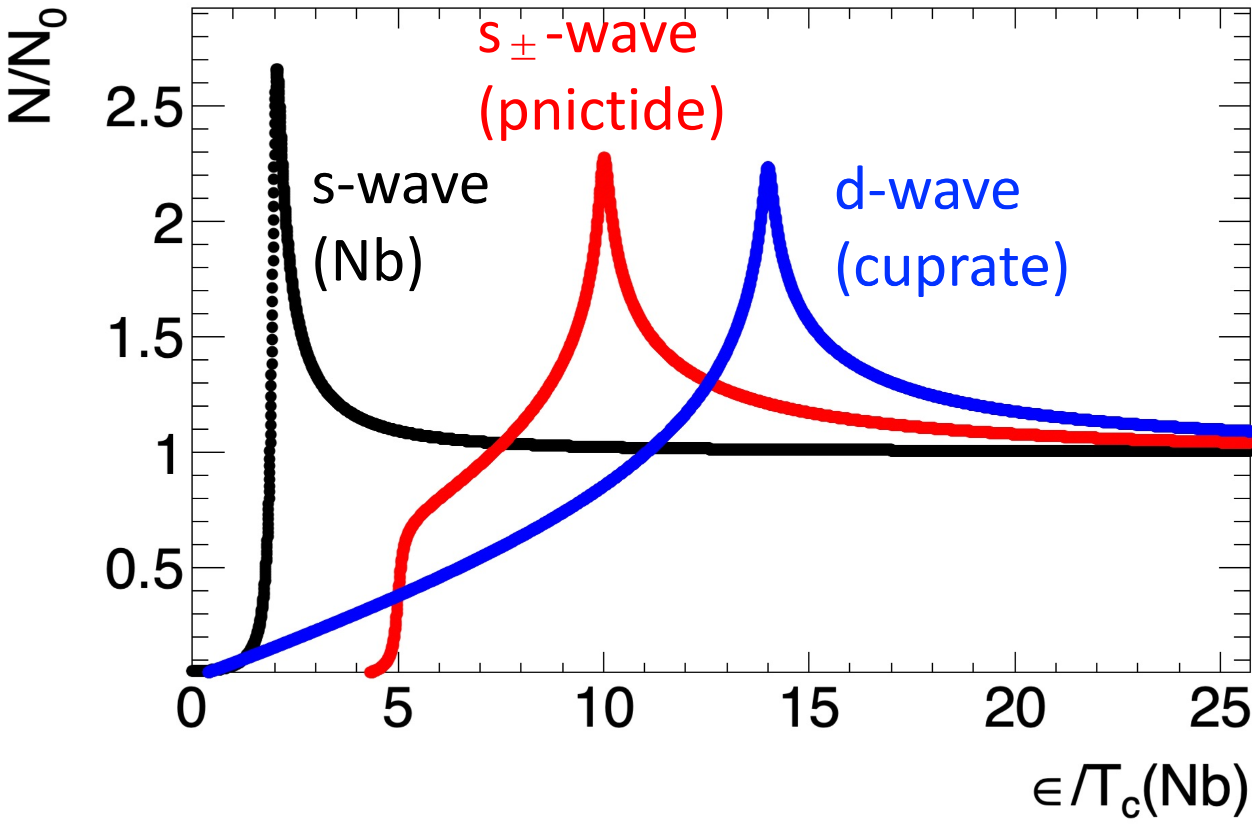
$$\Phi_{\beta_{1,2}} = \frac{1+\Phi_{\beta_{min}}}{2} \pm \frac{(1-\Phi_{\beta_{min}})}{2}\cos(2\phi_{1,2})$$

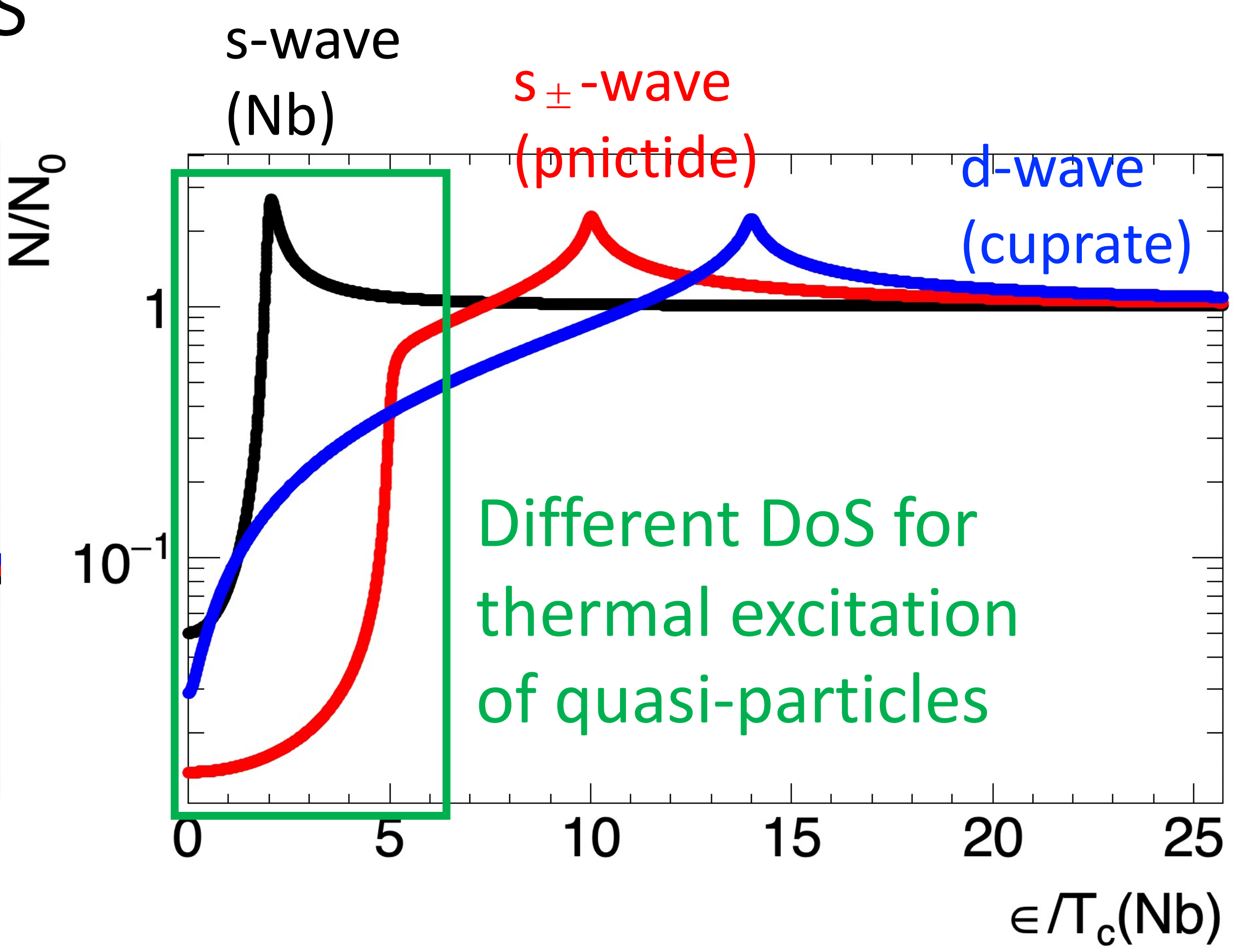
Y. Nagai et al New J. Phys. 10 103026 (2008)

Objectives

- Compare the RF loss by thermally excited quasiparticles in the Meissner state for these three families
- Can HTS be useful?

Result: density of states





Different DoS for thermal excitation of quasi-particles

The energy is normalized to $T_c(\mathrm{Nb}) = 9.25\ \mathrm{K}$

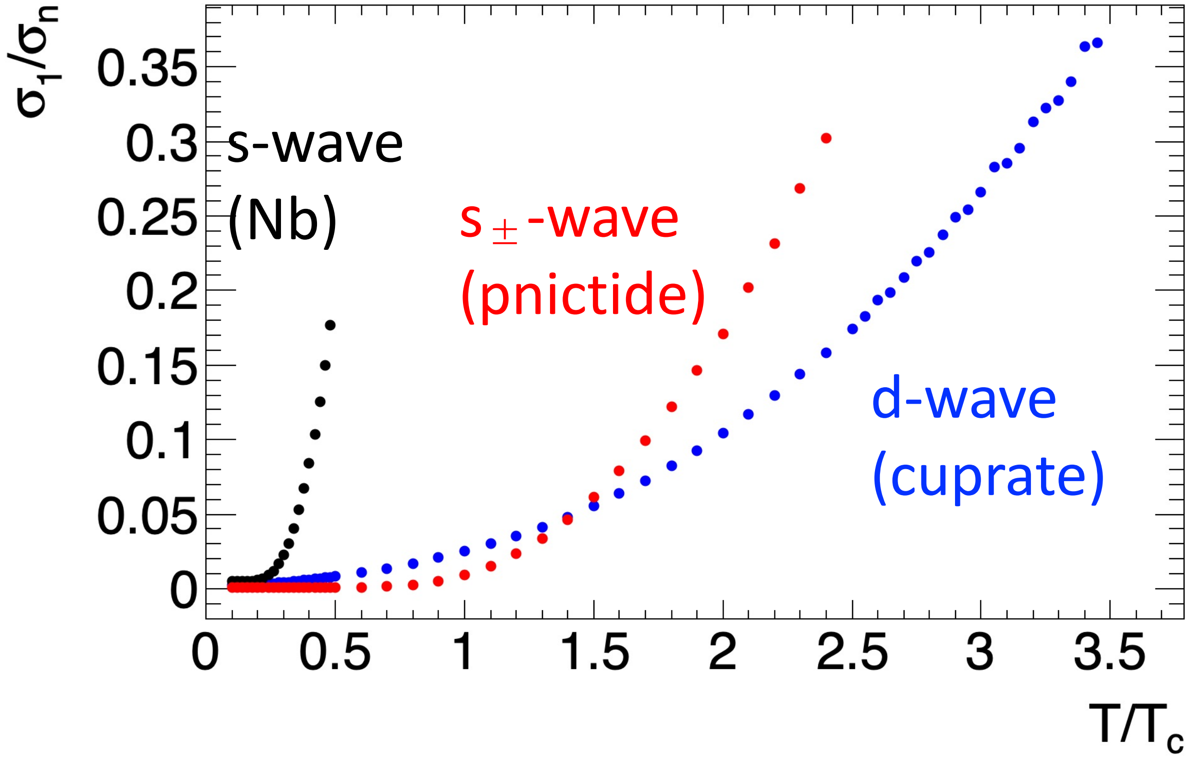
<u>Assumed parameters:</u>

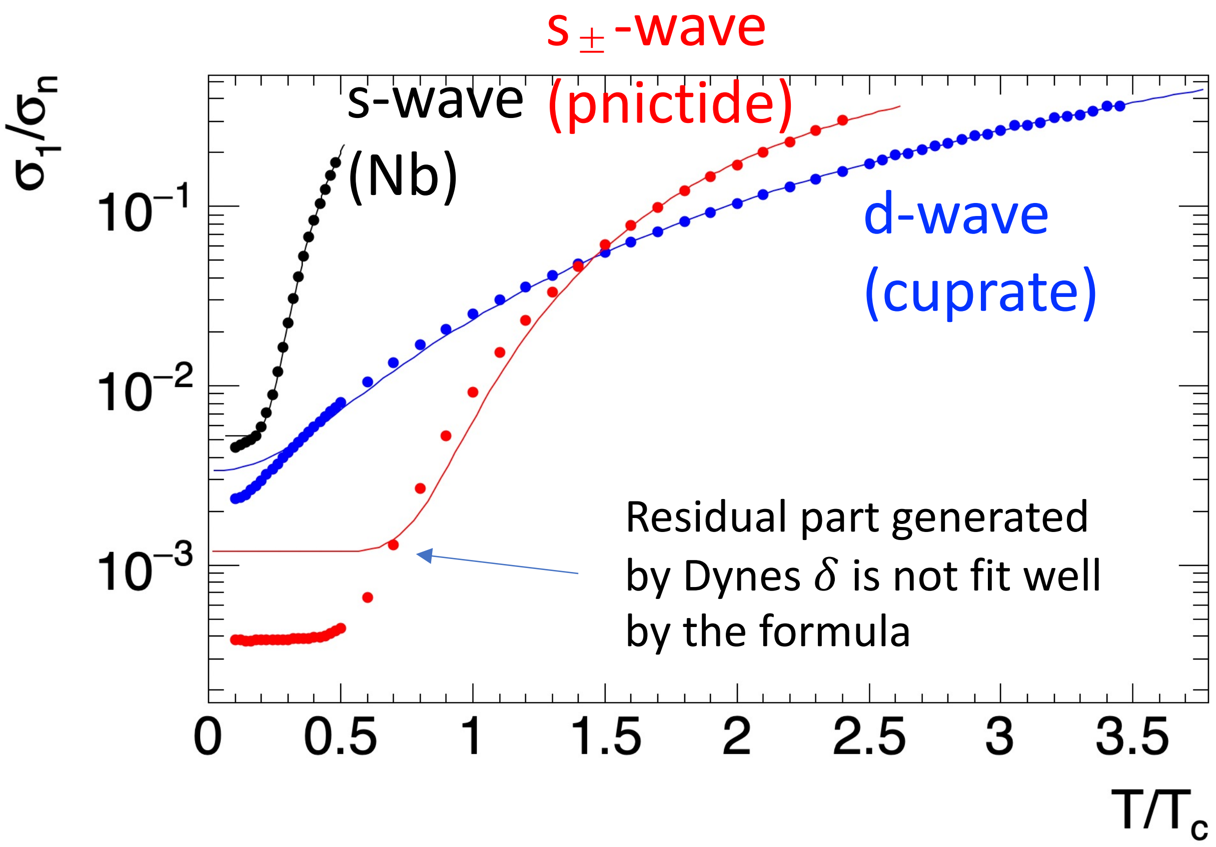
$T_c(\mathrm{pnictide}) = 5\times T_c(\mathrm{Nb})$
$T_c(\mathrm{cuprate}) = 7\times T_c(\mathrm{Nb})$
$\Delta_0 = 2\times T_c$

$\Phi_a = 1$
$\Phi_{\beta_{min}} = 0.5$
$\delta = 0.1$

$$\frac{\sigma_1}{\sigma_n} \sim \frac{2\sigma_n}{\hbar\omega}\left(1 - e^{-\omega/T}\right)\int_0^\infty e^{-\epsilon/kT} N(\epsilon)N(\epsilon+\hbar\omega)d\epsilon$$

σ_1 vs T: an example ($\omega = 0.02$~900 MHz)





Residual part generated by Dynes δ is not fit well by the formula

Best fitting functions

gap-full: $\frac{\sigma_1(T)}{\sigma_n} = \frac{A}{T}\exp\left(-\frac{\Delta}{T}\right) + B$

Gapless: $\frac{\sigma_1(T)}{\sigma_n} = CT^{\alpha} + B$

	Nb	pnictide
A	8.67 ± 0.23	23.8 ± 0.81
Δ	2.24 ± 0.01	8.43 ± 0.07
B	0.0052 ± 0.0003	0.0012 ± 0.0005

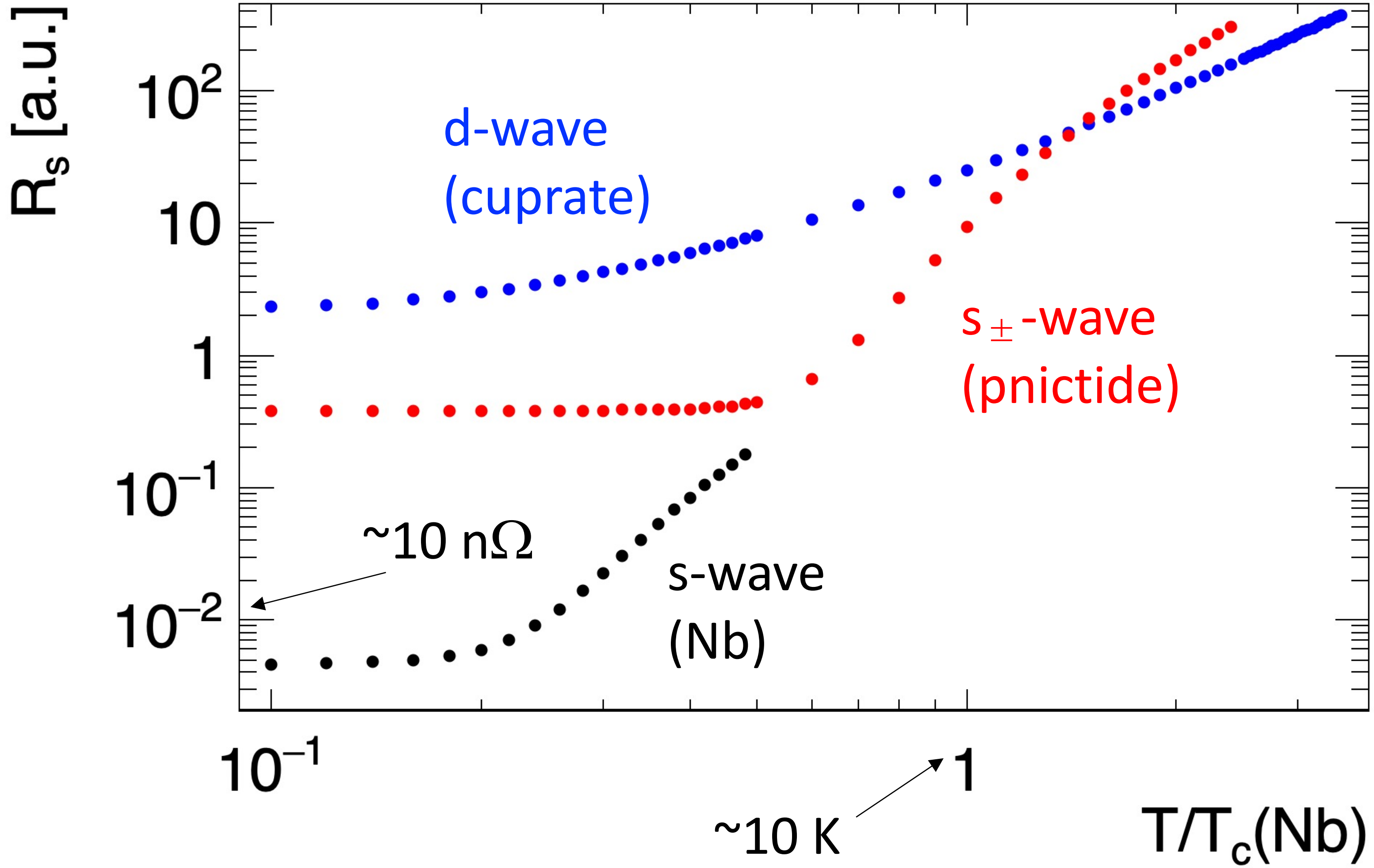
	cuprate
C	0.0201 ± 0.0003
α	2.341 ± 0.015
B	0.0034 ± 0.00044

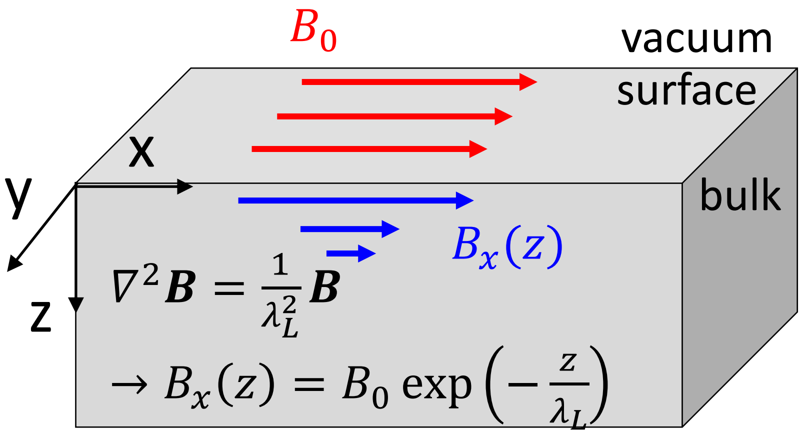
Surface resistance

$$Z_s = \sqrt{\frac{i\omega\mu_0}{\sigma_1 - i\sigma_2}} \xrightarrow{T\ll T_c,\,\sigma_1\ll\sigma_2} \sqrt{\frac{\mu_0}{\omega\sigma_2^3}}\left(\frac{1}{2}\sigma_1 + i\sigma_2\right) \to R_s = \mathrm{Re}(Z_s) = \frac{\mu_0\omega^2\lambda^3}{2}\sigma_1(T)$$

The penetration depth is factor 10 longer in HTS than Nb

→ RF field looks more materials → more loss





$$\nabla^2 \boldsymbol{B} = \frac{1}{\lambda_L^2}\boldsymbol{B}$$

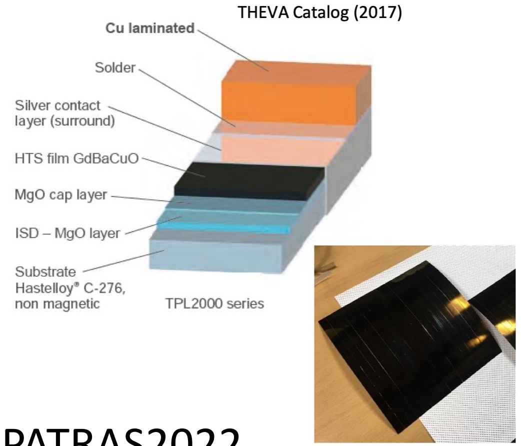
$$\to B_x(z) = B_0 \exp\left(-\frac{z}{\lambda_L}\right)$$

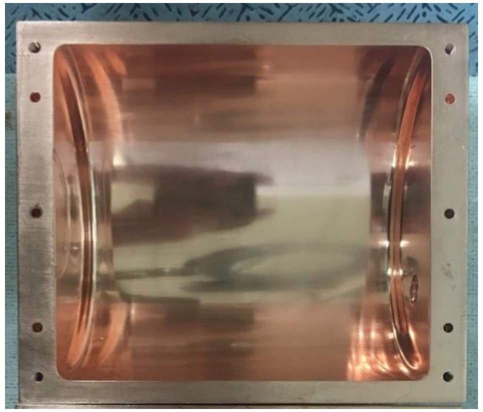
	λ_L [nm]
Nb	>36
pnictide	200-400
cuprate	130-170 / 500-850

There may be operational point in high T & shorter RF pulse

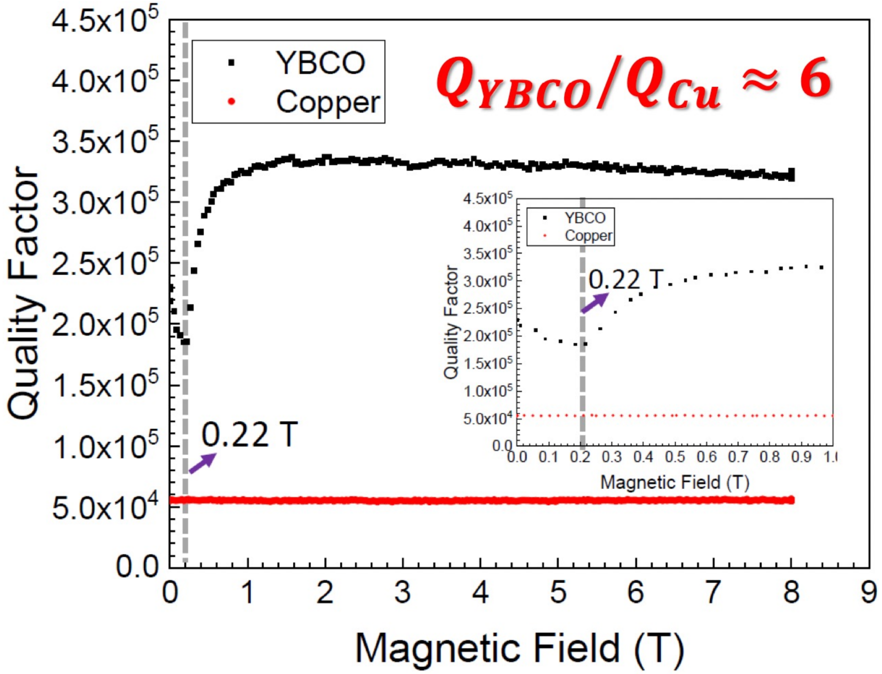
Cuprate SRF cavities for high-Q **under B** have been realized

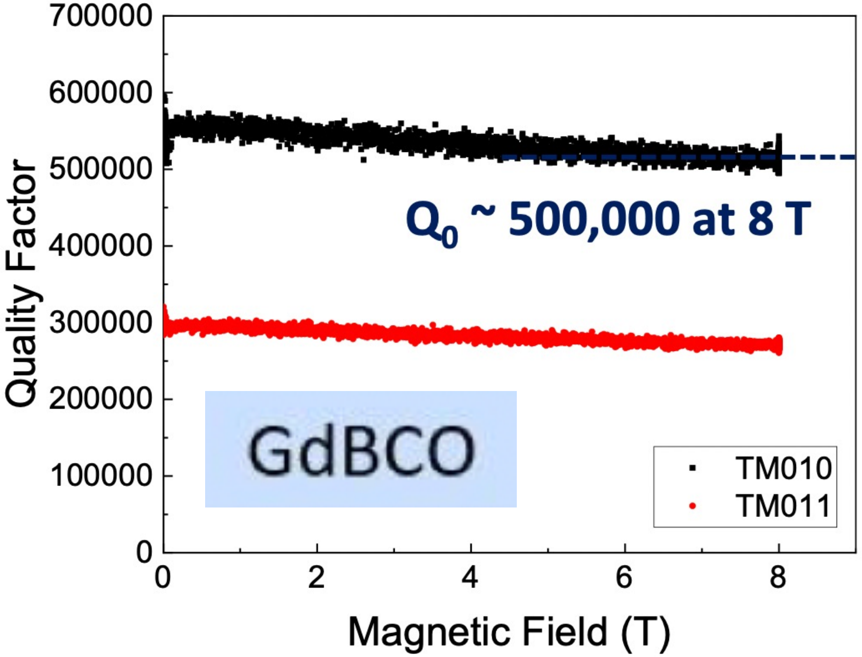
cuprate tapes on copper cavities

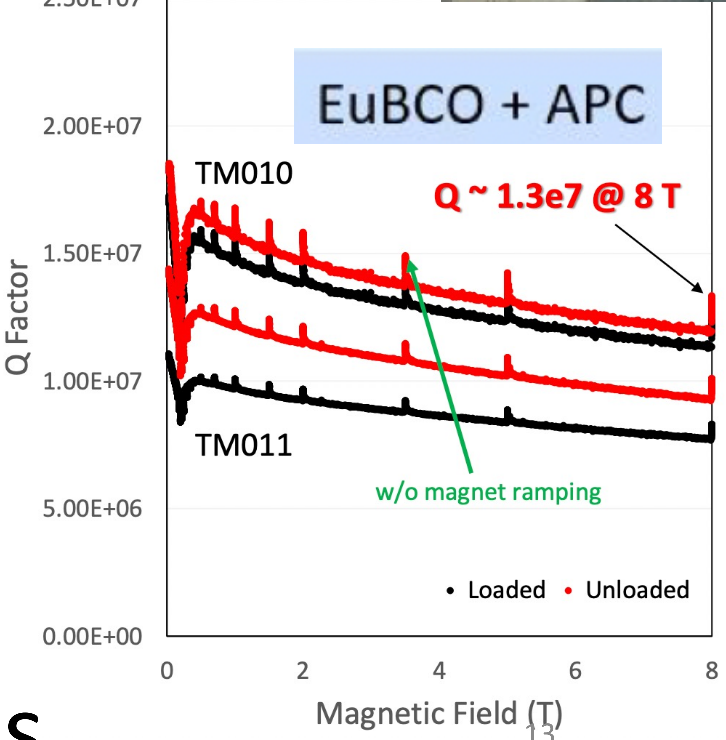




Danho Ahn PATRAS2022







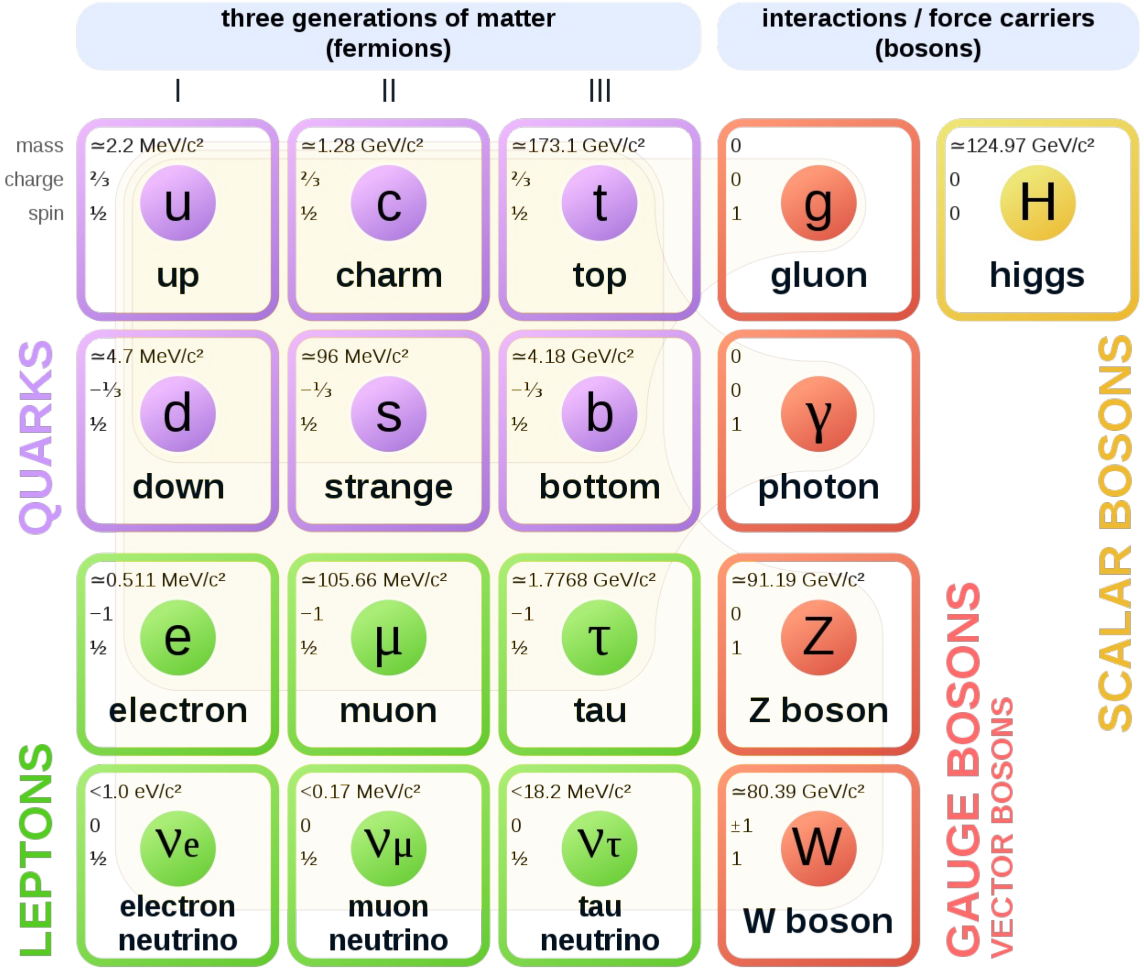
→ For dark matter experiments

Outline

- New superconductors for SRF accelerators
- Axion dark matter
- Gravitational waves

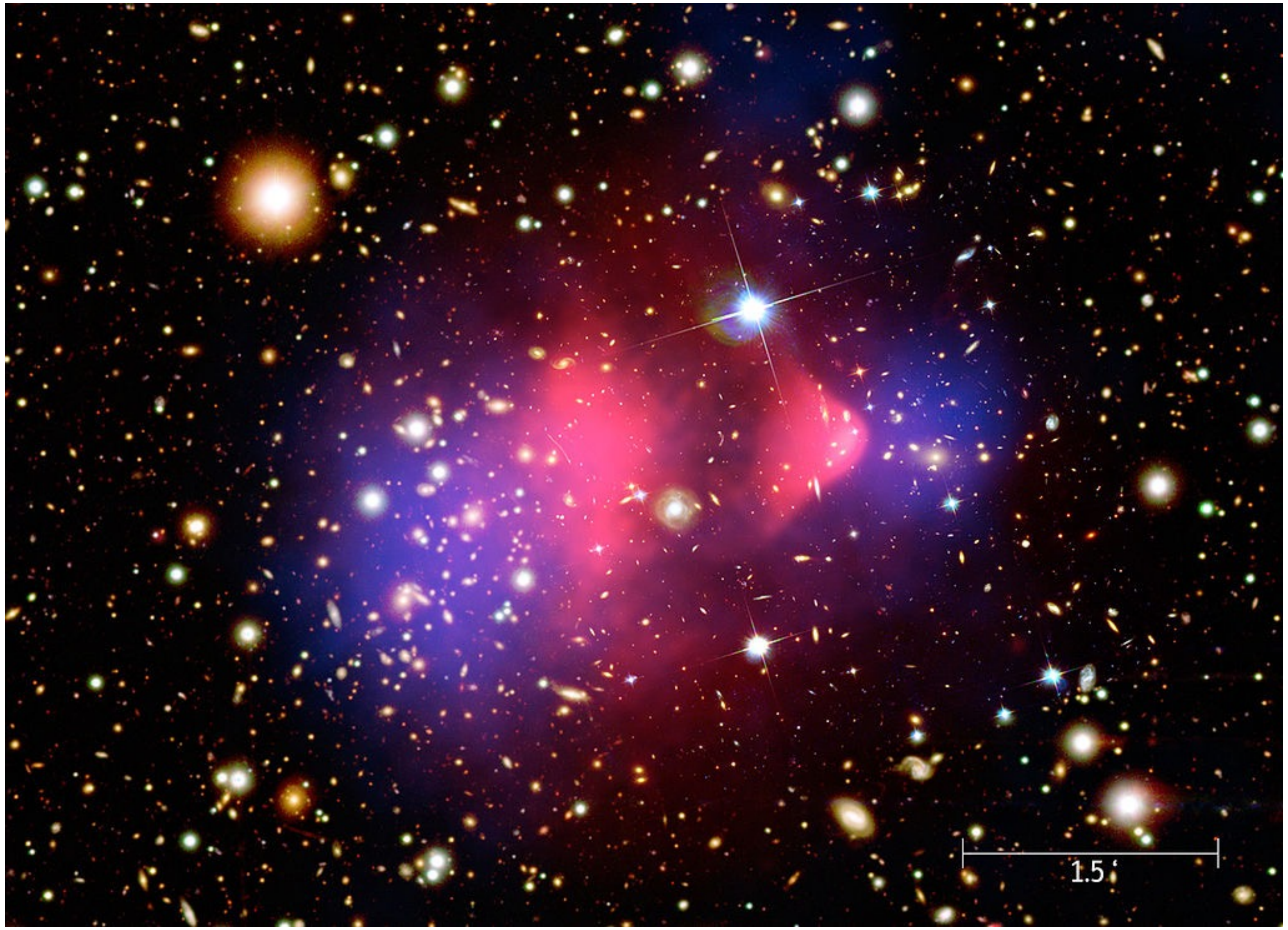
The Standard Model does not contain dark matter

Standard Model of Elementary Particles



mass charge spin	three generations of matter (fermions) I	 II	 III	interactions / force carriers (bosons)	
QUARKS	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson GAUGE BOSONS VECTOR BOSONS	

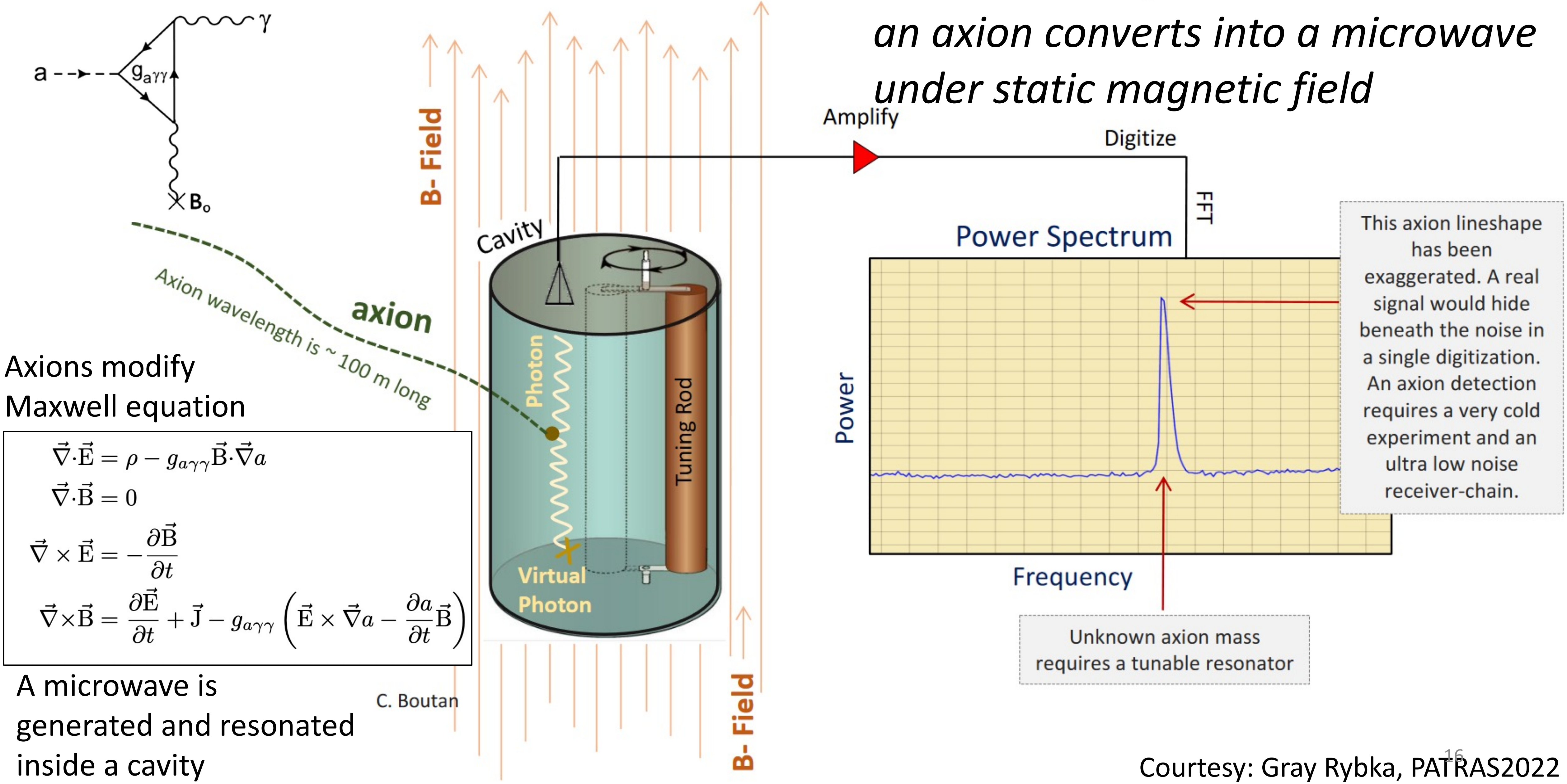
Dark matter evidence from astrophysics



Maybe something new to add to SM? → axions

Classical microwave is the mean to hunt axions

an axion converts into a microwave under static magnetic field



This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

Axions modify Maxwell equation

$$\vec{\nabla}\cdot\vec{\mathrm{E}} = \rho - g_{a\gamma\gamma}\vec{\mathrm{B}}\cdot\vec{\nabla}a$$

$$\vec{\nabla}\cdot\vec{\mathrm{B}} = 0$$

$$\vec{\nabla}\times\vec{\mathrm{E}} = -\frac{\partial\vec{\mathrm{B}}}{\partial t}$$

$$\vec{\nabla}\times\vec{\mathrm{B}} = \frac{\partial\vec{\mathrm{E}}}{\partial t} + \vec{\mathrm{J}} - g_{a\gamma\gamma}\left(\vec{\mathrm{E}}\times\vec{\nabla}a - \frac{\partial a}{\partial t}\vec{\mathrm{B}}\right)$$

A microwave is generated and resonated inside a cavity

C. Boutan

Courtesy: Gray Rybka, PATRAS2022

Axion Dark Matter eXperiment (ADMX)

Signal to Noise Ratio is the key for discovery

- Signal is a narrow peak ($f/\Delta f \sim 10^6$) from axion

$$P_S = (1.0\times10^{-22}\ \mathrm{W}) \times \left(\frac{V}{136\mathrm{L}}\right)\left(\frac{B}{6.8\mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g}{0.97}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{\mathrm{Q}}{50000}\right)$$

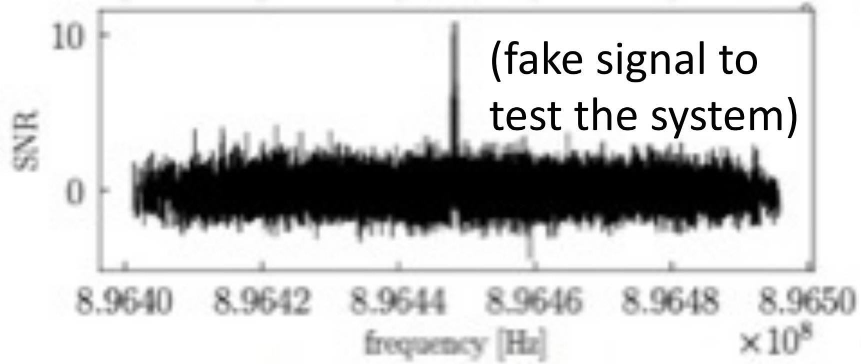
- Noise power spectral density

$$Q_N = \frac{h\nu}{e^{h\nu/k_BT}-1} + h\nu \underset{h\nu \ll k_BT_s}{\sim} k_BT_S = 1.4\times10^{-23}\left(\frac{T_S}{1\mathrm{K}}\right)\ \mathrm{W/Hz}$$

- Signal to noise ratio

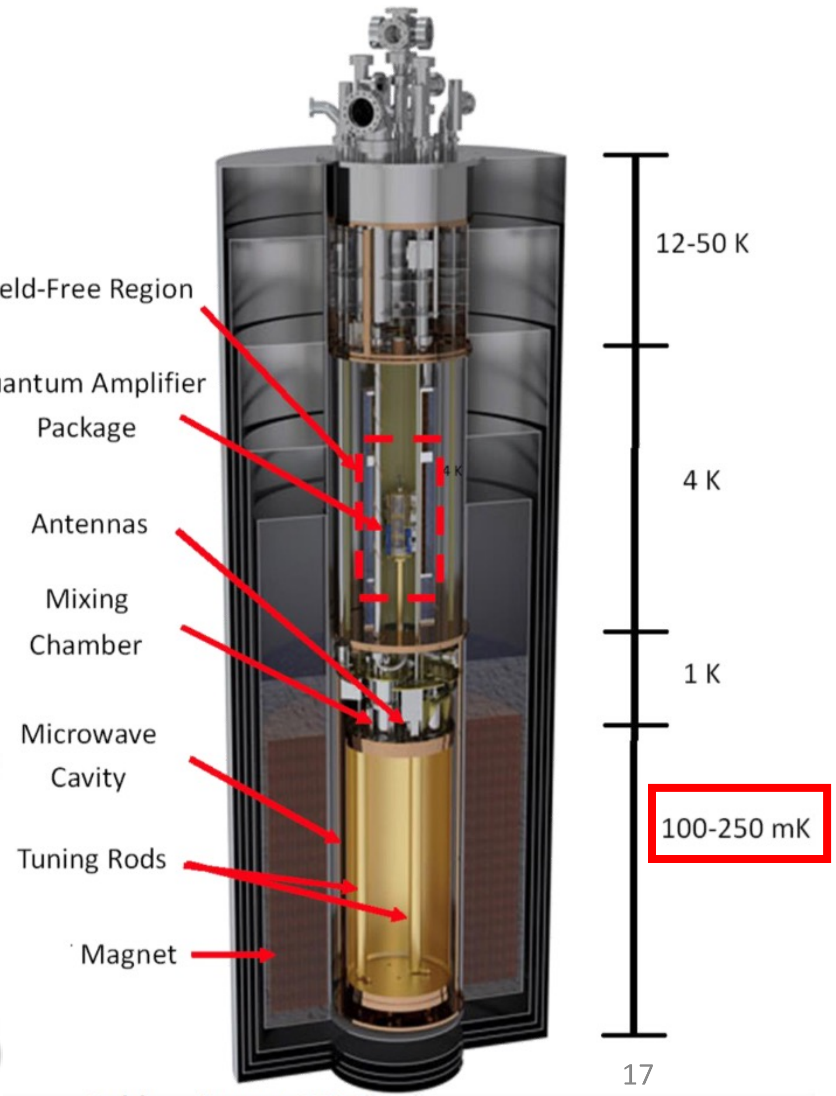
$$S/_N = \frac{P_s}{Q_N}\sqrt{\frac{t}{\Delta f}}$$

No discovery yet…



(fake signal to test the system)

arXiv:2010.00169



How to improve the sensitivity?

More signal

$$P_S = (1.0\times10^{-22}\ \mathrm{W})\times\left(\frac{V}{136\mathrm{L}}\right)\boxed{\left(\frac{B}{6.8\mathrm{T}}\right)^2}\left(\frac{C}{0.4}\right)\left(\frac{g}{0.97}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\boxed{\left(\frac{\mathrm{Q}}{50000}\right)}$$

Higher magnetic field while keeping the solenoid bore

How to get Higher Q?

→ HTS cavities

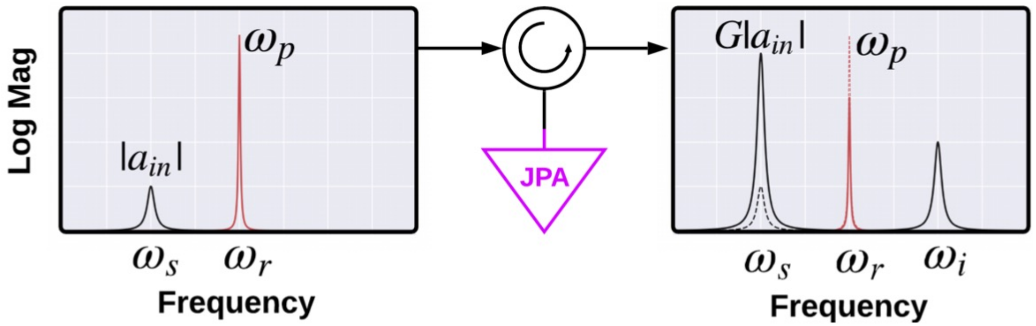
Less noise by cooling down

$$Q_N = \frac{h\nu}{e^{h\nu/k_B T}-1}\boxed{+h\nu} > h\nu = 4.3\times10^{-25}\,\mathrm{W/Hz}$$

Zero-point energy

→**S**tandard **Q**uantum **L**imit

ADMX reached SQL with Josephson Parametric Amplifier (in phase insensitive mode)



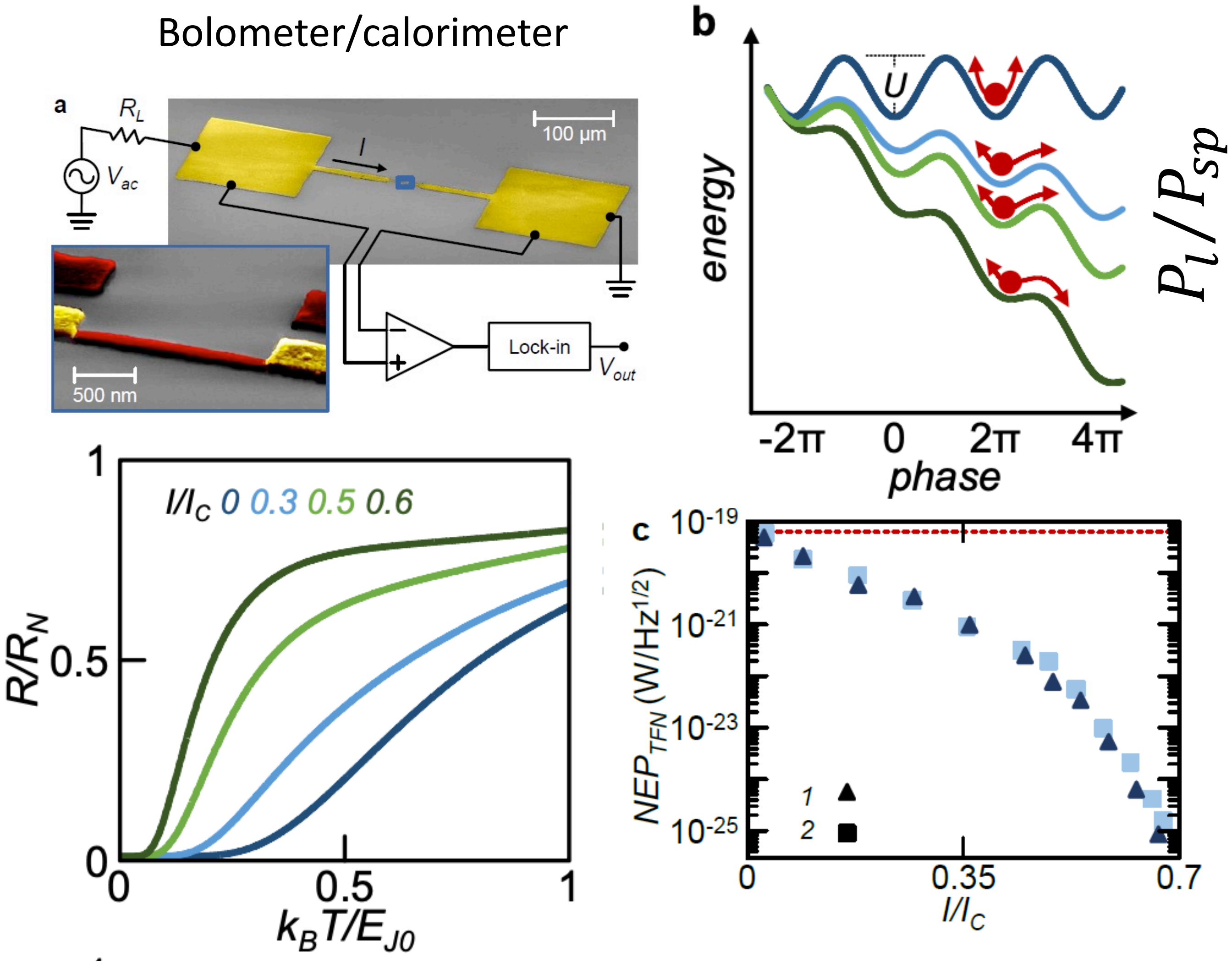
How to overcome SQL?

→ Single photon sensors

Single microwave photon sensors

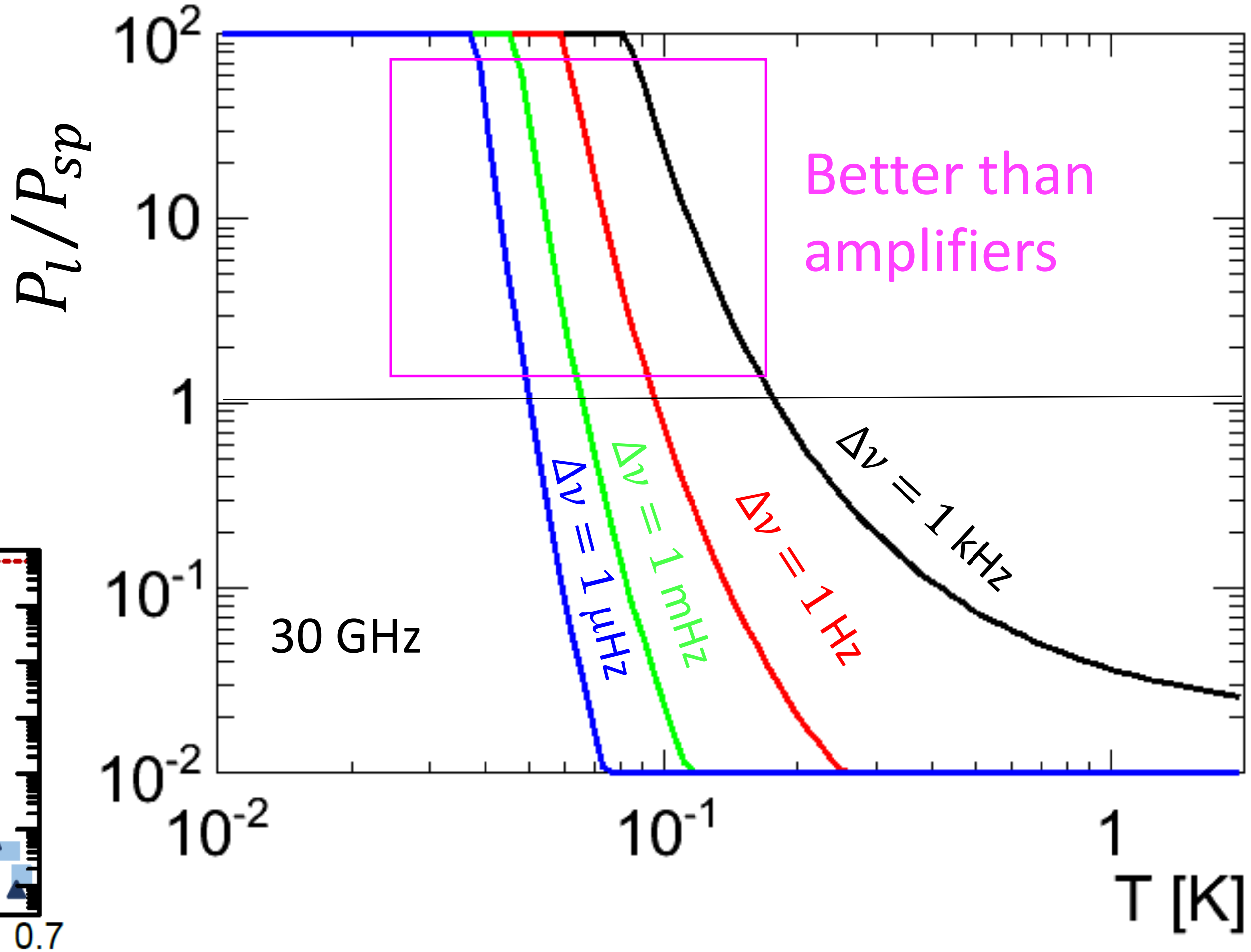
Current-biased Josephson Junction TES (JES)

Bolometer/calorimeter



F. Paolucci et al Phys Rev Appl. 14 034055 (2020)

S.K. Lamoreaux et al Phys Rev D 98 035020 (2013)

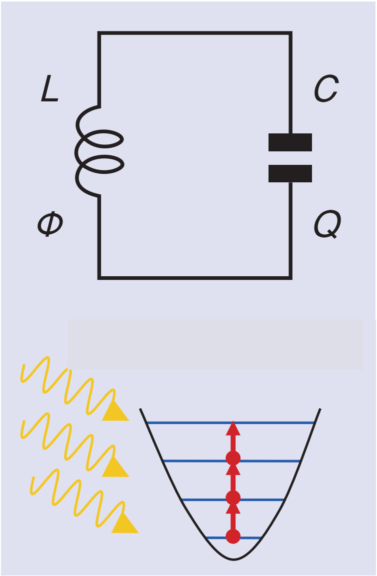


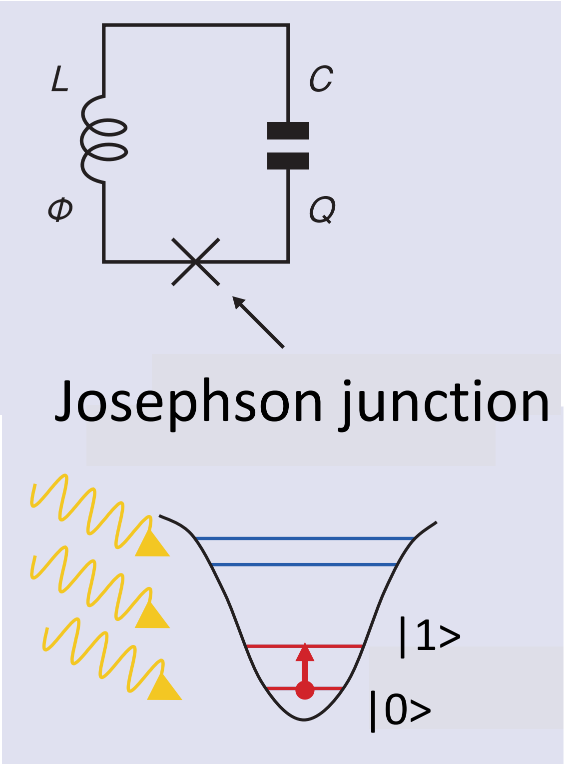
→ Synergy for qubits

Superconducting qubit based on a Josephson Junction

Key: quantized LC circuit

10GHz

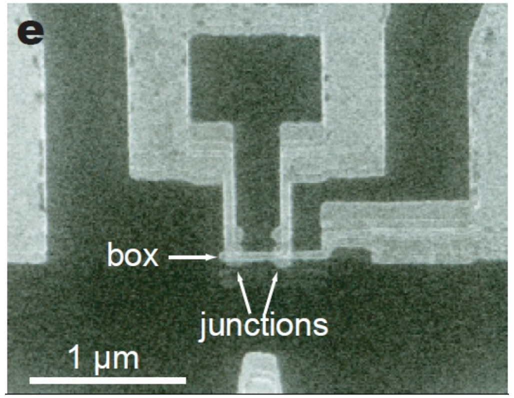




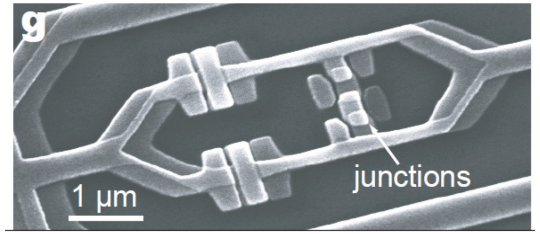
Harmonic oscillator has equally spaced many states
→ Not useful as qubit

JJ → anharmonic potential
→ selective |0> & |1>

charge qubit

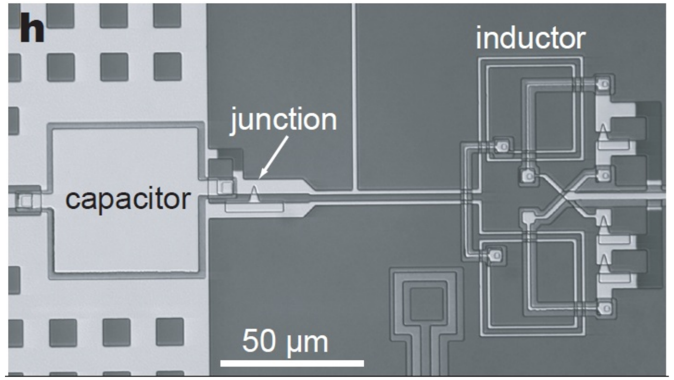


flux qubit

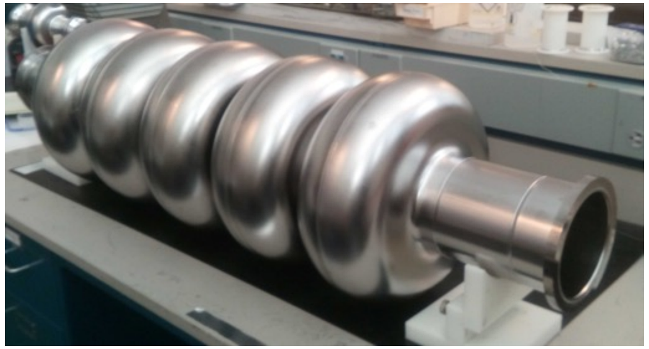


Three different implementations

phase qubit

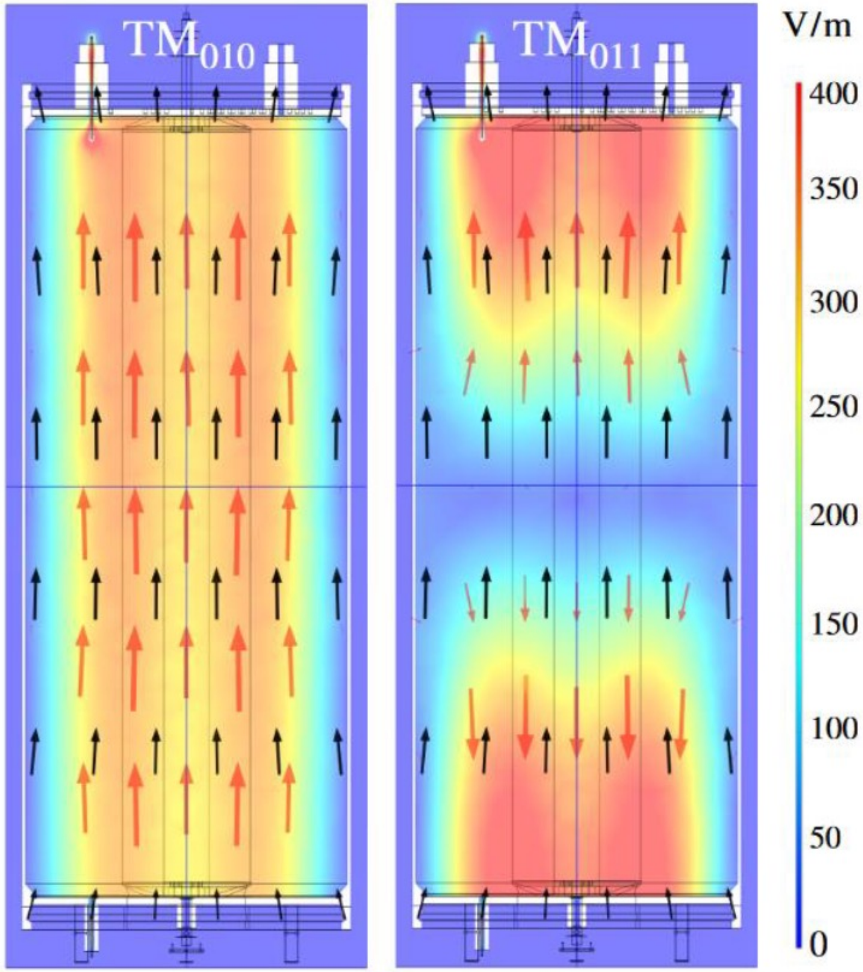


SRF cavity is also a (huge) LC circuit
→ Longer coherent length than existing qubits (qudits)



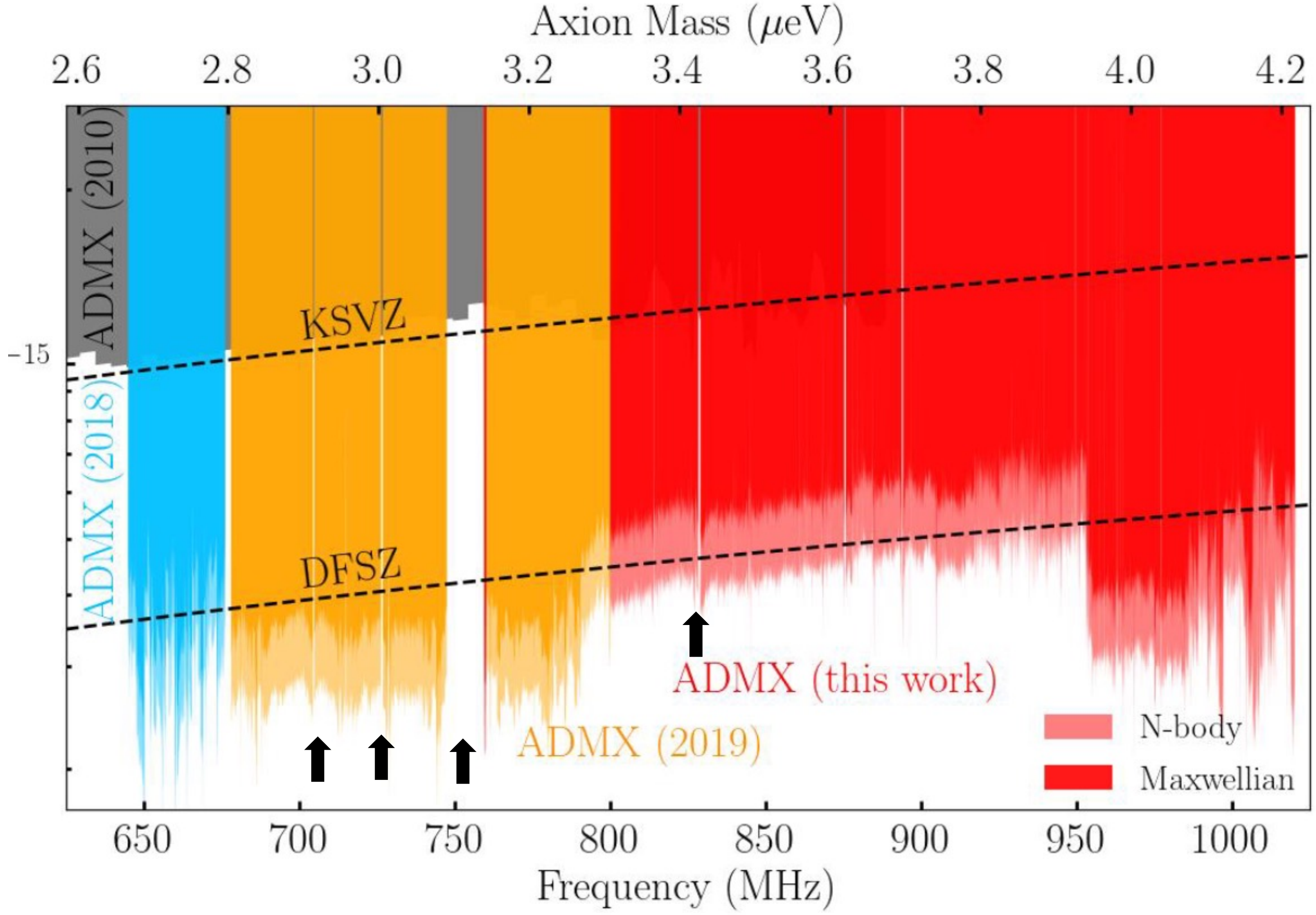
仙場 浩一 “超伝導量子ビットと単一光子の量子もつれ制御” NTT技術ジャーナル 2007.11 23

One important lesson from ADMX



Courtesy: Gray Rybka, “Current Status and Future Plans of ADMX”

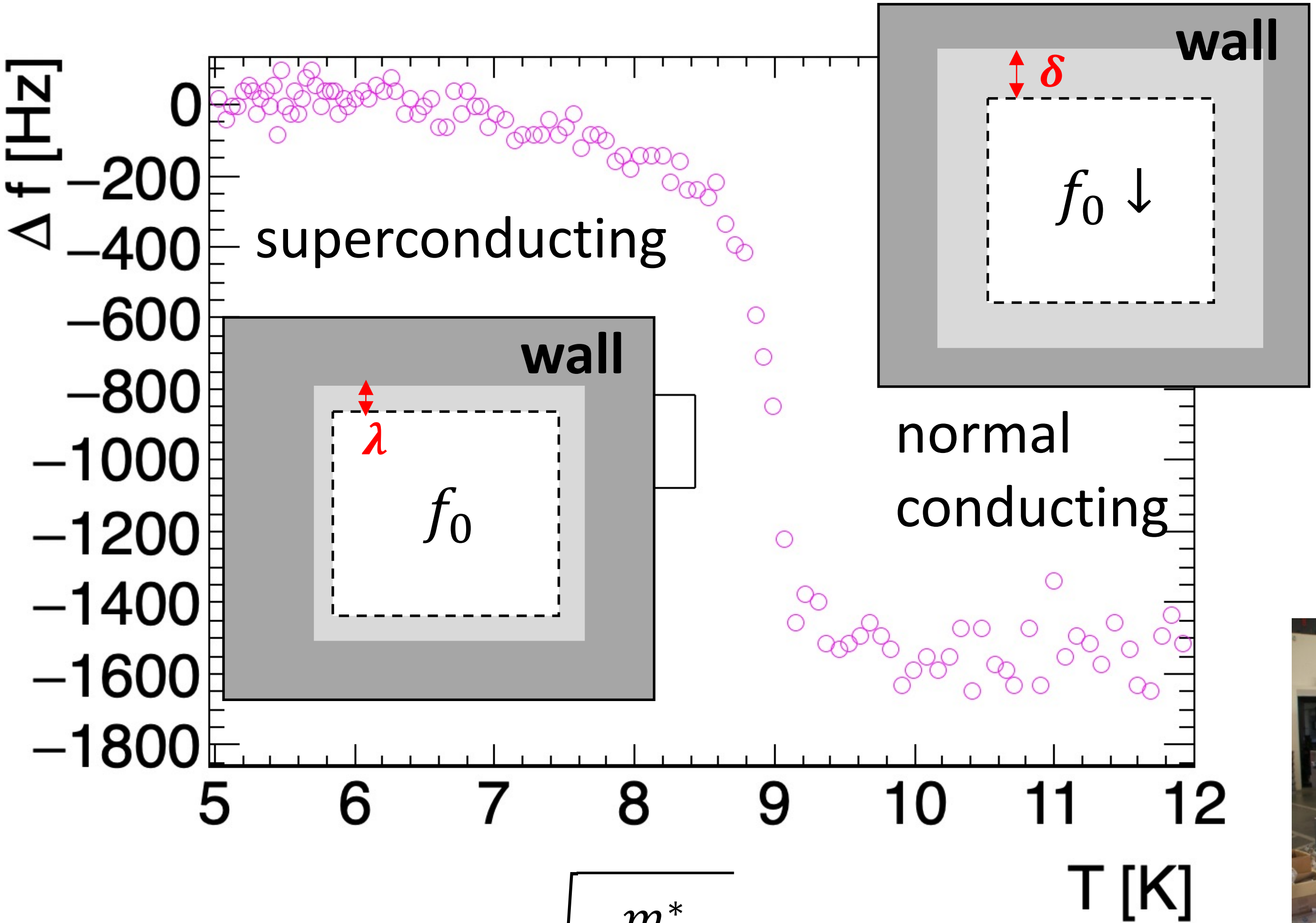
Mechanical tuning causes mode mixing



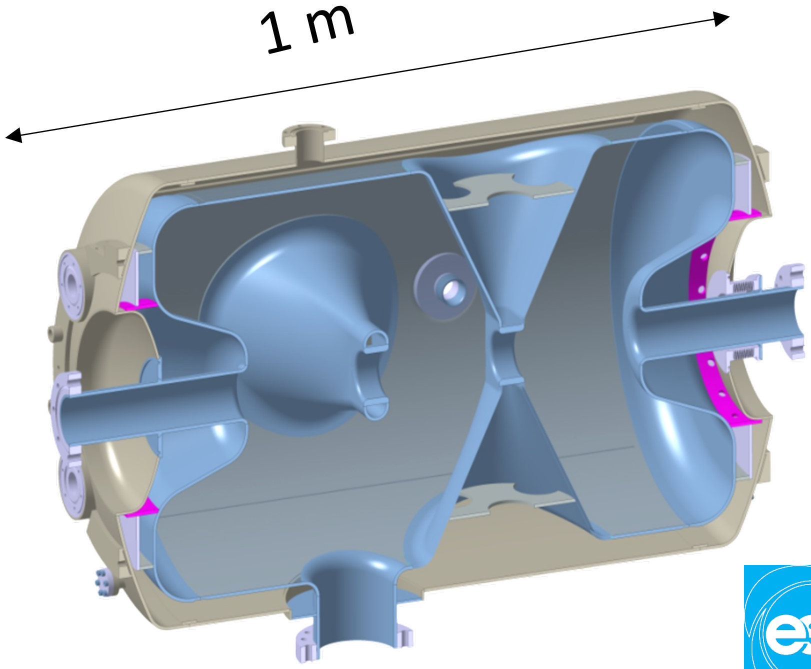
→ Can we tune the frequency non-mechanically?

Frequency is tunable in SRF: Cooper pair density

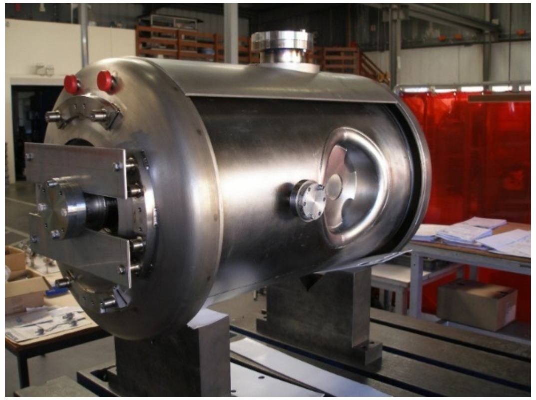
A niobium cavity at 352 MHz



$$\lambda_L = \sqrt{\frac{m^*}{\boldsymbol{n_s} e^2 \mu_0}}$$



EUROPEAN SPALLATION SOURCE



Theory: Usadel equation (BCS theory in the dirty limit)

$$\epsilon + is\cosh(u+iv) = \Delta\coth(u+iv)$$
$$\beta = (H_{DC}/2H_c)^2 = (J_{DC}/2J_d)^2$$
$$s = \exp(-2x/\lambda)\,\beta\Delta_0$$

$$\hat{G}^R = \begin{bmatrix} \cosh(u+iv) & e^{iQy}\sinh(u+iv) \\ -e^{-iQy}\sinh(u+iv) & -\cosh(u+iv) \end{bmatrix}$$

Green function gives all the information of the superconducting system

Solution PRL 113 087001 (2014)

$$\begin{cases} \Delta(s) = \Delta_0 - \pi s/4 \\ r(\epsilon,s) = [\epsilon^2\Delta^2 s^2 + (\epsilon^2 + s^2 - \Delta^2)^3/27]^{1/2} \\ \sinh 2u(\epsilon,s) = \left[(r+\epsilon\Delta s)^{1/3} - (r-\epsilon\Delta s)^{1/3}\right]/s \\ \sin v(\epsilon,s) = \left[-\Delta + (\Delta^2 - s^2\sinh^2 2u)^{1/2}\right]/2s\cosh u \end{cases}$$

For zero field $s \to 0$

$$\begin{cases} G^R(\epsilon) = \dfrac{\epsilon}{\sqrt{\epsilon^2-\Delta^2}} \\ F^R(\epsilon) = \dfrac{\Delta}{\sqrt{\epsilon^2-\Delta^2}} \end{cases}$$

$$\sigma_1/\sigma_n = \frac{1}{\hbar\omega}\int_{-\infty}^{\infty}[f(\epsilon) - f(\epsilon+\hbar\omega)][\,\mathrm{Re}G^R(\epsilon)\mathrm{Re}G^R(\epsilon+\hbar\omega) + \mathrm{Re}F^R(\epsilon)\mathrm{Re}F^R(\epsilon+\hbar\omega)]d\epsilon$$

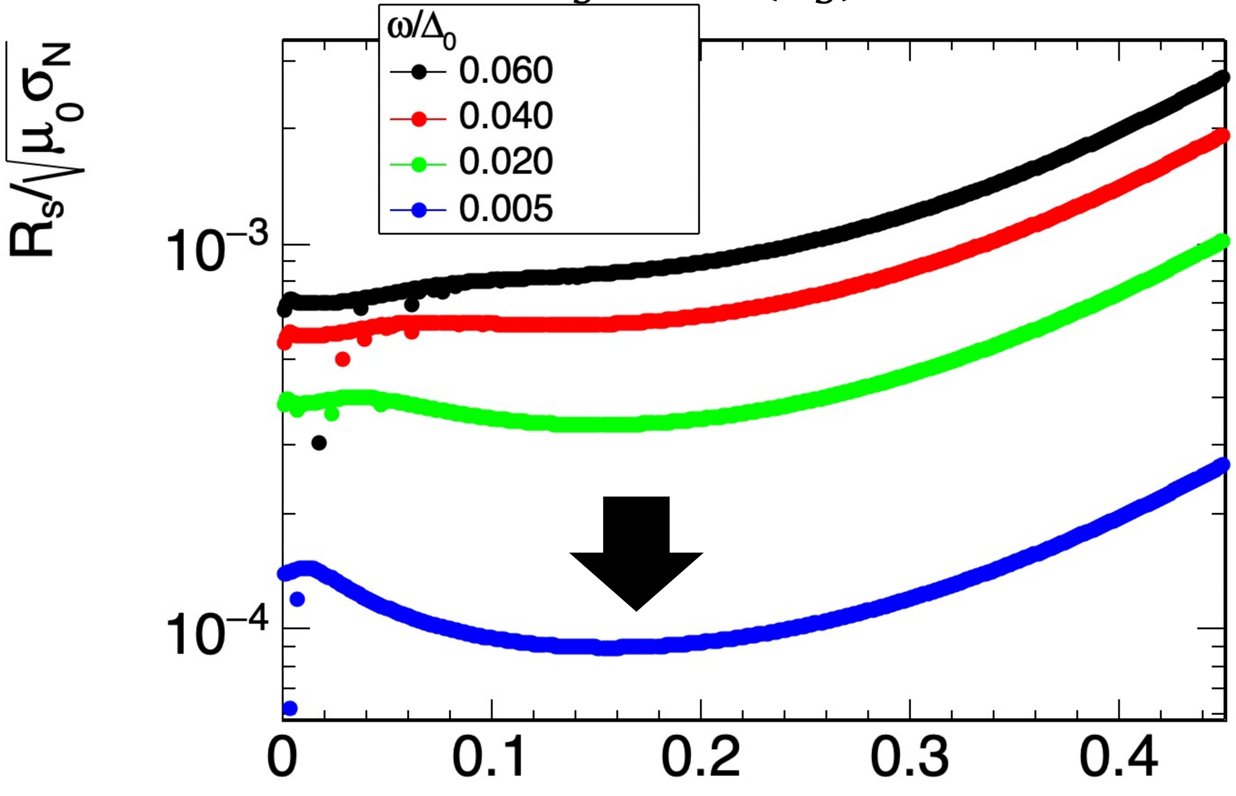
$$\sigma_2/\sigma_n = \frac{1}{\hbar\omega}\int_{-\infty}^{\infty}\tanh\frac{\epsilon}{2kT}[\,\mathrm{Re}G^R(\epsilon)\mathrm{Im}G^R(\epsilon+\hbar\omega) + \mathrm{Re}F^R(\epsilon)\mathrm{Im}F^R(\epsilon+\hbar\omega)]d\epsilon$$

Surface resistance / reactance

Surface impedance
in the Local limit

$$Z_s = \sqrt{\frac{i\omega\mu_0}{\sigma_1 - i\sigma_2}} \xrightarrow{\sigma_1 \ll \sigma_2} \sqrt{\frac{\mu_0}{\omega\sigma_2^3}}\left(\frac{1}{2}\sigma_1 + i\sigma_2\right)$$

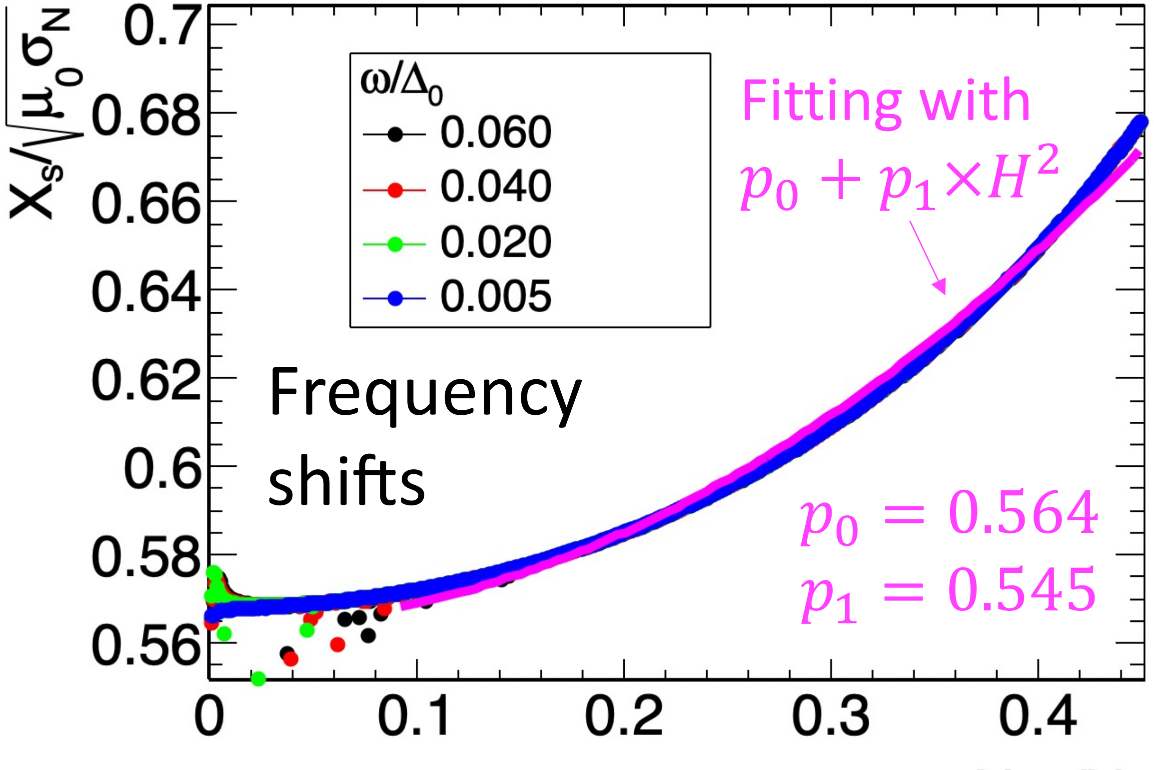
$R_s = \mathrm{Re}(Z_s)$



Q-factor

$Q_0 = G/R_s$

$X_s = \mathrm{Im}(Z_s)$



Fitting with
$p_0 + p_1 \times H^2$

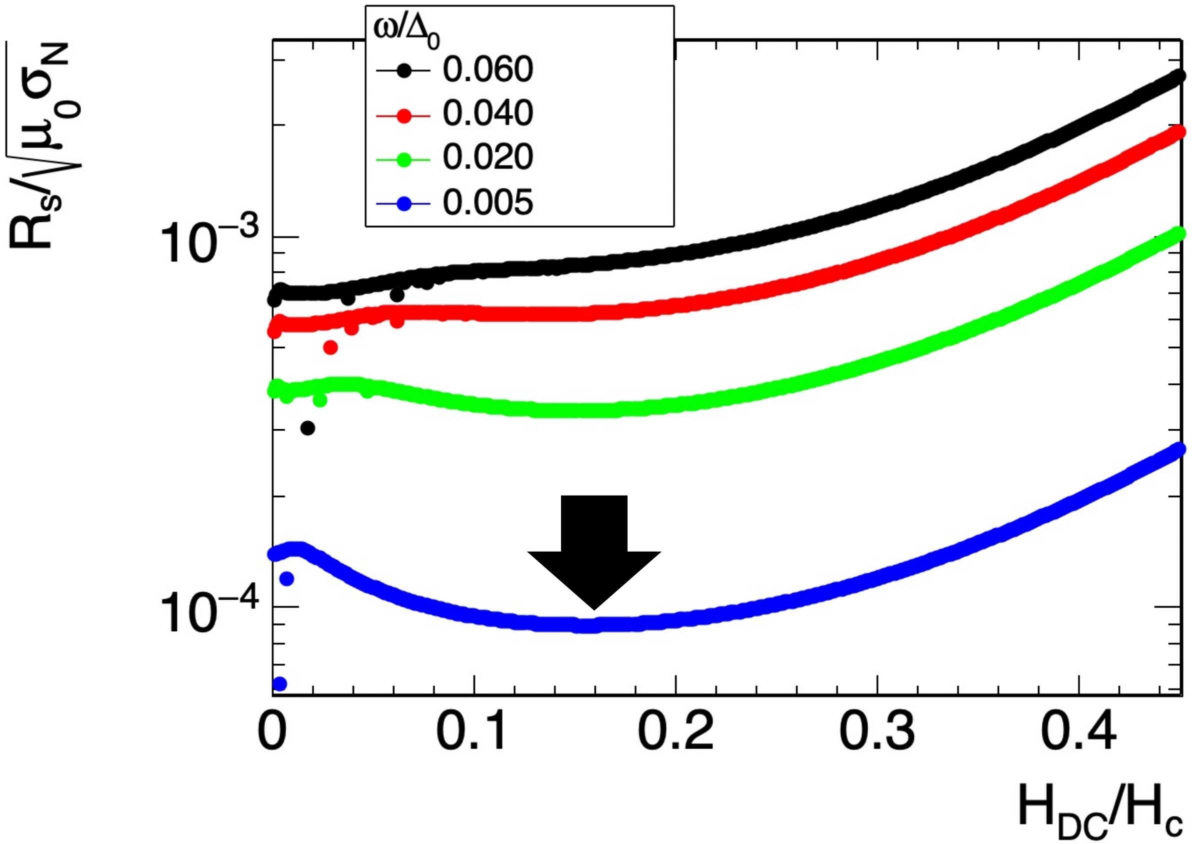
Frequency
shifts

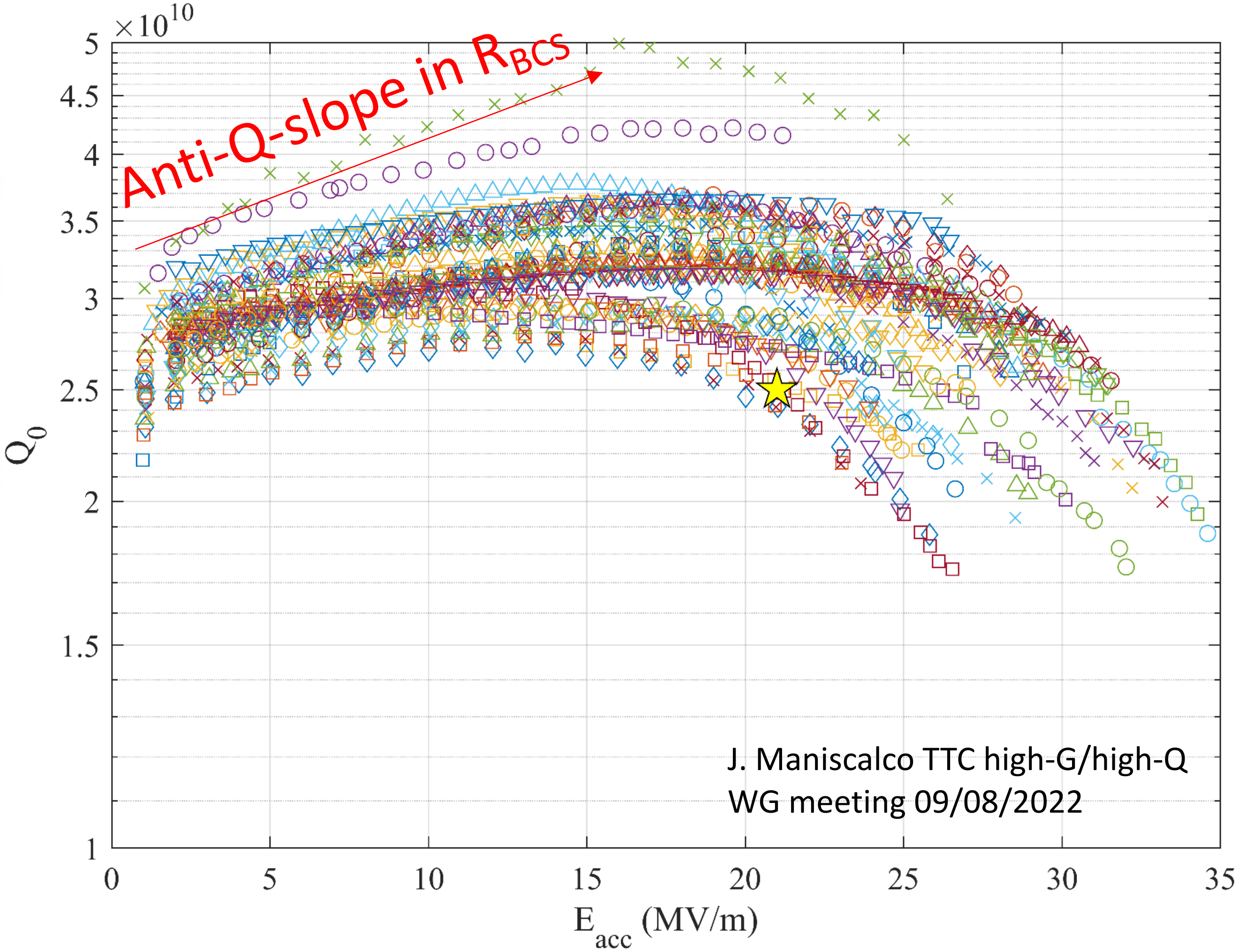
$p_0 = 0.564$
$p_1 = 0.545$

Surface inductance

$L_s = X_s/\omega$

Come back to SRF: anti-Q-slope in N-doped LCLS-II cavities





Anti-Q-slope in R_{BCS}

J. Maniscalco TTC high-G/high-Q WG meeting 09/08/2022

The theory is however not complete! New research direction!

→ Frequency dependence is not reproduced

Outline

- New superconductors for SRF accelerators
- Axion dark matter
- Gravitational waves

Two Phenomena to address GW via microwaves

The Einstein equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

can be expanded to the linear order with small strain h

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Mechanical deformation of a cavity wall

$$\frac{d^2x}{dt^2} = -\frac{1}{2}\frac{d^2h_{xx}}{dt^2}x + \frac{1}{2}\frac{d^2h_{xx}}{dt^2}y$$

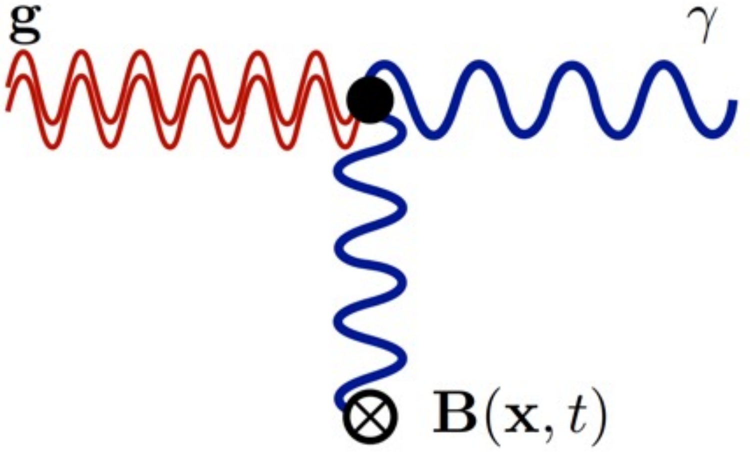
$$\frac{d^2y}{dt^2} = \frac{1}{2}\frac{d^2h_{xx}}{dt^2}x + \frac{1}{2}\frac{d^2h_{xx}}{dt^2}y$$

arXiv:gr-qc/0502054

Coupling to microwaves under static B

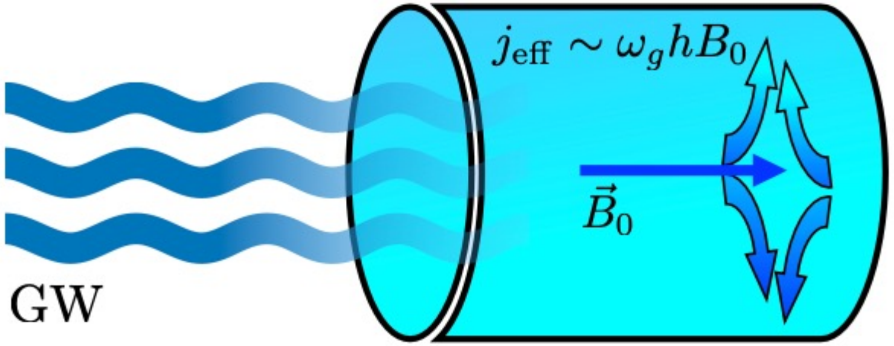
$$\Box h_{\mu\nu} = -16\pi T_{\mu\nu}$$

$$4\pi T_{\mu\nu} = F_{\mu\alpha}F_{\nu}{}^{\alpha} - \frac{1}{4} g_{\mu\nu} F_{\alpha\beta}F^{\alpha\beta}$$

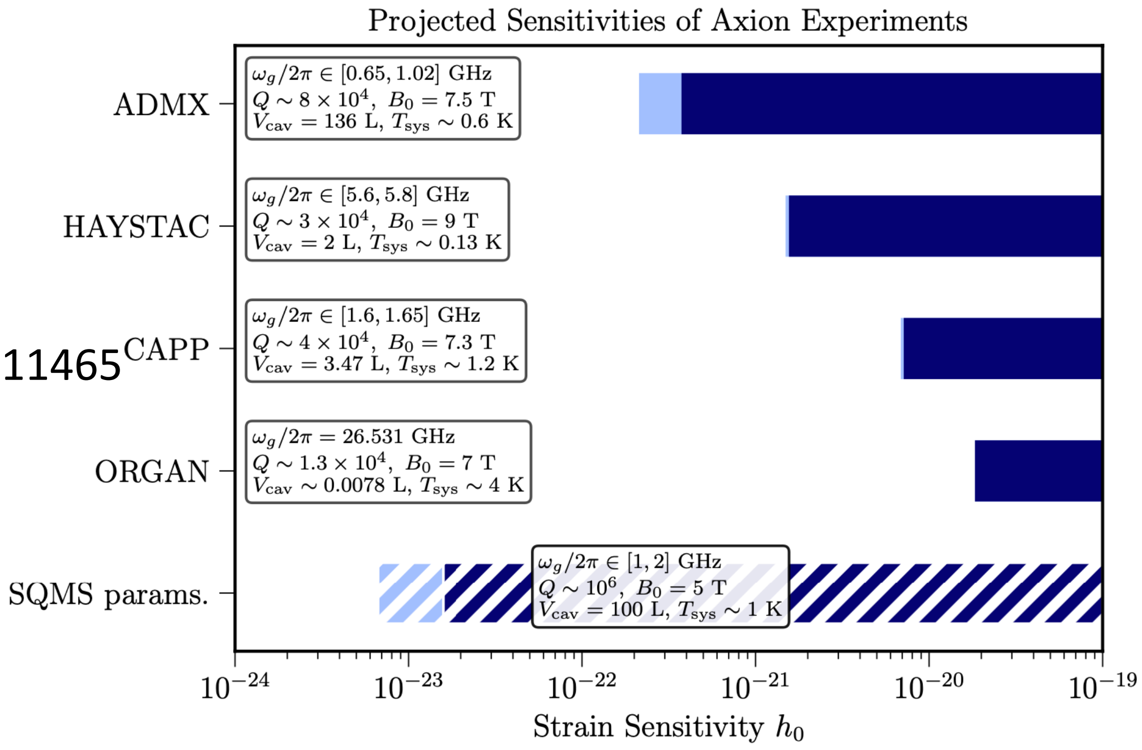


M. E. Gertsenshtein JETP 41 113 1961

RF cavity search for GW



arXiv:2112.11465



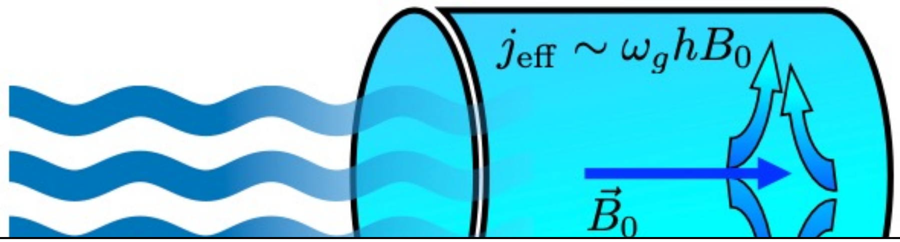
$$h_0 \gtrsim 3\times10^{-22} \times \left(\frac{1\ \text{GHz}}{\omega_g/2\pi}\right)^{3/2}\left(\frac{0.1}{\eta_n}\right)\boxed{\left(\frac{8\ \text{T}}{B_0}\right)}\left(\frac{0.1\ \text{m}^3}{V_\text{cav}}\right)^{5/6}\boxed{\left(\frac{10^5}{Q}\right)^{1/2}}\left(\frac{T_\text{sys}}{1\ \text{K}}\right)^{1/2}\left(\frac{\Delta\nu}{10\ \text{kHz}}\right)^{1/4}\left(\frac{1\ \text{min}}{t_\text{int}}\right)^{1/4}$$

High-Q under strong B is the key

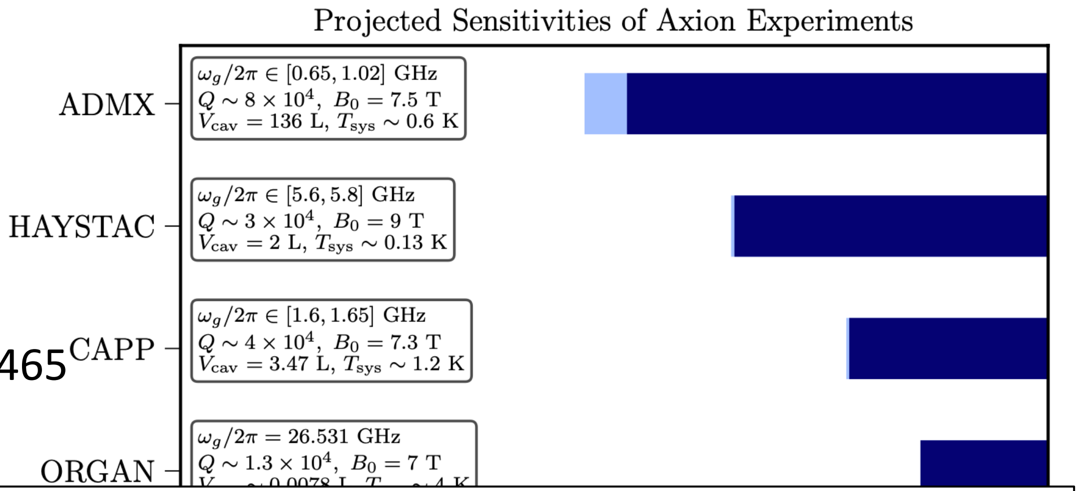
Potential sources (1 GHz GW): mergers of sub-solar masses

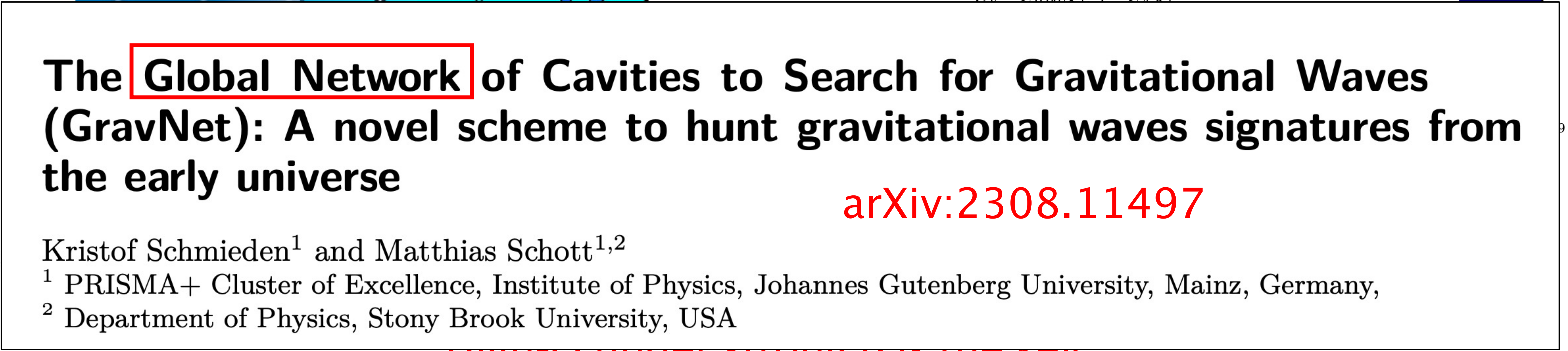
Primordial black hole merging $h_0 \sim 10^{-29} \times \left(\frac{1\ \text{pc}}{D}\right)\left(\frac{M_b}{10^{-11}\ M_\odot}\right)^{5/3}\left(\frac{\omega_g}{1\ \text{GHz}}\right)^{2/3}$

RF cavity search for GW



arXiv:2112.11465





The Global Network of Cavities to Search for Gravitational Waves (GravNet): A novel scheme to hunt gravitational waves signatures from the early universe

arXiv:2308.11497

Kristof Schmieden[1] and Matthias Schott[1,2]

[1] PRISMA+ Cluster of Excellence, Institute of Physics, Johannes Gutenberg University, Mainz, Germany,

[2] Department of Physics, Stony Brook University, USA

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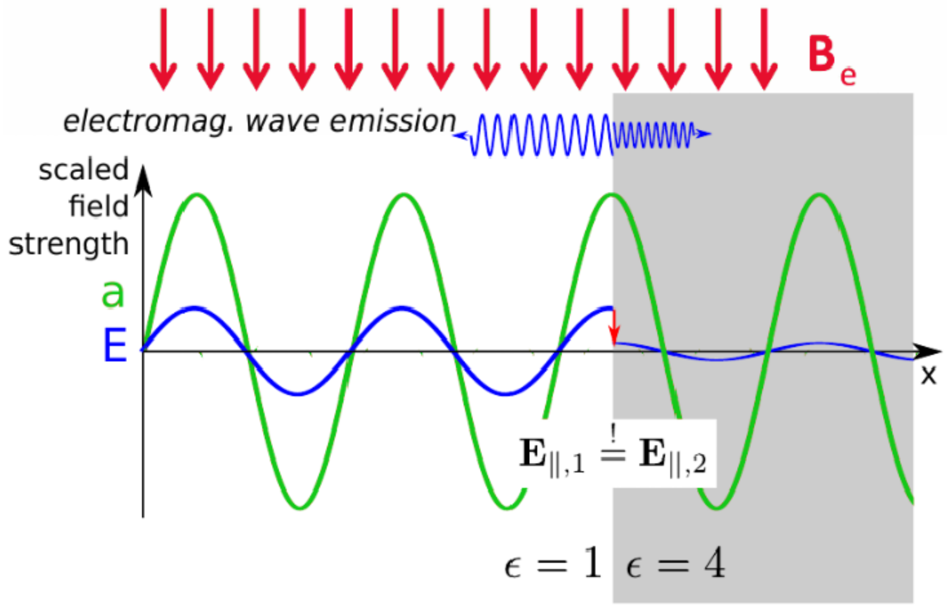
Conclusion

- HTS superconductors
  - Cuprates and pnictides may be the future of SRF (pulsed & >10 K)
  - Optical conductivity and surface impedance were newly calculated in the Meissner state
- Dark matter axion search
  - Dark matter axion may be addressed via microwave cavities
  - HTS cavities & single photon detectors are the next step
    - synergy with quantum computers
  - Non-mechanical frequency tuning may be inline to the state-of-the-art SRF cavity physics (anti-Q-slope)
- Gravitational wave search
  - GW may be addressed via microwaves
  - A similar setup as axion search is being proposed
  - Maybe on-site experiment at Orsay in the future?
- Pôle Accelerator has technical competence in RF and cryogenics

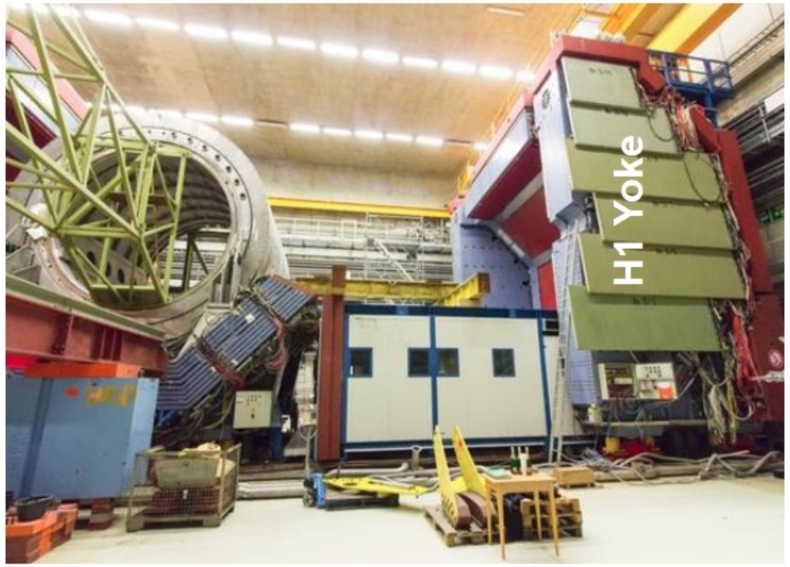
How to start with? → make use of the existing master project in IN2P3

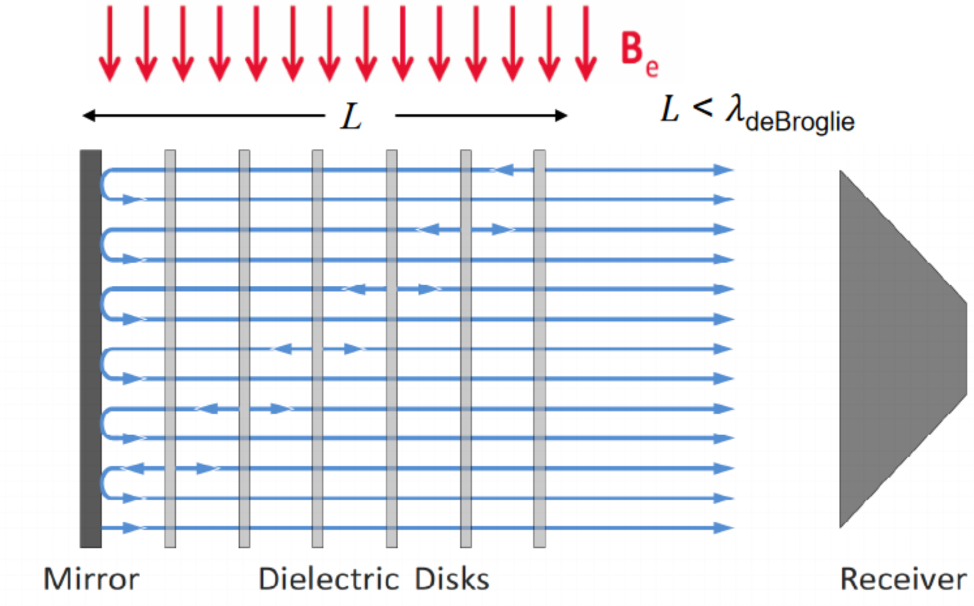
MADMAX (DESY)

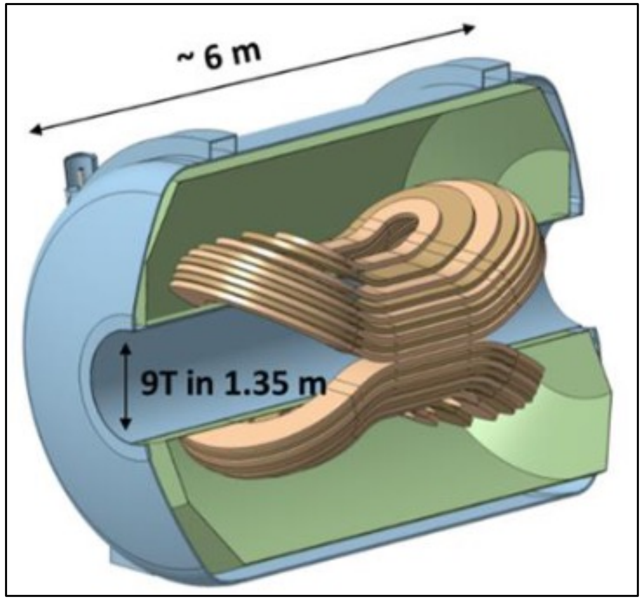
Courtesy: Antonios Gardikiotis, “Advances in searching for galactic axions with a Dielectric Haloscope”

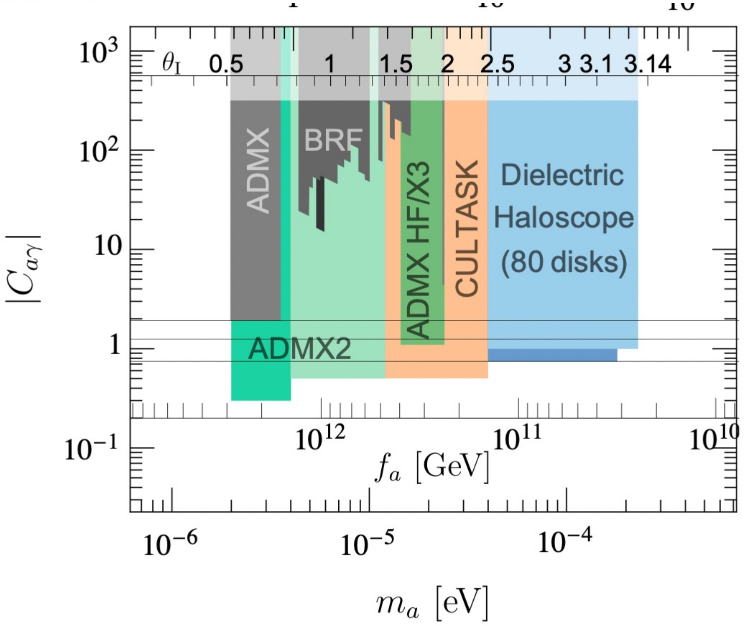


- Enhance the coherent microwave signal generated on the dielectric surface
- Dipole magnet (CEA)
- 25 GHz, 4 K, very low noise 10^{-23} W/Hz



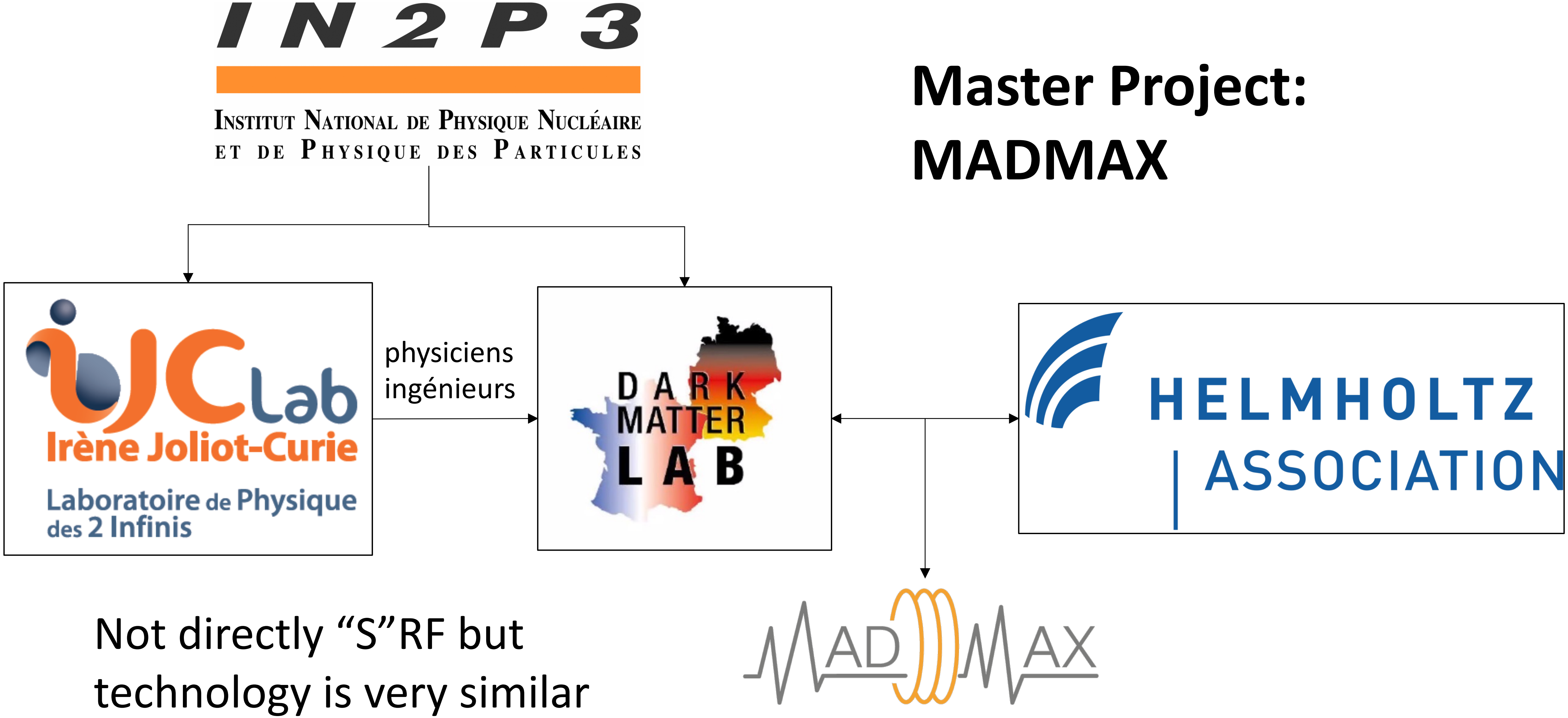






We will be in the collaboration via DMLab

Master Project:
MADMAX



Not directly “S”RF but
technology is very similar