CAPP-MAX
Status and Prospects

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*On behalf of **CAPP** collaboration,*
Y. Nakamura, Arjan V. Loo in University of Tokyo, RIKEN

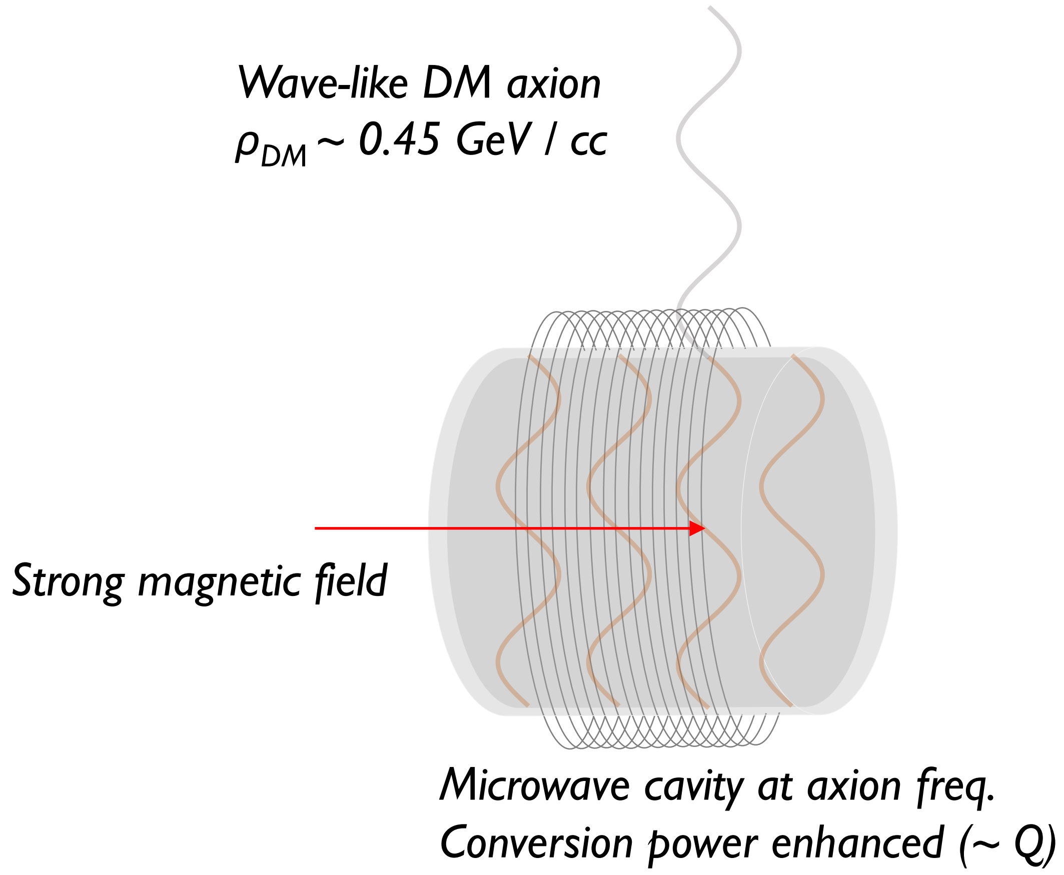
Axion haloscope

- Search for dark matter (DM) axions around the Milky way galaxy

Wave-like DM axion
$\rho_{DM} \sim 0.45$ *GeV / cc*

Axion haloscope

- Search for dark matter (DM) axions around the Milky way galaxy



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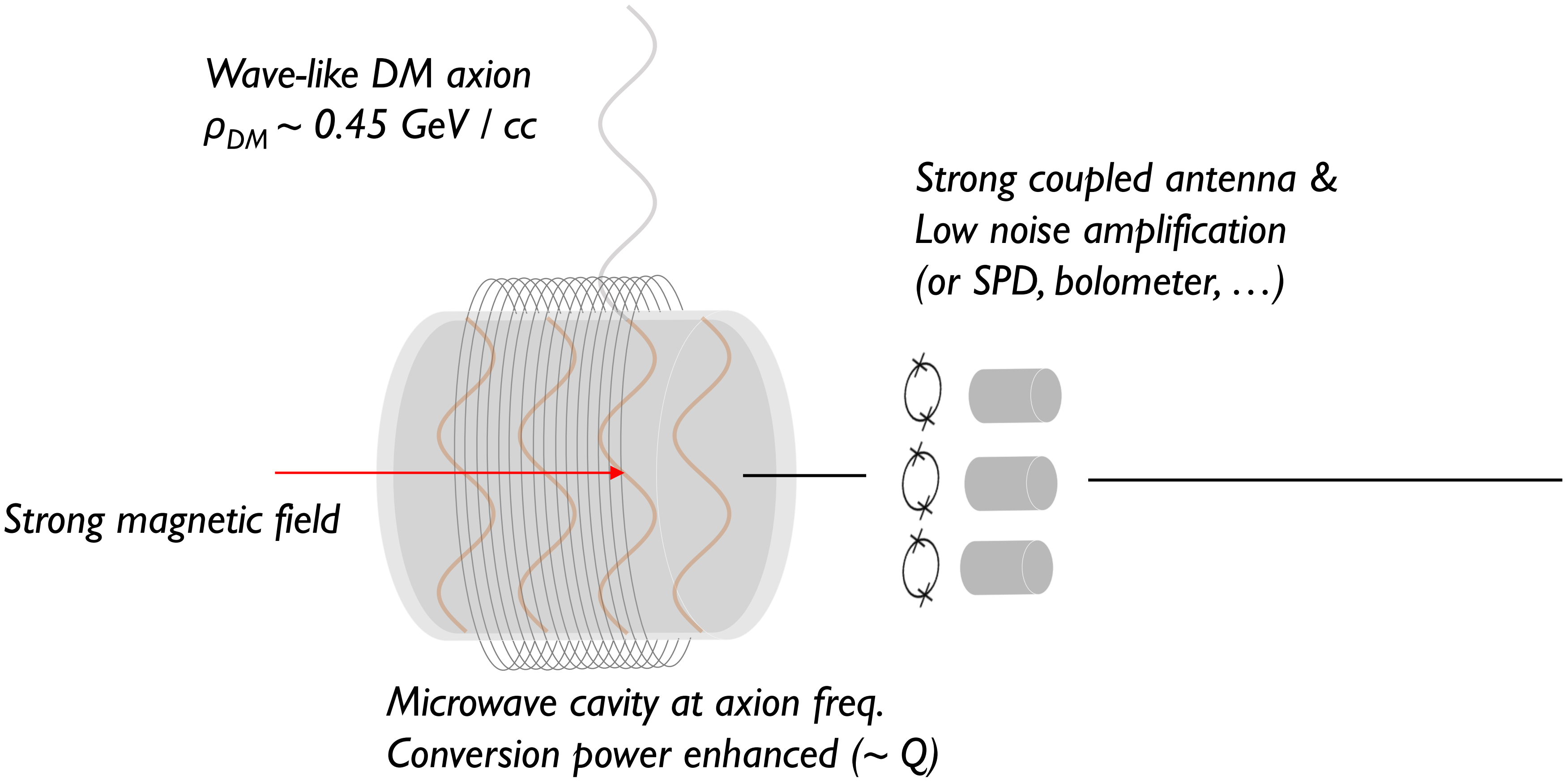
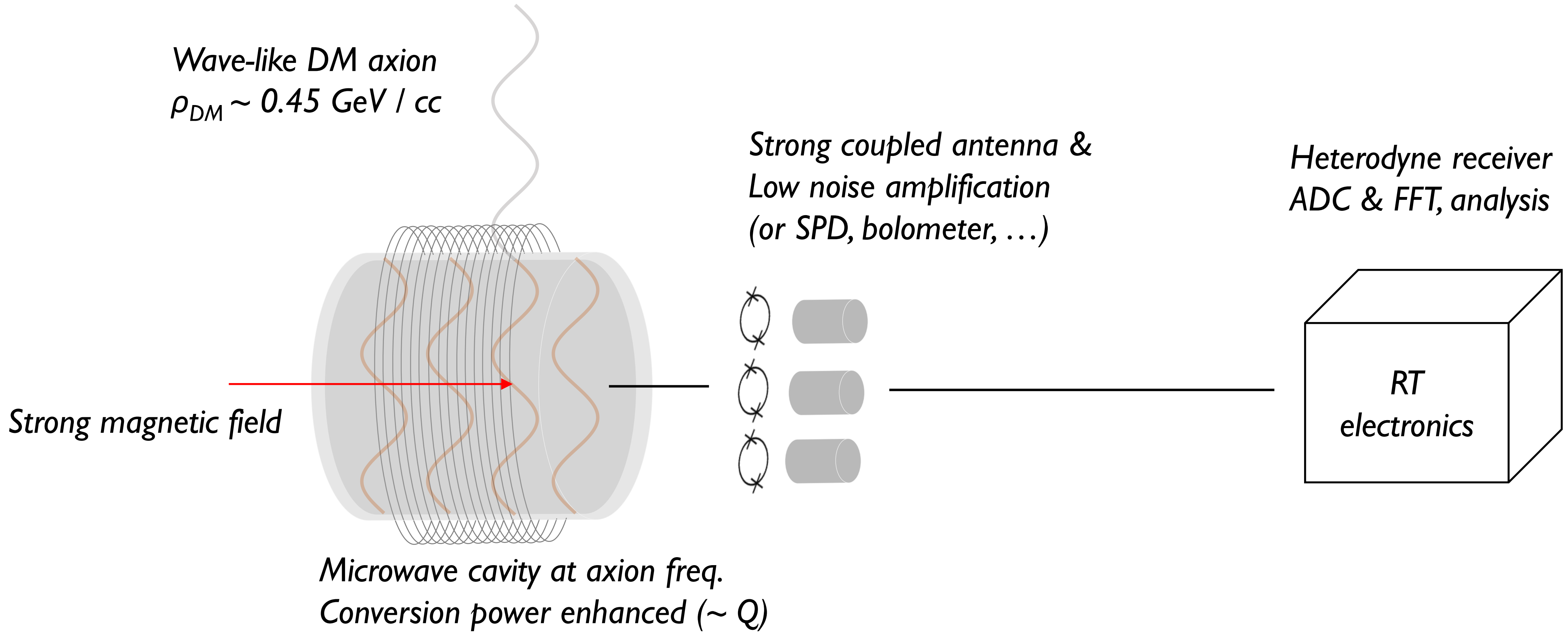


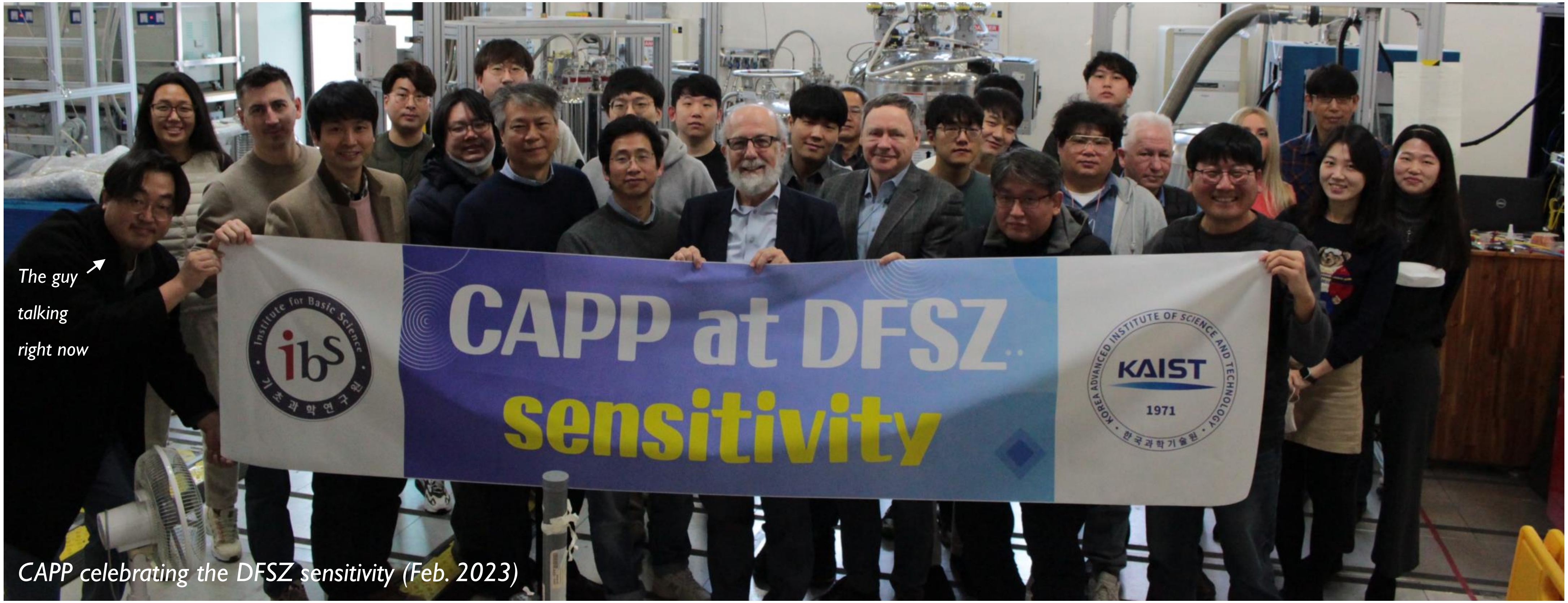
Axion haloscope

- Search for dark matter (DM) axions around the Milky way galaxy



CAPP-MAX (CAPP Main Axion eXperiment)

- *CAPP's flagship haloscope experiment*
- *First goal: 1 – 2 GHz with DFSZ*

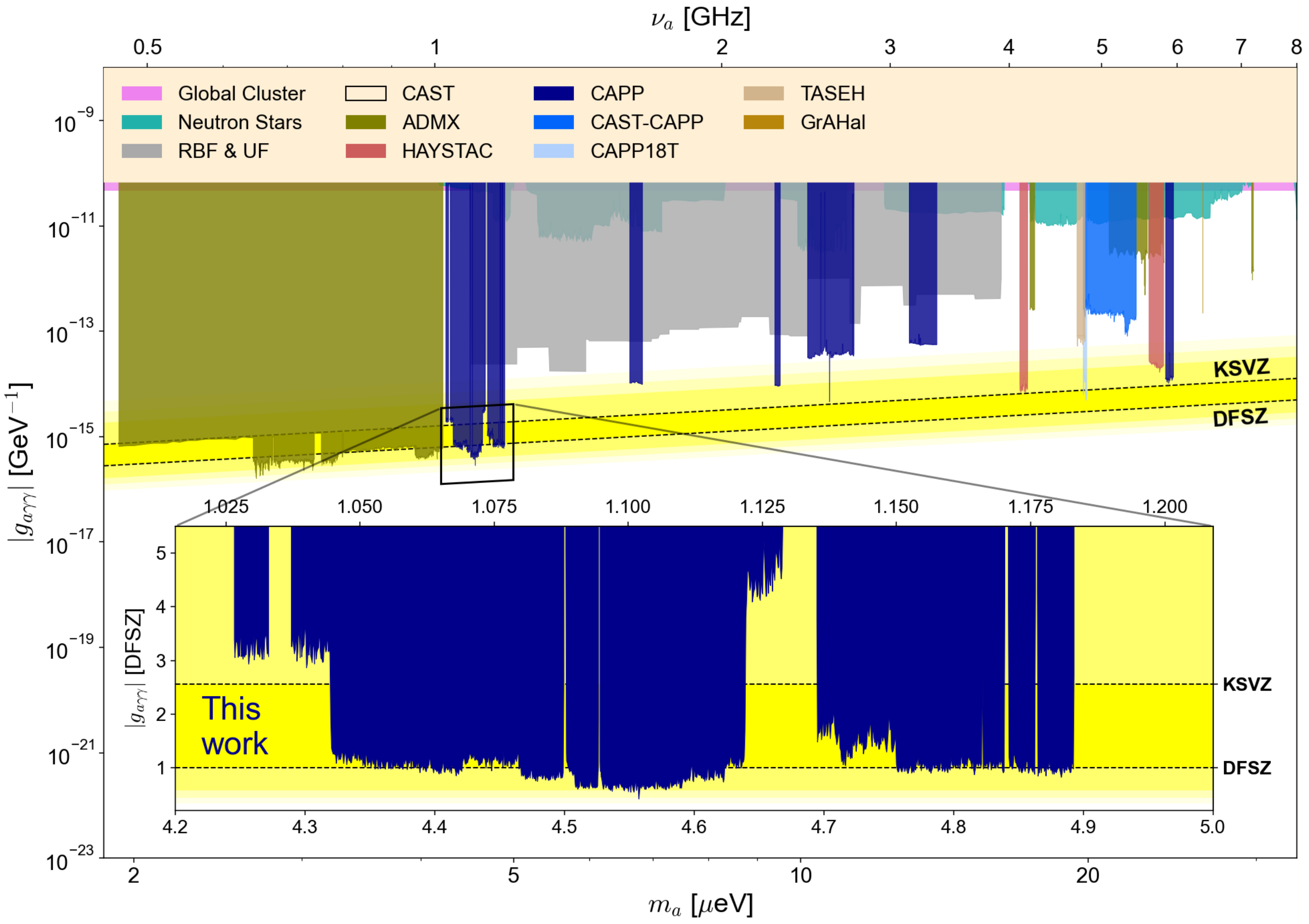


CAPP celebrating the DFSZ sensitivity (Feb. 2023)

Recent progress

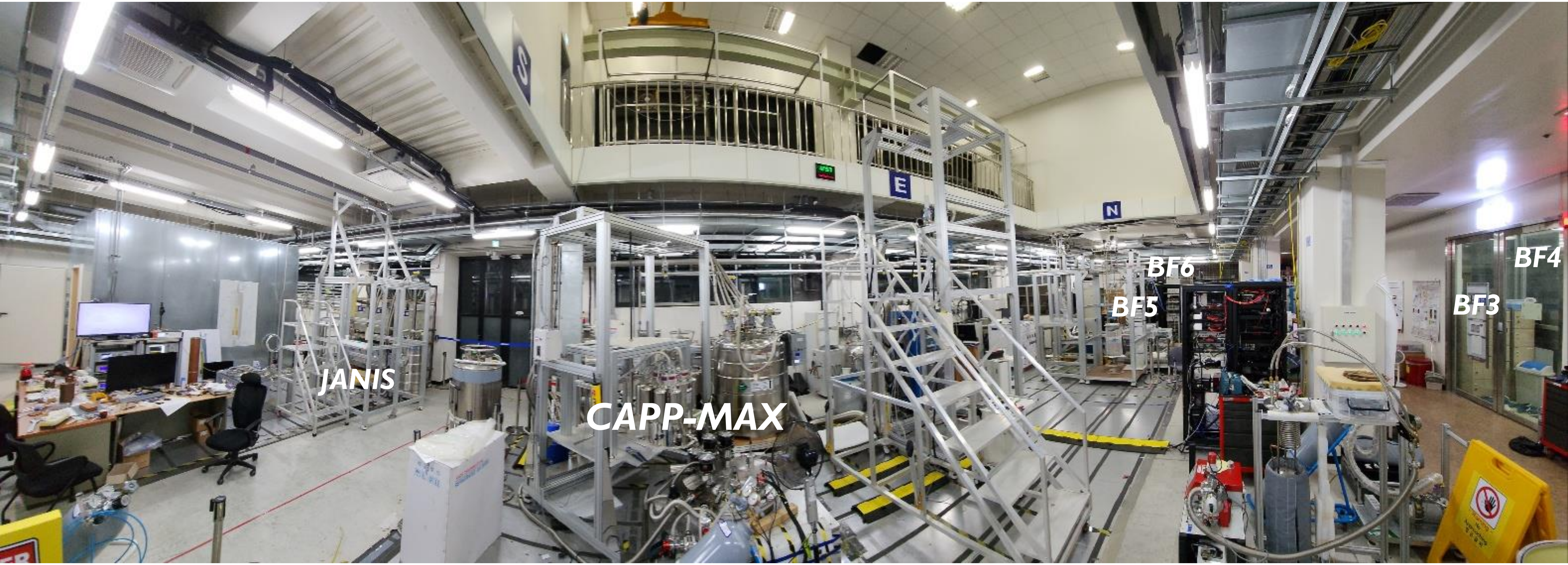
- *Homemade ultralight cavity (37-liters)*
- *3 parallel JPAs readout*
- *Physical temperature ~ 30 mK*
- $T_{syst.}$ *~ 230 mK (average)*

- *1.025 - 1.18 GHz scan finished*
  - *Submitted to PRX, accepted*

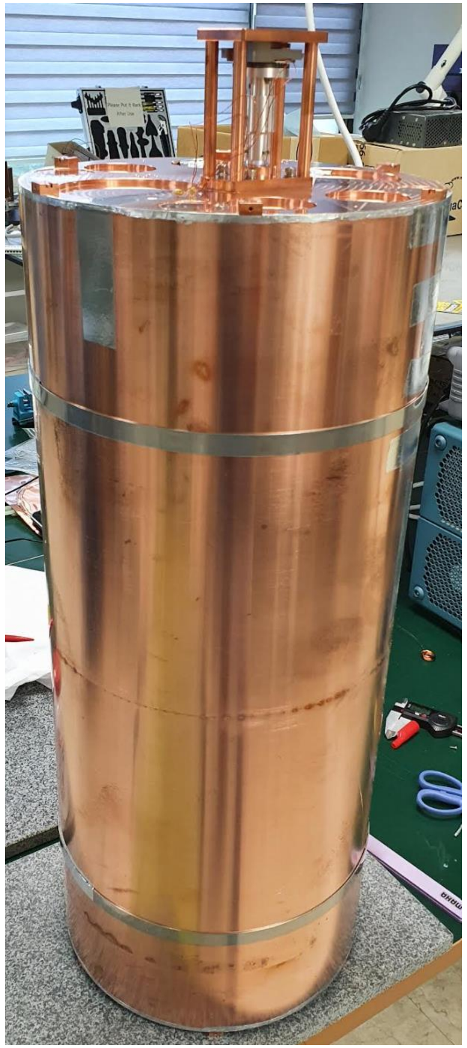


Axion quest 2024

Experiments at CAPP



The ultralight cavity



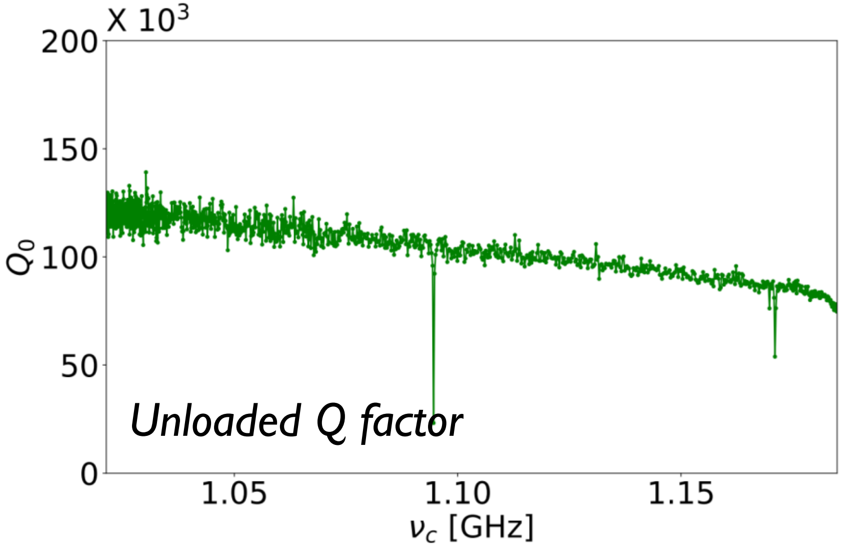
Made of copper foil

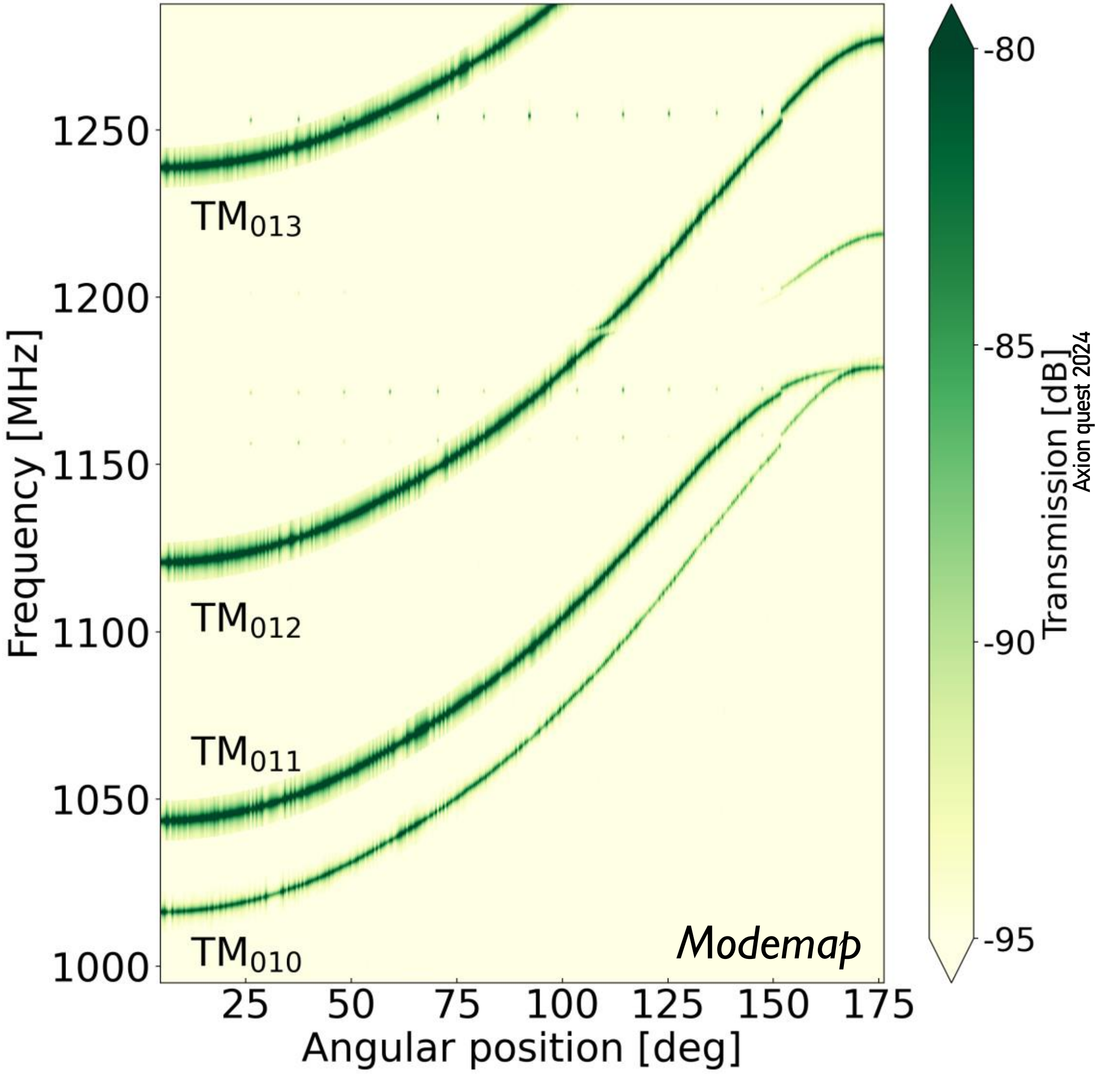
- *Very light / low thermal mass*
- *homemade / very cheap*

*Total weight ~ **5 kg***

1.02 – 1.18 GHz tuning range

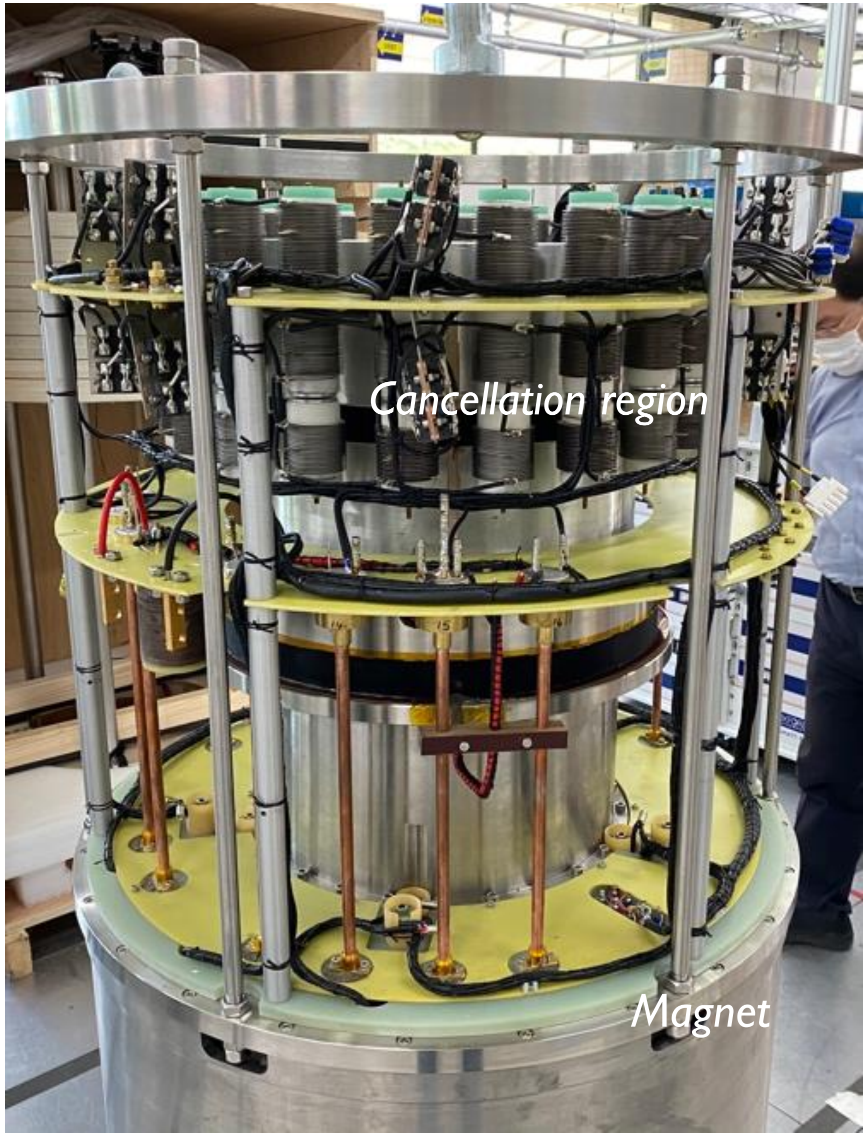
Geometrical factor ~ [0.5, 0.7]



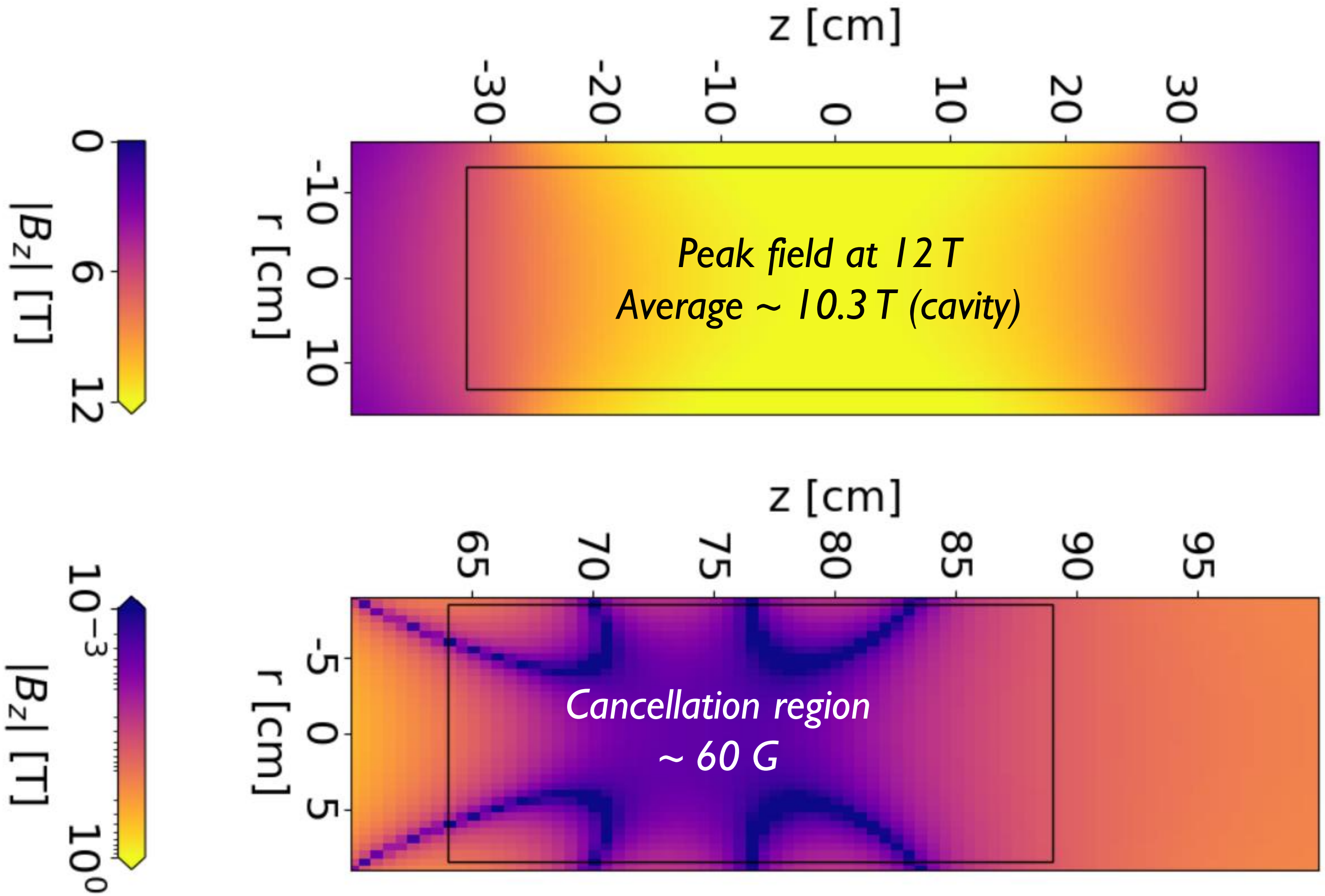


The magnet

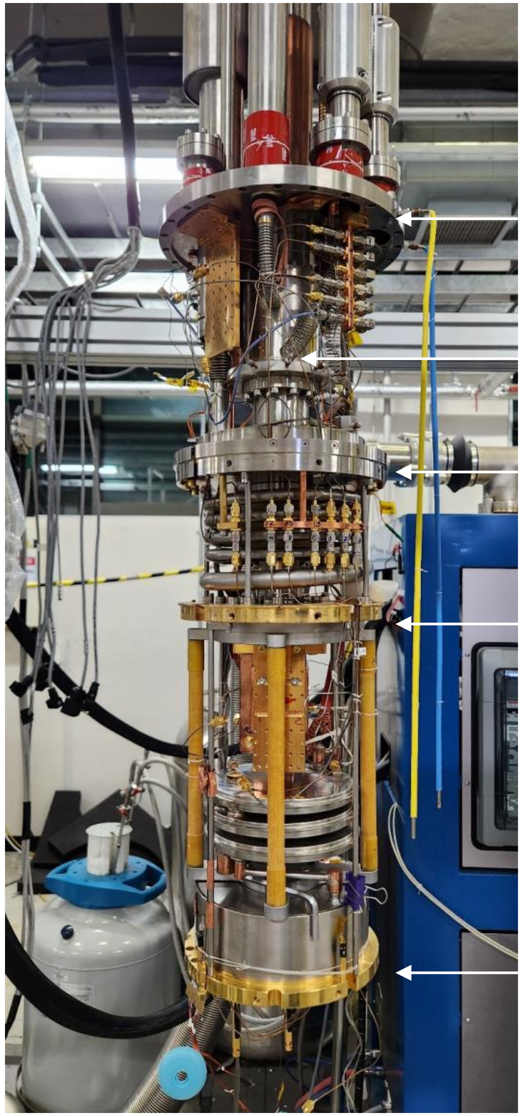
W Ma *et al*
2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012104



- *Nb_3Sn Superconducting coil*



The cryogenic system



4 K plate

1 K pot (1.5 K)

STILL (600 mK)

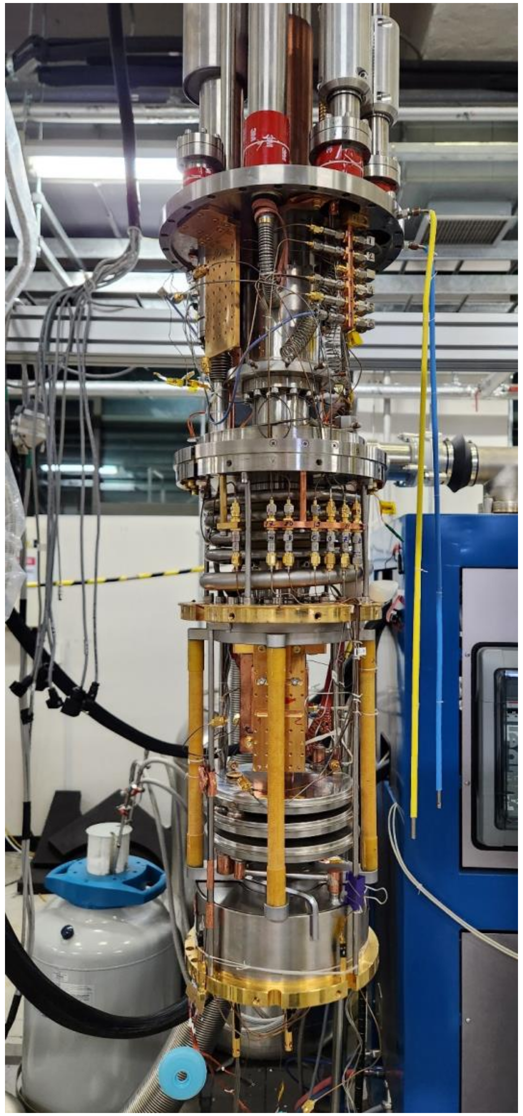
Cold plate (100 mK)

MXC plate (20 mK)

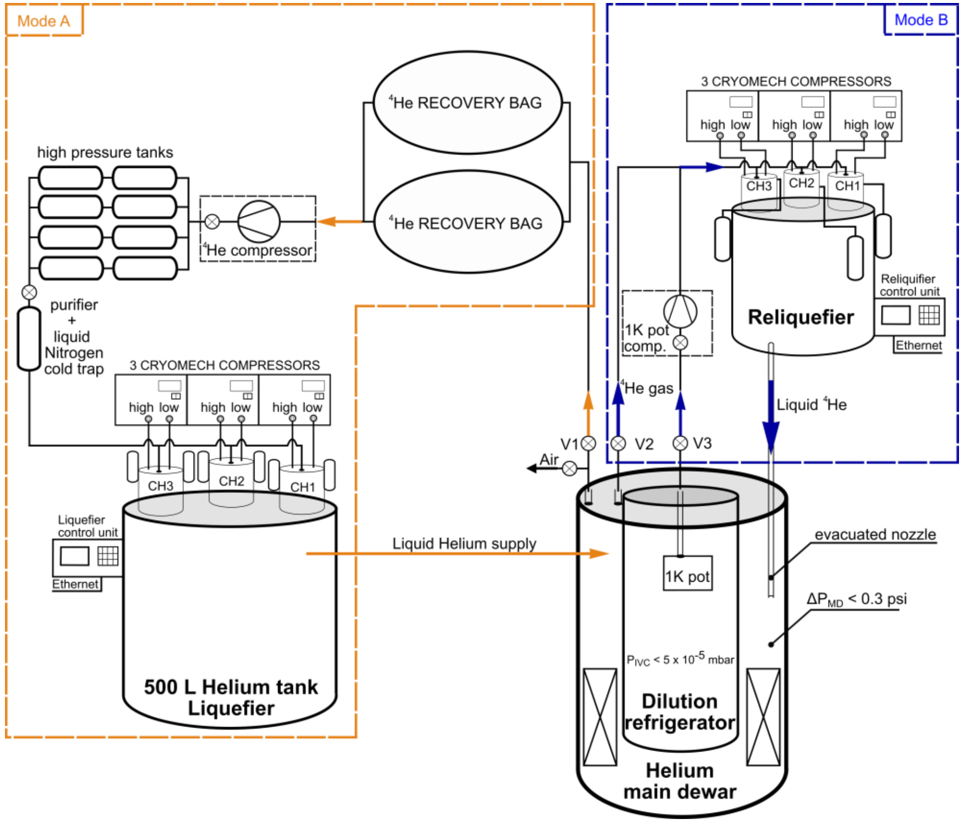
Wet type LEIDEN dilution refrigerator

- *5.6 mK of base temperature (bare fridge)*
- *Cavity temperature ~ 30 mK*

The cryogenic system



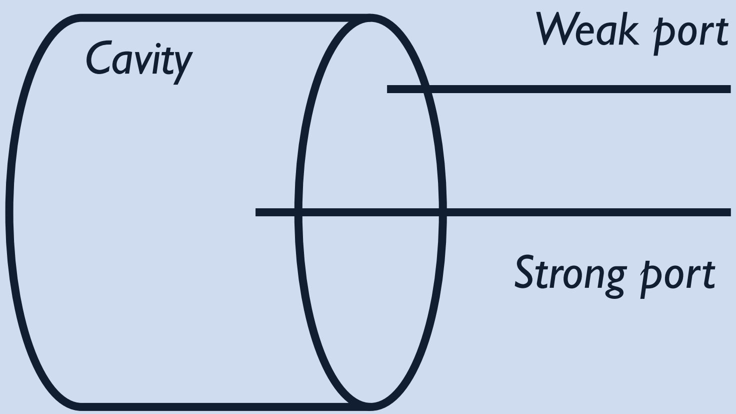
- *He recovery system ~ 160 L capacity*
- *He liquefier with 60 L / day rate*
- *He Re-liquefier with 60 L / day rate*



Axion quest 2024

Receiver chain

- *Signal resonated in the cavity*
- *Typical temperature ~ 30 mK*



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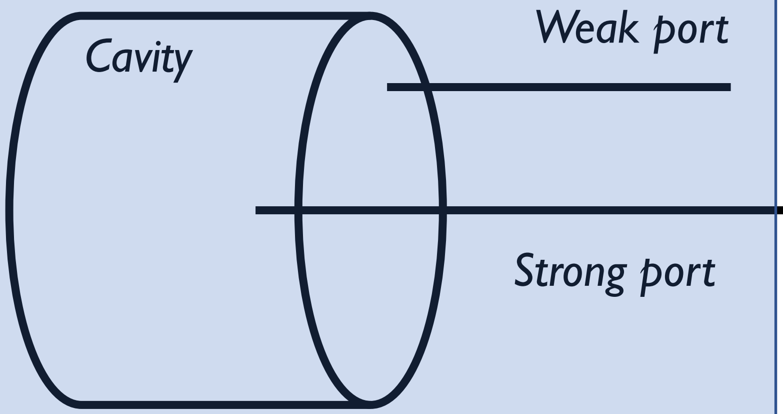
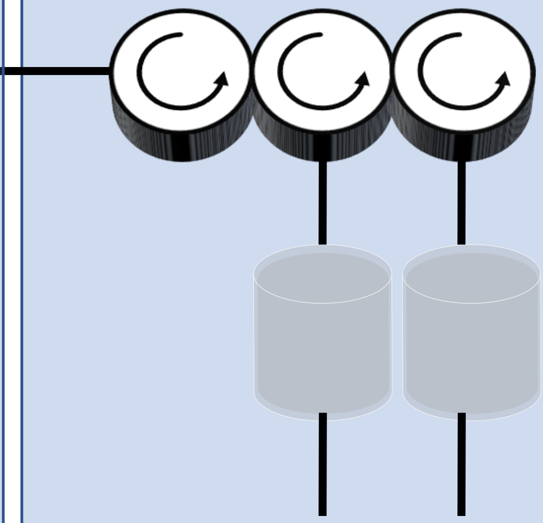


- *Primary amplification with JPA*
- *Typical gain ~ 20 dB*

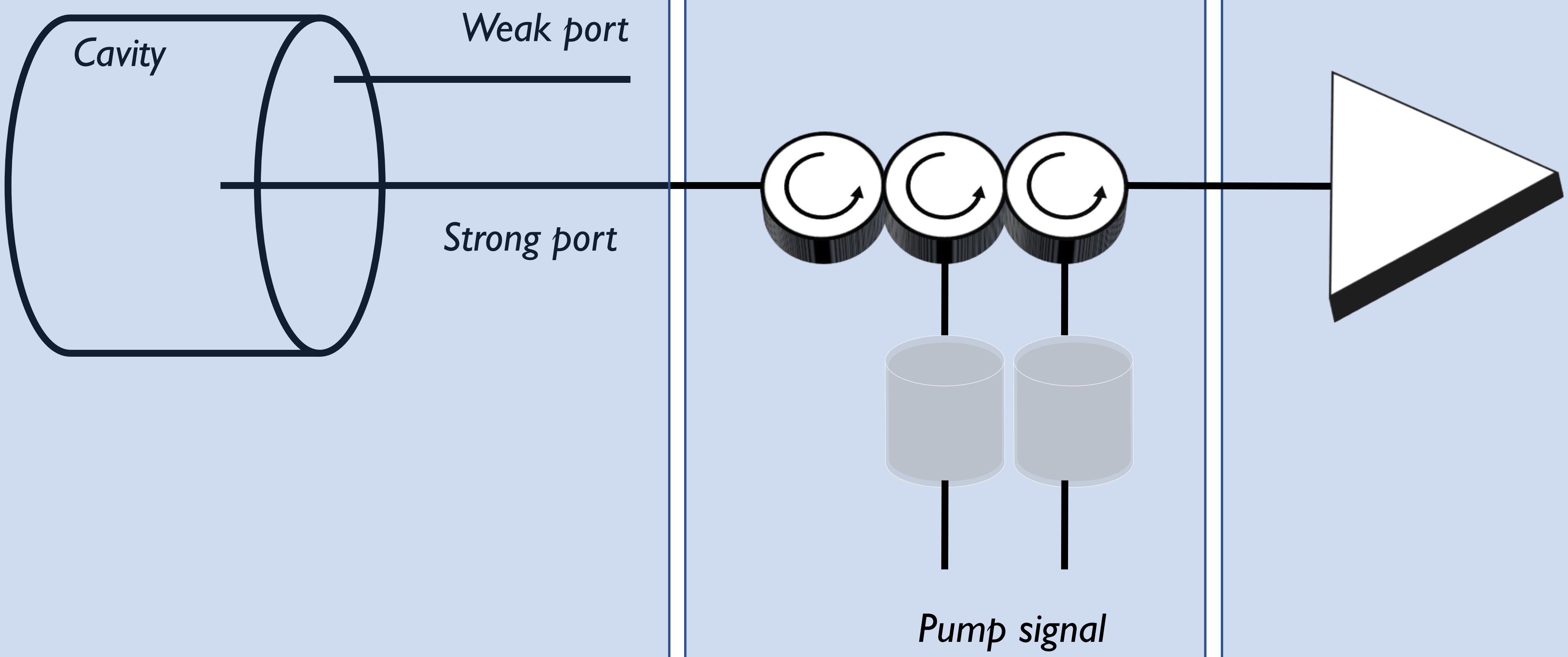


Receiver chain

- *Signal resonated in the cavity*
- *Typical temperature ~ 30 mK*

- *Primary amplification with JPA*
- *Typical gain ~ 20 dB*

- *Subsequent amplification*
- *Typical gain ~ 60 dB*



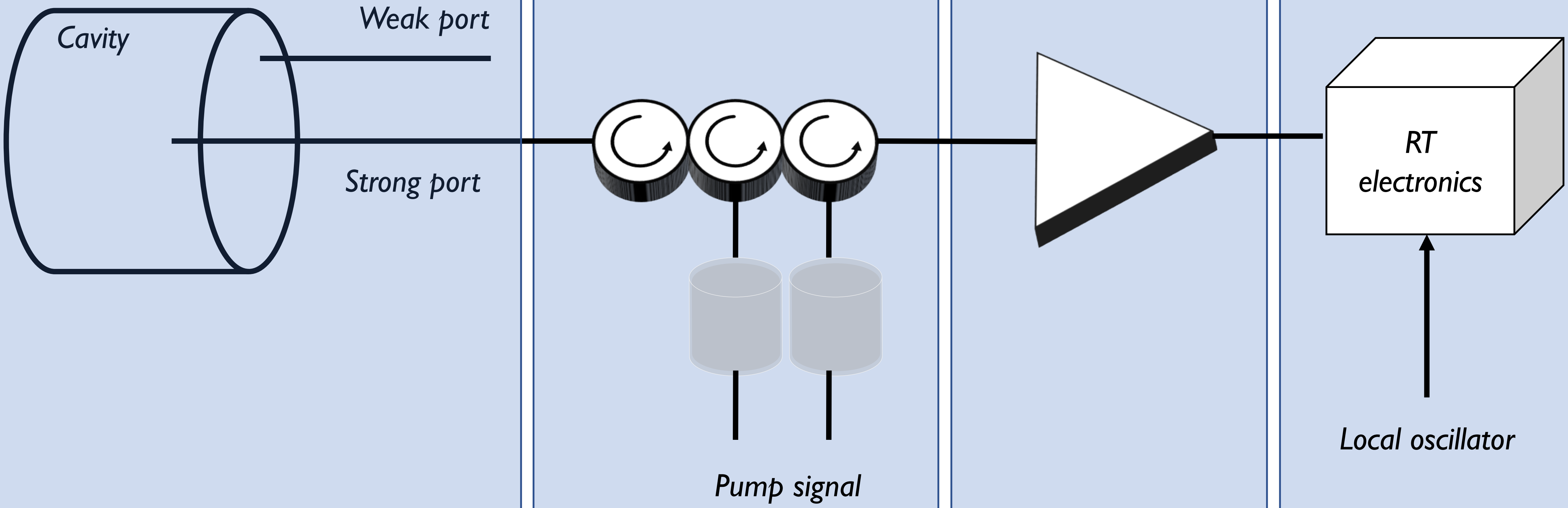
Receiver chain

- *Signal resonated in the cavity*
- *Typical temperature ~ 30 mK*

- *Primary amplification with JPA*
- *Typical gain ~ 20 dB*

- *Subsequent amplification*
- *Typical gain ~ 60 dB*

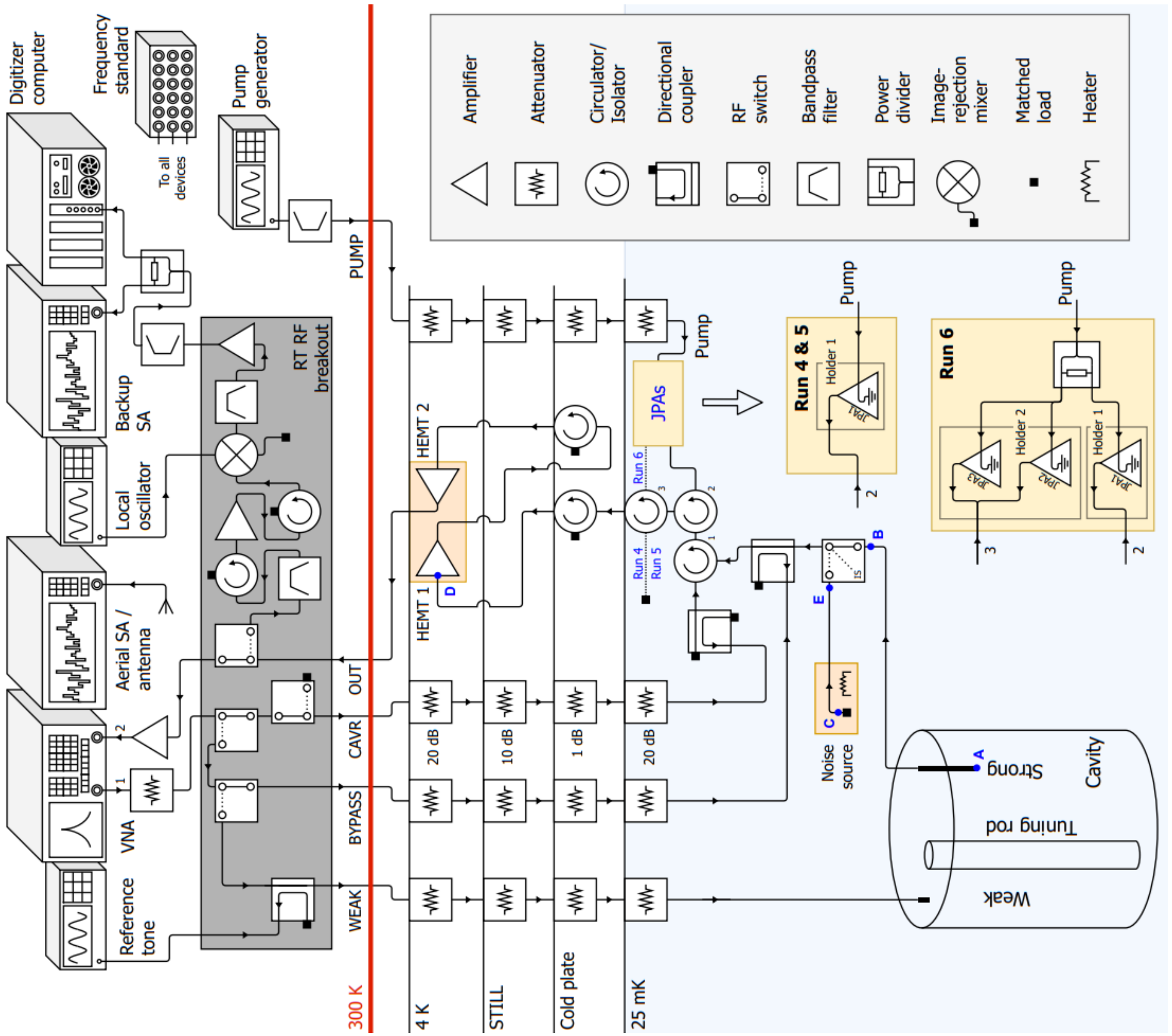
- *RF / IF amp*
- *Gain ~ 50 dB*
- *Downconversion*
- *ADC*



Receiver chain

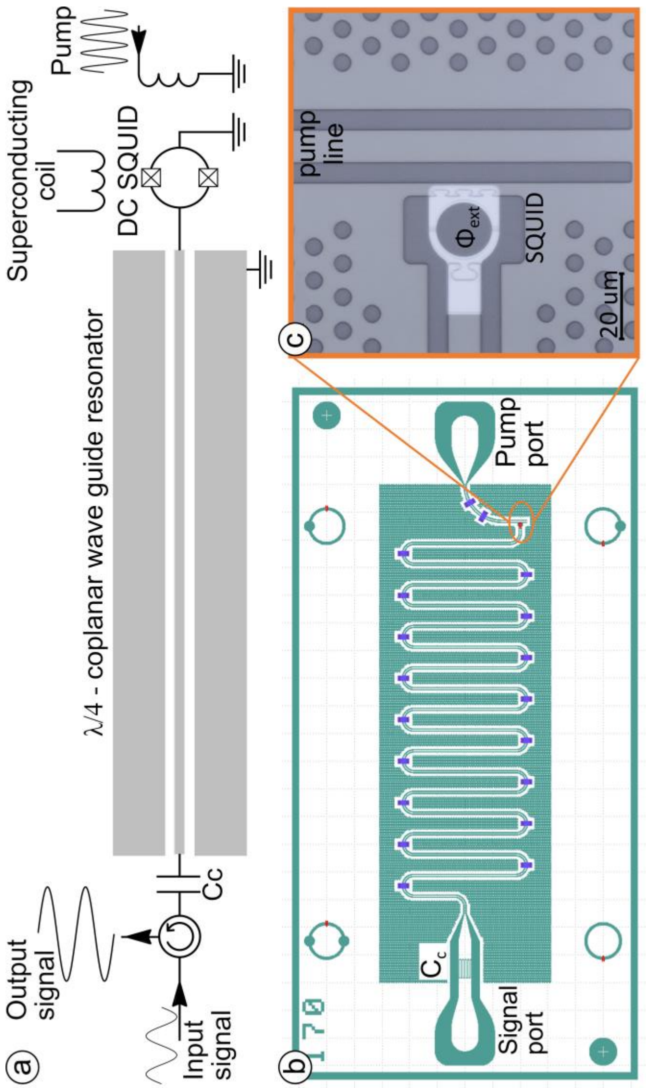
In practice…

- *Characterization lines*
  - *Weak / bypass / reflection*
  - *Cavity and chain characterization*
- *Noise source*
  - *Weakly coupled to the system*
  - <u>*Heating up to 400 mK → ΔT_{sys} < 1 mK*</u>
  - *JPA-off calibration / System noise double-check*
- *Cryogenic switch*
  - *Between cavity and noise source*
  - <u>*3rd phase (in between): upstream line-loss meas*</u>
- *RT breakout box*
  - *Remote-switching the measurement paths*
  - *Supplement RF / IF gain*
- *Backup SA / RF probe / Aerial SA*
  - *Help system cal. / candidate veto*



The Josephson Parametric Amplifier

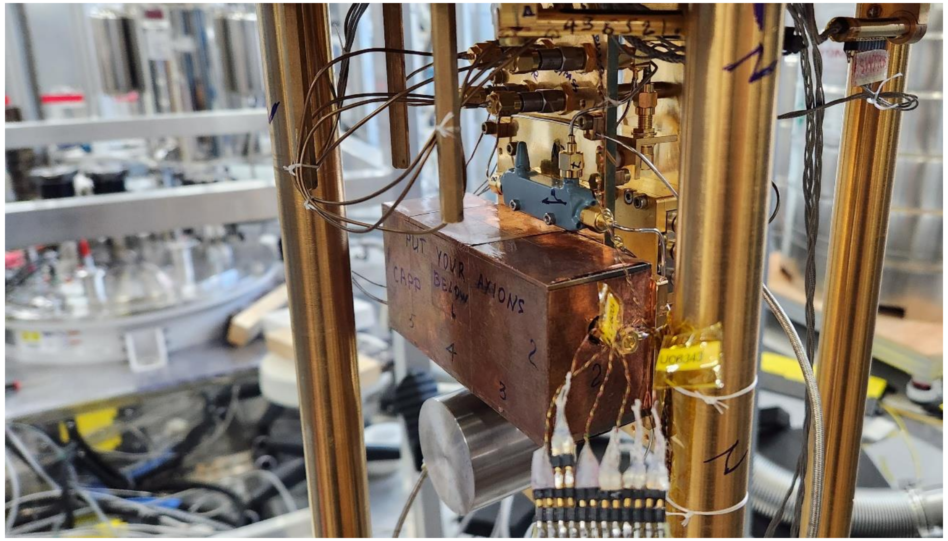
Sergey Uchaikin et al, Frontier Physics
10.3389/fphy.2024.1437680

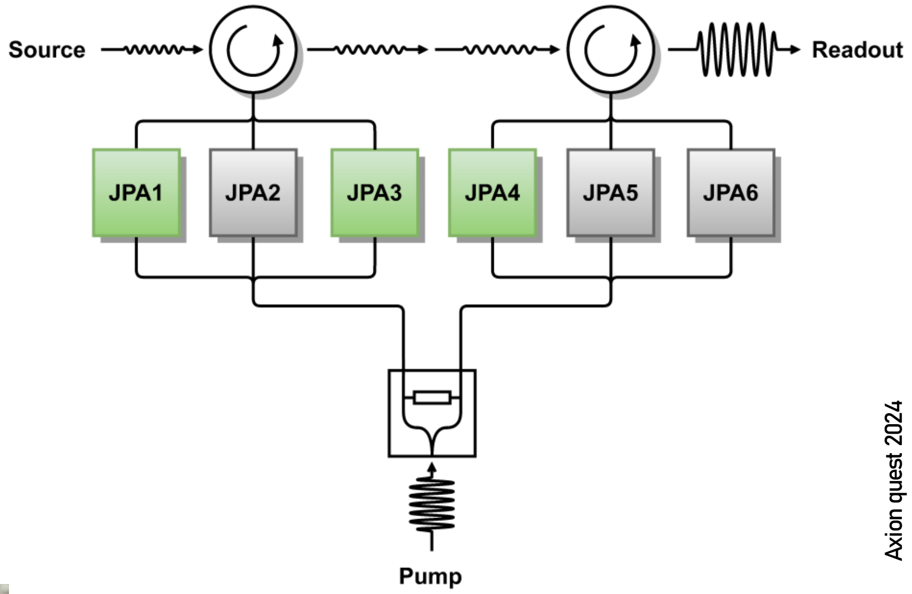


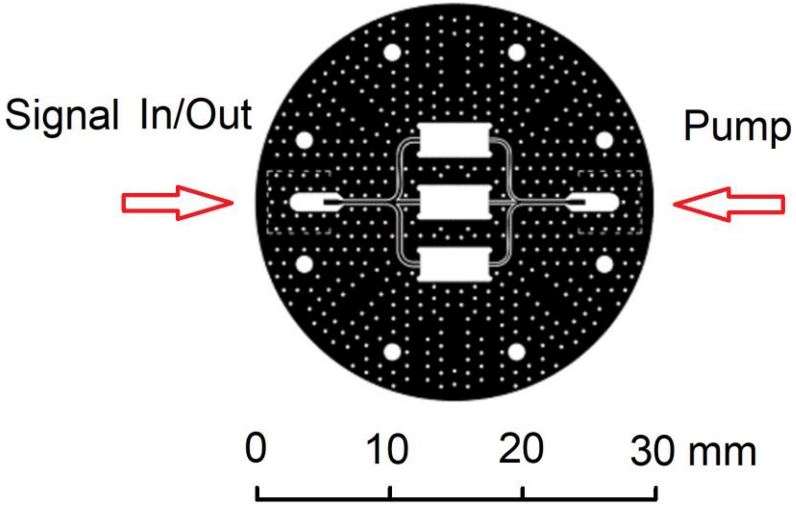
- *Flux-driven JPAs*
- *Collaborating with U. of tokey*

Parallel JPAs

- *3 JPAs bundled up*
- *Single holder / flux bias / pump*
- *Extending the amplifier's frequency range*





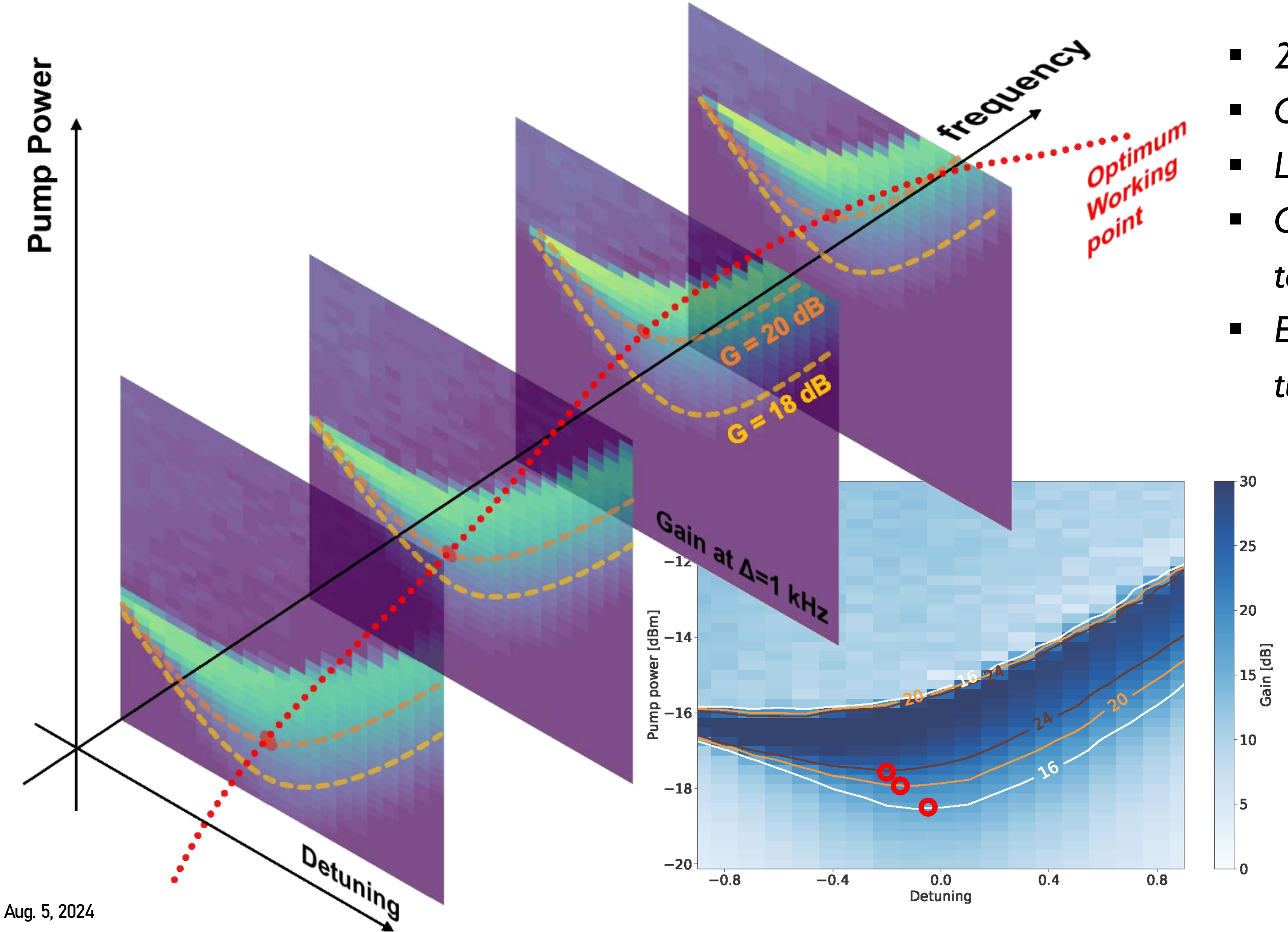


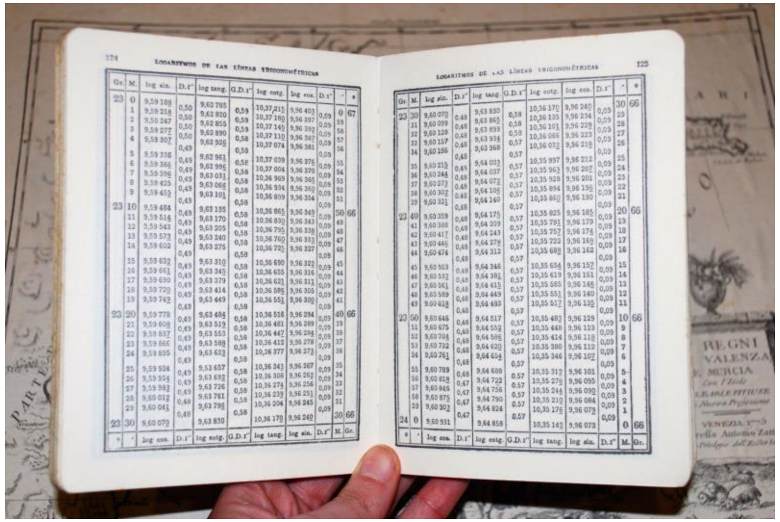
<u>More discussion in Boris' talk on Friday</u>

The Josephson Parametric Amplifier

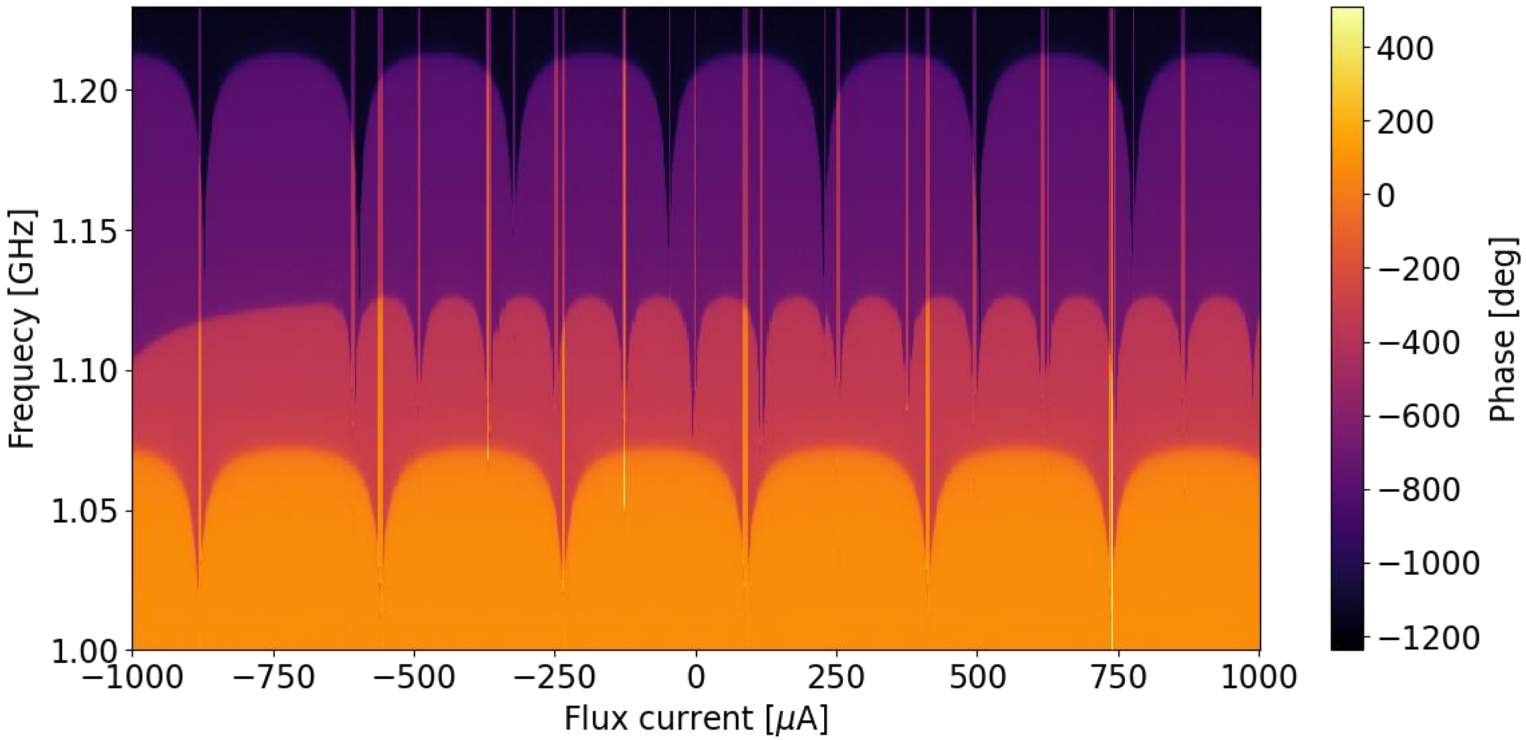
Caglar Kutlu et al,
arXiv:2305.08866

- *2D JPA Paramap ($f_{passive}$, P_{pump})*
- *Gain contour*
- *Lower pump power → Lower added noise*
- *Get the lowest P_{pump} in the contour of given target gain (typically 20 dB)*
- *Every 0.2 ~ 0.5 MHz, interpolated for each tuning step*





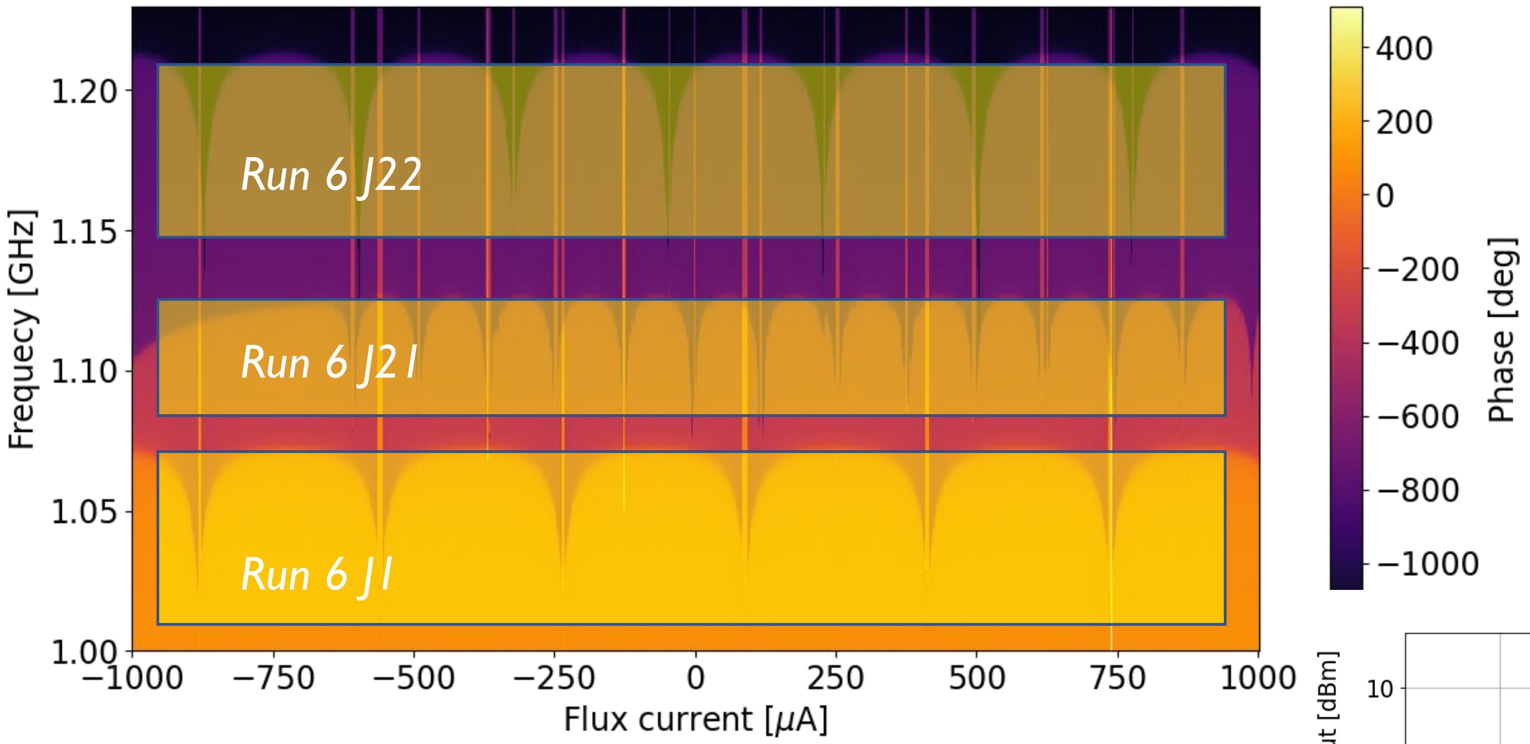
The Josephson Parametric Amplifier



3 Parallel JPA calibration

- *All tuned with one bias current circuit*
- *Frequency ranges are separated, no interference among them (mostly)*

The Josephson Parametric Amplifier



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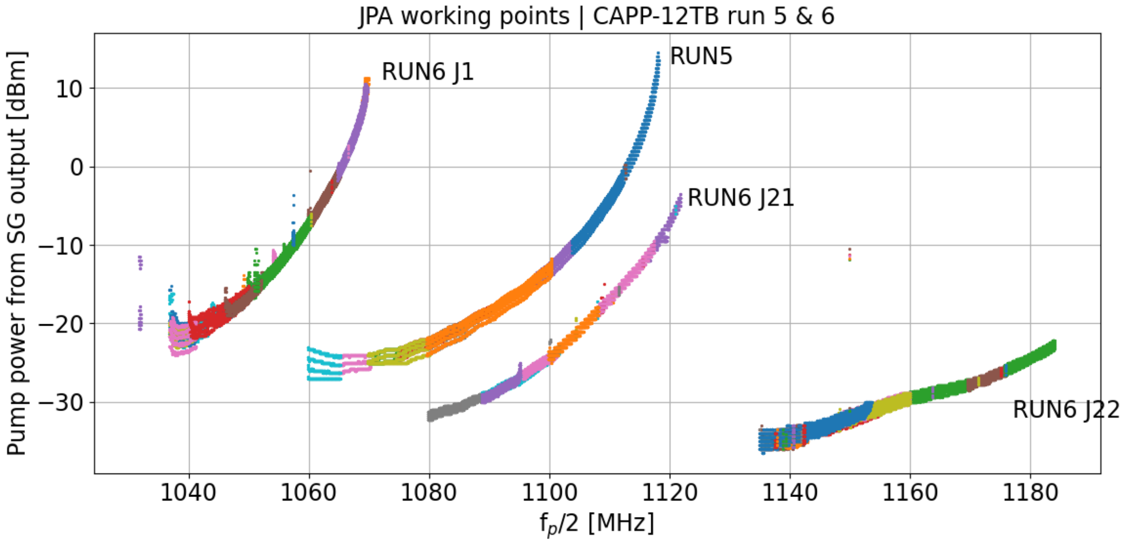
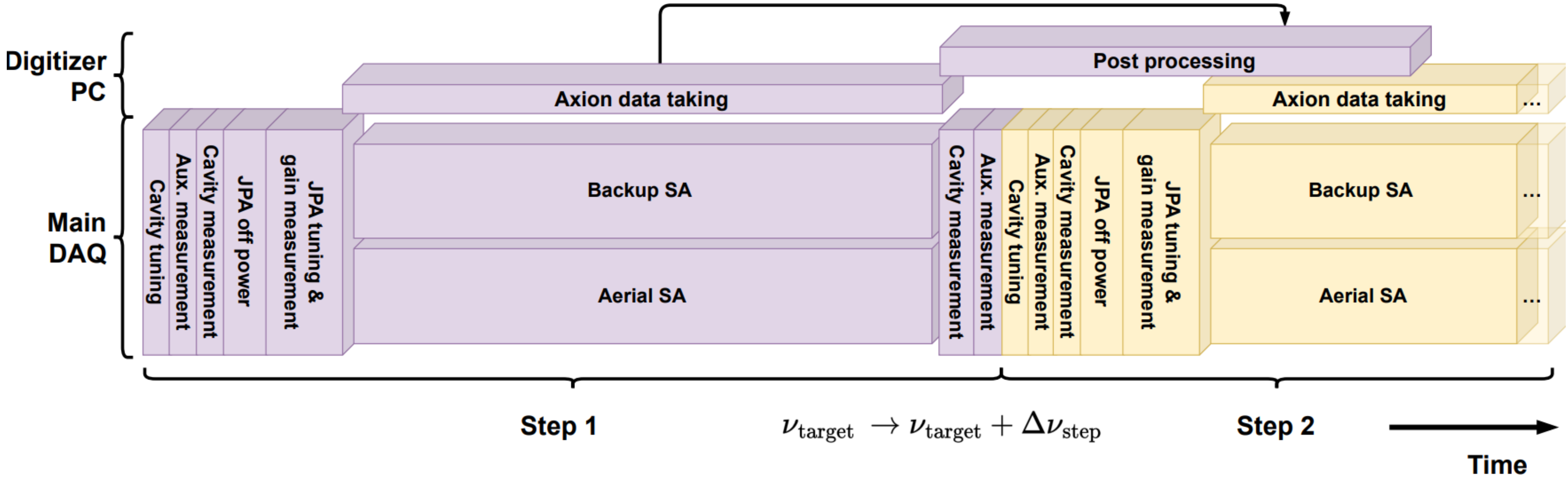


Successfully utilized in the science run (run 6)

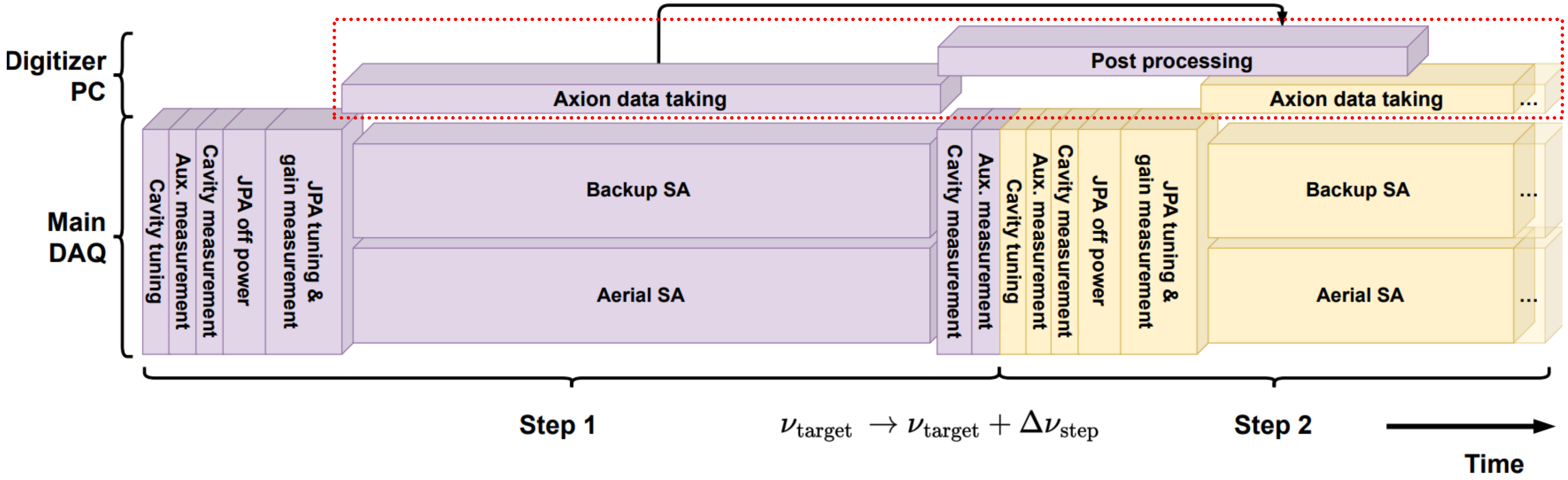
- *No degradation in noise / gain performance of JPAs*
- *Total coverage extended to 160 MHz (120 MHz overlap with cavity)*

DAQ iteration



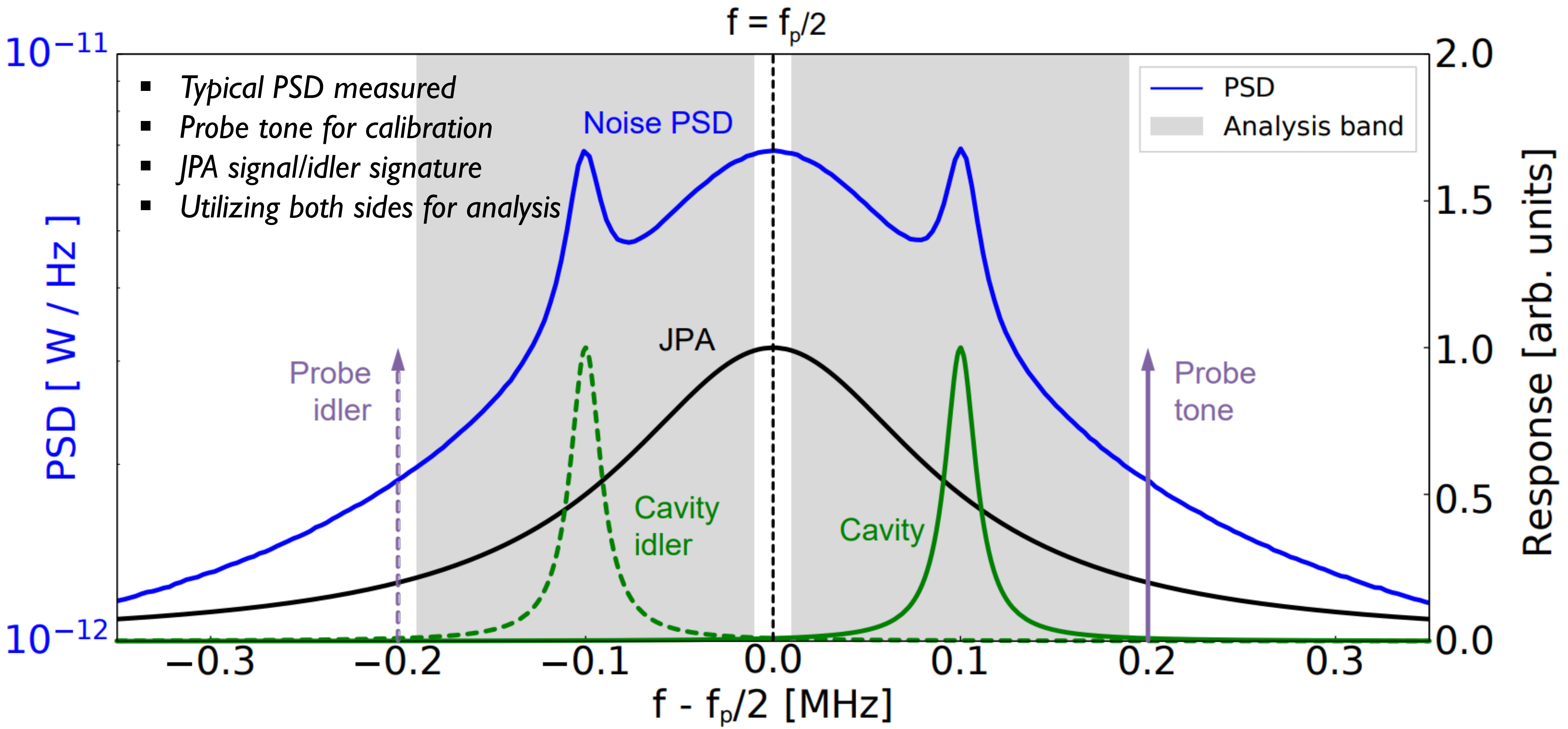
- *192 s acquisition with DAQ efficiency ~ 80%*
- *10 kHz tuning step*
- *3 MHz / day of fixed scanning speed*

DAQ iteration

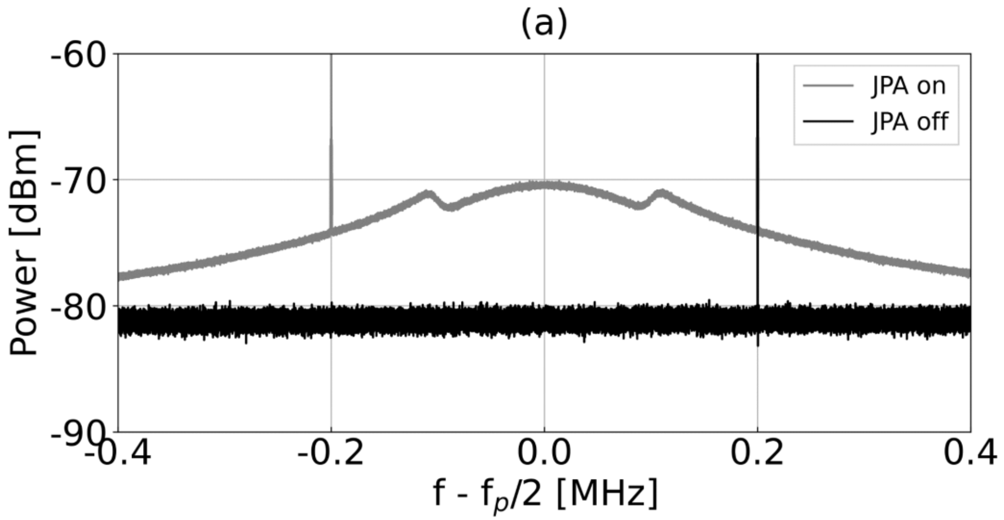


- *192 s acquisition with DAQ efficiency ~ 80%*
- *10 kHz tuning step*
- *3 MHz / day of fixed scanning speed*
- *Digitizer FIFO configuration*
- *Parallel FFT with 12 core CPUs*
- *45 MS/s sample rate | 10.7 MHz IF*

Data at a glance

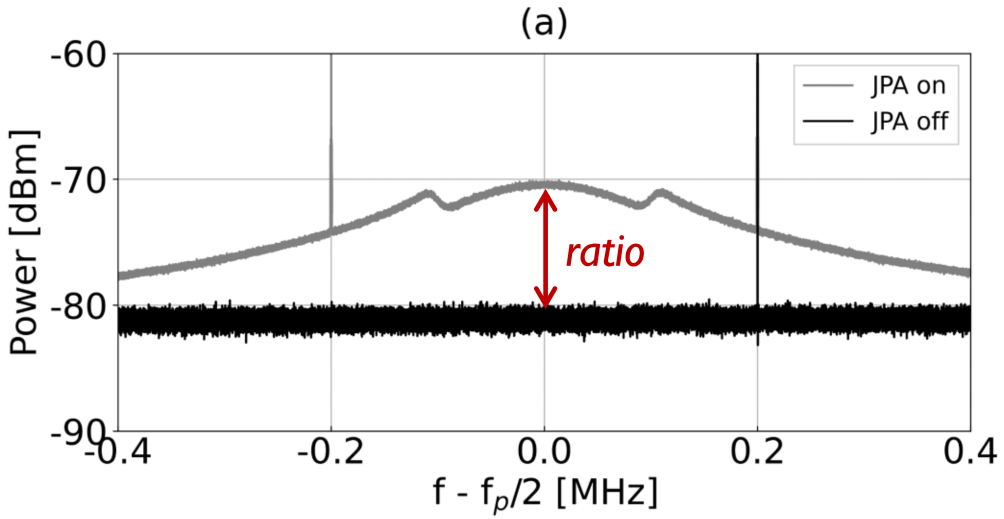


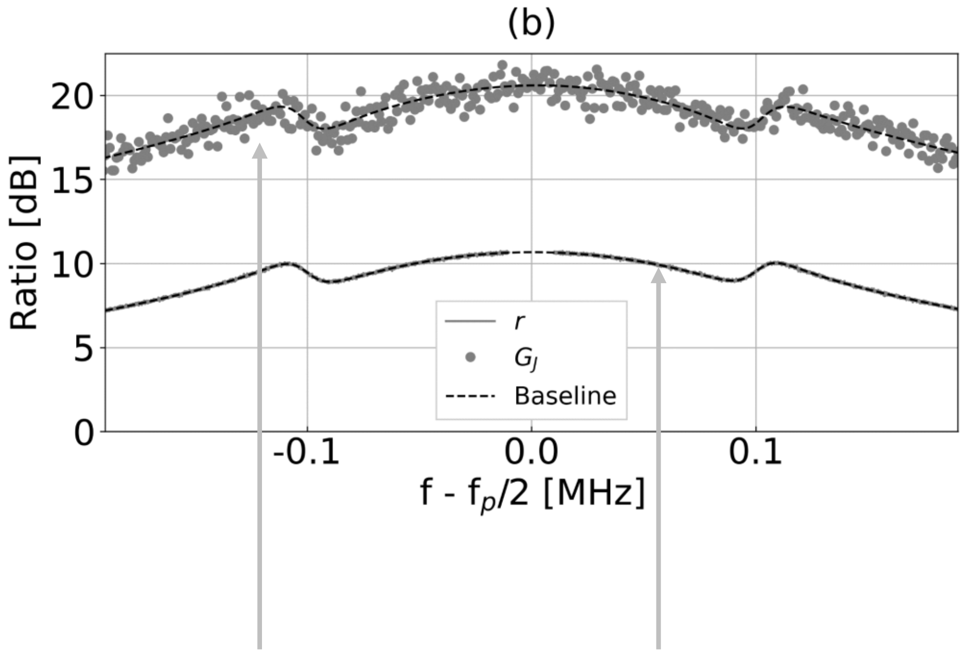
Calibration



- *JPA on/off measurement*
- *JPA gain / PSD ratio*

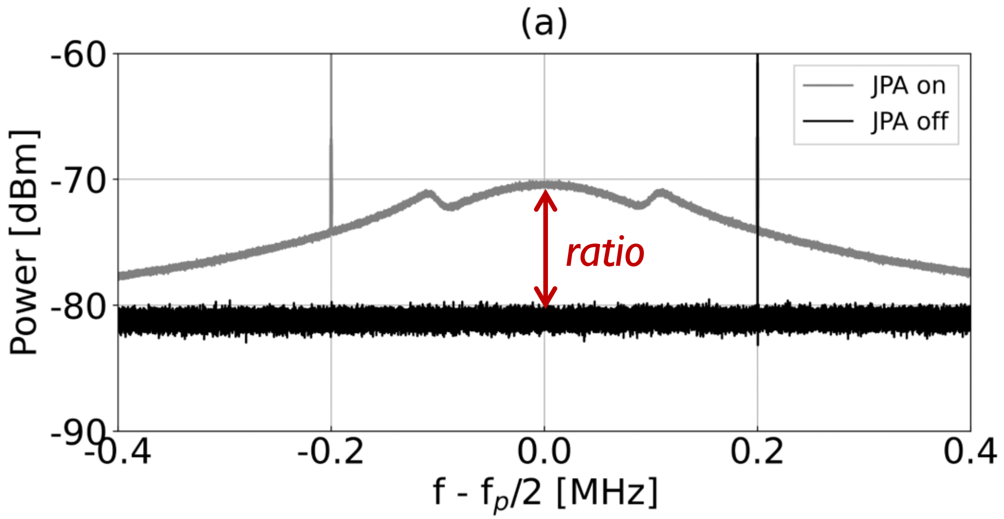
Calibration

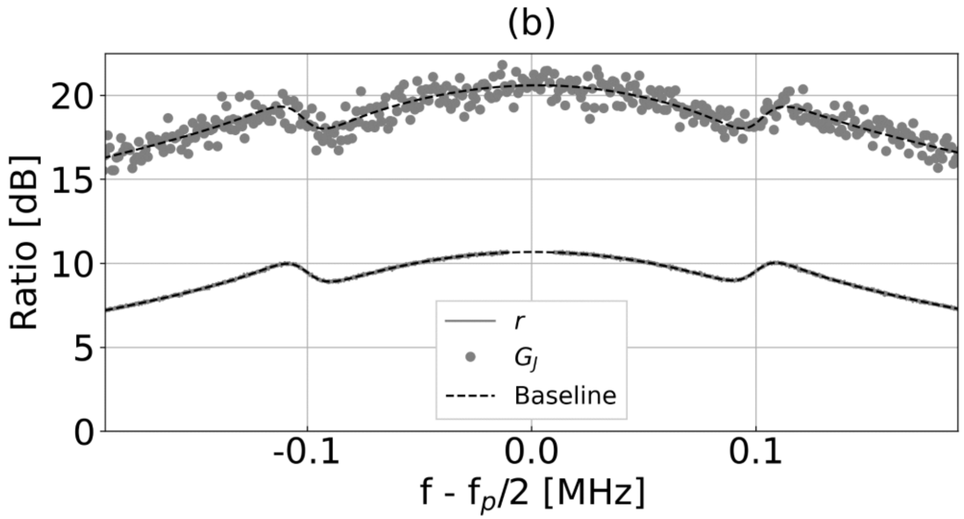


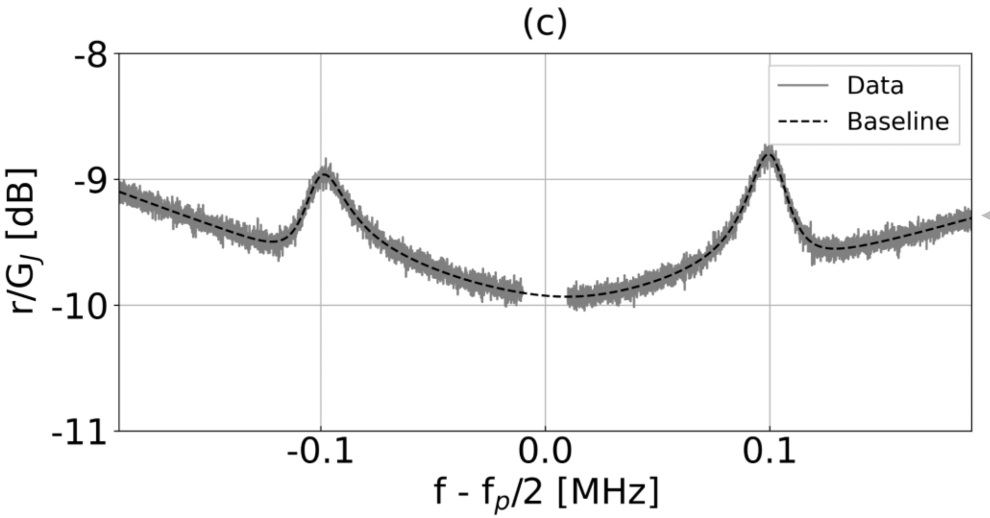


- $G_{JPA} = S_{21}^{ON} / S_{21}^{OFF}$ | $r = P^{ON} / P^{OFF}$

Calibration

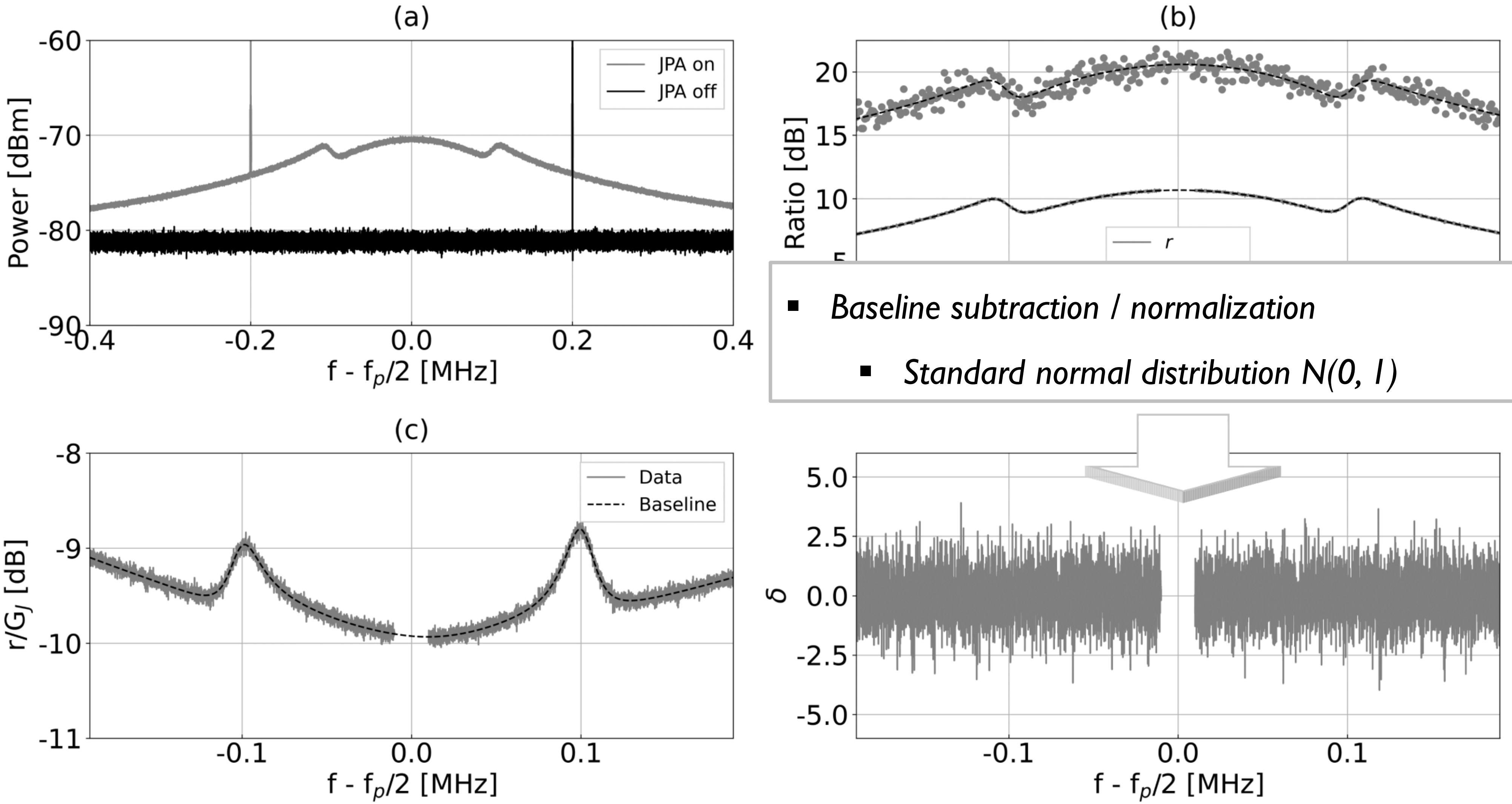






- $G_{JPA} = S_{21}^{ON} / S_{21}^{OFF}$ | $r = P^{ON} / P^{OFF}$
- *SNR improvement (SNRI)* $= G_{JPA} / r$
- *System noise* $= T_{sys}^{OFF}$ *x SRNI*

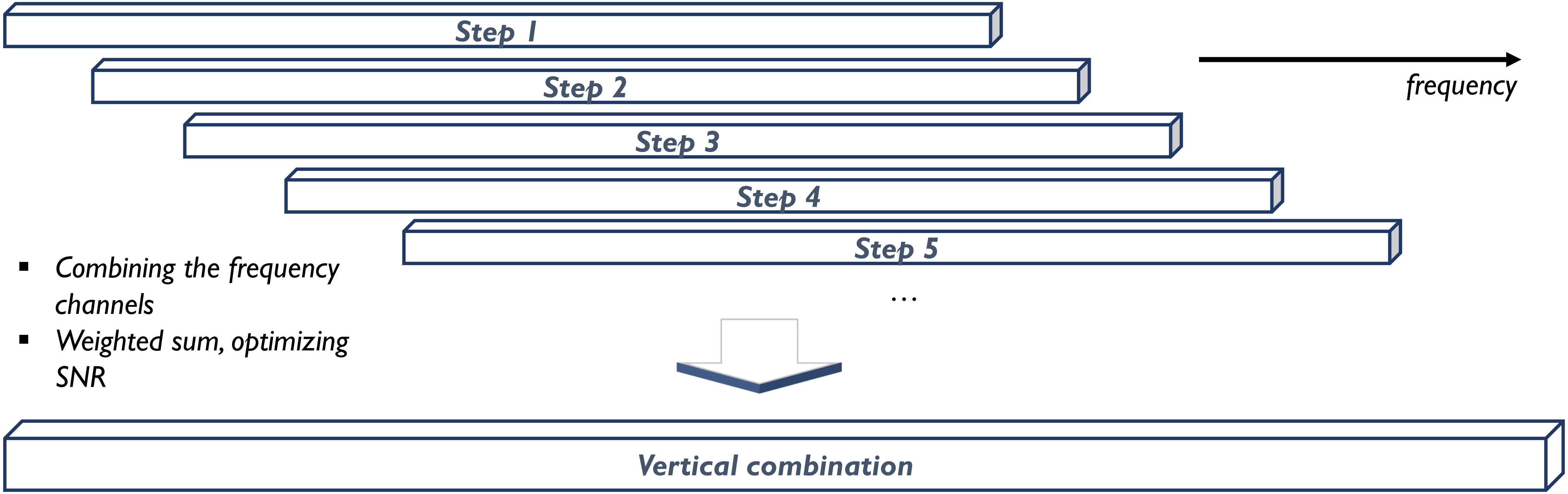
Calibration



- *Baseline subtraction / normalization*
  - *Standard normal distribution N(0, 1)*

Combining

Data analysis



- *Combining the frequency channels*
- *Weighted sum, optimizing SNR*

Data analysis

Step 1

Step 2

Step 3

Step 4

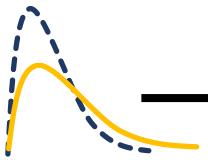
Step 5

…

frequency

- *Combining the frequency channels*
- *Weighted sum, optimizing SNR*

Vertical combination



Convolution

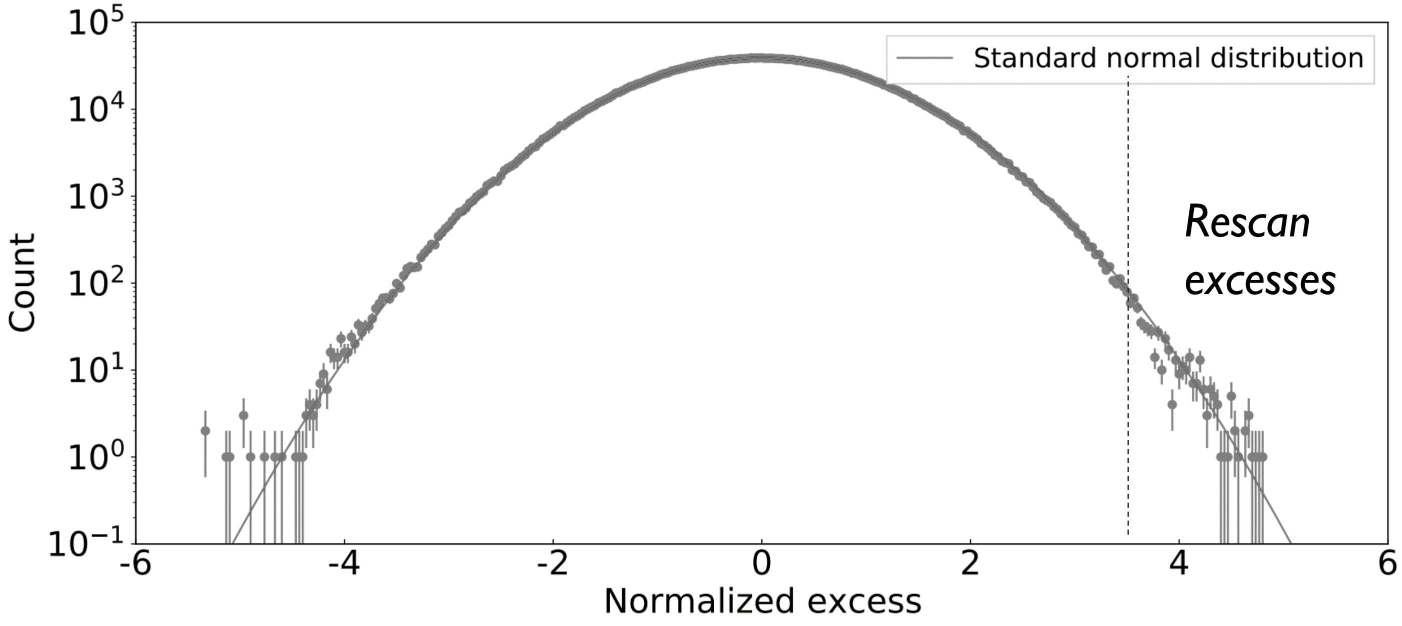
- *Convolving expected lineshapes (depending on the velocity dispersion models)*
- *Optimizing the detection rate of signals*

Horizontal combination

Rescan the candidates

Rescan target

- *With the grandspectrum ~ N(0, 1)*
- *90% confidence level at the target SNR = 5σ*
  - *3.718σ frequentist threshold for rescan candidates*
- *Total O(100) candidates*



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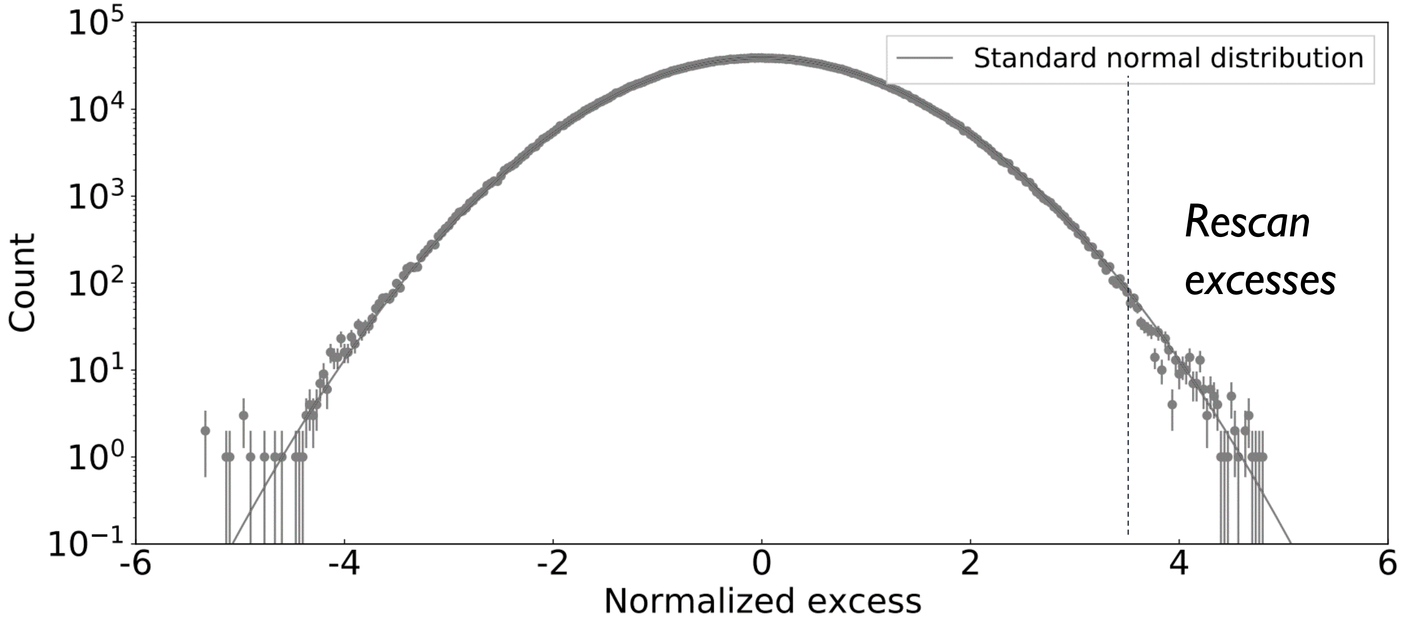
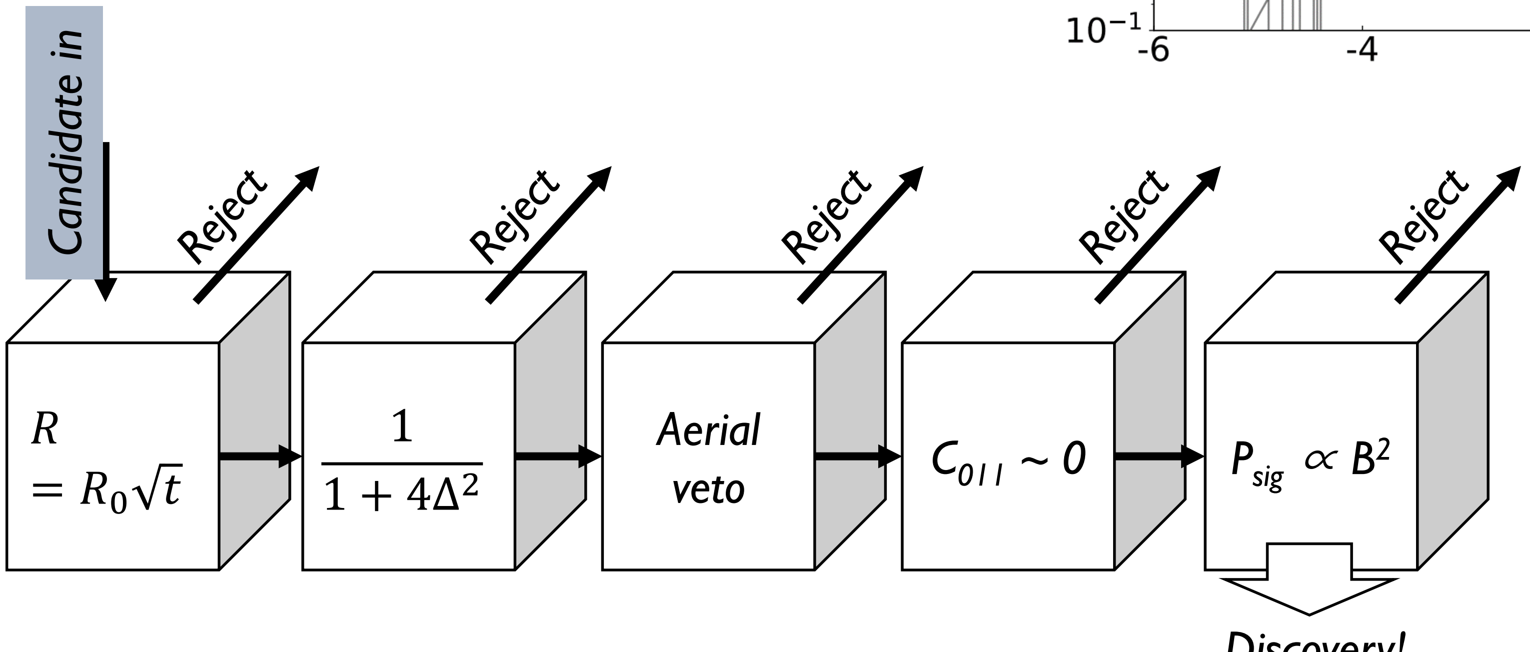
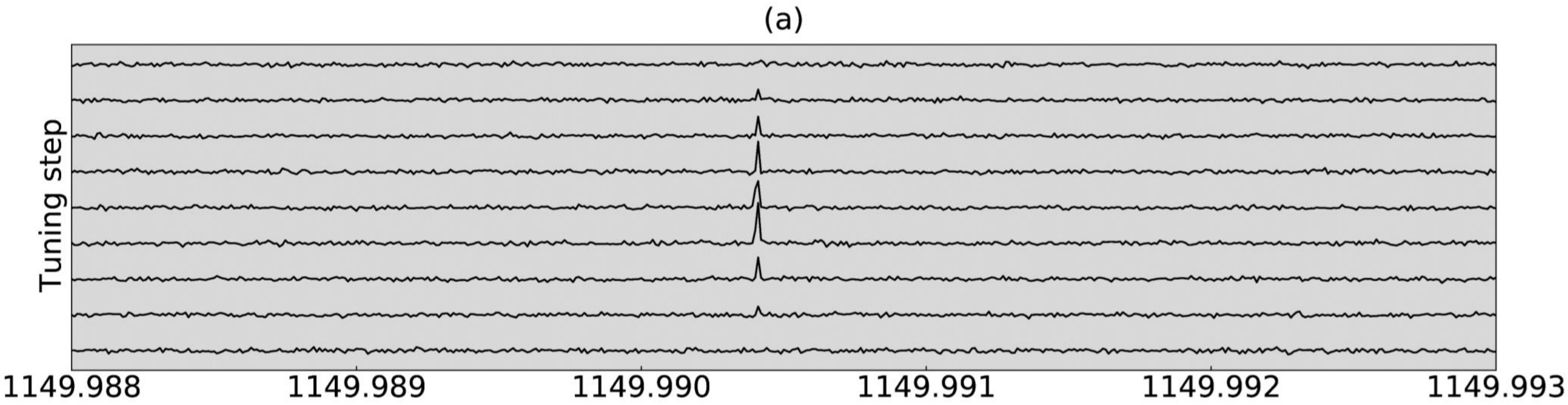




Rescan strategy

1. *Persistency*
2. *Lorentzian test (from cavity?)*
3. *Aerial antenna veto*
4. *TM_{011} mode (Geometrical factor)*
5. *Magnetic field dependence*

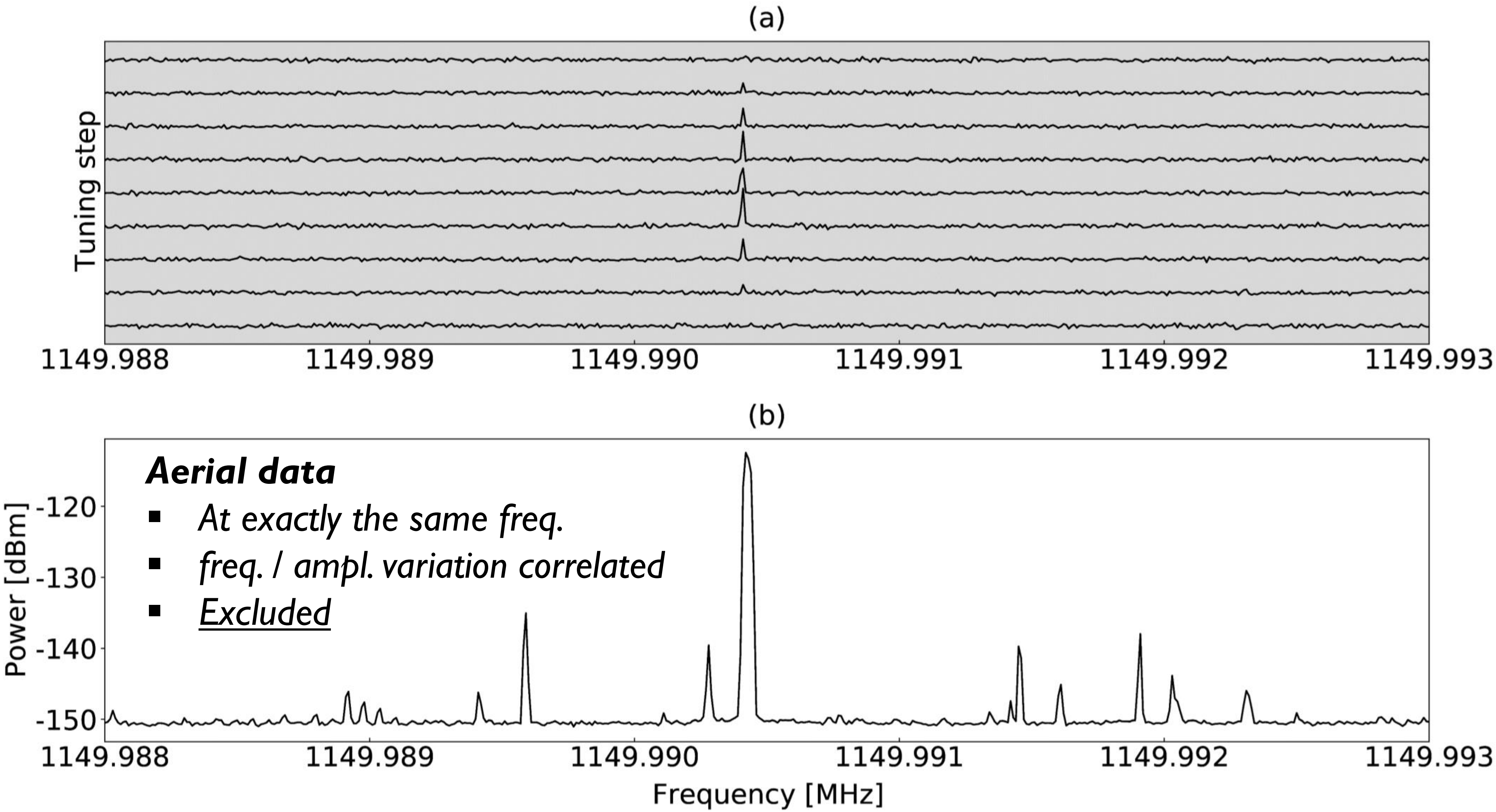
Rescan the candidates



Example of a candidate

- *Persistent signal*
- *Follows the expected Lorentzian distribution (as the cavity is tuned)*

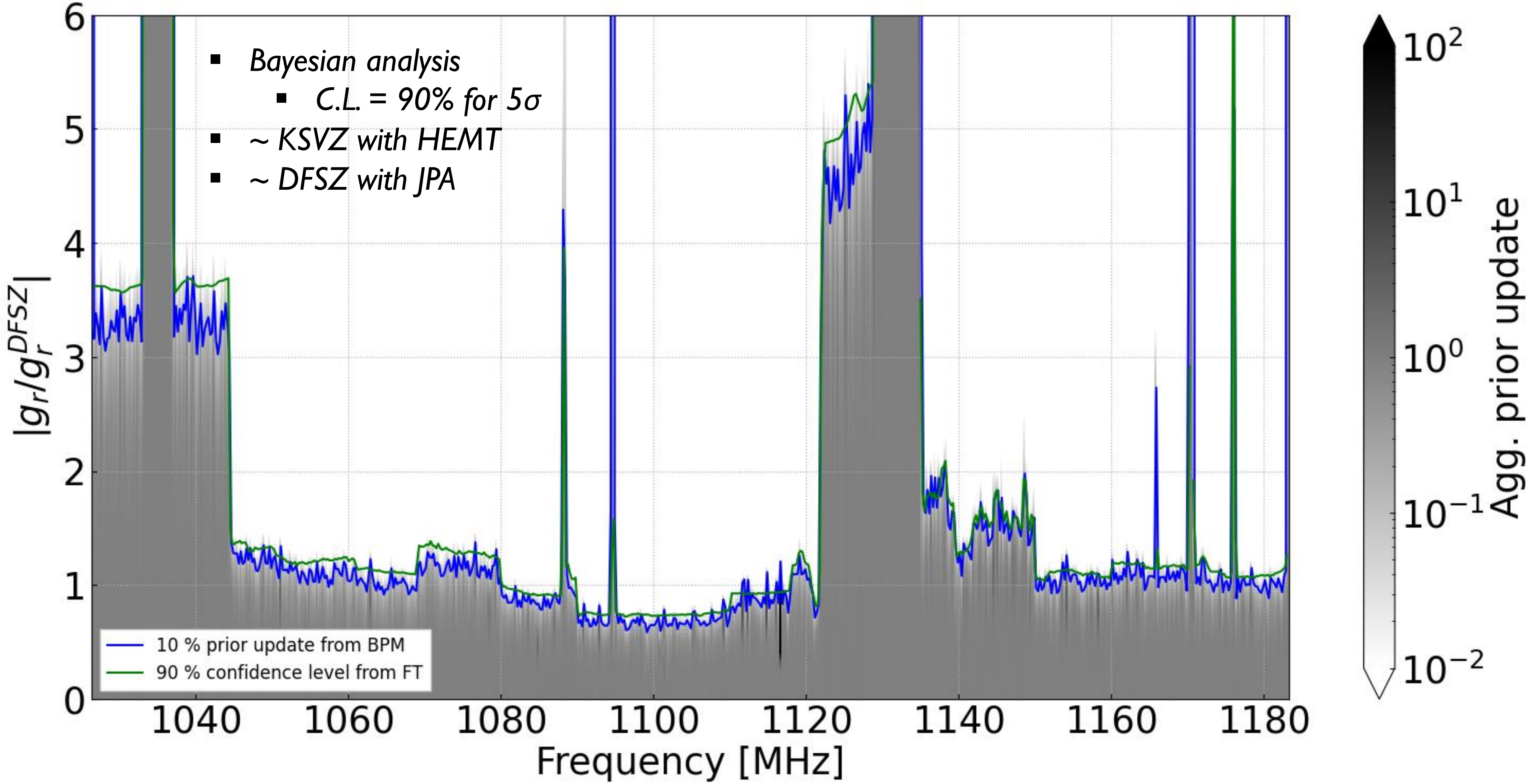
Rescan the candidates



Aerial data

- *At exactly the same freq.*
- *freq. / ampl. variation correlated*
- <u>*Excluded*</u>

Achieved limit on $g_{a\gamma\gamma}$

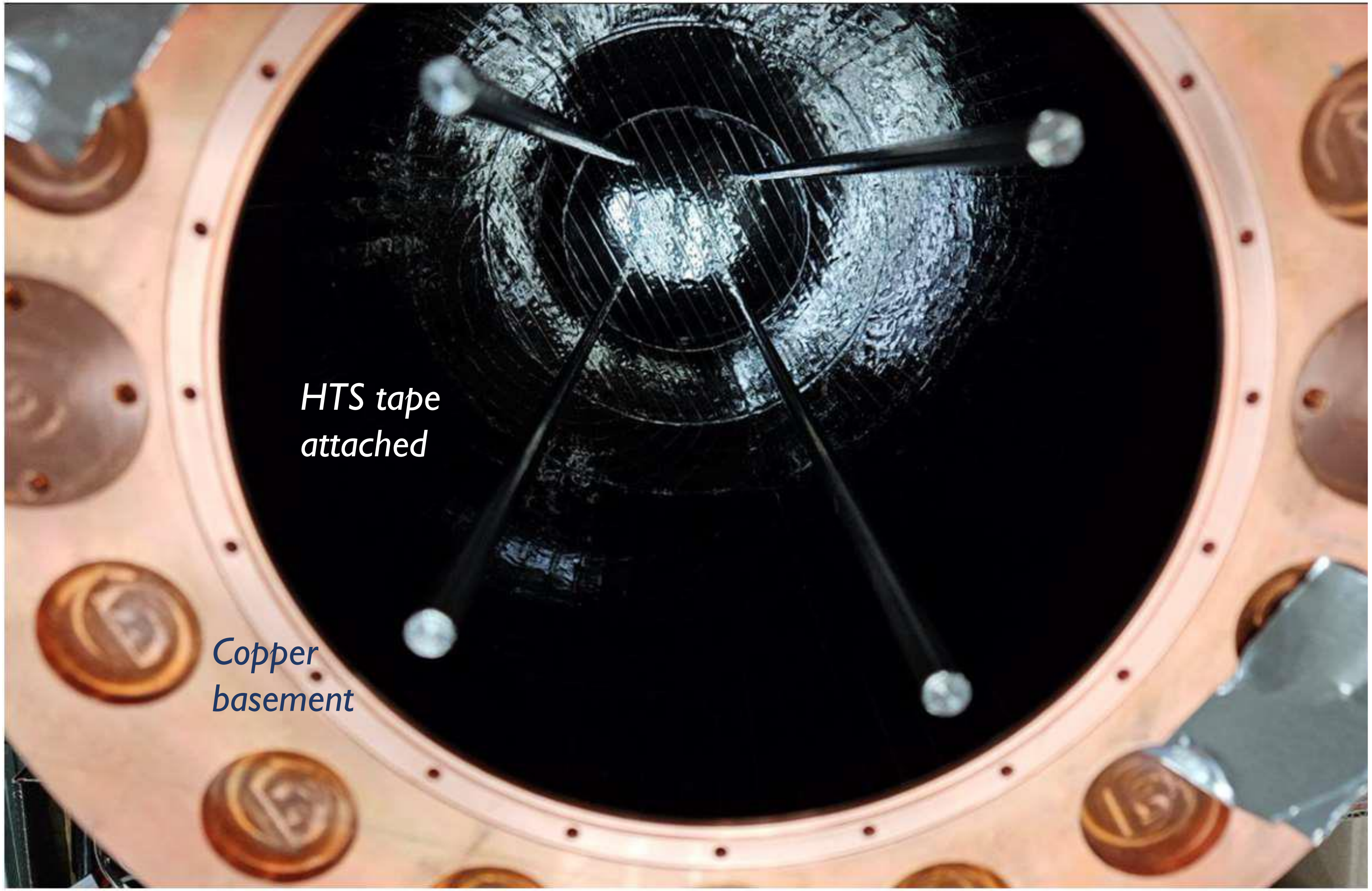


Upcoming run

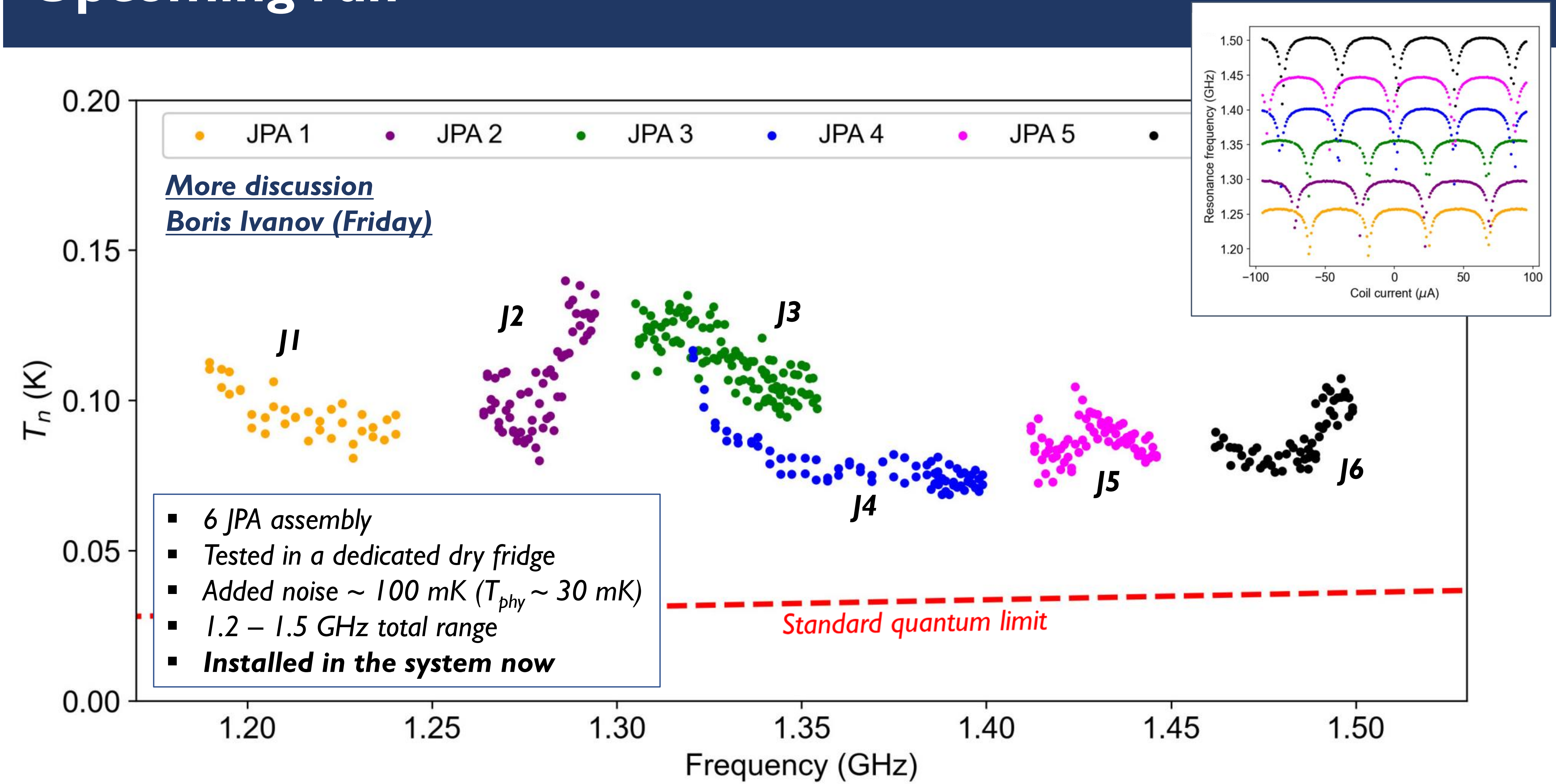
More discussion
Danho Ahn (Wednesday)

- *SC cavity with HTS tapes*
  - *All walls and the tuning rod*
- *Ultralight cavity design*
- *$Q_0 \sim 10^6$ at 10 K (test at cryocooler)*
  - *O(10) improvement*
- *1.2 – 1.5 GHz tuning range*
- ***Installed in the system now***

More discussion
Danho Ahn (Wednesday)



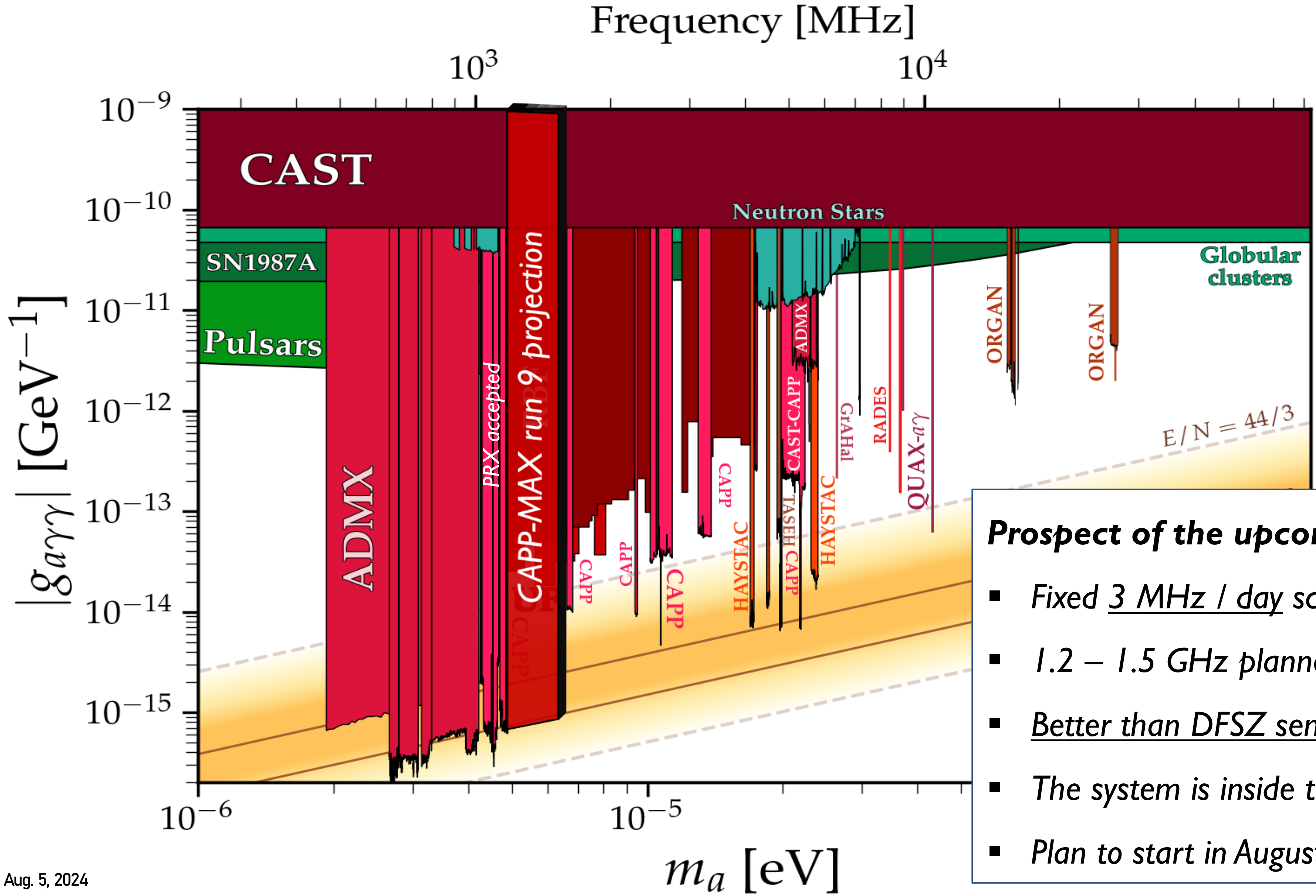
Upcoming run

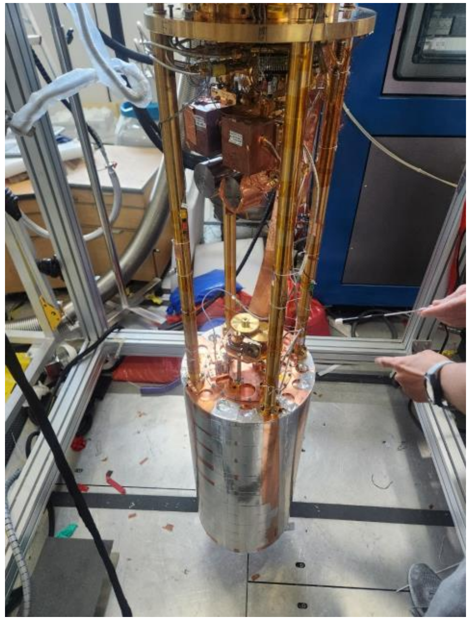


[More discussion Boris Ivanov (Friday)]

- *6 JPA assembly*
- *Tested in a dedicated dry fridge*
- *Added noise ~ 100 mK (T_{phy} ~ 30 mK)*
- *1.2 – 1.5 GHz total range*
- ***Installed in the system now***

Upcoming run





Prospect of the upcoming run

- *Fixed 3 MHz / day scanning speed*
- *1.2 – 1.5 GHz planned*
- *Better than DFSZ sensitivity*
- *The system is inside the LHe bath*
- *Plan to start in August (3 months planned)*

On the way!

Axion Search Experiments / CAPP-12TB Cryogenics Monitor
Experiment information
Exp no
2028
Run no.
308
Cooldown name
Run 9a
Exp. description
Run 9 setting up
Exp and Run Info
Run 9 about to go!
Cavity
Current resonance frequency
1.49374 GHz
Current quality factor
372410
Antenna coupling
0.2313
Cavity resonance frequency
Quality factor
Antenna coupling
Cryogenics monitor
Leiden pressures
Cavity measurement at 20 K
Q ~ 500 000 with the rod at the center (highest freq, lowest Q)
Stay tuned!