Kinetic Inductance Detectors for Astrophysical and Direct Dark Matter Detection

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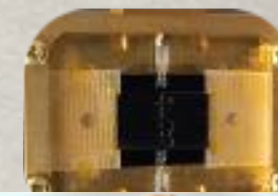
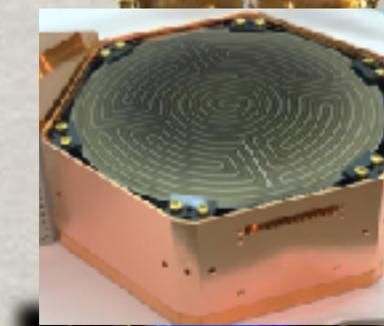
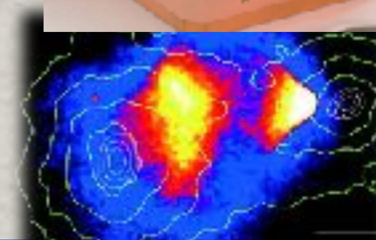
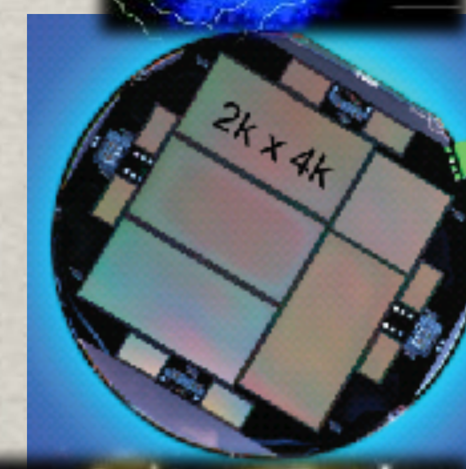
Dark Matter and Weak Interactions (Darkwin) Conference
International Institute of Physics, September 02-13, 2019

Outline

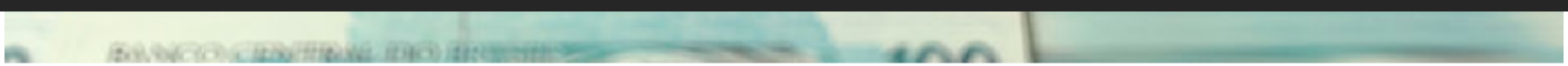
- Microwave Kinetic Inductance Detectors
- Motivations:
  - Direct Detection
  - Astrophysical constraints: strong lensing
- Current issues for ONIR MKIDS
- Design, simulation and fabrication
- Homogeneity
- Efficiency


NEWS · 19 AUGUST 2019

Brazil's budget cuts threaten more than 80,000 science scholarships

If the country's main science-funding agency doesn't get more cash soon, young researchers will stop getting paid.



The National Council for Scientific and Technological Development's scholarship budget was slashed by 21% this year.
ISTOCK.COM/MEDIAPRODUCTION

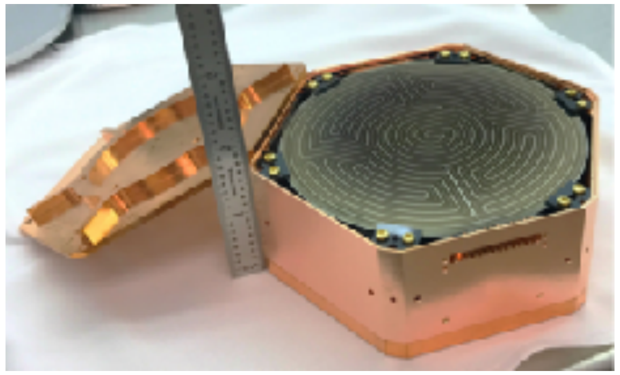
Funding crisis at Brazilian science agency could leave 80,000 researchers and students without pay

By Emiliano Rodríguez Mega | Aug. 19, 2019 , 5:30 PM

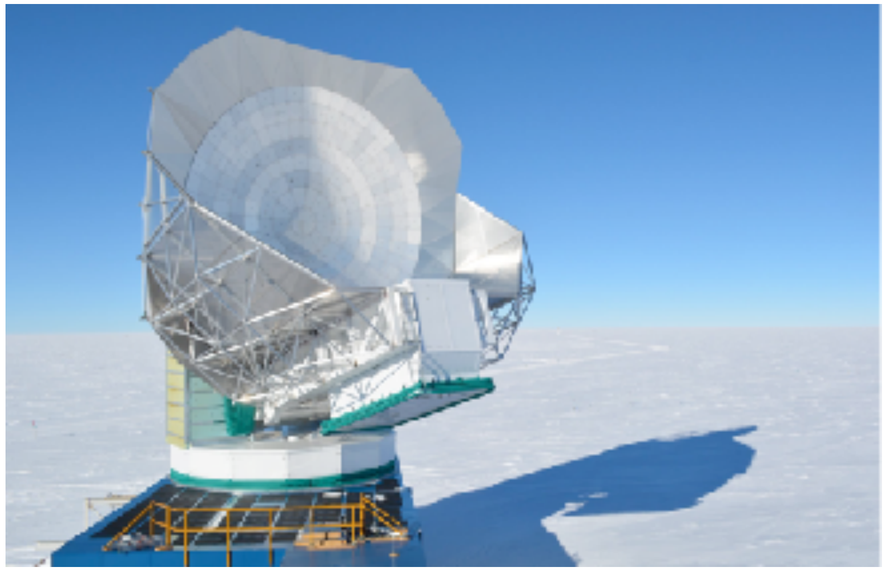
Superconducting Sensors for Astrophysics/ Cosmology and Dark Matter Detection

- Very sensitive due to the small energy gap Δ

  $\Delta \simeq 1.7\, k_B T_c$ ~ meV



- Superconducting Tunnel Junctions
- Transition Edge Sensors
  - Used at Atacama Cosmology Telescope (ACT), the Cryogenic Dark Matter Search (CDMS), the Cryogenic Rare Event Search with Superconducting Thermometers (CRESST), South Pole Telescope (SPT)…



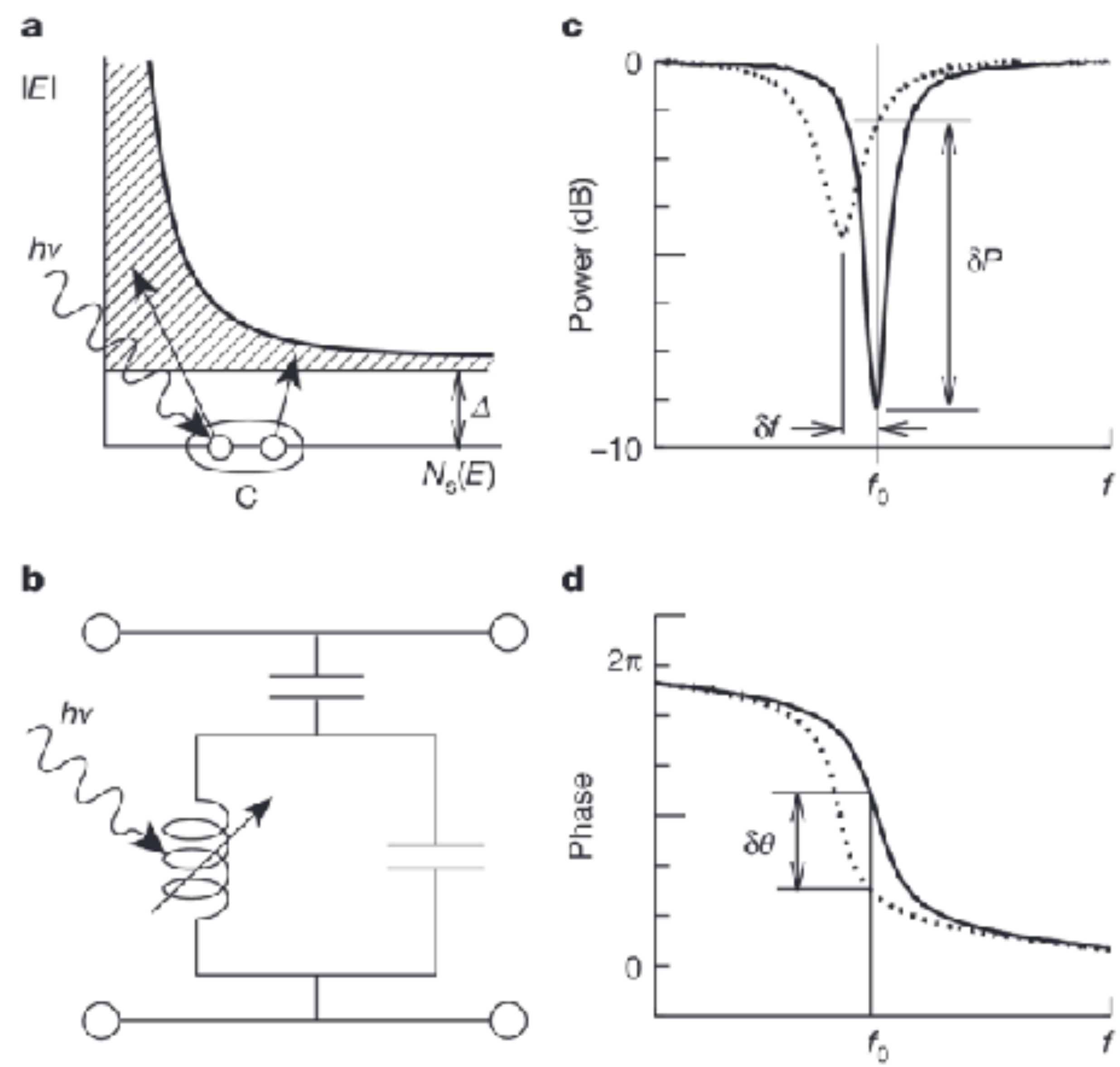
- Advantages: sensitiveness, negligible background
- Problems
  - Hard to multiplex
  - Expensive low temperature electronics

Microwave Kinetic Inductance Detectors

- Very sensitive due to the small energy gap

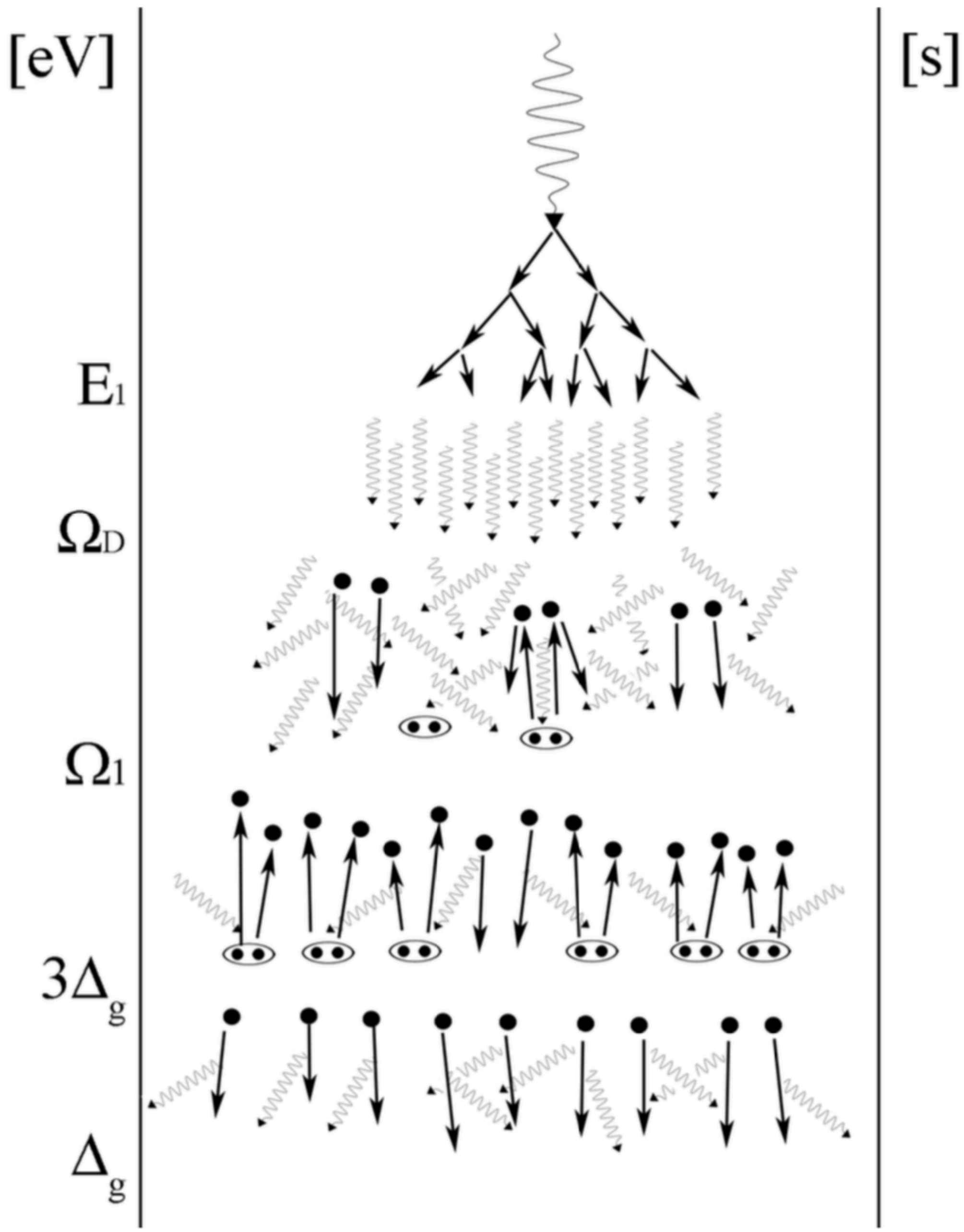
$$\Delta \simeq 1.7\, k_B T_c$$

- Resonant circuit
- Breaking of Cooper pairs changes kinetic inductance
- Coupled to a microwave transmission line
- Single photon changes transmission and phase
- Operates at ~$T_c/10$

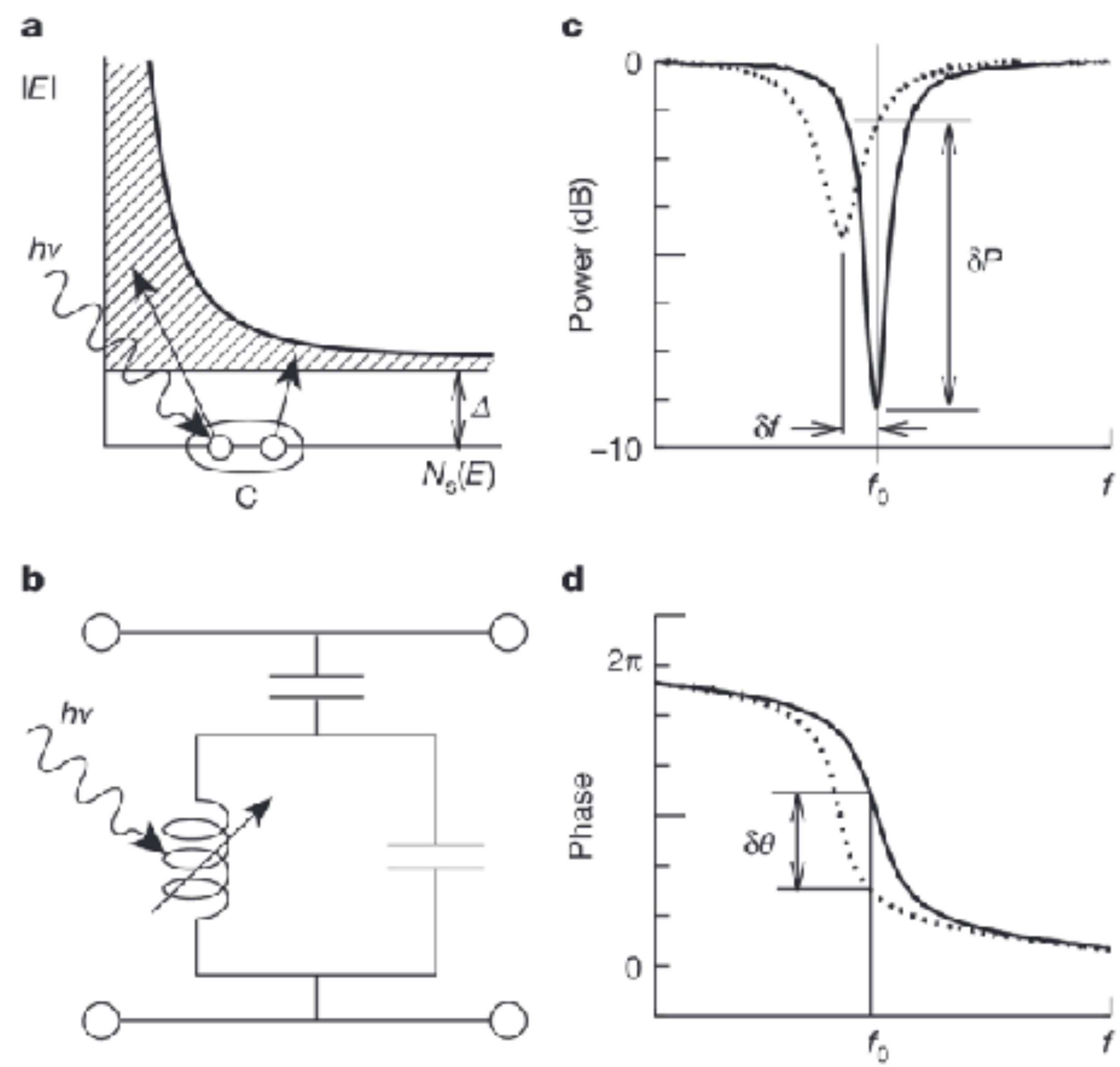


Day et al., Nature, 425, 817 (2003)

Microwave Kinetic Inductance Detectors

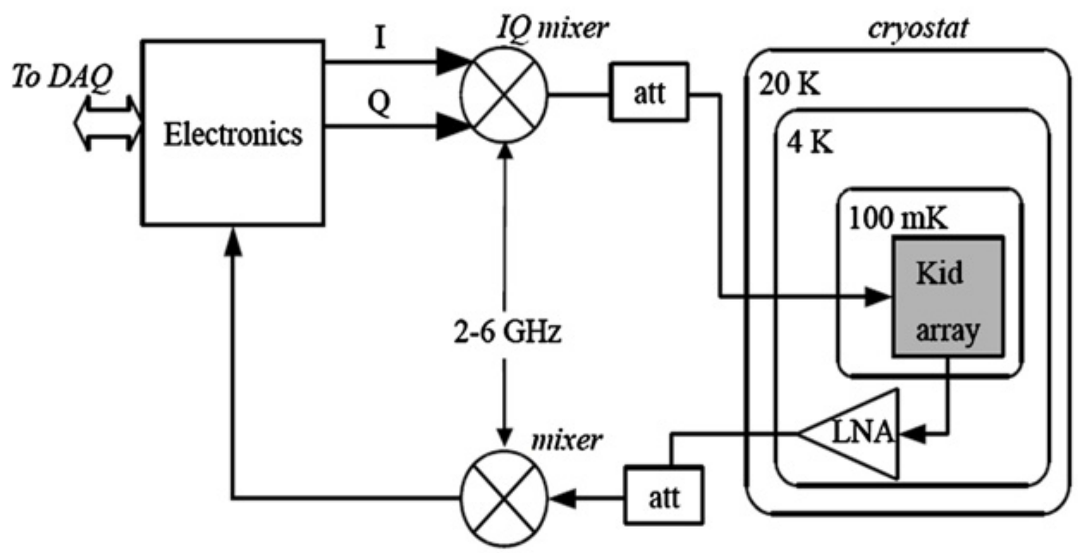


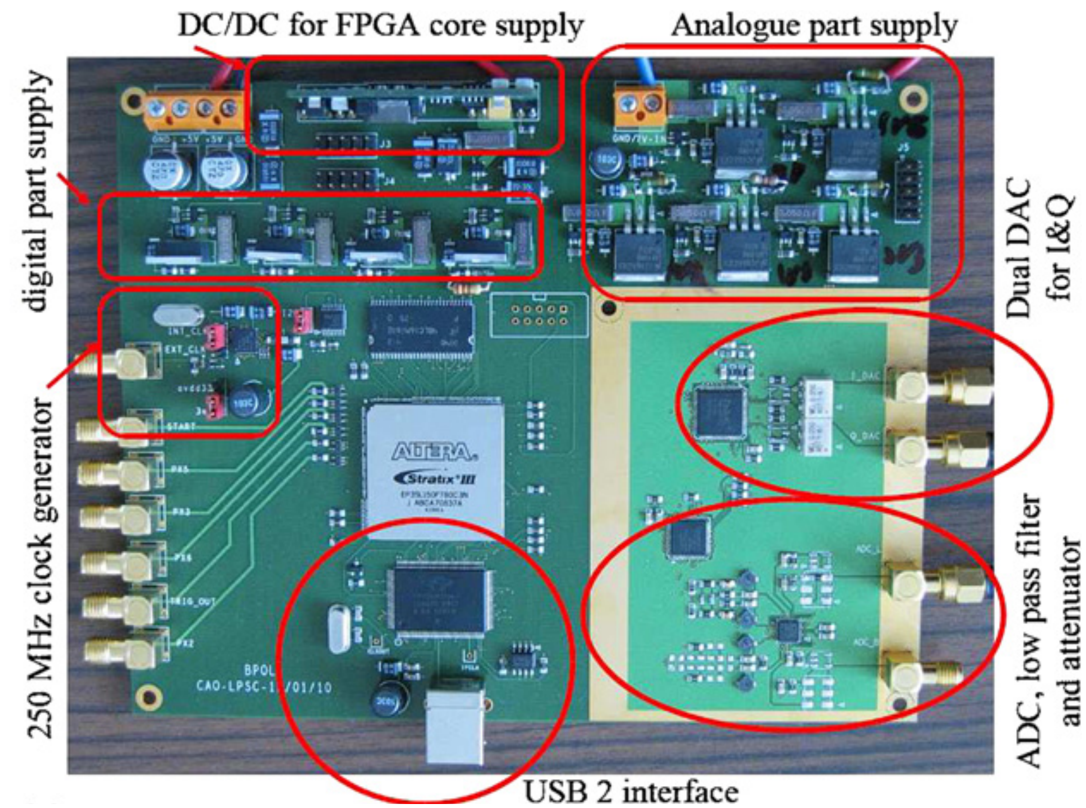
Energy downconversion,
phonons break Cooper pairs



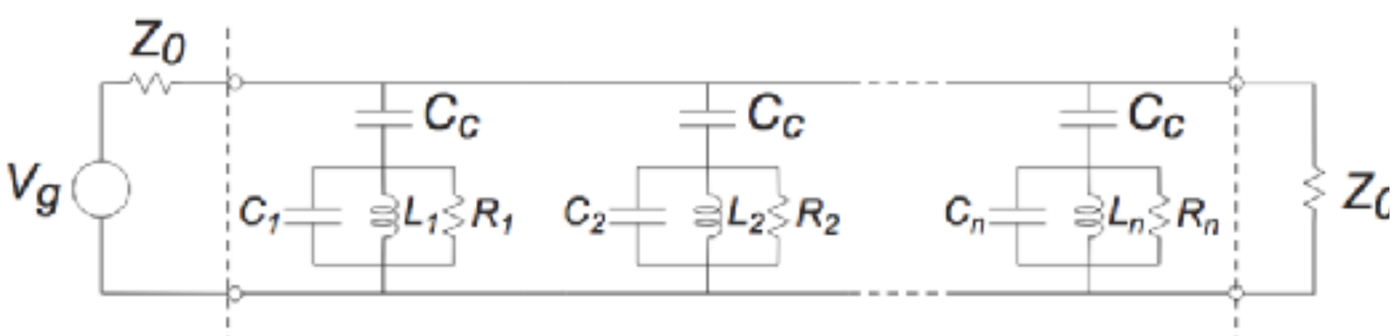
Day et al., Nature, 425, 817 (2003)

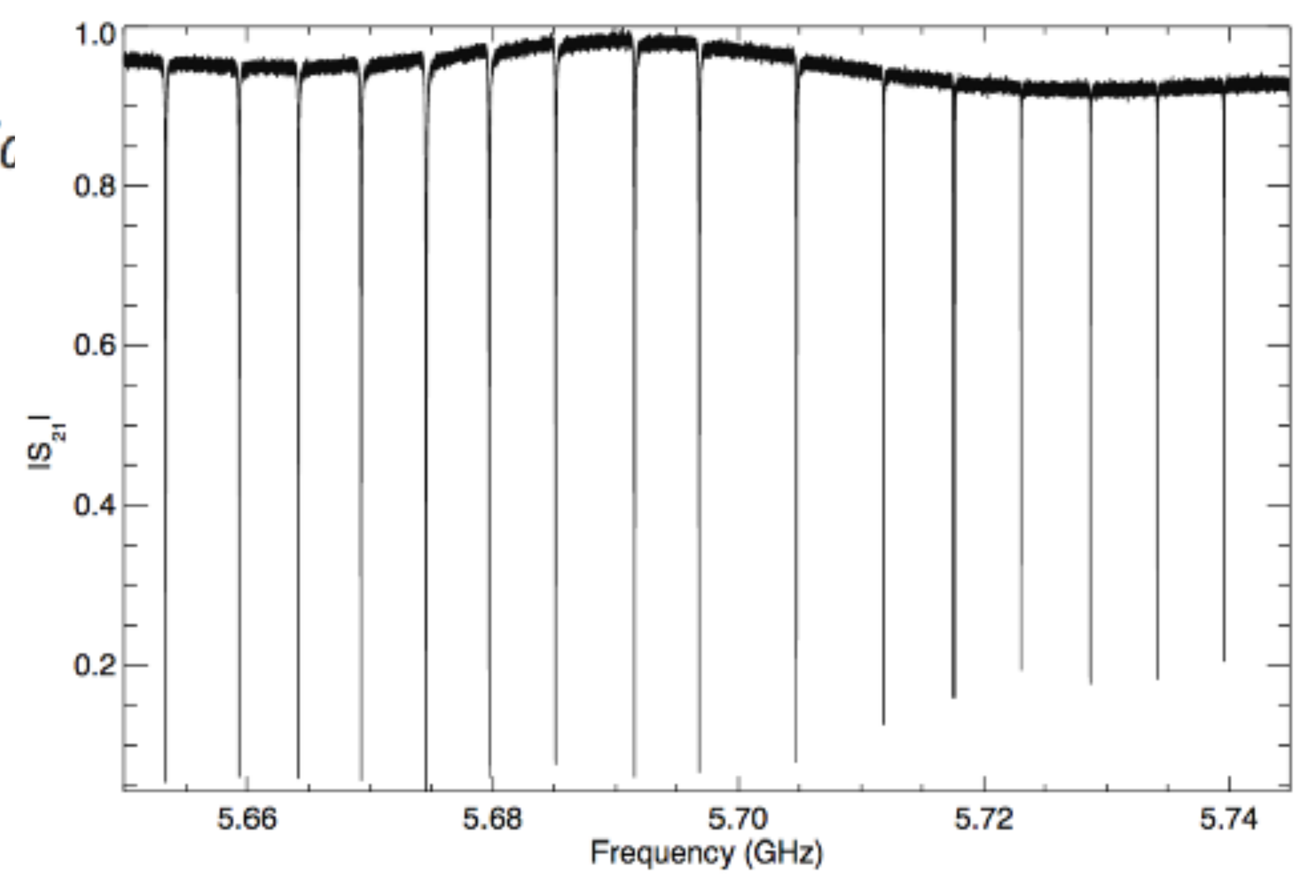
Microwave Kinetic Inductance Detectors





Probe signal, room temperature electronics

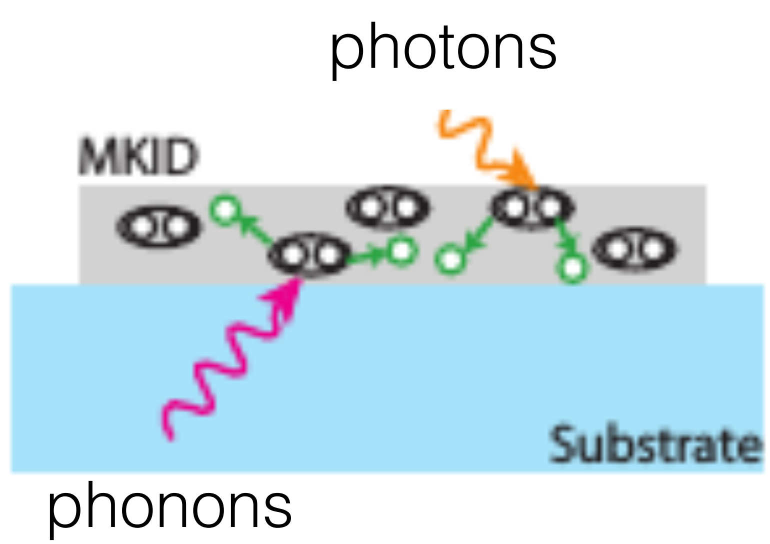




- Highly multiplexable in the frequency domain
- Microwave frequencies (0.1–20 GHz)
- Allows thousands of pixels to be read out over a single microwave cable

Microwave Kinetic Inductance Detectors

- can count single photons with no false counts
- energy determination (to several percent or better)
- arrival time (to a microsecond) of the photon

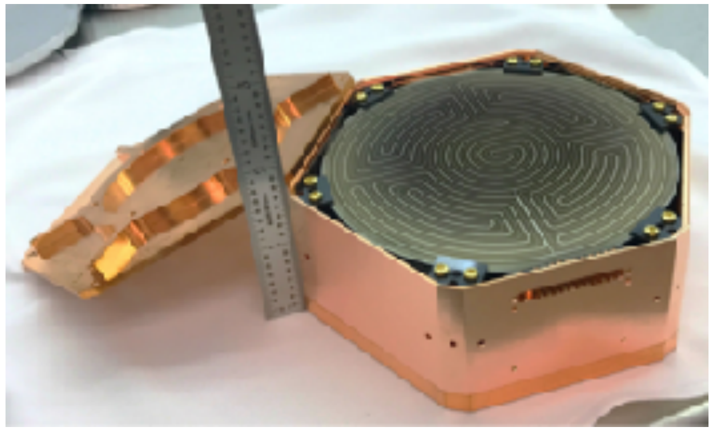


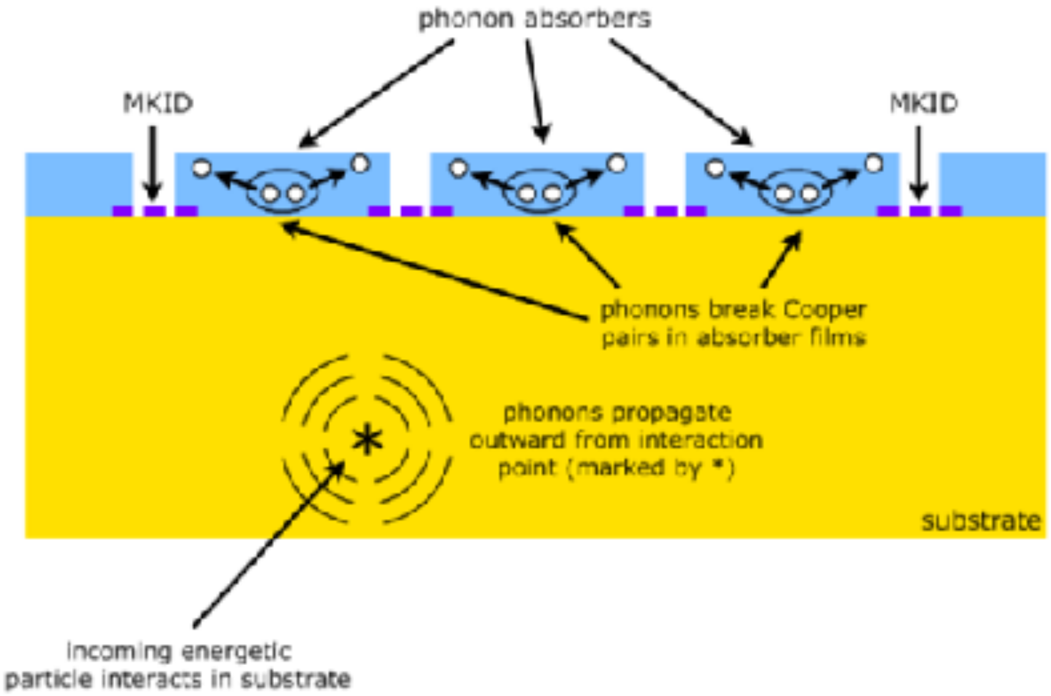
Applications:

- Optical, UV and IR astronomy
- Dark Matter detection
- neutrino detection
- quantum computing
- cosmic microwave background
- submm astronomy

MKIDs for Dark Matter Detection

- Phonon and light detectors using TES (CDMS, CRESST…)
- MKIDs: increased area coverage, finer pixelization, two-sided, scaling to higher mass, sensitivity, simplified readout
- MKIDs for beyond superCDMS
  - Surface vs. bulk Z-position separation provided by the phonon timing,
  - Relative phonon timing provides event XY position

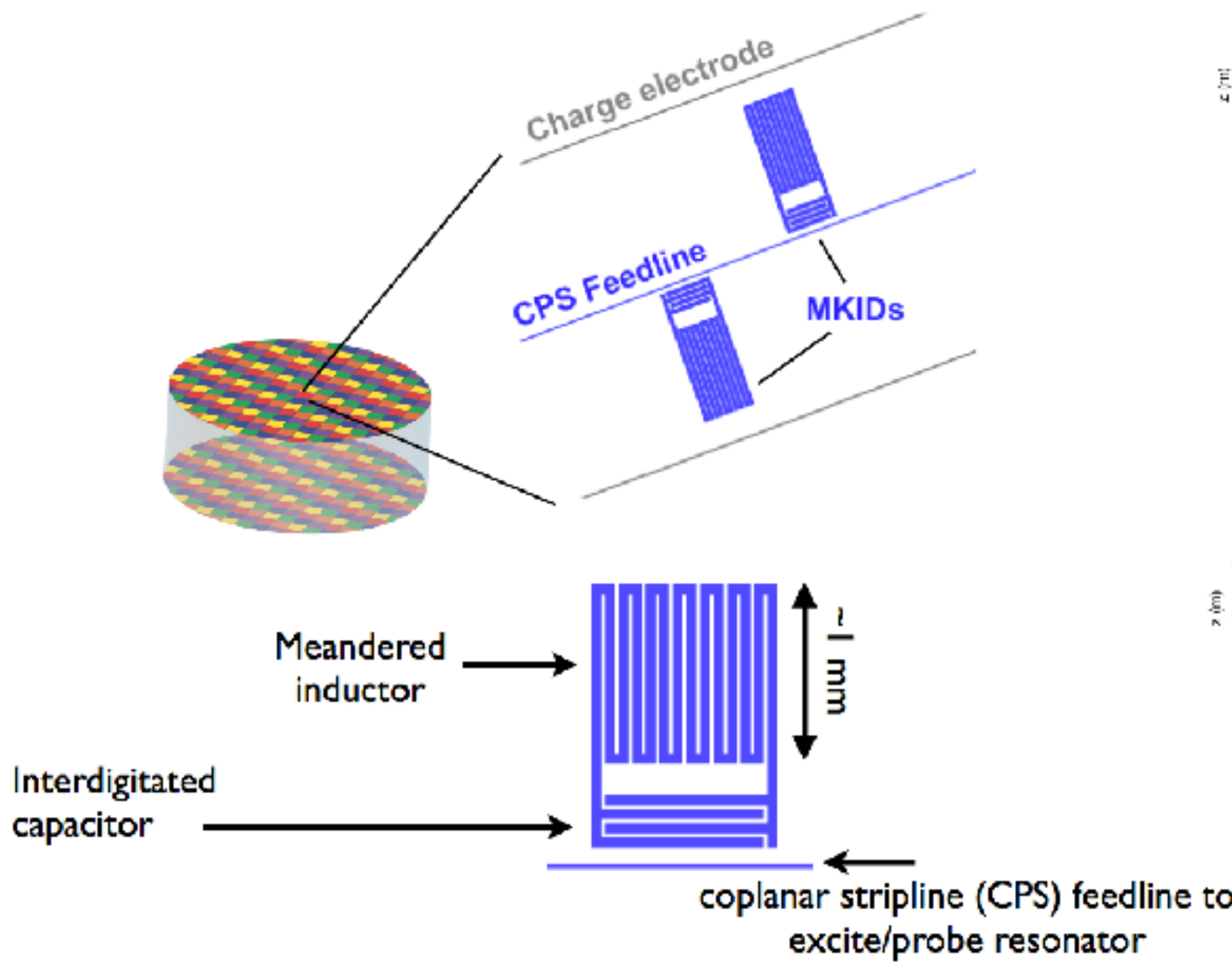


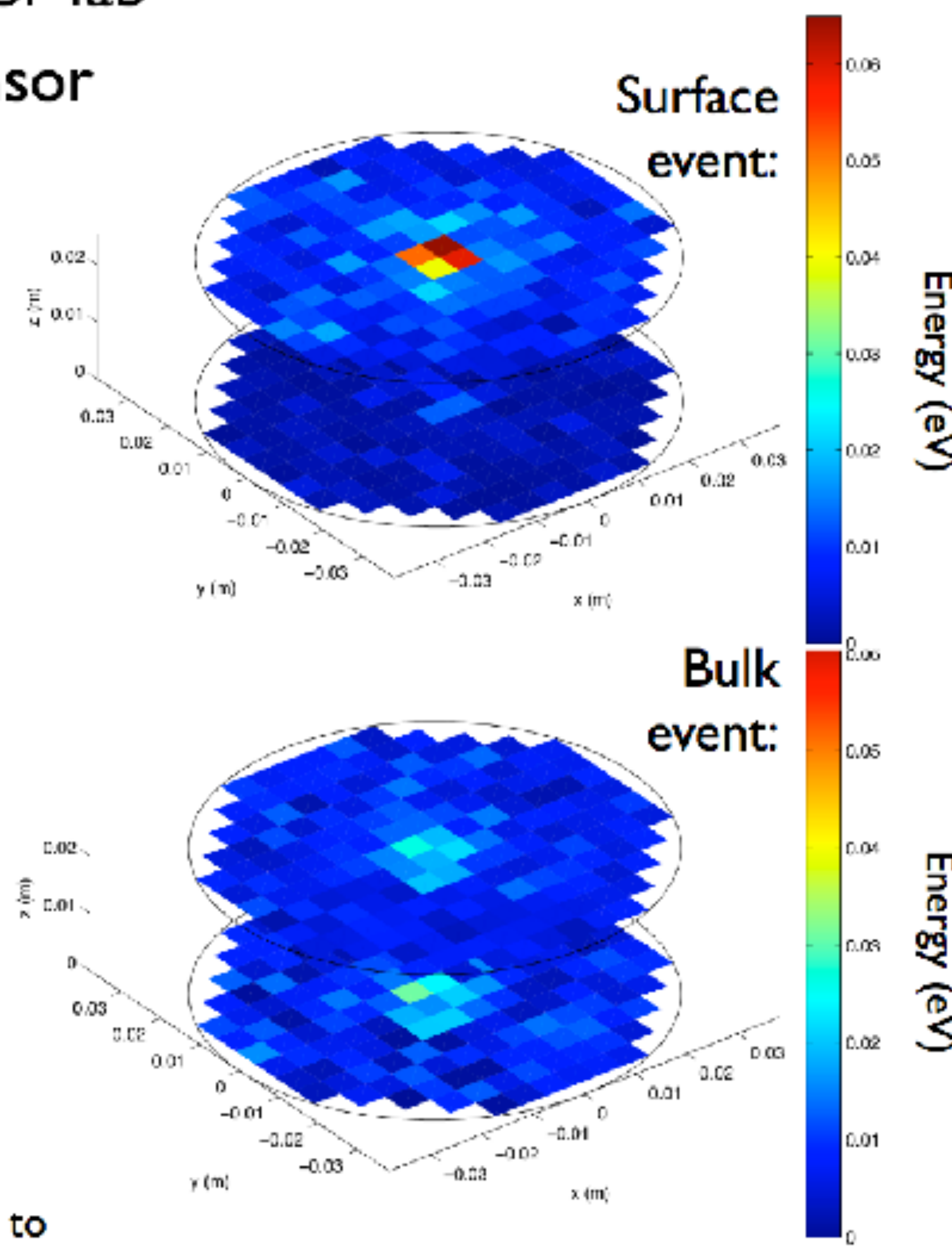


Golwala et al., 2008, J Low Temp Phys,151, 550

Phonon-Mediated DM Detection Using MKIDs

- Lumped-element designs enables large-area resonators for phonon sensing
- Single film, 10 μm features would simplify detector fab
- Multiplexing enables finely pixellated phonon sensor
  → better surface event rejection



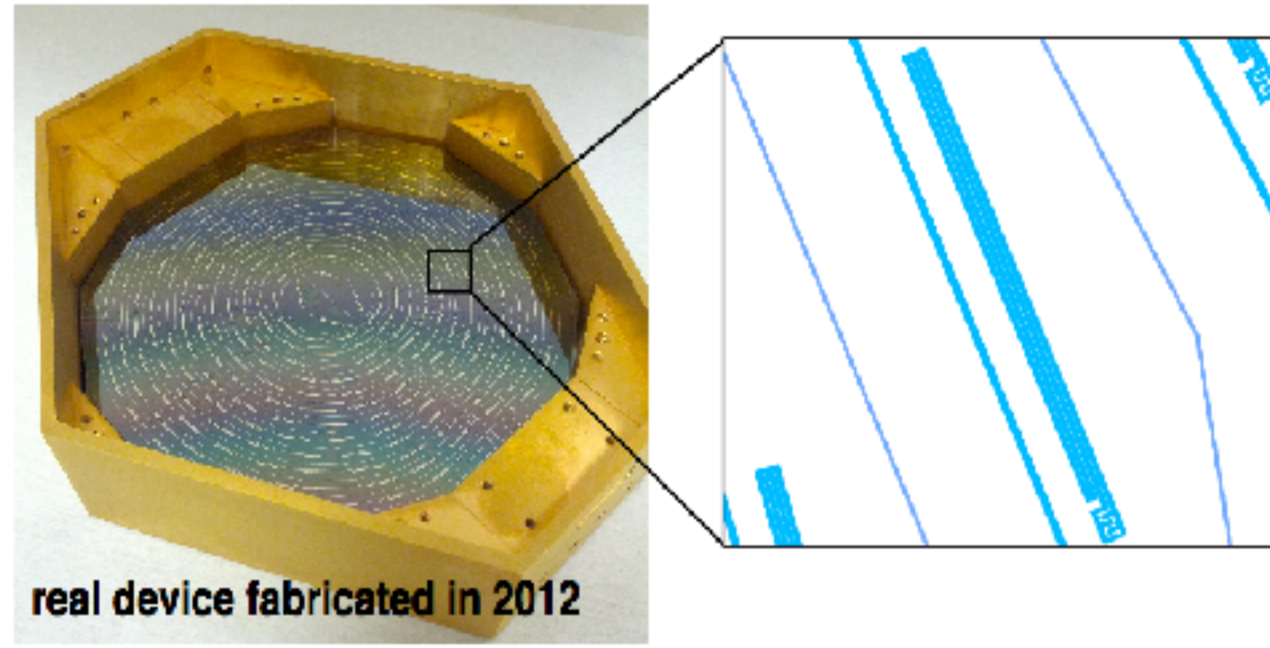


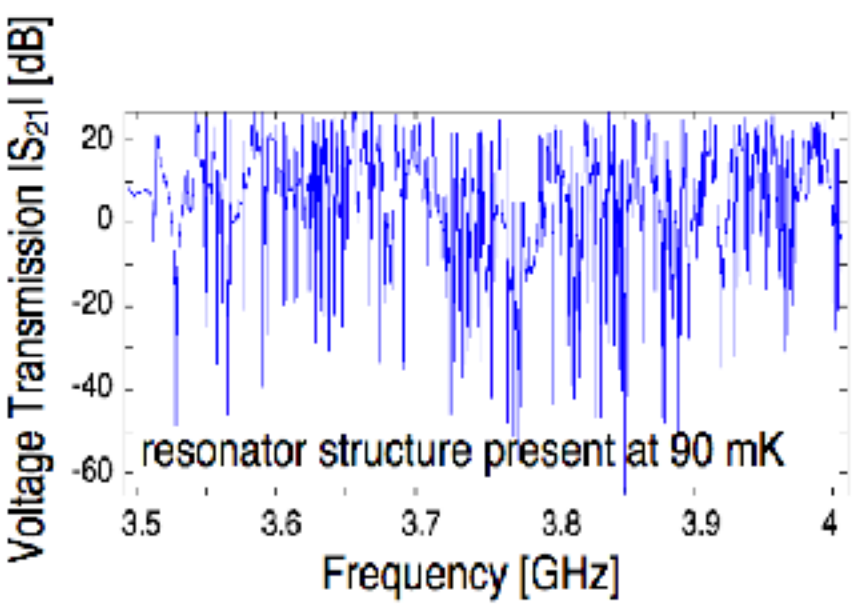
Figures by D. Moore

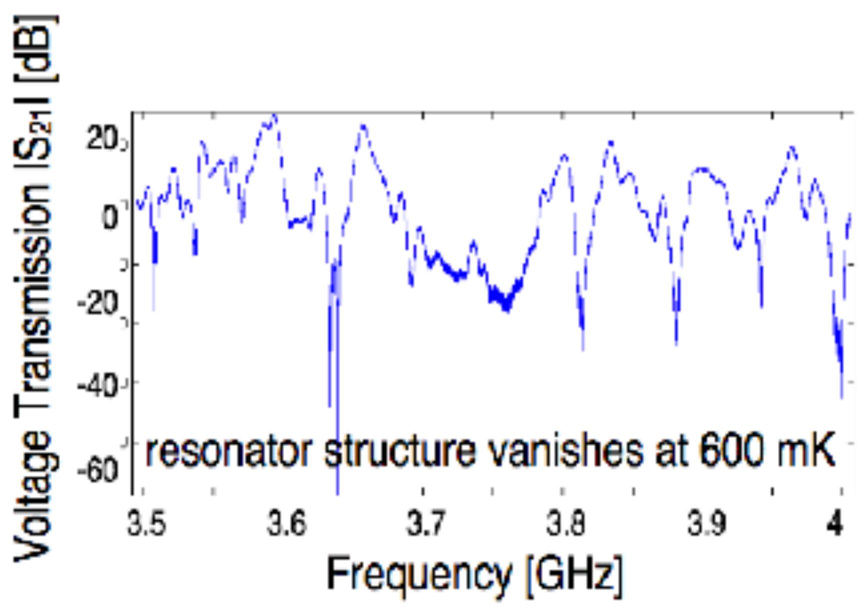
Full Size Prototype

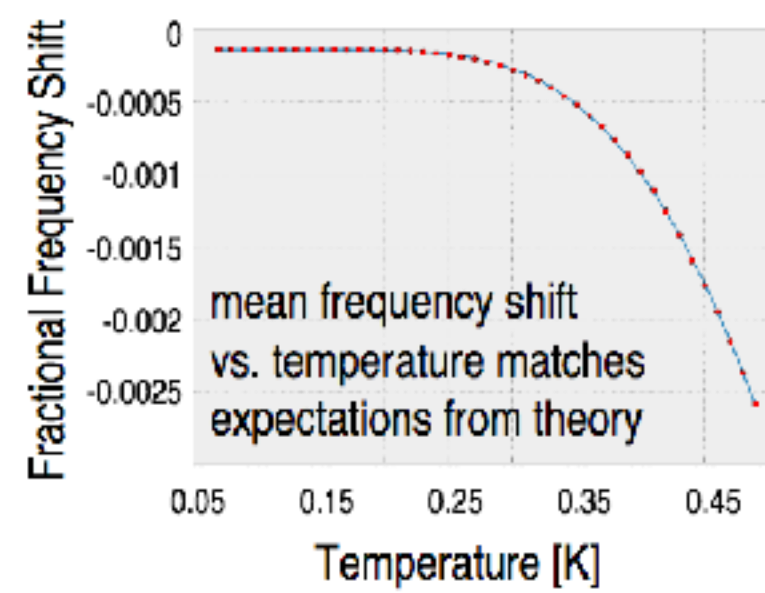
Working on scaling to
7.5-cm x 1-cm substrates

Have designed and
fabricated devices and acquired
characterization data









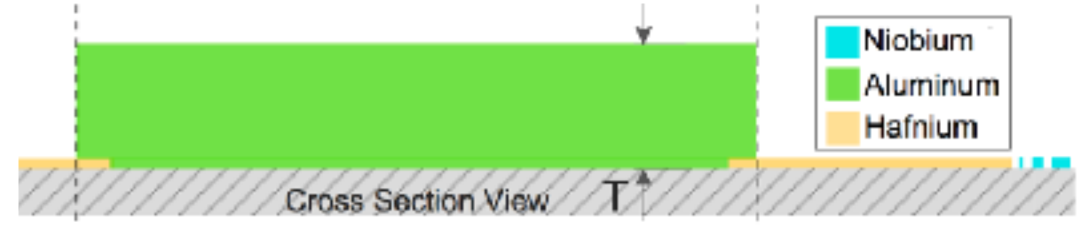
Working to understand RF structure of device with Nb version (4K testing)

Then pulse data

DOE HEP detector R&D grant awarded

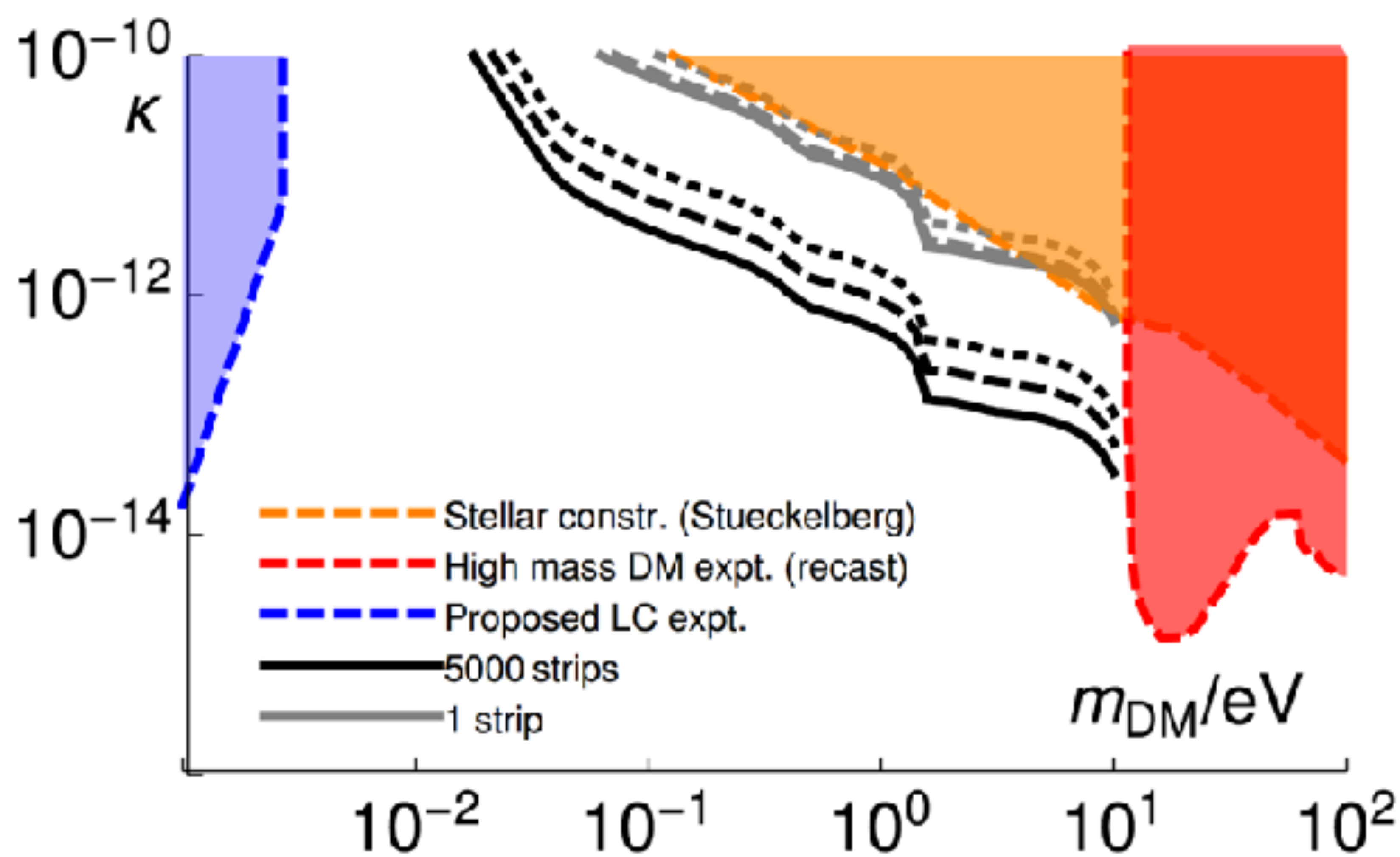
MKIDs for Light Bosonic Dark Matter

Dark photon detection with MKIDs strip detectors



Estimated Dark Photon Sensitivity

- Proposing 5000 MKID Strip Detectors
  = 10,000 MKIDs
  = 10 mm³ Al
  = 2 x 4” wafers
- 6 months
- 1, 10, 100 Background events



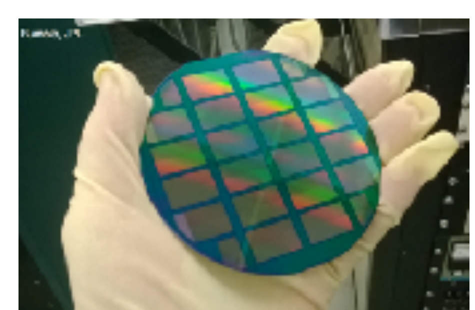
Miguel Daal, Dark Matter 2018

Optical and Near-Infrared applications

- photon counting detectors capable of measuring the energy and arrival time of individual OIR photons without read noise or dark current (vs. CCDs)
- much broader wavelength coverage than CCDs since the photon energy is always much greater than the gap energy.
  - CCD limited to about 0.35–1µm,
  - MKIDs are in principle sensitive from 0.1µm to > 5µm.
- Can be highly multiplexed: (Low resolution) Integral Field Spectrograph
- The wider wavelength coverage reduces the number of catastrophic failures in redshift determination (photometric redshifts).
- Real time detection may allow for post-processing PSF correction (akin to adaptive optics)
- Many potential applications, operating devices (ARCONS, Darkness)

Astro2020 APC White Paper arXiv:1908.02775v1

Optical and Near-IR Microwave Kinetic Inductance Detectors (MKIDs) in the 2020s



Astrophysical Constraints: Strong Lensing

Astrophysical/cosmological probes of Dark Mater physics

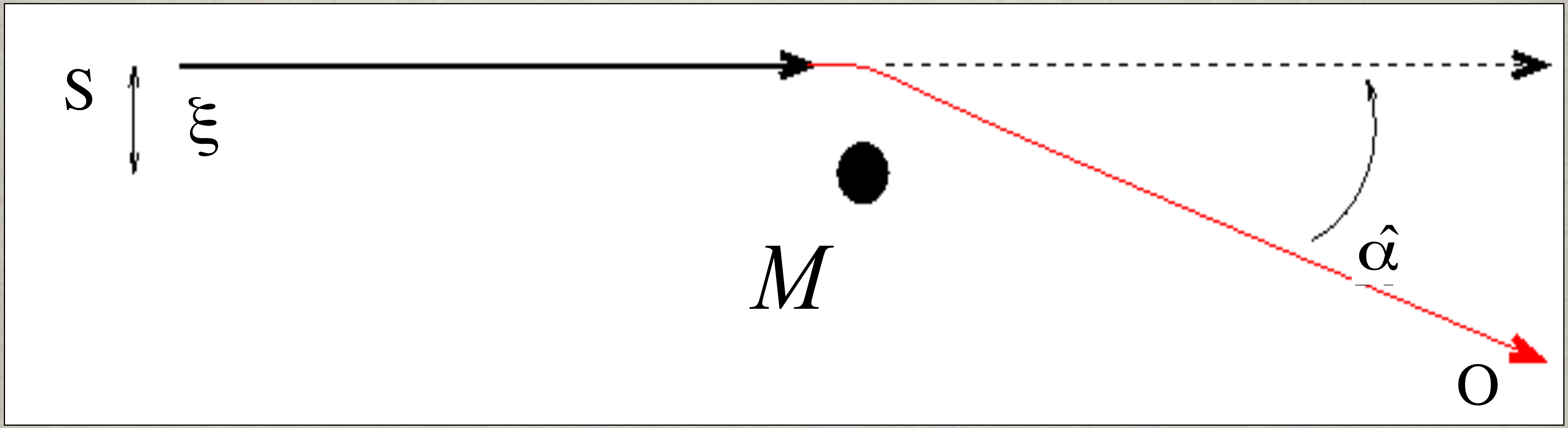
- "Small scale problems" in cosmology point do models beyond Cold Dark Matter (WIMP, axions)
- Probes
  - Ly-alpha: requires good spectroscopic resolution (radial direction)
  - dwarf galaxies: needs spectroscopy to resolve dynamics and wide fields
  - strong lensing: high spatial resolution, but only moderate redshift precision (global, not relative distances)
    - only application where small scale physics can be extracted with low resolution spectroscopy
    - Power of SL reconstruction and issue with redshifts

Bending of light by gravity

Null geodesic,
Fermat principle

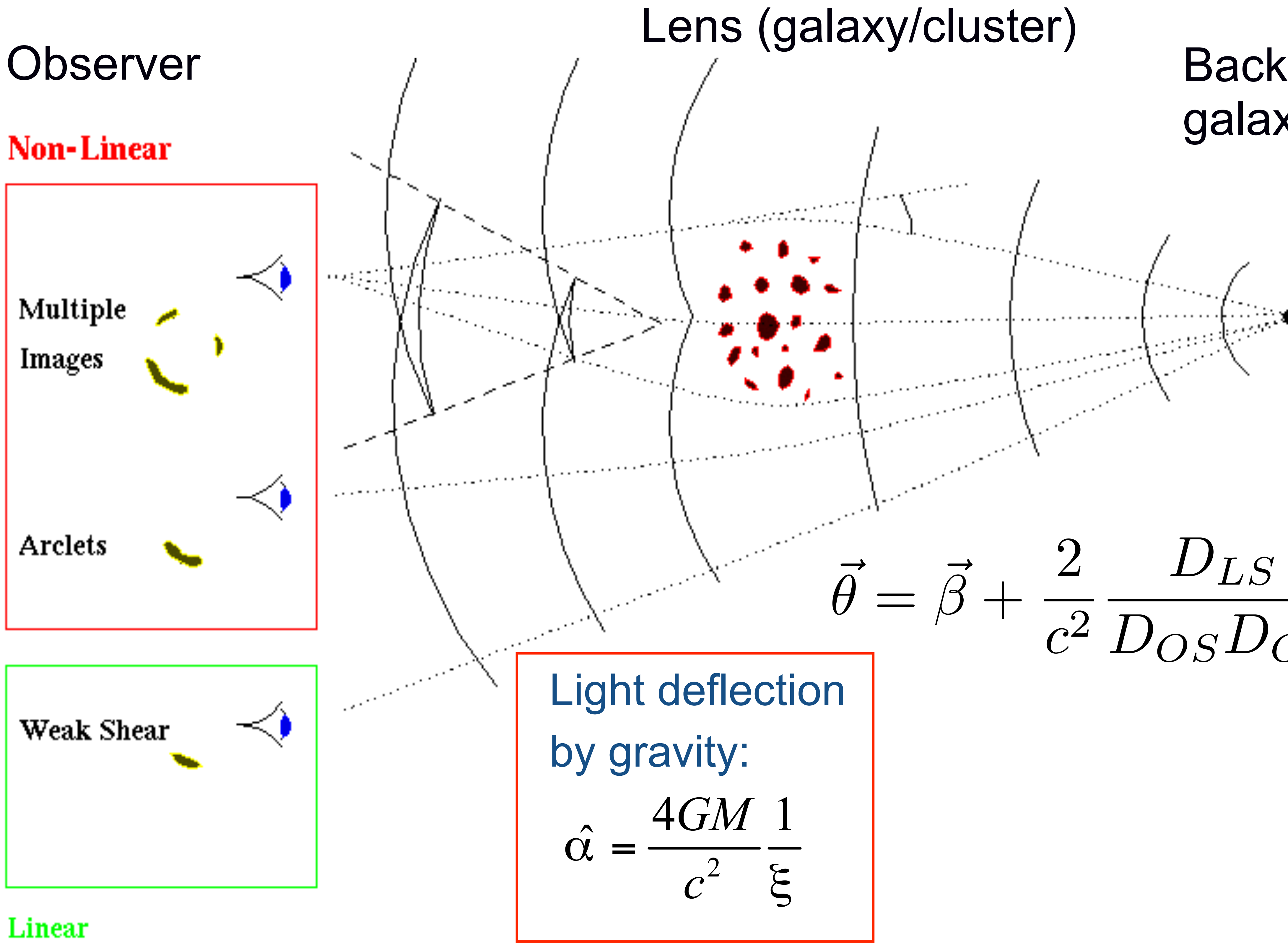
$$ds^2 = \left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

$$\frac{d\sigma}{dt} := c' = \sqrt{\frac{1 + 2\phi/c^2}{1 - 2\phi/c^2}} \simeq c\left(1 + \frac{2\phi}{c^2}\right)$$



Deflection angle (point source): $\hat{\alpha} = \frac{4\,G\,M}{c^2\,\xi} \quad \left(\hat{\alpha}_N = \frac{2\,G\,M}{c^2\,\xi}\right)$

Weak and Strong Lensing Effects



$$\vec{\theta} = \vec{\beta} + \frac{2}{c^2} \frac{D_{LS}}{D_{OS} D_{OL}} \nabla_\theta \psi \left(\vec{\theta}\right)$$

Light deflection by gravity:

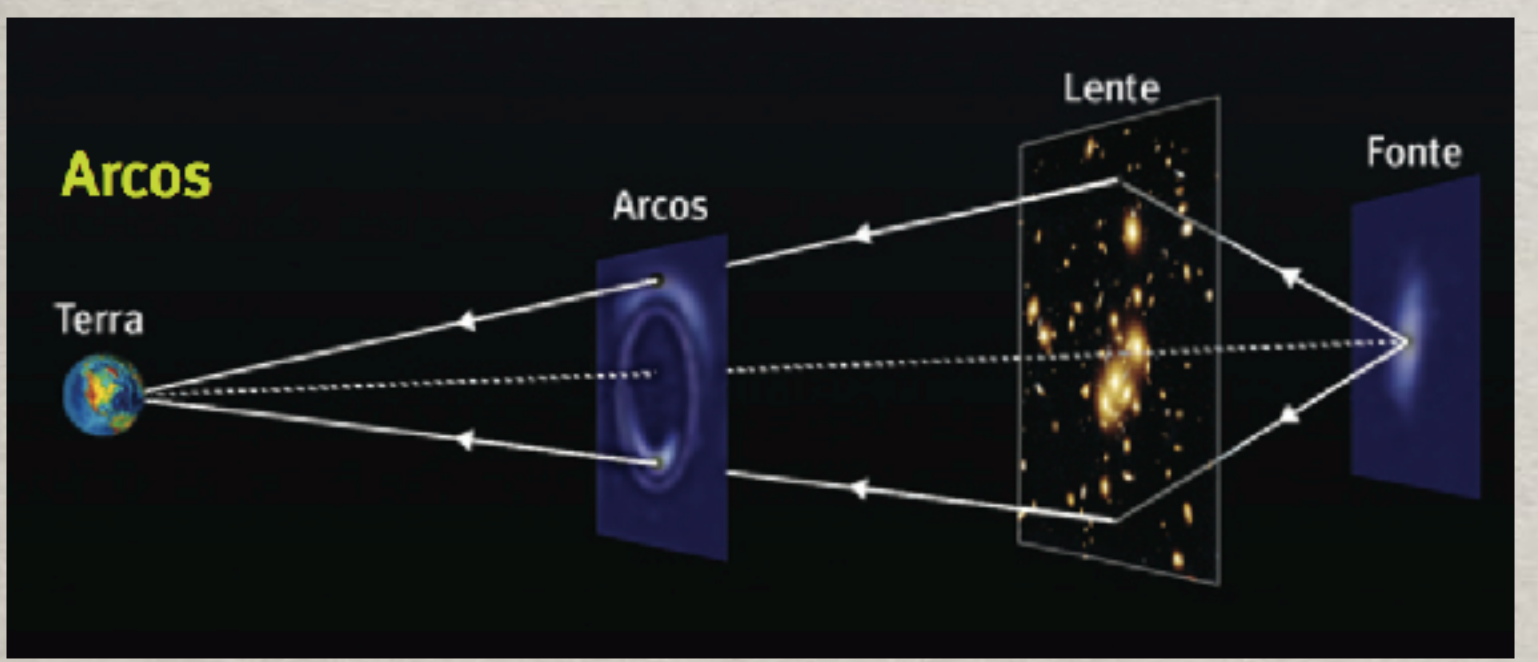
$$\hat{\alpha} = \frac{4GM}{c^2} \frac{1}{\xi}$$

Strong Lensing

- Multiple images, strong distortions, large magnifications, time delays
- Null geodesics
  - surface brightness conservation
  - achromatic

  } → Gravitational telescopes

  - Unique probe of the mass distribution in galaxies and clusters → DM, *b*
  - Provide complementary cosmological probes and tests of gravity



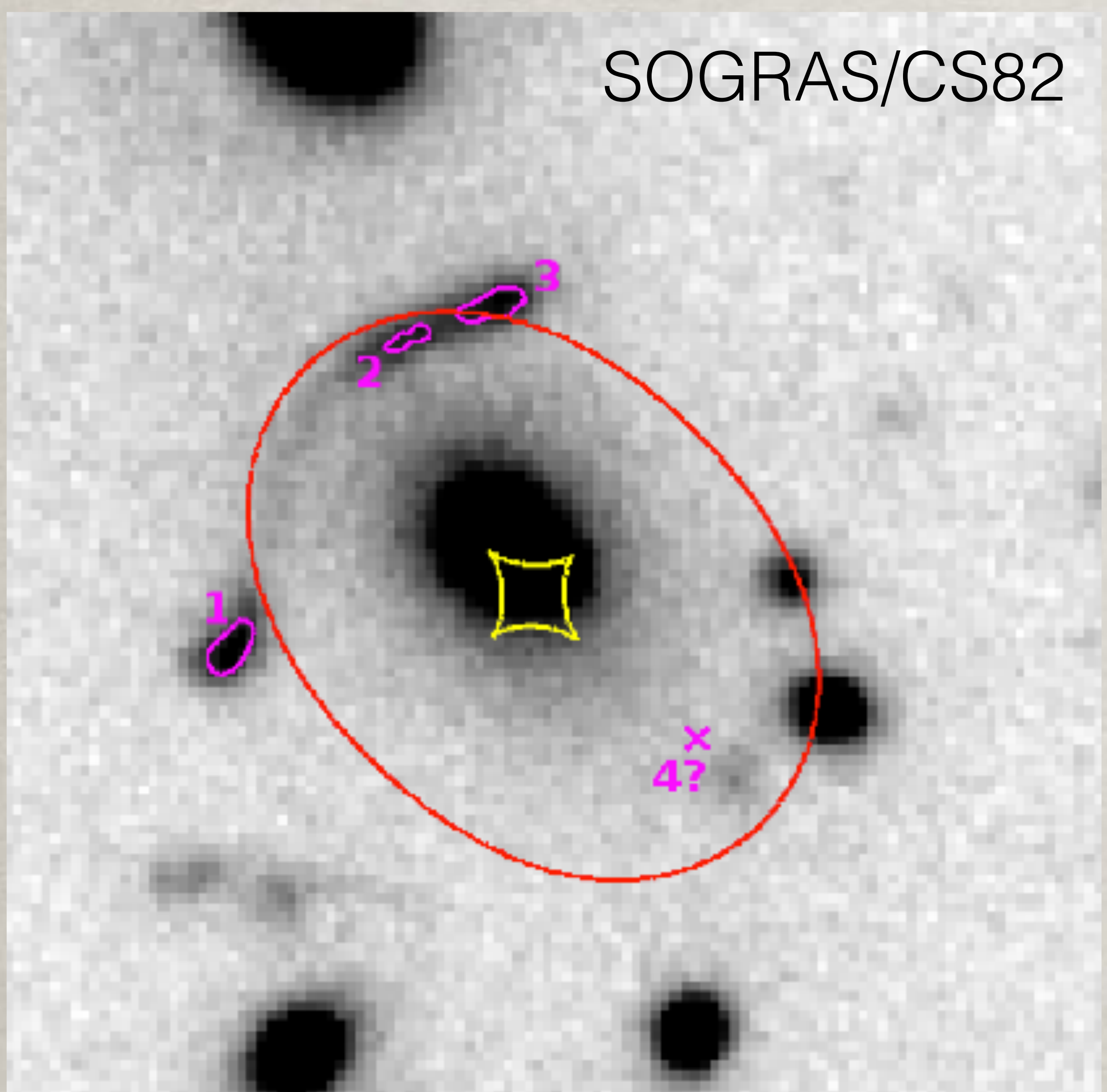
strong lensing, **weak gravity**

Gravitational arcs

Strong Lensing and Dark Matter

- Large-scale Geometry
  - Background cosmology: Ω_M
- Lens potential: Mass distribution
  - Dark Matter abundance and distribution (cusps, substructures?)
  - Primordial spectrum
  - Dark matter interactions
- Gravitational telescope
  - z ~ 2 – details of highly magnified galaxies (resolved!)
  - z ~ 6 – galaxy abundance at high-z
- Cold, warm, self-interacting, fuzzy?
- Challenges:
  - High-resolution, deep imaging; spectroscopy (including IFU)
  - Finding Strong Lenses (specially “golden lenses”)
  - Systematics

Inverse Modeling: Mapping the Mass



Use systems of multiple images to determine the lensing potential

$$\chi^2_{\text{lente}} := \sum_i \left(\frac{\vec{\theta}_i^{\text{obs}} - \vec{\theta}^{\text{mod}}\left(\vec{\beta}, \vec{\Pi}\right)}{\sigma_i^{\text{obs}}} \right)^2$$

Multiple image positions

Error on image positions

Methods: parametric (often “mass traces light”), free form

The more multiple images, the more constrains

Cluster x Galaxy scales

- Combination with independent mass constraints (e.g., x-ray, Sunyaev Zel’dovich, velocity dispersions) yields limits on cosmology or gravity

Galaxy Cluster Scale
Cosmological Constraints and more

$$\vec{\theta} = \vec{\beta} + \frac{2}{c^2} \frac{D_{LS}}{D_{OS} D_{OL}} \nabla_\theta \psi \left(\vec{\theta} \right)$$

Families of images with sources at different *redshifts*

☑ constraints on cosmology, in addition to the matter distribution

The ratio of angular diameter distances for 2 (or more) images with sources at different redshifts defines a ratio of families

$$\Xi(z_{\rm l}, z_{\rm s1}, z_{\rm s2}; \Omega_{\rm M}, \Omega_{\rm X}, w_{\rm X}) = \frac{D(z_{\rm l}, z_{\rm s1})}{D(0, z_{\rm s1})} \frac{D(0, z_{\rm s2})}{D(z_{\rm l}, z_{\rm s2})}$$

☑ Jullo et al. 2010, Science: example of competitive limits in cosmological parameters fom the Abell 1689 system

☑ **8** families of sources with z = 1.15 to 4.86

☑ Caminha et al. 2016: RXC J2248.7-4431 (Abell S1063), 16 sources, 47 images

☑ Magaña, Motta, Cárdenas, Verdugo, Jullo, 2015: Dark Energy models

Reminder: Angular Diameter Distance

In the wCDM model

$$p = w\rho$$

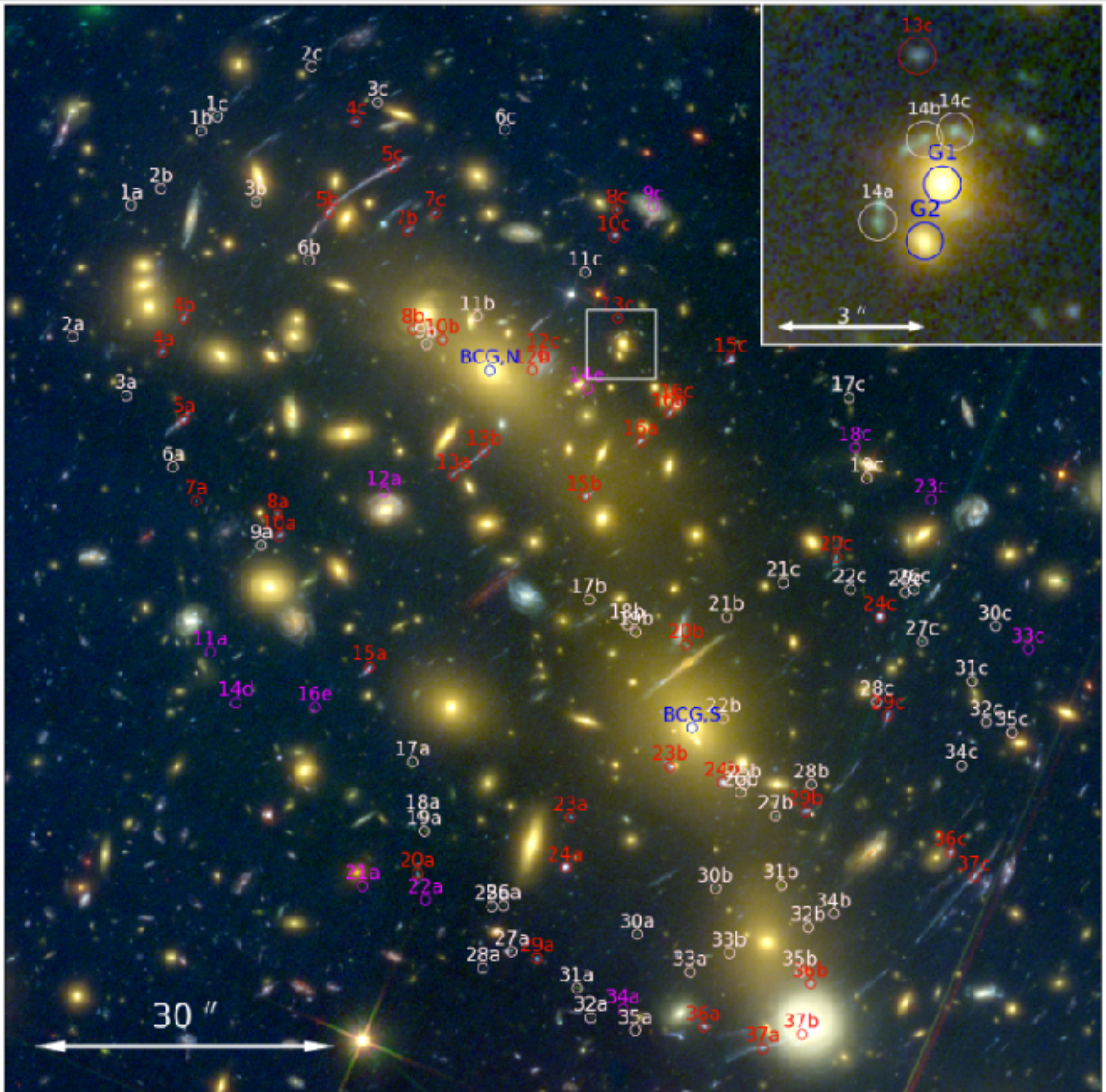
$$H^2(a) = H_0^2 \left[\Omega_r a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} a^{-3(1+w)}\right]$$

In the flat case

$$D_A\left(z_1, z_2\right) = \frac{\left(1+z_2\right)^{-1}}{H_0} \int_{z_1}^{z_2} \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \left(1-\Omega_M\right)\left(1+z'\right)^{3(1+w)}}}$$

$$D_{LS} = D_A(z_L, z_S)$$

Example MACS J0416.1-2403



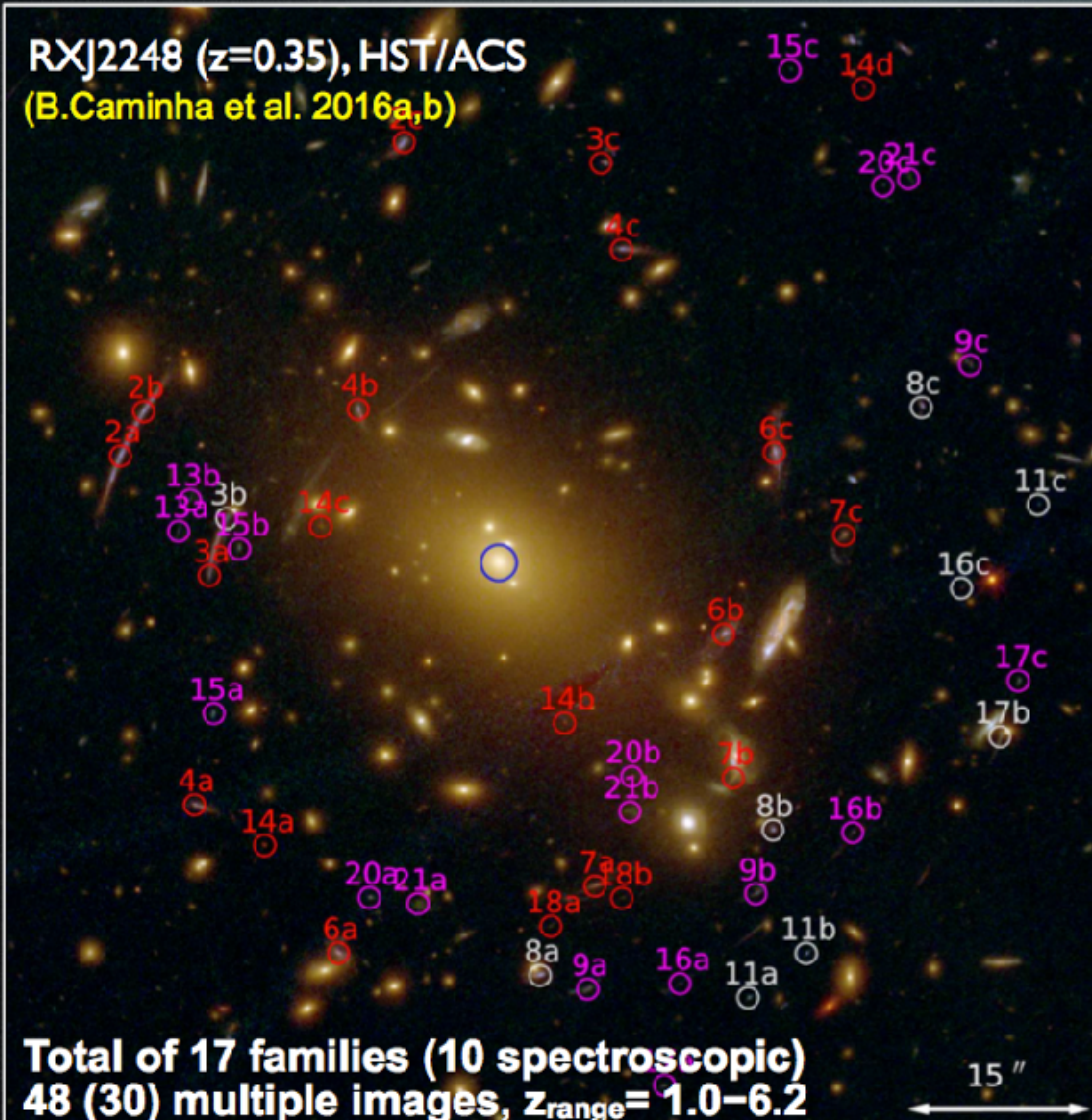
Caminha et al. 2016

- HST + MUSE **IFU**
- 102 multiple images!
- Discovery of new systems in the data cube
- Robust determination of projected mass
- Cosmological constraints
- Available redshifts and shear and convergence maps

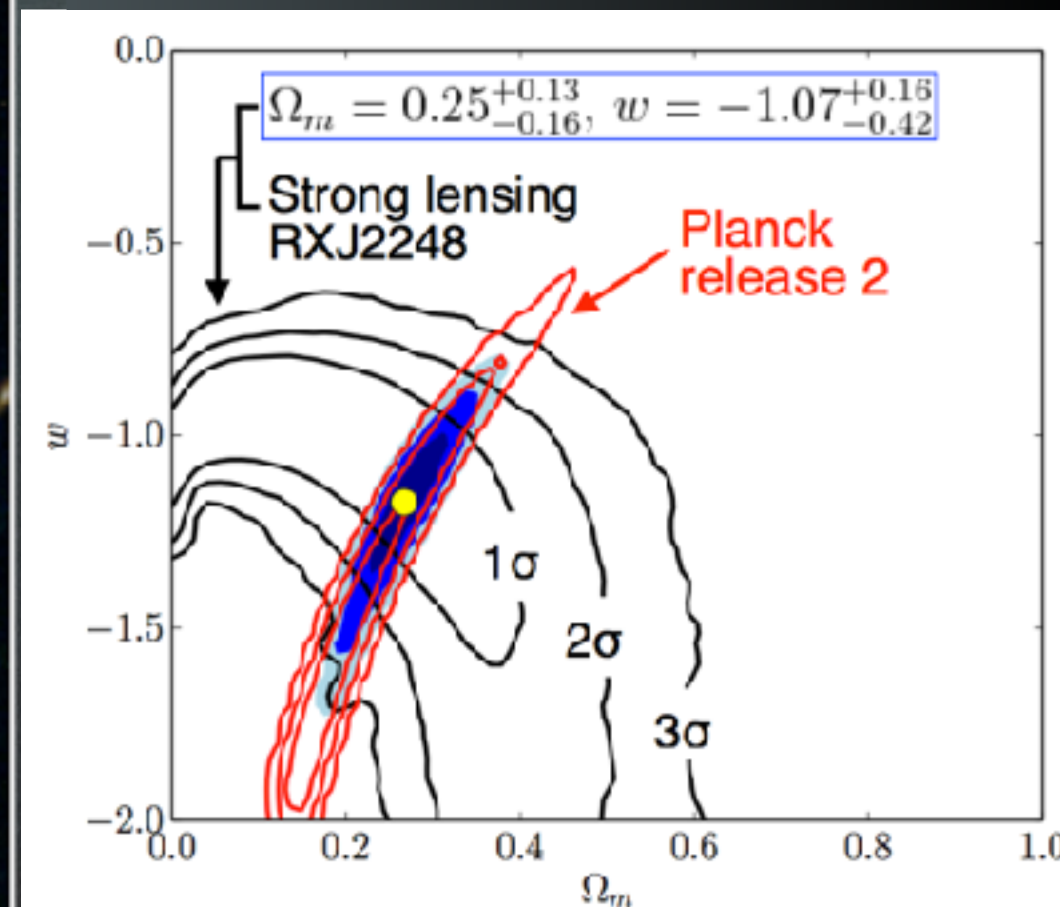
Cosmological Constraints

Caminha et al., 2016

Frontier Field Cluster AS1063 (aka RXJ2248)



MUSE SV programme + GO (PI: K.Caputi)
(Karman et al. 2015)
(W.Karman et al. 2016, arXiv/160601471)



1 arcmin² FoV
2.6 Å resolution (4800-9300 Å)
0.2 arcsec/pxl
Exp. = 5 hrs

New constraints from Abell S1063

- **Doubling the number of families of multiple images**
- **Comparison and combination with other observables**

Bom, MM, Caminha, Vitenti, Penna-Lima (2019, in prep.)

- Consistency test/proof of concept
- Validation of the mass model at small scales using supernovae:
  - Refsdal multiply image SN
  - Type Ia SN in galaxy and clusters

Limits from Strong Lensing only:

$$\Omega_M = 0.422^{+0.062}_{-0.274}$$

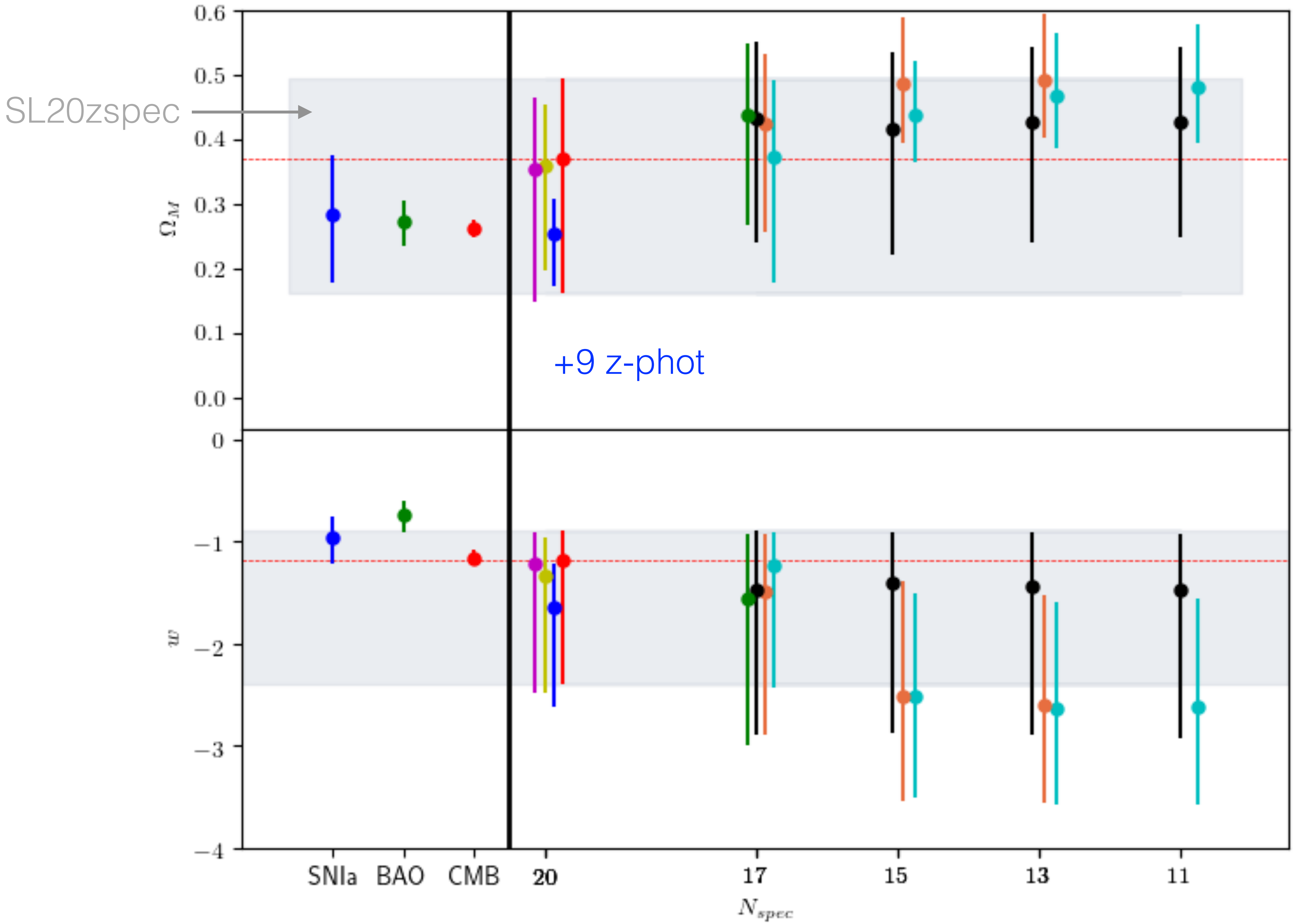
$$w = -0.911^{+0.030}_{-1.356}$$

Single system!

Improvement by combining with SL over each probe alone:

Probe	$\Delta\sigma_w$	$\Delta\sigma_{\Omega_M}$	ΔA_σ
SNIa	27%	23 %	31 %
BAO	29%	17%	28 %
CMB	44%	37%	36 %

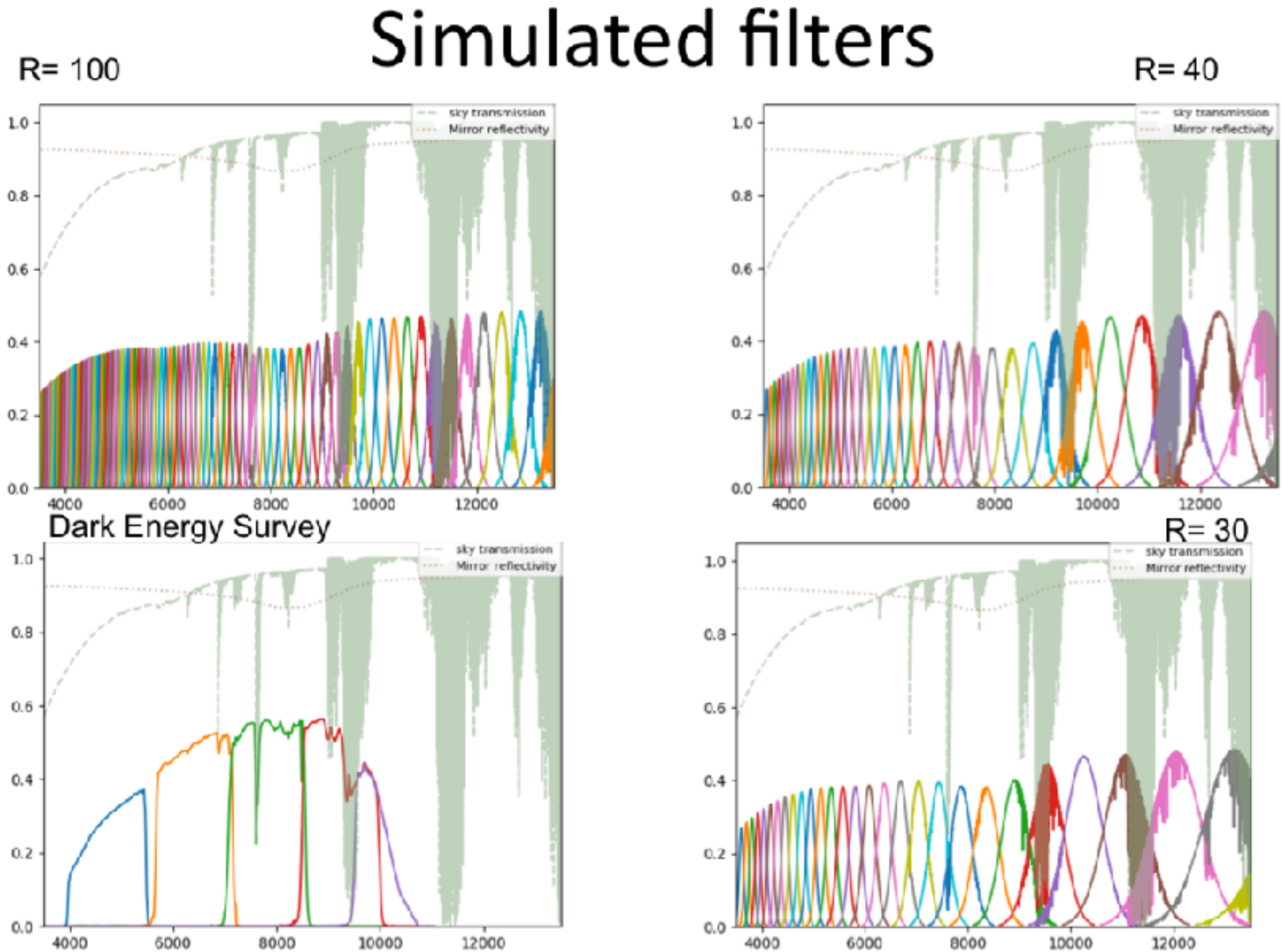
Photometric Redshifts



Bom, MM, Caminha, Vitenti, Penna-Lima (2019, in prep.)

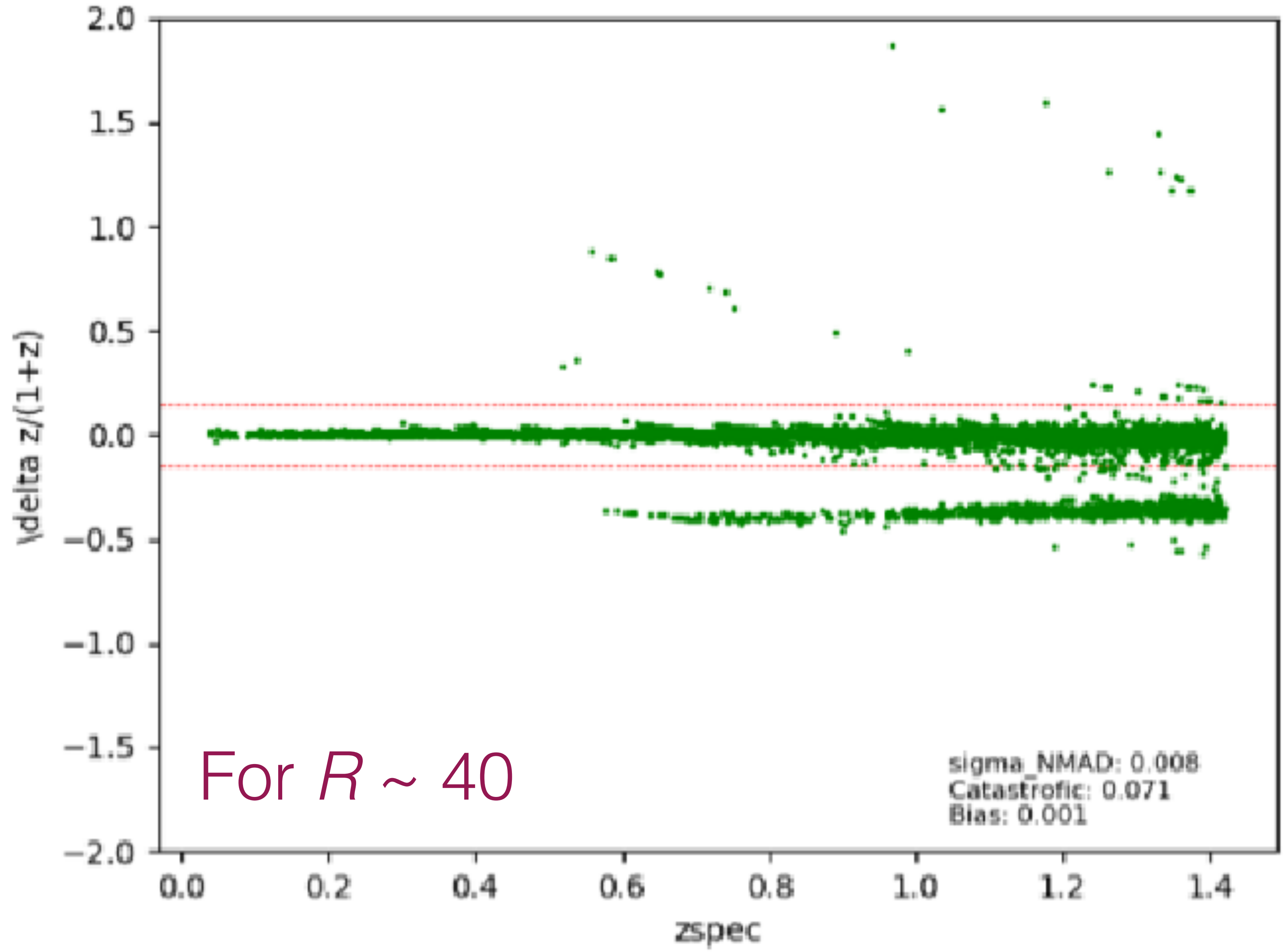
SL modelling needs R ~ 100?

Expected MKIDs redshift quality



Expected MKIDs redshift quality

- Using the MICE simulated galaxy catalog
- Interpolation of COSMOS real galaxy spectral energy distributions
- Improvement over standard photo-z (and "no photon left behind")
- Comparable to Giga-z results

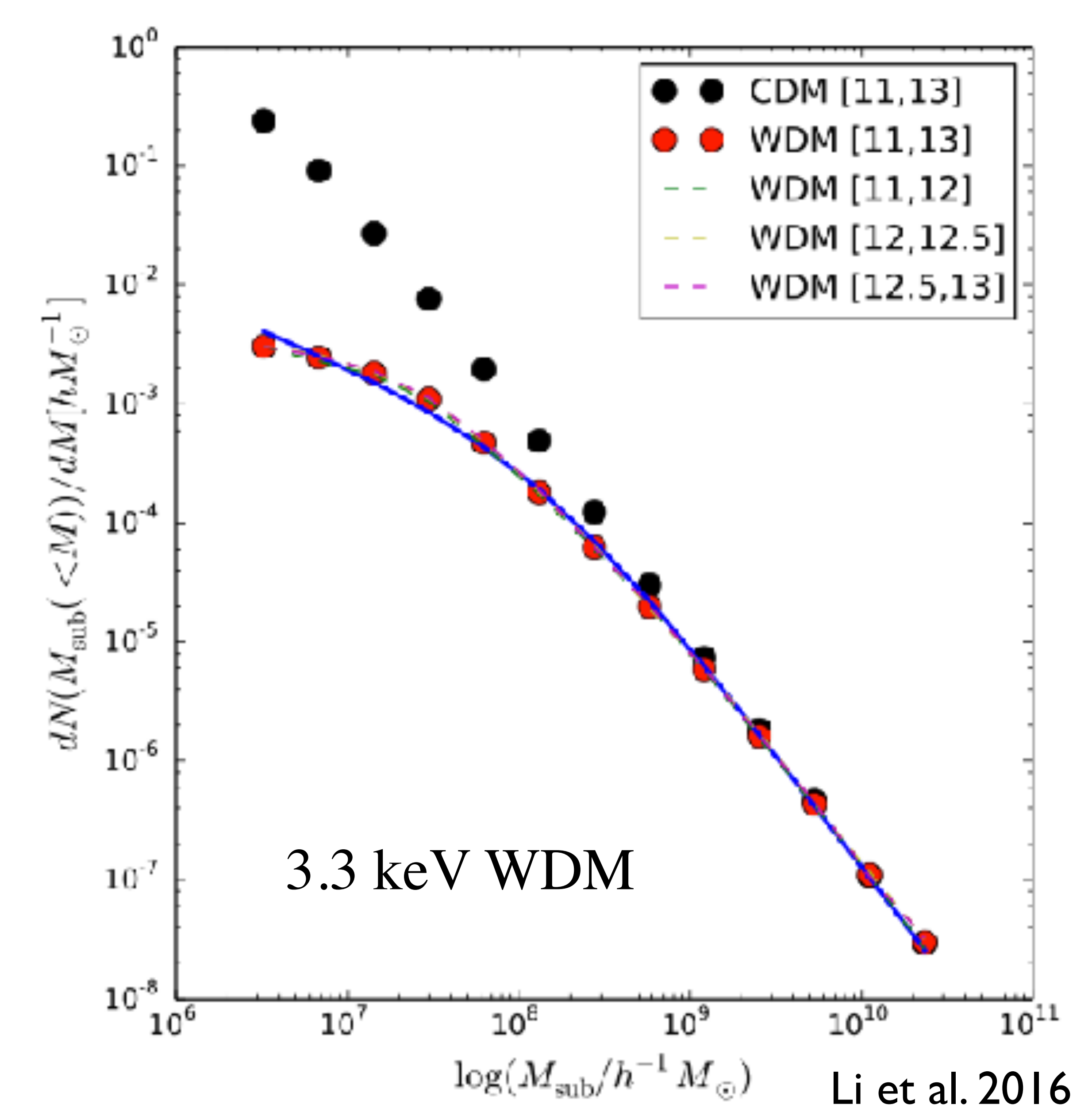


Bom, MM, Estrada (in prep.)

Dark Matter Properties

Substructures and WDM

- WDM produces a cutoff in the matter power spectrum (Bode et al. 2001), which leads to a break on the (sub-halo) mass function
- This cutoff can be probed by structures in small scales: abundance of small halos

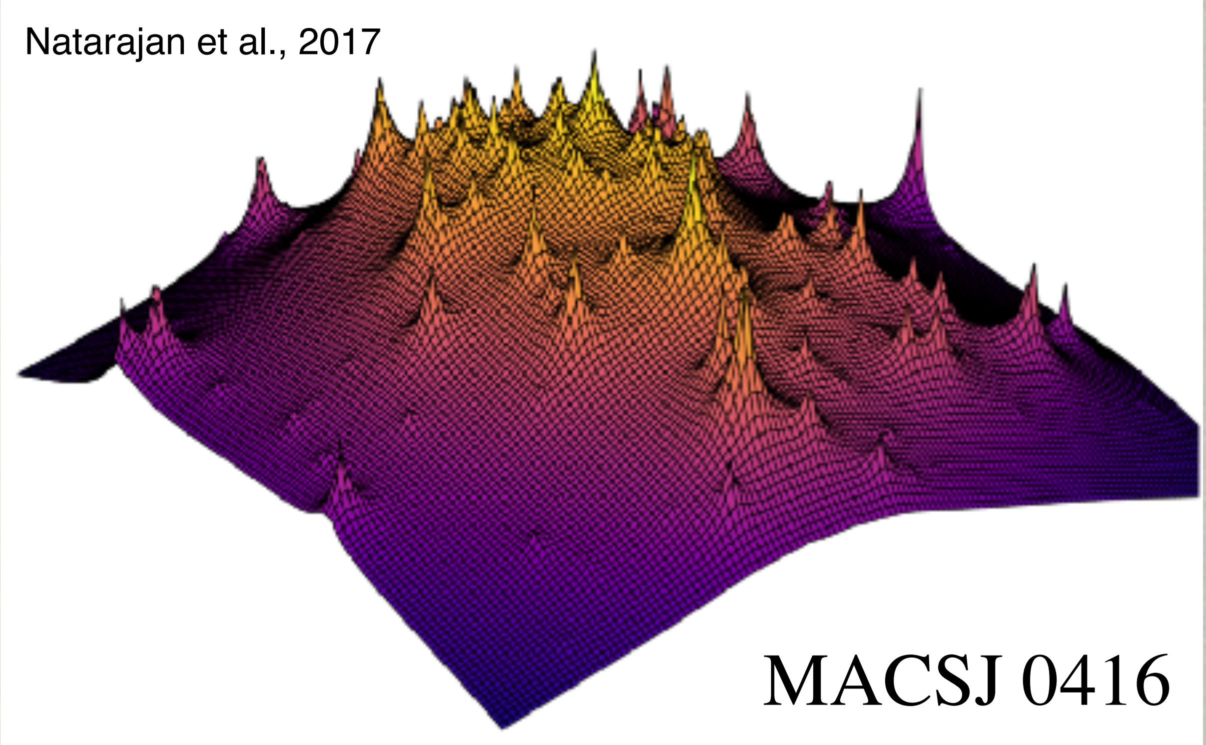


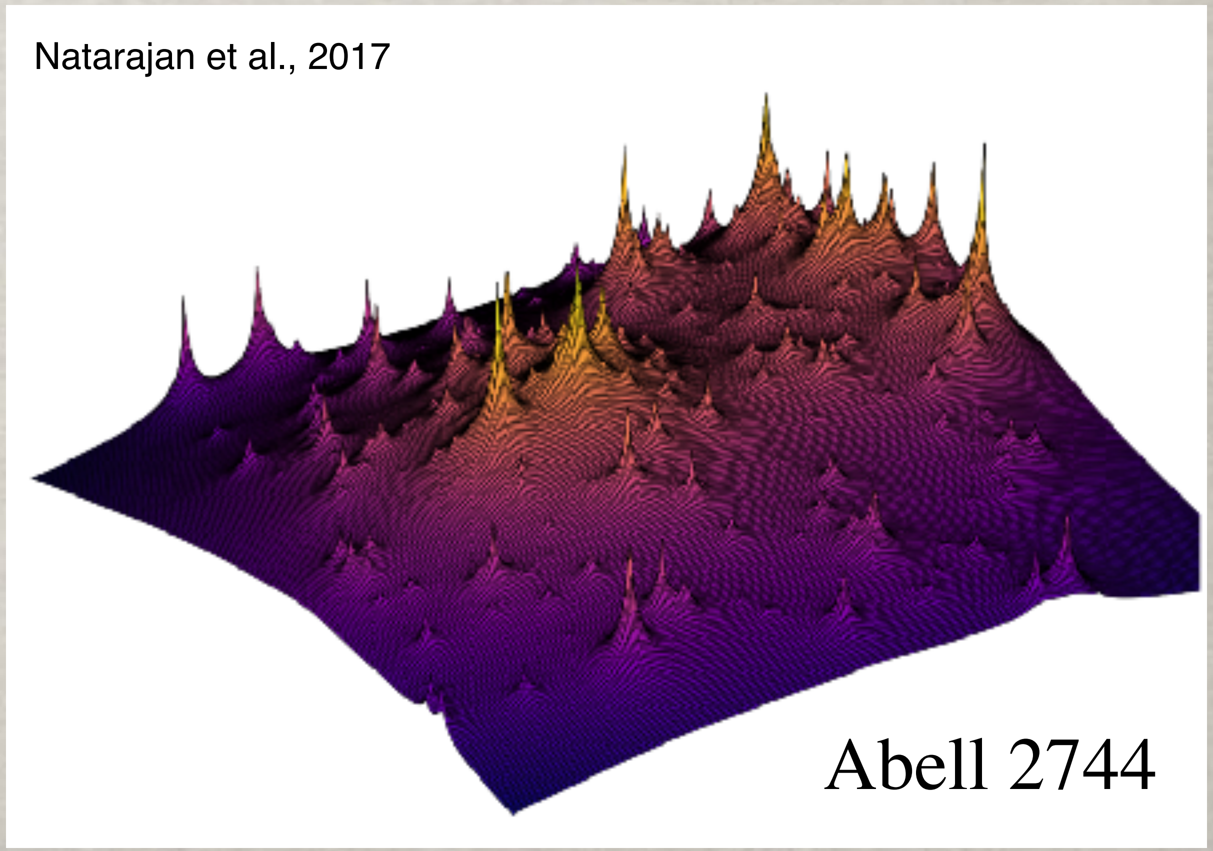
Li et al. 2016

Direct detection of substructure in clusters

Sub-halo power spectrum:

- Quantifying substructures in HFF

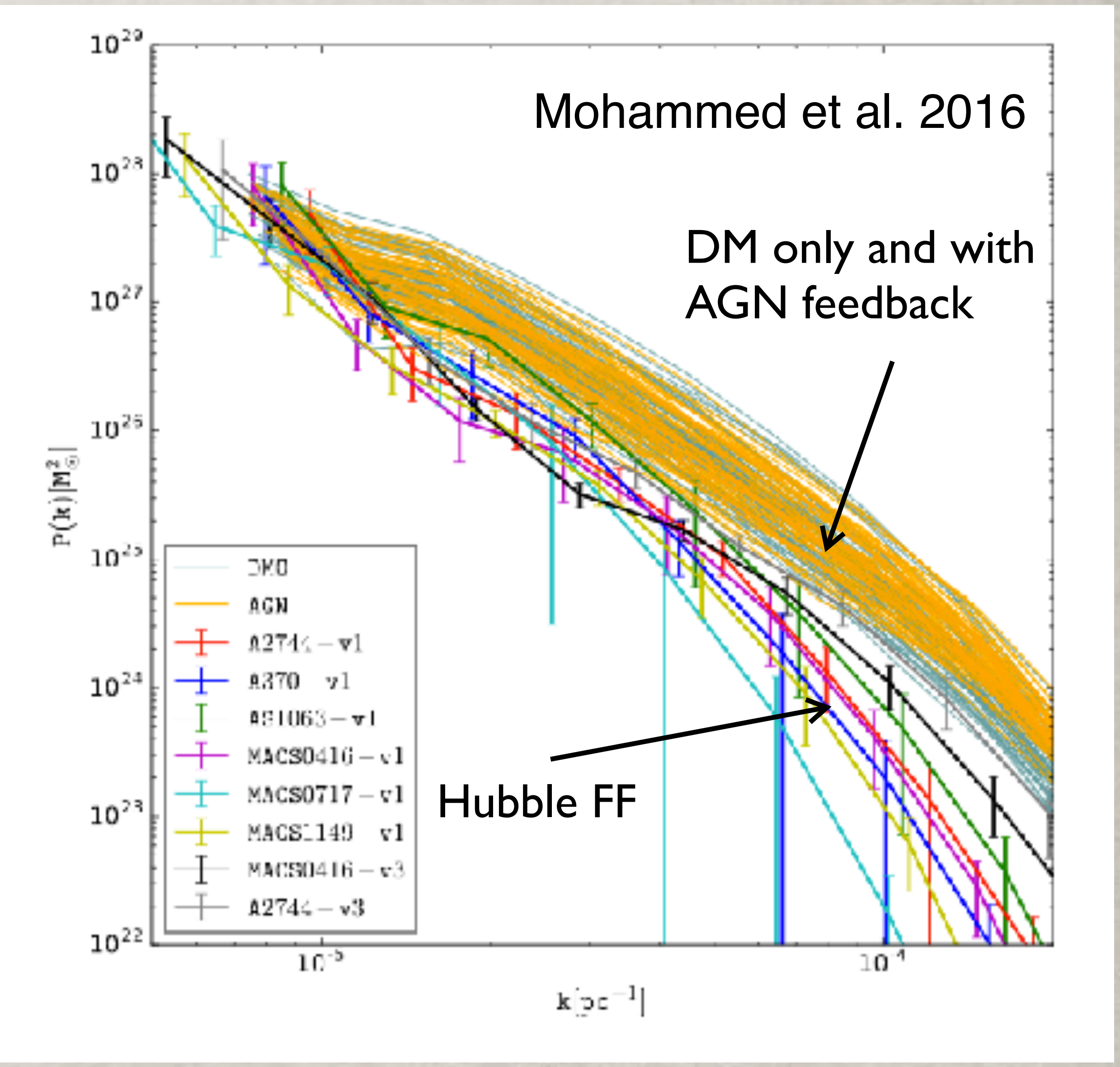




Direct detection of substructure in clusters

Sub-halo power spectrum:

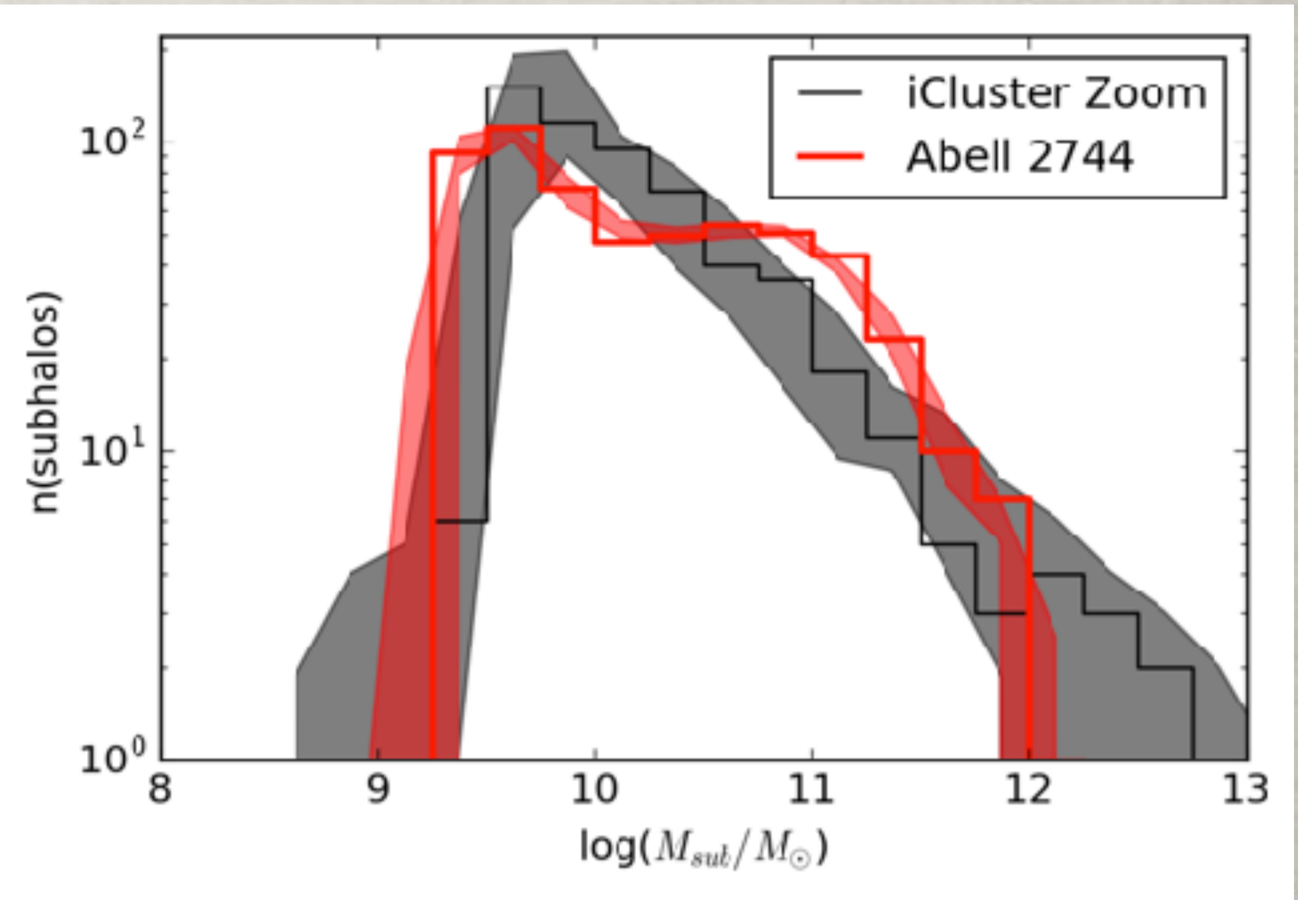
- Quantifying substructures in HFF
- Free form modelling: smaller power
- Evidence for WDM (Mohammed et al. 2016)
- Parametric (LTM) finds excess power: upper limit on self-interaction (Jauzac, M., et al., 2016)
- Free form agrees with LTM up to ~ 10 kpc (Sebesta et al. 2016) [139 lensed images]



Direct detection of substructure in clusters

Sub-halo mass function:

- Quantifying substructures in HFF
- Uses parametric modeling (LTM)
- Resolve DM haloes down to *M* ~ $10^{9.5}$ M_{Sun}
- Find agreement with LCDM
- Li et al. 2016: deviations occur for *M* < 10^9 M_{Sun} for m_{WDM} = 3.3 keV



Jauzac et al. 1702.04348

Move to lower masses: Einstein Rings!

Strong lensing and substructures

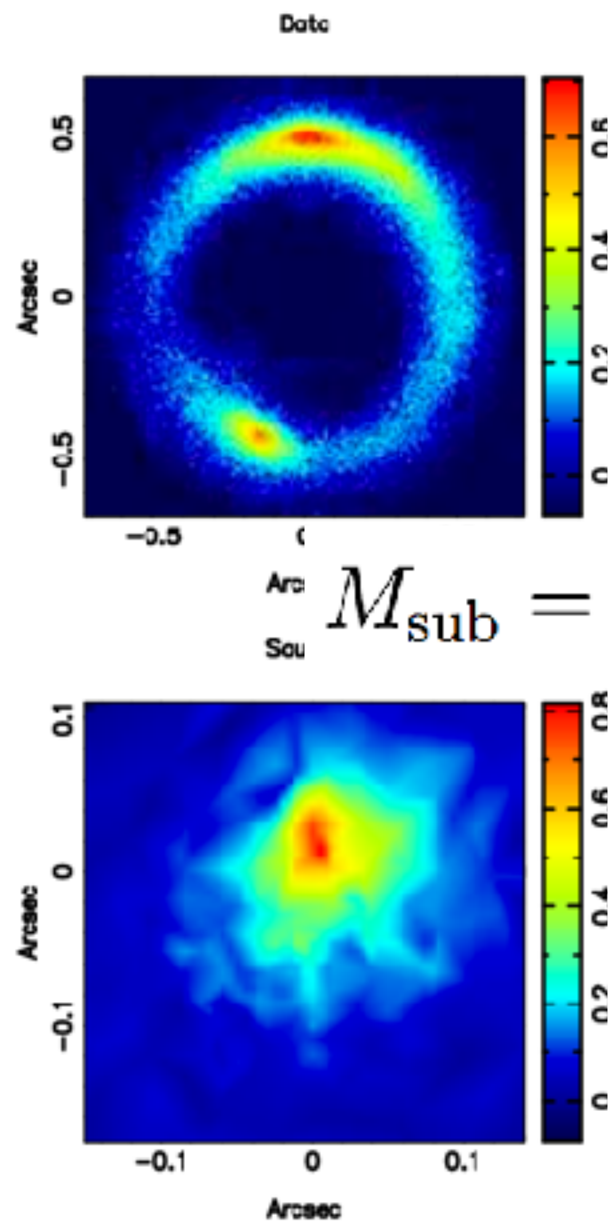
High sensitivity to small perturbations due to the caustic structure

MENU nature

Gravitational detection of a low-mass dark satellite galaxy at cosmological distance

S. Vegetti, D. J. Lagattuta, J. P. McKean, I

Nature **481**, 341–343 (19 January 2012)



- "Aside from direct or indirect detection of the dark matter particles themselves, Einstein ring systems currently offer the best astrophysical test of the nature of the dark matter" (Li et al. 2016)
- measurements of approximately 100 strong lens systems with a detection limit of $M_{low} = 10^7 h^{-1} M_\odot$ would clearly distinguish CDM from WDM in the case where this consists of 7 keV sterile neutrinos

Light-Matter Offsets

- Self-Intercting Dark-Matter predicts offsets between luminous and dark matter in dense regions of interacting systems: Smoking gun for SIDM
- Williams and Saha (2011): kpc-scale offsets in Abell 3827
- If interpreted solely as evidence for self-interacting dark matter:

$$\sigma/m \gtrsim 8 \times 10^{-31} \left(t/10^{10} yr\right)^{-2} cm^2 GeV^{-1}$$

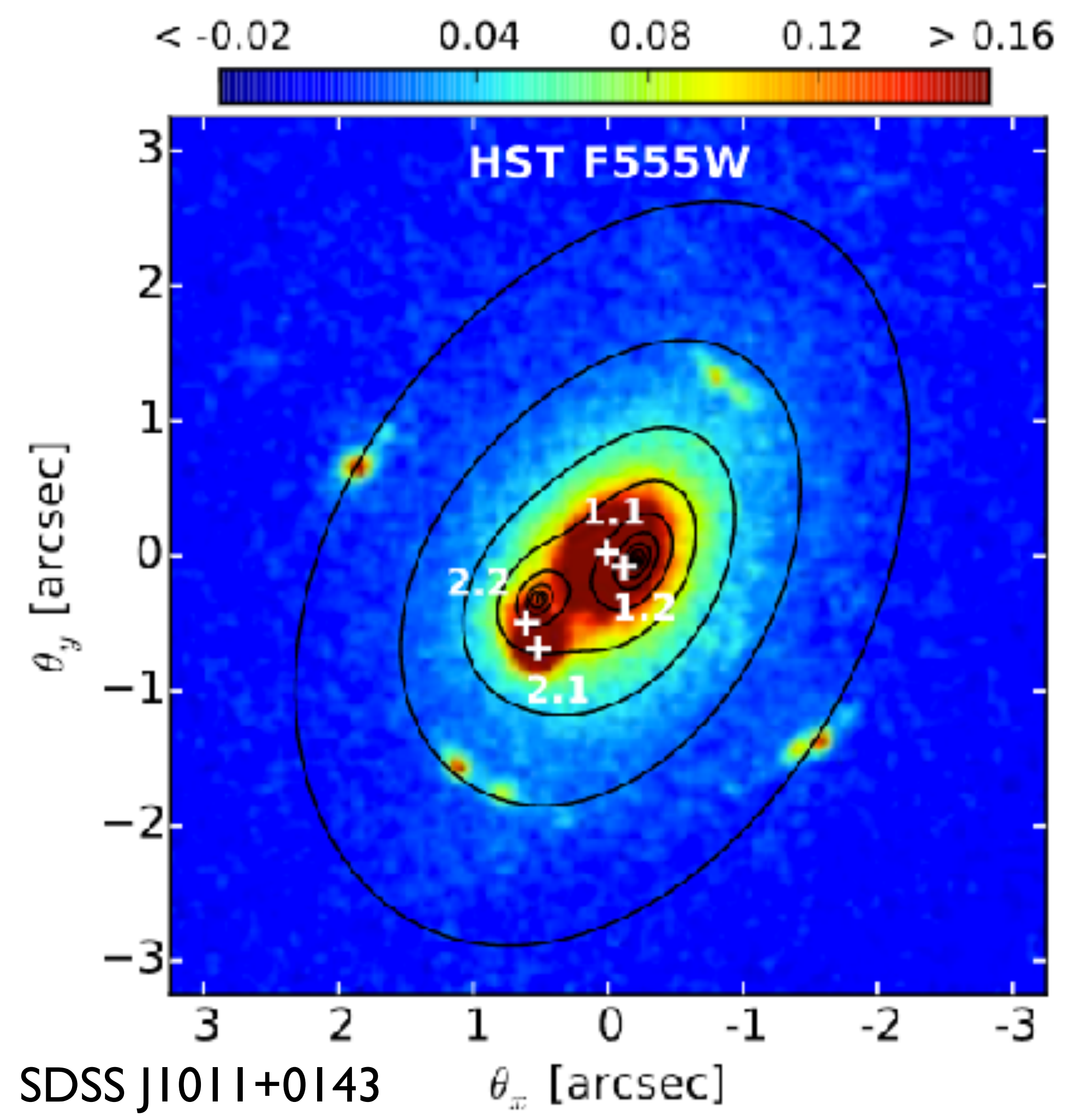
- Seen in clusters, e.g., Harvey et al., 2015, *The nongravitational interactions of dark matter in colliding galaxy clusters*, Science, 347, 1462 (2015)
- In a galaxy scale system (Shu et al. 2015):

$\sigma_{DM}/m \sim (1.7 \pm 0.7) \times 10^{-4}\ cm^2\ g^{-1} \times (t_{infall}/10^9\ yr)^{-2}$

- Kahlhoefer+ (2015), Wittman+ (2017): constraints overestimated

$$\sigma_{DM}/m_{DM} \lesssim 2\,\mathrm{cm}^2/\mathrm{g}$$

  - measurements, gastrophysics
  - Monteiro-Oliveira, et al. 2017: simulations (CDM + gas + galaxies)



SDSS J1011+0143

Gravitational telescopes: luminosity function of ultra-fraint UV galaxies at high-redshift

- Warm Dark Matter produces a cutoff in the matter power spectrum (Bode et al. 2001) and thus on the halo mass function

A STRINGENT LIMIT ON THE WARM DARK MATTER PARTICLE MASSES FROM THE ABUNDANCE OF $z = 6$ GALAXIES IN THE HUBBLE FRONTIER FIELDS

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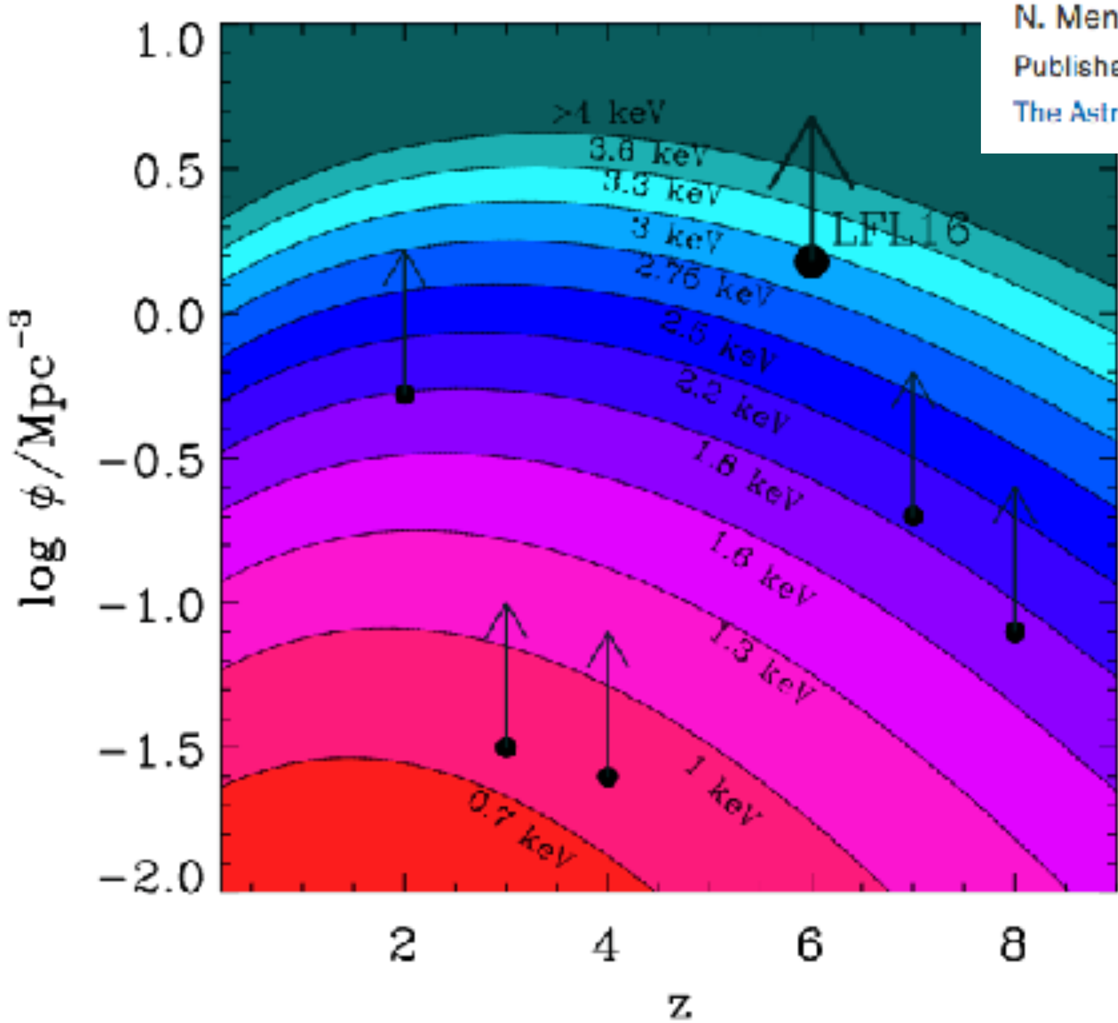


Mass of thermal relic WDM particles $m_X \geq 2.1$ keV at 3σ.

- Need to take into account uncertainties and systematics in the magnification
- Priewe, et al. 2017, Bouwens, et al. 2017

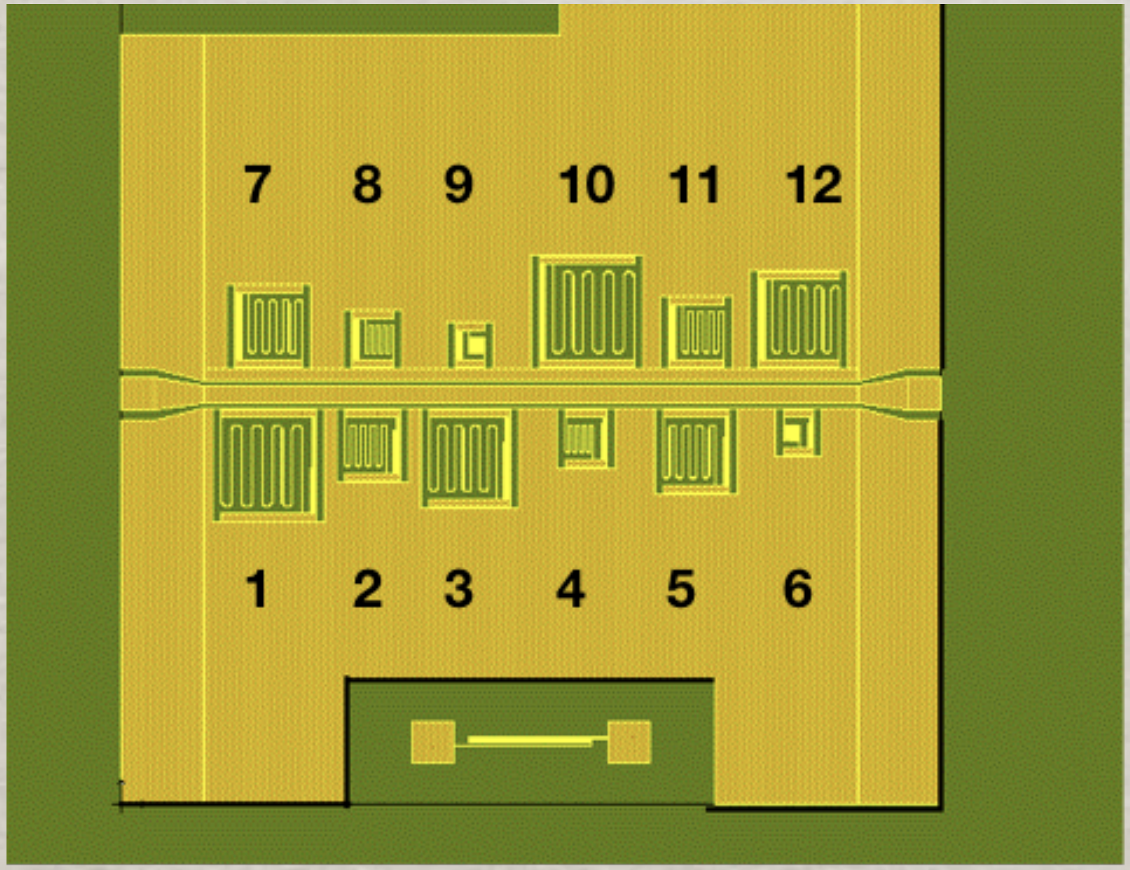
Current problems with OIR MKIDS

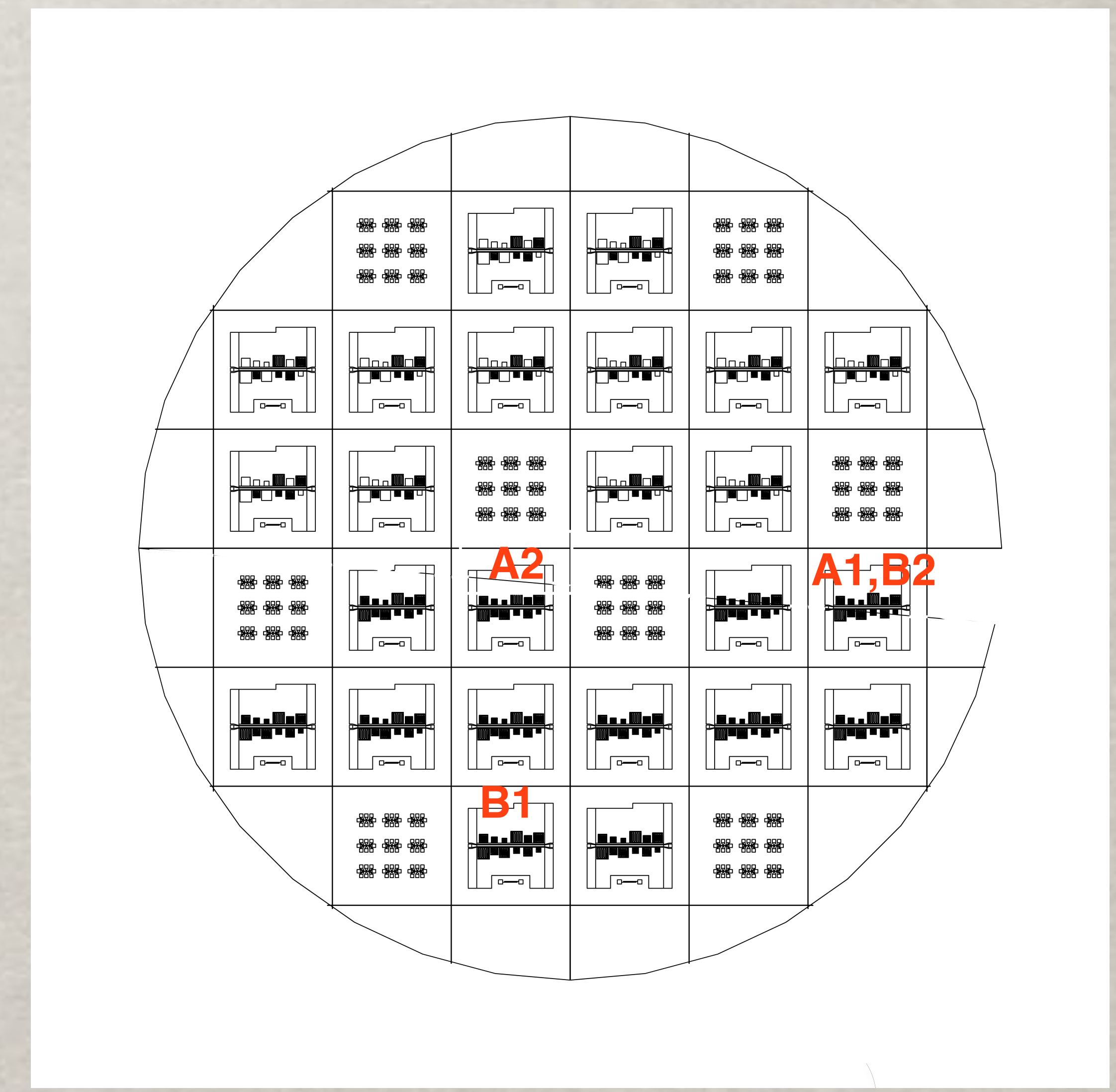
TiN, produced through Sputtering

- Frequency collisions (predictability/reproducibility)
- Change in frequency and quality factors on thermal cycles (stability)
- Low yield per pixel (~ 30%)
- Low resolution (killer for astrophysical applications for DM):
    - R = 12 @ 423 nm, = 6.8 @ 80 nm (x expected ~ 100)
- Proposed approach:
    - Atomic Layer Deposition
    - Build a prototype with few resonators
    - Produce several MKIDs, including different wafers
    - Test predictability: use simulations
    - Systematic study of predictability, reproducibility, stability and response to light

Design and simulations

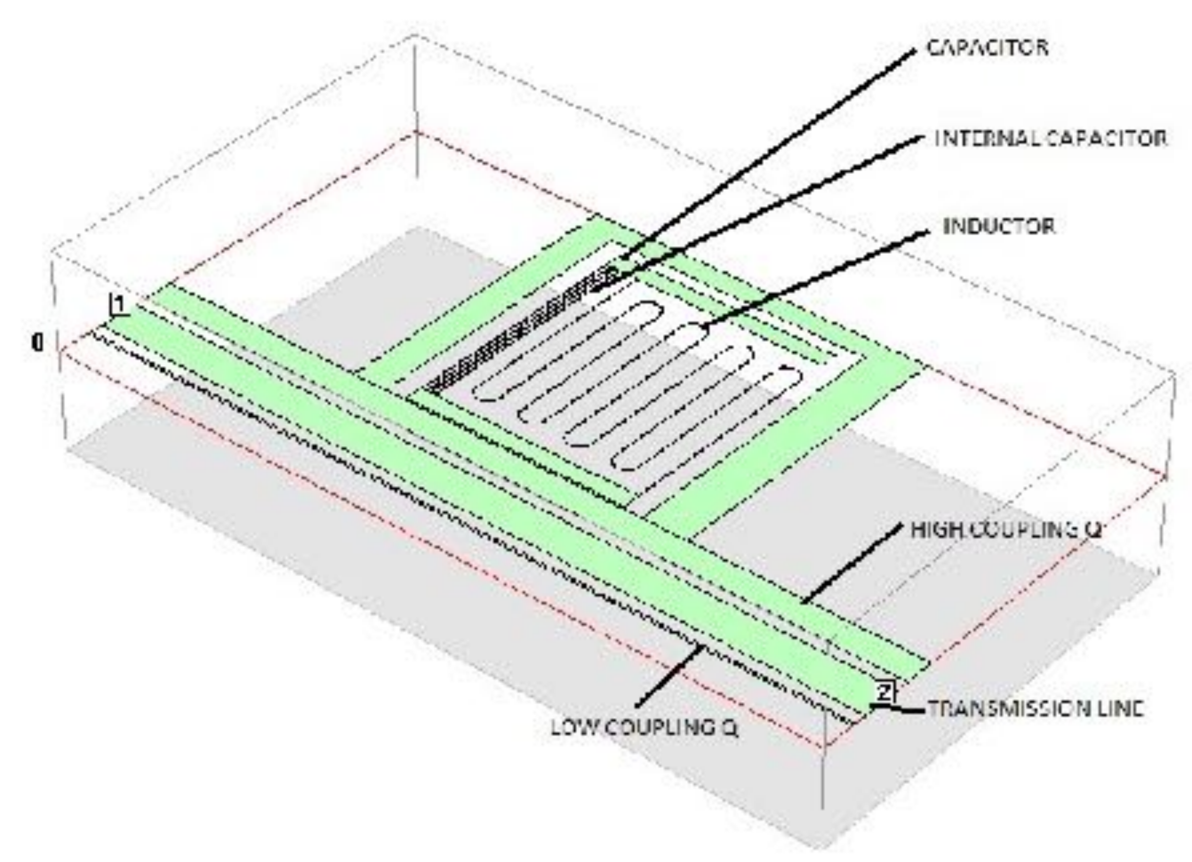
- 14 resonators per MKID with varying sizes and couplings (quality factors and resonance frequencies)

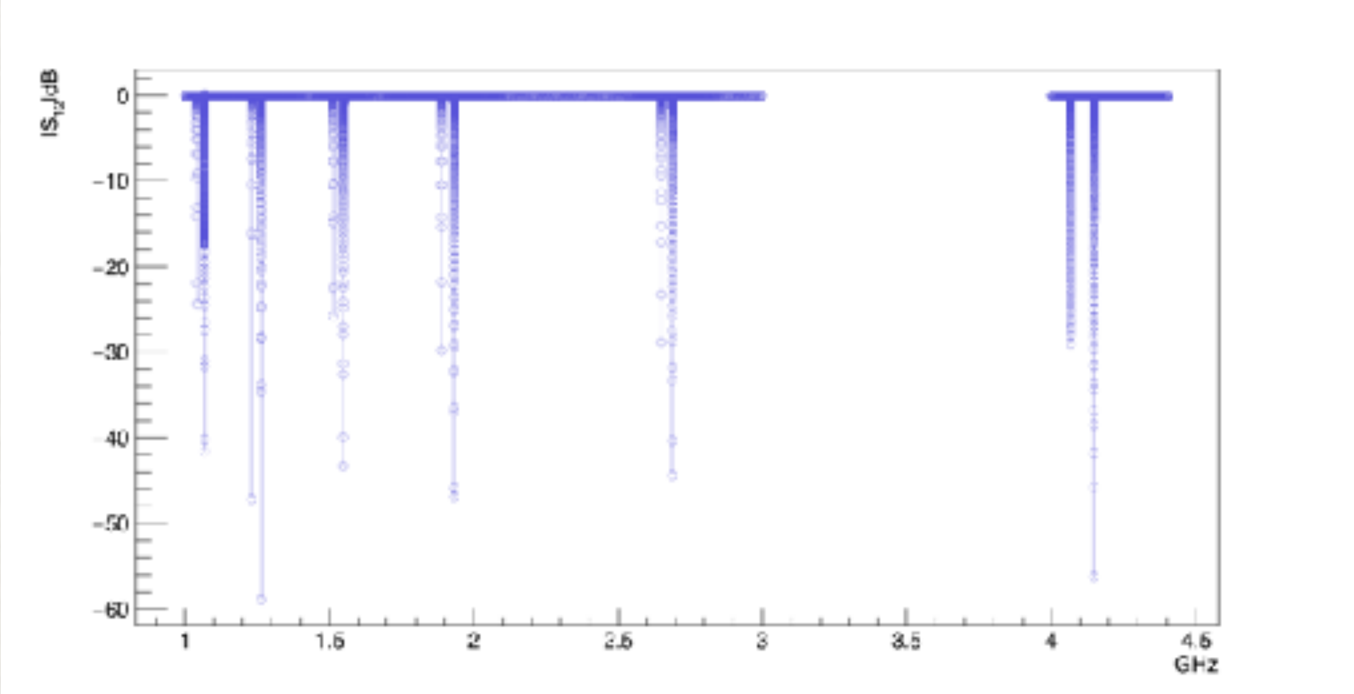




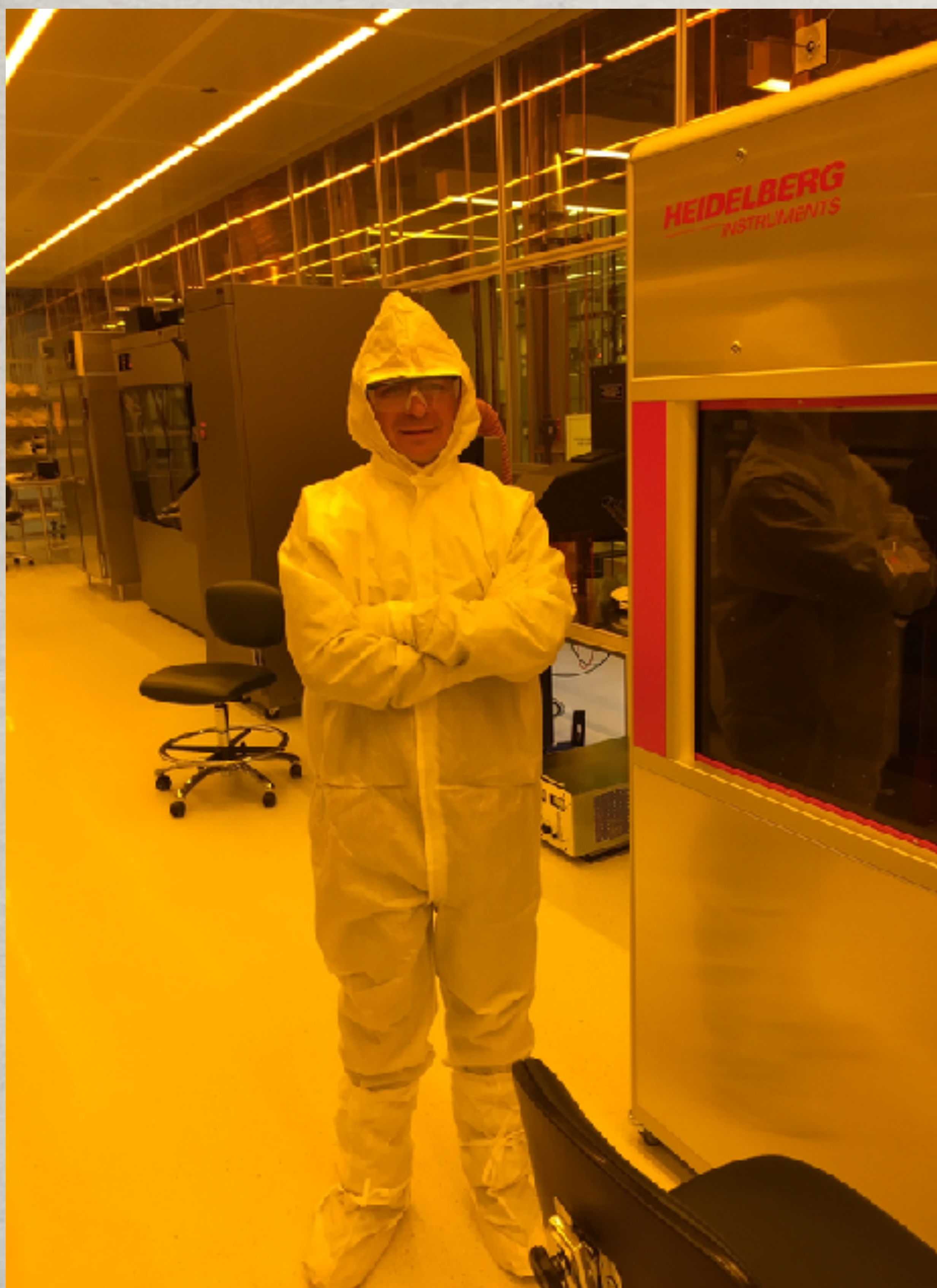
Design and simulations

- 14 resonators per MKID with varying sizes and couplings (quality factors and resonance frequencies)
- Simulations of each resonator with SONET



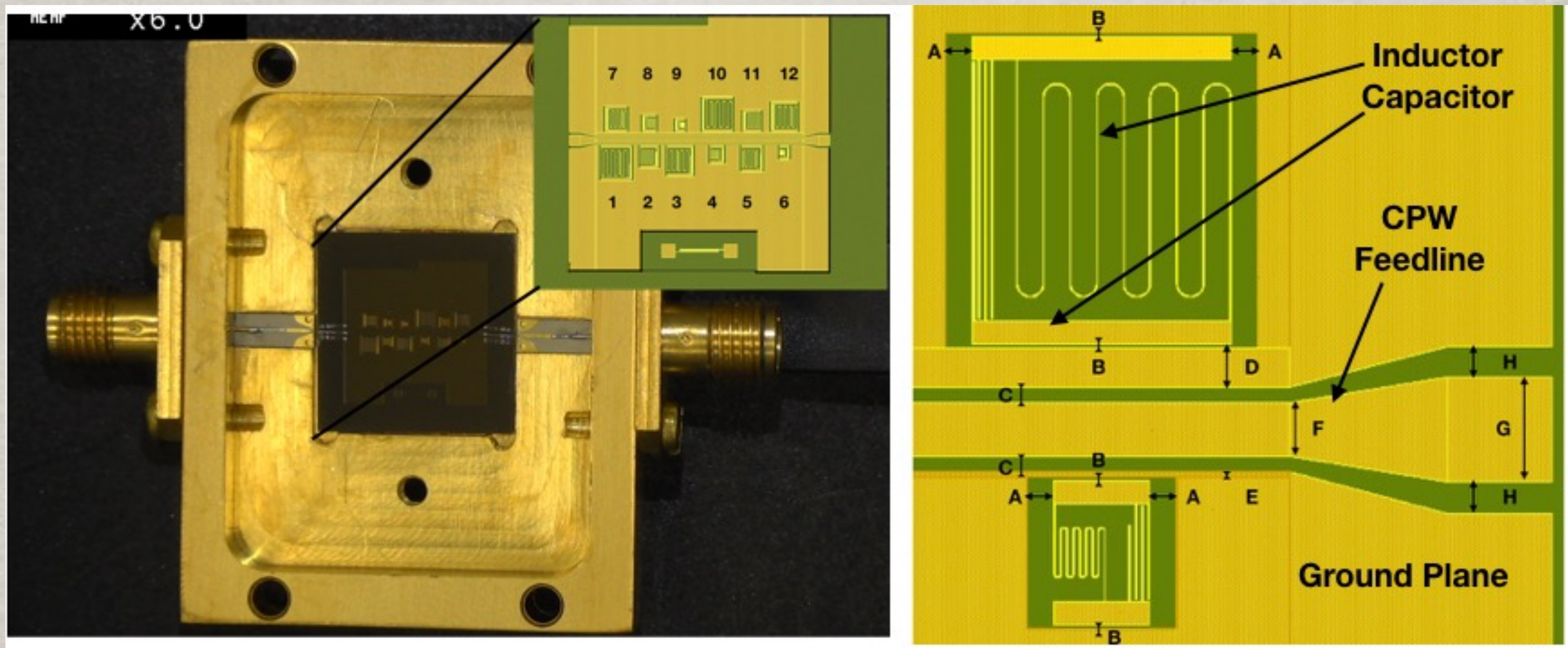


Fabrication at the Priztker Nanofabrication Lab



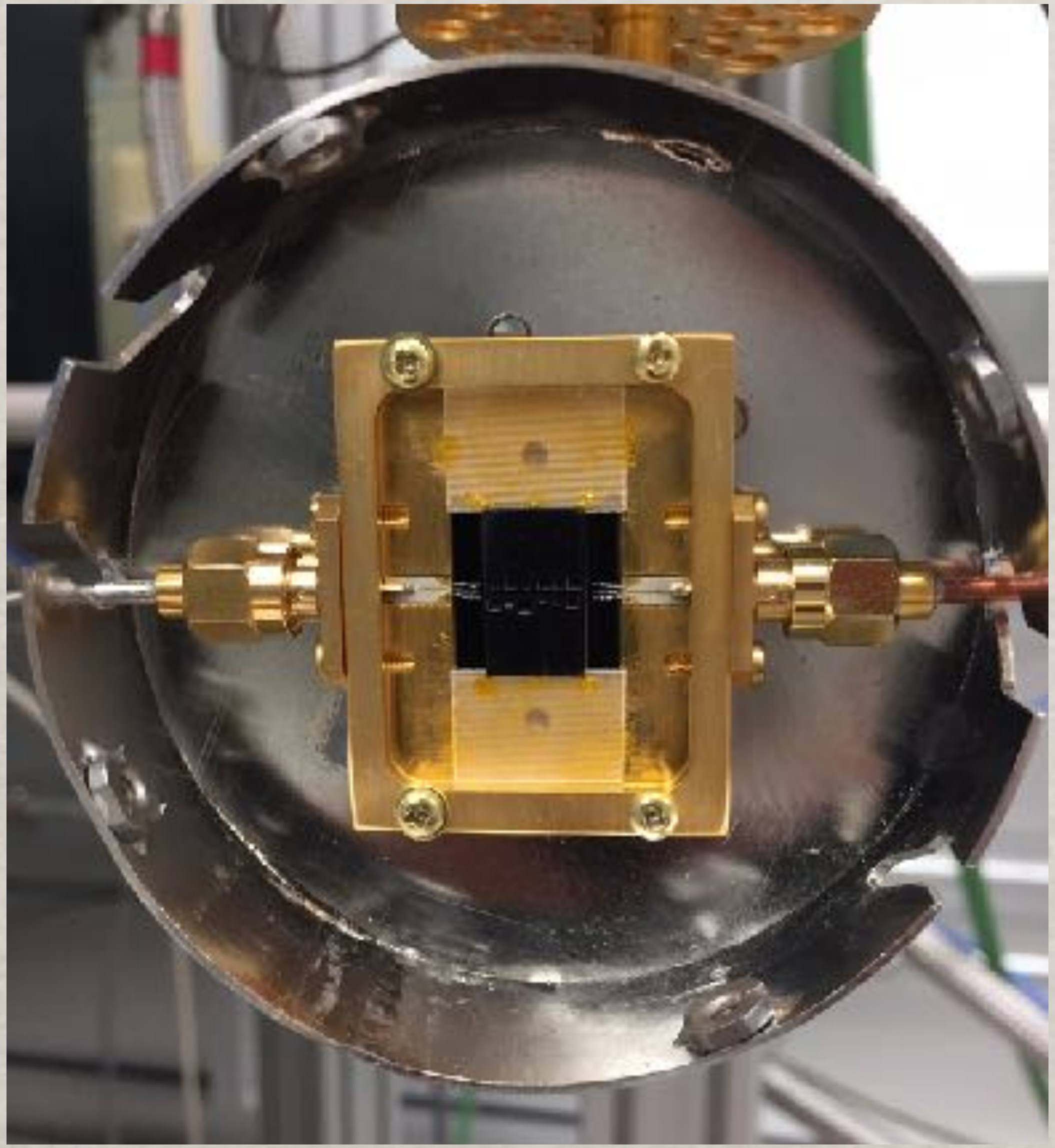
Experimental Setup

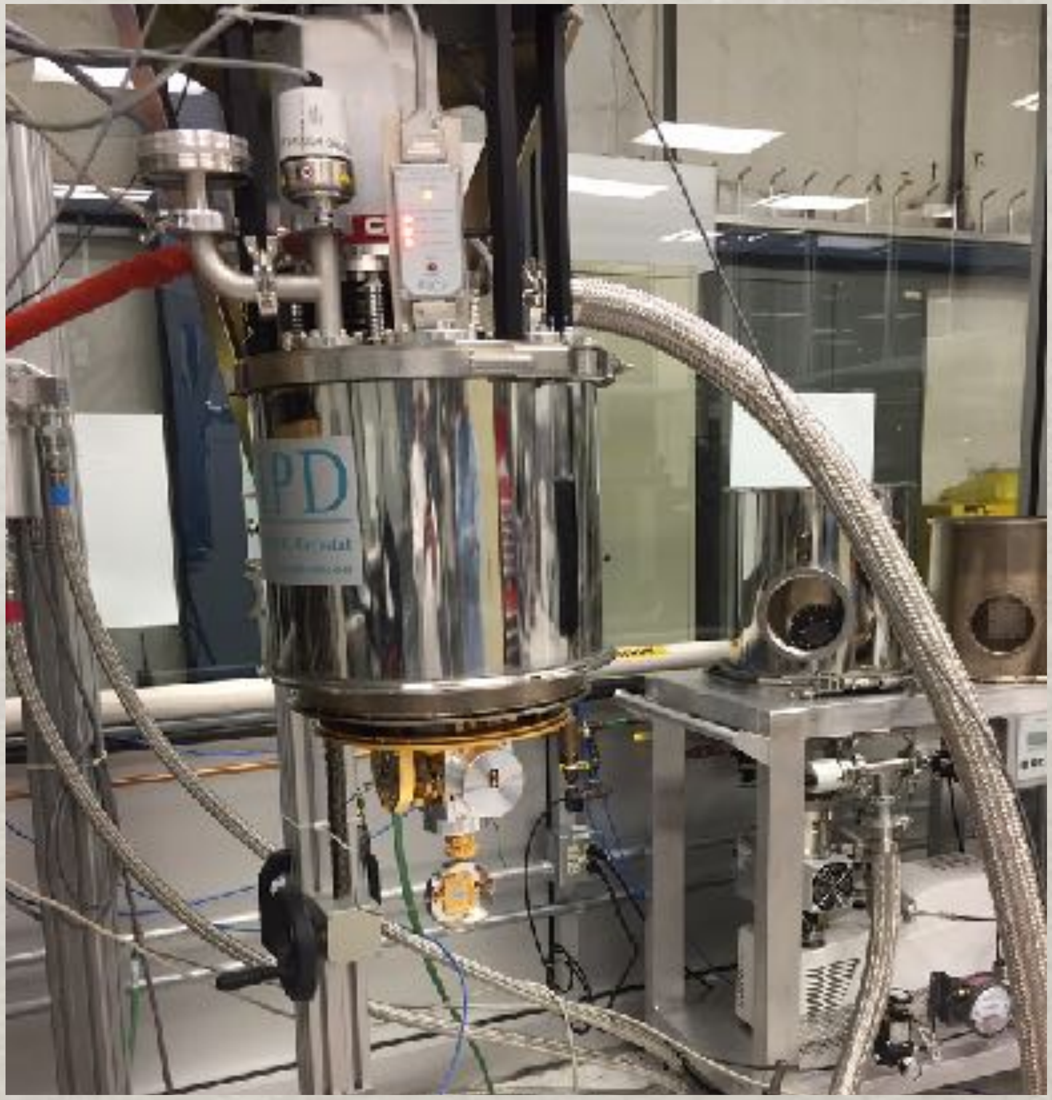
- Mounted in a gold plated cold box



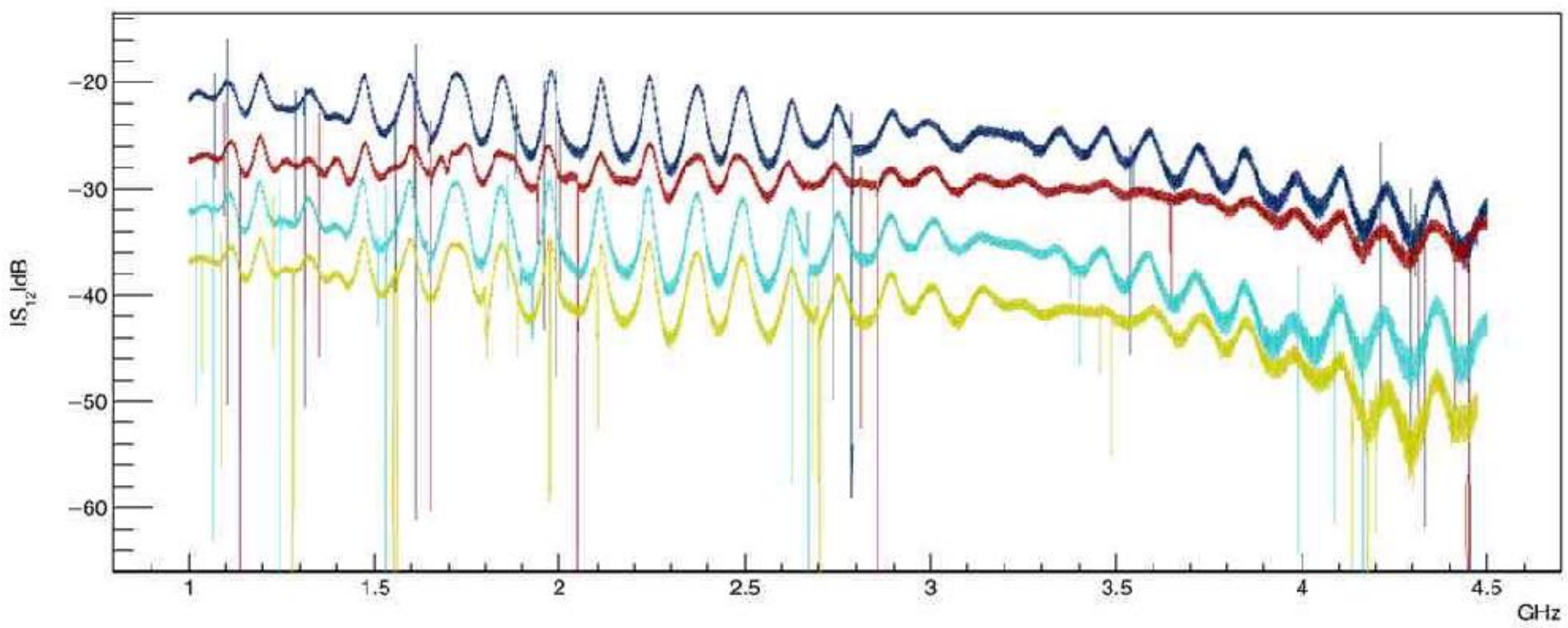
Experimental setup

- Mounted on an Adiabatic Demagnetization Refrigerator
- Connected to a network analyzer





Transmission Curves

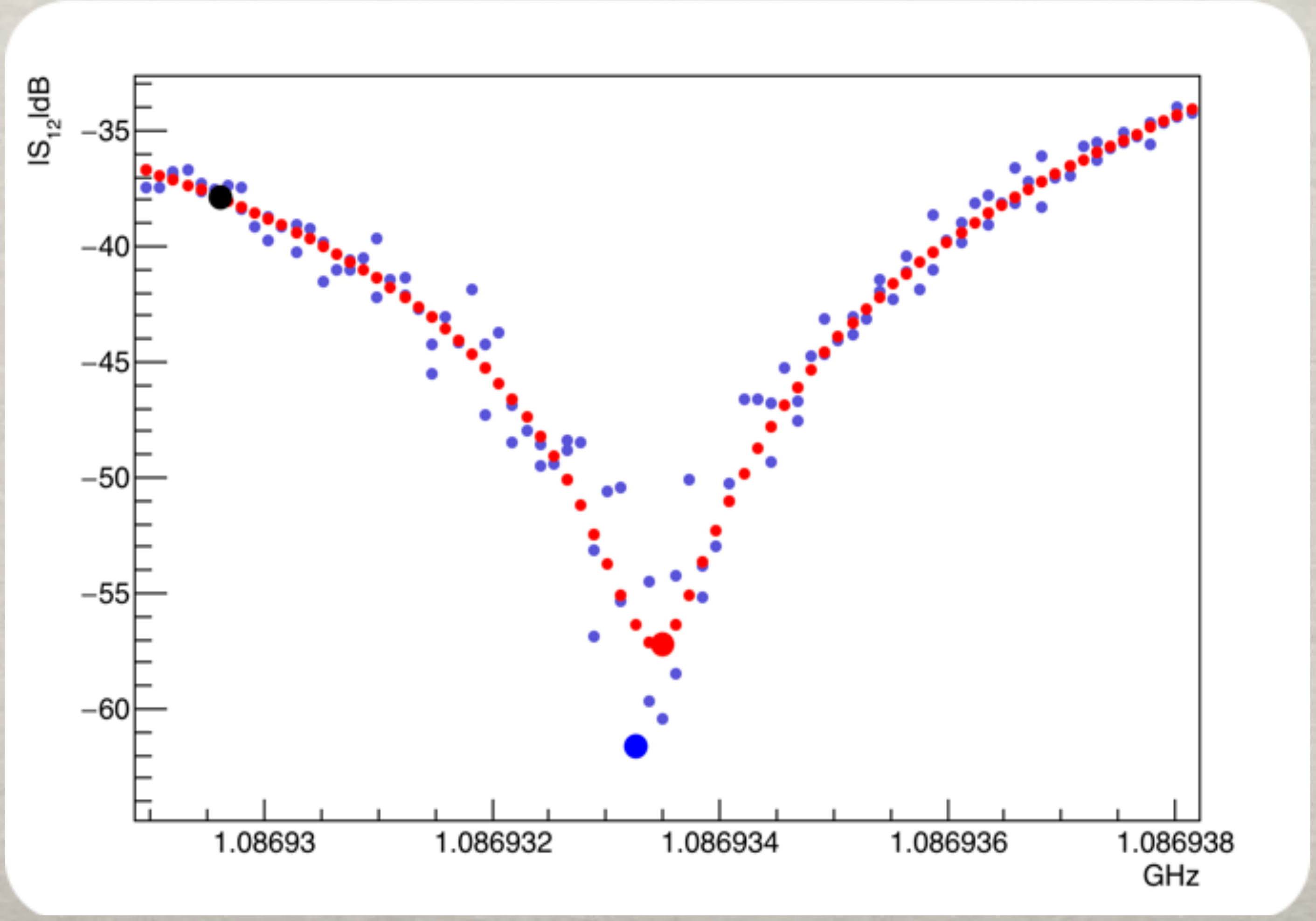


Obtaining the Resonator parameters

- Fitting the transmission curve

$$S_{12}(f) = a\exp(-2\pi j f\tau)\left(1 - \frac{Q_l/|Q_c|e^{j\phi_0}}{1 + 2jQ_l\left(\frac{f-f_r}{f_r}\right)}\right)$$

for each resonator and each operating temperature



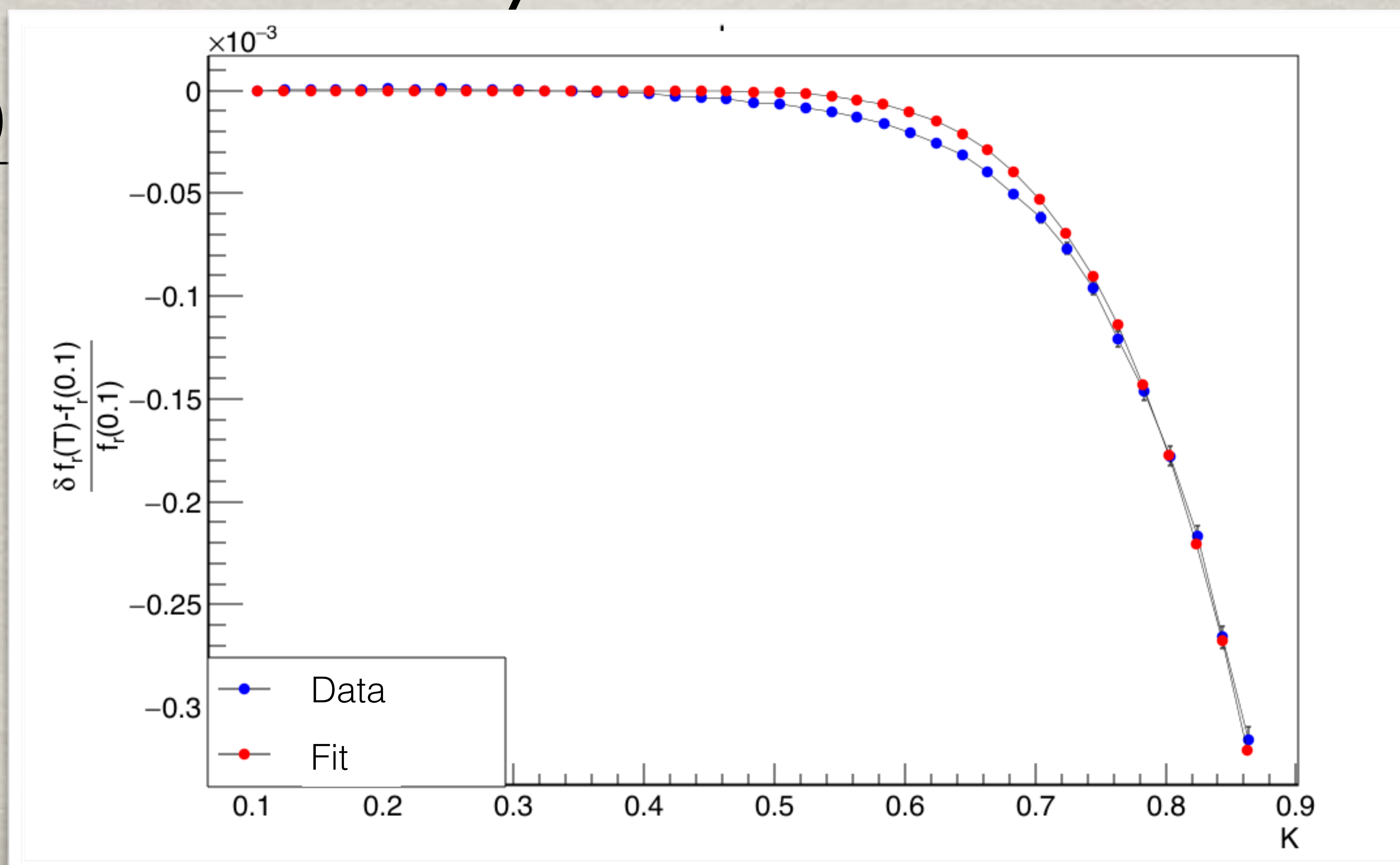
Measuring the critical temperature

- Fractional variation of resonant frequency

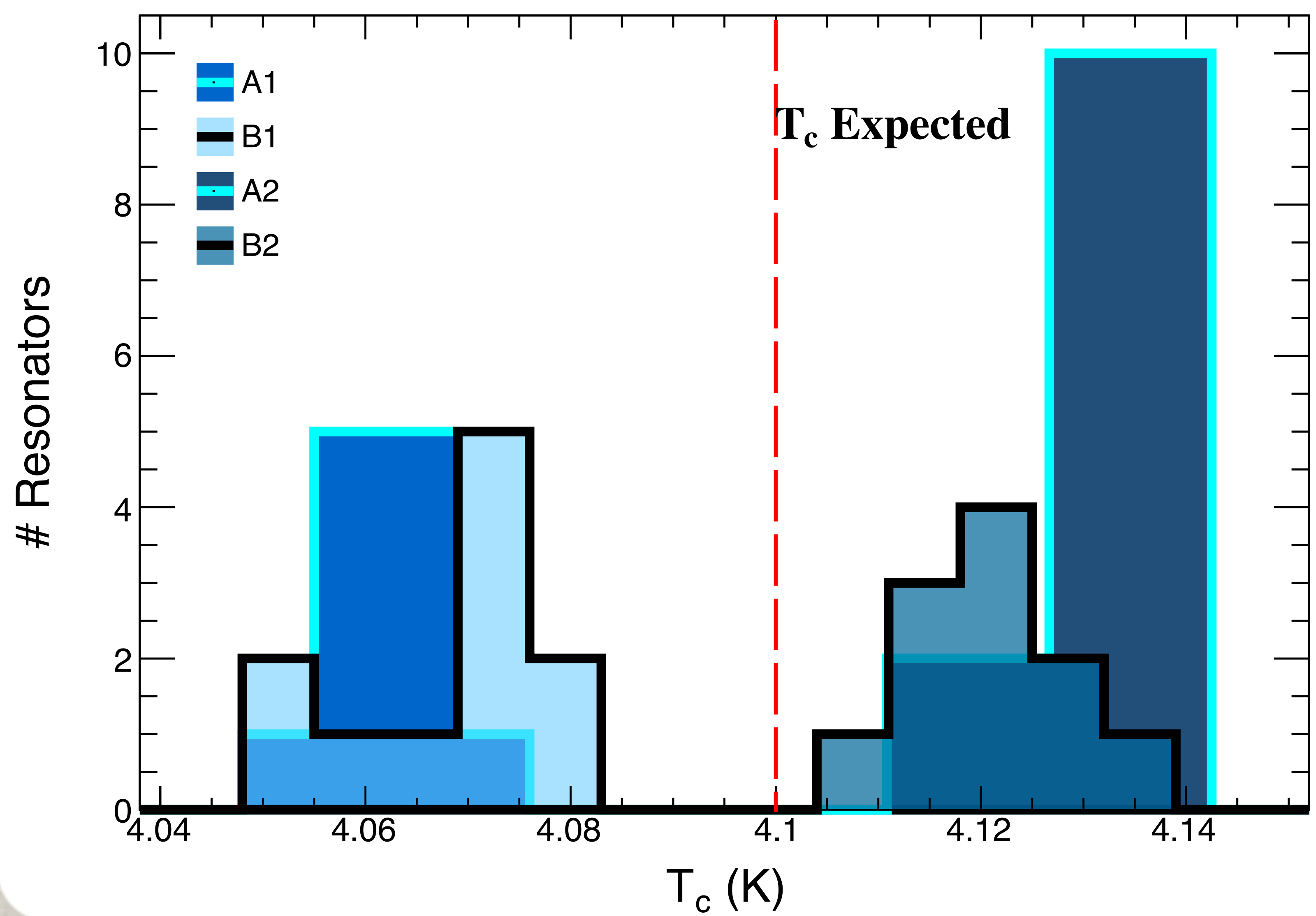
$$\frac{\delta f_r}{f_r} = \frac{f_r(T) - f_r(0)}{f_r(0)} = -\frac{1}{2}\alpha\frac{\delta\sigma_2(T)}{\sigma_2(0)}$$

- Mattis-Bardeen theory:

$$\frac{\sigma_2(T)}{\sigma_N}$$

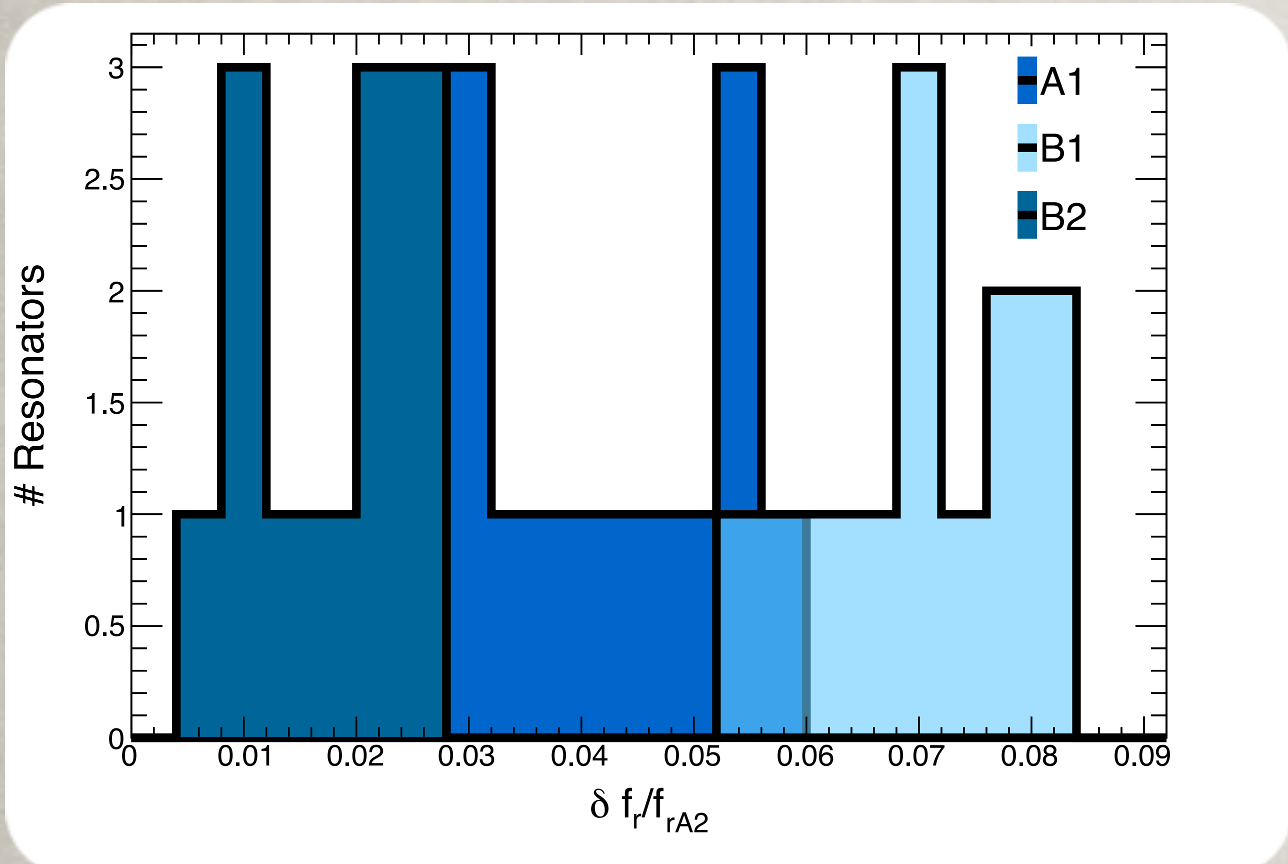


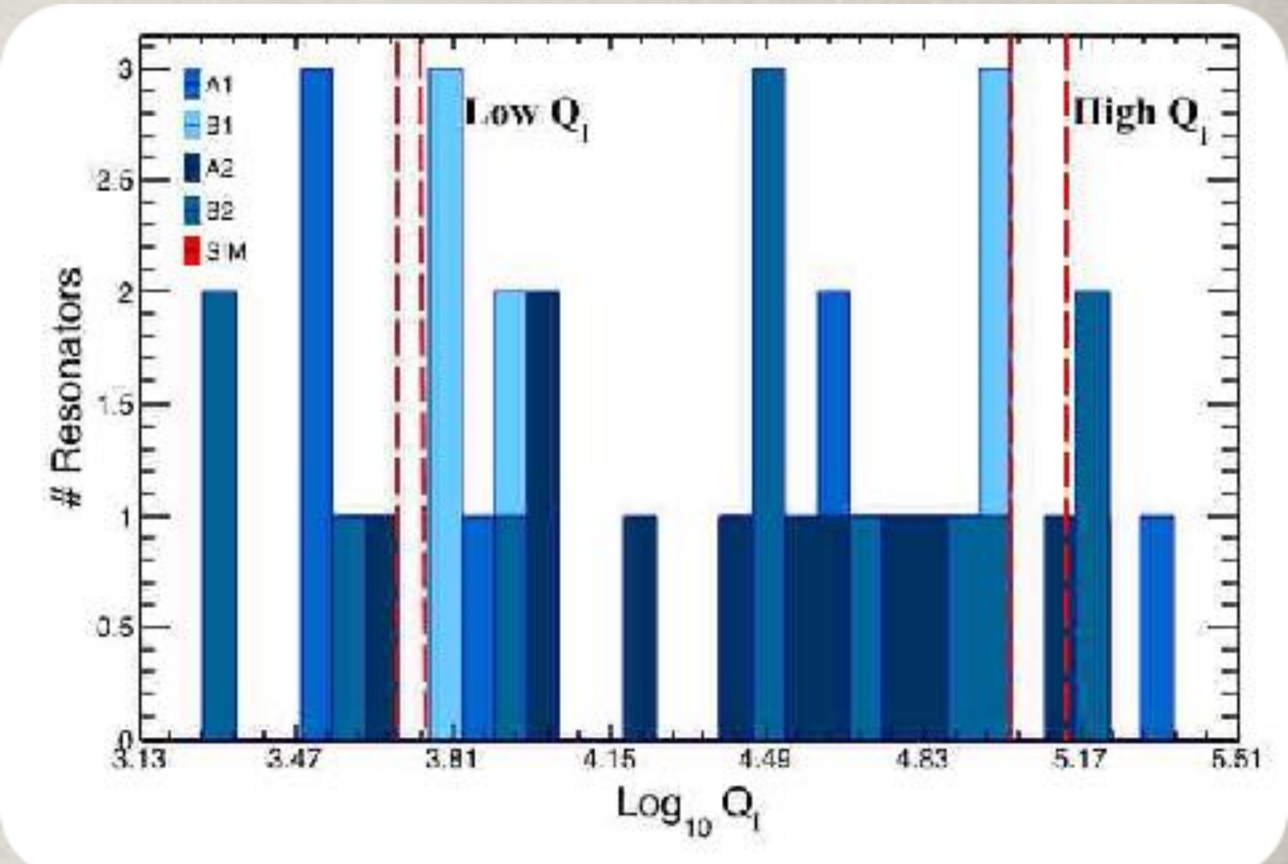
Homogeneity of critical temperatures



- Less than 1% variation within each MKID and same wafer MKIDs
- ~ 2% variation for different waffers

Frequencies and Quality Factors





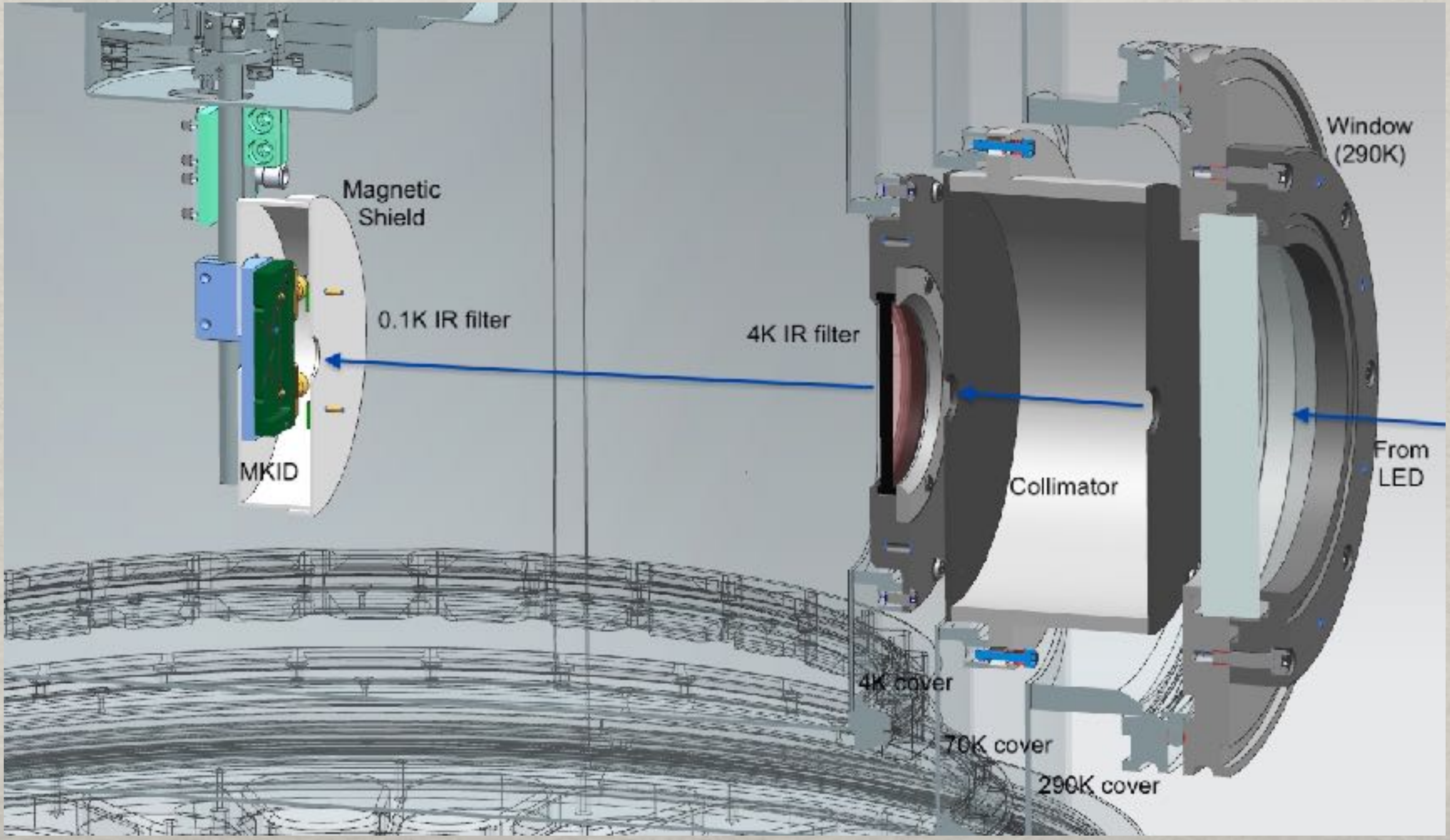
- Significant frequency variations
- Large quality factor variations
- Cannot reproduce them simulating changes in the fabrication process
    - Sizes, Si purity, etching…
- Problem with the transmission line?
- Intrinsic limitation for TiN MKIDs?

Shining photons to the MKIDS

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

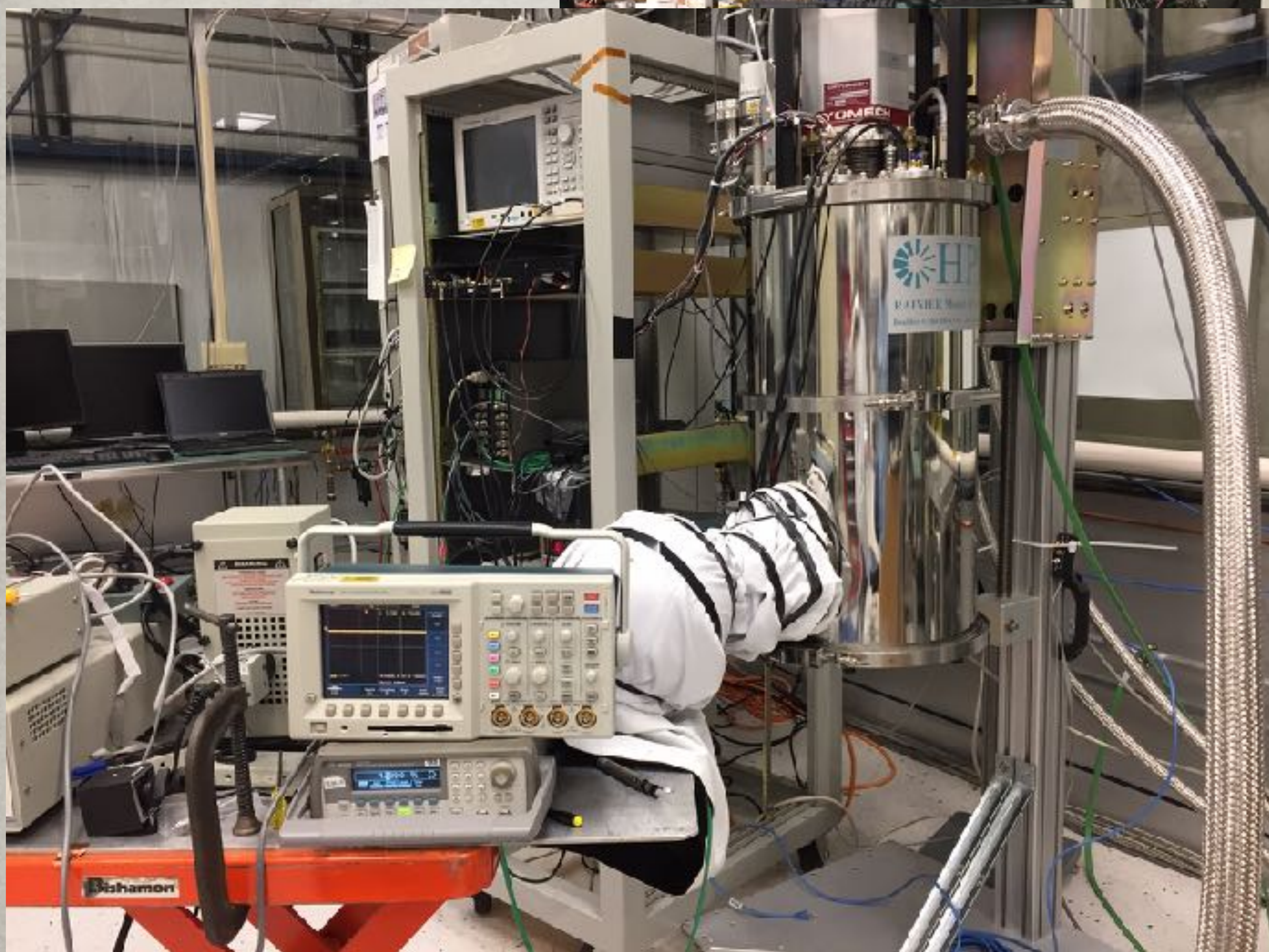
η efficiency - assumed to be 0.57 (from 1979 paper)

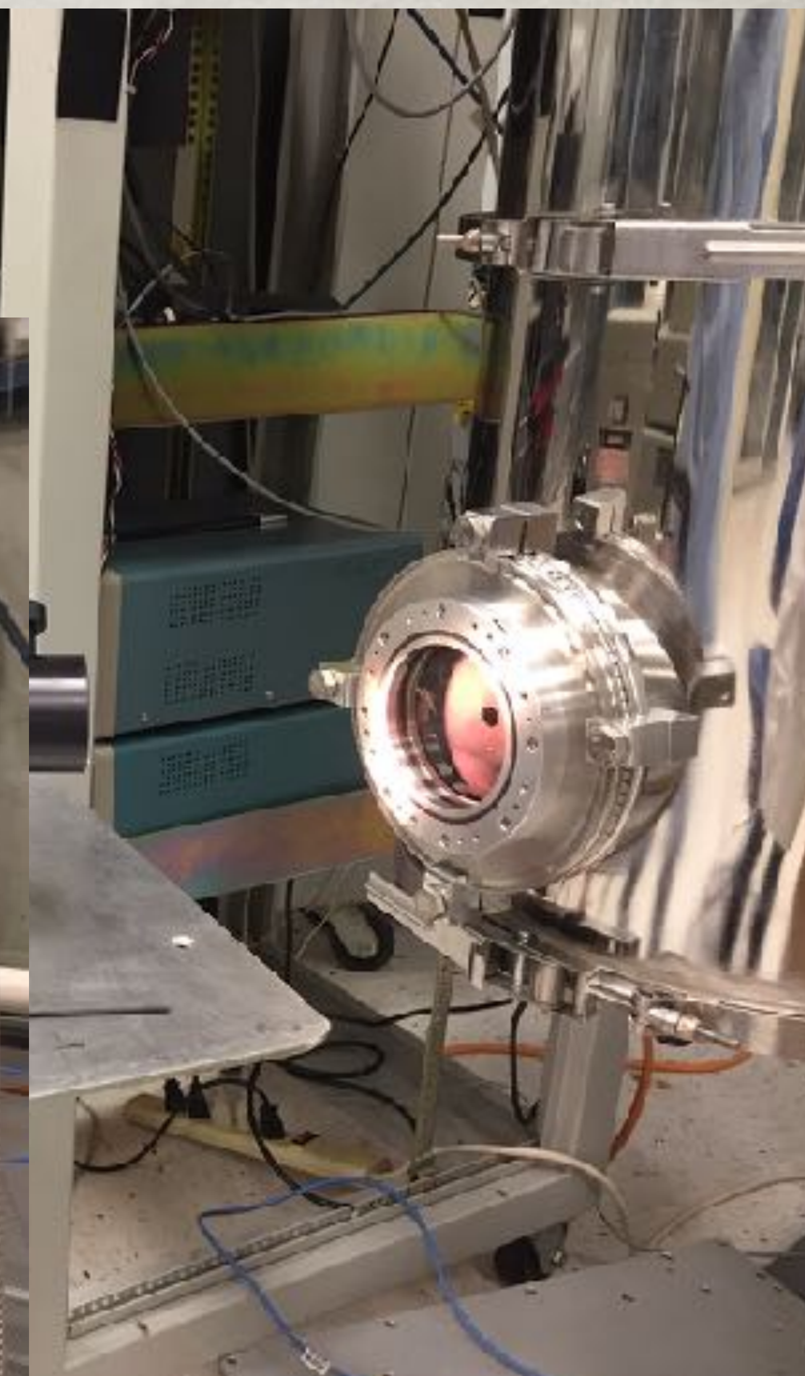
measure it experimentally!



Shining photons to the MKIDS

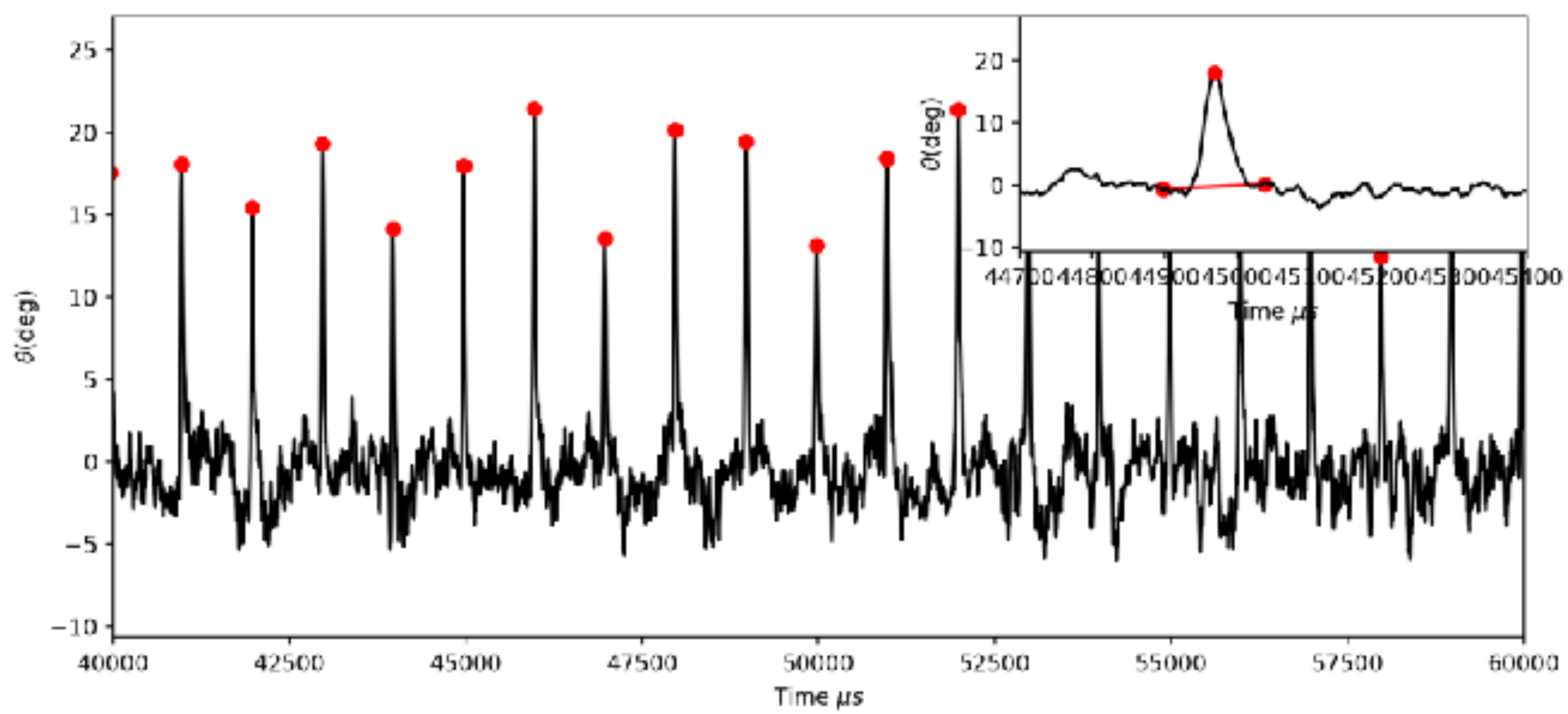
Single photon measurements usually with x-rays



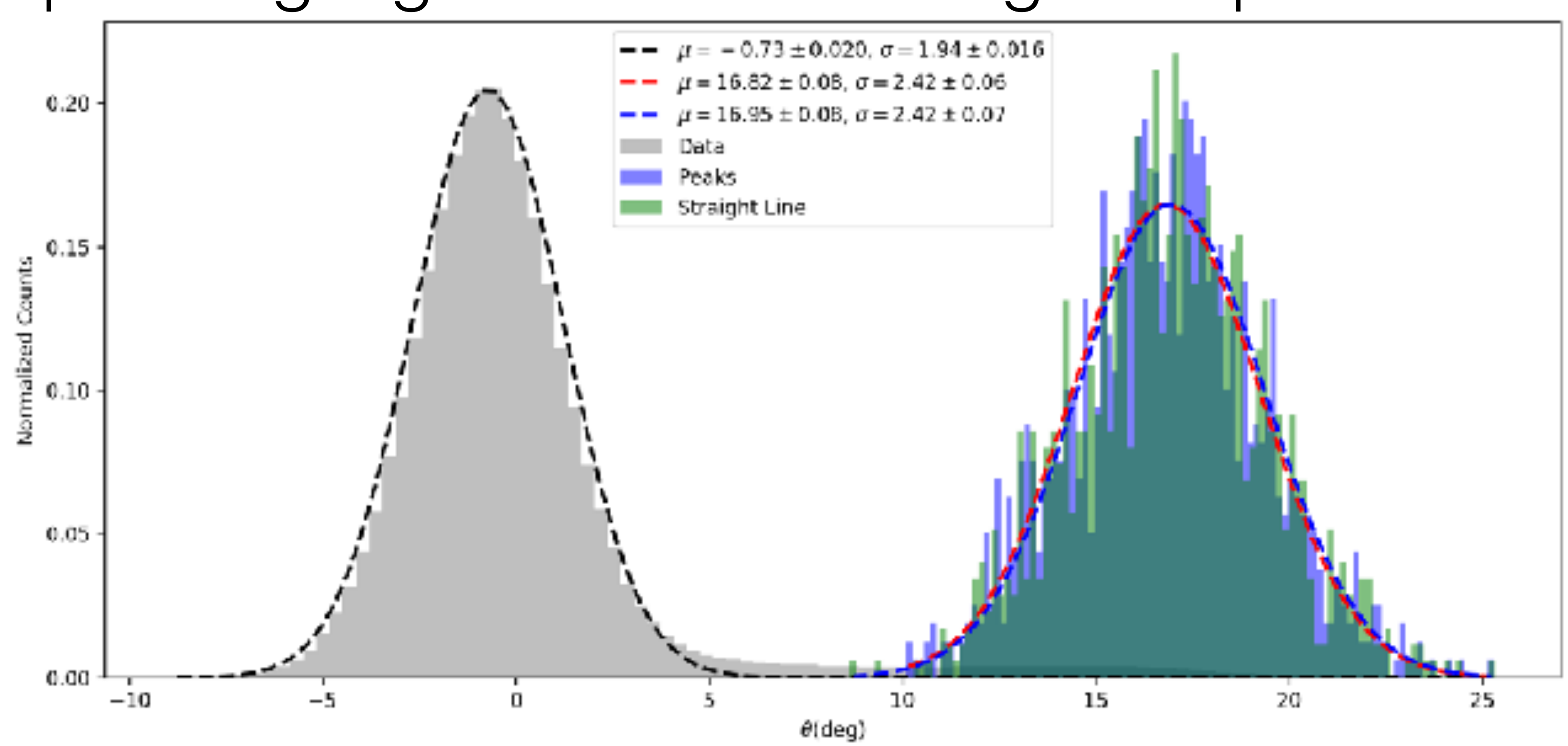


Measure phase shifts as a function of time for photon pulses

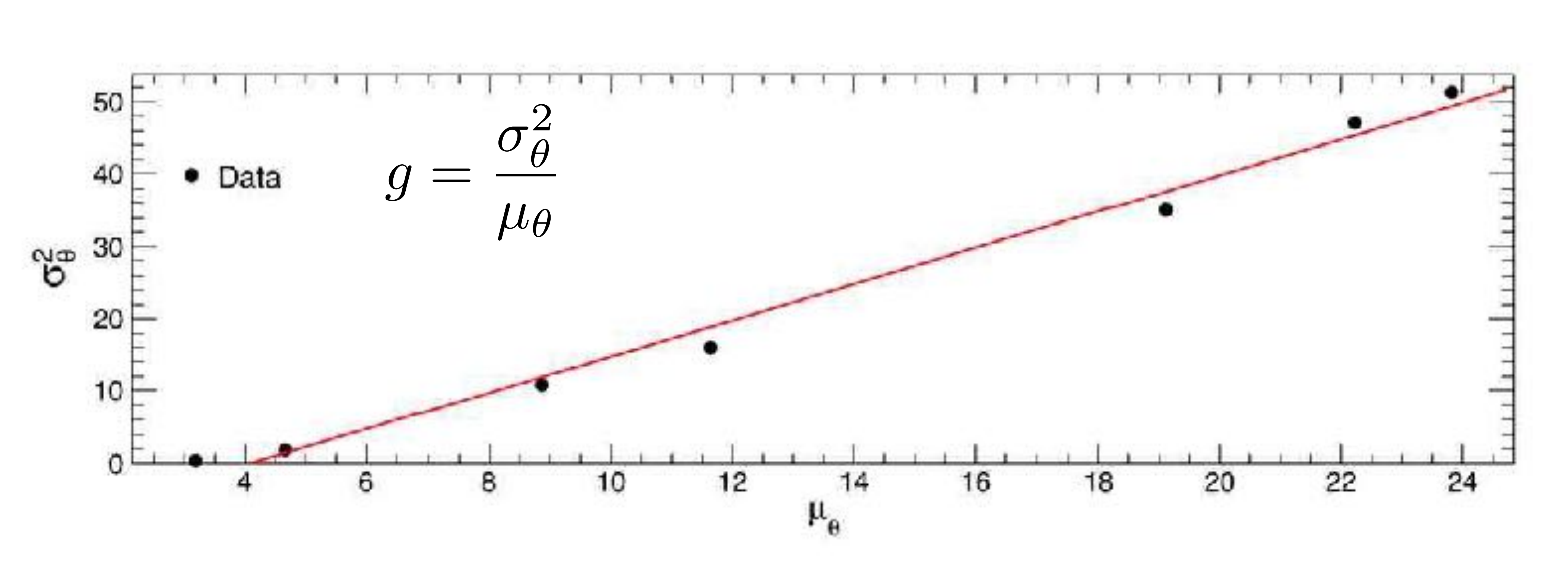
Shining photons to the MKIDS



separating signal to noise through the pulse timing



Measuring the gain and efficiency



$$\eta = \frac{g}{\theta_{N_{qp}}} \qquad N_{qp} = 2VN_0\sqrt{2\pi k_B \Delta T}e^{-\frac{\Delta}{k_B T}}$$

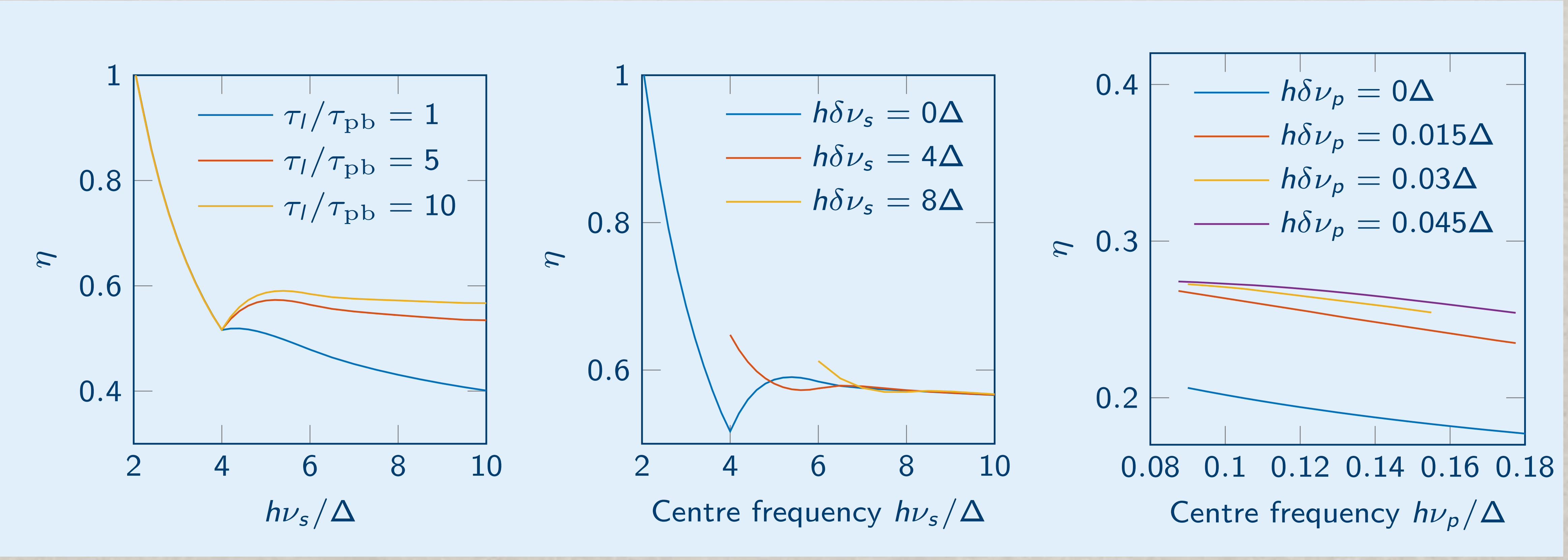
- Derived efficiency
  - no mask: 0.03 - 0.04 !
  - with mask: 0.004 - 0.007 !

Measuring the gain and efficiency

- Derived efficiency
  - no mask: 0.03 - 0.04 !
  - with mask: 0.004 - 0.007 !

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

- 1-2 orders of magnitude below assumed value! Explain worse resolution?
- Energy loss to the bulk in the downconversion chain?



Recent theoretical calculations, but not down to our low energies

Concluding remarks

- MKIDs are promising for direct dark matter detection and astrophysics
- Novell: simulations, ALD fabrication, efficiency measurement
- ALD MKIDs are more uniform and stable, but not predictable
- OIR TiN MKIDs have a much lower efficiency than expected, explaining the worse energy resolution
- Current *R* for TiN probably not enough for SL studies of DM properties
- Future
  - complete characterization of fabricated MKIDs
  - test new designs to improve efficiency
  - move to other materials (PtSi?) and/or wavelengths
  - use for DM detection?