MUSCAT and Toltec

Dublin KIDs workshop

Dublin 7th September 2017

Scope of talk

- Overview of the MUSCAT project and the team
- Instrument overview
- System design considerations
- Detector design consideration and rational

- Audience knowledge may vary so feel free to ask question.

What is MUSCAT?

- **M**exico **U**K **S**ubmm **C**amera for **A**s**T**ronomy
- A collaboration between INAOE and Cardiff to build a 1.1mm receiver for the LMT but extended to the wider scientific communities in both Mexico and the UK.
- Primary aims
  - Provide technology transfer to Mexico from the UK
  - Achieved by building a large scale photometer in Cardiff using visiting Mexican researchers.
  - Kindle a long term scientific relationship between the UK and Mexico
  - Achieved via a short science project collaborating being conducted between UK and Mexican astronomers

Current Team

UK main team

- Doyle (UK PI)
- Pascale (Data analysis)
- Hargrave (Optics)
- Mauskopf
- Brien (Cryogenics)
- Rowe (Readout)

UK additional support

- Eales (Astronomy)
- Gear (Astronomy)
- Peretto (Astronomy)
- Ade (Filters and advice)
- Tucker (Filters)
- Moseley (EM design)
- Zhu (EM design)
- Pisano (EM design)

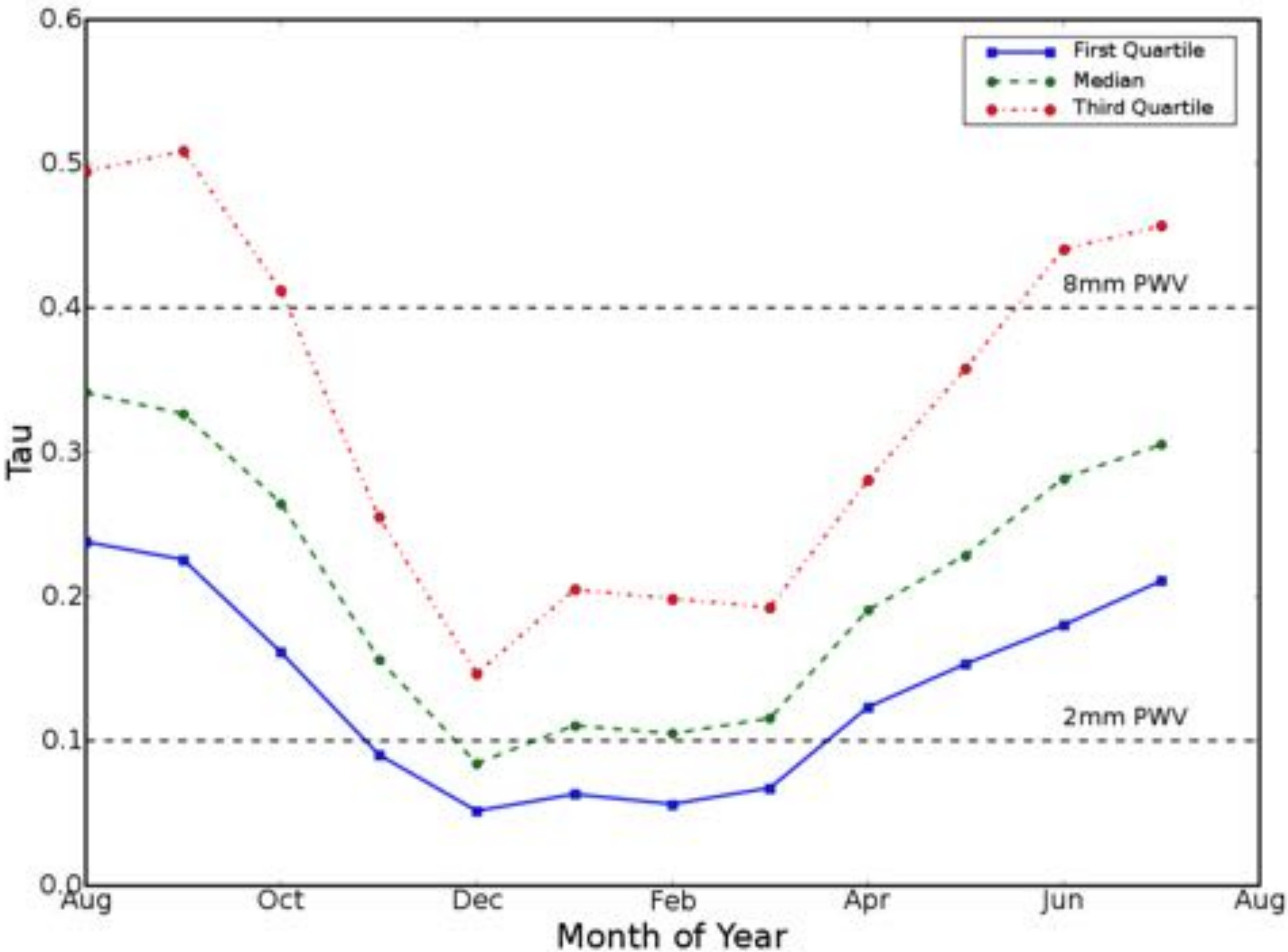
Mexico

- Hughes(Mexican PI)
- Castillo (System design)
- Ferrusca
- Velazquez
- 3 PDRAs

What is the LMT?

- **The Large millimeter Telescope**
- **Located on top of Sierra Negra, Mexico's 5th highest mountain – Altitude 4640m (15,200 ft)**
- **Diameter 50m – World's largest single dish telescope operating at mm wavelengths.**
- **Dry high altitude site with good but seasonal observing conditions**

Typical observing conditions at the LMT site

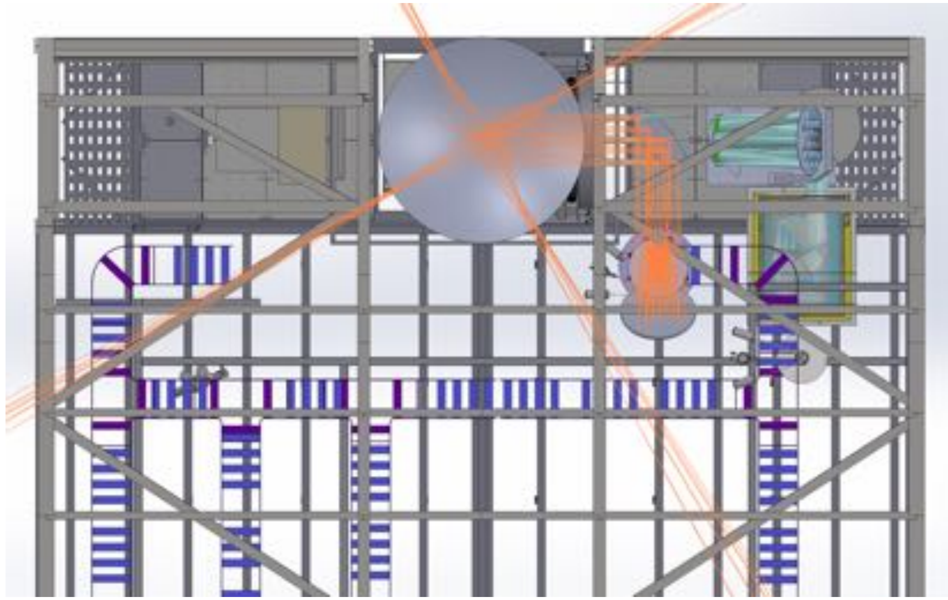


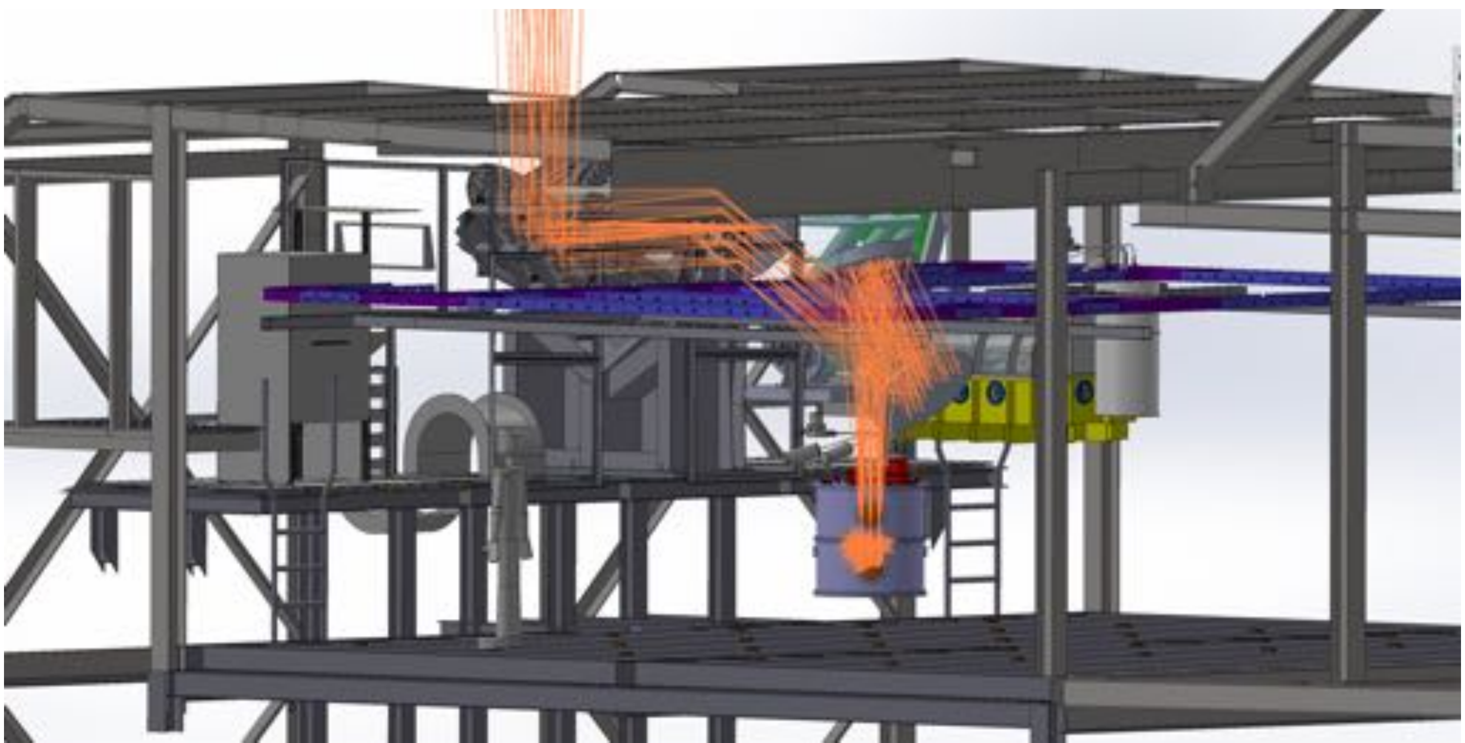
Instrument details

- Proposed 1000 pixel 1.1mm camera but will aim for full FOV (4’) ≈ 1800 dual polarisation detectors.
- A instrument platform that can be used in the future as a technology demonstrator.
  - For example On-chip spectrometer or 850µm focal plane
  - Requires frequency independent cold optics (reflective)
  - 100mK Focal plane stage

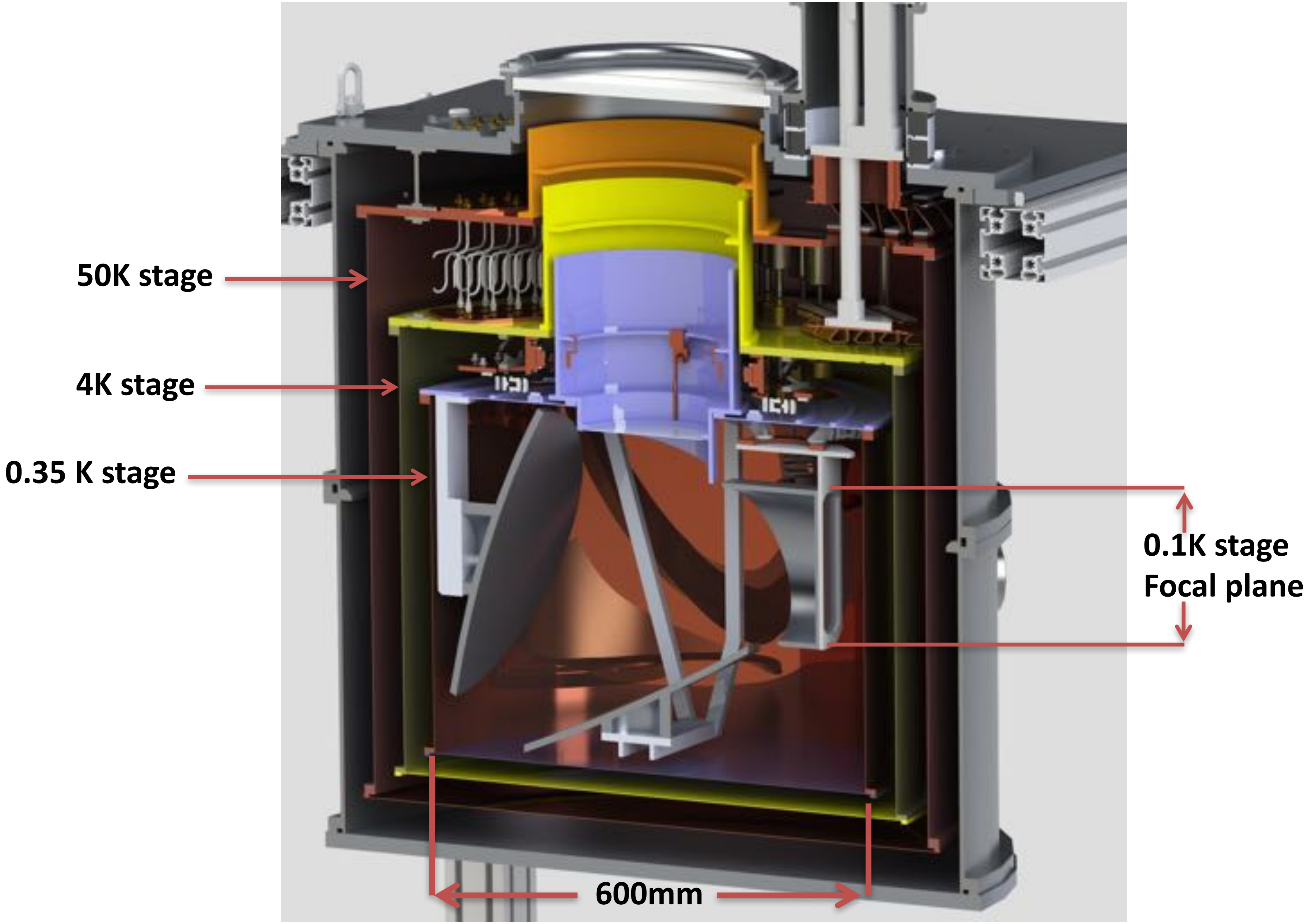
- **Original timescale for deployment on to the LMT 2.5 years. Now aiming for installation summer of 2018.**

System Overview



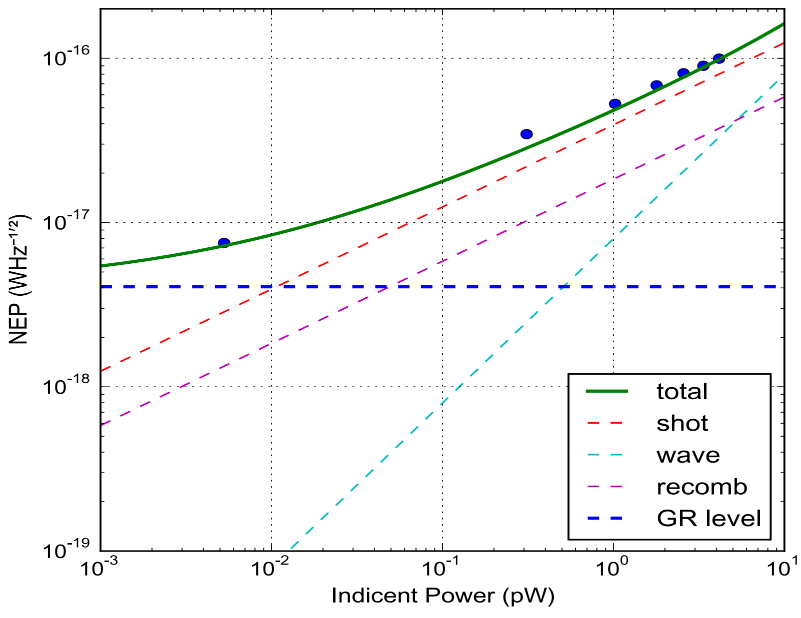


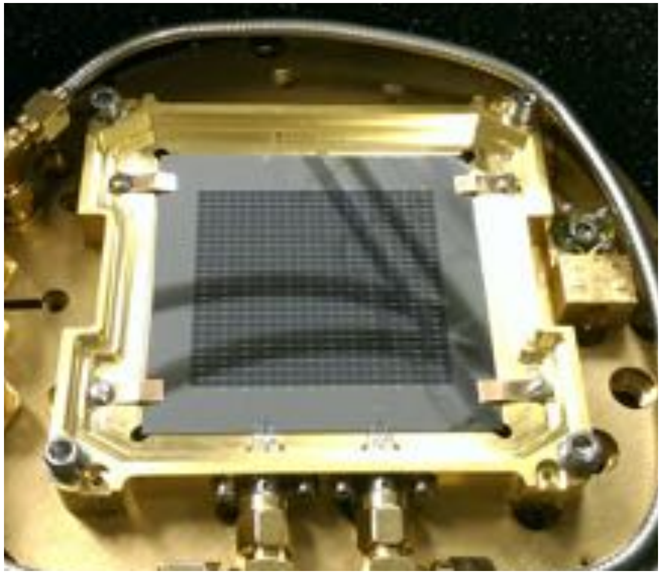
System Overview



Detector Arrays

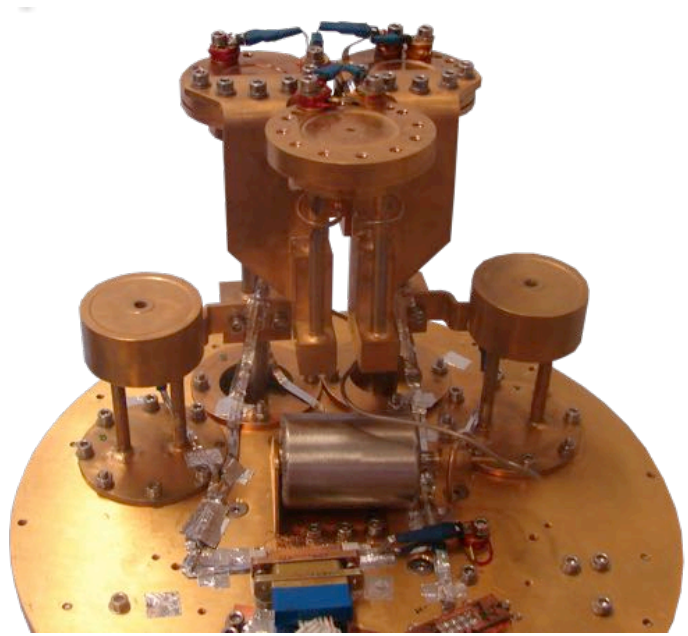
- MUSCAT will the Cardiff developed LEKID detector.
- Proven technology with high MUX ratios that are relatively simple to fabricate
- Currently investigating novel horn coupling techniques
- System is adaptable to horn or open array formats.





New cryogenic Technology

- MUSCAT will employ a compact **continuous** dilution refrigeration system developed by Cardiff and Chase Cryogenics.
- First on-sky demonstration of this cost effective and compact sub-K cooler.
- Base temperature of order 90mK under 3uW load
- No external infrastructure required



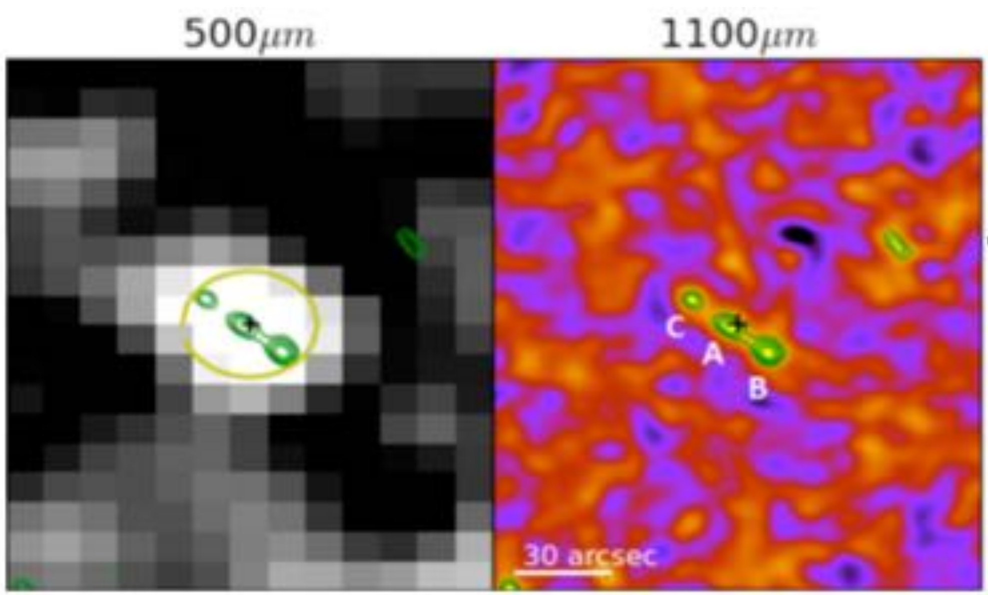
So why build yet another mm/submm camera?

- Superior telescope and site gives faster mapping speeds

  MUSCAT 3.0 $Deg^2/mJy^2/hour$
- Higher angular resolution enabling new science
  - NIKA 2 IRAM 11” @1.2mm
  - SCUBA 2 13” @850um and 7.9” @ 450um
  - MUSCAT 5” @ 1.1mm
- Future UK access to mm/sub mm telescopes is uncertain
- Kindles new collaborations between UK and Mexico

New Science Enabled by MUSCAT

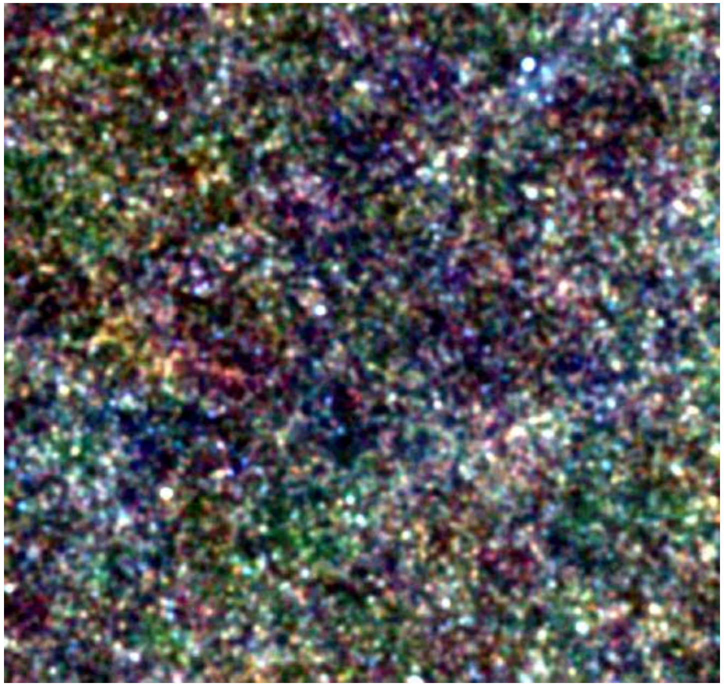
- MUSCAT provides higher resolution observations of SPIRE sources in the H-ATLAS field.
- This allows optical counterparts to be assigned to ALL H-ATLAS sources allowing analysis of galaxy evolution out to Z=3 (12bn years)

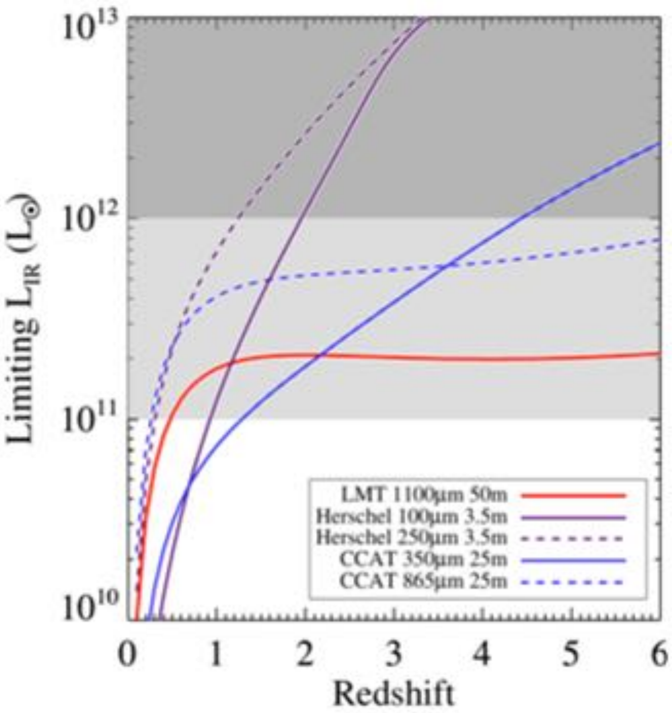


SPIRE 500µm (36” FWHM) and 32m-LMT/AzTEC 1.1mm (5” FWHM) images of H-ATLAS GAMA source G12.MF.49632 showing the advantage of increased sensitivity and resolution. MUSCAT with the 50-m LMT

New Science Enabled by MUSCAT

- **Beating the confusion limit.**
- Looking for sources with no SPIRE counterparts (Z>3), basic properties, such as redshifts, stellar masses and star-formation rates, can be estimated allowing a study of when galaxy started to form.

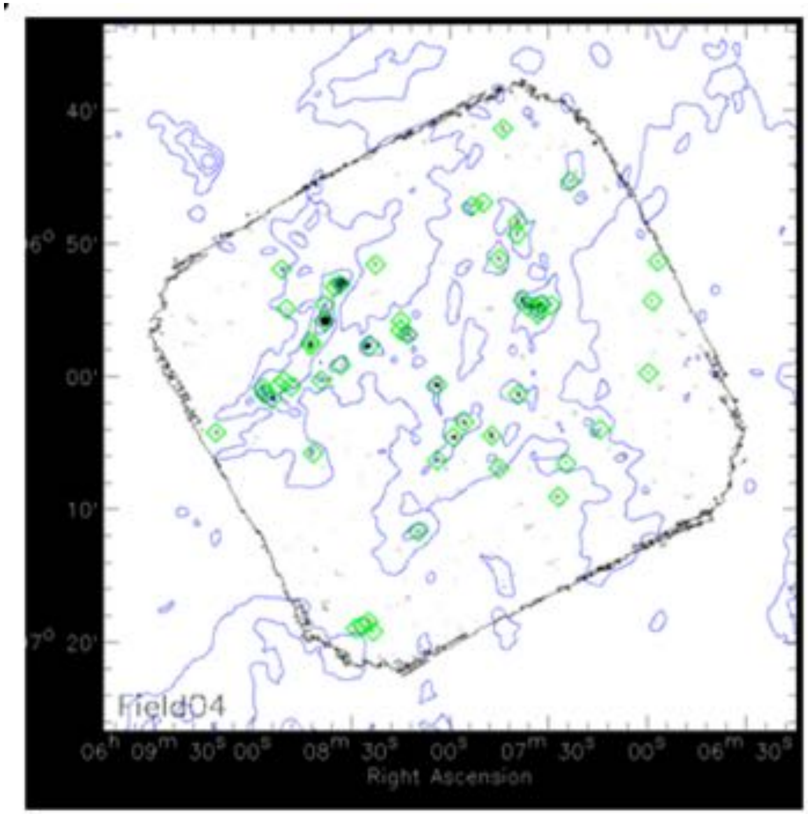




New Science Enabled by MUSCAT

- **Mapping star forming regions**
- Typically target the Gould belt to observe filament structure and star forming regions. Distances less than 400pc
- MUSCAT sensitivity and resolution allows larger galactic surveys out to 4kpc.

Blue contours – SPIRE 500um map
Green diamonds – Resolved stellar cores using Aztec on the 32m LMT (8" beam)



Beyond MUSCAT

- LMT Now – 4’ FOV, 32m
- LMT 2017 – 4’ FOV 50m 5’’ Resolution @1.1mm

MUSCAT

- Single Channel at 1.1 mm
- Ideally fill the FOV (4’)
- 1800 Detectors
- Continuous operation
- Delivery 18 months (Early 2018)
- Will become a technology demonstrator once Toltec is installed
- **Mapping Speed 3 Deg^2 /mJy^2/hr**

Toltec

- 3 Channels at 2.1, 1.4 and 1.1 mm
- All polarisation sensitive
- Will fill the FOV (4’)
- 3600, 1800, 900 Detectors
- 1800, 900, 450 Pixels
- Continuous operation
- Delivery 30 months (Early 2019)
- **Mapping Speed 31, 9.5, 5 Deg^2 /mJy^2/hr**

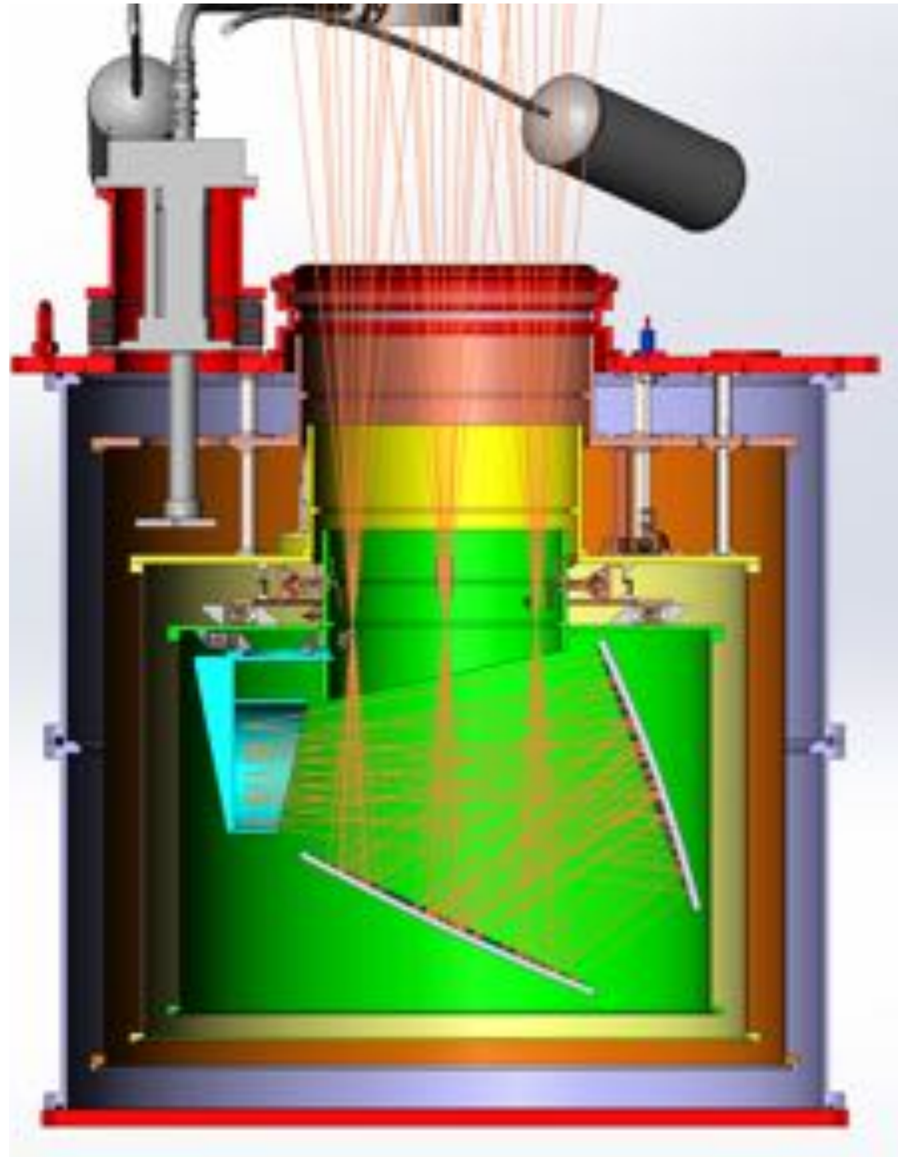
Design considerations for a large format mm wave KID camera

- Want to maximise mapping speed – fill the FOV with background limited detectors
- Want to minimise stray light – Mapping speed α NEP^2.
- Potential sources
  - Off-axis
  - Filter heating or IR leaks
  - Detector leakage

$$NEP = \sqrt{2h\upsilon P}$$

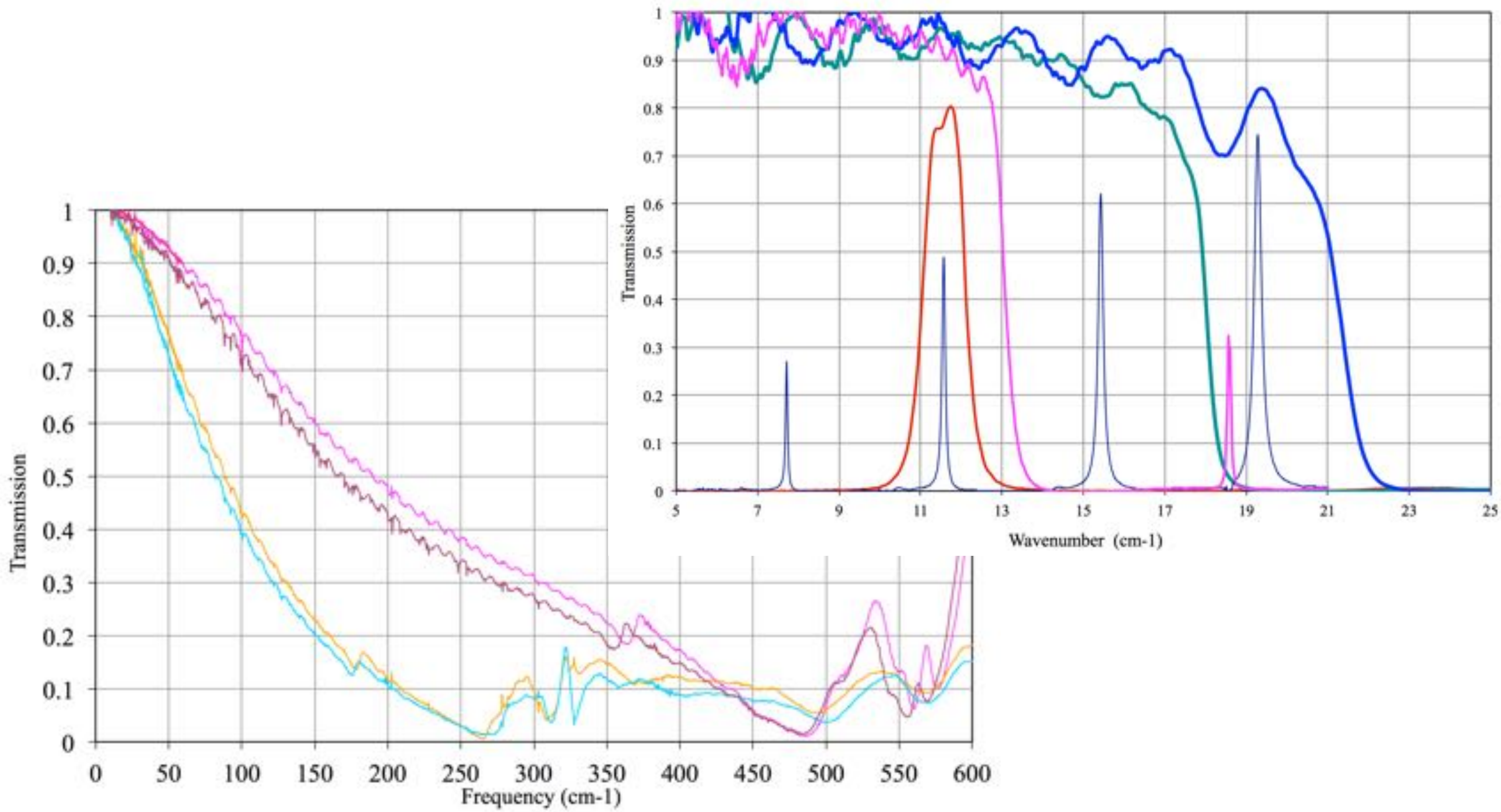
Off axis stray light in or out of band

- Horn couple
- Add baffling structures

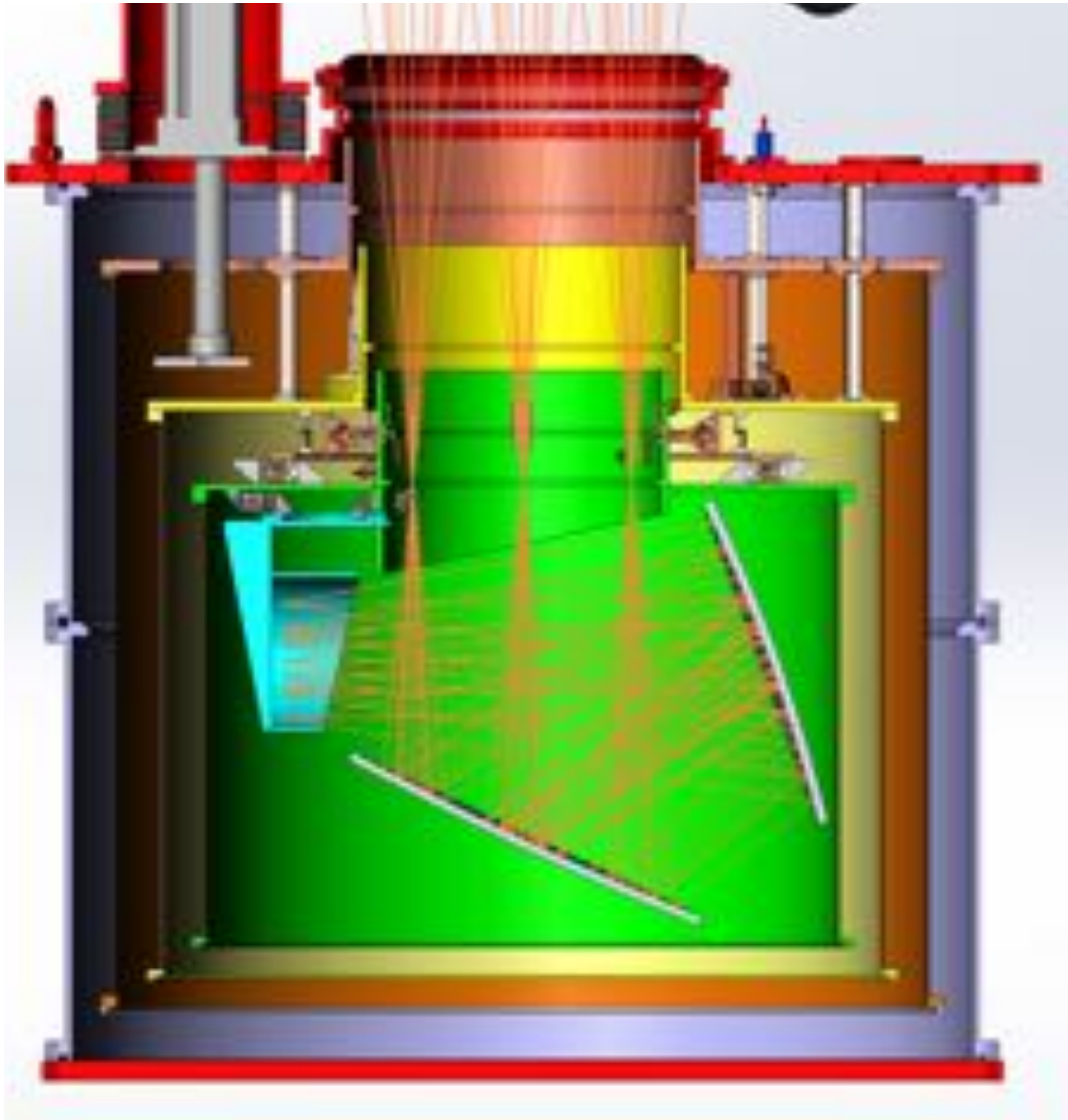


Filter heating – out of band stray light

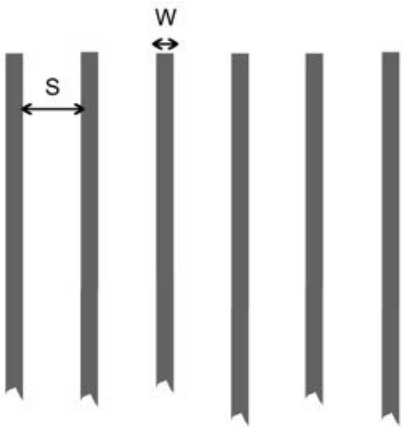
- Cardiff filters give excellent mm and THz filtering but are opaque in the IR.
- Have poor thermal conductivity so can only cool radiatively.
- Thin “shading” filters reject IR and do not radiate.
- Need to provide an environment that allows thicker filters to cool .

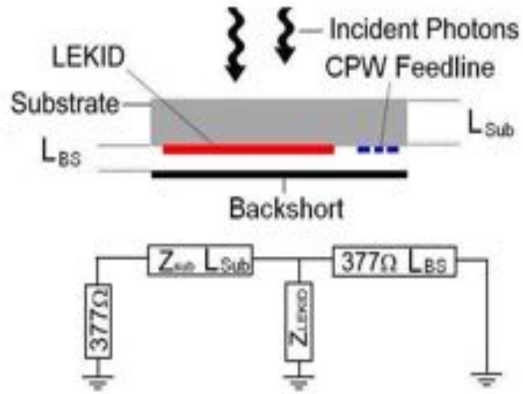


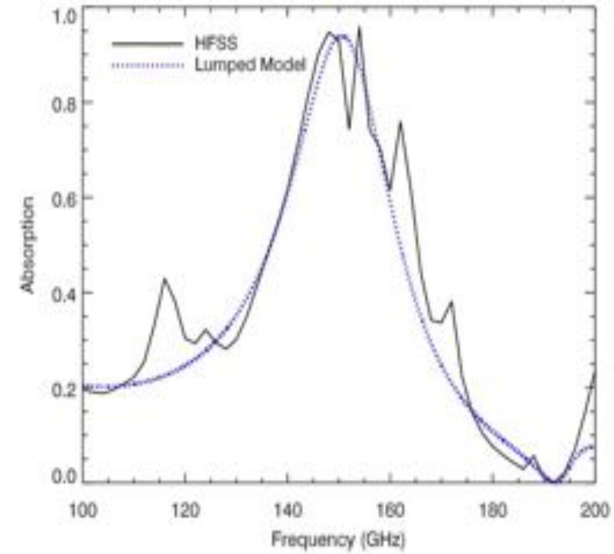
Filter heating – out of band stray light



Optical coupling to a single polarization LEKID meander





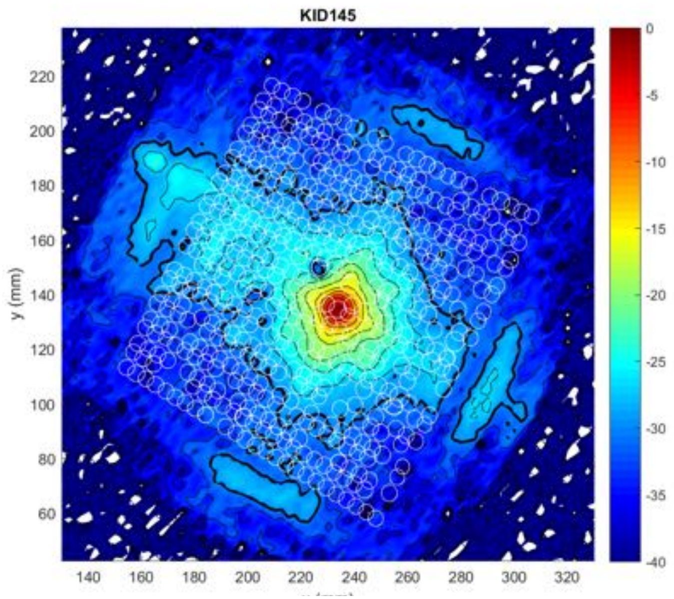


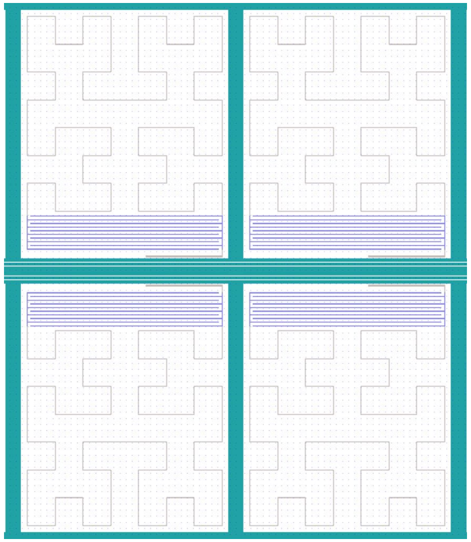
$$R_{eff} = R_{Sheet}\frac{s}{w} \qquad L_{eff} = \frac{S}{2\pi c}\ln\left[\operatorname{cosec}\left(\frac{\pi S}{W}\right)\right]377$$

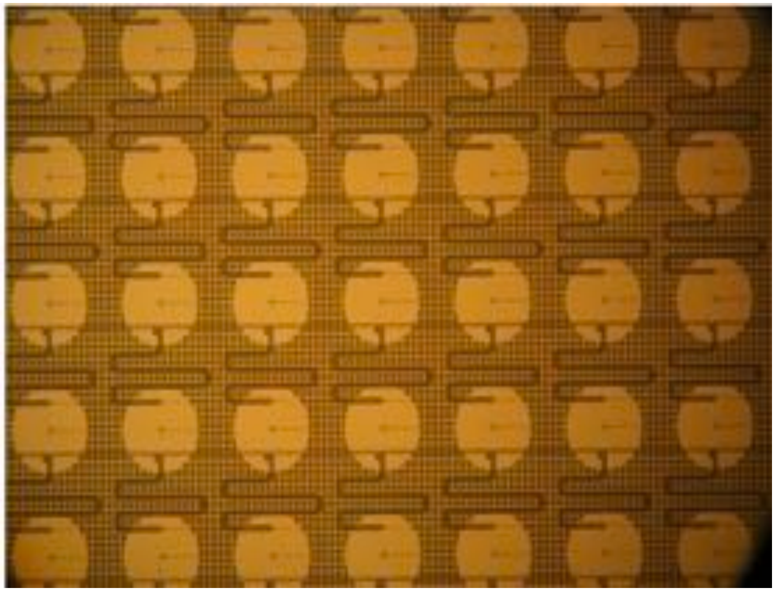
$$Z_{LEKID} = R_{eff} + j\omega L_{eff}$$

Difficult to achieve broadband absorption high frequencies with low R_{sheet} materials such as Aluminium (typically 1 Ohm / sq)

Detector leakage



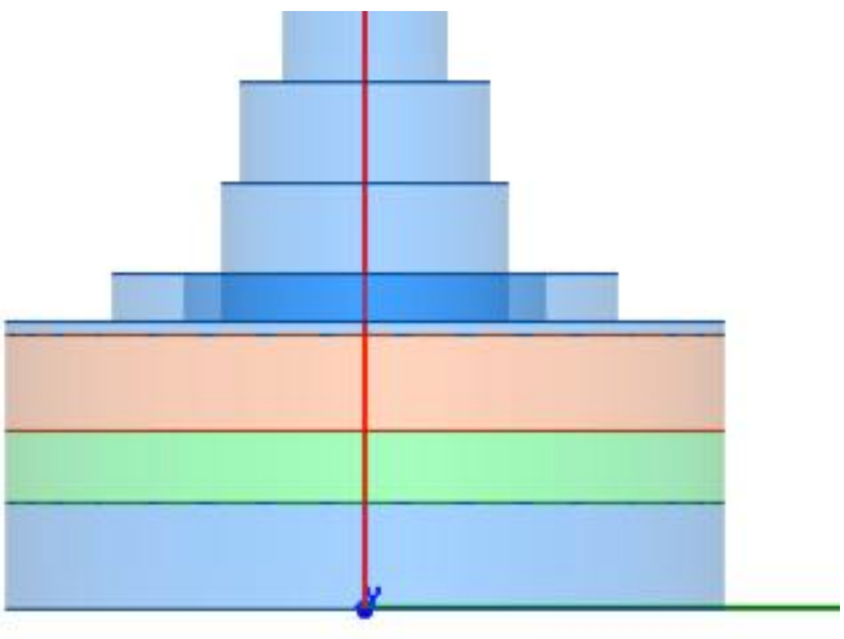


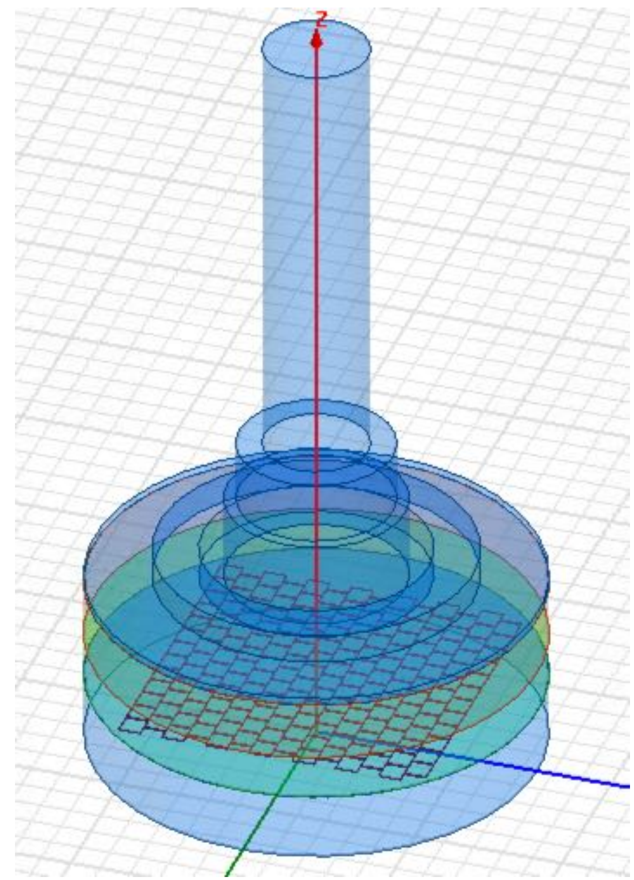


Open format LEKID array architectures do not lend themselves easily to stray light absorbers as used in SPACEKIDs antenna coupled devices.

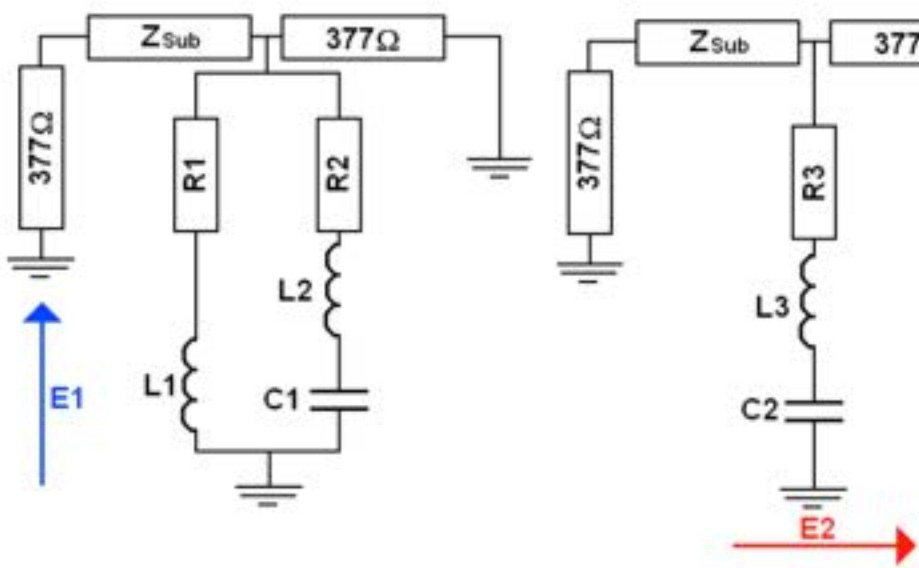
Proposed Detector design - Absorber

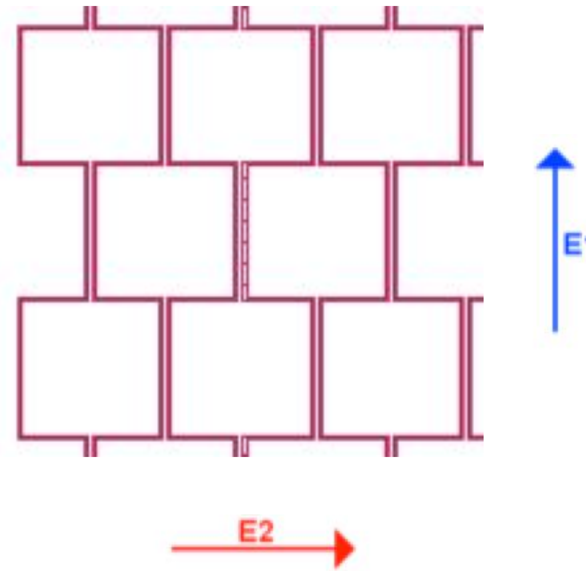
- Horn coupled with AR layer and choke to maximise absorption and minimise leakage.
- Potentially provides space between detectors for stray light absorbers.
- Reduces dead space on array (feedline and capacitor)

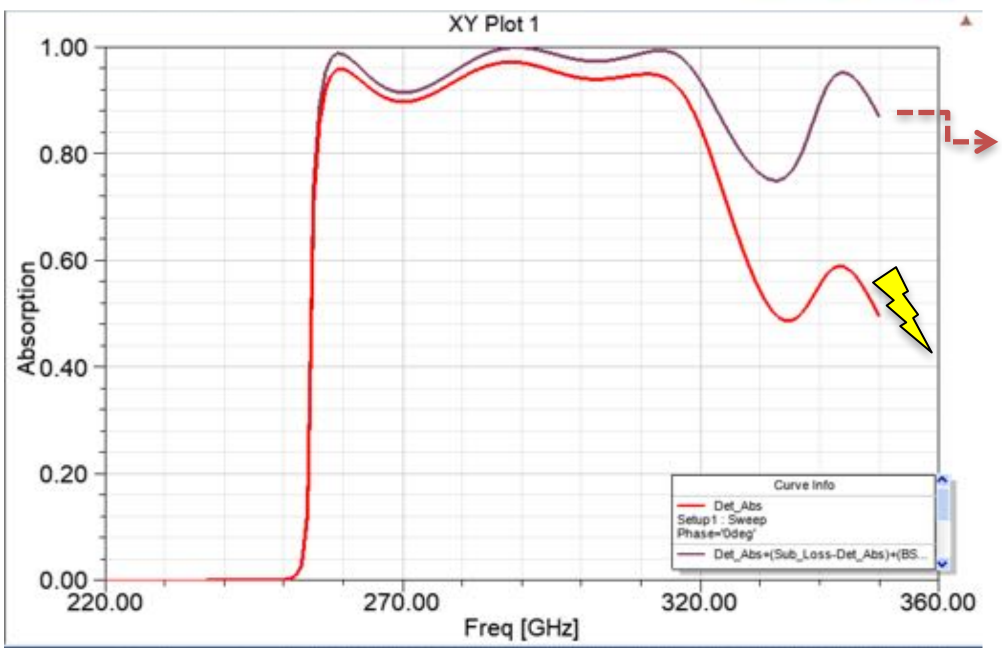


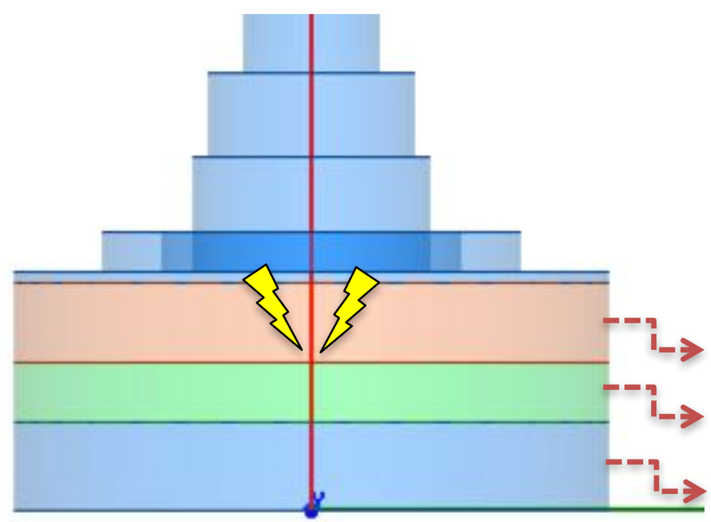


Detector Absorption



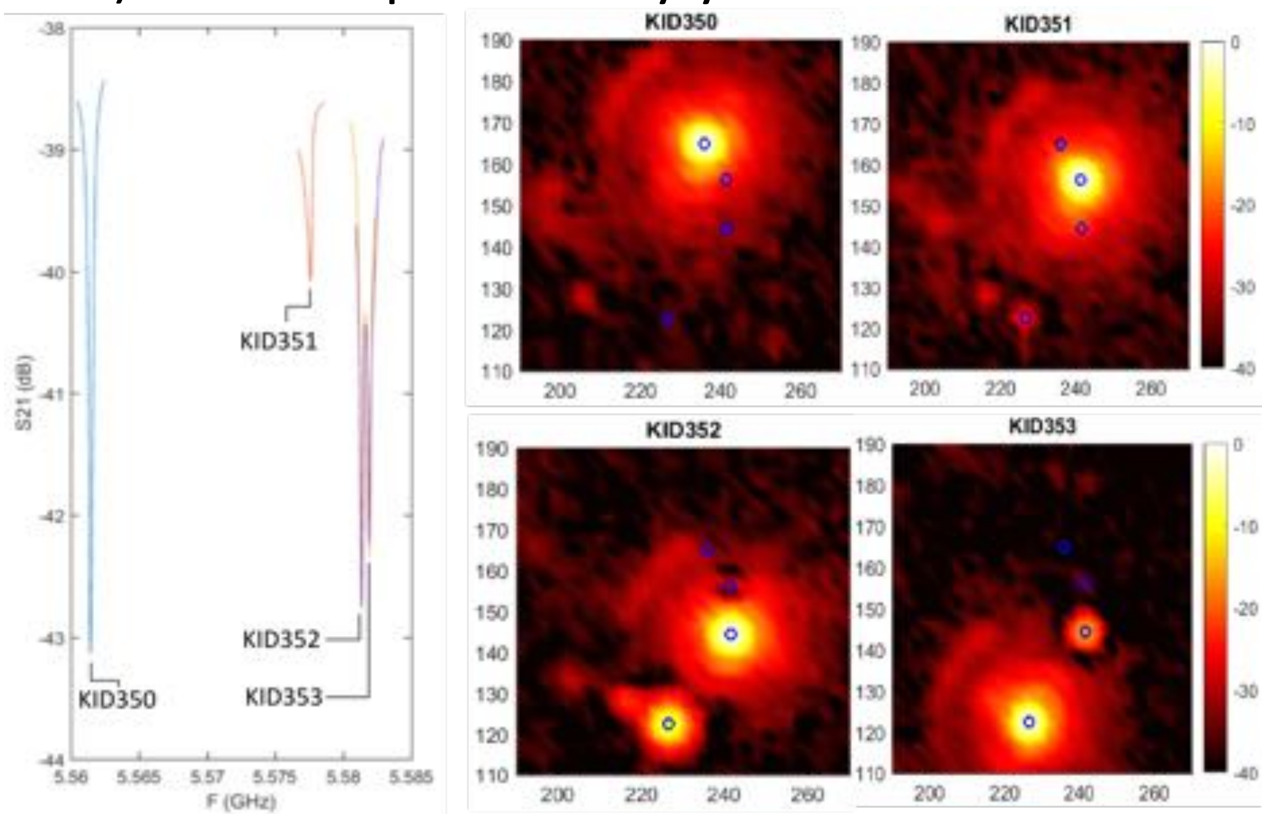




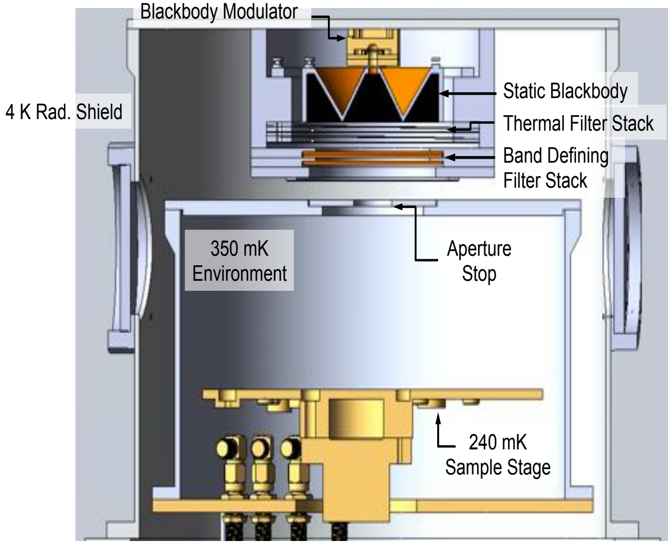


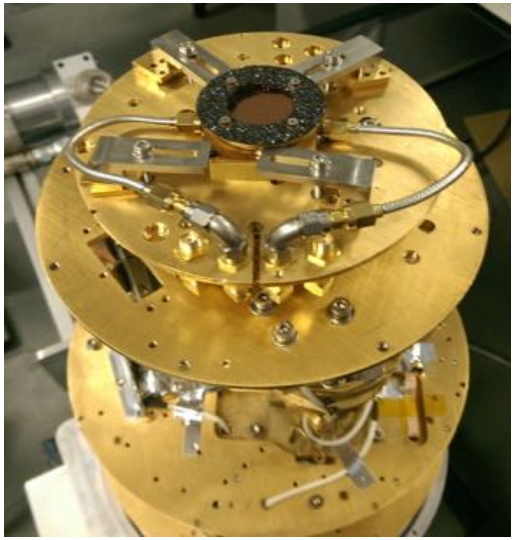
Detector F_0 and volume

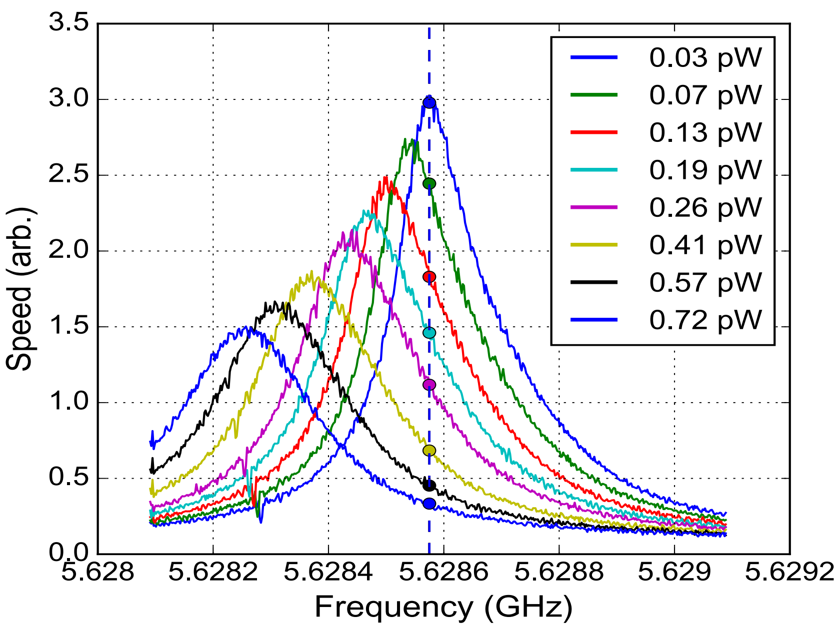
- Want to maximise number of resonator per unit bandwidth of readout.
  - Roach-2 has 500MHz readout bandwidth.
  - Avoid resonator clashes by making resonator width narrow (high Q factor) hence improve array yield.

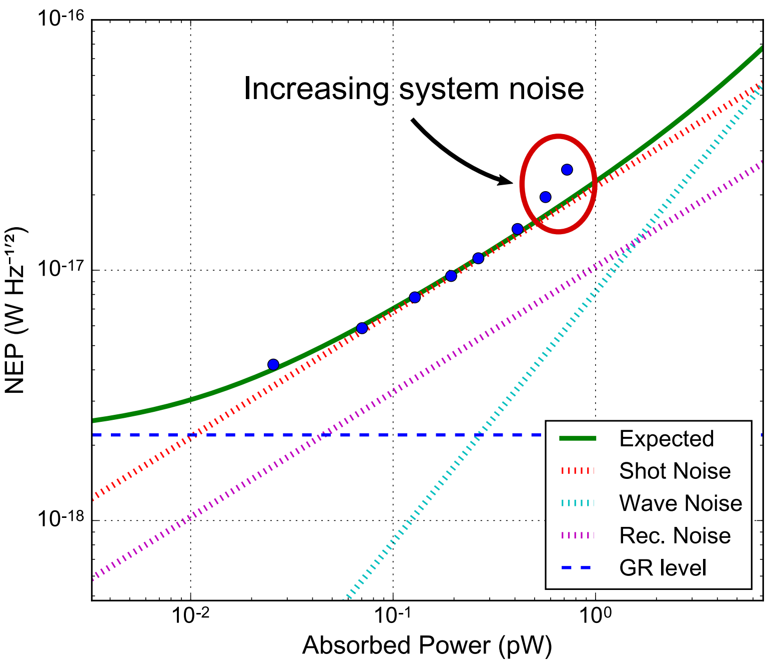


Problems with high backgrounds



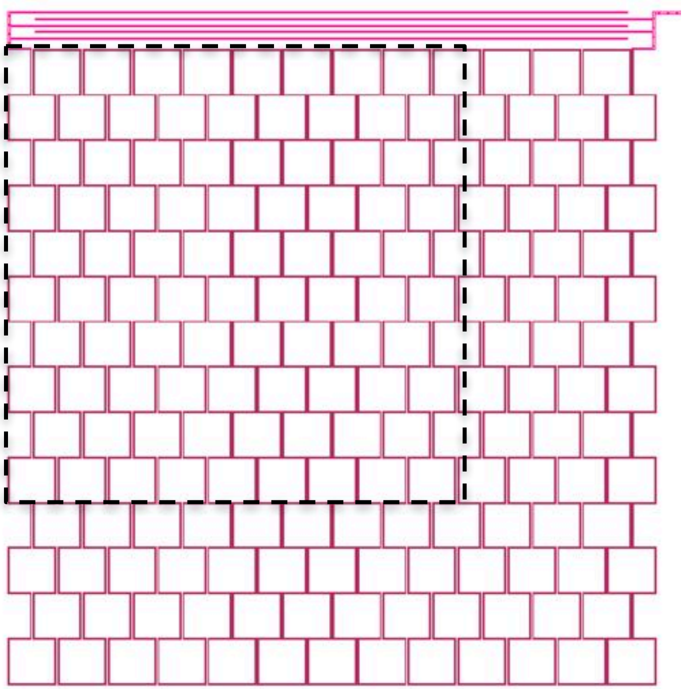






Plan to use large meander volumes

- Large volumes allows for:
  - Natural low resonant frequencies
    - Lower RF losses
    - Narrow resonator bandwidths
  - Longer quasi-particle lifetimes under optical loading
  - No loss in responsivity if α (L_k/L_{total}) is kept constant



Study resonator properties under a constant load typically expected from the LMT sky at 1.1mm.

Vary volume by changing meander length

Fix film thickness

Fix Capacitance

Effective temperature and volume

$$n_{qp} = 2N_0\sqrt{2\pi k_B T\Delta}\exp\left(-\Delta / k_B T\right)$$

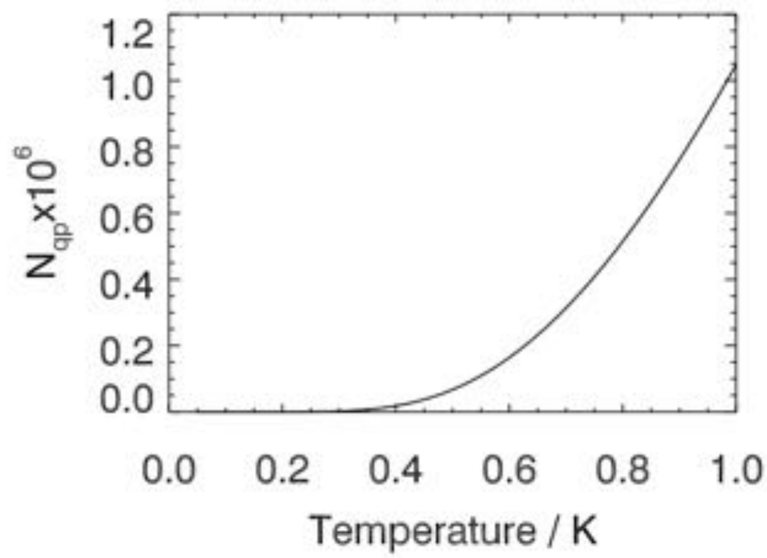
$$\tau_{qp} = \frac{\tau_0}{\sqrt{\pi}}\left(\frac{k_B T_c}{2\Delta}\right)^{5/2}\sqrt{\frac{T_c}{T}}\exp(\Delta / k_B T)$$

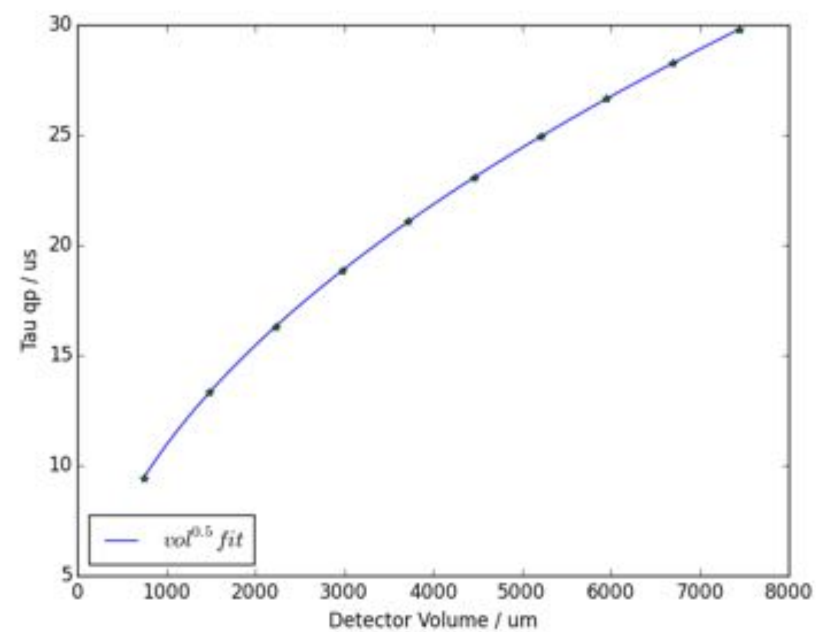
$$\tau_{qp} = \frac{N_0\tau_0}{N_{qp}}\frac{k_B^3 T_c^3}{2\Delta^2}$$

$$N_{qp} = \frac{P_{opt}\tau_{qp}\eta}{2\Delta} \qquad \tau_{qp}\ \alpha\ n_{qp}$$

$$N_{qp} = \sqrt{\frac{P_{opt}N_0\tau_0}{2}}\left(\frac{k_B T_c}{\Delta}\right)^{3/2}\sqrt{vol}$$

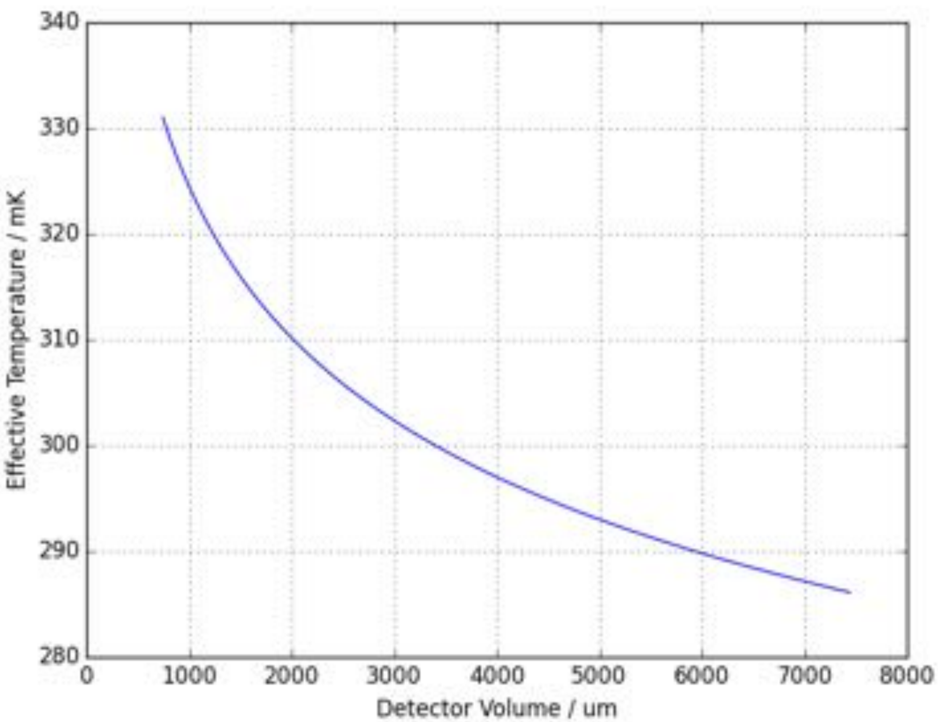
$$N_{qp} = Vol \times 2N_0\sqrt{2\pi k_B T\Delta}\exp\left(-\Delta / k_B T\right)$$





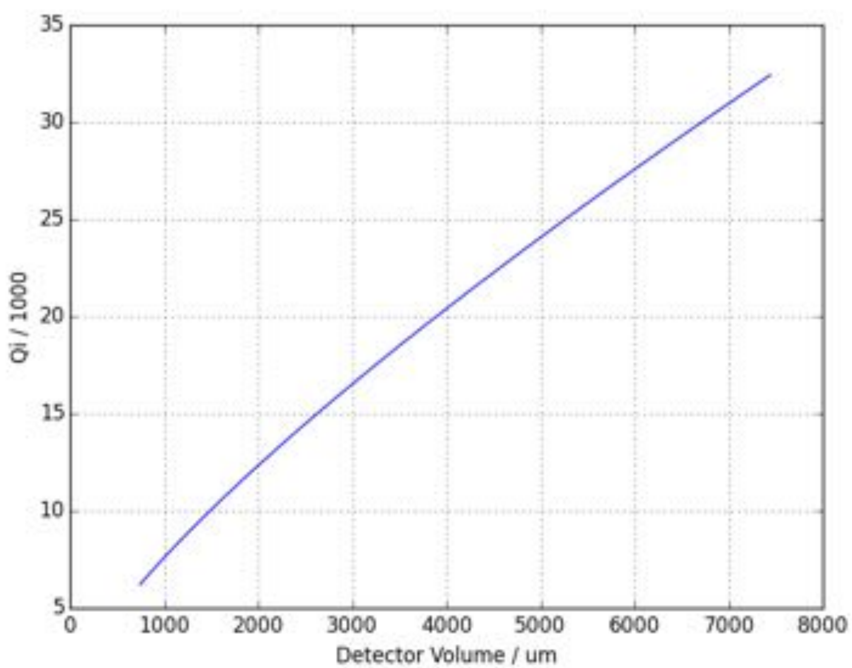
Scaling volume effective temperature

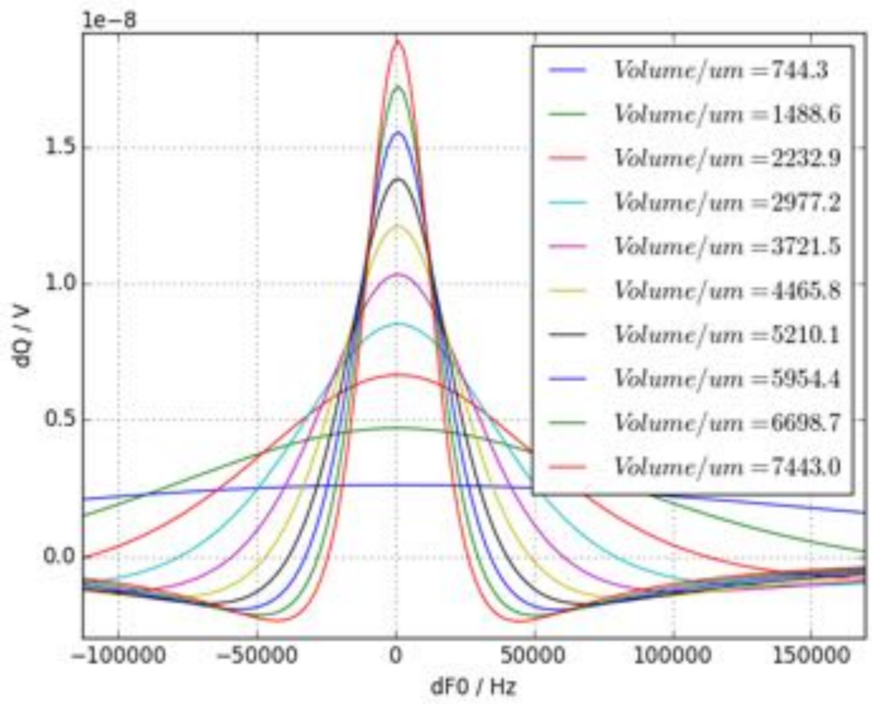
- Number of pairs broken per second is constant.
- But lifetime scales as $vol^{0.5}$
- N_{qp} increases as $vol^{0.5}$
- n_{qp} increases as N_{qp}/vol so scales as $vol^{-0.5}$



Effects on Q and resonator responsivity

- Q_i will increase with decrease in effective temperature and F0 (both reduces RF losses)
- Set Q_c=Q_i to maximise response
- Assume readout power reduces linearly with Q_T.



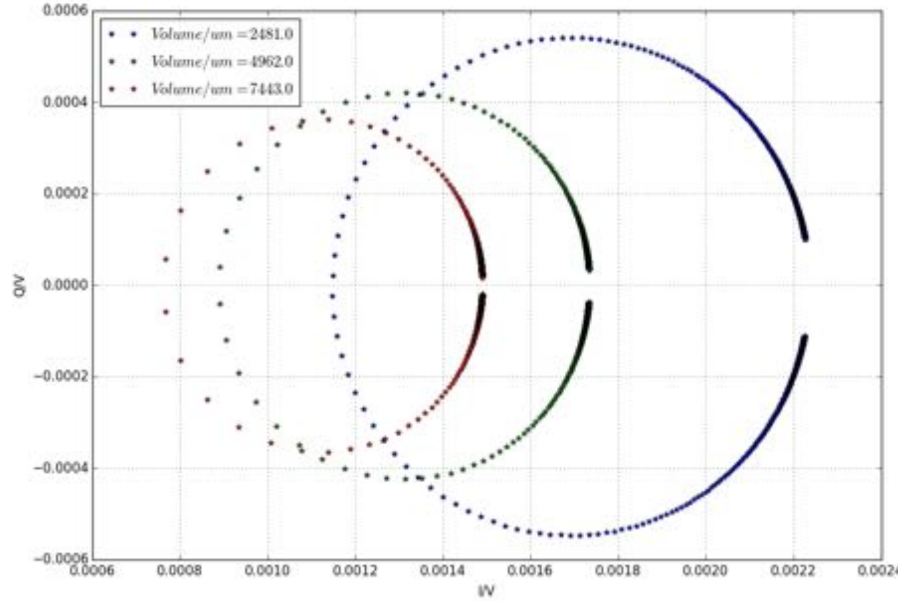


Bottom line on responsivity – No change

Increases as vol$^{0.5}$
τ_{qp} increasing

$$dF_0 = -\frac{1}{2}\frac{\alpha}{L_k}F_0 dN_{qp}$$

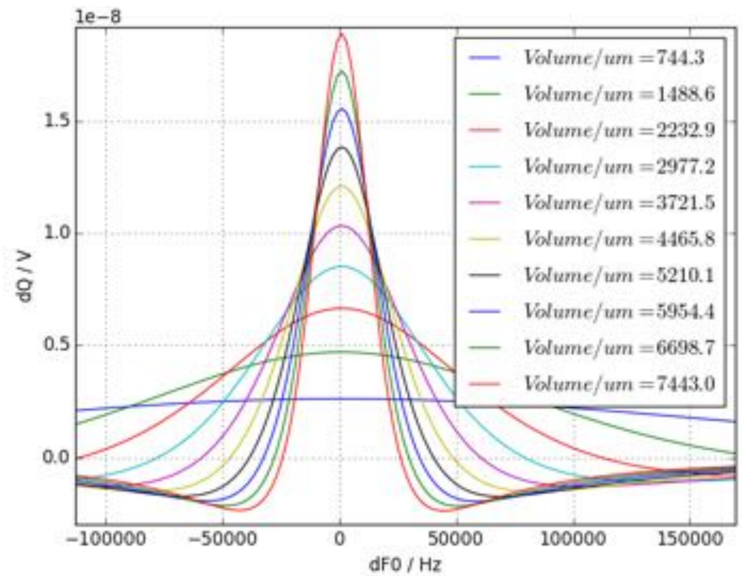
Decreases as vol$^{0.5}$
L_{total} α meander length



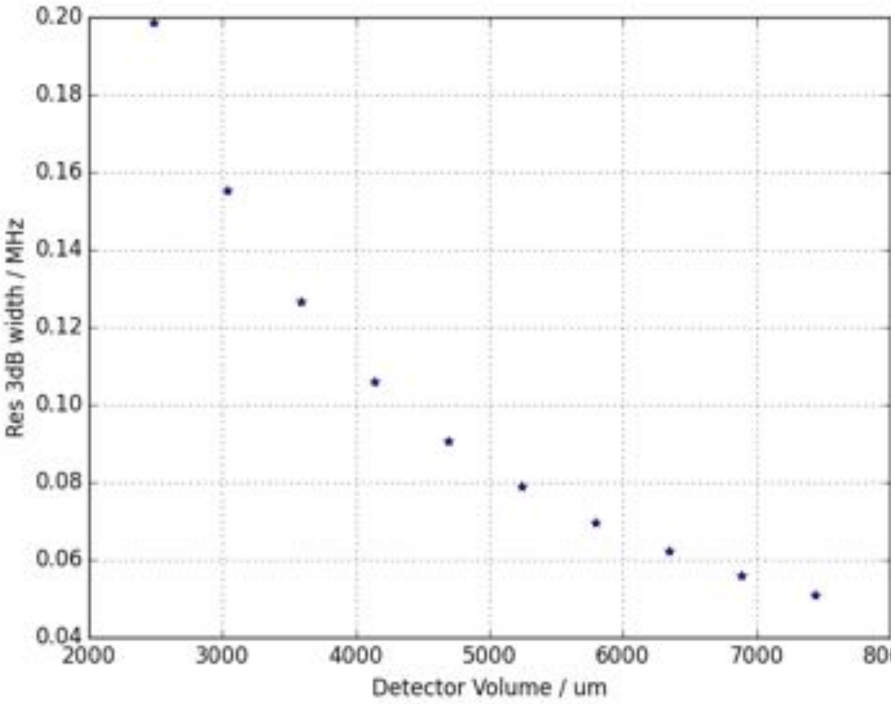
$$dQ = \frac{dQ}{dF_0}dF_0$$

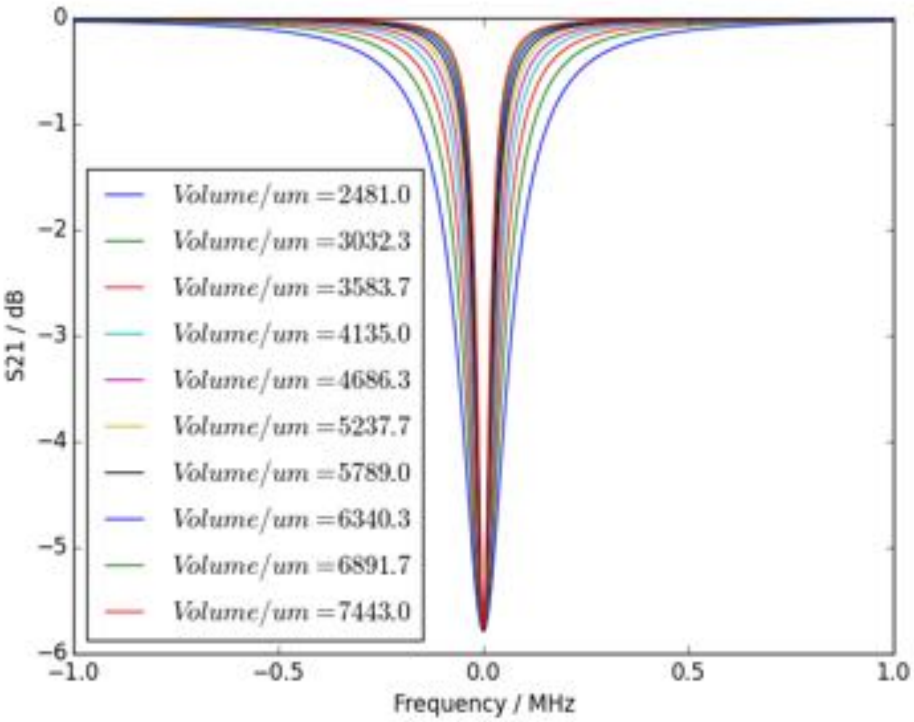
Decreases with
$1/L_k$

Increases with
resonator response



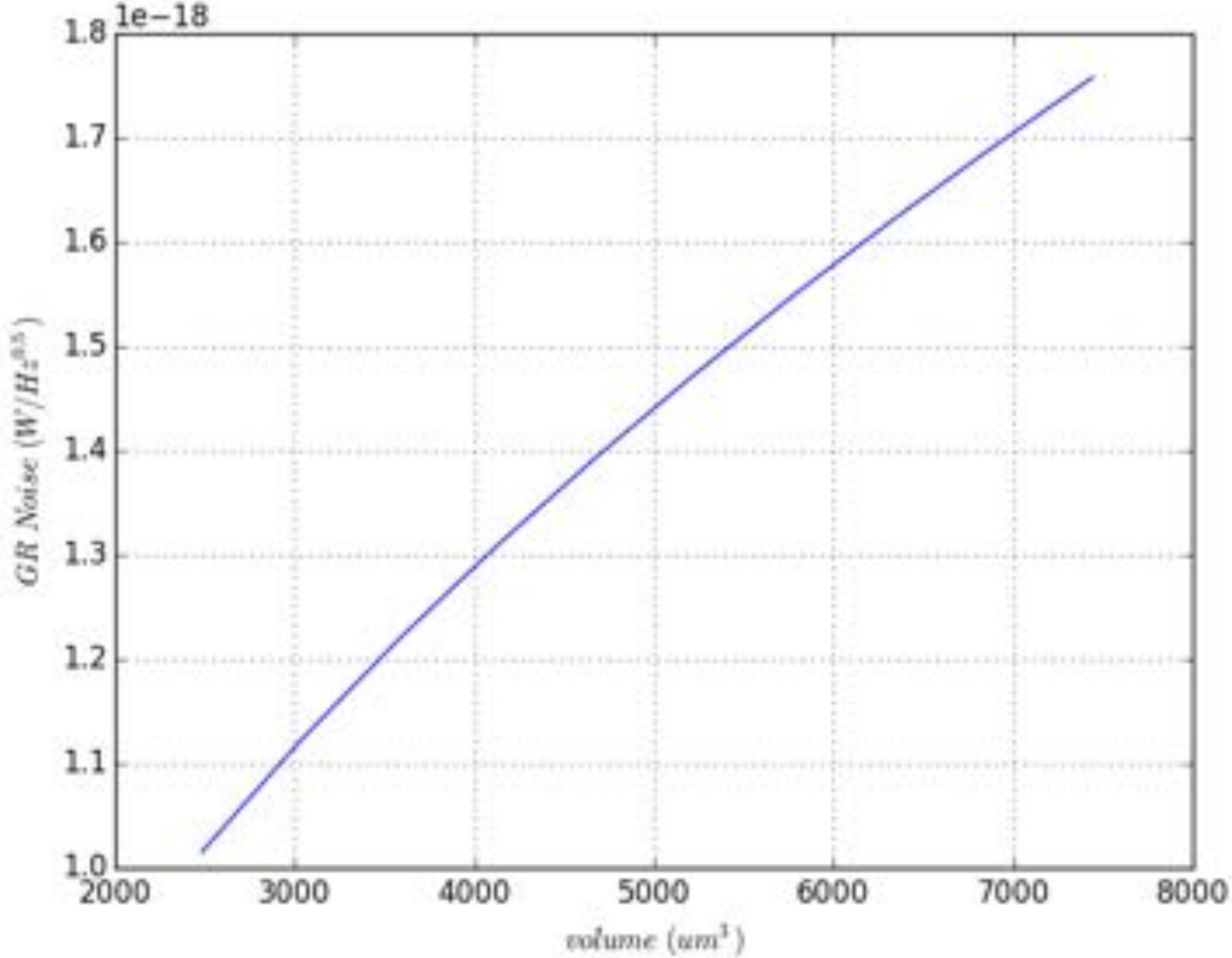
Potential improvement in MUX ratios





Reduction in 3dB bandwidth of around a factor of 4 for a volume scaling of 10

GR Noise at 200mK



MUSCAT in the Long term

- MUSCAT will be superseded by Toltec in 2019
- MUSCAT system is adaptable
- Possible upgrades are
  - Alternative channels (850um or 3mm)
  - New technology (On-chip spectrometer)
  - New array (open array to allow raw mapping to be faster than Toltec)

Conclusion

- Cardiff and INOAOE are developing a 1.1mm photometer that will:
  - Provide high mapping speeds.
  - Provide higher resolution than any existing mapping facilities
  - Enable a wealth of new science
  - Prove new technology towards future experiments
  - Begin a formal collaboration between the UK and Mexico and give UK astronomers access to the LMT.
  - Proposes to use horn coupled LEKID architecture to maximise detector yield and MUX ratios.

- MUSCAT will be superseded by Toltec however:
  - We will have completed to science aims before the Toltec installation
  - We are part of the Toltec collaboration and MUSCAT will assist its development
  - MUSCAT’s role can change and remain active on the LMT