The Next-generation Extended-Wavelength Multiband Sub/millimeter Inductance Camera (NEW-MUSIC)

Sunil Golwala

mm Universe 2025

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Caltech

Jet Propulsion Laboratory
California Institute of Technology

Institute of High Energy Physics
Chinese Academy of Sciences

UNIVERSIDAD DE CONCEPCION

Wilf Family FOUNDATIONS

Outline

Science targets for a multi-band mm/submm focal plane with mJy sensitivity

3 minute integration on ~FoV-scale field (7' initially; 14' full focal plane)

band [GHz]	90	150	220	270	350	405
rms depth [mJy]	1	2	2	3	4.5	9
5σ detection limit [mJy]	5	11	10.5	19	22	47

Design and demonstrations to date of NEW-MUSIC enabling technology:

Al(-Ti)/a-Si:H Parallel Plate Capacitor (PPC)-KIDs microstrip-coupled to multi-band hierarchical phased-array antennas

Instrument Configuration and Deployment

Conclusions and outlook

Motivation

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Multi-band spectral coverage
- 80-420 GHz: substantial scientific potential
  - Six spectral bands available most of the time at excellent sites
  - Many astrophysical emission mechanisms accessible:

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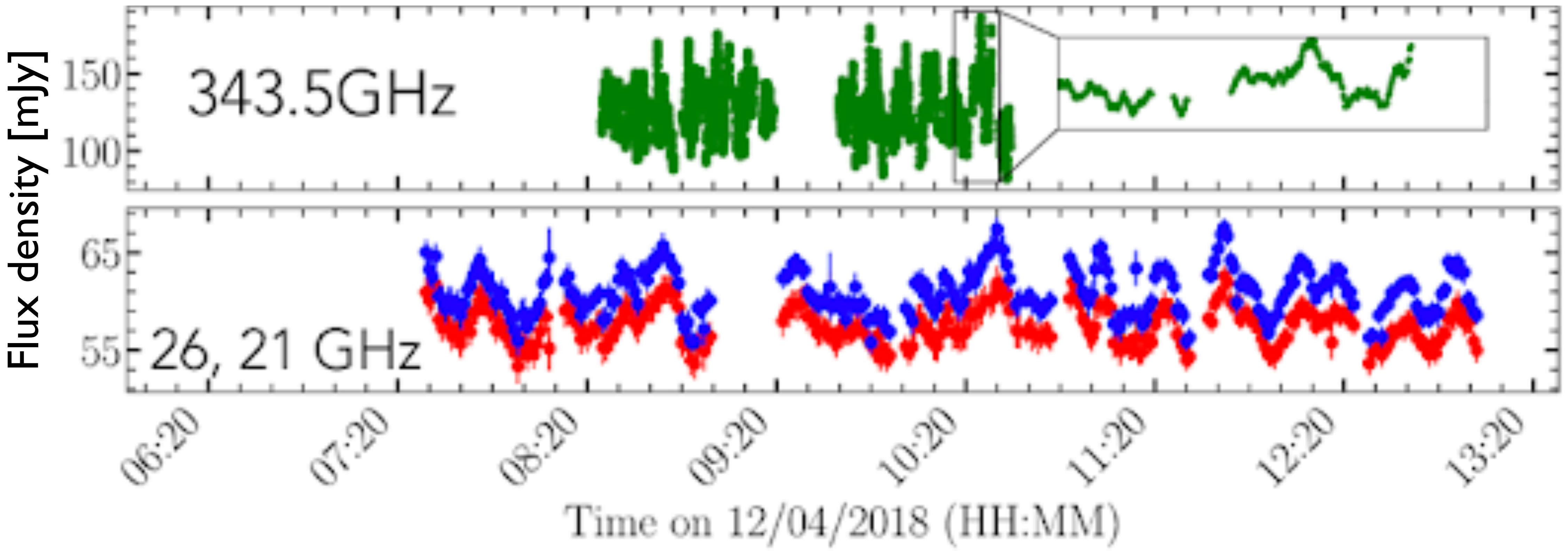
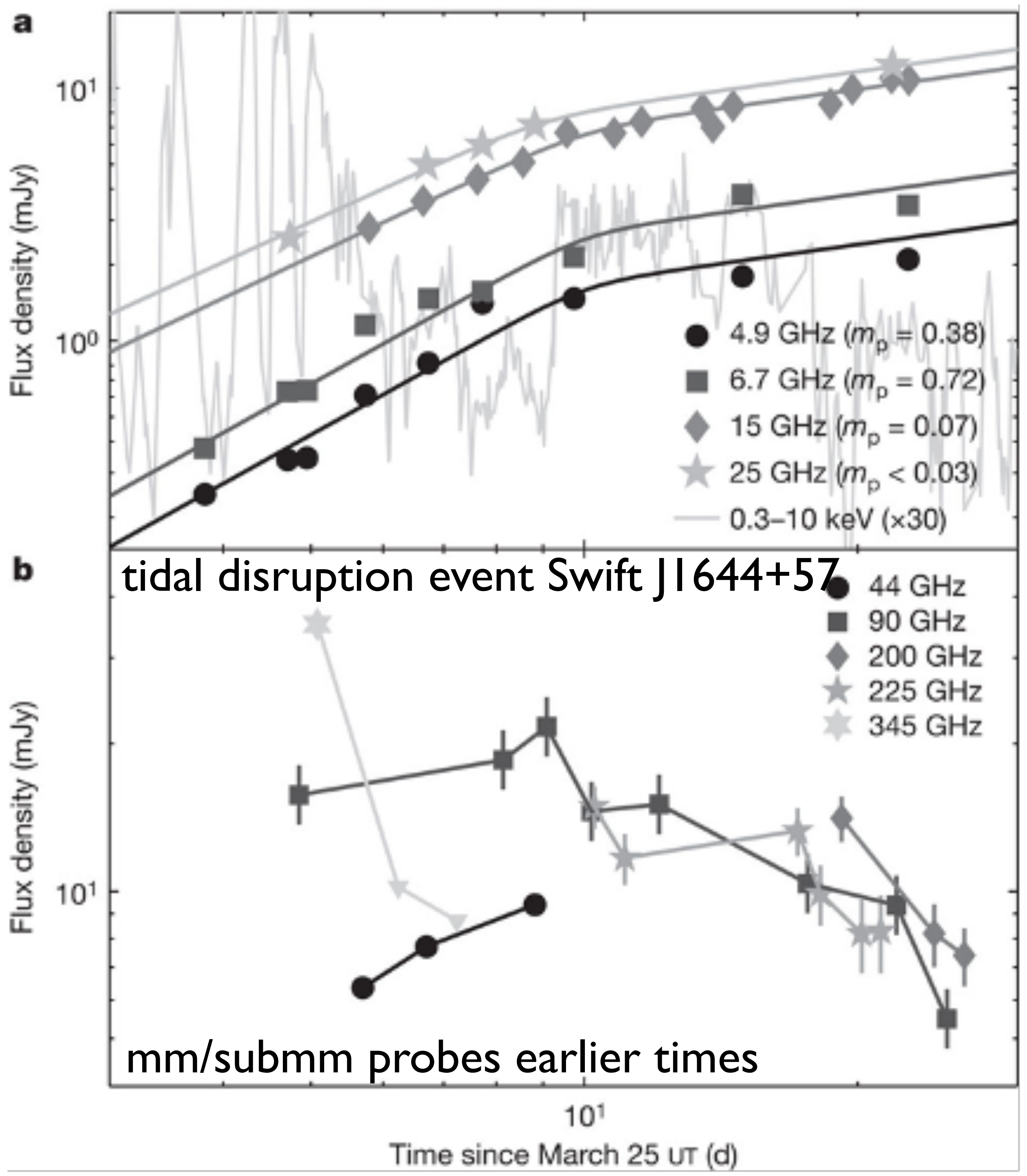
binary black hole MAXI J1820+070: Much richer behavior in mm/submm





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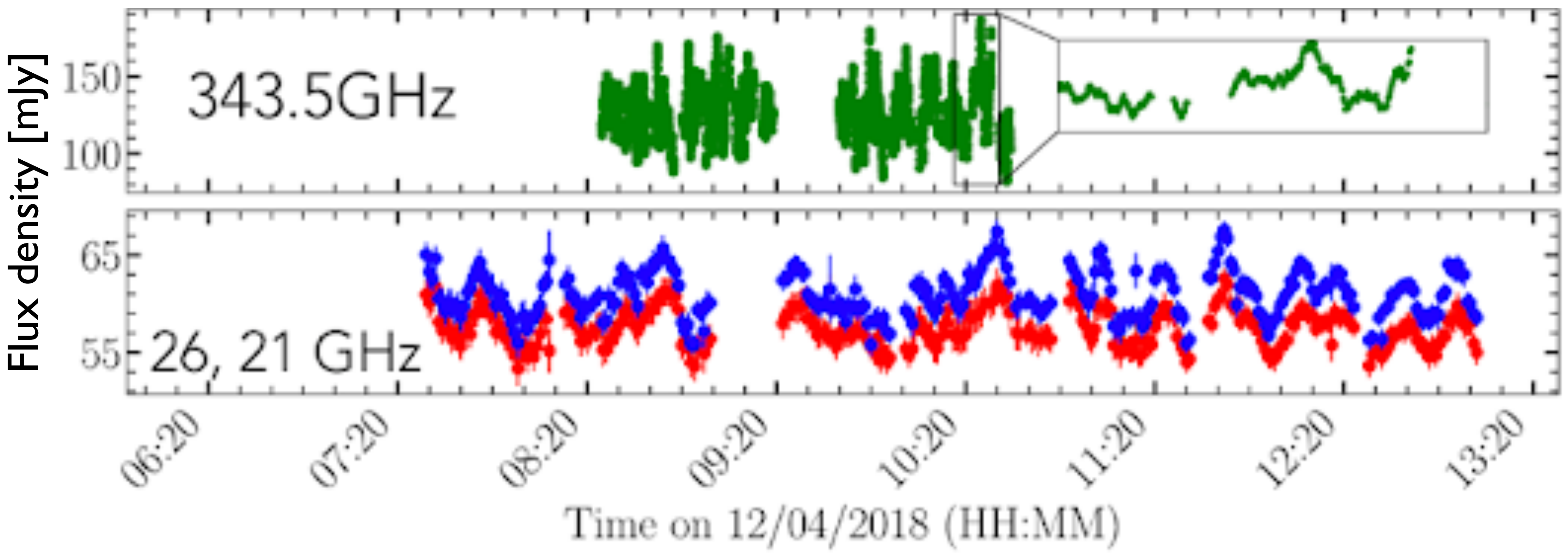

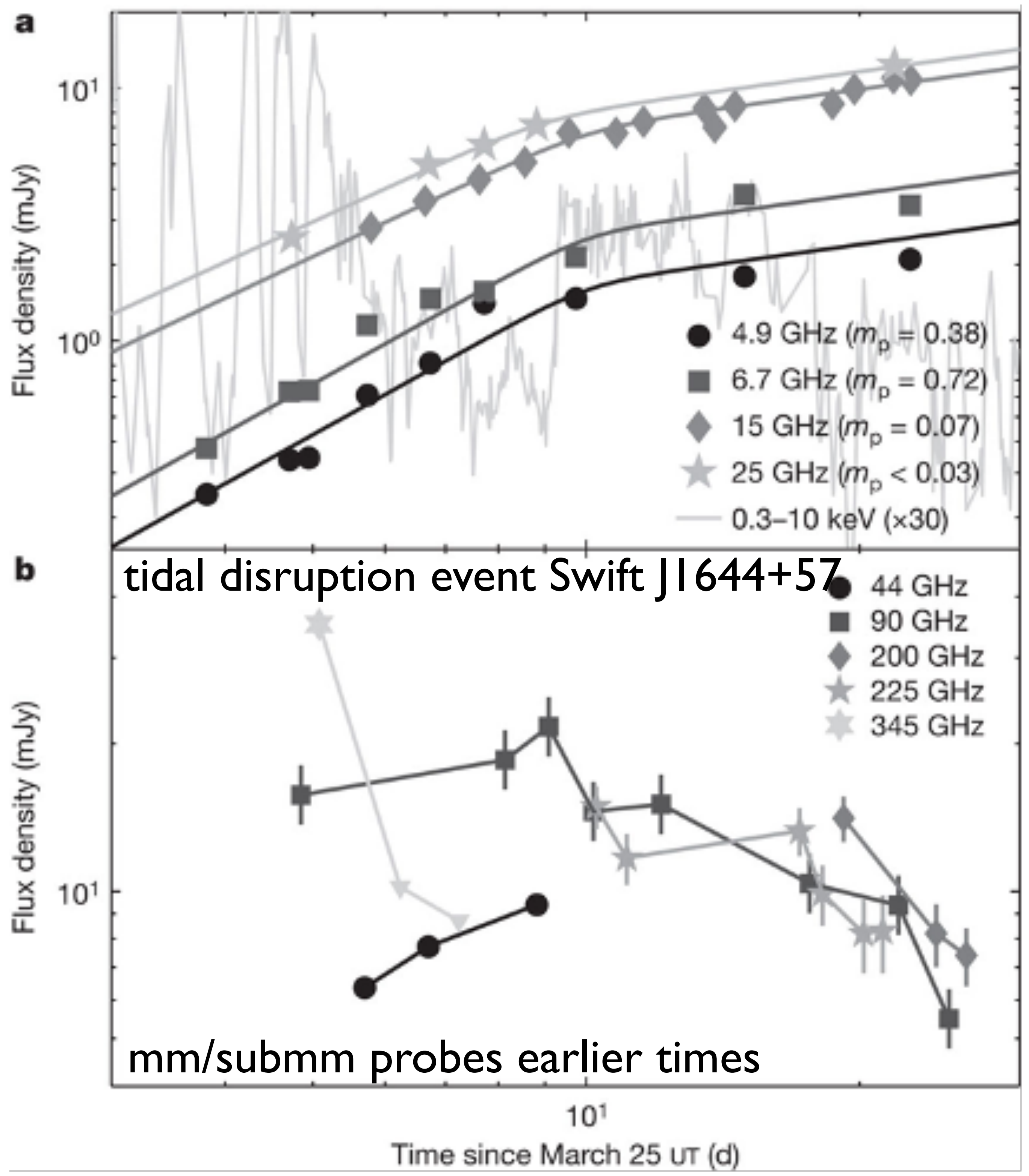

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    - Broad spectral coverage critical to multi-line observations

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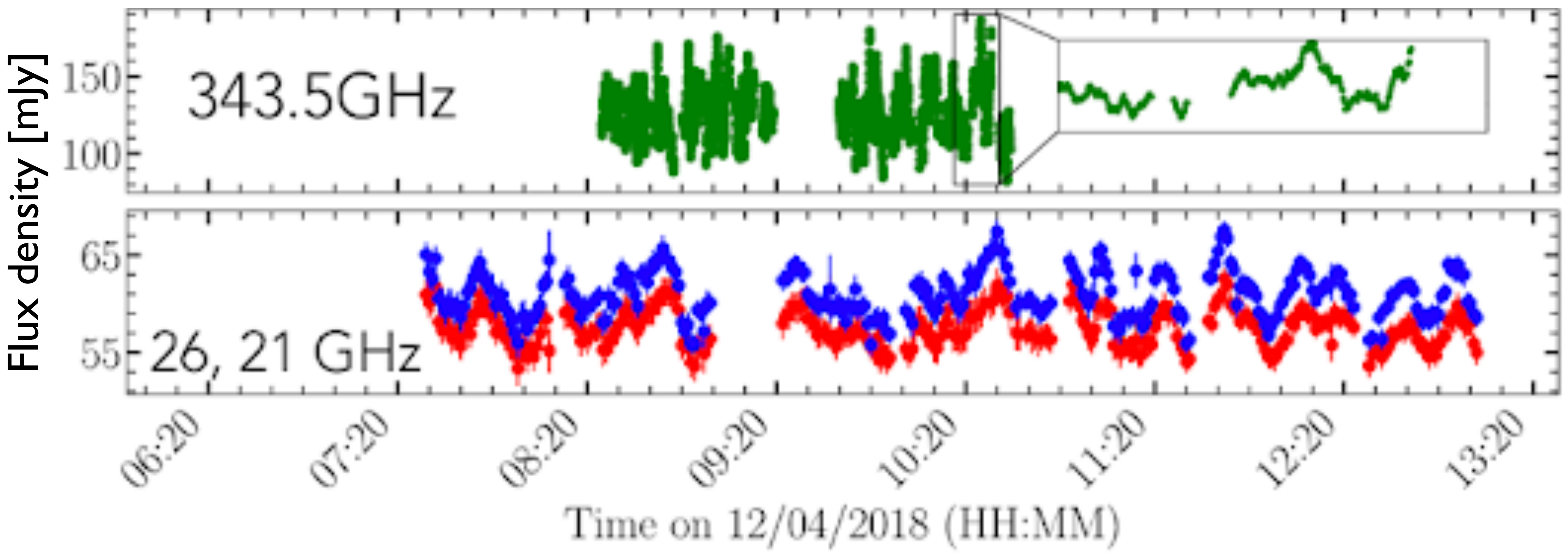

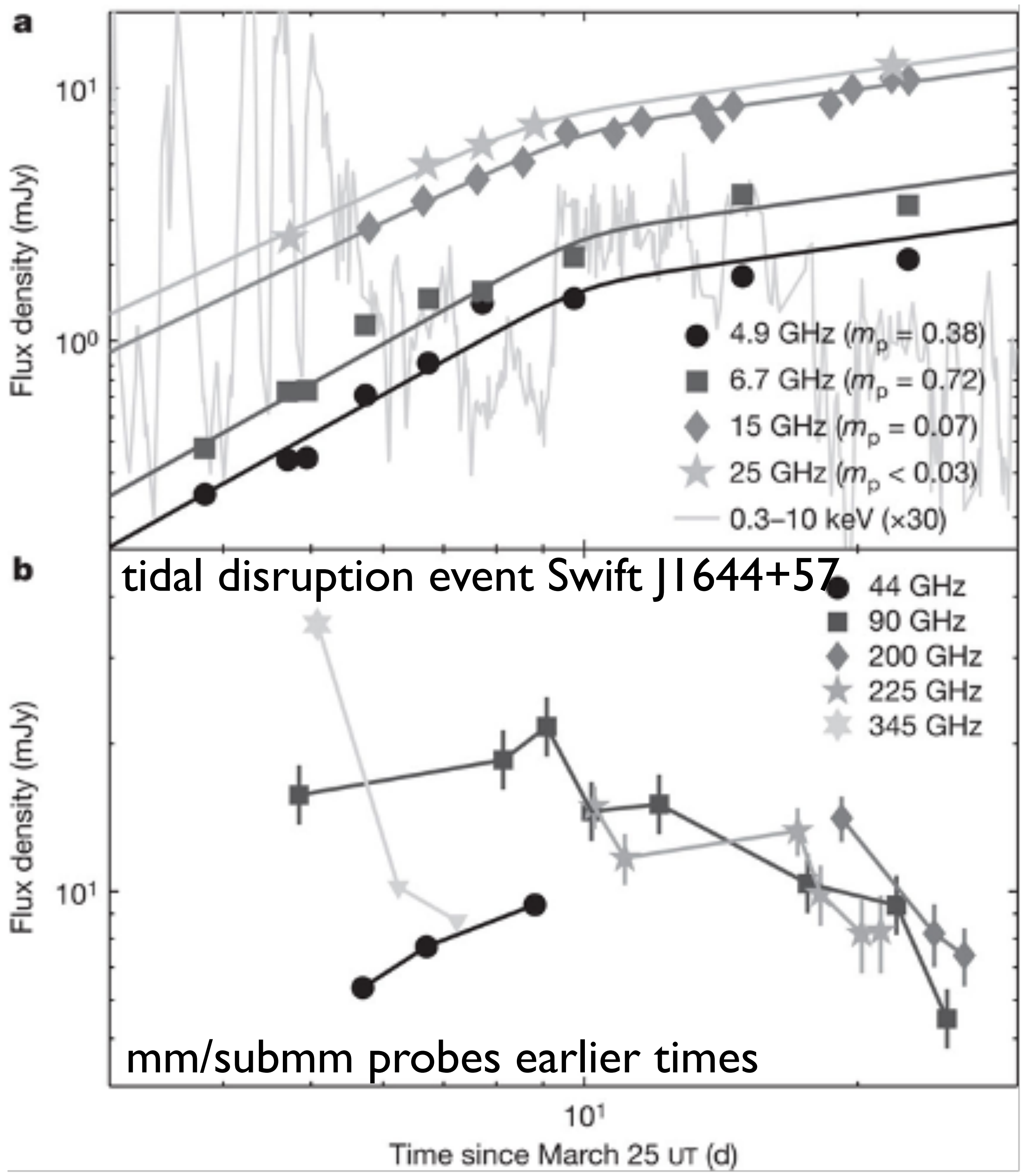

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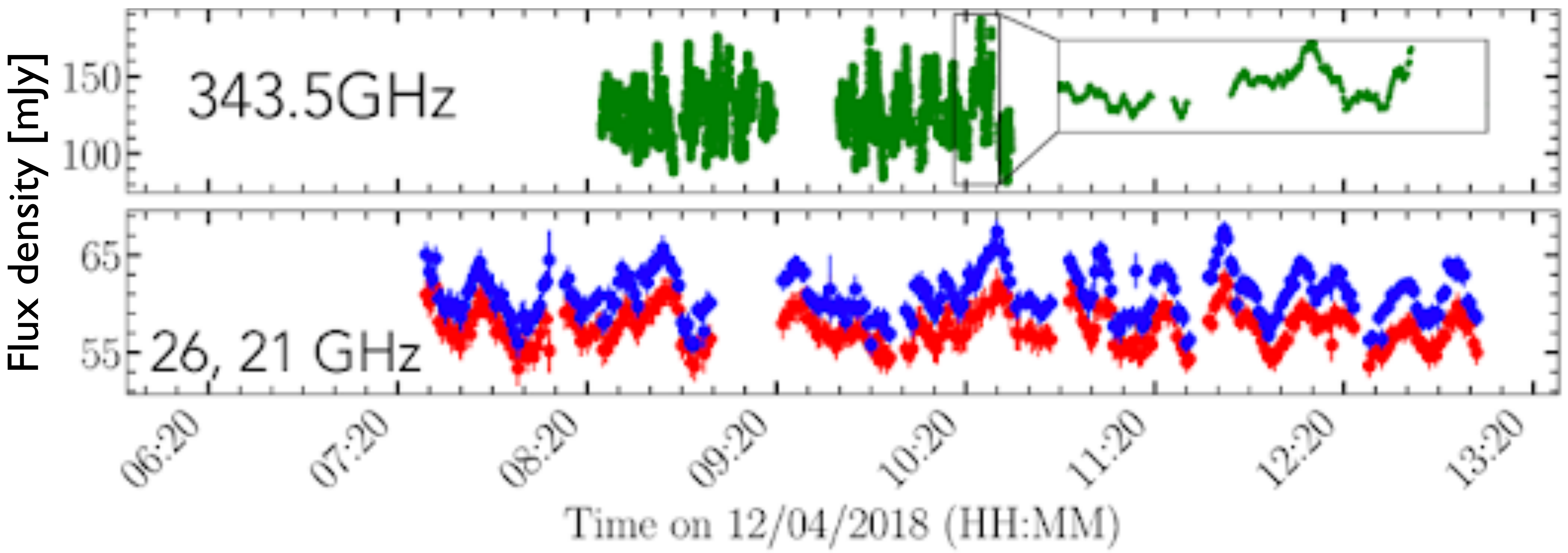
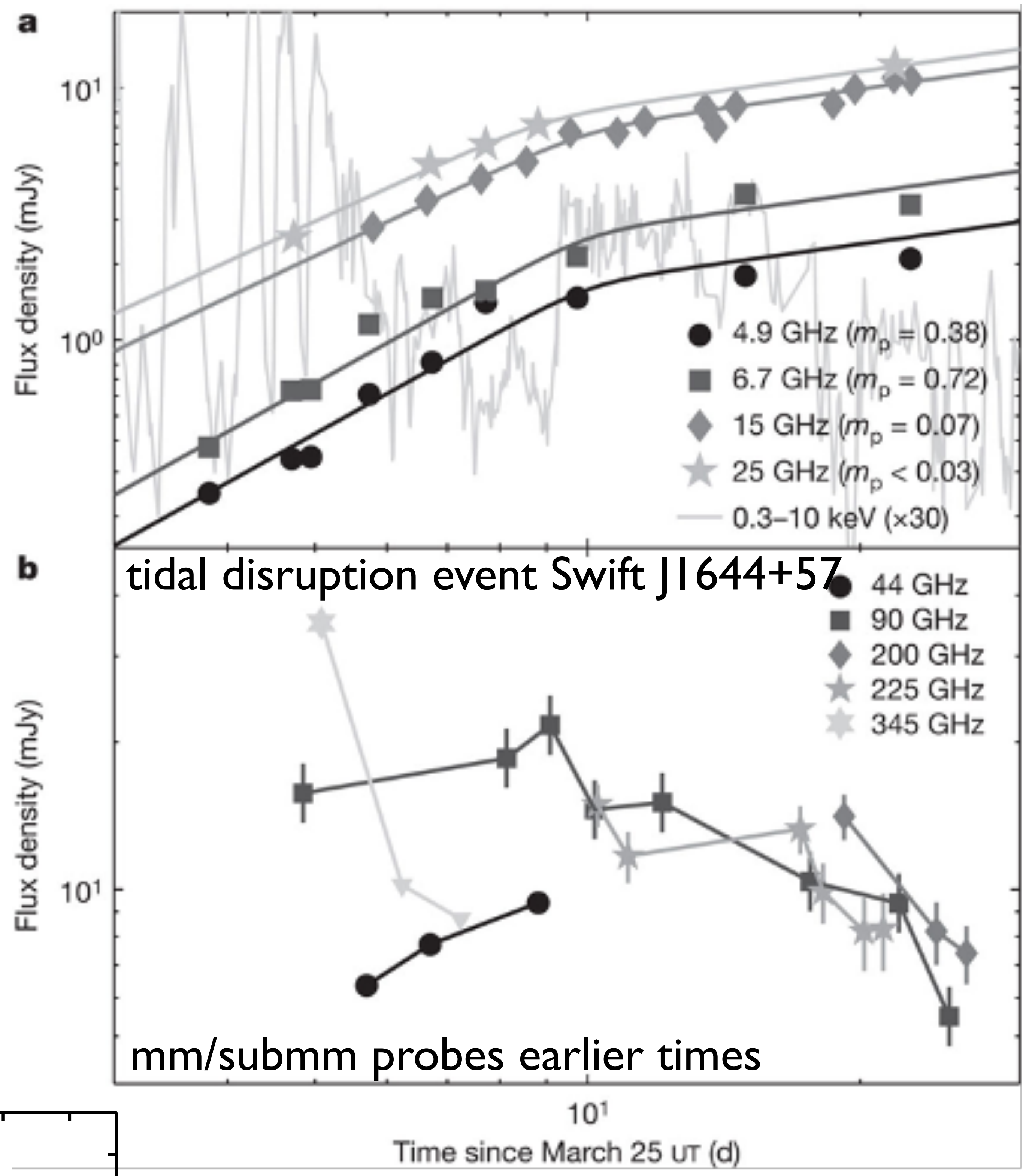
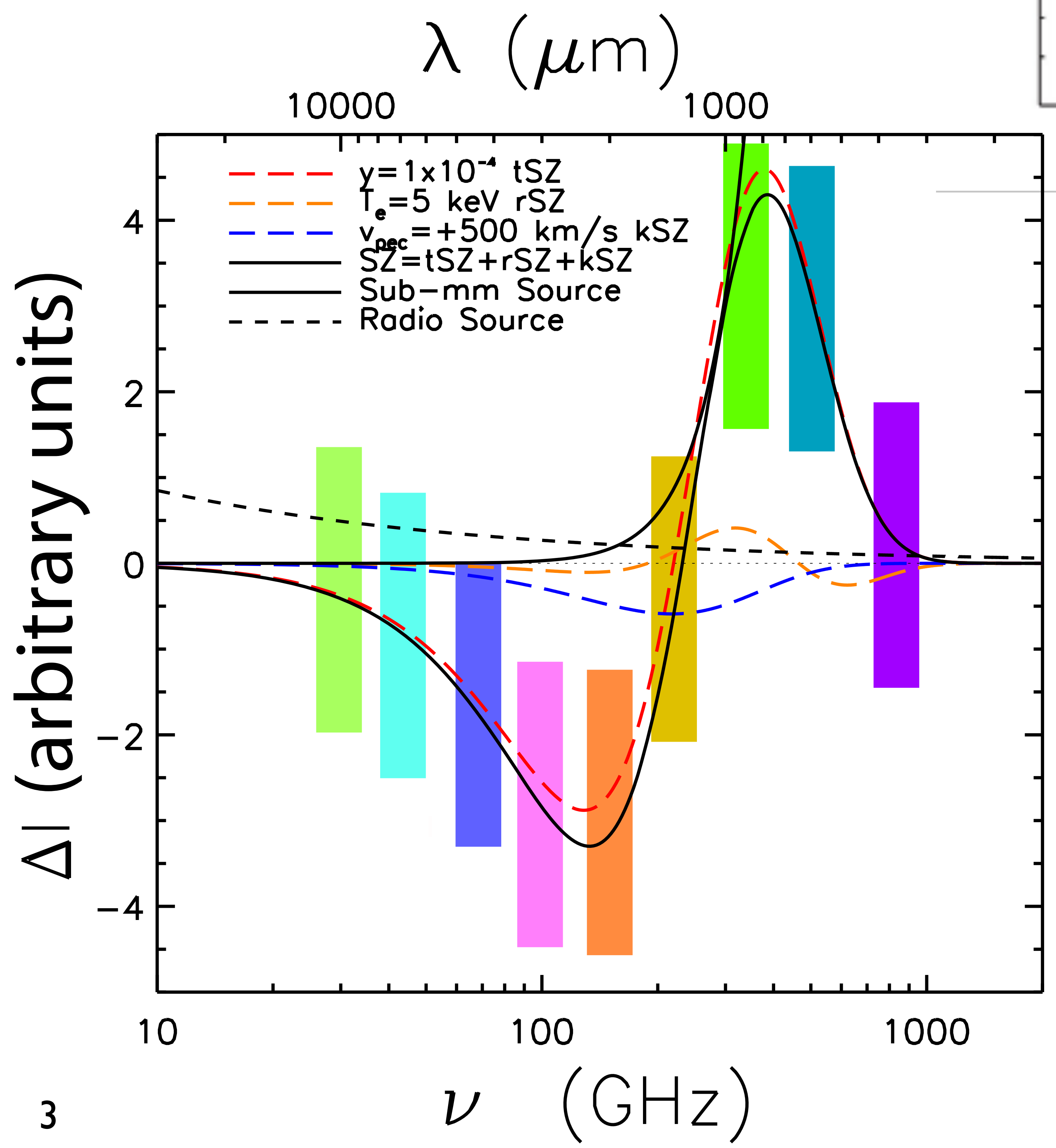
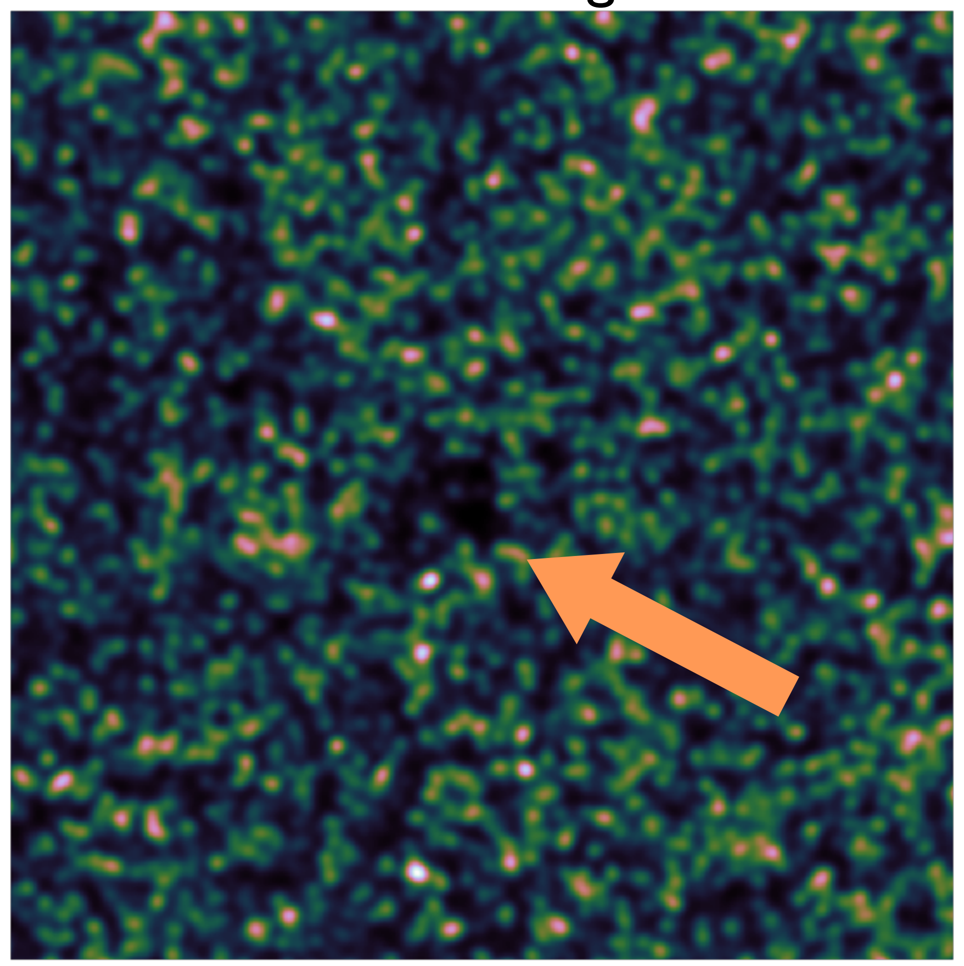




Multiple bands critical for separation of kinetic and relativistic SZ from thermal SZ and dusty galaxies



dusty galaxies in cluster field incl. lensing deficit



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Science targets complementary to wide-area CMB surveys

- Triggered, flexible cadence 6-band follow-up 80-420 GHz
- SZ/dust mapping of individual large clusters and nearby galaxies
- Small, deep fields for SZ from CGM in lower mass galaxies
- Multi-band integral field unit (IFU) spectroscopy

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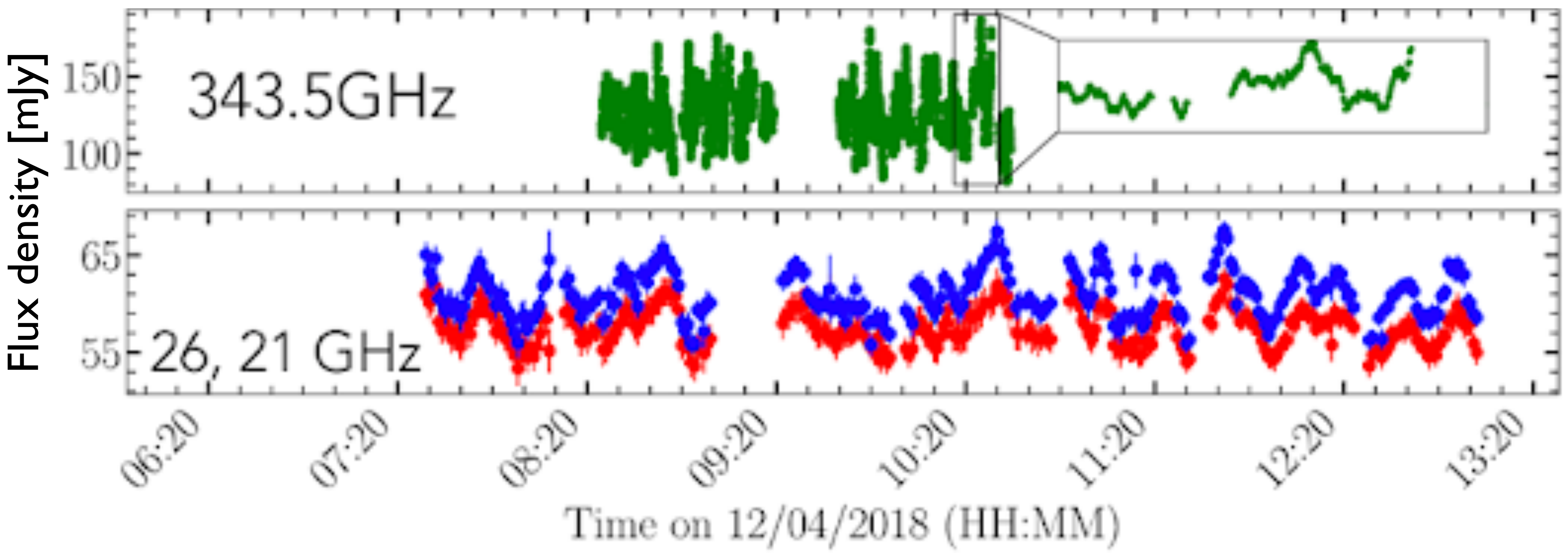

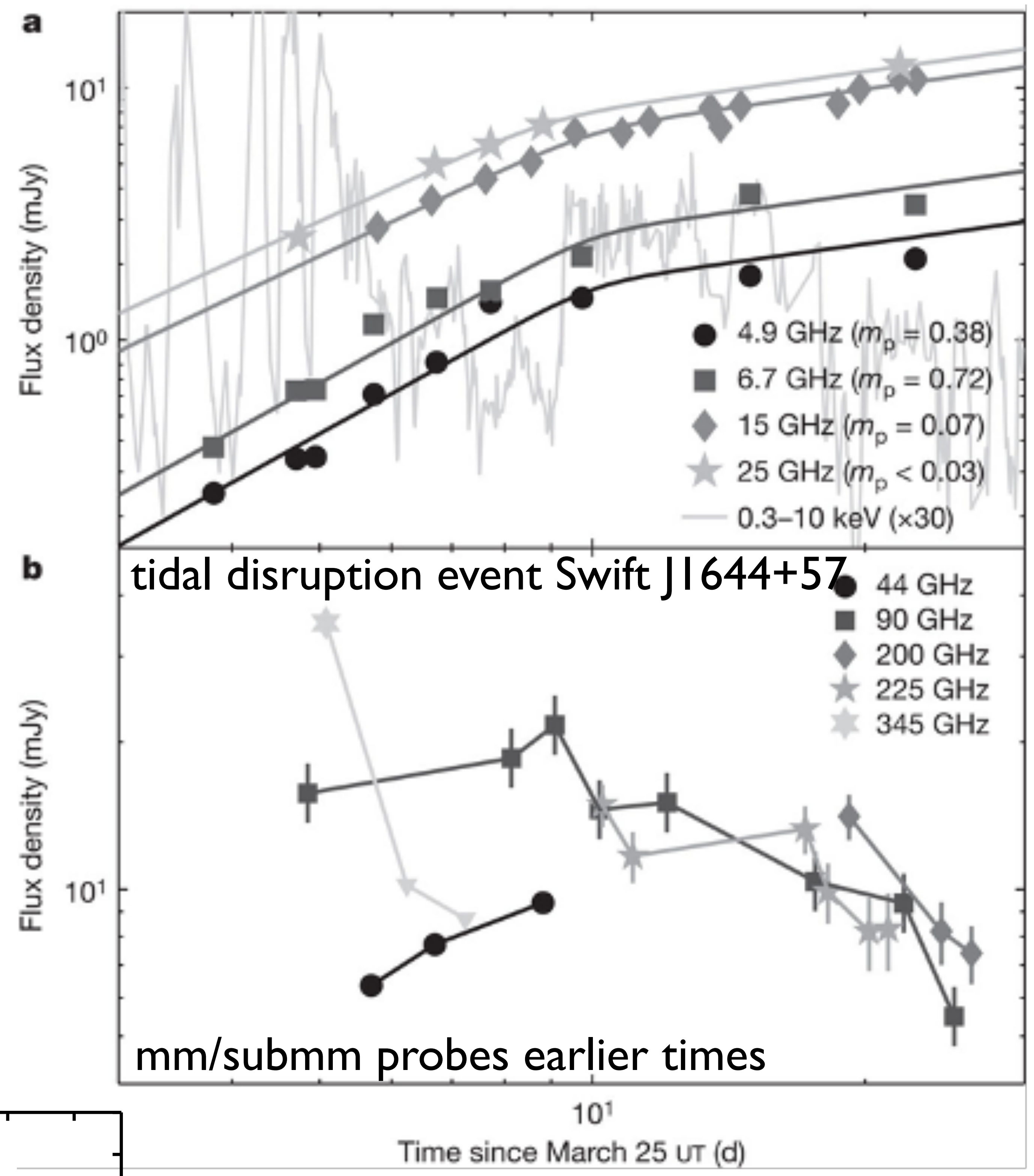

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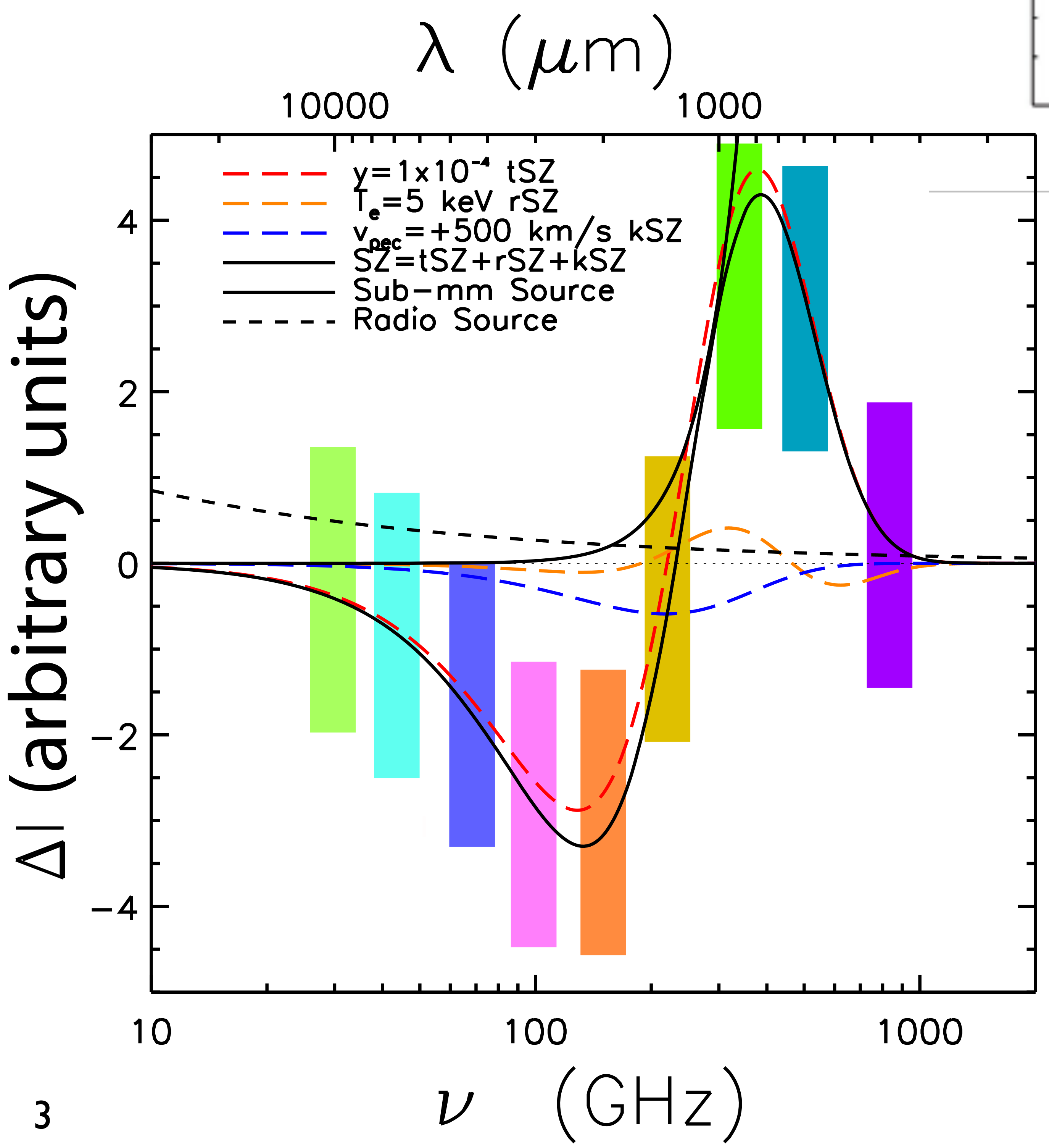

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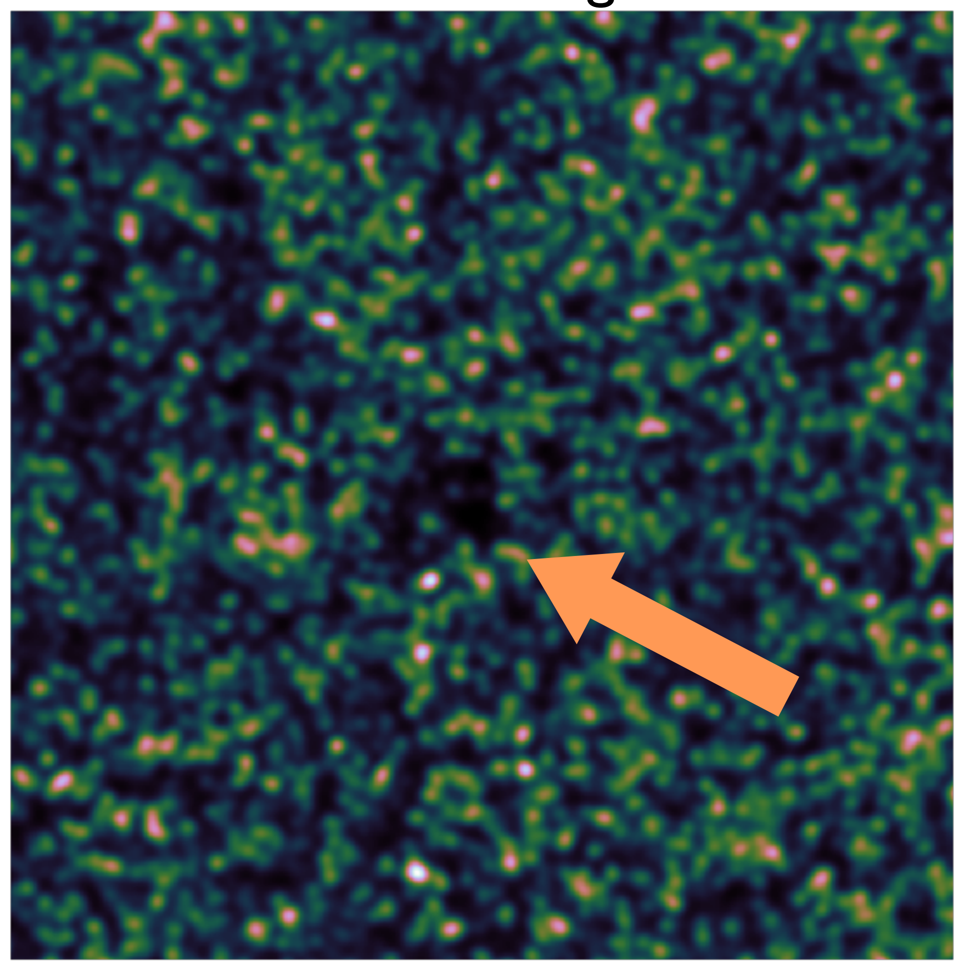

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Technology development transformative for future wide-field 30m-50m mm/submm telescope

- Natural next step in mm/submm, complement to ALMA
- Multi-band pixels and IFUs offer significant gain in science/$

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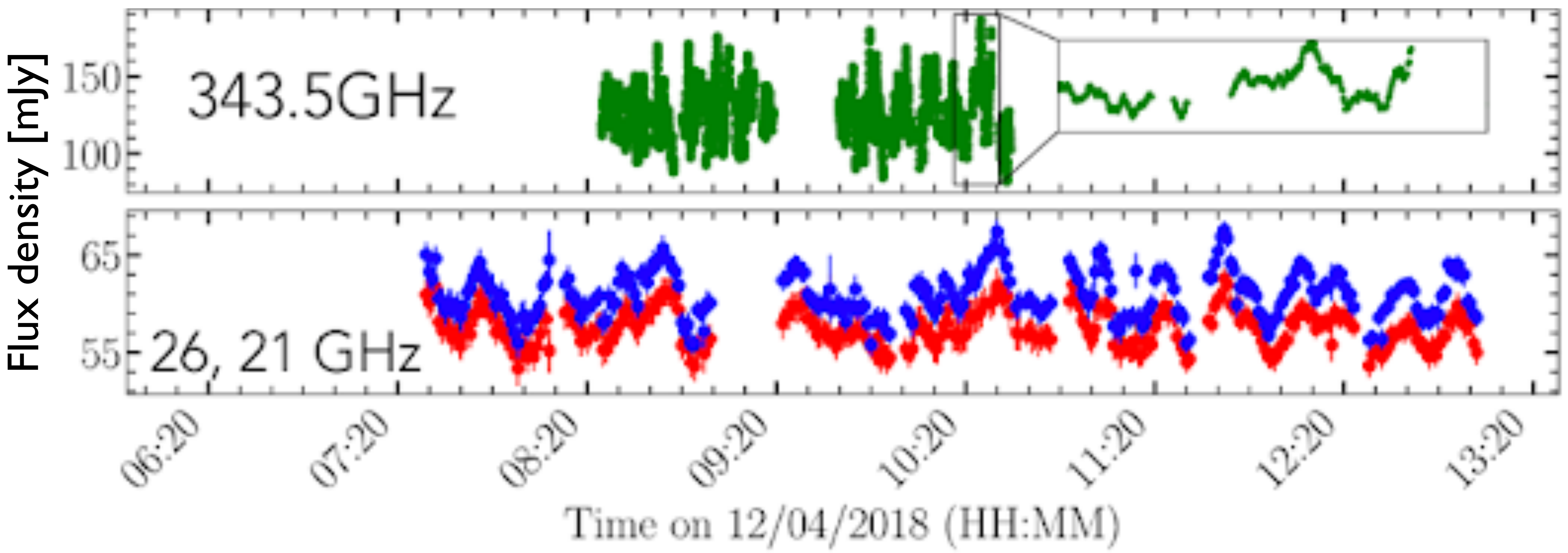

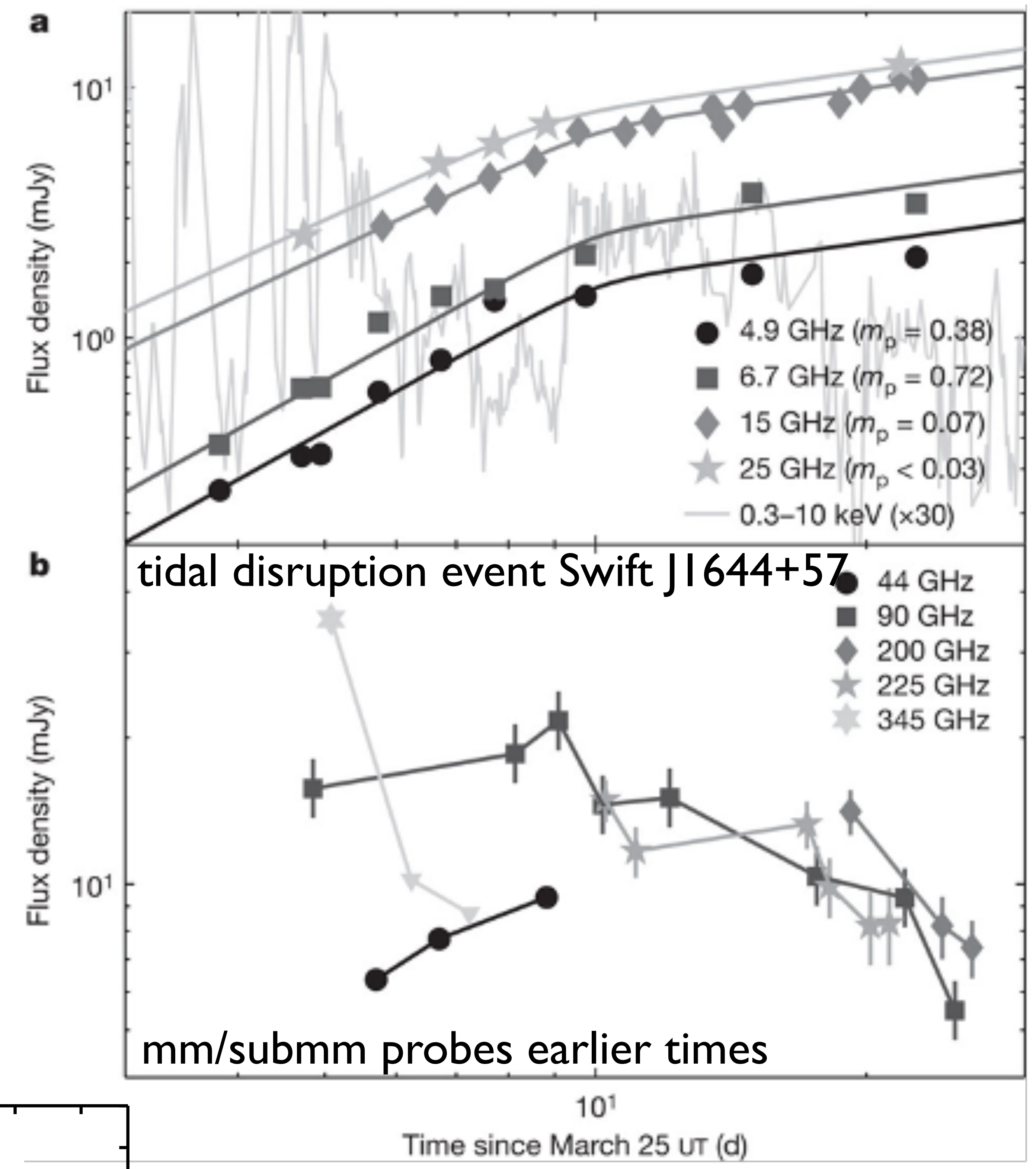

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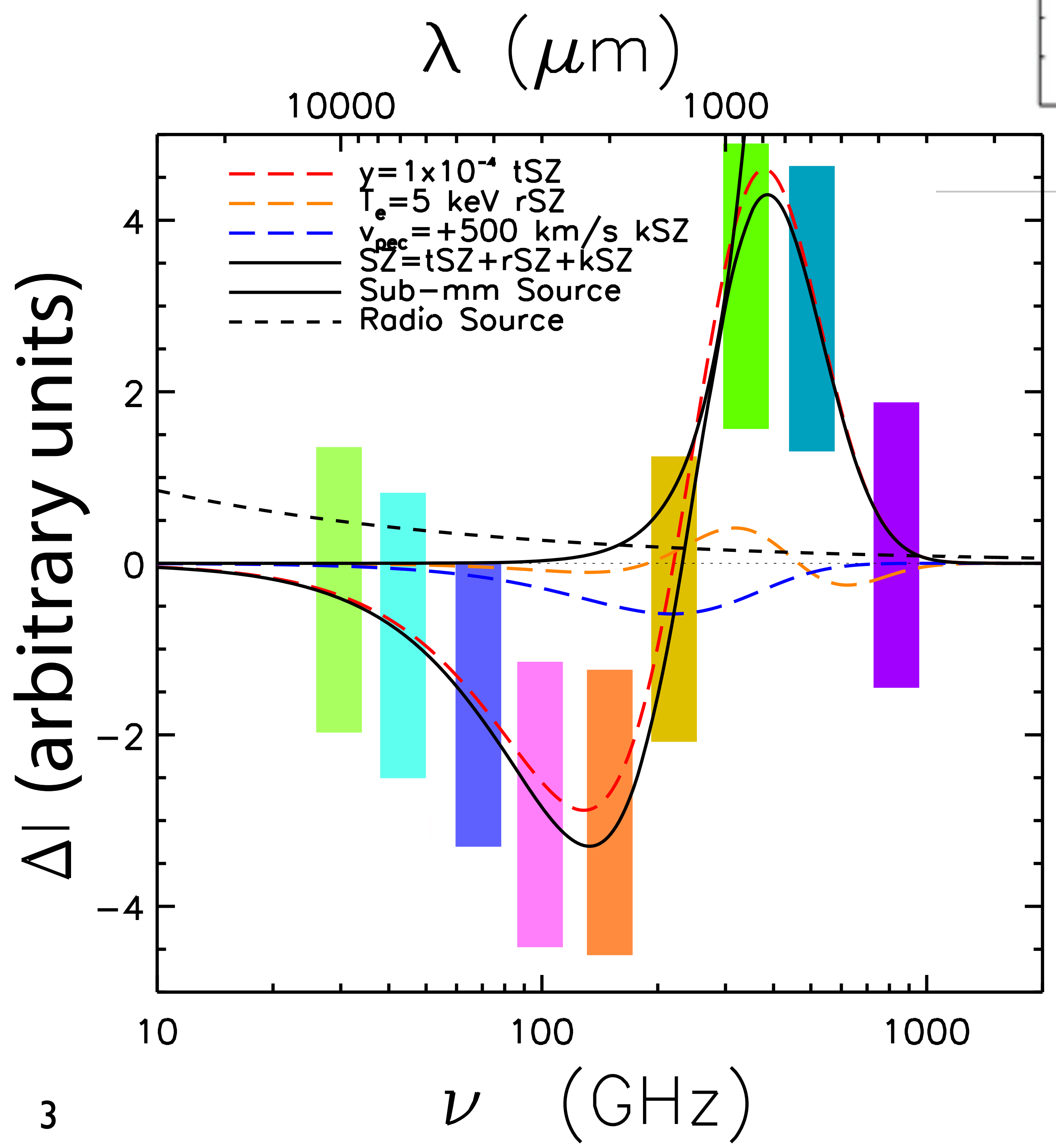

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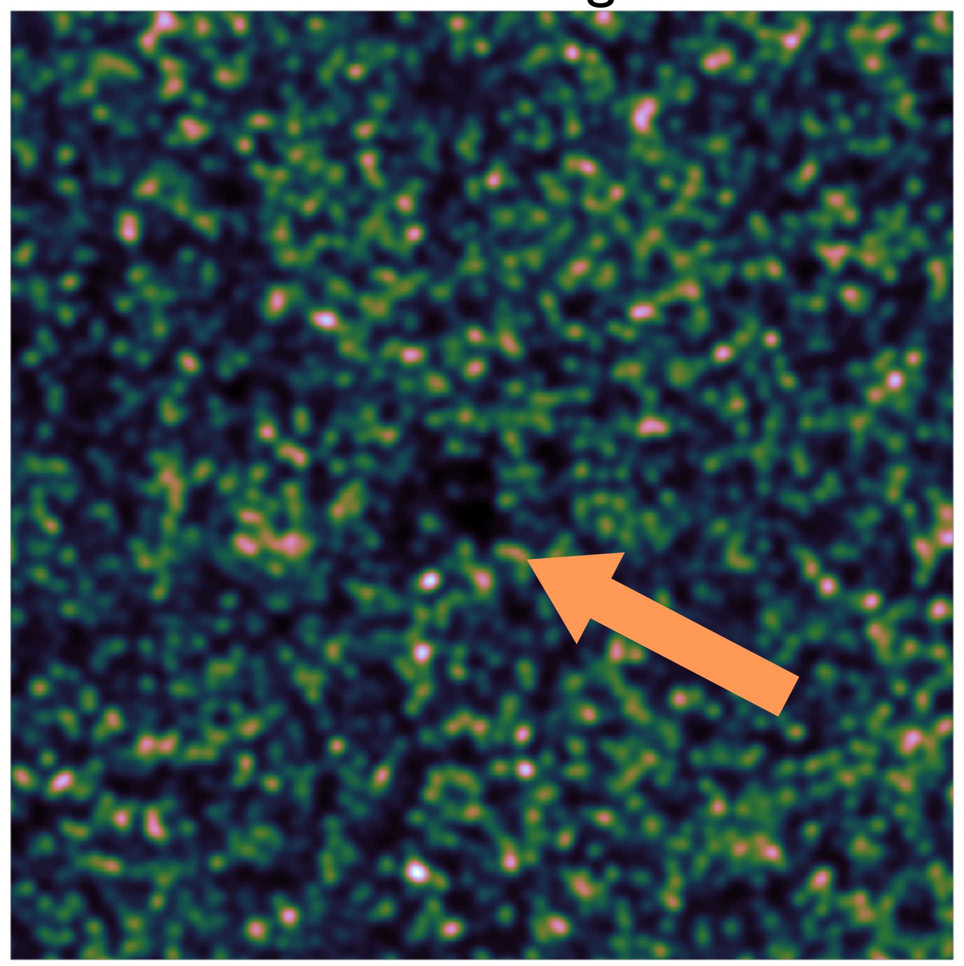
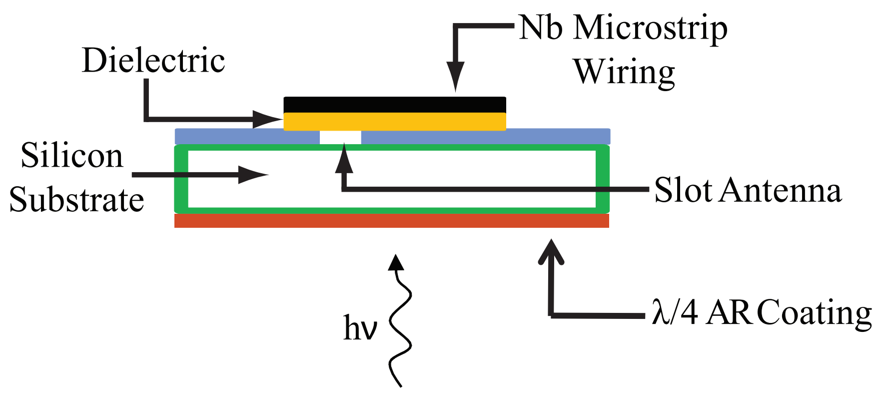
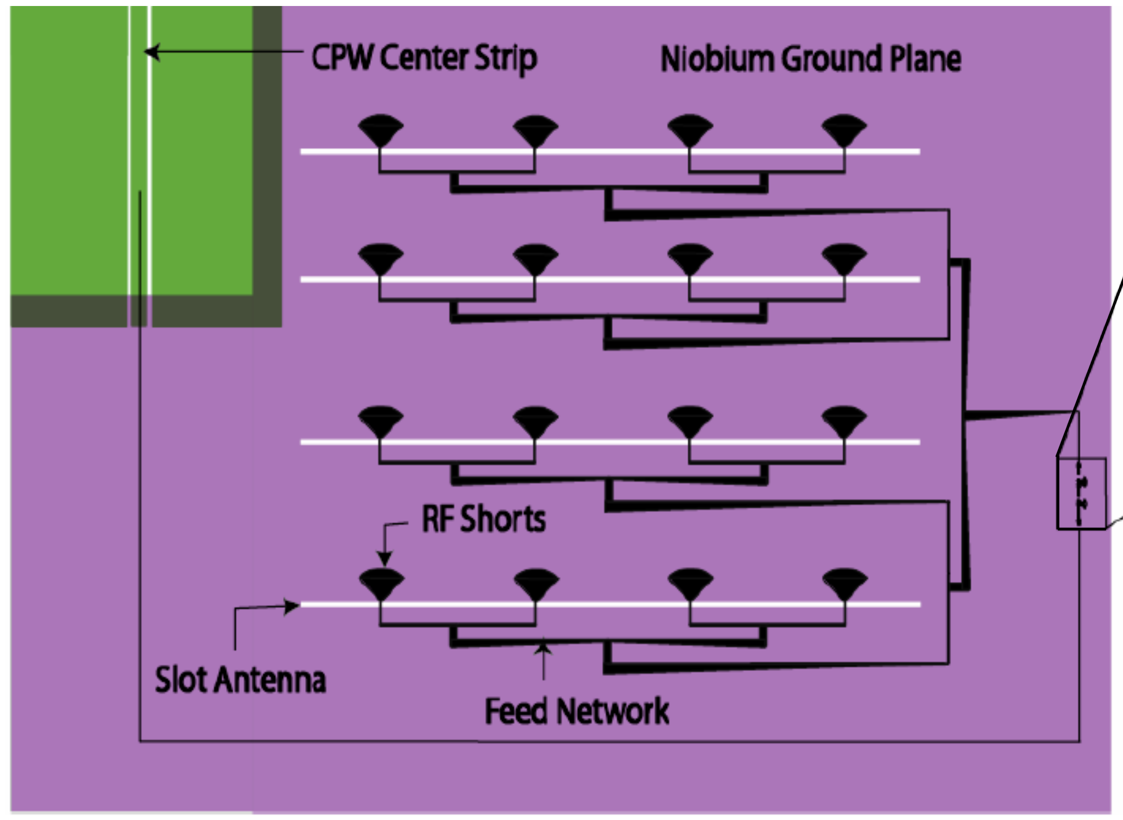


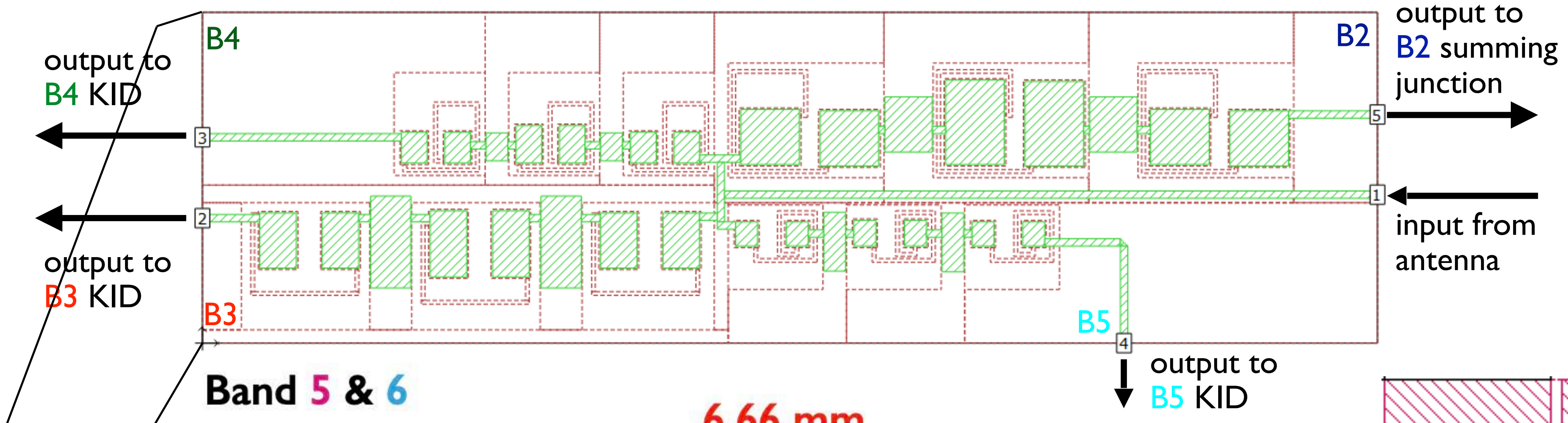
Al(-Ti)/a-Si:H PPC-KIDs microstrip-coupled to multi-band hierarchical phased-array antennas

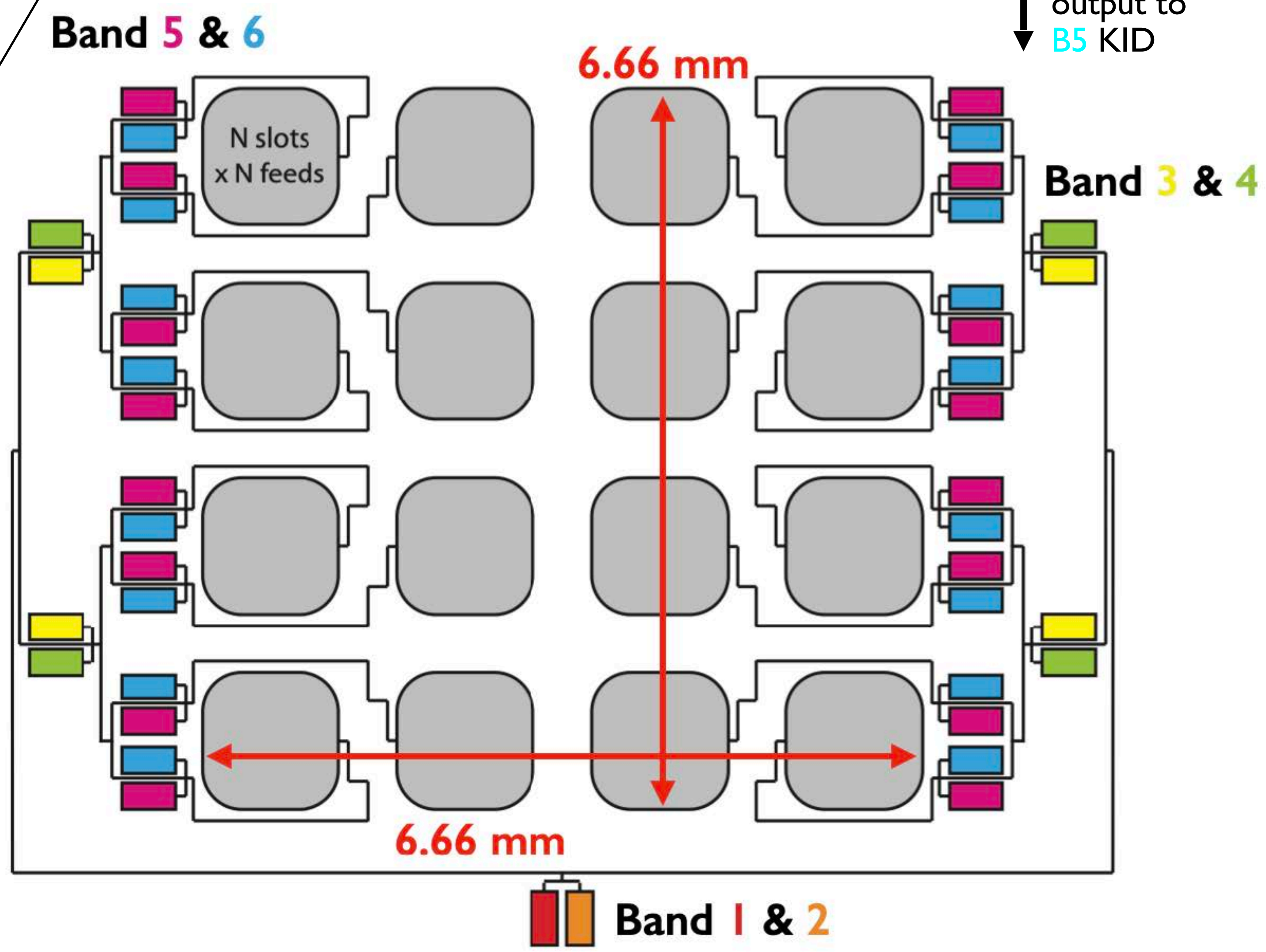
band	ν [GHz]	$\Delta\nu$ [GHz]
B1	90 GHz	35 GHz
B2	150 GHz	40 GHz
B3	230 GHz	35 GHz
B4	290 GHz	40 GHz
B5	345 GHz	30 GHz
B6	405 GHz	25 GHz

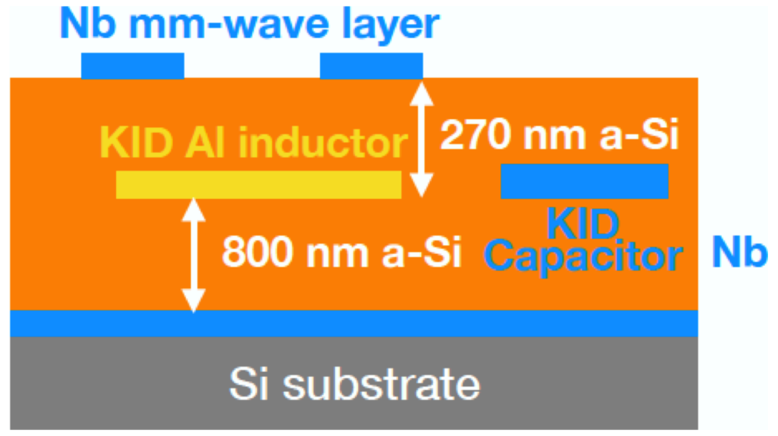




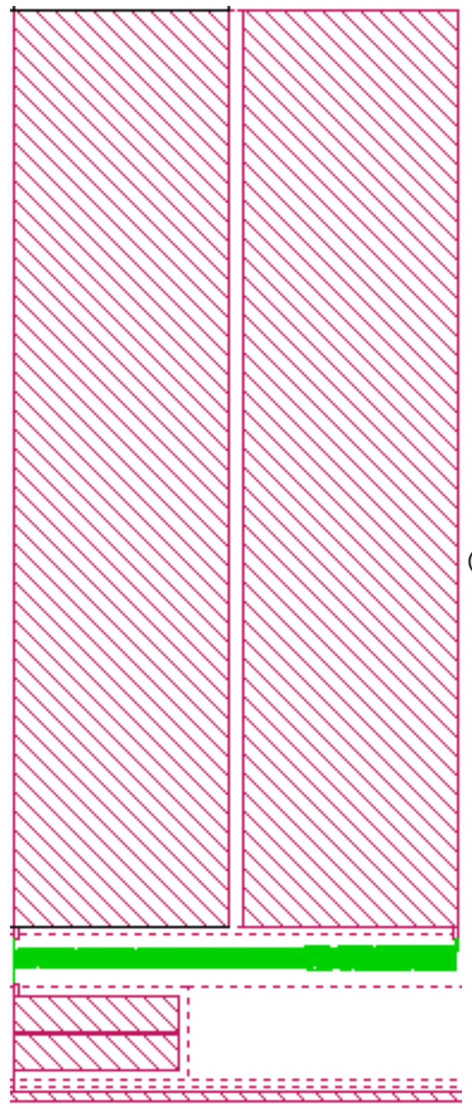
Lumped-element mm-wave BPFs



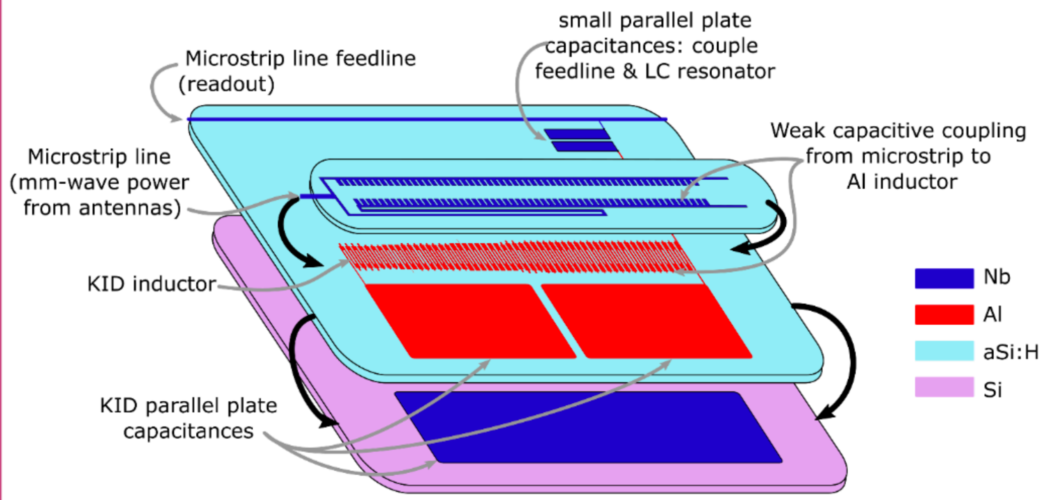




microstrip coupling to a-Si:H embedded KID

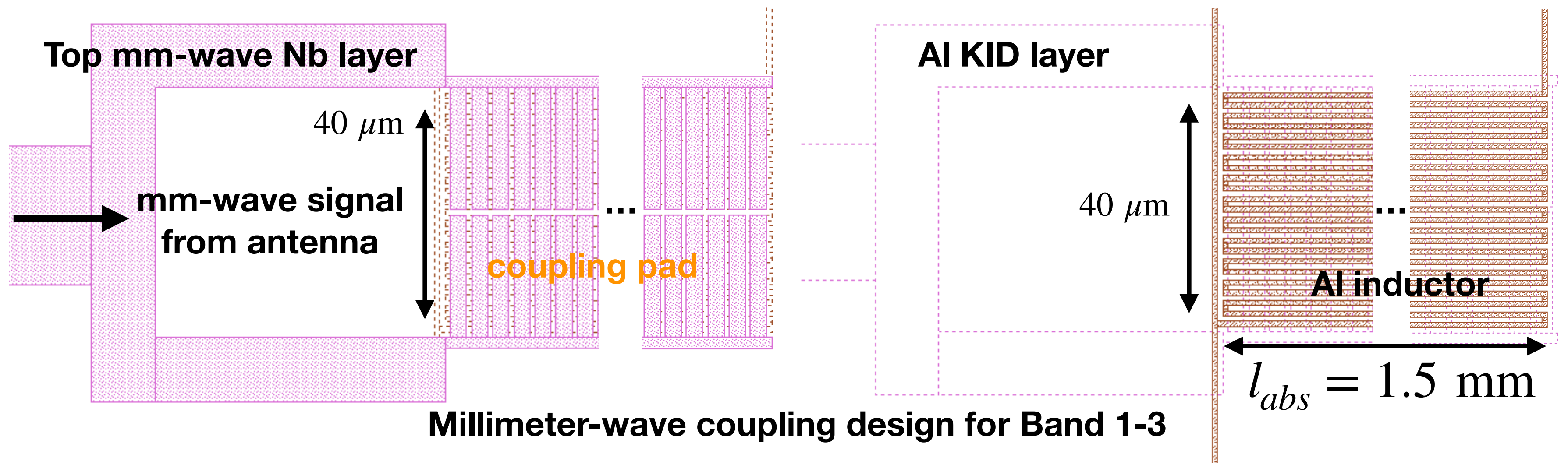


Large a-Si:H PPC to yield acceptable TLS noise (testing can size reduction)

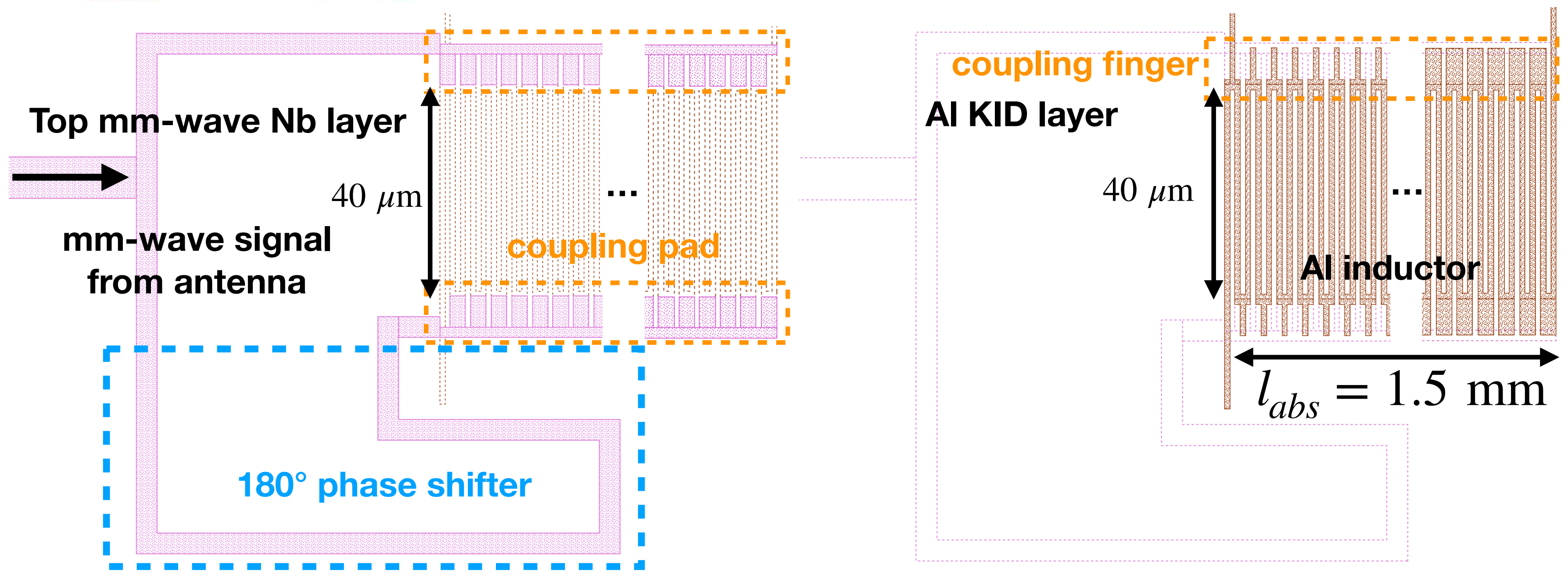


pixel scales with Airy spot size via frequency-selective hierarchical summing

microstrip-coupled PPC-KID; Al → Al-Ti to access B1 in process



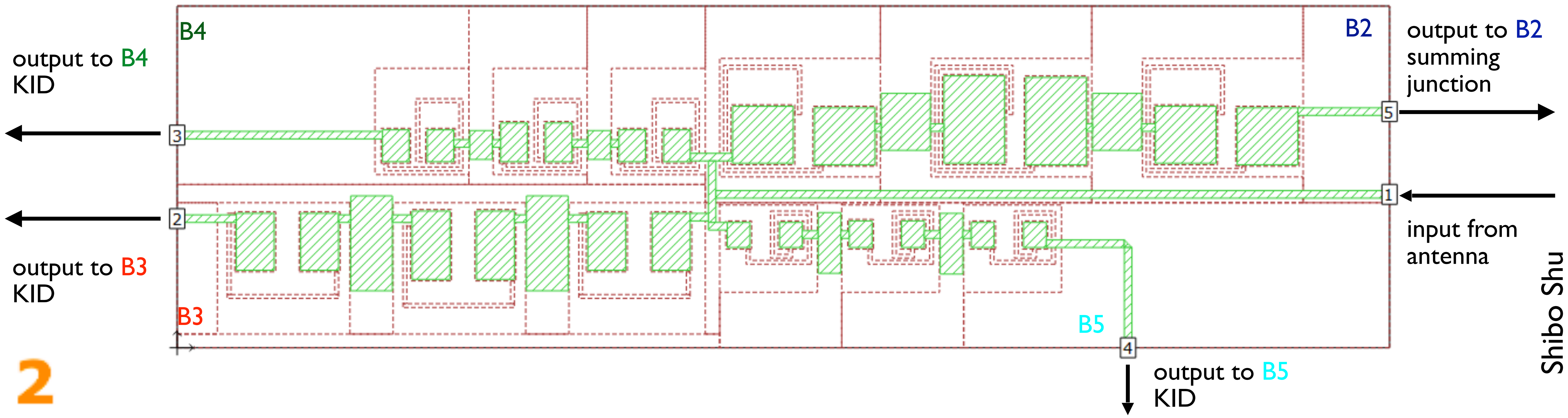
Millimeter-wave coupling design for Band 1-3

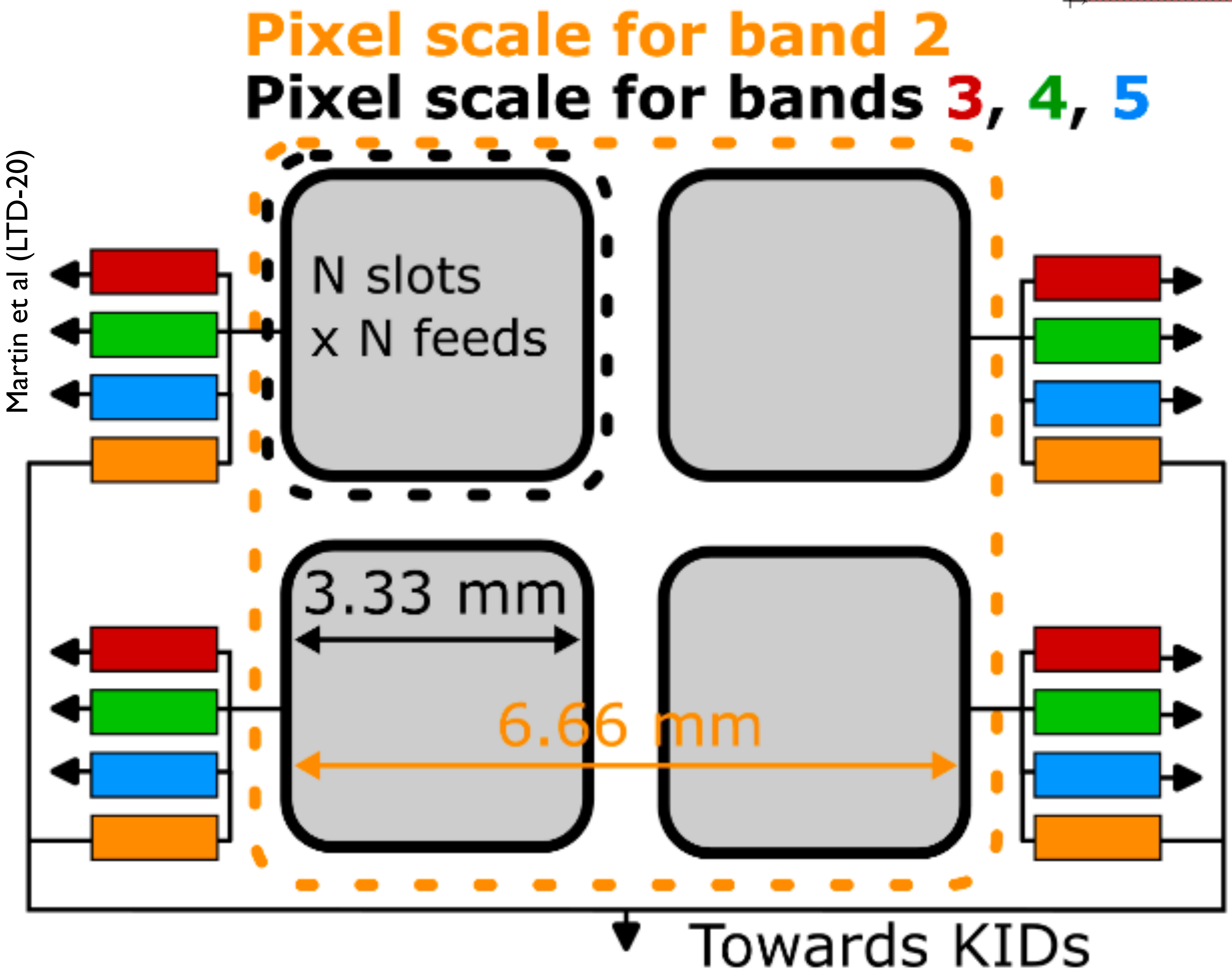


Millimeter-wave coupling design for Band 4-6

Golwala et al (SPIE 2012)
Ji et al (SPIE 2014)
Shu et al (LTD-19)
Martin et al (LTD-20)
Defrance et al (PRMat 2024)
Defrance et al (APL 2025)

Two-Scale, Four-Band Hierarchical Antenna Demonstrator





32x32 slots/feeds for fundamental elements

BPFs on each fundamental element

2x2 summed array

Uses two-layer meta-material silicon AR

- Defrance et al (Appl Opt 2018)
- Three and four-layer demonstrated
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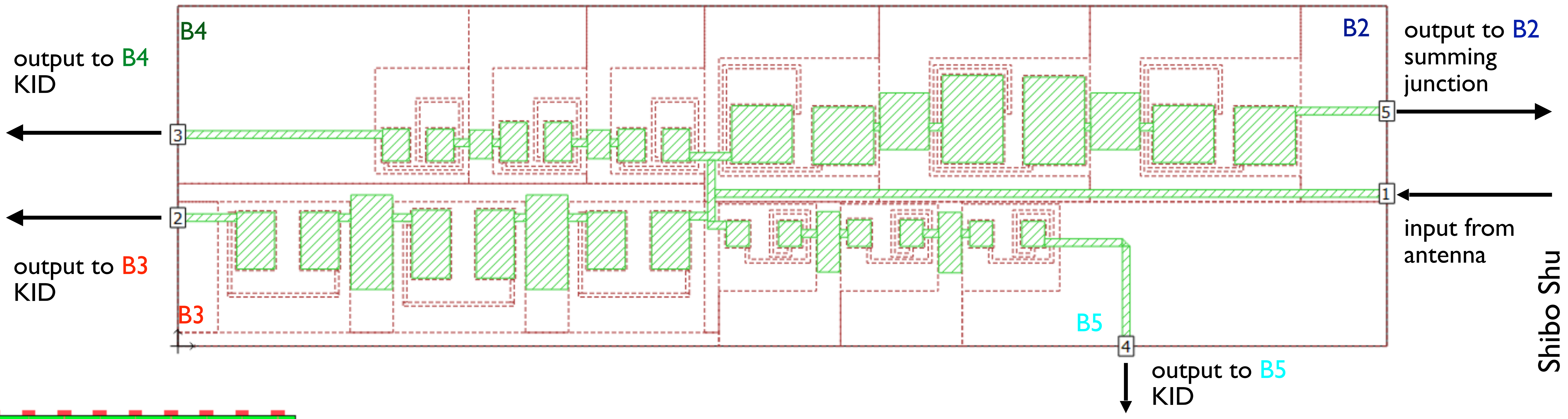

Peter Day, Shibo Shu

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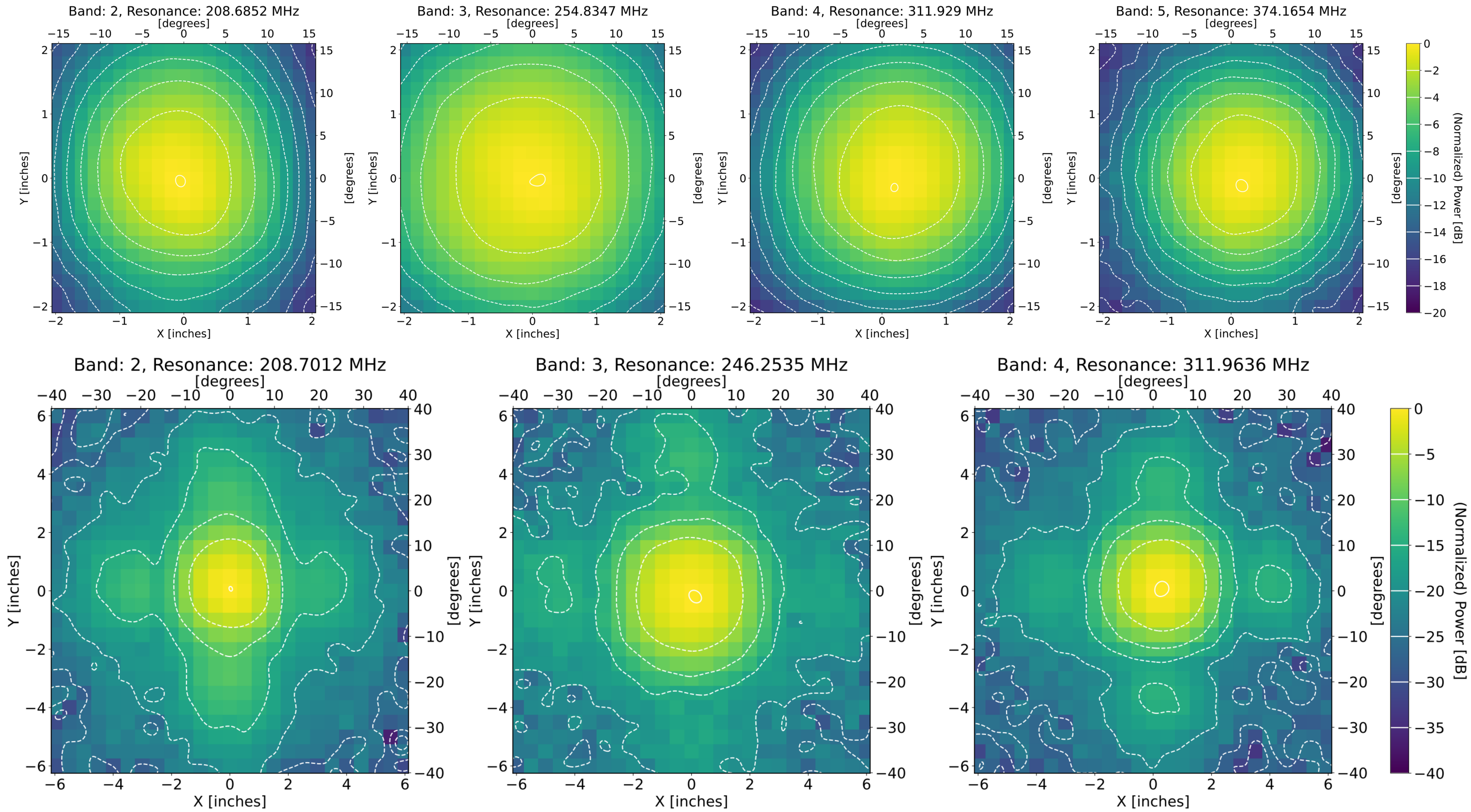
Two-Scale, Four-Band Hierarchical Antenna Beams

Central lobe

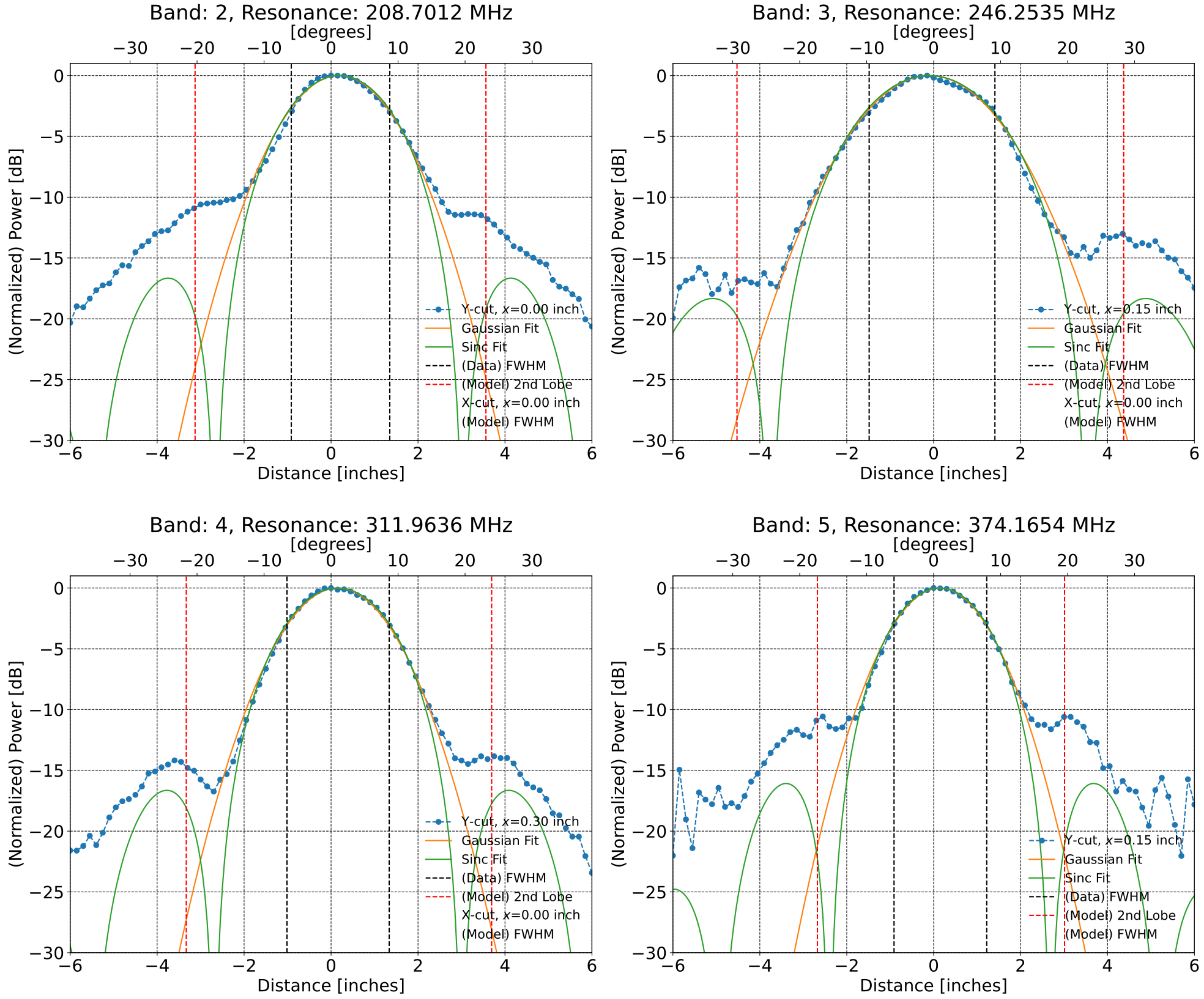
Sidelobes (would be terminated on cold stop)



Junhan Kim; Martin et al (LTD-20)

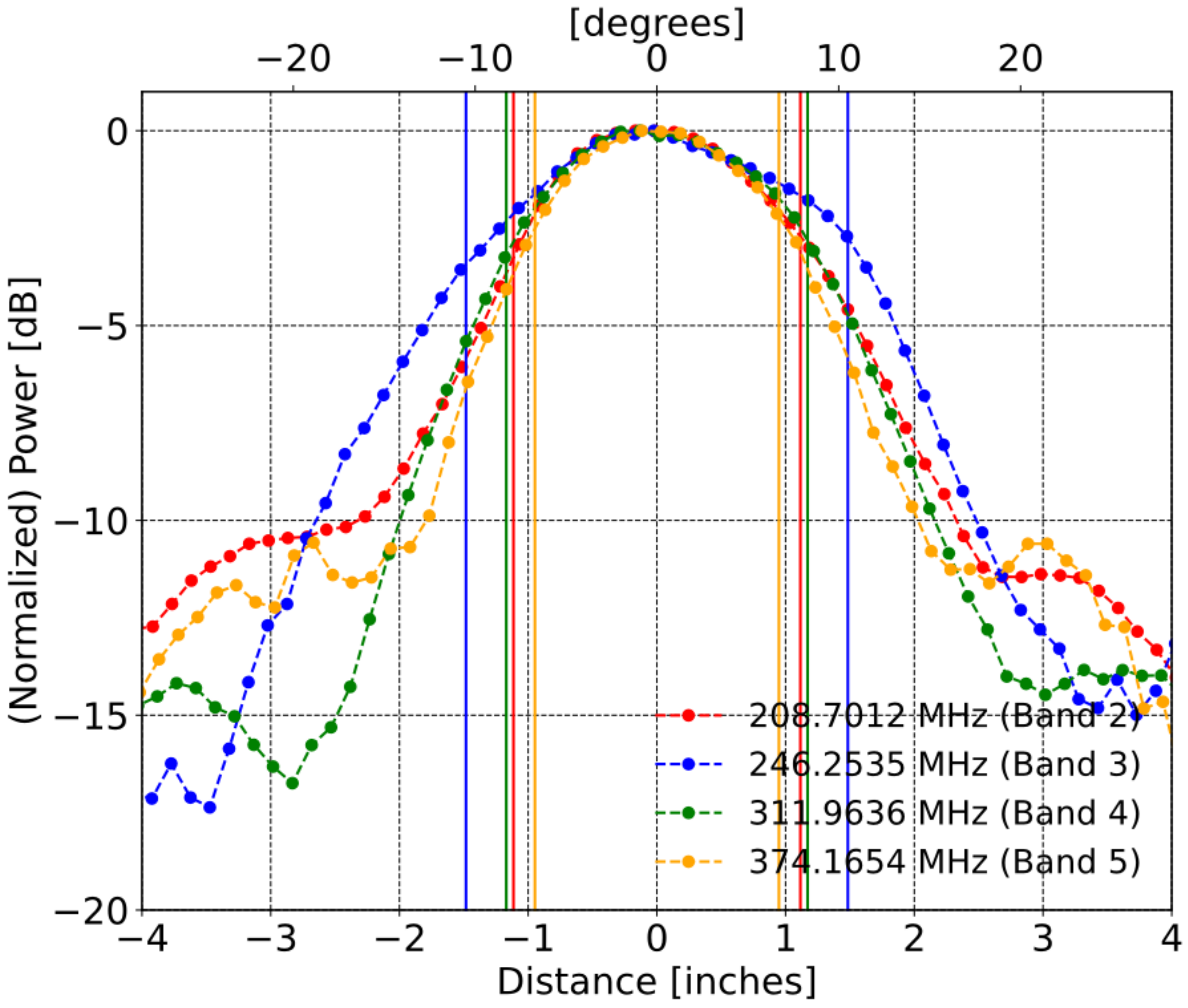
Two-Scale, Four-Band Hierarchical Antenna Beams

Beams match expectations well down to -10 dB
Need to understand modest asymmetries, relatively high sidelobes for B2 and B5



Beam FWHM vs. frequency matches expected scaling with λ including summing for B2:
FWHM(B2) < FWHM(B3), FWHM(B2) ~ FWHM(B4)

Band	2	3	4	5
FWHM [deg]	17.2	22.9	18.1	14.6



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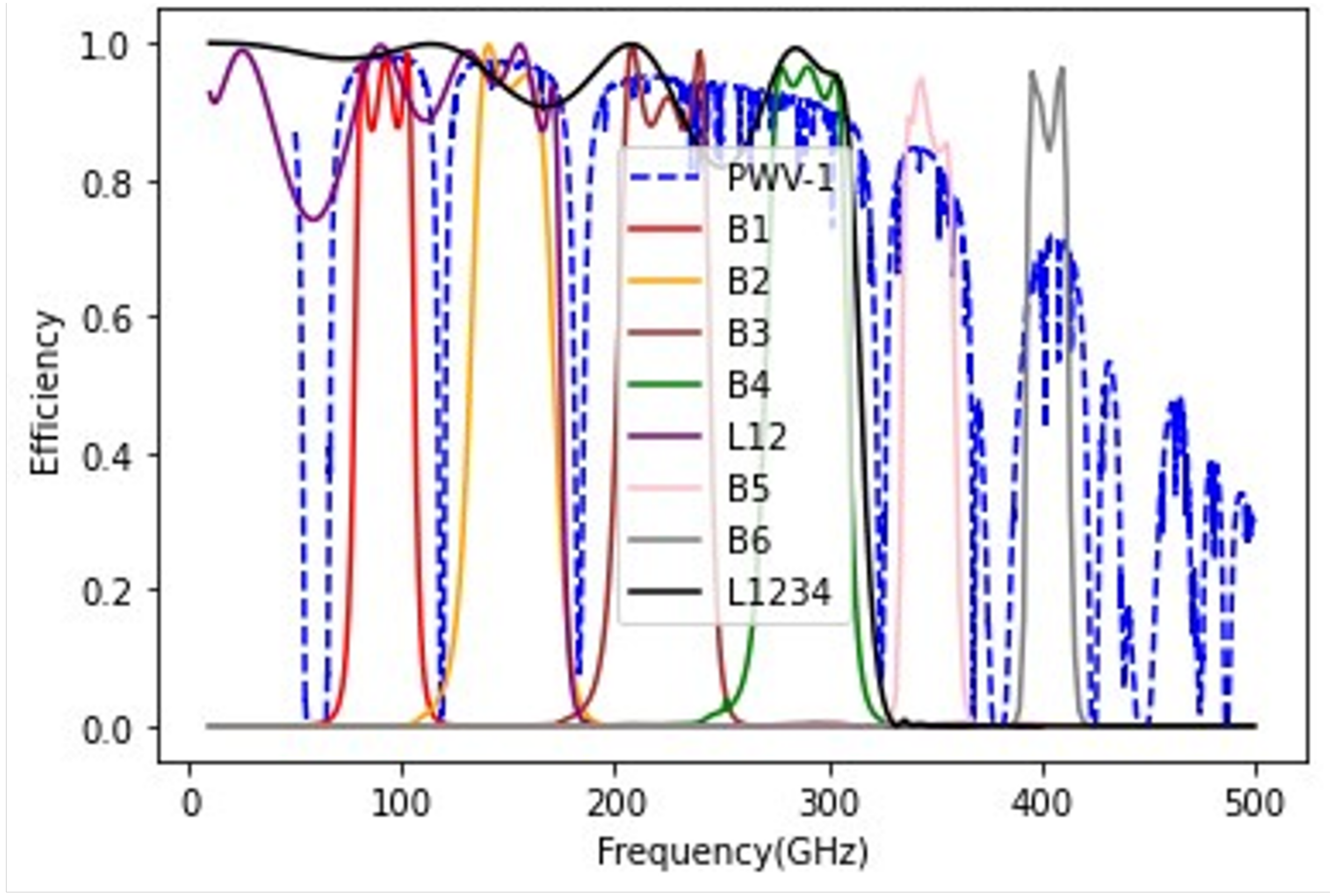
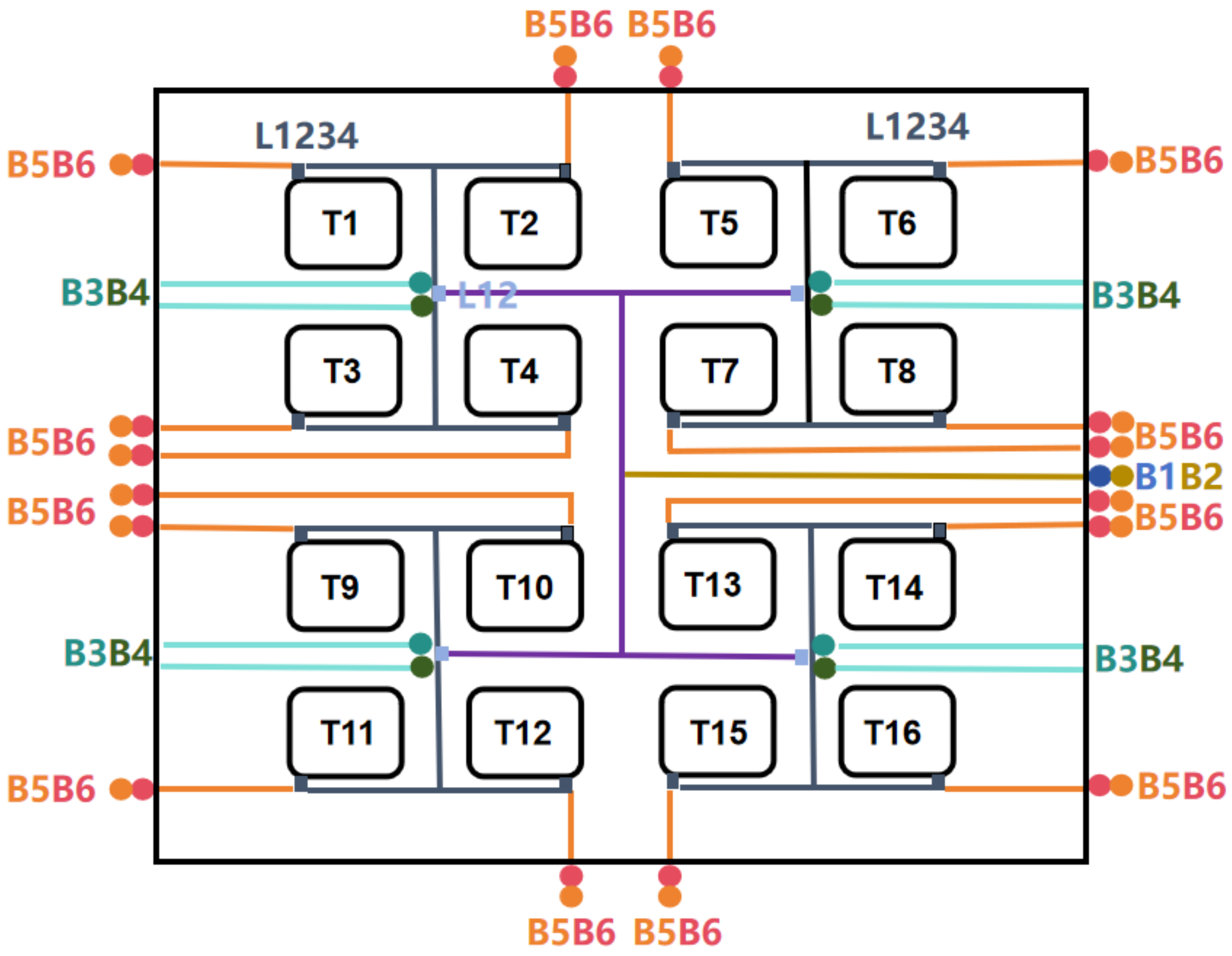
Split fundamental antennas into 16x16 quadrants

BPF/BPF/LPF banks must be placed inside array

- Gaps comparable to 2-scale
- Filter design completed (Sonnet sims)
- GDS file ready to go on mask





Crystal Huang, Shibo Shu

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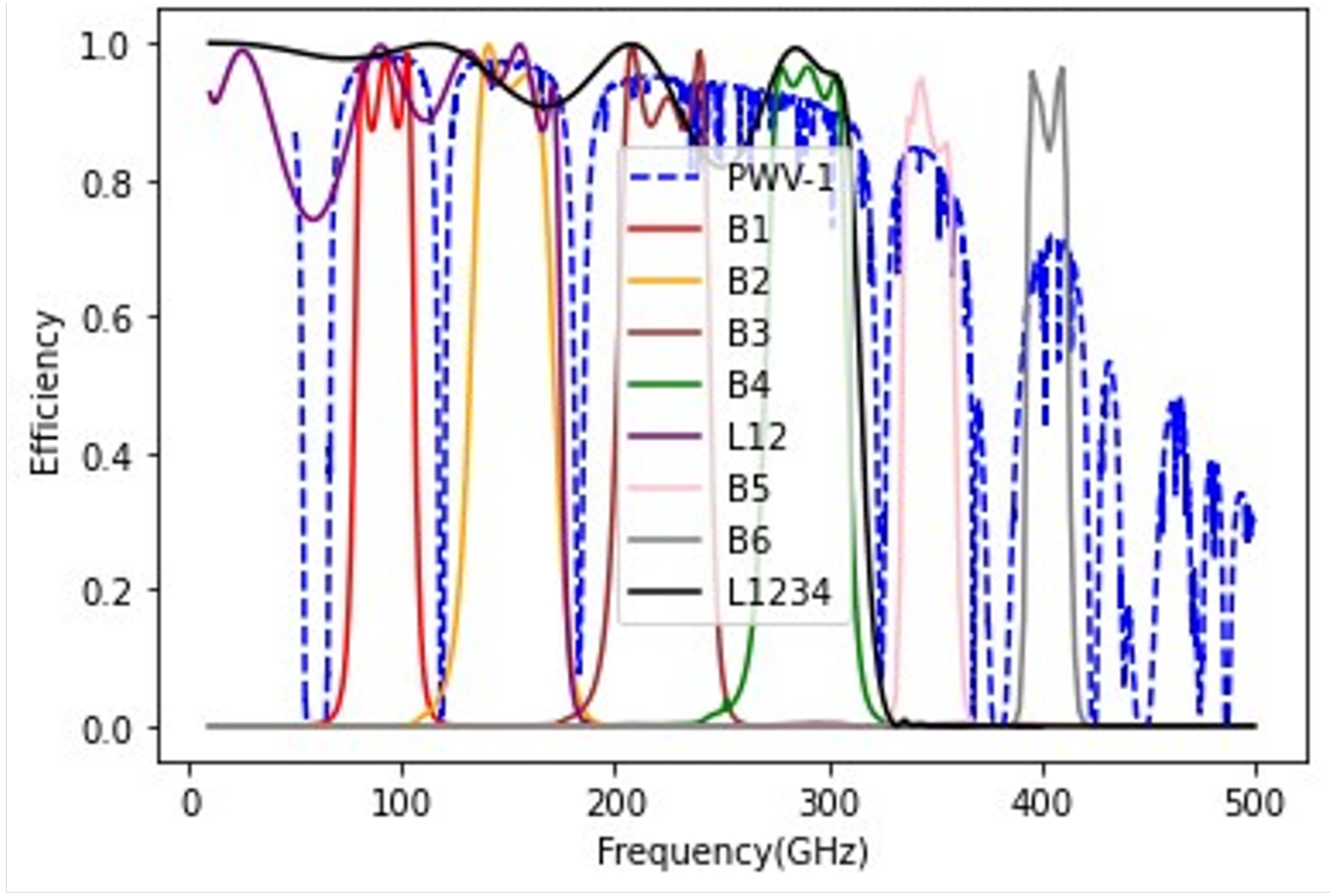

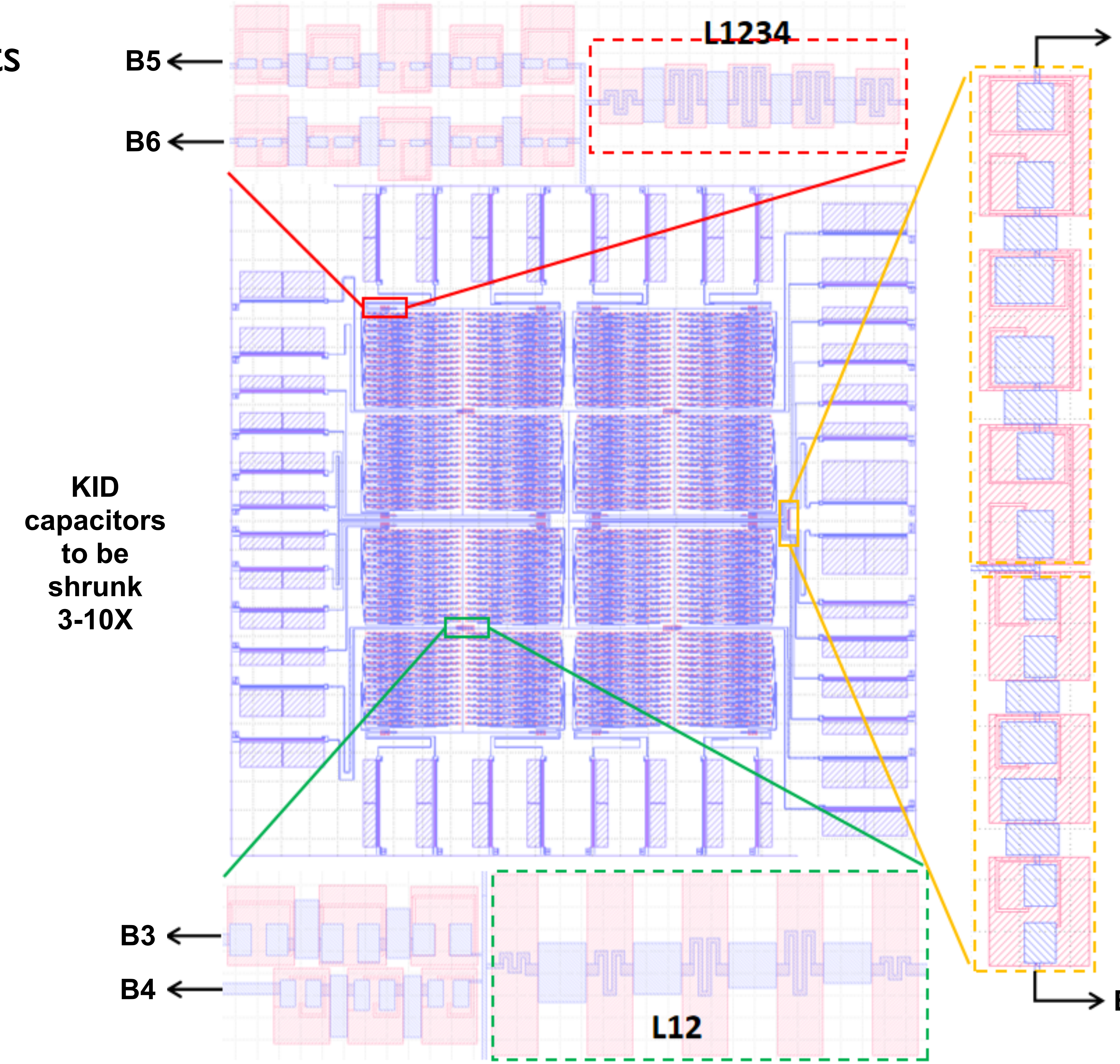

Crystal Huang, Shibo Shu

Noise Performance — Under Optical Load

$$S_{N_{qp}}^{tot} = S_{N_{qp}}^{GR} + S_{N_{qp}}^{\gamma} \approx \frac{V}{R}\left[1 + \eta_{pb}\left(\frac{h\,\nu}{2\,\Delta} + \frac{\eta_{opt}\,k_B\,T_{load}}{2\,\Delta}\right)\right]$$

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Lifetime limited by recombination of optically generated qps $\Longrightarrow S_{N_{qp}}^{tot}$ linearly related to T_{load}

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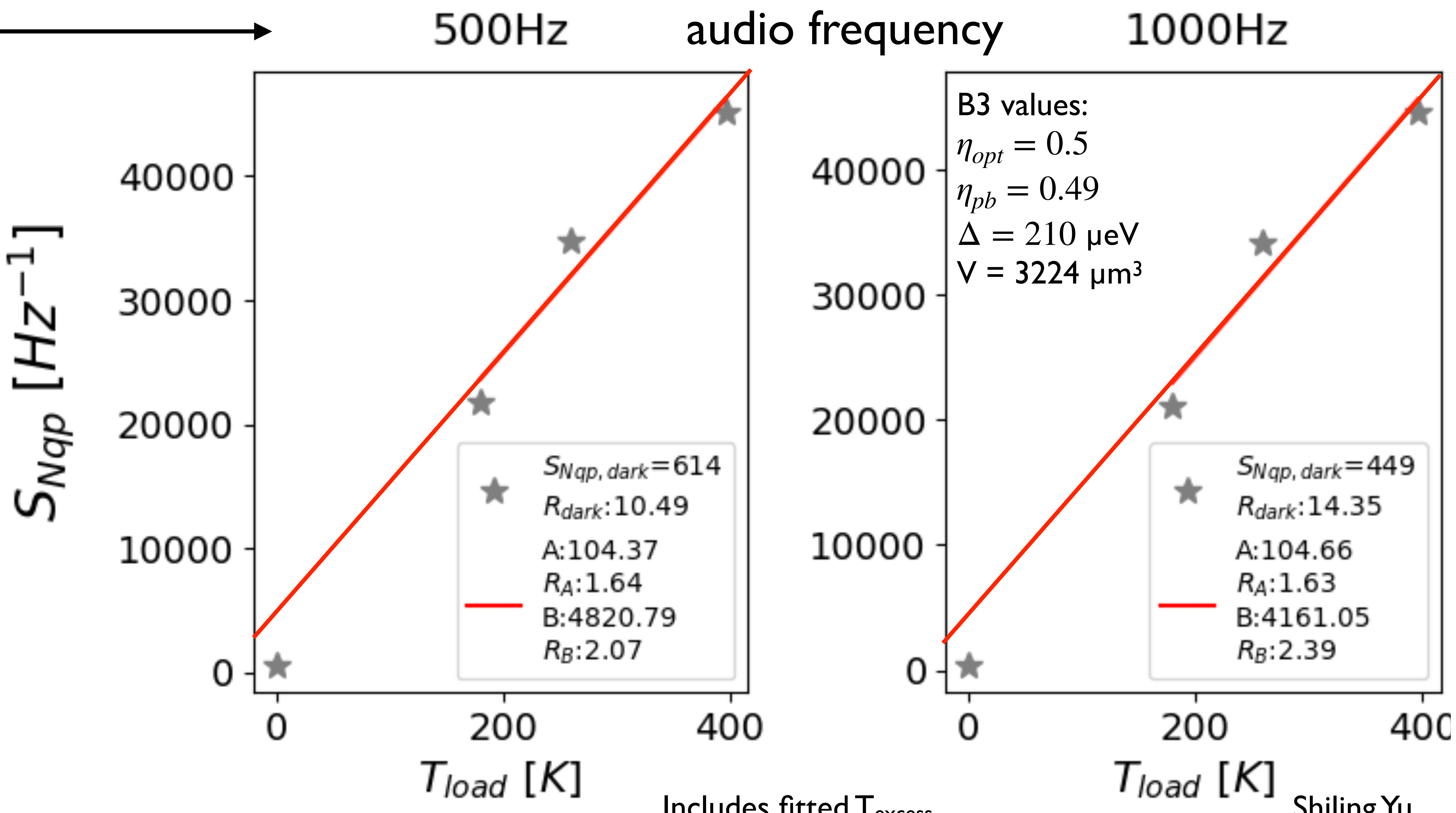
Verified with cold (77K), mirror (150K), and hot (300K) loads



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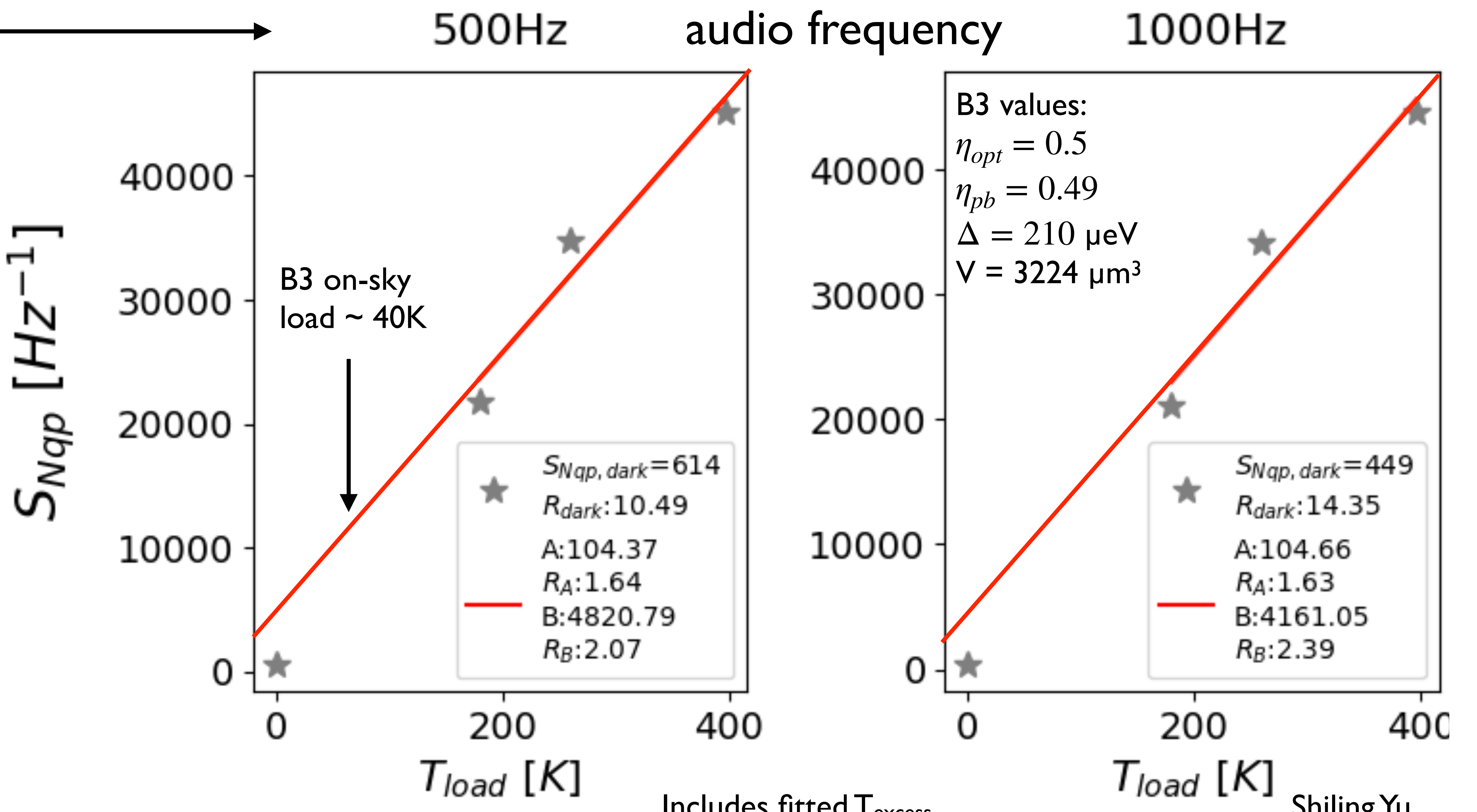

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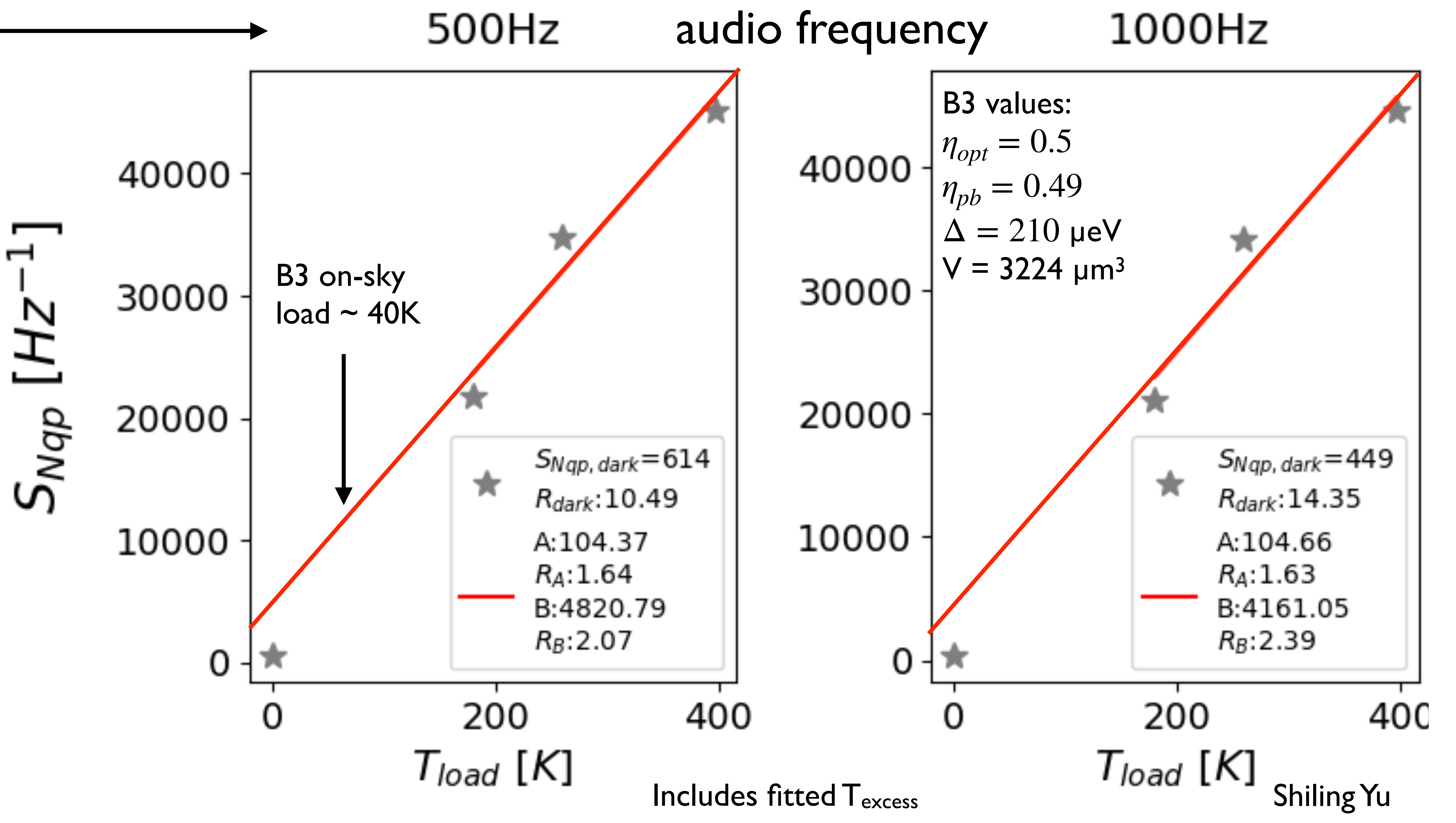
<u>Key takeaway</u>: Always enough responsivity to be GR or photon-noise-limited:

$$S_{N_{qp}}^{GR} + S_{N_{qp}}^{\gamma} \gg S_{N_{qp}}^{amp} + S_{N_{qp}}^{TLS}$$



Noise Performance at Low Frequency

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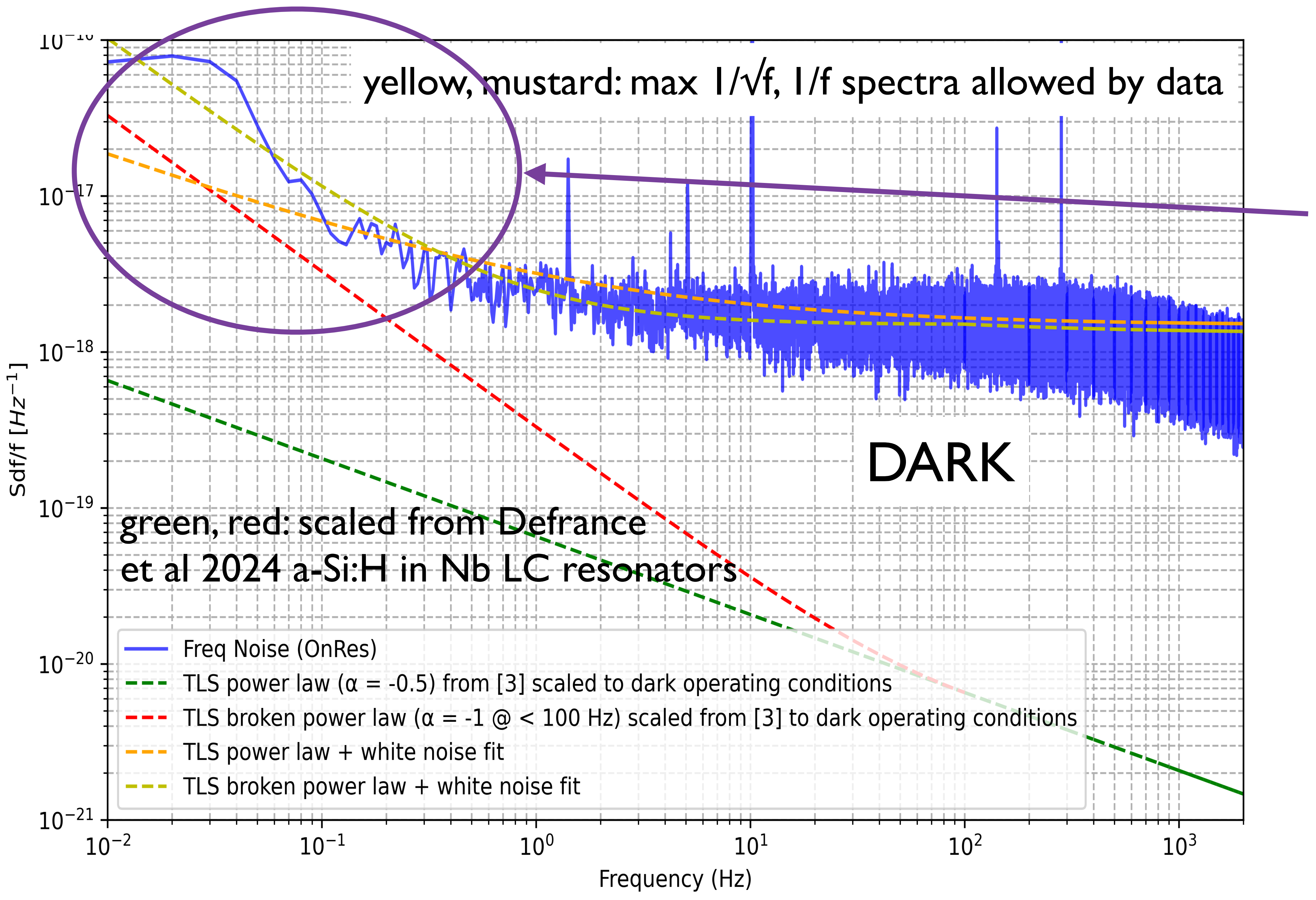

Noise under dark conditions white down to $\lesssim$ 0.1 Hz

- TLS noise subdominant to GR noise
- Residual low-frequency noise probably removable electronics noise

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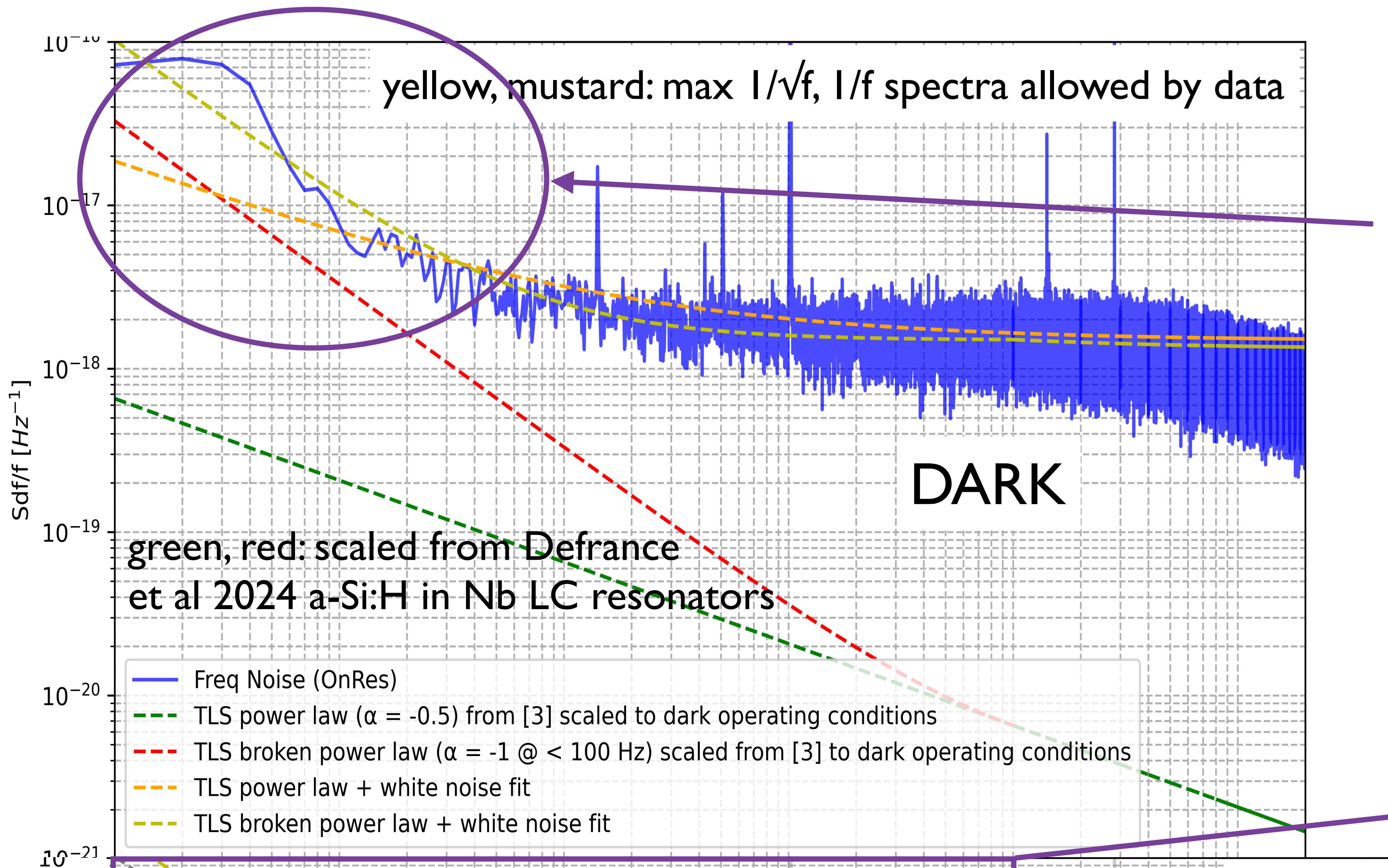
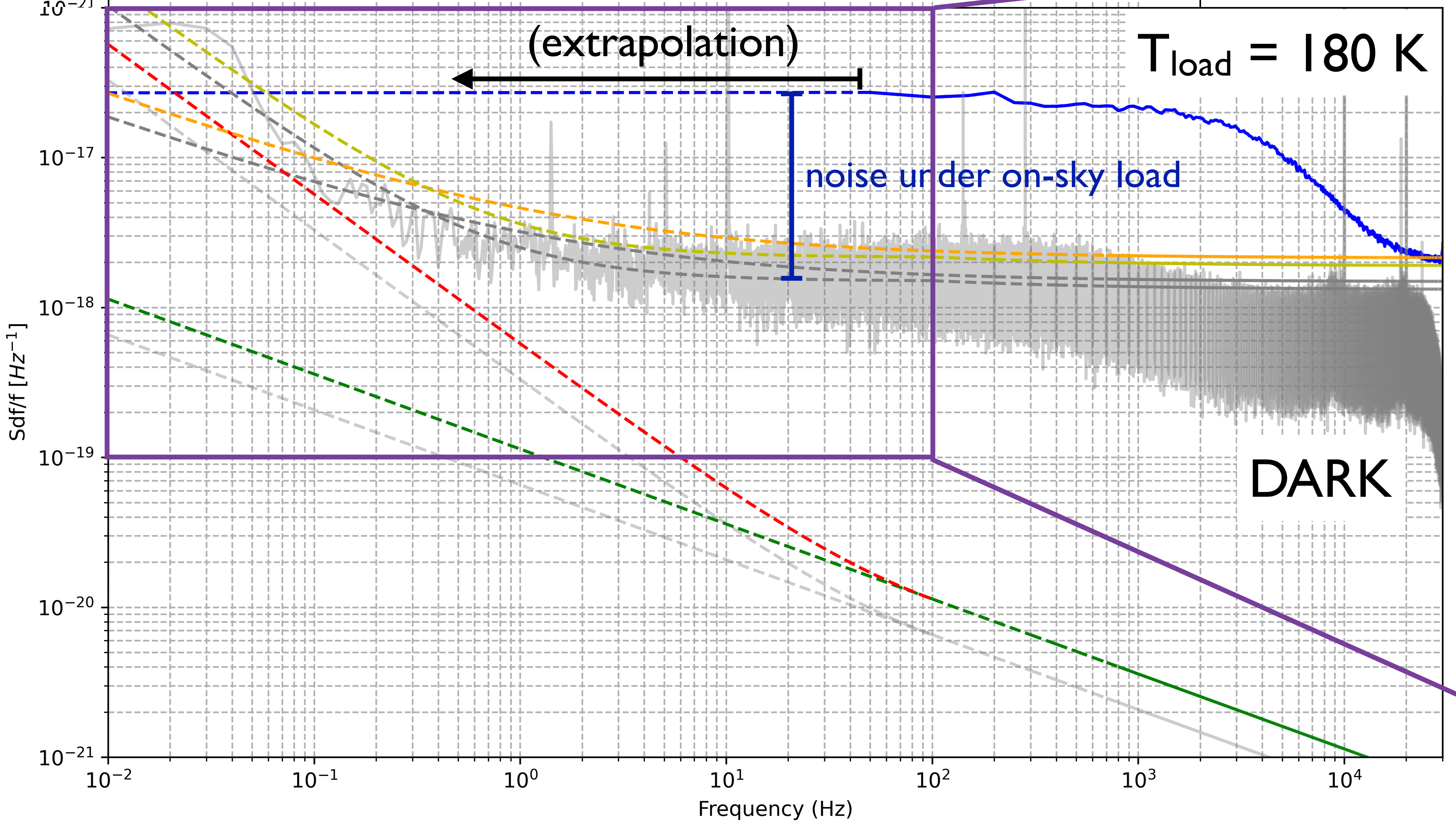
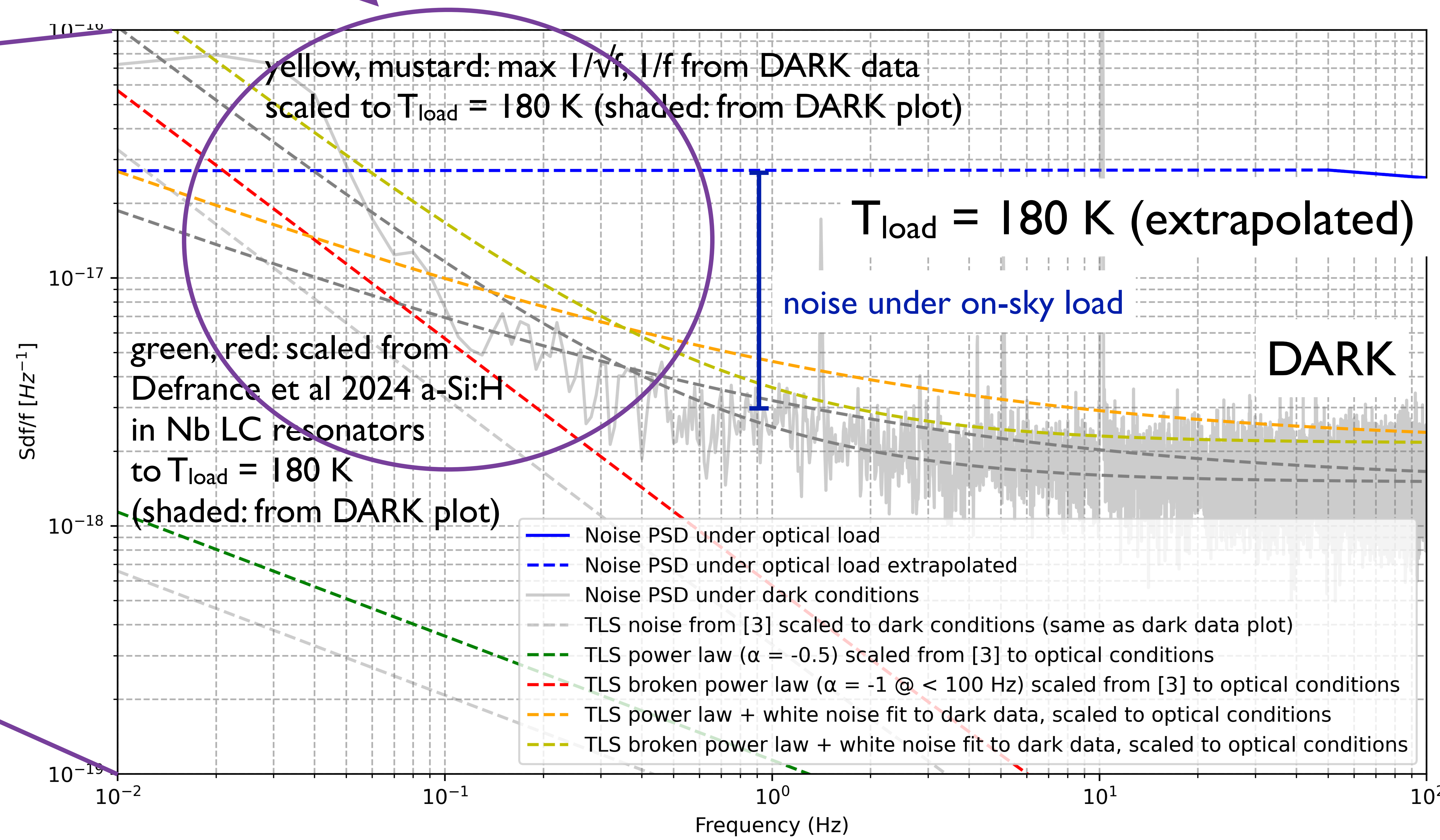
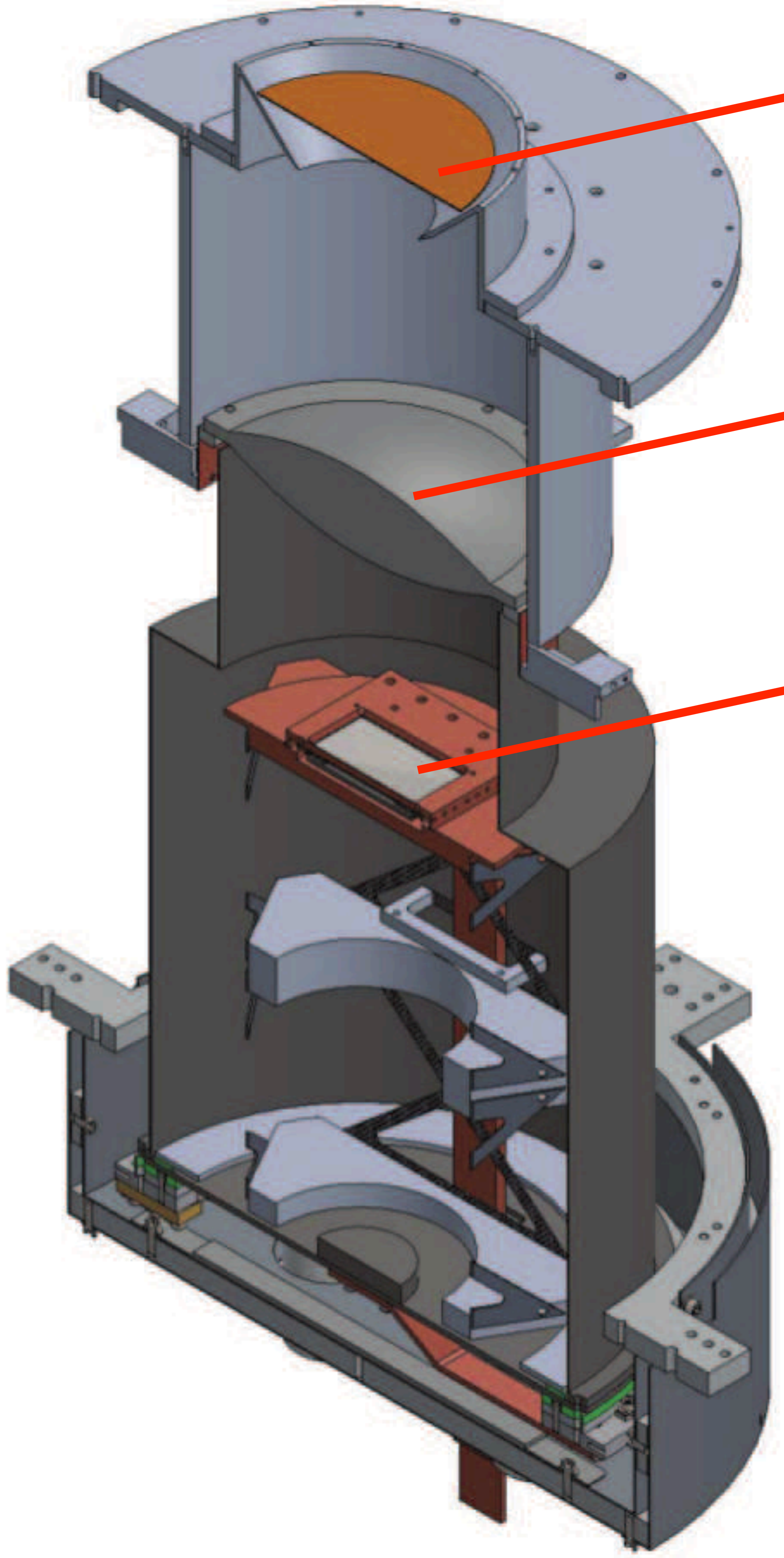


- Noise under dark conditions white down to $\lesssim 0.1$ Hz
  - TLS noise subdominant to GR noise
  - Residual low-frequency noise probably removable electronics noise
- Noise under optical load should be white down to $\lesssim 0.1$ Hz
  - Even for maximal TLS noise scaled from dark data





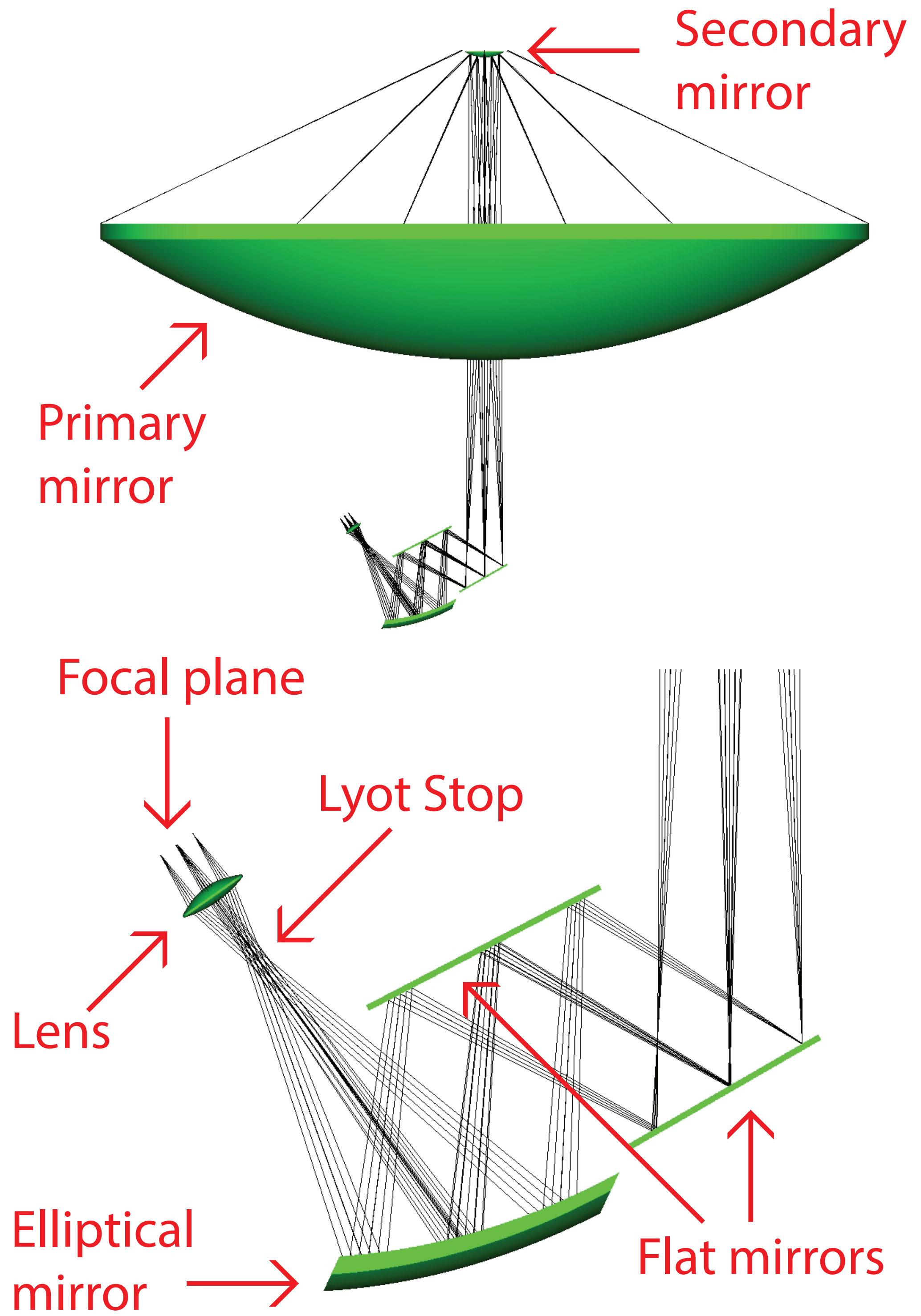
Instrument Configuration and Deployment



Lyot stop and mesh filter

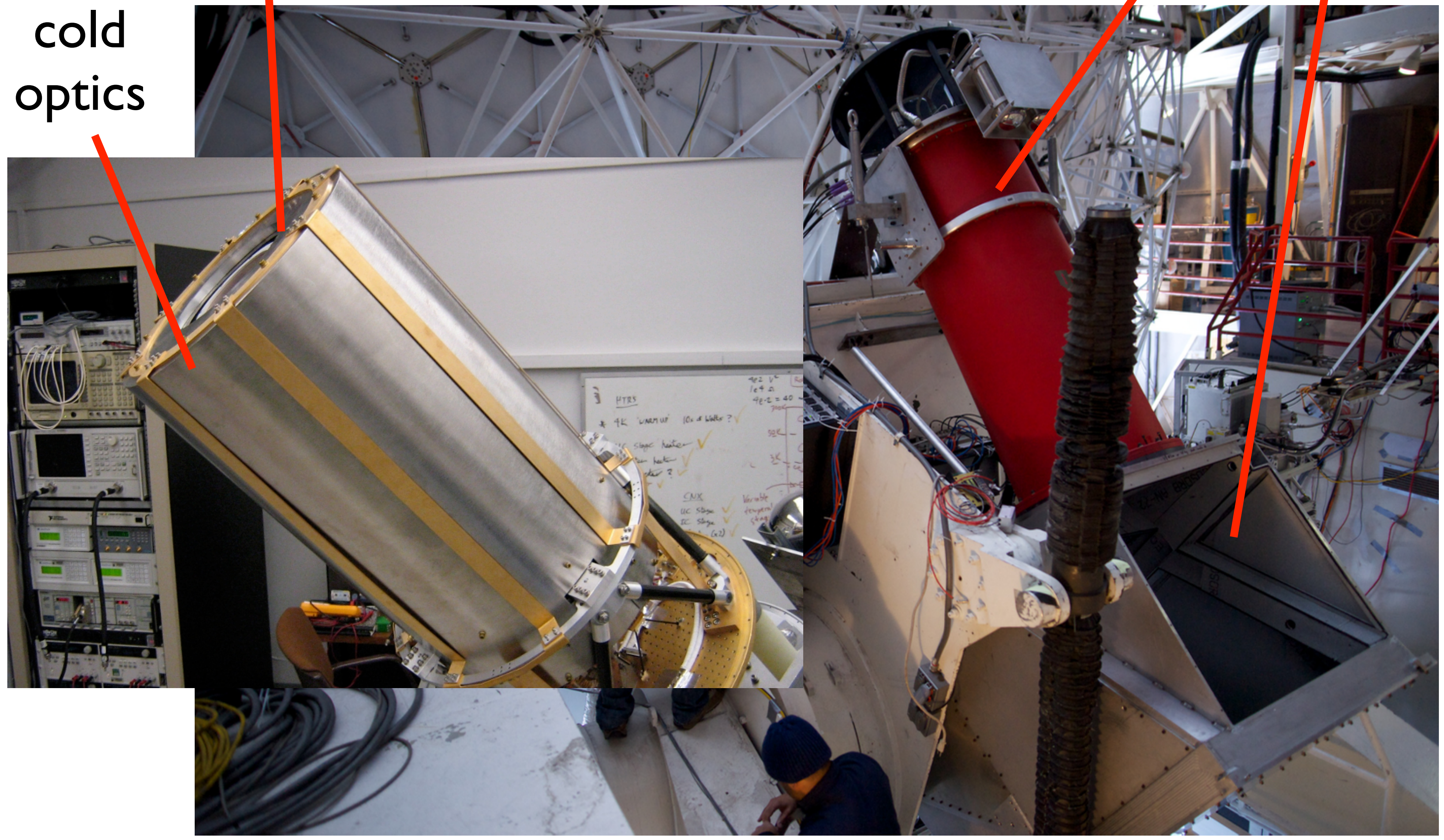
4K lens

FPU



magnetic shield, cold optics

dewar and relay optics



Instrument Configuration and Deployment

Reuse MUSIC cryostat

Optics

- External relay optics incl. ellipsoid
  + internal 4K HDPE lens + Lyot stop
- f/2.19 already, reduce to f/1.72
- Replace baffling with new, blacker materials
  - (e.g., Wollack et al 2016, Xu et al 2021, Inoue et al 2023)
- Filtering/AR
  - Baseline: HDPE lens + Teflon filters (2-layer porex AR)
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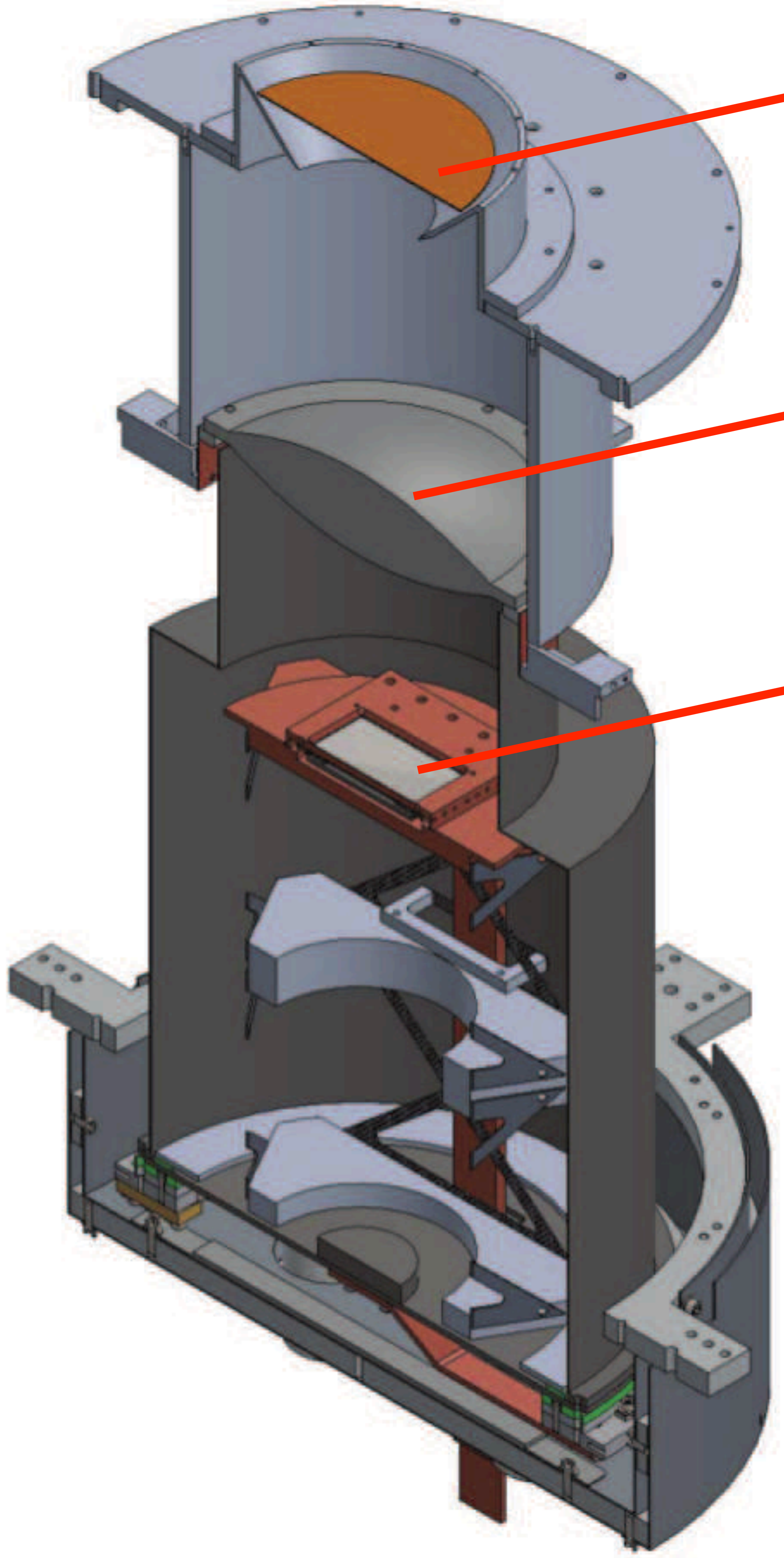
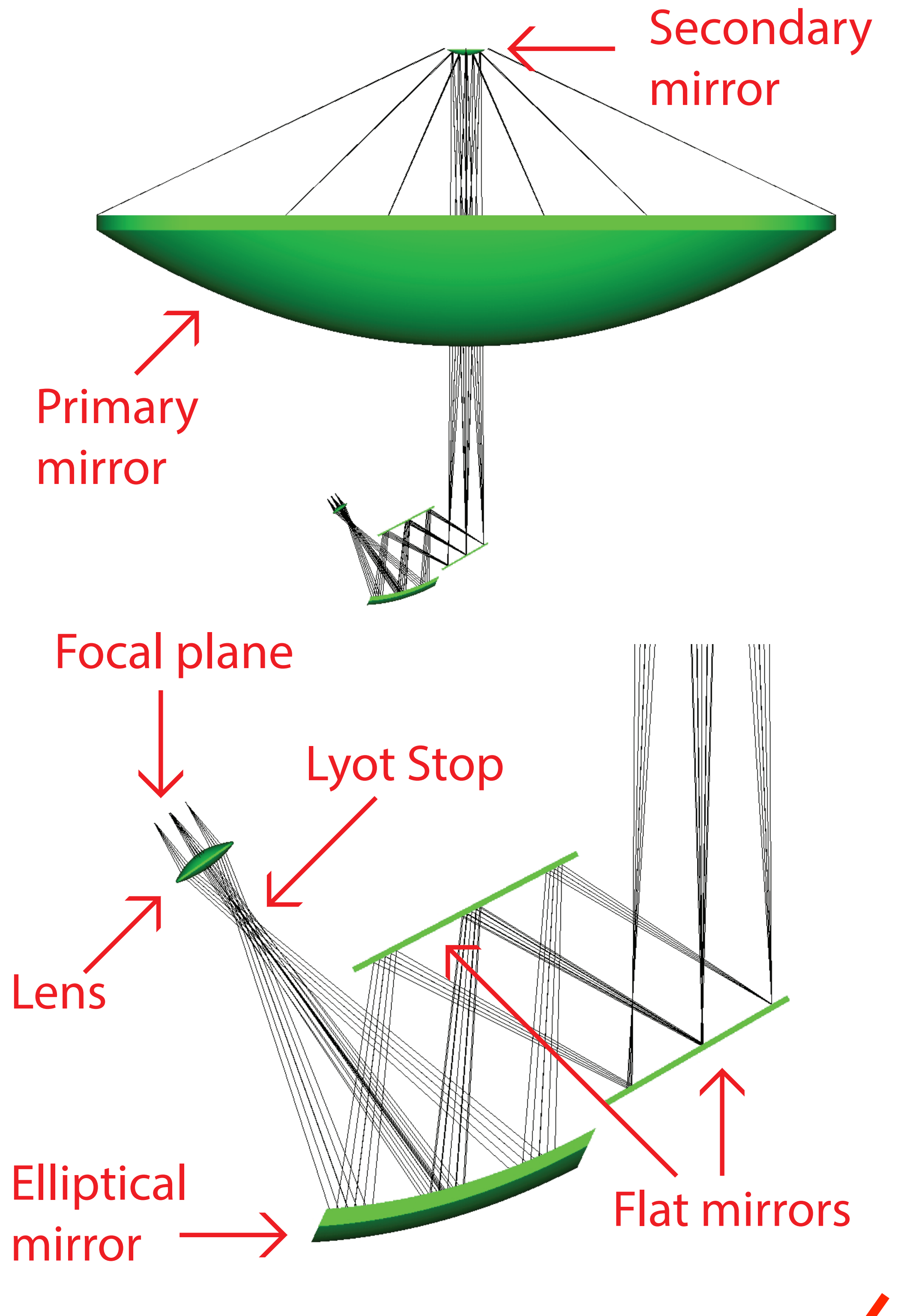
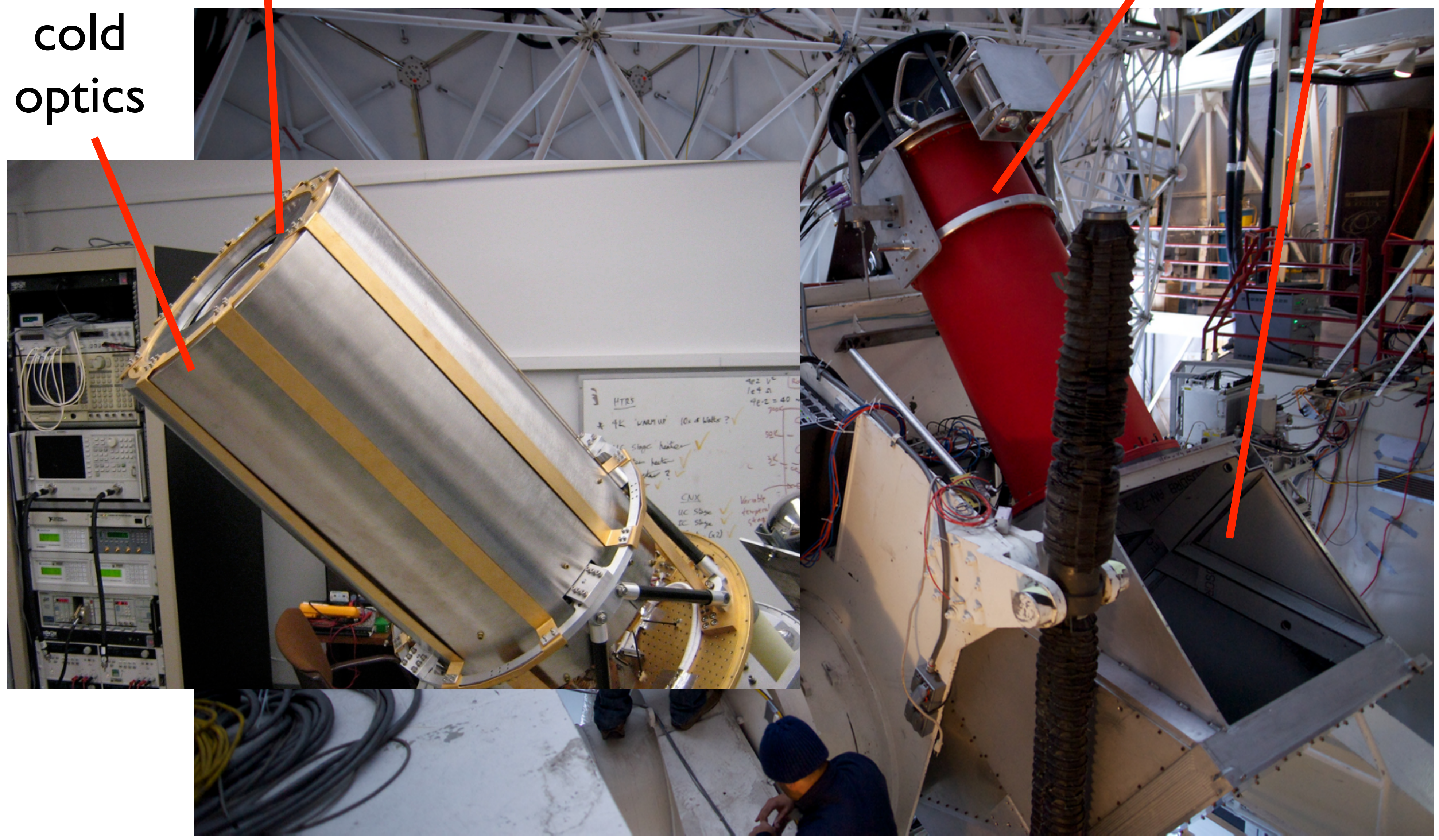
Cryogenics

- Extant Chase ^{3}He/^{3}He/^{4}He fridge + Cryomech PT-415
- Incorporates 2-layer magnetic shield







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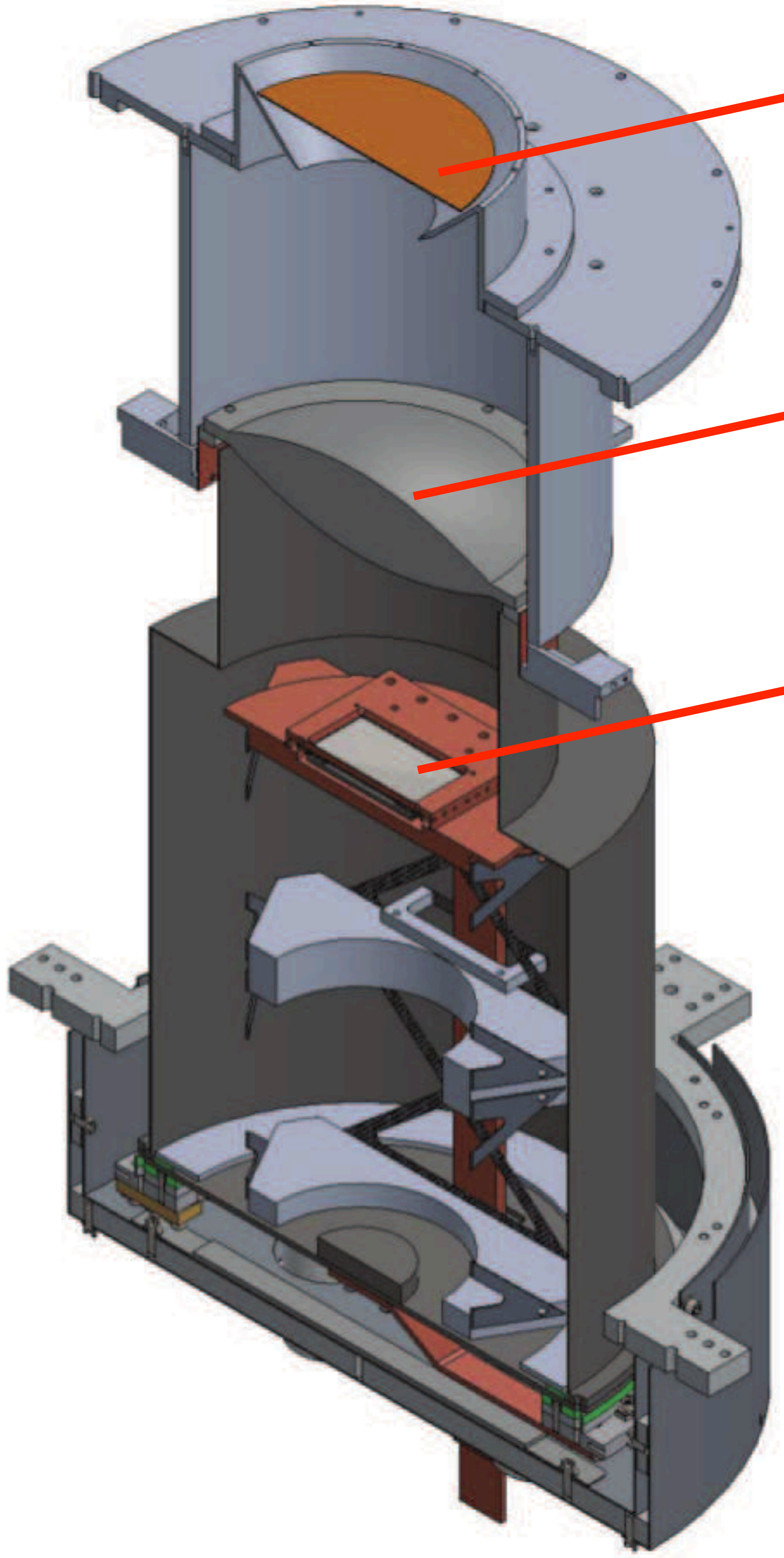
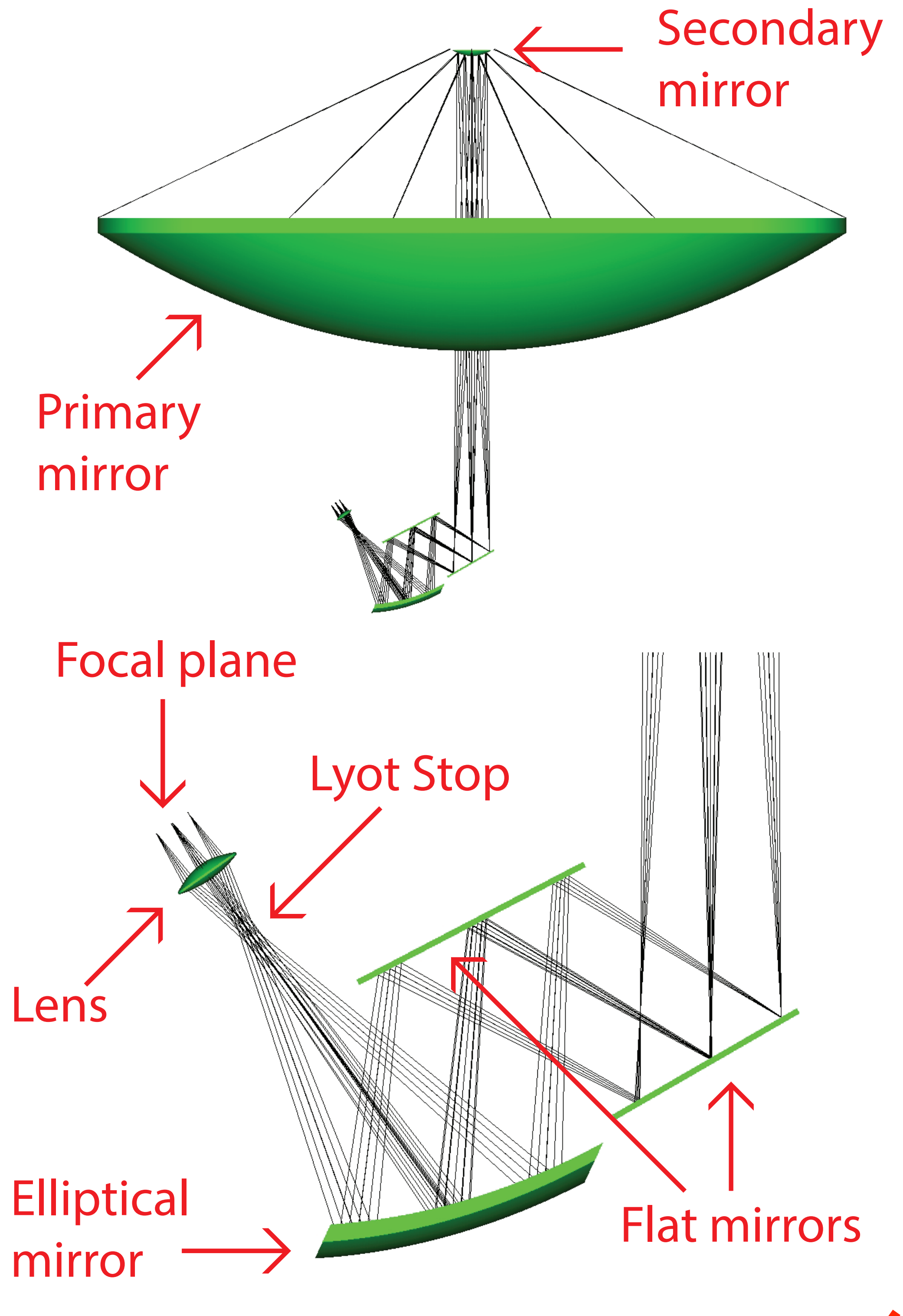
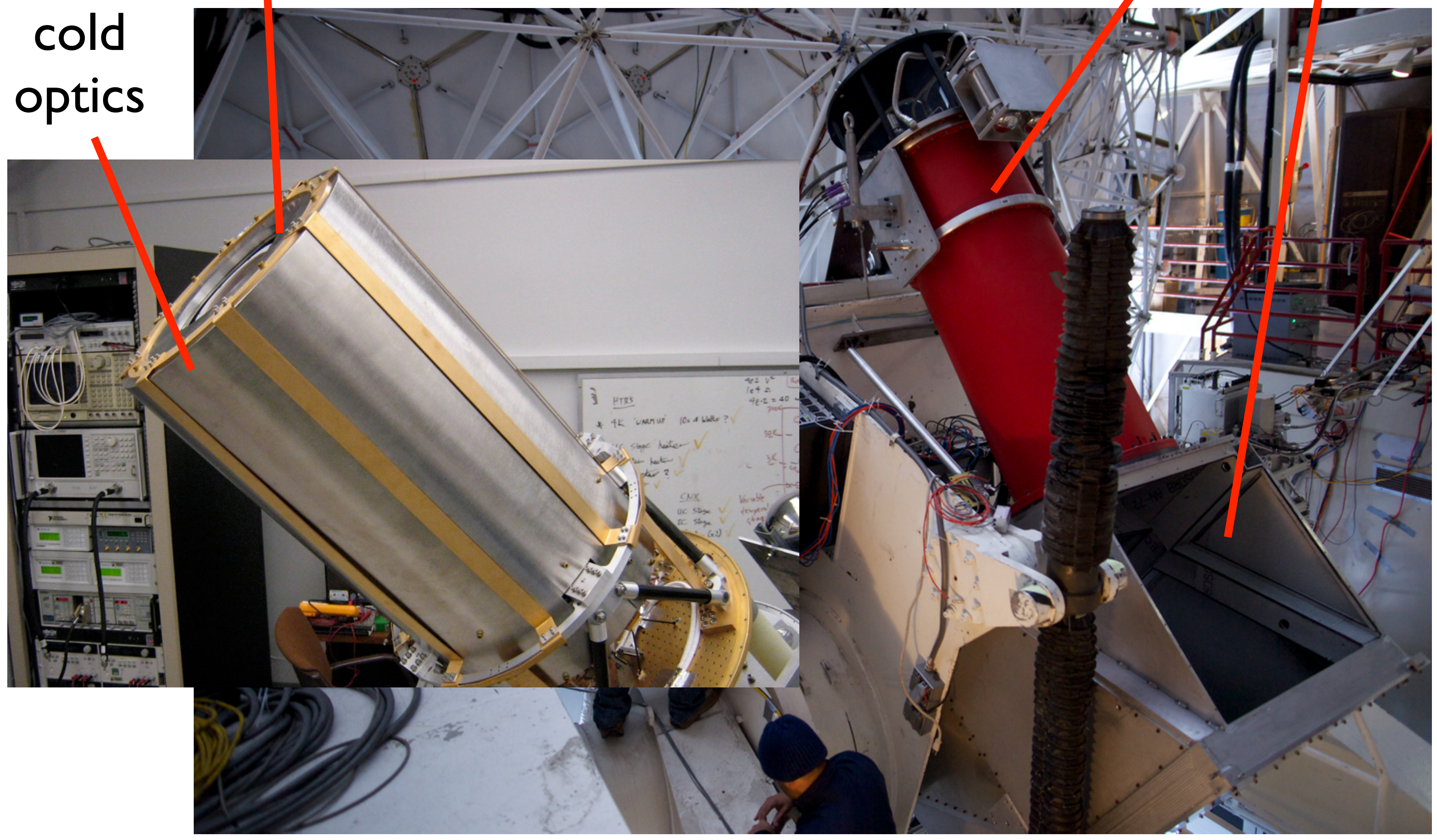
Readout

RFSoC system; e.g. ASU development for CCATp







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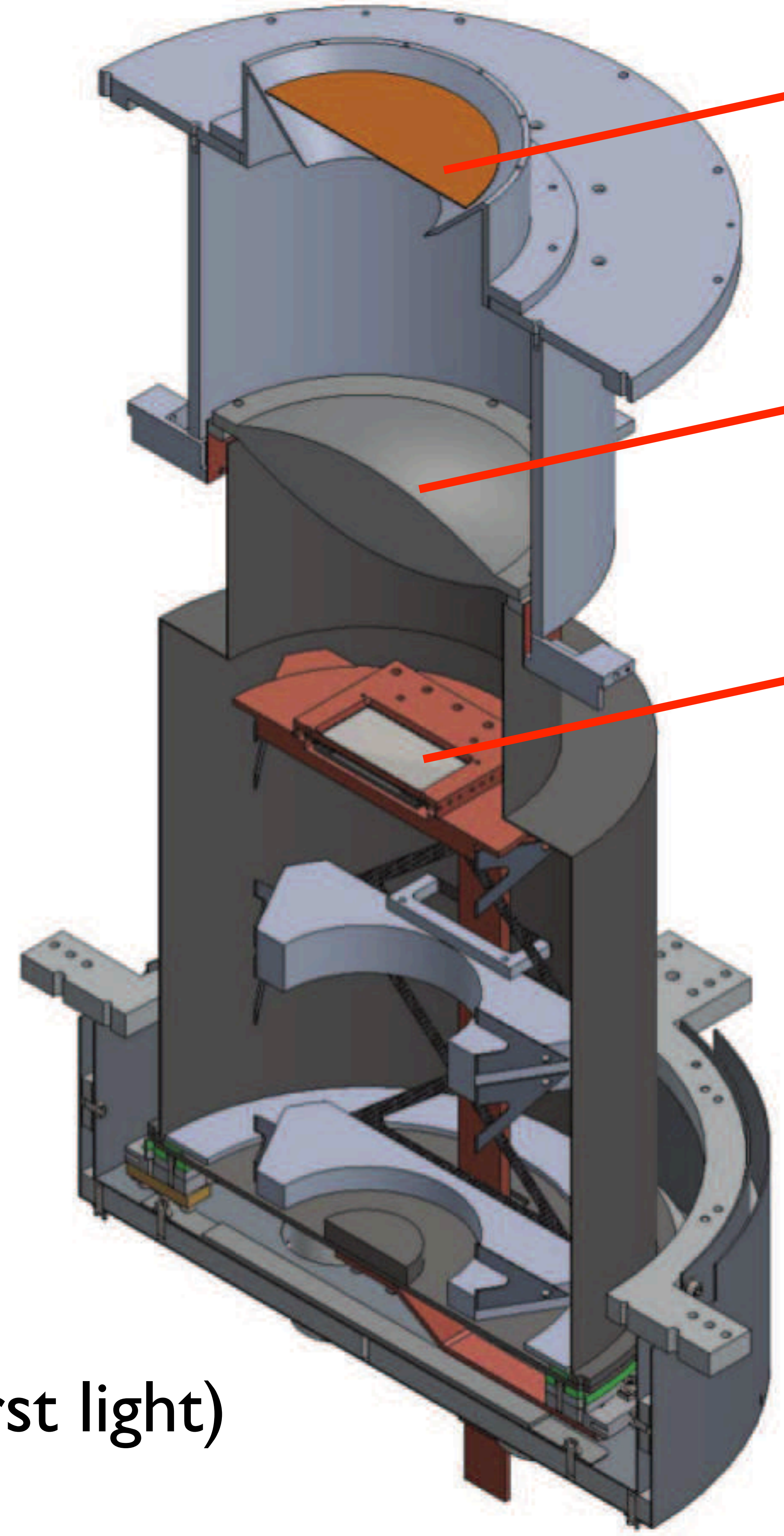
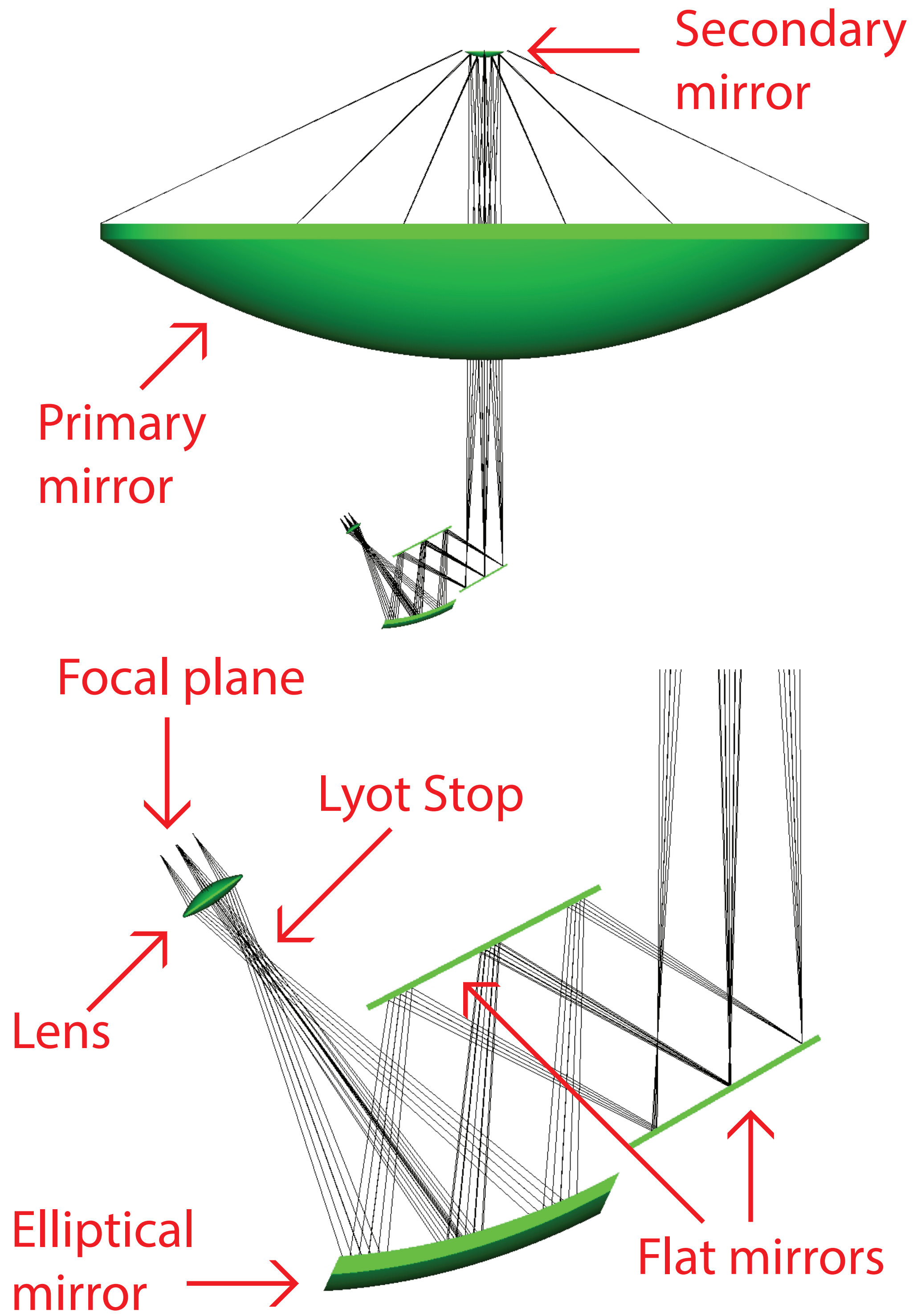
Readout

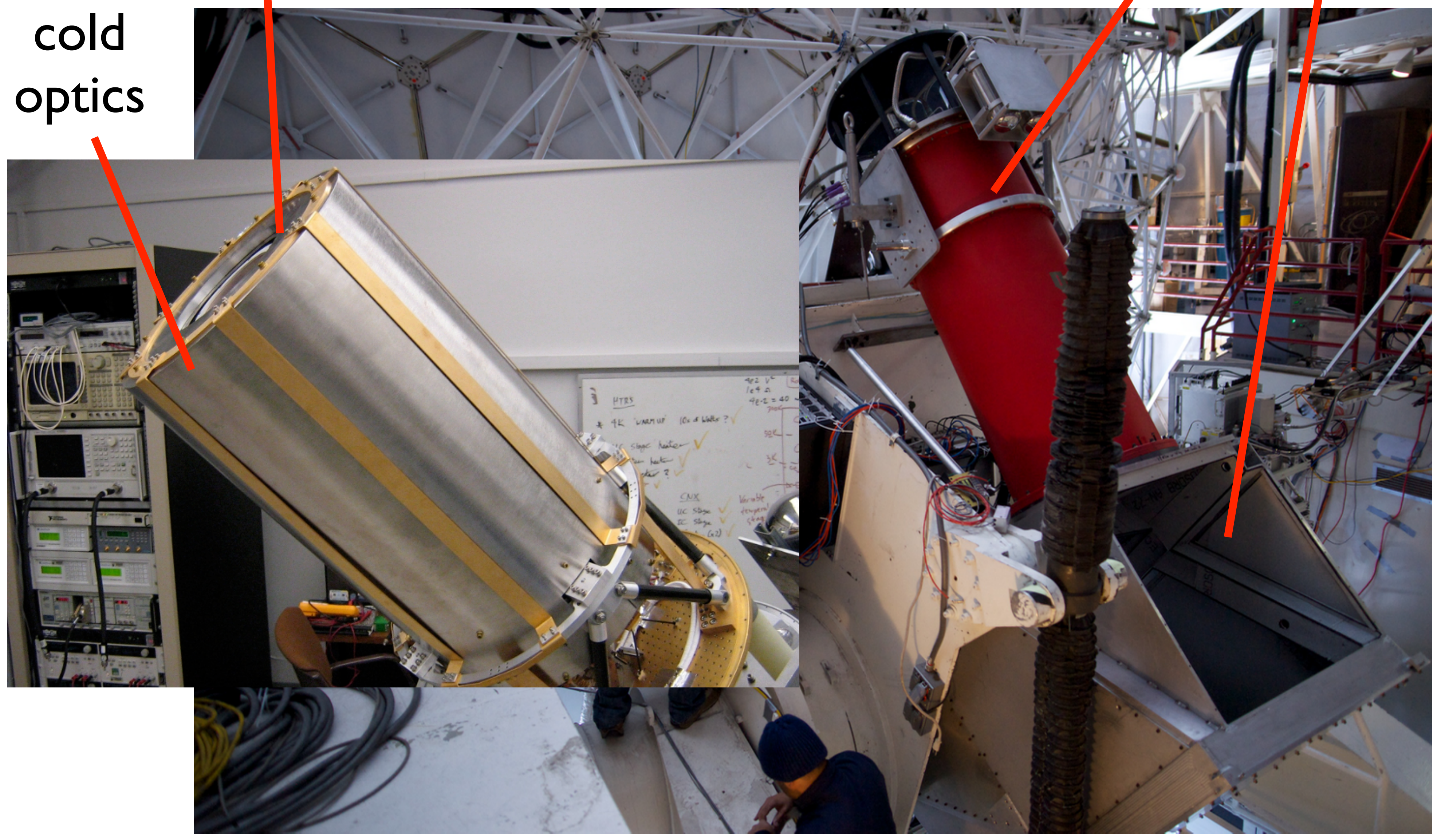
- RFSoC system; e.g. ASU development for CCATp

Deploy to Leighton Chajantor Telescope (2027 first light)

- Move of CSO telescope to Chajnantor Plateau
  - telescope packed, working on agreements and site infrastructure
- 1/4 FPU initially (16 x B1/B2, 64x B3/B4, 256 x B5/B6) for time-domain astronomy
  - 2024 NSF ATI proposal: excellent reviews 😀, no funding 😢😤🤯😱😬
- Upgrade to full FPU for deep survey fields after science demonstration







Conclusions and Outlook

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Key demonstrations in hand for new mm/submm focal plane architecture for NEW-MUSIC

- Multi-band hierarchical antennas incl. bandpass filters
  - ✓ Two-scale beams incl. hierarchical summing
    - Three-scale design ready for fab
  - ✓ Bandpasses for four bands
    - Six-band design ready for fab

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Microstrip-coupled Al/a-Si:H PPC KIDs

- ✓ Optical Efficiency (incl. 2-layer AR) (see backup)
  - Improve dewar windows at high frequency, 4-layer AR
- ✓ Yield — good start! (see backup)
  - Need more data; develop C trimming
- ✓ ~~direct absorption~~ (see backup)
- ✓ TLS noise of a-Si:H PPCs low enough
  - Subdominant down to ~0.1 Hz, probably lower
- ✓ GR-noise-limited down to $\lesssim$ 0.1 Hz dark
- ✓ Photon/GR-noise-limited under optical load
  - Need to test to low frequency under relevant loads (40K-150K)
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Focal plane can be integrated with existing MUSIC cryostat and optics

Plan to deploy 1/4 NEW-MUSIC to LCT in 2027

- Funding-permitting…
- Time domain science immediately
- Cluster science early on
- Full FPU will enable deep survey fields

3 minute integration on ~FoV-scale field (7’ initially; 14’ full focal plane)

band [GHz]	90	150	220	270	350	405
rms depth [mJy]	1	2	2	3	4.5	9
5σ detection limit [mJy]	5	11	10.5	19	22	47

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Filterbank spectrometer with a-Si:H resonant filters and PPCs

- R = 300 and R > 10^4 designs on next mask!
- Small enough to put KIDs in focal plane!

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Promising and transformative technology for a future 30m-50m mm/submm telescope!

Backup Slides

Bandpasses and Optical Efficiency

Two-scale antenna + four bands + μstrip-coupled PPC-KIDs

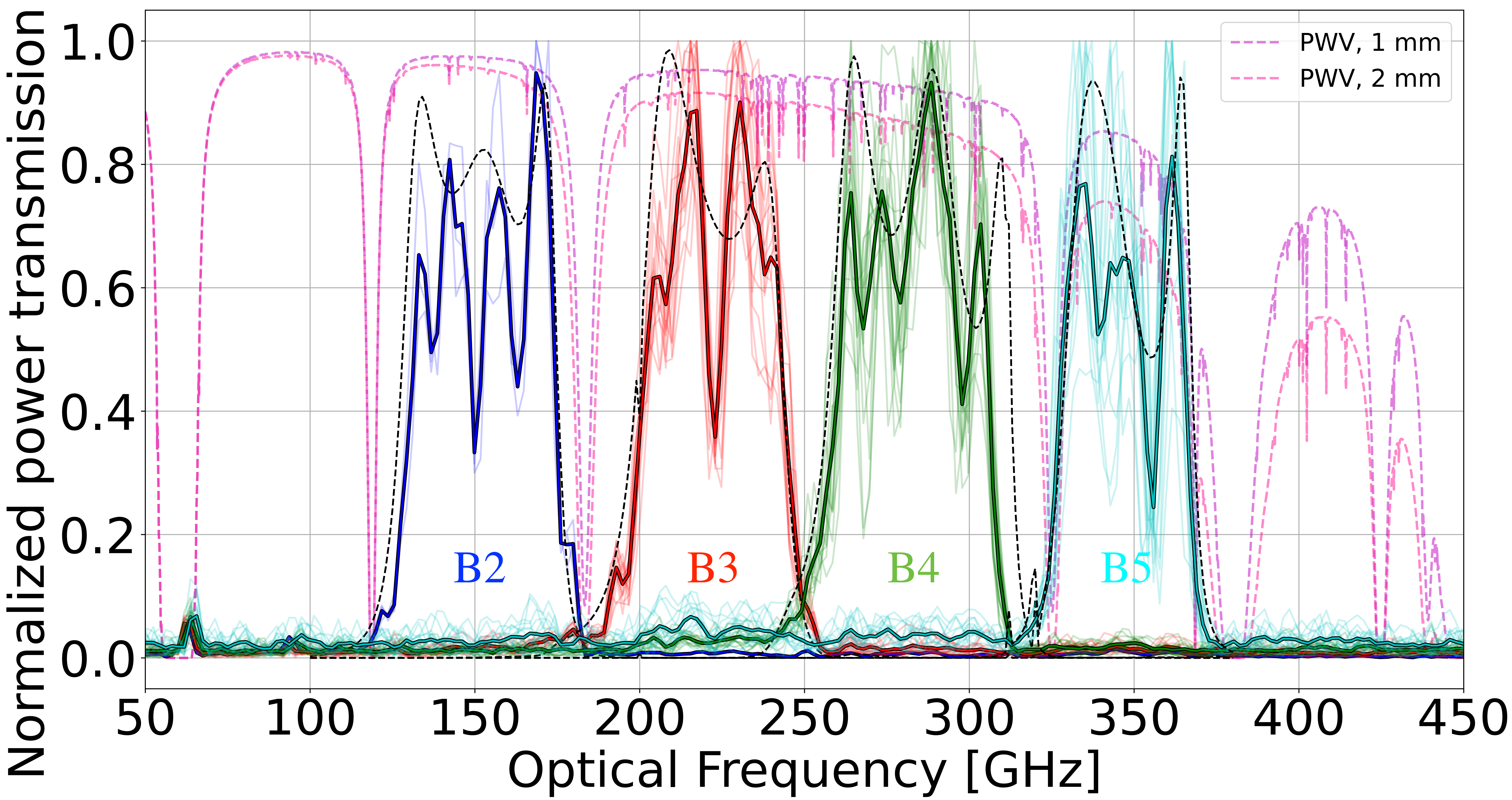
Bandpasses largely meet expectations!

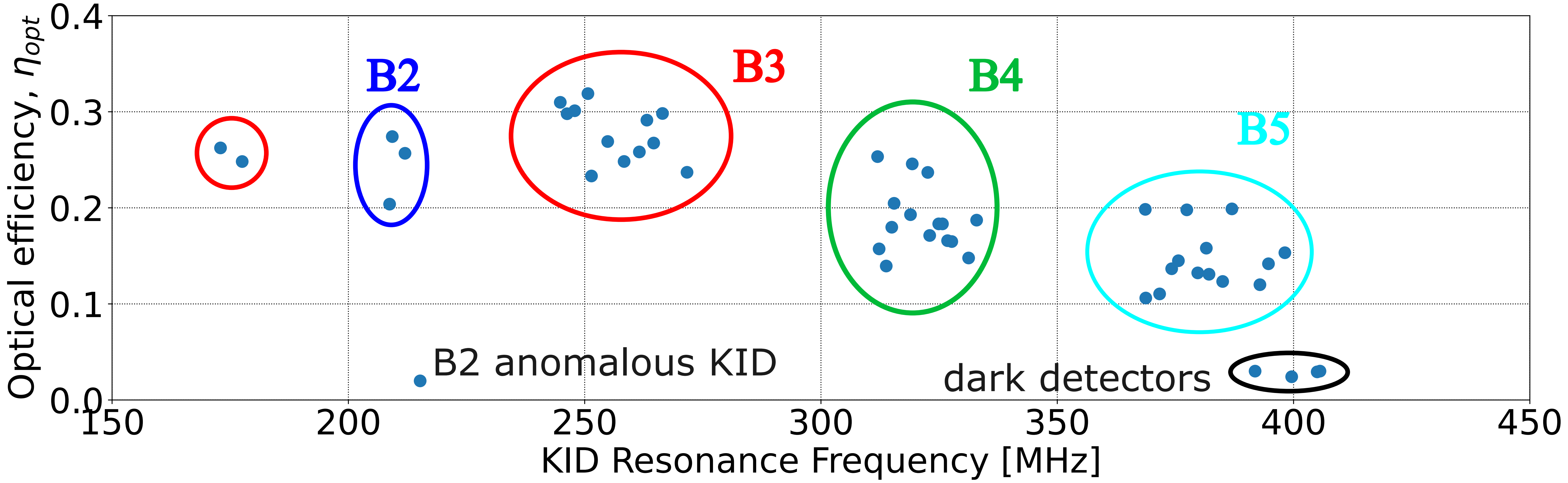
- Filters have been tweaked to better match atmospheric windows
- Need to understand ripple (deeper than expected)

Optical efficiency reasonable!

- Total optical efficiency = $\eta_{opt}\,\eta_{pb}$
  - $\eta_{pb} = 0.65, 0.49, 0.45, 0.41$ (Guruswamy et al. 2014)
- Dewar window/filters not optimal for higher bands
  - UHMWPE, Teflon
  - Two-layer Si AR for 200-300 GHz
  - Unlikely to be loss in microstripline

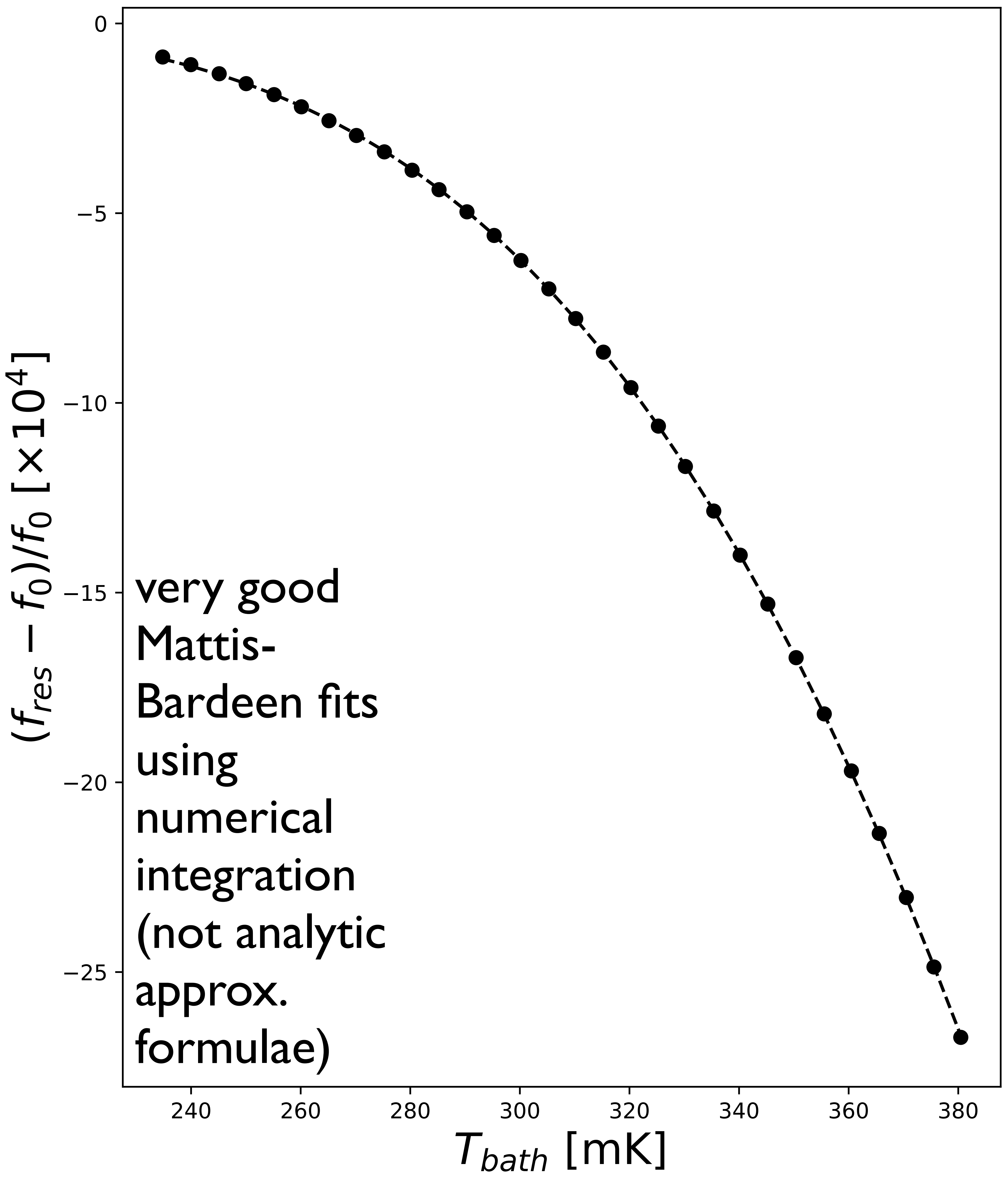
Yield: 49/56 and 47/56. Good start!



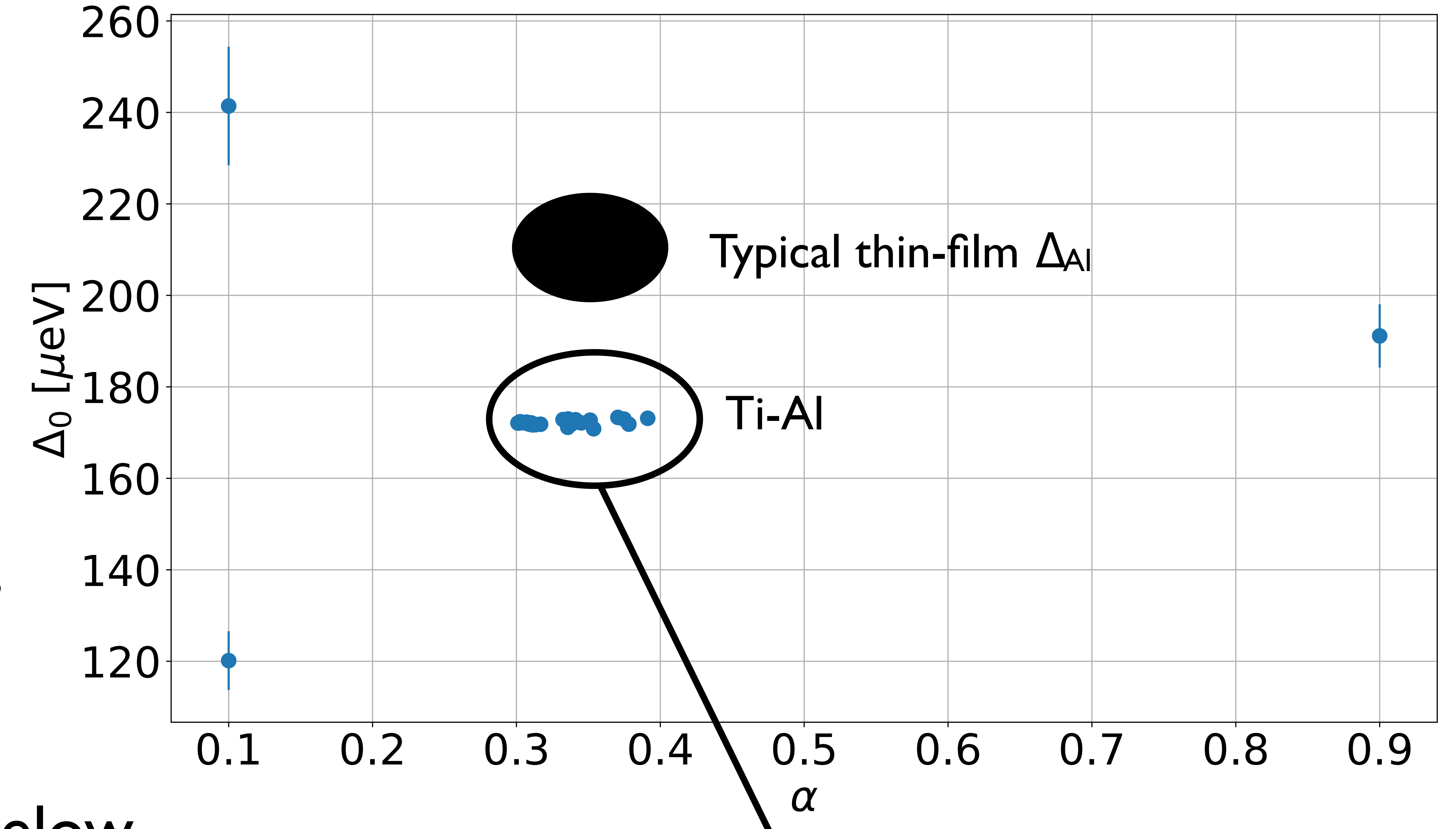


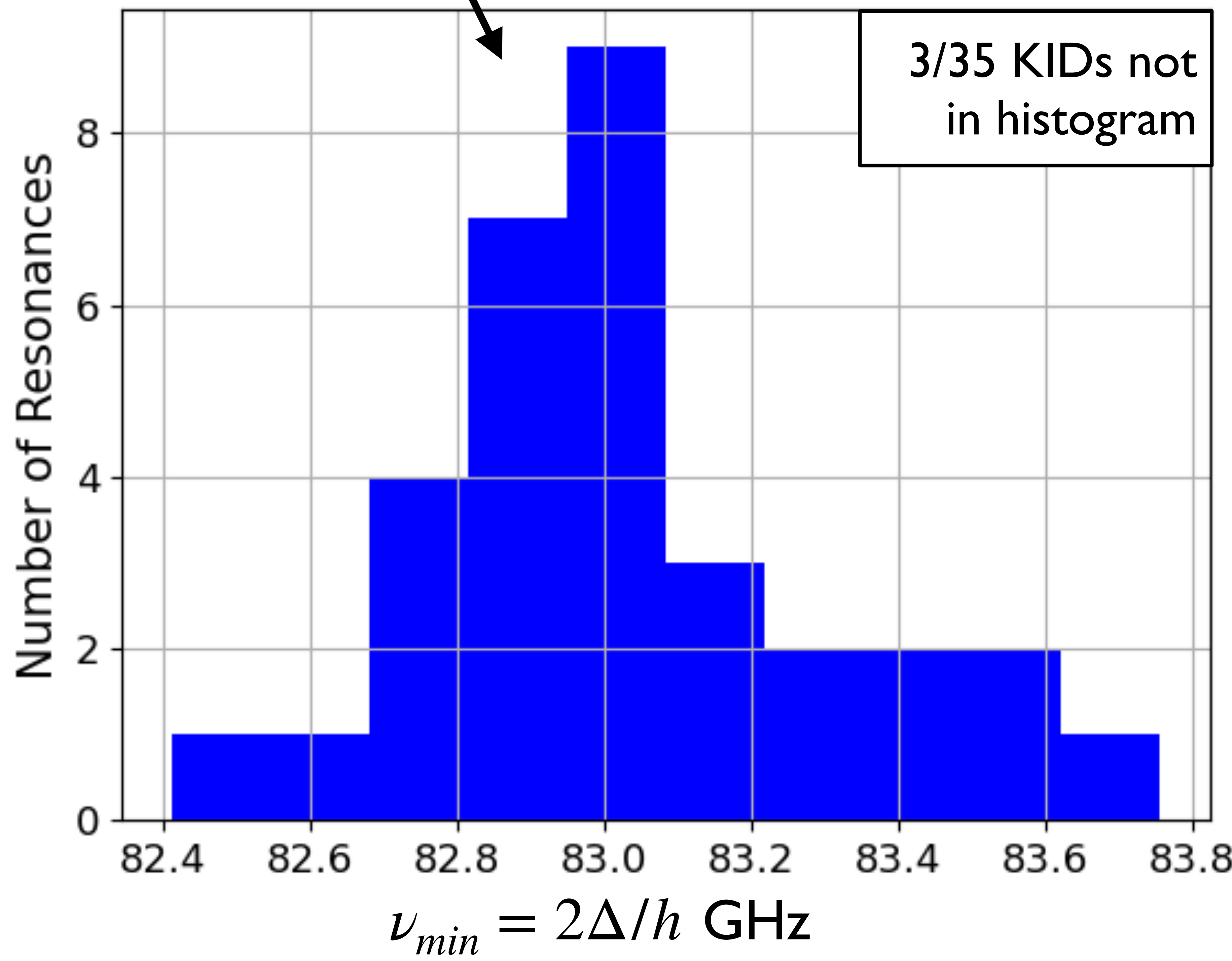
Jean-Marc Martin; Martin et al (LTD-20)

Ti-Al for 90 GHz (B1)



- Many groups pursuing Ti-Al bi- and trilayers for 90 GHz KIDs
- 3-5 nm of Ti below and above 100 nm Al seems to provide almost exactly the right gap parameter for B1!
- Q_i ~ 8-10k at 240 mK, so may need to limit to B1 KIDs to ensure high N_{mux}

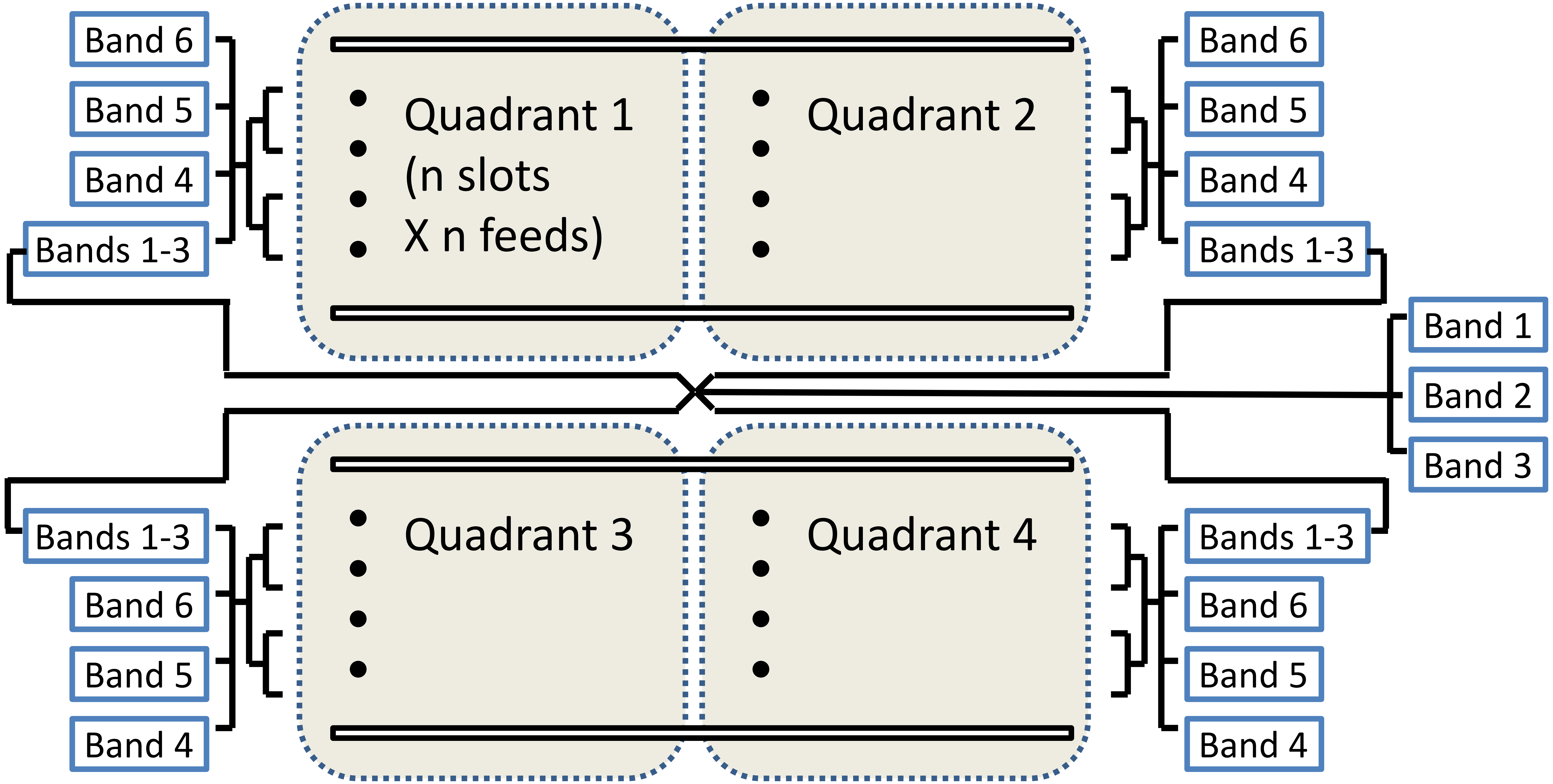




Wideband Hierarchical Antennas

Same focal plane area can be used for multiple spectral bands

Pixel size scales with wavelength to ensure good matching to Airy function



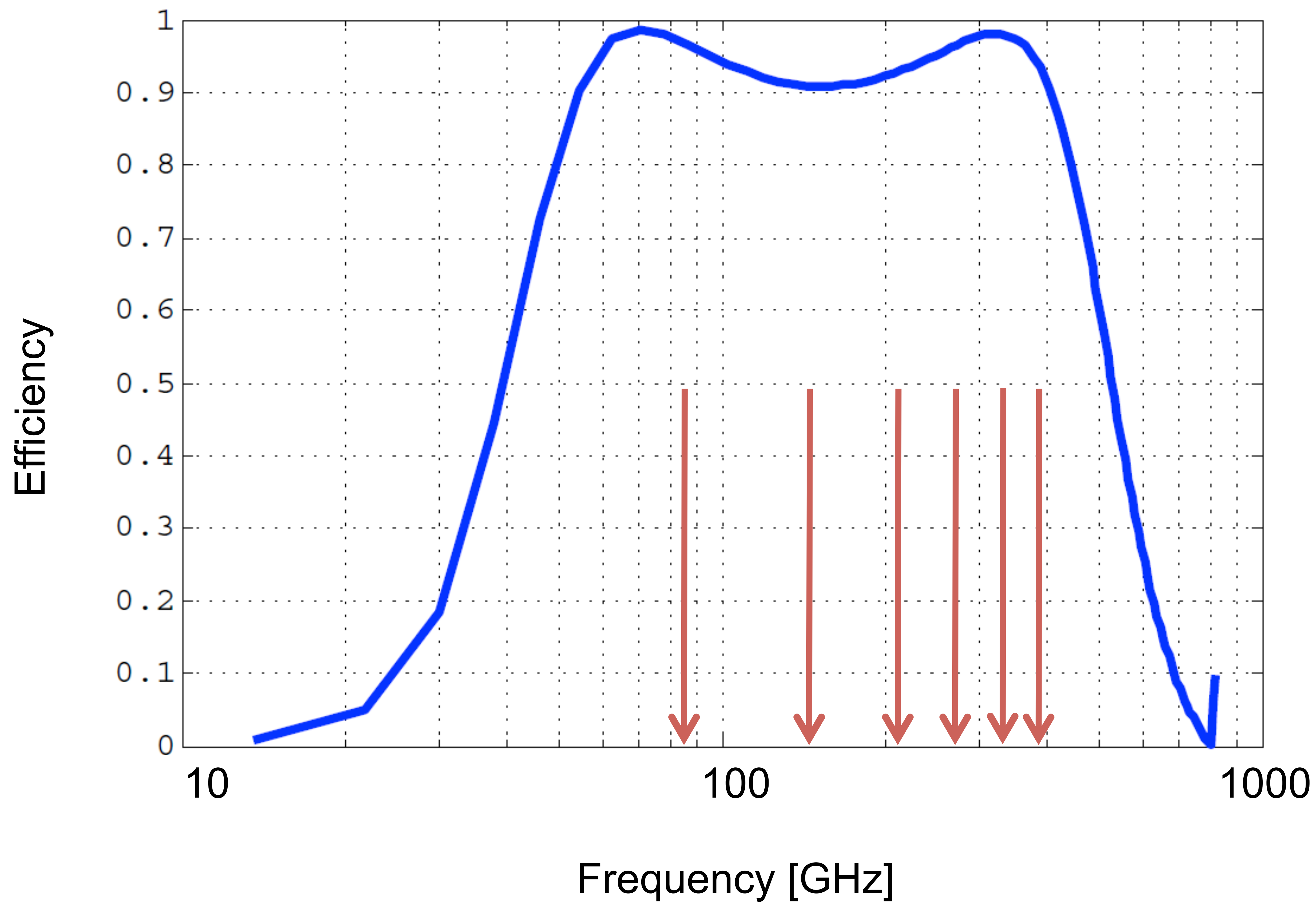
P. Day

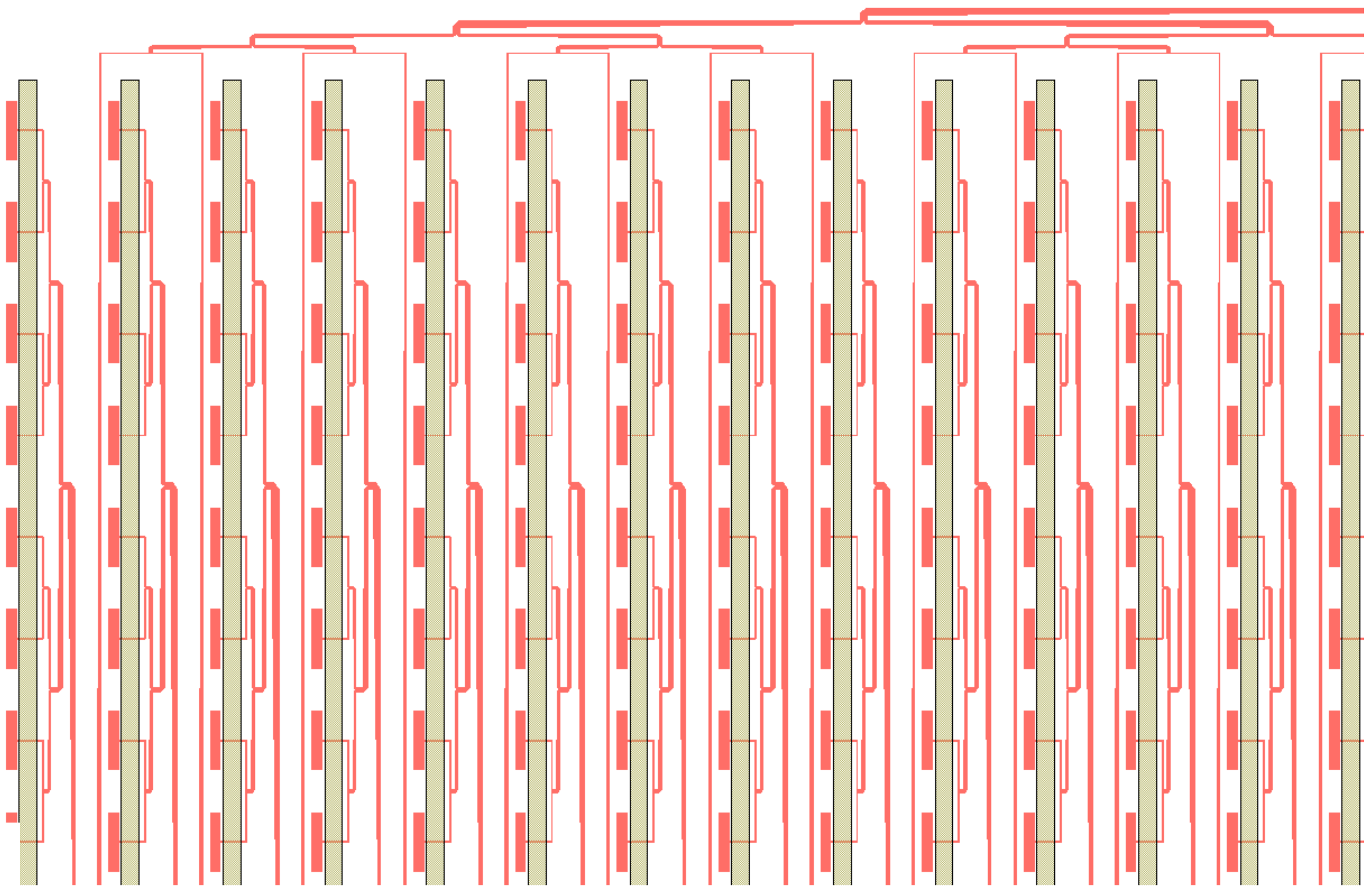
Wideband Hierarchical Antennas

design has intrinsically large bandwidth, almost ~7.5:1! (slight tweaking needed)

slot, tap spacing: 104 µm
slot width: 18 µm
feed impedance: 54 Ω (1 µm line)
tuning capacitor: -40i Ω at 100 GHz
dielectric: 1070 nm a-Si:H
backshort distance: 150 µm
32x32 array, 3.3 mm on a side

P. Day

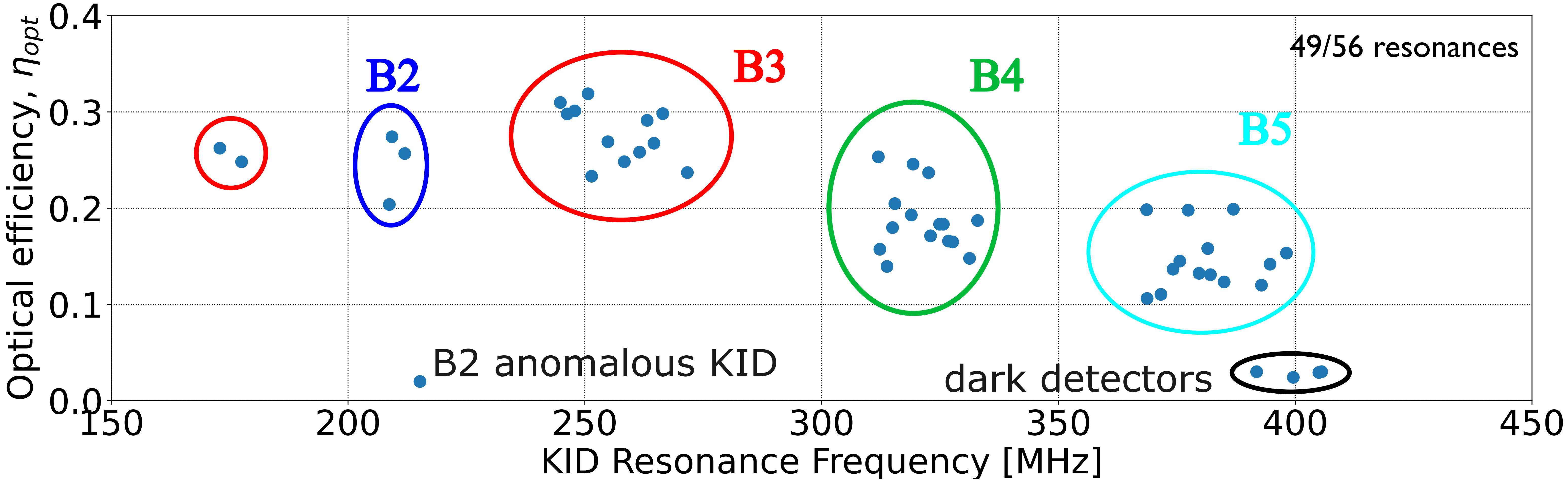




Non-Antenna Response (Direct Absorption)

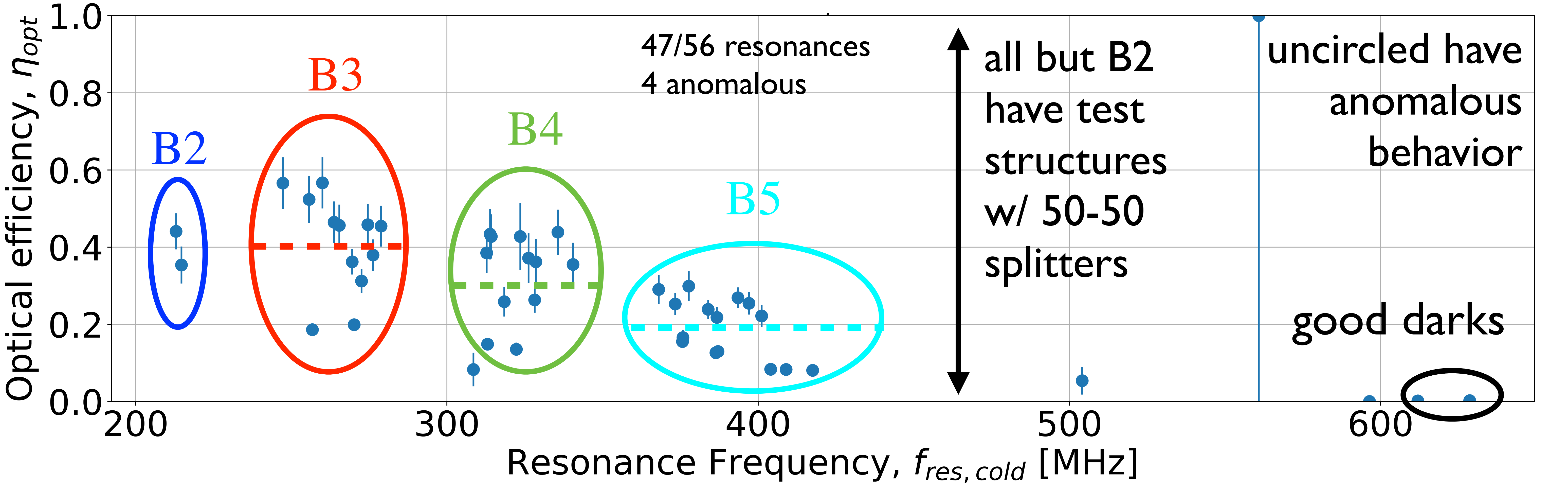
Key design goal:

- mitigate direct absorption by KID
  - Inductor < 1 μm from ground plane
  - Parallel-plate capacitor with
    - Middle plate integral to ground plane (not an island — use virtual ground)
    - Top plates < 1 μm from ground plane
  - Microstrip feedline: no CPW gaps in ground plane



Constraints on direct absorption:

- Allow all resonators three contributions
  - direct optical response η_{opt}
  - heating of wafer $P_{tile} = g(T_{tile}^n - T_{bath}^n)$
  - temperature calibration offset T_{offset}



Jean-Marc Martin

- Results:
  - $P_{opt}^{dark} / P_{opt}^{light} \lesssim 1\,\%$ in spite of broader bandwidth of darks (~120-420 GHz)
  - $T_{tile} - T_{bath}$ varies with T_{bath} but not T_{load}, depends on resonator, larger for darks
    $\Longrightarrow$ probably a model systematic (soaking up imperfect M-B fit), not real tile heating

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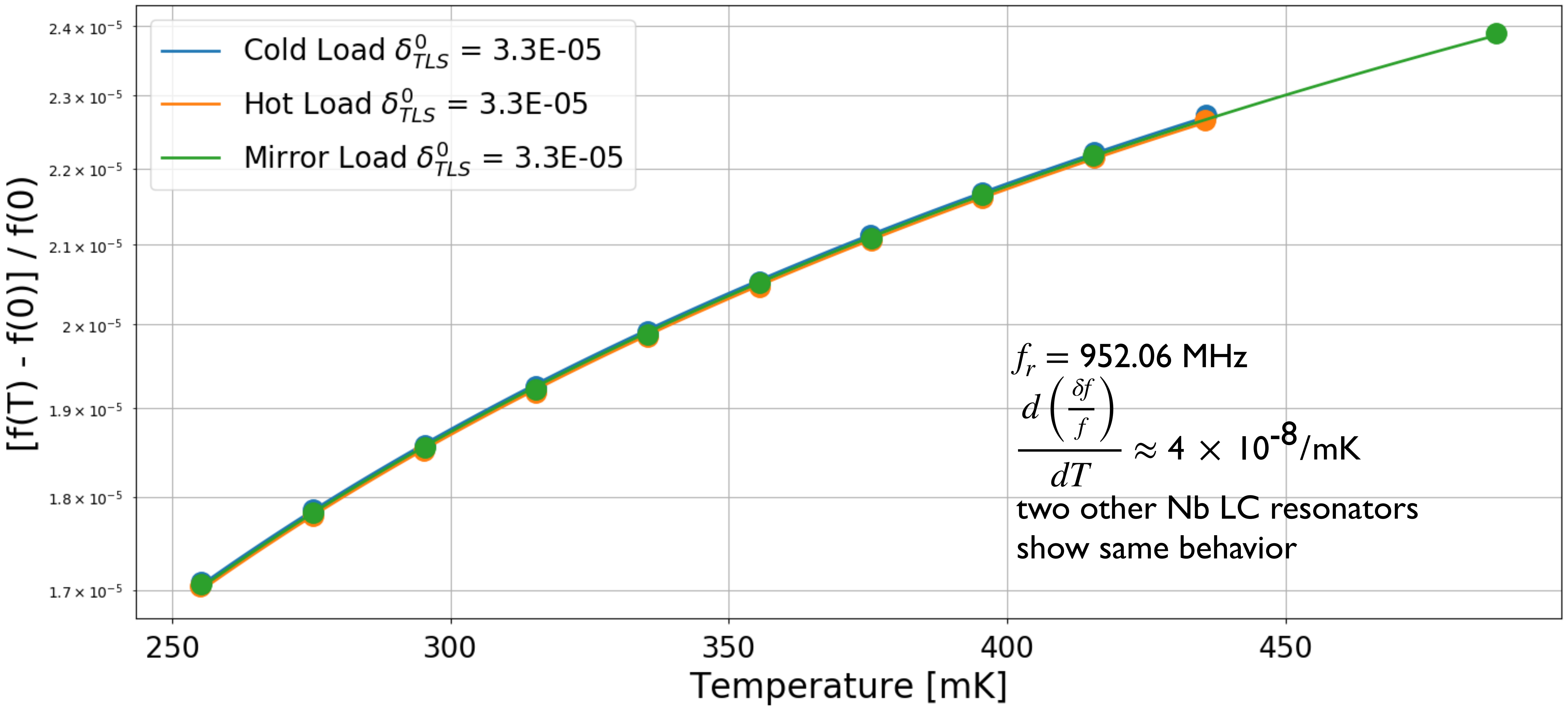
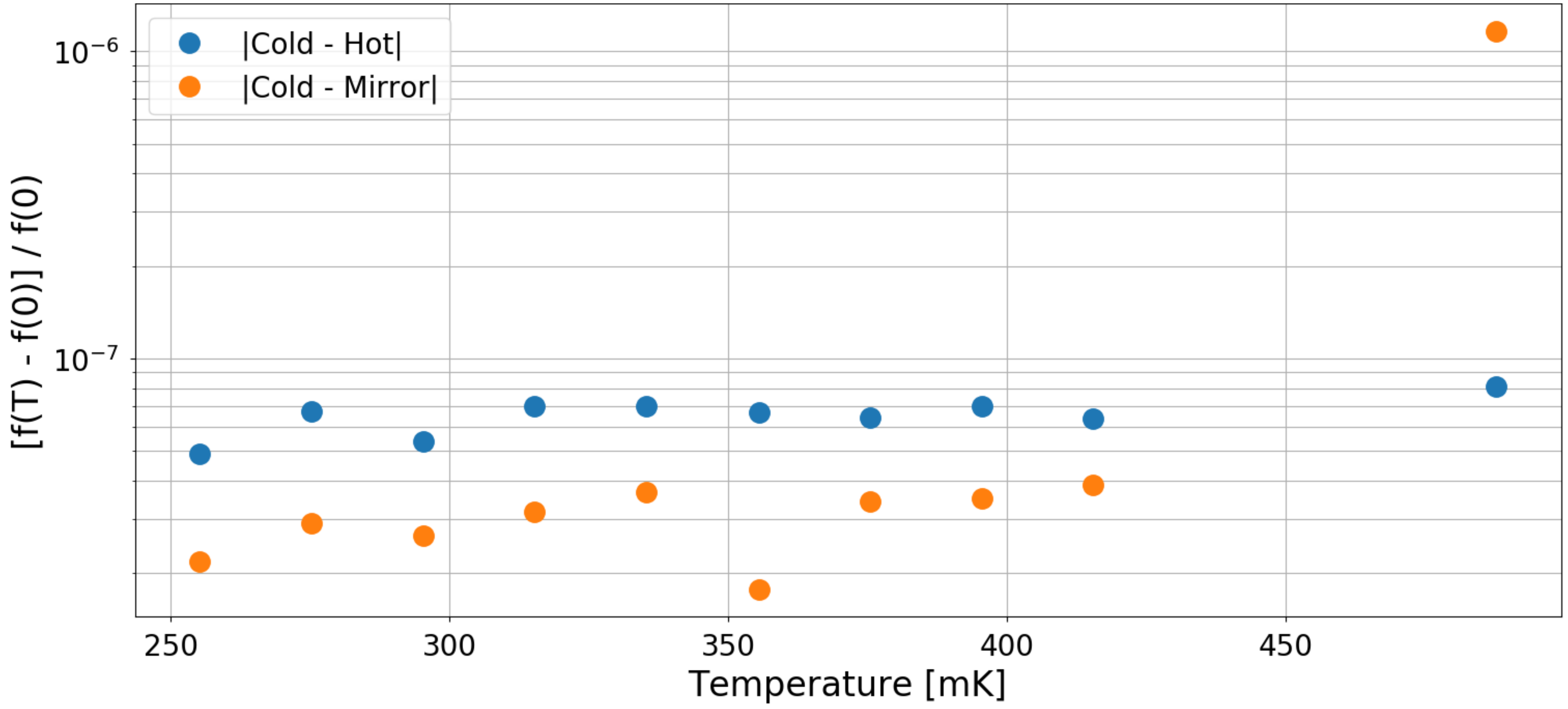
Can also test for tile heating using
- Nb LC resonators with a-Si:H PPCs
  - Mainly intended to measure RF loss
  - Also act as differential thermometers!
  - $\delta f/f \lesssim 10^{-7}$ between hot, mirror, cold $\Longrightarrow \Delta T \lesssim 3$ mK
  - Confirms tile heating implied by hot/mirror/cold/dark M-B fits is not real





Shiling Yu, Fabien Defrance, Jean-Marc Martin

Noise Performance — Dark

GR noise visible well above amplifier noise

$S_{N_{qp}} \sim$ ind. of T as expected for R-limited behavior

$S_{N_{qp}} \propto 4\,\tau_{qp}\,N_{qp}$

$$\mathrm{NEP}_{qp} = \frac{\Delta}{\tau_{qp}}\,S_{N_{qp}}^{1/2}$$

no correction for η_{pb}, but also no η_{pb} uncertainty

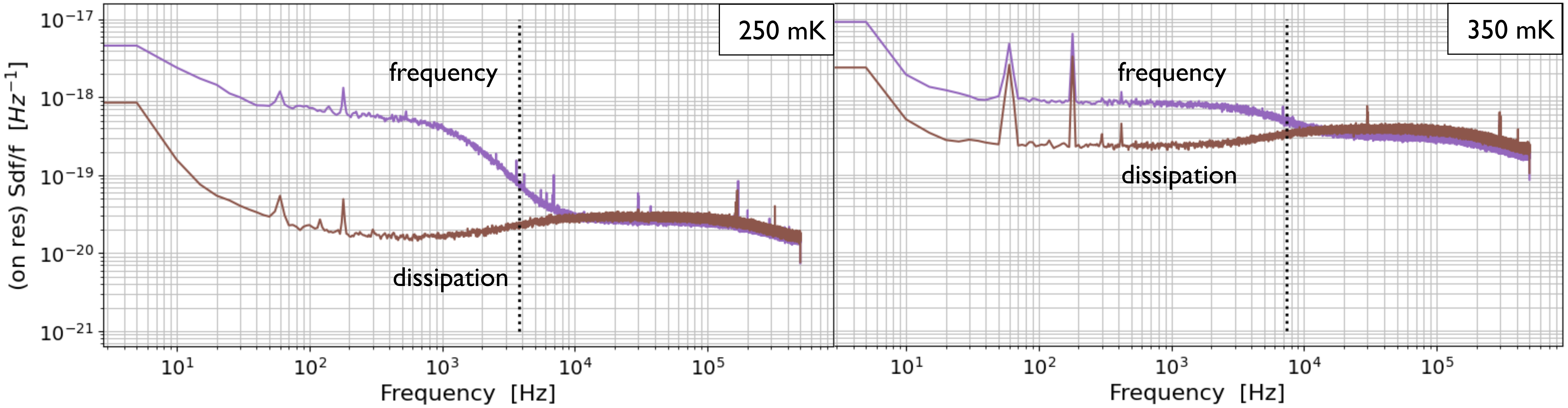
$\mathrm{NEP}_{opt} = \mathrm{NEP}_{qp}/\eta_{pb} \approx 1.5 - 2.5\,\mathrm{NEP}_{qp}$

$\eta_{pb} = 0.41 - 0.65$

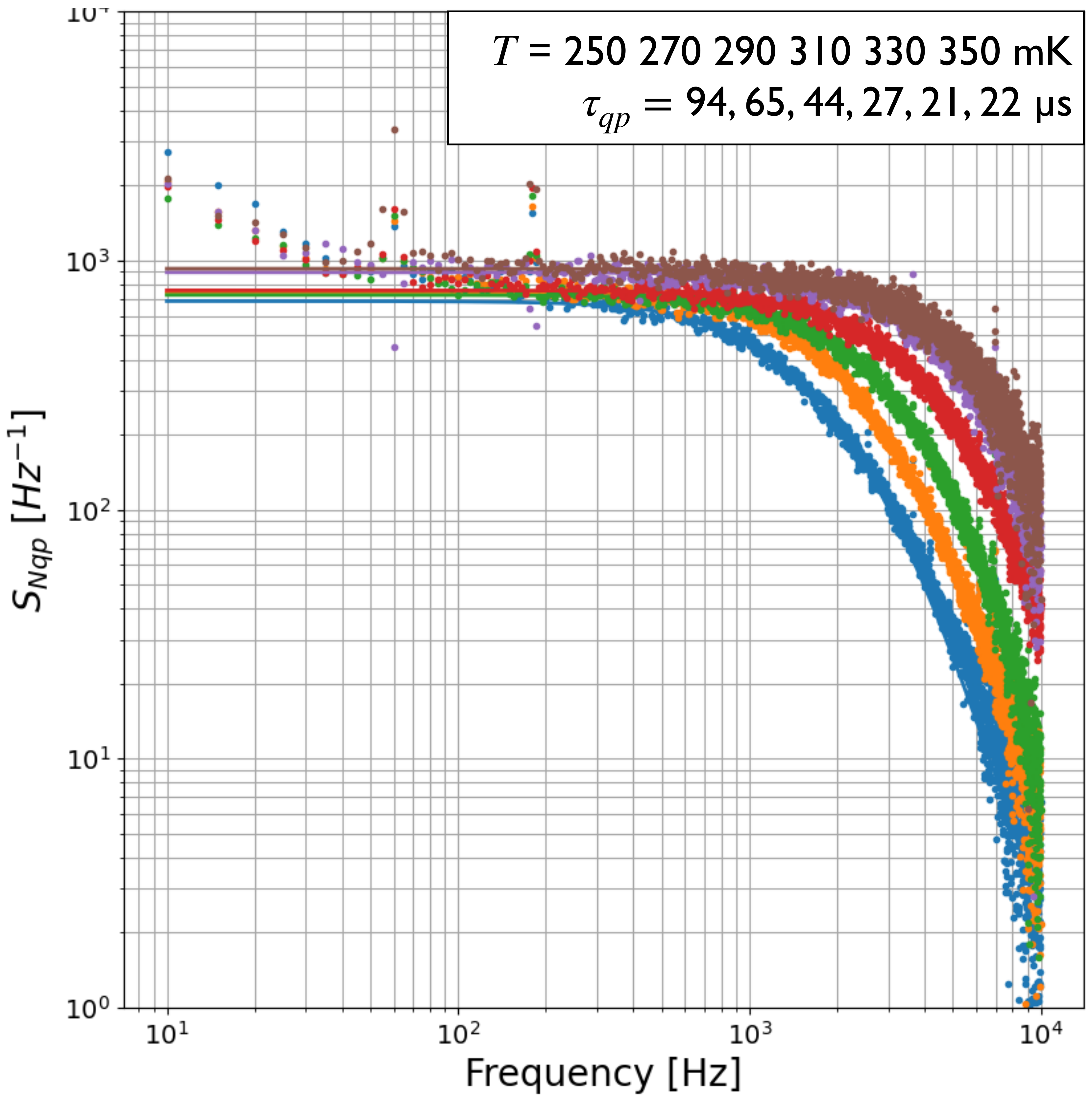
(Guruswamy et al. 2014)

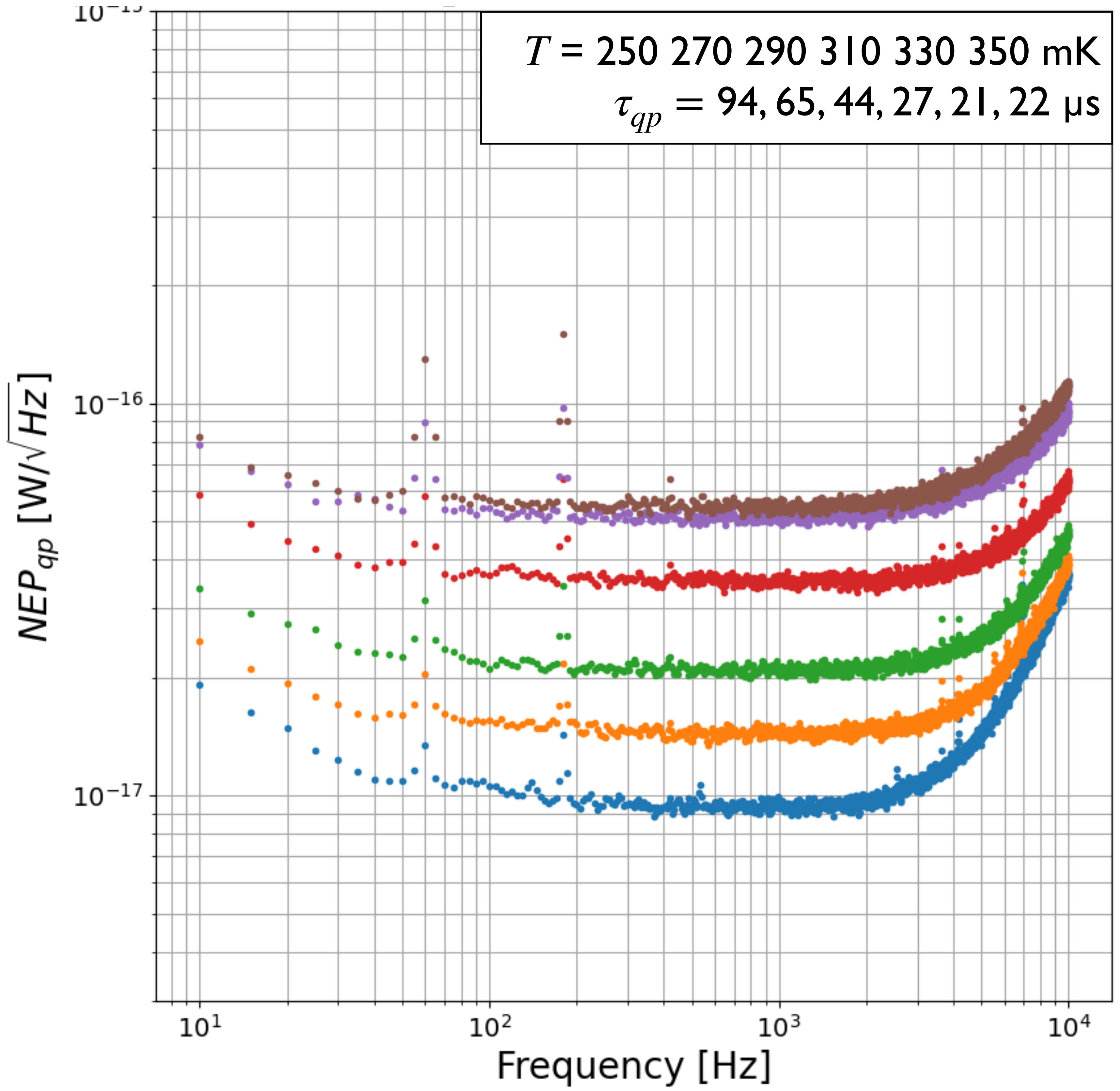
$T = 310 - 330$ mK has τ_{qp}, N_{qp} comparable to behavior under telescope optical load $\Longrightarrow$ realistic GR noise contribution

Need to validate with AlMn (in process)



Shiling Yu, Fabien Defrance



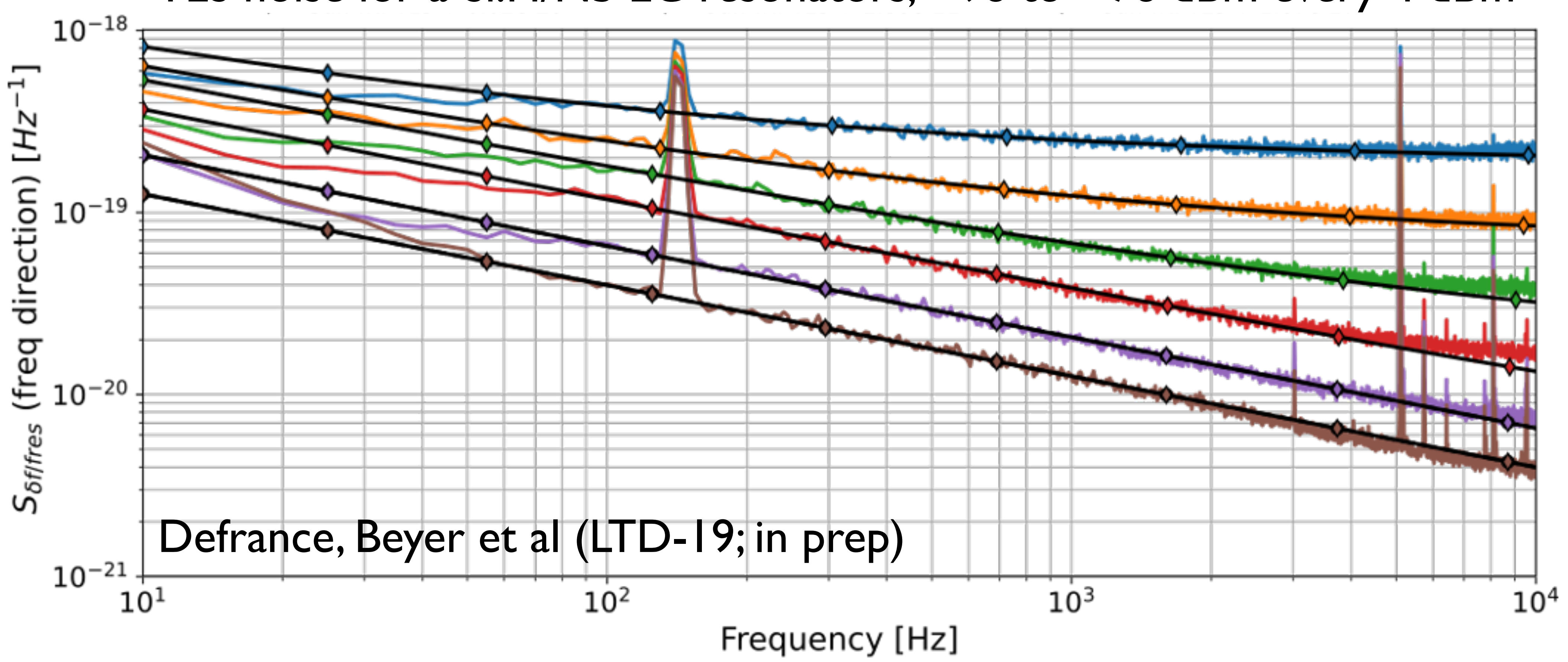


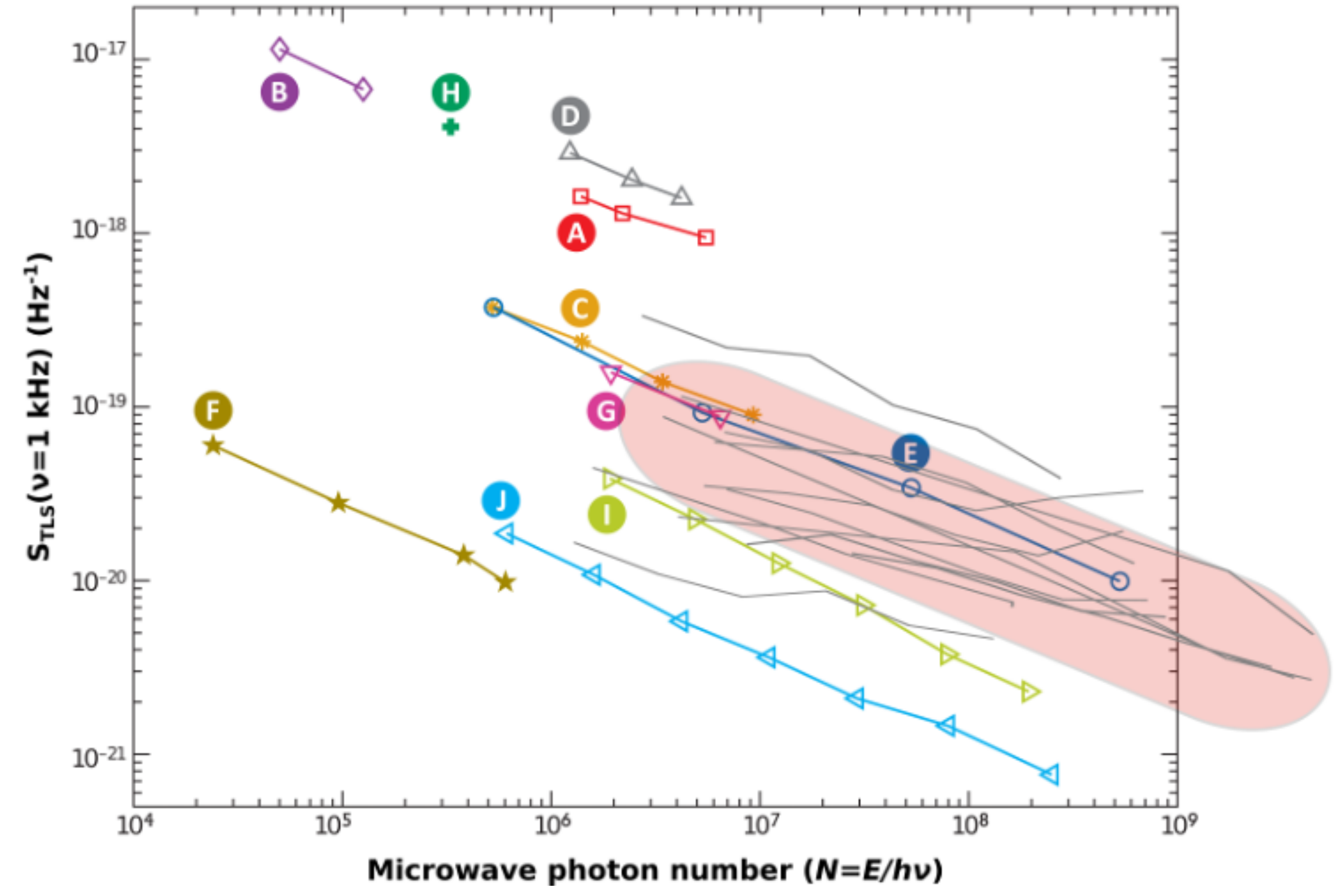
Noise Performance — TLS Noise Level

$$|\vec{E}| = \frac{\sqrt{\langle V^2 \rangle}}{d} = \frac{1}{d}\sqrt{\frac{W_e}{C_0}} = \sqrt{\frac{1}{\epsilon A_0 d}}\sqrt{\frac{P_{read}}{2\pi f_{res}}\frac{Q_r^2}{Q_c}}$$

$$S_{TLS} = S_{TLS}^{r}\left(\frac{T}{246\ mK}\right)^{-0.8}\left(\frac{A_C}{A_{C1}\ or\ A_{C2}\ or\ A_{C3}\ m^2}\right)^{-1}\left(\frac{E}{E_{avg1}\ or\ E_{avg2}\ or\ E_{avg3}\ V/m}\right)^{-1}$$

TLS noise for a-Si:H/Nb LC resonators, −98 to −78 dBm every 4 dBm

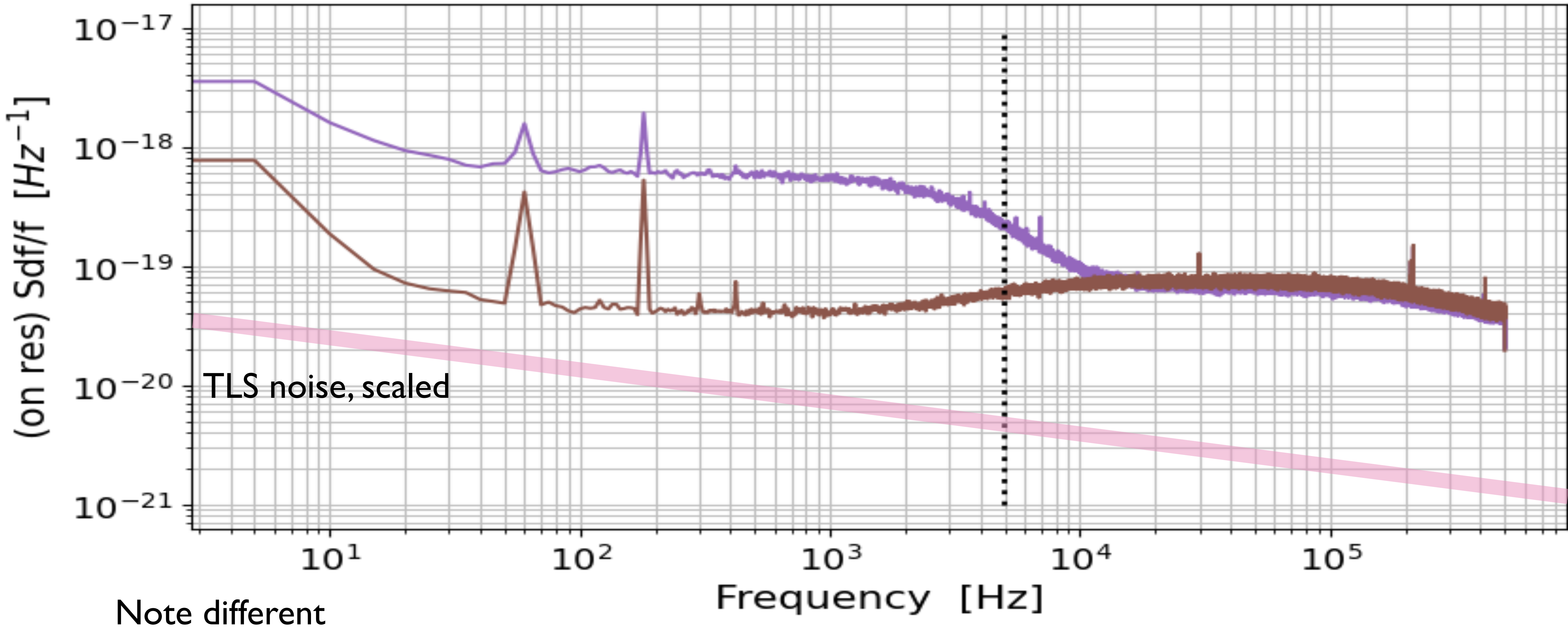




Conclusions:

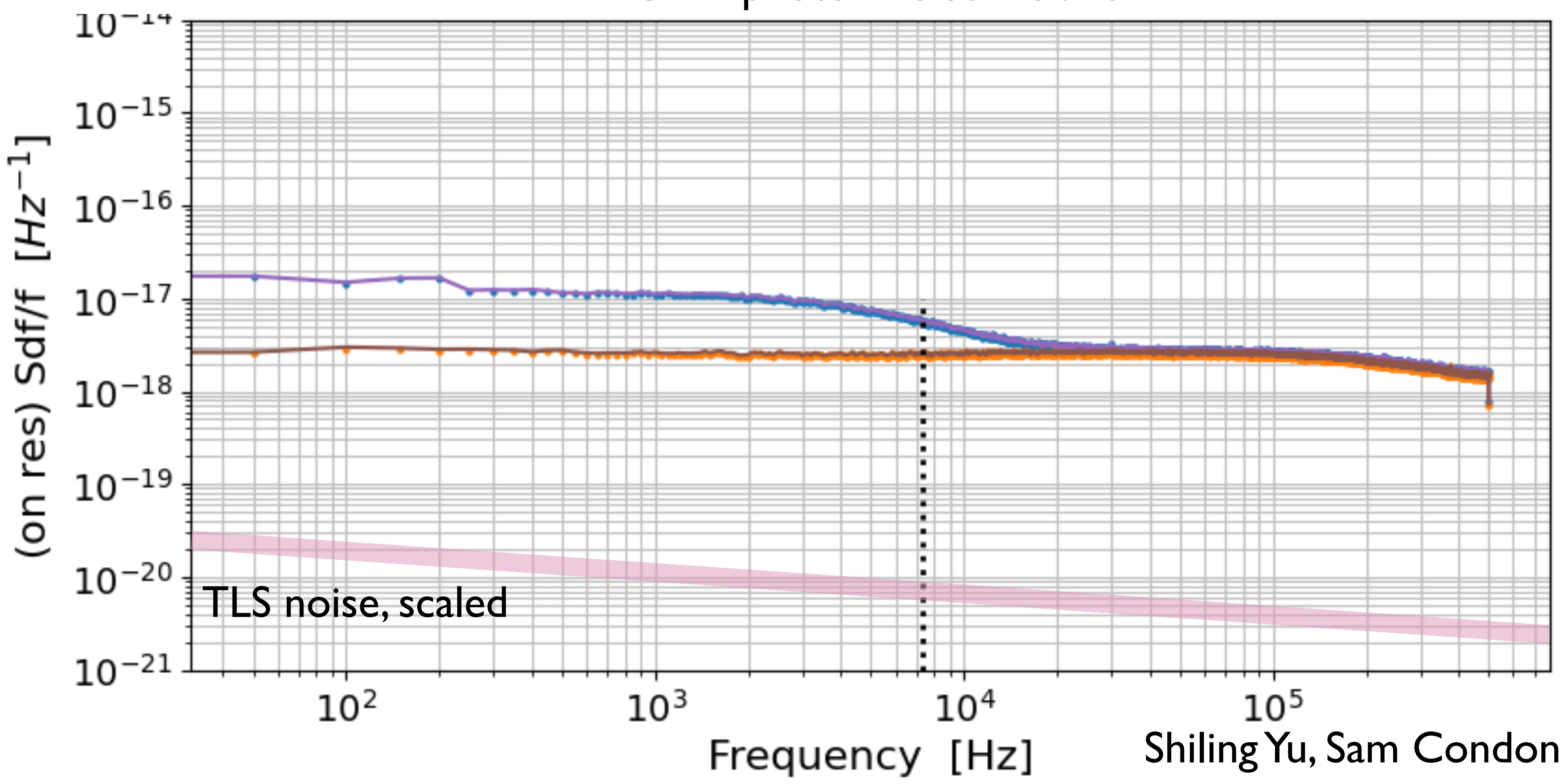
- TLS noise likely small compared to GR + photon noise
- Need to confirm via explicit measurement down to 0.1-1 Hz
- If confirmed, can reduce capacitor area

Total noise, a-Si:H/Al KID, dark, 310 mK
(n_{qp} ~ that expected under on-sky load ~ 40K, but no photon noise)



Note different frequency axes have been aligned!

Total noise, a-Si:H/Al KID, T_{load} = 77K+150K
GR + photon noise included



Shiling Yu, Sam Condon

Noise Performance — Under Optical Load — Backup

$$\frac{\eta_{pb}\,P_{opt}}{\Delta} = V\,R\,n_{qp}^2 = \frac{R\,N_{qp}^2}{V} = \frac{1}{2}\,\frac{N_{qp}}{\tau_{qp}}$$

Note the 1/2! It comes from $\tau_{qp} = \dfrac{1}{2\,R\,n_{qp}} = \dfrac{V}{2\,R\,N_{qp}}$

$$\frac{\eta_{pb}\,dP_{opt}}{\Delta} = 2\,V\,R\,n_{qp}\,dn_{qp} = \frac{dN_{qp}}{\tau_{qp}} \quad\Longrightarrow\quad \frac{dN_{qp}}{dP_{opt}} = \eta_{pb}\,\frac{\tau_{qp}}{\Delta} = \frac{\eta_{pb}}{\Delta}\,\frac{V}{2\,R\,N_{qp}} = \frac{1}{2}\,\frac{N_{qp}}{P_{opt}}$$

$$\left(\mathrm{NEP}_{opt}^{\gamma}\right)^2 = 2\,P_{opt}\,h\,\nu + 2\,\frac{P_{opt}^2}{\Delta\nu} = 2\,\eta_{opt}\,k_B\,T_{load}\,\Delta\nu\,h\,\nu + 2\,\eta_{opt}^2\,k_B^2\,T_{load}^2\,\Delta\nu$$

$$S_{N_{qp}}^{\gamma} = \left(\mathrm{NEP}_{opt}^{\gamma}\right)^2\left(\frac{dN_{qp}}{dP_{opt}}\right)^2 = \left[2\,P_{opt}\,h\,\nu + 2\,\frac{P_{opt}^2}{\Delta\nu}\right]\frac{N_{qp}^2}{4\,P_{opt}^2} = \left[h\,\nu + \frac{P_{opt}}{\Delta\nu}\right]\frac{\eta_{pb}}{2}\,\frac{V}{R\,\Delta}$$

$$= \eta_{pb}\,\frac{V}{R}\left[\frac{h\,\nu}{2\,\Delta} + \frac{\eta_{opt}\,k_B\,T_{load}}{2\,\Delta}\right]$$

$$S_{N_{qp}}^{GR} = 4\,\tau_{qp}\,N_{qp} = \frac{V}{R}\left[1 + \left(\frac{N_{qp}^{th}}{N_{qp}}\right)^2\right] \qquad S_{N_{qp}}^{GR} = 4\,\tau_{qp}\,N_{qp} \approx \frac{V}{R}$$

$$S_{N_{qp}}^{tot} = S_{N_{qp}}^{GR} + S_{N_{qp}}^{\gamma} = \frac{V}{R}\left[1 + \left(\frac{N_{qp}^{th}}{N_{qp}}\right)^2 + \eta_{pb}\left(\frac{h\,\nu}{2\,\Delta} + \frac{\eta_{opt}\,k_B\,T_{load}}{2\,\Delta}\right)\right]$$

$$S_{N_{qp}}^{tot} = S_{N_{qp}}^{GR} + S_{N_{qp}}^{\gamma} \approx \frac{V}{R}\left[1 + \eta_{pb}\left(\frac{h\,\nu}{2\,\Delta} + \frac{\eta_{opt}\,k_B\,T_{load}}{2\,\Delta}\right)\right]$$

Can show, for recombination-limited qp lifetime: linear relationship between $S_{N_{qp}}^{tot}$ and T_{load}

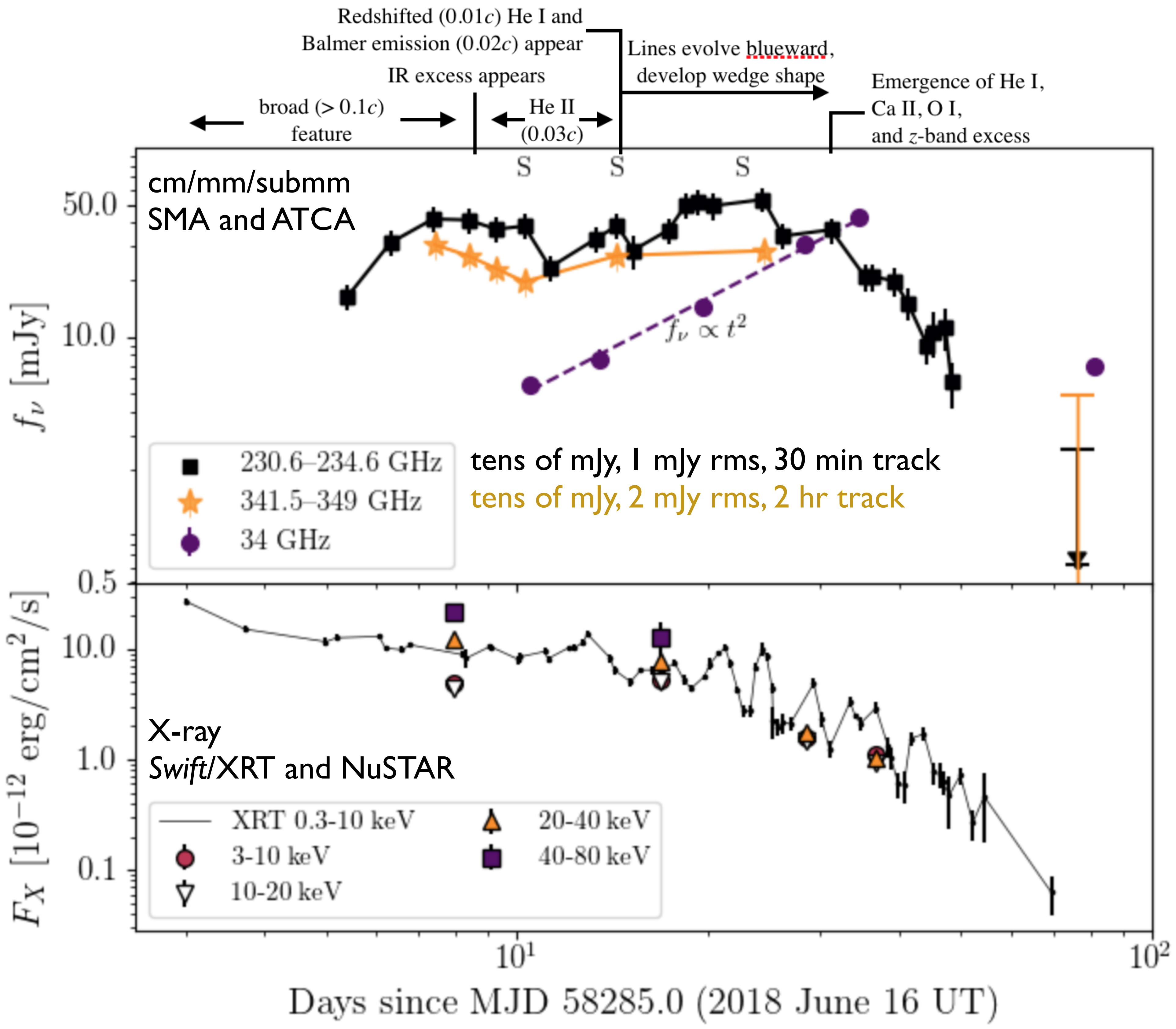
Dark data measures first term (independent of T_{bath}!) and thus R.

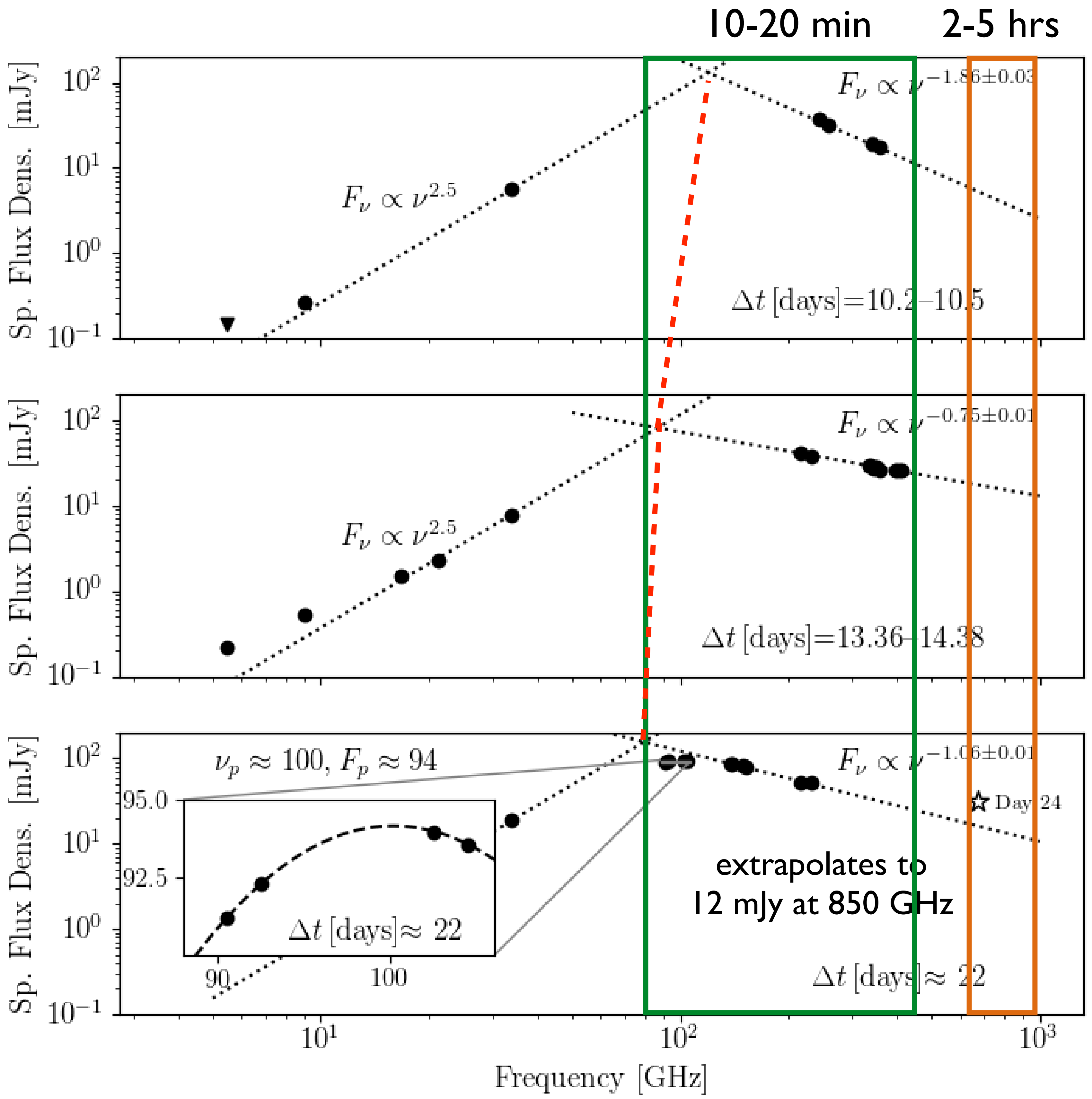
Offset and coefficient measure different combinations of Δ, η_{pb}, η_{opt}; can measure or check any two.

Dependence on R?

$$\mathrm{NEP}_{qp} = \frac{2\,R\,N_{qp}}{V}\,\Delta\left[S_{N_{qp}}^{tot}\right]^{1/2} = 2\,\Delta\left\{\frac{R\,N_{qp}^2}{V}\left[1 + \left(\frac{N_{qp}^{th}}{N_{qp}}\right)^2 + \eta_{pb}\left(\frac{h\,\nu}{2\,\Delta} + \frac{\eta_{opt}\,k_B\,T_{load}}{2\,\Delta}\right)\right]\right\}^{1/2} = 2\sqrt{\Delta}\left\{\eta_{pb}\,P_{opt}\left[1 + \left(\frac{N_{qp}^{th}}{N_{qp}}\right)^2 + \eta_{pb}\left(\frac{h\,\nu}{2\,\Delta} + \frac{\eta_{opt}\,k_B\,T_{load}}{2\,\Delta}\right)\right]\right\}^{1/2}$$

AT2018cow: Fast Blue Optical Transient, well-studied in mm/submm





Strong sync from mildly relativistic shock wave in dense CSM, $n_e \sim 10^5$ cm^{-3}

ν_p yields shock parameters: R_{outer} , B field, energy, speed, density of medium, $\nu_{\rm cooling}$

NEW-MUSIC depth in 12 min integration

band [GHz]	100	150	220	270	350	405
depth [mJy rms]	0.5	1	1	1.5	2	4

Very visible w/NEW-MUSIC!

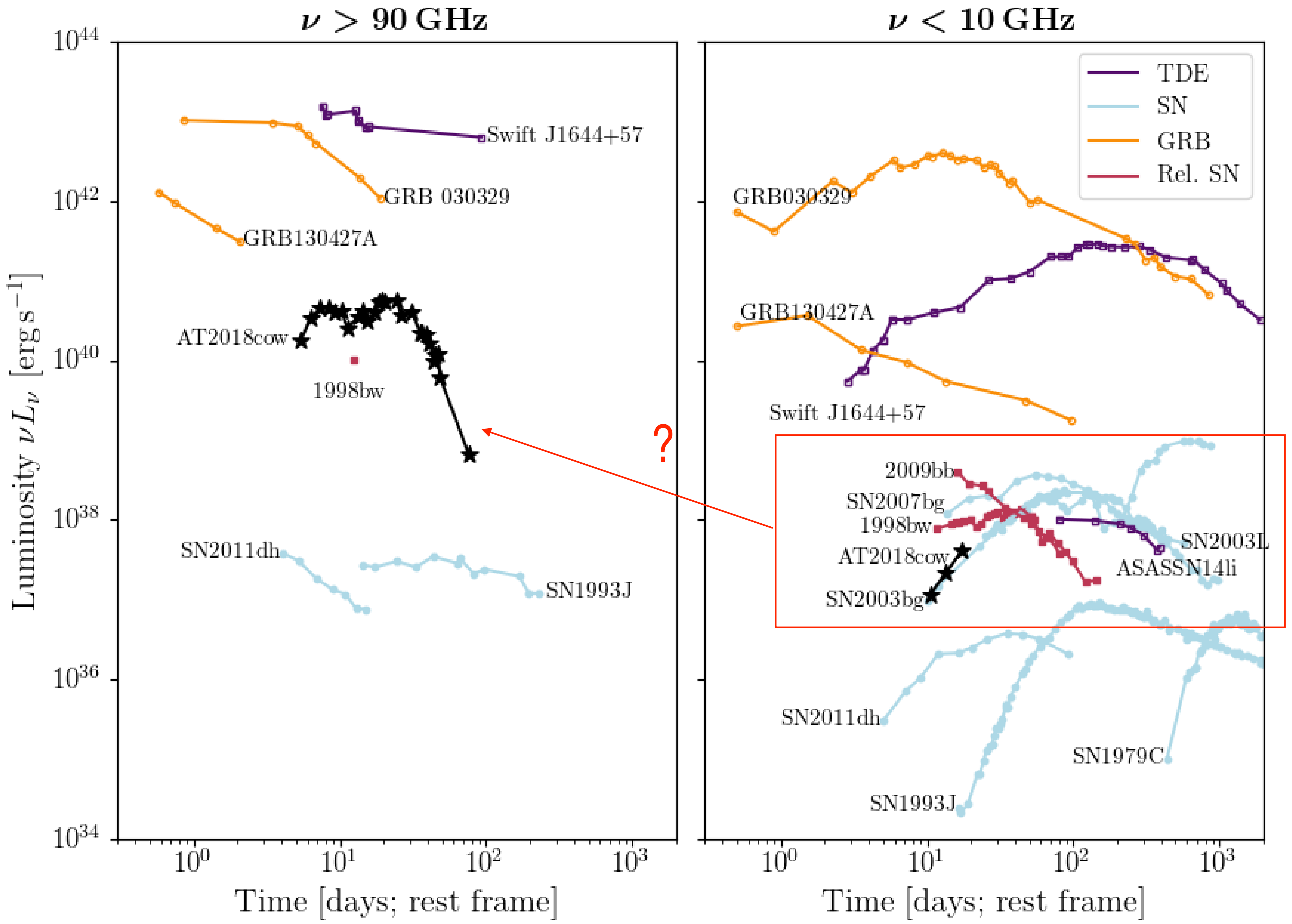
- 10-20 min to reach same depth/SNR in 6 bands
- Sync peak location unclear at t < 20 days, but perhaps > 300 GHz until day 6-7

mm emission self-trigger for 650/850 GHz

- search for non-thermal components
- hints of NIR excess seen

Implications for Transients with LCT

Early comparisons to objects with similar radio luminosities (luminous SNe, luminous TDEs) suggest that they too might have had bright, early mm/submm emission



Rates estimates are promising

band [GHz]	100	150	220	270	350	405
depth [mJy rms]	0.5	1	1	1.5	2	4

Rates for 5_σ = 5 mJy at 90 GHz (3-min integration) (Anna Ho)

Class	Luminosity [10^{27} erg/s/Hz]	Horizon [Gpc]	Rate [/yr/Gpc^3]	[/yr]
SNe	1	0.013	100,000	0.4
Interacting SNe	100	0.130	10,000	37
FBOT	1,000	0.410	100	12
LLGRB	100	0.130	1,000	3.7
LGRB θ_{obs} < 0.2	100,000	4.090	0.3	34
LGRB 0.2 < θ_{obs} < 0.4	30,000	2.240	1	23
LGRB 0.4 < θ_{obs} < 0.8	1,000	0.410	5	0.5
relativistic TDEs	20,000	1.800	0.03	0.3

The Galaxy-CGM-IGM Connection and the Inefficiency of Star Formation in Galaxies: Calorimetry of the Hot CGM via Thermal SZ

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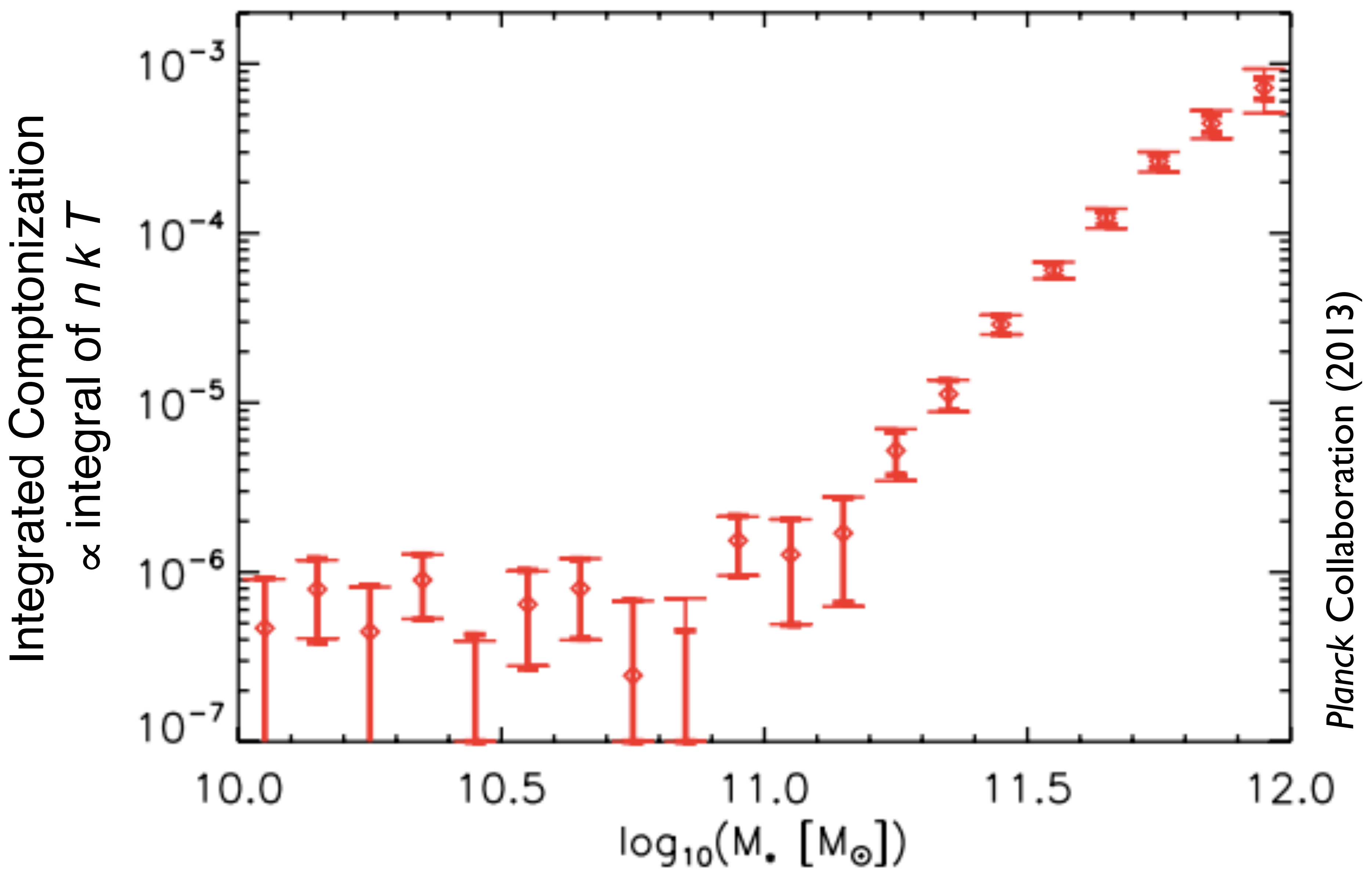

Thermal SZ (tSZ) measures
n k T = thermal energy density
→ integrated tSZ is calorimeter of energy in the hot CGM

Self-similarity expected to hold for masses at which all baryons can be retained: closed box, scale-invariant

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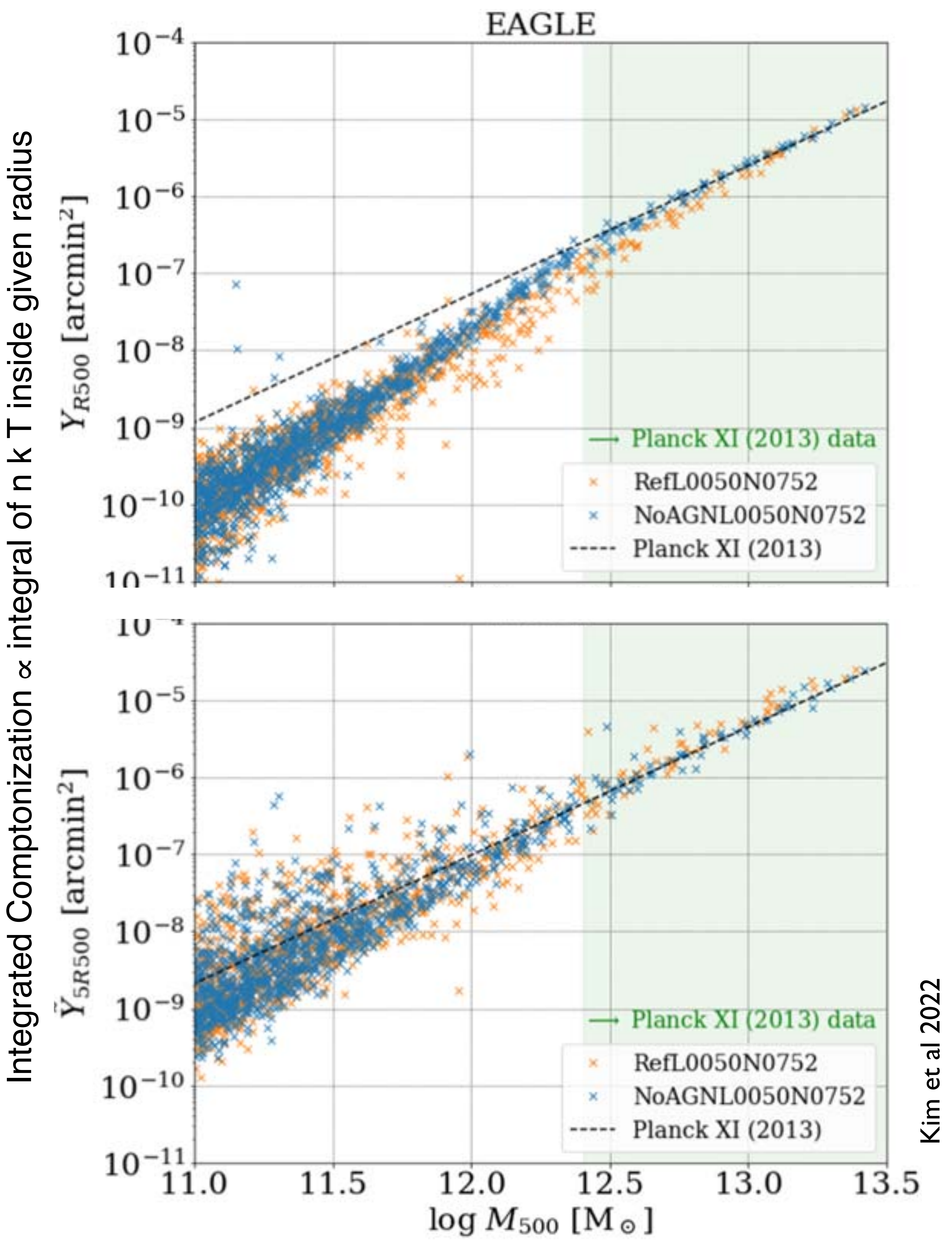

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Lower mass galaxies: simulations say winds drive baryons out of near CGM

Maybe a contributor to SF inefficiency:
- winds heat CGM at high M,
- flow out to high *R* at lower M

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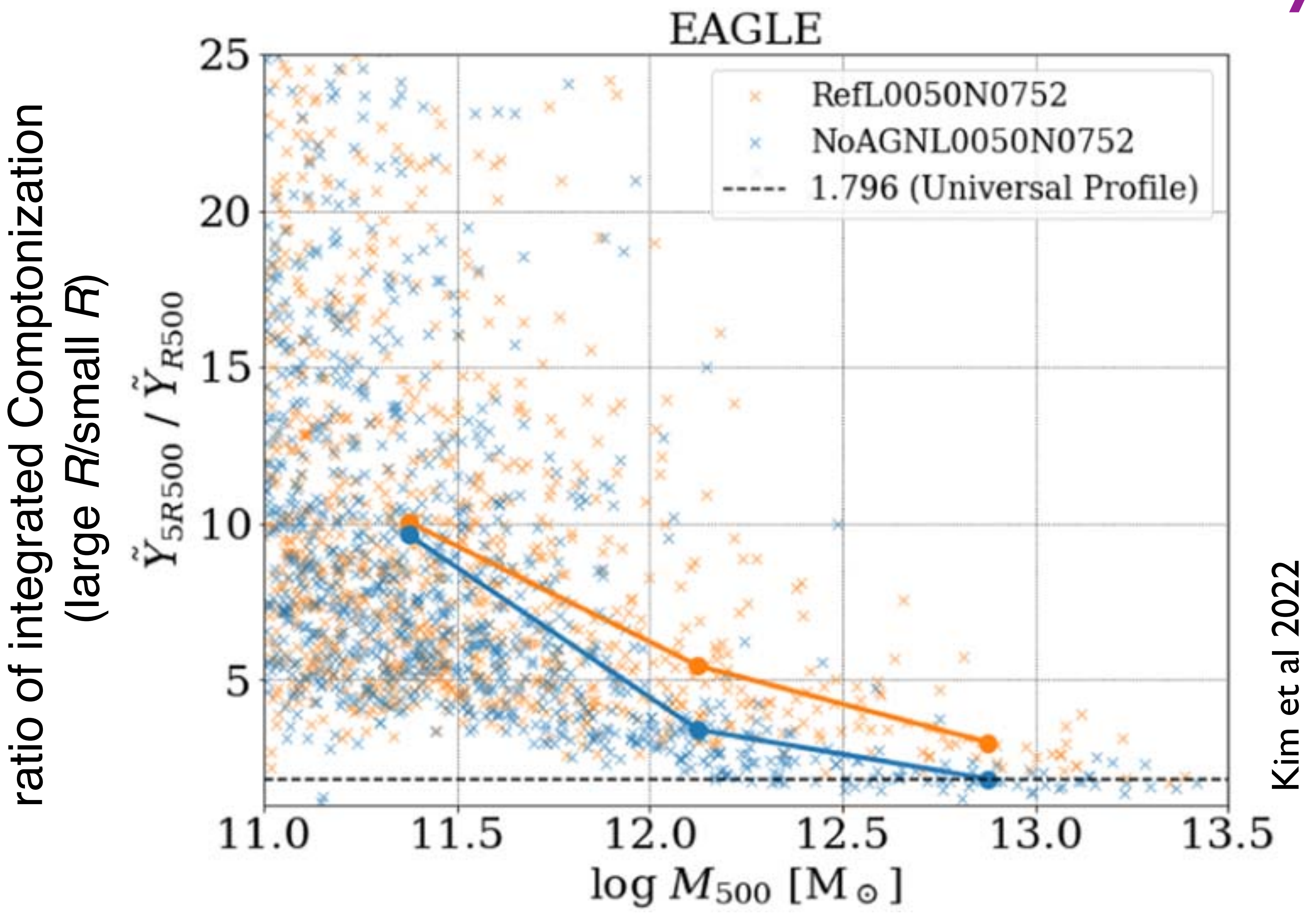

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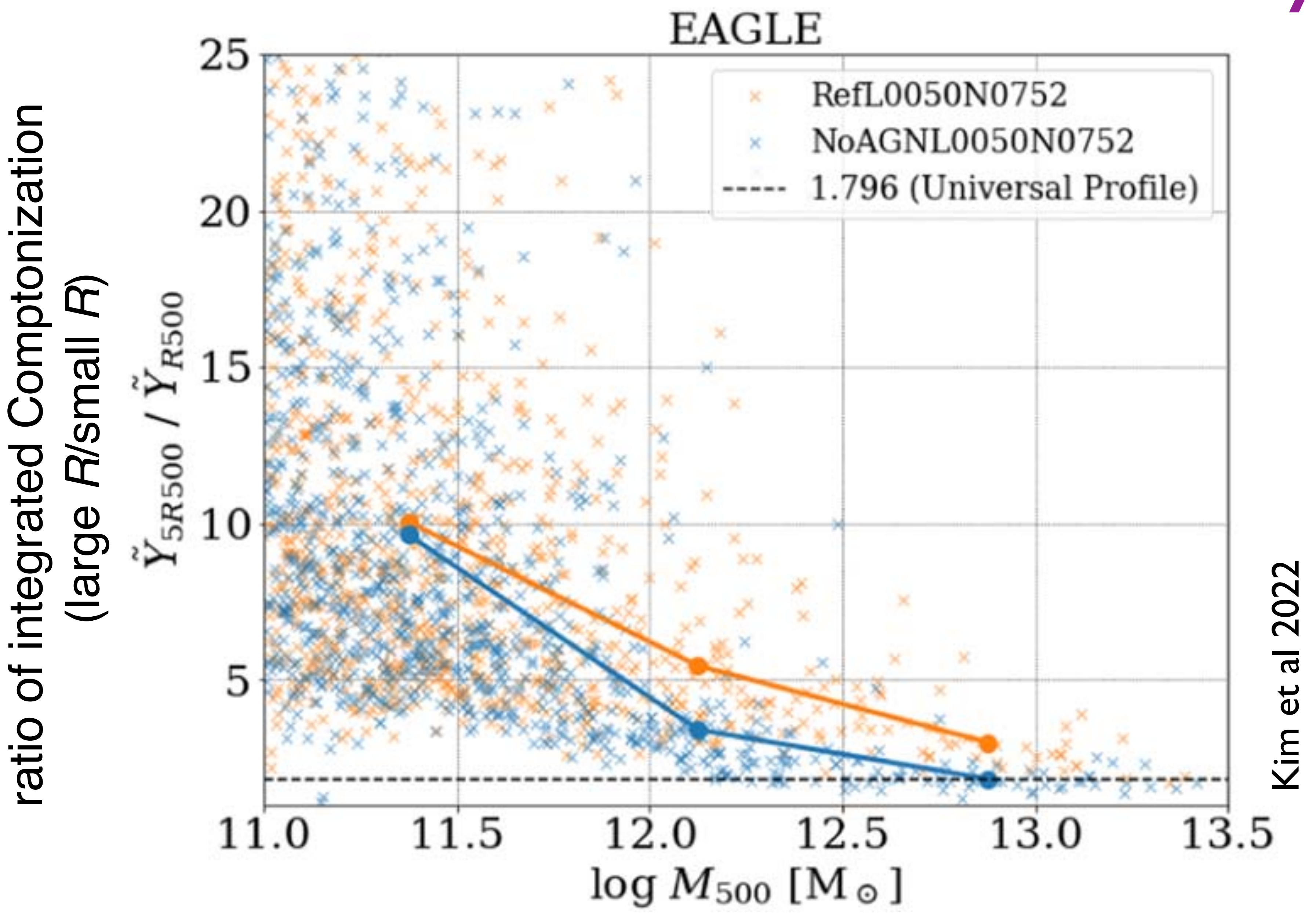

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- x10 colder CGM in smaller galaxies
- CR not lost in larger galaxies

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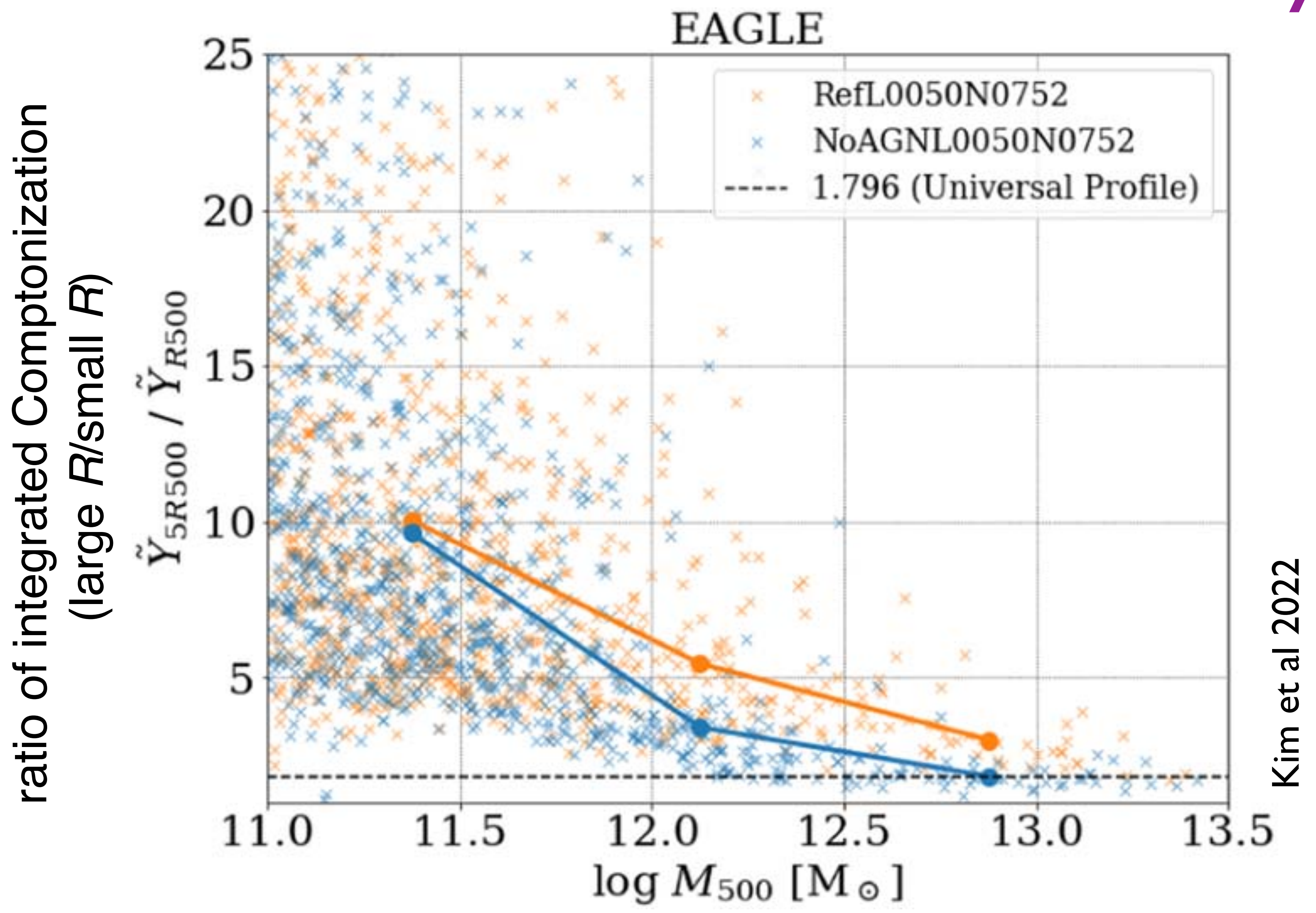

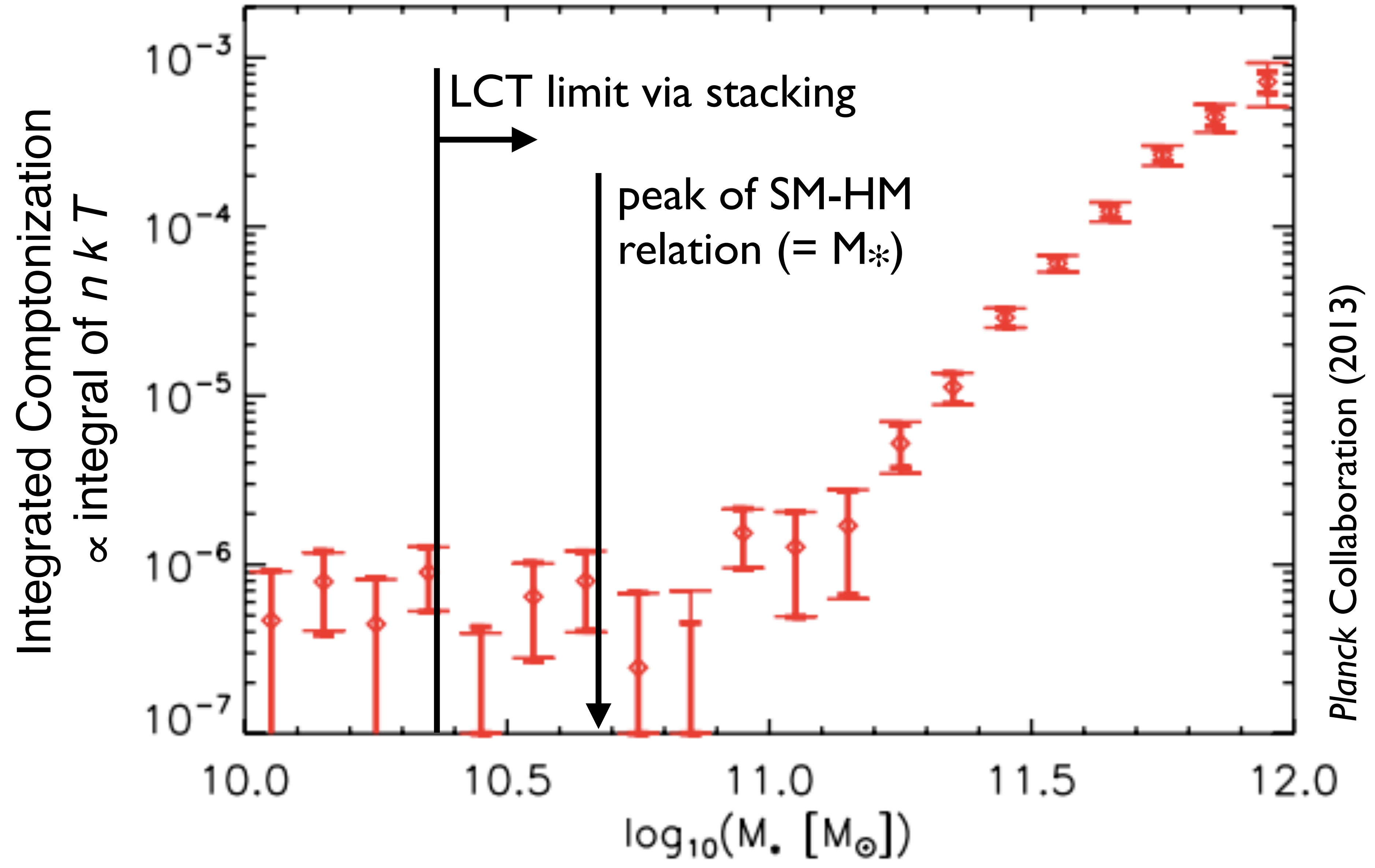

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Need to measure down to lower masses!
- LCT capable of reaching to galaxy stellar masses below the peak of the SF efficiency function