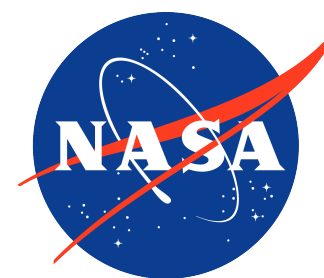


Astrophysics with Quantum Probes

R. Basu Thakur. Aug 13th 2026, KIPAC/Stanford

Caltech



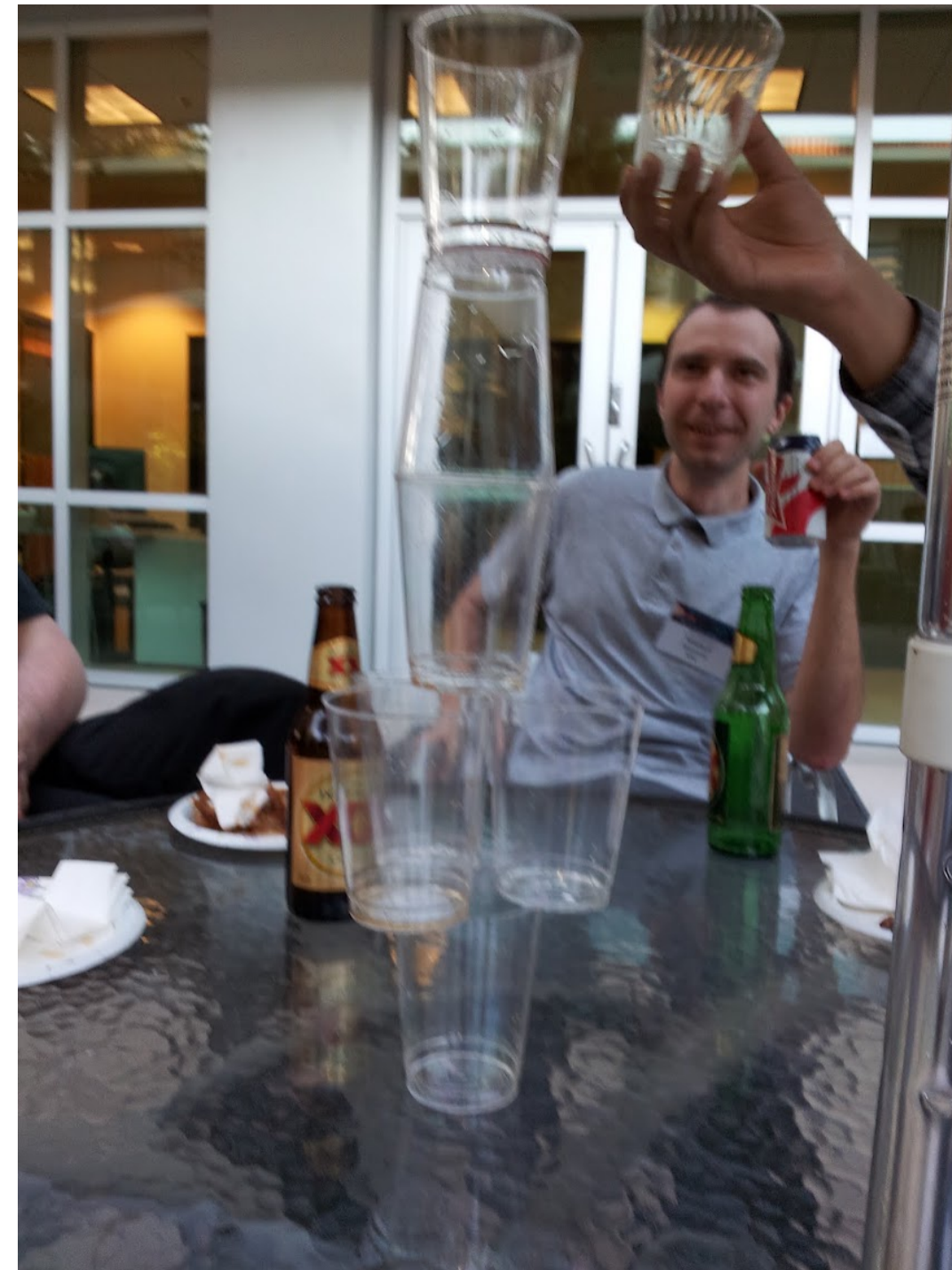
Jet Propulsion Laboratory
California Institute of Technology

SSI is an amazing experience

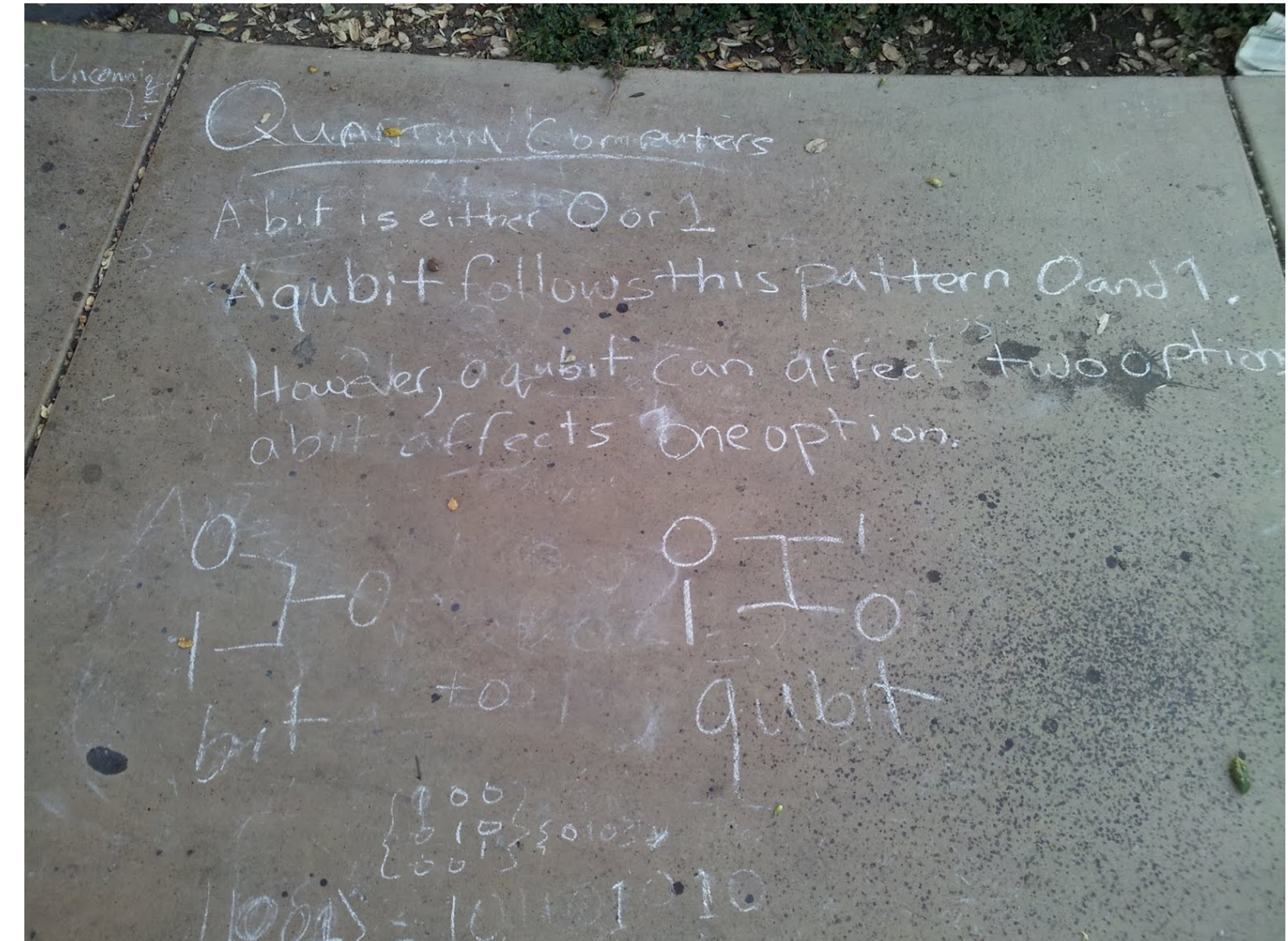
2



I had asked C.L.K for intro on CMB ... he gave us homework !



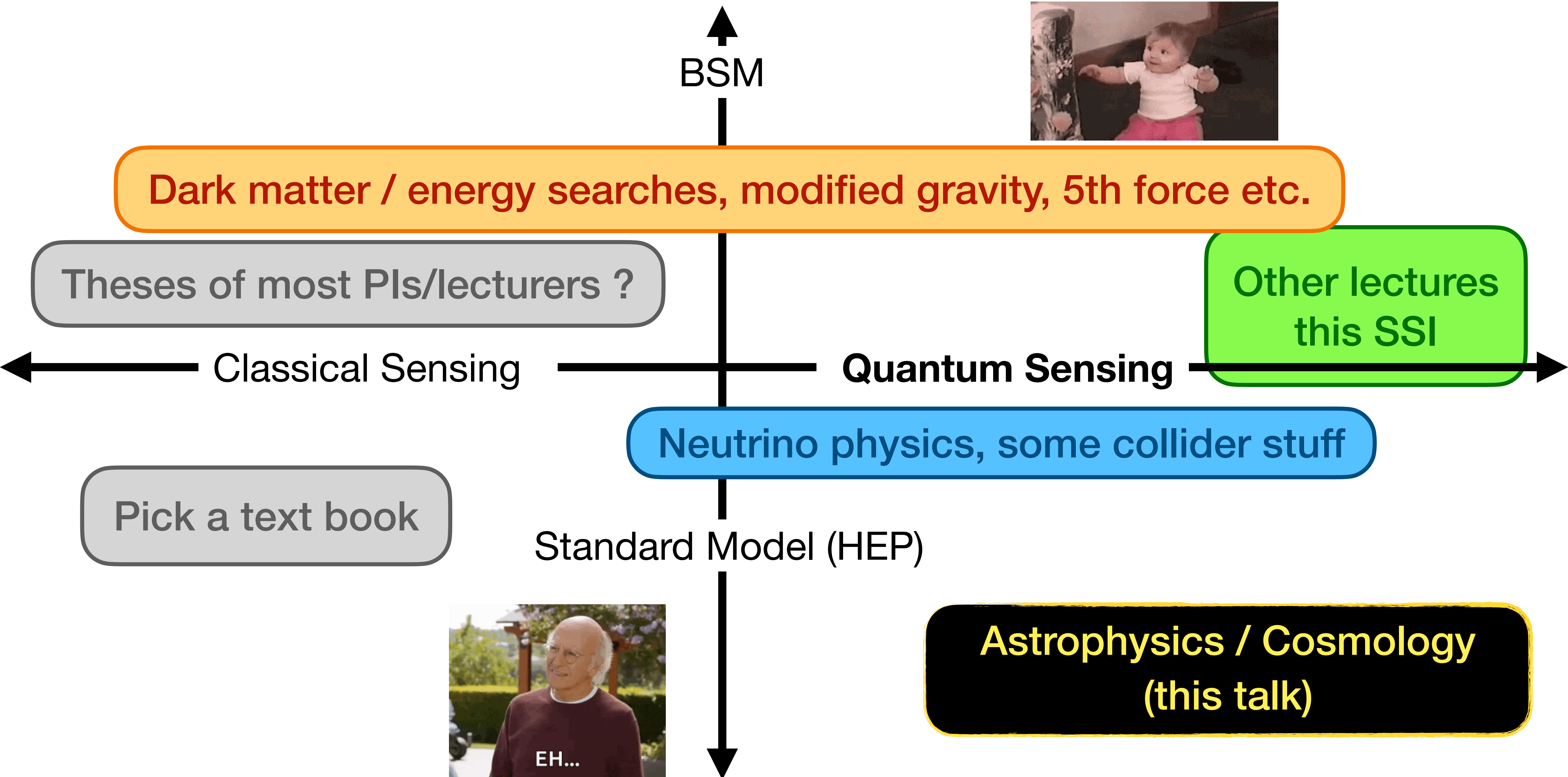
After A.L's inflation lecture, fine-tuning of instability was explored empirically



SLAC thinking about the quantum industry way back then ... writing on the floors

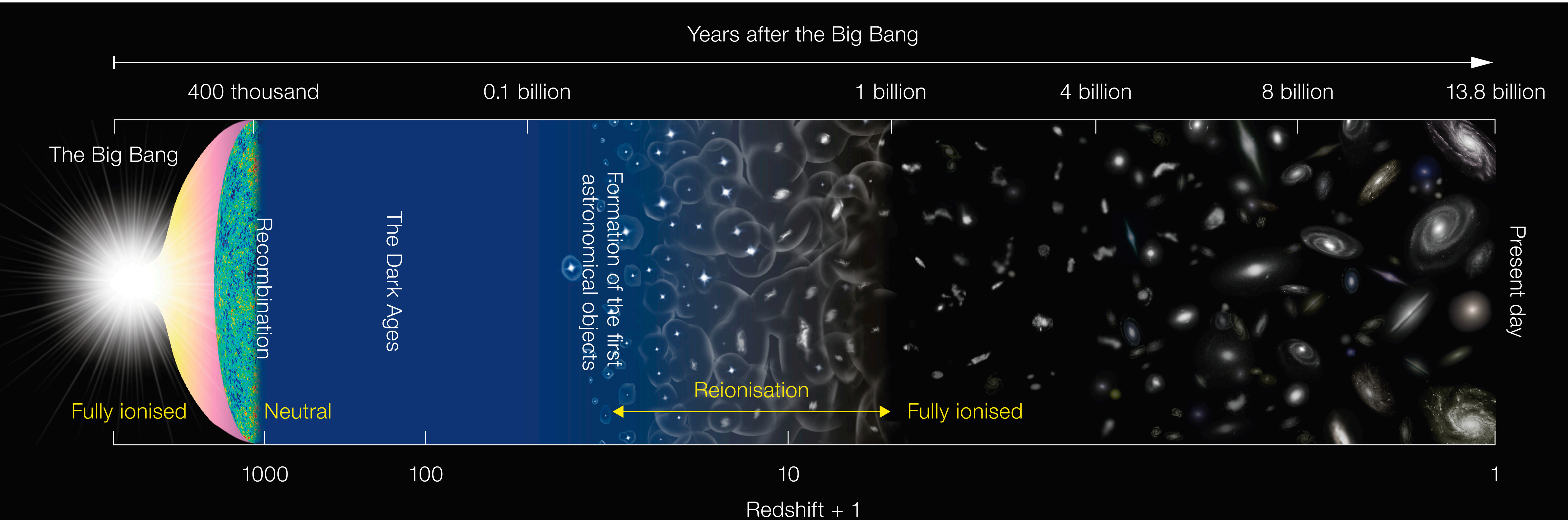
Introduction

3



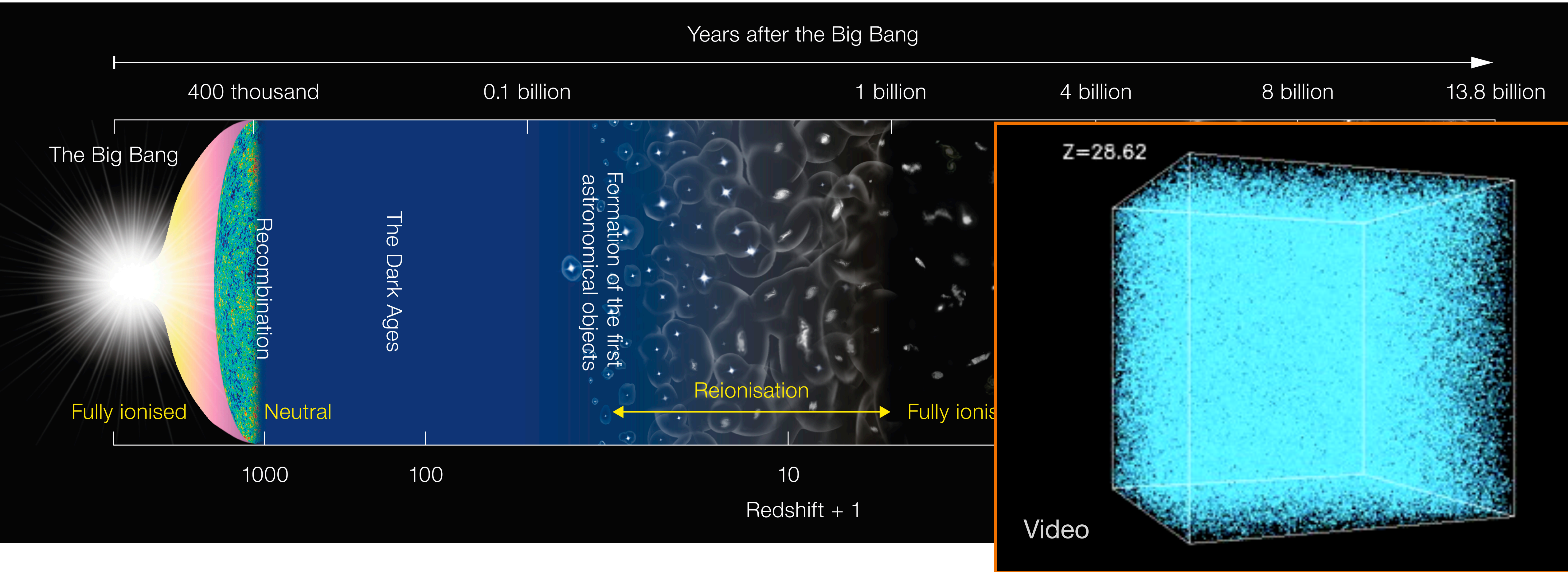
Introduction

4



Introduction

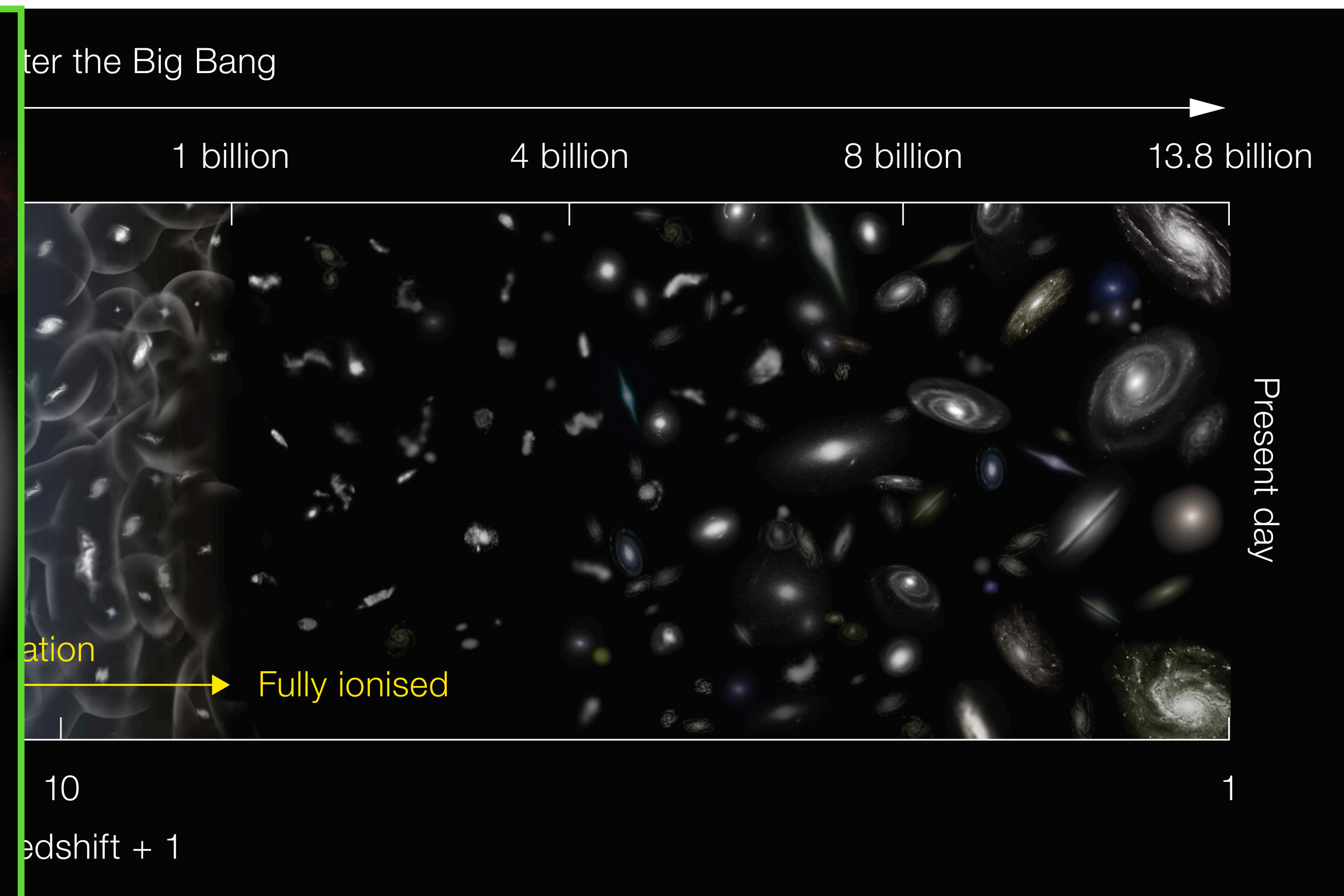
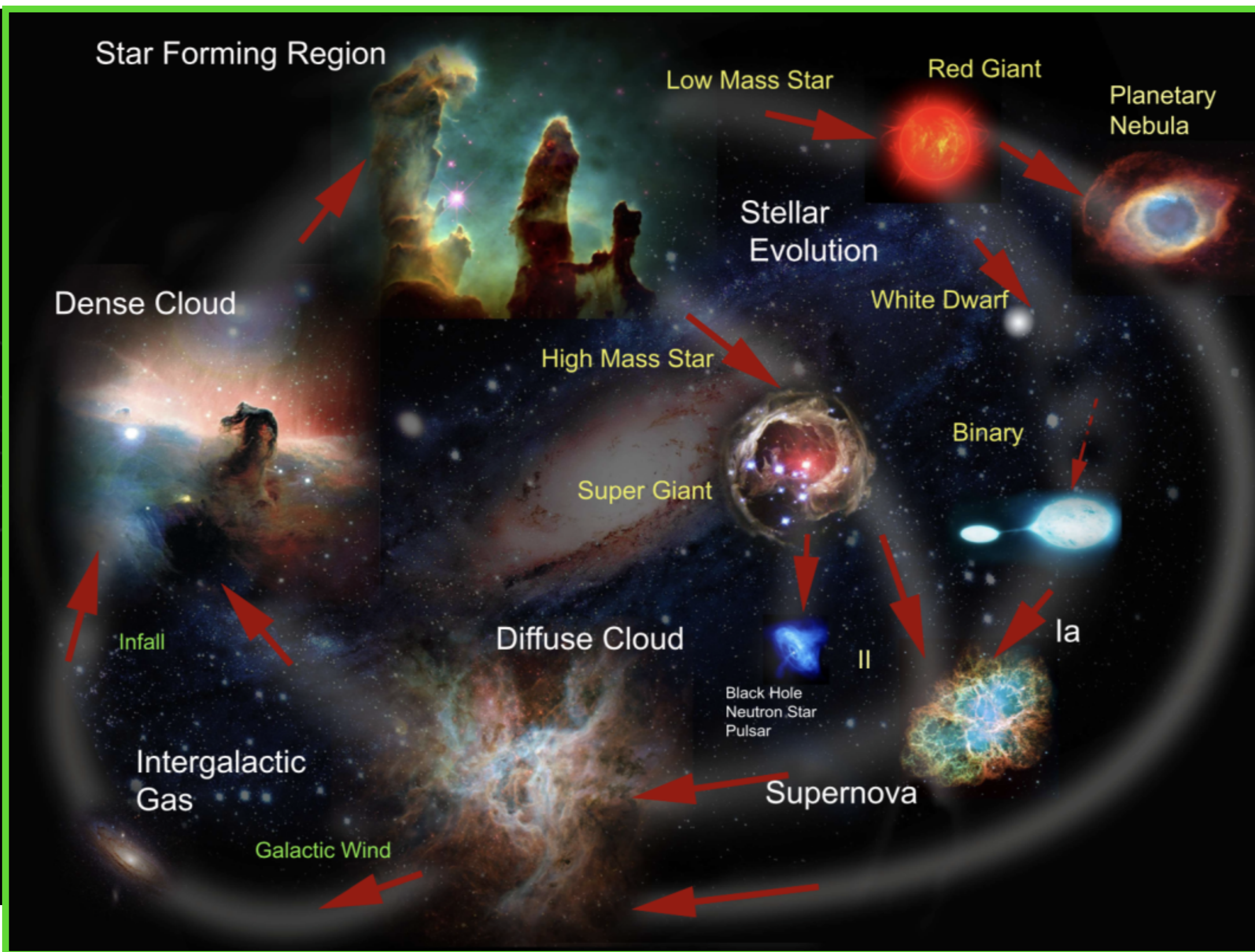
5



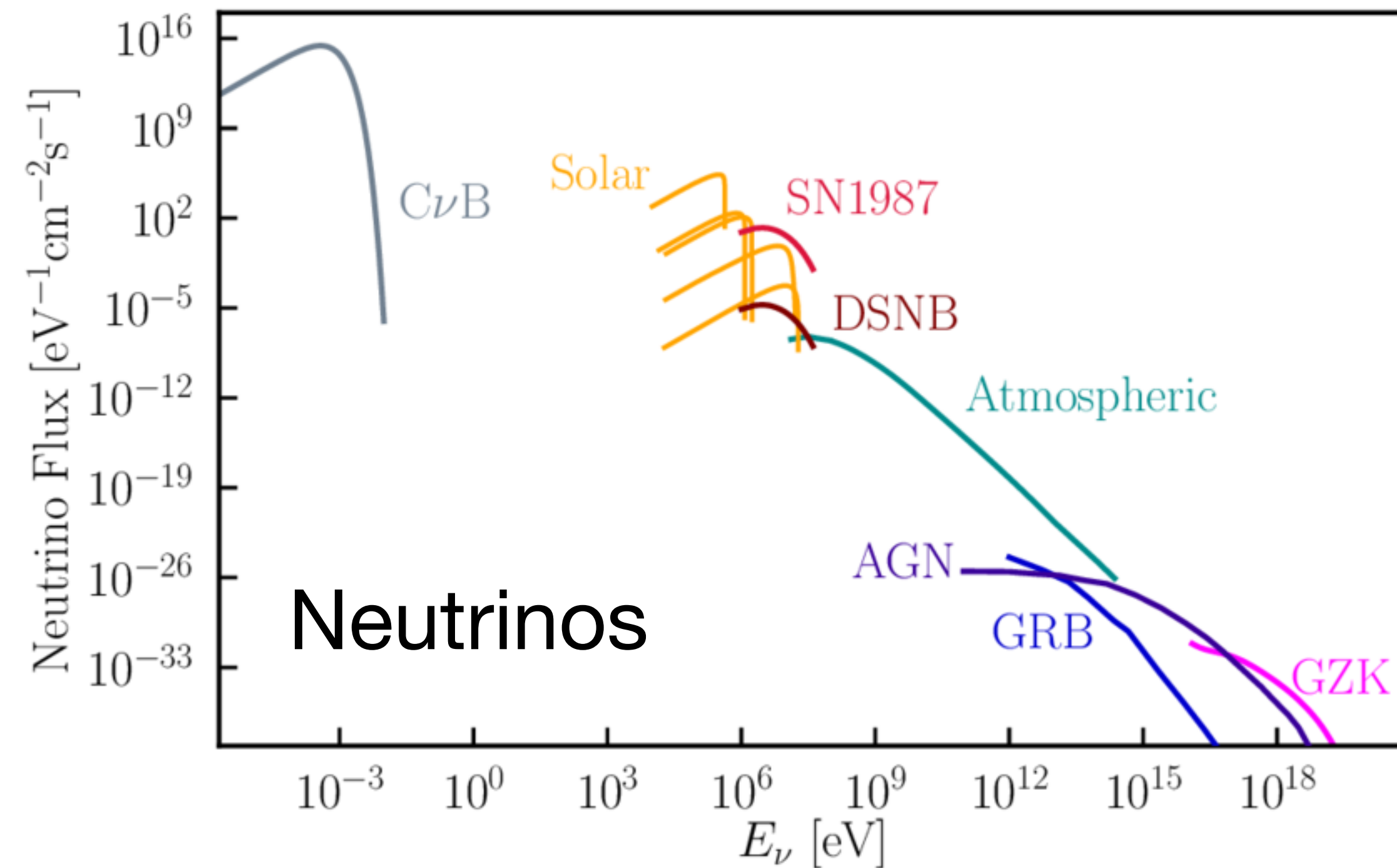
Cosmology: large scale structures and their statistics.
inflation, curvature of the universe, role of dark matter / energy
with photons, neutrinos and gravity in seeding galaxies

Introduction

6

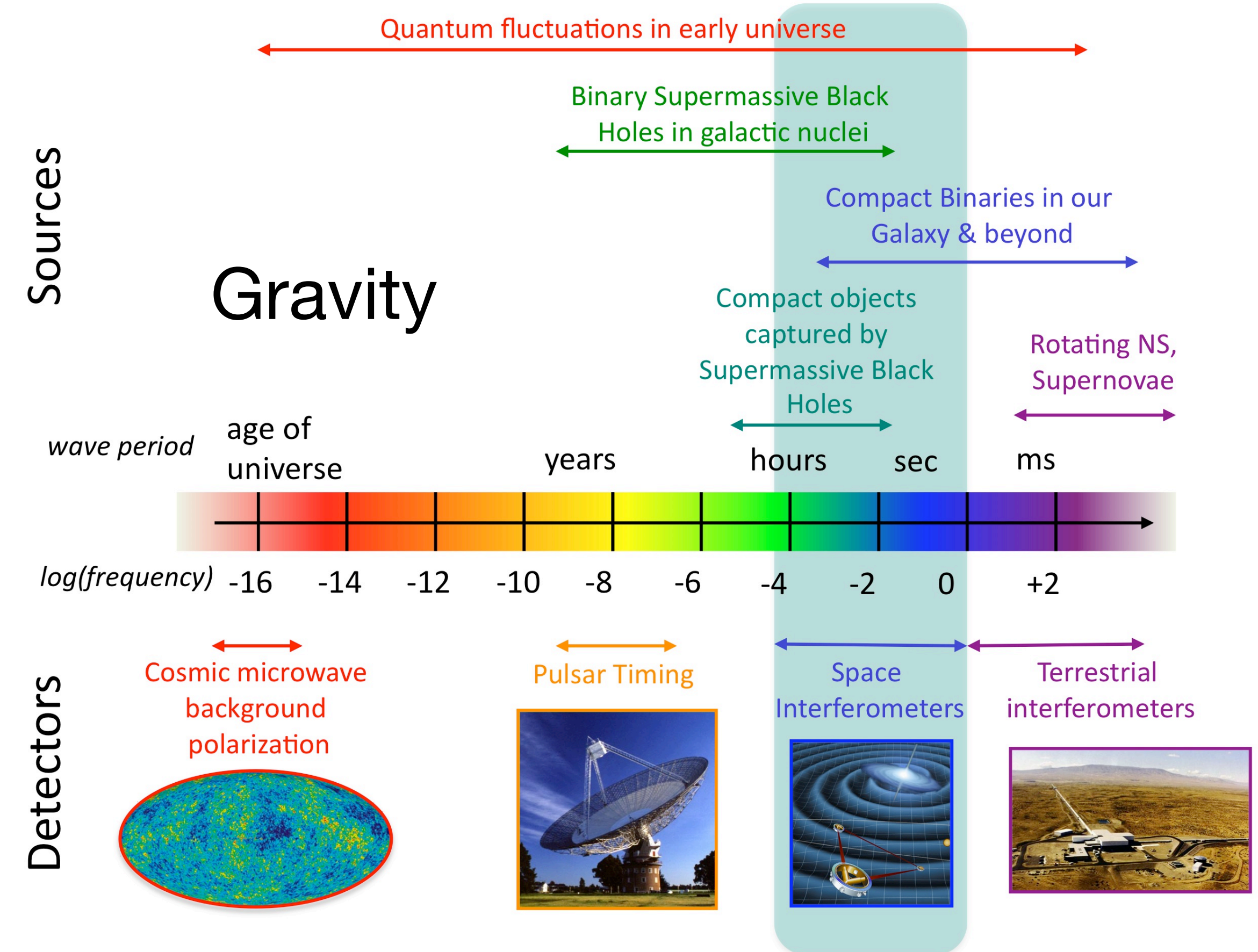


Astrophysics: How do galaxies form? Star formation rates, energetics and feedback (baryons), the taxonomy and genealogy of “modern” objects and the physics that connects them



$\nu > 1 \text{ GeV}$ detected or soon to be detected with XENON, IceCube etc.
Quantum Sensing not needed

CνB is undetected, and quantum sensing (what?) will be needed



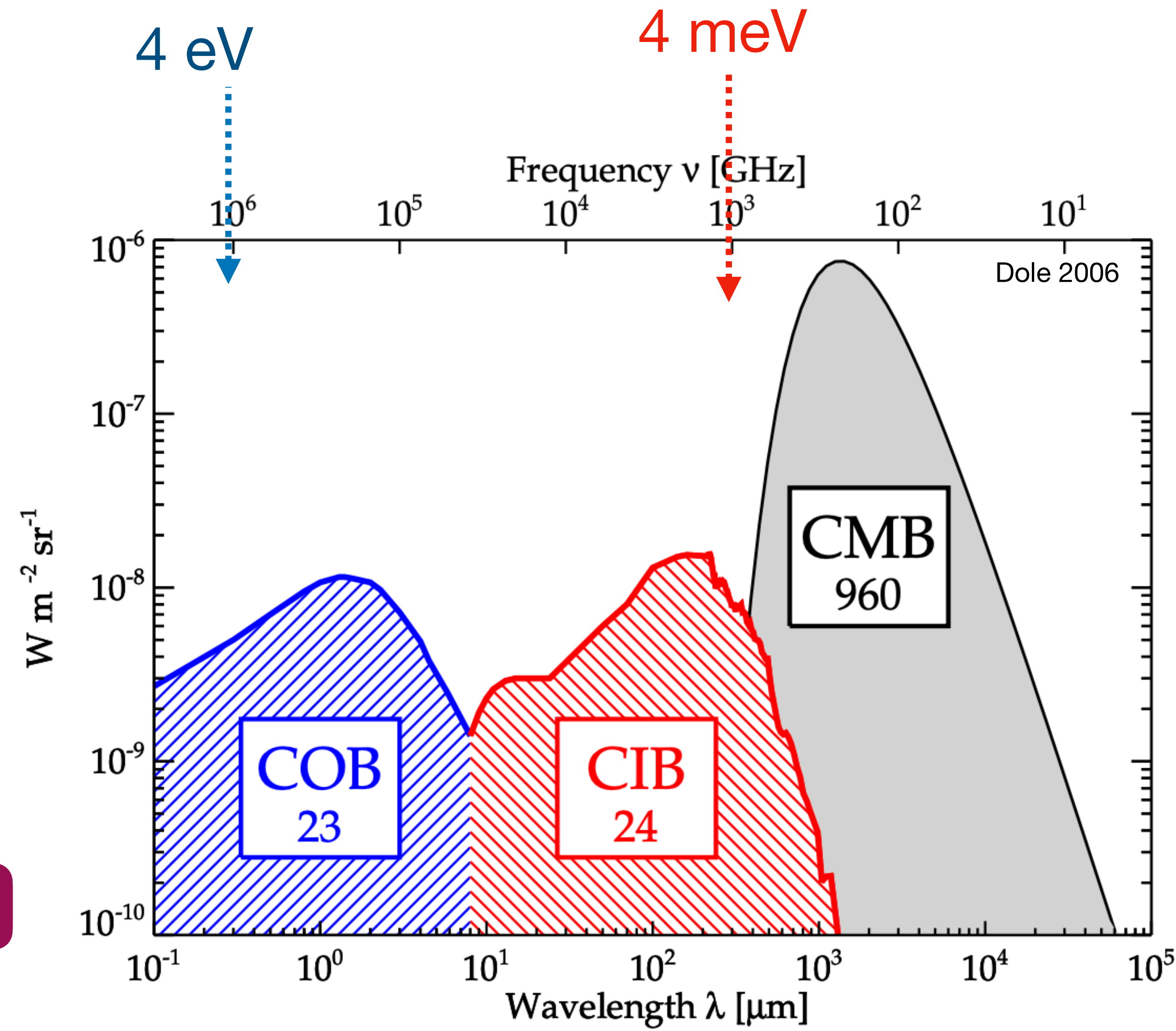
Classical sensing likely ok

Quantum Sensing

Novel **GW** searches like Gertsenshtein effect might benefit from Quantum Sensing

Probes with light

8



Photons are not rare in an integral measure (plot)

$$\frac{\delta P}{\langle A\Omega \rangle} \left[\frac{\text{W}}{\text{m}^2 \text{sr}} \right]$$

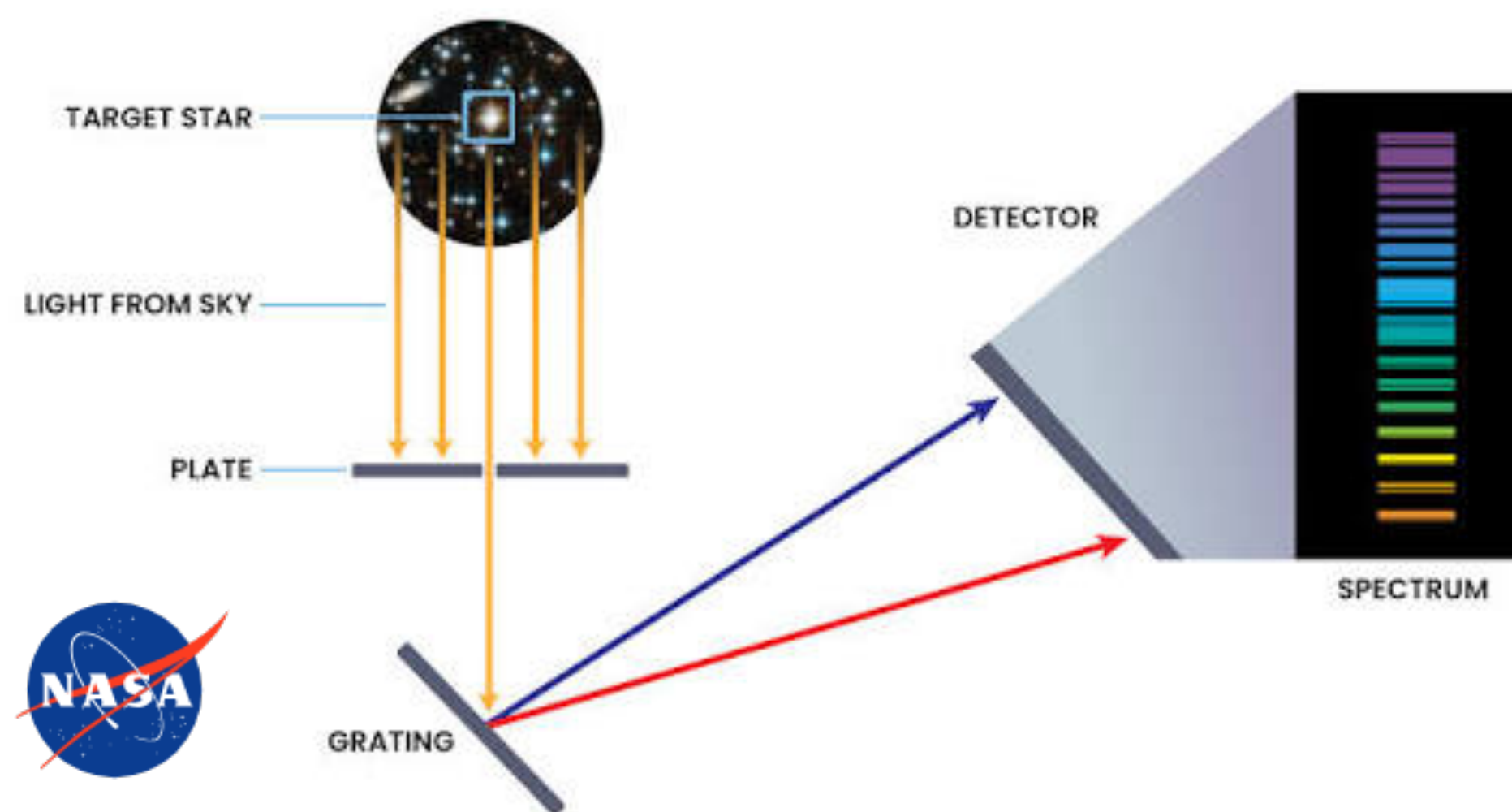
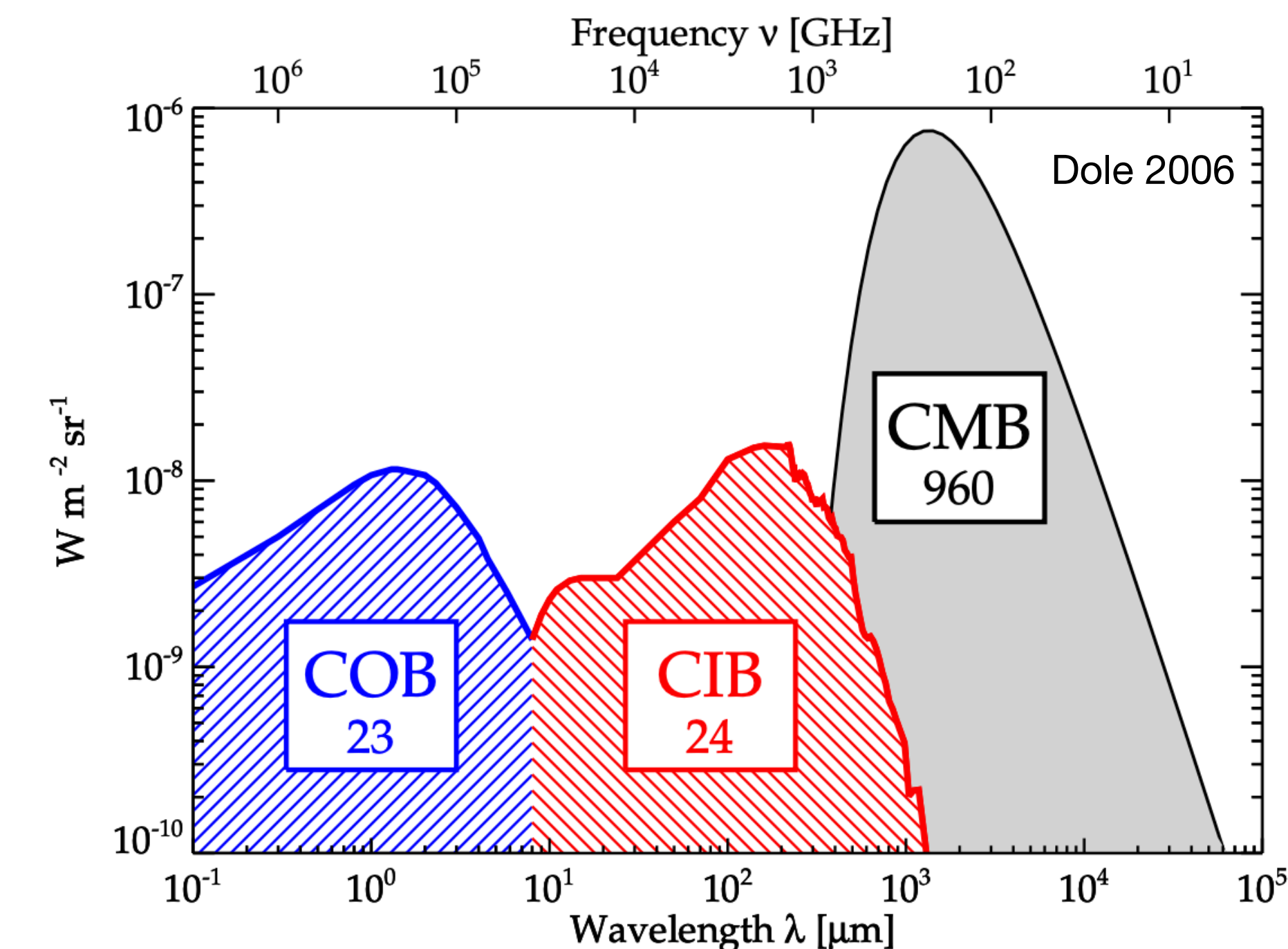
>10¹² CMB photons /s/ fingertip

γ X-rays

All the photons out there

Probes with light

9



Narrow spectral or sky regions are fainter

spectral resolution

$$\Delta P = \Delta \nu \cdot A \Omega \cdot B(\nu)$$

Brightness

patch of sky

$$B(\nu) = 2h\nu \left(\frac{\nu}{c} \right)^2 n(\nu)$$

Also relates to flux

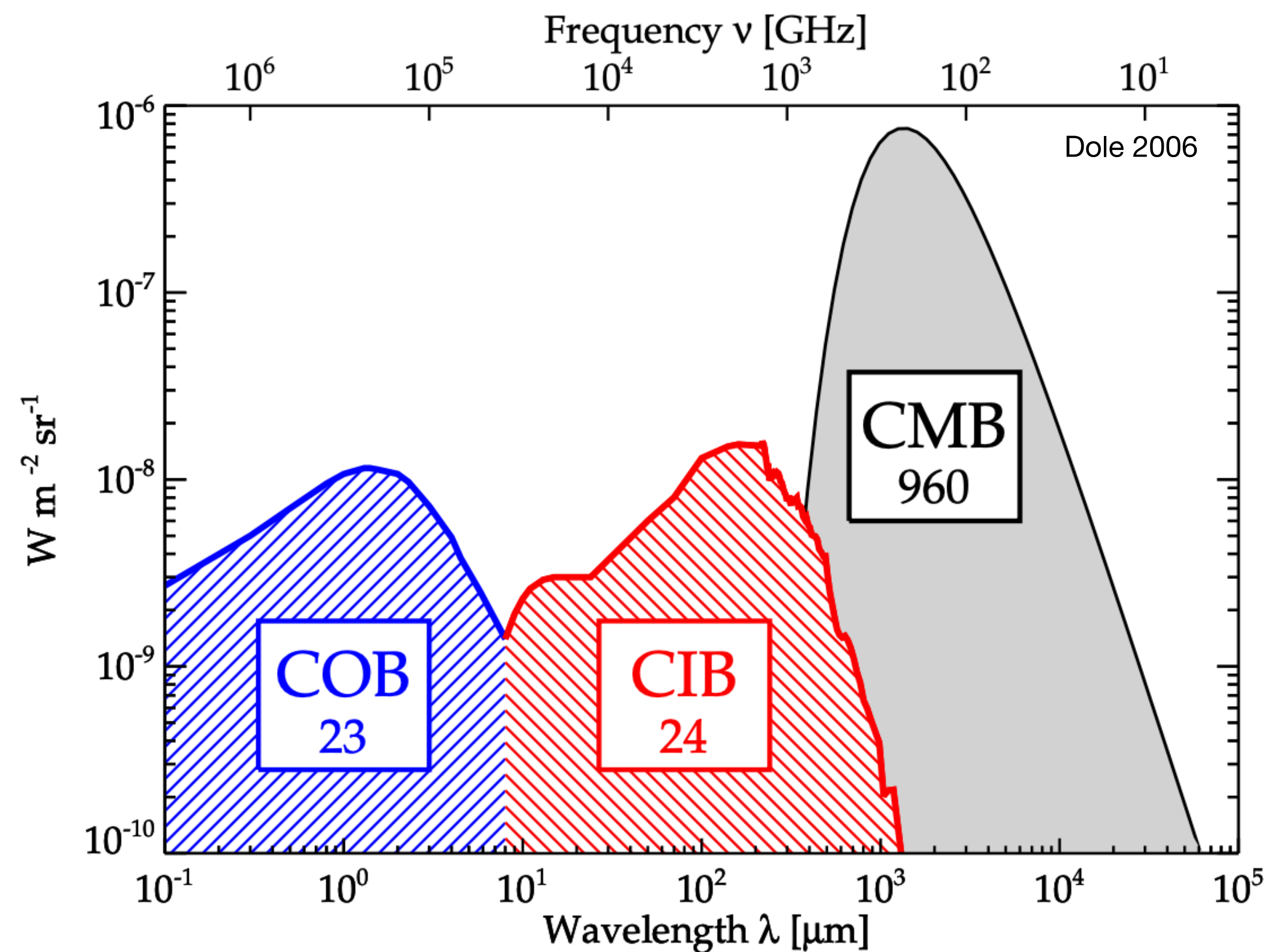
Quantum!

$$P \approx h\nu \cdot (n_\gamma / s)$$

Homework: relate flux to occupation number to bunching stats

Probes with light

10



~ very hot,
lot's of KE

~20K Gray body

2.7K Black
body

**Practically all of these photons
are thermal in origin**

$$B(\nu) = 2h\nu \left(\frac{\nu}{c}\right)^2 n(\nu)$$

↑
Quantum!

So, n is mostly boring:

$$n(\nu) \sim \frac{\epsilon(\nu)}{(\exp(h\nu/k_B T_\star) - 1)}$$

Not obvious if QS can revolutionize
Astrophysics in broad-strokes

So

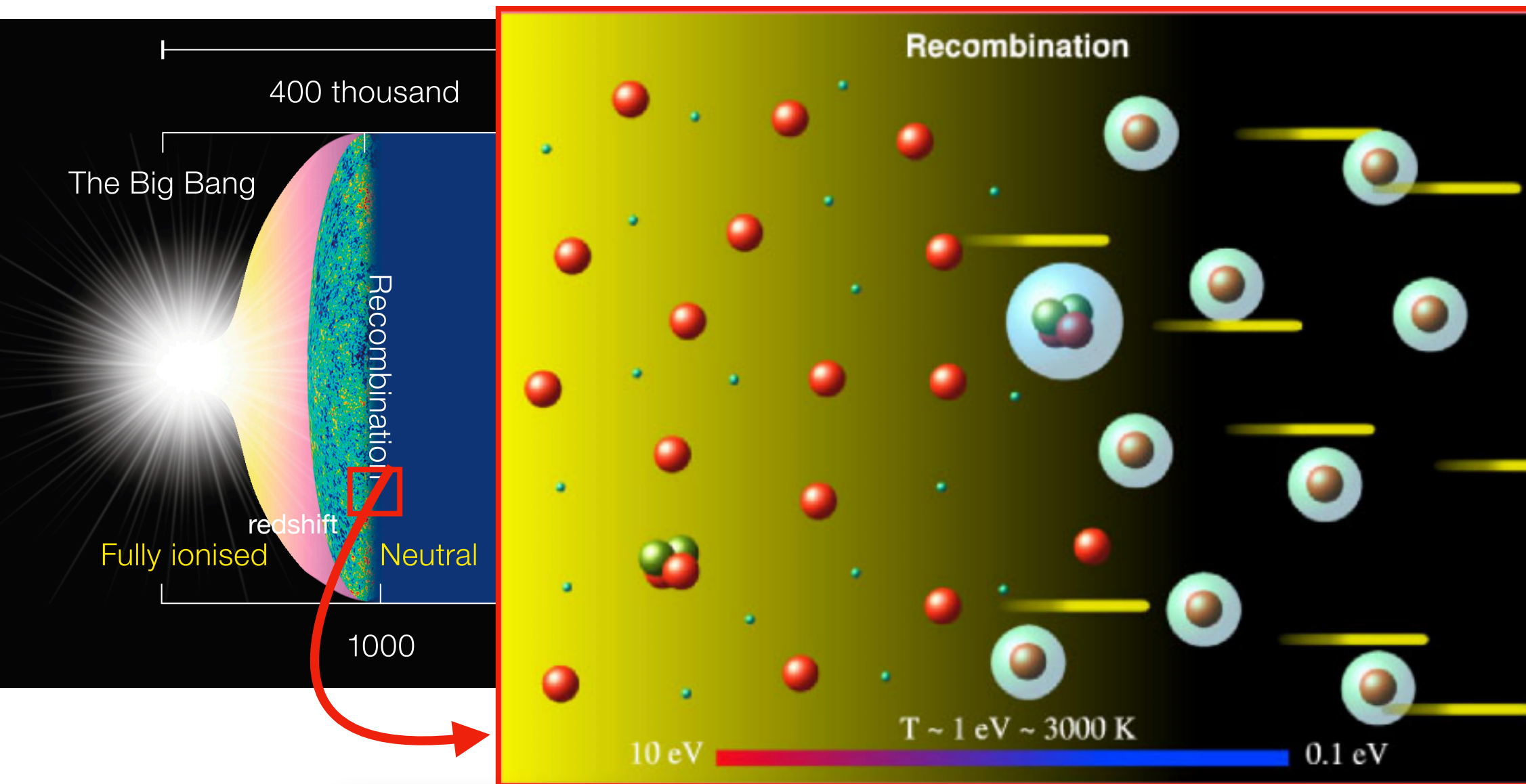
11

Why give this lecture? Why am I here?

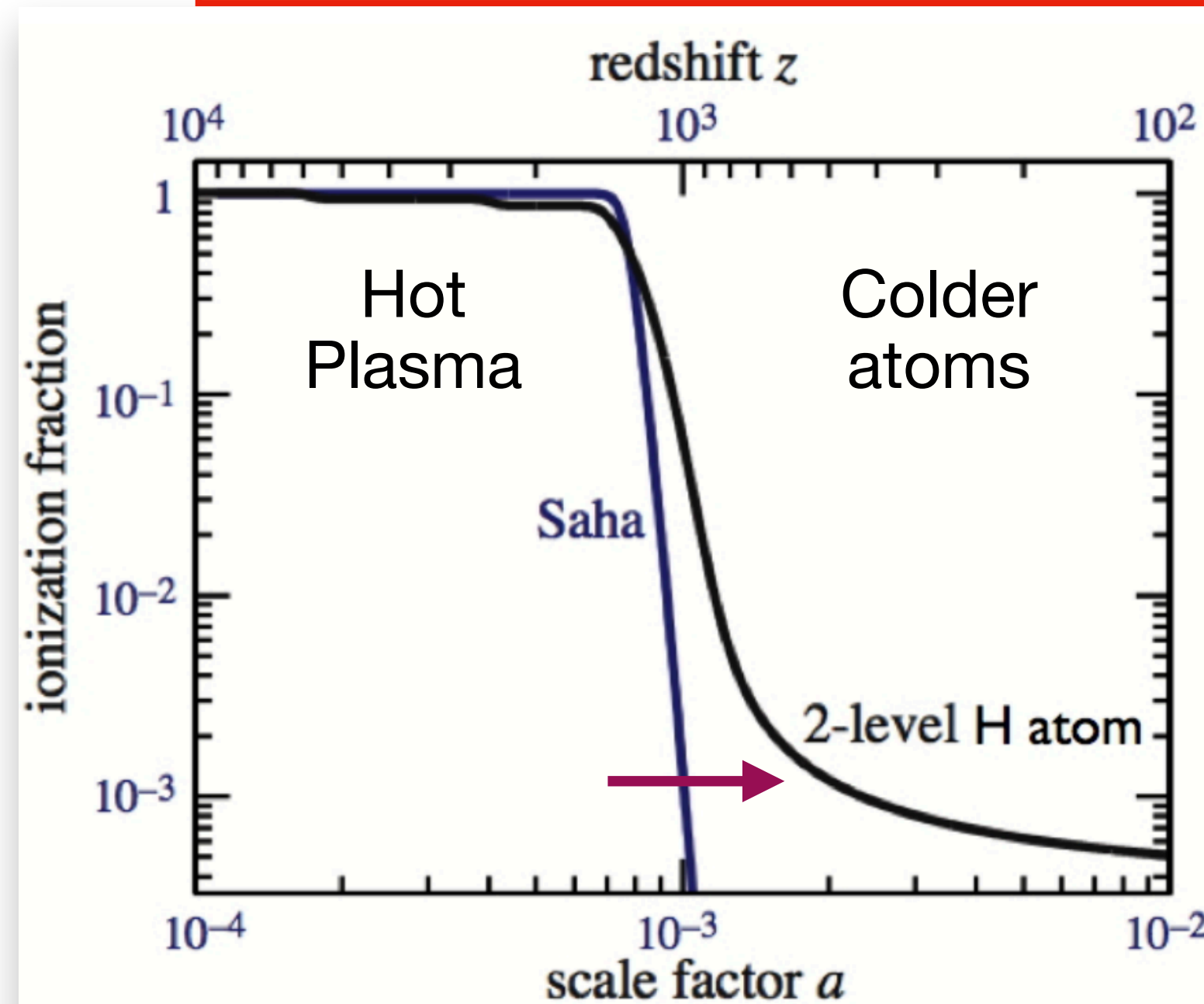
Careful case-by-case science $\Leftrightarrow$ technology
development showcases quantum advantage

**JPL Q-tech enabling Cosmo./Astro. for NASA
(and backing DOE efforts) will be discussed**

S.C. physics, see O' Brien, Ramanathan, Chang, Baxter and others, SSI'26



Hot & dense universe after the Big Bang
Expansion, increasing redshift → Cooling



Neutral atoms form when it's just cold enough
... sudden transparency everywhere at once

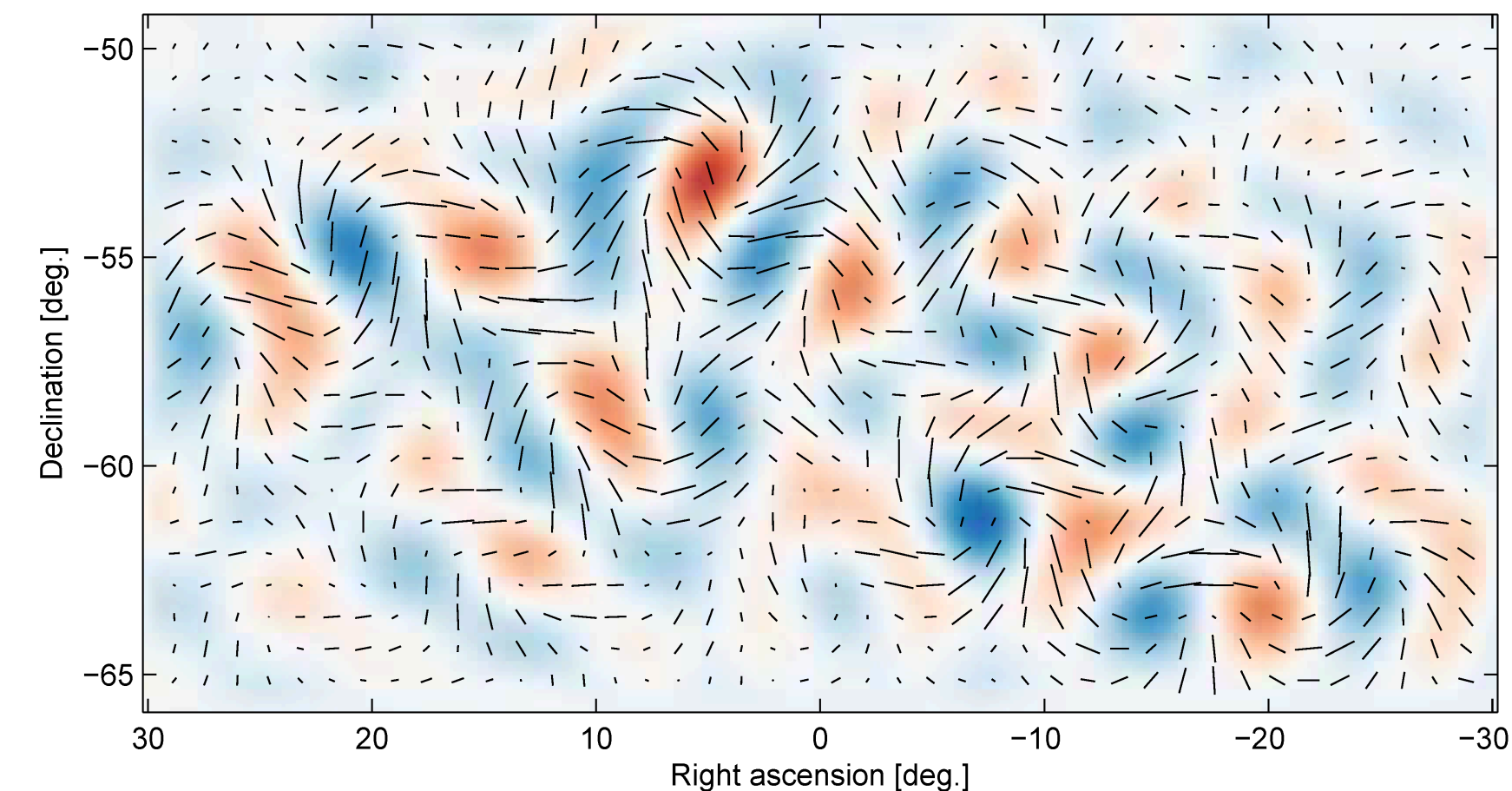
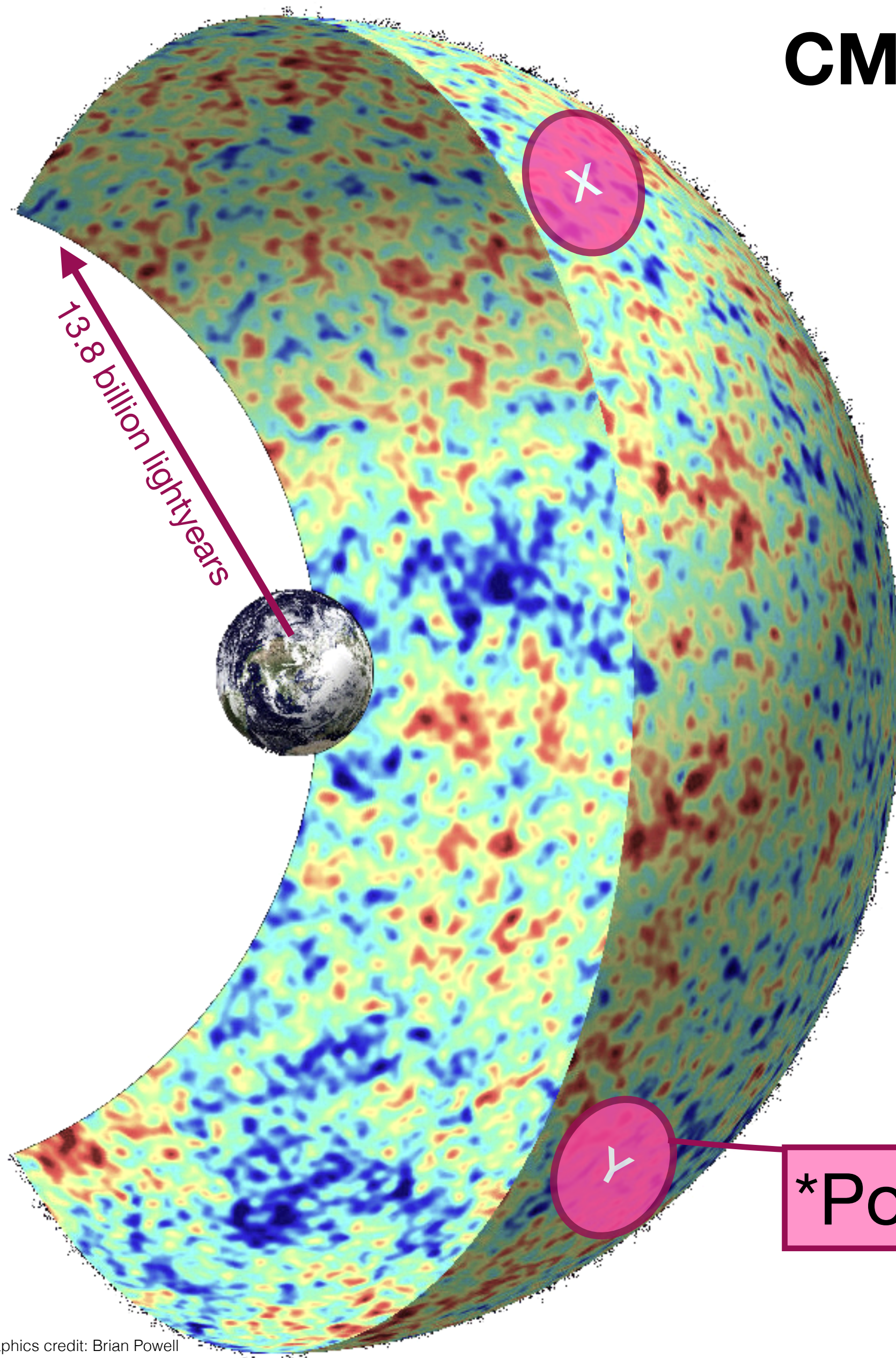
These free streaming photons, considering red-shifting, constitutes the CMB

CMB, 2.7 K BB texture at the scale of μK - nK encodes:

Abundance of dark matter/ energy, baryons, neutrinos and photons, i.e., ΛCDM

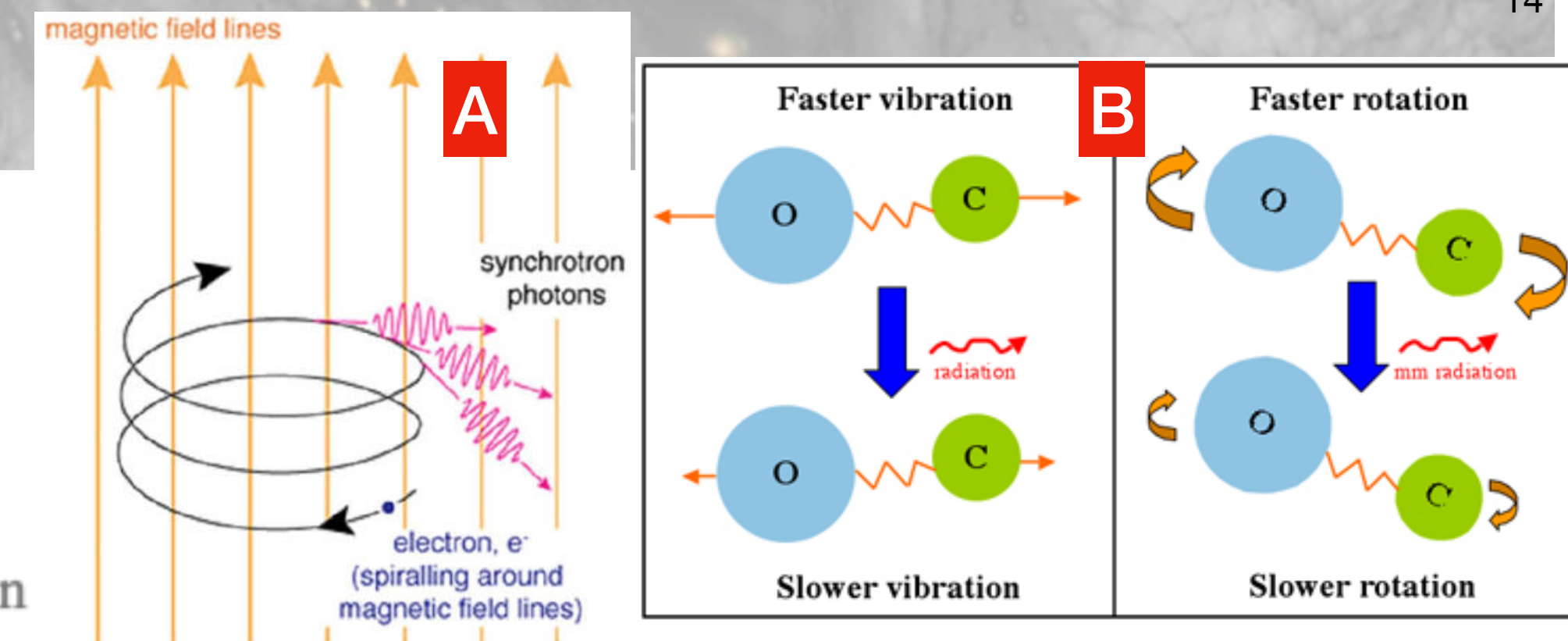
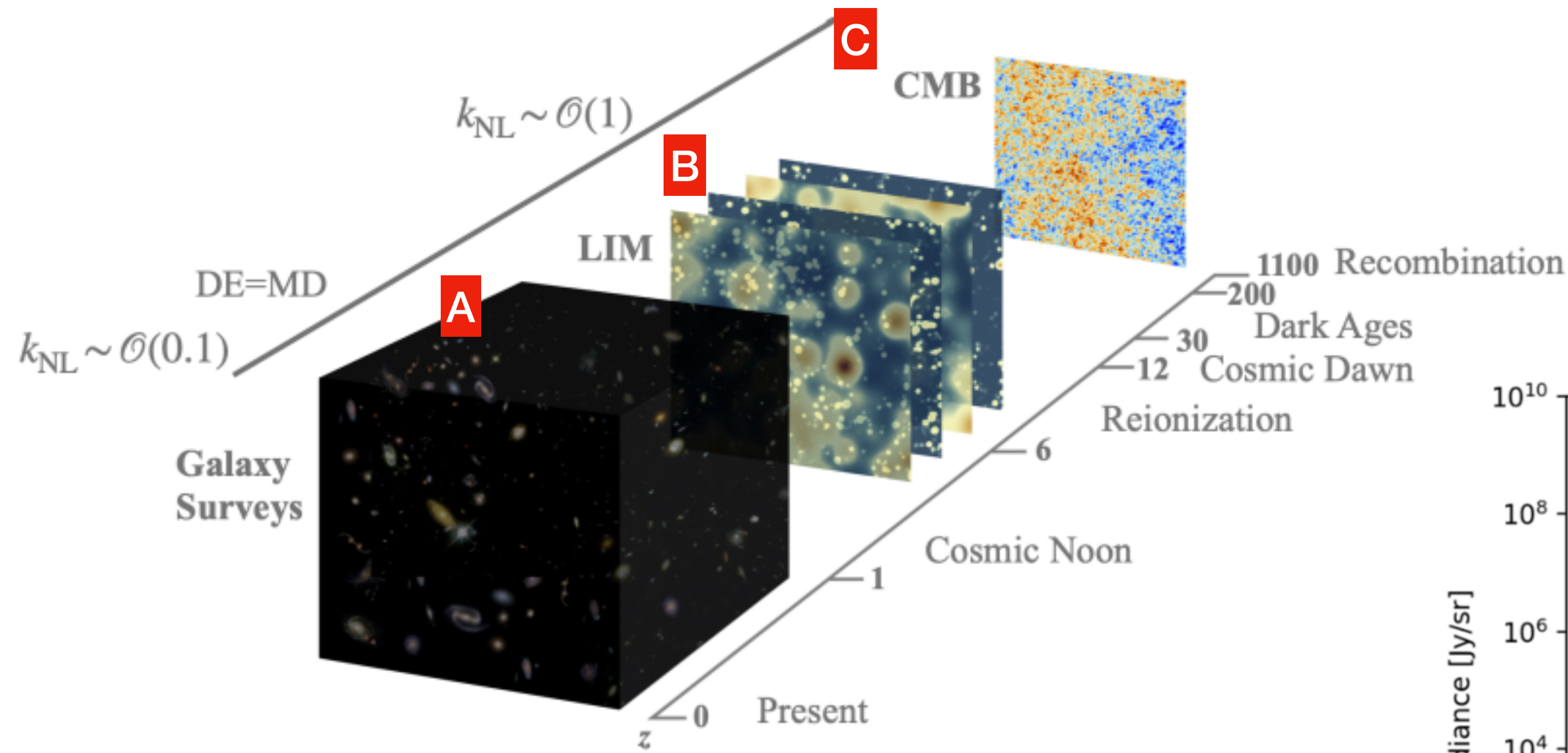
Age, size and curvature of the universe

Primordial fluctuations & *correlations* encode inflation* (10^{16} GeV) which stretched out initial quantum fluctuations, leading to over-densities today (us)



*Polarized texture

CMB and LIM at cm-waves

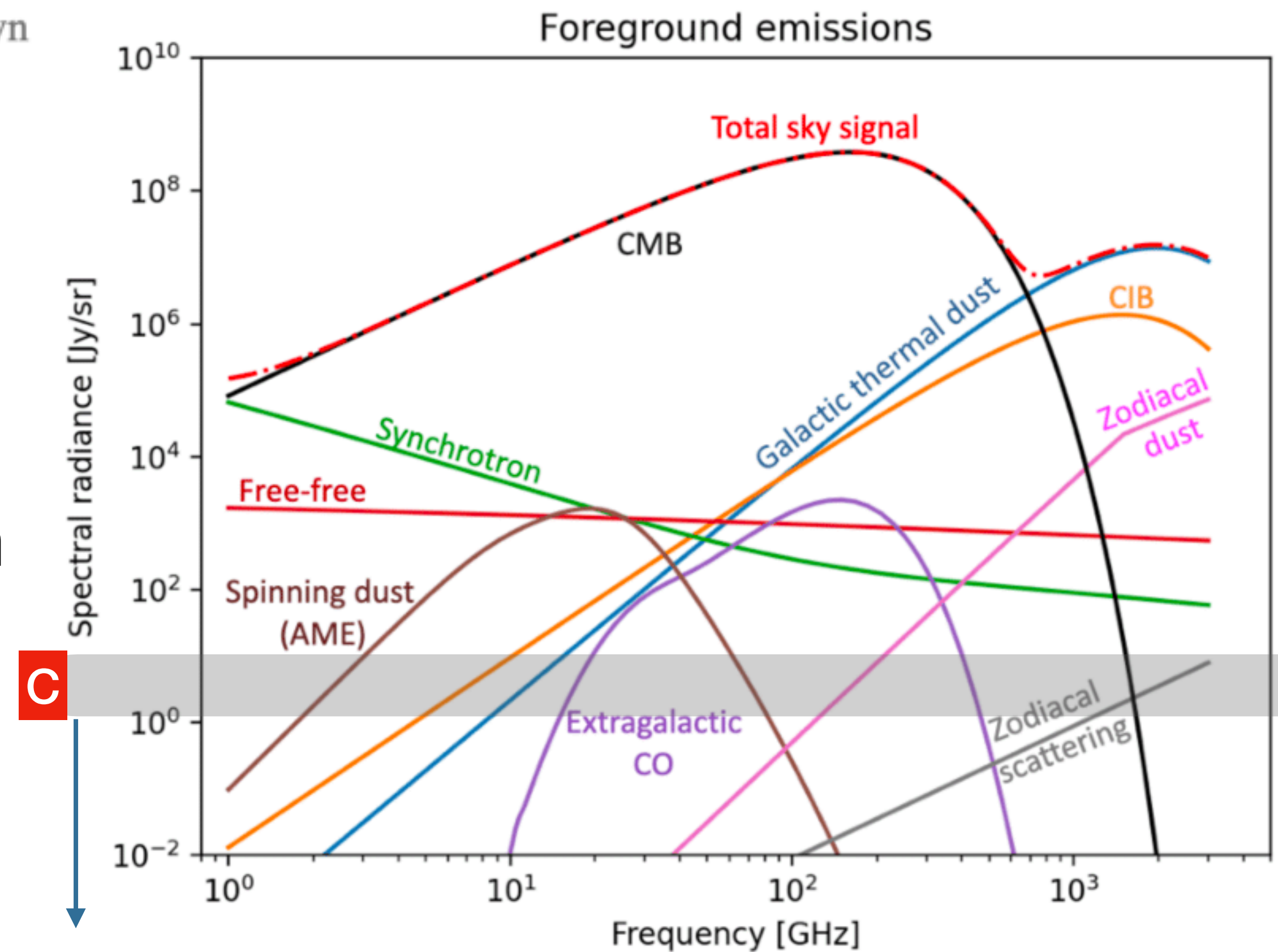


But there's literally the whole universe between the CMB and us!

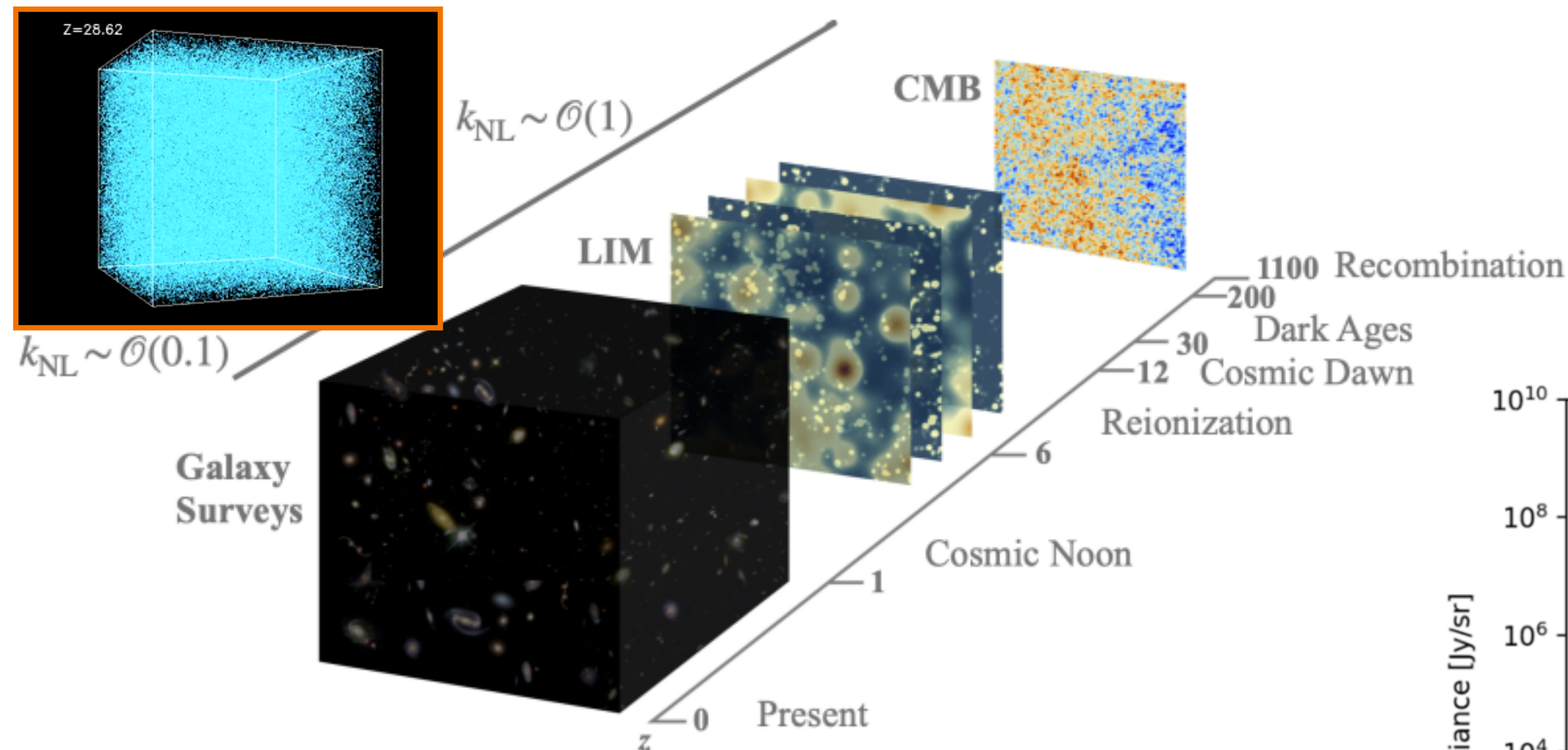
Huge number of complex foregrounds ...

Good science targets in their own right!

E.g. CO and synchrotron



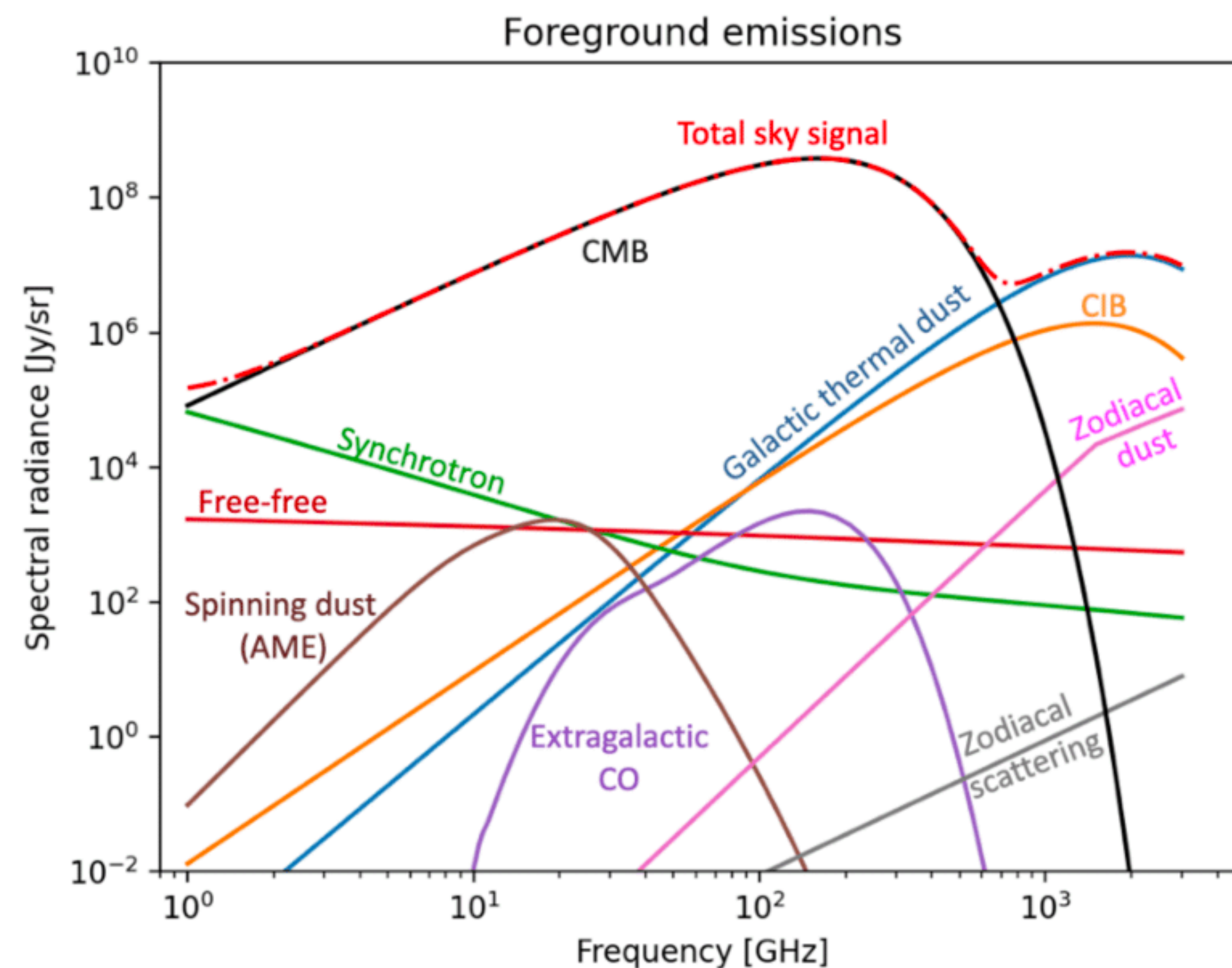
CMB sensitivity target for NASA Probe



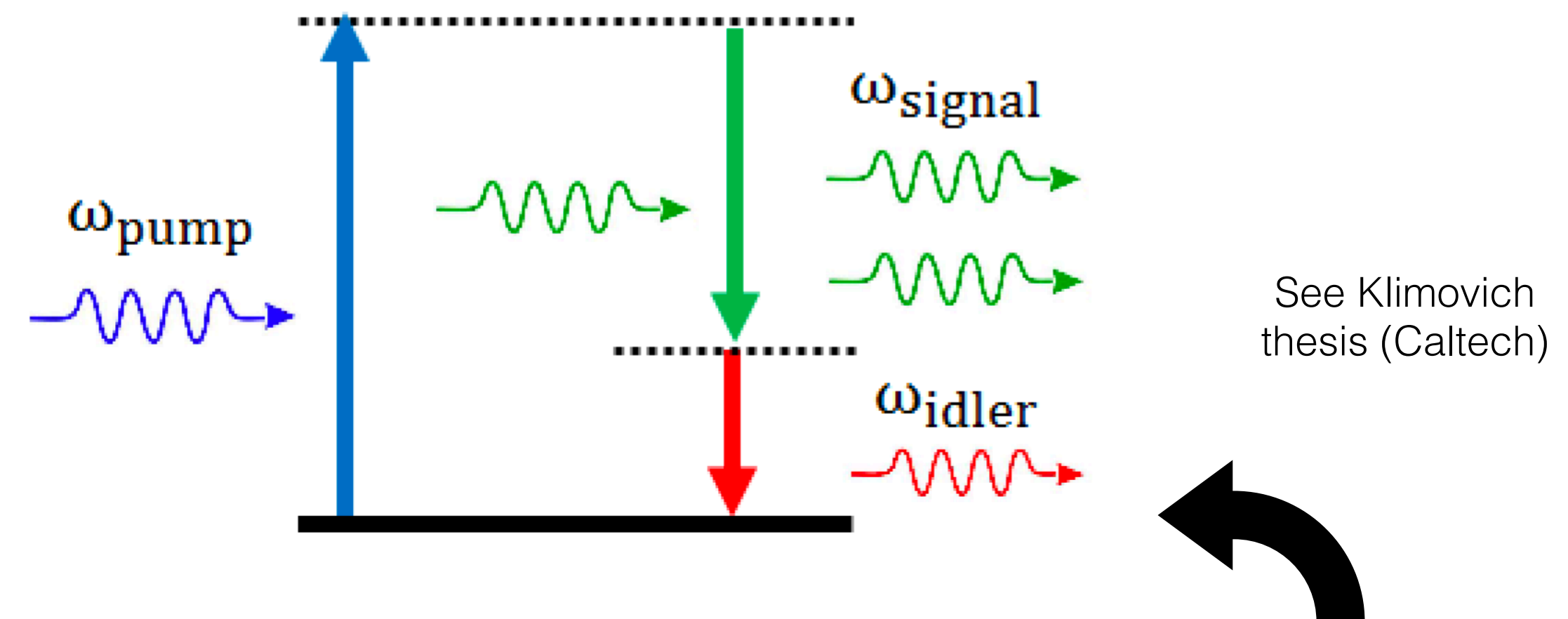
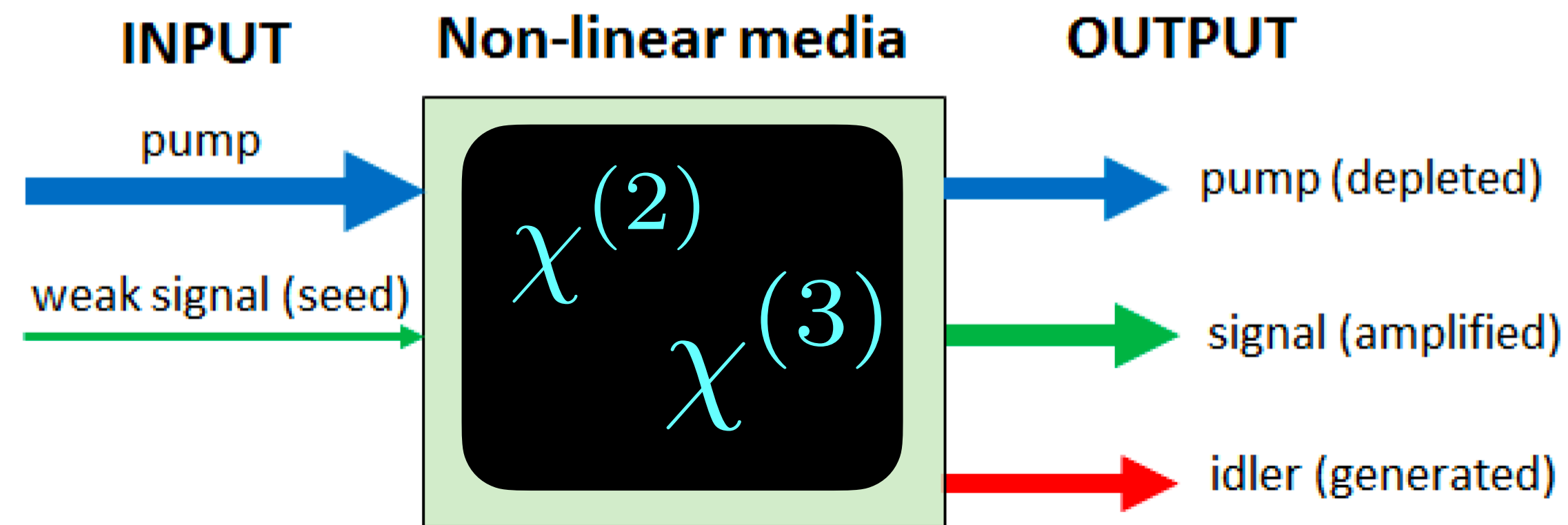
CO mapping (10-100 GHz, ~sub-GHz res.) synergistic with synchrotron science

CO in molecular clouds trace structure formation from $z = 7-0$ (13 Gyrs to present)

Mapping CO line intensity captures structure formation, DM/DE/gravity etc.



Traveling Wave Parametric Amplifiers (TWPAs)

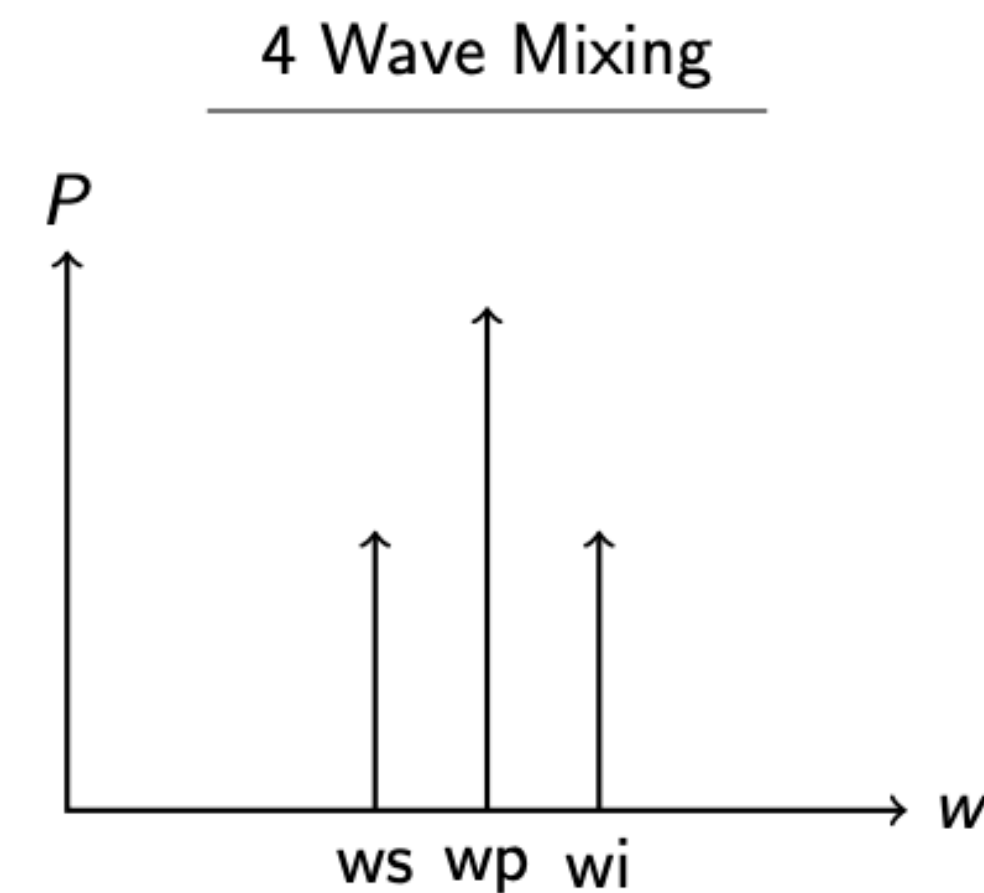


TWPAs are a common Quantum Optics tool

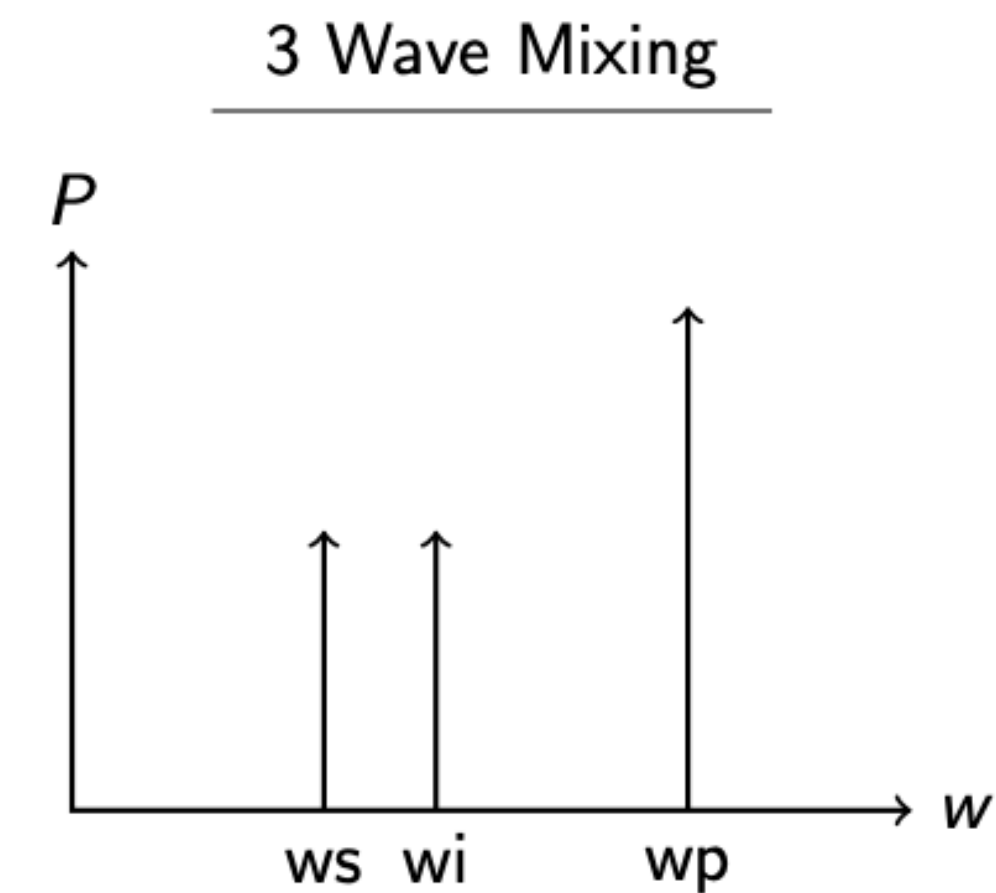
$$H_{\text{int}} = \hbar g_0 \sqrt{n_p} \left(a_s^\dagger a_i^\dagger e^{-i\omega_p t} + a_s a_i e^{+i\omega_p t} \right)$$

A nonlinear medium enables mixing of tones

Done optimally, phased power from a strong pump amplifies a weak signal



$$2\omega_p = \omega_s + \omega_i$$



$$\omega_p = \omega_s + \omega_i$$

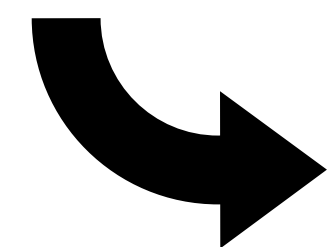
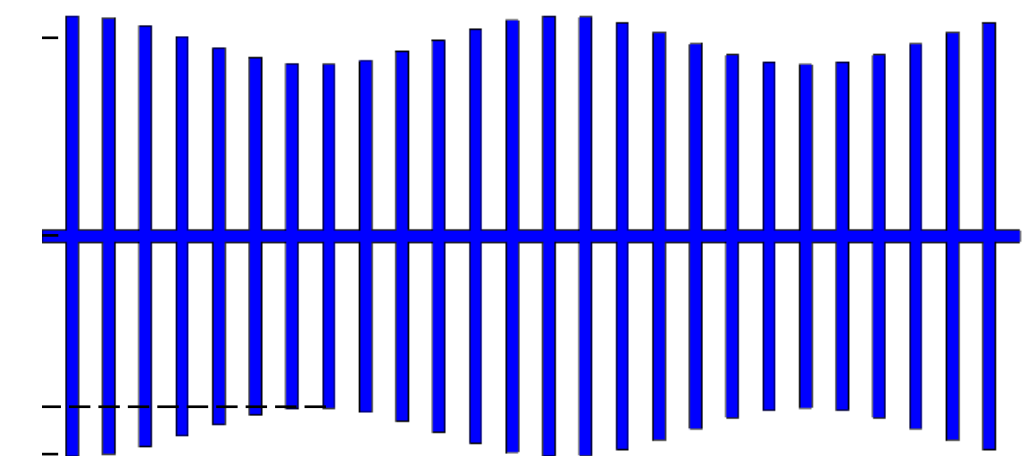


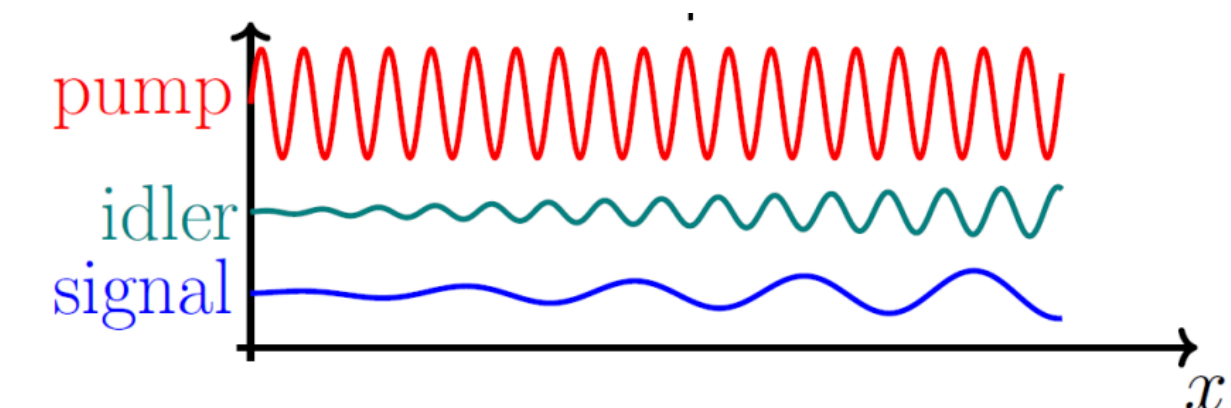
Figure 1 consists of two panels. The left panel is a schematic diagram of a ladder network, showing a series of inductors (L) and capacitors (C) connected in a ladder configuration. The right panel is a scanning electron micrograph (SEM) of the device. It shows a central narrow transmission line and horizontal lines (fingers) used to tune the impedance of the high inductance (central) narrow transmission line. A scale bar at the bottom right indicates 40.0 μm. The SEM image also includes technical data: JPL 3.0kV 8.0mm x1.30k SE(UL).



$$\mathcal{L}(I) = \mathcal{L}_0 \left(1 + \left(\frac{I}{I_*} \right)^2 \dots \right) =$$

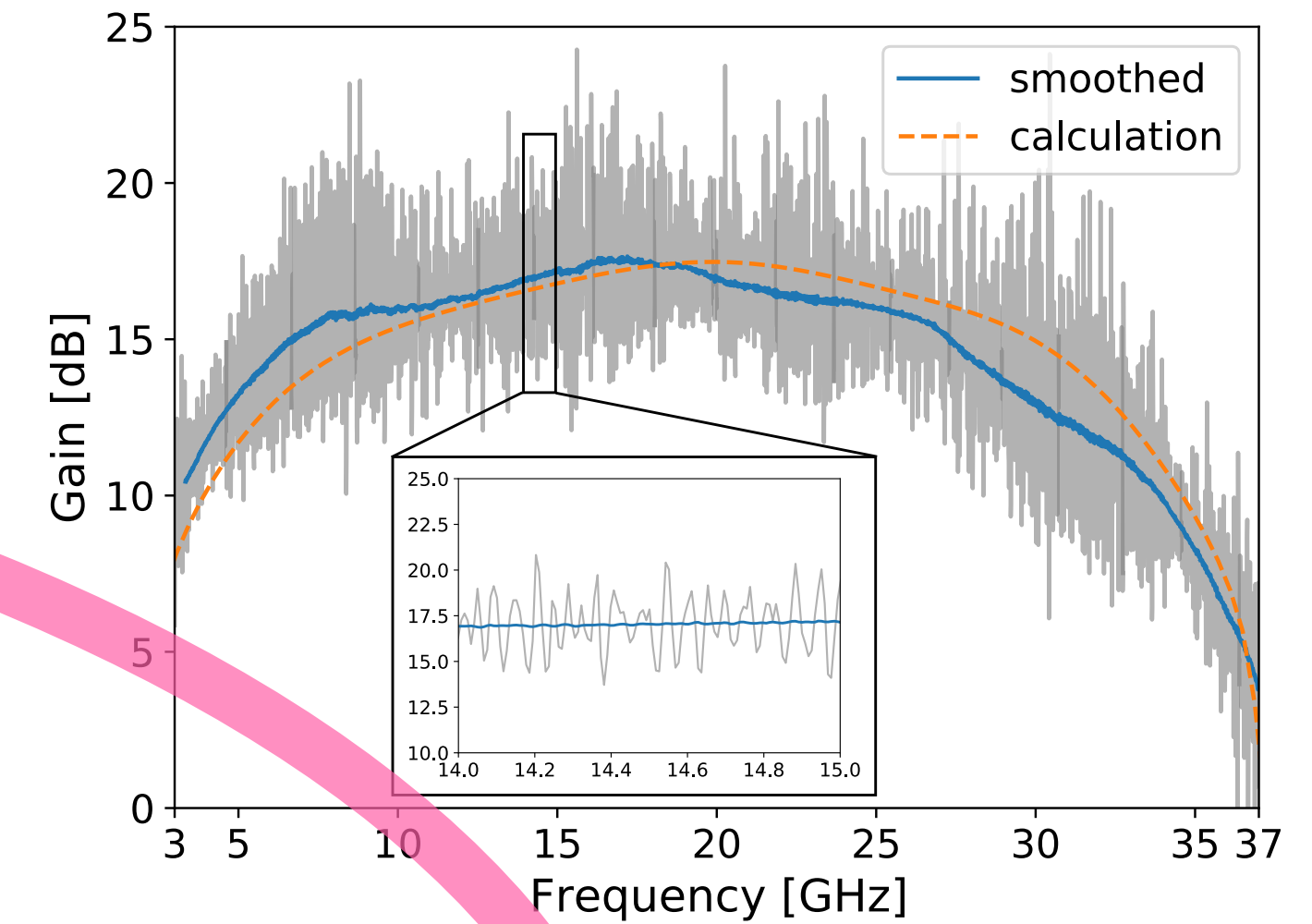
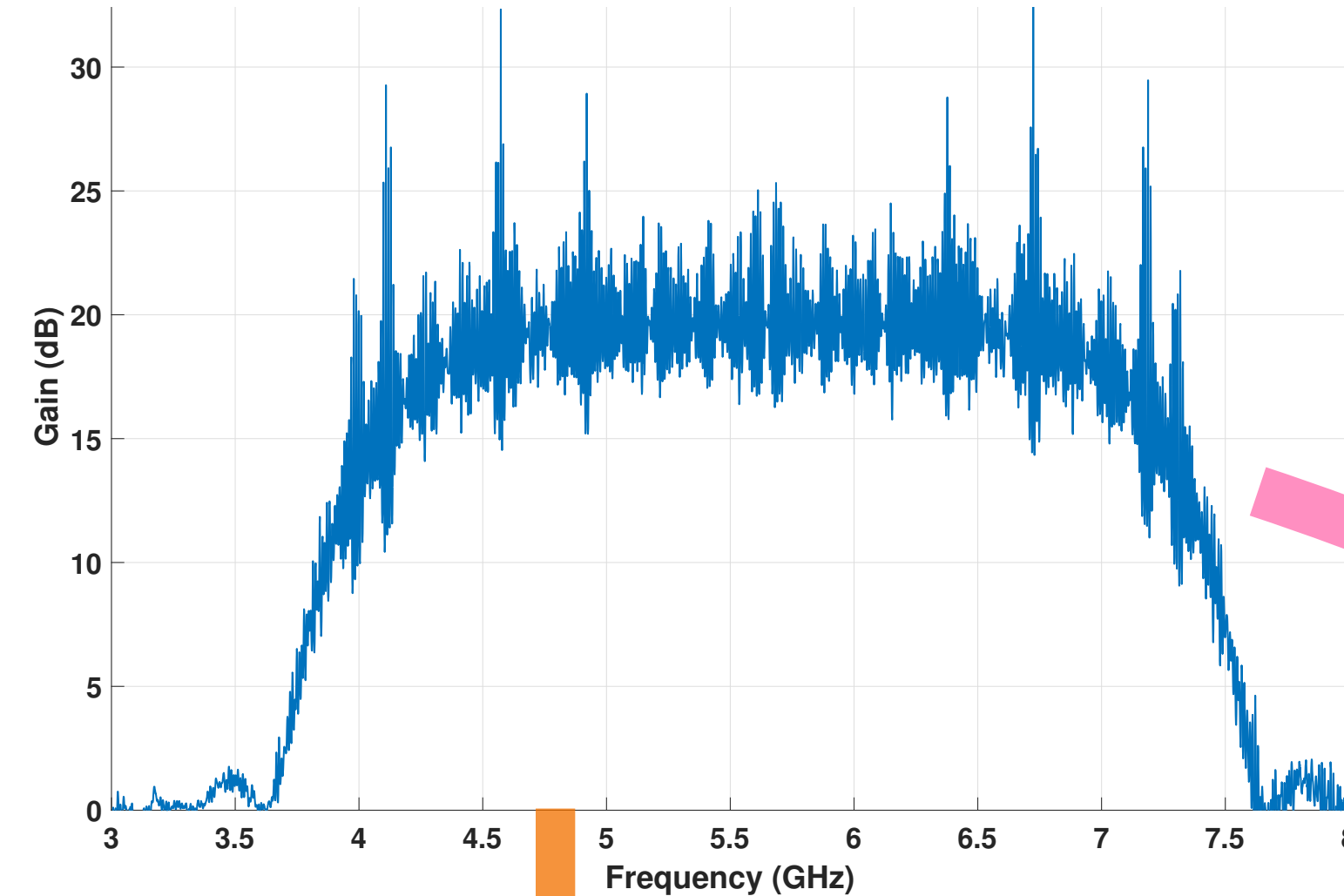
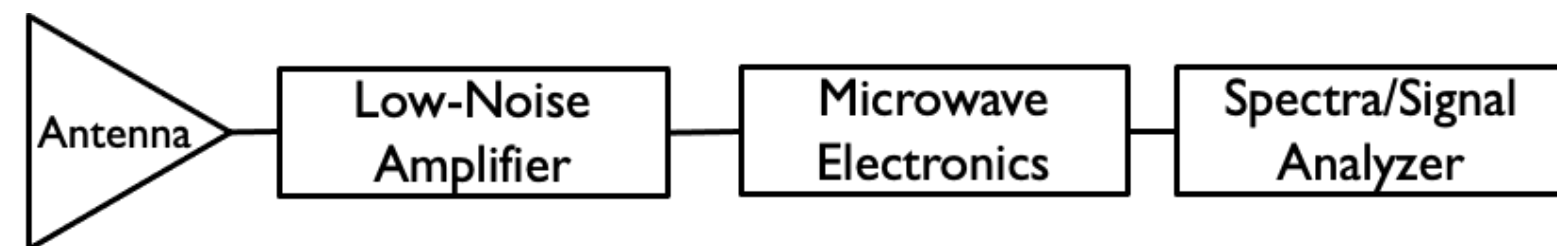
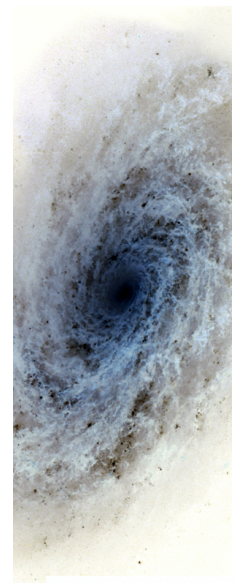


Phasing by modulating impedance along the line



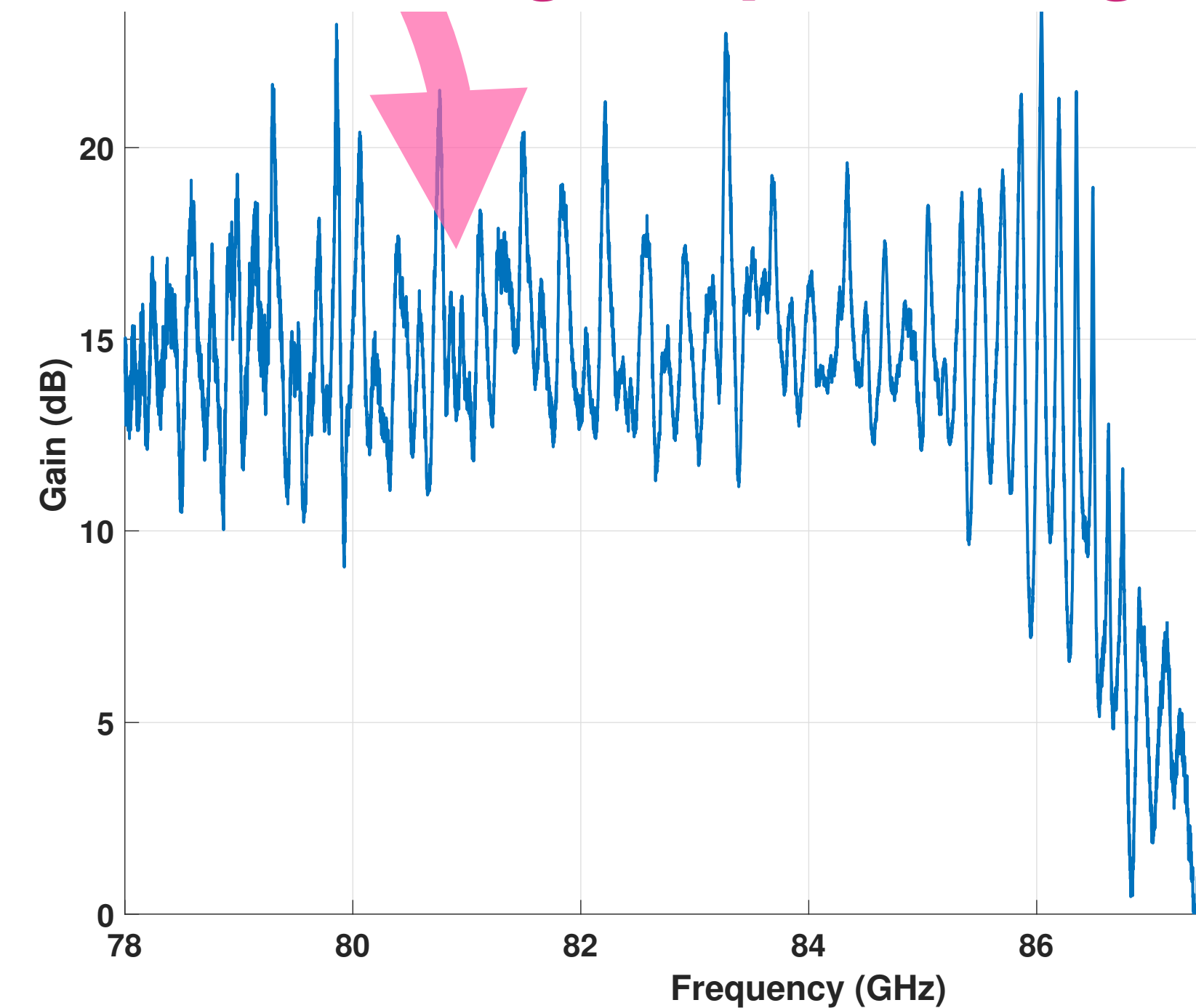
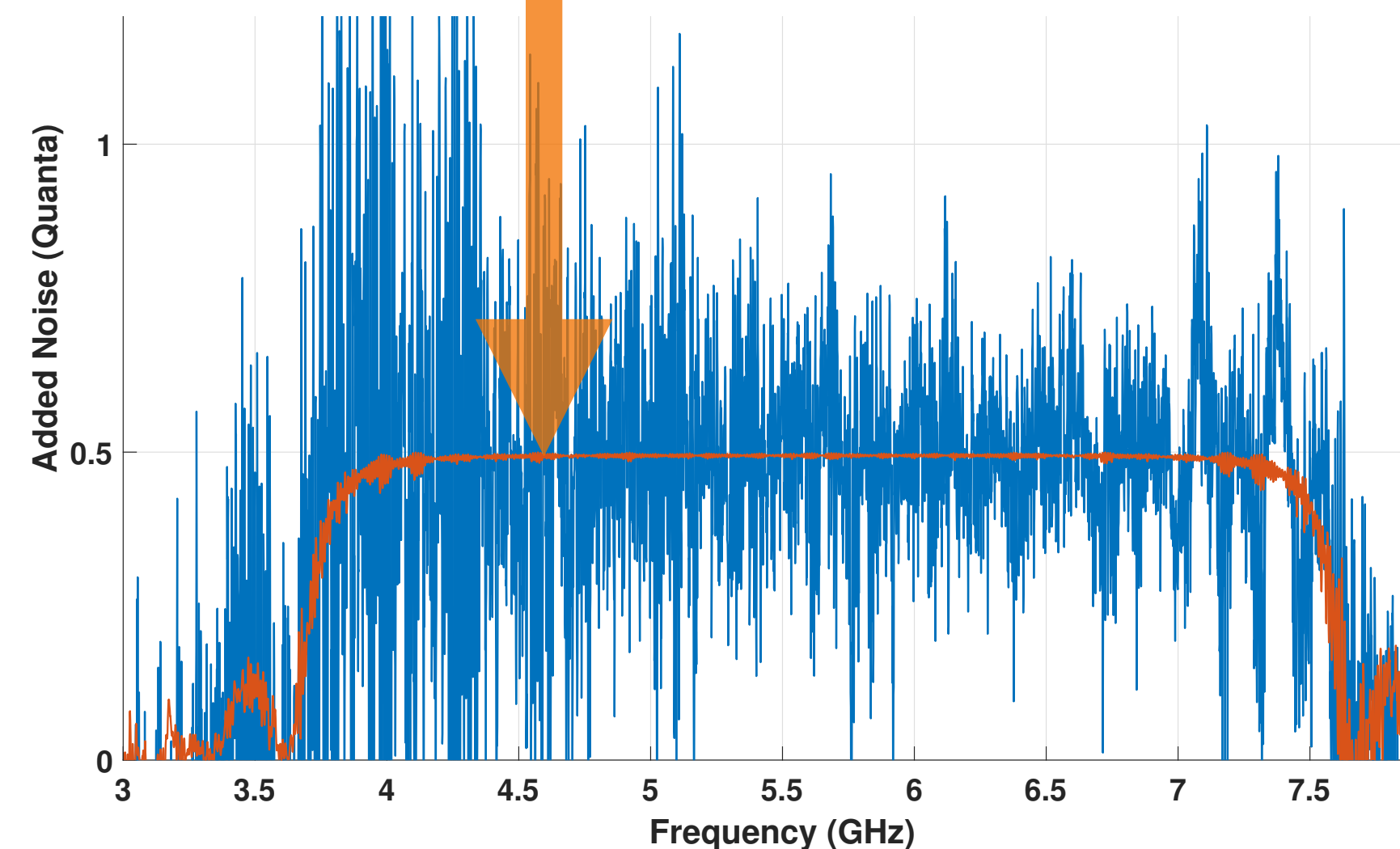
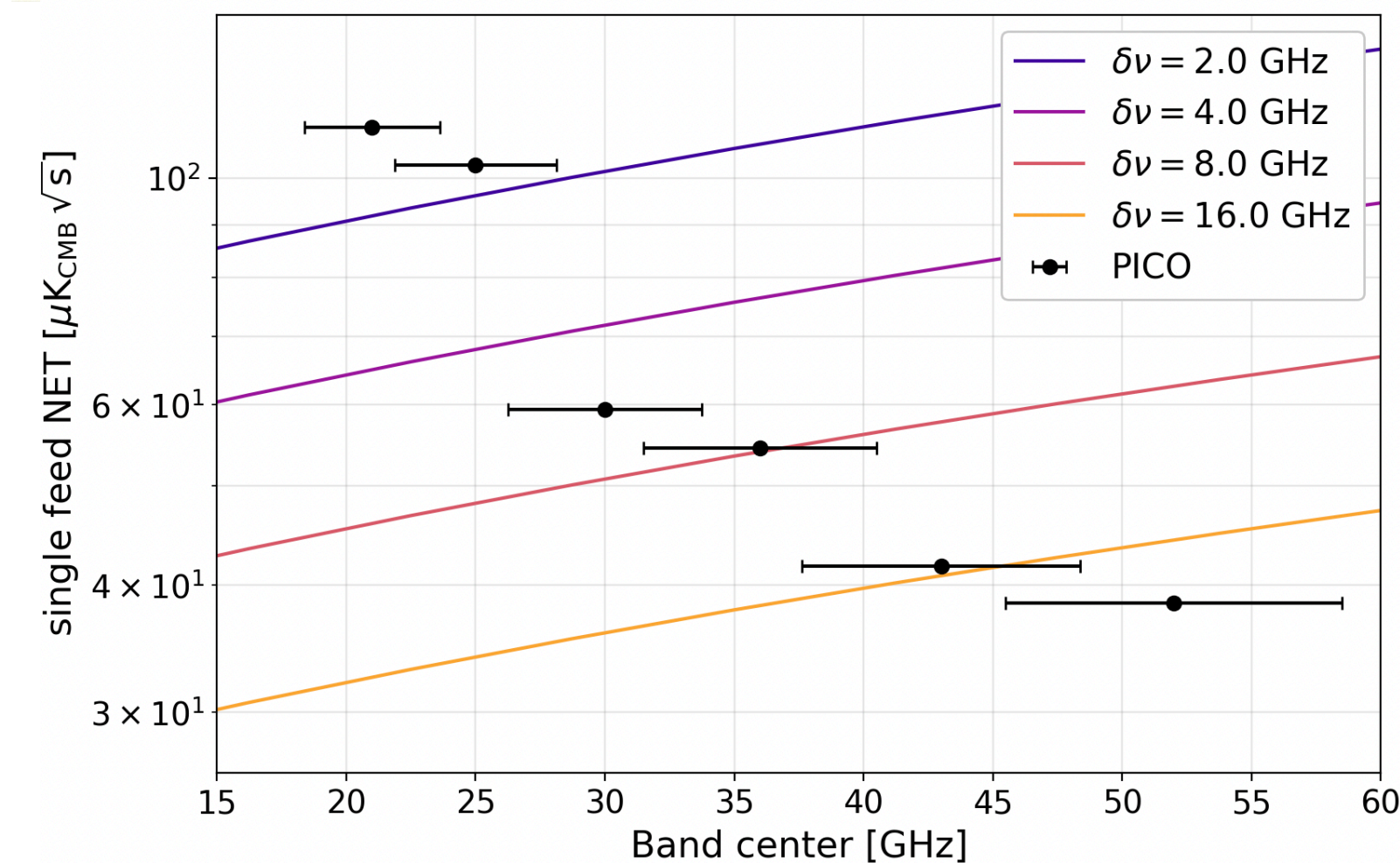
Building a quantum radiometer 1-100 GHz:

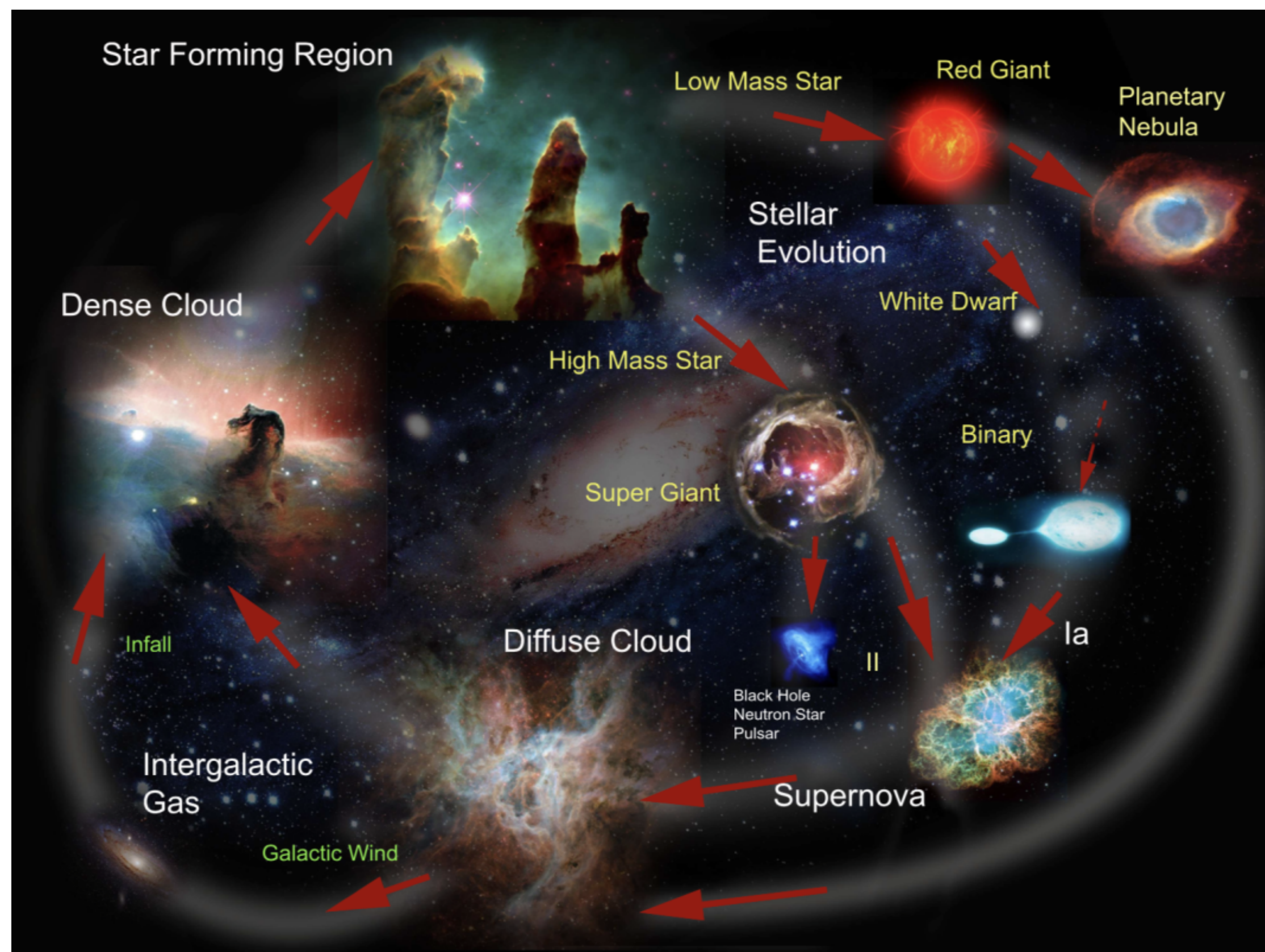
Over octaves, measure thousands of spectral channels, all at SQL !



Gain translates to noise quanta, SQL = 0.5

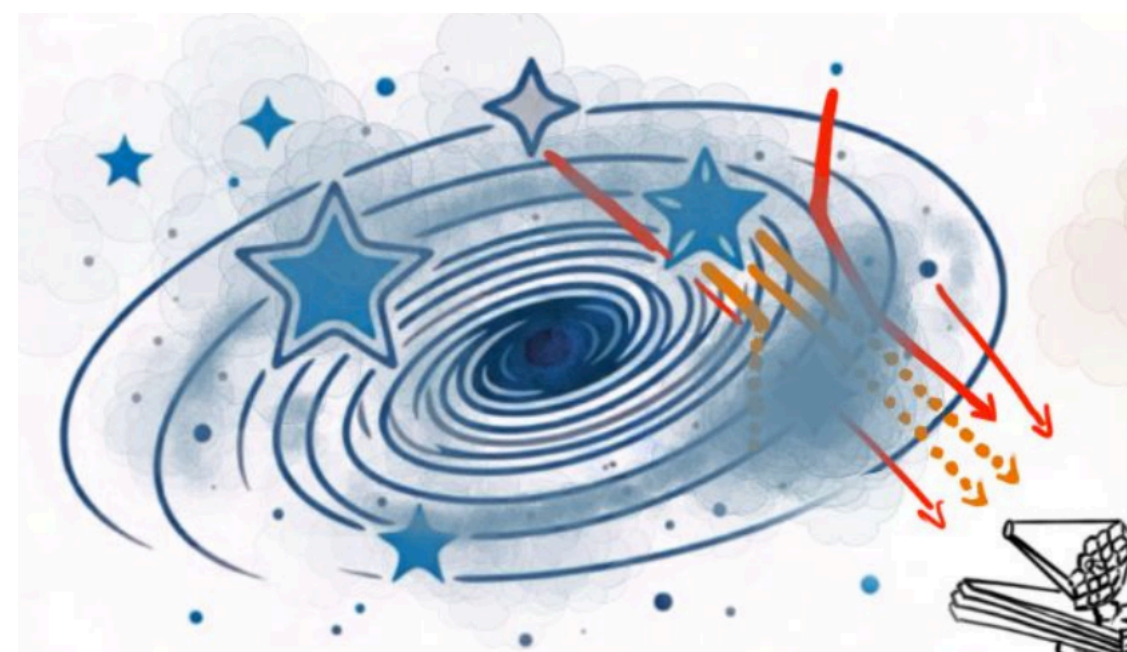
Ever increasing freq. coverage





Molecular / atomic excitations are at $\sim \text{eV}$ scale ($\sim \mu\text{m}$). H-atom, Quantum-101

Redshifting, moves these to far-IR



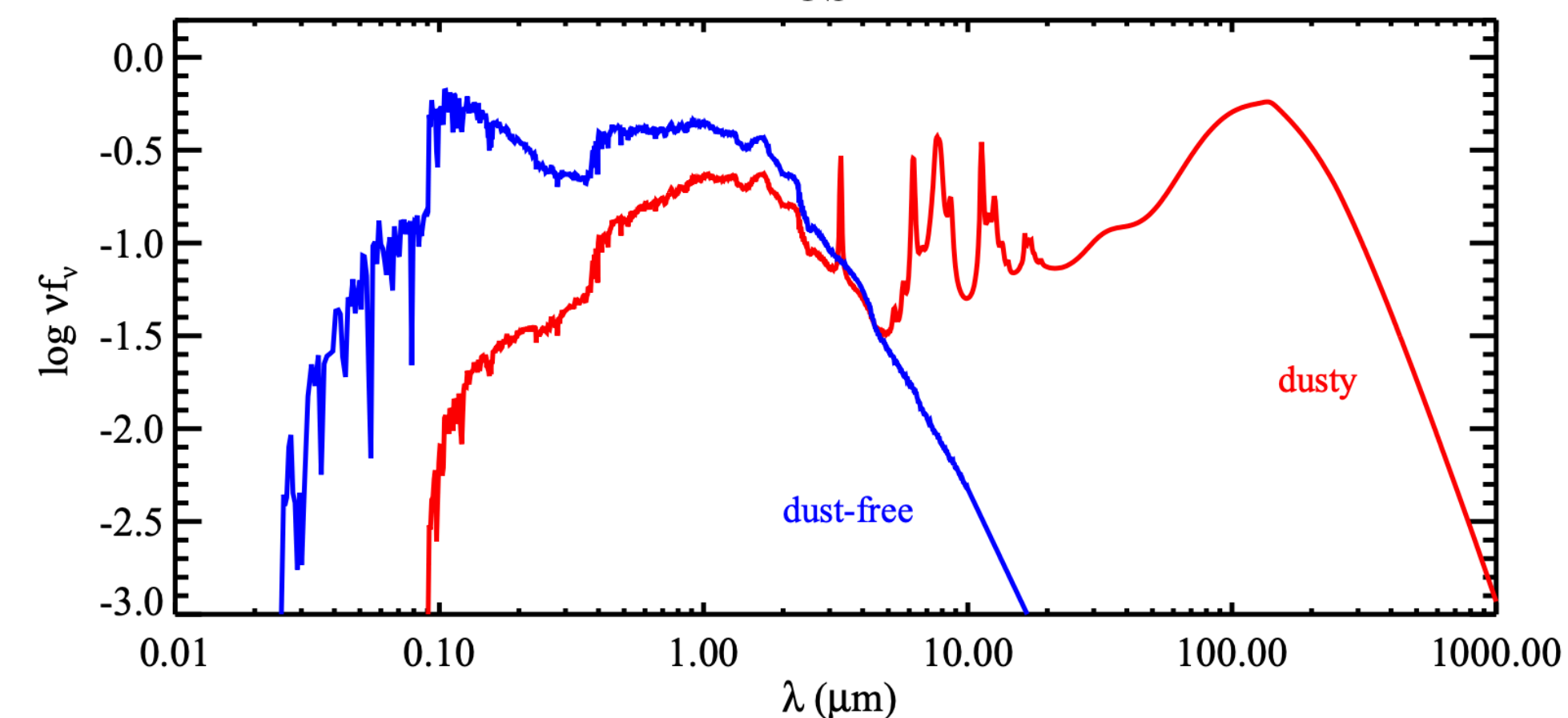
Extinction, scattering, reprocessing of UV/optical in interstellar dust far-IR is the only way



30 THz or
124 meV

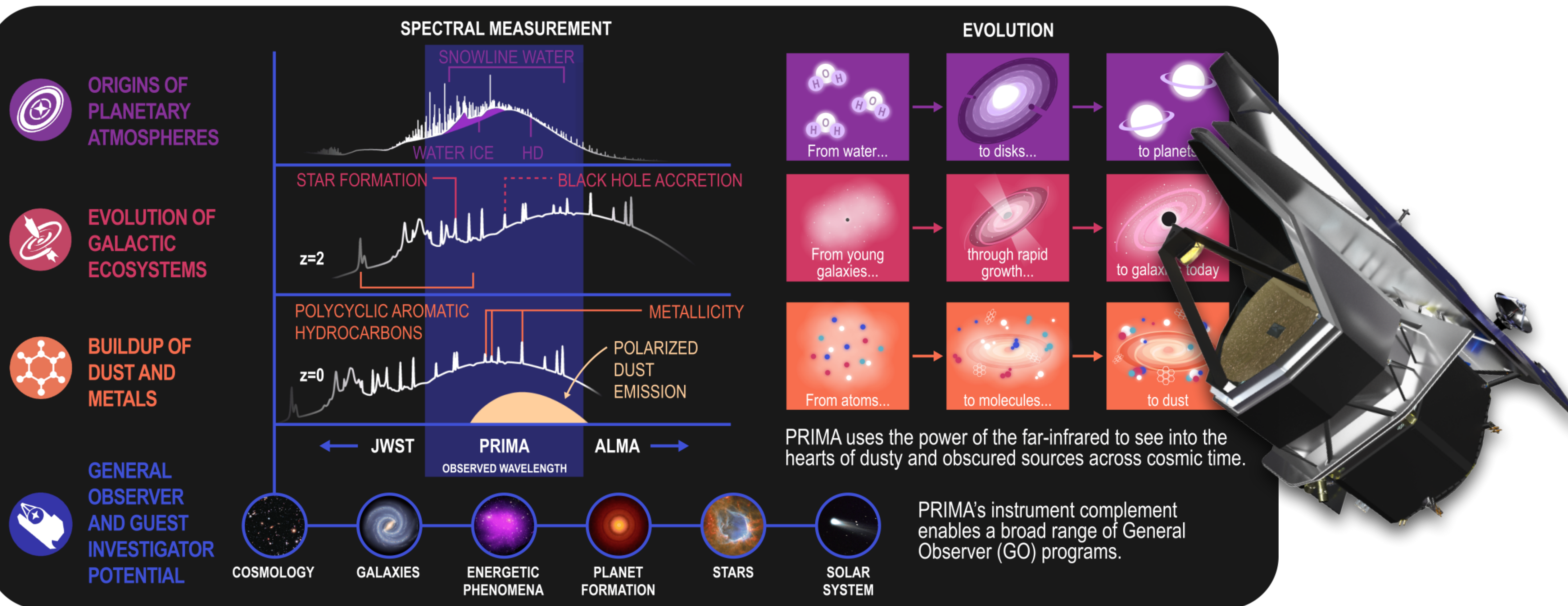
Wavelength λ [μm]

3 THz or
12.4 meV



Far-IR Astrophysics

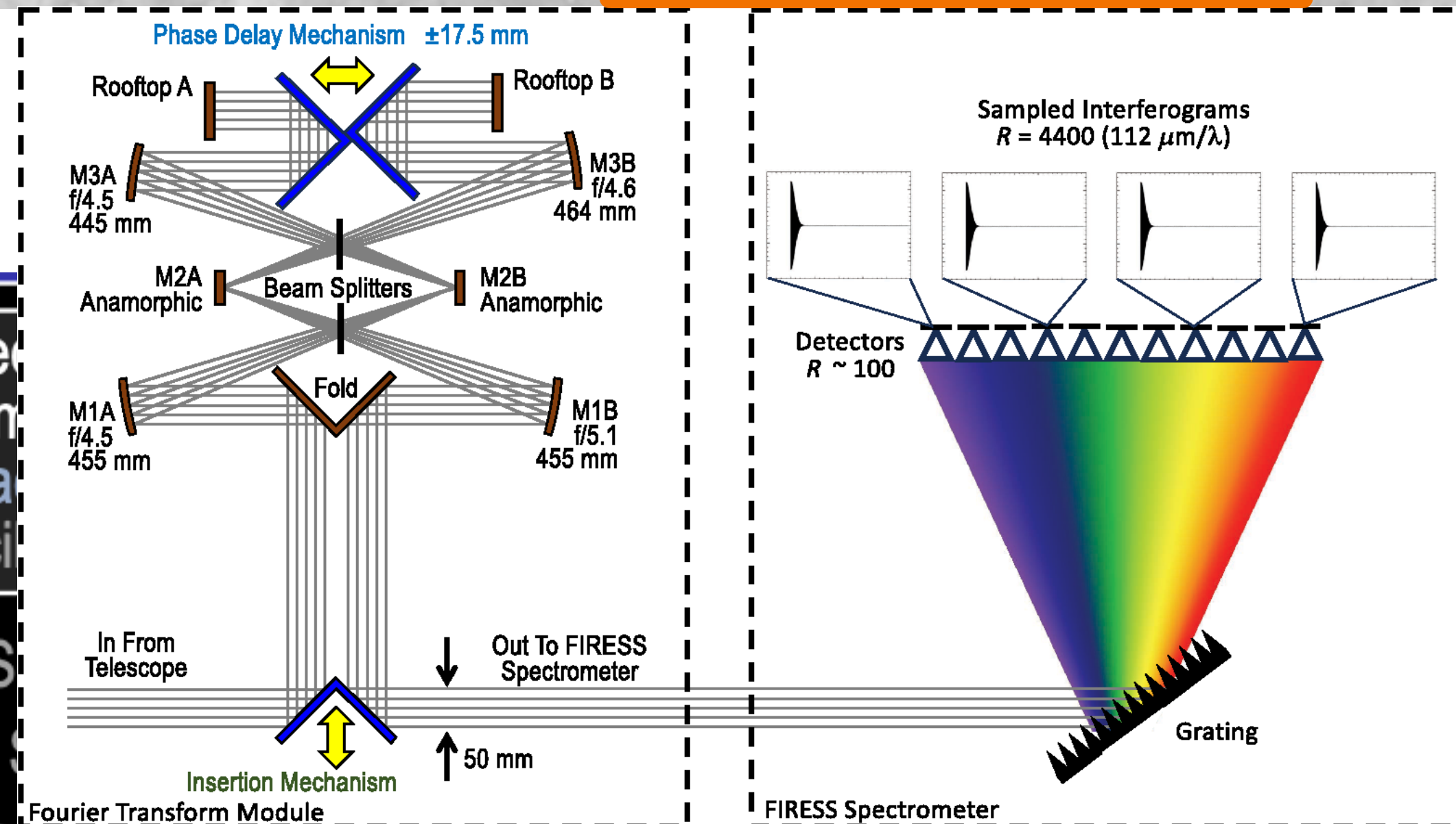
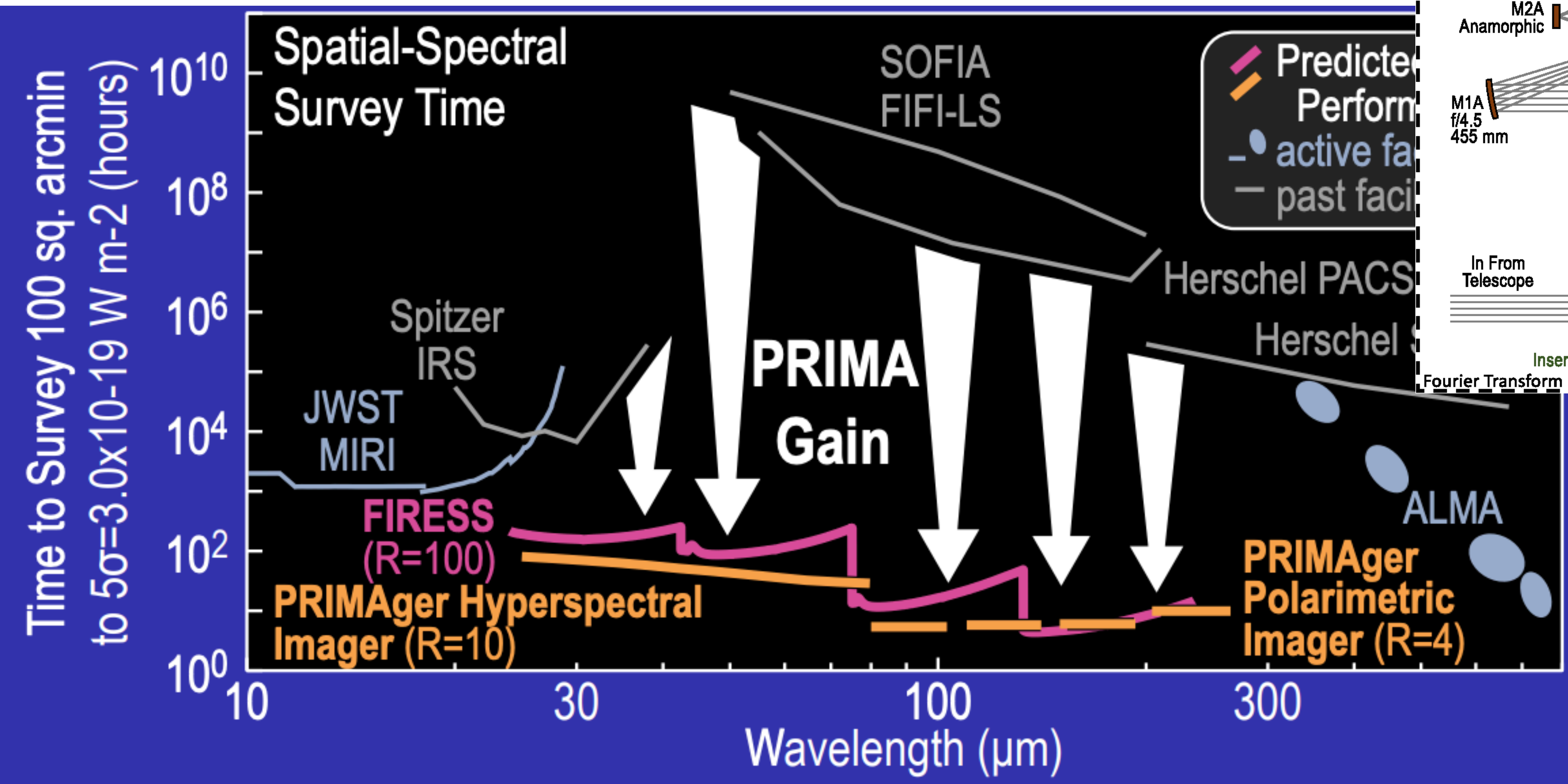
The PProbe for-Infrared Mission for Astrophysics



Massive community support behind this \$1B proposed mission, see:

<https://prima.ipac.caltech.edu/page/go-science-book-vol2>

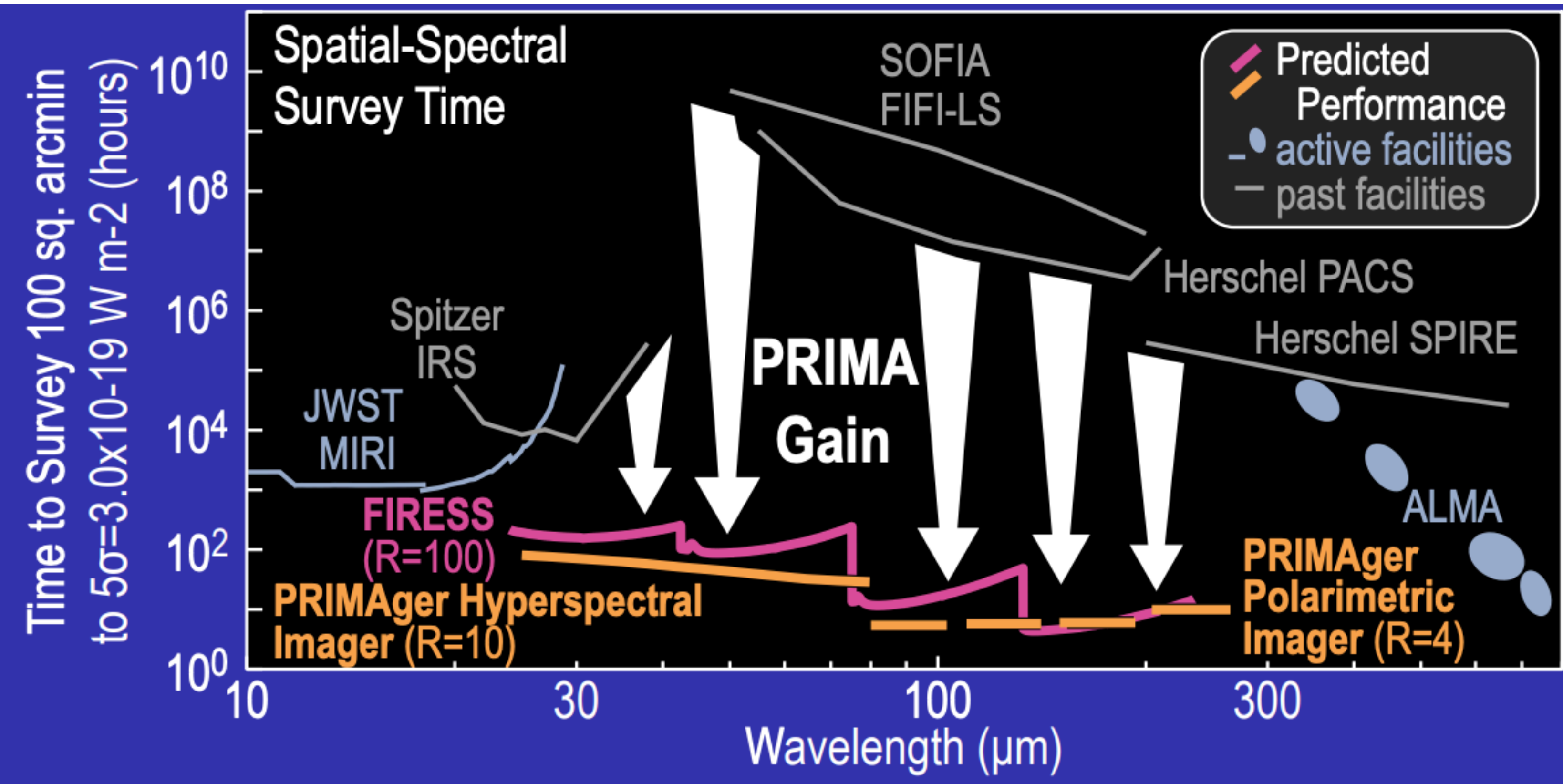
<https://prima.ipac.caltech.edu/page/fact-sheet>



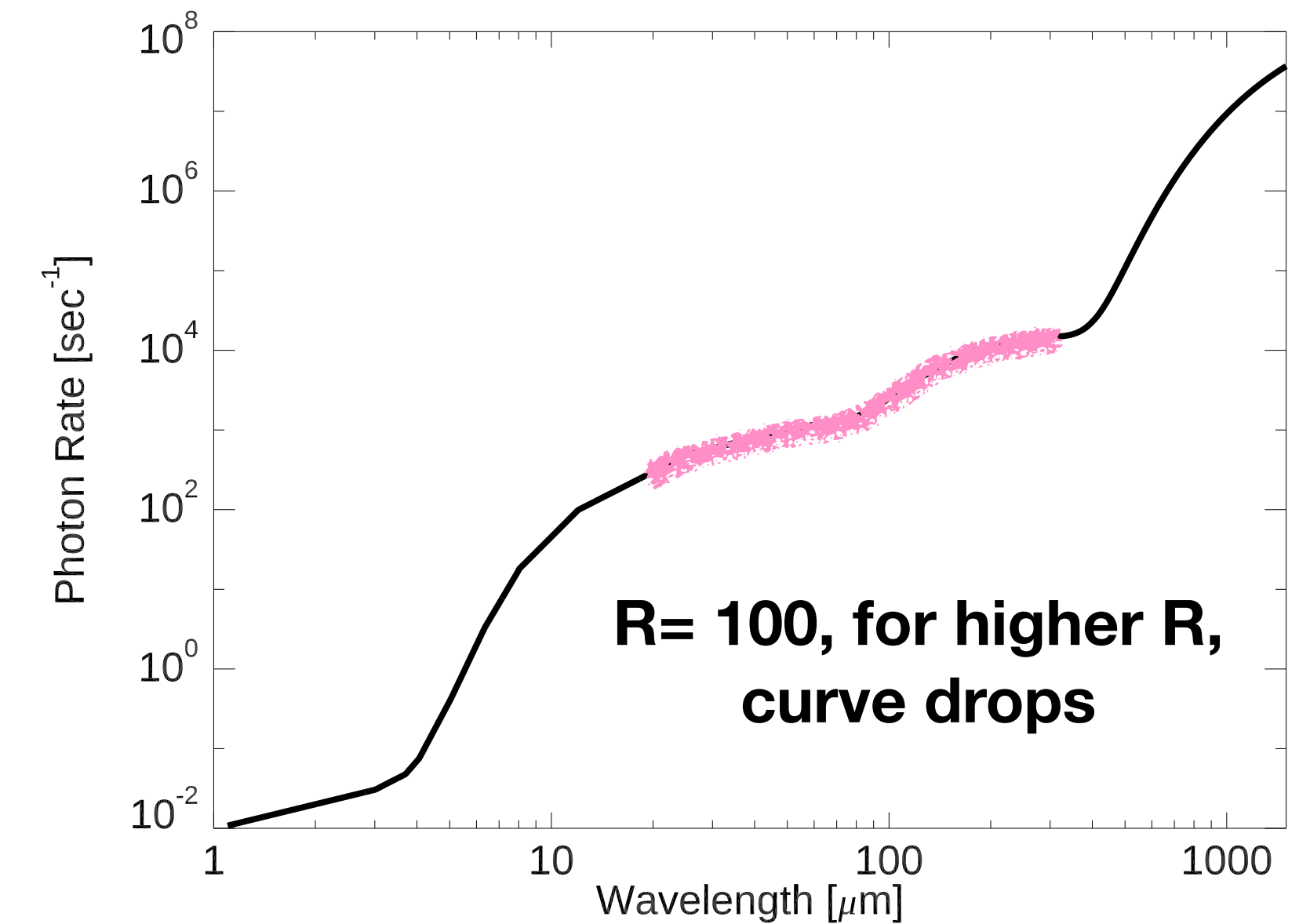
R is the mean number of spectral channels

$$R = \frac{\bar{\nu}}{\delta\nu} = \frac{\delta\lambda}{\bar{\lambda}}$$

PRIMA complements JWST & ALMA



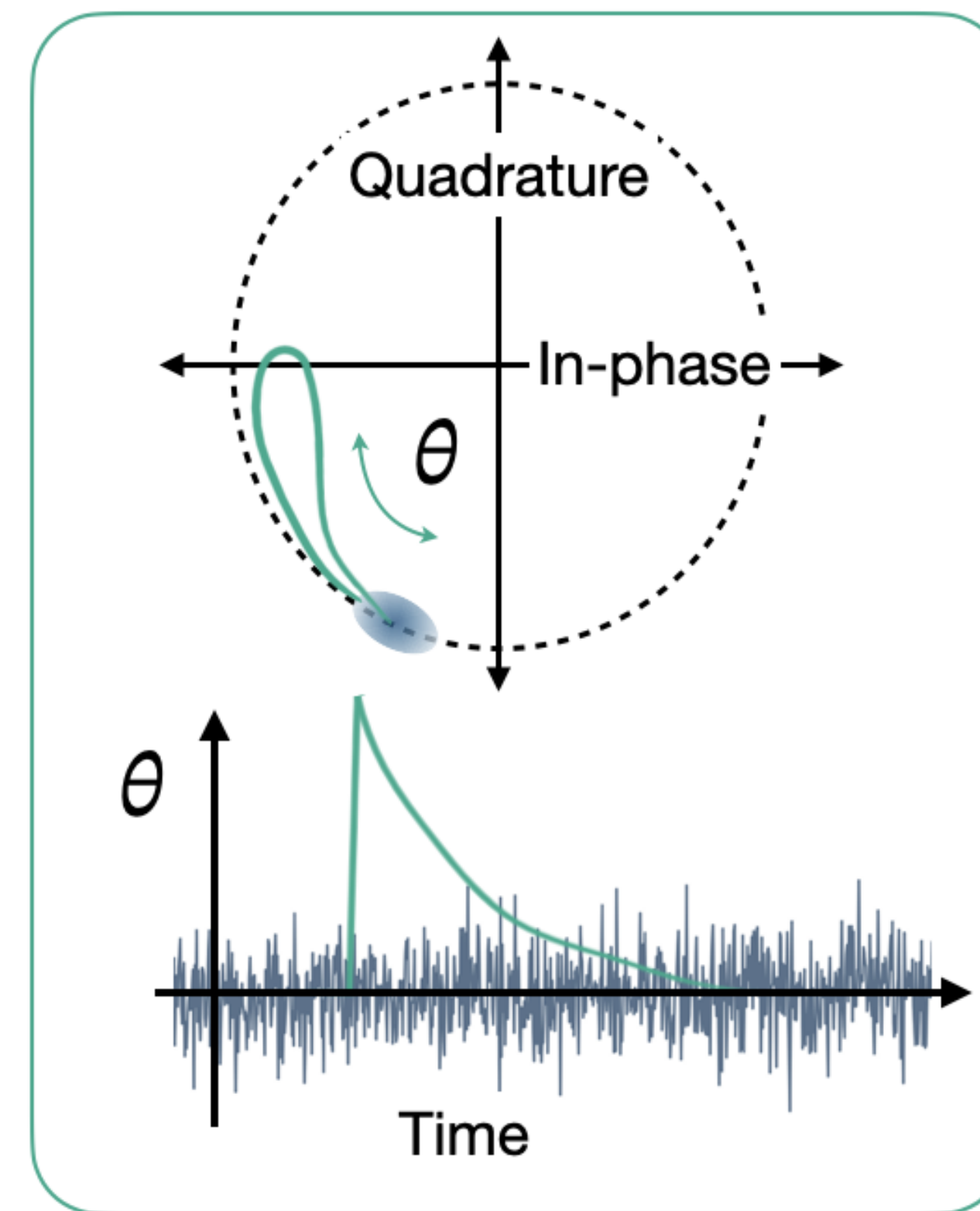
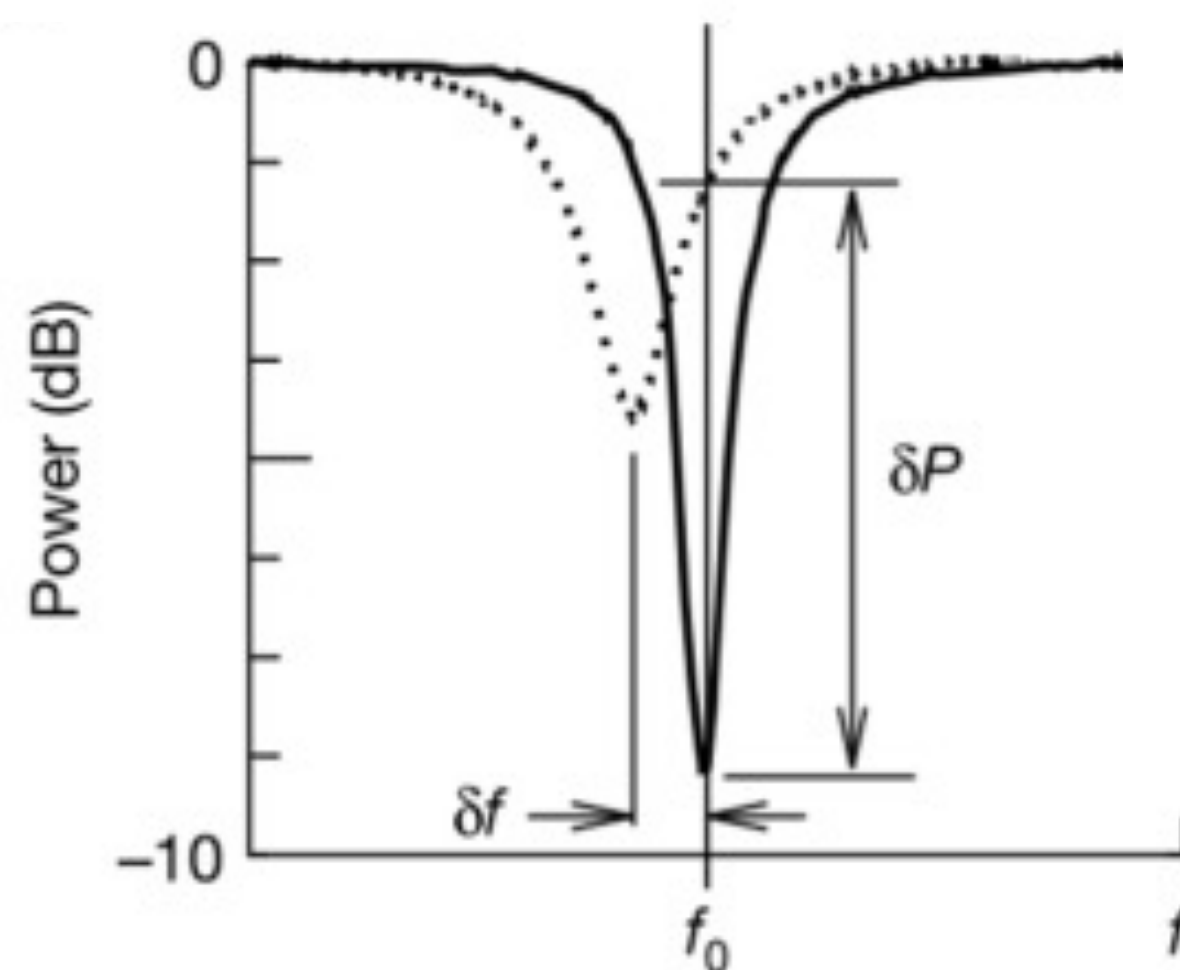
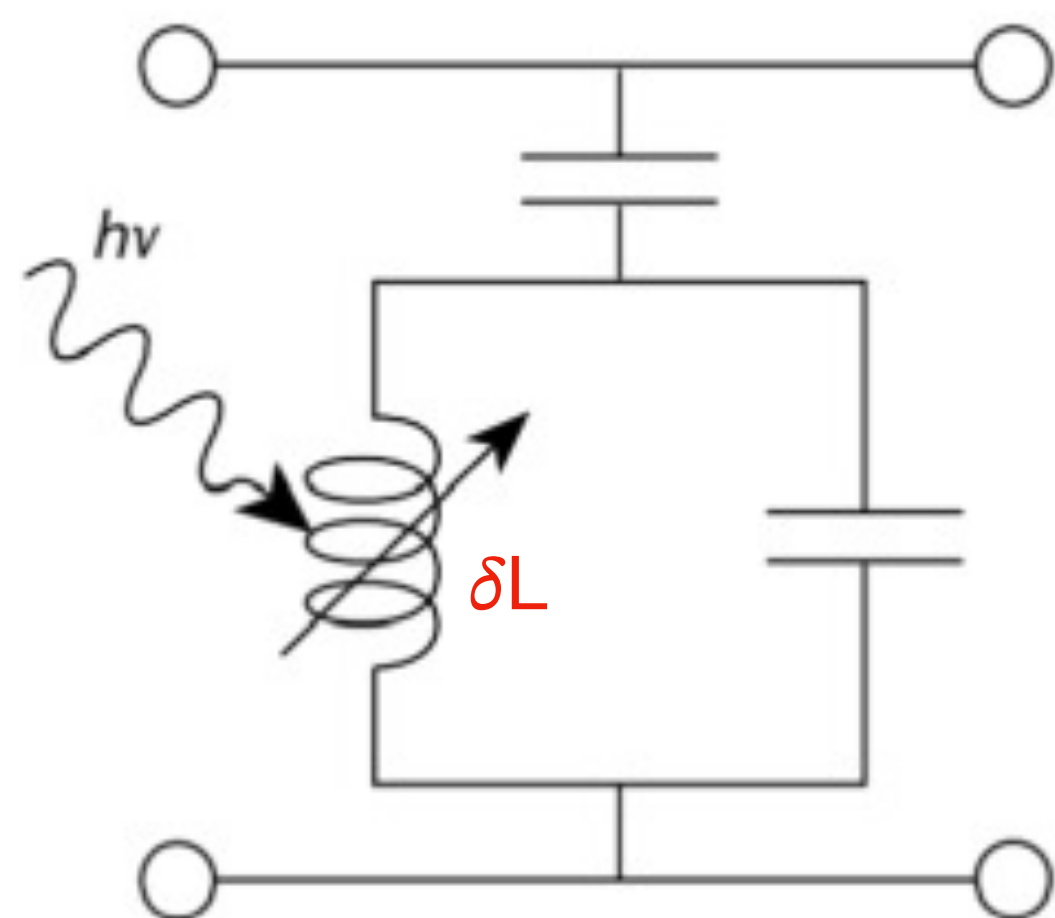
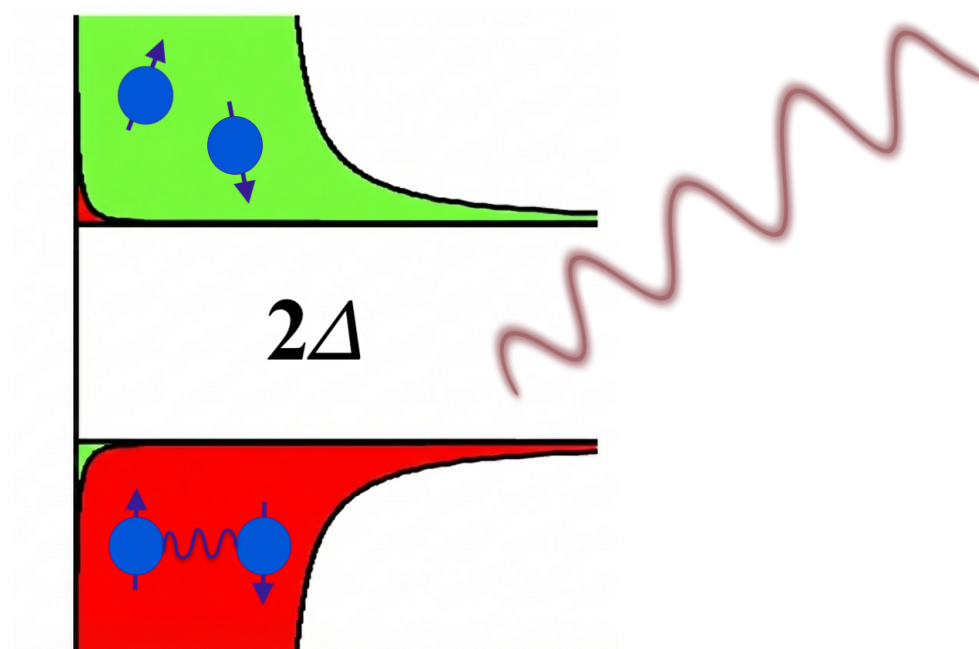
PRIMA spectral resolution (R) goes up to 4400



$R > 100$, in space, implies photon counting measurements

Kinetic Inductance Detectors (KIDs) are superconducting LC resonators

Photon absorption
($h\nu > 2\Delta$) breaks
Cooper-pairs $\rightarrow \delta L \rightarrow \delta f$



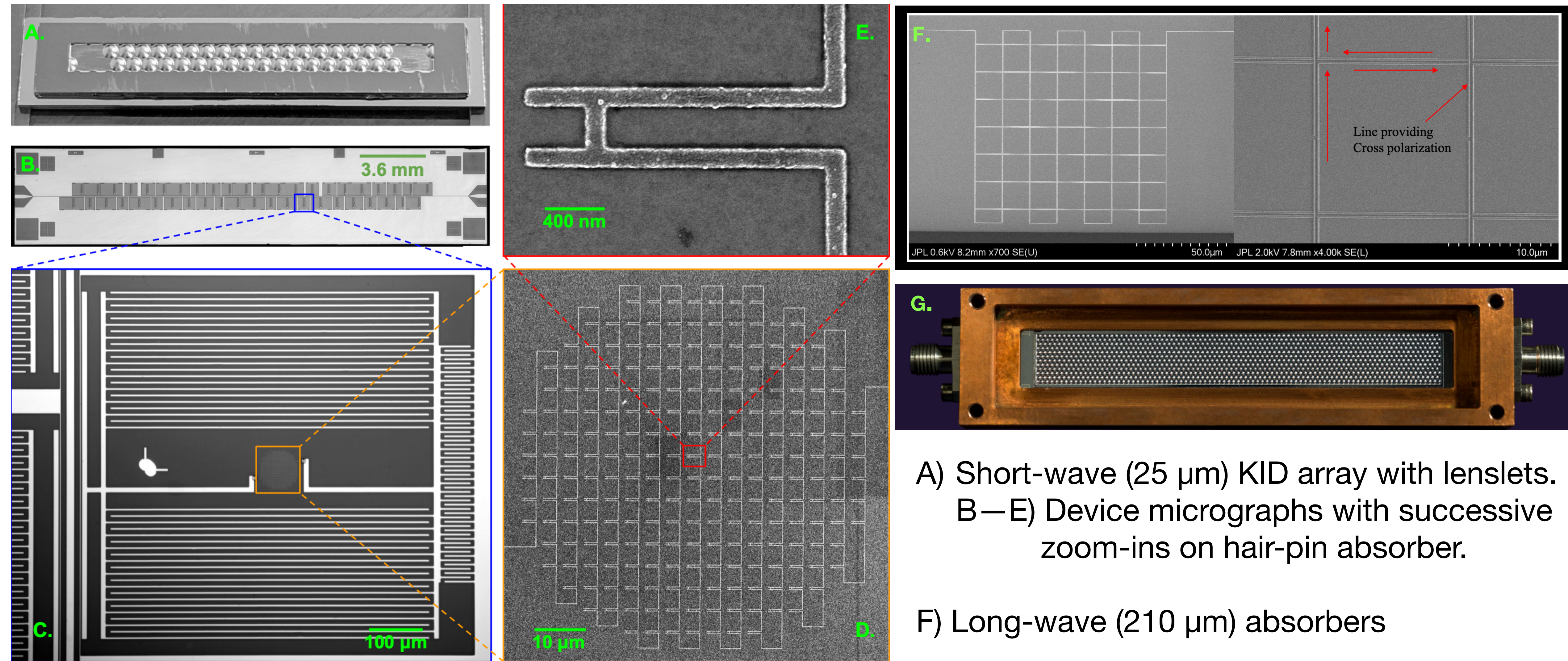
Single photon
signal is a sharp
change in N_{qp}

System
equilibrates
with a time
constant τ_{qp}

~ 125 /s ($25 \mu\text{m}$) photons under 1 aW
Need to reach $\text{NEP} \approx 10^{-19} \text{W} \sqrt{\text{Hz}}$

Sense one photon at a time, 1000x
over for focal planes in space!

Made in JPL's Micro Devices Lab

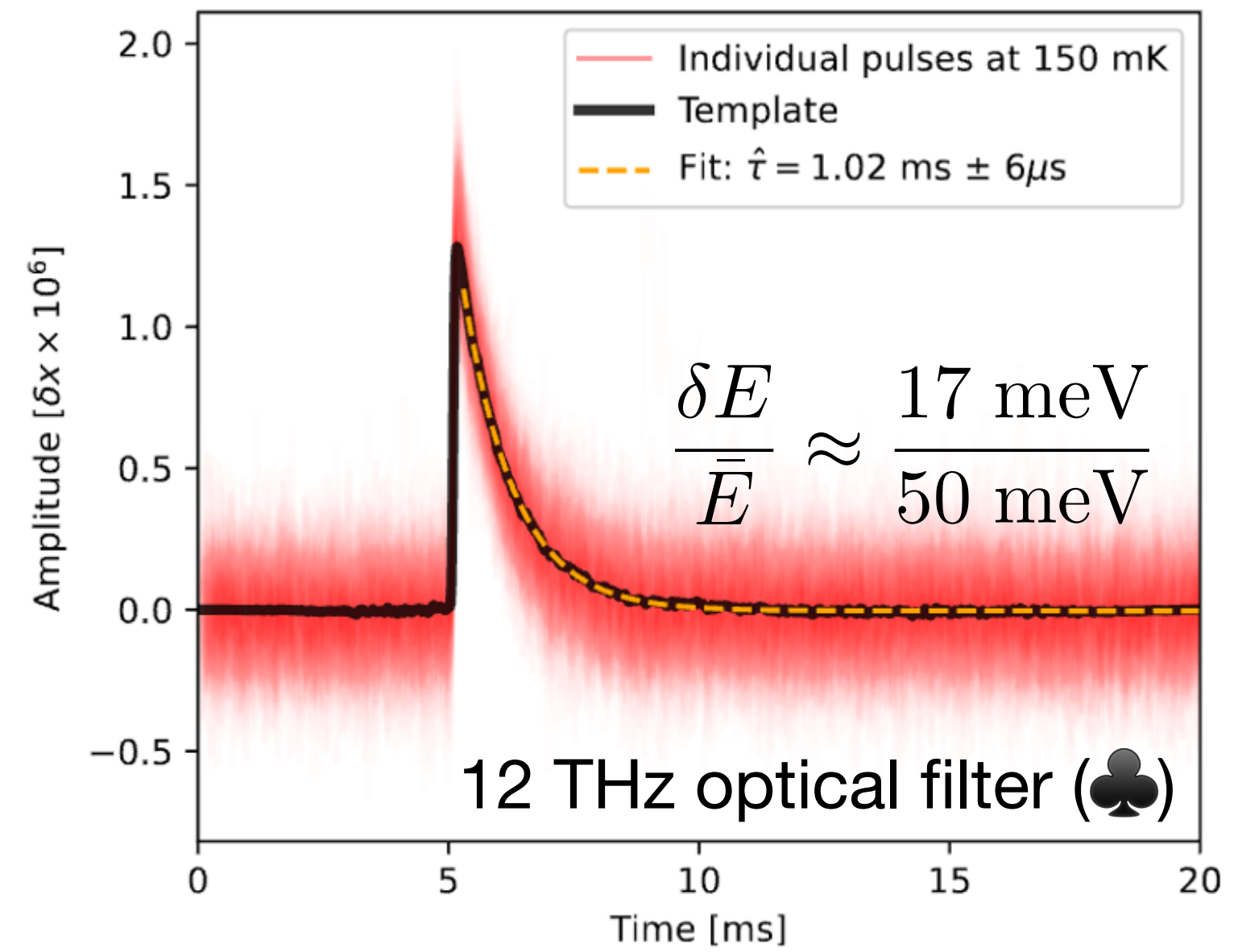
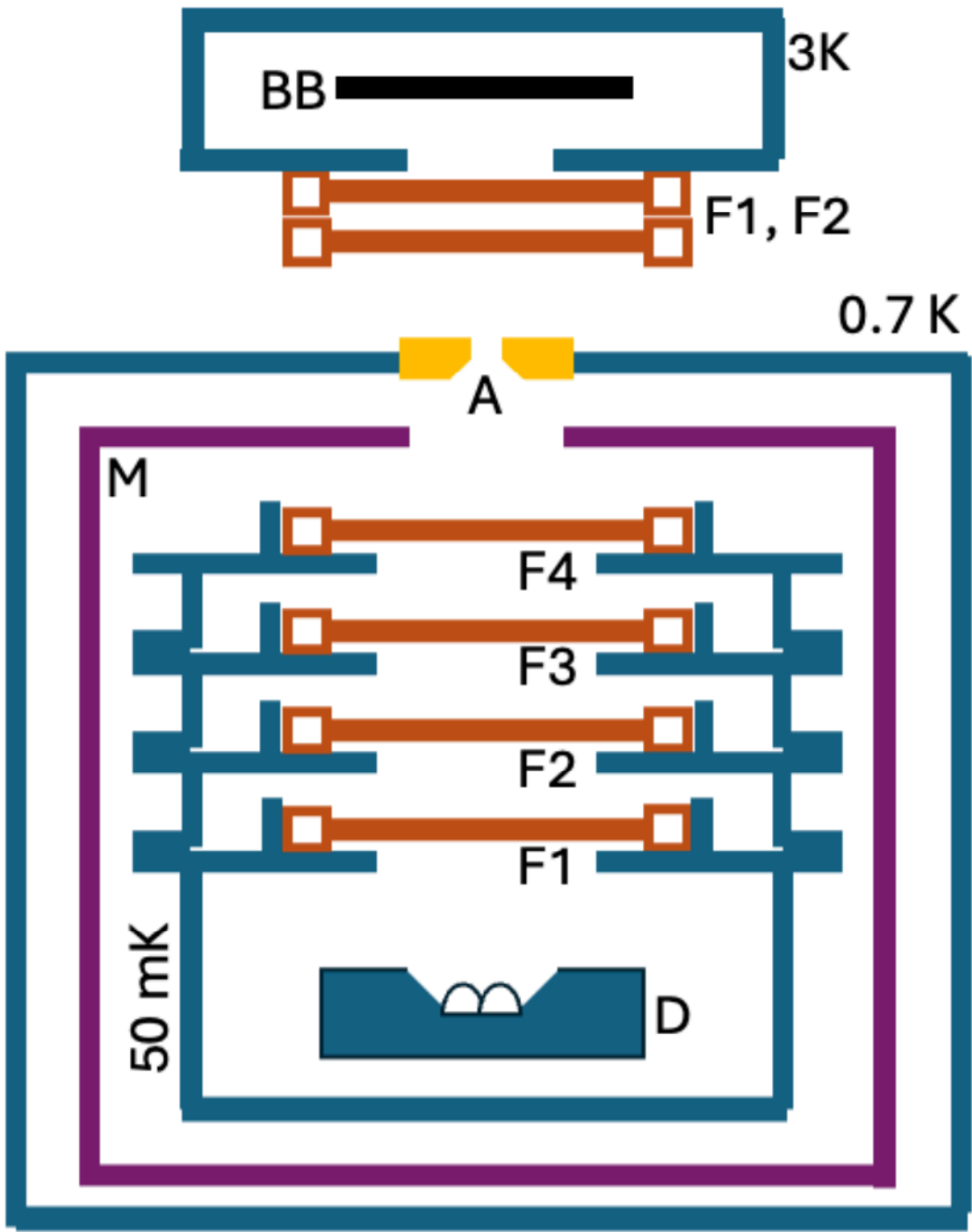


A) Short-wave (25 μm) KID array with lenslets.
B—E) Device micrographs with successive zoom-ins on hair-pin absorber.

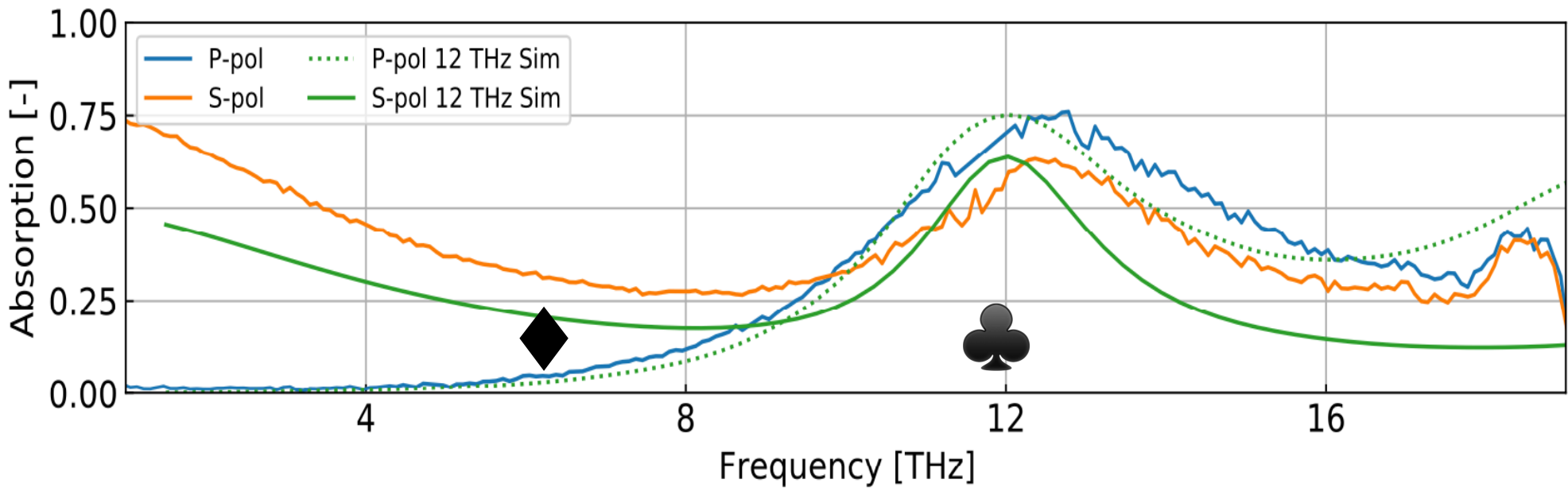
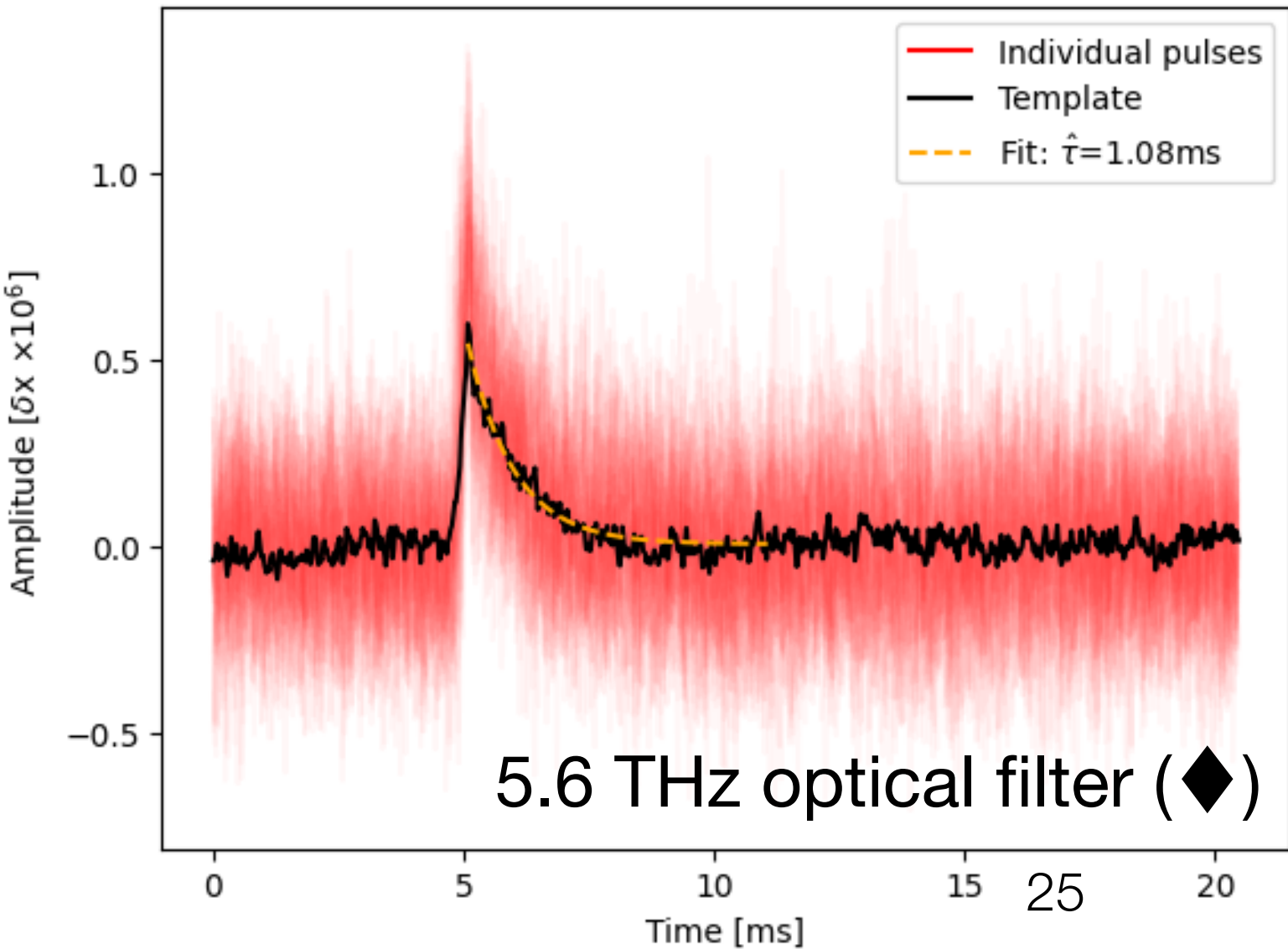
F) Long-wave (210 μm) absorbers

G) Both made into kilopixel flight-like arrays

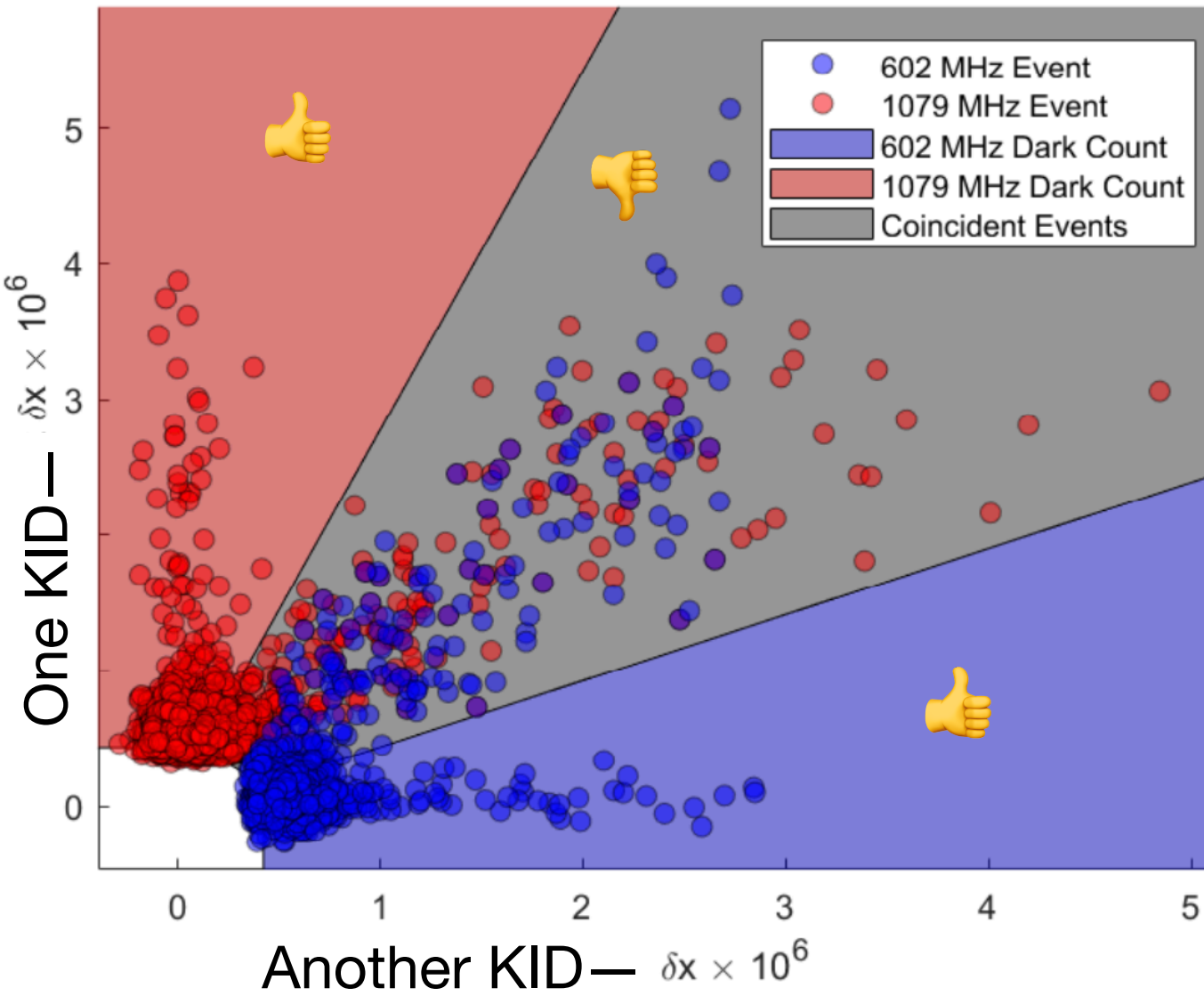
Measurement & calibrations with blackbody & optical filters



Single photon pulses

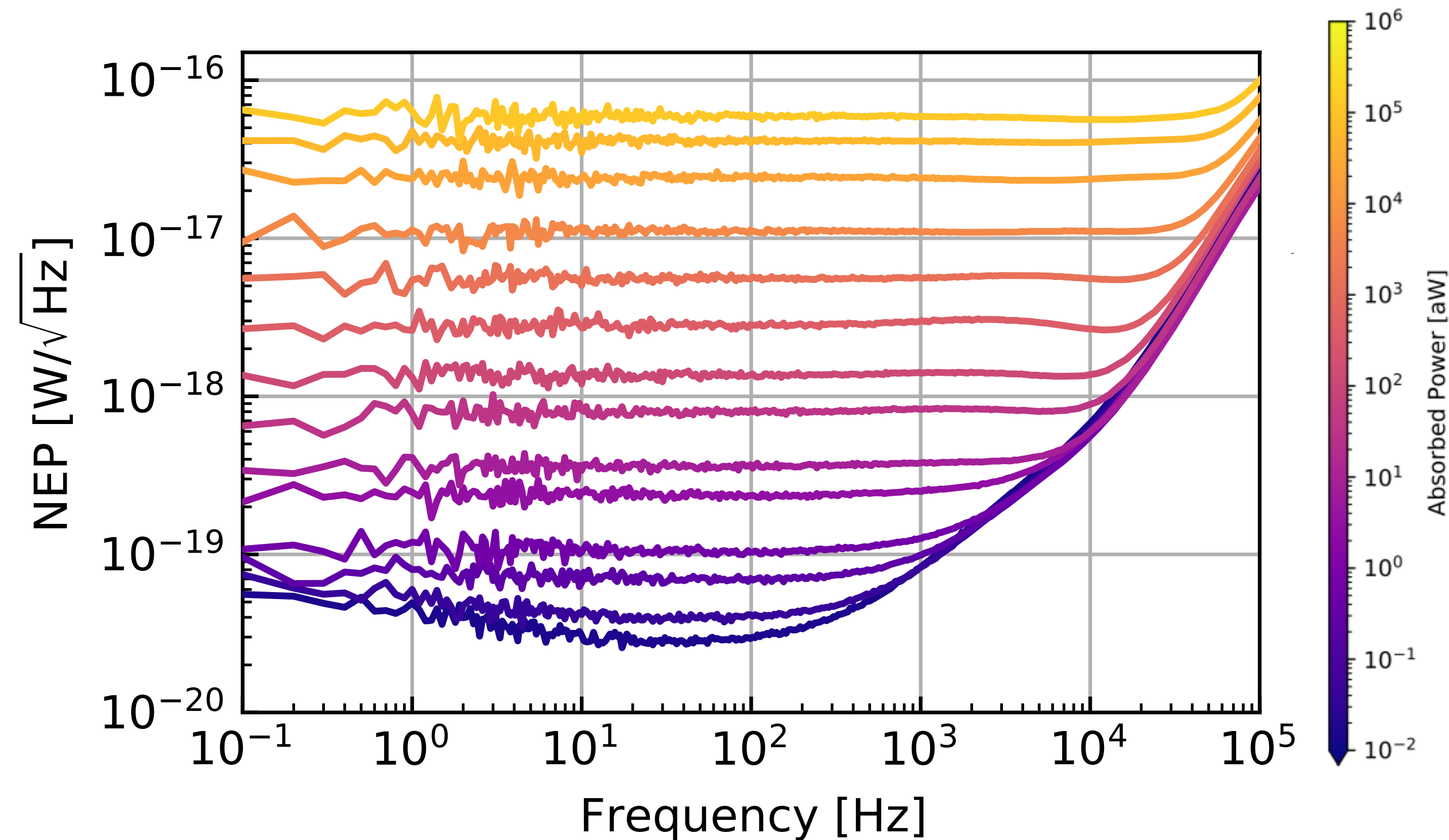


Veto-ing against coincident pulses, dark count rate is 5 mHz



$NEP \sim h\nu\sqrt{DCR} \approx 5 \times 10^{-22} \text{ W}/\sqrt{\text{Hz}}$

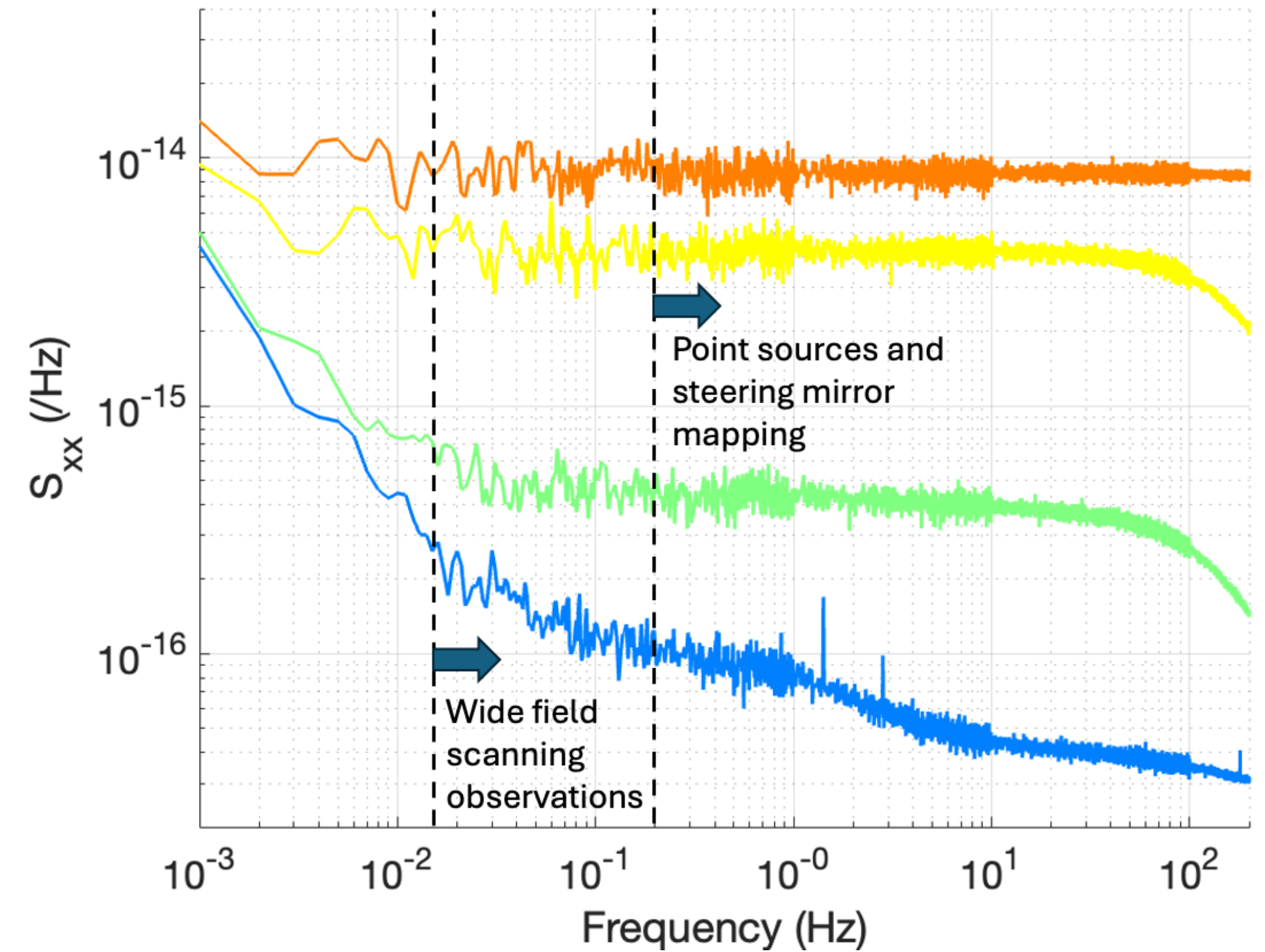
Noise spectra from 10^{-2} to 10^{-6} aW



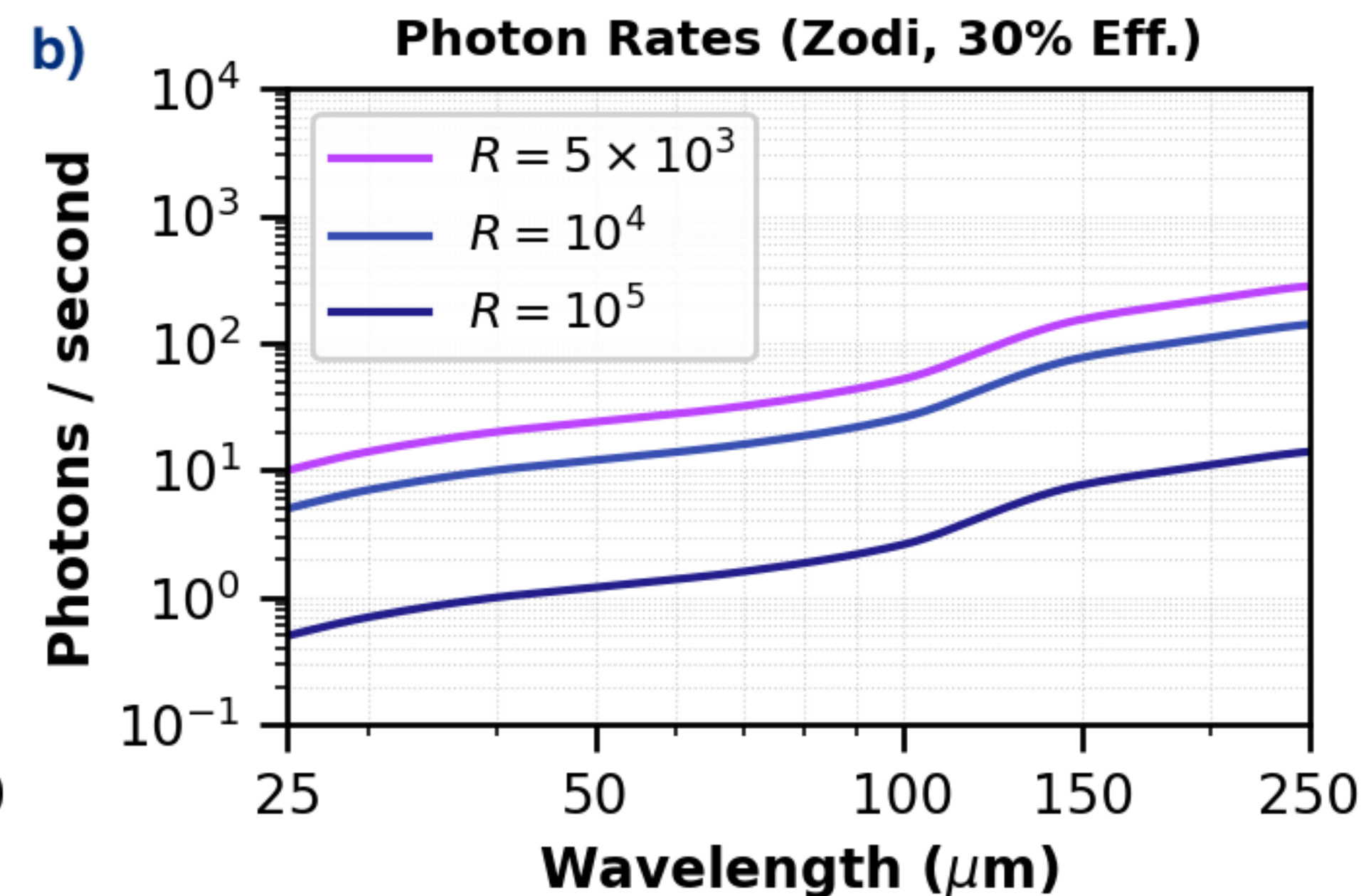
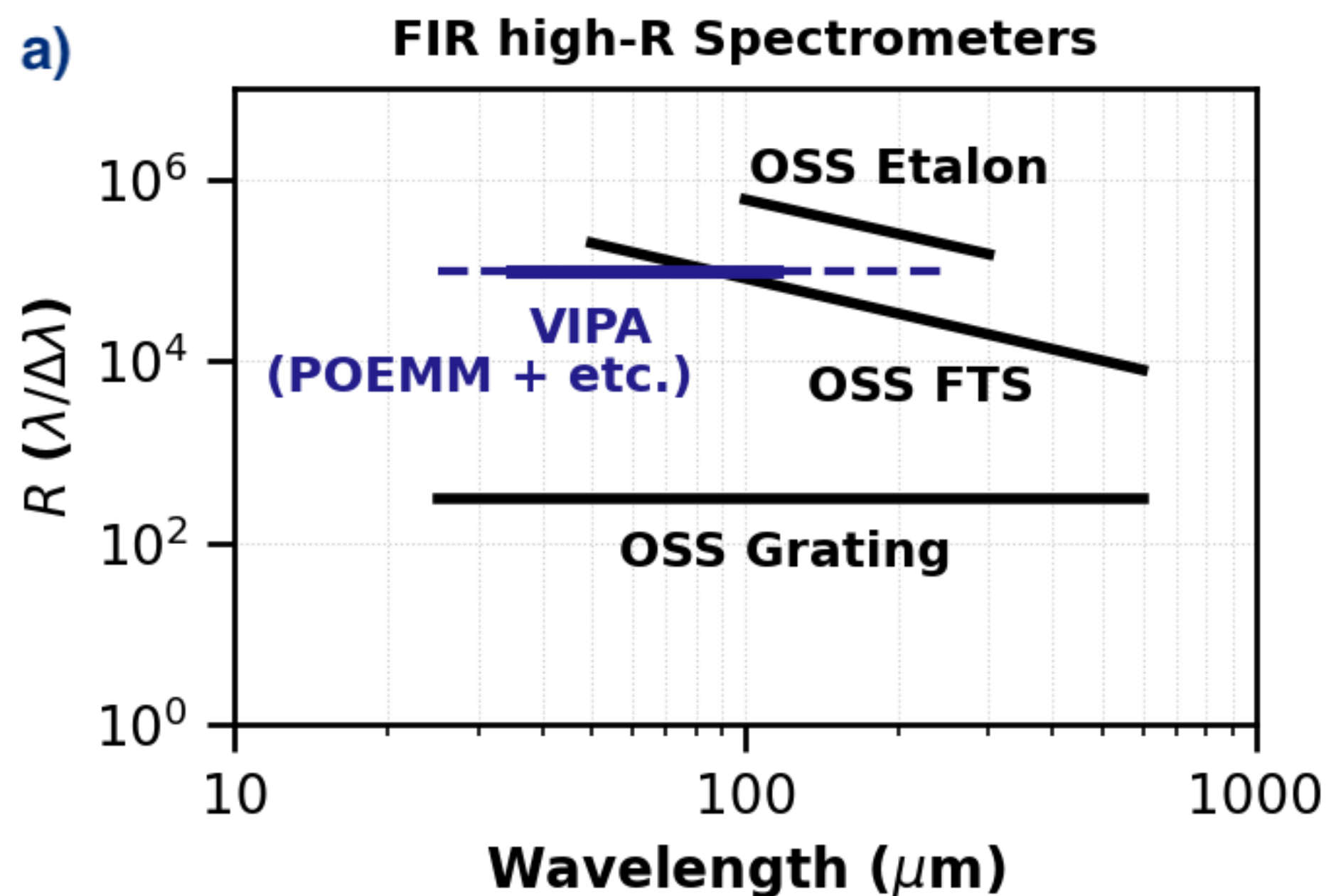
NEP is shot-noise-limited over six orders of magnitude.

Sensitivity maintained down to vanishingly small P_{abs}

Stability out to $O(100)$ s



Frequency noise PSD for $P_{\text{abs}} = 0$ aW, 0.6 aW, 11 aW and 3.5 fW.



What would NASA need for a Far-IR Flagship called for in the Astro2020 Decadal report?*

** Probe ~\$1B, Flagship ~\$10B*

Need to push photon counting limit with kilopixel arrays to match R

Science cases define R , cryogenic telescope sets background ... MKIDs still awesome for energy resolution and multiplexing

SNR is color dependent

Compare 12 and 5.6 THz photons in the same MKID

Pulse height as
fractional freq. shift

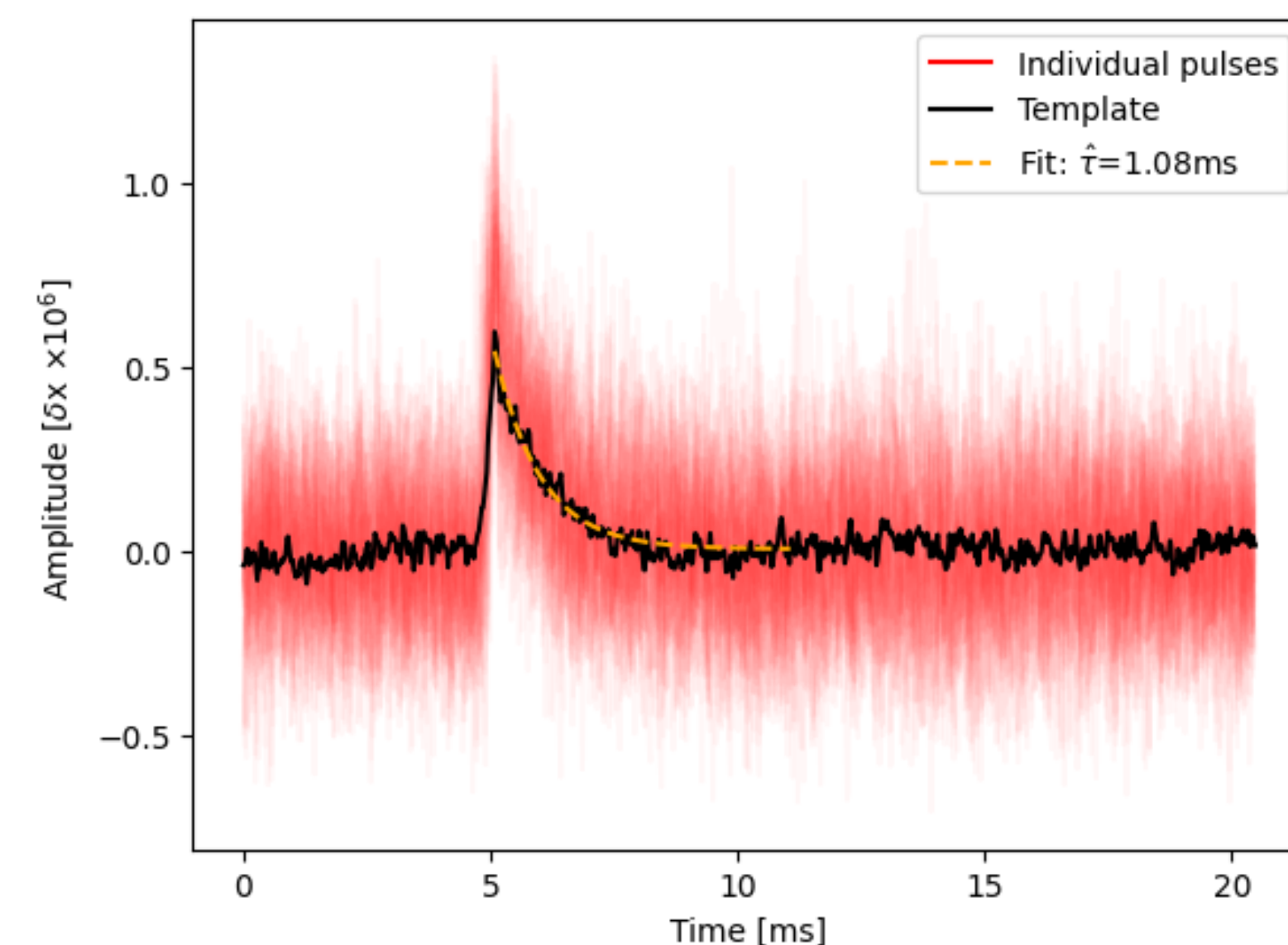
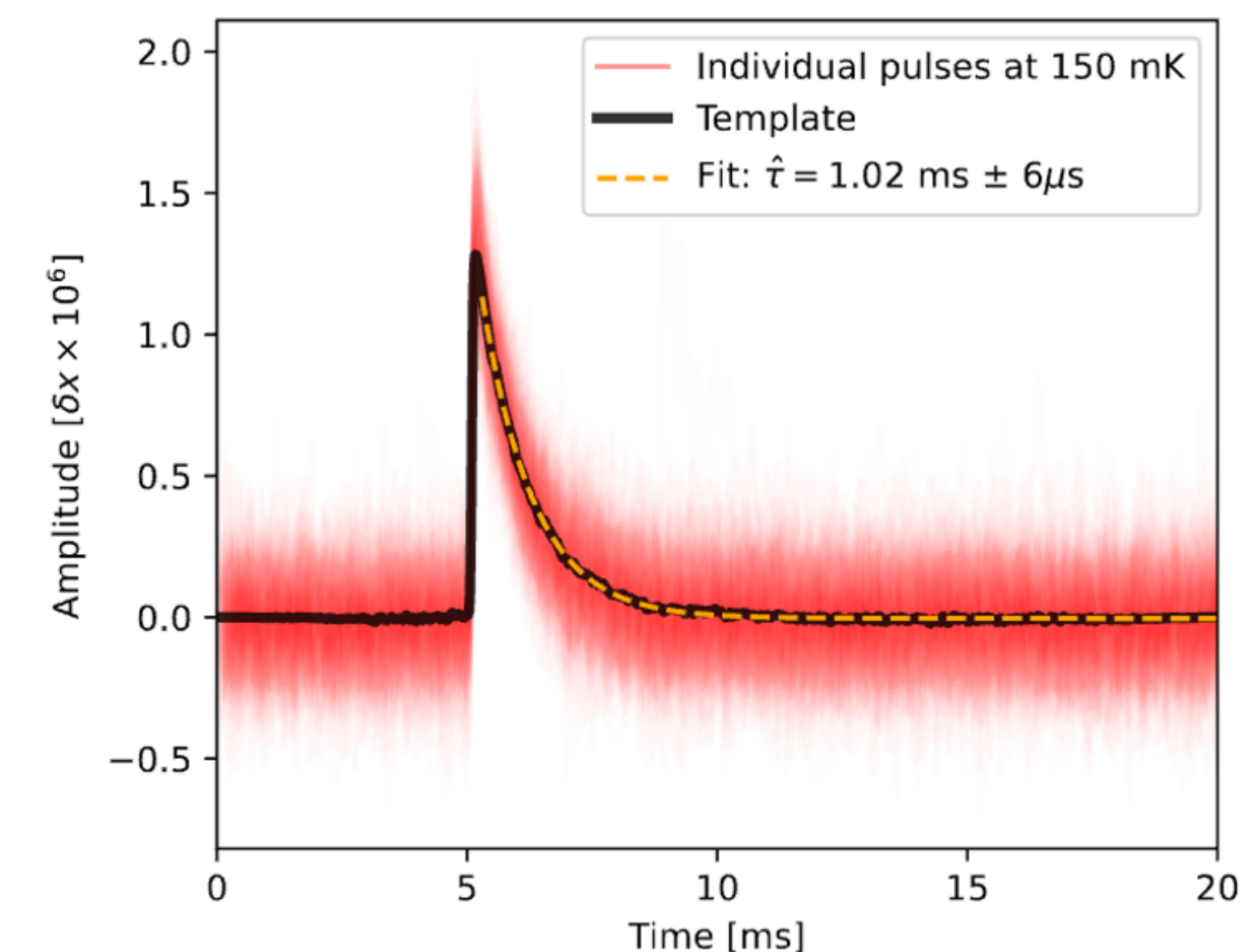
$$\Delta x = \left(\eta_{pb} \frac{E_{\gamma}}{\Delta} \right) \times \left(\frac{\delta x}{\delta N_{qp}} \right)$$

Number of qps generated

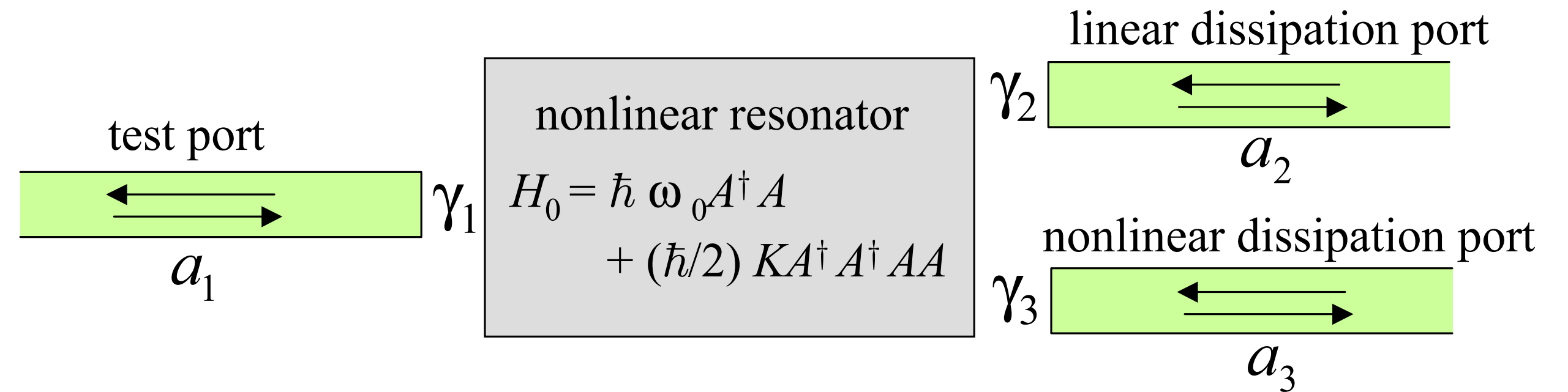
Fractional freq. shift
per quasiparticle

$$\frac{\delta x}{\delta N_{qp}} = \frac{1}{2} \alpha \gamma_s S_2(f_{res}, T) \frac{1}{V n_c}$$

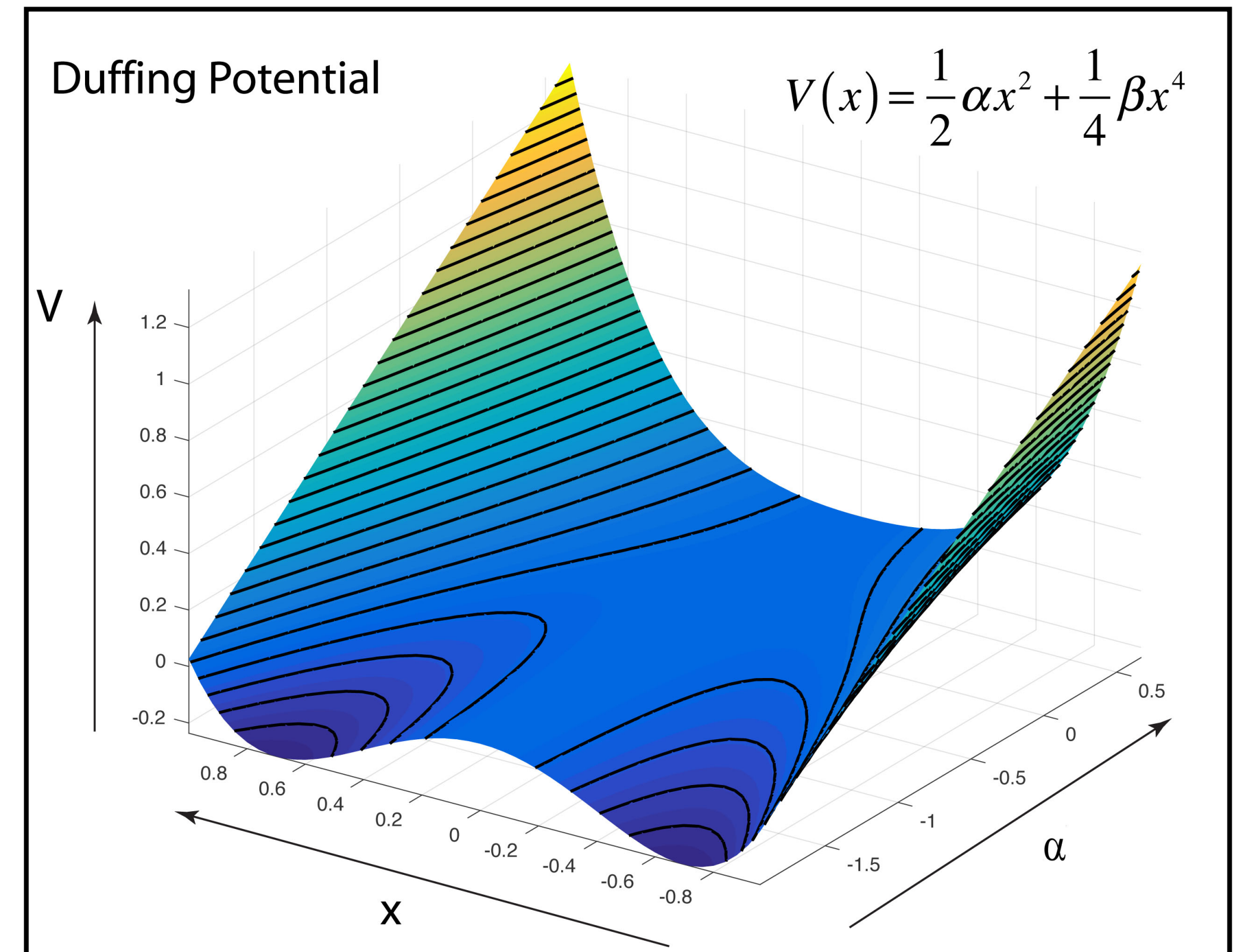
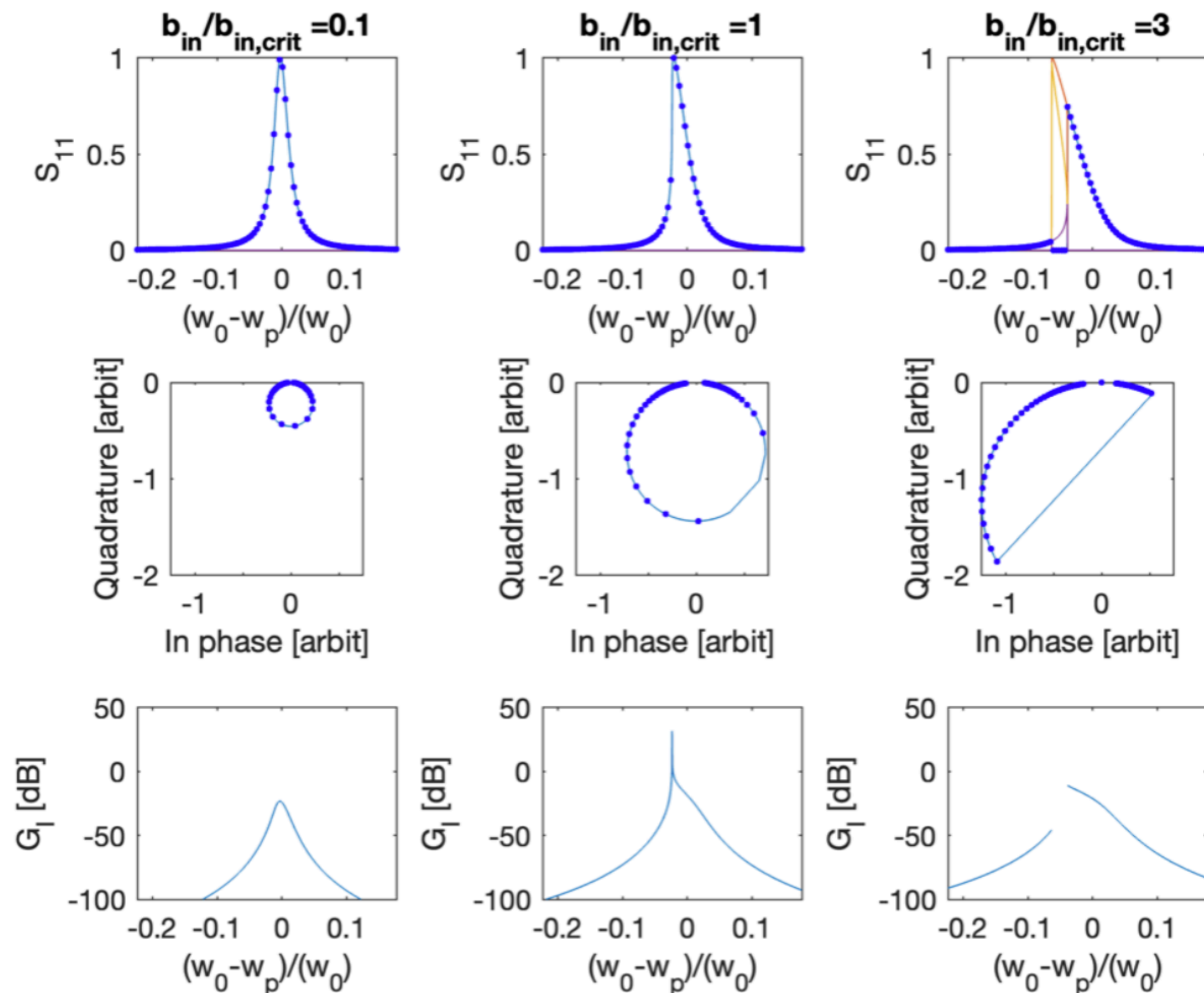
Reduce gap & volume - but limited runway
ask me during Q&A



Kerr nonlinearity allows for quartic tuning of a SHO ... common qubit physics and quantum optics tool



J. Lightwave Technol. 24, 5054-5066 and Phys. Rev. E 74, 046619



Non Linear KIDs:

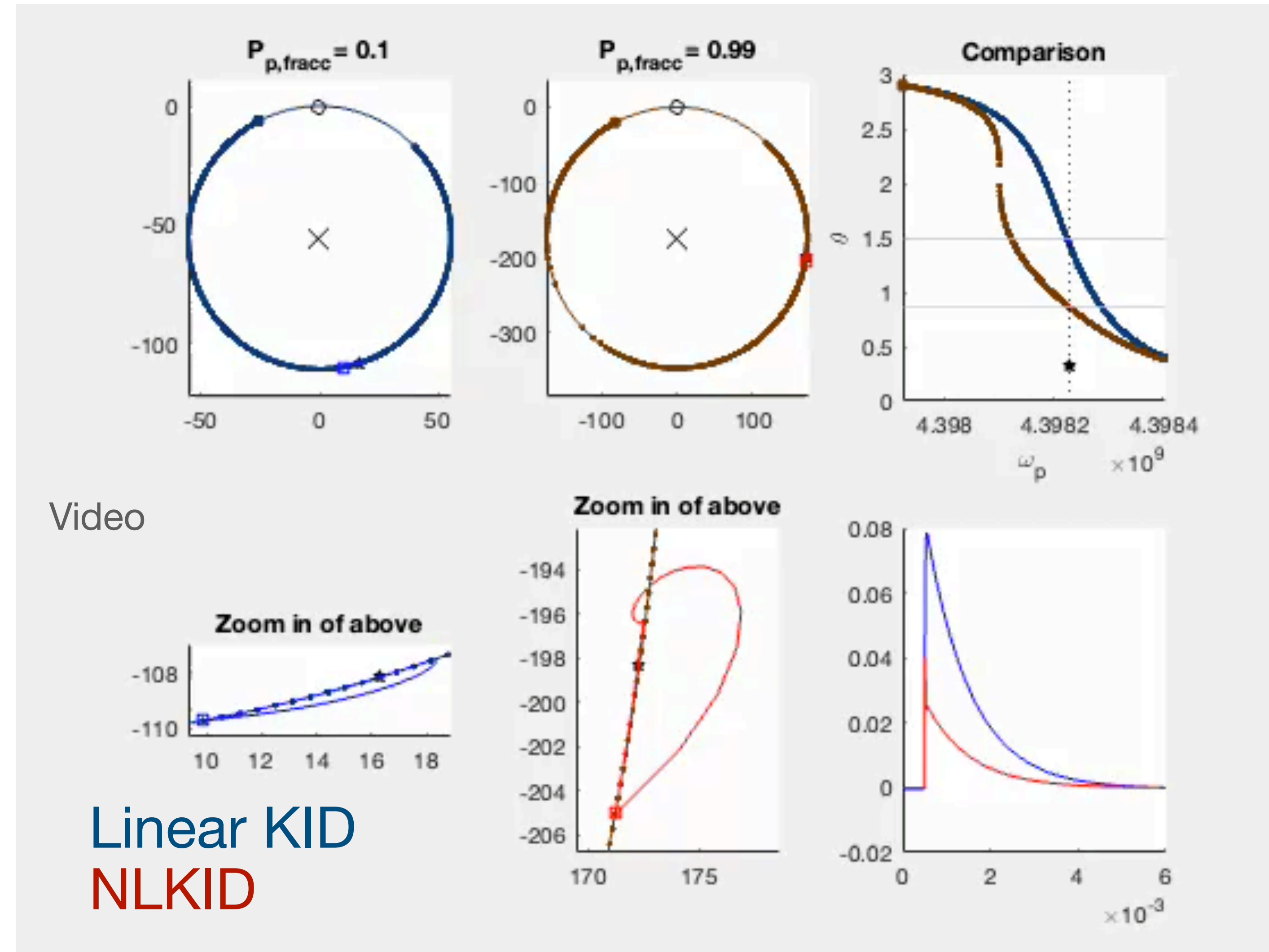
Kerr nonlinearity couples a strong pump to a weak signal

Strong pump makes it a “NL”KID

$$L_k(I) \approx L \left(1 + \alpha \left(\frac{I}{I_*} \right)^2 \right)$$

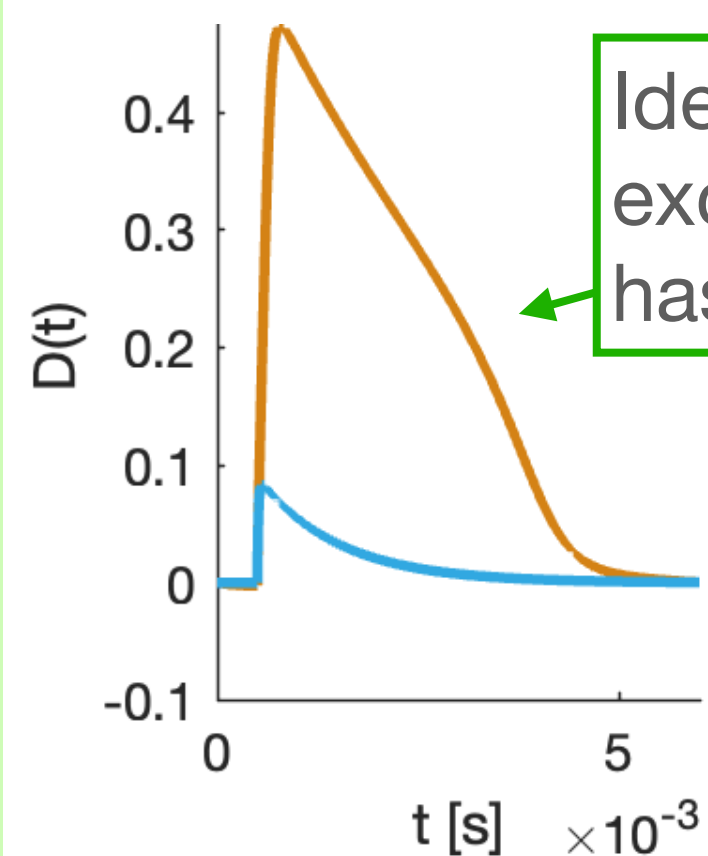
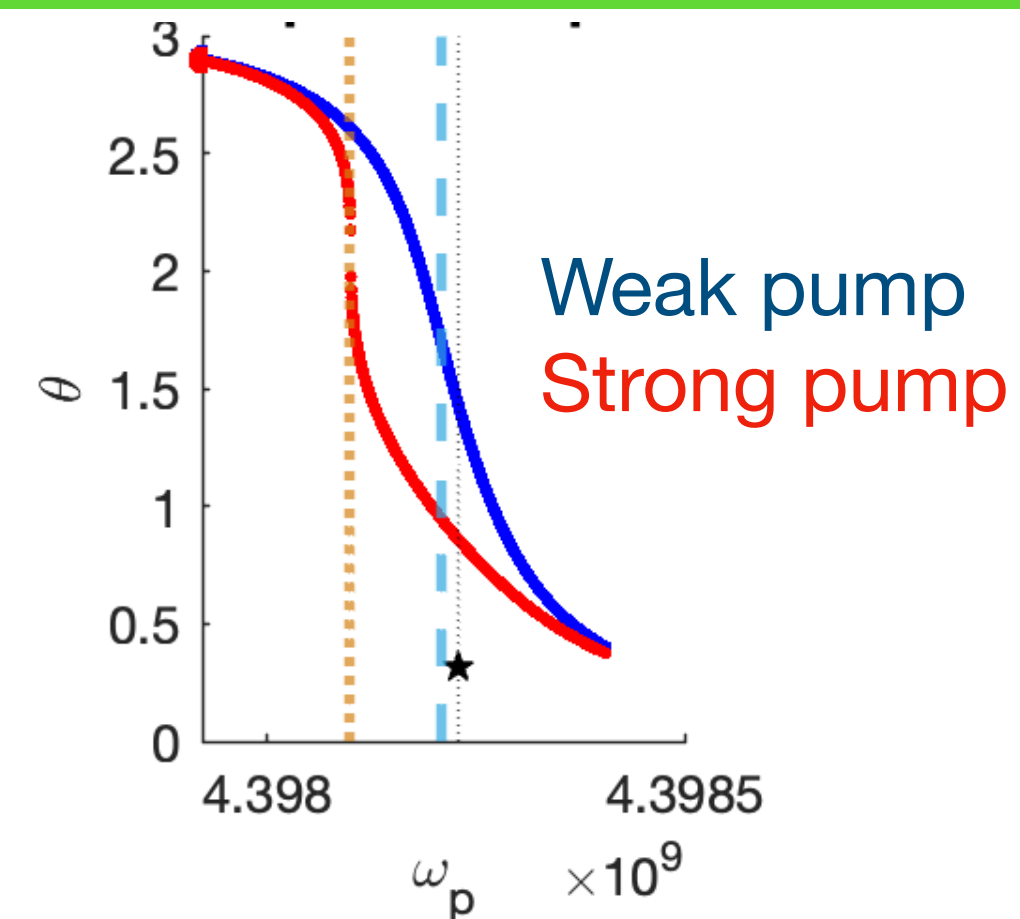
$$K = \frac{3}{4} \alpha \frac{\hbar \omega_0^2}{I_*^2 L}$$

Only one tone per KID, and in situ amplification



New quantum optical detector realized!

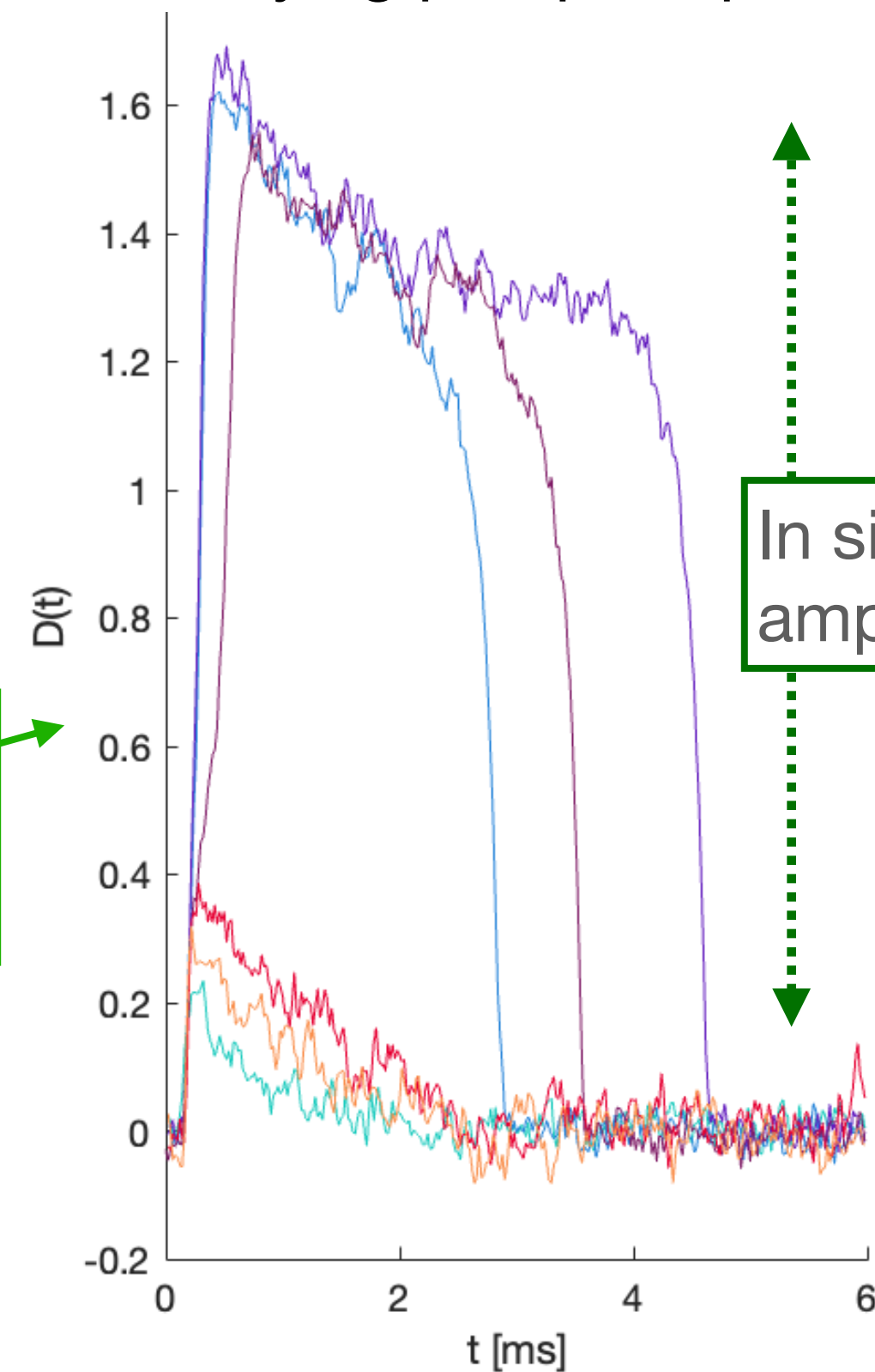
Quantum Optics simulation



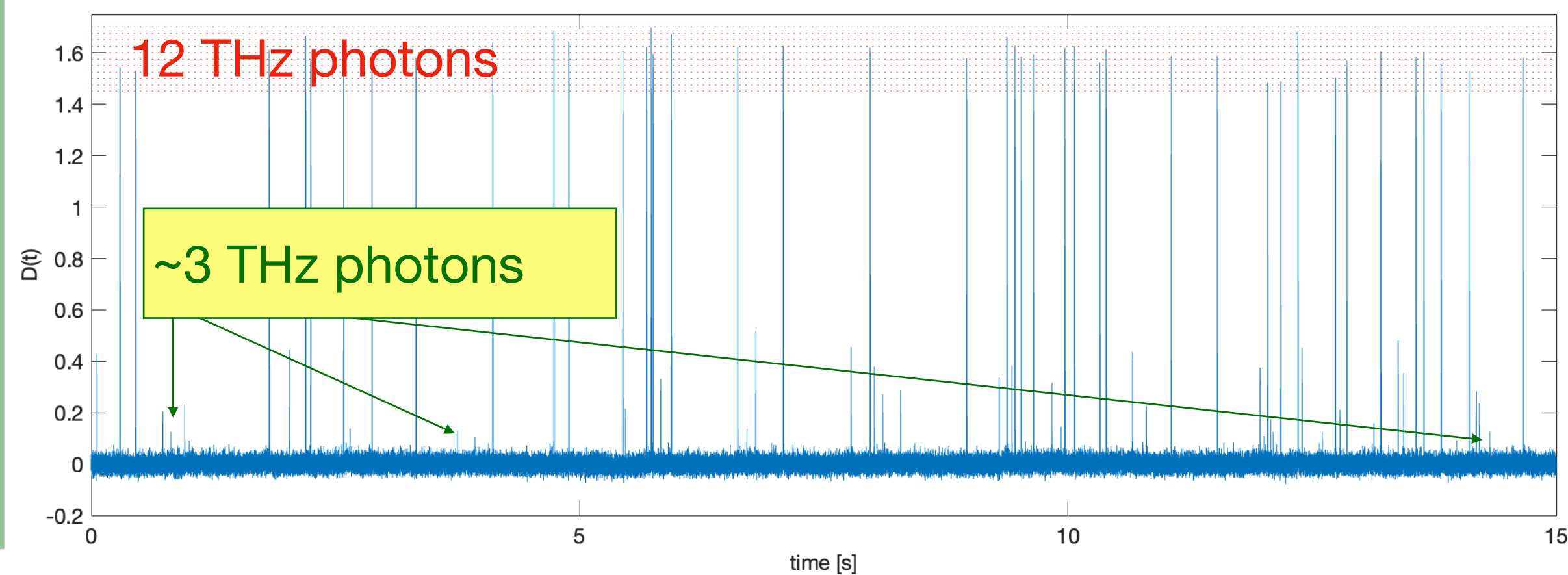
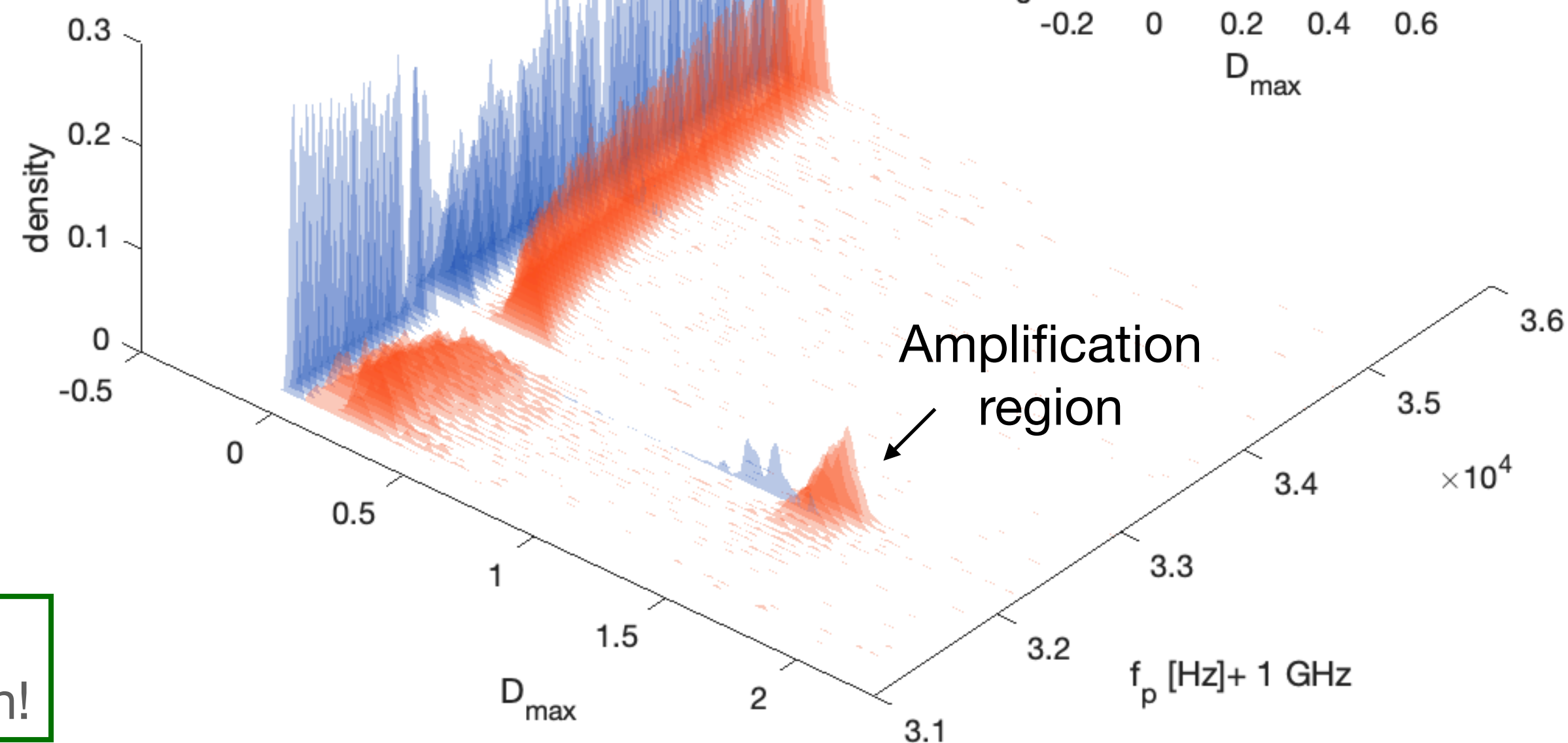
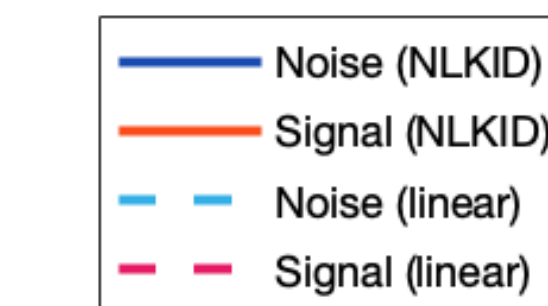
Identical photo-excitation, NLKID has a larger pulse

Data

12 THz pulses in our NLKID, strong pump power but varying pump frequencies



Non Linear KID

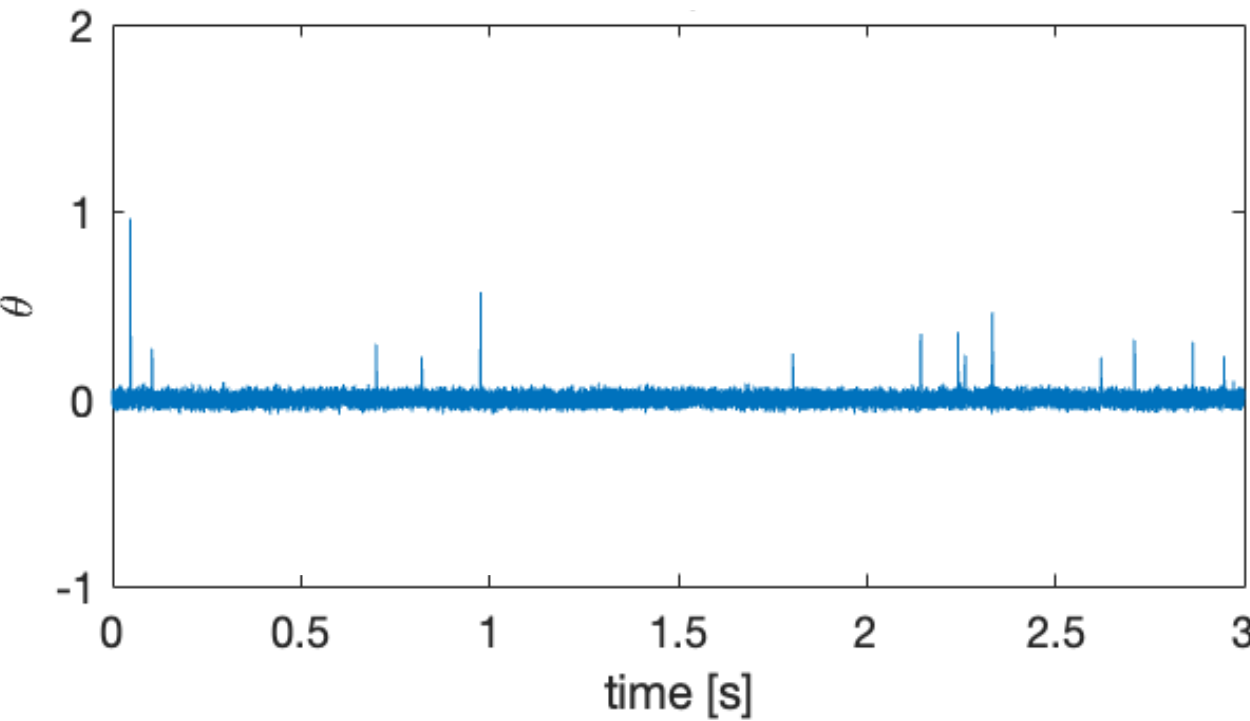


$$\text{SNR} \equiv \frac{(\text{E}[\mathcal{P}_S] - \text{E}[\mathcal{P}_N])^2}{\text{Var}[\mathcal{P}_S] + \text{Var}[\mathcal{P}_N]} \sim \left(\frac{\langle \text{pulse-amplitude} \rangle}{\sqrt{2} \times \text{noise-RMS}} \right)^2$$

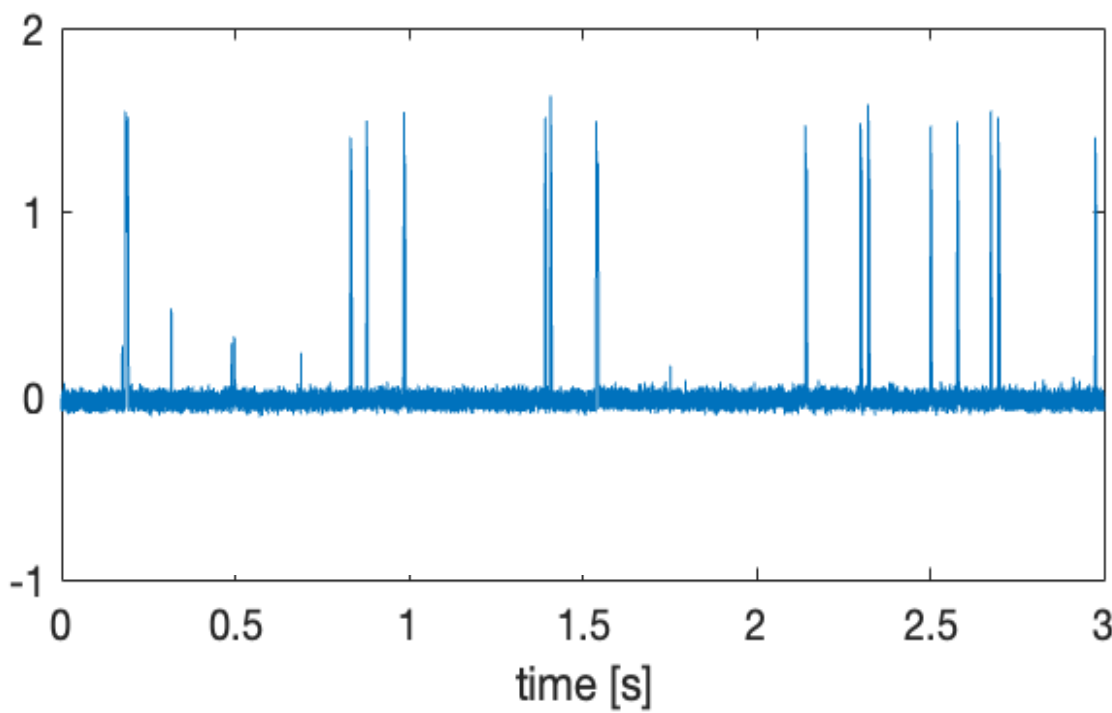
a) Study summary	Nominal (linear) KID operations	Good nonlinear KID operations	Suboptimal nonlinear KID operations	Bad nonlinear KID operations
SNR	14	745	5	N/A
log ₁₀ (Instab)	10 ^{-2.8}	10 ^{-1.53}	10 ^{-2.8}	> 10 ^{-0.7}

b) Time stream examples:

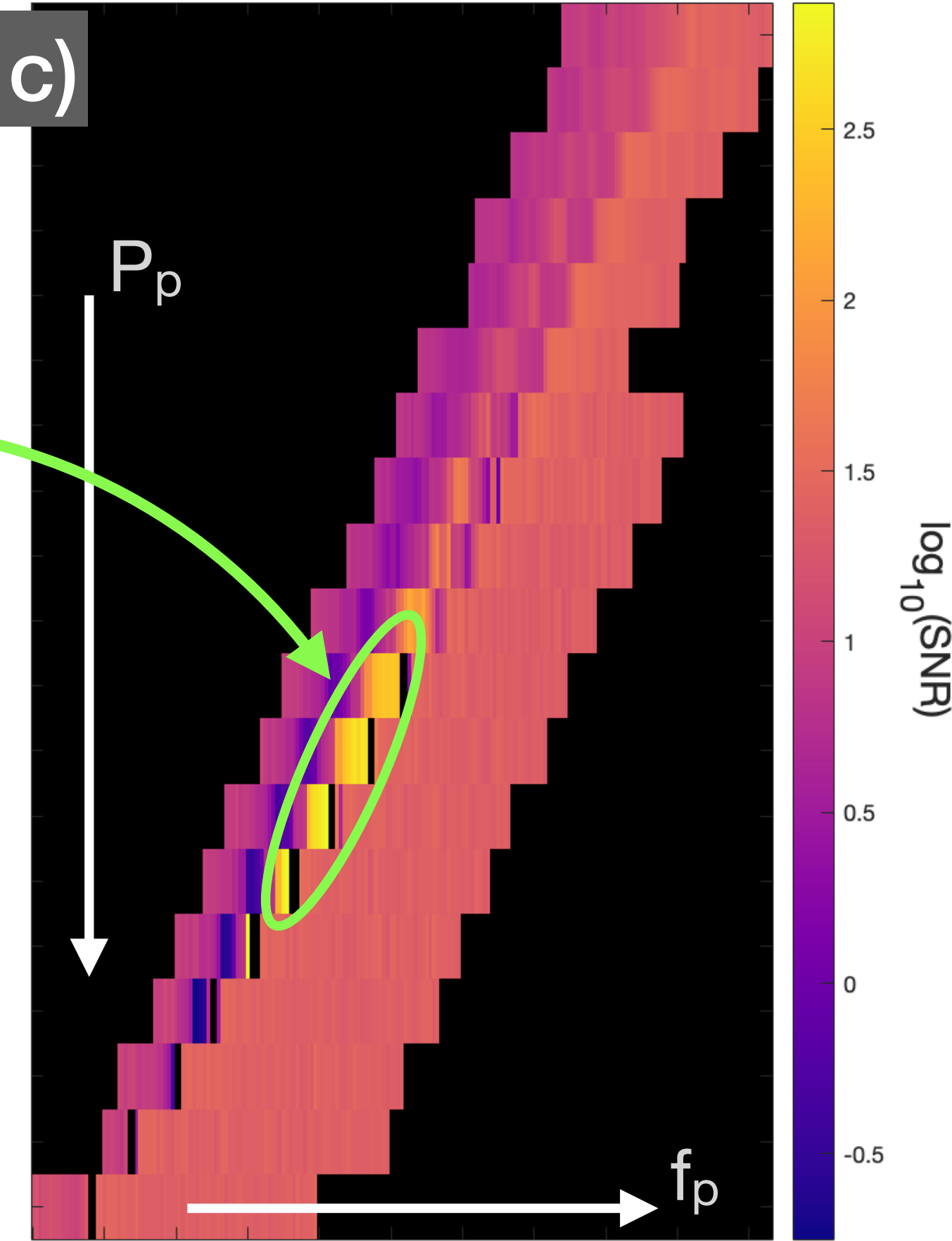
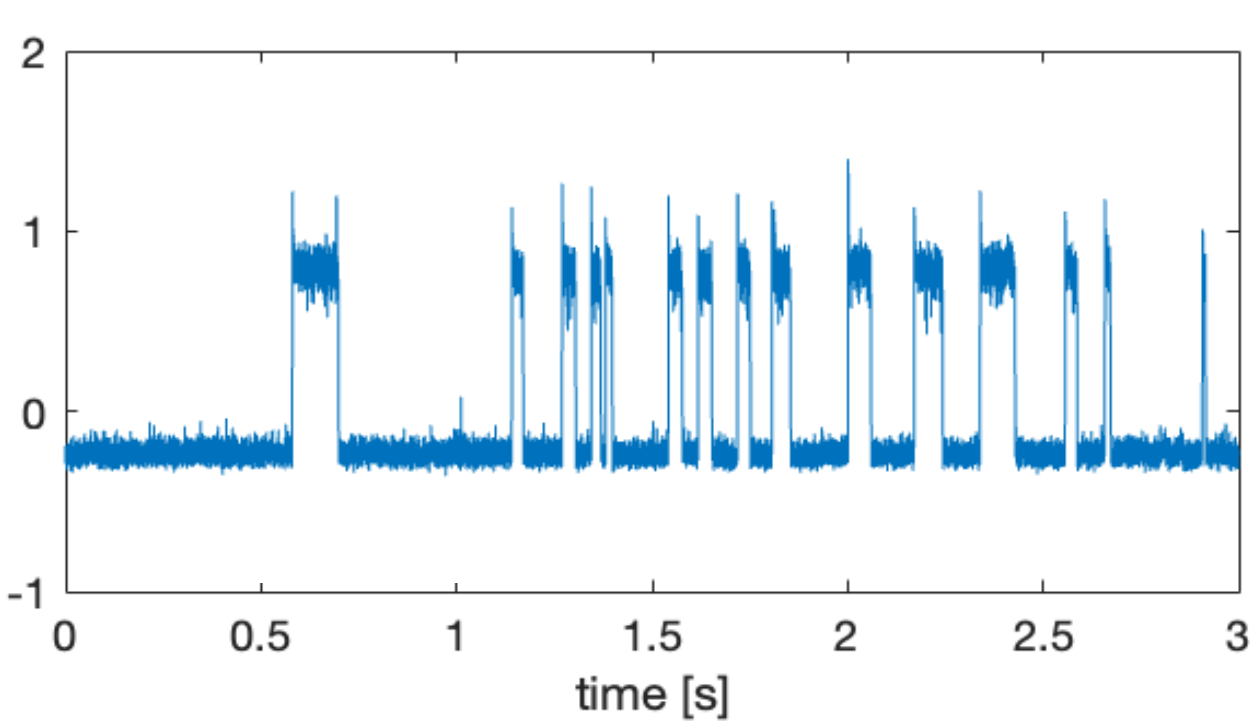
Small gain & stable

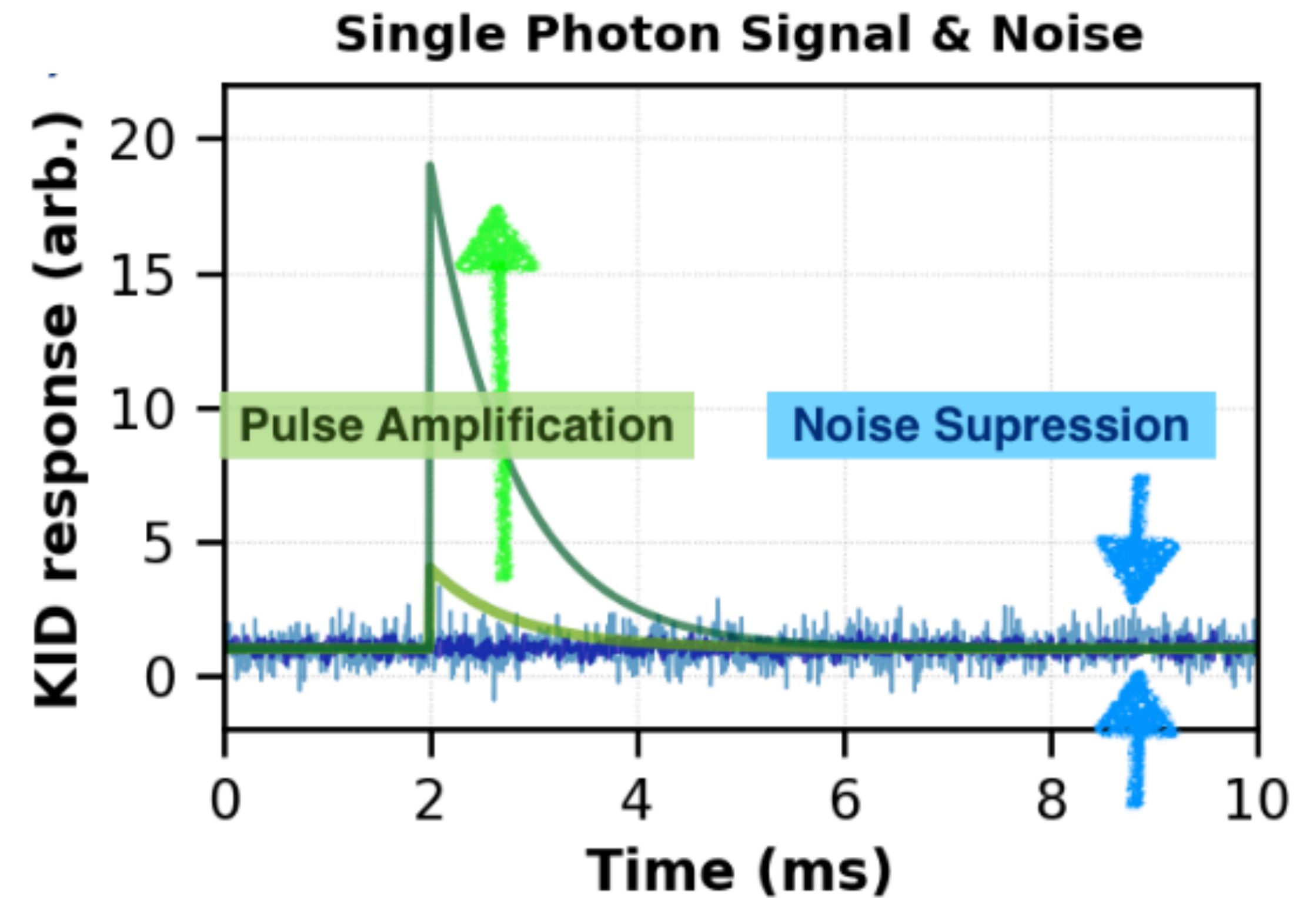
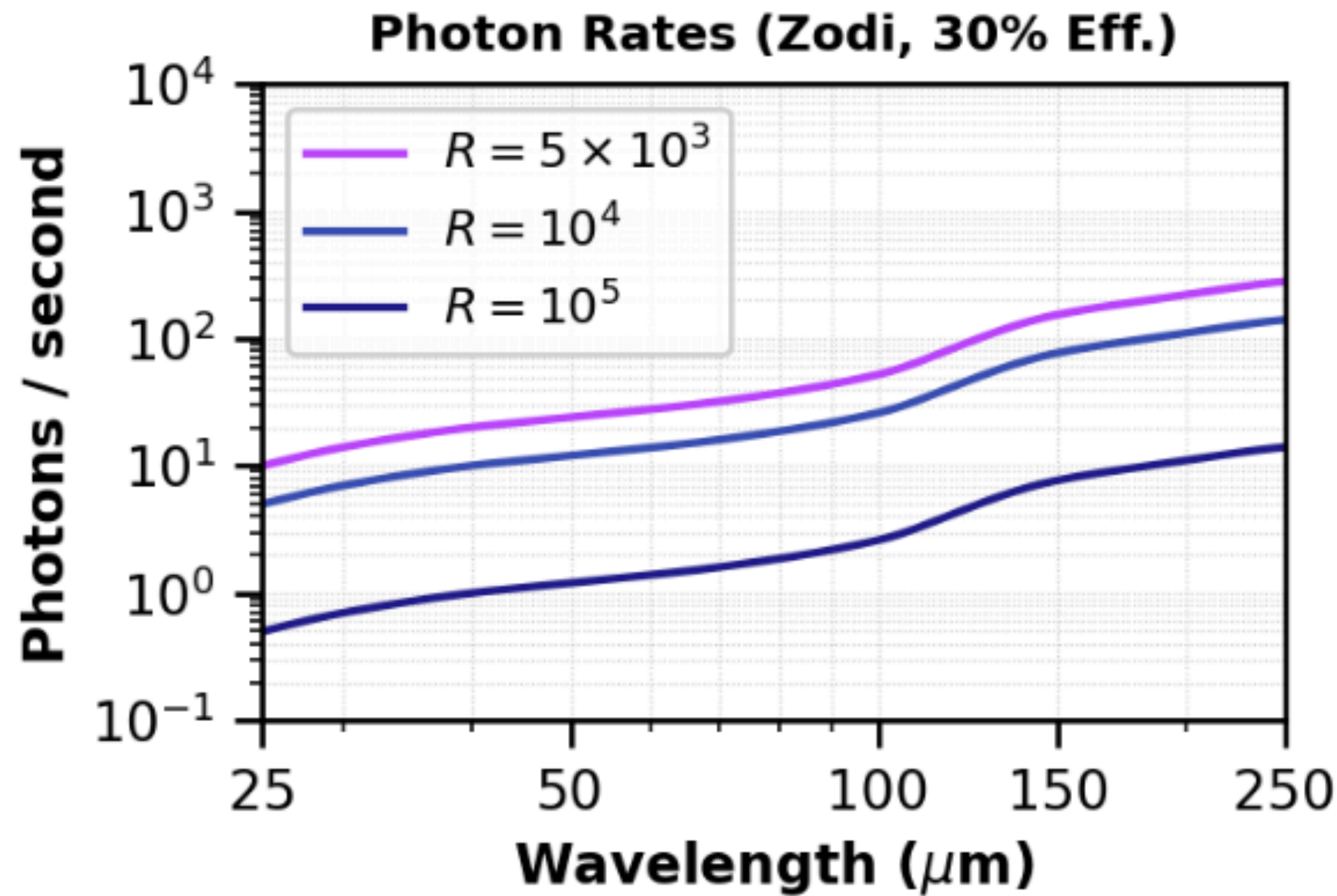


Large gain & stable



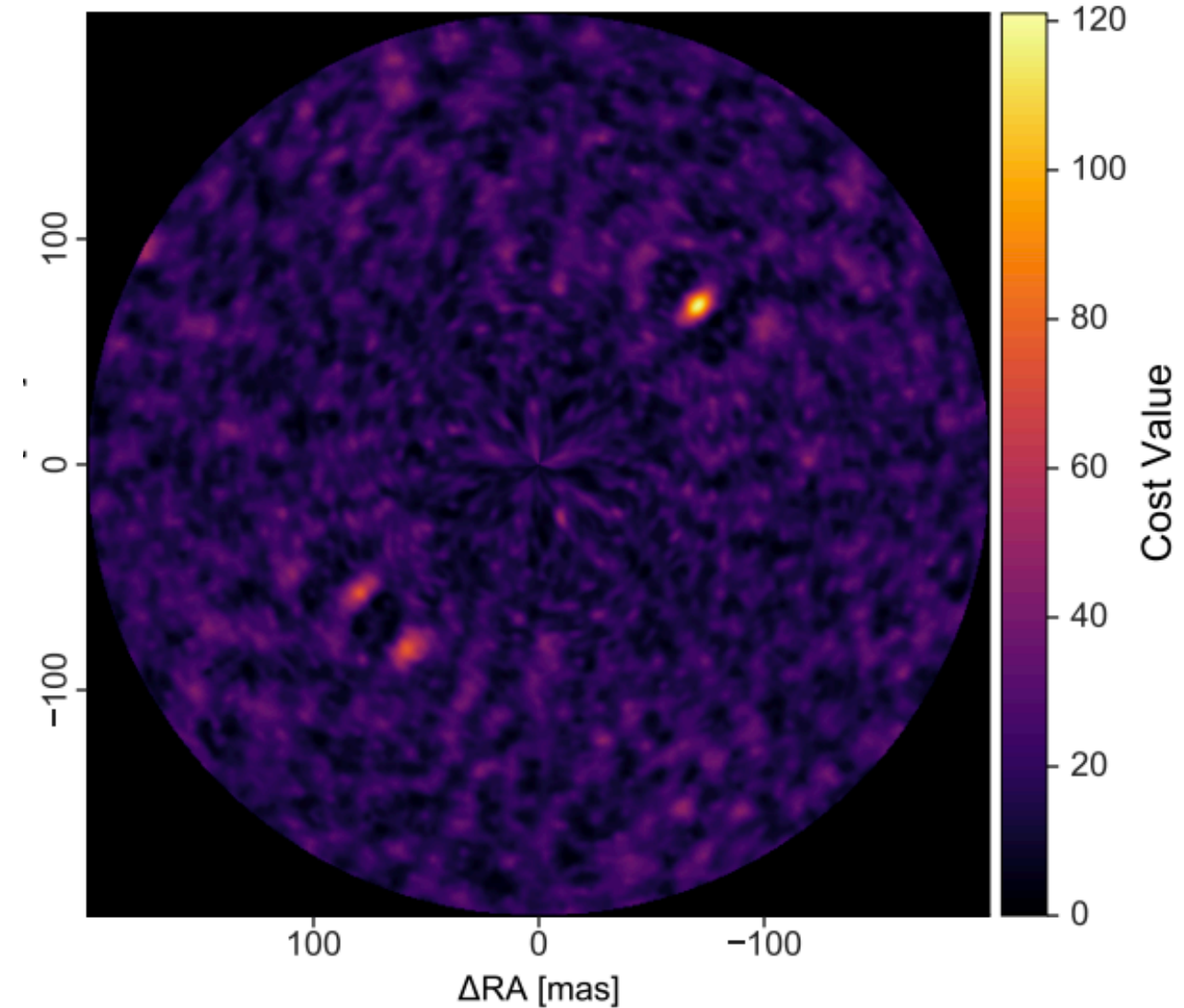
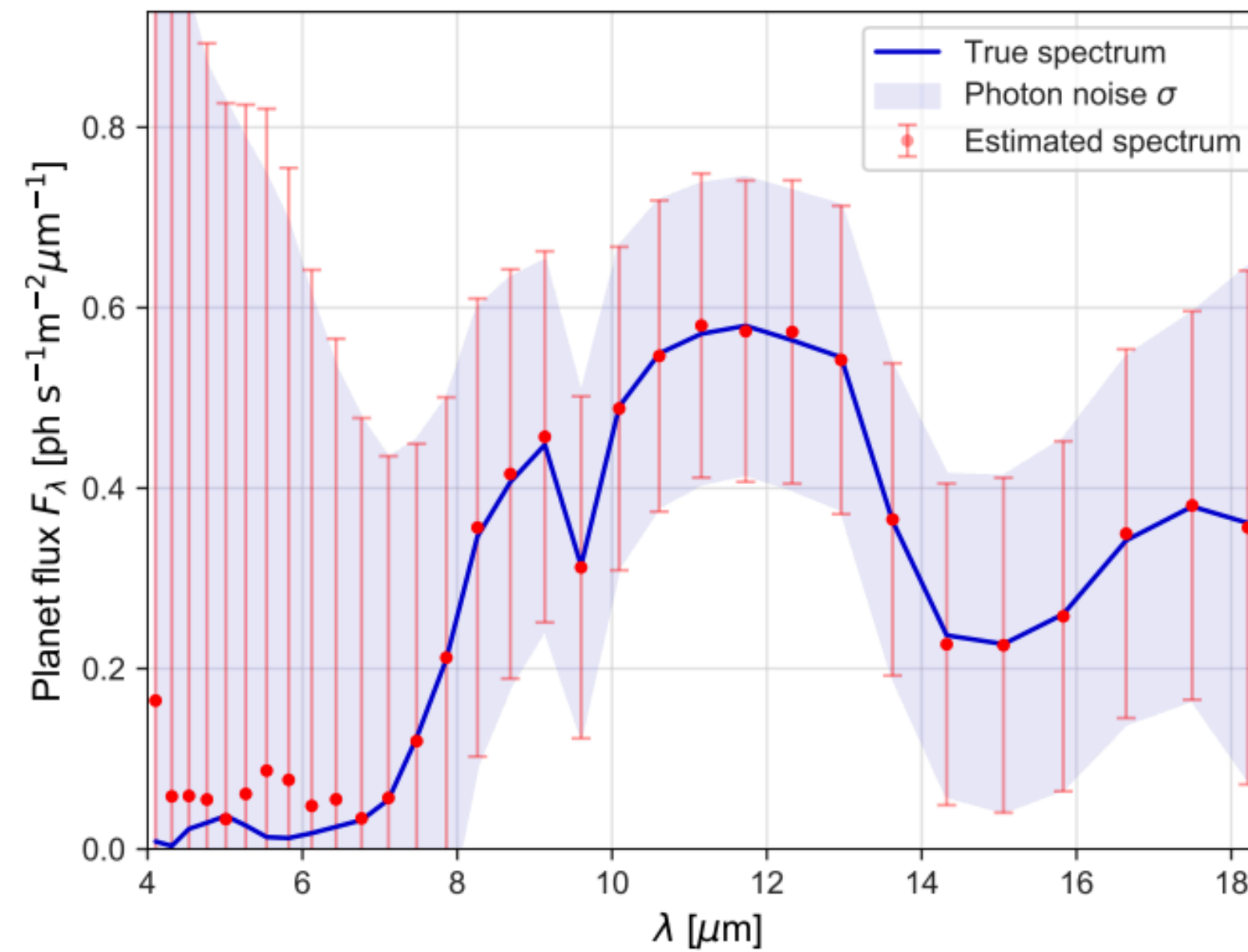
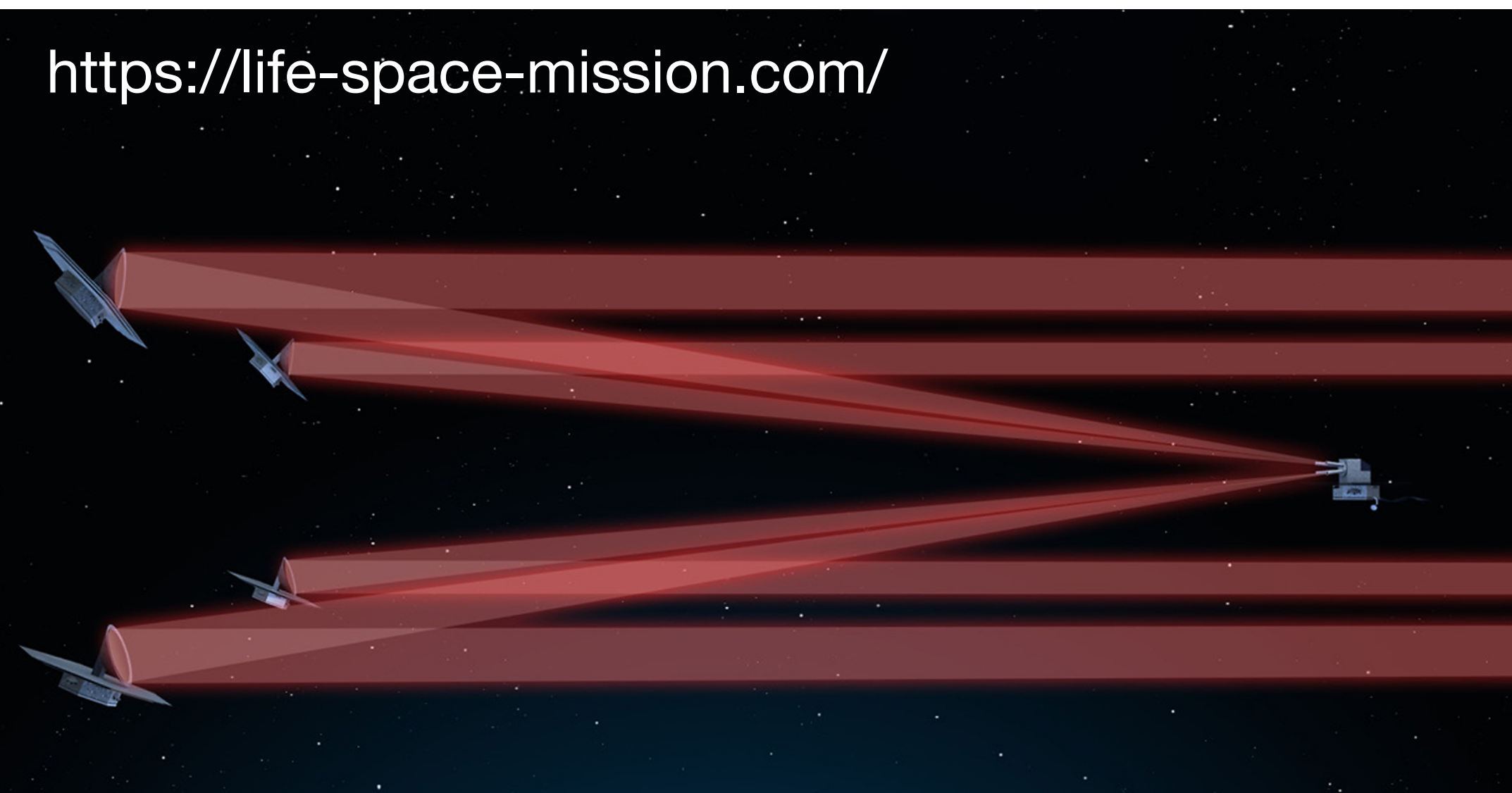
Large gain & unstable





Grand plan for Far-IR flagship:

KI-TWPAs for noise suppression
 NLKID for SNR maximization in low-flux observations
 Use linear mode ops (Same KIDs) for high flux targets



LIFE (Large Interferometer for Exoplanets) study of Earth-like exoplanets.

Planetary systems < 65 light years. Interferometry to null bright host star signal.
Very low mid-IR photon flux !!

Mid-IR photon counting MKIDs to the rescue. Similar to Far-IR work in spirit.

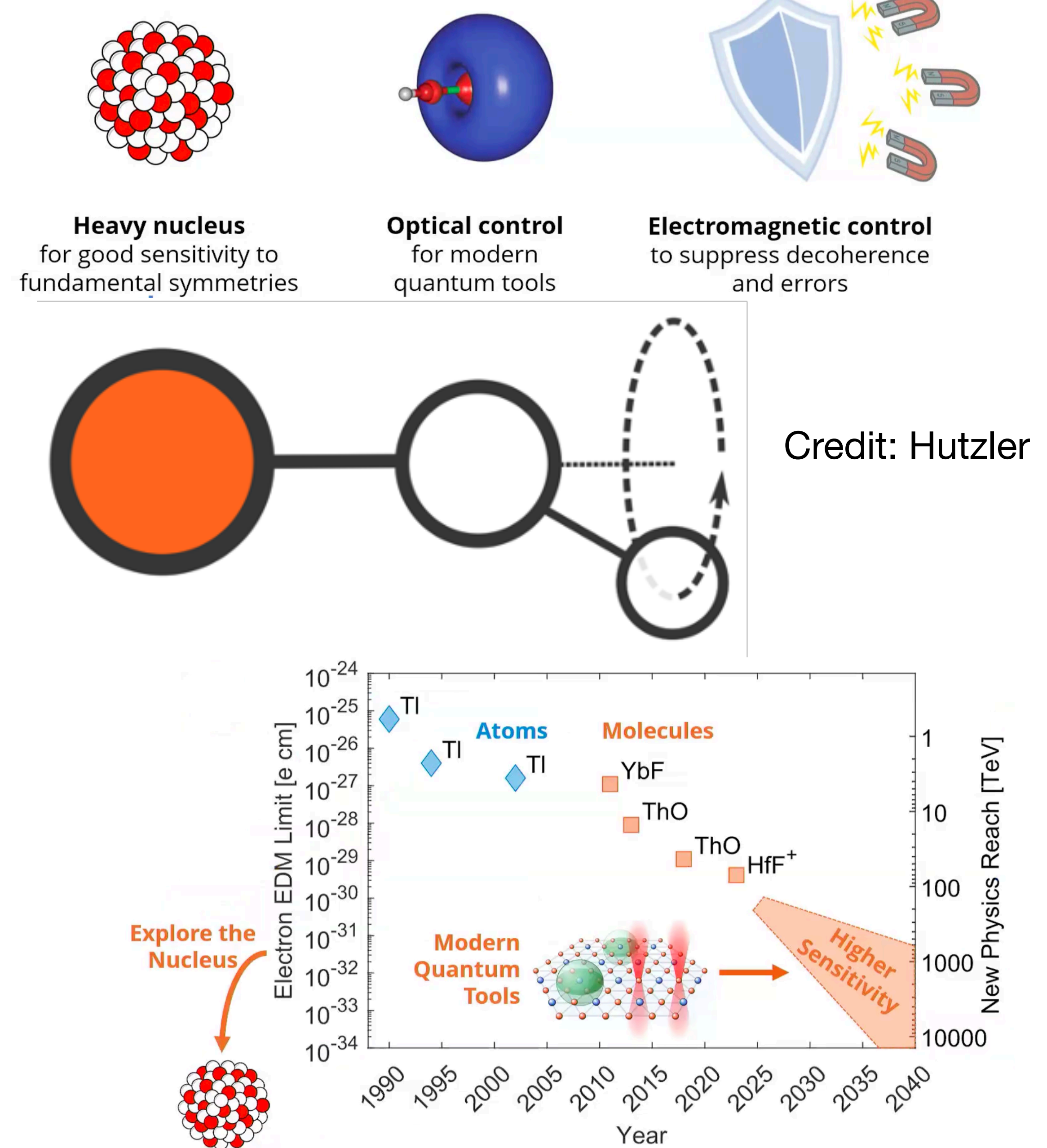
Engineered molecules for QS and lab astrophysics (not LIFE!) :

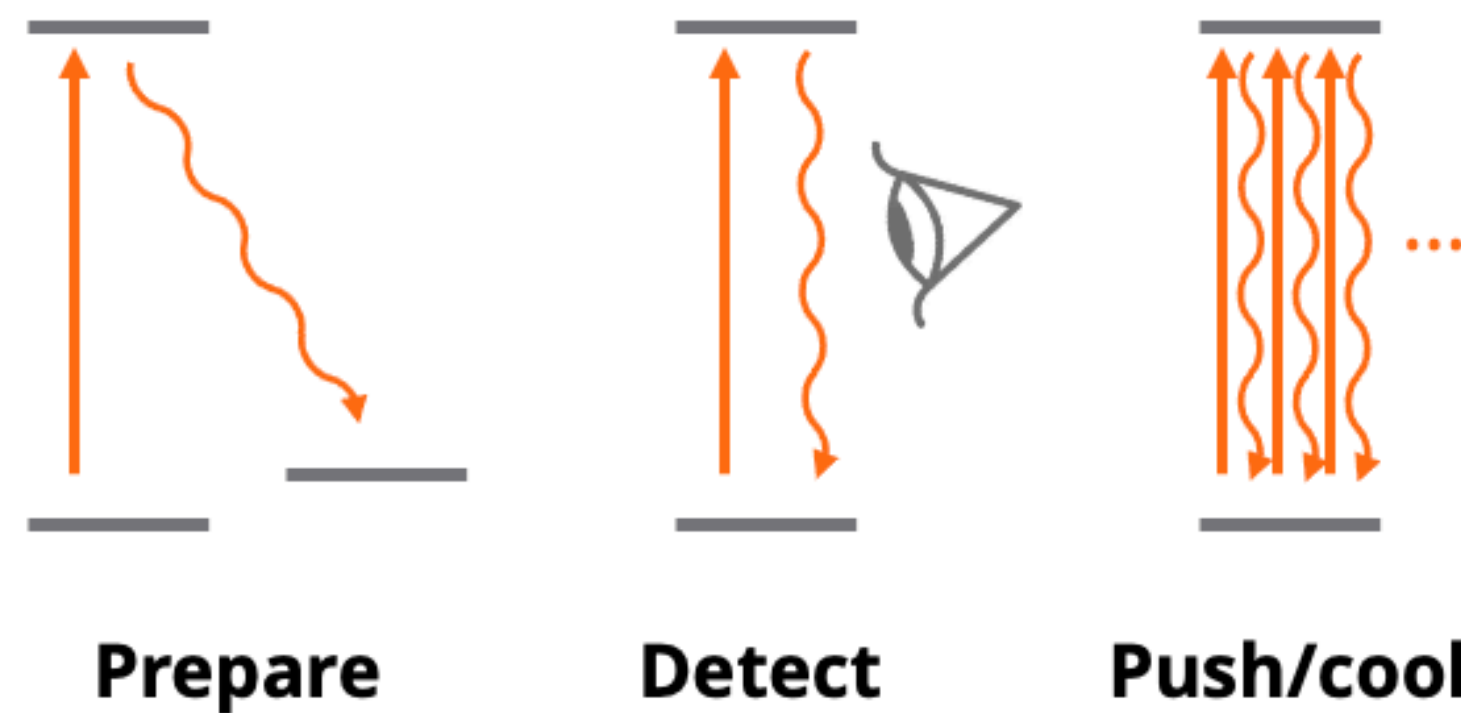
Extreme Internal fields amplify symmetry violations.

Pear-shaped nuclei boost hadronic sensitivity, lab astrophysics probes

Parity doublets cancel systematic noise. Also EMI suppression.

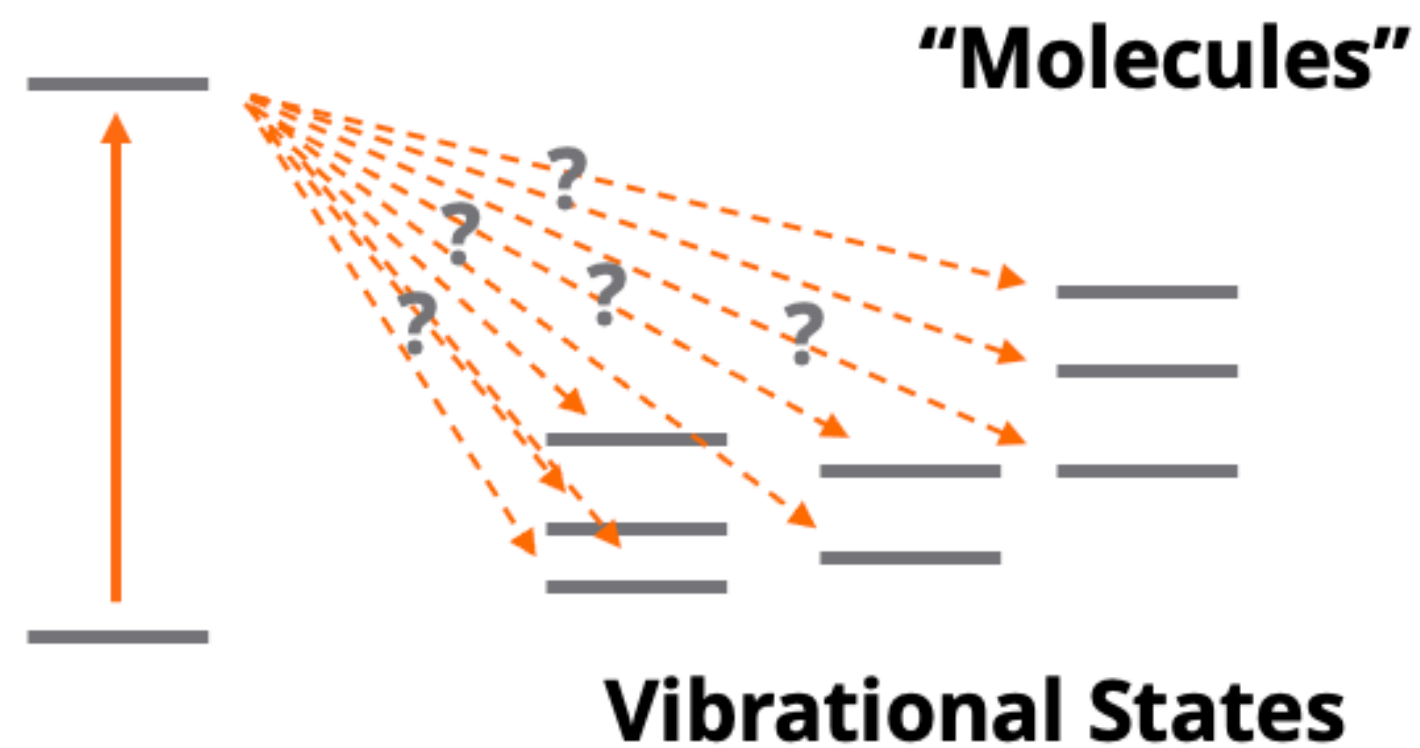
Other applications: BB sensing, Quantum-controls and simulators etc.



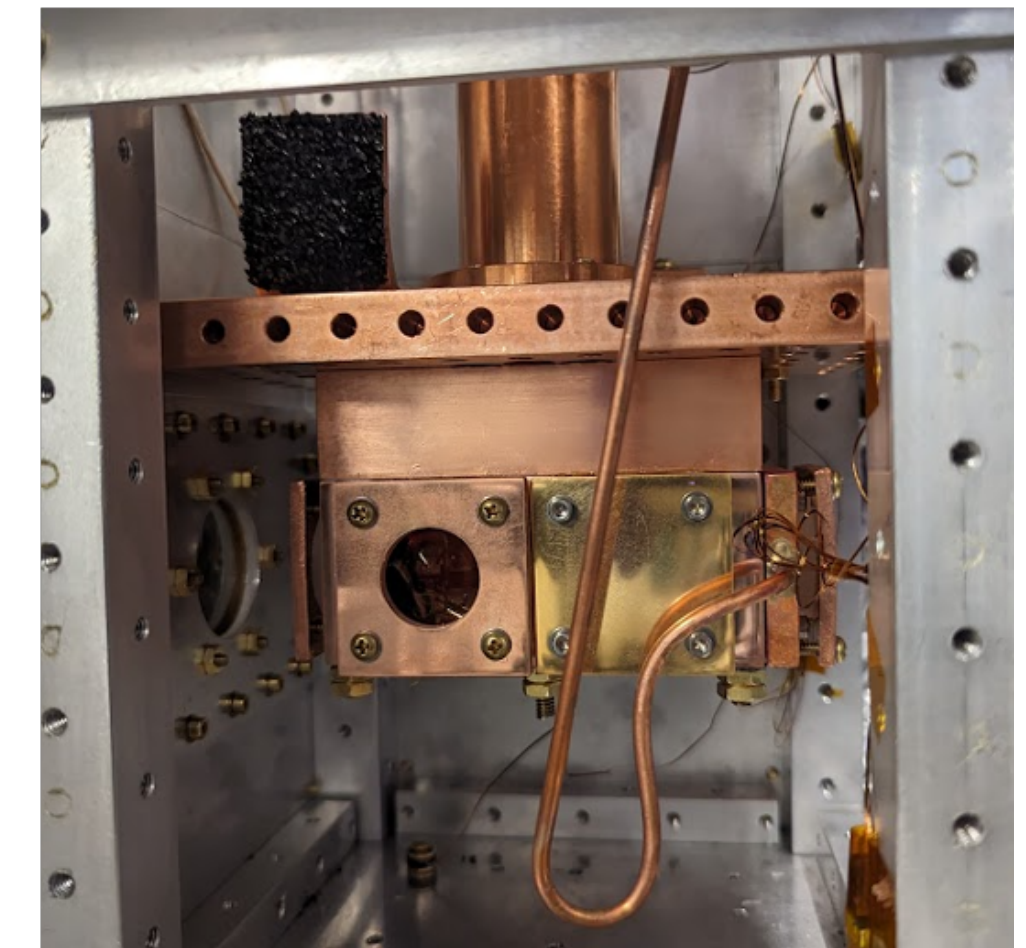
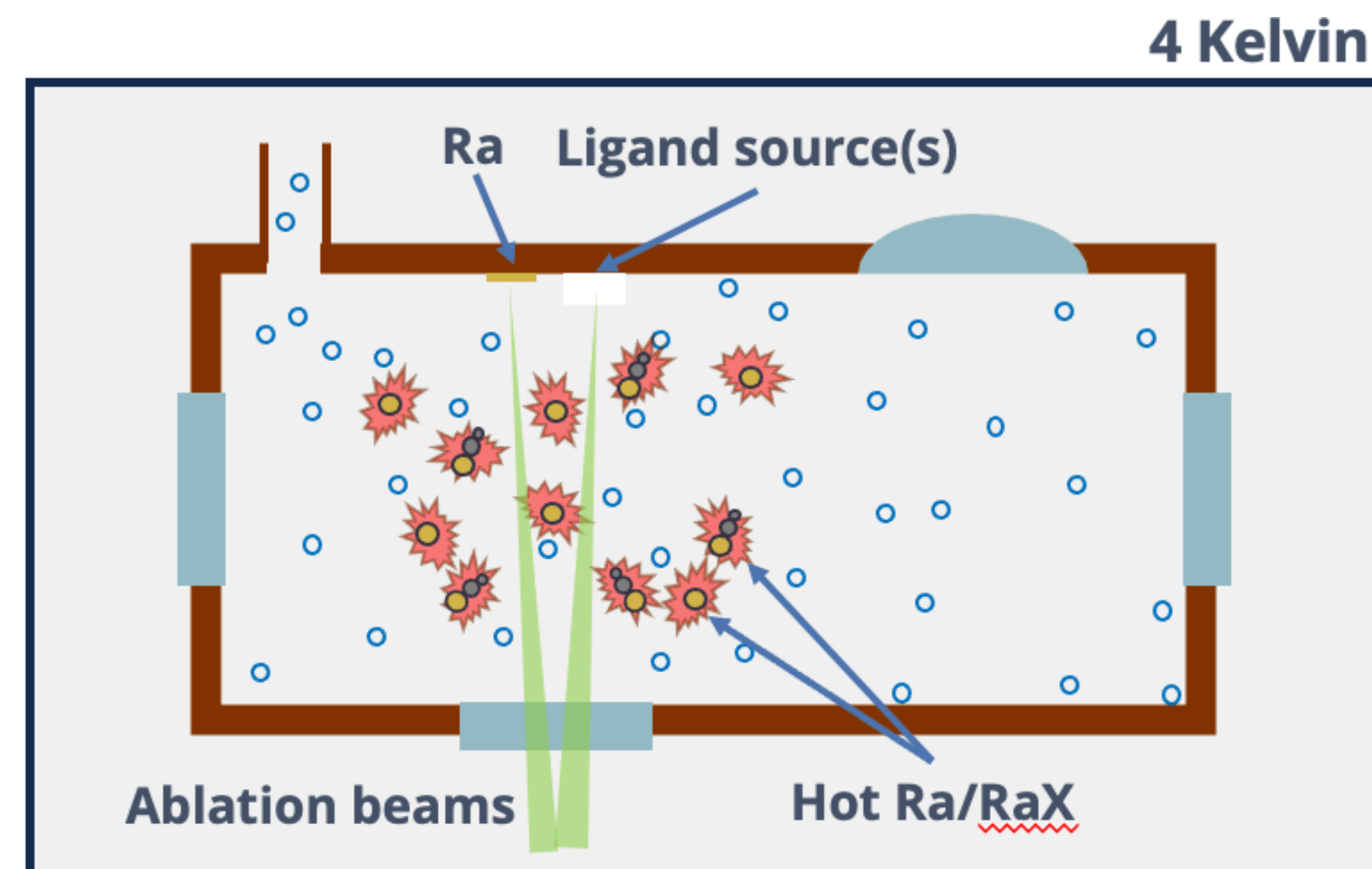


Groundbreaking efforts in cryogenic gas-cells, but

Molecules will have roto-vibrational states with energies **in the far to mid-IR!**
(recall our cold molecules in space)



A complexity price for flexibility ...
 vibrational states can blow up
 density-matrix uncertainties



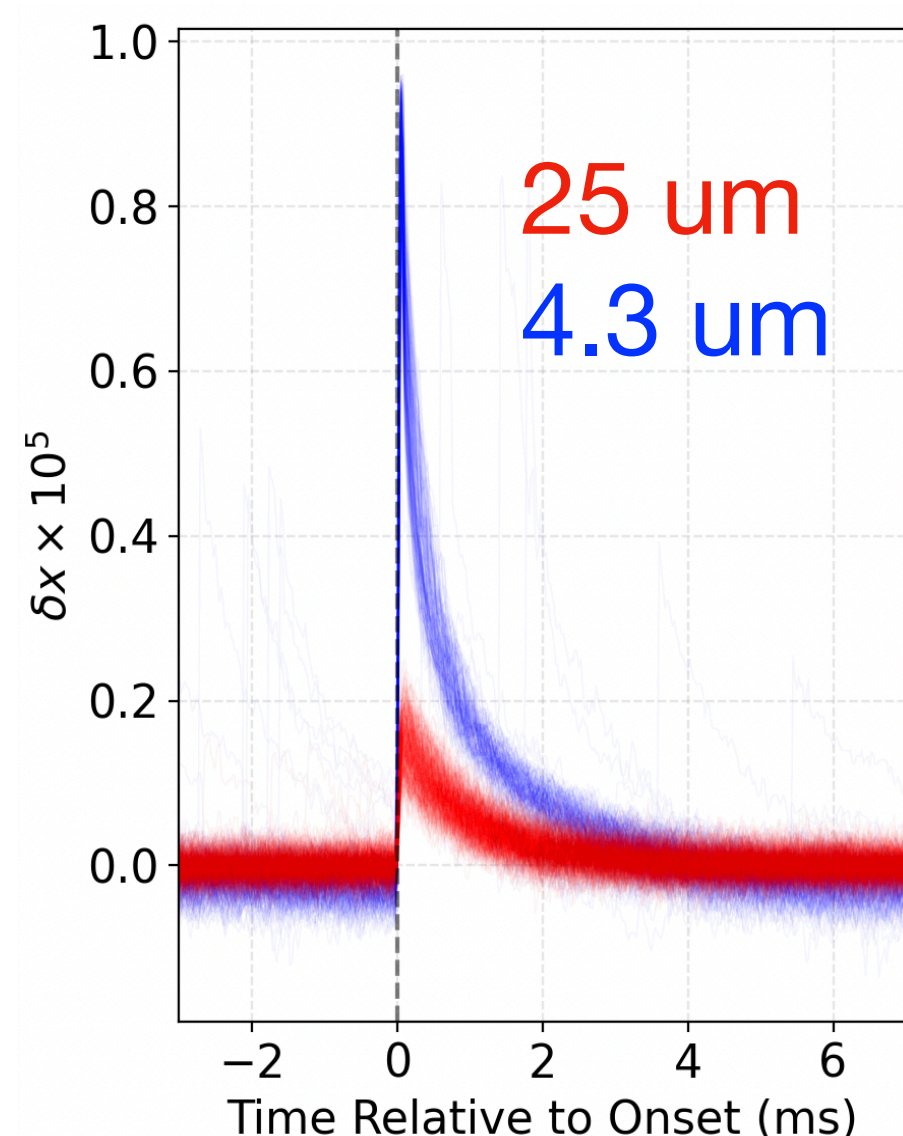
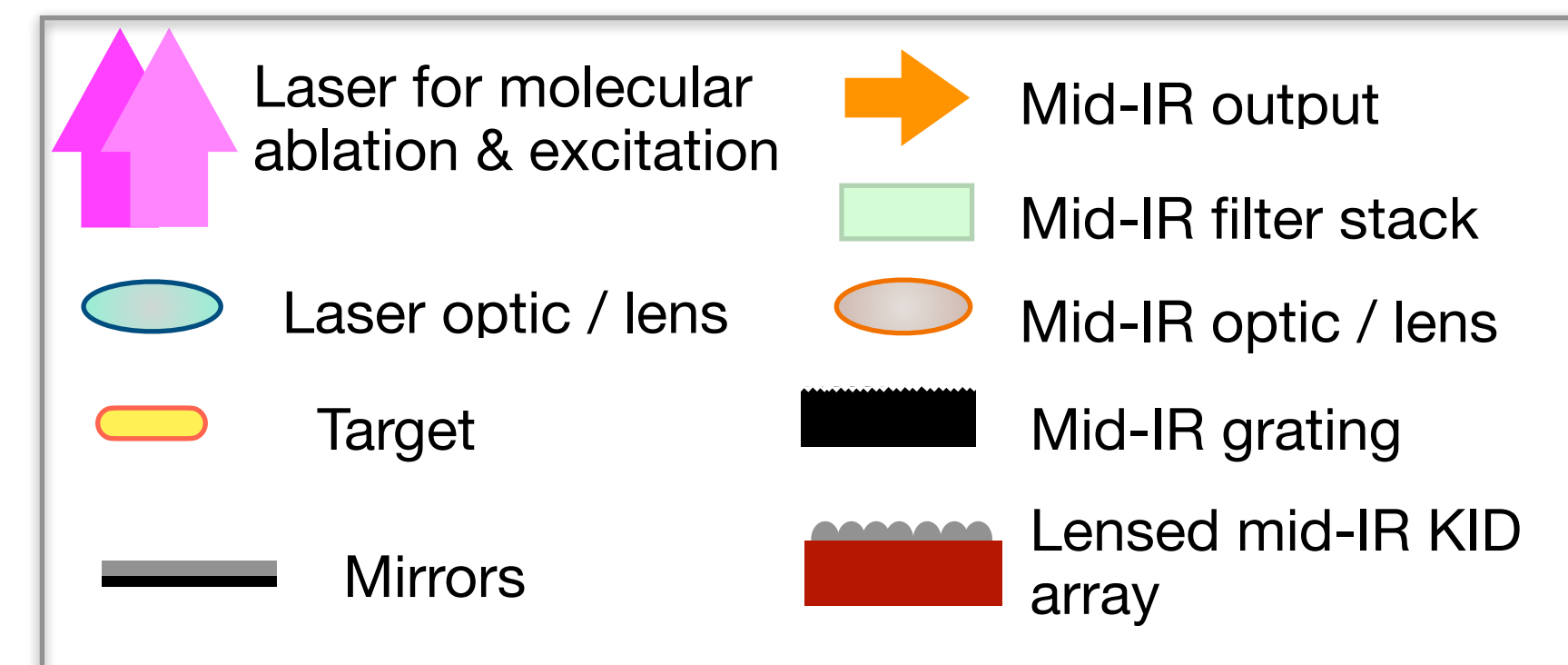
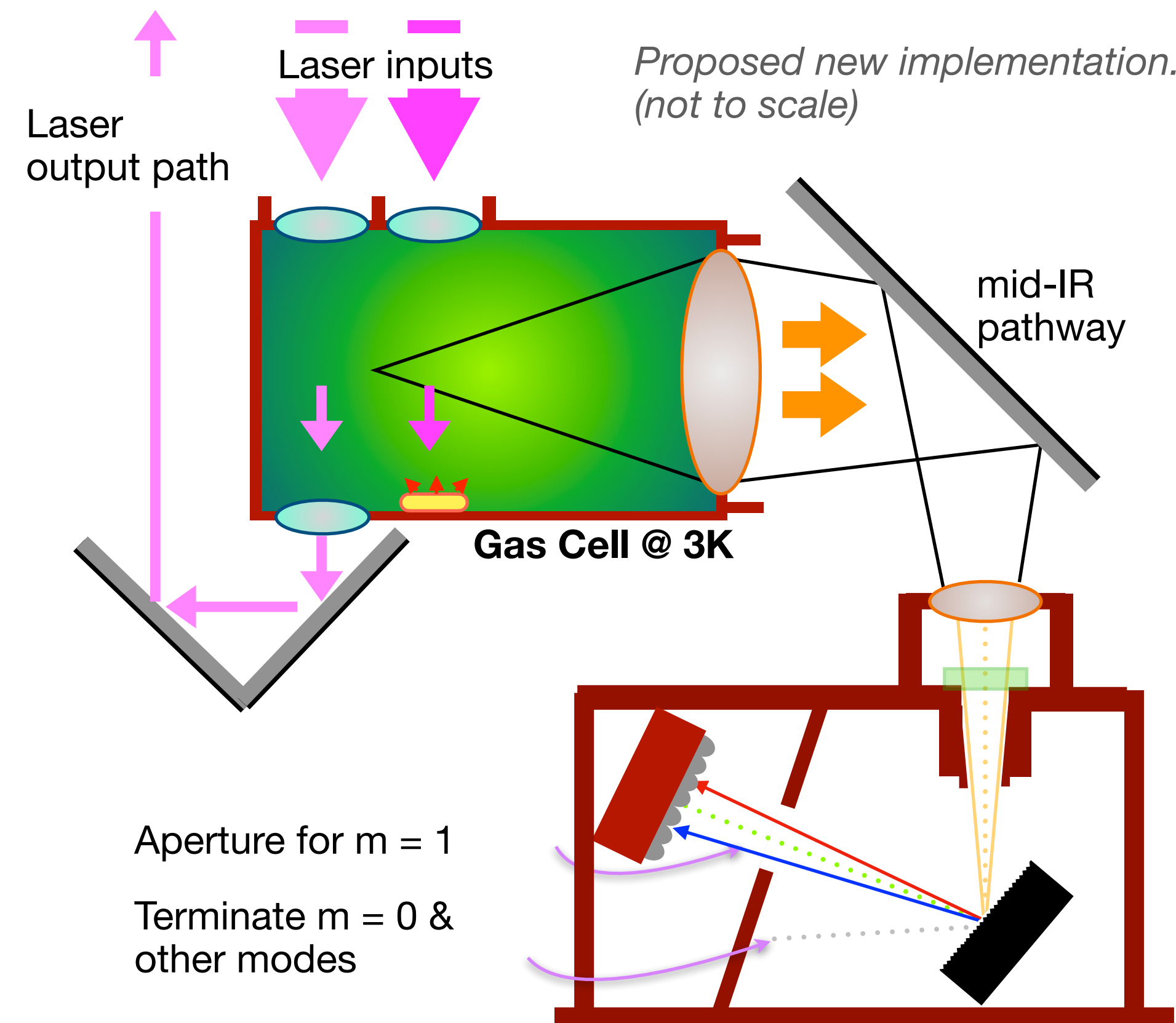
A KID array, via a grating, directly sees the excited molecules

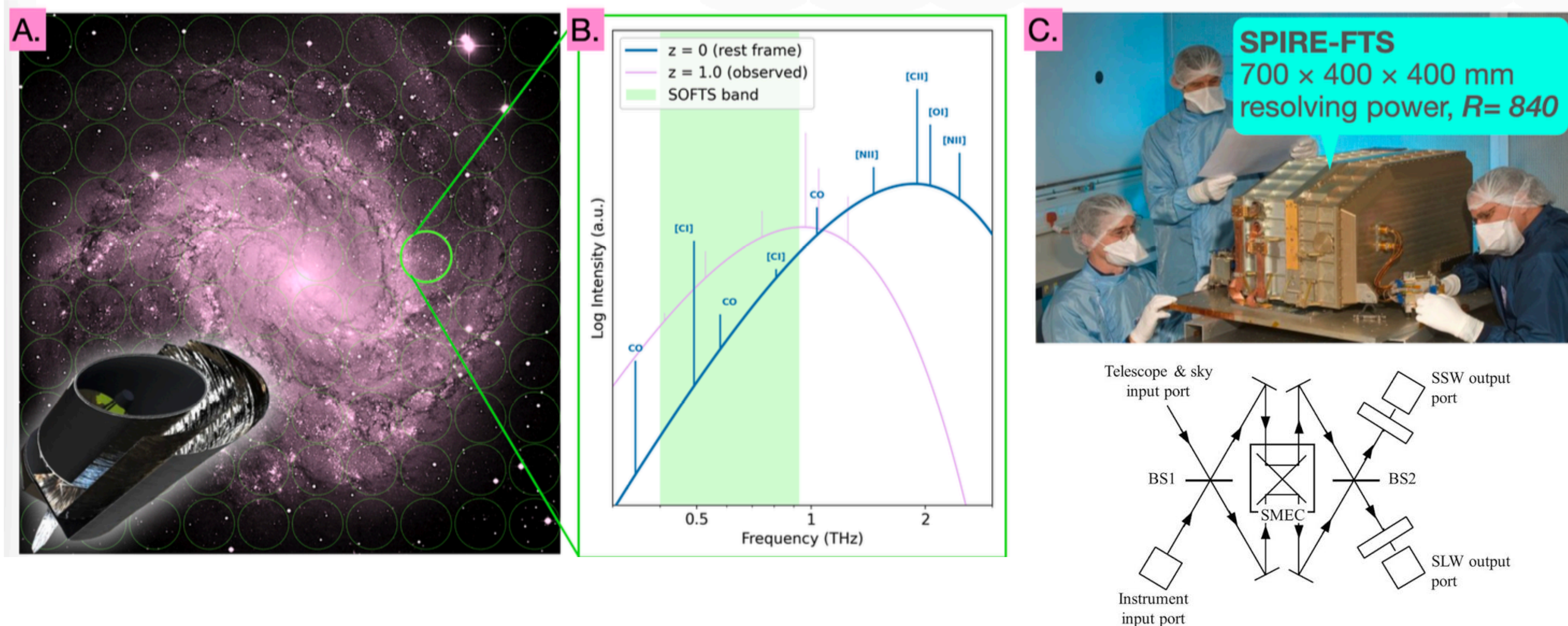
Goal: direct measurements of *mid/far-IR transitions* ... full transition spectrum to reduce uncertainty, improve precision further

Incidentally & directly helps with LIFE!

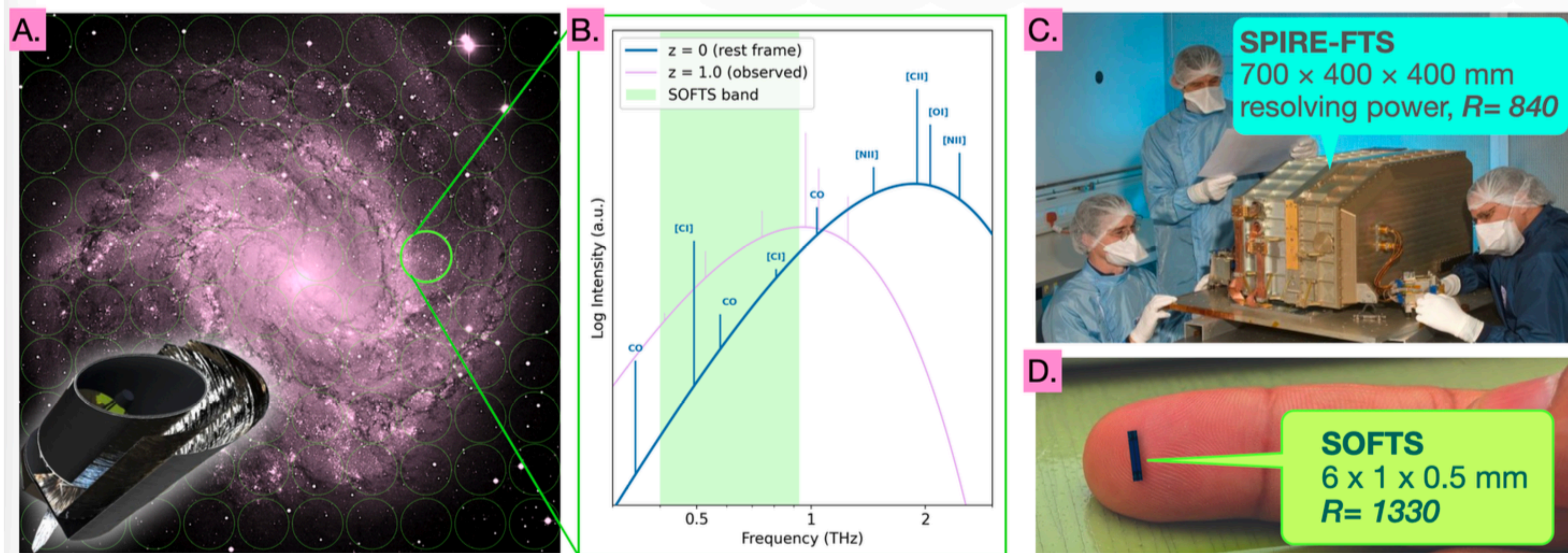
Same meta-structure inductor from PRIMA in midIR (~10 μm)

New project, just building up MKIDs, the “telescope” it WIP





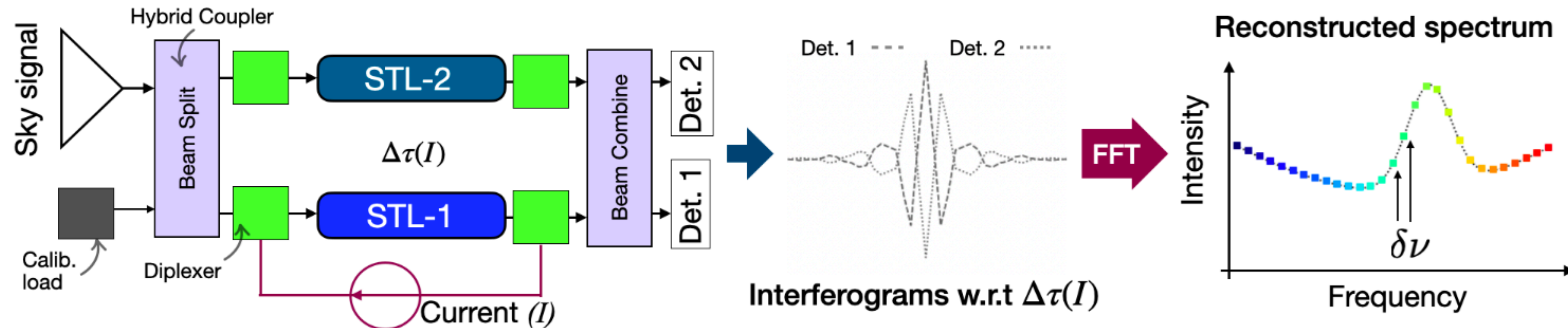
A different but ultimate target in Far-IR astro is to do spectro-imaging. In sub-THz, SPIRE's FTS (Mach Zehnder) revolutionized astrophysics... but they are heavy, slow, bulky and mechanical.



Basu Thakur et al, JLTP, Volume 211, Issue 5-6, p.227-236

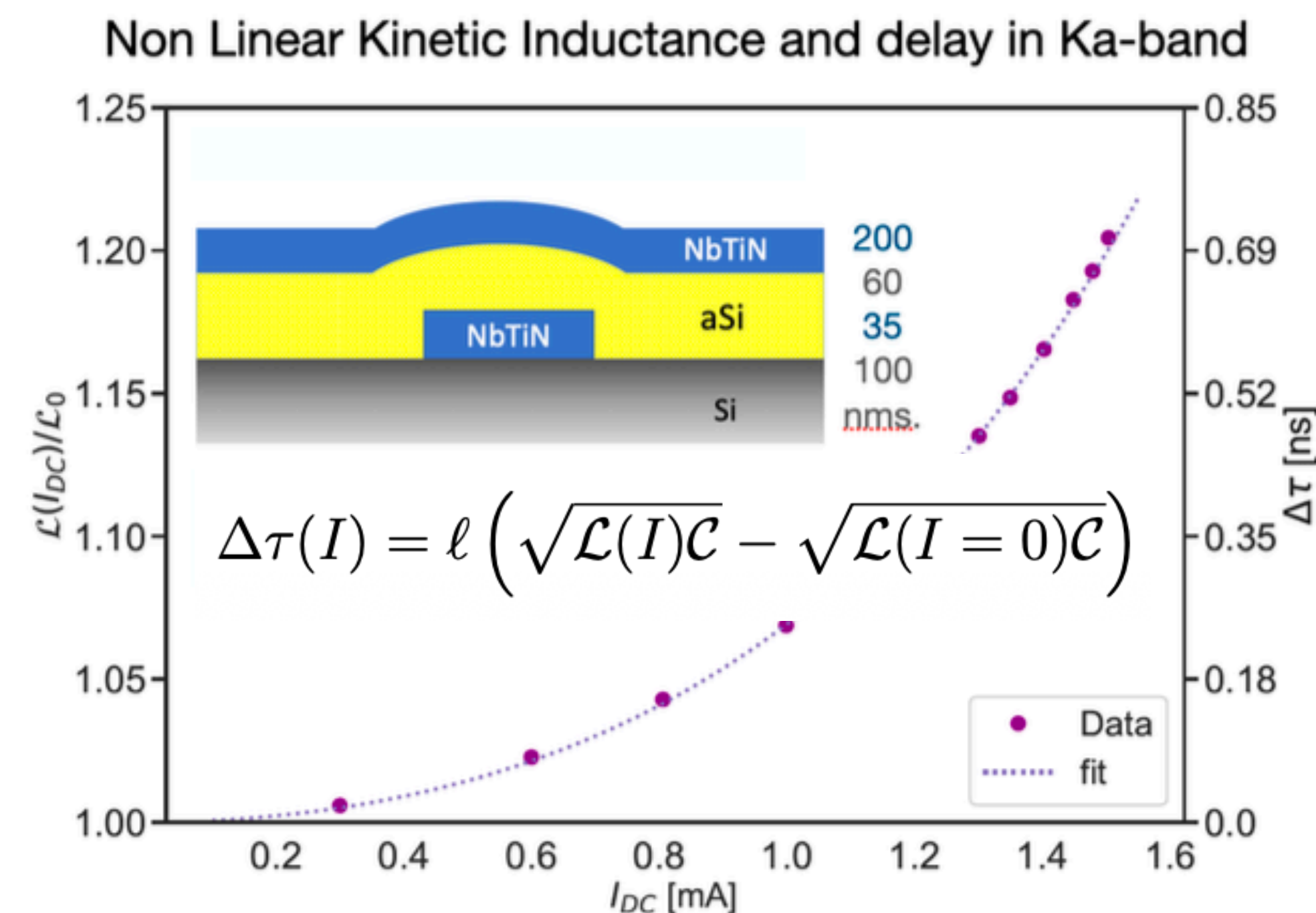
Per beam on the sky, obtain spectroscopy efficiently
SPIRE like FTSs are heavy, slow, bulky and mechanical.

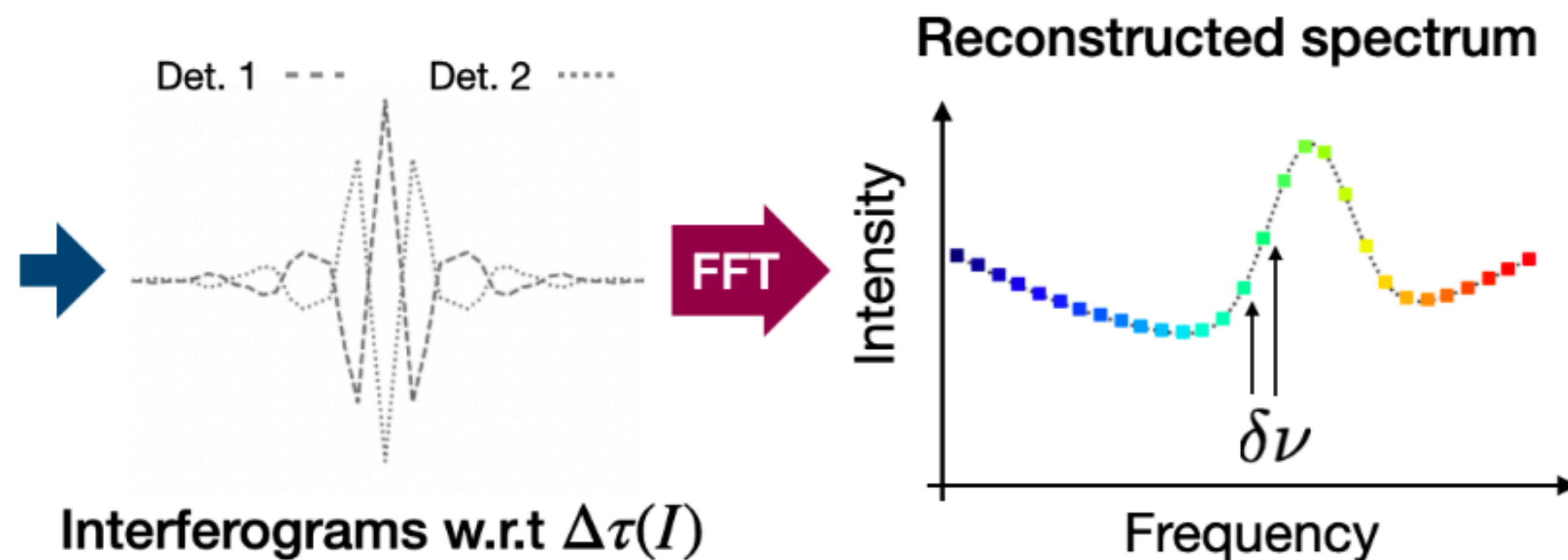
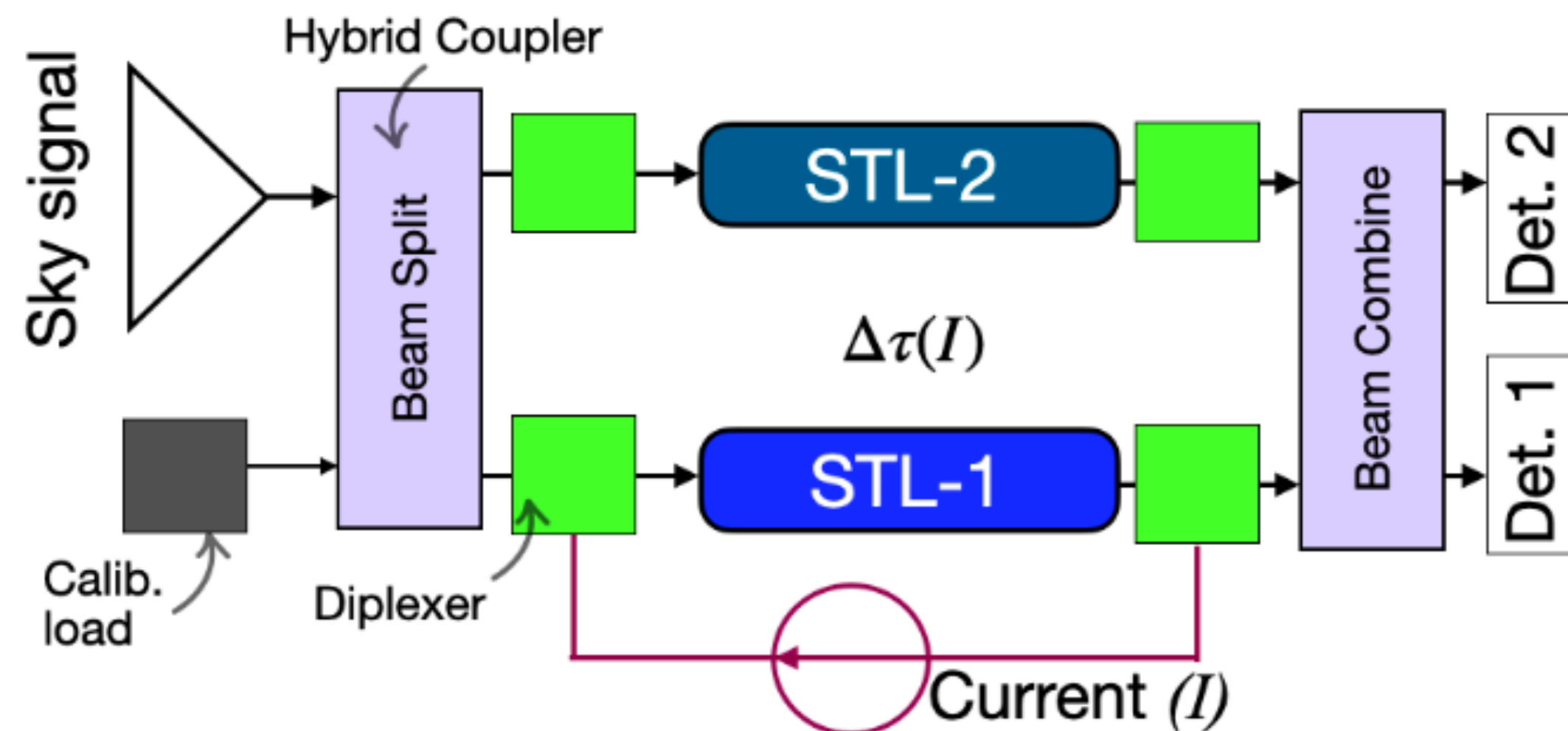
We have an on-chip solution. Each spatial pixel can now be its own FTS



Nonlinear Kinetic Inductance allows for adjusting delay with current bias
Don't need any moving mirrors!

Photonic on-chip MZI by integrating microwave circuit elements.
 Large KI leads to 0.1% c phase velocities, therefore ultracompact

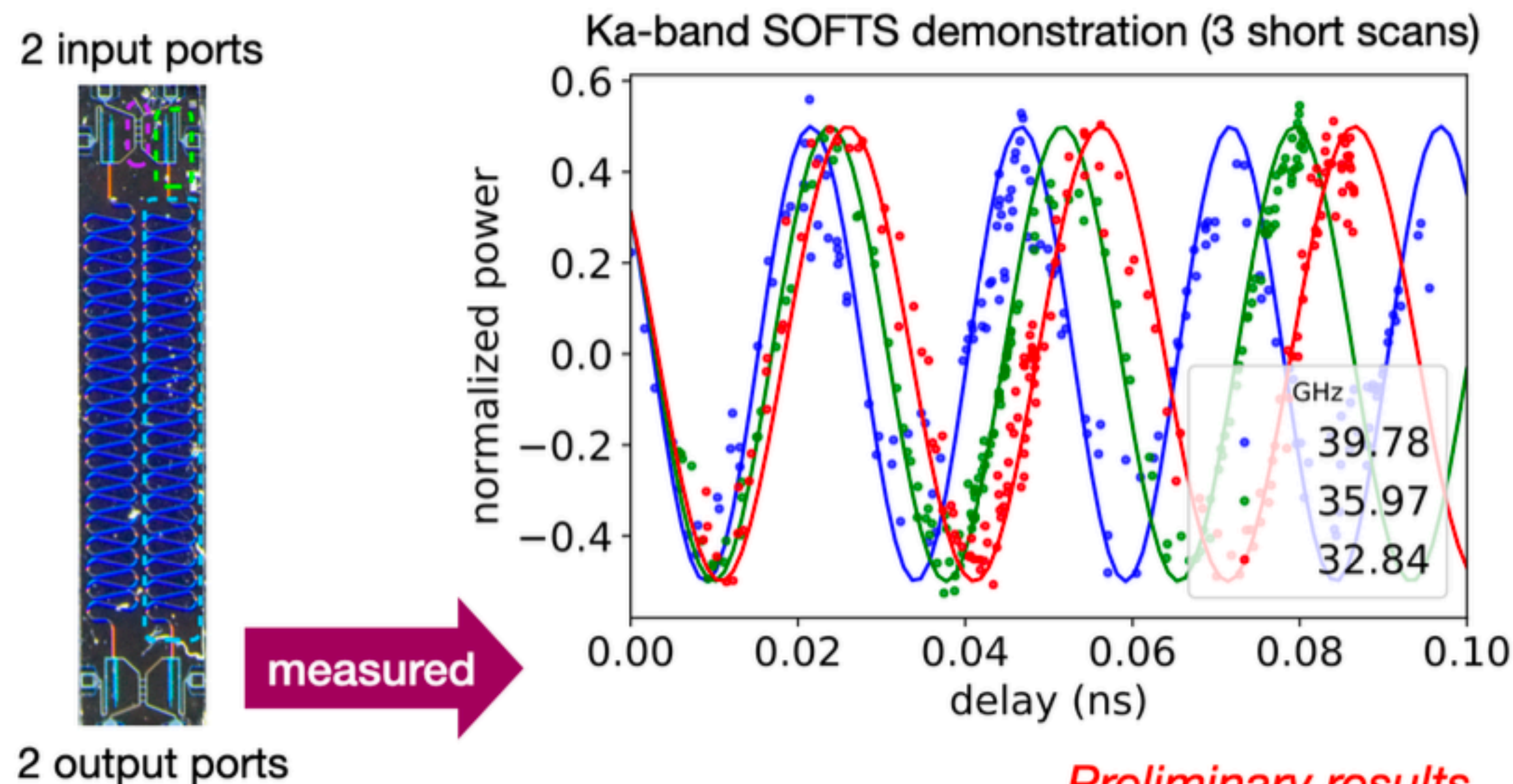




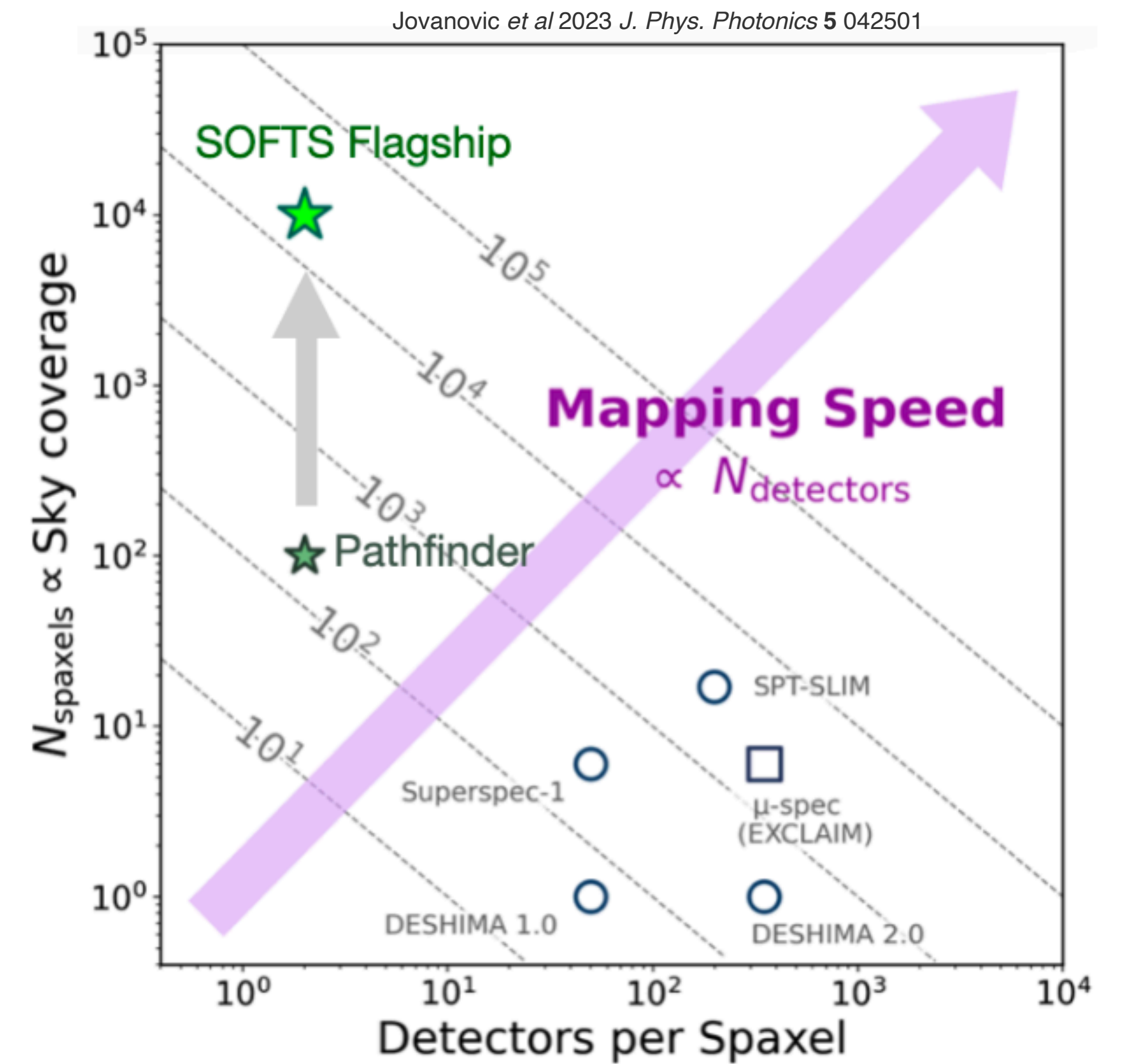
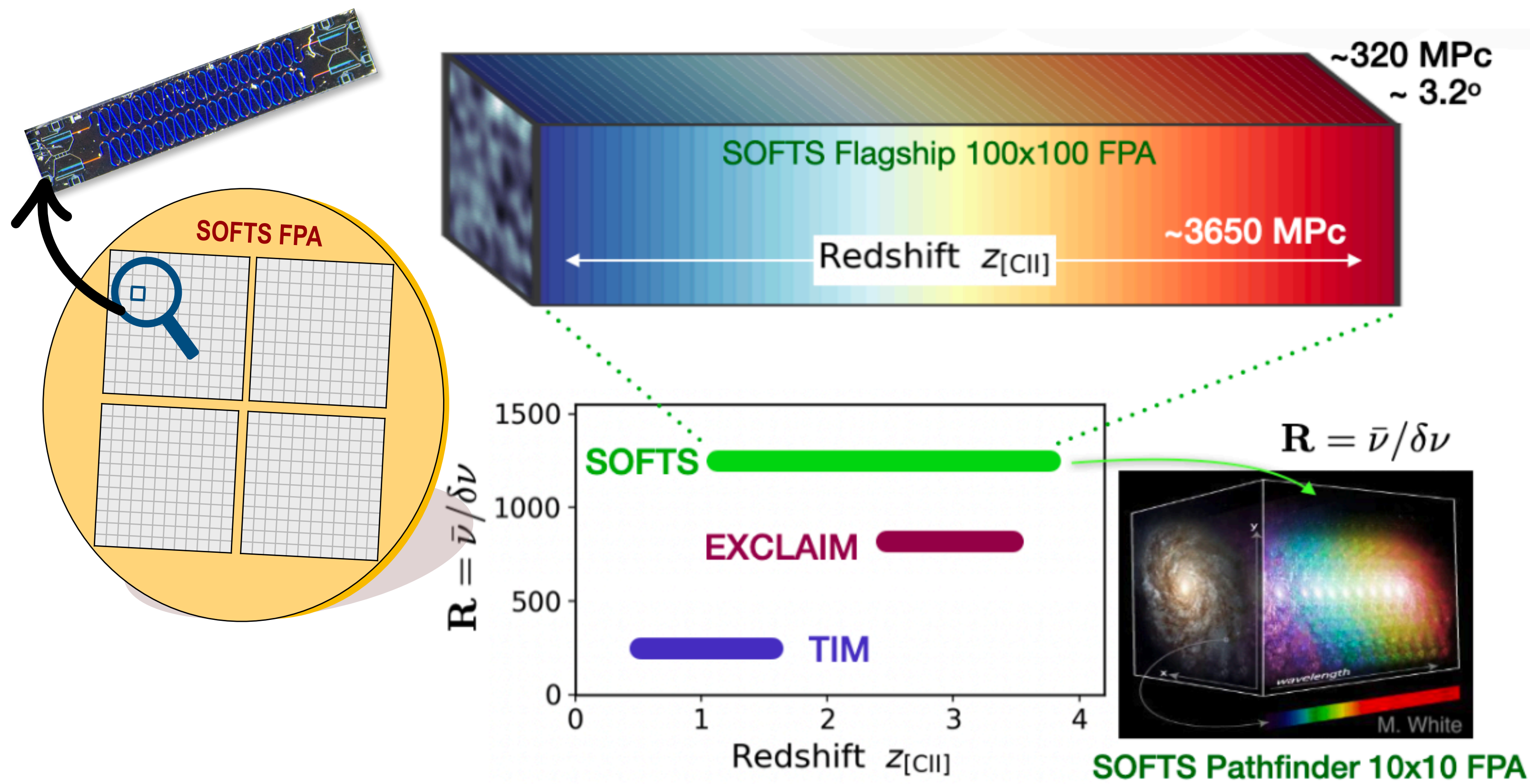
Low frequency 1-40 GHz SOFTS demonstrated with NbTiN

Using MgB_2 to extend to THz

S.C. MZI implies a nice Quantum Optics testbed for other science



Preliminary results



A Pathfinder balloon telescope (\$10M) can be used to 2x Herschel's (>\$500M) HERCULES catalog, much more cheaply

Large survey size enabled by SOFTS useful for Line Intensity Mapping in a Flagship telescope

Astrophysics with Quantum Probes

From coherent to incoherent photons, from detectors to interferometers, from molecules in space to those hand-made, lots of QS work at JPL/Caltech.

$t \geq 2024$

$t \gtrsim 2035$

$t > 2040$

New Ideas ?!

*M/NL-KID for Far-IR
Astrophysics*

*Mid-IR “ for exoplanets &
molecular QS*

KI-TWPA for CMB, LIM

SOFTS for QO & astro

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Hutzler is supported by Gordon & Betty Moore, DOE and Caltech President’s awards

Our students are supported by NASA NSTGRO, NSF GRFP grants and Caltech fellowships

JPL’s innovations in Quantum Sensors, but, for Astro!

Technology	Science & Pls
KI-TWPA	Qubit R/O (Day). CMB & Synchrotron (Day, Basu Thakur), Dark Matter (Basu Thakur, Ramanathan)
MKID	Day, Zumdzinass at large
Single-photon far-IR MKID	Day, Basu Thakur and others
“ mid-IR MKID	Day (Exoplanets), Quantum precision (Basu Thakur, Hutzler)
NLKID	Far-IR Astro and Dark matter (Basu Thakur, Day)
QCD	Far-IR Astro and Dark matter (Echternach, Shaw)
SOFTS	Far-IR Astro (Basu Thakur, Cunnane, Day)
SNSPD	Astro and Quantum Sensing (Shaw et al)