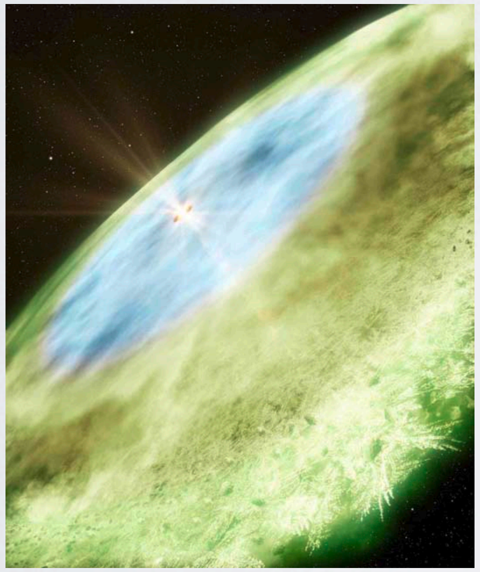
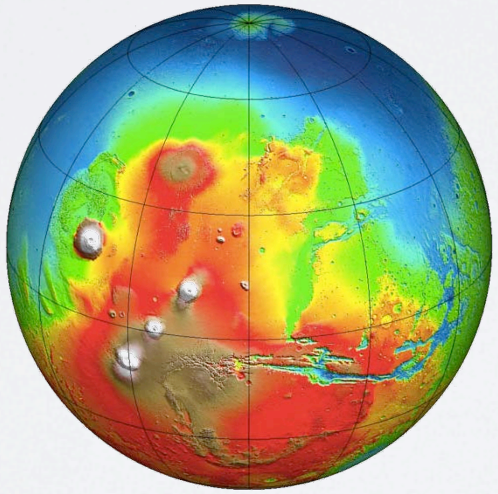
CALIFORNIA INSTITUTE OF TECHNOLOGY

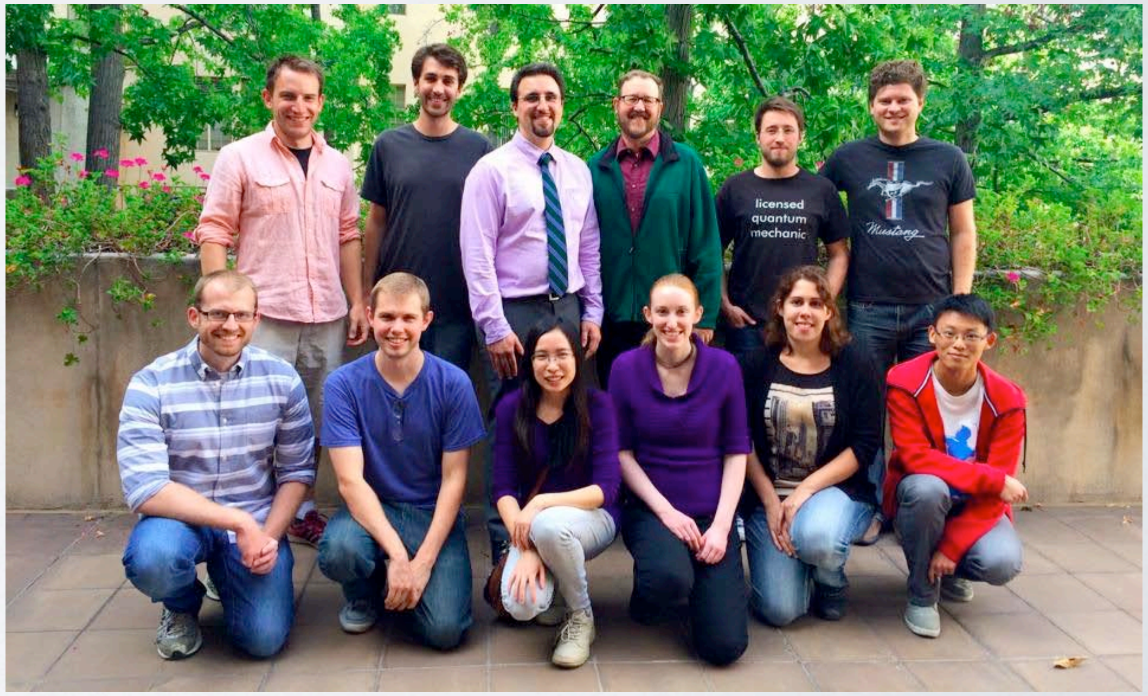
Remote Sensing/*In Situ* Space Applications of TeraHertz (THz)Frequency Combs

Outline:

- What is the TeraHertz (THz) window?
- What are THz photons good for (Astro/PS)?
- Why/How THz comb spectroscopy?
- What's next?/Closing Remarks





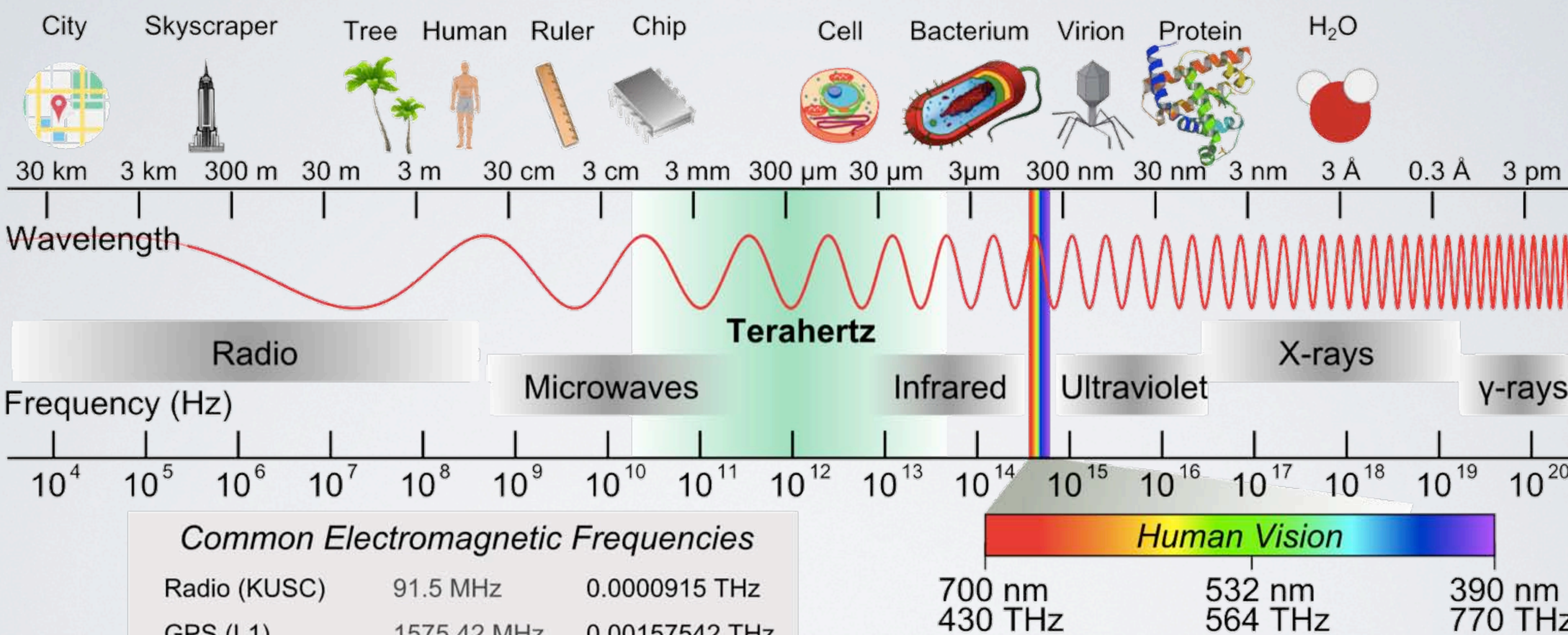


Geoffrey A. Blake
Division of Chemistry & Chemical Engineering,
Division of Geological & Planetary Sciences

KISS Optical Comb Workshop – Nov. 3rd, 2015

Light-Matter Interactions and the THz Window

We use spectroscopy that spans the spectrum from microwave through infrared/near-optical frequencies, with a focus on TeraHertz (THz) studies:



Common Electromagnetic Frequencies

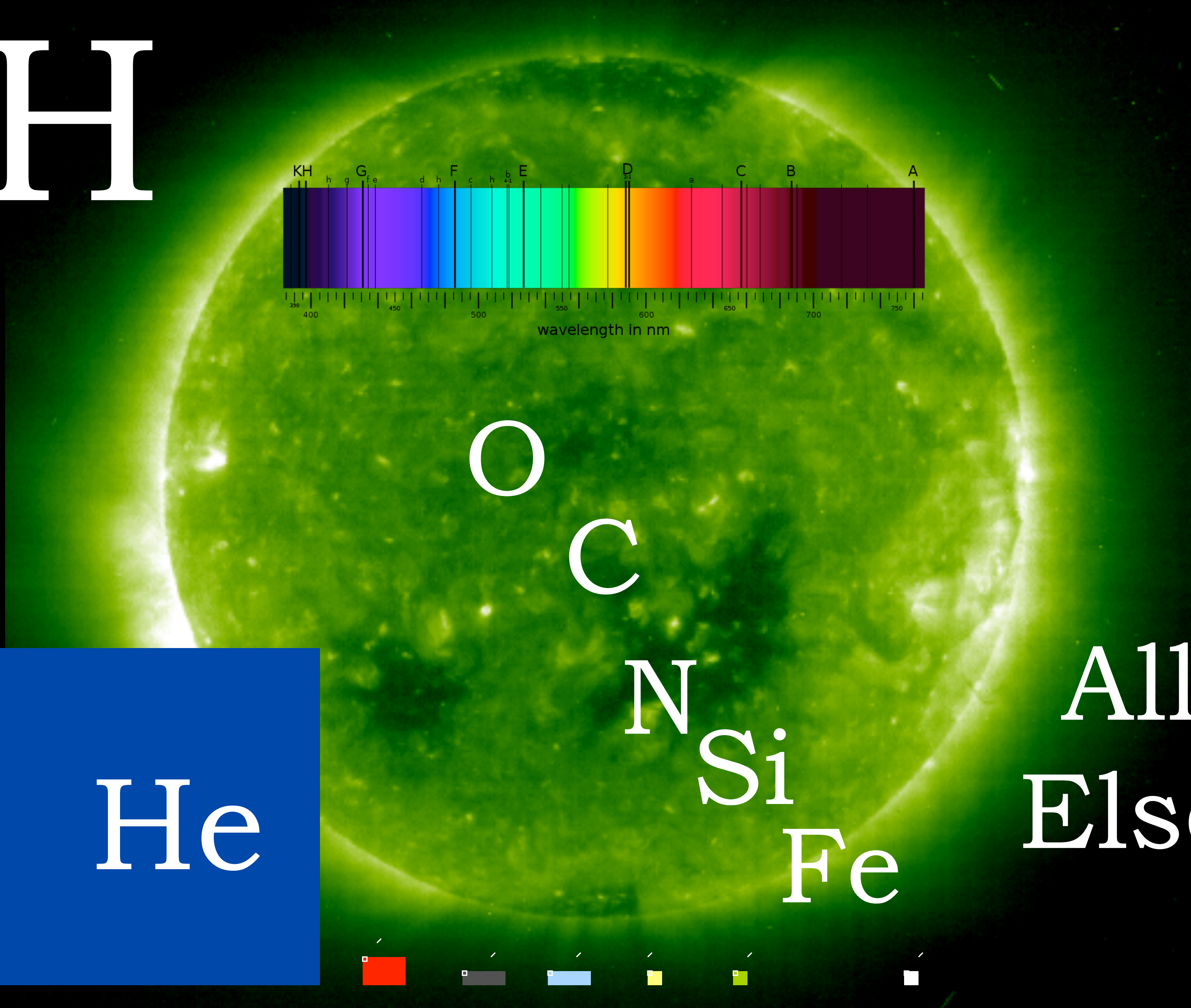
Radio (KUSC)	91.5 MHz	0.0000915 THz
GPS (L1)	1575.42 MHz	0.00157542 THz
Wi-Fi	2.4 GHz	0.0024 THz
Mobile (GSM)	850 MHz	0.000850 THz

1 THz < > 1 ps < > 33 cm^{-1} < > 0.3 mm < > 48 K < > 4.1 meV

The photospheres of stars tell us what they are made of…

The Astronomer’s Periodic Table (after B. McCall)

H



O

C

N

Si

Fe

All Else

He

$[O,C] \sim 10^{-4}[H]$

$[N] \sim 10^{-5}[H]$

$[Si,Fe] \sim 10^{-6}[H]$

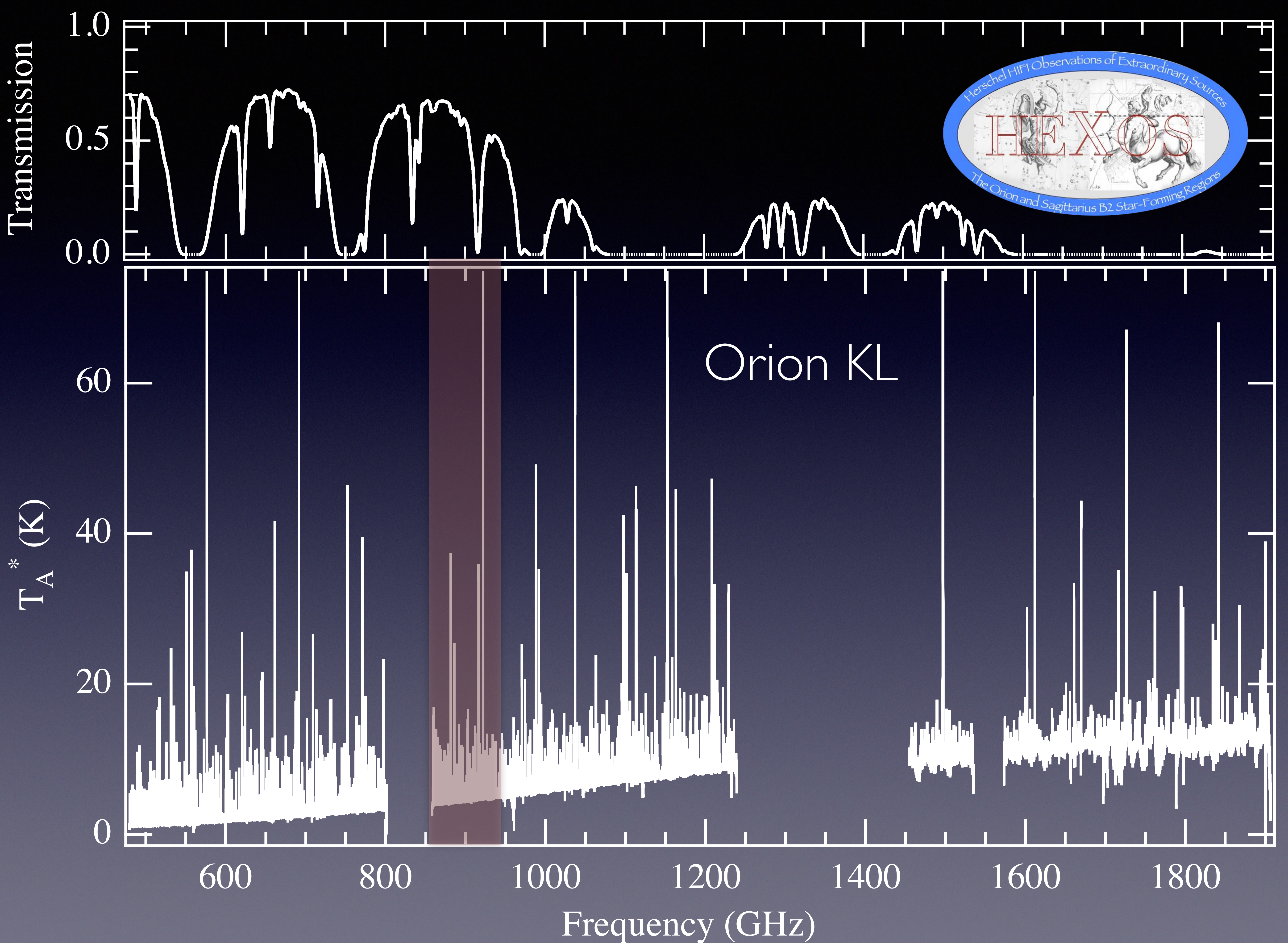
H, H_2, He very hard to see.

Dust+Ice/Gas~1%

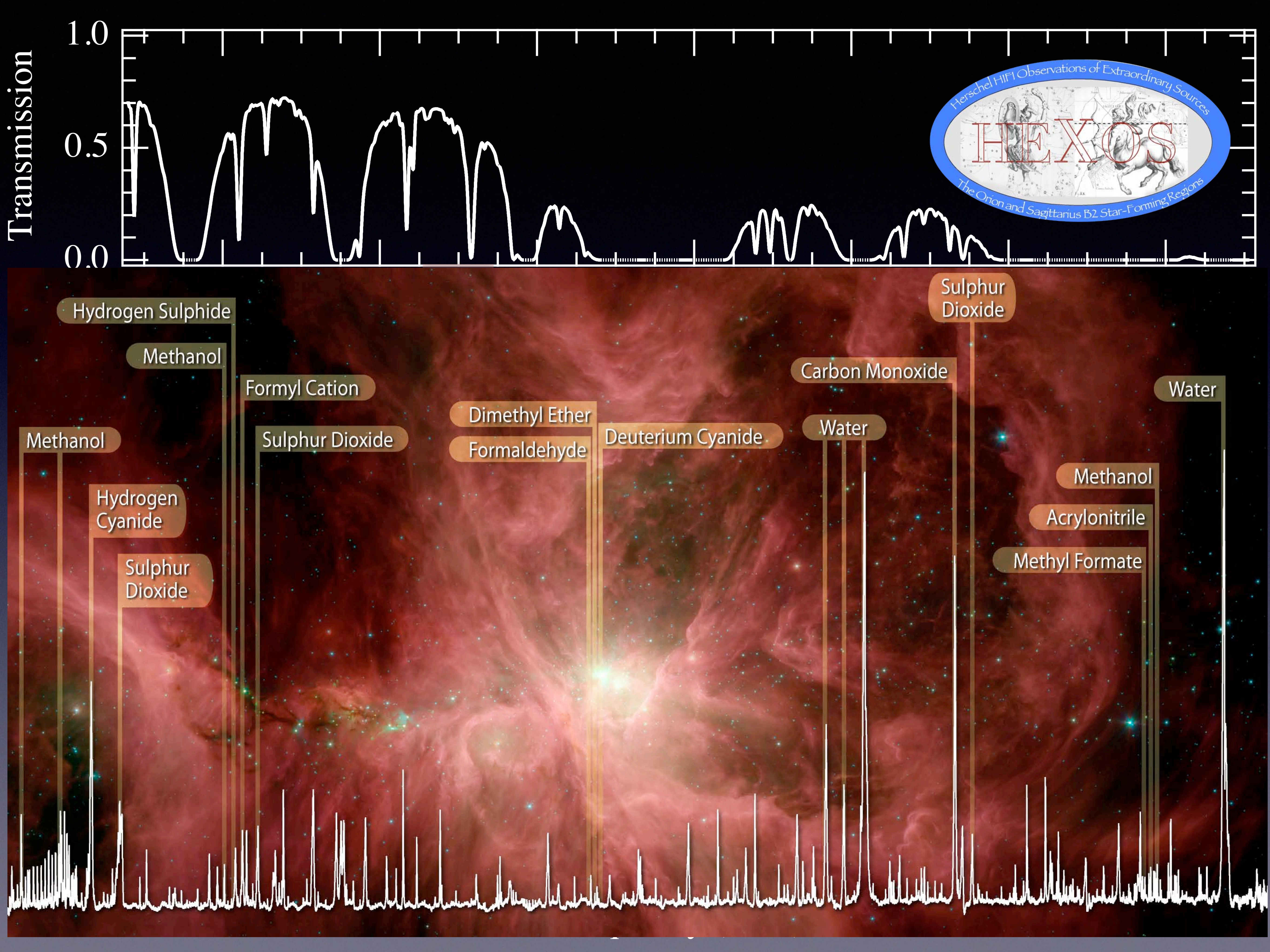
… and serve as *beacons* for exoplanet searches.

Astrochemistry & THz Photons: Star & Planet Formation

The dense gas and dust that forms stars, and the disks around young stars, are so opaque/cold that only THz and longer wavelength photons can penetrate them.



Transmission
1.0
0.5
0.0
Herschel HIFI Observations of Extraordinary Sources
HEXOS
The Orion and Sagittarius B2 Star-Forming Regions
Orion KL
T_A^* (K)
60
40
20
0
600
800
1000
1200
1400
1600
1800
Frequency (GHz)



Transmission
1.0
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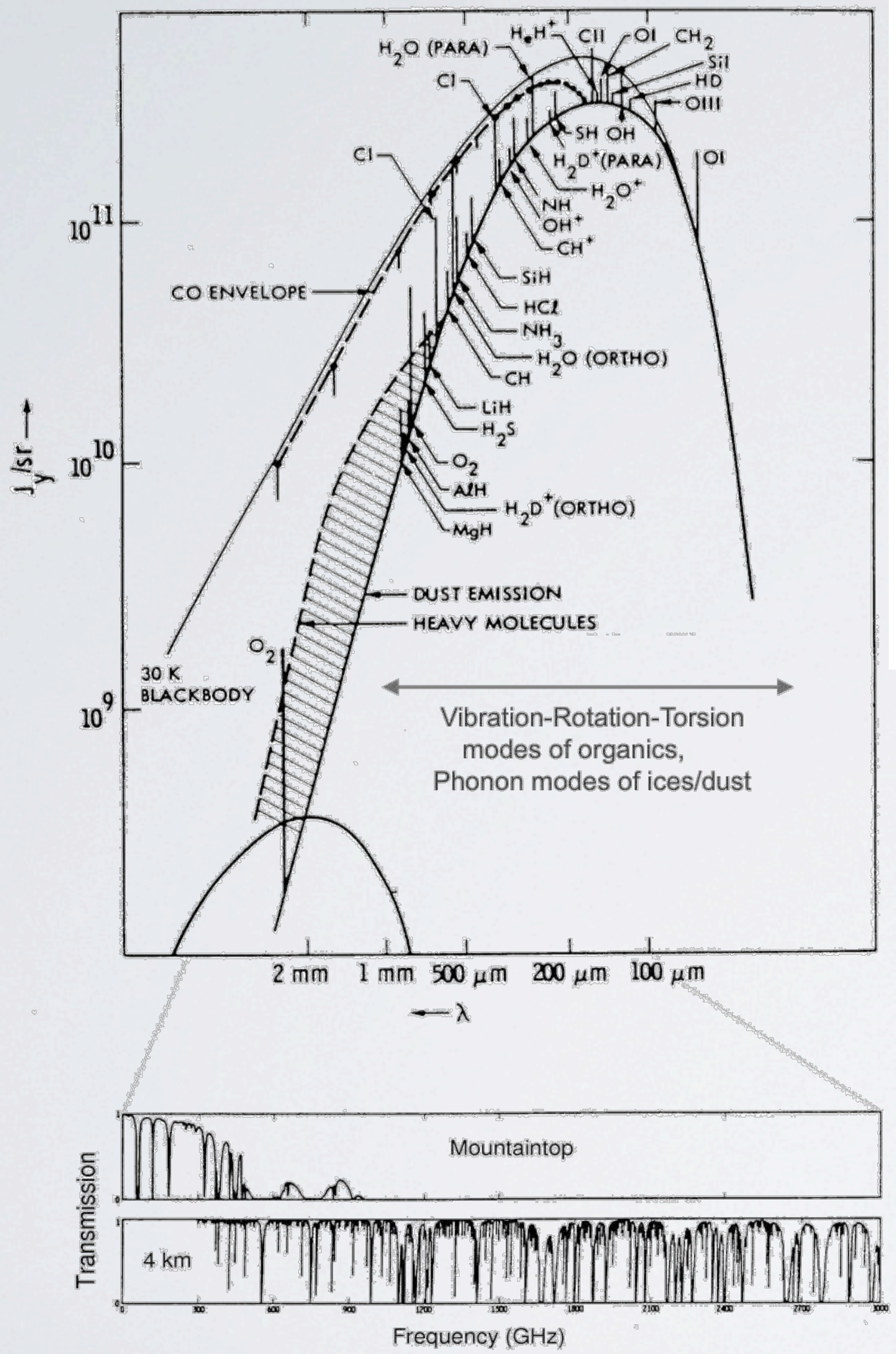
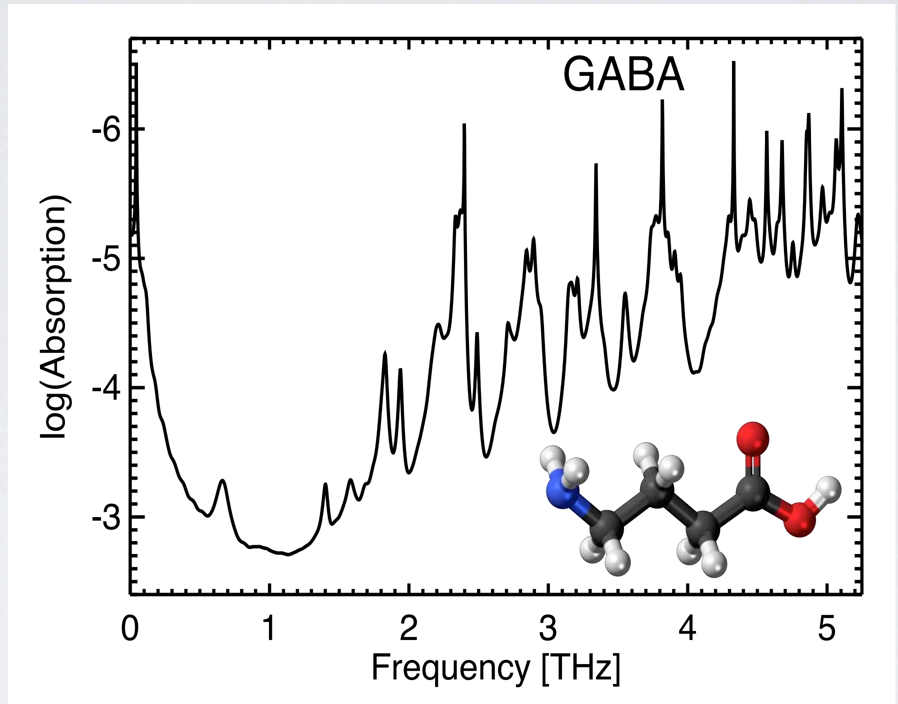
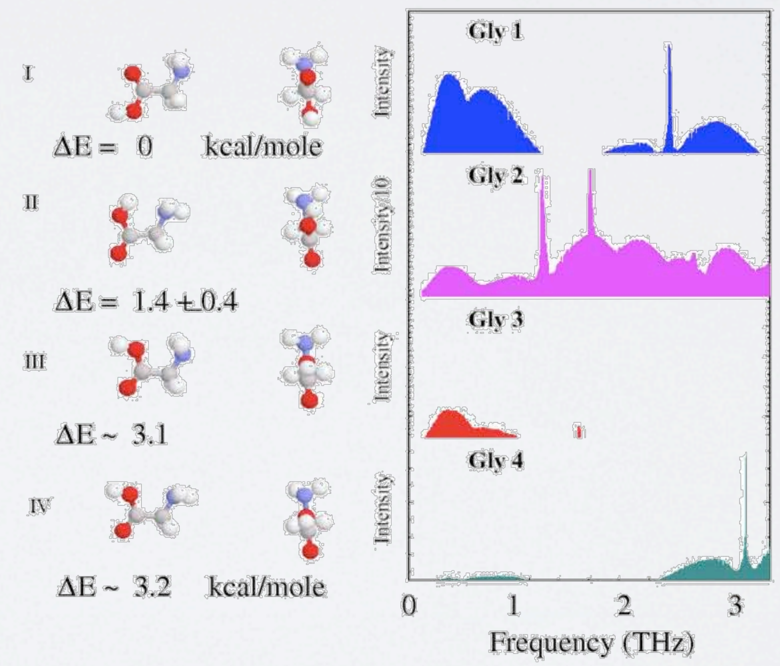
Hydrogen Sulphide
Methanol
Formyl Cation
Sulphur Dioxide
Methanol
Hydrogen Cyanide
Sulphur Dioxide
Dimethyl Ether
Formaldehyde
Deuterium Cyanide
Water
Carbon Monoxide
Sulphur Dioxide
Water
Methanol
Acrylonitrile
Methyl Formate

THz photons, Astrochemistry & the Ground-Based Challenge







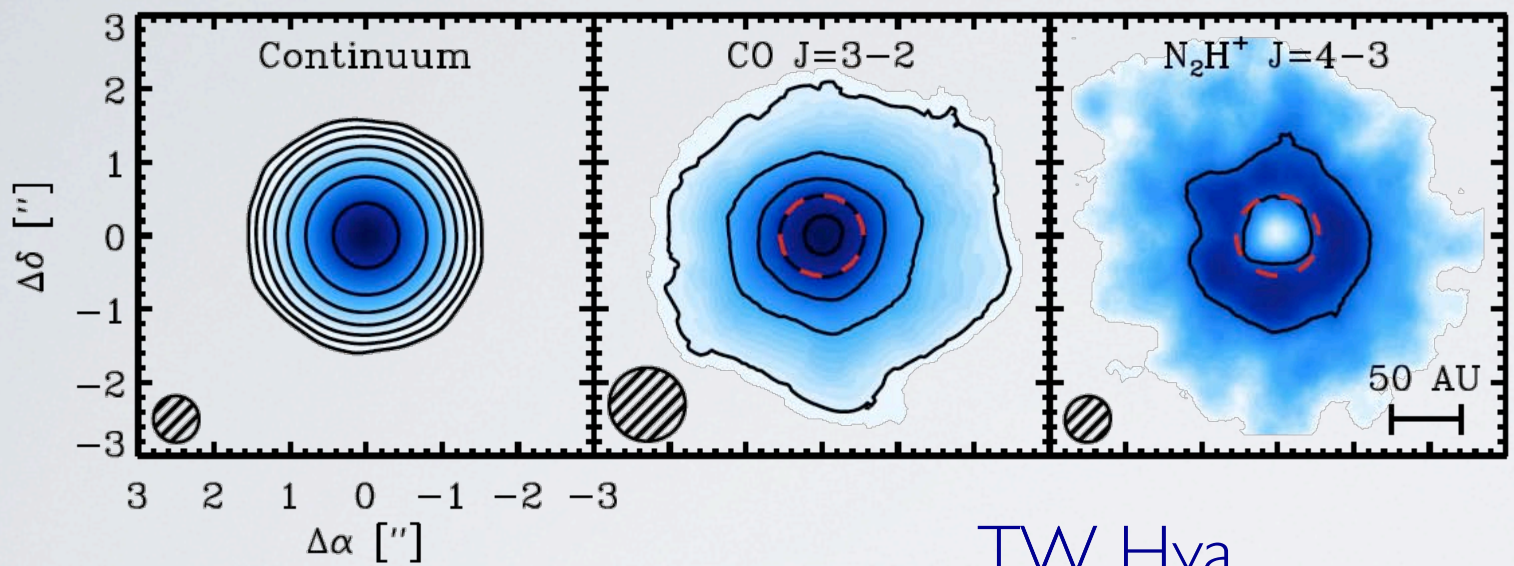
Search strategy?

Use the low energy, large amplitude torsional modes that are active in both the gas phase and in the solid state.

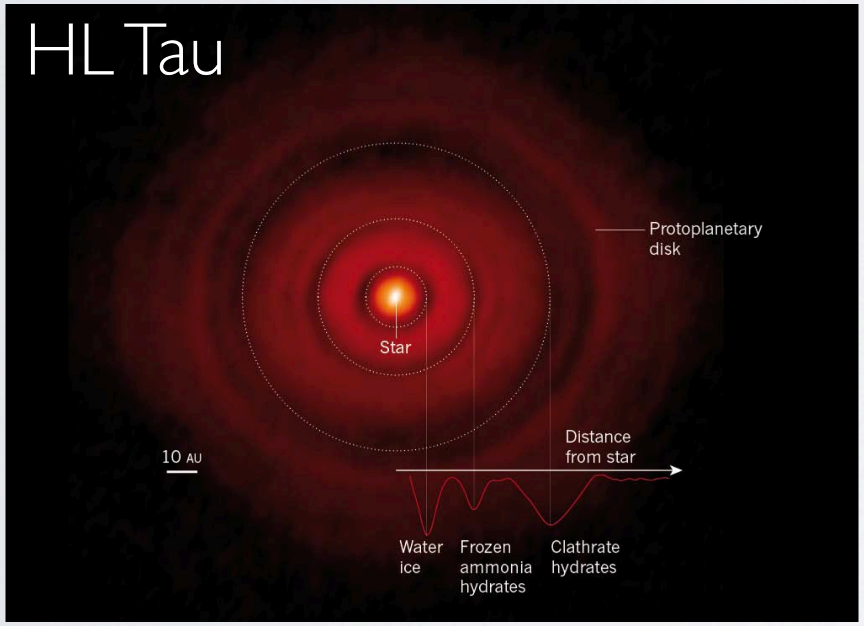
Requires highly sensitive, ***broad*** coverage lab & astronomical data – THz of BW, lines ~MHz!

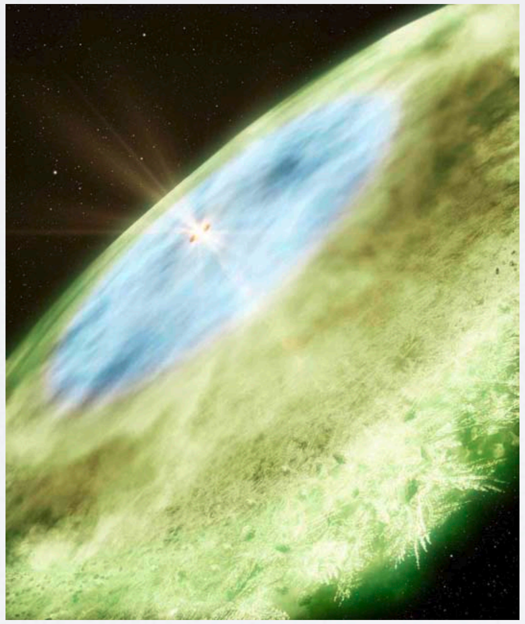
THz photons & Astrochemistry. I. Dust & Small Molecule Examples

Probes of cold matter, such as in star/planet formation:

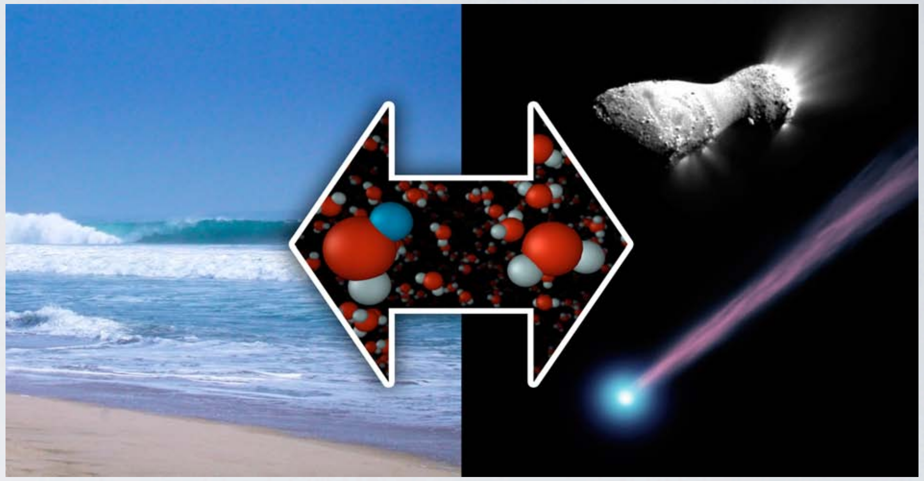


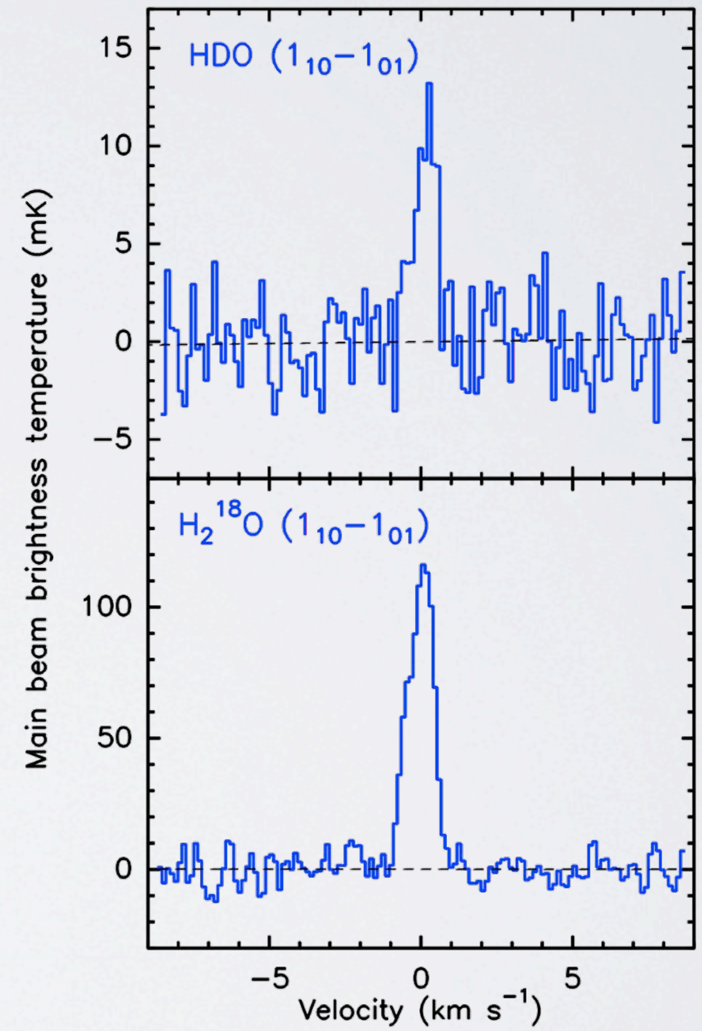
TW Hya





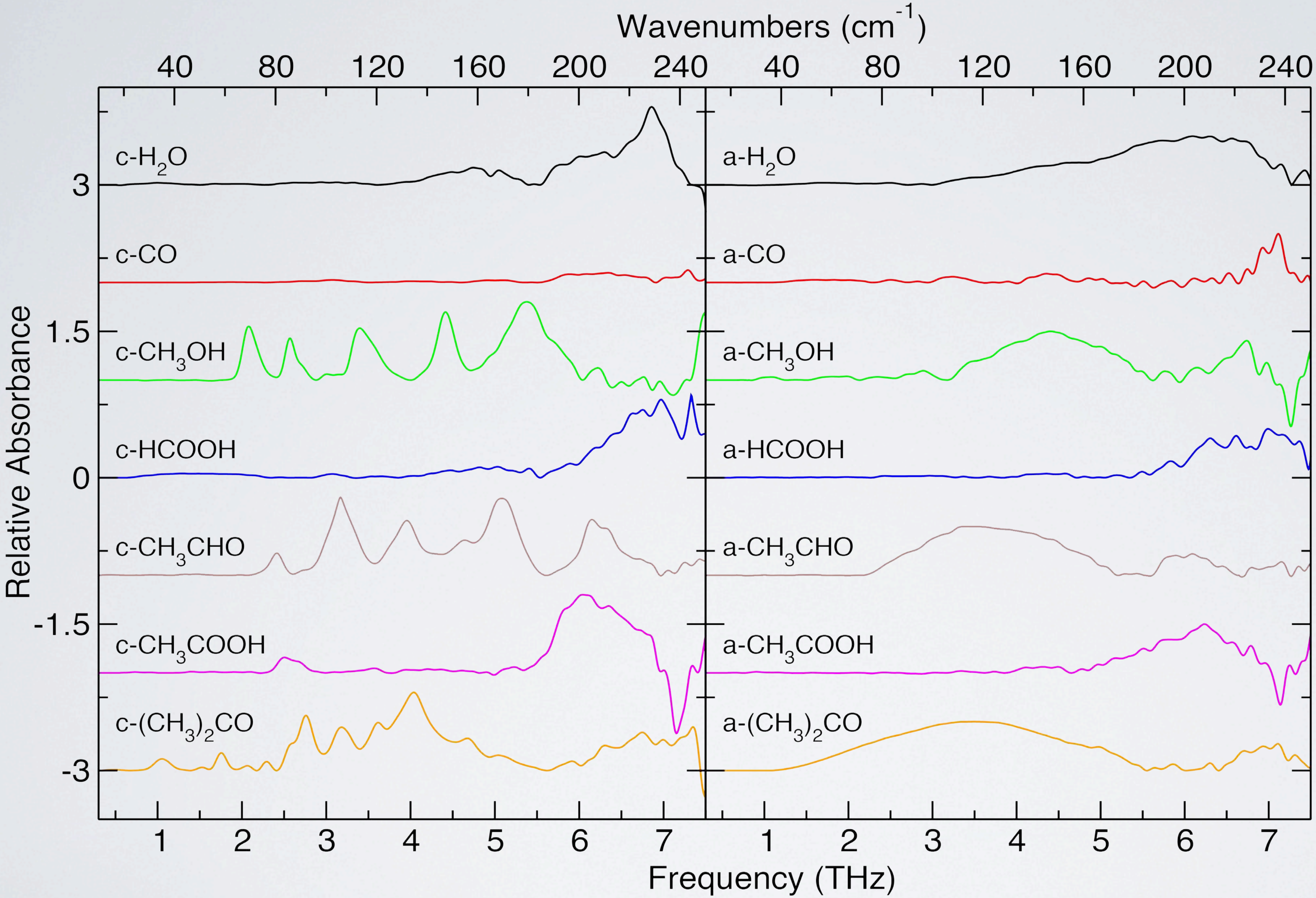
Dust & Gas: Snow lines & young planets, C. Qi, K. Öberg et al. (2013), *Science*; G. Blake & E. Bergin (2015), *Nature*





Lines: Cometary water D/H, P. Hartogh et al. (2011), *Nature*

THz TDS of Molecular Ices



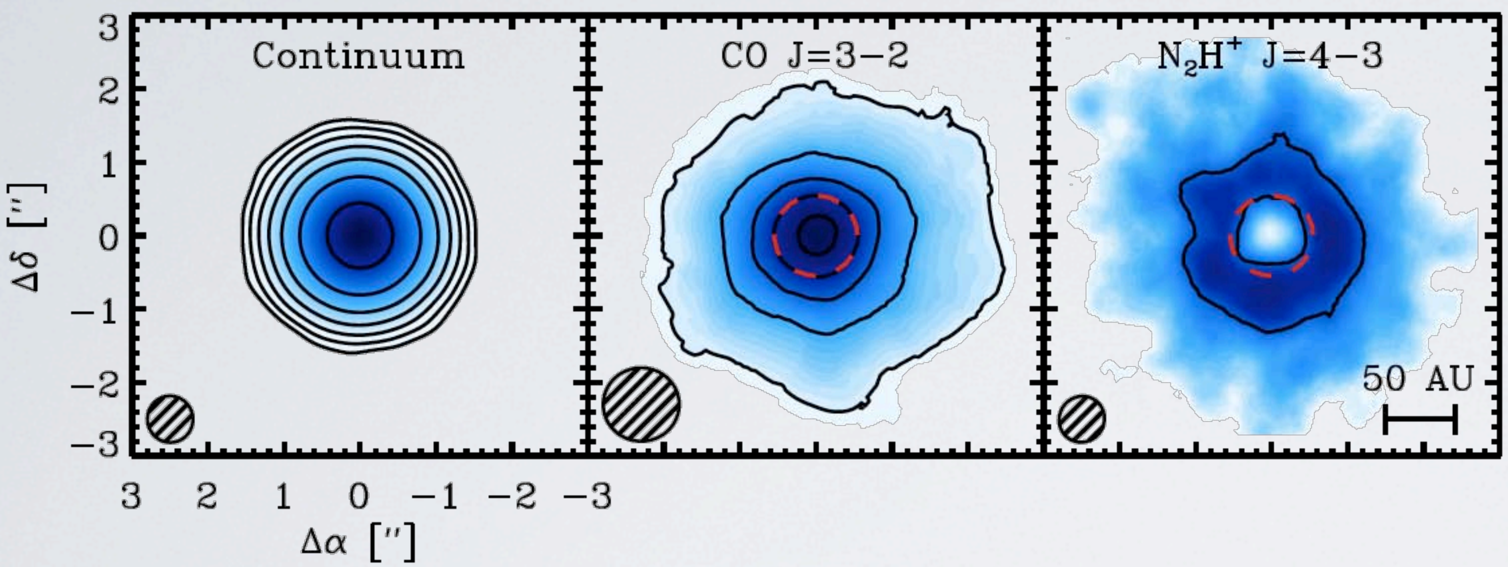
THz spectra are highly sensitive to the long range structure of the ices.

Rapidly becomes a theoretical challenge!

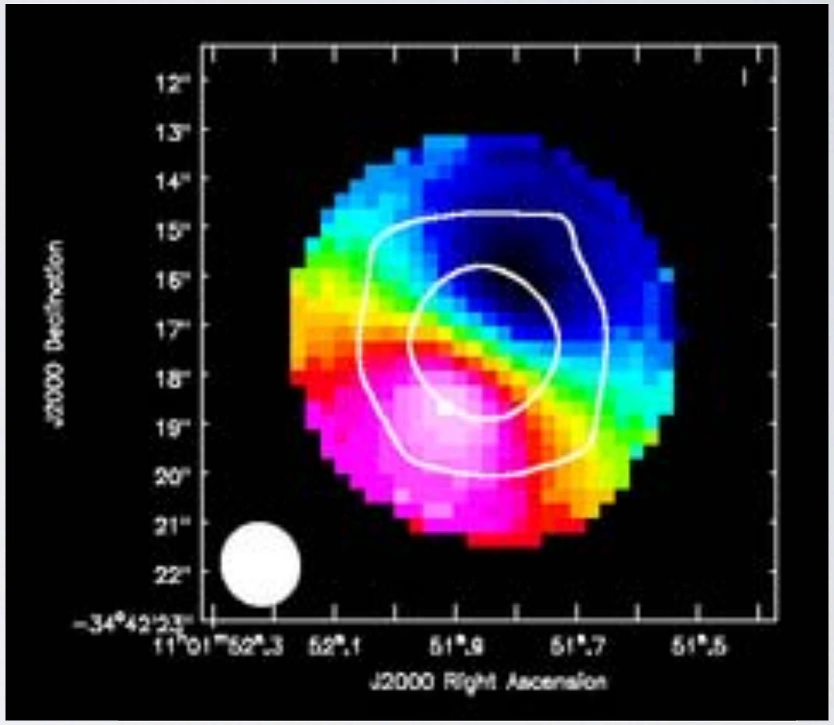
S. Ioppolo, M. Allodi, B. McGuire

THz photons & Protoplanets. A possible RV analog?

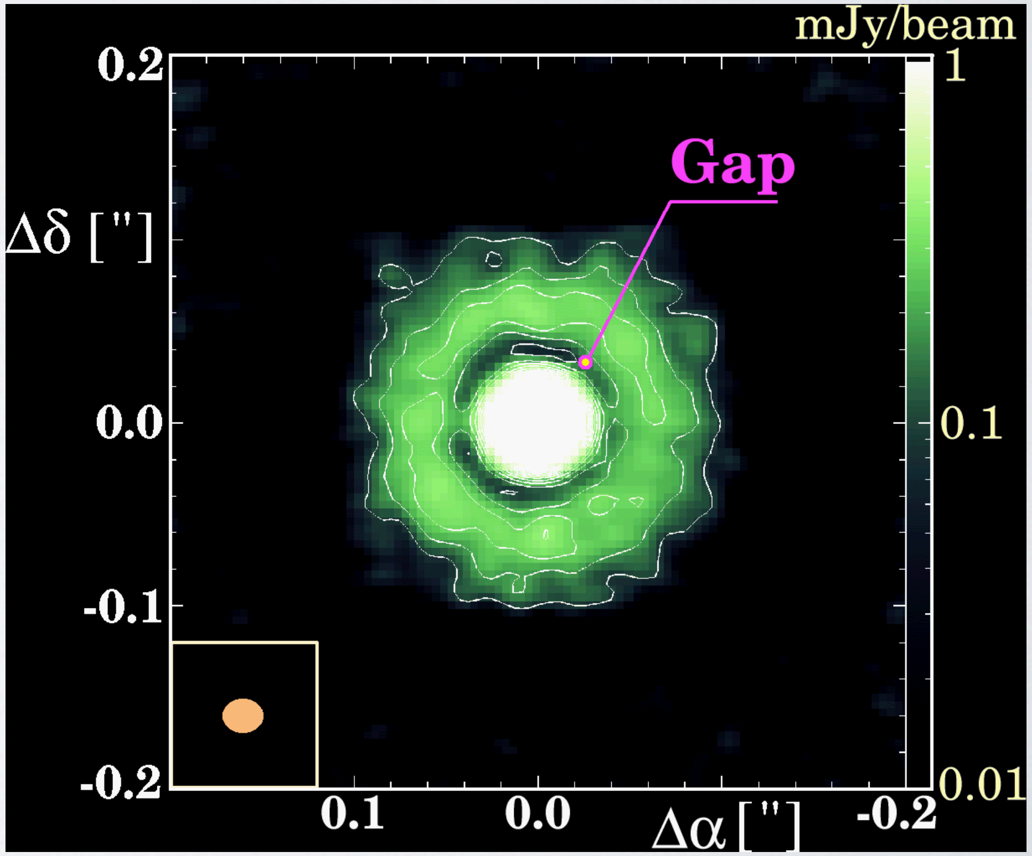
Probes of cold matter, such as in star/planet formation:



Gas in TW Hya (SV Data)



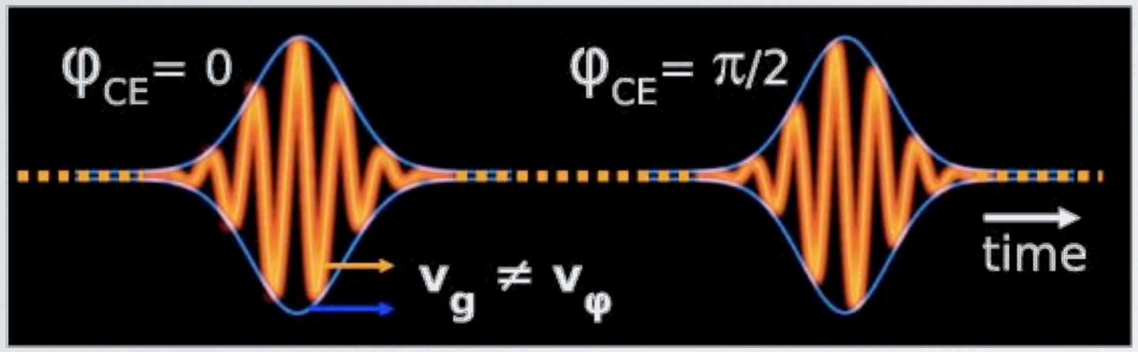
Disk emission is the beacon that is modulated by the formation and migration of protoplanets! Like RV data, need hundreds to thousands of lines studied in the time domain to detect orbital signatures versus other sources of variability.

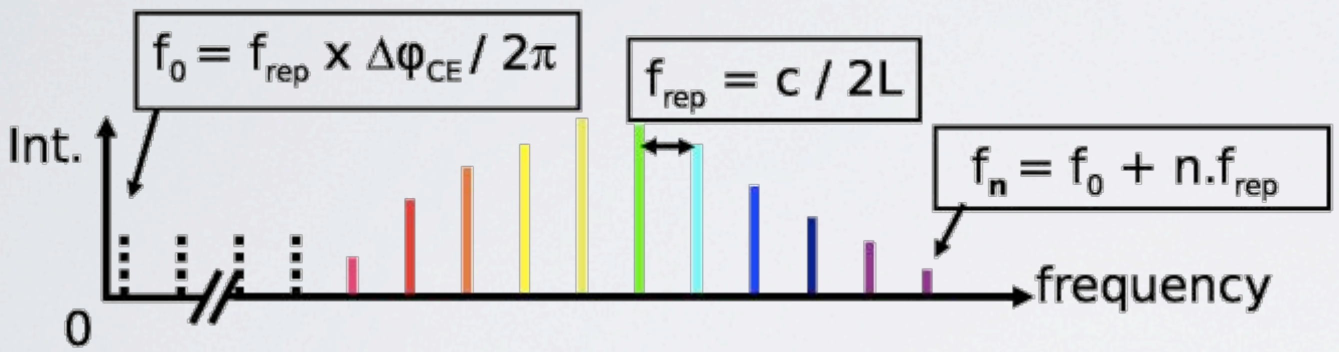


Wolf et al. 2002, ApJ 566, L97.

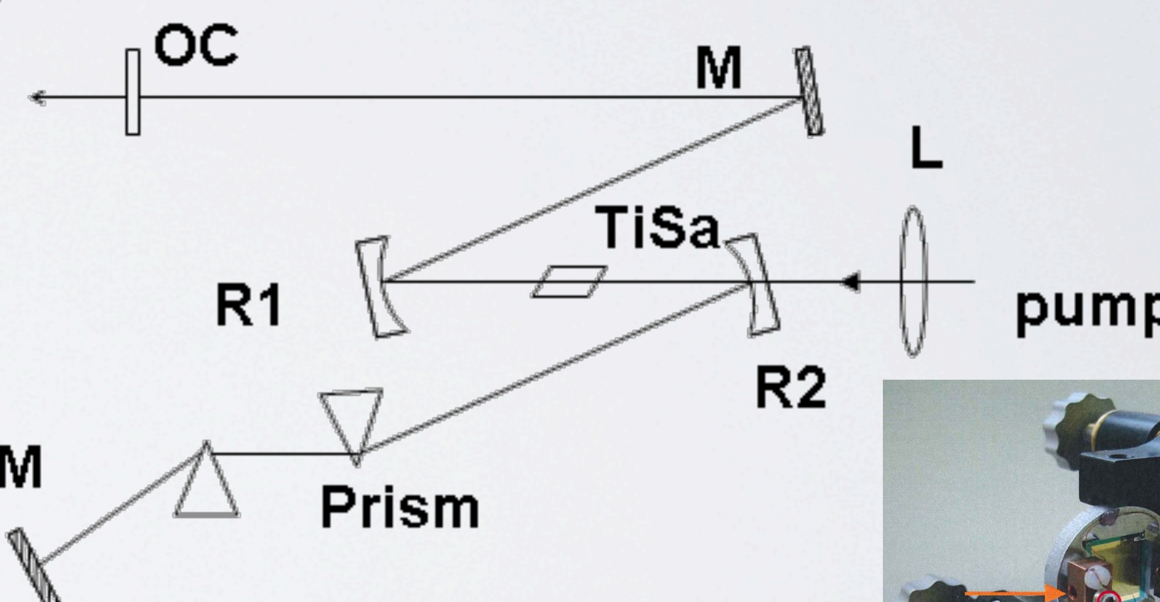
How might we addressing these challenges?

Femtosecond Lasers & Frequency Combs (Hall, Hänsch et al.)

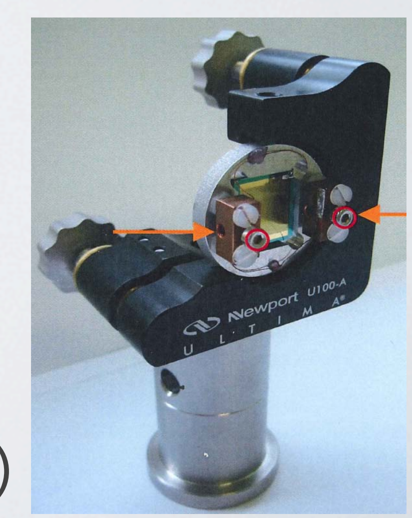




Ti:Sapphire oscillators are our current workhorses, with 800 nm average power in the Watt range and pulse durations <20 fs.



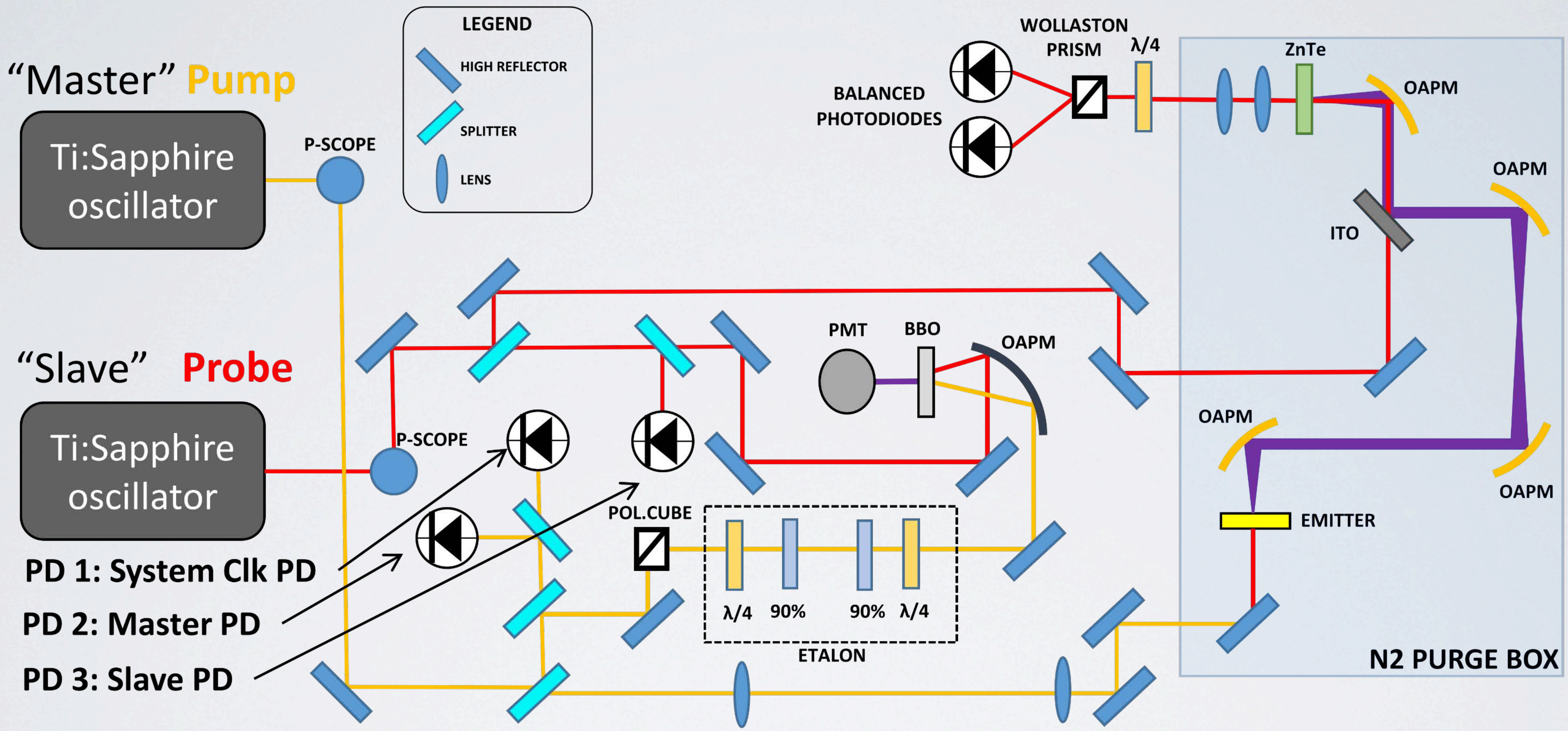
Can work either in the time or frequency domain, key issue is the coherence (or dephasing) time of the molecular system.



Photoconductive THz emitter
(100 mW 800 nm/10 µW THz)

Howmight we addressing these challenges? Our lab work…

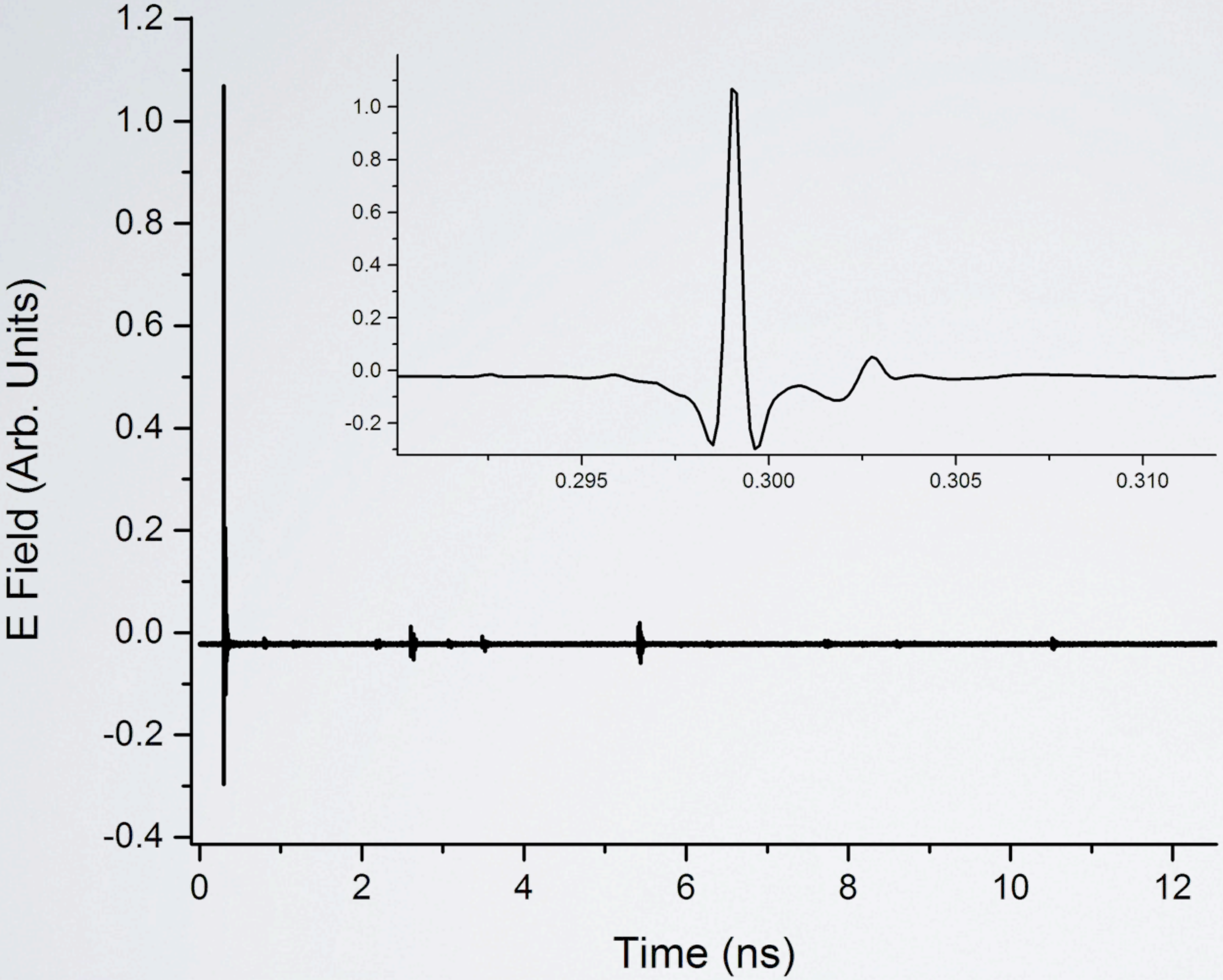
Can transduce fs frequency combs into the THz:



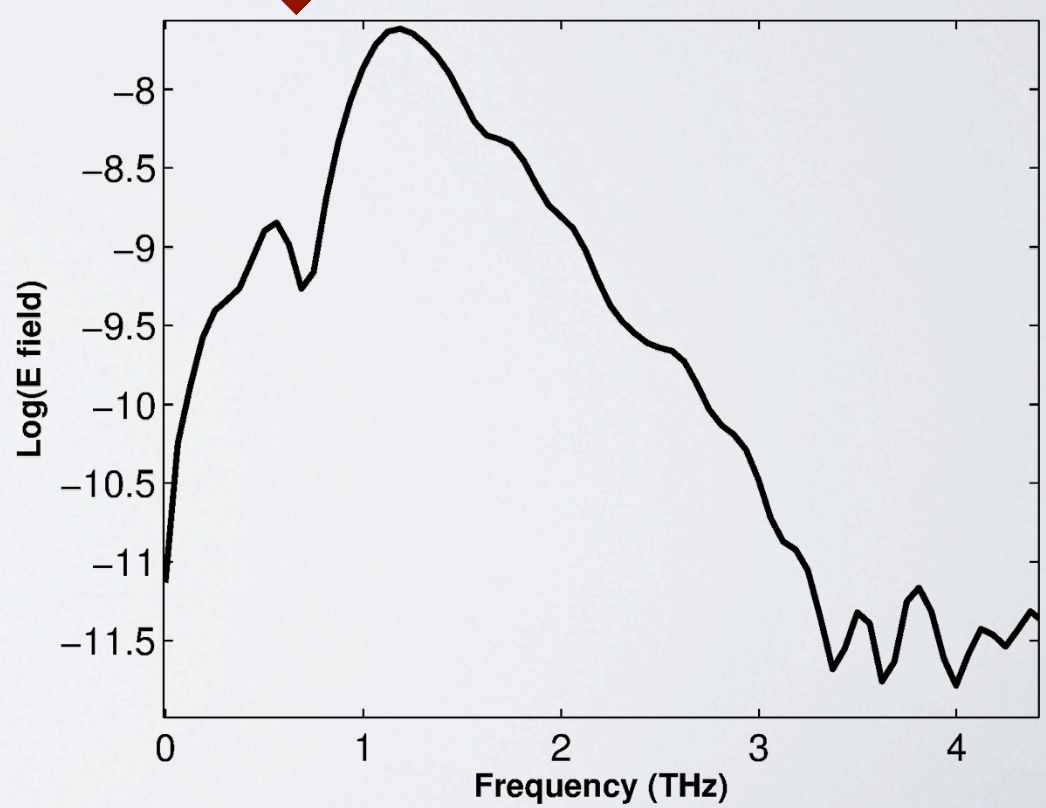
Offset & phase lock two Ti:Sapphire oscillators, read out THz waveform over many pulses (D. Holland, J. Good theses).

How are we addressing these challenges? III.

Can transduce fs frequency combs into the THz (CEP is fixed):

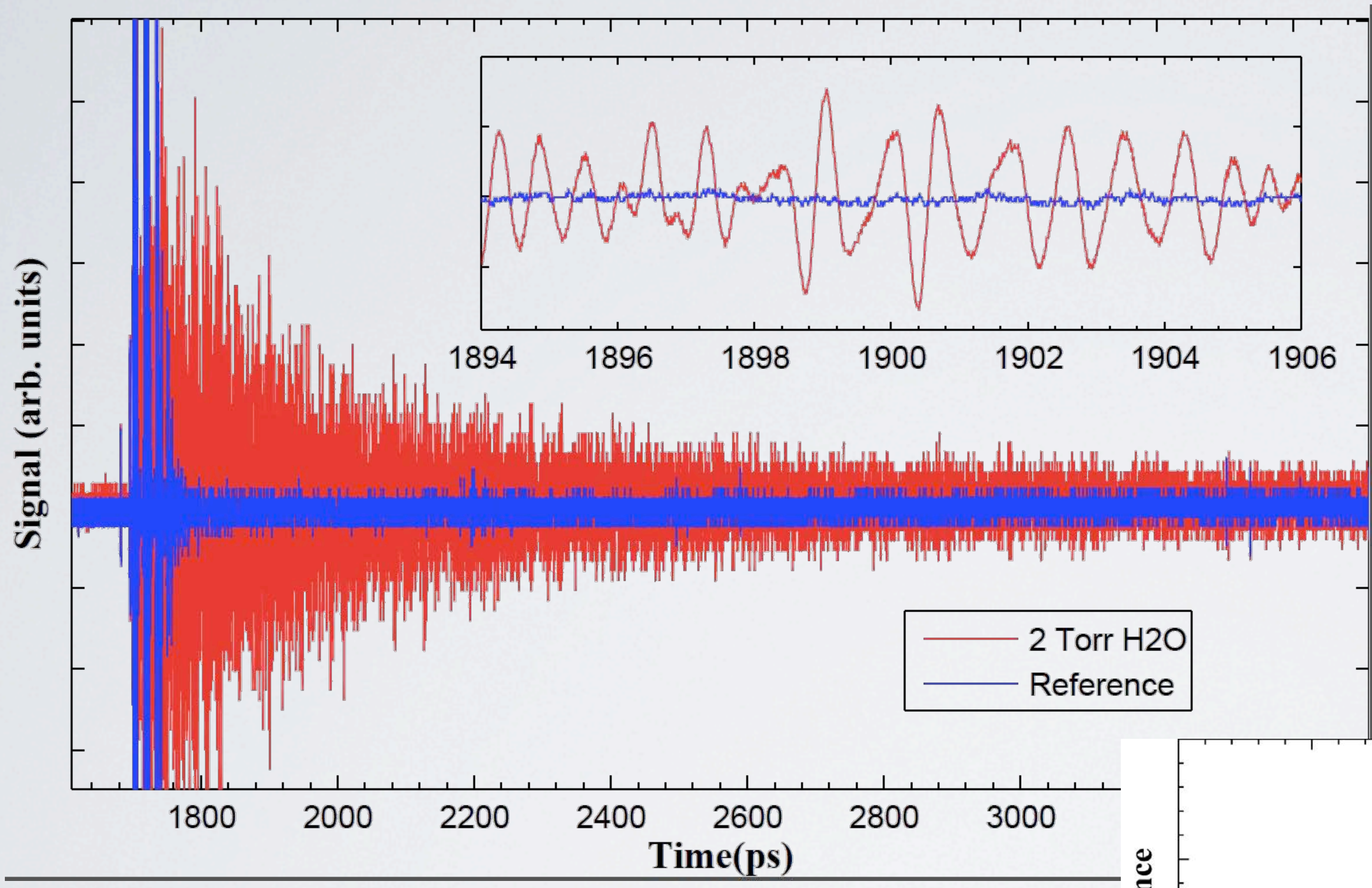


Fourier transform to frequency domain

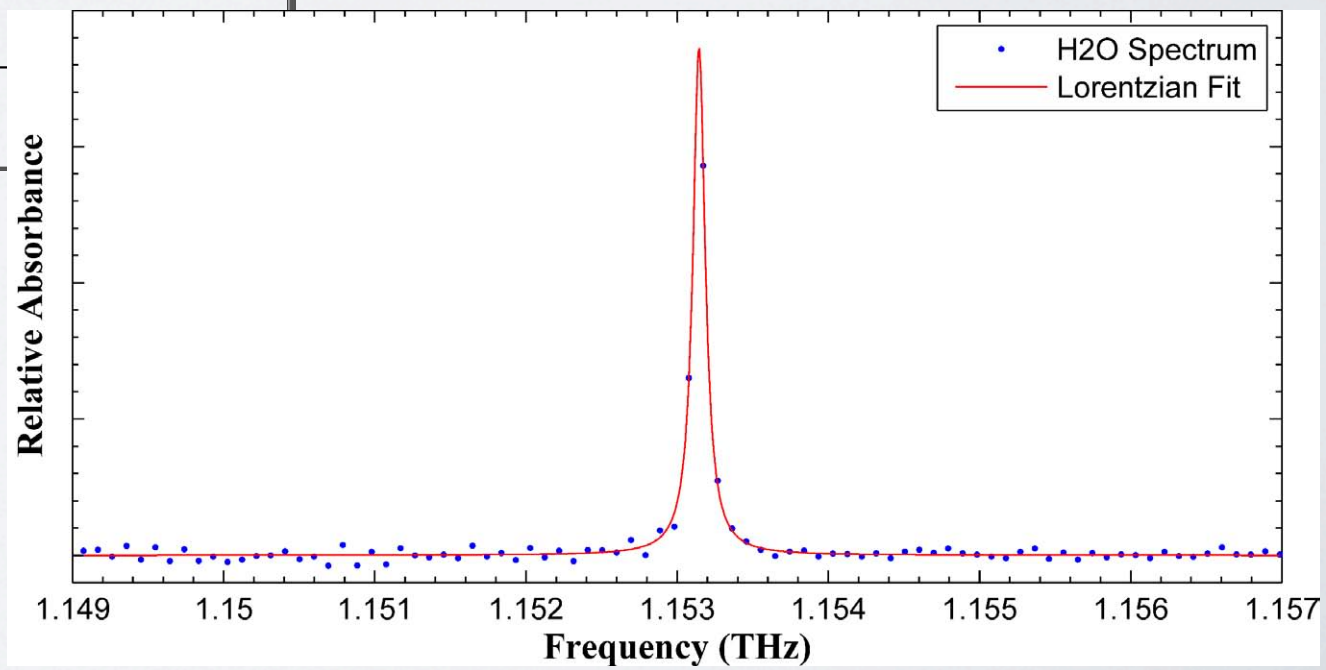


With an 80 MHz oscillator, THz pulses arrive every 12.5 nanoseconds.

Can transduce fs frequency combs into the THz:



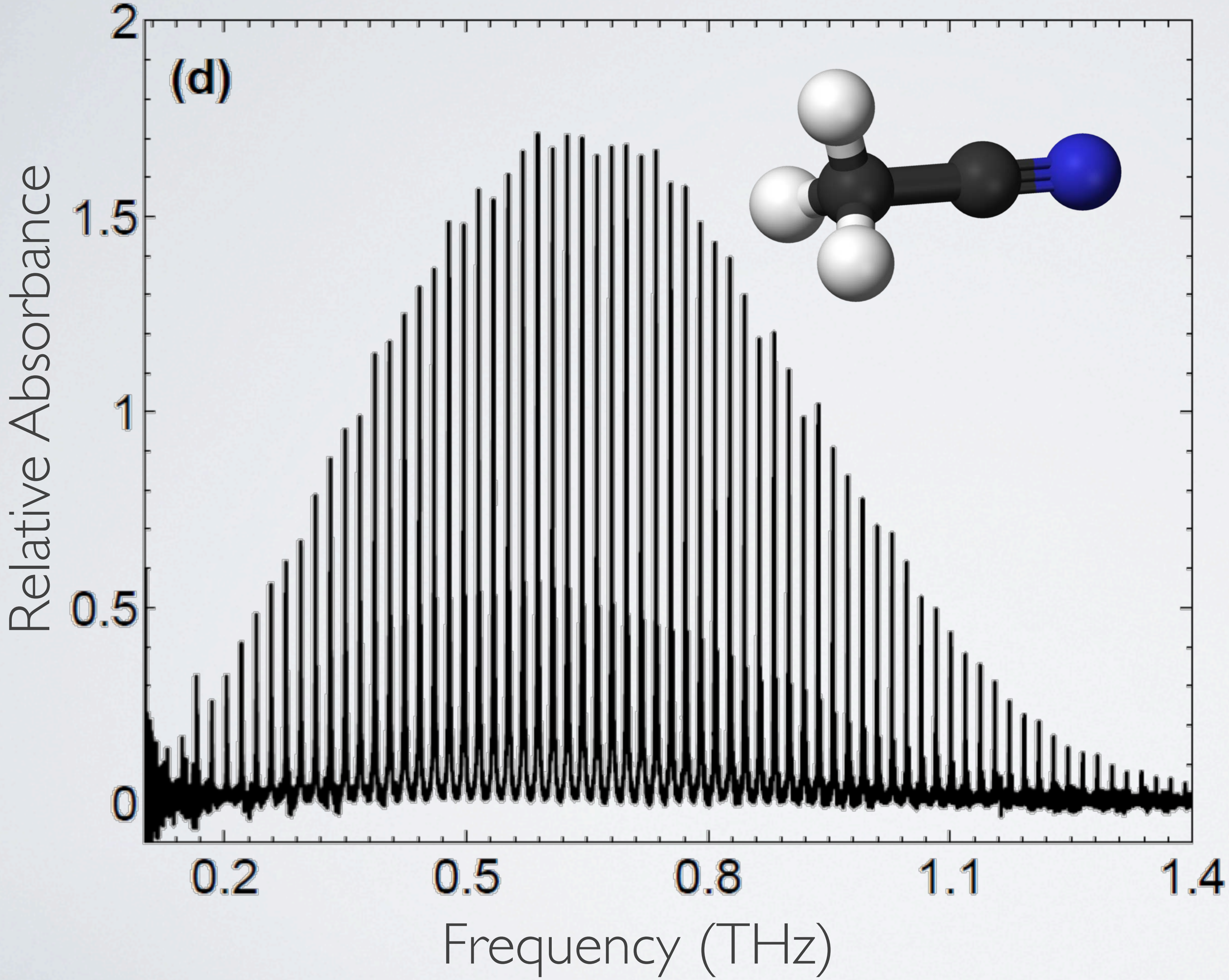
Fourier transform to frequency domain



Enables high resolution spectroscopy, easily achieves 80-100 MHz resolution, like a 3 m delay line (Nyquist sampling).

How are we addressing these challenges? III.

Can transduce fs frequency combs into the THz:

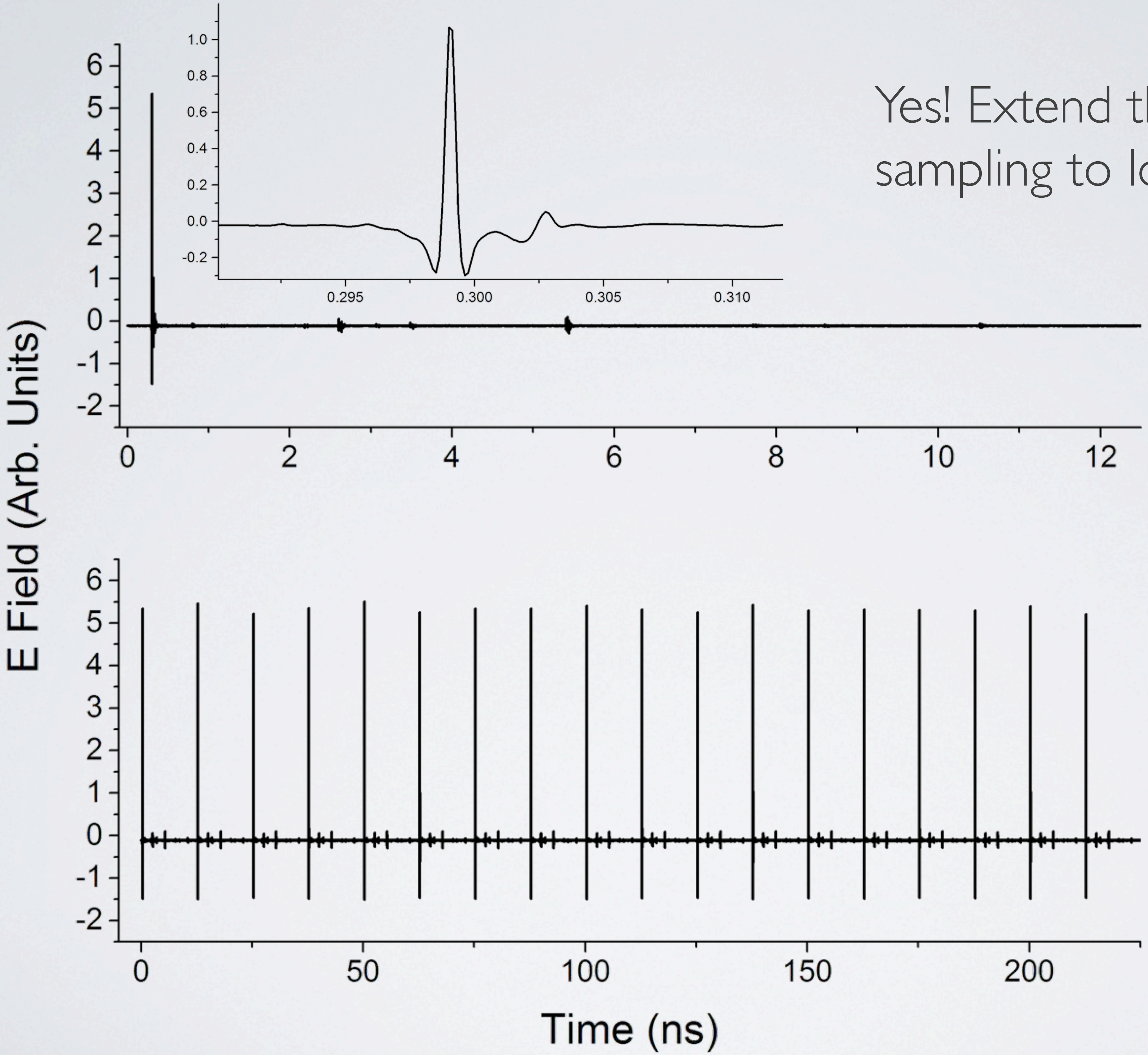


Good relative intensities across the full bandwidth, and there is no source modulation necessary. Thus, true lineshapes can be obtained even at high pressure. This is a big advantage!

Can we do better?

J. Good, I. Finneran

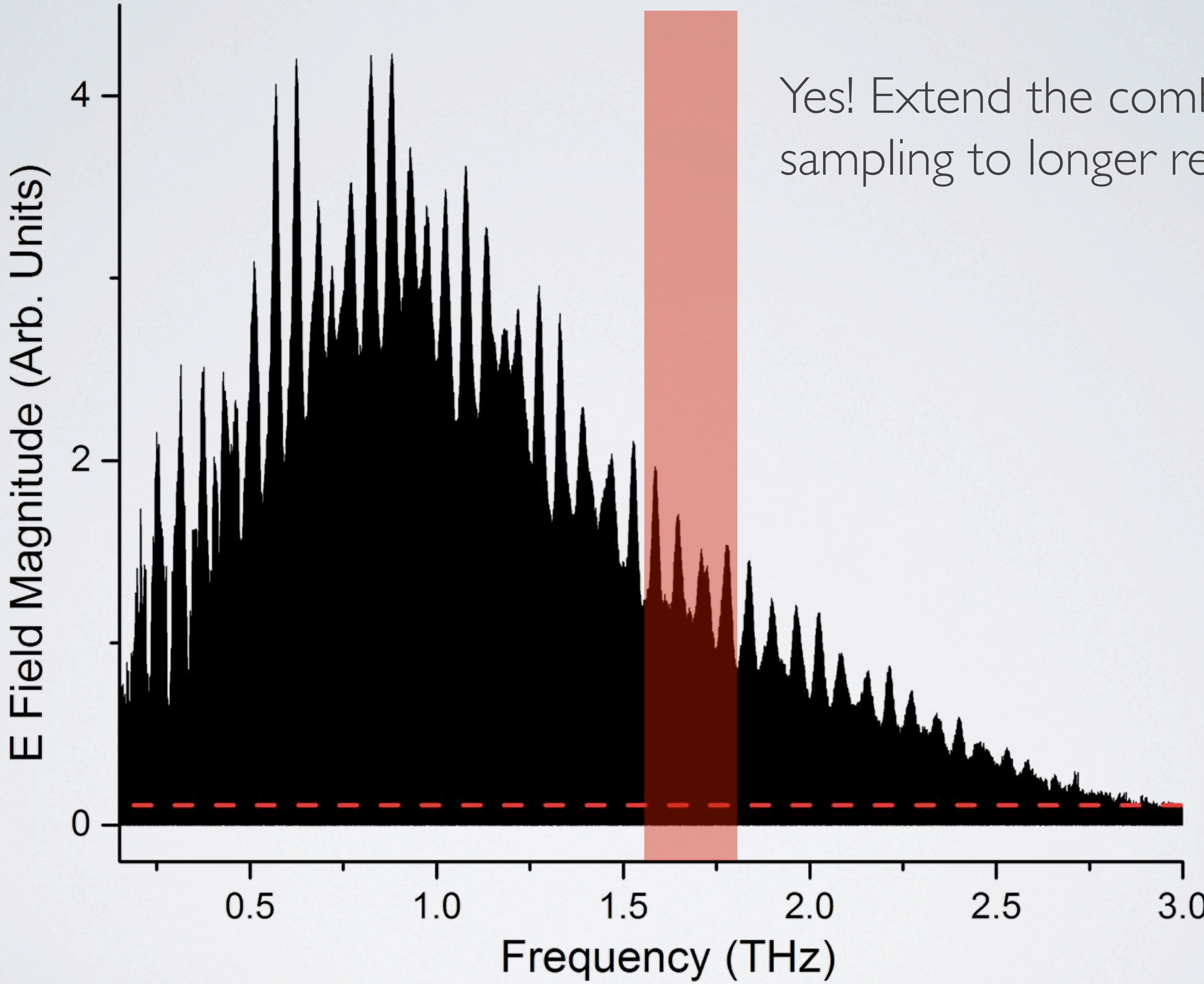
How are we addressing these challenges? IV.



Yes! Extend the comb sampling to longer records…

Finneran, Ian A., et al. "Decade-Spanning High-Precision Terahertz Frequency Comb." *Physical Review Letters* 114.16 (2015): 163902.

How are we addressing these challenges? IV.



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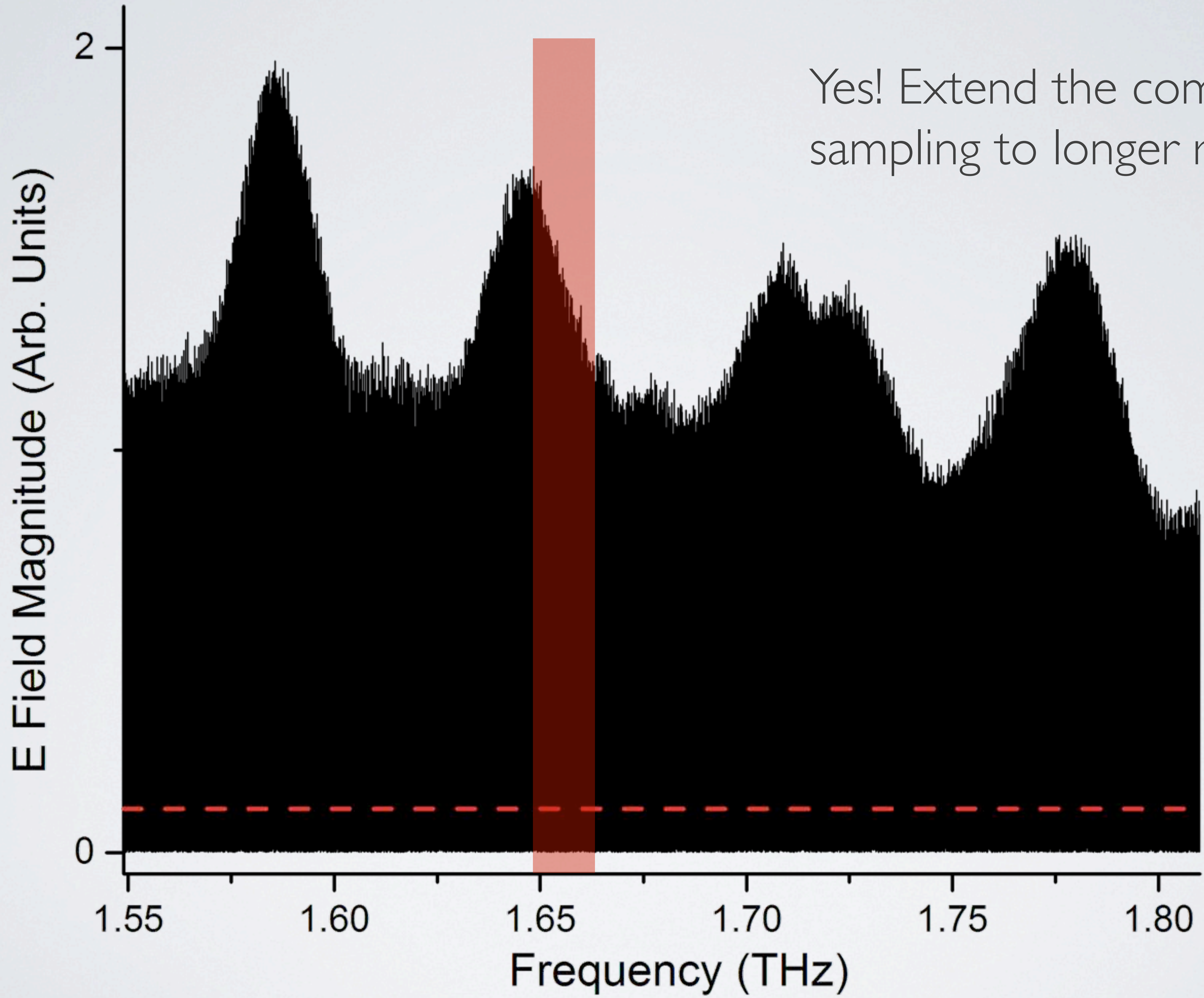

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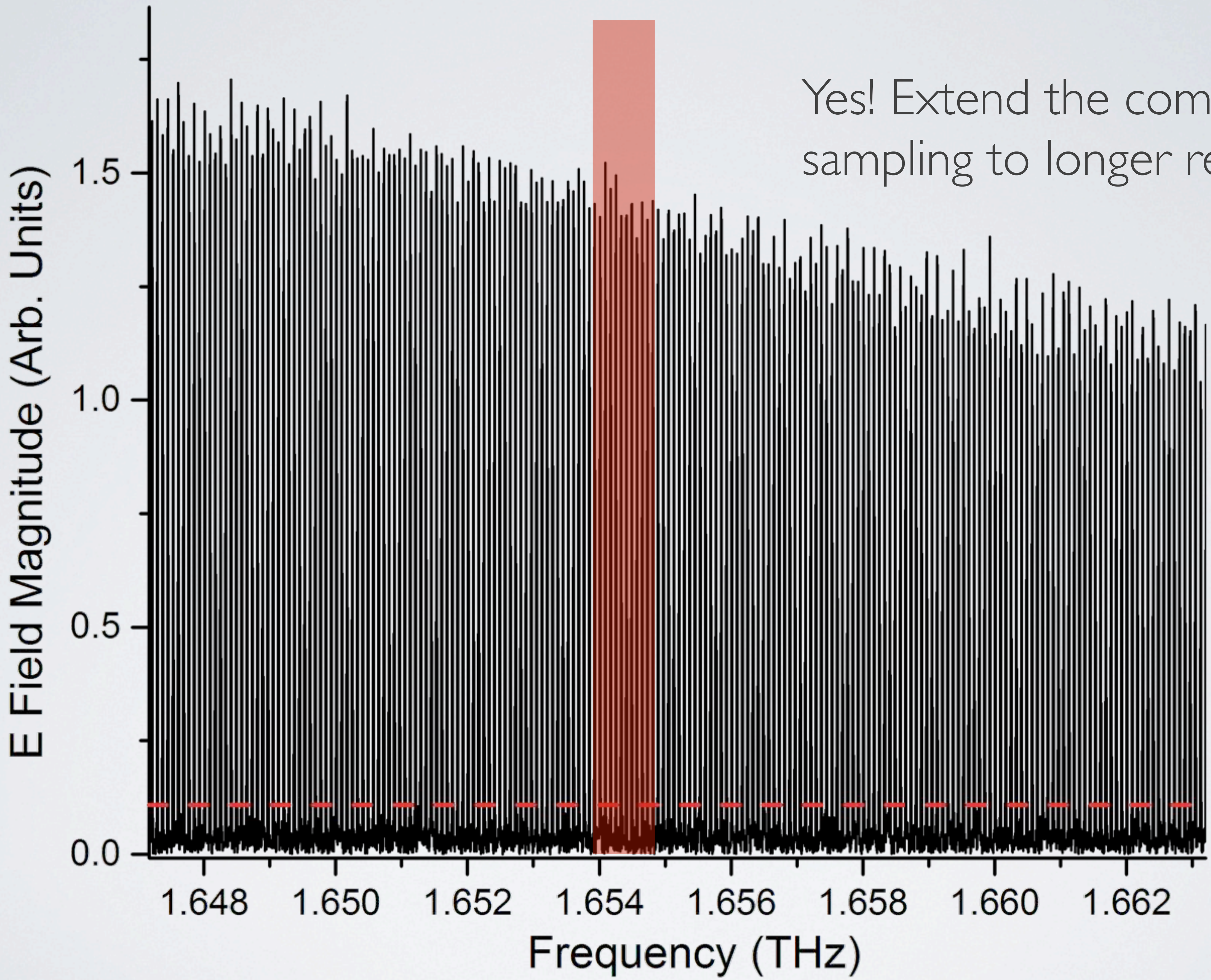

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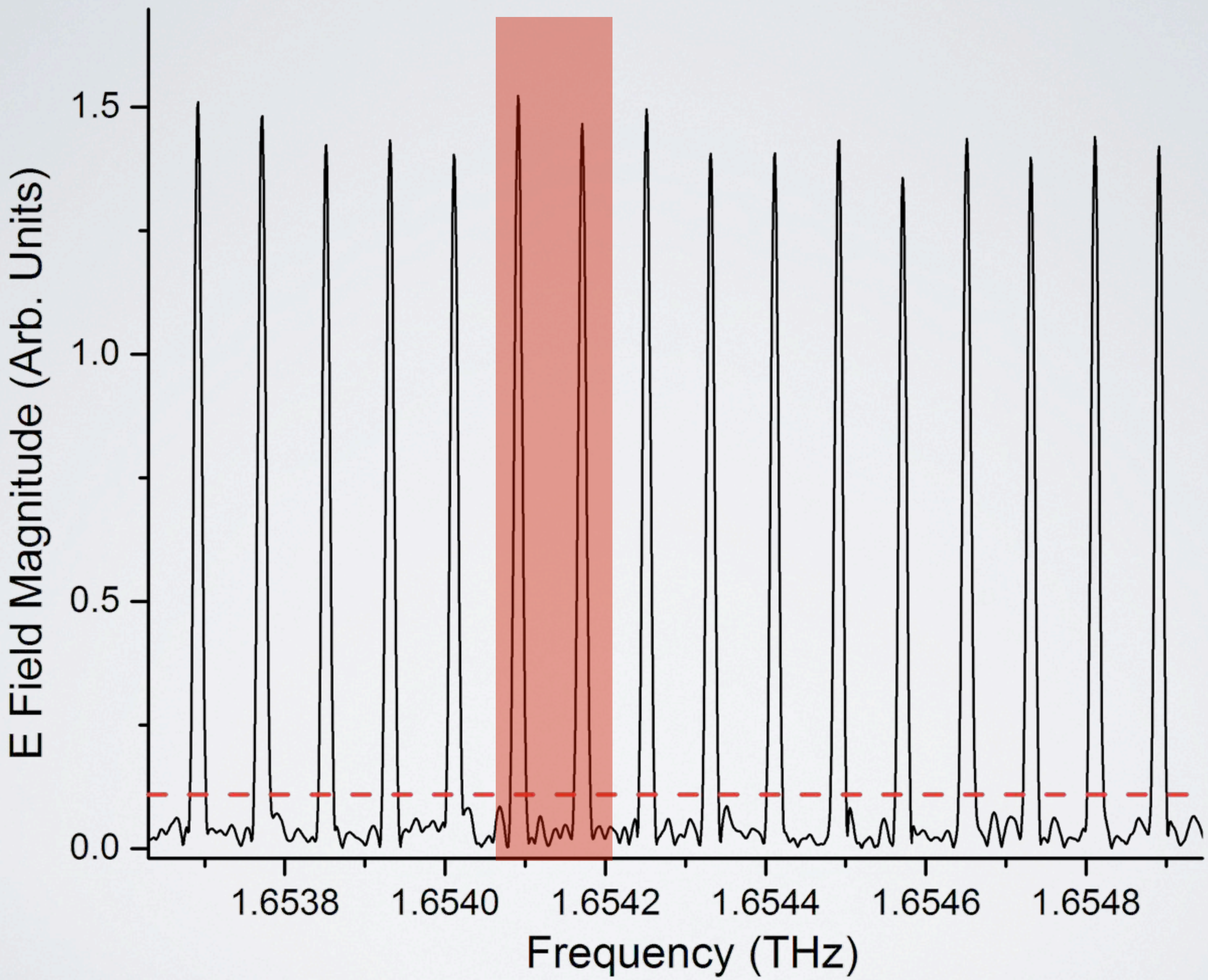

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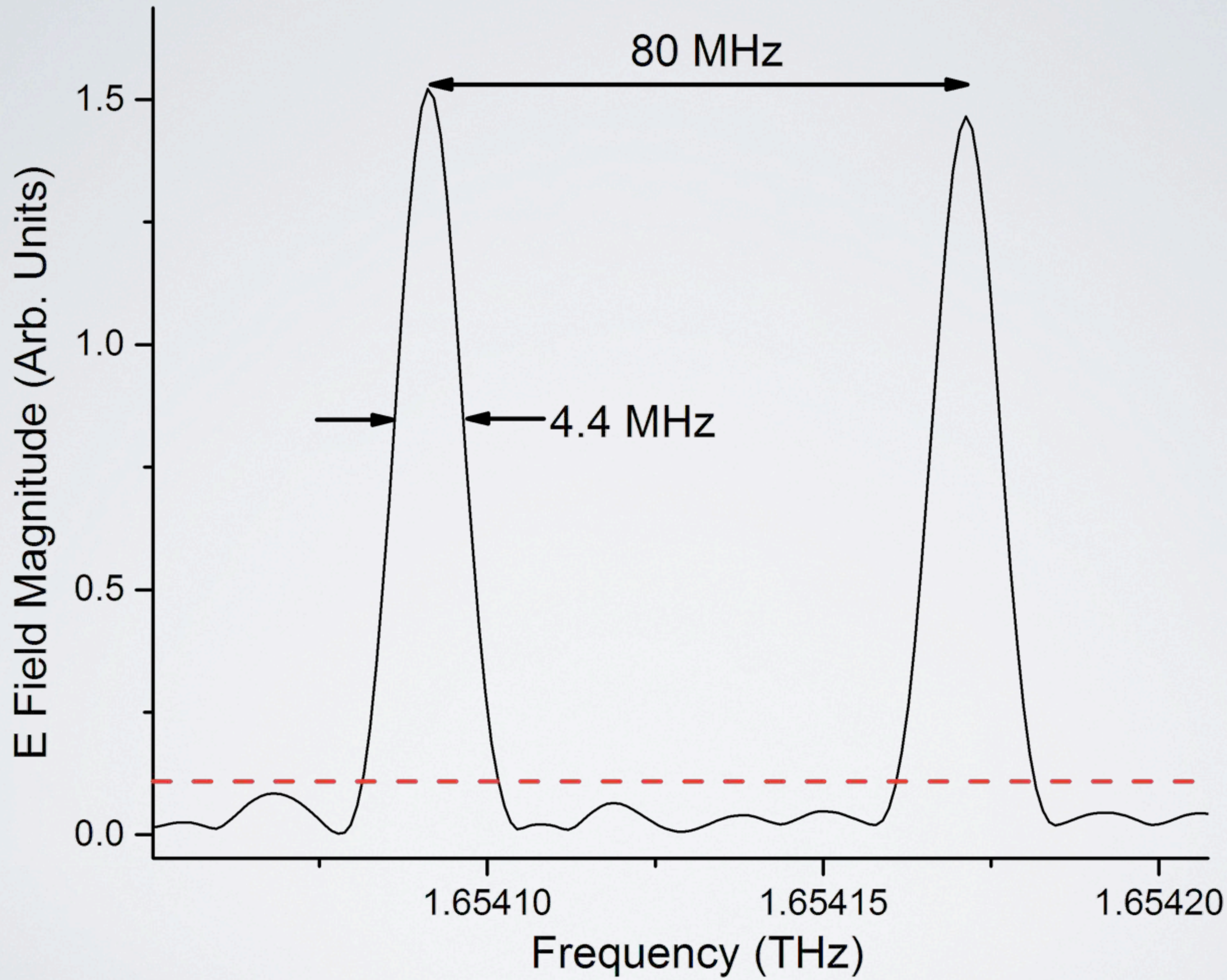
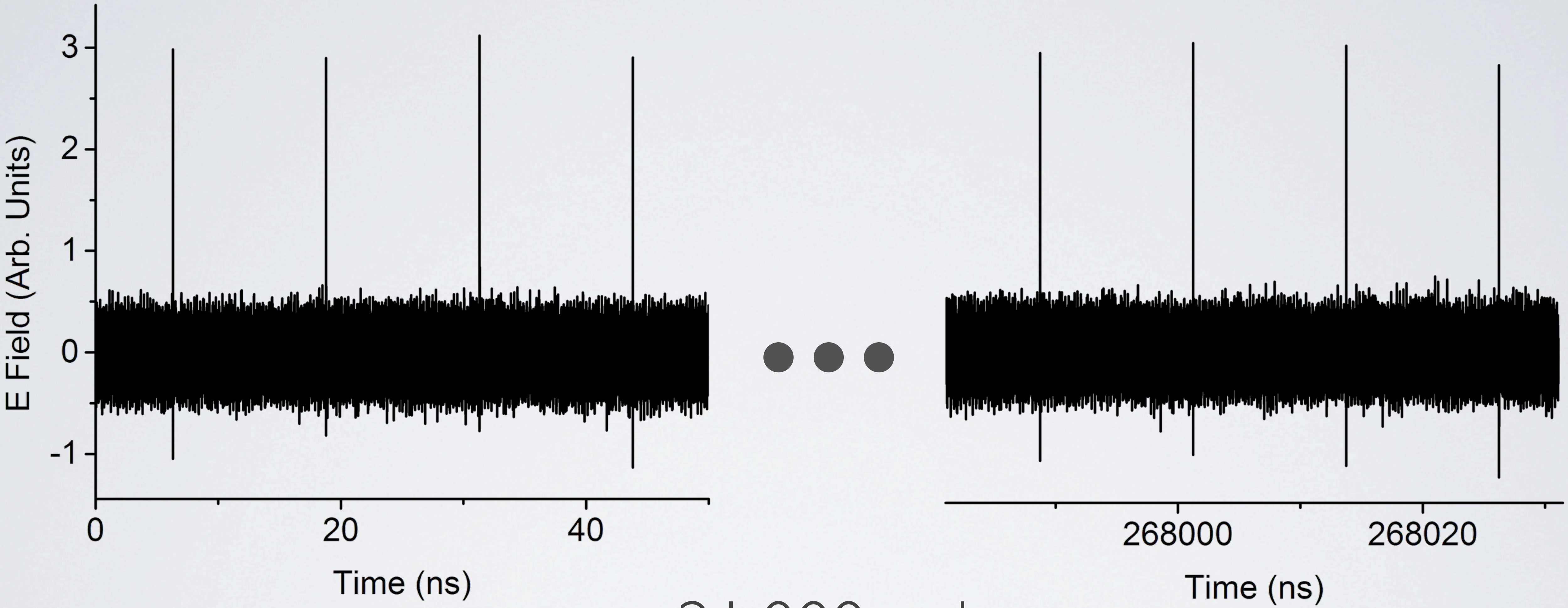


Finneran, Ian A., et al. "Decade-Spanning High-Precision Terahertz Frequency Comb." *Physical Review Letters* 114.16 (2015): 163902.

How are we addressing these challenges?   IV.

Equivalent to 40 km delay line at Mach 1.1!

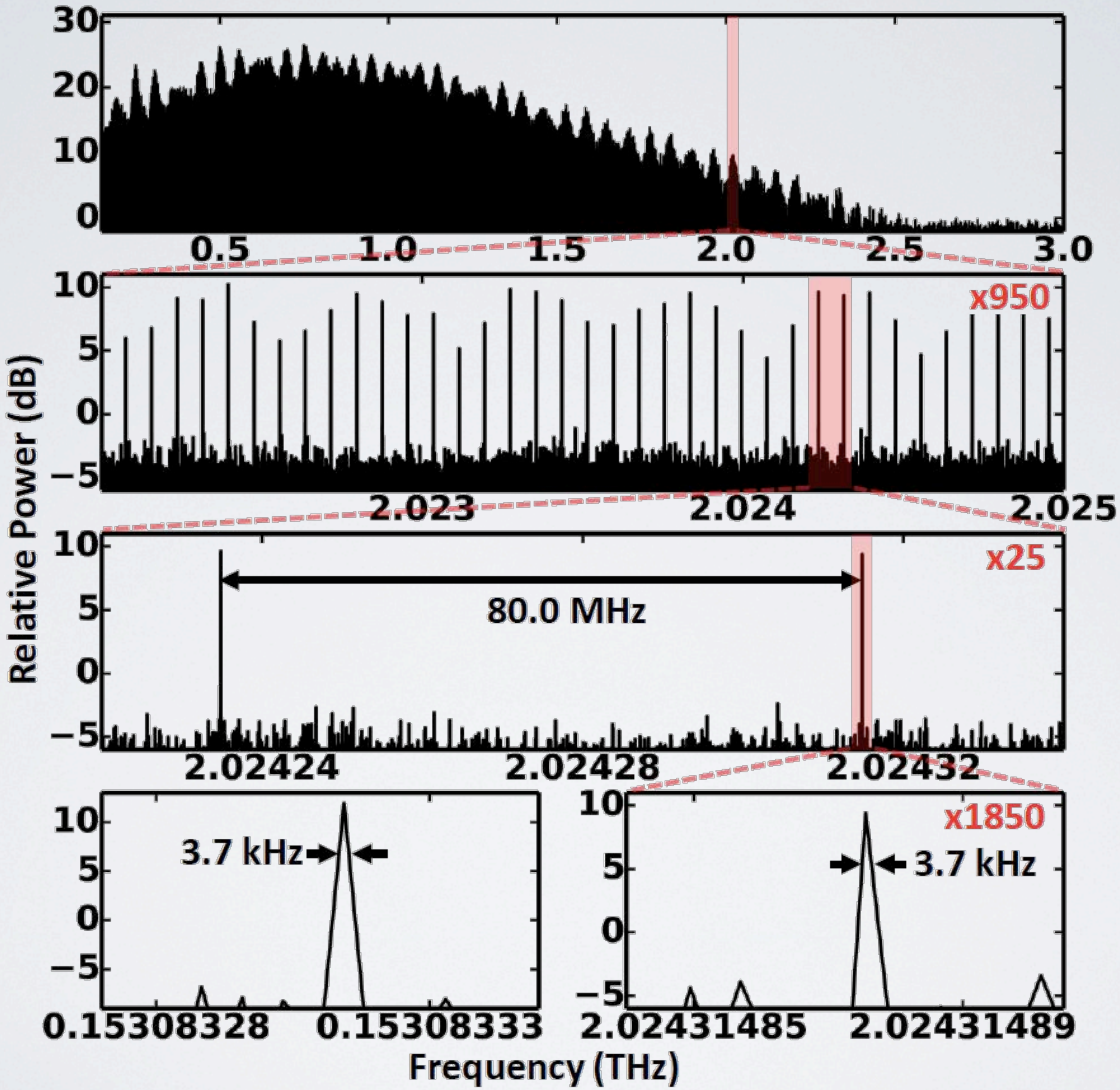


>21,000 pulses

107 seconds lab time
with 200 Hz offset

Finneran, Ian A., et al. "Decade-Spanning High-Precision Terahertz Frequency Comb." *Physical Review Letters* 114.16 (2015): 163902.

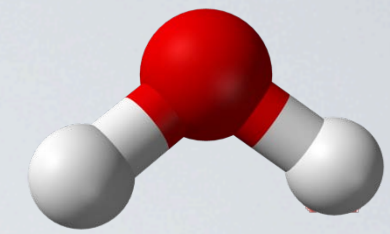
How are we addressing these challenges? IV.

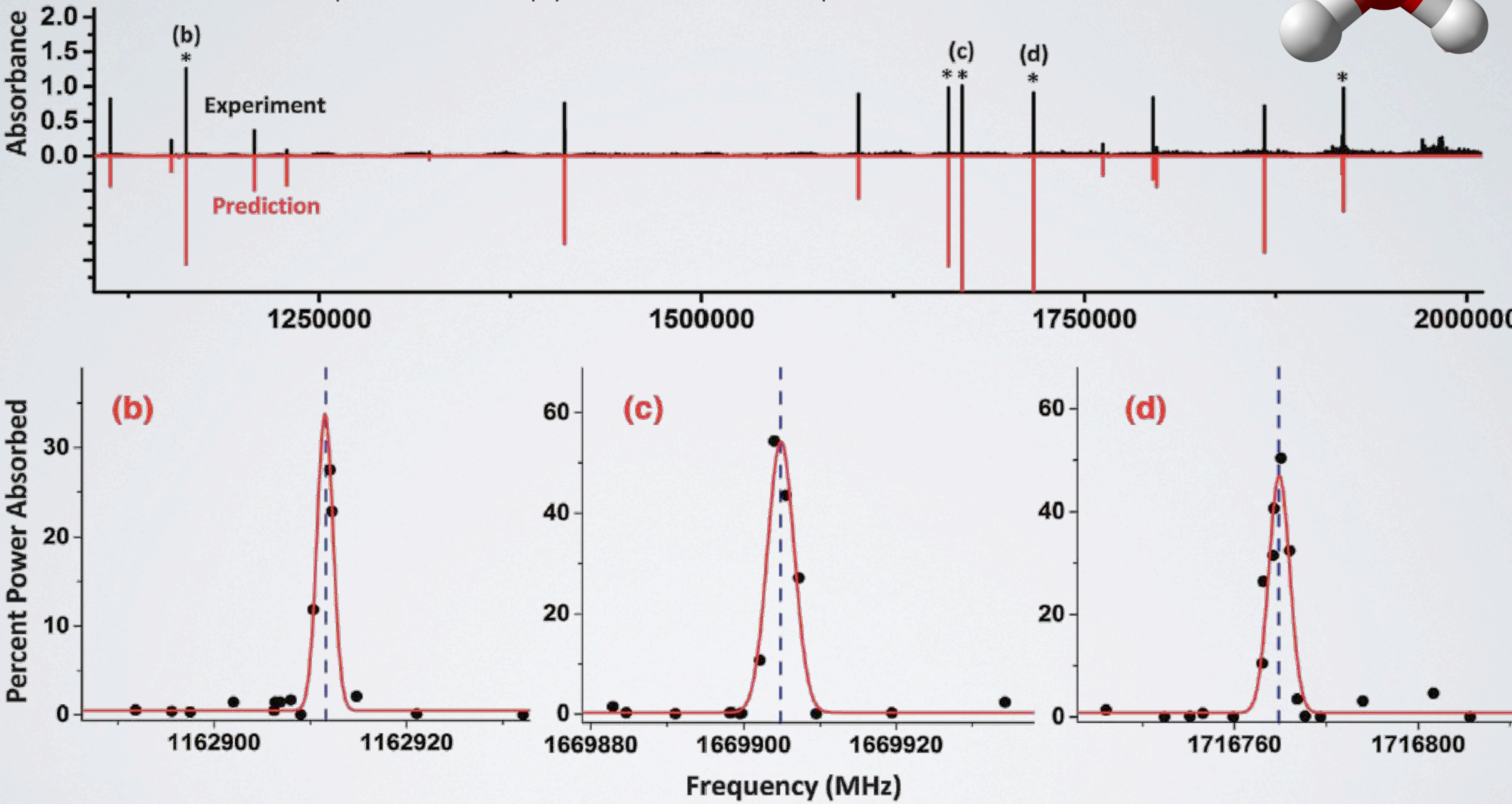


Finneran, Ian A., et al. "Decade-Spanning High-Precision Terahertz Frequency Comb." *Physical Review Letters* 114.16 (2015): 163902.

How are we addressing these challenges? IV.

Comb Spectroscopy of Water Vapor





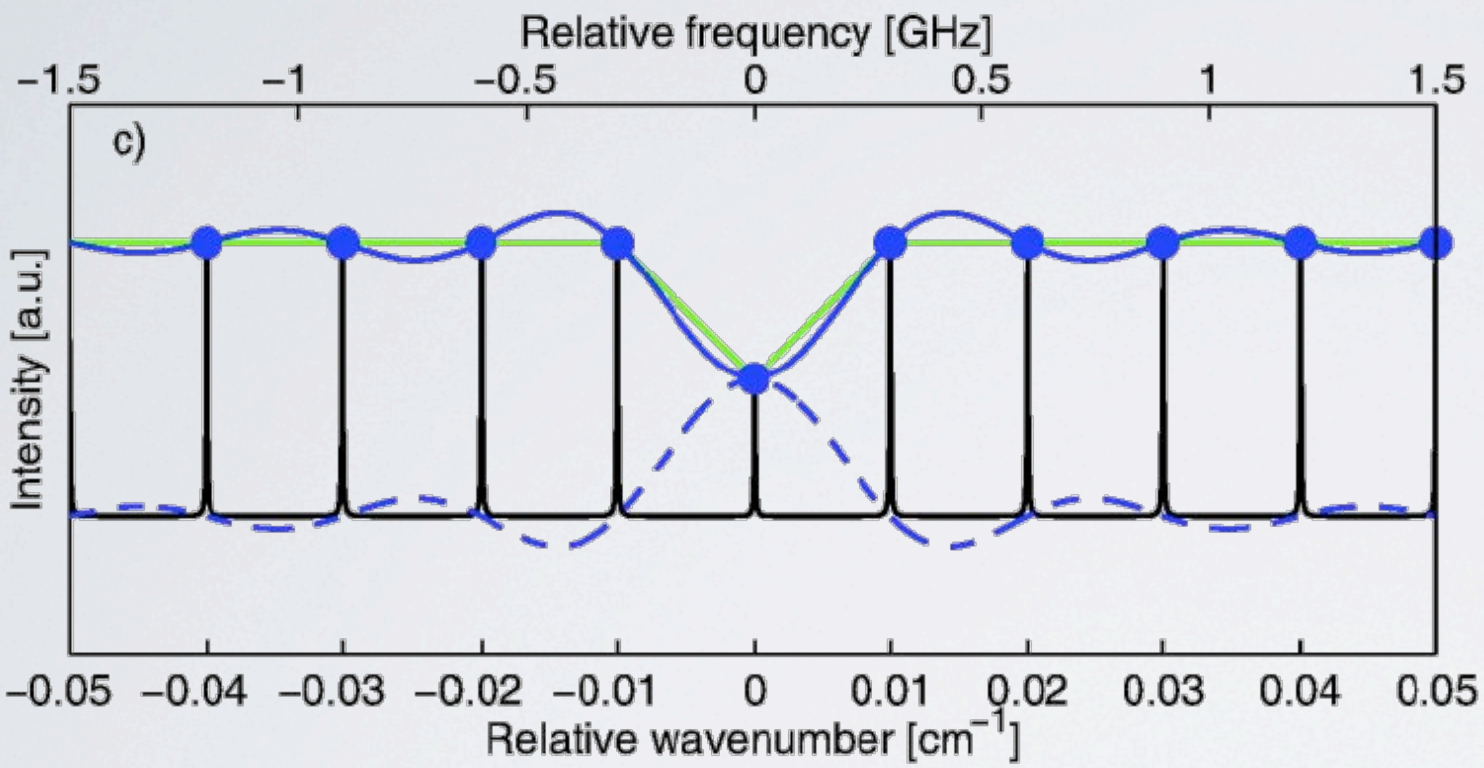
Enables high resolution spectroscopy, but the low pulse energy limits the THz bandwidth and sensitivity.

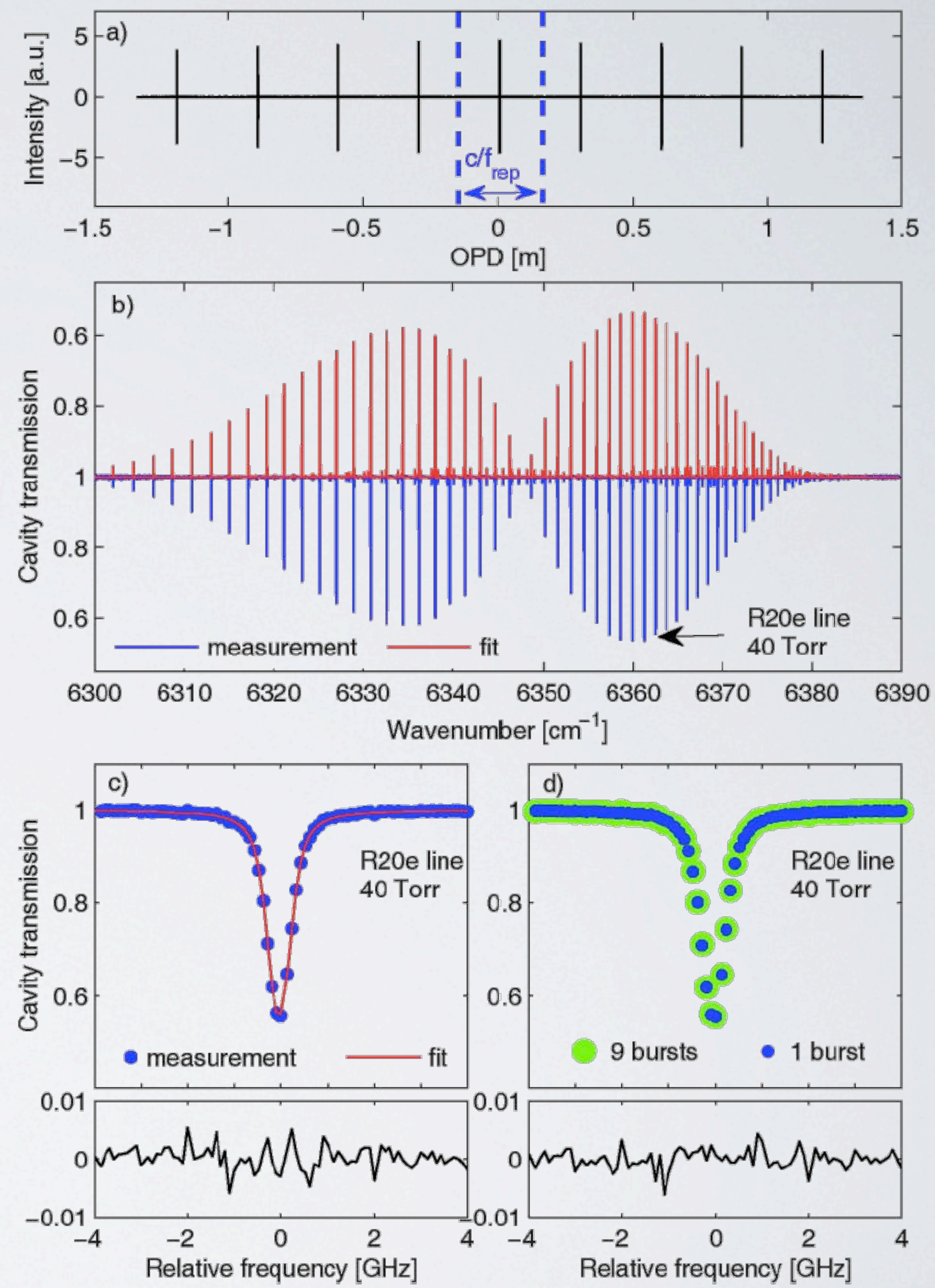
Solution?

Finneran, Ian A., et al. "Decade-Spanning High-Precision Terahertz Frequency Comb." *Physical Review Letters* 114.16 (2015): 163902.

How are we addressing these challenges? IV.

Sample precisely at comb the spacing:





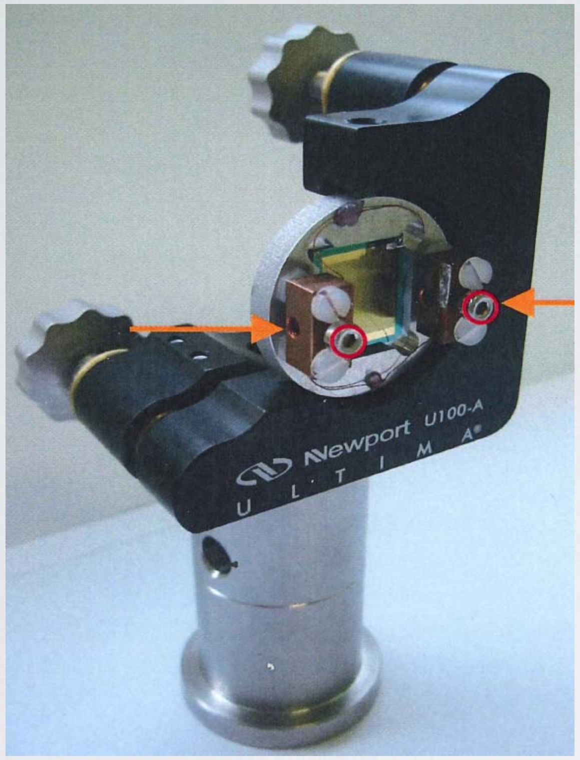
Use the coherent nature of the comb to isolate individual comb teeth with only a 'Nyquist' sampling of the FSR… This alone should improve the dynamic range by 10 dB.

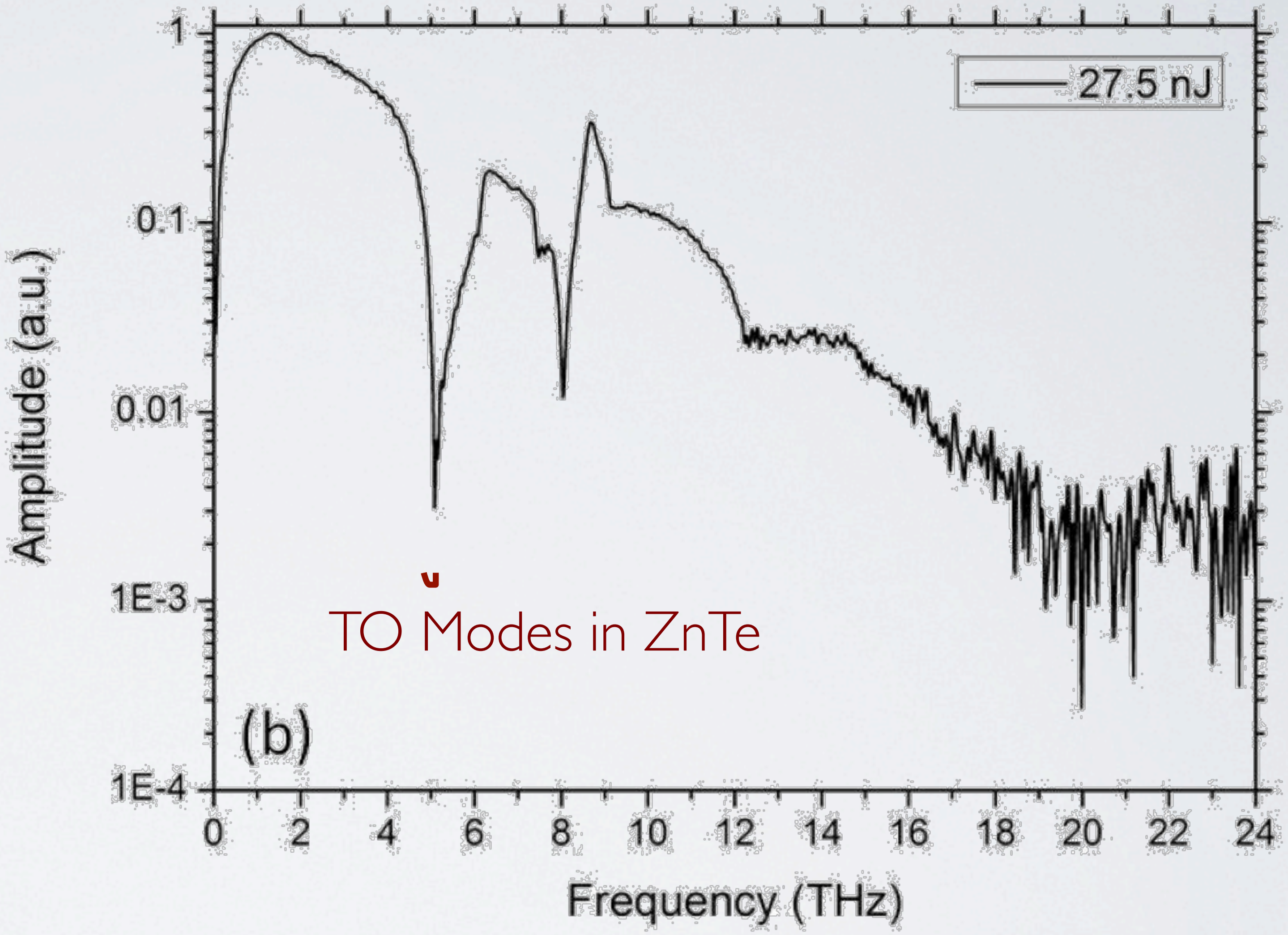
Solution?

Figures from Maslowski, P. J et al arXiv:1505.07706 (2015).

How are we addressing these challenges? IV.

Reflection-mode LTG-GaAs emitter performance:



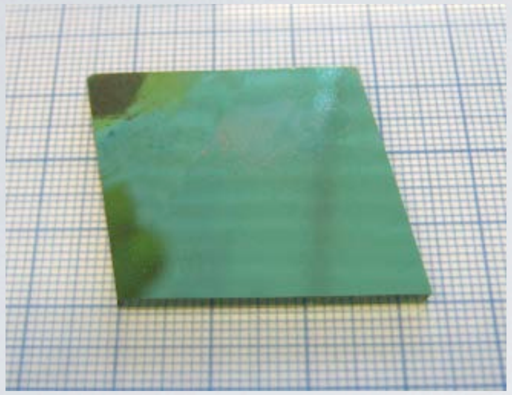


With proper pulse compression in the dual oscillators, and collecting THz pulses in a reflection geometry, the 10 dB bandwidth can be extended to ~10 THz. Conversion efficiency is low (10^{-4}).

Solution?

Figure from Hale, P. J., et al Optics express 22.21 (2014): 26358-26364.

Better THz TDS Conversion Efficiency? Enter DSTMS, DAST Emitters.



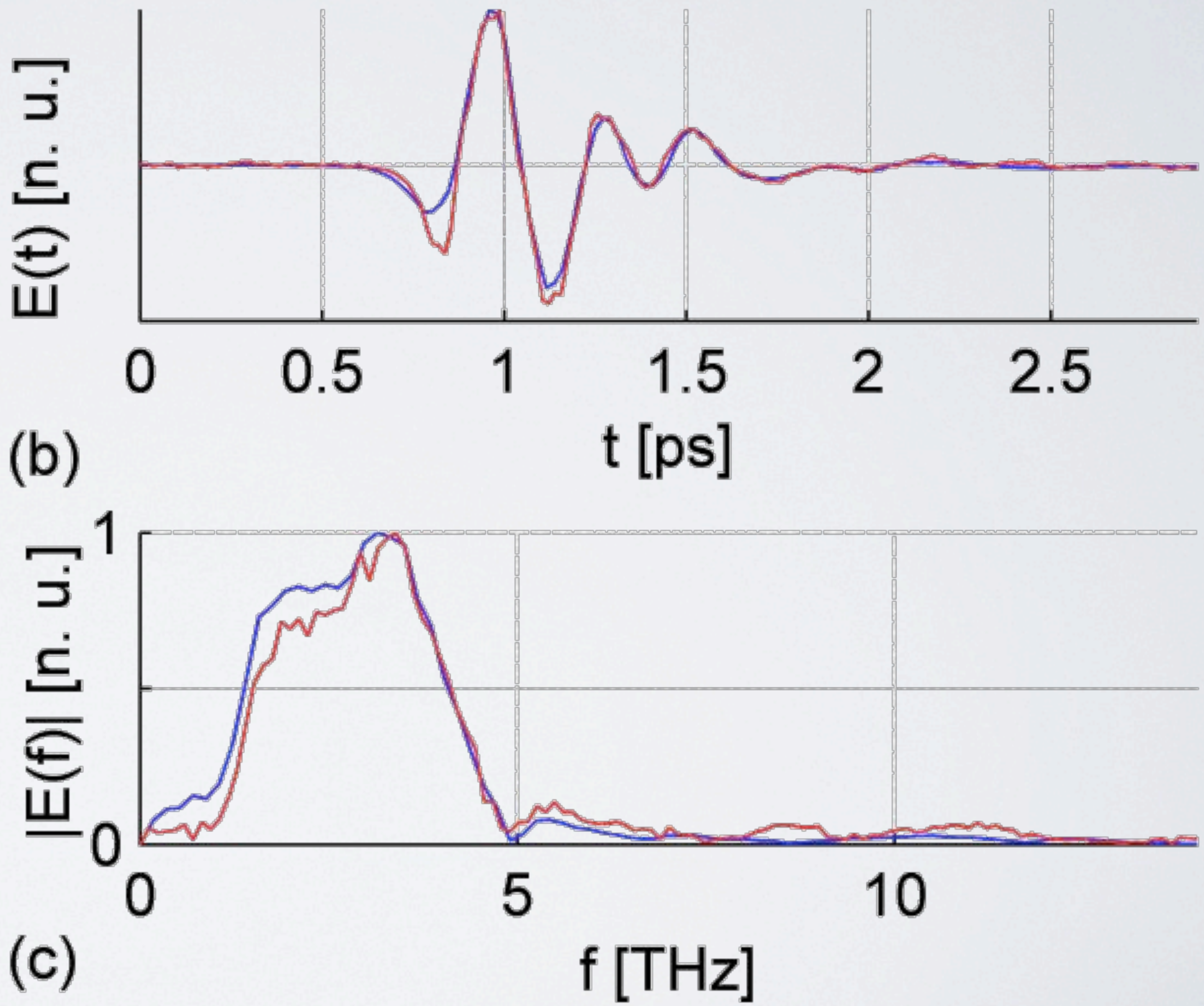
DSTMS: 4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate

Typically pumped at ~1.4-1.5 µm, w/OPA or fiber laser.

Bandwidth up to 5 THz, not as broad as plasma.

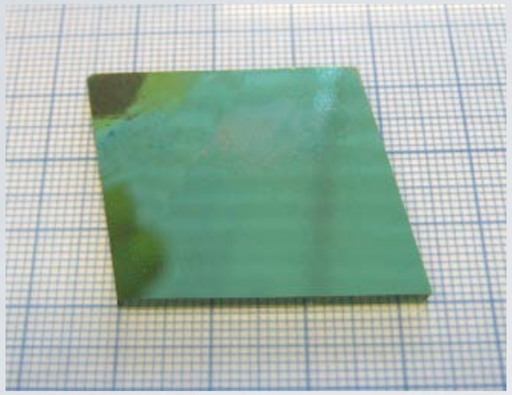
Efficiency 2-3%, field strength at focus >50 MV/cm (regens), average THz power potentially into 10's of mW!

Electro-optic generation, faithfully follows input light.

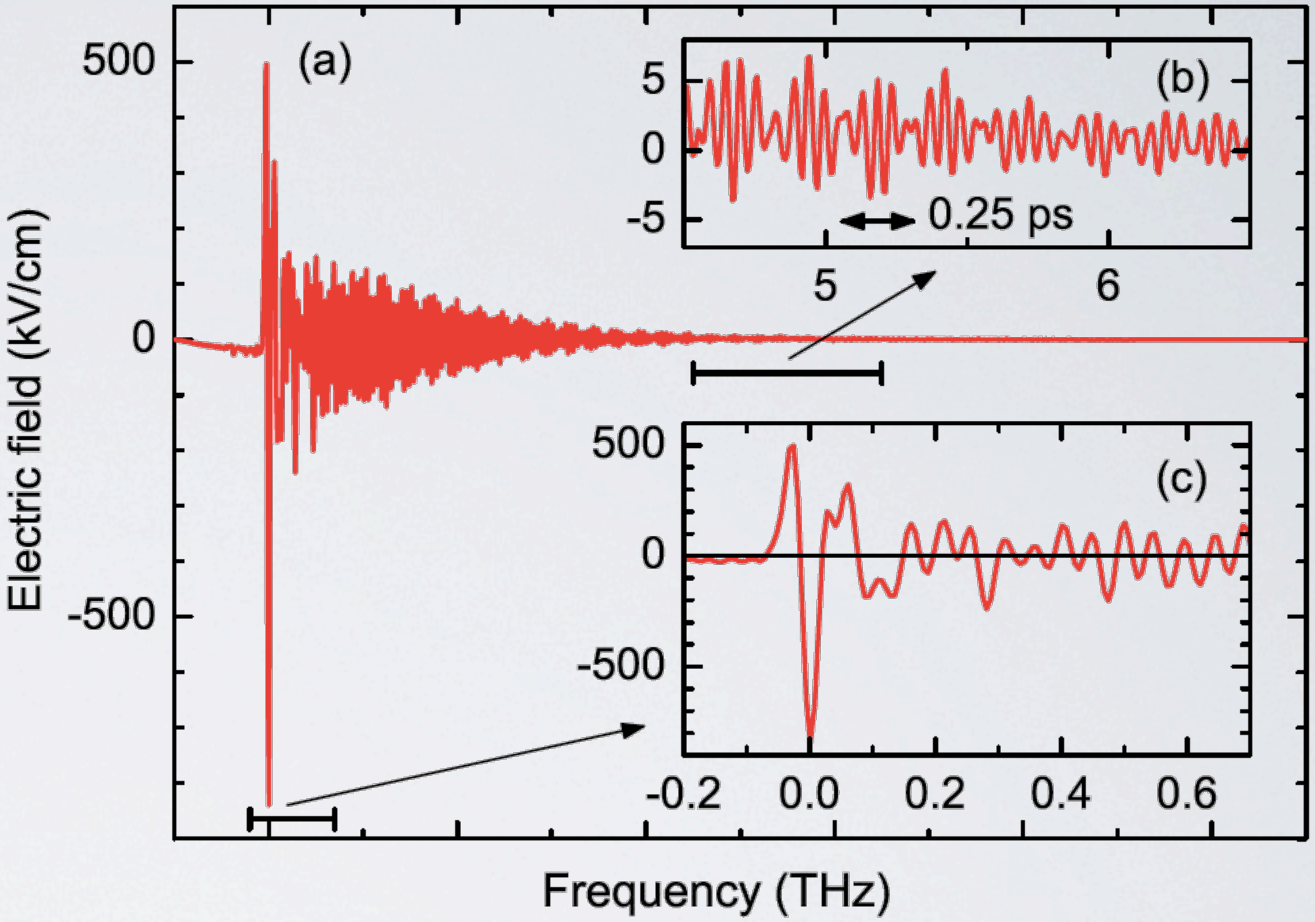


Prof. C.P. Hauri (RSI), Rainbow Photonics

Better THz TDS Conversion Efficiency? Enter DSTMS, DAST Emitters.



DSTMS



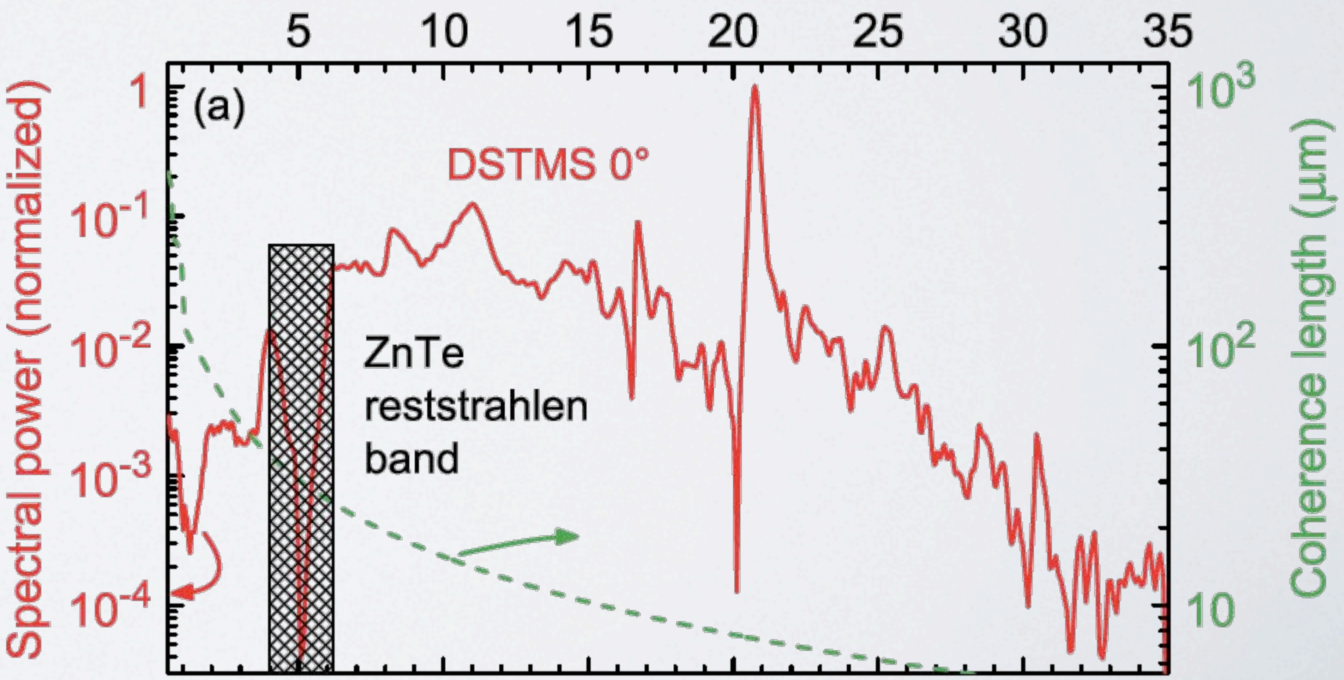
Typically pumped at ~1.4-1.5 μm, w/OPA or fiber laser.

Bandwidth up to 5 THz, not as broad as plasma.

Efficiency 2%, field strength at focus >50 MV/cm!

Electro-optic generation, faithfully follows input light.

Recent 800 nm pumping (Elsaesser group) has dramatically improved performance!



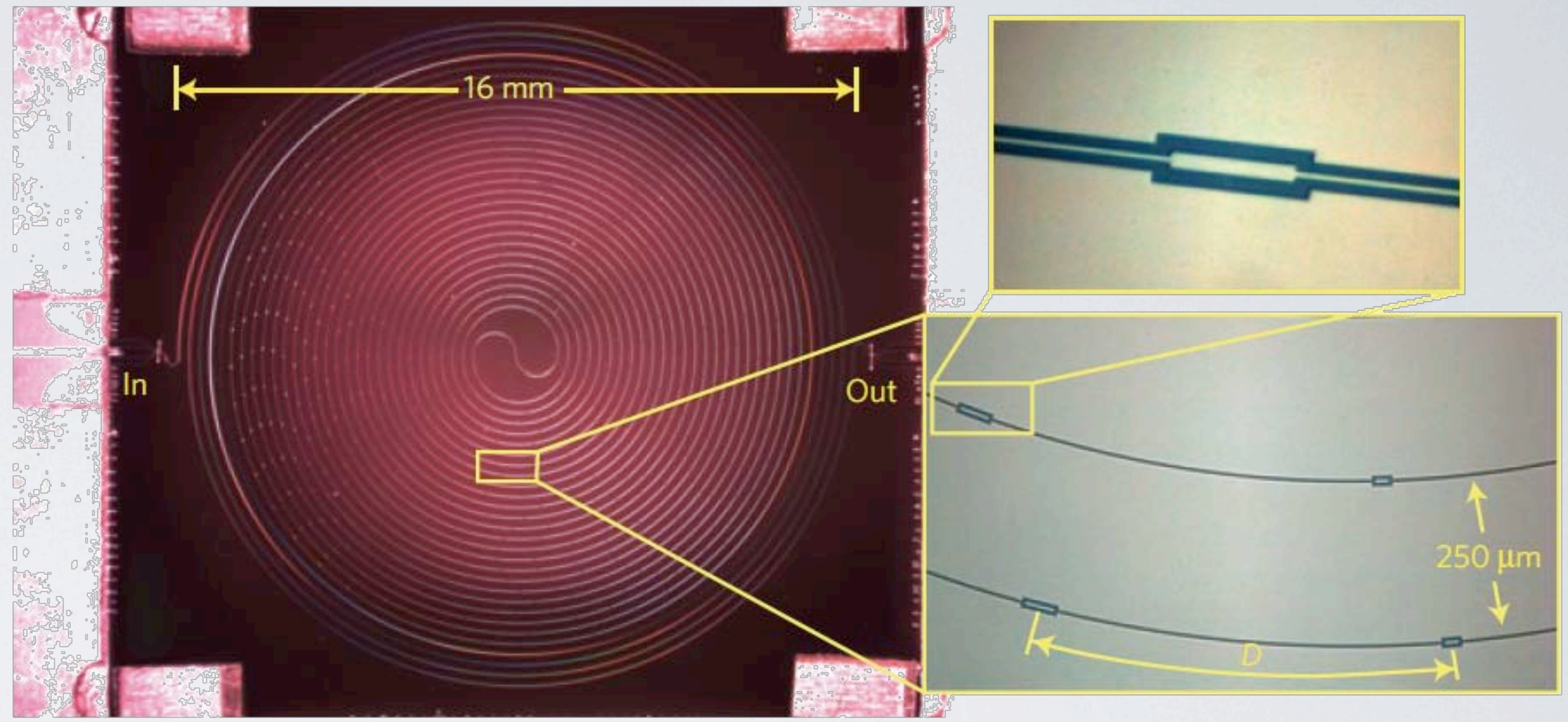
Somma et al., Optics Letters **40**, 3404(2015)

Comb driven THz Heterodyne?

nature physics ARTICLES
PUBLISHED ONLINE: 8 JULY 2012 | DOI:10.1038/NPHYS2356

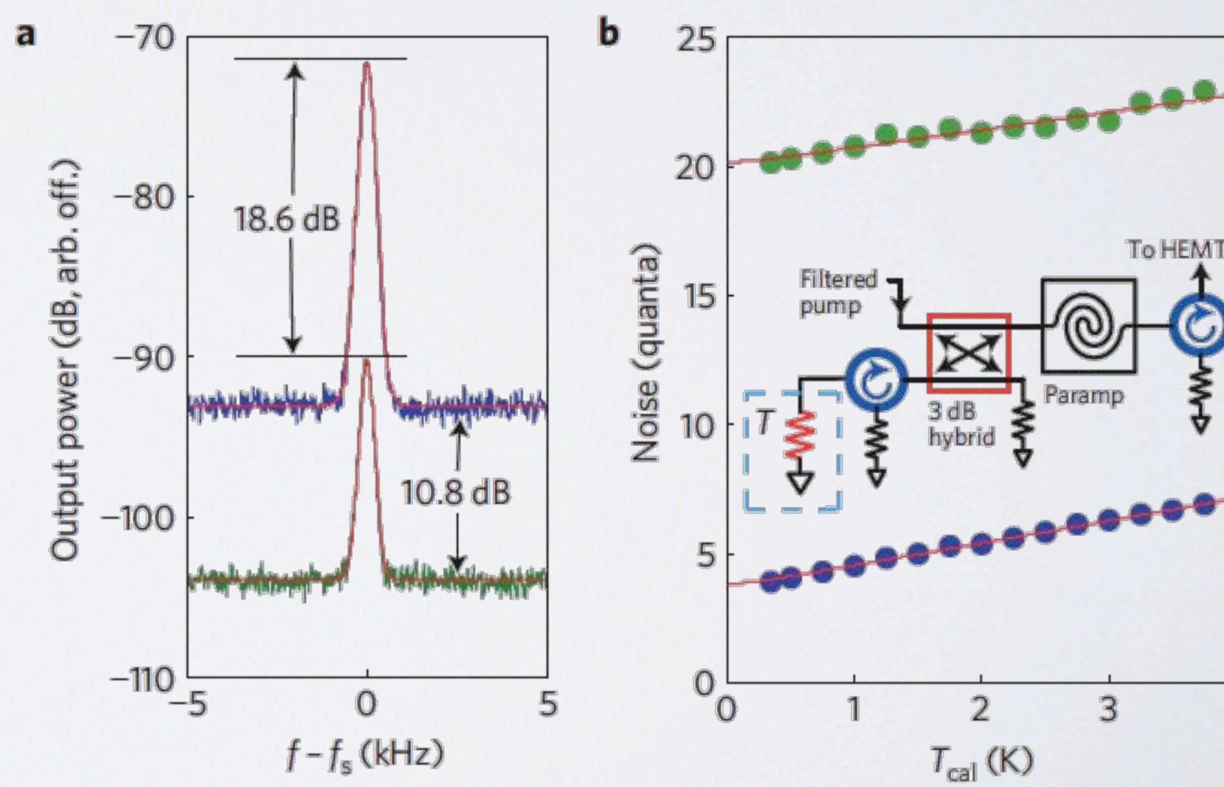
A wideband, low-noise superconducting amplifier with high dynamic range

Byeong Ho Eom[1], Peter K. Day[2*], Henry G. LeDuc[2] and Jonas Zmuidzinas[1,2]



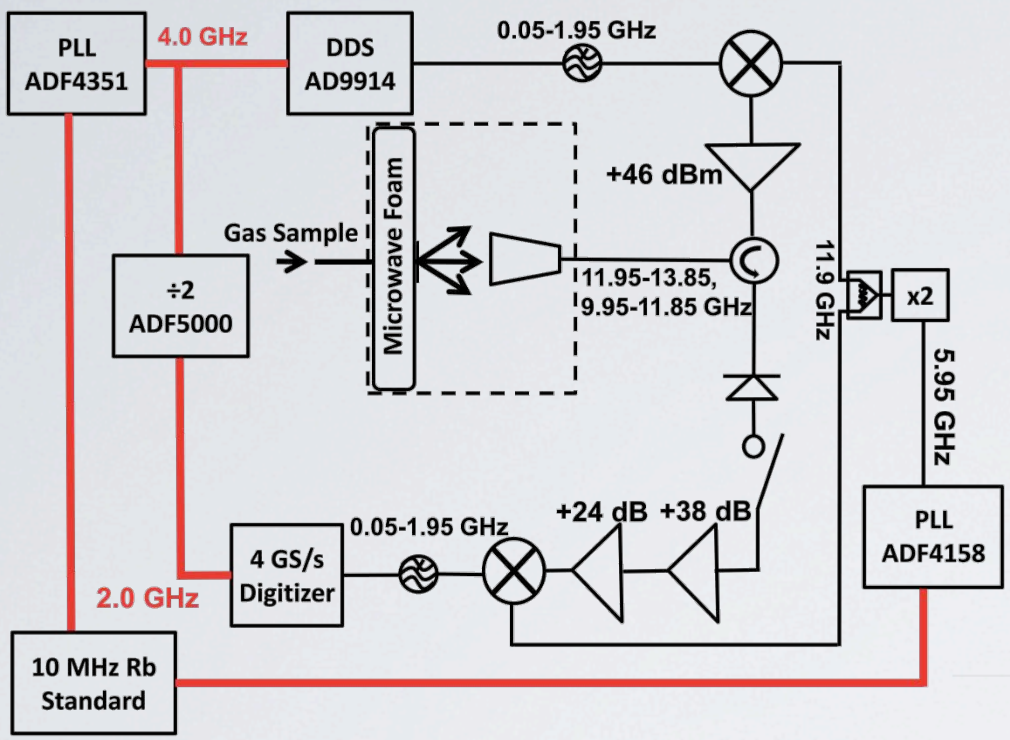
Potential significant advantage:
Amplify first, then mix.

When the LSB of the parametric amplifier is used, the frequency BW can exceed a factor of ten (0.1-1 THz, for example).



Photon occupation number now large, keys issues are then:
The performance of the THz mixer when pumped by the comb vs. a CW LO.
How do deal with the IFs/backends.

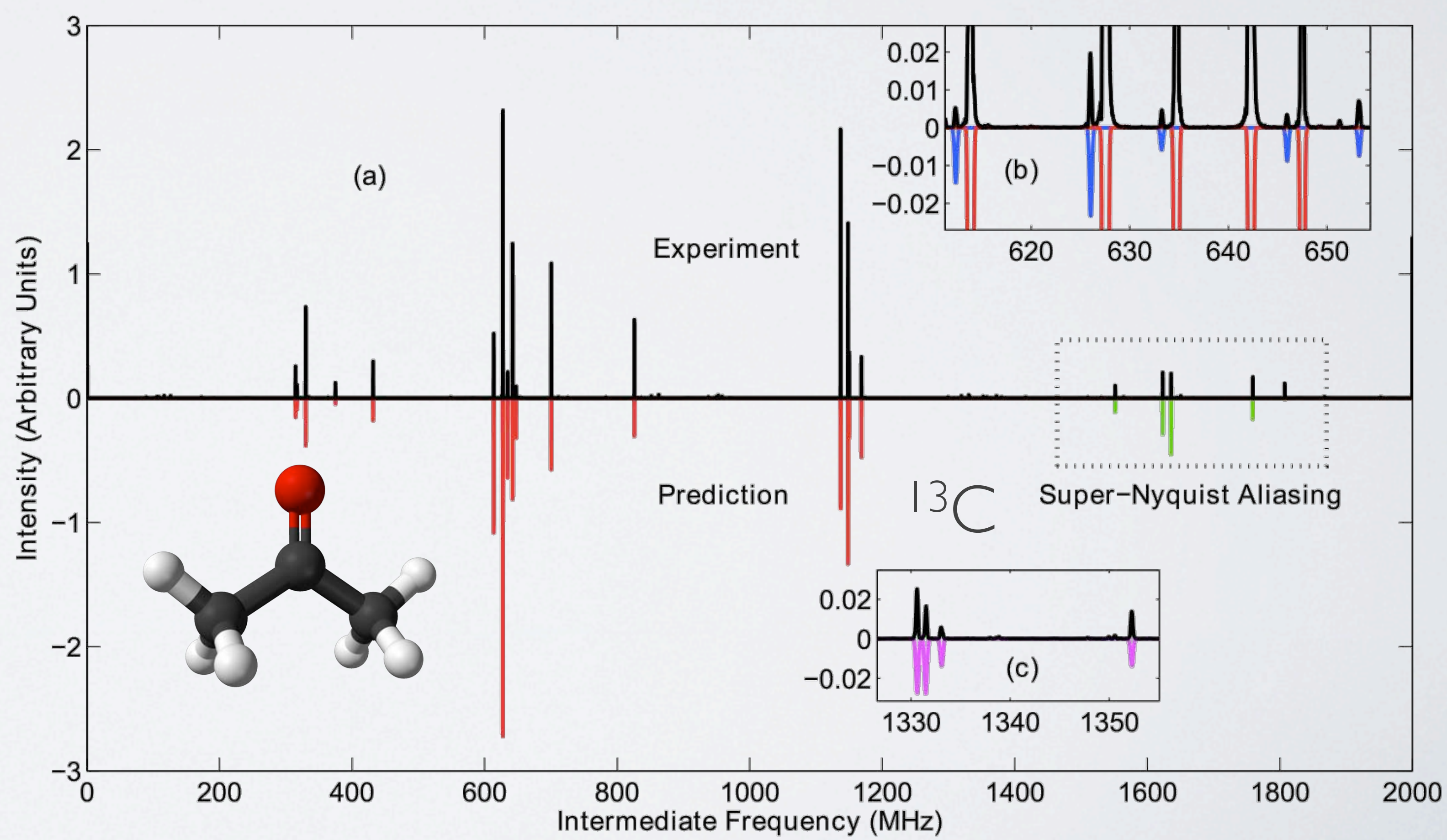
In situ? Combs versus Chirped Pulse-Fourier Transform Spectroscopy…



For microwave/mm-wave probes, combs will need to compete with the Chirped Pulse-FTMW mode invented by the **Pate lab (UVa)**.

Basic idea: Generate a swept frequency pulse whose duration is << the dephasing time. Collect FID, Fourier transform to yield spectrum.

Our twist? W/JPL engineering help, use direct digital synthesis to create a modular, wideband, sensitive, lightweight & low cost instruments.



I. Finneran, P.B. Carroll et al. 2013, *RSI*

Closing Thoughts & Acknowledgements

THz Combs:

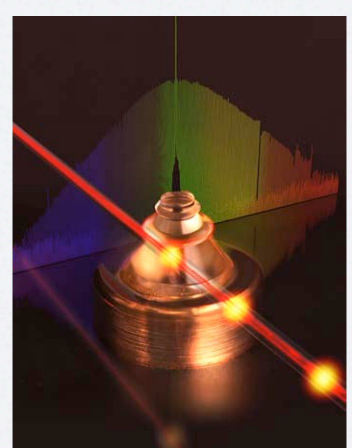
The good:

- Do not need to CEP stabilize mode-locked laser.
- Can easily cover the full frequency range of interest.

The challenges:

- Wall plug efficiency is low.
- Unclear how well heterodyne systems will perform under comb pumping.
- Cryogenics necessary?

Micro-combs in the THz regime (w/THz multipliers or QCLs, for example)?



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Thank you for your attention!