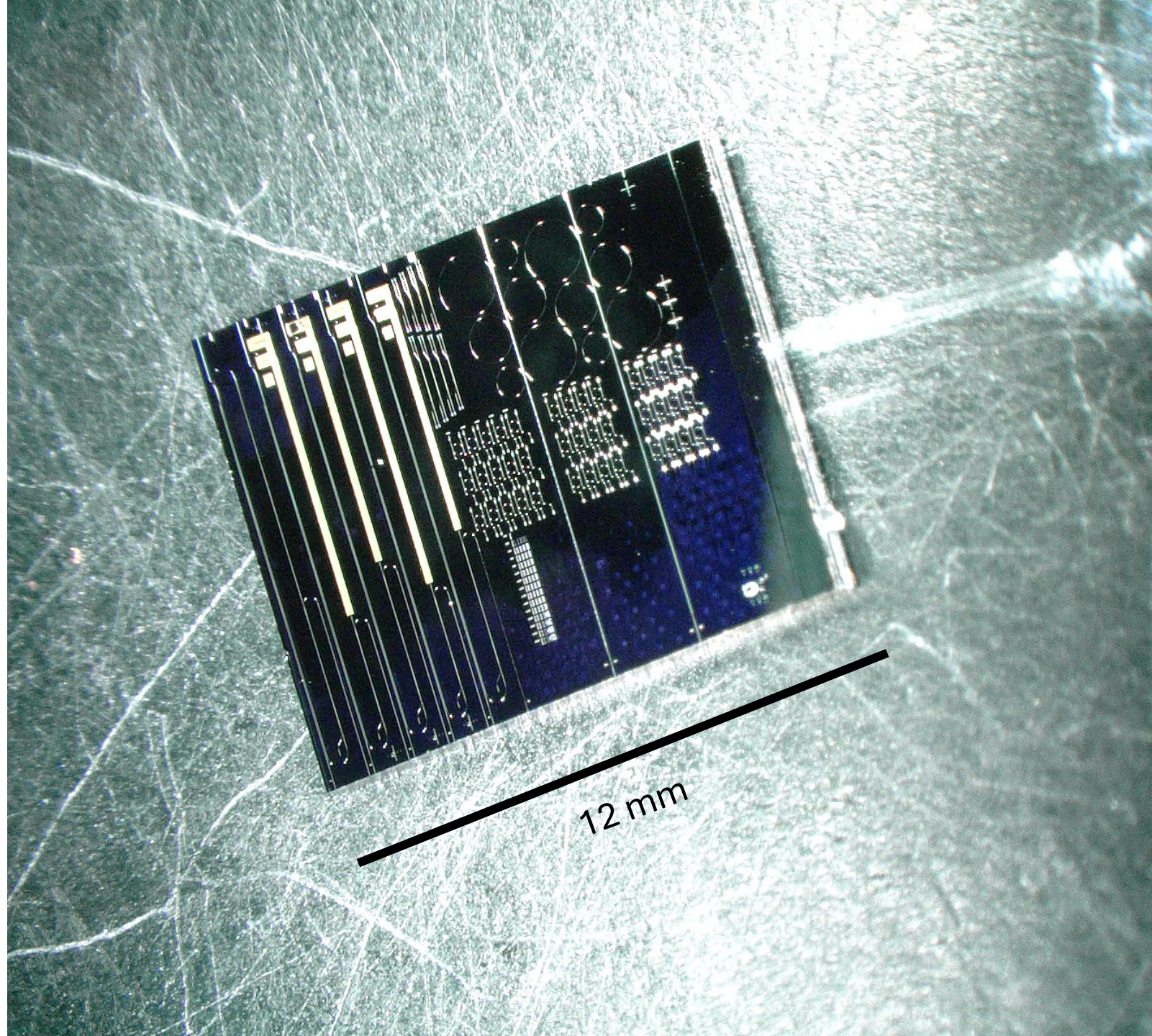


Telecom-Pumped Mid-Infrared Frequency Comb Generator on Thin-Film Lithium Niobate

Alex Hwang*, **Ethan Rosenfeld***,
Hubert Stokowski, Ziyu Wang, Martin
Fejer, Amir Safavi-Naeini

Stanford University, California, United States



Integrated frequency comb sources



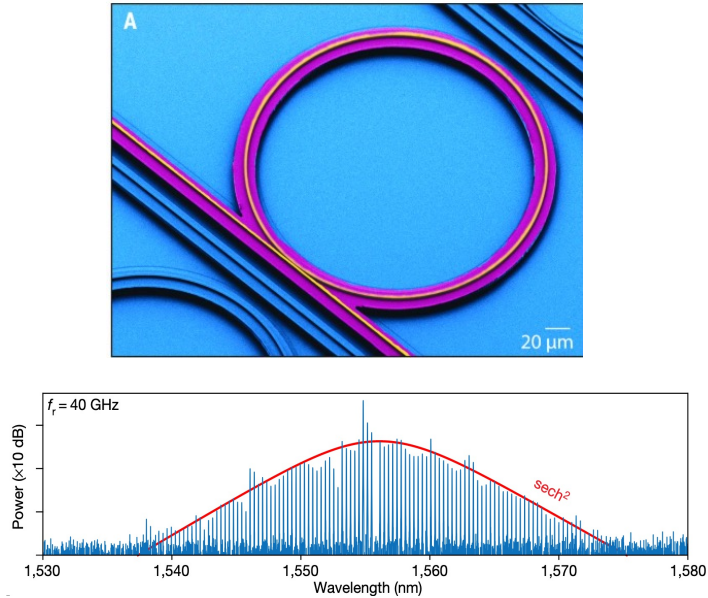
Bulk-optical frequency comb



Chip-integrated microcomb

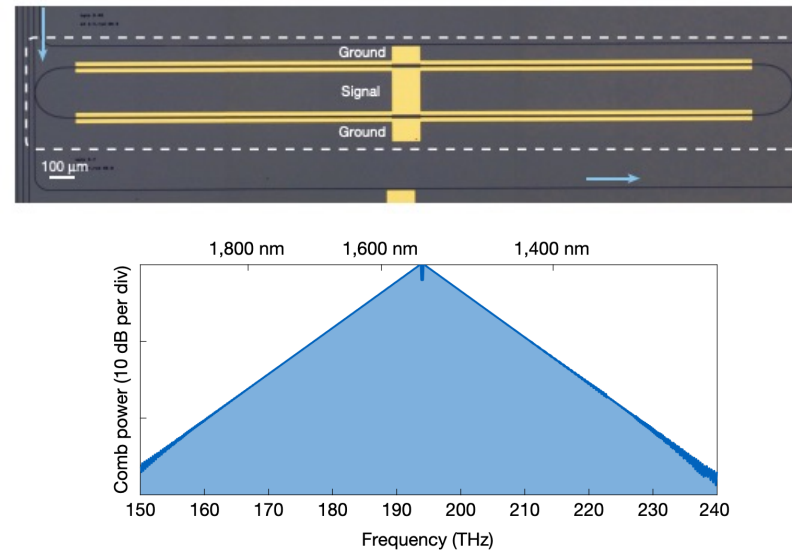
21st century advances in microcombs

Kerr



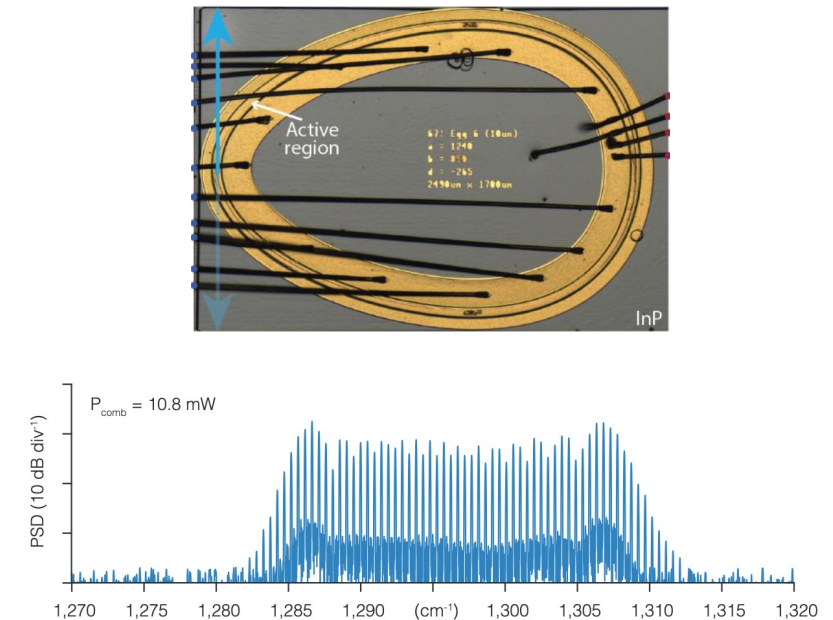
Okawachi et. al. Opt. Lett. **36** (2011)
Brasch et. al. Science **351** (2015)
Yu et. al. Optica **3** (2016)
Stern et. al. Nature **562** (2018)
Shen et. al. Nature **582** (2020)
+ many others

Resonant electro-optic



Zhang et. al. Nature **568** (2019)
Hu et. al. Nat. Phot. **16** (2022)
Zhang et. al. Nature **637** (2025)
+ many others

Modulated laser/parametric oscillator



Guo et. al. Science **382** (2023)
Stokowski et. al. Nature **637** (2024)
Heckelmann et. al. Science **382** (2025)
Letsou et. al. Optica **13** (2026)
Marzban et. al. Nat. Phot. **20** (2026)
+ many others

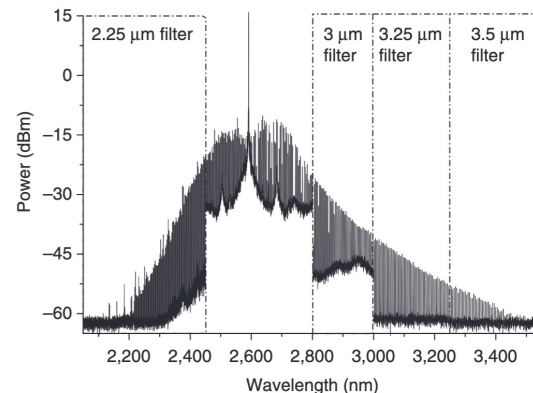
***excluding pulse-pumped sources**

Existing microcomb sources in the mid-infrared

Kerr microcombs →

Highly broadband but

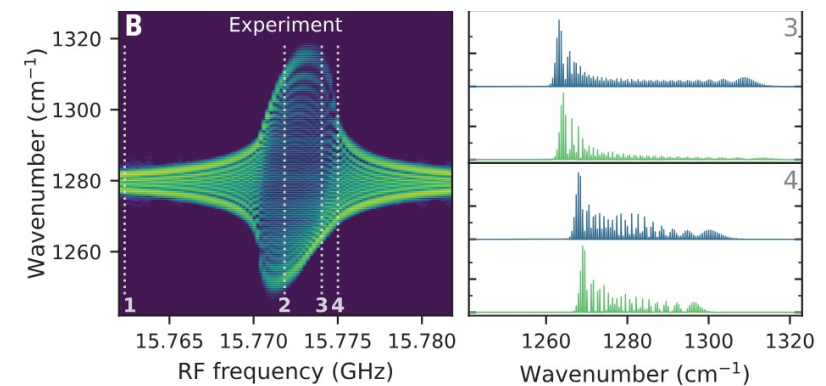
- *requires strong coherent MIR pump*
- *large FSR*
- *power per line decays rapidly from pump*



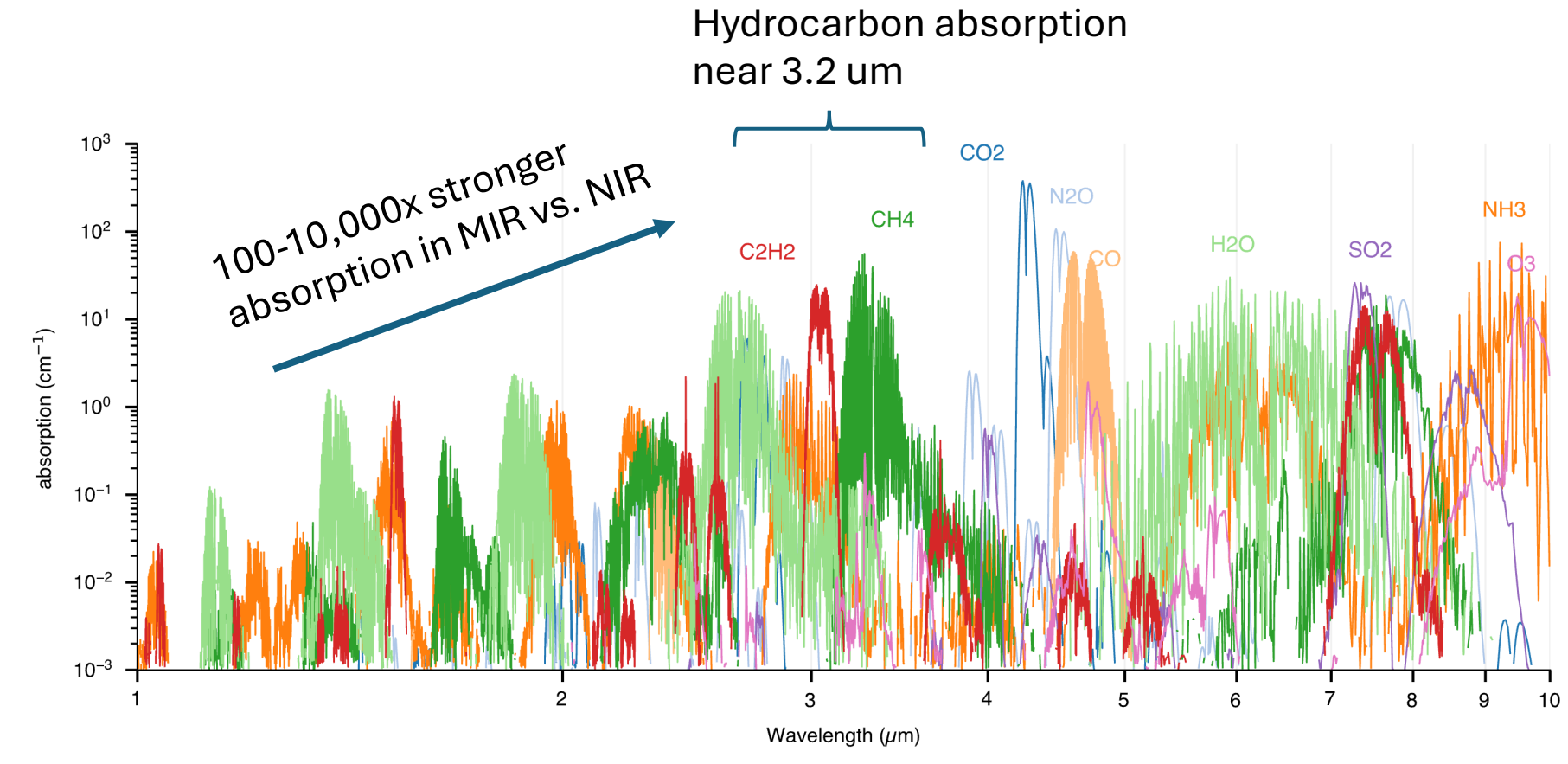
Frequency-modulated quantum cascade lasers →

Electrically pumped but

- *typically operate beyond 7 μm*
- *recent development*



Deployable mid-infrared sensing limited by light sources



III/V lasers
(mature, broadly tunable)



Interband cascade lasers
(less mature, narrowly tunable)



Quantum cascade lasers
(mature, narrowly tunable)

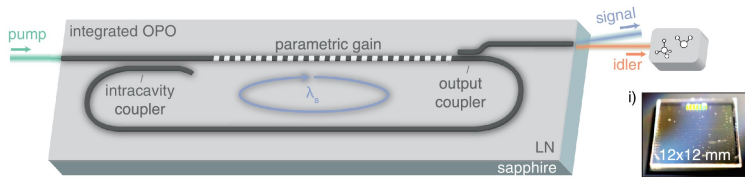
Thin-film lithium niobate (TFLN) is nearly ideal for MIR

- Transparent out to 5 μm
- Large $\chi^{(2)}$ coefficient for nonlinear optics
- Strong Pockels effect for EO modulation
- High-confinement waveguides for dispersion engineering

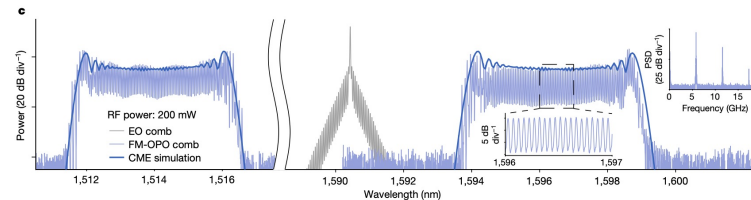
HL HYPERLIGHT

LIGHTIUM

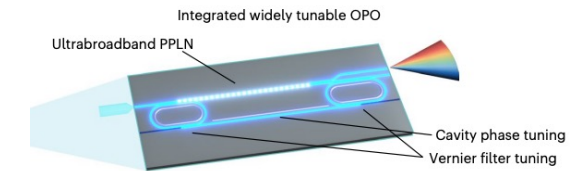
TFLN wafer-scale foundries exist now!



Hwang et. al. Optica **10** (2023)

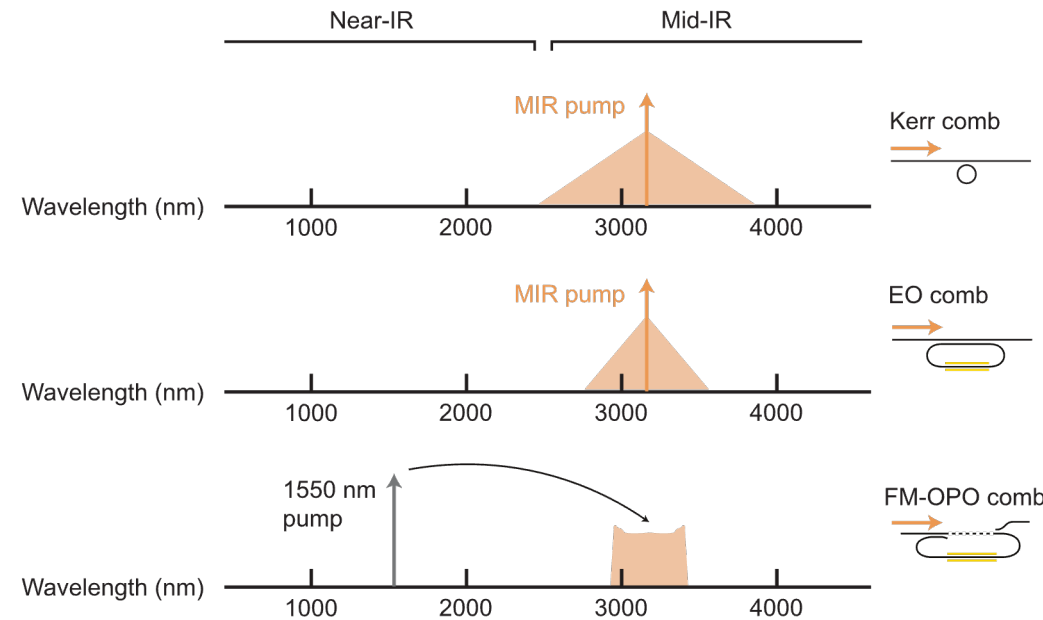


Stokowski et. al. Nature **637** (2024)

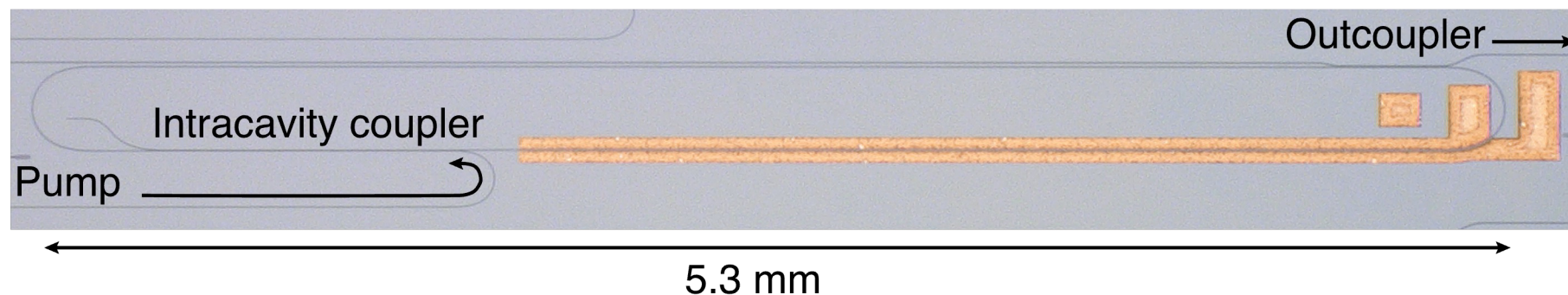


Hwang et. al. Nat. Phot. **10** (2026)

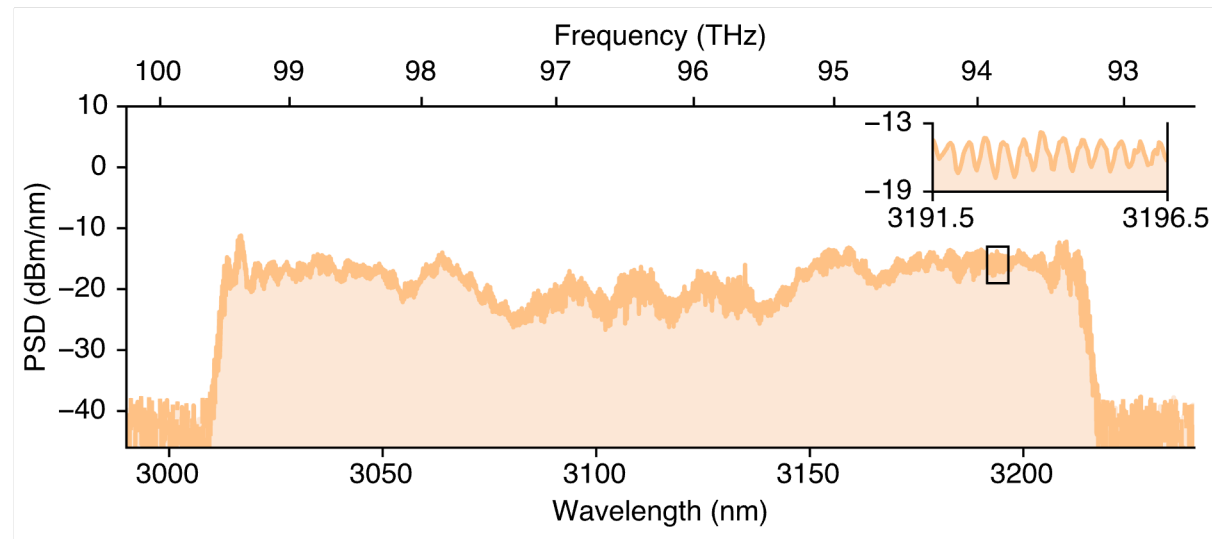
This work: a mid-infrared frequency-modulated parametric oscillator (FM-OPO)



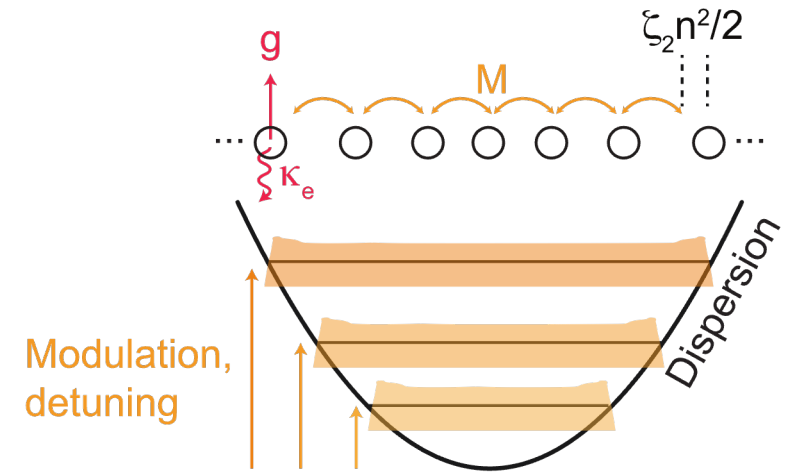
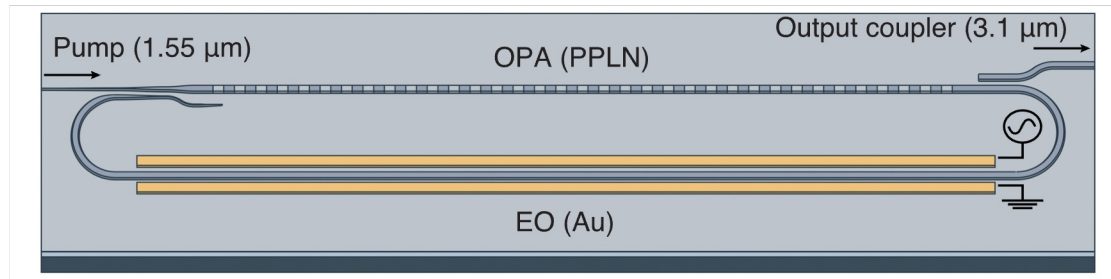
*A telecom-pumped
mid-infrared comb
source*



Broad comb from a CW 1550 nm laser



Nonlinear dynamics in the FM-OPO



Coupled mode equations for intracavity fields:

$$\dot{a}_n = \underbrace{\left(-\frac{\kappa_s}{2}\right)}_{\text{Loss}} + i \underbrace{\left(\Delta_s - \frac{1}{2}\zeta_{2,s}n^2\right)}_{\text{Dispersion}} a_n - \underbrace{2igb a_{-n}^*}_{\text{Parametric gain}} - i \underbrace{M_s (a_{n+1} + a_{n-1})}_{\text{Modulation}}$$

Time dynamics

Fourier transform in steady state (gain = loss)

$$\partial_t \psi = i \left[\Delta_s + \frac{\zeta_{2,s}}{2} \partial_q^2 - 2M_s \cos q \right] \psi$$

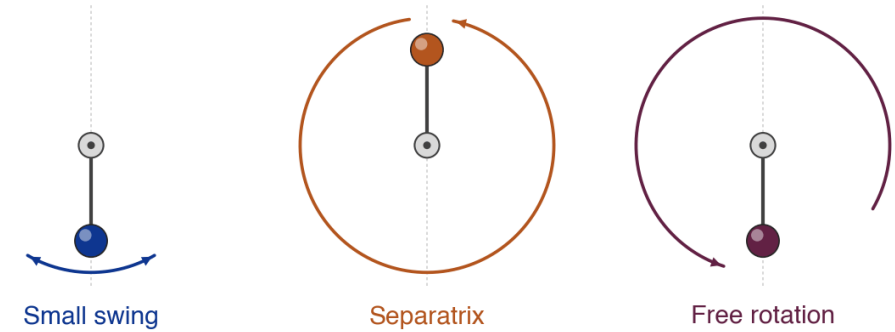
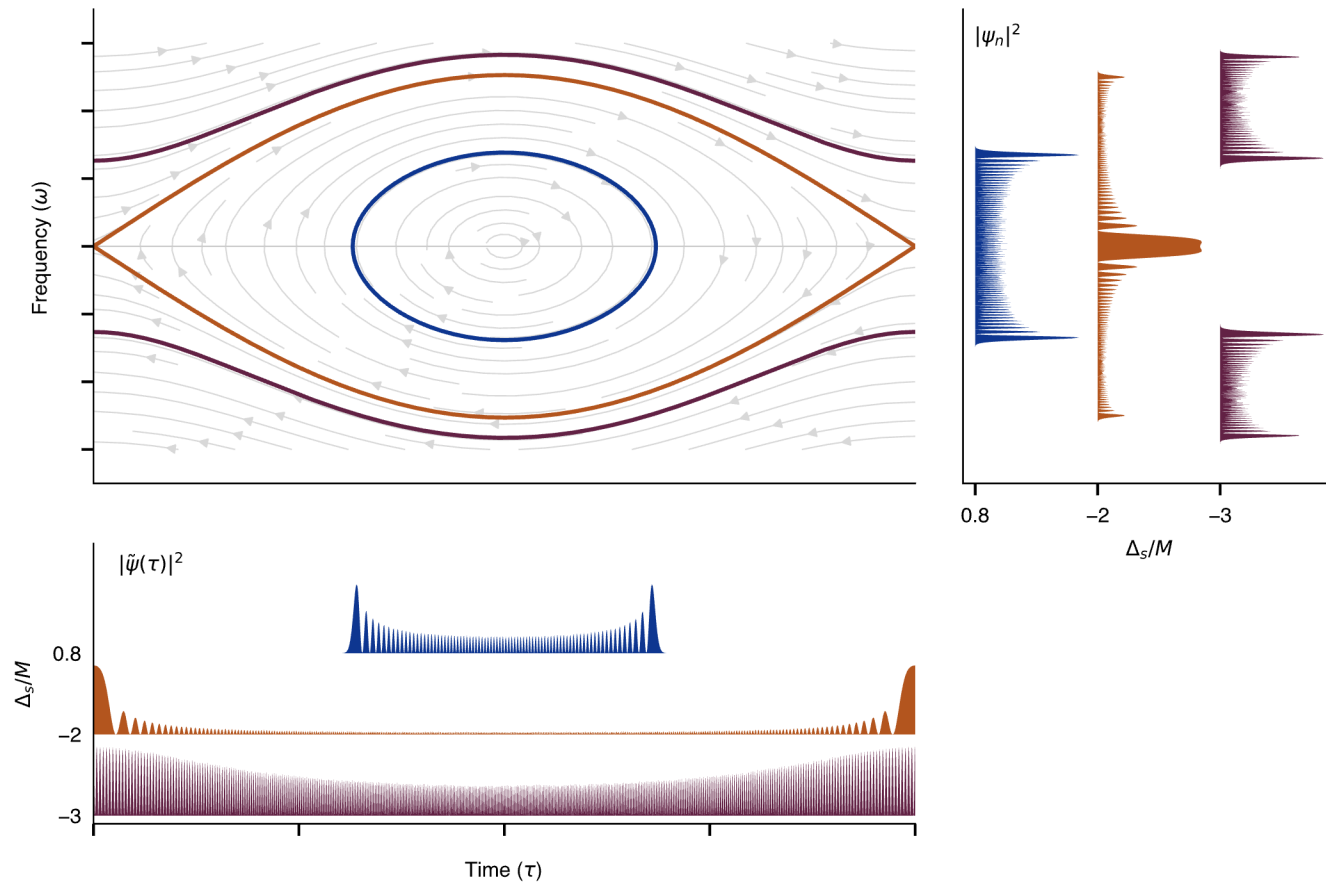
FM-OPO has equivalent dynamics to quantum pendulum!

$$\partial_t \Psi = i \left[-\frac{1}{2I} \partial_\theta^2 - mgl \cos \theta \right] \Psi \quad \longleftrightarrow \quad \partial_t \psi = i \left[\Delta_s + \frac{\zeta_{2,s}}{2} \partial_q^2 - 2M_s \cos q \right] \psi$$

Schrödinger equation for pendulum

Time-evolution of FM-OPO supermode

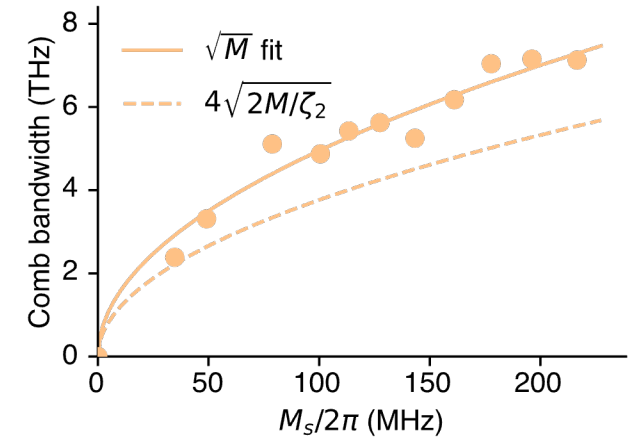
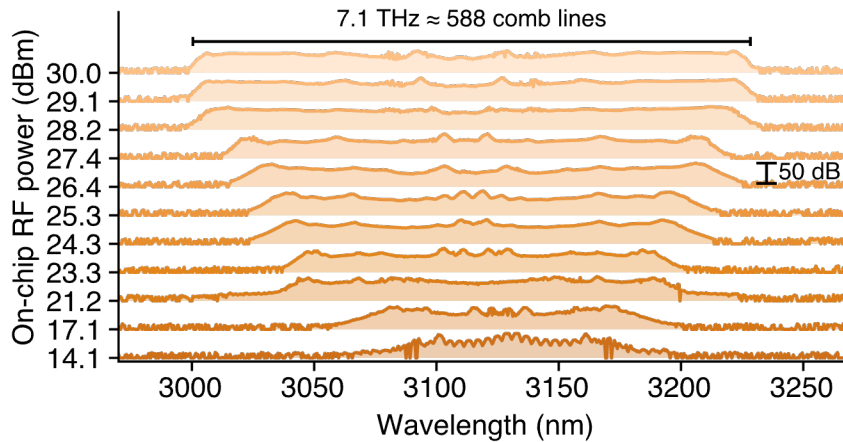
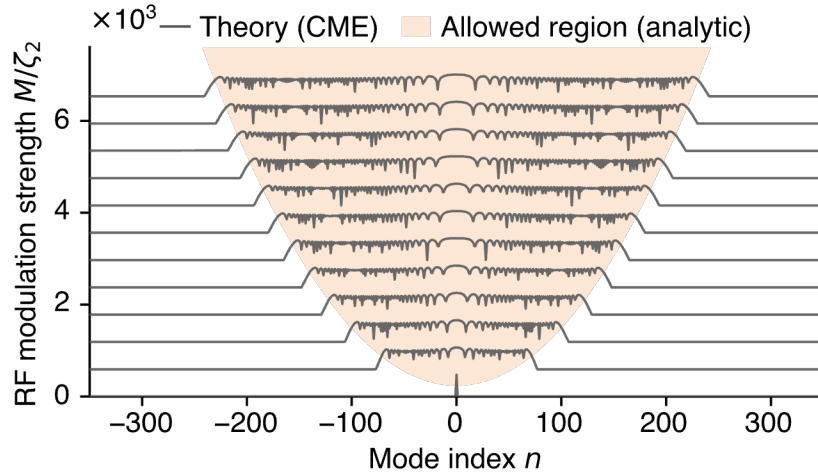
Pendulum phase space picture



Leads to simple
inequality for comb
bandwidth

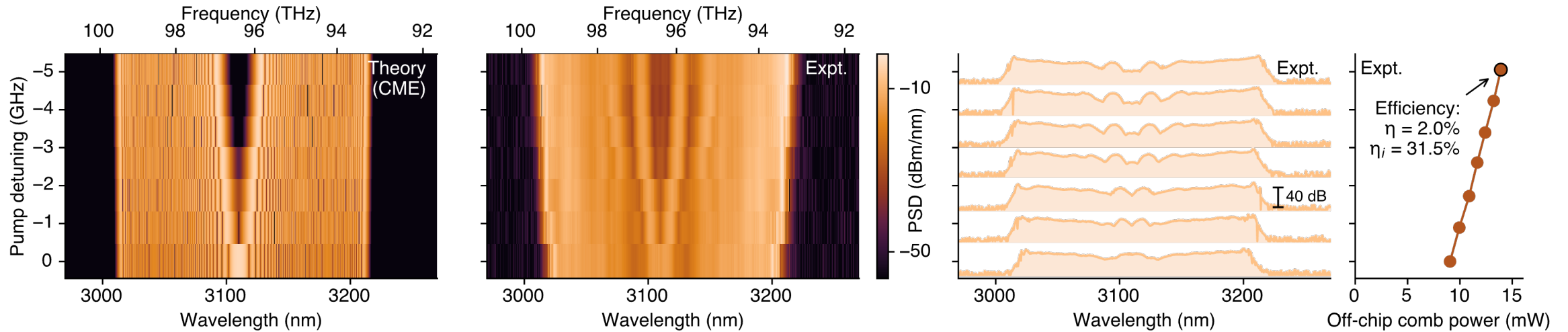
$$\left| \zeta_{2,s} n^2 - 2\Delta_s \right| \leq 4M_s$$

Comb bandwidth



Square root dependence on modulation, identical to frequency-modulated laser combs with fast gain

Pump tuning

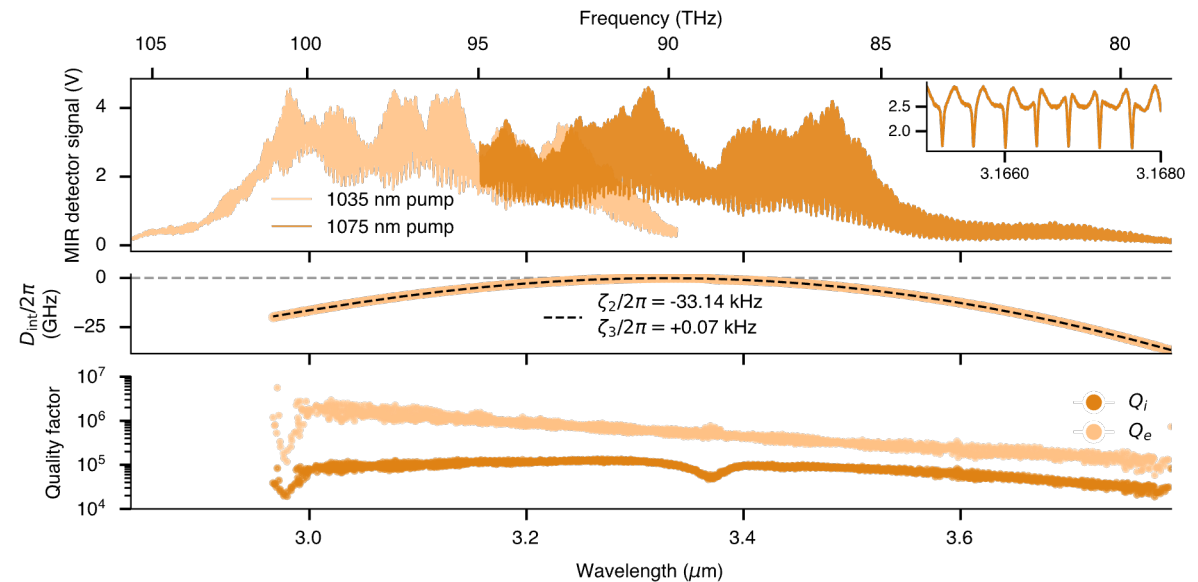


Steady-state coupled mode equations accurately model comb tuning with pump laser detuning

Mid-infrared cavity characterization

Widely-tunable difference-frequency generation allows broadband OPO cavity spectroscopy

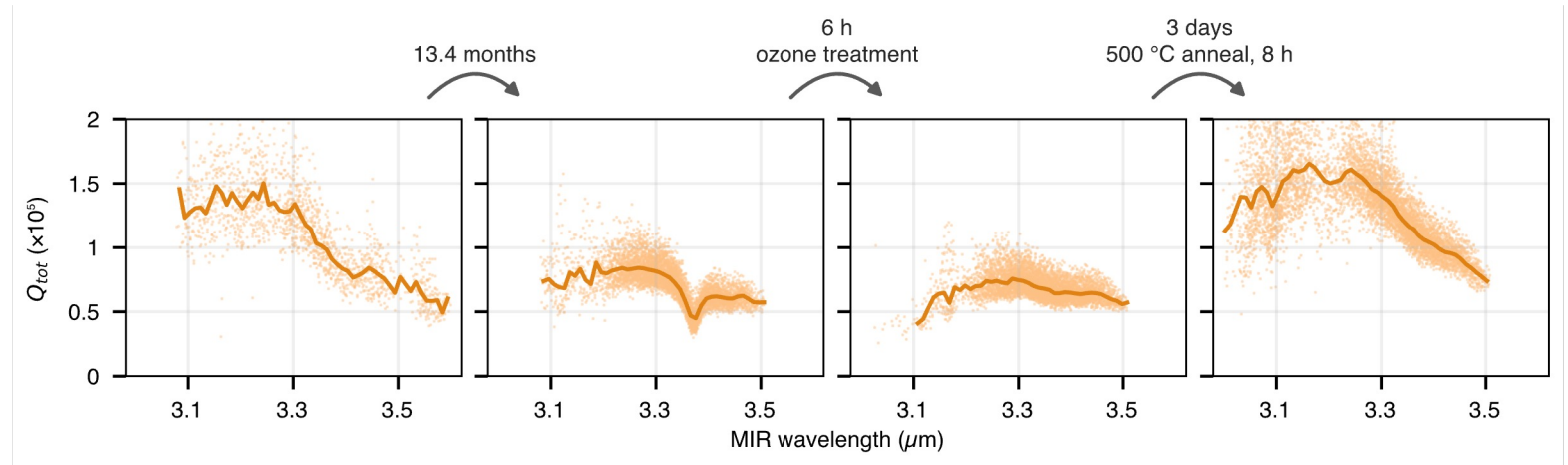
Mid-infrared integrated dispersion and loss measured over ~800 nm of bandwidth



MIR loss in TFLN waveguides

Typical MIR $Q = 100,000 \rightarrow$
525 mW threshold

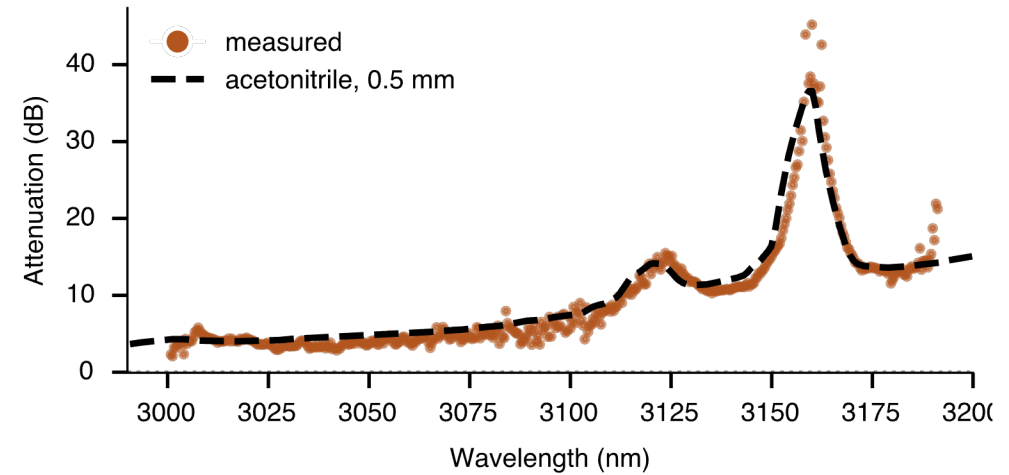
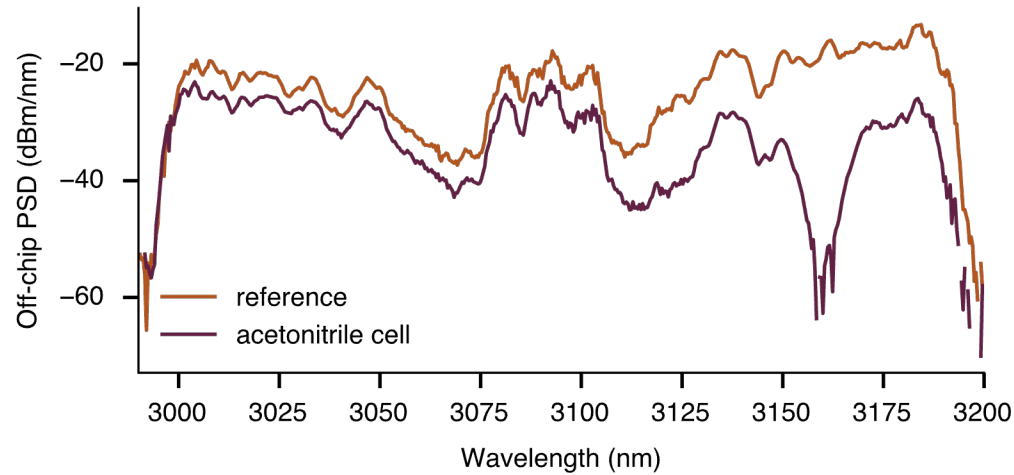
- Ozone removes hydrocarbon peak
- Annealing reduces loss to initial levels



$$P_{th} \propto \frac{1}{Q_s^2}$$

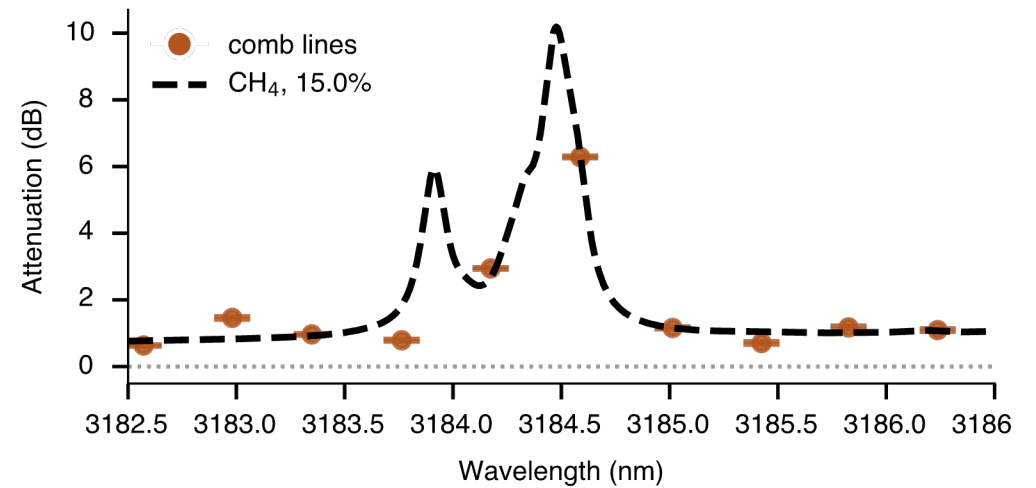
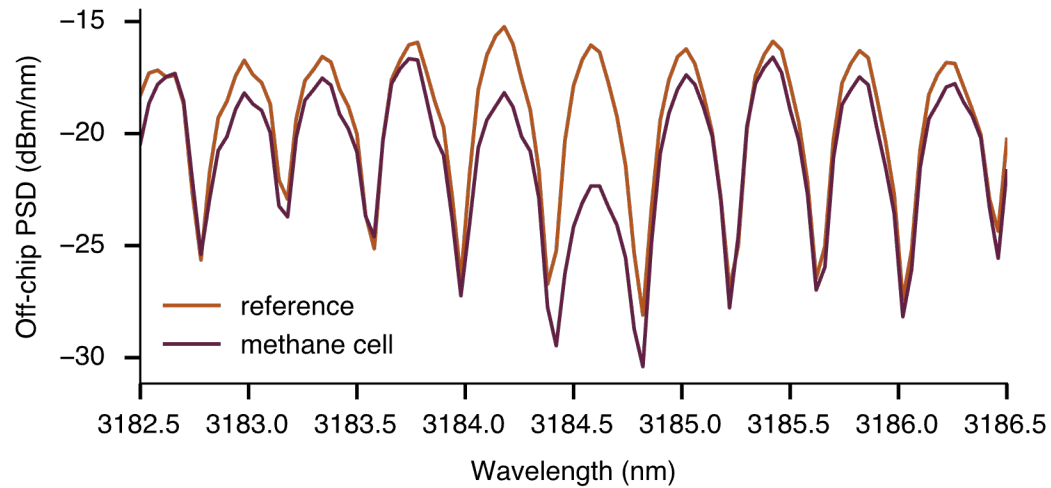
Need to study MIR loss channels in more detail...

Absorption spectroscopy of liquid acetonitrile



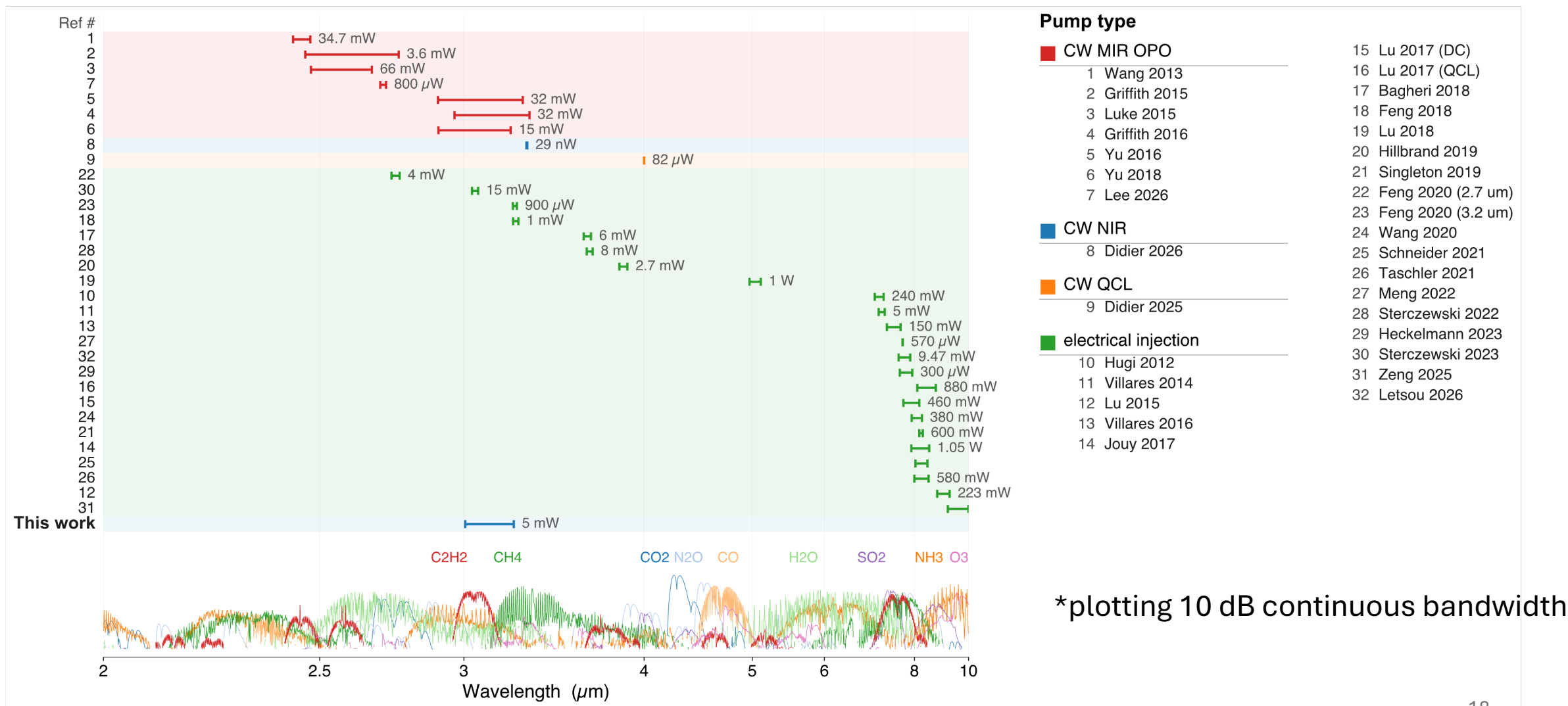
Spectroscopy of ~THz scale liquid absorption features

Absorption spectroscopy of gaseous methane

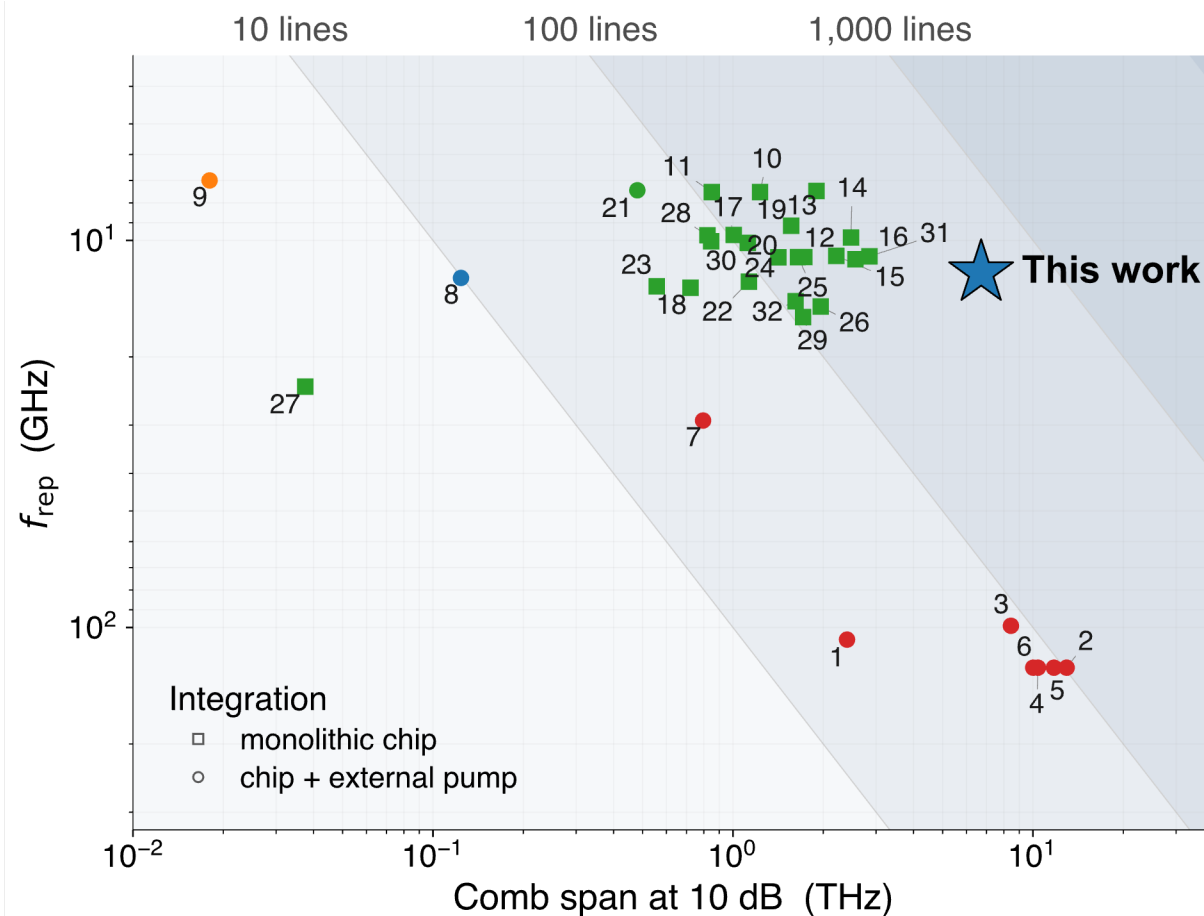


Spectroscopy of ~GHz scale gas absorption features

Coverage map of existing MIR microcombs



Dense & broad MIR microcombs are hard to come by



Pump type

CW MIR OPO

- 1 Wang 2013
- 2 Griffith 2015
- 3 Luke 2015
- 4 Griffith 2016
- 5 Yu 2016
- 6 Yu 2018
- 7 Lee 2026

CW NIR

- 8 Didier 2026

CW QCL

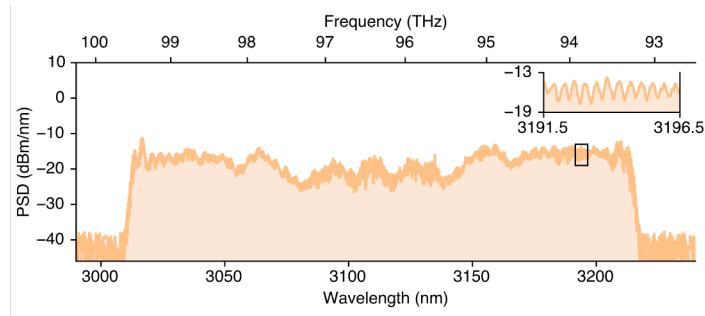
- 9 Didier 2025

electrical injection

- 10 Hugi 2012
- 11 Villares 2014
- 12 Lu 2015
- 13 Villares 2016
- 14 Jouy 2017

- 15 Lu 2017 (DC)
- 16 Lu 2017 (QCL)
- 17 Bagheri 2018
- 18 Feng 2018
- 19 Lu 2018
- 20 Hillbrand 2019
- 21 Singleton 2019
- 22 Feng 2020 (2.7 μm)
- 23 Feng 2020 (3.2 μm)
- 24 Wang 2020
- 25 Schneider 2021
- 26 Taschler 2021
- 27 Meng 2022
- 28 Sterczewski 2022
- 29 Heckelmann 2023
- 30 Sterczewski 2023
- 31 Zeng 2025
- 32 Letsou 2026

Conclusion & Acknowledgements



This work

- 7 THz wide MIR frequency comb from a CW 1550 nm laser
- Theory of FM-OPO analogous to quantum pendulum

Future work

- Study mid-infrared loss channels to lower threshold
- Explore singly-resonant OPO for easier tuning

People



Alex Hwang*, **Ethan Rosenfeld***, Hubert Stokowski,
Ziyu Wang, Martin Fejer, Amir Safavi-Naeini



Funders



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Sustainability Accelerator

