Future Heterodyne Instrumentation

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SFB 956 “Conditions and Impact of Star Formation”

- **Introduction: SOFIA and mid- to high resolution spectroscopy**
- **detection technologies and present limitations**
  - **detector limitations**
  - **local oscillator limitations**
  - **observatory embedding & infrastructure**
- **summary**

Introduction: SOFIA and mid- to high resolution spectroscopy

- **SOFIA's uniqueness**
  - **mid- to high-resolution spectroscopy throughout the FIR and MIR**
    - **plus: occultations**
    - **plus: polarization**
- **reason (space vs. airborne):**
  - **residual background (assumption: background limited direct detectors) from**
    - **warm telescope**
    - **atmosphere**

    make broadband observations from space more sensitive
  - **(mid- and) high-spectral resolution instruments are bulky and complex**
    - **volumen, mass, power limits and**
    - **vibration specifications for satellite launch**

    make them very difficult to built and too costly for space

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detection methods: direct detection vs. coherent detection

- fundamental limits: direct detection always wins
- but: real-life
  - optical losses at high spectral dispersion
  - geometrical constraints due to fundamentals of diffraction optics

  cross-over in competing sensitivity as function of resolving power and wavelength
  - at highest spectral resolution and longer wavelength, heterodyne is more sensitive
  - high resolution across many pixels on the sky hits limits in pre-detection dispersion

- focal plane arrays
  - direct detection: integral field spectroscopy through image slicing
  - heterodyne: close packing and high level of integration of optics, mixers, cold IF starts to allow larger arrays

- SOFIA gives good examples for state-of-the-art instruments
  - EXES
  - FIFI-LS
  - GREAT/upGREAT

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present limitations for heterodyne technology

- broad instantaneous spectral coverage & tunability needs
  - sensitive mixing across broad IF band
    - SIS-mixers
      - can provide more than 10 GHz IF bandwidth
      - but are limited (at present) to 1.4 THz RF
    - perspective to extend SIS-technology up to >= 2 THz
      - superconducting material
      - .....
  - local oscillator technology
    - available output power
    - tuning range
    - spectral purity and stability

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technology: LO limitations

- multiplier chains
  - output power
    - sufficient power for single pixel up to 2.7 THz (4.7 THz)
    - sufficient power for modest size arrays up to 2 THz
  - spectral purity
    - frequency multiplication leads to severe problems with out-of-band LO noise

- photonics Local Oscillator (LO)
  - very limited output power (at present usable only up to < 1THz)
  - very attractive due to large instantaneous tuning range

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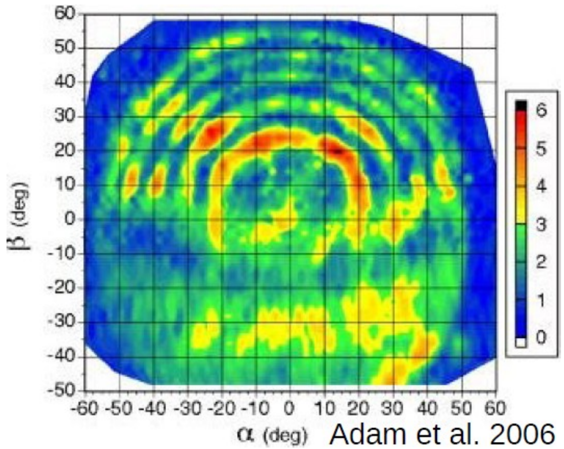
technology: LO limitations

- **Quantum Cascade Lasers**
  - **very attractive due to high output power**
  - **but**
    - **beam pattern of poor quality**
    - **frequency purity marginally sufficient**
    - **stability problems**
    - **small tuning range, difficult to meet nominal frequency**
  - **ongoing developments to improve on these**



Adam et al. 2006

Future Heterodyne Instrumentation
(Ringberg Workhshop on Spectroscopy with SOFIA)

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- **Quantum Cascade Lasers (QCL)**
  - **ongoing developments**
    - **better design and process control in manufacturing of QCL device**
      - › **better meet specs in frequency and power requirements**
    - **central issue**
      - › **high reflectivity of resonator facet (intrinsic to device)**
        - » **many attempts w/r to coating etc., so far unsuccessful**
        - » **new approach (KOSMA, M. Justen)**
          - waveguide embedding to match impedance
      - › **allows to couple power out into beam pattern defined by waveguide/horn**
      - › **will allow to lock QCL to external cavity**
        - » **tuning over broader range**
        - » **better frequency control / stabilization**

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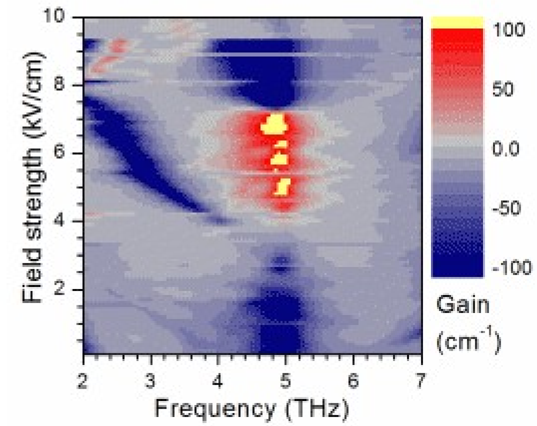
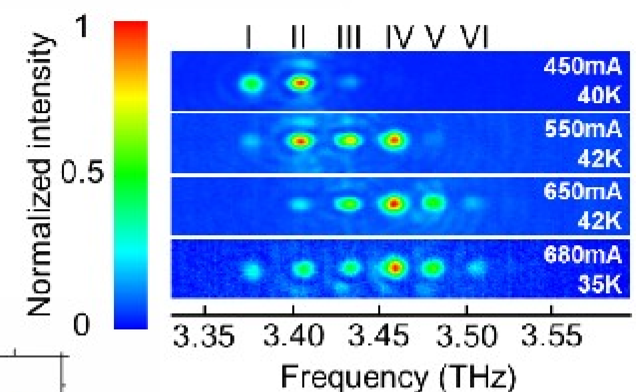
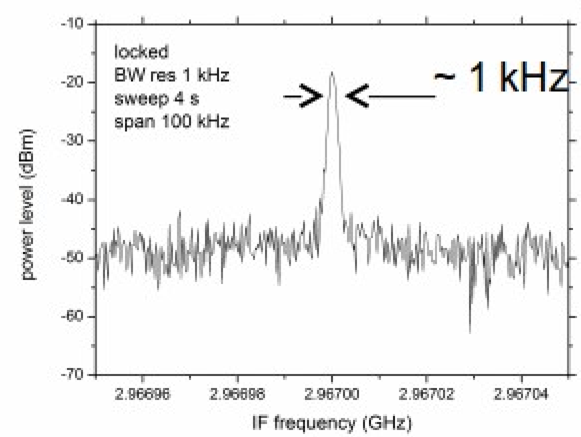
QCL development at DLR-WS / upGREAT (Hübers)

- New band design for higher output power (>1mW 4.7THz)
- External cavity for larger frequency coverage (>400GHz) and improved frequency tunability/agility
- Frequency stabilization / PLL with an external reference source (superlattice multiplier)







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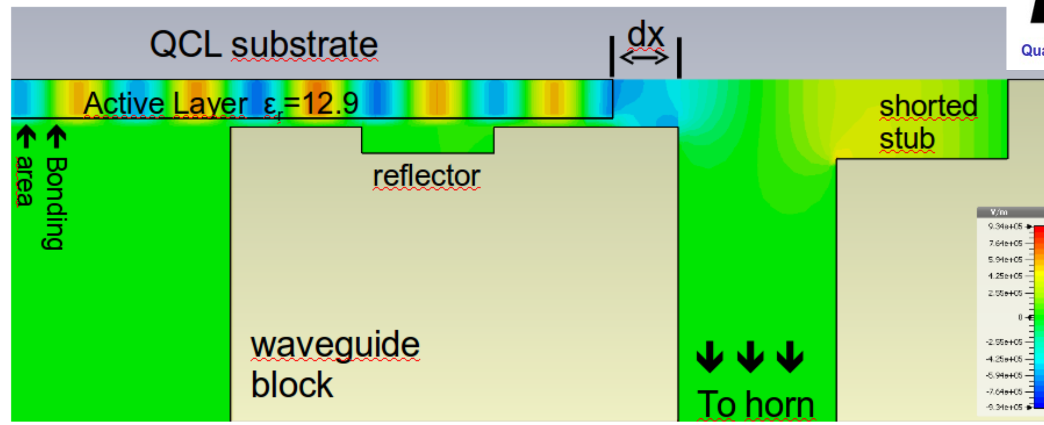
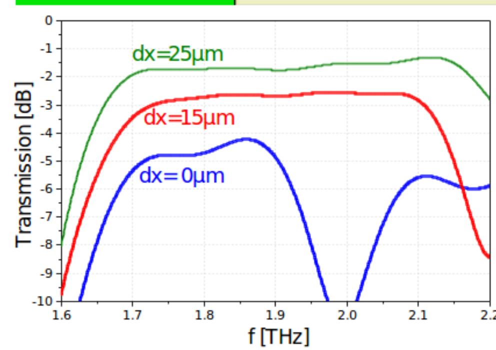
QCL development at KOSMA/ETH

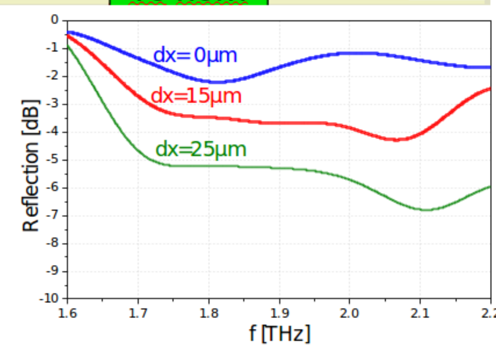
impedance matching to horn output by waveguide embedding

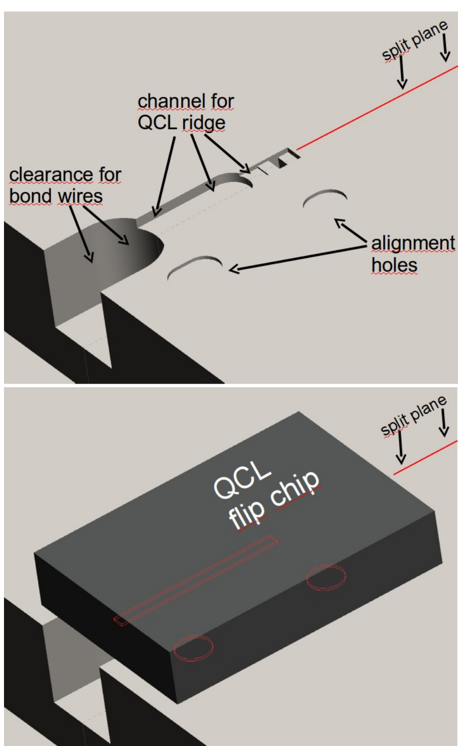
- **single mode beam by definition**
- **effectively AR-coating of QCL facet**

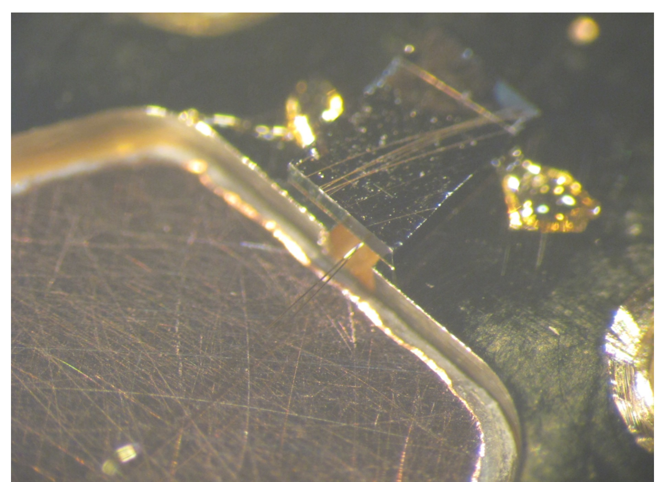
How the transition works?











M. Justen, K. Otani, M. Beck, D. Turčinkov, F. Castellano, U.U. Graf and J. Faist, KOSMA & ETH

Universität zu Köln
ETH Zürich
Quantum Optoelectronics Group

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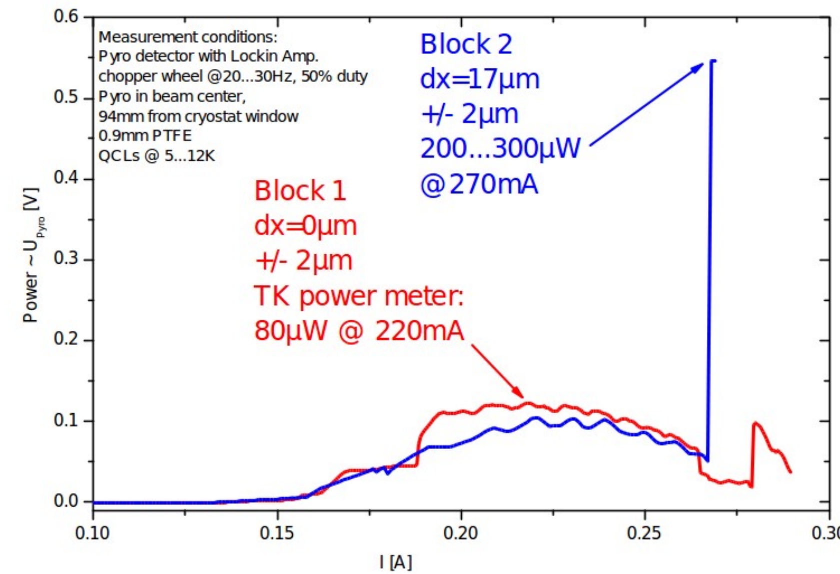
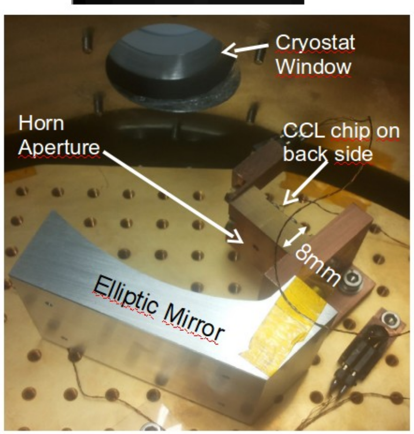
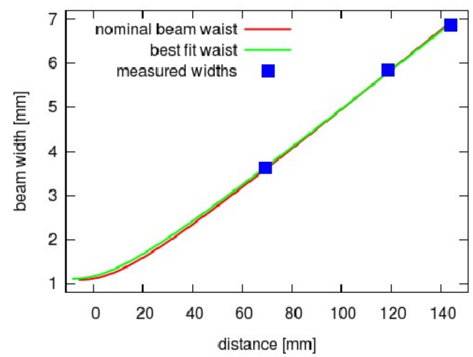
Power Measurements



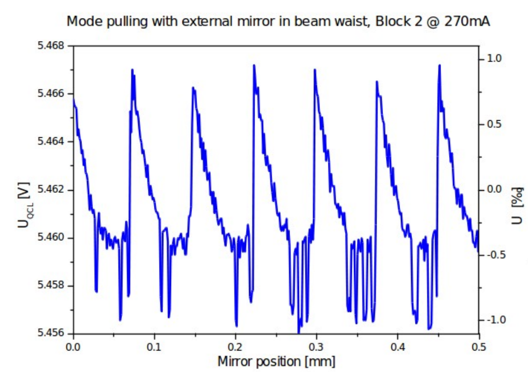


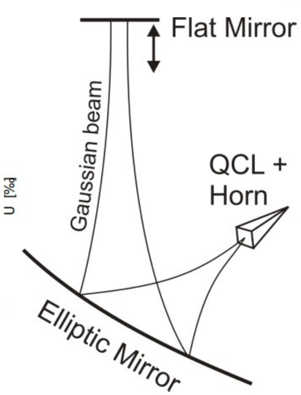


Measurement setup:

- QCL block mounted in 4K cryostat
- Diagonal horn with w=0.315mm, same dimensions as VDI LO horn
- Beam pattern transformed by elliptical mirror (f=28mm)

External Cavity pulling





M. Justen, K. Otani, M. Beck, D. Turčinkov, F. Castellano, U.U. Graf and J. Faist, KOSMA & ETH impedance matching to horn output by waveguide embedding

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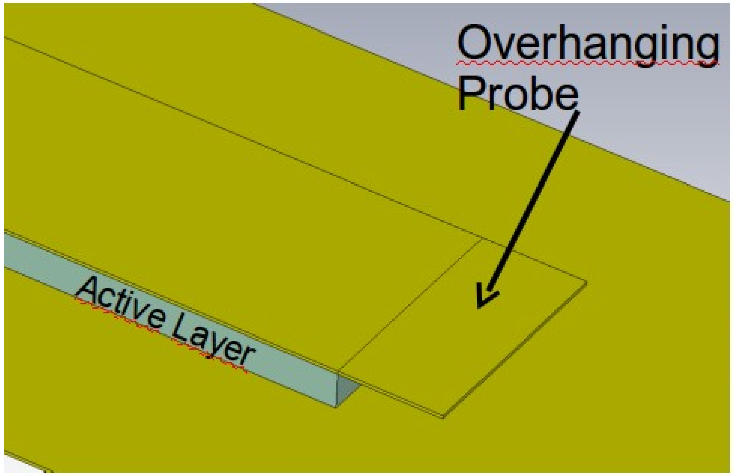
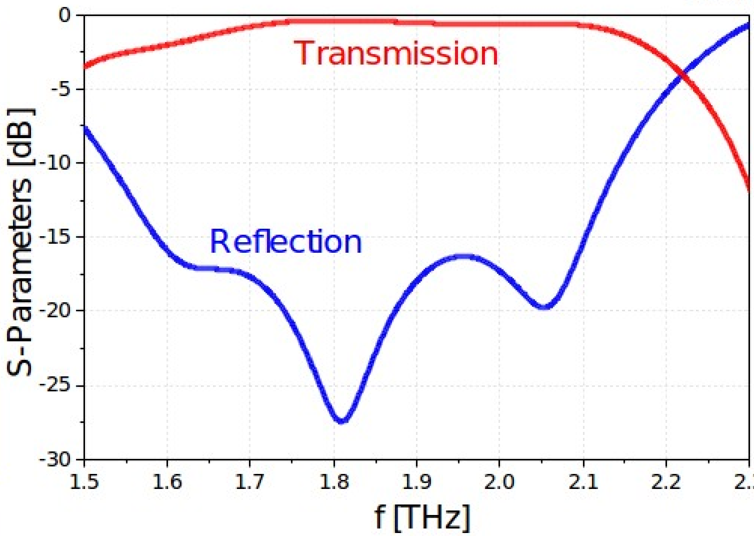
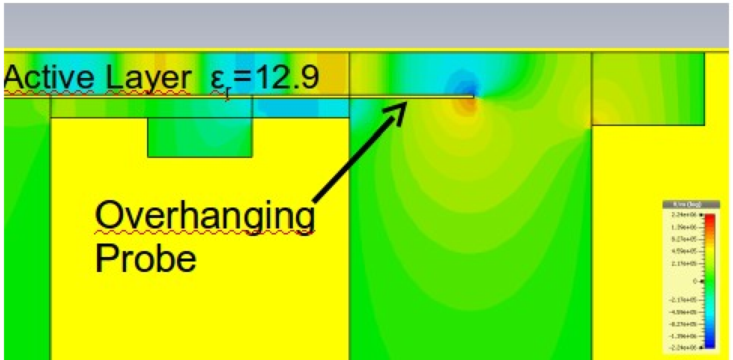
M. Justen, K. Otani, M. Beck, D. Turčinkov, F. Castellano, U.U. Graf and J. Faist, KOSMA & ETH

External Cavity - Could We Open the Internal Cavity ?







- Very low facet reflectivity!
- Difficult to fabricate! Details: See Thesis of D. Turčinková

perspectives for future heterodyne instrumentation

- **the following based on "SOFIA winter-school 2014"-discussion**
  - **extend GREAT to full coverage in 0.5 to 5 THz region**
    - **science goal: astrochemistry and physics of protostellar cores**
      - compact sources; no mapping, i.e. single pixel
      - instantaneous bandwidth as high as possible
  - **optionally also 28 µm H_2 (10.07 THz)**
    - evaluate comparison with EXES sensitivity on-the-sky
    - absorption against embedded cores
    - mapping of weak emission ?
  - **plan and build largest format possible heterodyne array for [CII] 150 µm and [OI] 63 µm**
    - science goal: physics of star forming ISM; Milky Way and nearby galaxies
      - extended sources; mapping on moderate to large spatial scales
      - a few GHz of instantaneous bandwidth is sufficient

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SIS mixers up to about 2 THz
-- broad IF-bandwith achievable
-- hight LO-power demands acceptable

HEB development towards higher IF bandwidth
-- MgB_2 material (Chalmers University, JPL)
shows perspetives for feasibility of
IF bandwidth up to 10 GHz

(Cunnane et al., IEEE Transactions on Appl.Superconductivity 25, 2300206, 2015)

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- **focalplane array systems**
  - **drive**
    - **opto-mechanical complexity**
    - **cryo power load**
    - **overal power consumption for signal processing**
  - **need for close-cycle coolers**
    - **large arrays: separate cooler for frontend (-4K) and for cold IF (>~9K)**
  - **backend**
    - **DFFTs have sufficient bandwith**
    - **compromising resolution/number of spectral channels against power consumption**
    - **rule of thumb (present): 50-100W per pixel**

      I.e. 5-10kW alone for the backends/signal processing
  - **these problems are no show-stoppers but need flexibility on observatory side**

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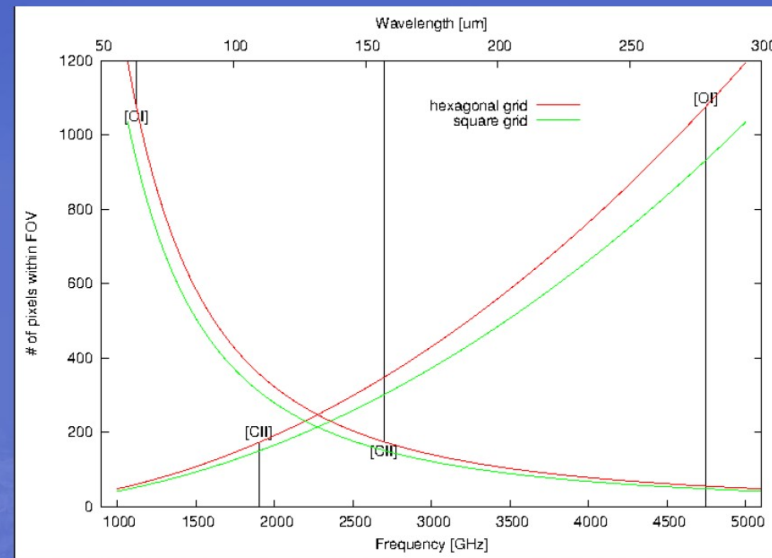
Field of View

- SOFIA's FOV is 8 arcmin ∅, 50 arcmin^2
- Beam FWHM is ~0.1" x λ / µm
- Minimum Beam Spacing in Heterodyne System is ~2.2 x FWHM

→ each beam covers 0.038"^{2} x (λ / µm)^2

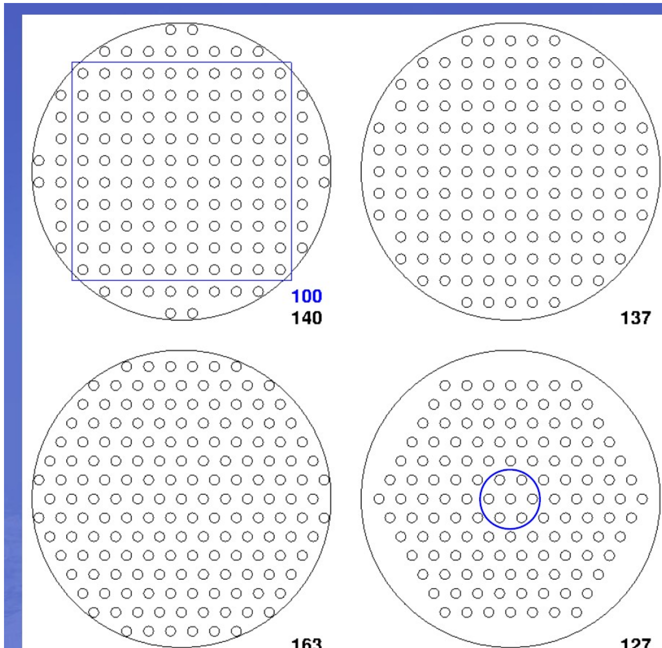
FOV limits at most important frequencies



- <172 pixels at [CII] (1900 GHz, 158 µm)
- <1075 pixels at [OI] (4745 GHz, 63 µm)

SOFIA Winter School – February 13, 2014 5

Pixel-# @1.9 THz



up to 163 pixels possible

technical reasons (LO-distribution, manufacturing) may limit to 100 or even 64 pixels

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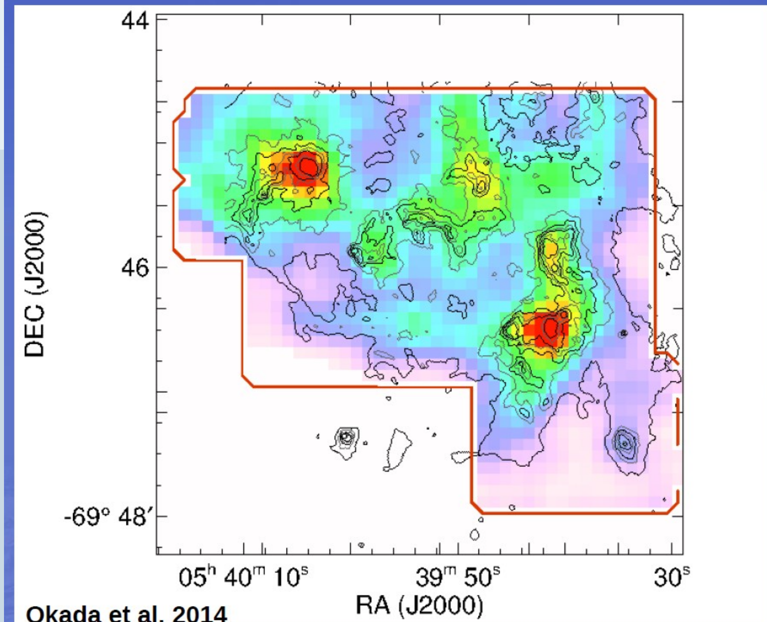
U.Graf,
SOFIA Winter School 2014,
“Large Heterodyne Arrays for SOFIA”

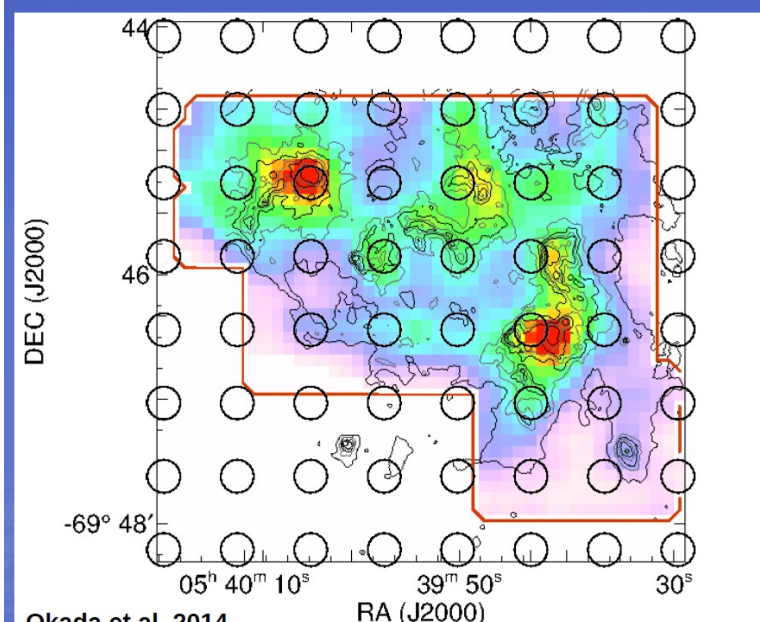
Size comparison: N159



3.25 h GREAT observing time
~15 sec / point

~$10 / flight-sec
→ > $100000

Size comparison: N159



3.25 h GREAT observing time
~15 sec / point

64 pixel array requires ~25 pointings for Nyquist sampling

⇒ 6 min plus overhead

< $5000

U.Graf,
SOFIA Winter School 2014,
"Large Heterodyne Arrays for SOFIA"

SFB 956
Cologne | Bonn

Future Heterodyne Instrumentation
(Ringberg Workshop on Spectroscopy with SOFIA)

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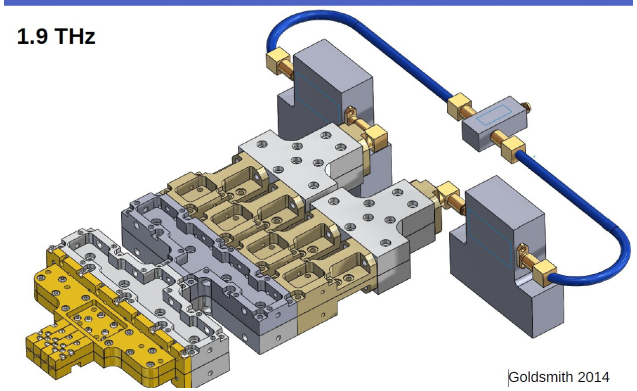
SOFIA Winter School 2014,
“Large Heterodyne Arrays for SOFIA”

JPL 4 pixel multiplier chain concept

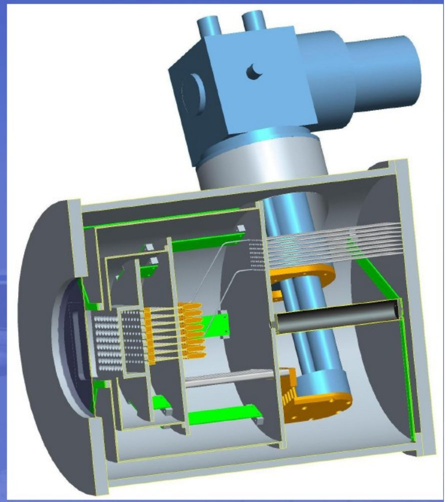
1.9 THz



Goldsmith 2014

Possible Frontend Design

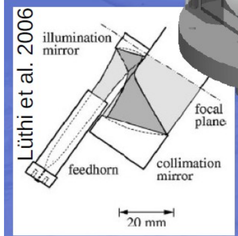
- (2x) 64 pixels
- individual mixer blocks
- waveguide LO coupling
- closed cycle refrigerator
- QCL LO conveniently mounted on 1st stage of refrigerator

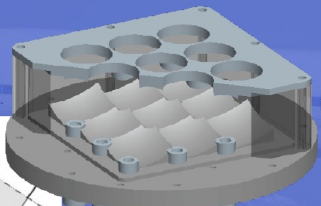


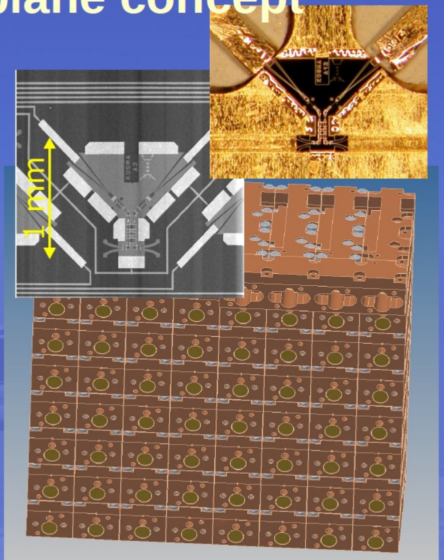
CHAI frontend concept

Possible focal plane concept

- Balanced HEB mixers
- Waveguide coupled LO
- CHARM fore-optics if needed





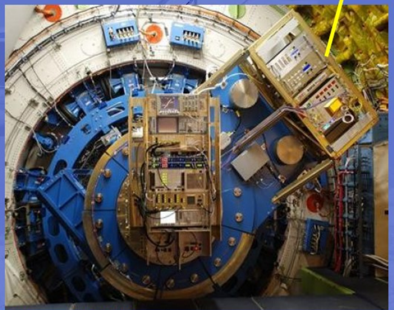


CHAI 8x8 focal plane unit

2 x 100 pixels...

- require 25 8-channel backends
  - 325 kg
  - 5 kW
- need approximately factor of 3 reduction in volume, mass and power consumption
- Alternative: backends not in CWR. Problem: cabling, RF over fiber?

CWR



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Mar 16th, 2015

observatory environment and programmatics

- **SOFIA's virtue is in the possibility to continuously upgrade instruments**
  - **needs pro-active approach by project to identify and provide best support for new instrumentation**
    - commonality, e.g. cryo-cooler, dewar design
    - power budget available on airplane
    - transparent and easy certification rules and procedures
  - **needs confidence by the community at large in SOFIA's mid-term perspectives**
    - full flight rate supported
    - transparent and coherent envolvement of community in SOFIA's advisory structure and reviews
    - mid-term commitments and stable budget

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Summary: future SOFIA heterodyne instrumentation

- extend GREAT to full coverage in 0.5 to 5 THz region
  - science goal: astrochemistry and physics of protostellar cores
    - moderate cost, step-by-step approach
    - will happen one way or the other
- optionally also 28 µm H_2 (10.07 THz)
  - evaluate comparison with EXES sensitivity on-the-sky
    - substantial investment in detectors and QCLs (new material) needed
    - might happen (science case & competition with EXES)
- plan and build largest format possible heterodyne array for [CII] 150 µm and [OI] 63 µm
  - science goal: physics of star forming ISM; Milky Way and nearby galaxies
    - major investment of personel resources and investment
    - will only get realized with positive mid-term perspective for SOFIA (past 2018 SSR)

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