Karlsruhe Institute of Technology

6. Sep 2017, 17:30-18:00 PM
2017 SJTU-KIT Collaborative
Research Workshop
"Particles and the Universe"

Terahertz techniques to explore the early universe, plasma acceleration and particle physics

Erik Bründermann

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Honorable Guest Professor of Shizuoka University (since 2009), Graduate School of Science and Technology, Department of Nanovision Science, Hamamatsu, Japan

www.ibpt.kit.edu/eb

Institute for Beam Physics and Technology (IBPT), Dept. Accelerator Research

49° 1′ N - 8° 24′ O

Dissecting the title:

Terahertz techniques

to explore the

early universe

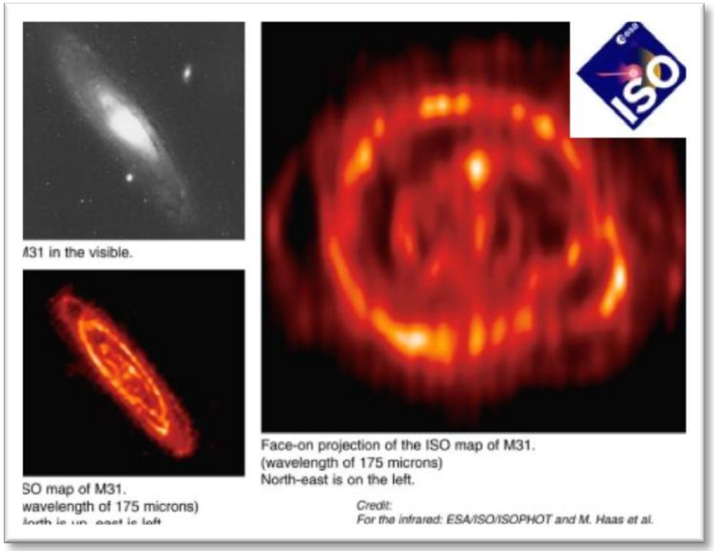
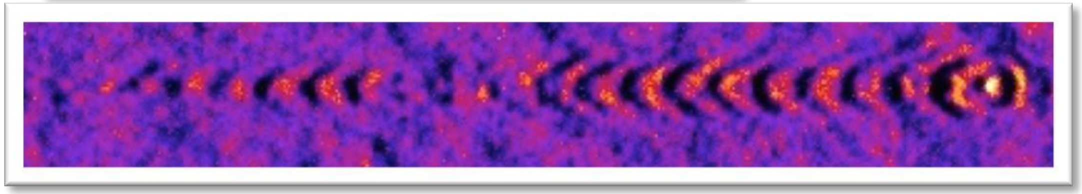


Image Source: ISO_reveals_Andromeda_s_invisible_rings

plasma acceleration

and

particle physics



R. Aßmann for the Helmholtz preparation team, The Accelerator Technology HElmholtz iNfrAstructure (ATHENA) Project, Image source: The ATHENA Project slide 13

Schwab, M B., Sävert, A., Jäckel, O., Polz, J., Schnell, M. et al., Few-cycle optical probe-pulse for investigation of relativistic laser-plasma interactions, *Appl. Phys. Lett.*, 103(19): 191118 (2013), DOI: 10.1063/1.4829489

"the universe in the lab"

Background …

www3.mpifr-bonn.mpg.de/div/effelsberg/40years/history.html accessed: 2013-07-01

www.mpifr-bonn.mpg.de/ accessed: 2013-07-01

DLR

www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10252/ accessed: 2013-07-01

CENTER FOR PARTICLE ASTROPHYSICS
NSF SCIENCE & TECHNOLOGY CENTER

1995,1997-1999 E.E. Haller, B. Sadoulet

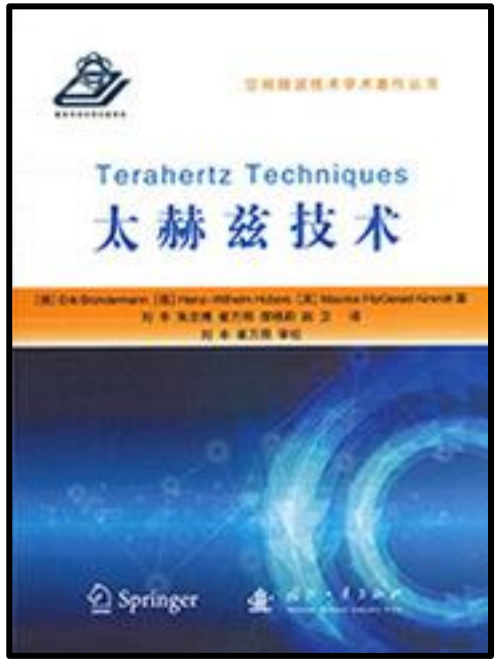
today: Berkeley Cosmology Group (BCG)

BERKELEY LAB

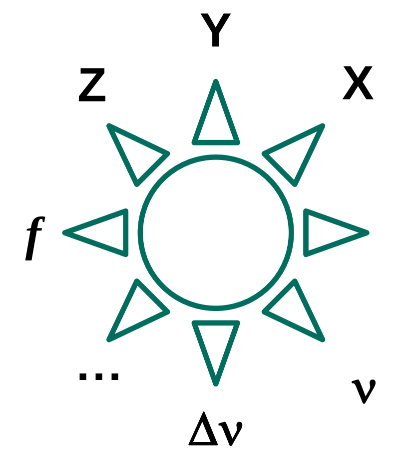
Supported by

Alexander von Humboldt Stiftung/Foundation

TeraHertz Techniques and translation



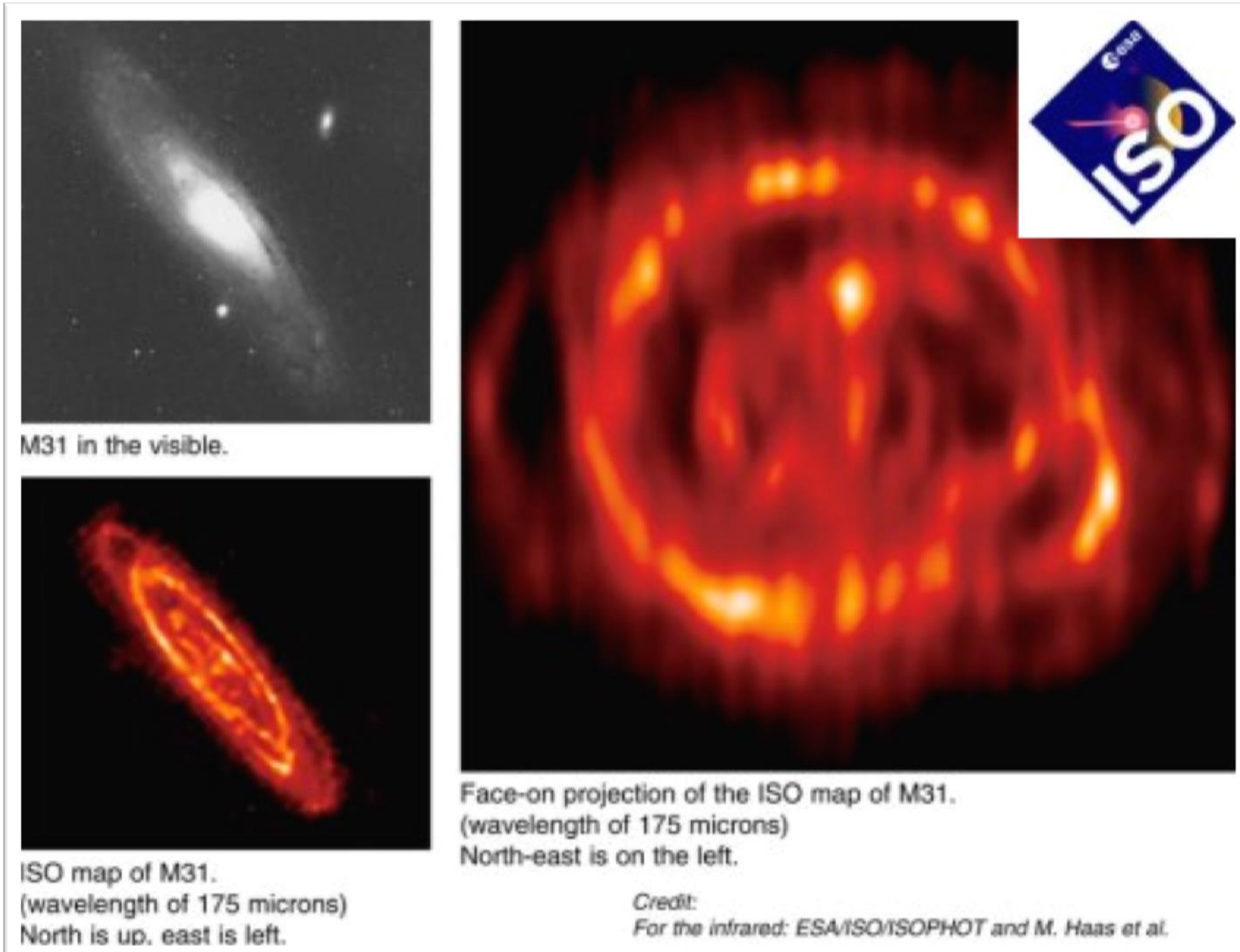
布伦德曼, **胡**贝尔, **金米特**
太赫兹技术
Translation published Feb. 2016
translated by Feng LIU (刘丰) *et al.*
RMB 64.10 (amazon.cn, 5 Sep 17)



E. Bründermann, H.-W. Hübers, M. F. Kimmitt, **Terahertz Techniques**
in Series: Springer Series in Optical Sciences, Vol. 151, Springer-Verlag (2012)
Link: http://www.springer.com/gb/book/9783642025914

M.F. Kimmitt, Far-infrared Techniques, Pion Ltd. (1970)
THz Pioneer M.F. Kimmitt, Co-inventor of world's first THz laser in 1960s

THz astronomy – starforming regions
Andromeda‘s invisible rings: 175 µm (1.7 THz)



M31 in the visible.

ISO map of M31.
(wavelength of 175 microns)
North is up, east is left.

Face-on projection of the ISO map of M31.
(wavelength of 175 microns)
North-east is on the left.

Credit:
For the infrared: ESA/ISO/ISOPHOT and M. Haas et al.

01/01/1998
12:00 am

http://www.esa.int/spaceinimages/Images/1998/01/ISO_reveals_Andromeda_s_invisible_rings

Andromeda galaxy M 31

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VIS

KPNO (λ/nm):
B (445), V (551), R (658)

IR

11000 snapshots, 24 µm
25 Aug 2004, Nasa Spitzer

far-IR

IR 24 µm, far-IR 70 µm, 160 µm
12.5 THz, 4,3 THz, 1.9 THz

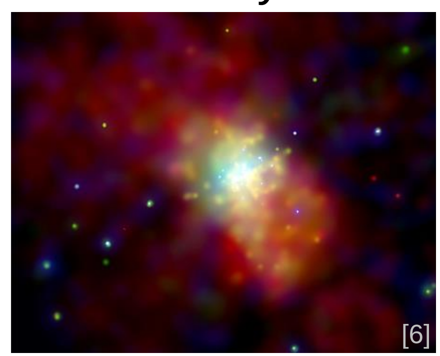
Starburst galaxy M 82

VIS

KPNO (λ/nm):
B (440), V (555), R (700)

IR

X-ray



Courtesy: NASA/JPL-Caltech and hubblesite.org NASA/CXC/JHU/D.Strickland

VIS + IR + X-ray

NASA, ESA, CXC, and JPL-Caltech

accessed 04. Sep 2017: [1] http://coolcosmos.ipac.caltech.edu/images/133, [2] 134, [3] 135, [4] 136, [5] 137,
[6,7] http://hubblesite.org/image/1878/news/59-irregular-galaxies

Starburst galaxy M 82

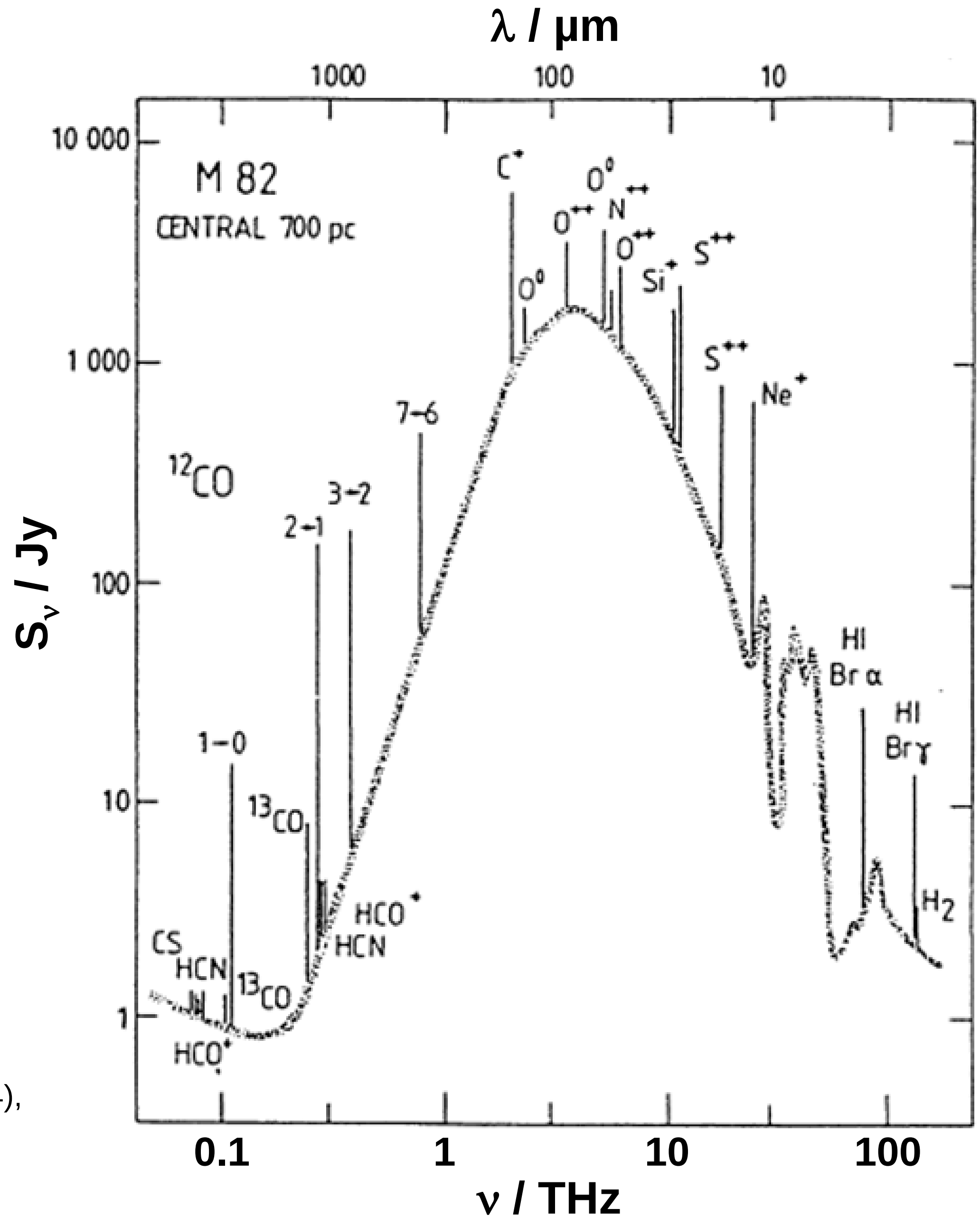
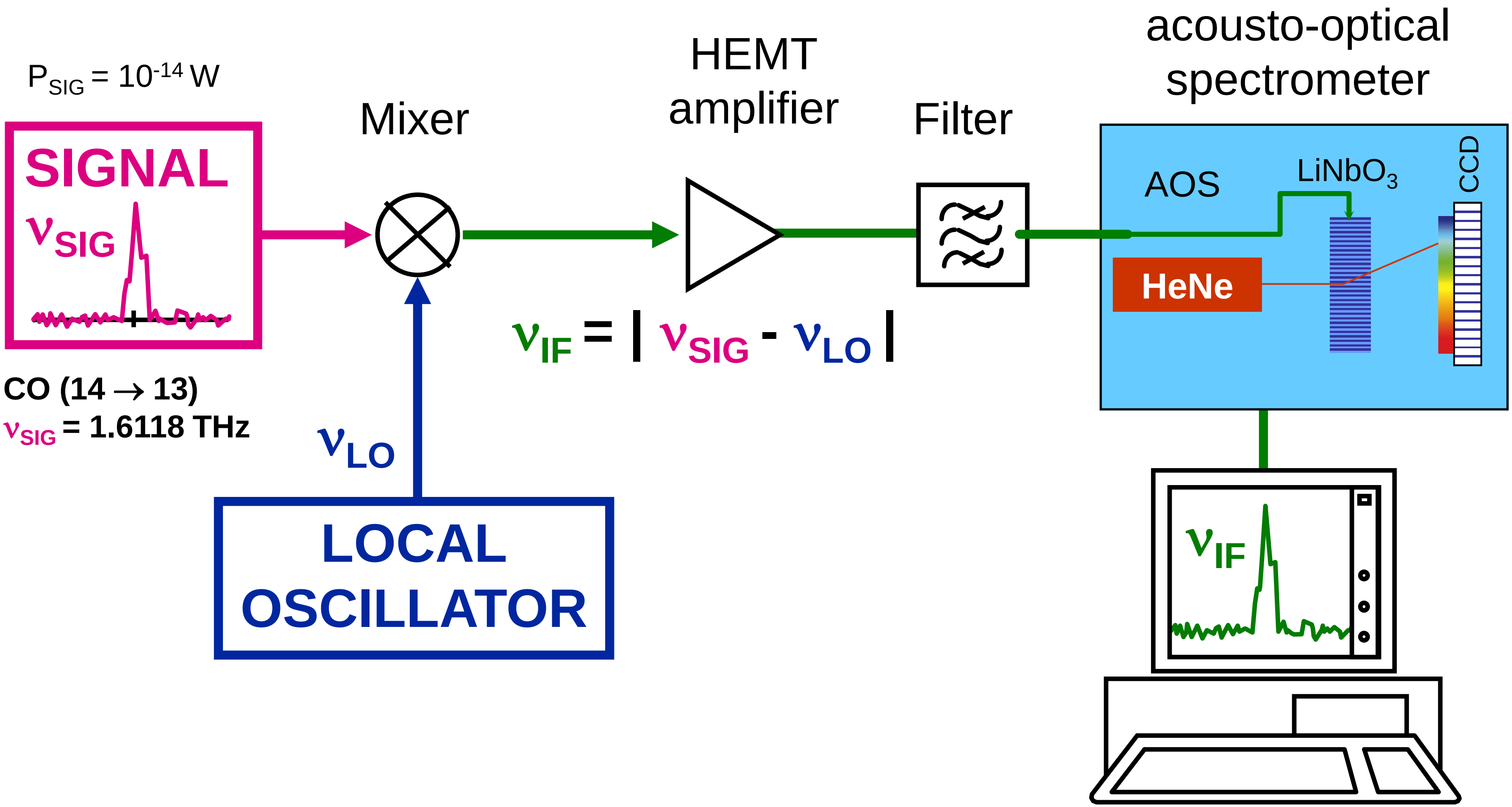


Fig. 2
(compiled by Reinhard Genzel)
in A.F.M. Moorwood,
Starburst Galaxies,
Space Science Reviews **77**(3-4),
pp. 303-366, 1996
DOI: 10.1007/BF00226226

Molecular Radio = heterodyne spectroscopy

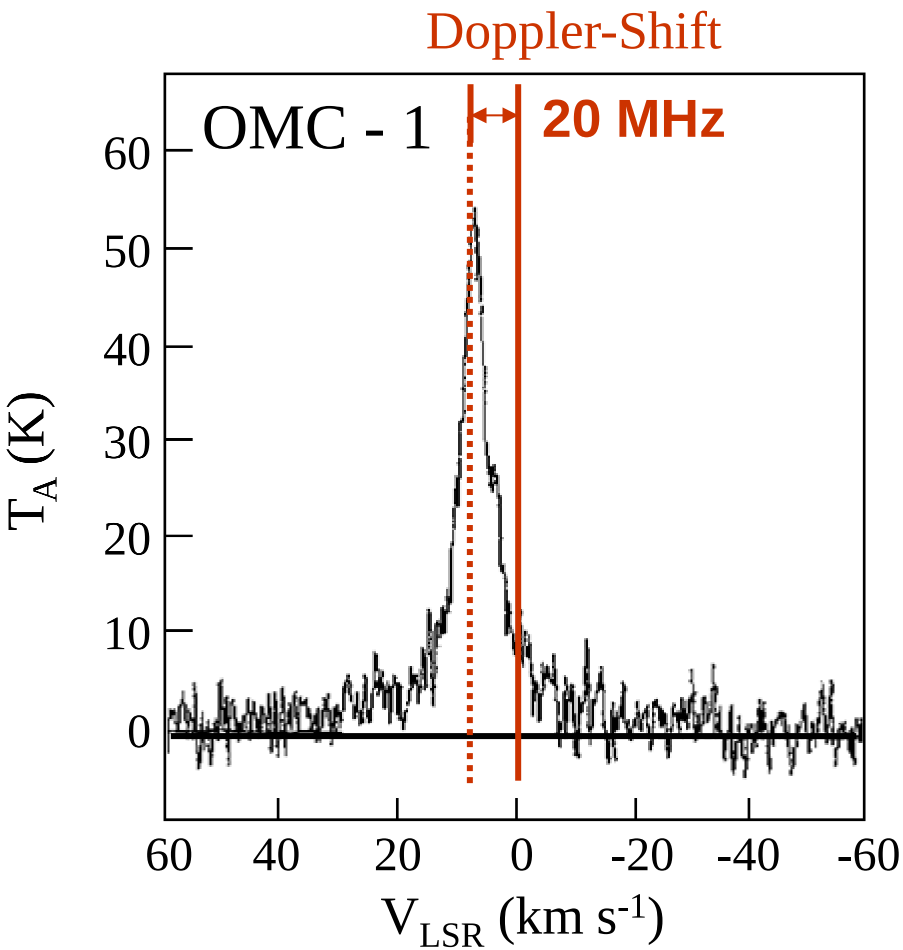


MPI for Radioastronomy, Bonn

E. Bründermann, H.P. Röser, A.V.Muravjov, S.G. Pavlov, V.N. Shastin, Infrared Phys. Technol. 36(1), 59-69 (1995). DOI:10.1016/1350-4495(94)00054-O

AOS 2048 DETECTORS
$\Delta\nu_{RES}$= 0.2 km/s, $\Delta\nu$= 1 MHz
$\Delta\nu_{BW}$ = 1400 MHz := 260 km/s

CO (J=7 → 6), ν = 0.806652 THz in Orion Molecular Cloud 1



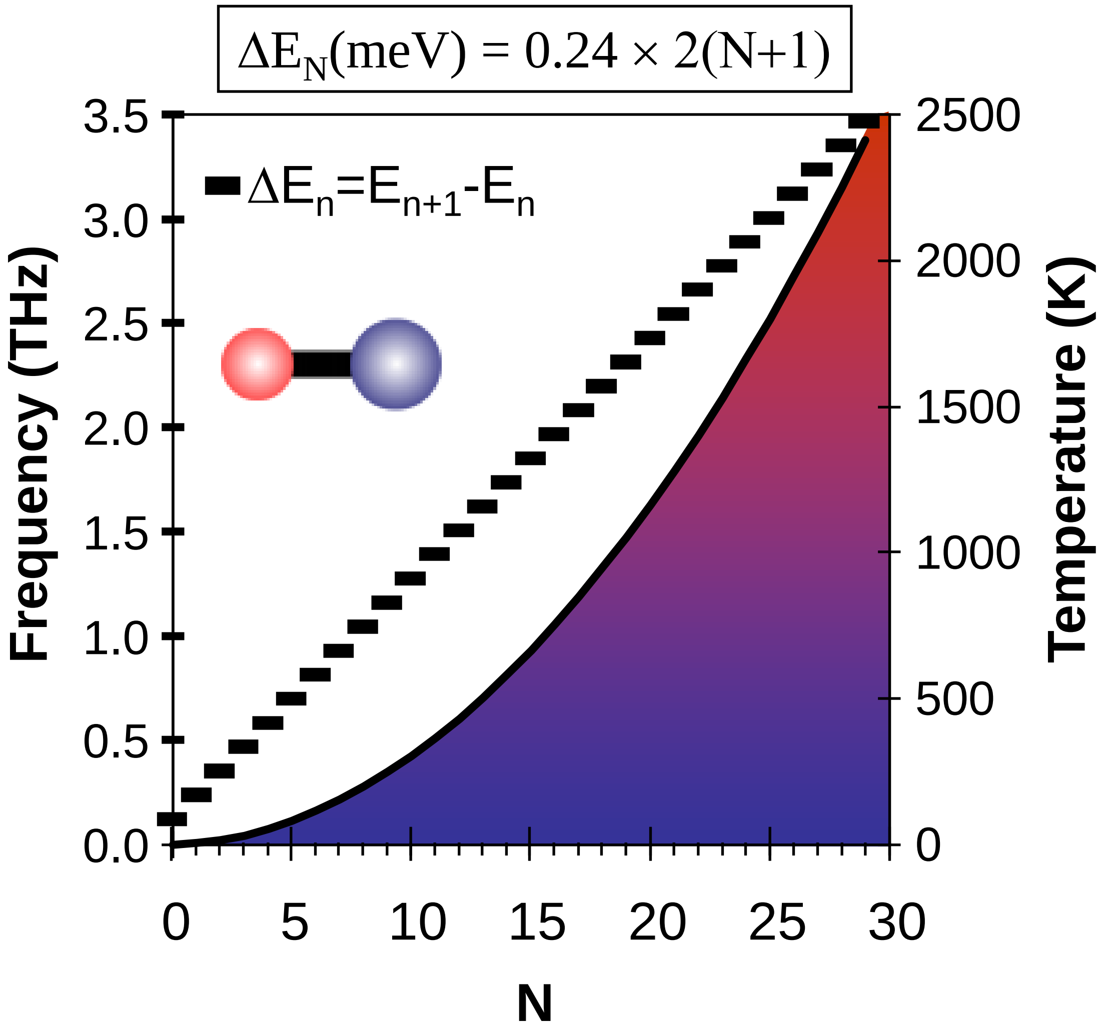
$$\frac{\Delta v}{c} = \frac{\Delta \nu}{\nu}$$

Linewidth ⇒ p
Frequency shift ⇒ v
Population ⇒ T

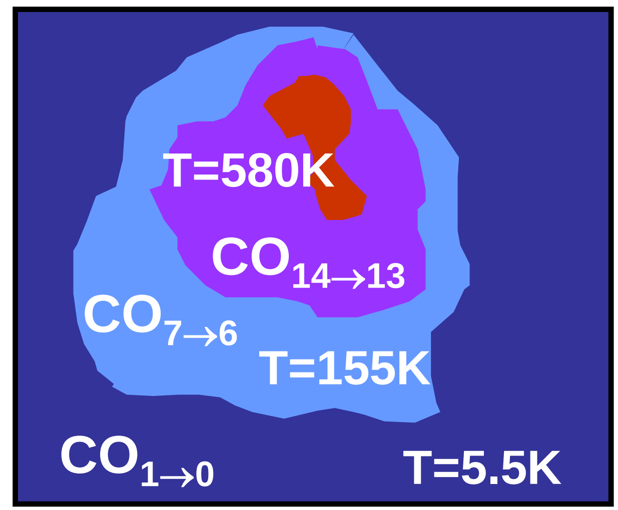
Kuiper Airborne Observatory (KAO)

Schmid-Burgk, J., Densing, R., Krügel, E., Nett, H., Röser, H. P., Schäfer, F., Schwaab, G., van der Wal, P., and Wattenbach, R., Extended CO (J = 7-6) emission from Orion molecular cloud 1 - Hot ambient gas, two hot-outflow sources, Astron. Astrophys. 215, 150-164 (1989), http://articles.adsabs.harvard.edu//full/1989A%26A...215..150S/0000150.000.html

CO (J+1) → J ⇒ Temperature

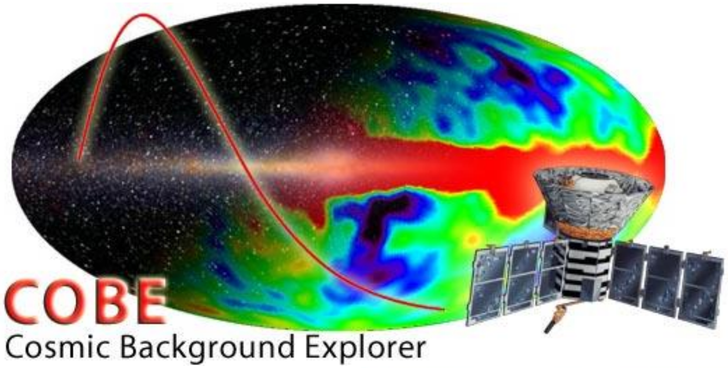


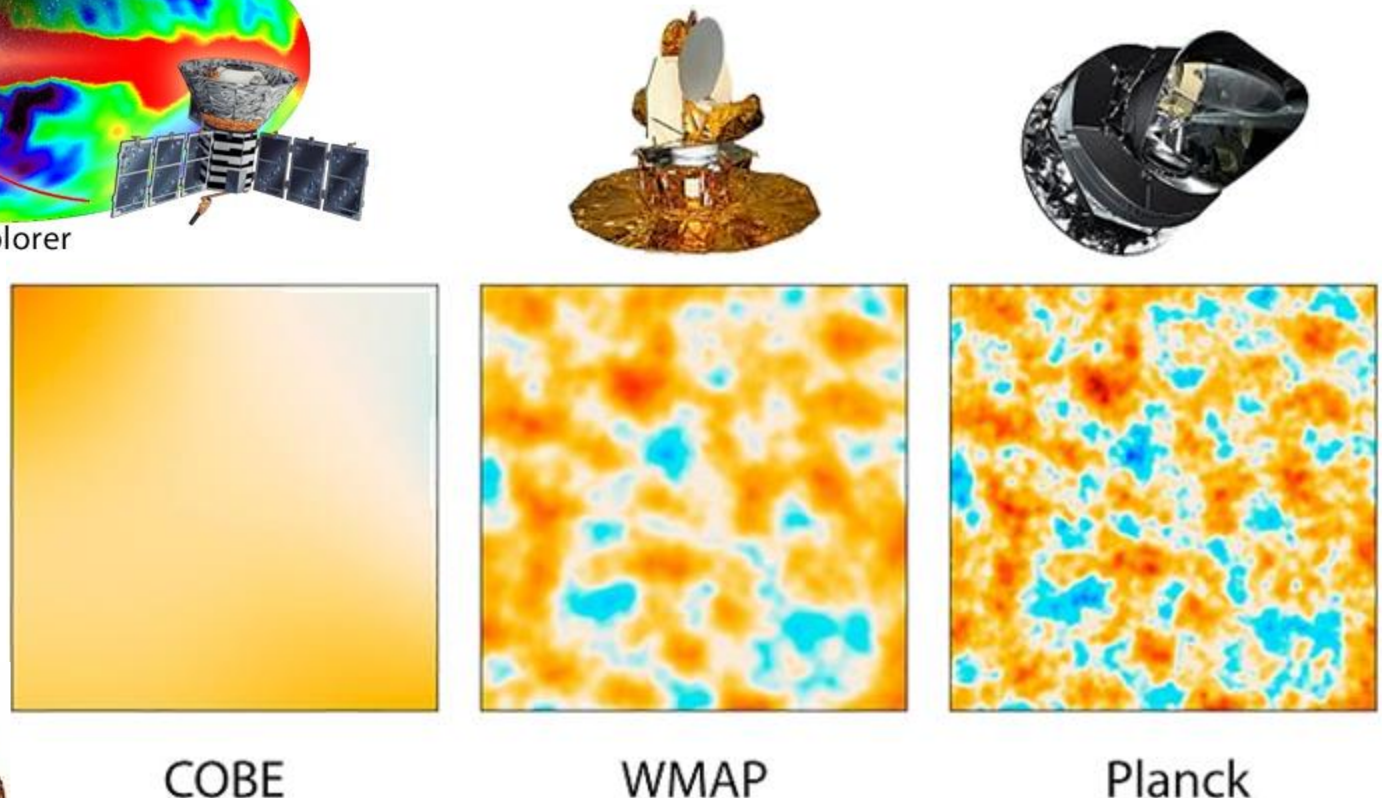
Hot Spot in space



^{12}CO (1→0) (2600 µm)
^{12}CO (14→13) (186 µm)

CMB comparison: COBE, WMAP and Planck cosmic microwave background radiation





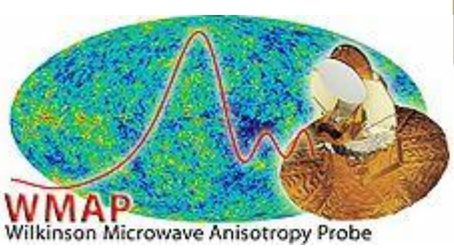
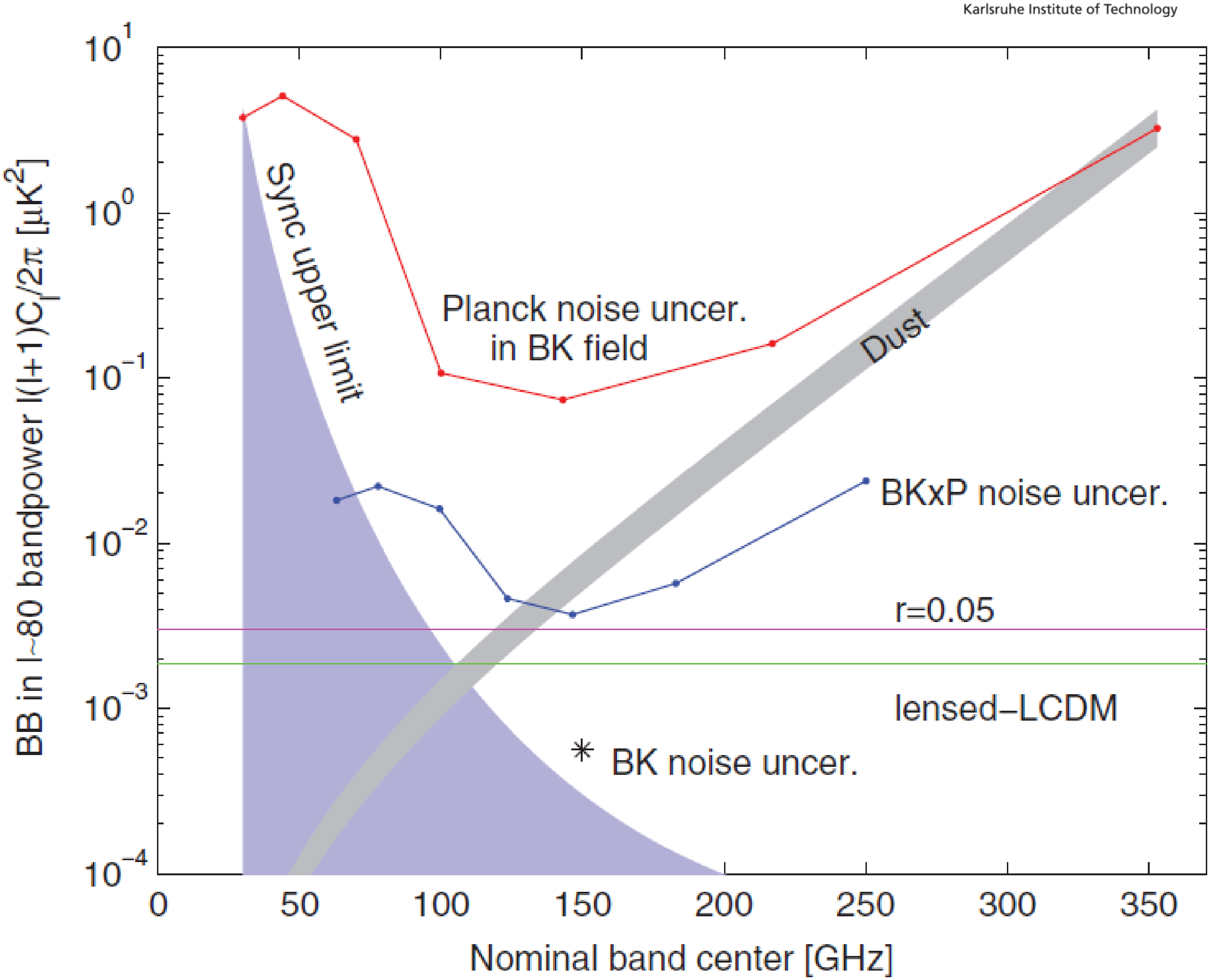


Image: en.wikipedia.org/wiki/File:PIA16874-CobeWmapPlanckComparison-20130321.jpg, accessed: 2013-07-01

Joint Analysis of BICEP2/Keck Array and Planck Data

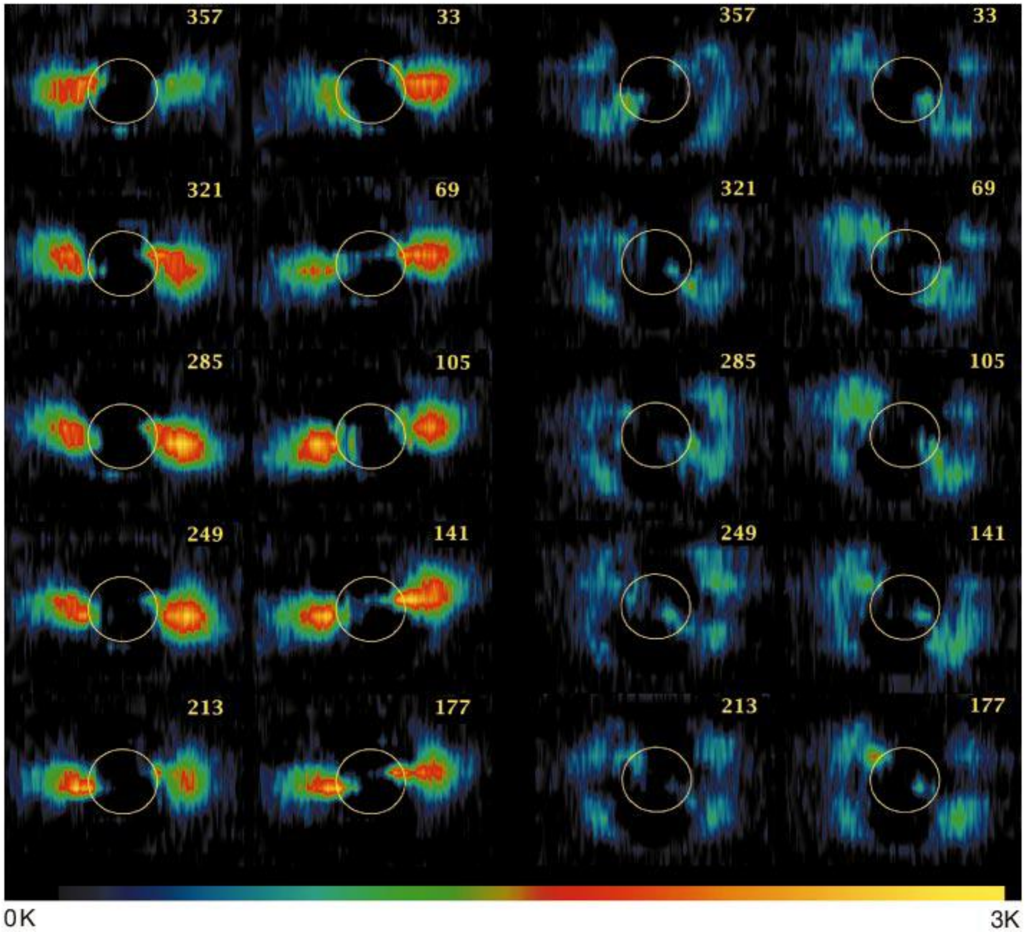
Planck (GHz)

30
44
70
100
143
217
353



P. A. R. Ade et al. (BICEP2/Keck and Planck Collaborations)
Phys. Rev. Lett. 114, 101301 (2015), DOI: 10.1103/PhysRevLett.114.101301

Distribution of ultra-relativistic electrons in Jupiter's inner radiation belts

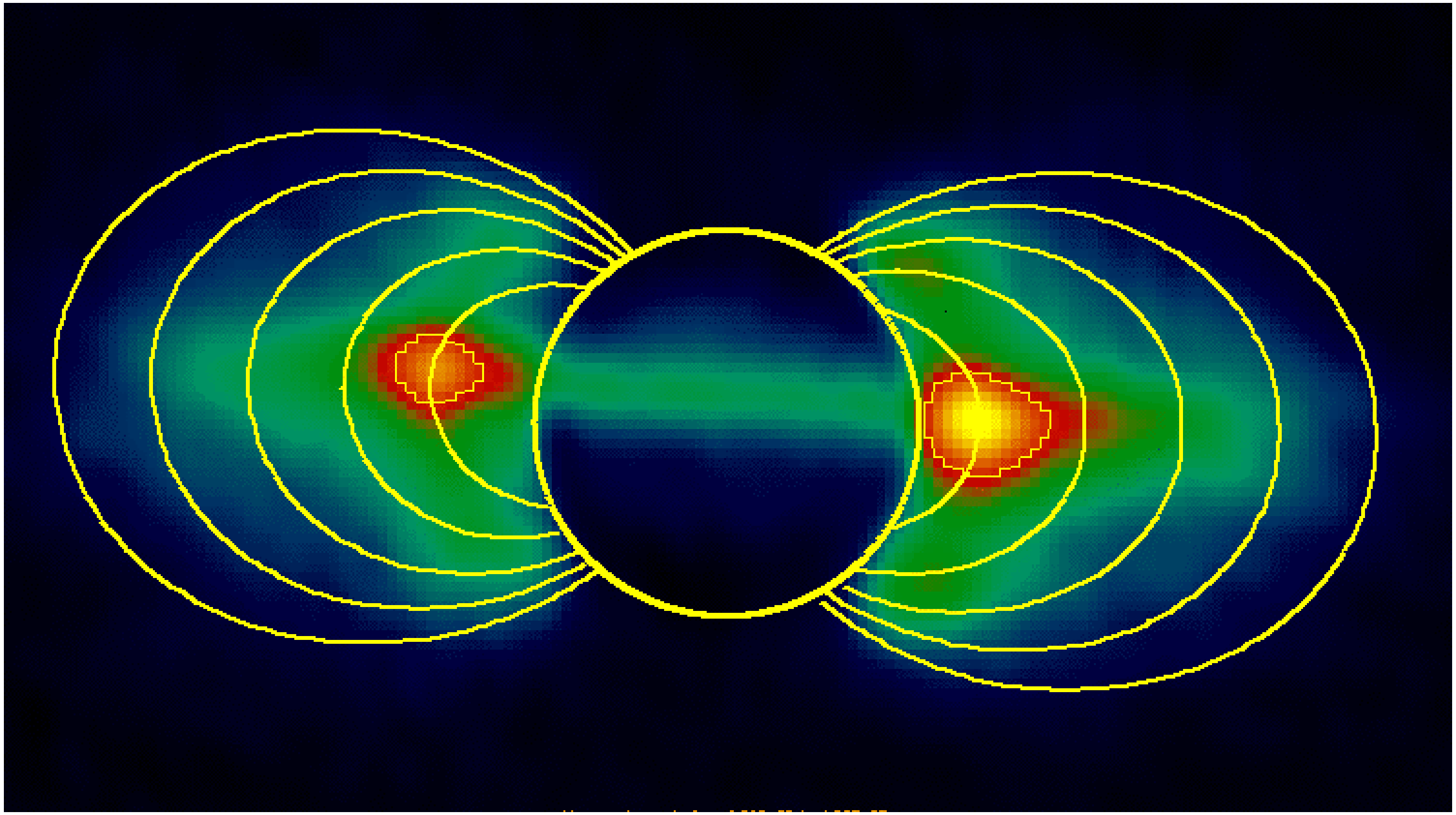


Synchrotron radiation
(50 MeV)
measured by
Cassini spacecraft

Energy gain due to
plasma waves
in Jupiter's
magnetic field

Ultra-relativistic electrons in Jupiter's radiation belts, S. J. Bolton, M. Janssen, R. Thorne, S. Levin, M. Klein, S. Gulkis, T. Bastian, R. Sault, C. Elachi, M. Hofstadter, A. Bunker, G. Dulk, E. Gudim, G. Hamilton, W. T. K. Johnson, Y. Leblanc, O. Liepack, R. McLeod, J. Roller, L. Roth and R. West, Nature **415**, 987-991 (28 February 2002), doi:10.1038/415987a

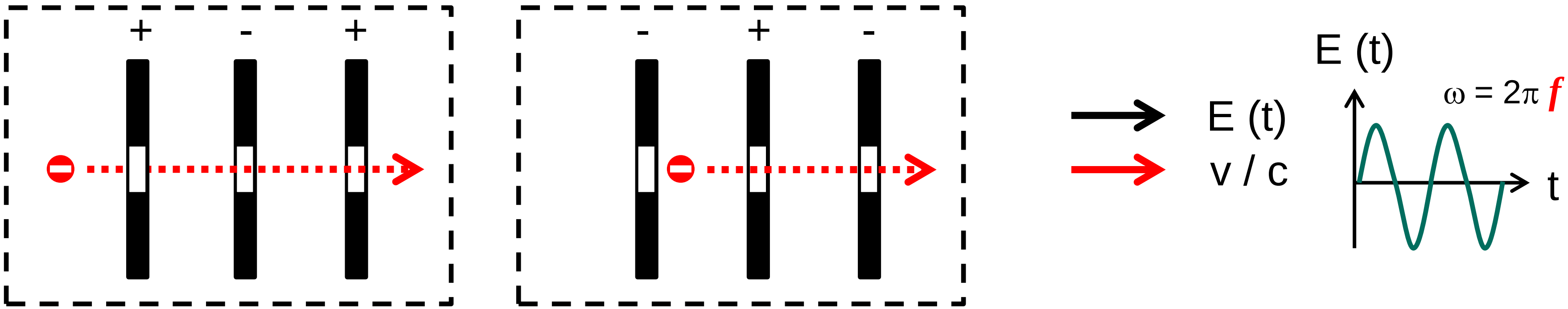
Distribution of ultra-relativistic electrons in Jupiter's inner radiation belts



Animation of Jupiter's Synchrotron Radiation Torus. Credit: NASA/JPL - Caltech

Ultra-relativistic electrons in Jupiter's radiation belts, S. J. Bolton, M. Janssen, R. Thorne, S. Levin, M. Klein, S. Gulkis, T. Bastian, R. Sault, C. Elachi, M. Hofstadter, A. Bunker, G. Dulk, E. Gudim, G. Hamilton, W. T. K. Johnson, Y. Leblanc, O. Liepack, R. McLeod, J. Roller, L. Roth and R. West, Nature **415**, 987-991 (28 February 2002), doi:10.1038/415987a

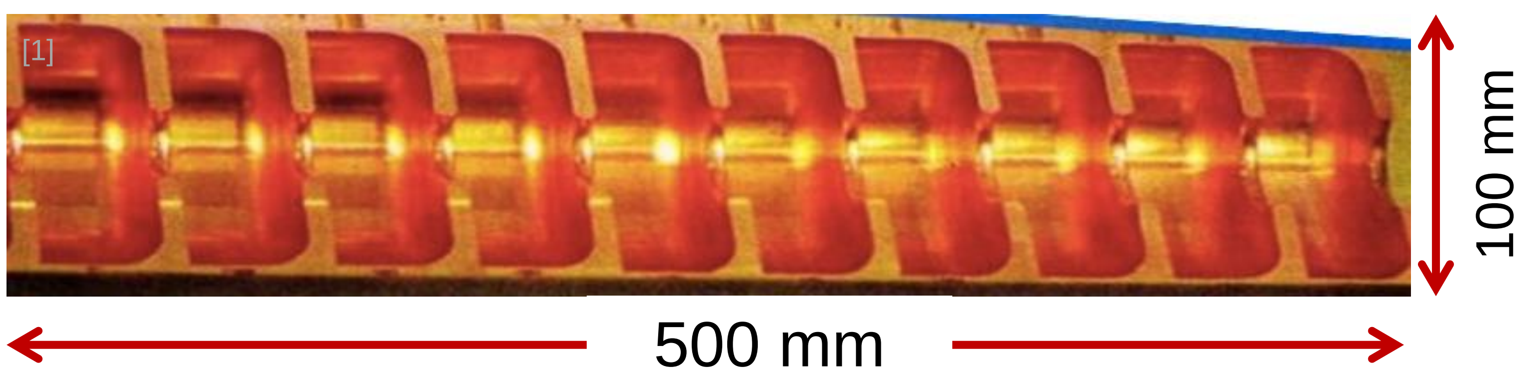
Acceleration



Conventional Technology

(S band, linear accelerator, Cu, RF/µwave)

20 MV/m



[1] Image Source: R. Aßmann for the Helmholtz preparation team, The Accelerator Technology HElmholtz iNfrAstructure (ATHENA) Project, Image source: The ATHENA Project slide 13

Laser Wake-Field Acceleration

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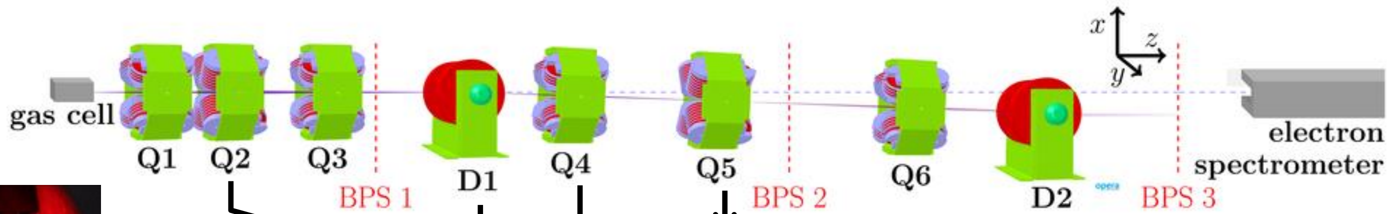
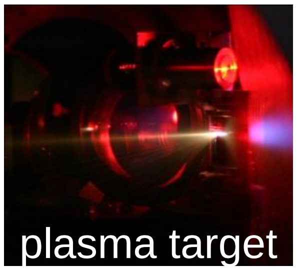
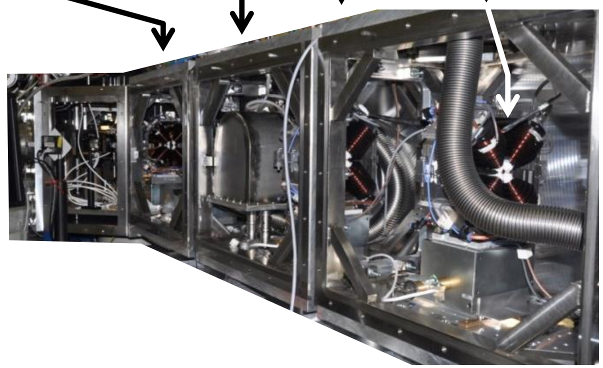


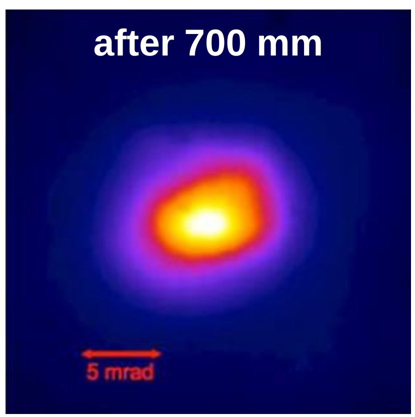


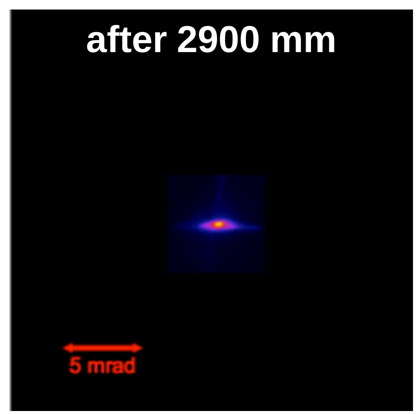
laser shock-wave
40-200 TW,
25-40 fs, 1-2 J



KIT's experimental setup at LWFA at Jena

electron transport line





HI Jena
Helmholtz Institute Jena

Karlsruhe Institute of Technology

Beam transport system from a laser wakefield accelerator to a transverse gradient undulator, Proc. IPAC2014, THOBA03, 2014 Ch. Widmann, V Afonso Rodriguez, N. Braun, M. Nicolai, A. Papash, M Reuter, R. Rossmanith, A. Sävert, W. Werner, M. C. Kaluza, A. Bernhard, and A.-S. Mueller, http://accelconf.web.cern.ch/accelconf/IPAC2014/papers/thoba03.pdf

Shrink accelerators by 1000! (km become m)

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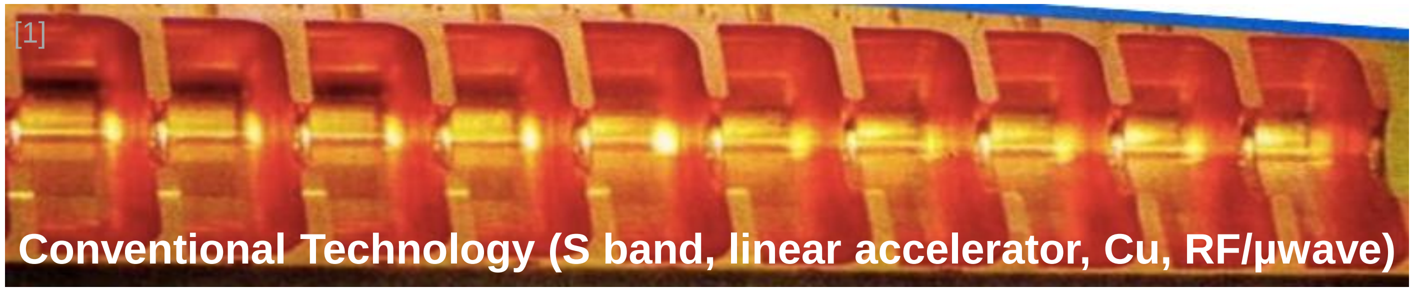
20 MV/m

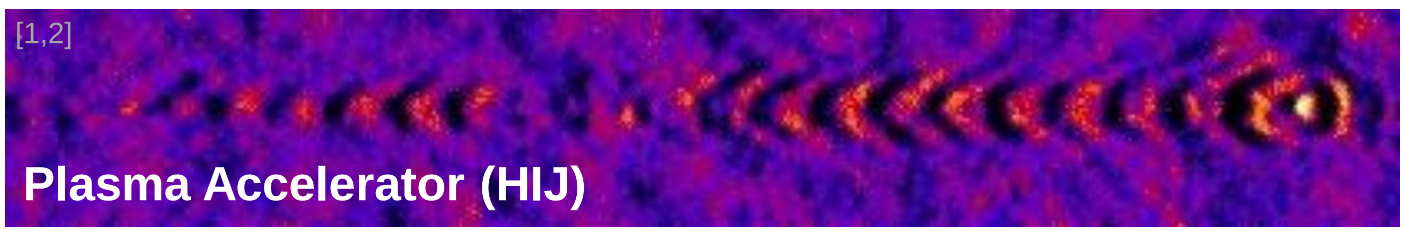
Factor >1000

100,000 MV/m



100 mm

500 mm



0.04 mm

Compact: 0.25 mm

[1] Image Source: R. Aßmann for the Helmholtz preparation team, The Accelerator Technology HElmholtz iNfrAstructure (ATHENA) Project, Image source: The ATHENA Project slide 13
[2] Schwab, M B., Sävert, A., Jäckel, O., Polz, J., Schnell, M. et al., Few-cycle optical probe-pulse for investigation of relativistic laser-plasma interactions, *Appl. Phys. Lett.*, 103(19): 191118 (2013), DOI: 10.1063/1.4829489

IBPT's electron & photon diagnostics

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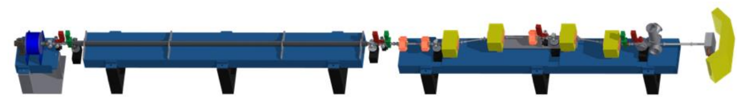
- synchrotron radiation from **free electrons** is broad band from 0 Hz to X-rays for GeV beams, iCBS (γ)
- short pulses contain broad bands of frequencies
  - 100 fs ~ bandwidth 0 Hz to >3 THz
  - 1 fs ~ bandwidth 0 Hz to >300 THz
- **plasma** emits broadband radiation
- mandates:
  - broadband, fast, and array technology
  - electron beam, photon and plasma diagnostics



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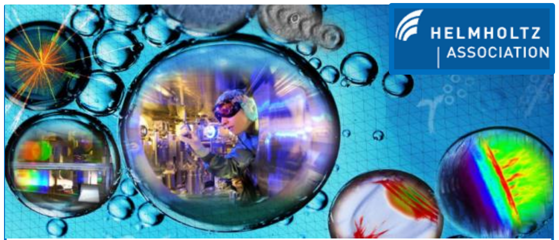
Federal Ministry of Education and Research

NeoDyn 05K16VKA
Speaker: A.-S. Müller
KIT (IMS, IEKP, LAS)
TU Dortmund, TU Dresden
(3 years, 2016-2019)



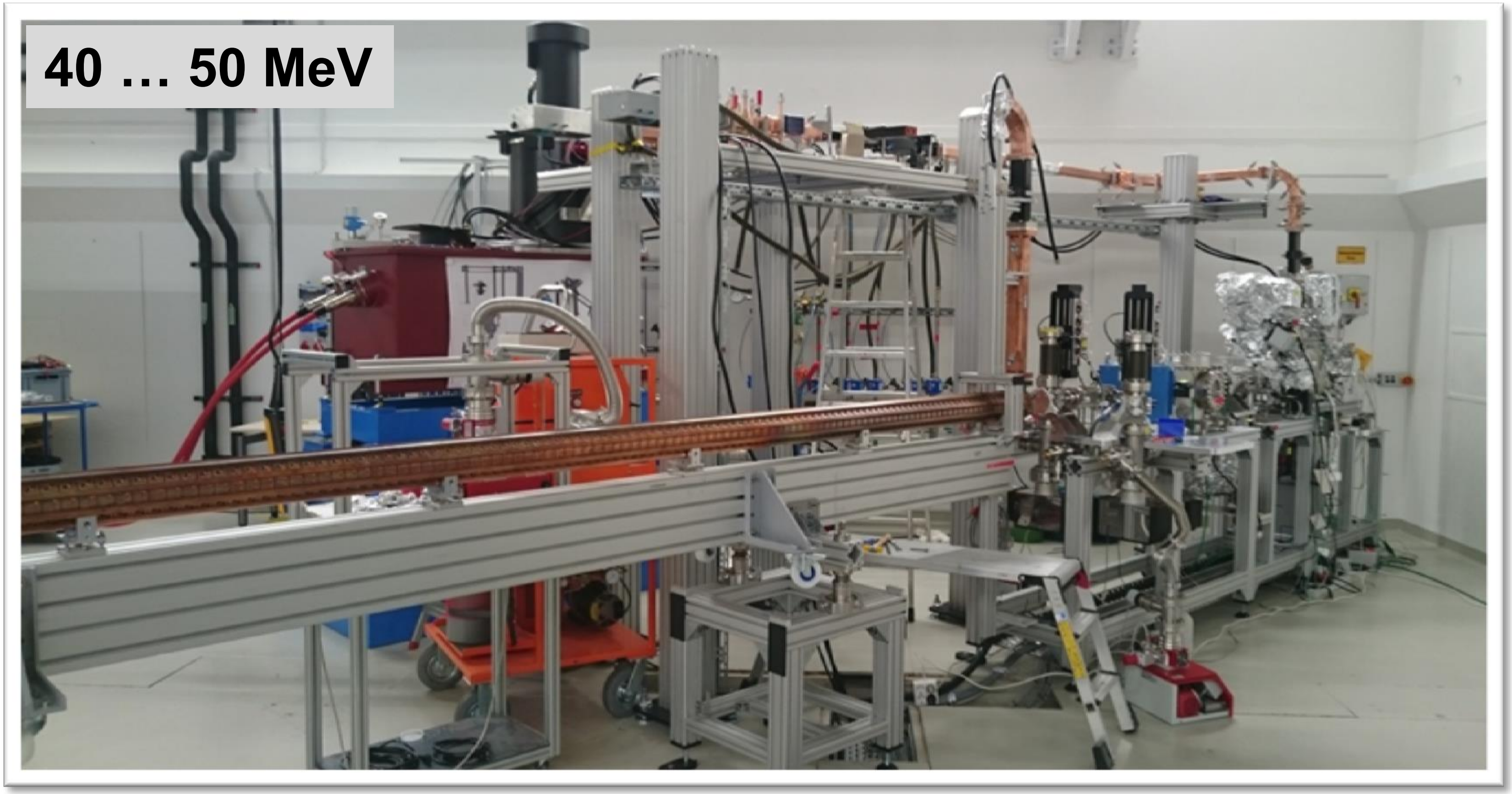
Plasma accelerators (IVF)
Probing the femto-scale dynamics of relativistic plasmas
HZDR, DESY/UHH, HI-Jena/GSI, KIT
(3 years, 2017-2019)

MT ARD

MT-ARD sub-topic 3
ps and fs electron and photon beams
DESY, FZJ, HZB, HZDR, KIT
(5 years, 2015-2019)

FLUTE

Institut für Beschleunigerphysik und Technologie



FLUTE tour: Friday, 8 Sep 2017, 9:30-10:00

Accelerator and terahertz light - FLUTE

VIDEO

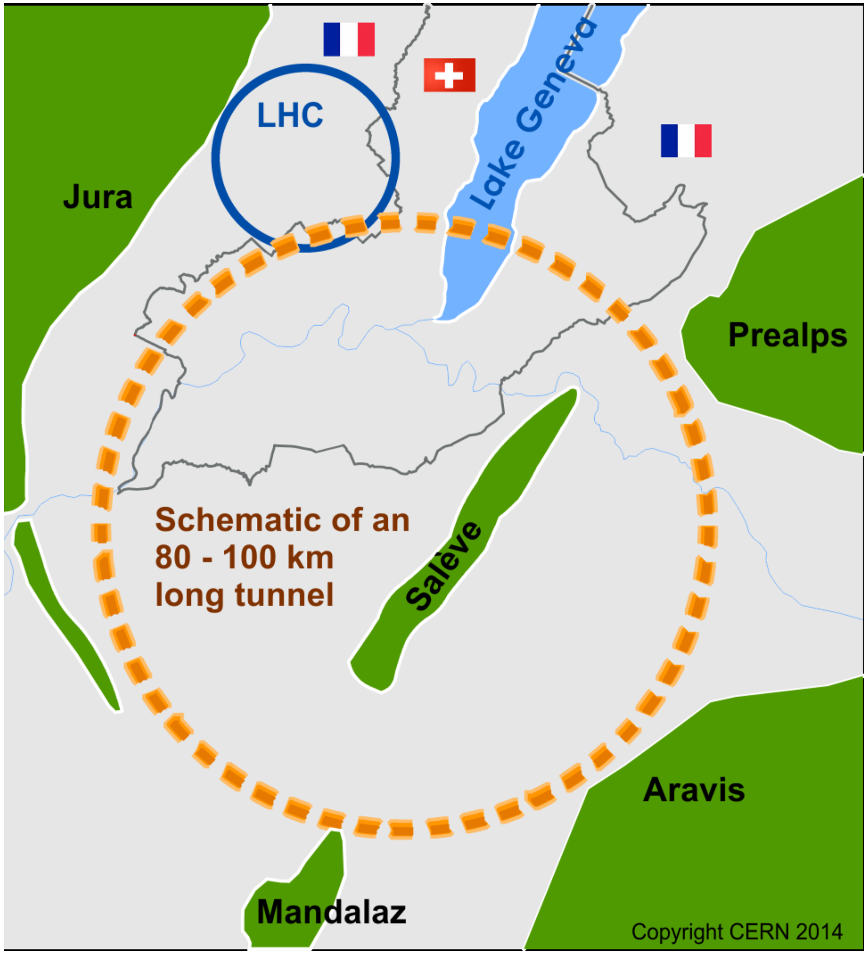
https://www.sek.kit.edu/downloads/PI094_Flute.mp4

Karlsruhe Research Accelerator (KARA)
110-m electron storage ring

e- source: **90 keV**, racetrack microtron: **0.09 … 53 MeV**
booster synchrotron: **50 … 500 MeV**, e- storage ring: **0.5 … 2.5 GeV**

Future Circular Collider (FCC) Study

https://fcc.web.cern.ch/



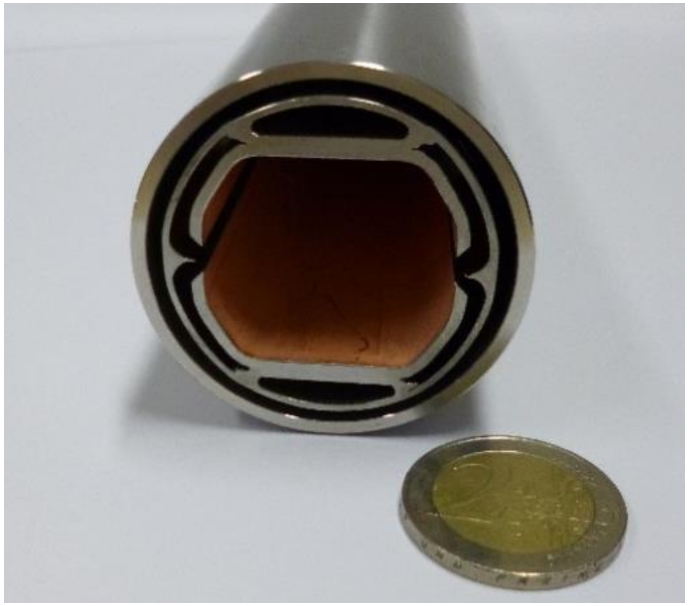
International FCC collaboration (host lab: CERN) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements (16 T)
  → 100 TeV pp in 100 km
- ***e^+e^-* collider (*FCC-ee*)**
  as potential first step
- ***p-e* (*FCC-he*) option**
  integration 1 IP, FCC-hh & ERL
- HE-LHC with FCC-hh technology

From: R. Kersevan, CERN-TE-VSC, The Vacuum System of the Future Circular Collider: Challenges and Innovations
KIT, Karlsruhe, Workshop: Beam Dynamics meets Vacuum, Collimations, and Surfaces
https://indico.gsi.de/event/5393/session/7/contribution/7, slide 2

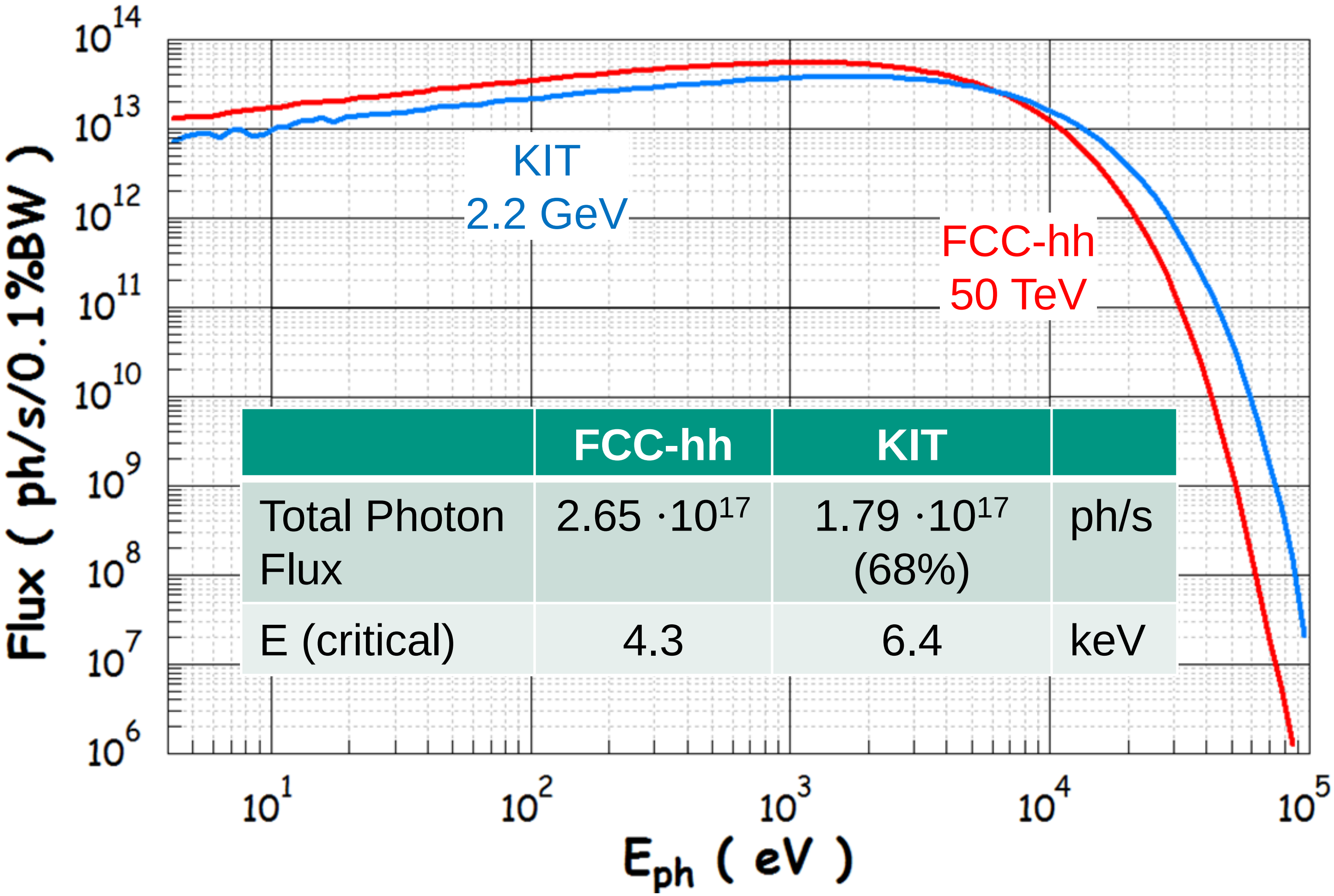
FCC H2020 Project: EuroCirCol

https://fcc.web.cern.ch/eurocircol



From: R. Kersevan, CERN-TE-VSC, The beam pipe for FCC pp: design and expected results from tests at ANKA, KIT, Karlsruhe, Workshop: Beam Dynamics meets Vacuum, Collimations, and Surfaces https://indico.gsi.de/event/5393/session/7/contribution/9, slide 22

Task 4.6: Measurements on cryogenic beam vacuum system prototype



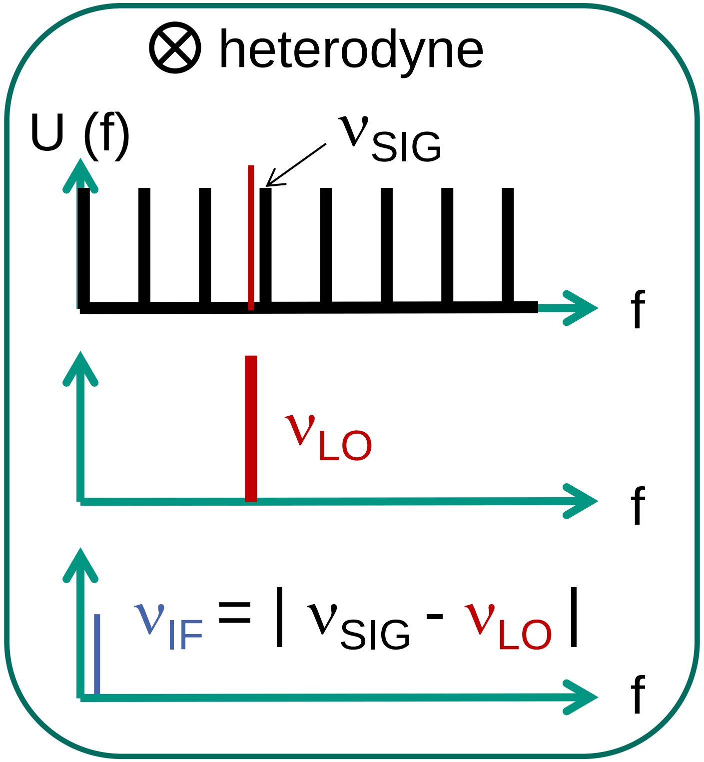
	FCC-hh	KIT	
Total Photon Flux	$2.65 \cdot 10^{17}$	$1.79 \cdot 10^{17}$ (68%)	ph/s
E (critical)	4.3	6.4	keV

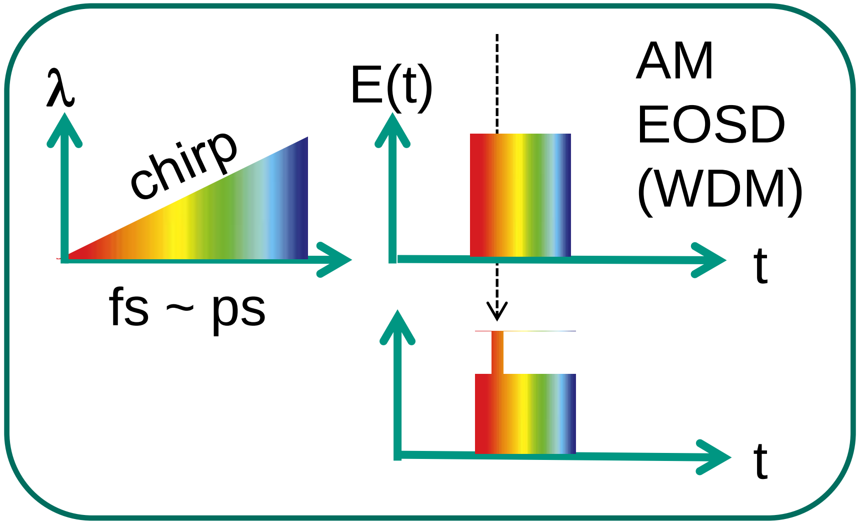
VIDEO

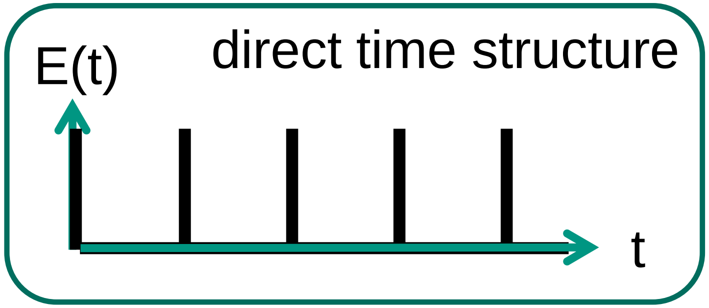
Adapted from: R. Kersevan, CERN-TE-VSC, KIT, Karlsruhe, Workshop: Beam Dynamics meets Vacuum, Collimations, and Surfaces
The Vacuum System of the Future Circular Collider: Challenges and Innovations, https://indico.gsi.de/event/5393/session/7/contribution/7,
The beam pipe for FCC pp: design and expected results from tests at ANKA, https://indico.gsi.de/event/5393/session/7/contribution/9, slides: 2, 4
VIDEO: https://indico.cern.ch/event/556692/contributions/2487658/attachments/1468086/2270751/FCC_Beam_Screen_Test_Line_Installation_at_ANKA_Short.mp4

How to detect a THz photon / wave?

Back-End Detection	Method
GHz	down-conversion, mixing, non-linear, heterodyne (= FM- radio), …
THz	electronics, quasi-optics, direct detection, …
Visible	up-conversion, non-linear, electro-optics, EOSD, WDM, …



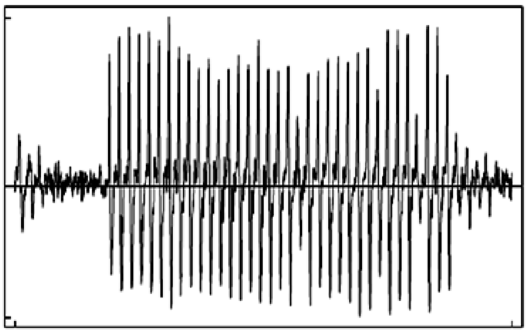


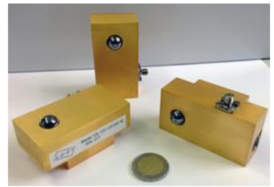


THz diagnostics in time and frequency

- **signal time structure**

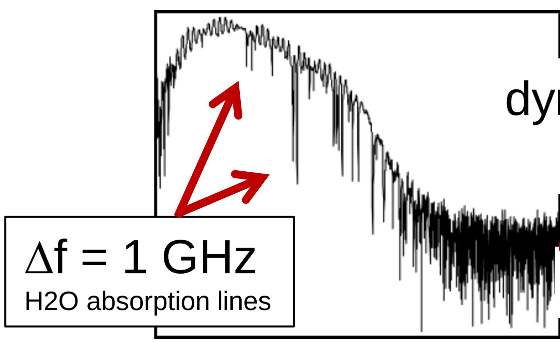
KIT IBPT





$\longleftarrow$ Δt = 100 ns $\longrightarrow$

- **frequency coverage**

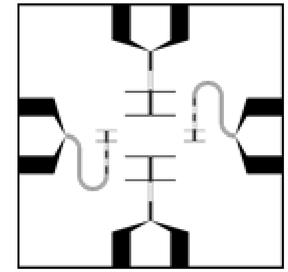


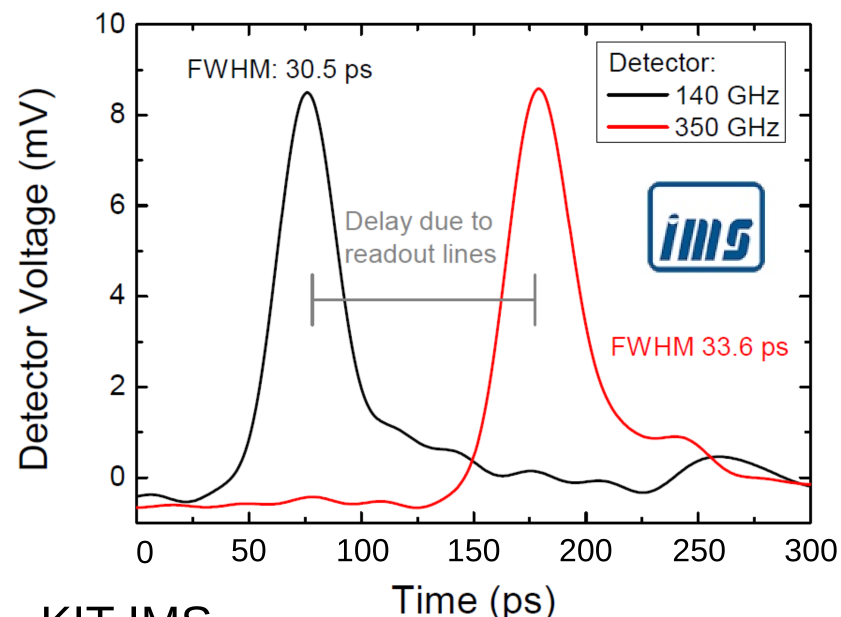
dynamic range: > 10^6

noise floor

$\longleftarrow$ $\Delta\nu$ = 5 THz $\longrightarrow$

- **signal time structure at different THz frequencies**





KIT IMS

A. Schmid, M. Brosi, E. Bründermann, K. Ilin, B. Kehrer, A. Kuzmin, S. Kuznetsov, A.-S. Müller, J. Raasch, M. Schuh, P. Schönfeldt, M. Siegel, J. L. Steinmann, S. Wünsch, Single-Shot Spectral Analysis of Synchrotron Radiation in THz Regime at ANKA, Int. Particle Accelerator Conf. (IPAC2016), 115-117 (2016). | DOI: mopmb016

Using FLUTE photo-injector laser: terahertz coherent Raman scattering

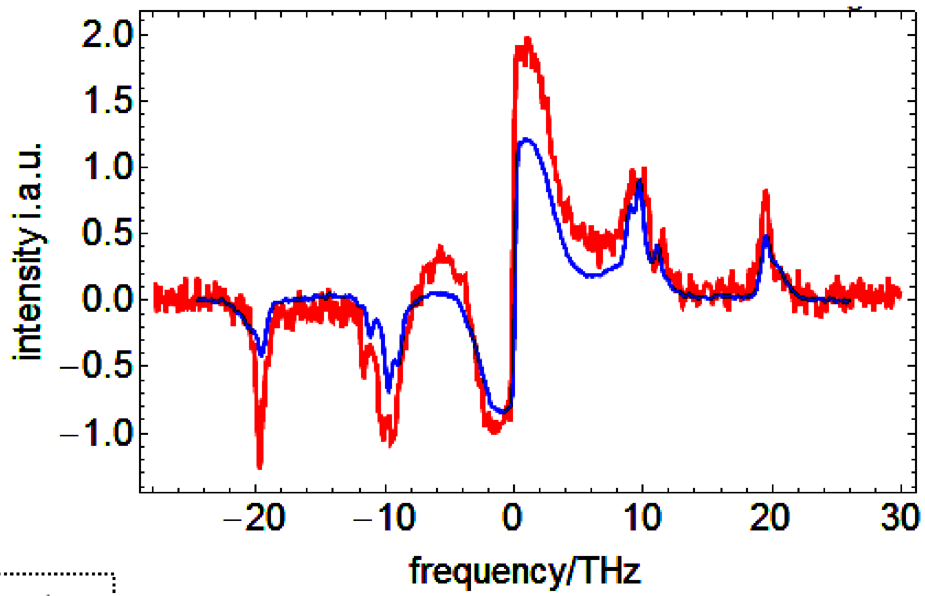
Recent experiments

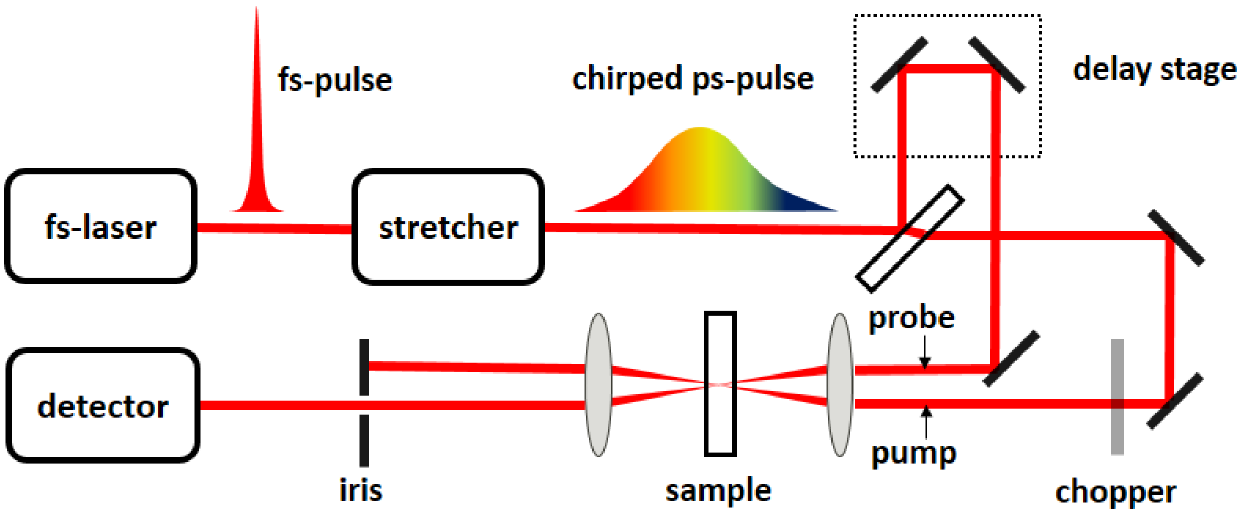
with fs to ps chirped pulses

Terahertz transients with

20 THz bandwidth

corresponds to ~18 fs



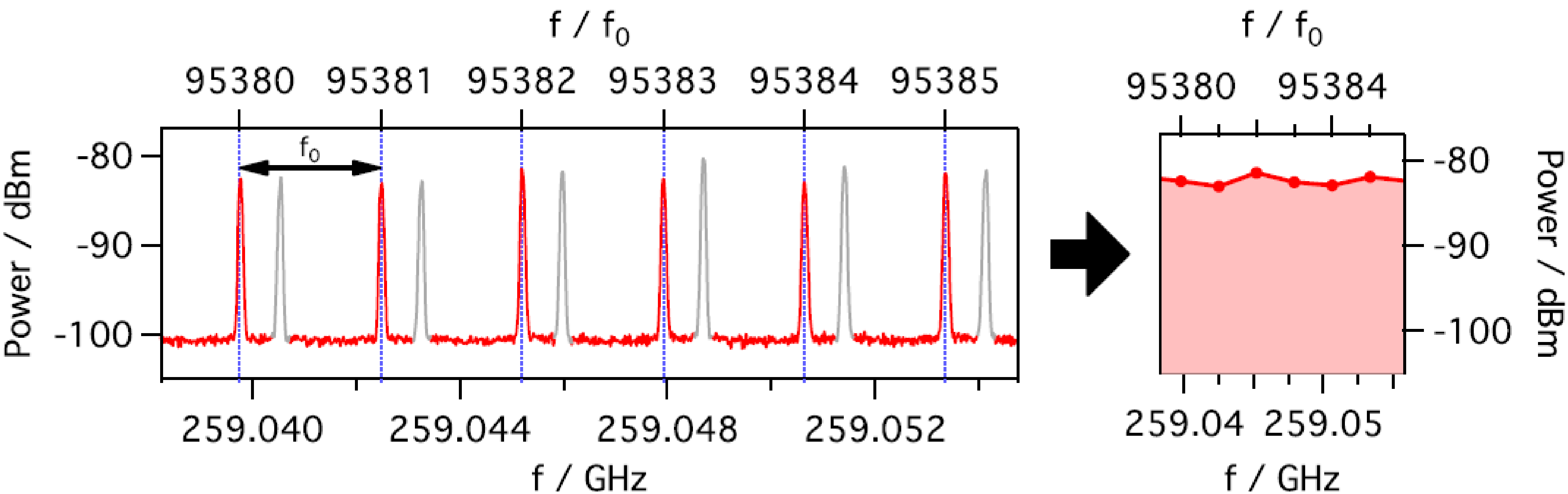


Courtesy: S. Funkner (KIT IBPT)

Institute for Beam Physics and Technology (IBPT)
Department of Accelerator Research

Frequency-comb spectrum of periodic-patterned signals

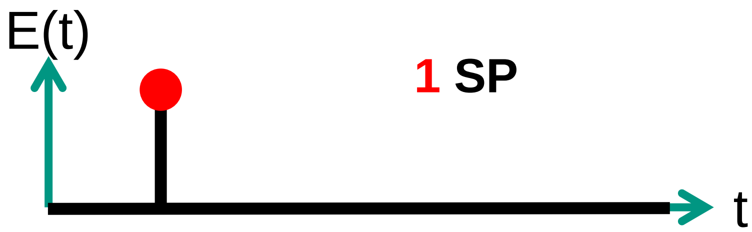
PRL **117** 174802 (2016)



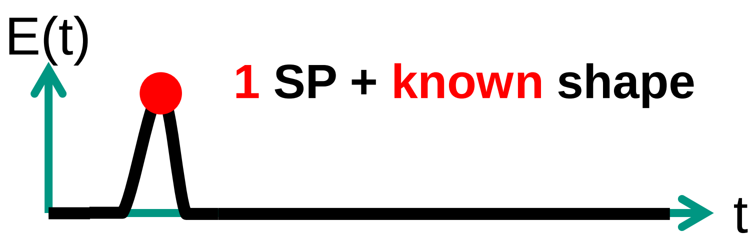
- **THz heterodyne detection of coherent synchrotron radiation**
- **discrete revolution frequency harmonics**
- **signal at ~100’000 harmonic** (f_0 = 2.72 MHz)

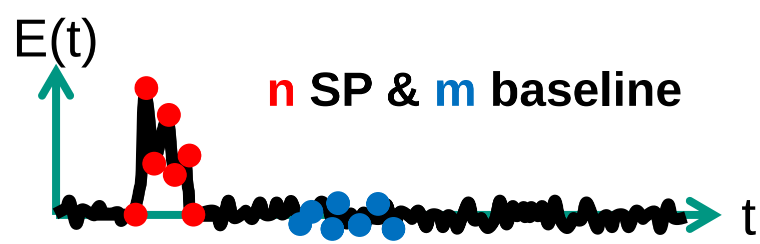
Frequency-comb spectrum of periodic-patterned signals, J. L. Steinmann, E. Blomley, M. Brosi, E. Bründermann, M. Caselle, J. L. Hesler, N. Hiller, B. Kehrer, Y.-L. Mathis, M.J. Nasse, J. Raasch, M. Schedler, P. Schönfeldt, M. Schuh, M. Schwarz, M. Siegel, N. Smale, M. Weber, and A.-S. Müller, Phys. Rev. Lett. 117, 174802 (2016). | DOI: 10.1103/PhysRevLett.117.174802

Sampling points (SP)



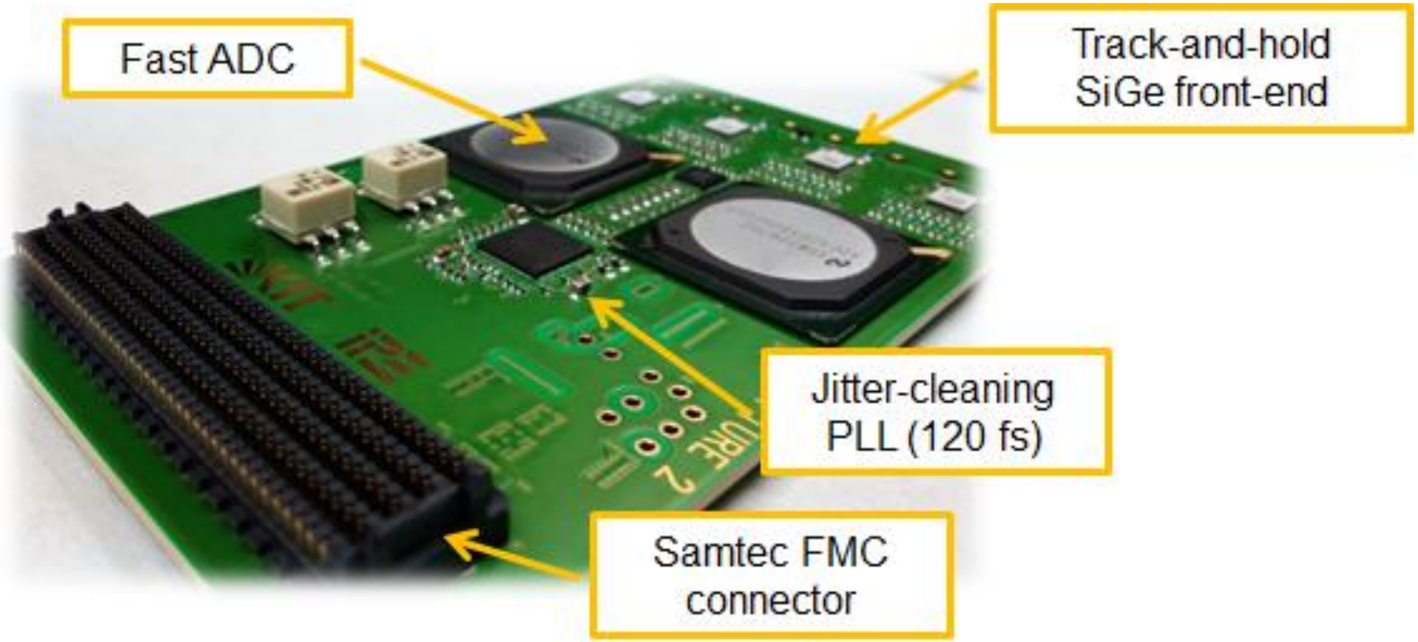
Δt	Method
ps	electronics, down-conversion, …
fs	optics, up-conversion, …
as	optics, streaking (THz, optical), …





KAPTURE V.2: compact & high sampling rate

- design targets
  - very wide frequency: 0.2 - 3.5 GS/s per sampling channel
  - modular design; half-size PCB; 2 KAPTURE connected to 1 readout card
  - MicroTCA standard: form factor mechanically/electrically compatible



KAPTURE-2. A picosecond sampling system for individual THz pulses with high repetition rate
M. Caselle, L.E. Ardila Perez, M. Balzer, A. Kopmann, L. Rota, M. Weber, M. Brosi, J. Steinmann,
E. Bründermann, A.-S. Müller, JINST 12, C01040 (2017). | DOI: 10.1088/1748-0221/12/01/C01040

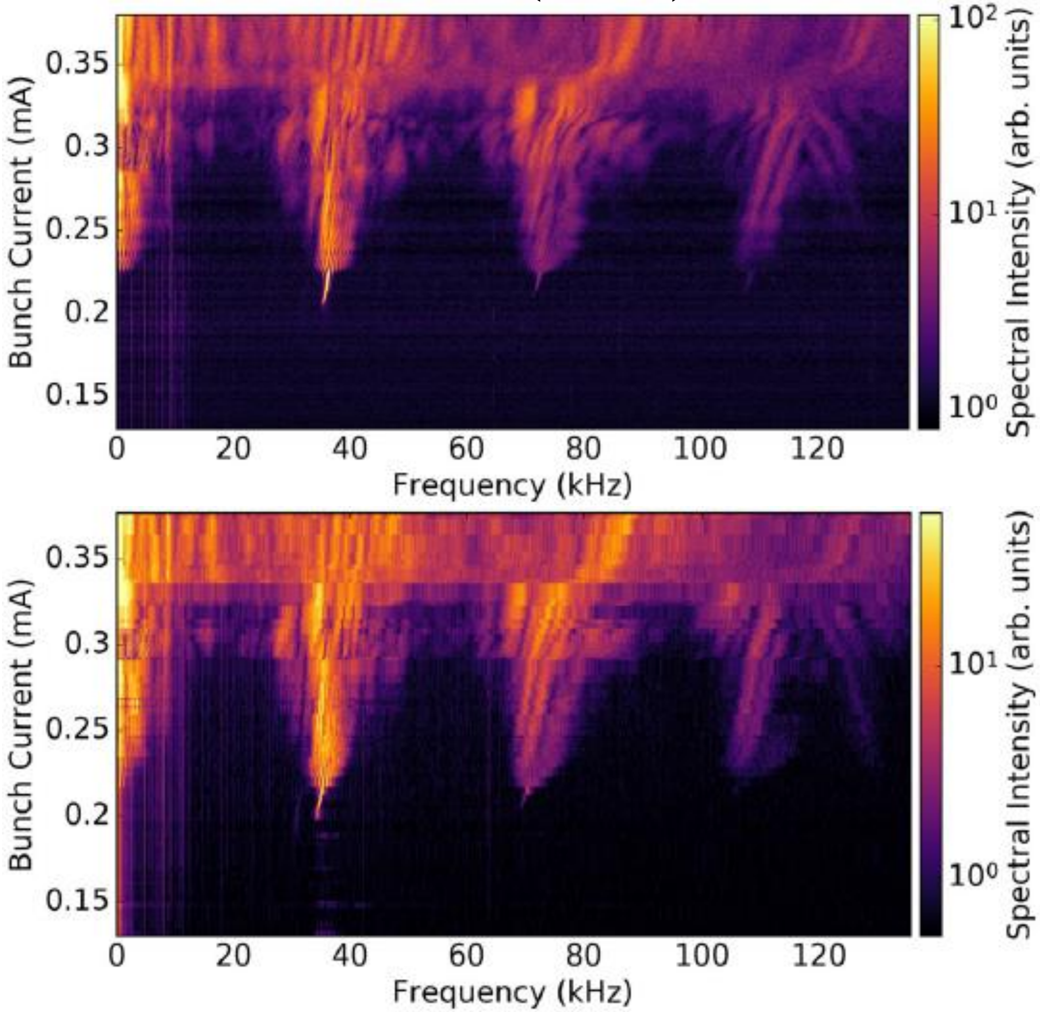
Spectrogram

Editors' Suggestion

PRAB **19** 110701 (2016)

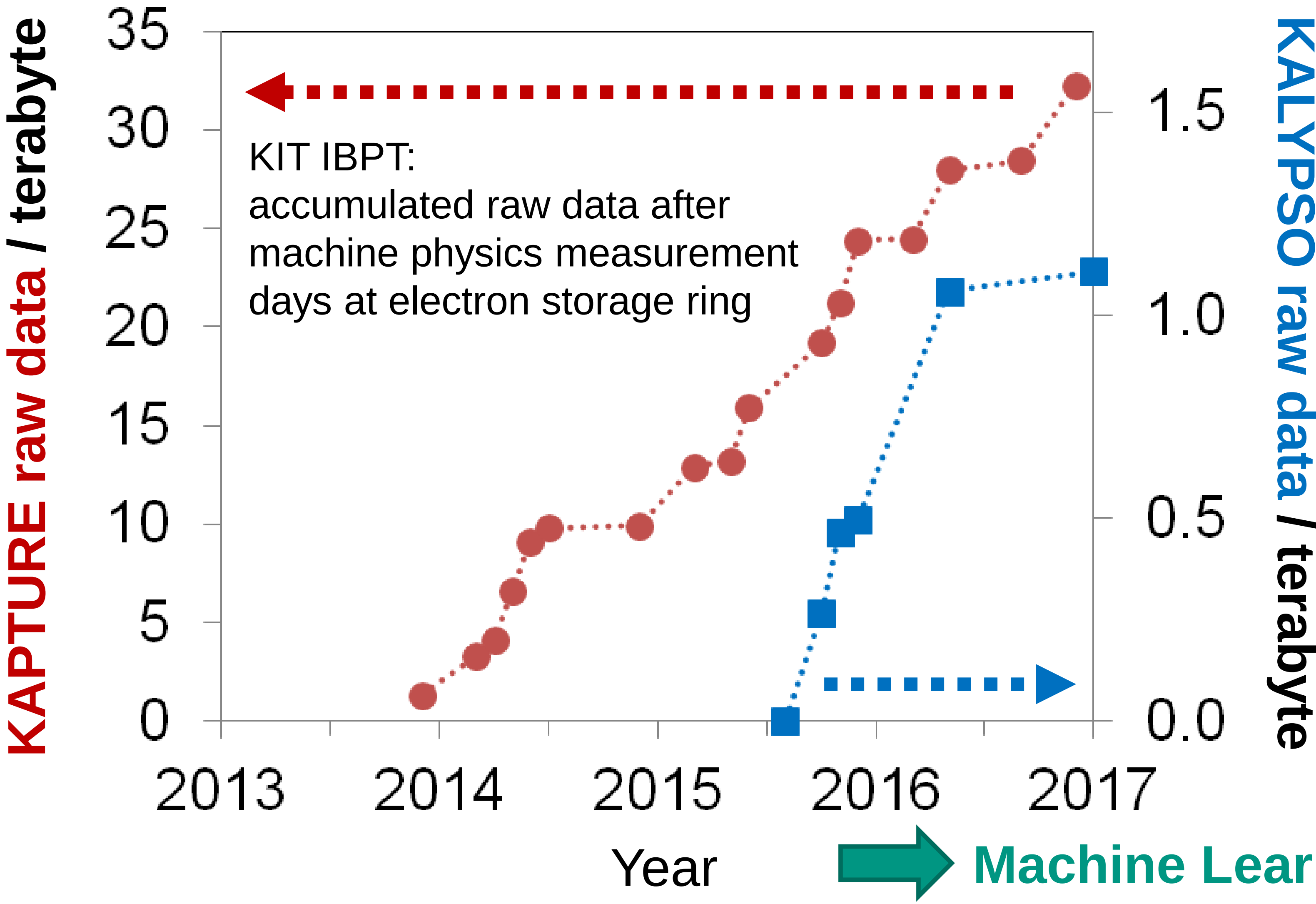
- regular electronics
- single e-bunch
- current decay
- precise current sampling
- **hours**

- **KAPTURE**
- 184 different e-bunches
- 184 different currents
- **1 second**
  - 2.7 million data sets (x184)
- **snapshot** measurements
  - **systematic studies**



Fast mapping of terahertz bursting thresholds and characteristics at synchrotron light sources,
M. Brosi, J. L. Steinmann, E. Blomley, E. Bründermann, M. Caselle, N. Hiller, B. Kehrer, Y.-L. Mathis, M.J. Nasse, L. Rota, M. Schedler, P. Schönfeldt, M. Schuh, M. Schwarz, M. Weber, A.-S. Müller, Phys. Rev. Accel. Beams 19, 110701 (2016). | DOI: 10.1103/PhysRevAccelBeams.19.110701

KAPTURE and KALYPSO – Terabyte Data



Machine Learning

Institute for Beam Physics and Technology (IBPT)
Department of Accelerator Research

Summary

Terahertz techniques

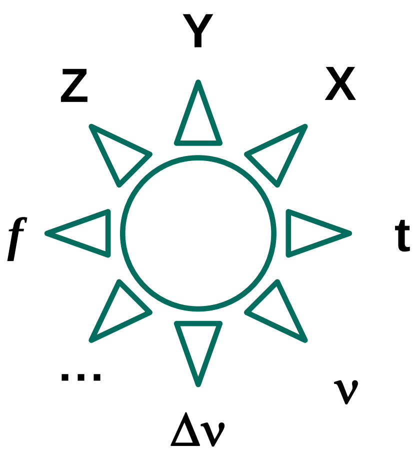
to explore the

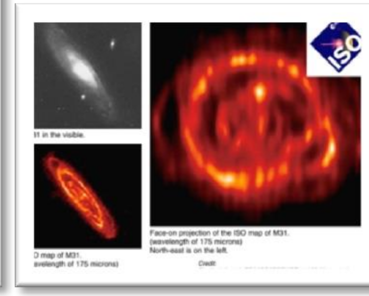
early universe

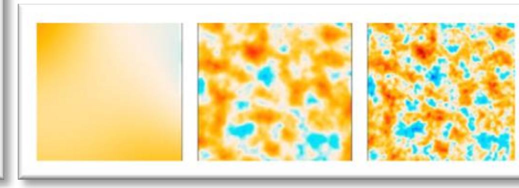
plasma acceleration

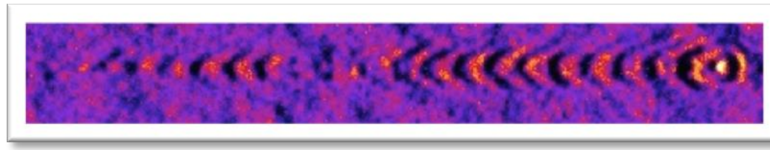
and

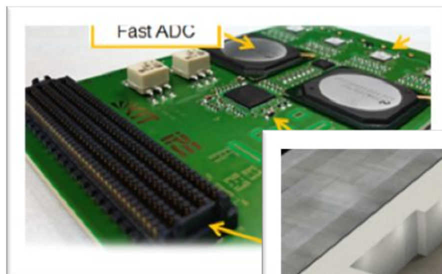
particle physics

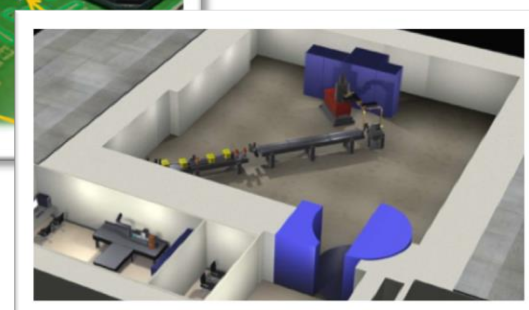


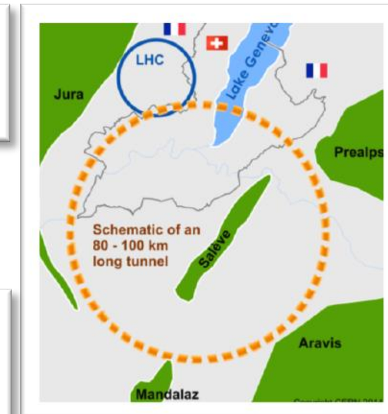












"the universe in the lab"