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Addressing superconductivity with accelerator-based infrared and THz radiation sources

A. Perucchi, P. Di Pietro, P. Dore, S. Lupi

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Istituto Officina dei Materiali

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TeraFERMI

SISSI

www.elettra.eu

Outline

1. **Infrared Spectroscopy and Superconductivity**

2. THz superconducting gaps
3. Addressing electron correlation with high-pressures

4. Non-linear THz spectroscopy
5. The TeraFERMI project

6. Conclusions and outlook

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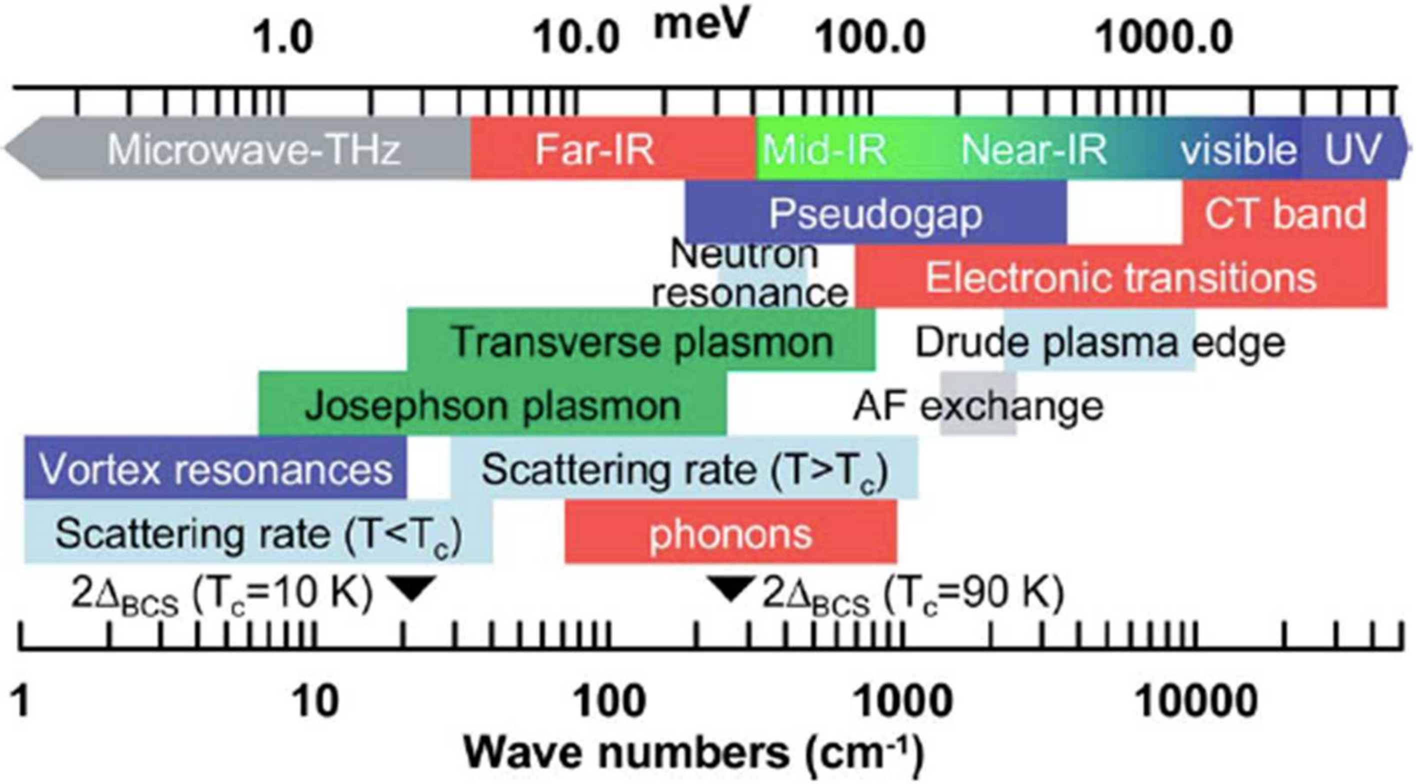
IR energy scales and Superconductivity



Basov, Timusk, RMP 2005

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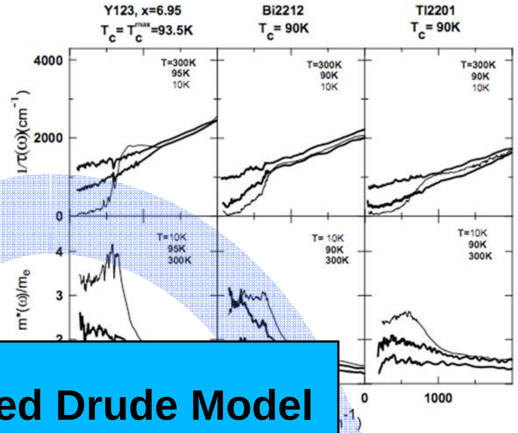
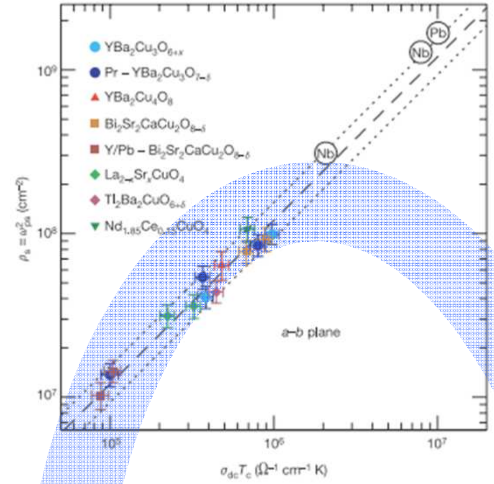
IR Spectroscopy and Superconductivity

Puchkov et al. 1996

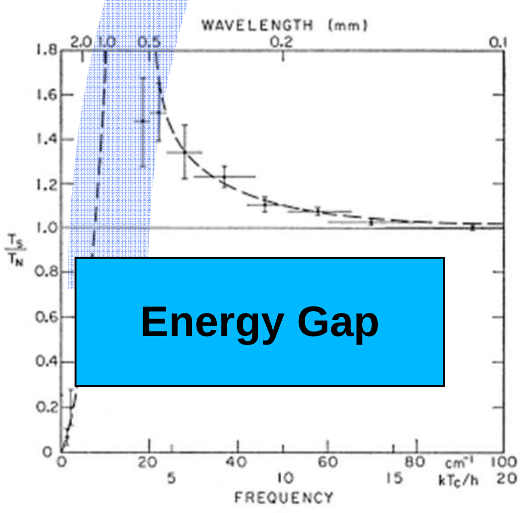


Extended Drude Model

Homes et al. 2004

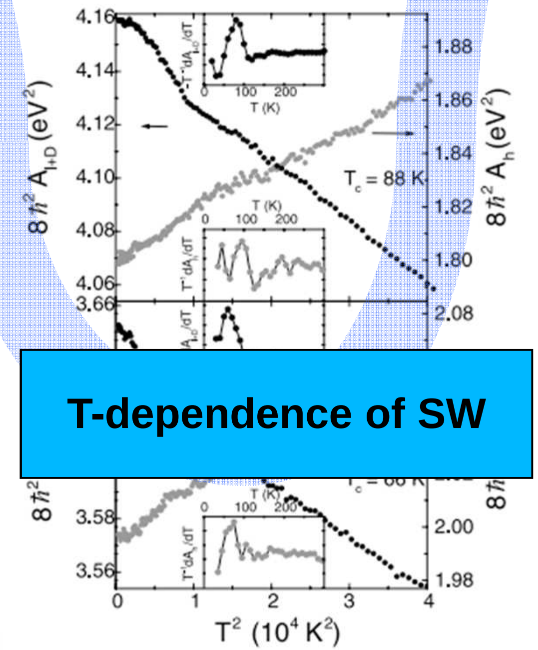


Universal scaling relation



Energy Gap

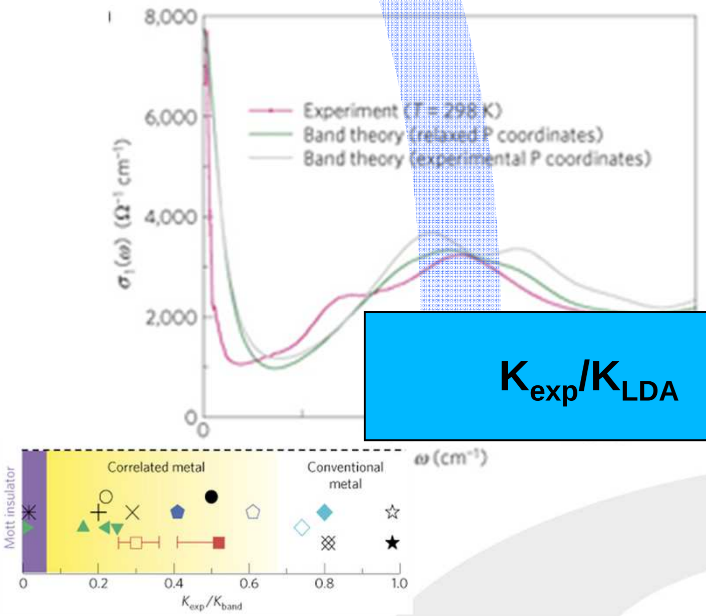
Glover and Tinkham 1956



T-dependence of SW

Molegraaf et al. 2002

Qazilbash et al. 2009



K_{exp}/K_{LDA}

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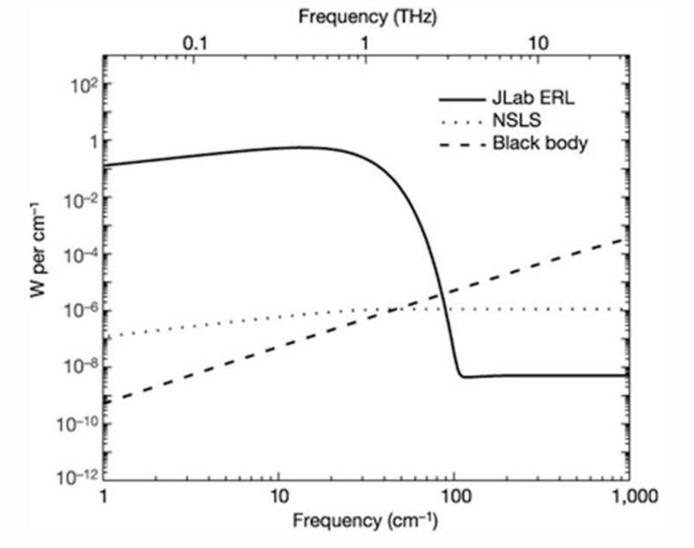
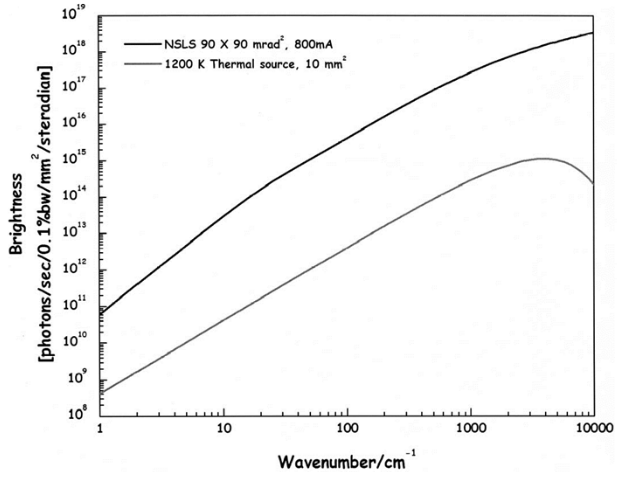
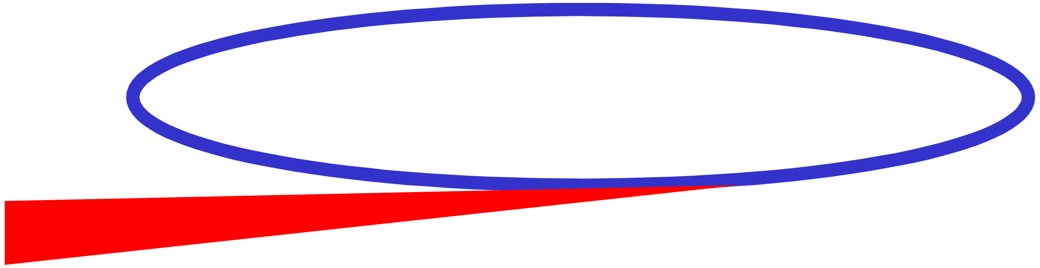
Infrared Synchrotron Radiation advantages

Carr *et al.* (Nature, 2002)

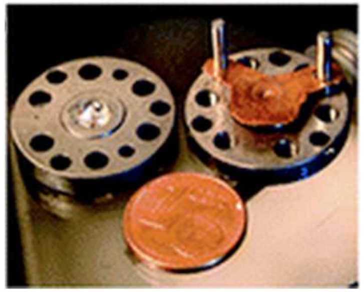




Increased flux in the THz range
⬆ Superconducting gaps



Increased brightness in the
whole IR range
⬆ High-Pressure
measurements in a DAC

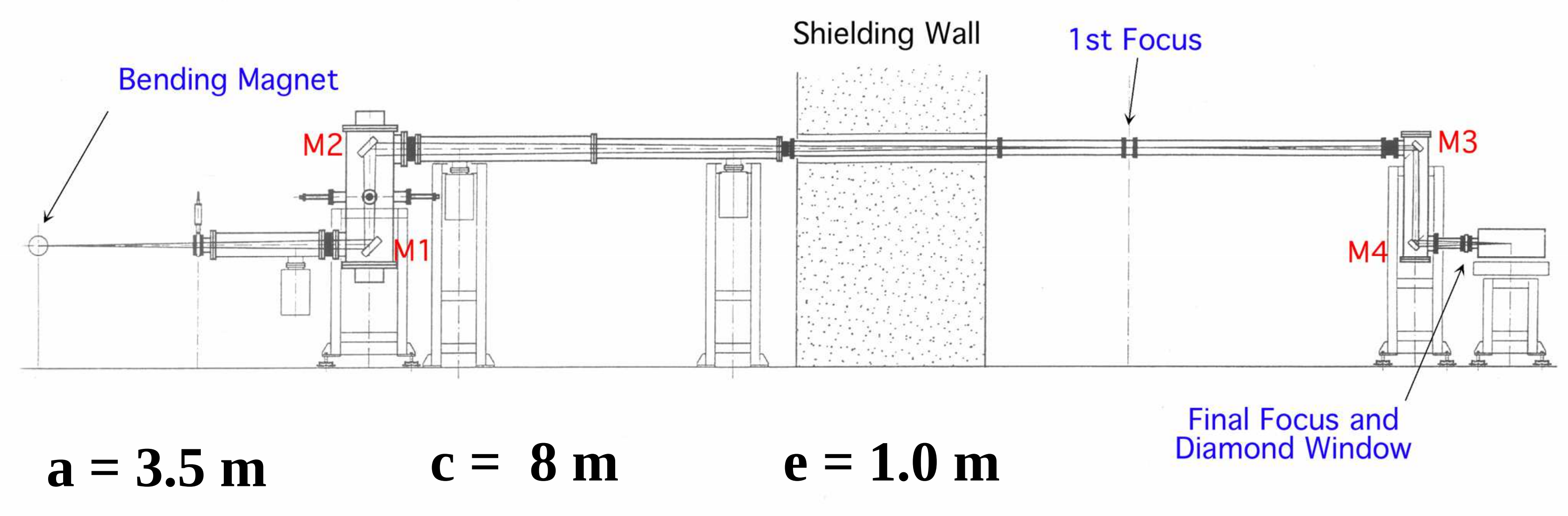


SISSI

Synchrotron Infrared Source for Spectroscopy and Imaging

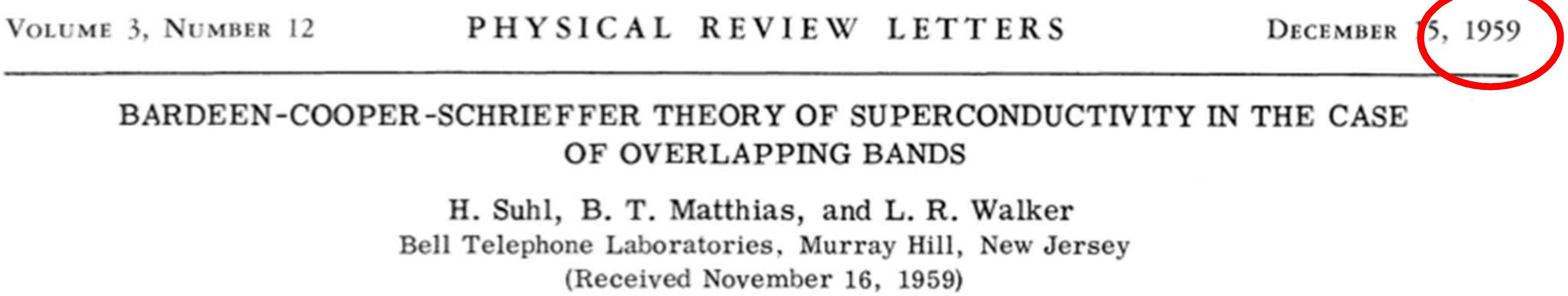
Radiation is collected over a solid angle of 65 mrad (H) x 25 mrad (V)

M1 Plane mirror
M2 Ellipsoidal mirror
M3 Plane mirror
M4 Ellipsoidal mirror



a = 3.5 m
b = 1.0 m
c = 8 m
d = 3.0 m
e = 1.0 m
f = 1.0 m

Multi-gap superconductors



VOLUME 3, NUMBER 12 PHYSICAL REVIEW LETTERS DECEMBER 15, 1959

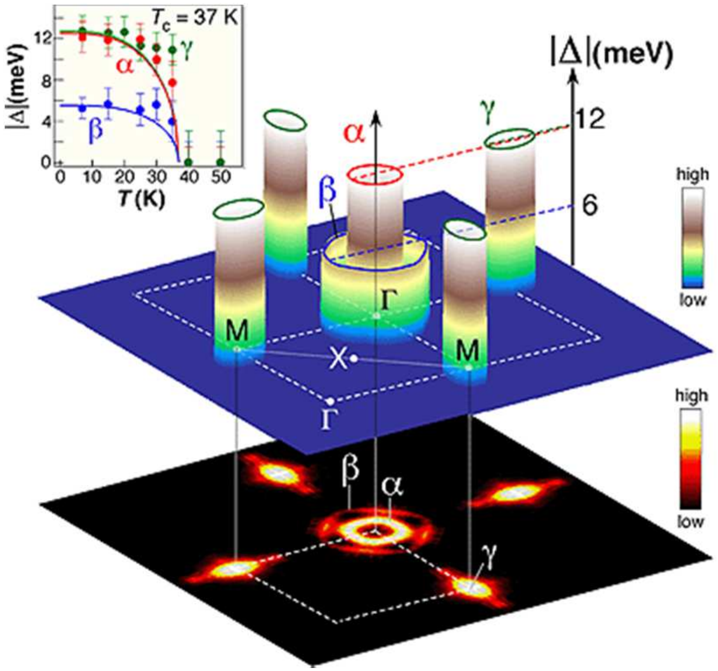
BARDEEN-COOPER-SCHRIEFFER THEORY OF SUPERCONDUCTIVITY IN THE CASE OF OVERLAPPING BANDS

H. Suhl, B. T. Matthias, and L. R. Walker
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received November 16, 1959)

Several bands crossing the Fermi level is not sufficient to have considerable many-band effects in superconductivity. Only when the bands have a very different physical origin, multigap effects take place. **Interband scattering has to be low!**

In 2001, multigap superconductivity has been demonstrated for the first time to take place in a real material, as MgB_2.

Multigap SC has been proposed for transition metals, A15 compounds, Copper-oxide high-Tc, Heavy Fermions, Pnictides →



M. Norman, Physics (2008)

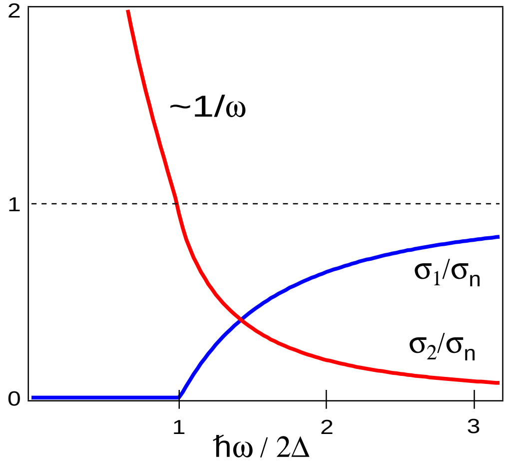
BCS-like electrodynamics

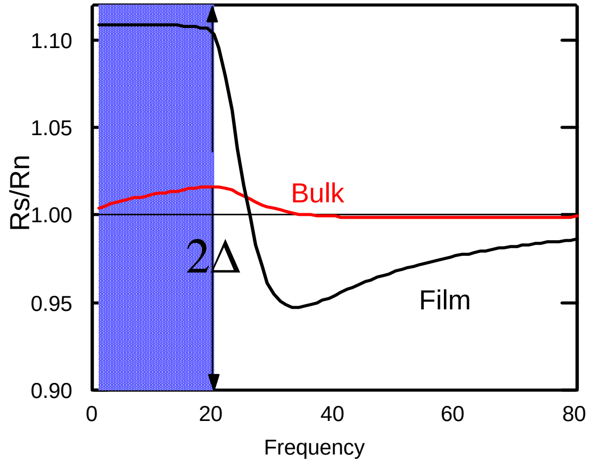
Superconductivity is ruled by *low-energy* electrodynamics:
The Superconducting Gap size and shape provide information on the nature and symmetry of pairing

$$2\Delta / k_B T_C = 3.52 \quad \longrightarrow \quad \mathrm{Tc} \approx 10\ \mathrm{K}\ ⌫\ 2\Delta \approx 1\ \mathrm{THz}$$

Synchrotron advantage at THz frequencies with both coherent and incoherent sources

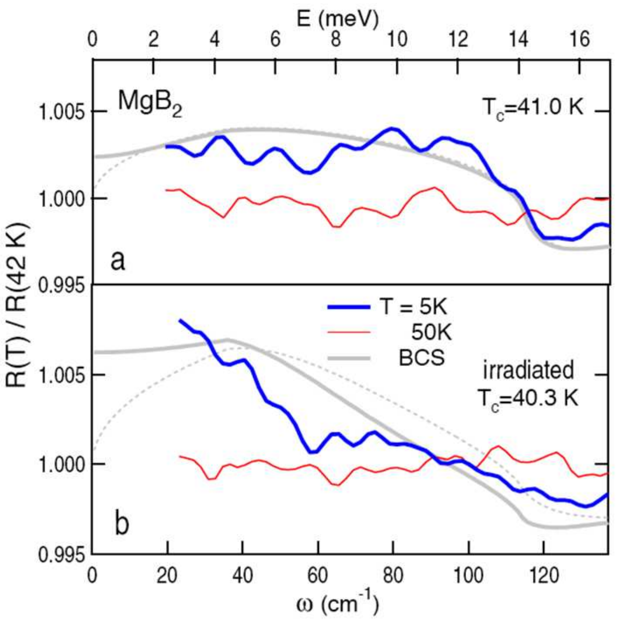
The Mattis-Bardeen (MB) relations are derived within the BCS theory, for a s-wave SC in the dirty limit
(extension to arbitrary impurity scattering by Zimmermann)





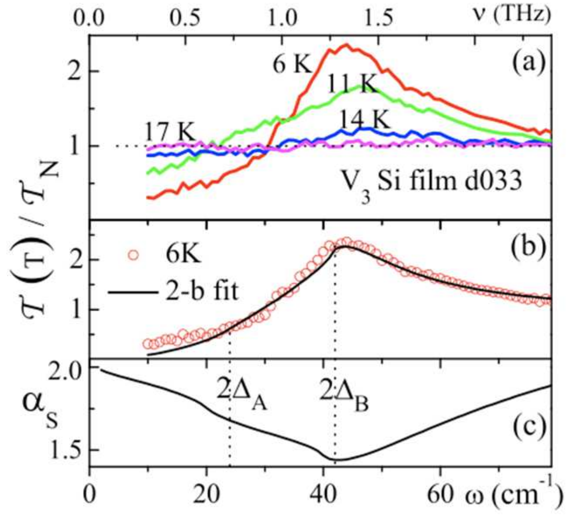
MG Superconductors THz studies @ SISSI

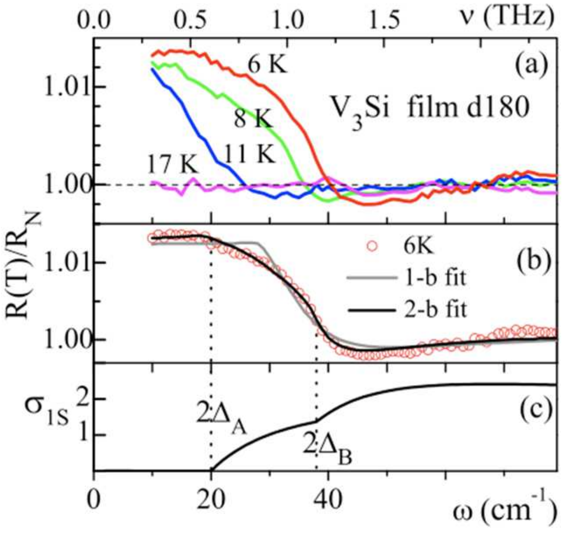
MgB_2



Ortolani PRB (2008)

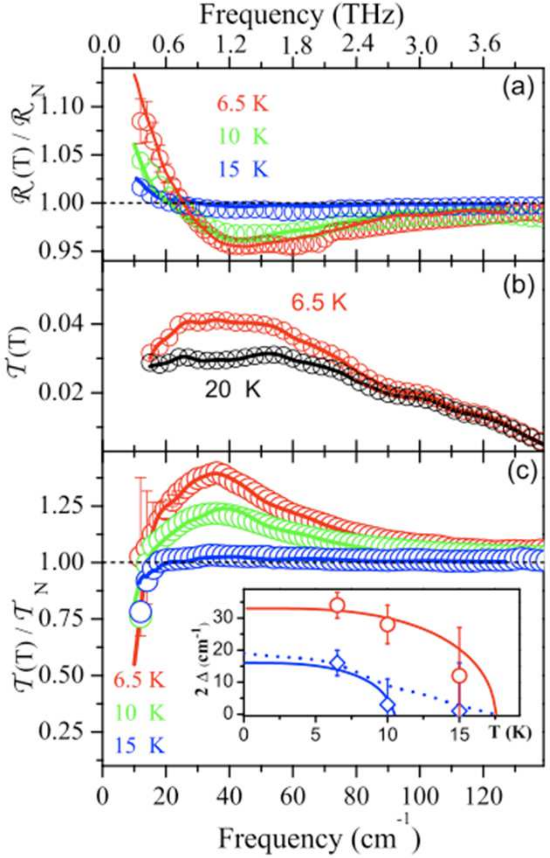
V_3Si





Perucchi PRB (2010)

$Ba(Fe,Co)_2As_2$



Perucchi EPJB (2013)

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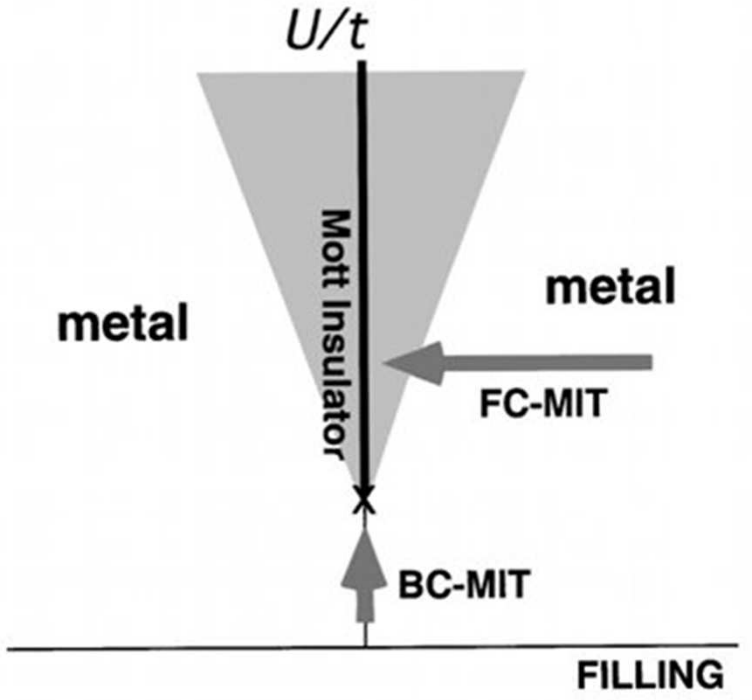
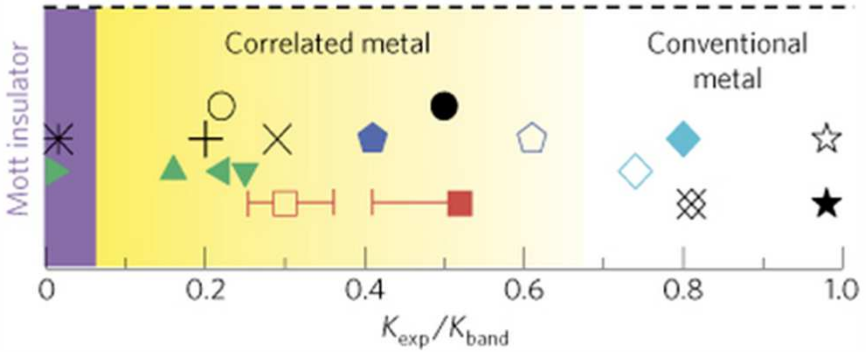
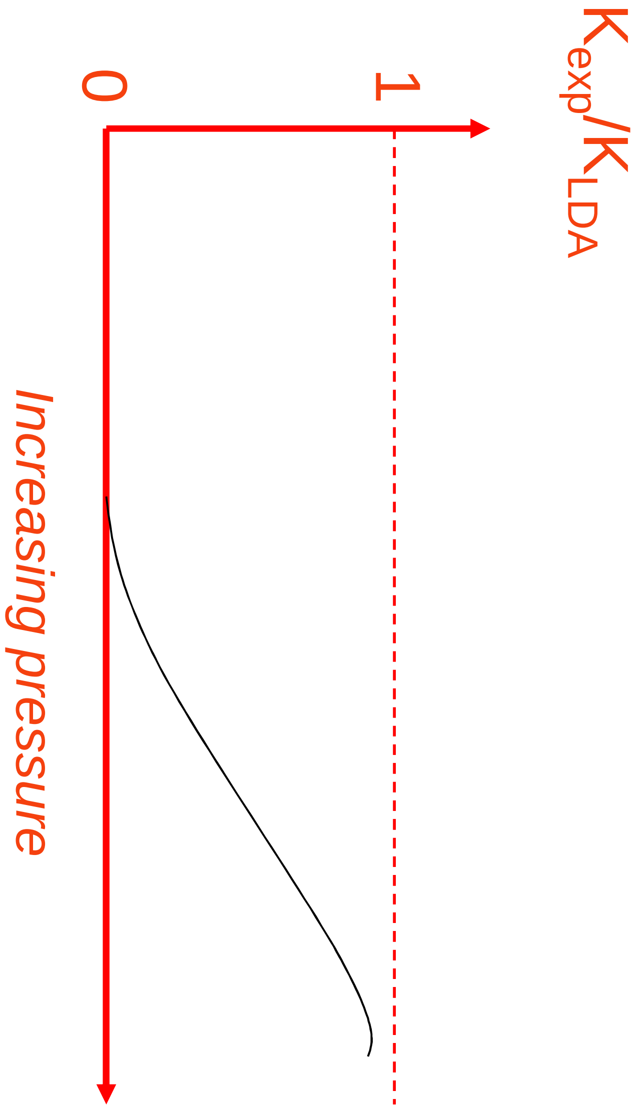
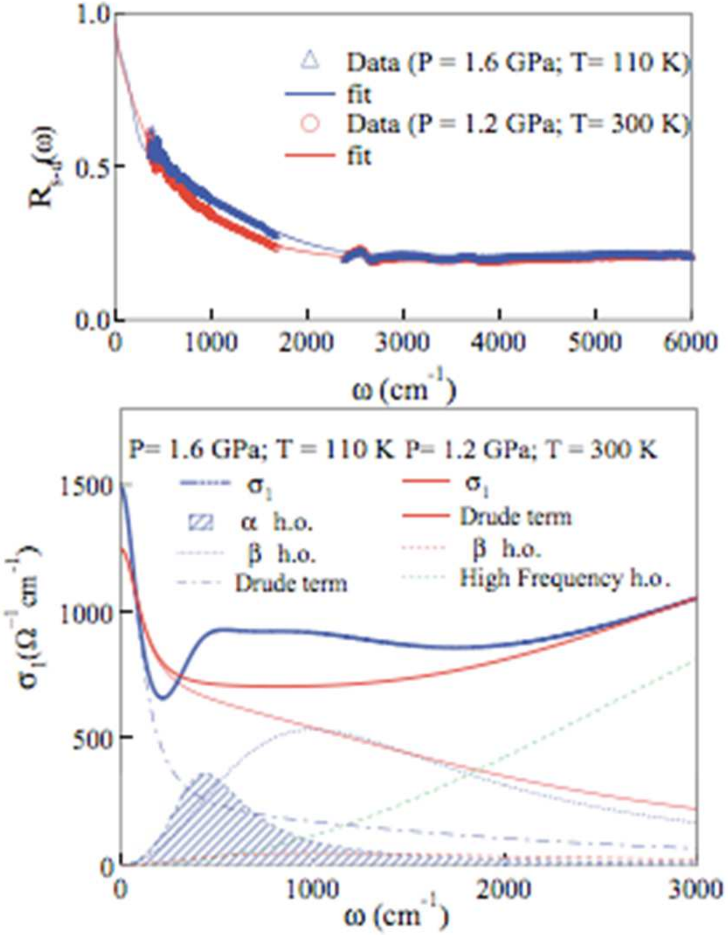
Correlation strength and High Pressures



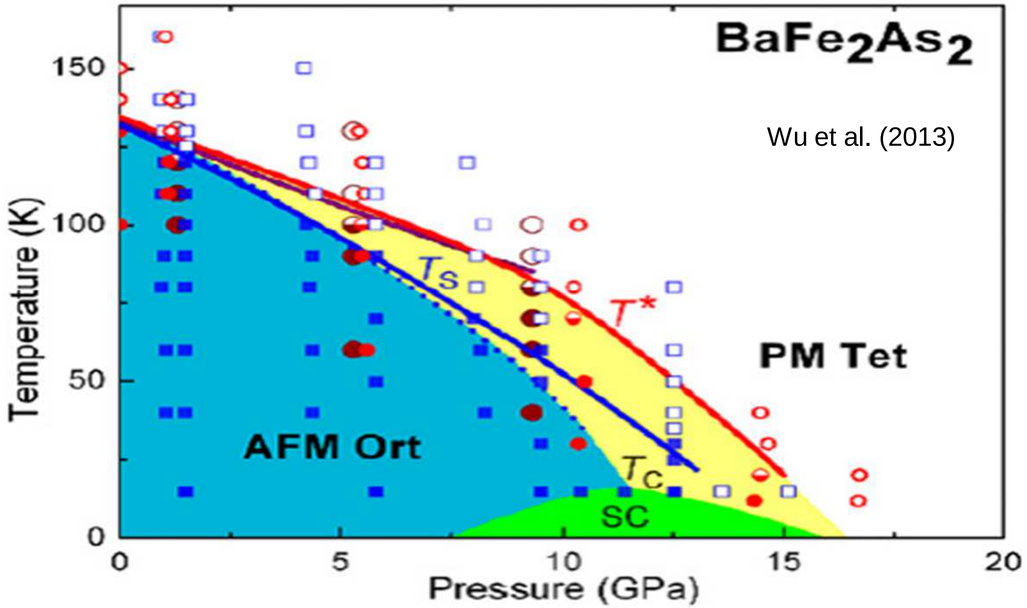




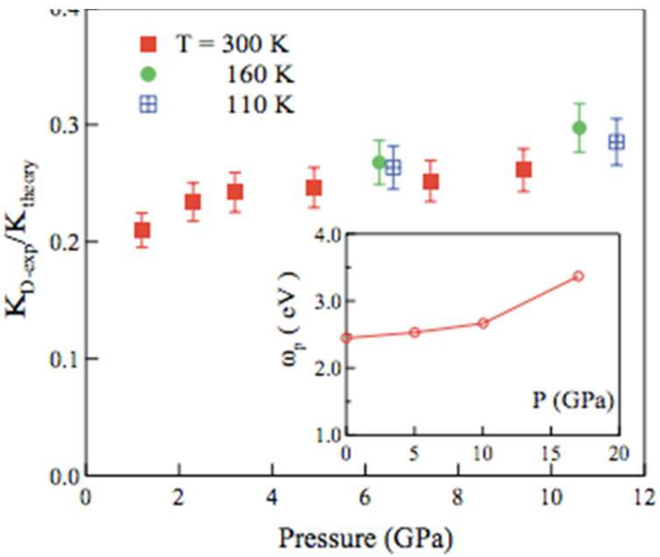
Ba-122 at High-Pressures



Baldassarre PRB (2012)



Wu et al. (2013)



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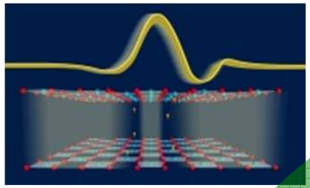
Non-linear THz optics at MV/cm

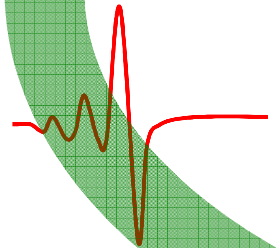
THz light couples with electronic, vibrational and magnetic excitations

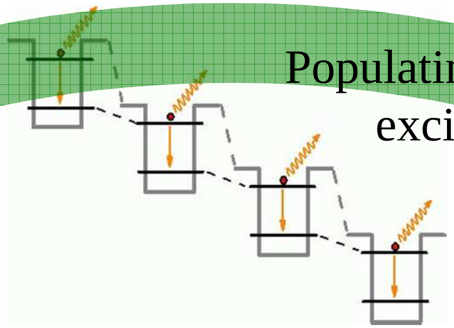


Dienst, 2011

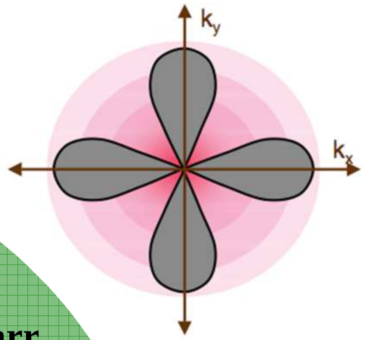
Electronic response under giant quasi-static fields

E_c critical field



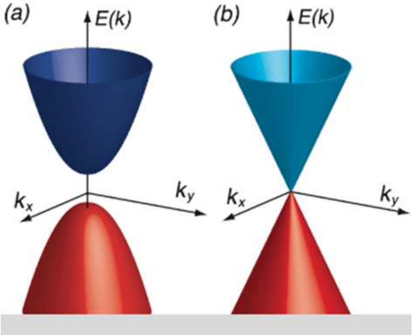


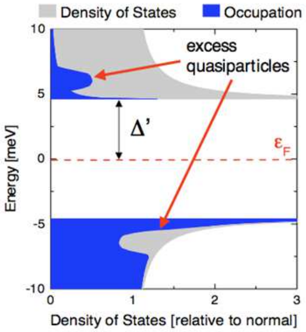
Populating low-energy excited states



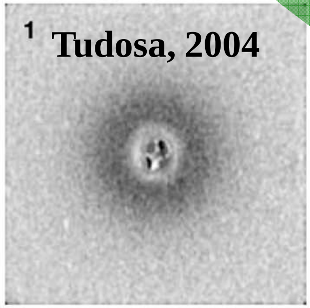
Narrow-band THz excitation to limit starting population energy

From L. Carr



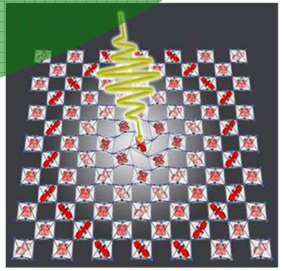


Ultra-fast structural distortions and lattice control



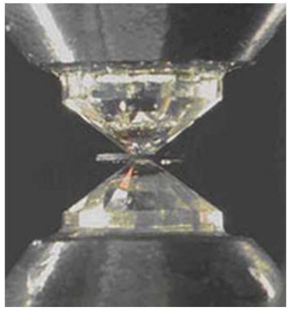
Tudosa, 2004

Ultra-fast magnetic switching (B~0.3 T)

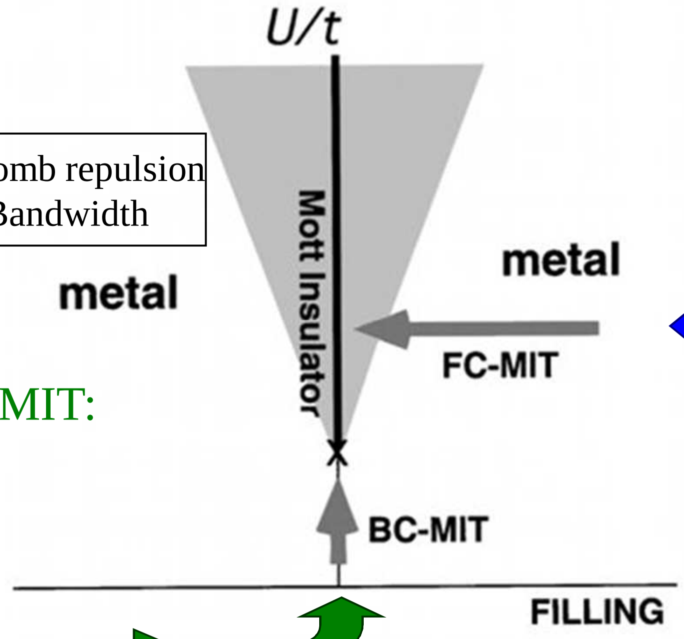


Rini, 2007

Manipulating Mott Insulator-to-Metal Transitions



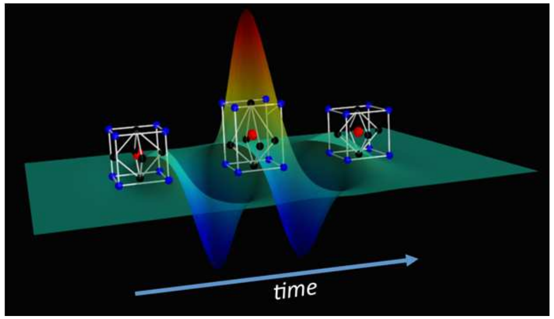
U Coulomb repulsion
t Bandwidth

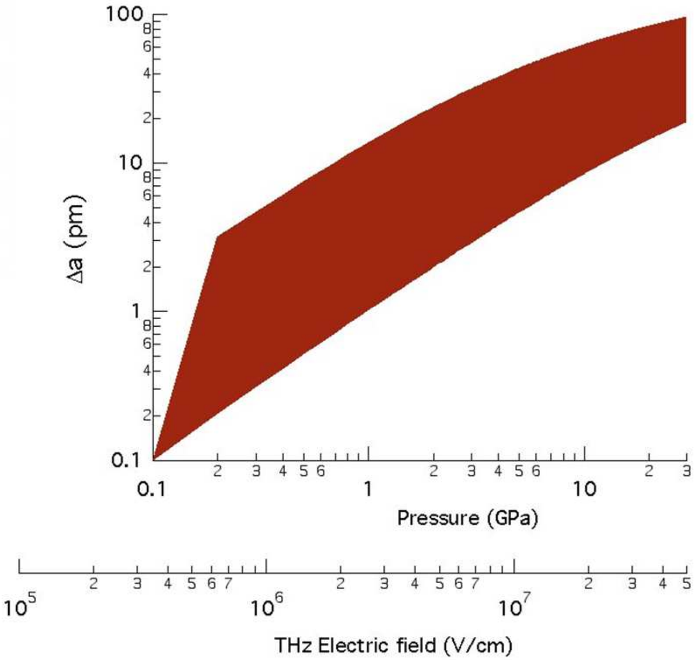


Filling-Controlled MIT:
- *static* (doping)
- *dynamic* (photoexcitation)

Bandwidth-Controlled MIT:
- *static* (pressure)
- *dynamic* (?)

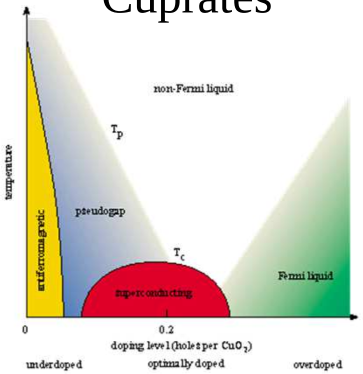
THz pulses in the MV/cm range can drive lattice displacements in the pm range

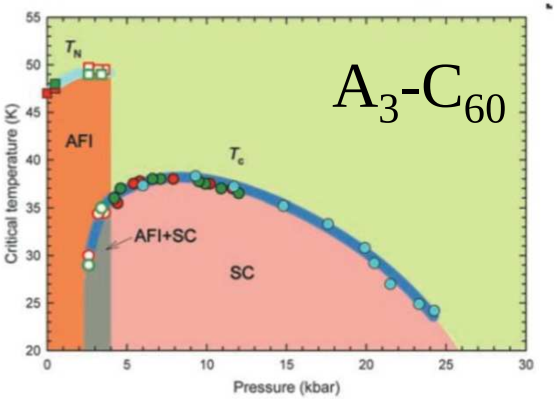




Superconductivity in Fullerides

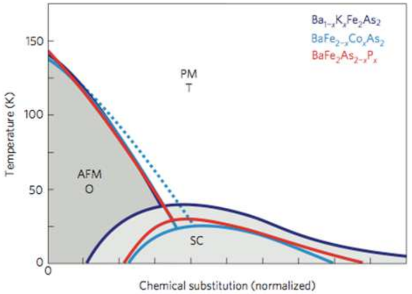
Cuprates





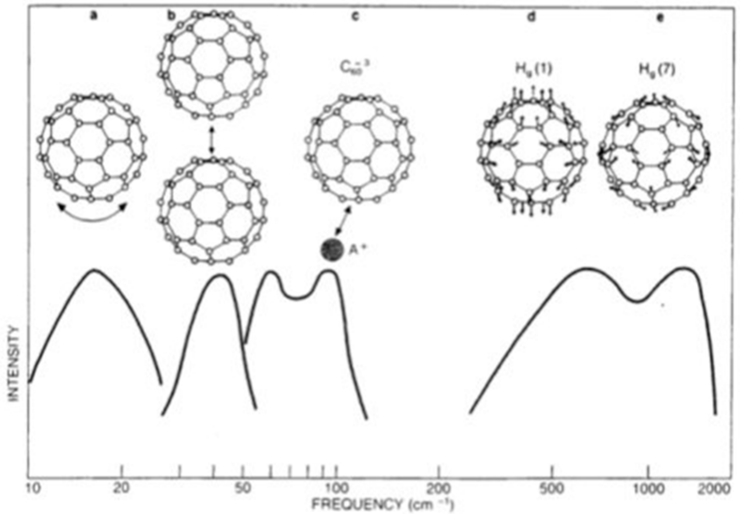
A_3-C_{60}

Pnictides



Superconductivity close to an AF state: one general mechanism for HTSC ?

“Conventional” BCS-like features (isotope effect, s-wave gap) together with the presence of strong correlation (large U, magnetism).



Retardation effects are poorly understood because of possible breakdown of adiabatic approximations (W~0.5 eV vs. ω_{ph}~0.2 eV)

Time-resolved studies of the electronic response upon lattice excitations

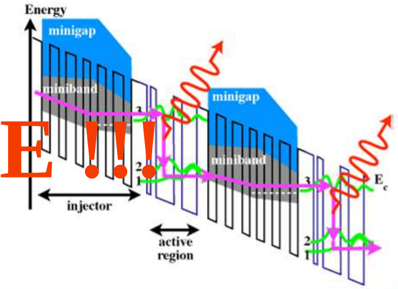
Need of employing THz pulses

- ***short*** (on the fs time-scale)
- ***broadband*** (over the largest possible phonon range)
- ***powerful*** (MV/cm)

The THz Gap

Backward-Wave-Oscillators

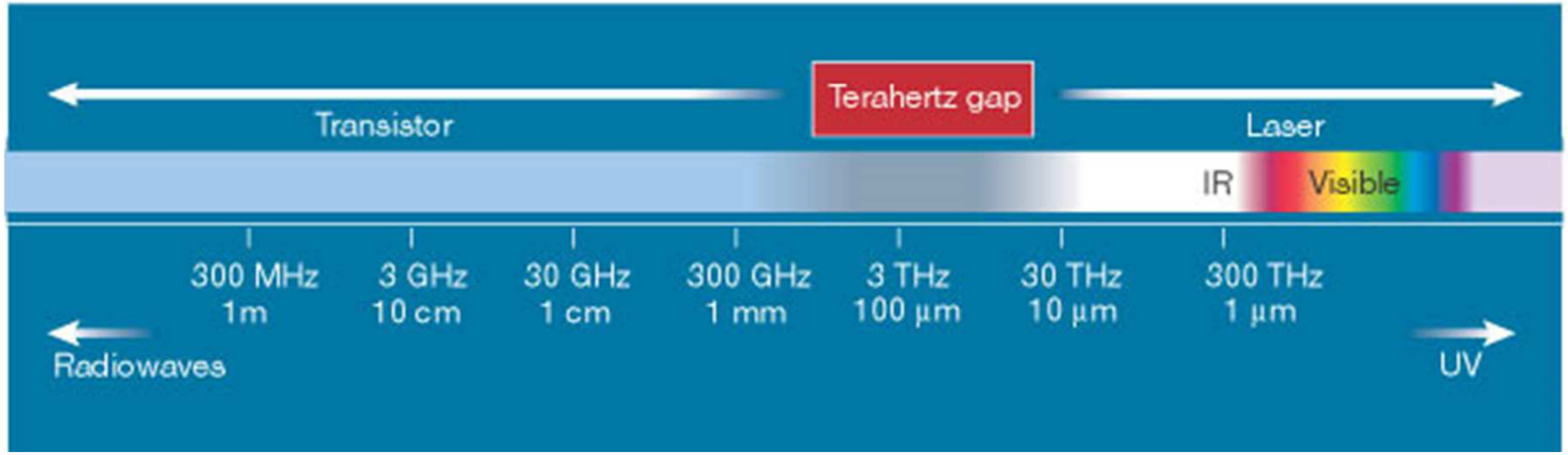
Quantum Cascade Lasers



NO TIME STRUCTURE !!!

Gas Lasers (CO_2 and CO_2-pumped)

Si /Ge Lasers



FEL-CATS

CLIO

fs scale not accessible

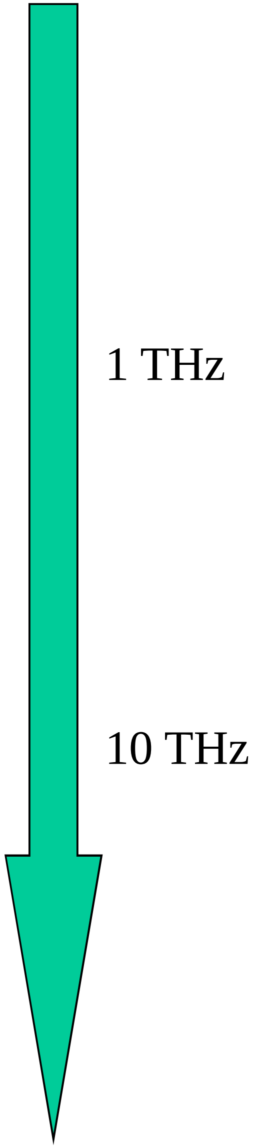
UCSB

THz Free-Electron-Lasers

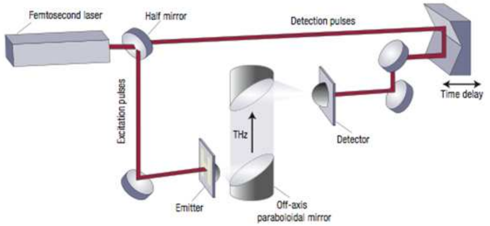
FELIX

FELBE

THz femtosecond sources



THz
Time Domain Spectroscopy



Photoconductive Antennas
GaAs, TiO_2, …
Optical Rectification
ZnTe, GaP, $LiNbO_3$, etc.
Up to 10’s μJ per pulse

RESTSTRAHLEN BAND GAP

(Optical Rectification in Organic Materials DAST, OH1, DSTM)

Optical Parametric Amplifiers
Tunable, Narrow-Band
Typically 1-10 μJ per pulse above 15 THz

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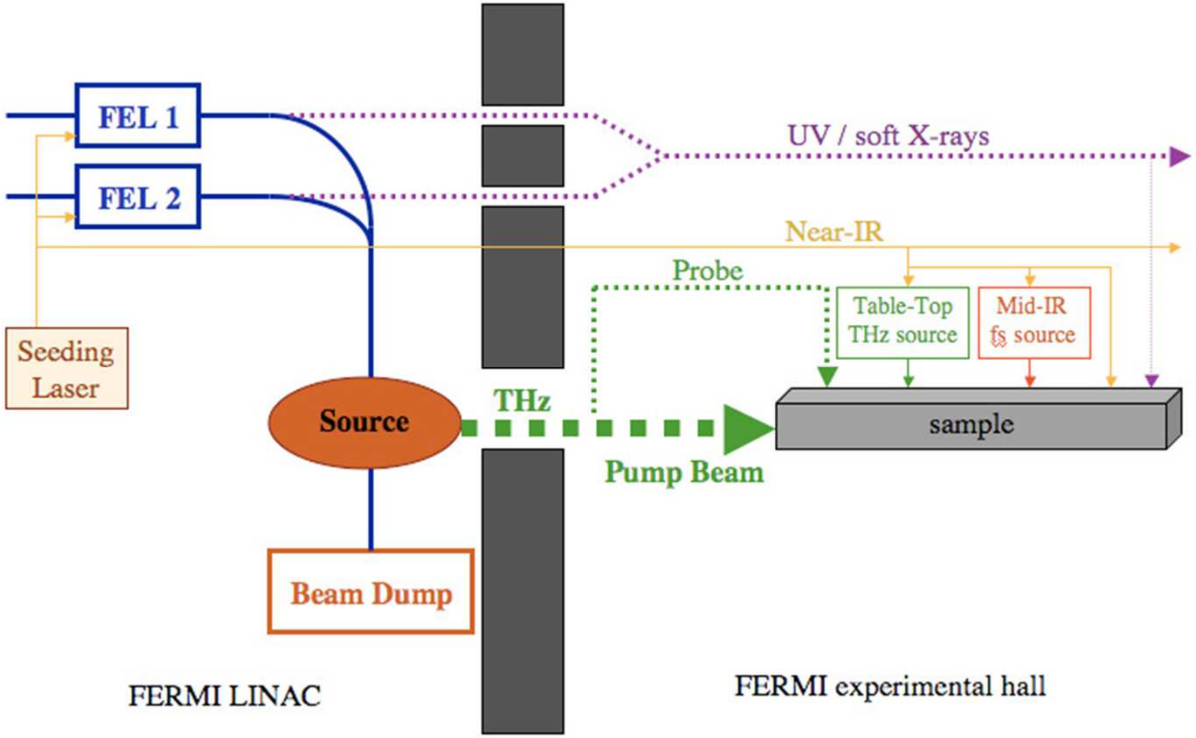
The TeraFERMI idea

Exploiting the properties of the FERMI-FEL electron beam to produce
Short (sub-ps), Powerful (>MV/cm), Broadband (0.1-10 THz)
THz pulses to be used as a **Pump** beam for ultrafast nonlinear spectroscopies

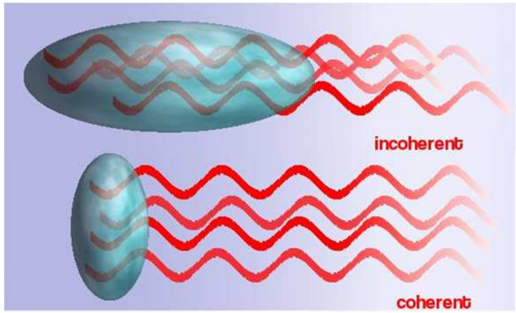


Exploiting the already existing LINAC: Reduced construction and operation costs

Parasitic THz emission: TeraFERMI will not affect overall FEL available beamtime
THz light always available
Possibility for THz pump / FEL probe

Accelerator-Based Coherent THz emission

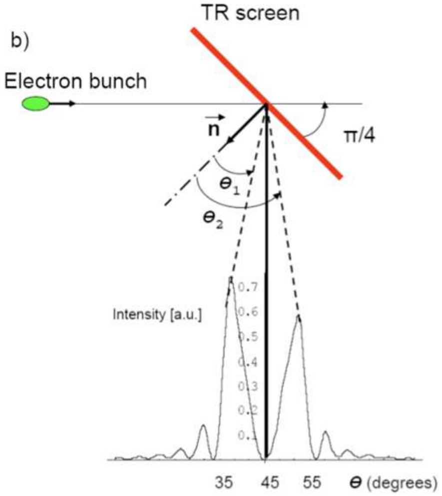
Extending the FEL’s advantages into the THz region



$$N\left[1+Nf(\omega)\right] \qquad f(\omega)=\int_{-\infty}^{+\infty}\rho(t)\exp(-i\omega t)\,dt$$

N ~ $6.24 \cdot 10^{7}$ @ 1pC Storage-Rings
N ~ $6.24 \cdot 10^{10}$ @ 1nC Single-pass accelerators

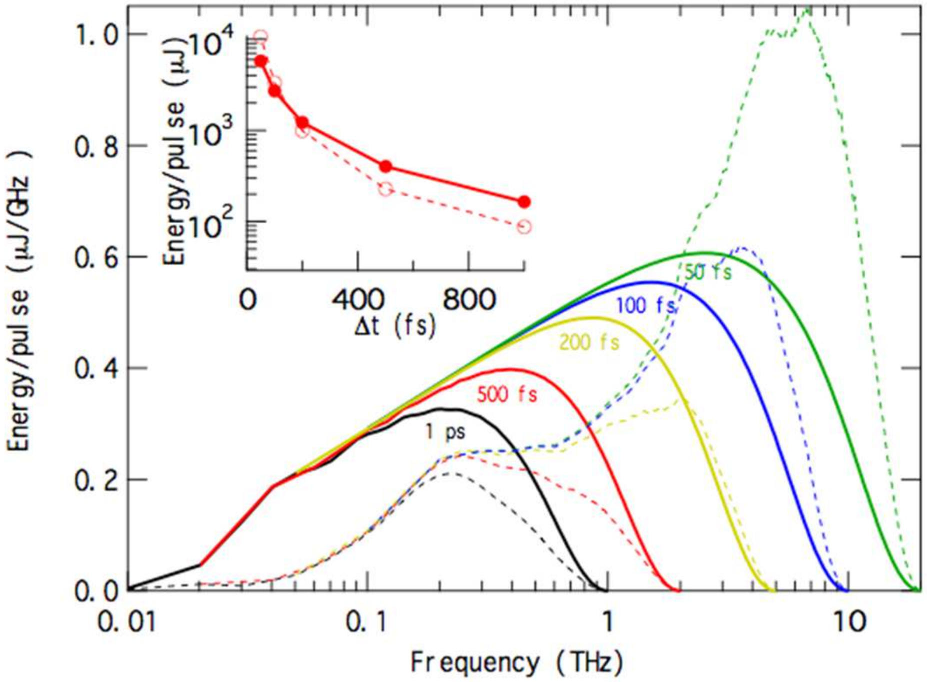
Transition Radiation occurs when relativistic electrons cross the boundary between two media of different dielectric constant



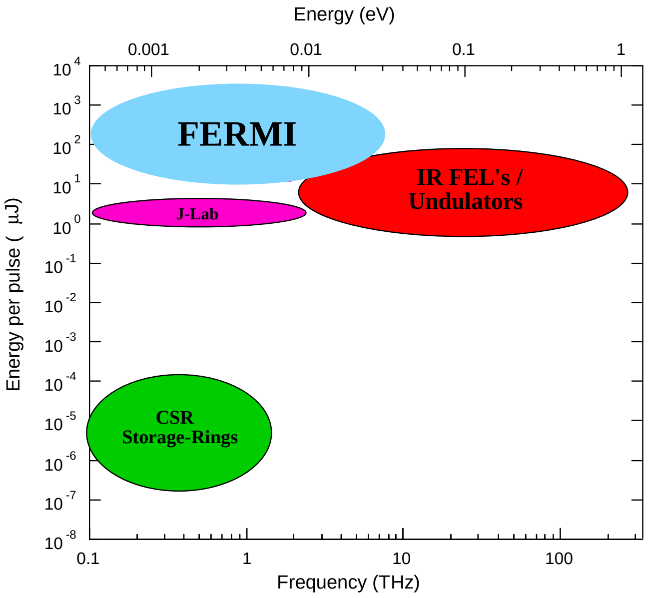
The Ginzburg-Frank equation:

$$\frac{d^2U}{d\omega d\Omega}=\frac{e^2}{4\pi^3\varepsilon_0 c}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}$$

Expected Performance

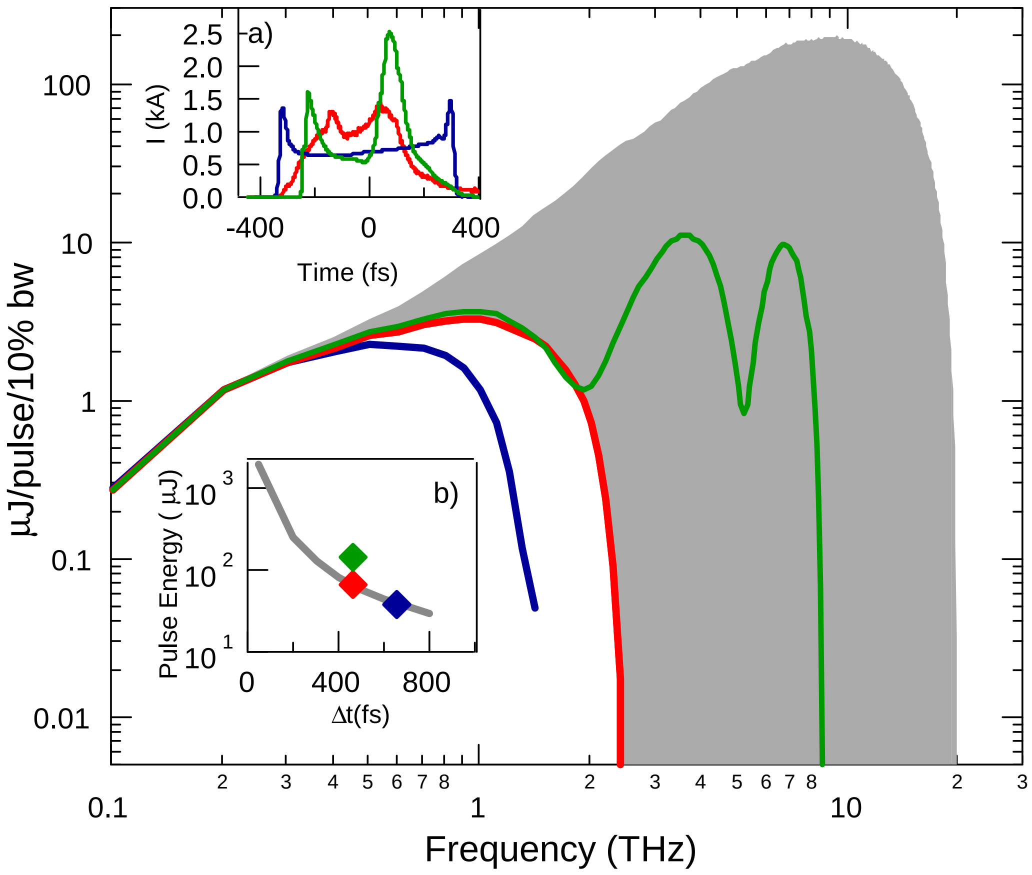


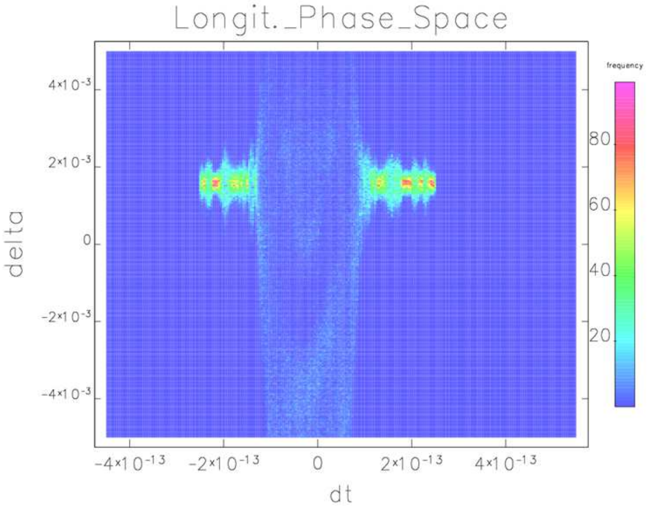
1 nC charge
Flat-top profile

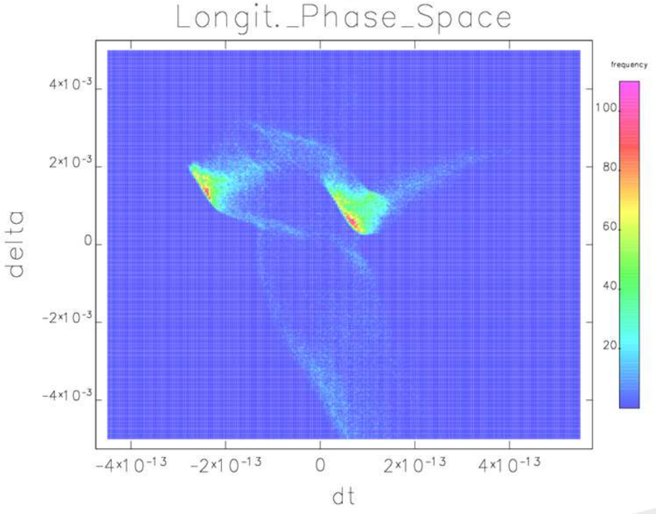


- Energy: $10^{-4} \div 10^{-3}$ J / pulse
- Peak Power: $10^{8} \div 10^{10}$ W
- Electric Fields: 1-100 MV/cm
- Magnetic Fields ~ T

Performance under FEL operation







INSTM FUTURO IN RICERCA

iom Istituto Officina dei Materiali

Conclusions

Exploiting synergies between accelerator-based THz sources

SISSI

Stable, high brightness IR-THz source (10 mm to visible range)

Superconducting gaps, collective modes, High-Pressure studies

TeraFERMI

Ultra-short, high-power THz pulses between 1 mm - 20 μm (0.3 -15 THz)

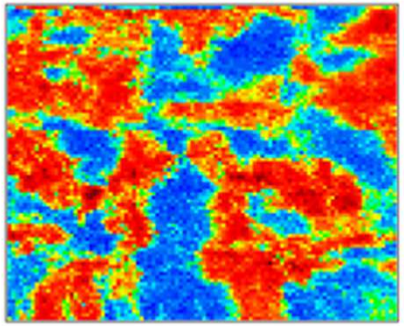
Access to the Reststrahlen-band gap!

Pumping on electronic, vibrational, magnetic excitations

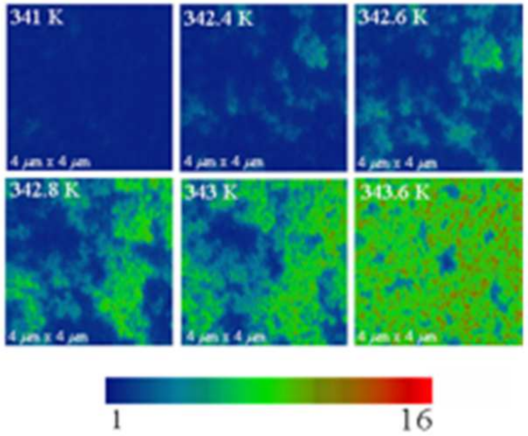
Outlook - Near-Field THz Spectroscopy

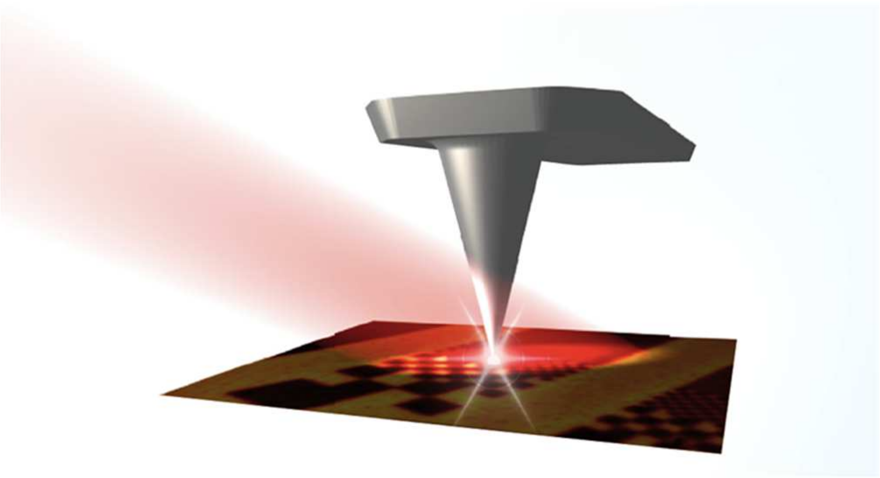
Phase separation phenomena are ubiquitous in strongly correlated electron systems

V_2O_3 (*Lupi, 2010)*



VO_2 *(Qazilbash, 2007)*





Probing free carriers,
SC gaps, vibrational modes on
the local scale with nm resolution

➔ High brightness, THz broadband sources
Synchrotrons, FEL's

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Thank you!