

New Materials for THz and IR Applications

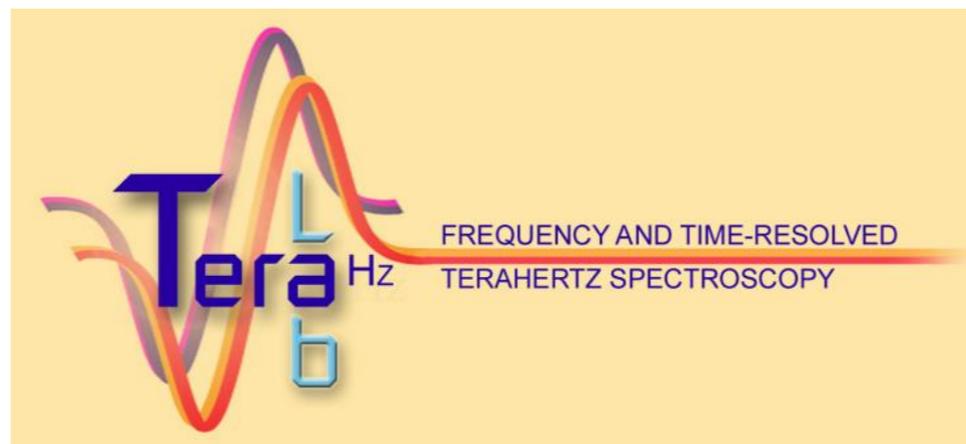
Stefano Lupi

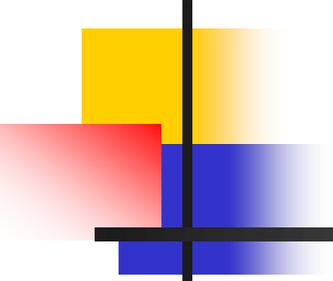
TERALAB

Department of Physics and INFN,
Sapienza University of Rome, Italy



SAPIENZA
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Outline

- New Sources: Properties and Requirements;
- Actual Detectors;
- New Materials:
 1. 3D Topological Insulators;
 2. Graphene;
 3. Transitional Metal Oxides;
- New THz beamline@SPARC_LAB
- Conclusions and Perspectives;

Electromagnetic Spectrum

THz region: Collective Excitations in Macromolecules and exotic electronic materials

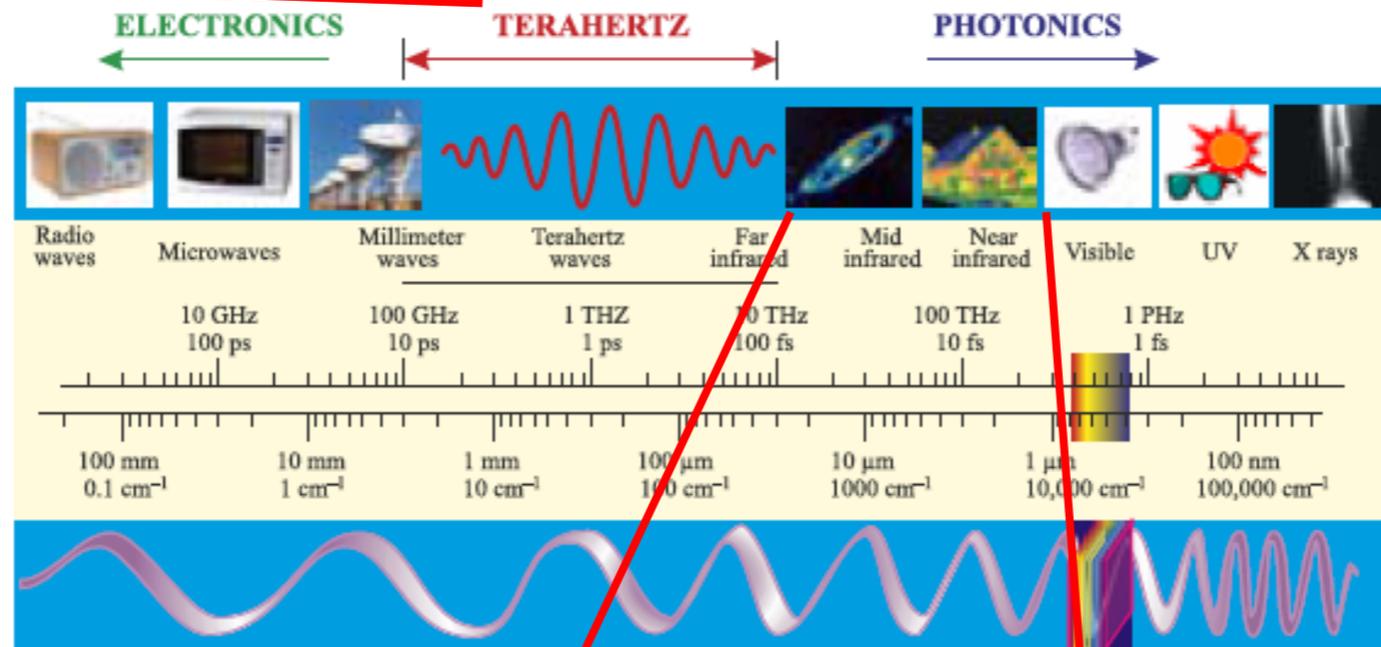


Fig. 1. The electromagnetic spectrum.

IR Units: $200 \text{ cm}^{-1} = 300 \text{ K} = 25 \text{ meV} = 50 \mu\text{m} = 7 \text{ THz}$

FIR MIR NIR

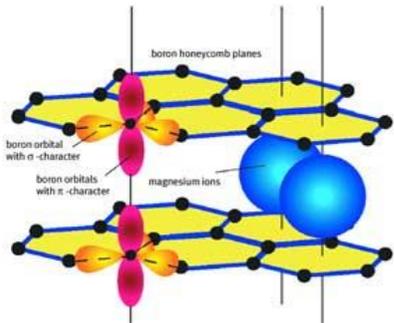
Phonons;
Drude absorption;
Gaps in superconductors;
Molecular Rotations;

Molecular Vibrations
Fingerprints for
Chemistry, Biology,
And Geology

Molecular Overtones and
Combinations bands;
Excitons;
Gaps in semiconductors

Applicazioni THz-IR

Fisica dei Materiali



Grafene e Metateriali 2D
Elettrodinamica e trasporto
Detectors

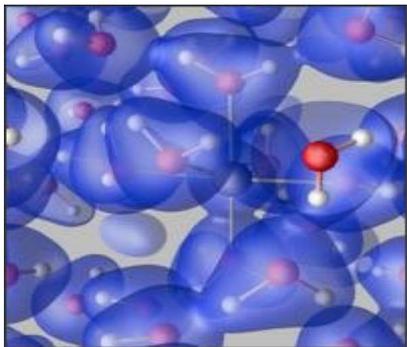
Superconduttività

Gap energetica
Simmetria del parametro d'ordine
Determinazione del peso del condensato
Dinamica veloce delle coppie di Cooper

Transizioni di fase

Controllo del magnetismo
Controllo delle transizioni strutturali

Chimica dei Materiali

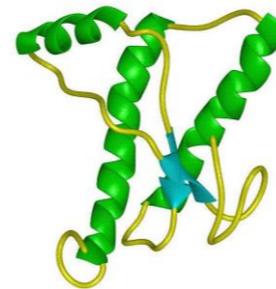


Soluzioni

Legame Idrogeno
Interazioni Van der Waals
Dinamica veloce e controllo e attivazione delle reazioni chimiche

Batterie Li

Scienze della vita



Macromolecole

Studio e controllo della conformazione
Macromolecolare
Dinamica veloce delle macromolecole

Imaging

Tomografia 3Dimensionale di tessuti
Diagnostica tumorale
Microscopia al di là del limite di diffrazione

Nuove Tecnologie e Nuove Tecniche di Accelerazione

Tecnologie THz-IR

Detectors

Materiali innovativi ottici
Imaging THz e IR
Accelerazione e Diagnostica di particelle

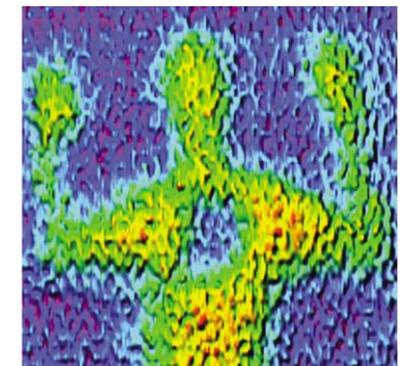
Controllo industriale

Controlli qualità

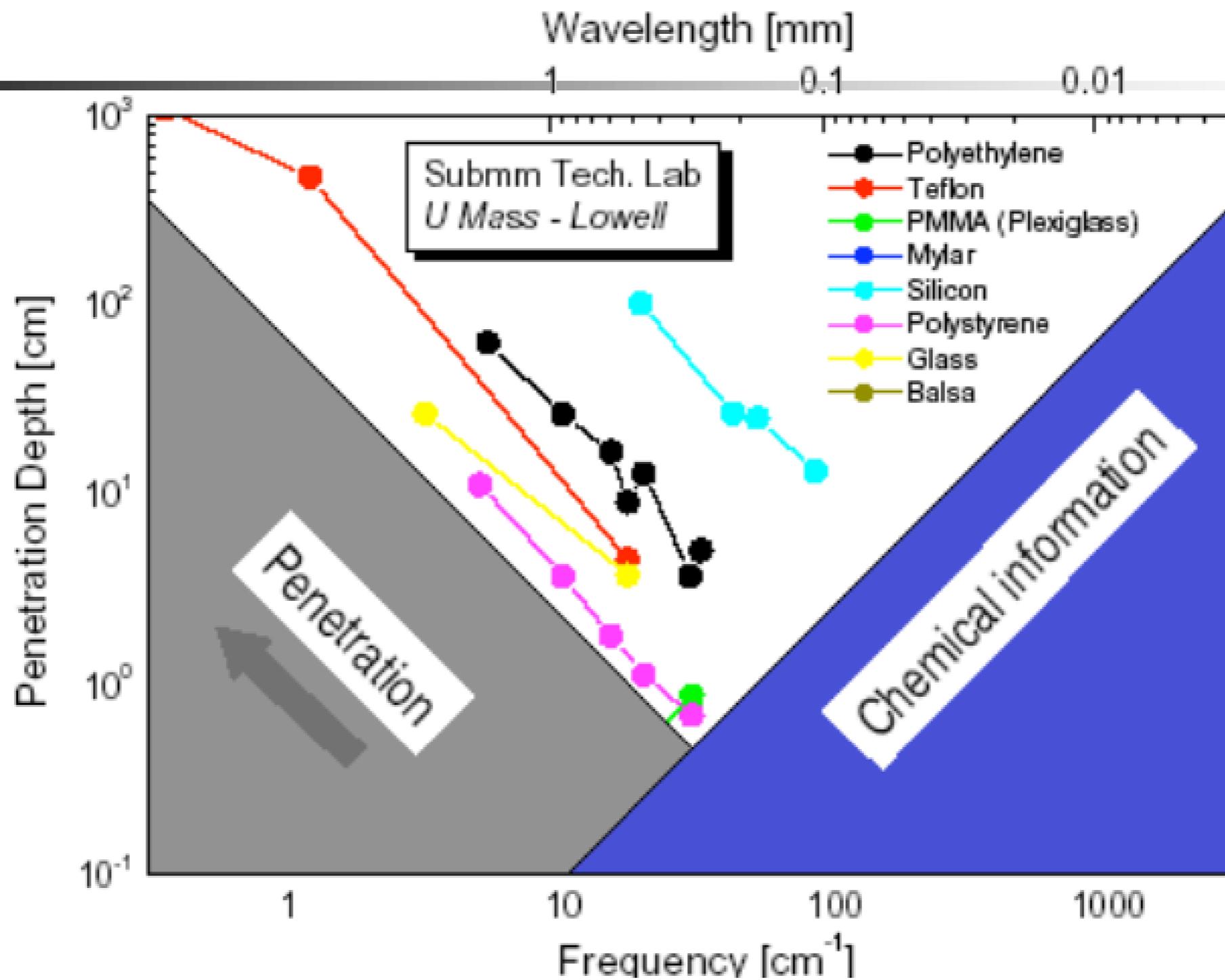
Sicurezza

Bio-hazard

Sicurezza alimentare



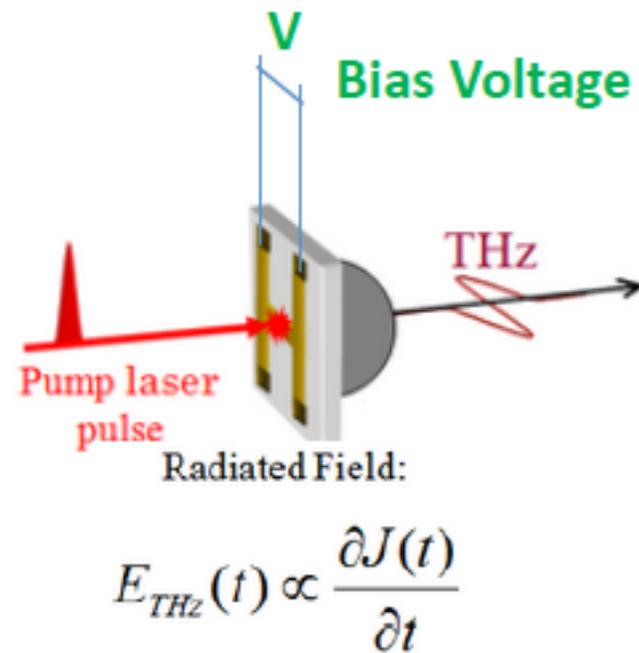
Penetration vs. Chemical Recognizing



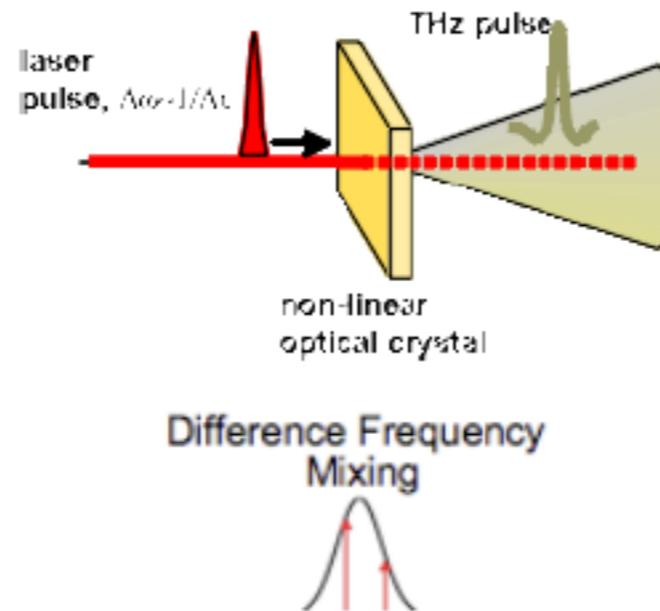
Terahertz Sources

Laser based Sources:

Photoconductive Antennas (PCA)

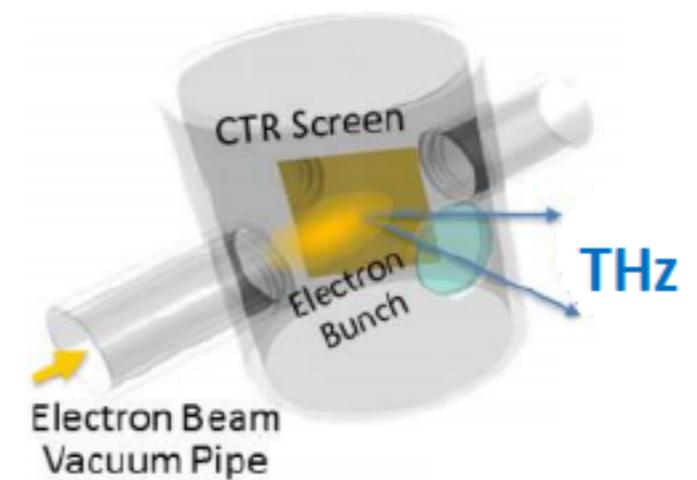


Non-linear Crystals (NLC)



Free electrons based Source

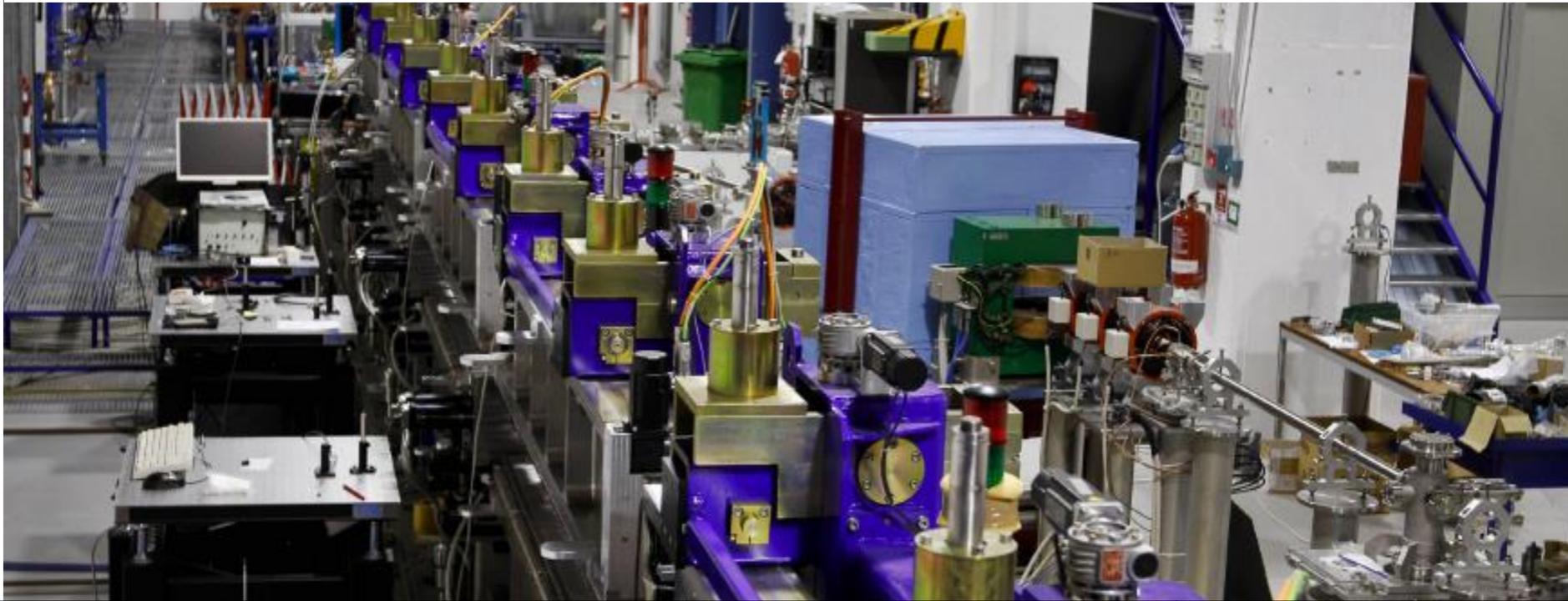
Coherent Transition Radiation (CTR)



	Average THz Power	THz Energy per Pulse	Repetition Rate	Pulse duration	Spectral Range	Lock-in Freq. Oper.
PCA	1 μ W	~pJ	80 MHz	~1	~1 THz	10 KHz
NLC	1 μ W	~ pJ	80 MHz	< 0.15	> 3 THz	~ 1 KHz
CTR	300 μ W	>30 μ J	10 Hz	< 0.2	> 3 THz	--

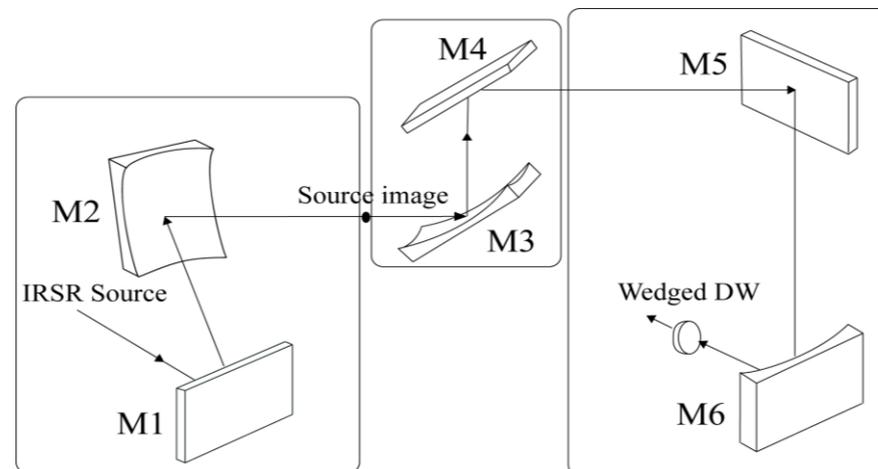
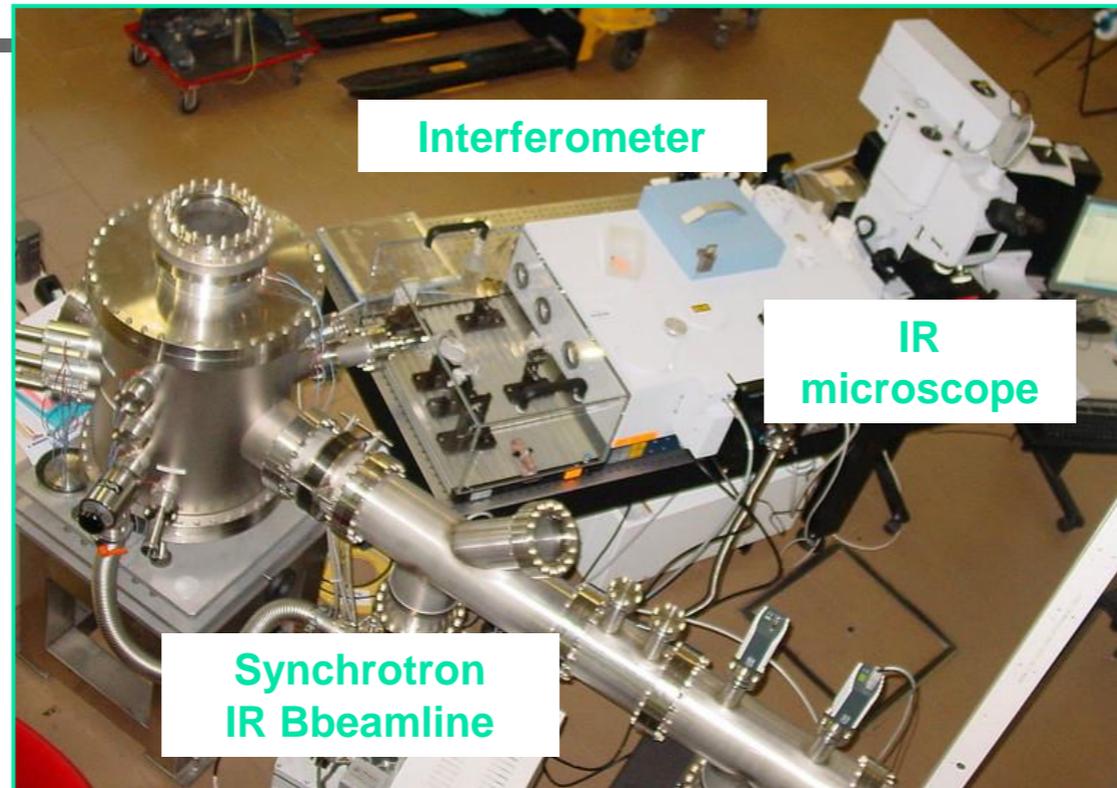
SPARC THz Source

Free Electron Laser SPARC@LNF

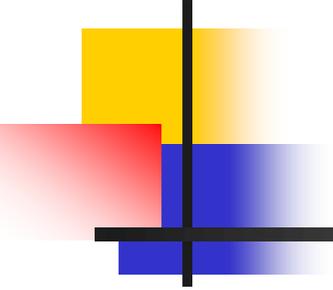


	Electron beam energy	Charge	Δt (bandwidth)	THz pulse energy	E-field
THz@SPARC	120 MeV	500 pC	150 fs (3 THz)	$\approx 30 \mu\text{J}$	MV/cm

Synergy with SINBAD@DAΦNE IR Beamline



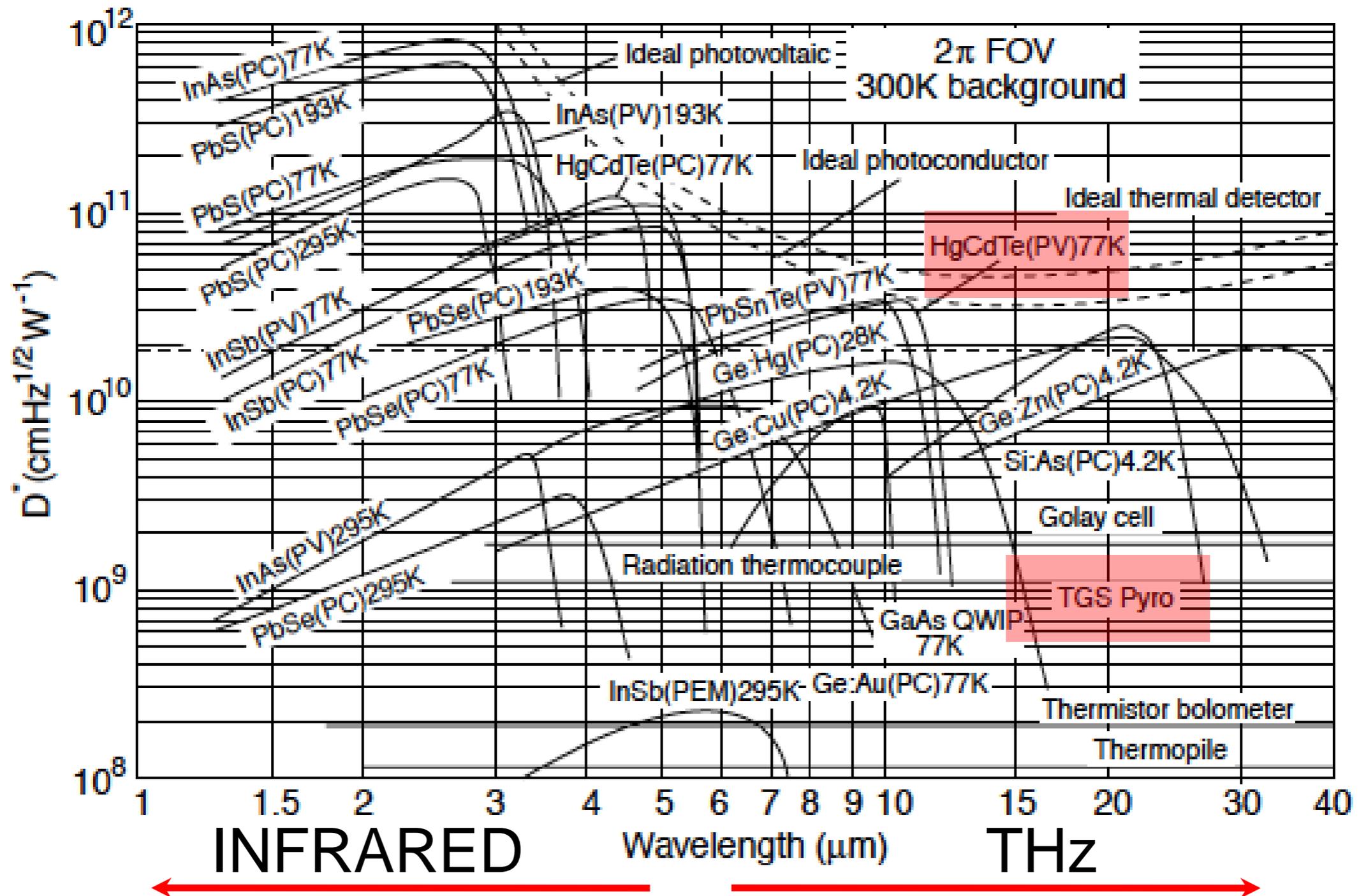
The optical layout



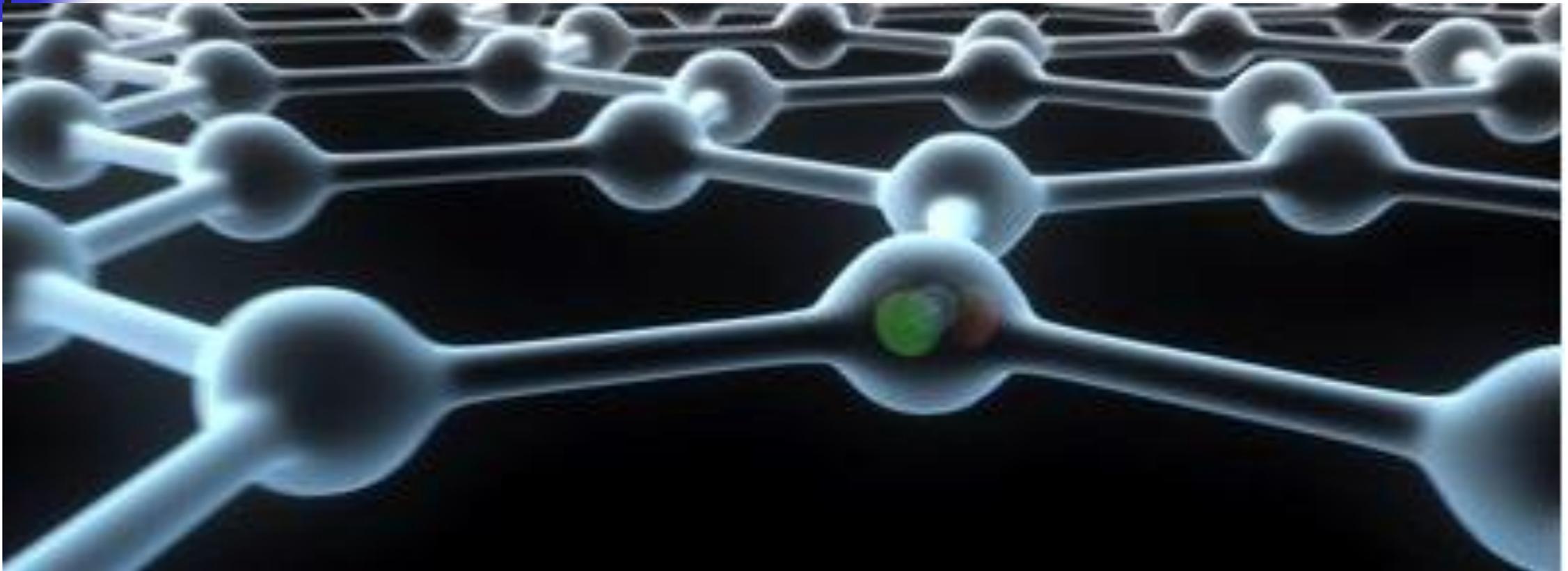
Requirements

1. Fast Detectors → Fast material response;
2. Broad Spectral range and flat response;
3. Non linear response;
4. Beyond the diffraction limit;

Conventional Detectors



2D Dirac Materials



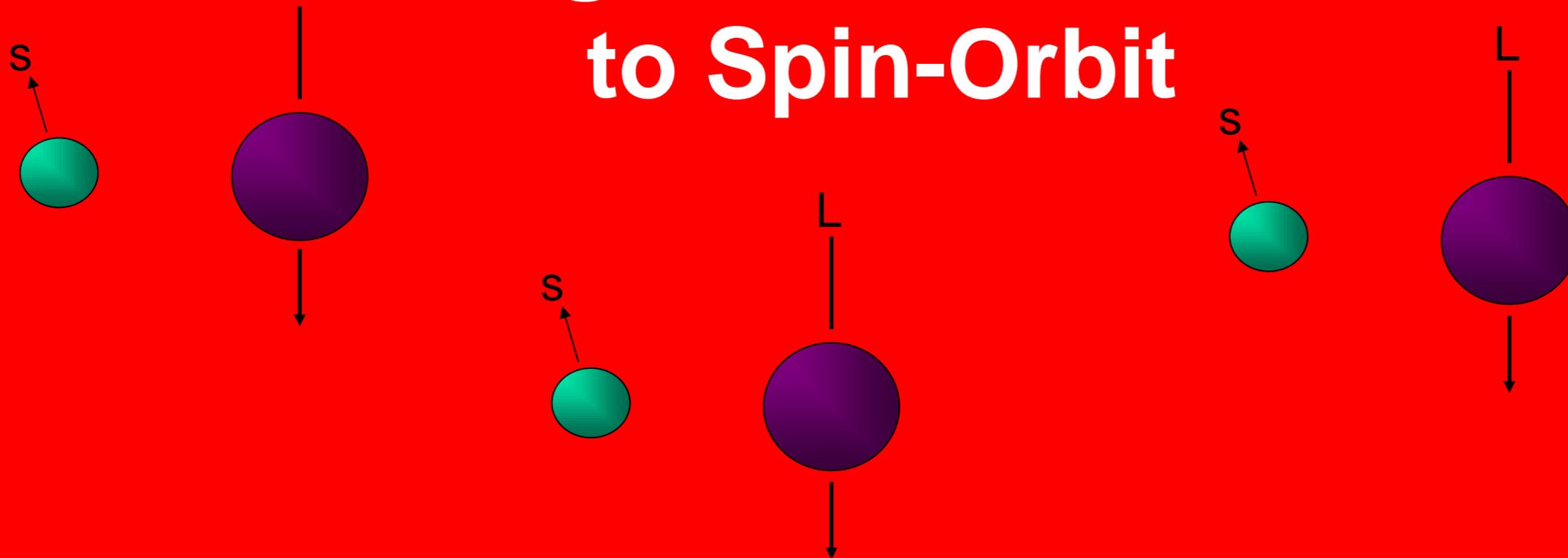
Graphene

- 2D zero gap semiconductor;
- When doped \rightarrow 2D Dirac metal $E(k) = \hbar v_F k$;

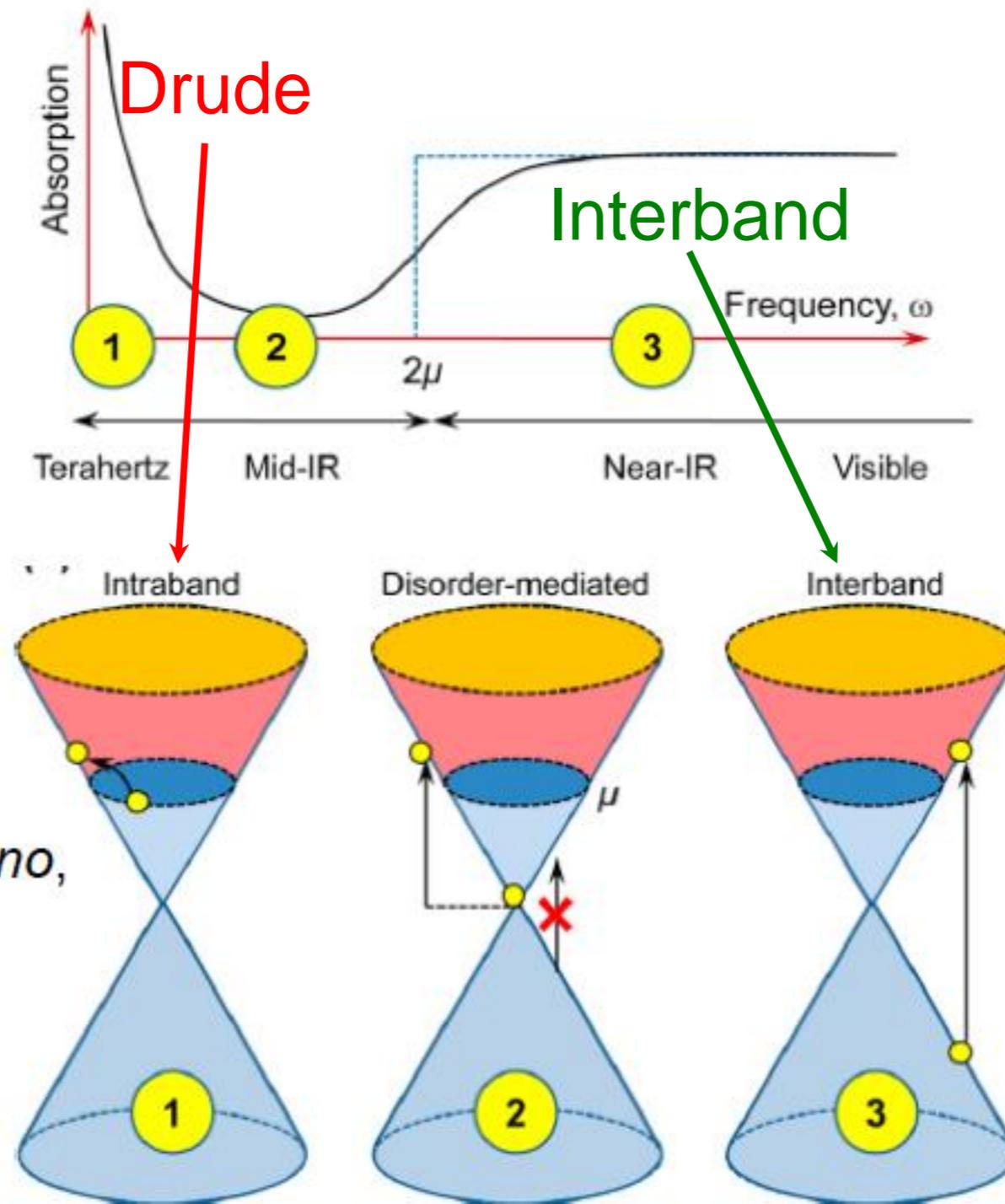
Topological Insulators

Dirac Metallic Surface

Insulating state in the bulk due to Spin-Orbit



2D Electrodynamics



T. Low *et al.*, *ACS Nano*,
2014, 8, 2

2D Dirac Materials as Frequency Transducers

According to the classical equation of motion one electron in an electric field E is accelerated with a momentum variation $dp/dt = -eE$.
 Actually the linear/non-linear regimes can be estimated through the ratio

Massive Electrons

$$\varepsilon(p) = \frac{p^2}{2m}$$

$$d\varepsilon = \frac{p_x}{m} (-eE_0 \sin \omega t)$$

Electromagnetic Momentum

For n electrons one has an

Putting $\omega = 10^{14}$ Hz and p_F

optical functions start to be dependent on the applied electric field.

$$J_x(t) = -en v_x = \frac{ne^2 E_0}{m\omega} \sin \omega t$$

For instance: $T = T(\omega, E_0) \rightarrow$ Induced Transparency

Linear current vs. E Harmonic Generation Nonlinear current vs. E

Dirac Electrons

$$p = \hbar k$$

$$eE = \hbar \omega$$

$$Q = \left[\frac{eE}{\hbar \omega} \right] / \frac{p_F}{\hbar} = \frac{p_F}{\hbar \omega} \frac{eE}{\hbar \omega}$$

$$\varepsilon(p) = v_F \sqrt{p_x^2 + p_y^2}$$

$$\frac{d\varepsilon}{dp_x} = v_F \frac{p_x}{\sqrt{p_x^2 + p_y^2}} = -v_F \operatorname{sgn} \omega t$$

Fermi Momentum

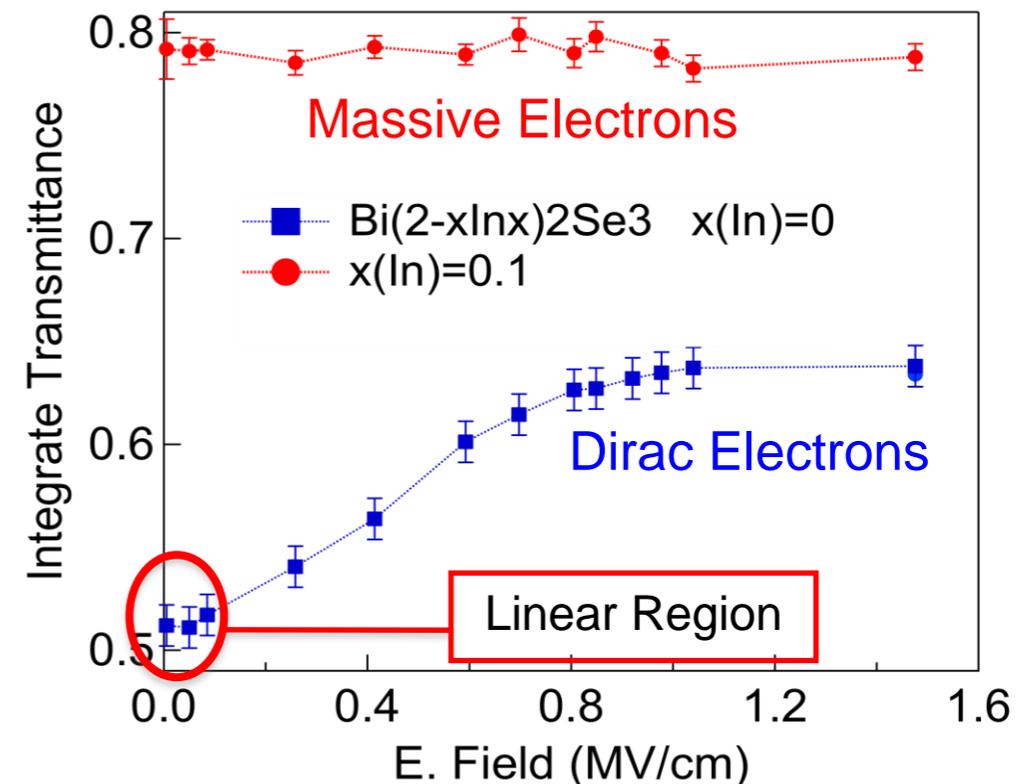
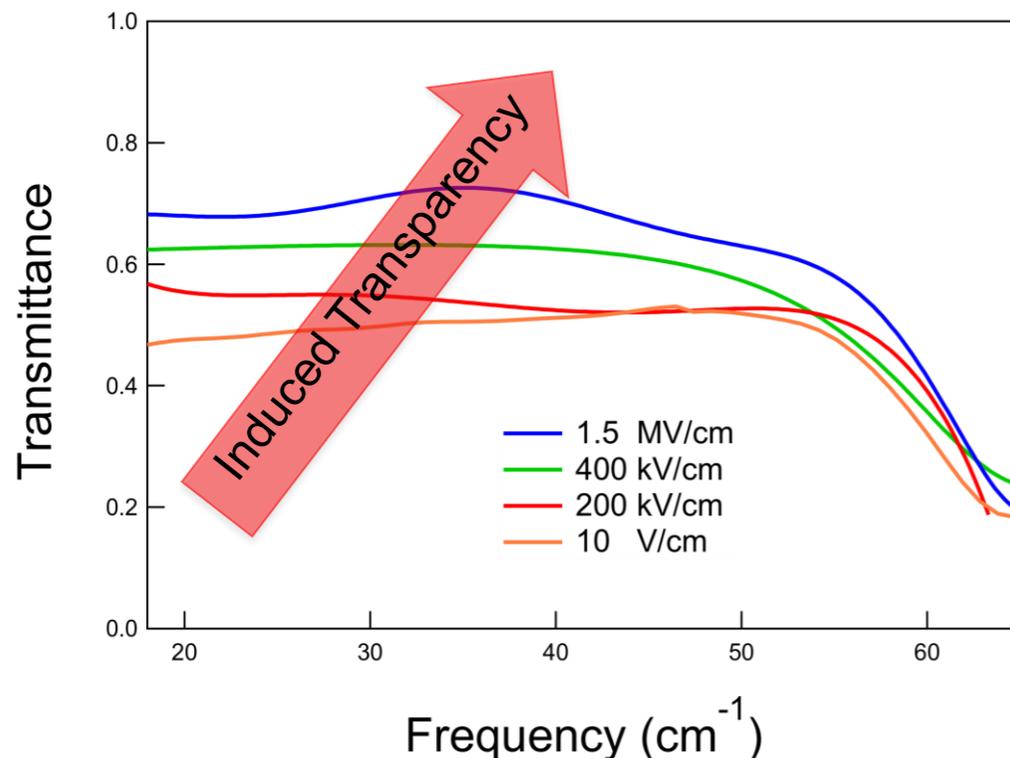
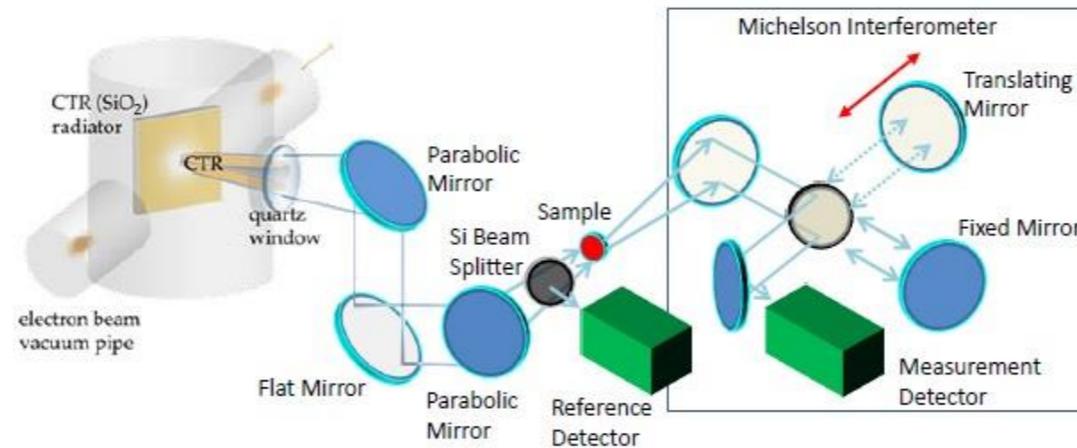
For n electrons one has an

electric current when the

$$J(t) = -en v_x(t)$$

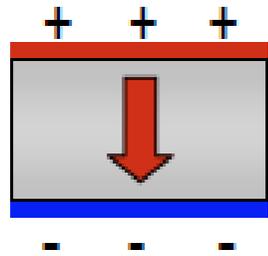
$$= e^2 n v_F \frac{4}{\pi} \left[\sin \omega t + \frac{1}{3} \sin 3\omega t + \dots \right]$$

Non Linear THz effect in Topological Insulators and Harmonic Generation



2D Plasmonics

Plasma oscillations = density fluctuations of free-electrons



Plasmons in the bulk oscillate at ω_p determined by effective mass m^* and 3D charge density N

$$\omega_p = \sqrt{\frac{Ne^2}{m^* \epsilon_0}}$$

Graphene Sheet

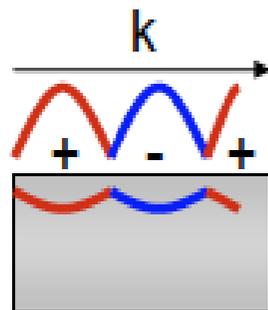
Nano-structure

Graphene Sheet

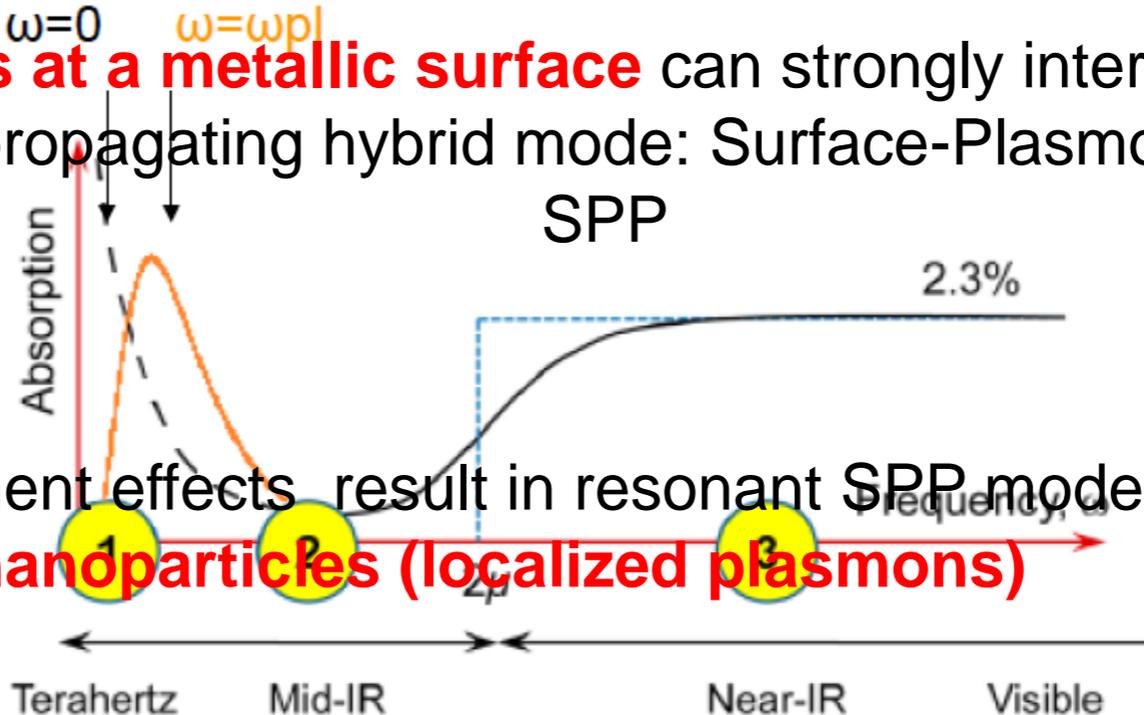
Graphene nanostructure

Drude transport

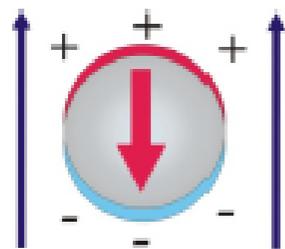
Plasmon mode



Plasmons at a metallic surface can strongly interact with light forming propagating hybrid mode: Surface-Plasmon-Polariton

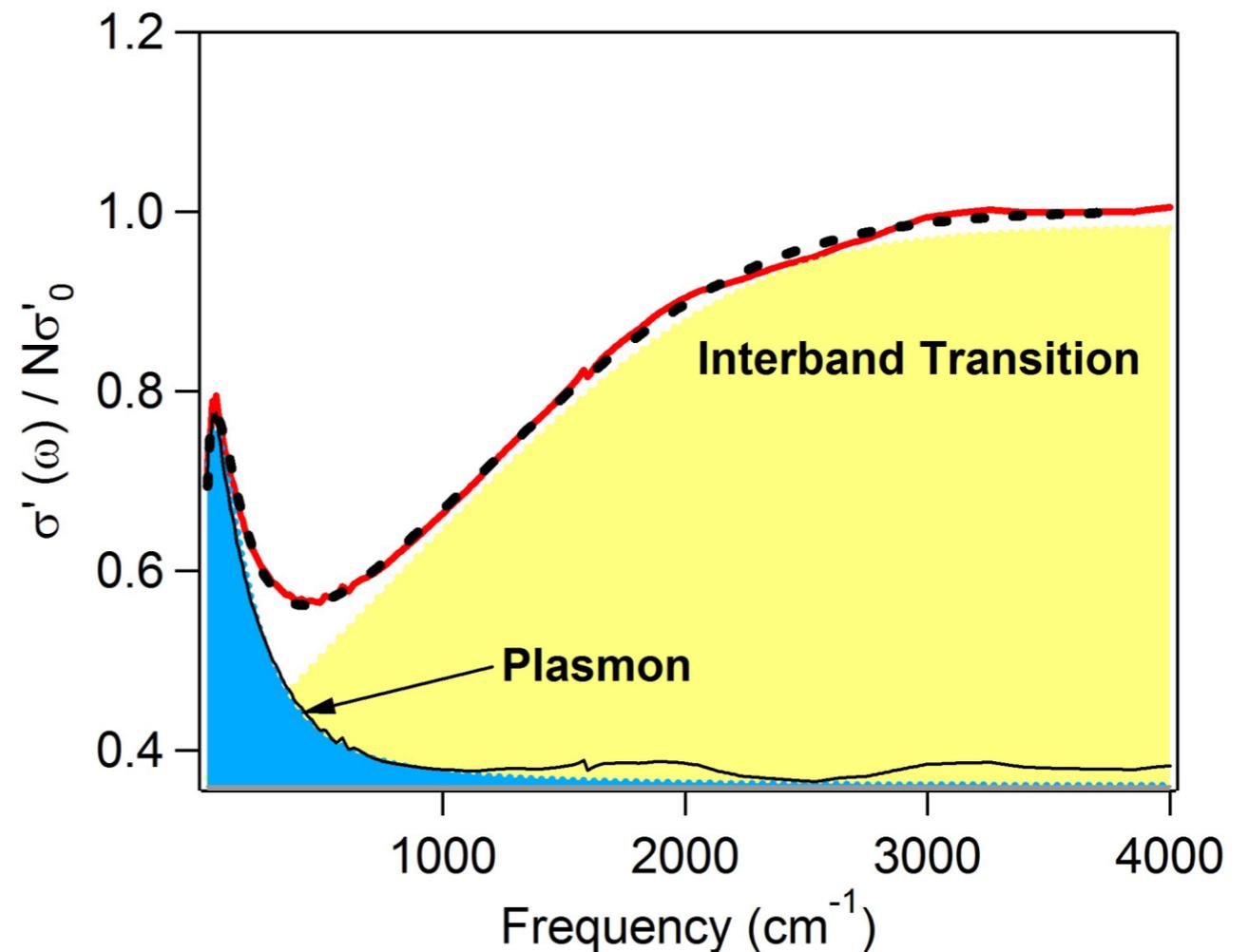
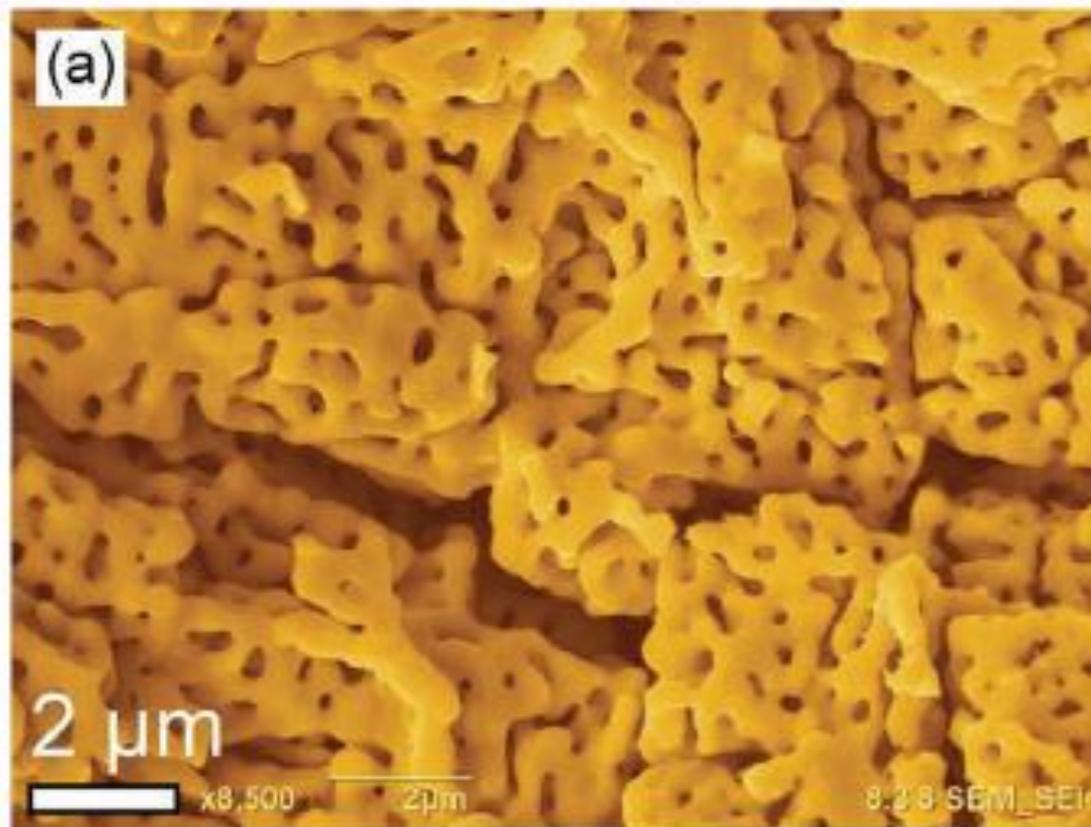


Confinement effects result in resonant SPP modes in **nanoparticles (localized plasmons)**



Plasmonics in Nanoporous Graphene

in collaboration with Y. Ito (Tokyo Univ.), A. Marcelli (INFN-LNF)



F. D'Apuzzo et al, 2015

Superconductivity-Induced Transparency in Terahertz Metamaterials

Odetta Limaj,^{*,†,⊗} Flavio Giorgianni,[†] Alessandra Di Gaspare,[‡] Valeria Giliberti,^{‡,§} Gianluca de Marzi,[⊥] Pascale Roy,^{||} Michele Ortolani,[§] Xiaoxing Xi,[△] Daniel Cunnane,[△] and Stefano Lupi[#]

[†]INFN and Department of Physics, Sapienza University of Rome, Rome, Italy

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[⊥]ENEA, Frascati Research Centre, Frascati, Italy

^{||}Synchrotron SOLEIL, Gif-sur-Yvette, France

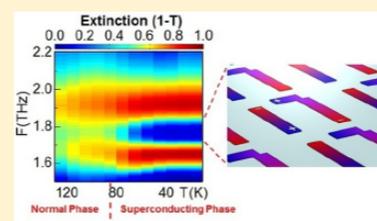
[△]Department of Physics, Temple University, Philadelphia, Pennsylvania 19122, United States

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[⊗]Institute of Bioengineering, École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland

 Supporting Information

ABSTRACT: A plasmonic analogue of electromagnetically induced transparency is activated and tuned in the terahertz (THz) range in asymmetric metamaterials fabricated from high critical temperature (T_c) superconductor thin films. The asymmetric design provides a near-field coupling between a superradiant and a subradiant plasmonic mode, which has been widely tuned through superconductivity and monitored by Fourier transform infrared spectroscopy. The sharp transparency window that appears in the extinction spectrum exhibits a relative modulation up to 50% activated by temperature change. The interplay between ohmic and radiative damping, which can be independently tuned and controlled, allows for engineering the electromagnetically induced transparency of the metamaterial far beyond the current state-of-the-art, which relies on standard metals or low- T_c superconductors.



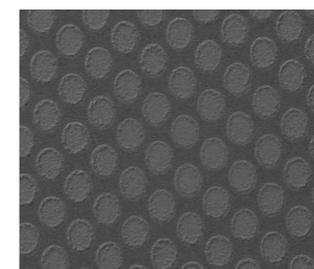
Observation of Dirac plasmons in a topological insulator

P. Di Pietro^{1,2}, M. Ortolani^{2,3}, O. Limaj^{2,4}, A. Di Gaspare³, V. Giliberti^{2,3}, F. Giorgianni^{2,4}, M. Brahlek⁵, N. Bansal⁵, N. Koirala⁵, S. Oh⁵, P. Calvani^{1,2} and S. Lupi^{2,4,6*}

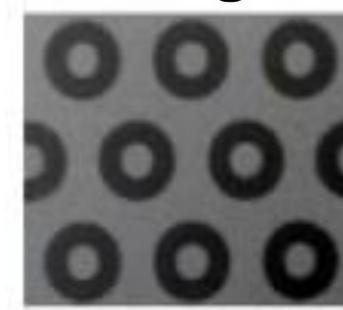
Ribbons



Disks

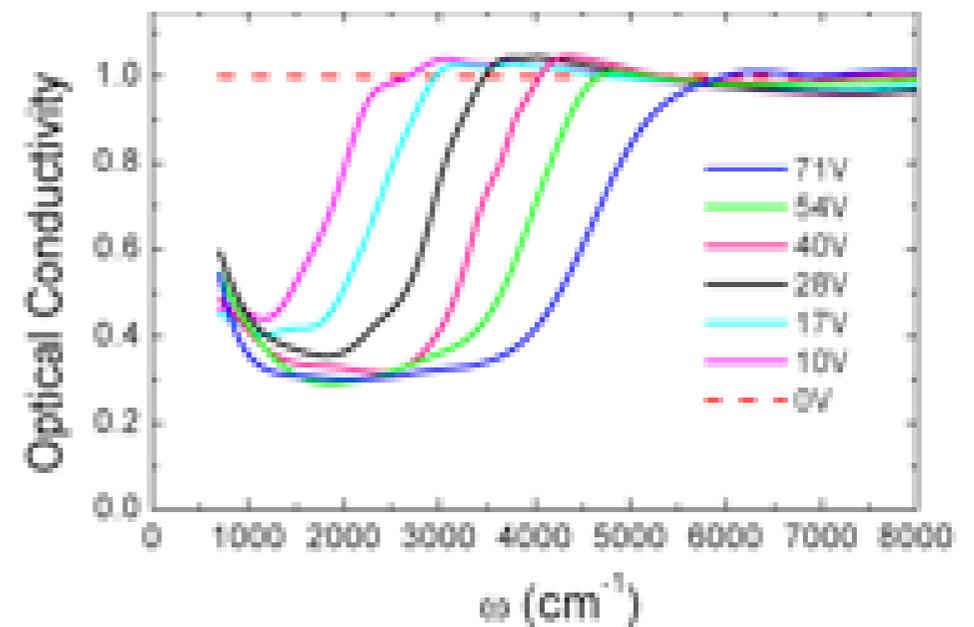
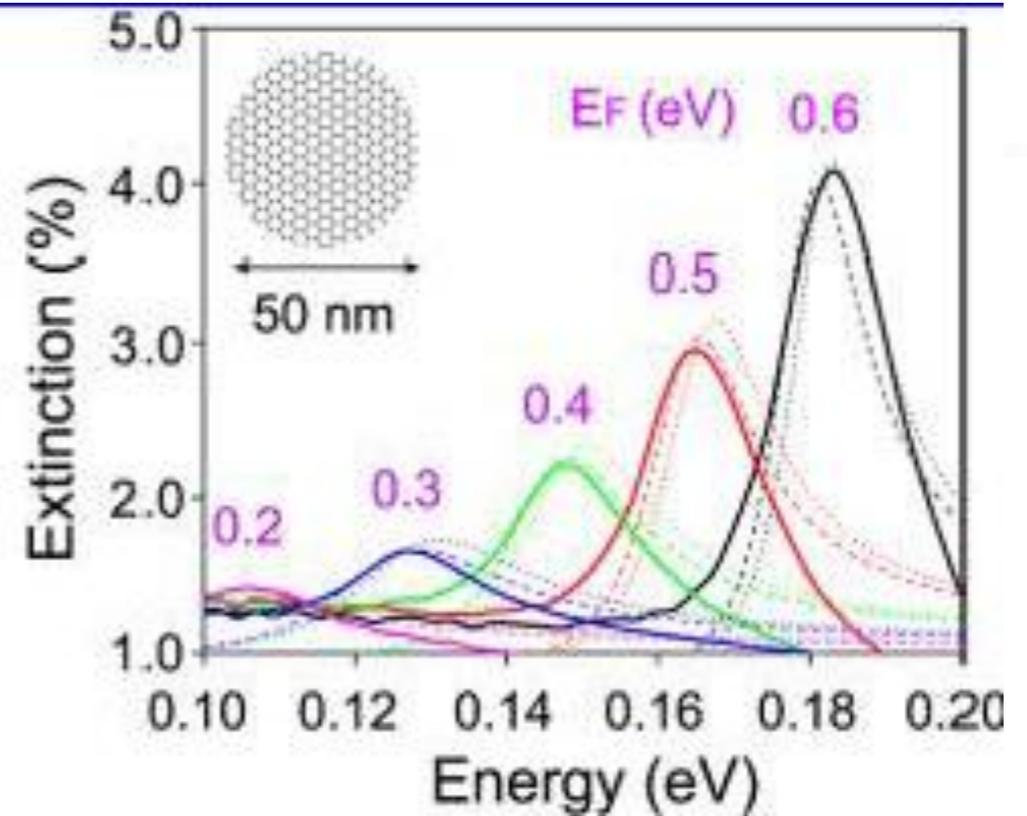
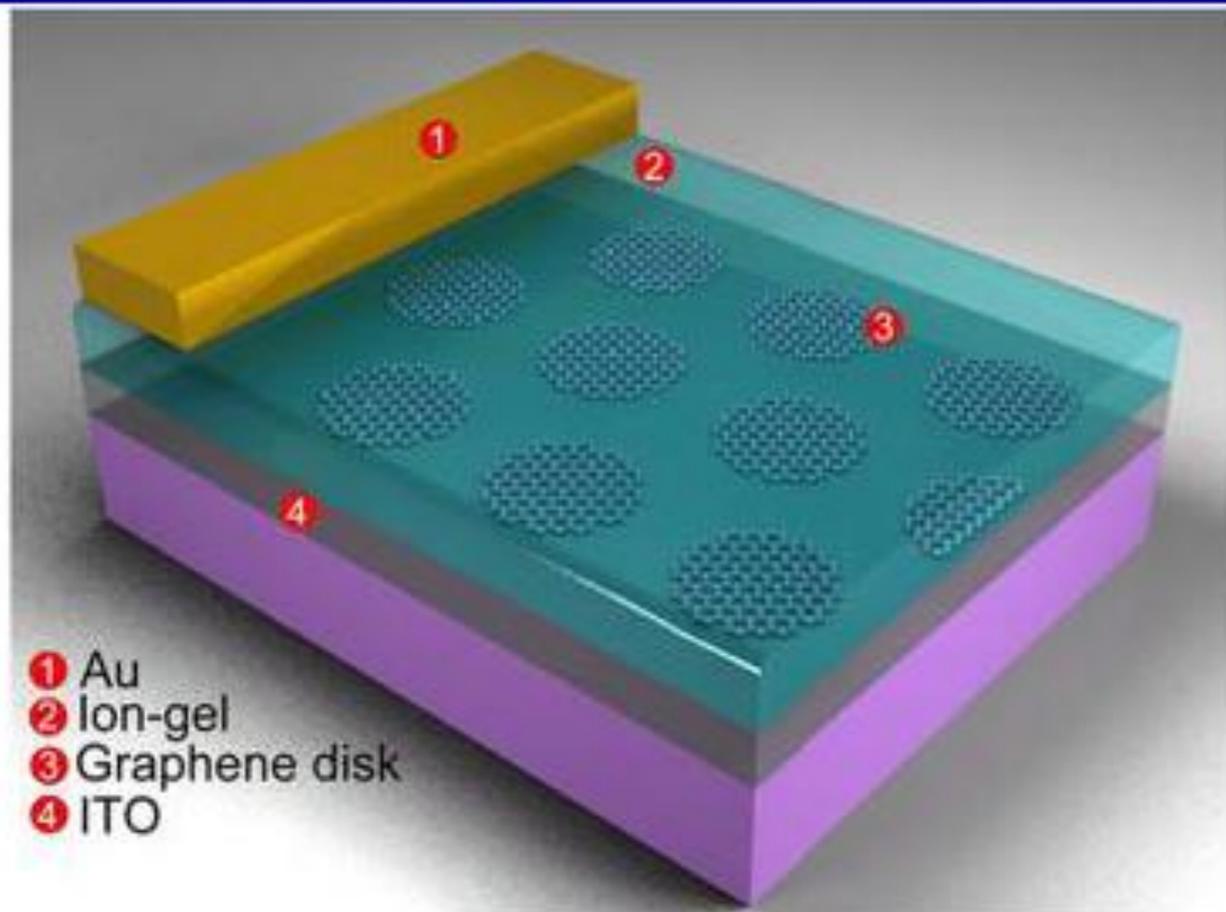


Rings



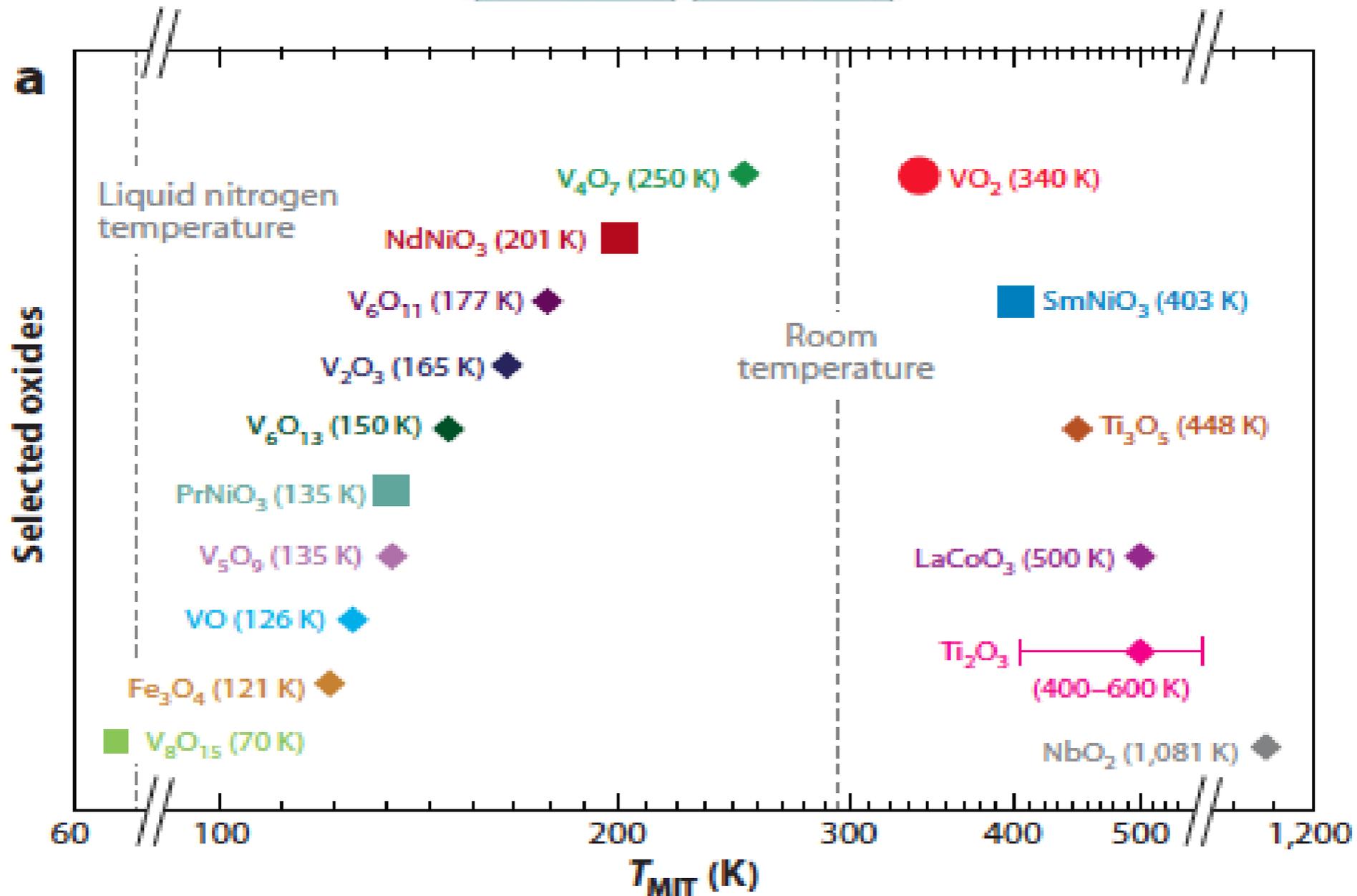
2D Tunable Plasmonics

in collaboration with J.G. De Abajo (Spain), R. Gonnelli, Politecnico Torino and INFN



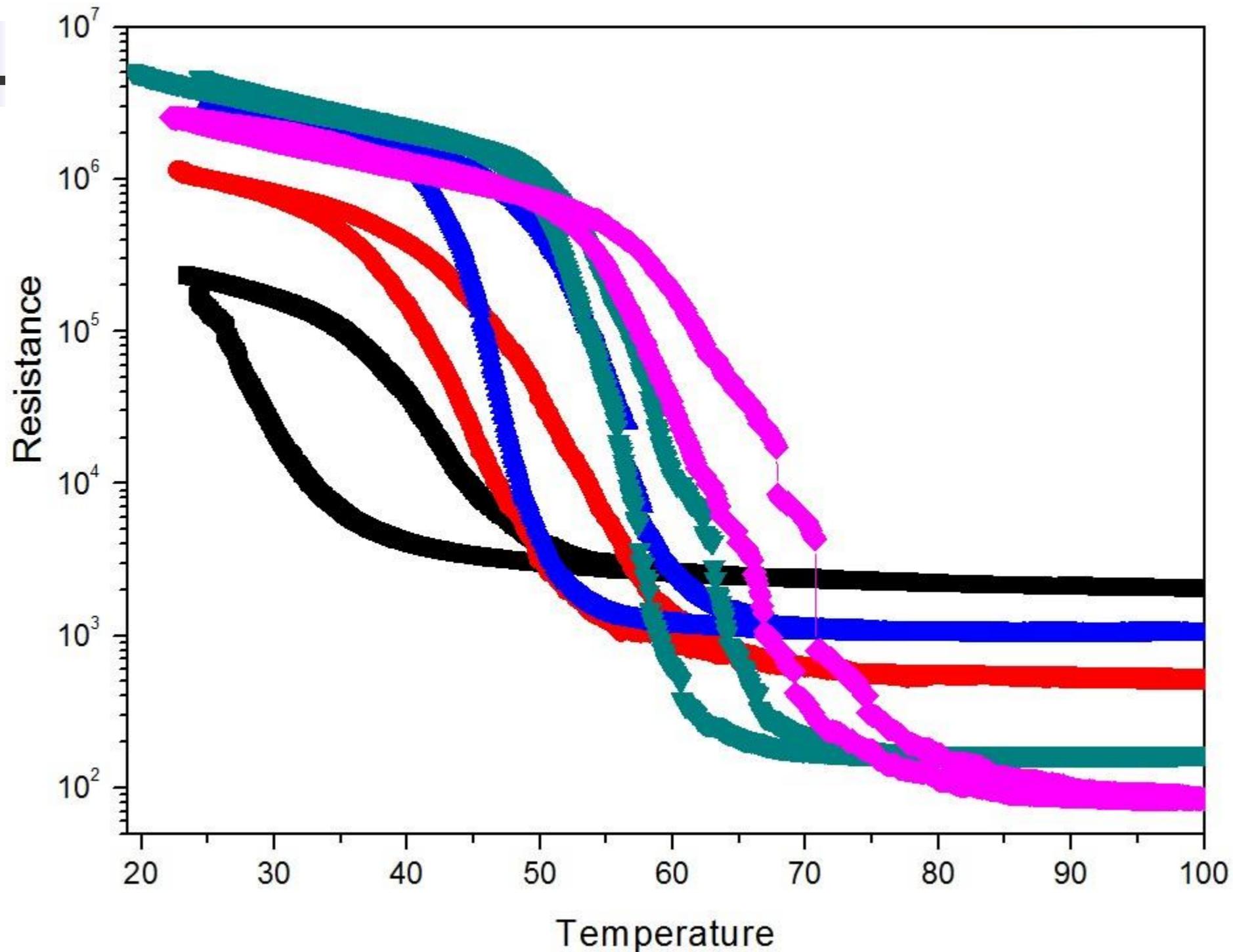
J. G. De Abajo et al, ACS Nano

Metal-Insulator Transition in selected oxides

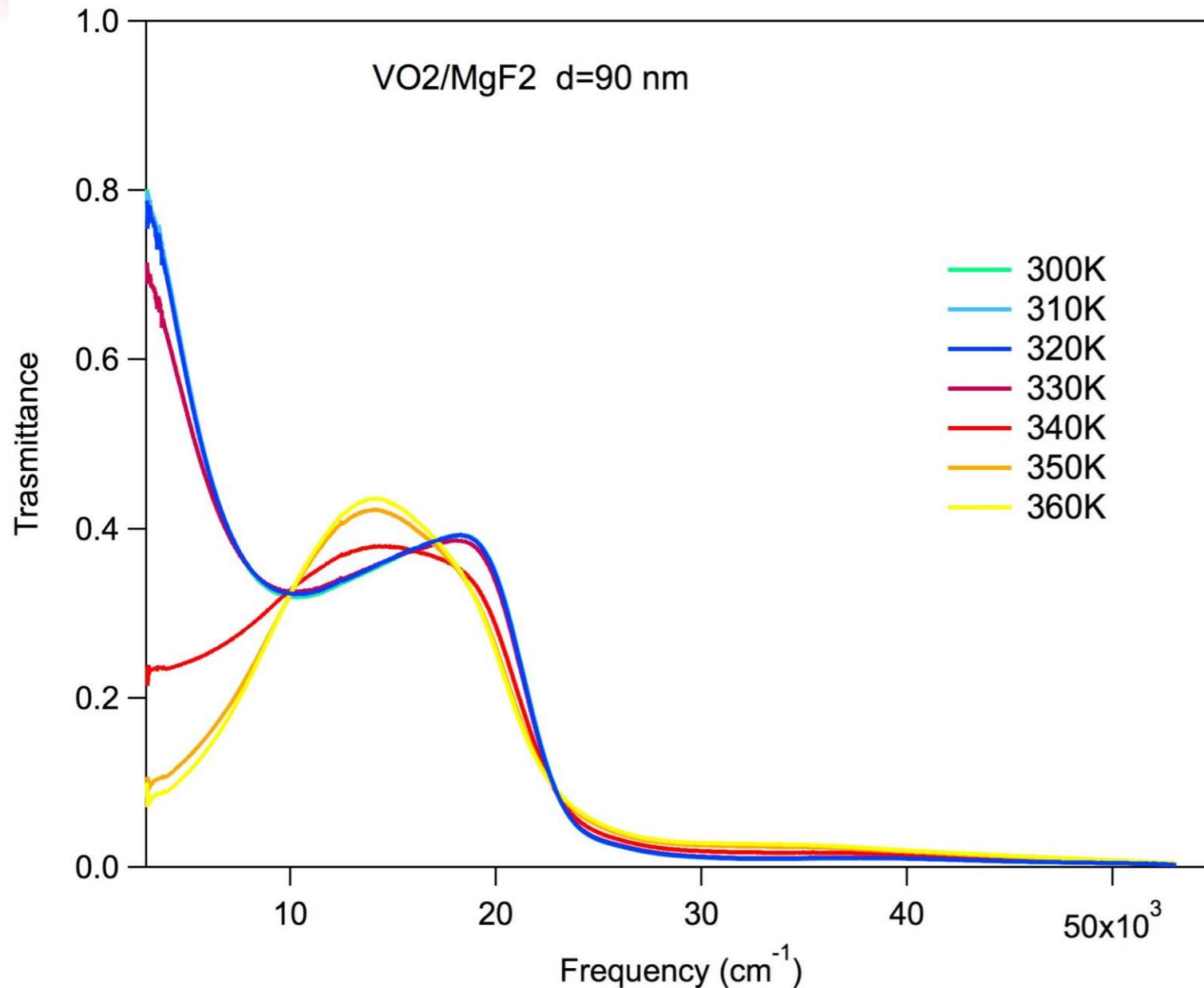


VO₂ Films

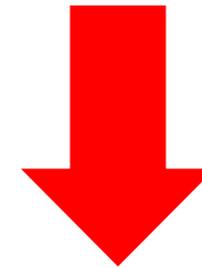
In collaboration with Z.Y. Wu, Univ. of Science and Tech. Hefei China and
A. Marcelli LNF-INFN



VO₂ Transmittance vs. MIT



Strong Dependence on T



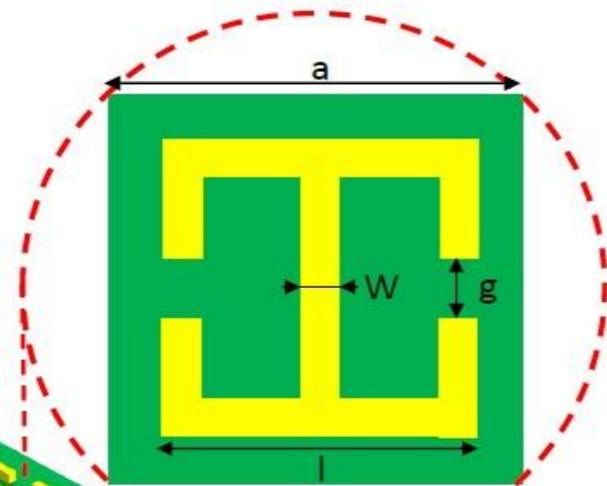
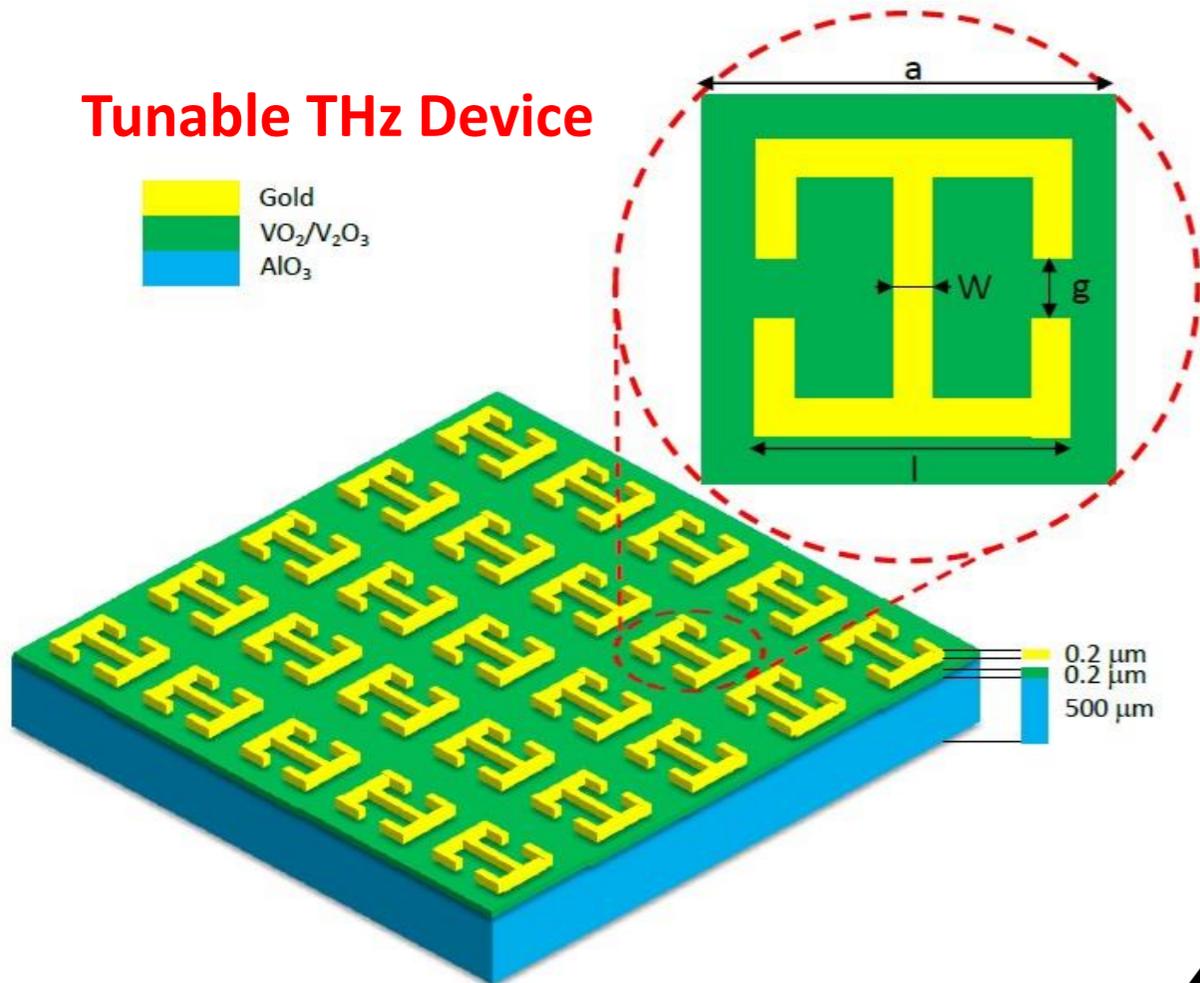
VO₂ Bolometer
and THz Camera

V₂O₃ based devices

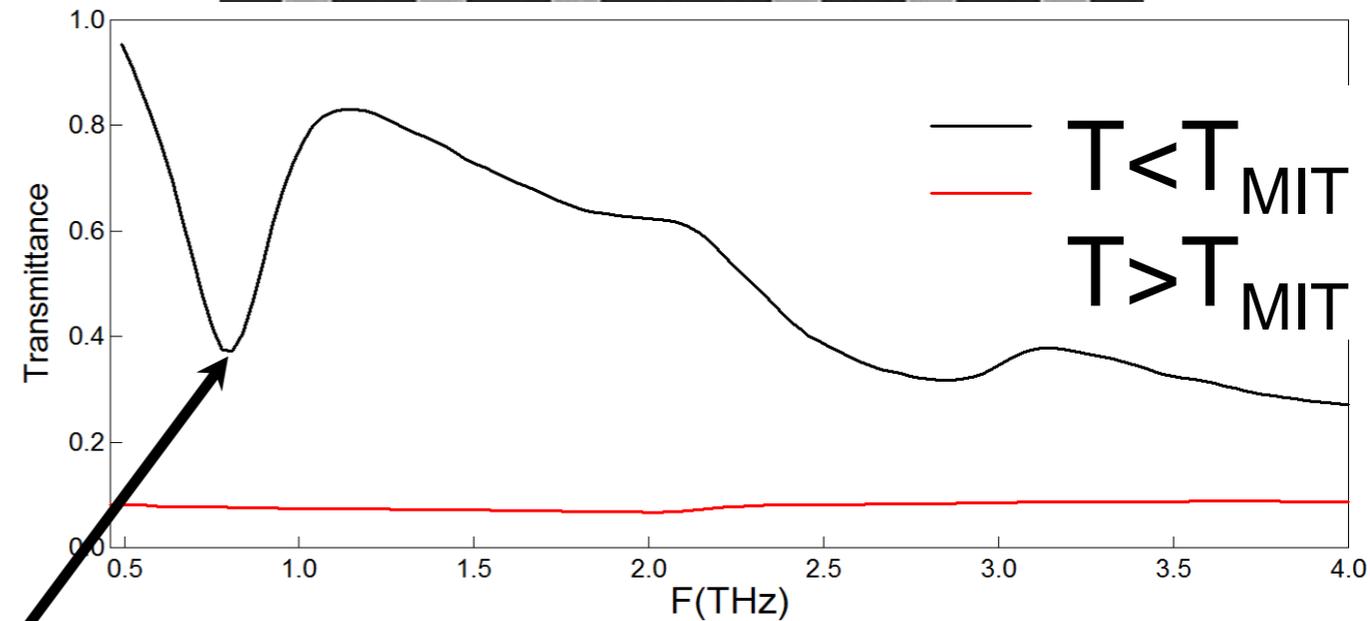
(in collaboration with University of Pavia and IIT)

Study of transmittance vs THz intensity of V₂O₃ resonators

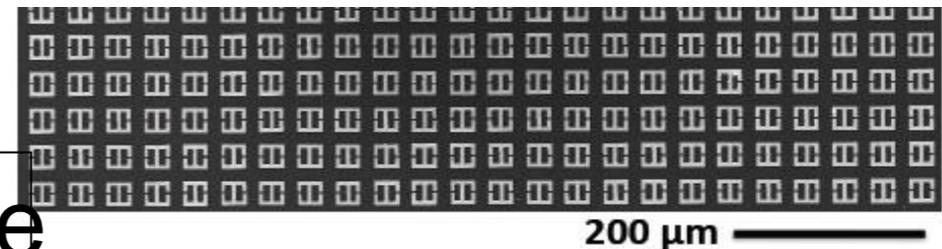
Tunable THz Device



Low THz Field Transmittance



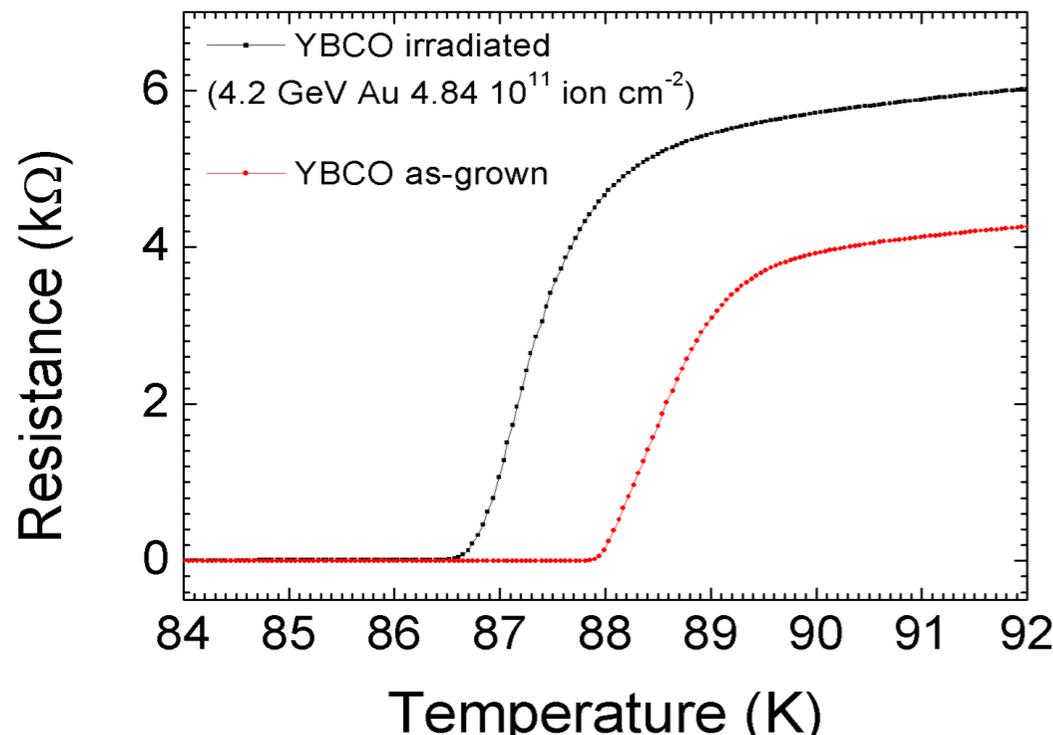
LC Resonance



Sviluppo di detectors THz basati su HCTS

Torino+LNS+Roma I+LNF

- **High-temperature superconducting (YBCO) detector, operating above the liquid Nitrogen temperature;**
- **Local nanostructuring with high energy heavy ions (HEHI) for reducing the critical temperature (*controlled* ΔT_c) and increasing the resistance versus temperature slope ($\partial R/\partial T$);**

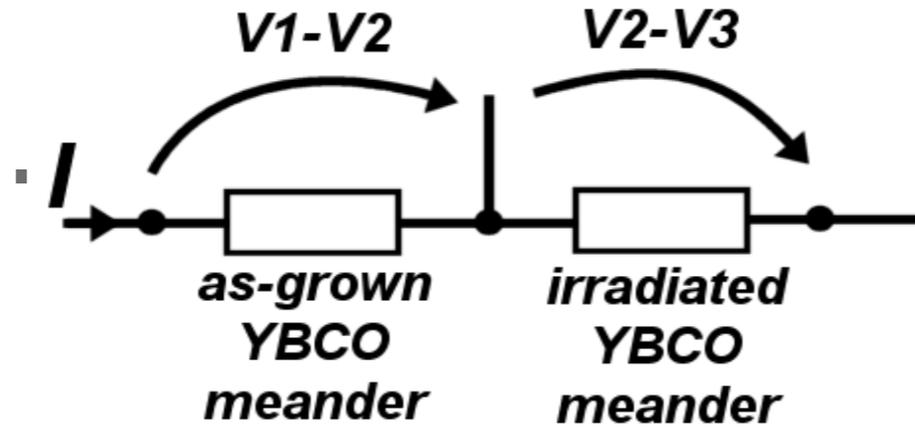
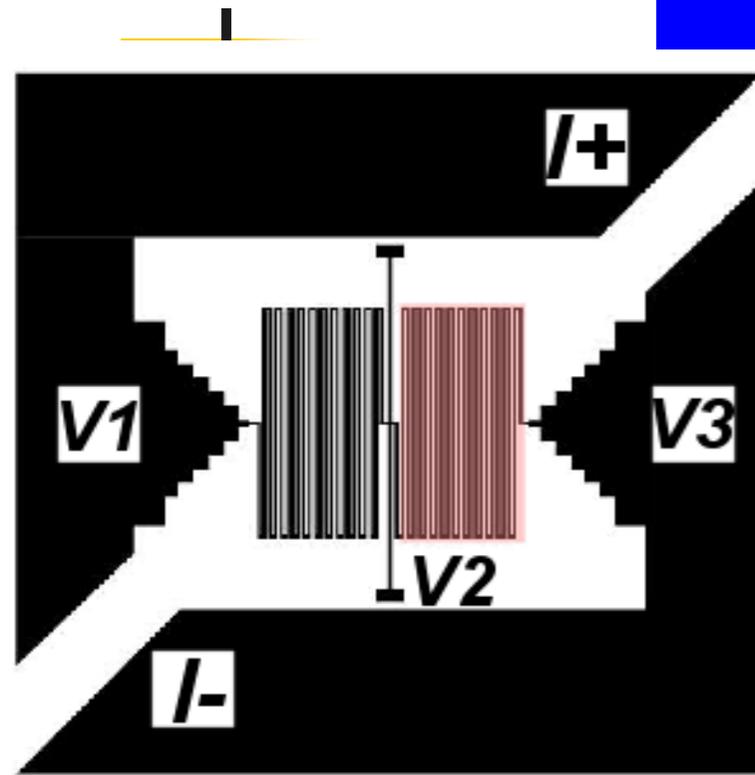


Control of T_c $\Delta T_c = 2$ K

Slope $\partial R/\partial T > 5$ kW/K

Increased (higher sensitivity)

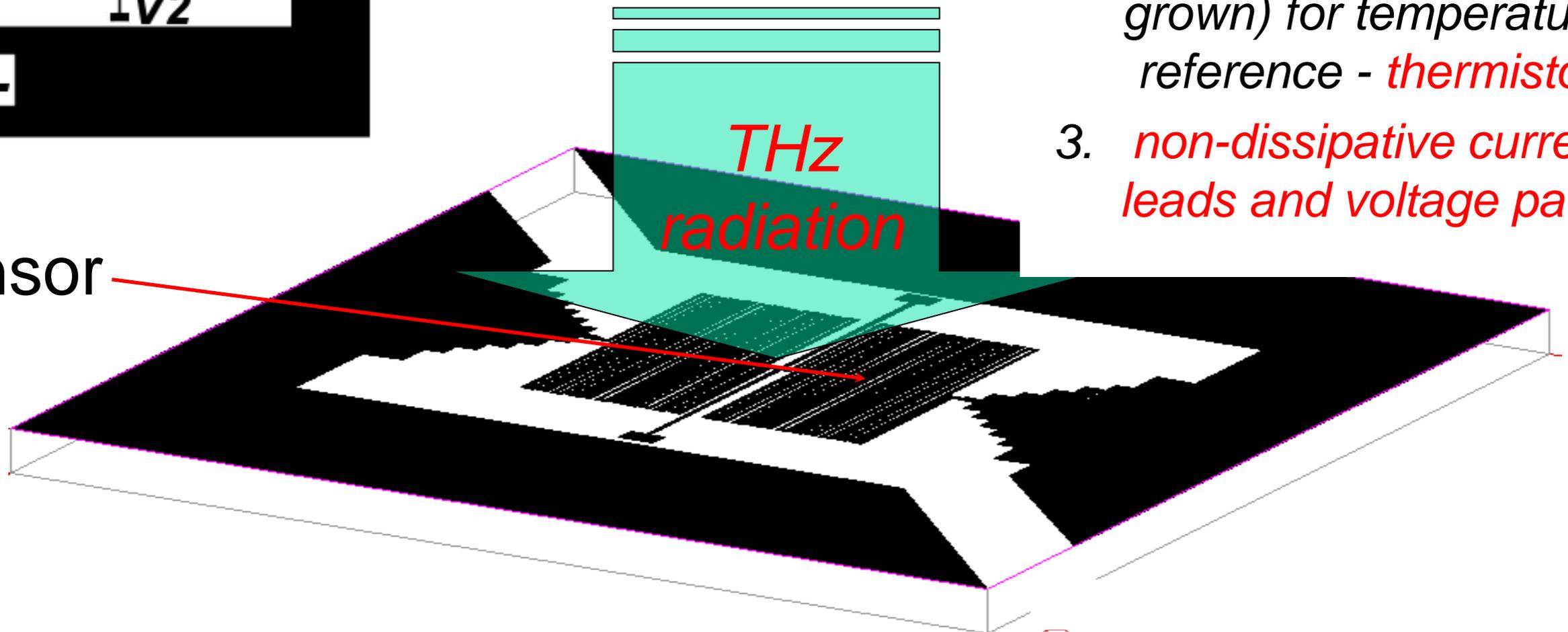
Device Layout



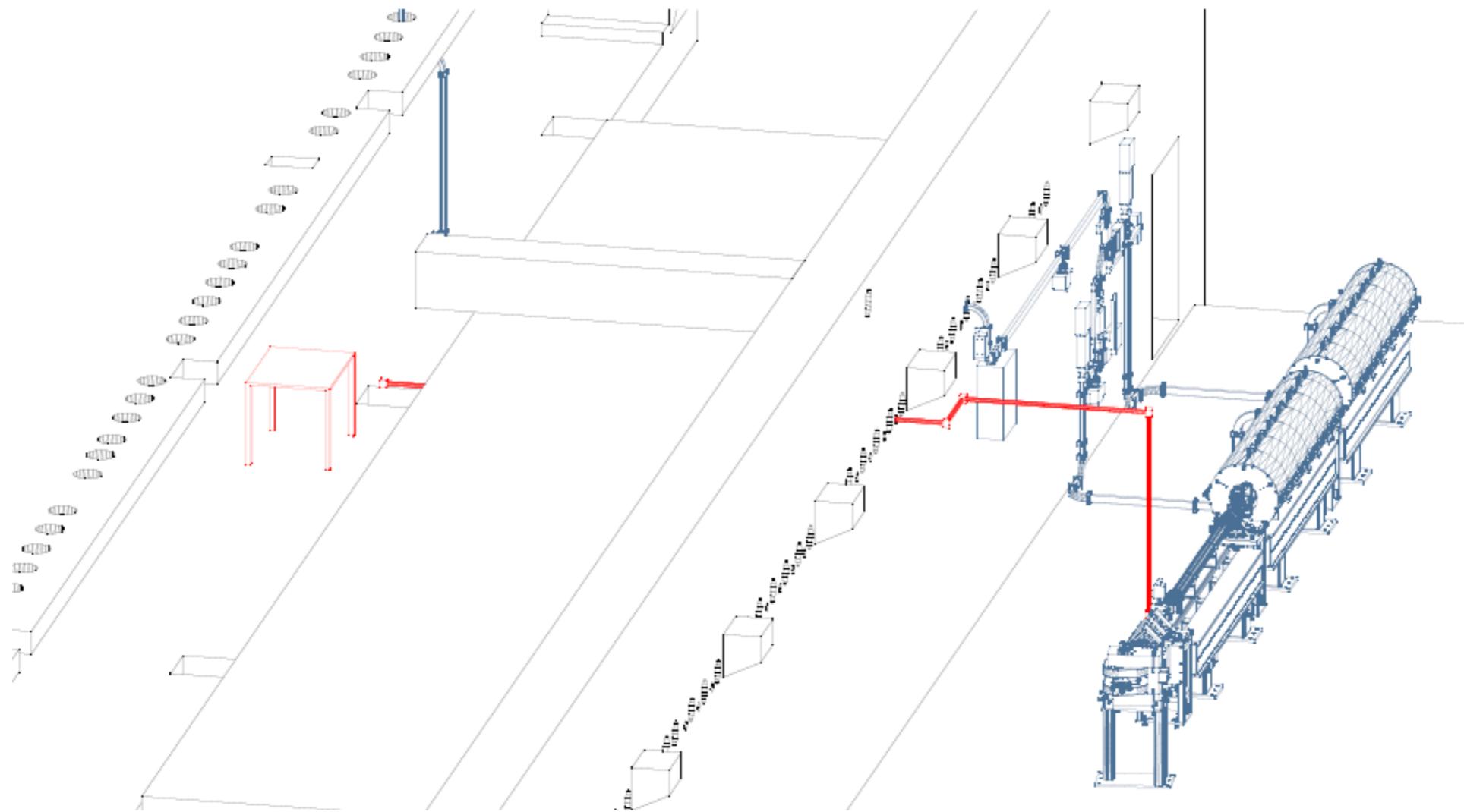
Three integrated devices:

1. one meander is *uniformly irradiated* – **sensor** (YBCO with reduced T_c)
2. reference meander (as-grown) for temperature reference - **thermistor**
3. **non-dissipative current leads and voltage pads**

sensor



Project for a THz Beamline



F. Giorgianni, et al

Conclusioni e Prospettive

- 1) C'è estremo interesse nella generazione e uso della radiazione THz per diagnostica e esperimenti di spettroscopia e biomedica;
- 2) La sorgente THz a SPARC è estremamente competitiva in ambito mondiale
 $E \approx 1.5 \text{ MV/cm}$; $B \approx 1 \text{ T}$ con durate inferiori a 100 fs;
- 3) Costruzione di una beamline esterna al bunker di SPARC;