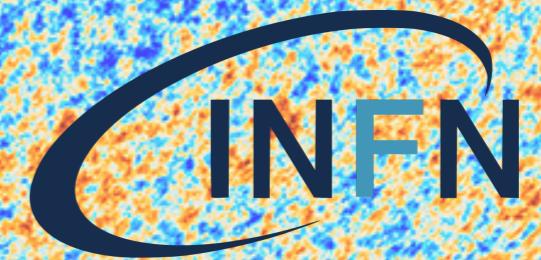


The measurement of the B-mode polarization of the CMB: the path towards the next space experiment

Giovanni Signorelli
INFN Sezione di Pisa

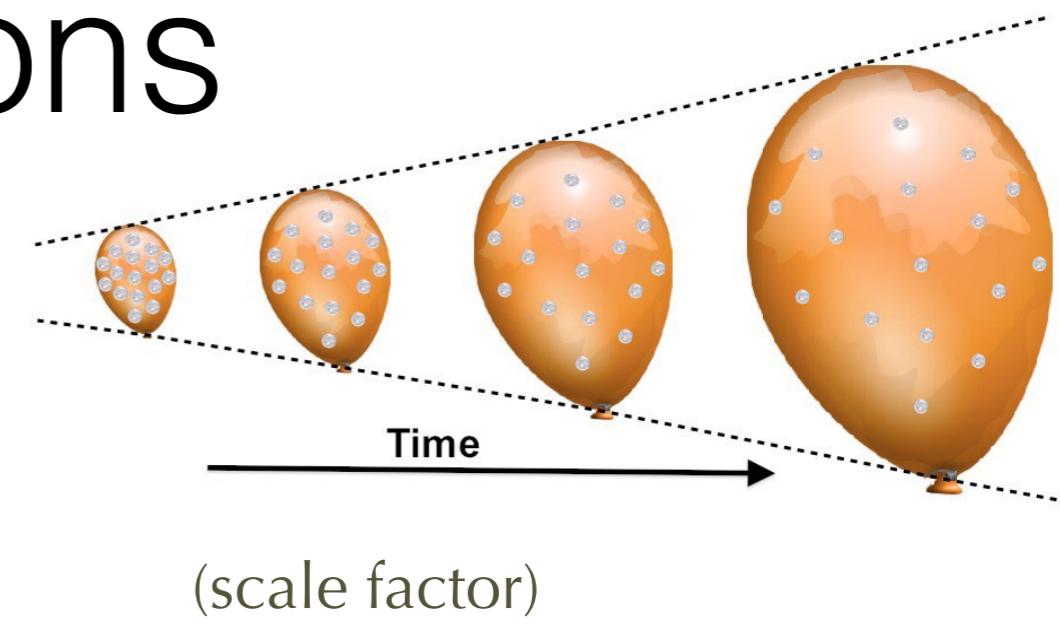


Summary

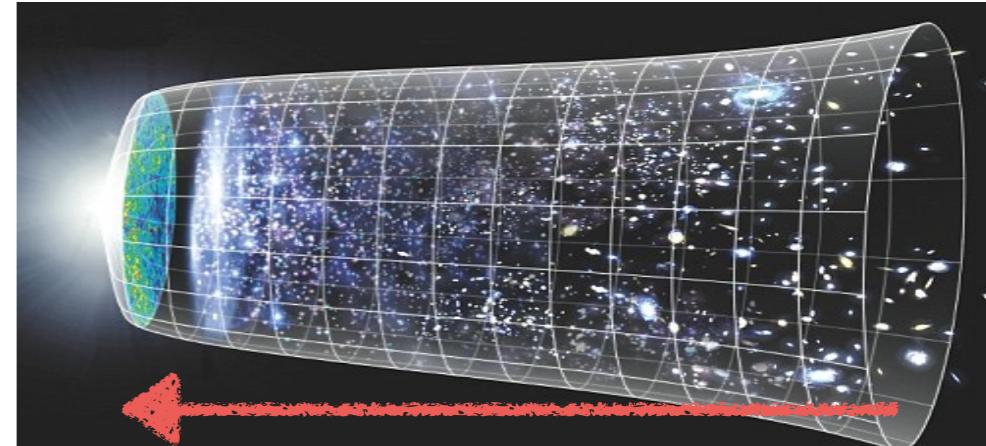
- A brief summary of CMB and inflation
- How do we look at the CMB (detectors & electronics)
- Ground, balloon and satellite experiments

Assumptions

- the Universe is expanding and cooling



- $g_{\mu\nu}(t) = a(t) \times g_{\mu\nu}$
- $\frac{\dot{a}}{a} = \mathcal{H} = f(\text{matter, radiation, energy})$
- Time can be rewound to t=0 (Big Bang)
 - 14 Gyrs ago

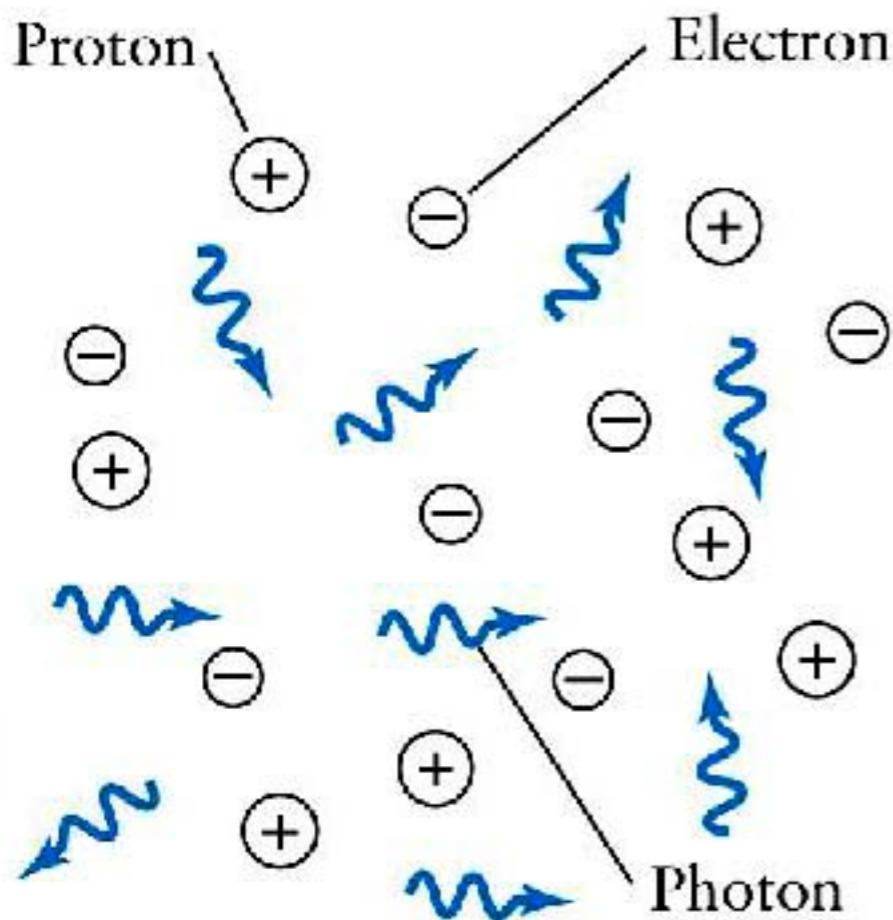


What is CMB

Flash of orange light emitted at t=380 000 years (decoupling)

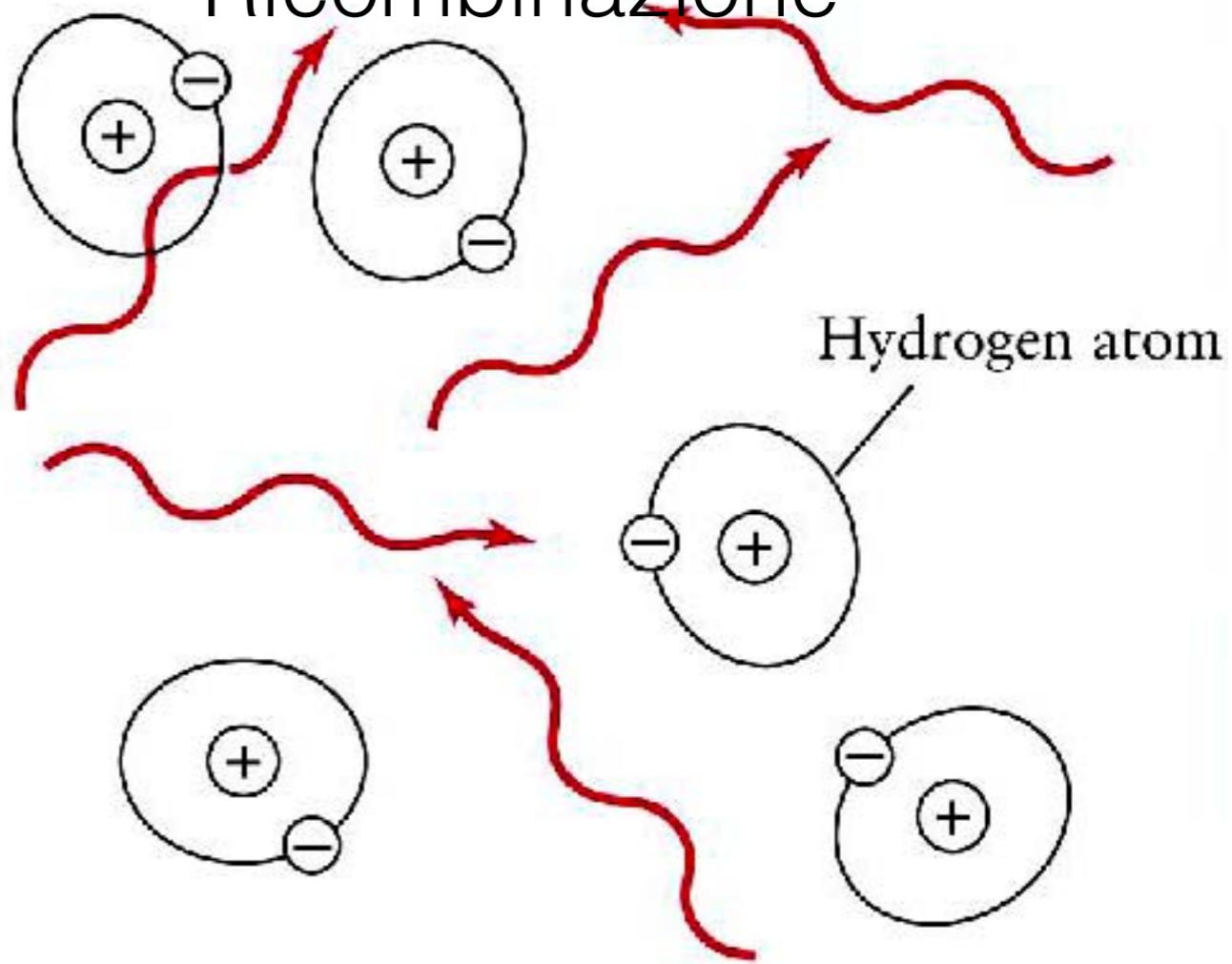


Plasma



Universo Opaco

Ricombinazione



Universo trasparente

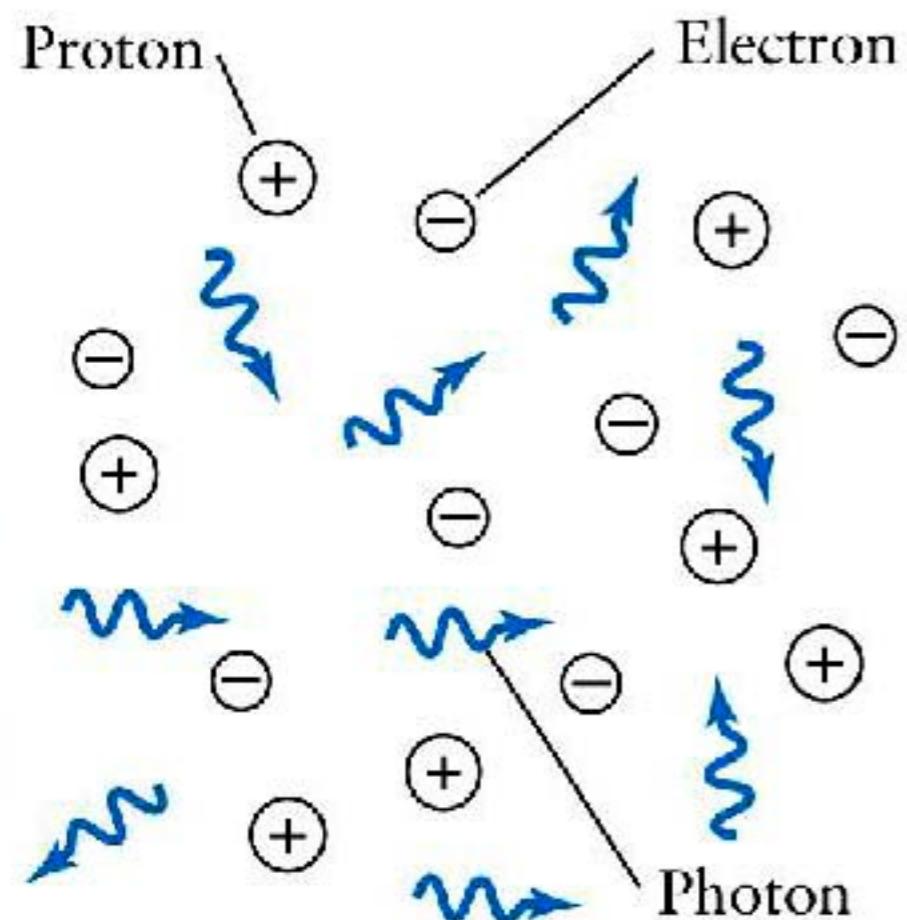
$t = 0 \longrightarrow t \approx 380\,000 \text{ anni} \longrightarrow \text{ora}$

$$n_\gamma \approx 10^{10} n_b$$

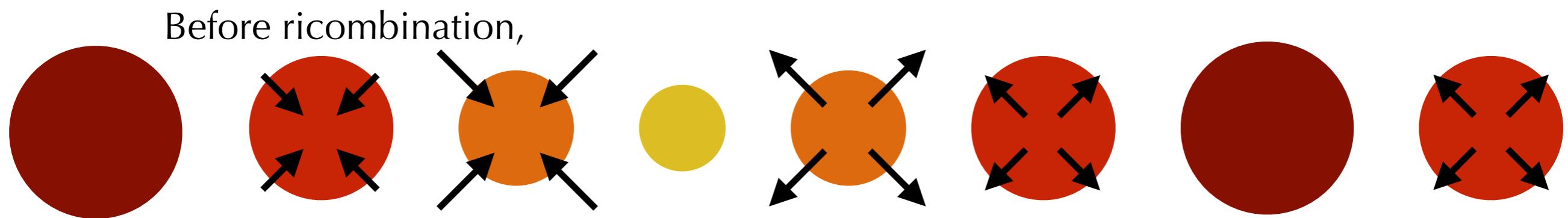
$$13.6 \text{ eV} \rightarrow 1/4 \text{ eV} \approx 3000 \text{ K}$$

Plasma

Ricombinazione

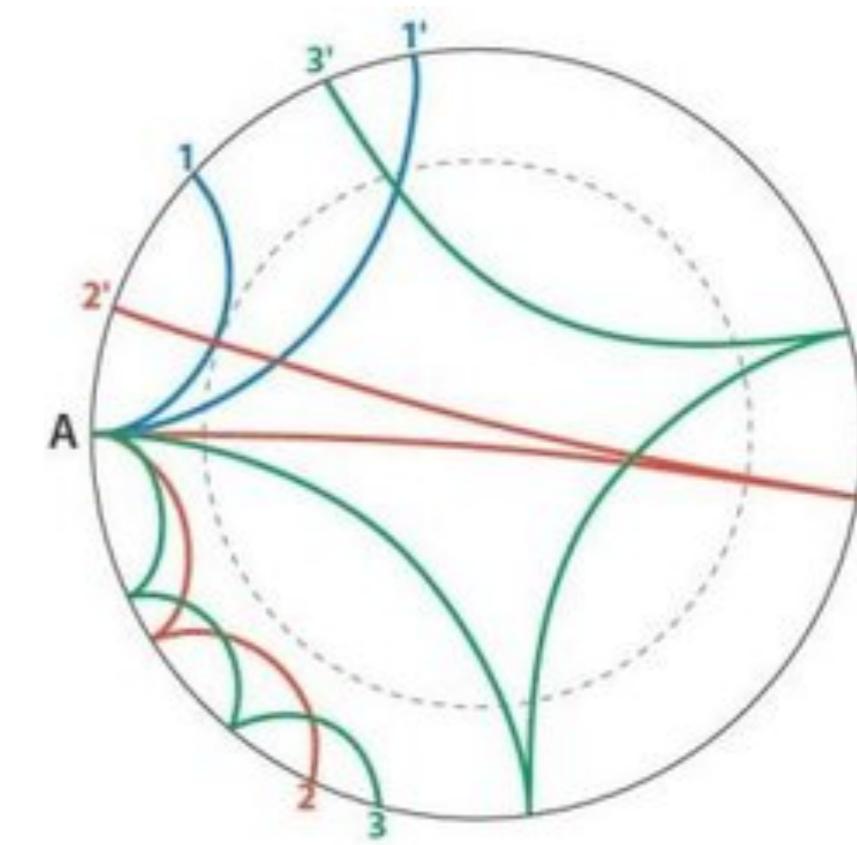
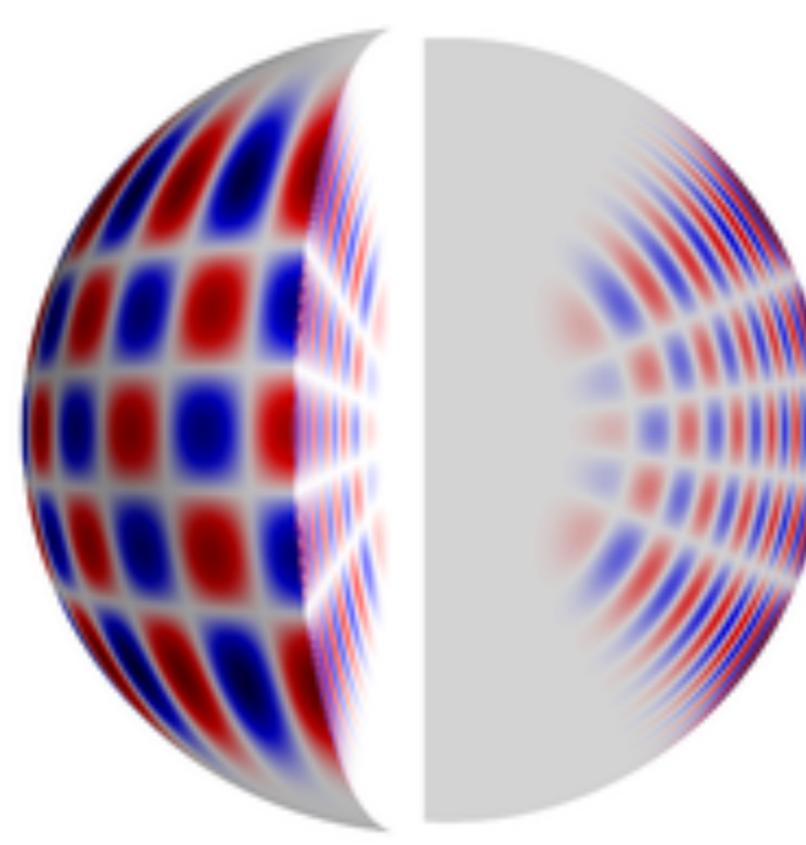
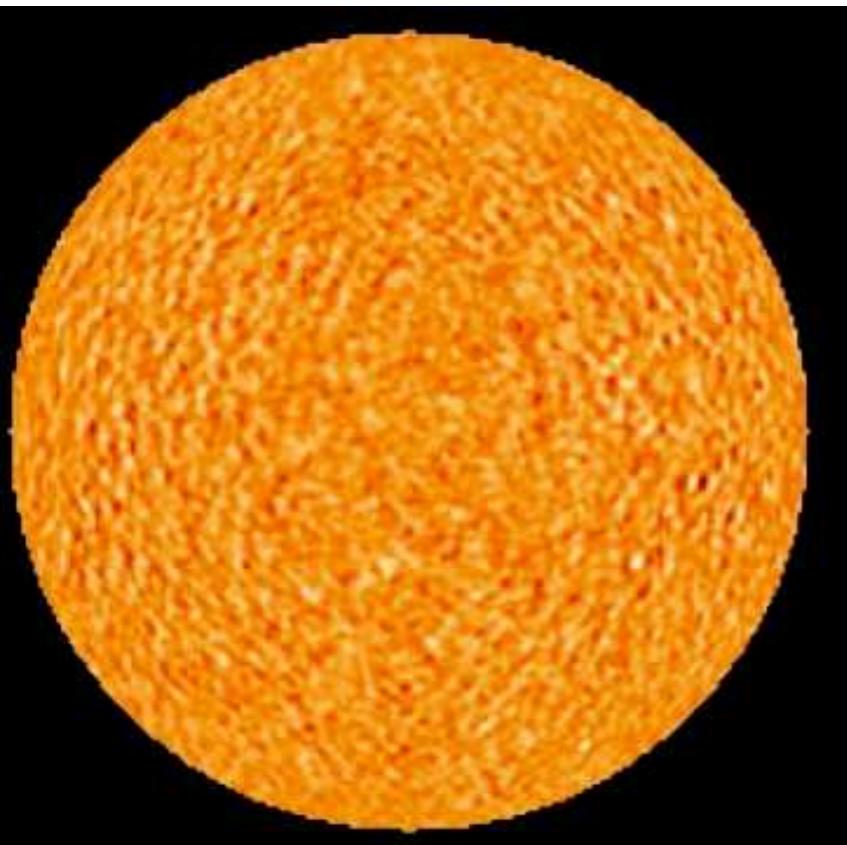


Before recombination,



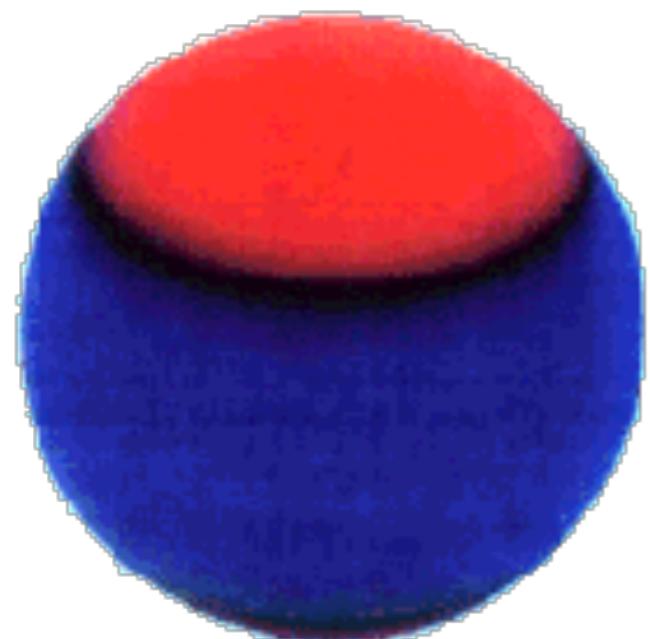
Il Sole: esempio di plasma oscillante

- Oscillazioni nel plasma \Rightarrow oscillazioni del sole \Rightarrow Eliosismologia

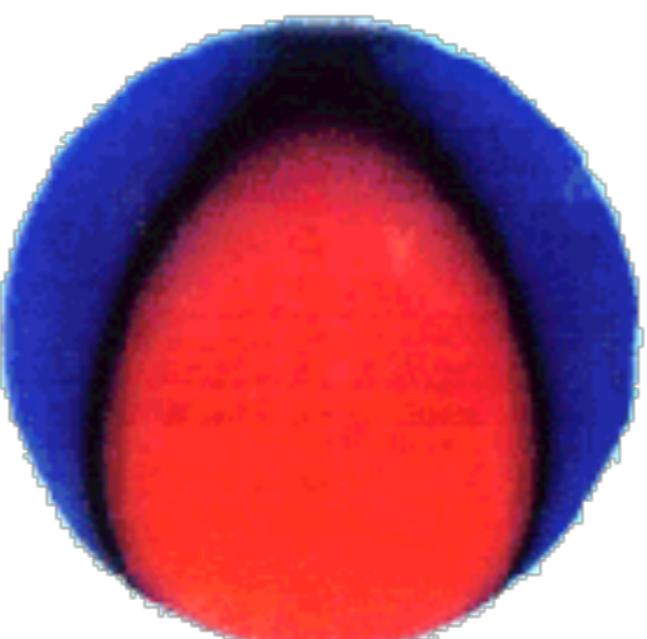


- Le oscillazioni permettono di studiare la struttura interna del sole
- Le fluttuazioni non si possono propagare in maniera arbitraria ma sono costrette dalla geometria ad assumere ben determinate proporzioni secondo quelli che sono i modi normali di oscillazione

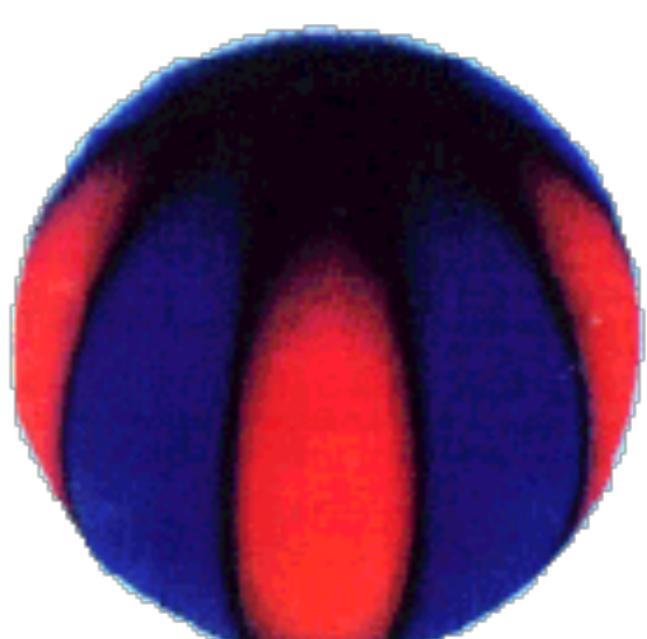
Modi normali di oscillazione della sfera



$L = 2$
 $M = 0$



$L = 2$
 $M = 2$



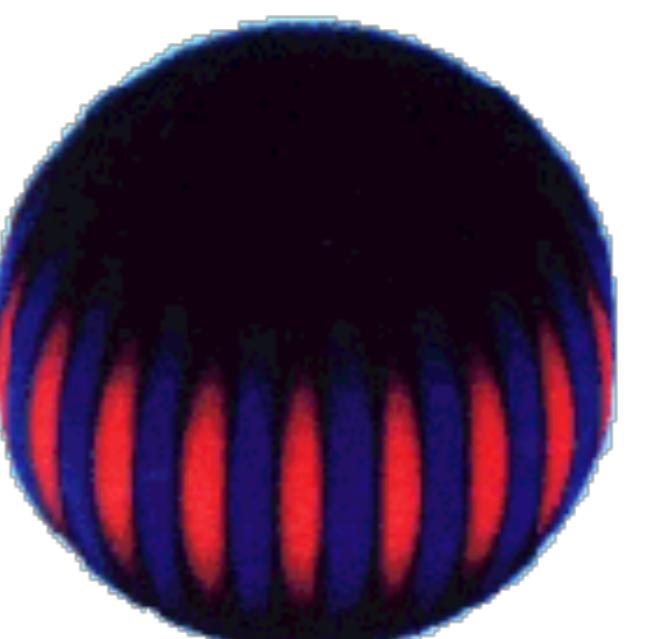
$L = 5$
 $M = 5$



$L = 20$
 $M = 0$



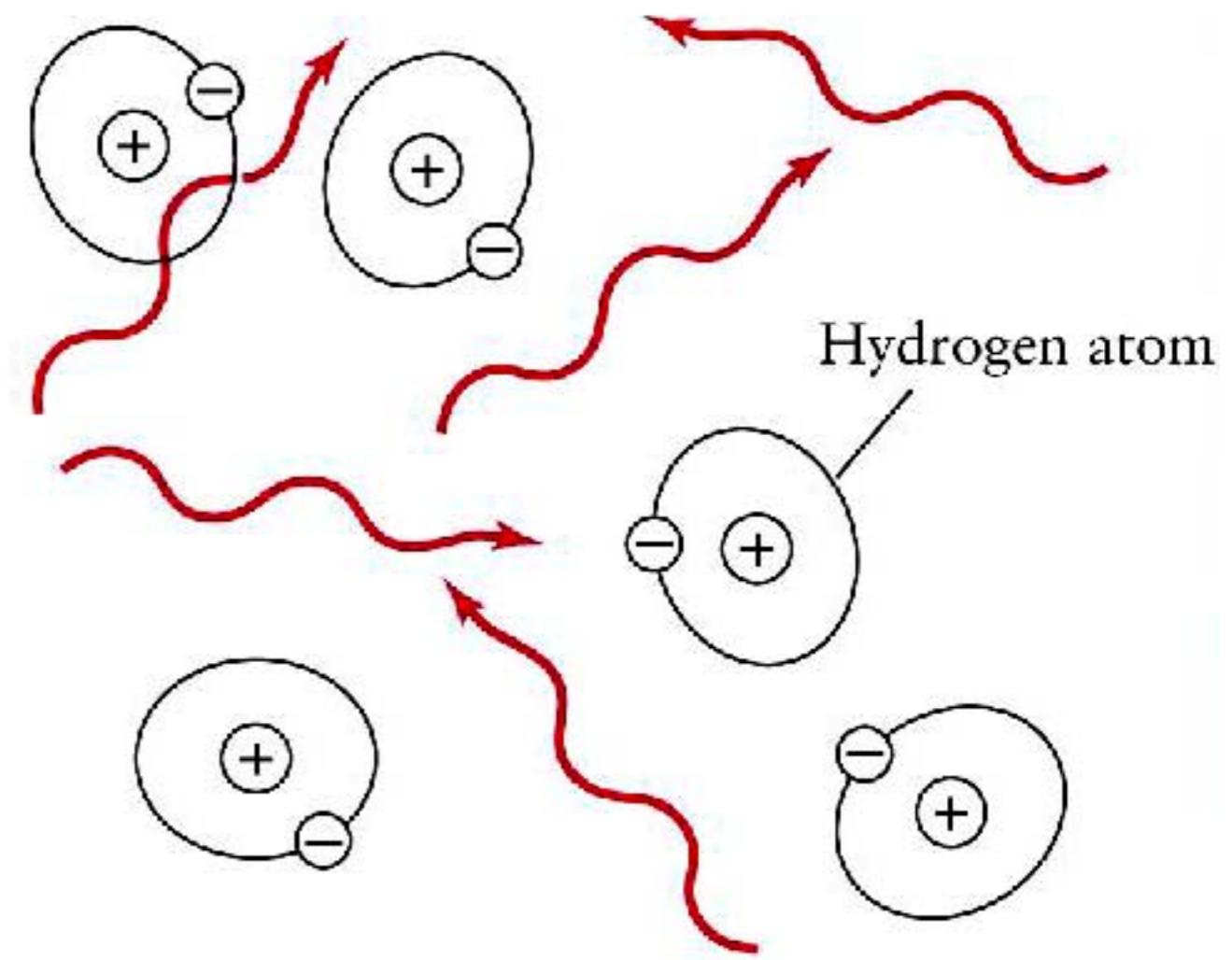
$L = 20$
 $M = 17$



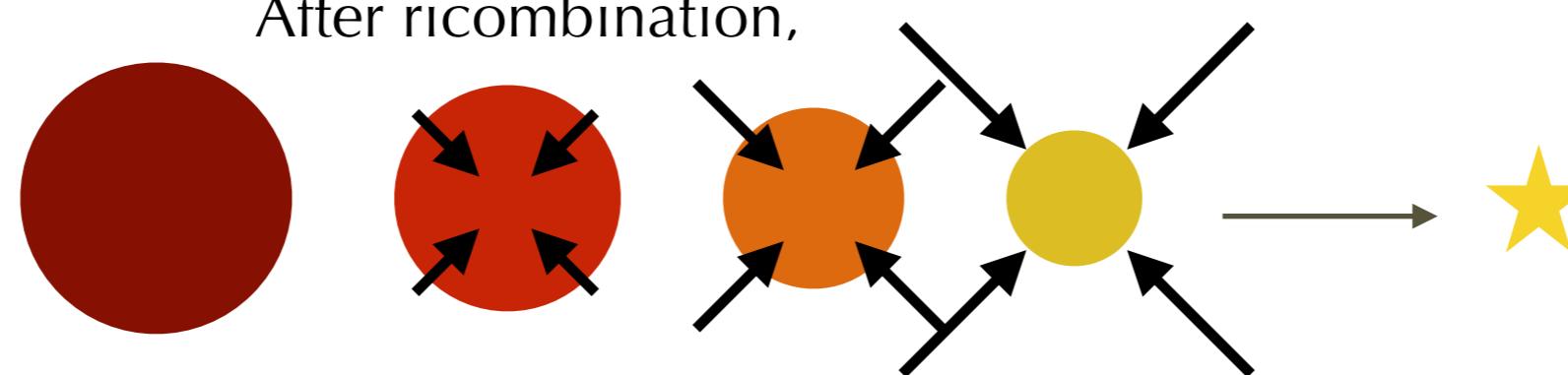
$L = 20$
 $M = 20$

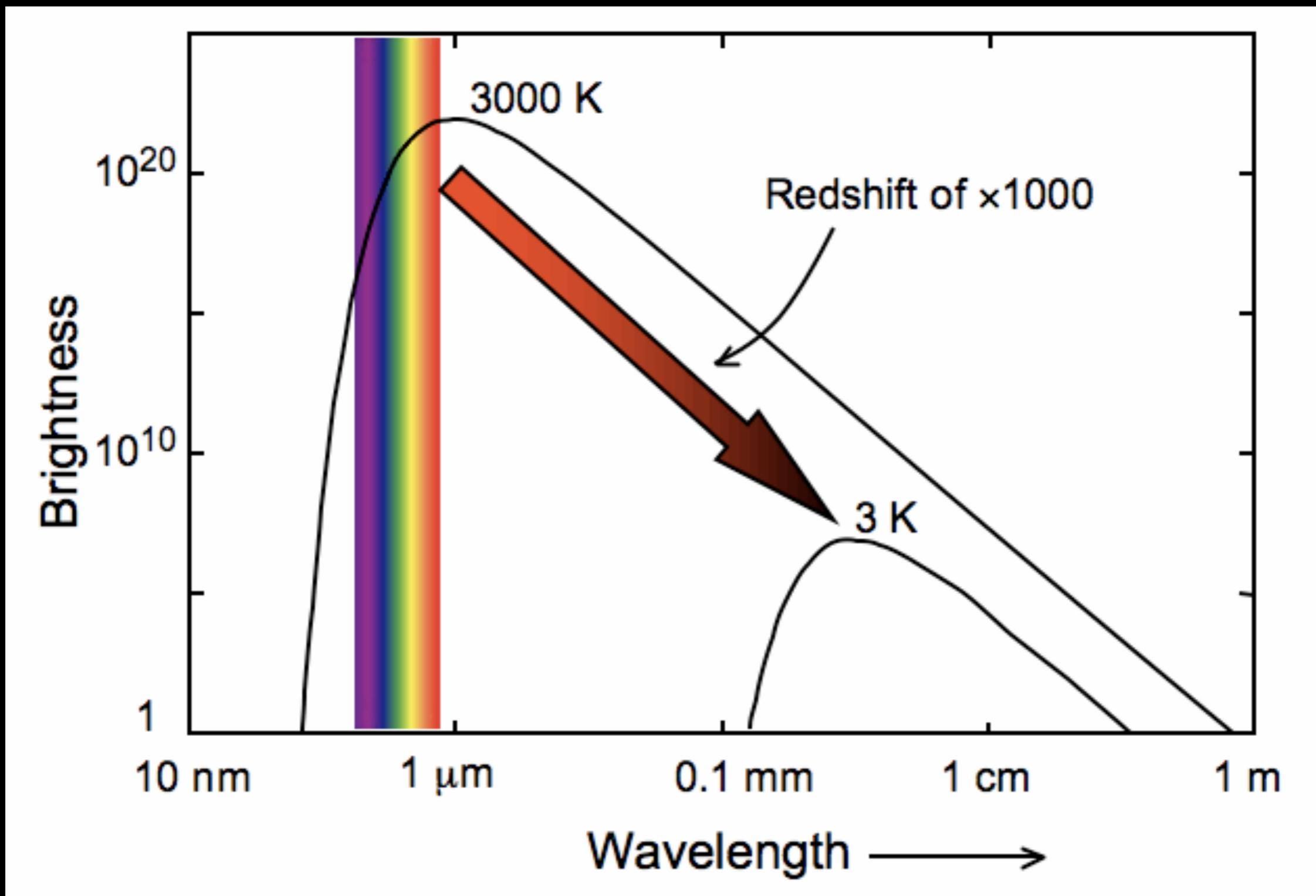
Plasma

Ricombinazione



After recombination,

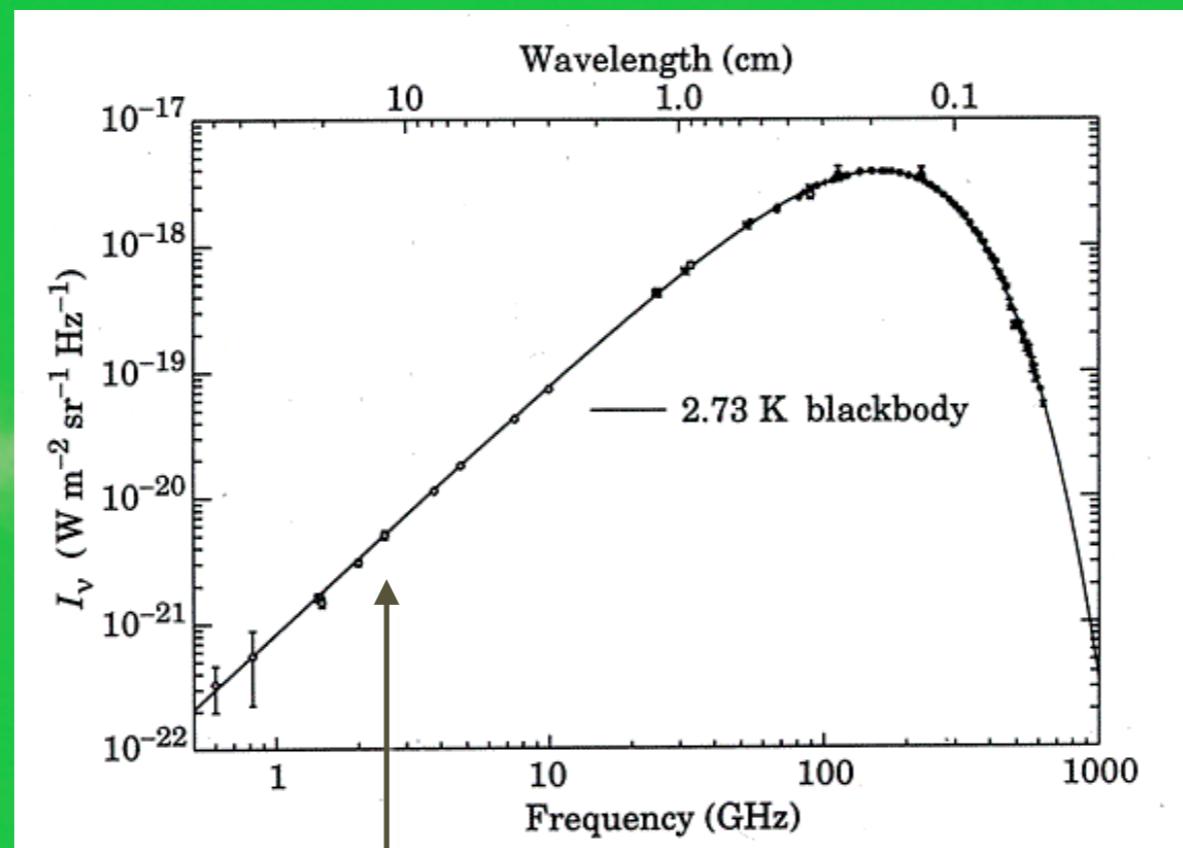






Le strutture che vediamo ora derivano dalle fluttuazioni iniziali

Spettro (di corpo nero) isotropo a 2.73 K

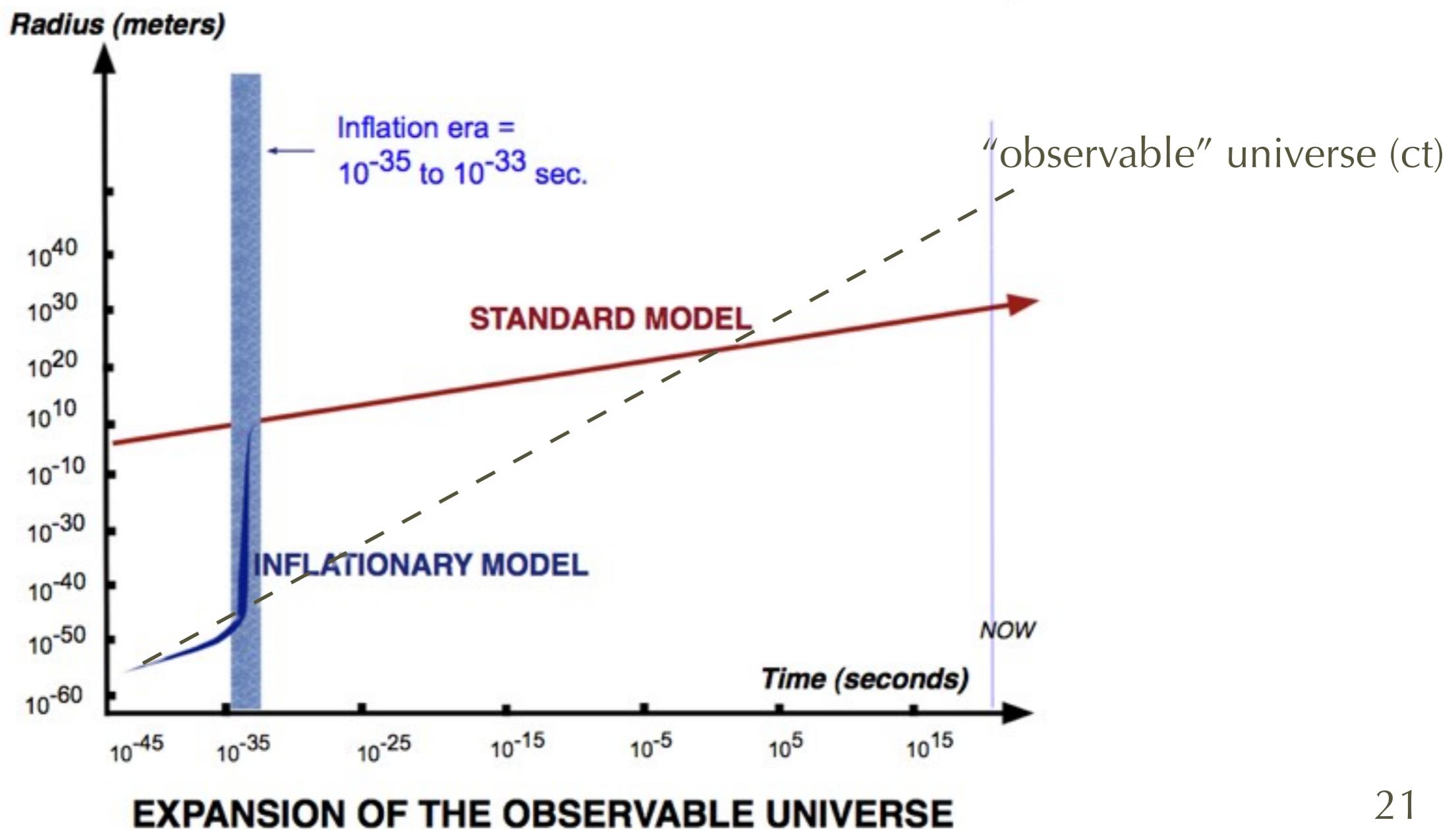


20



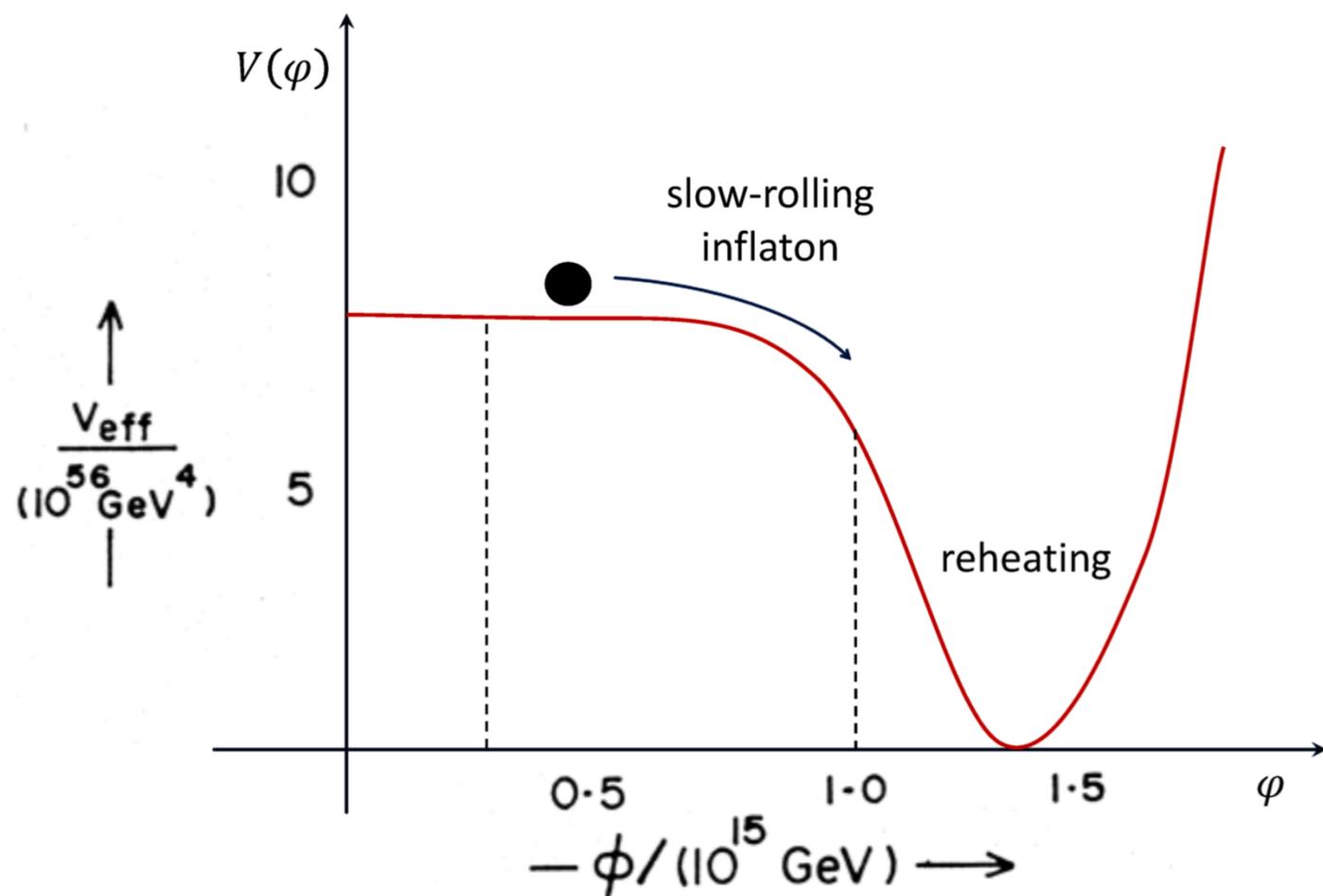
Isotropia “eccessiva”

- Stessa temperatura in regioni di universo che non sono mai state in contatto causale
- Una delle ragioni dell'introduzione dell'inflazione cosmologica
 - superluminal expansion of metrics avvenuta tra 10^{-36} e 10^{-33} secondi dopo il Big Bang



Cos'è l'inflazione

- L'energia dell'universo primordiale è dominata dal potenziale **dell'inflatone**
- L'inflatone, originariamente in un **minimo locale** del potenziale, rotola lentamente verso il **vero minimo**



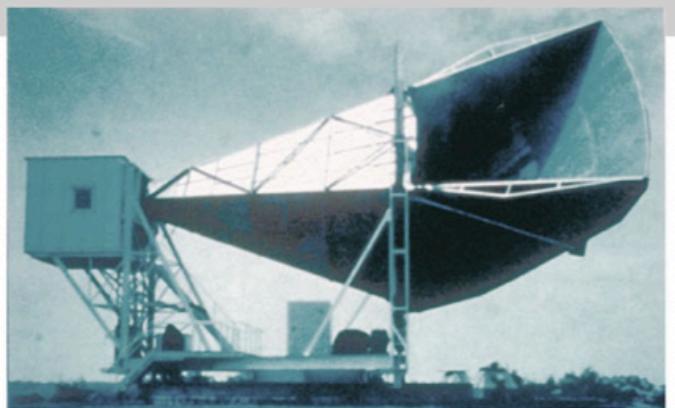
$$\mathcal{H} = \left(\frac{\dot{a}}{a} \right) = \text{cost}$$
$$a(t) = a_e e^{\mathcal{H}(t-t_e)}$$

fattore 2^{60}

- **Dilatazione** dello spazio, in particolare della metrica
- **Fluttuazioni quantistiche** \Rightarrow origine delle **anisotropie**

1965

O(1)



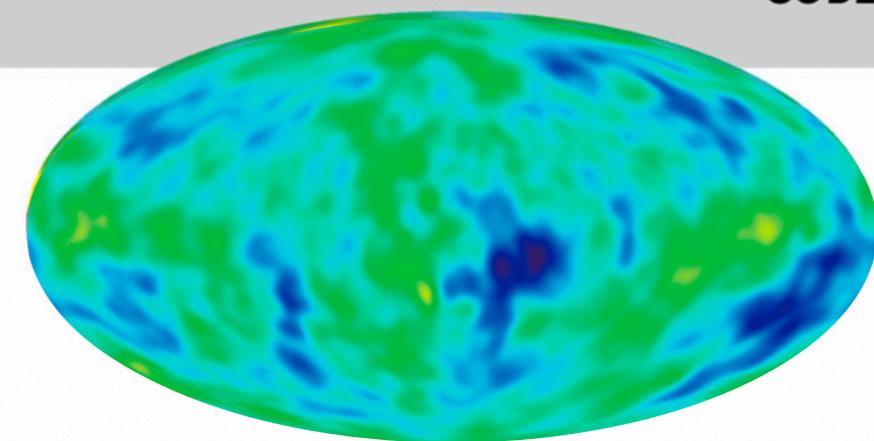
Penzias and Wilson



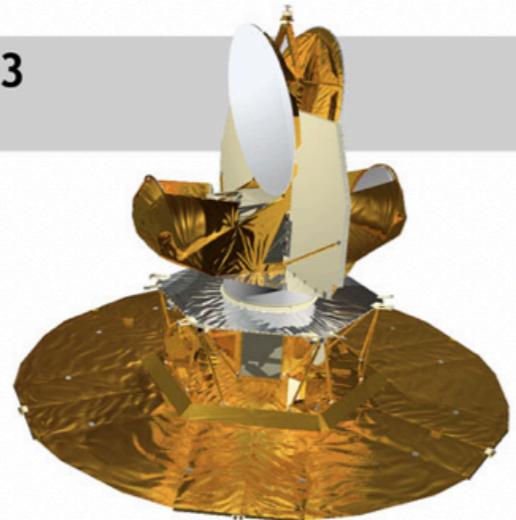
1992



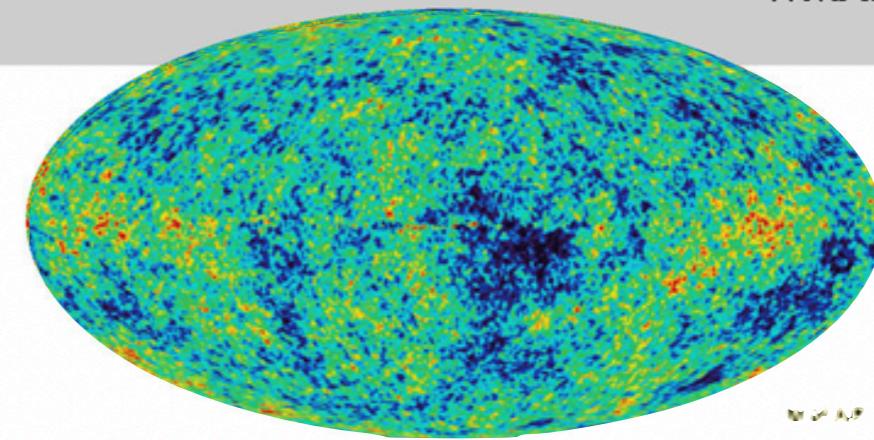
COBE



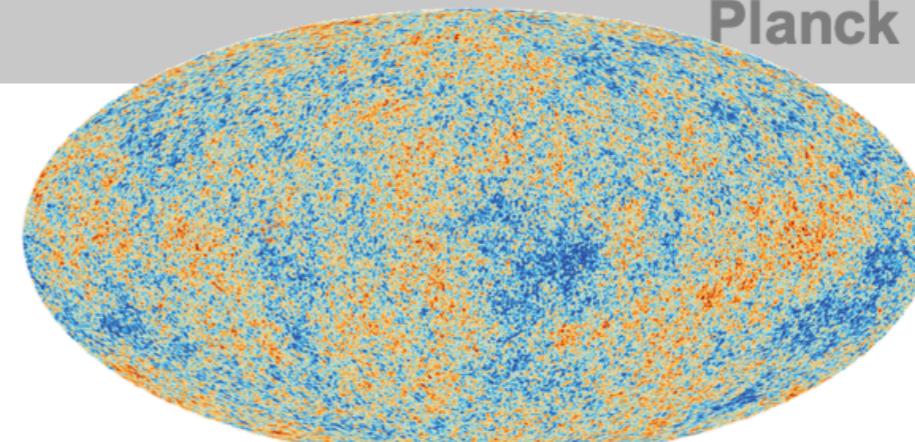
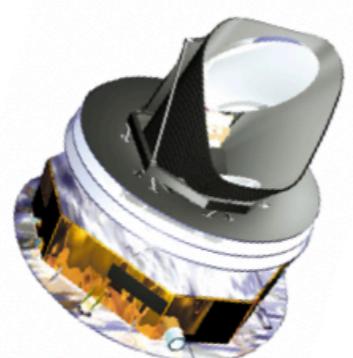
2003



WMAP



2009 2018



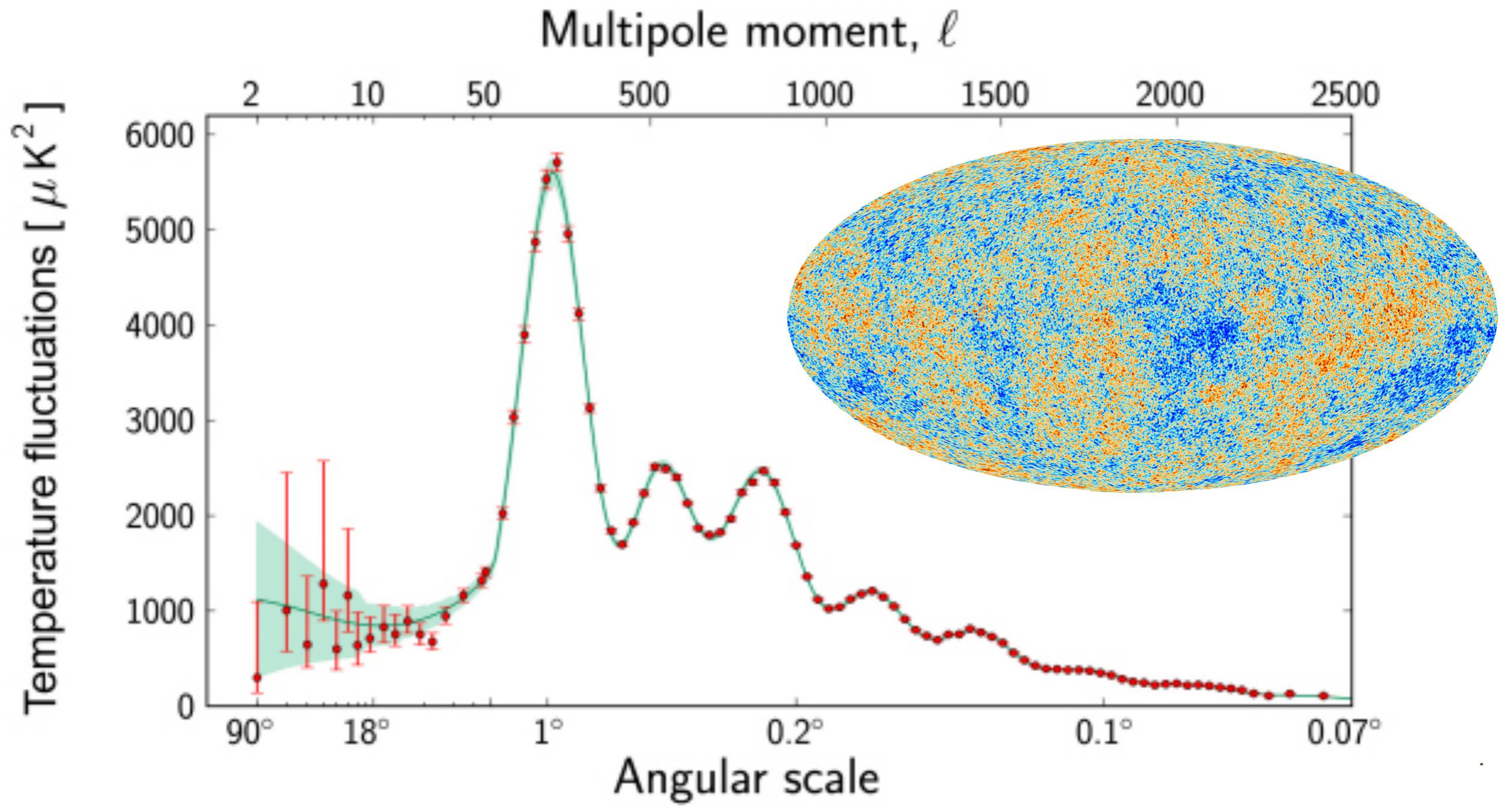
O(10^{-4})

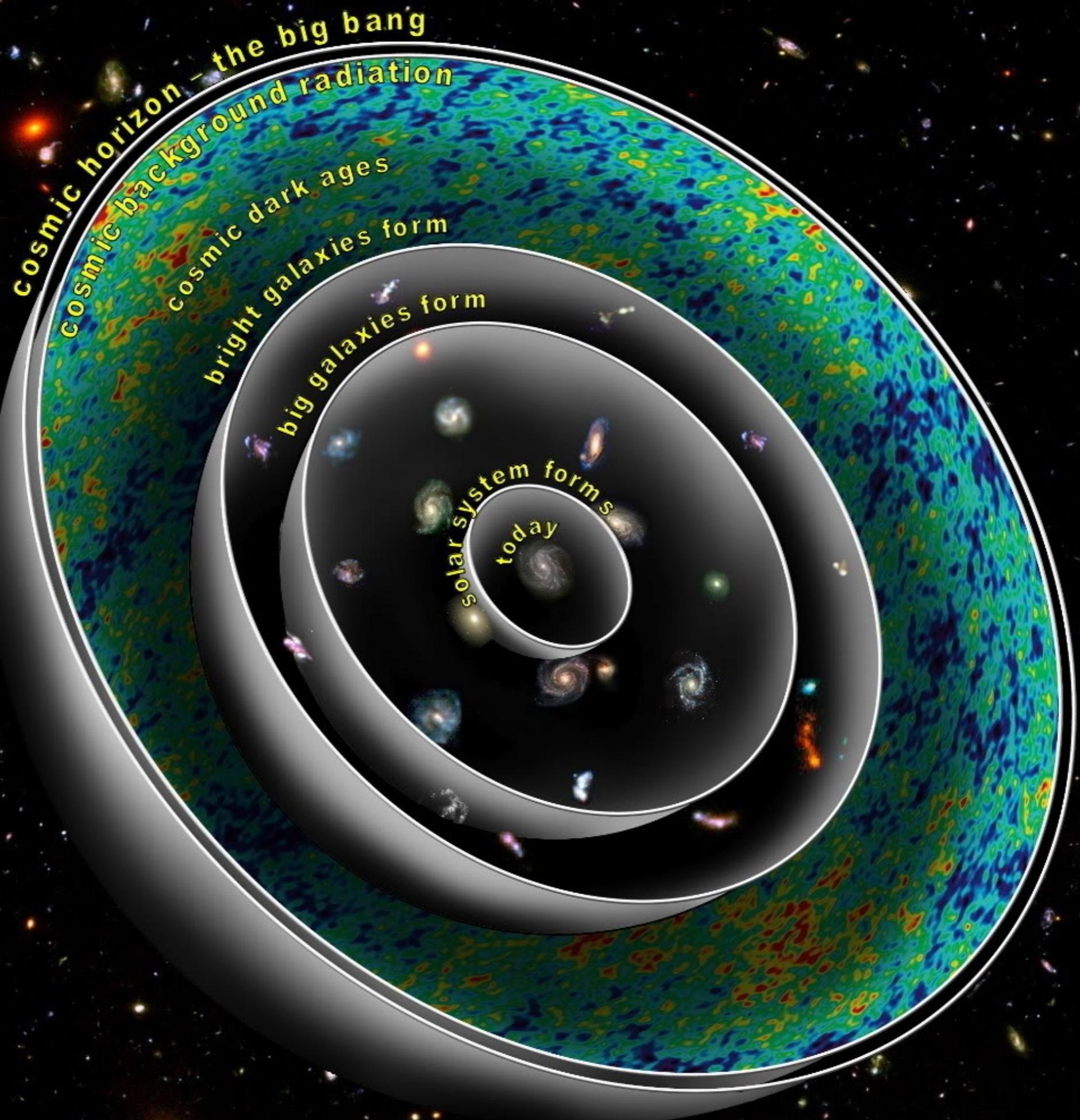
Risoluzione spaziale



Planck fit a 6 parametri

- dimensione dell'universo connesso all'istante del decoupling nella scala attuale (\rightarrow universo è piatto)
- quantità di materia (barioni/radiazione) al momento del decoupling
- parti dell'universo correlate su scale maggiori di quelle causali (ct0)



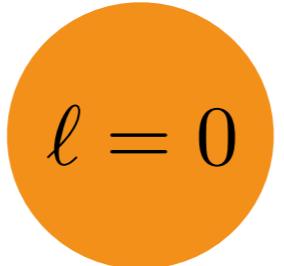
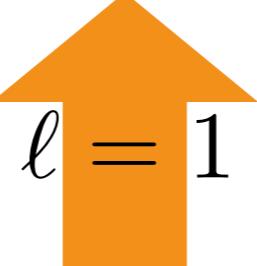
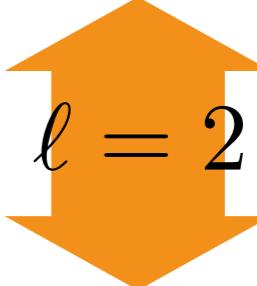


- La metrica viene “dilatata”
- Le fluttuazioni della metrica vengono espansate di un fattore $2^{60} \sim 10^{18}$

$$g_{\mu\nu} = \begin{pmatrix} & \\ & 4 \times 4 \\ & \end{pmatrix} \rightarrow 3 \times 3$$

$$M_{ij} = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} = \lambda \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & x & y \\ -x & 0 & z \\ -y & -z & 0 \end{pmatrix} + \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & -a-d \end{pmatrix}$$

$$9 = 1 + 3 + 5$$

 $\ell = 0$
  $\ell = 1$
  $\ell = 2$

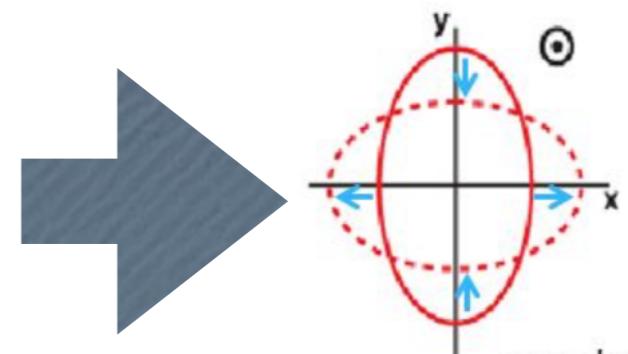
- Fluttuazioni

scalari

vettoriali

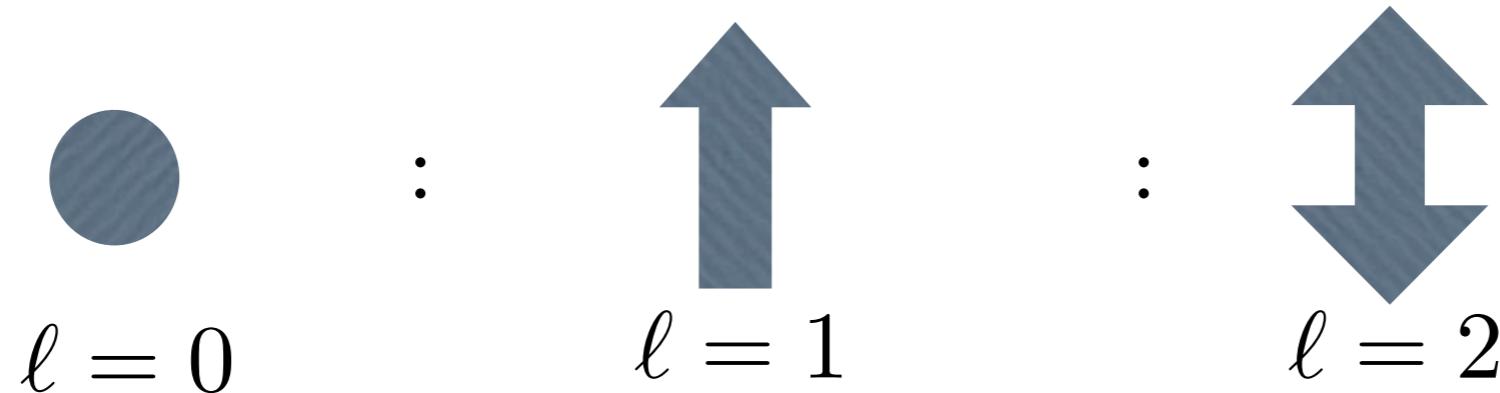
tensoriali

- Onde Gravitazionali Primordiali!



Boom!

- Abbiamo trovato il modo di **passare** al di là dello **schermo**
- Ci passiamo con le **onde gravitazionali primordiali**
 - la cui ampiezza è fissata da $V(\phi)$ scala di energia dell'inflazione
- **Come** le osserviamo?
 - Dobbiamo trovare un **osservabile** che ha $\text{spin}=2$
 - **Polarizzazione!**



- **Polarizzazione** della CMB \Rightarrow spettro di **GW** primordiali \Rightarrow Potenziale **inflazione**

Affermazioni

Studiando la polarizzazione della CMB
possiamo risalire ai primi istanti
di vita dell'universo (10^{-35} sec)

Possiamo risalire alla scala di energia
dell'inflazione che è correlata alla scala di energia
di Grande Unificazione ($10^{15 \div 16}$ GeV)

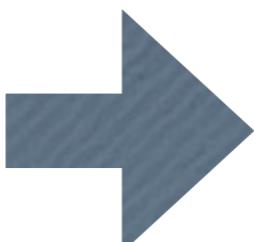
scalar perturbation spectrum

$$\Delta_{\mathcal{R}}^2(k) \equiv \frac{k^3}{2\pi^2} \langle |\mathcal{R}|^2 \rangle = \frac{1}{8\pi^2} \frac{H^2}{M_{\text{Pl}}^2 \epsilon}$$

tensor perturbation spectrum

$$\Delta_b^2(k) \equiv 2 \frac{k^3}{2\pi^2} \langle |h_{p,k}|^2 \rangle = \frac{2}{\pi^2} \frac{H^2}{M_{\text{Pl}}^2}$$

tensor-to scalar ratio related to inflation potential scale

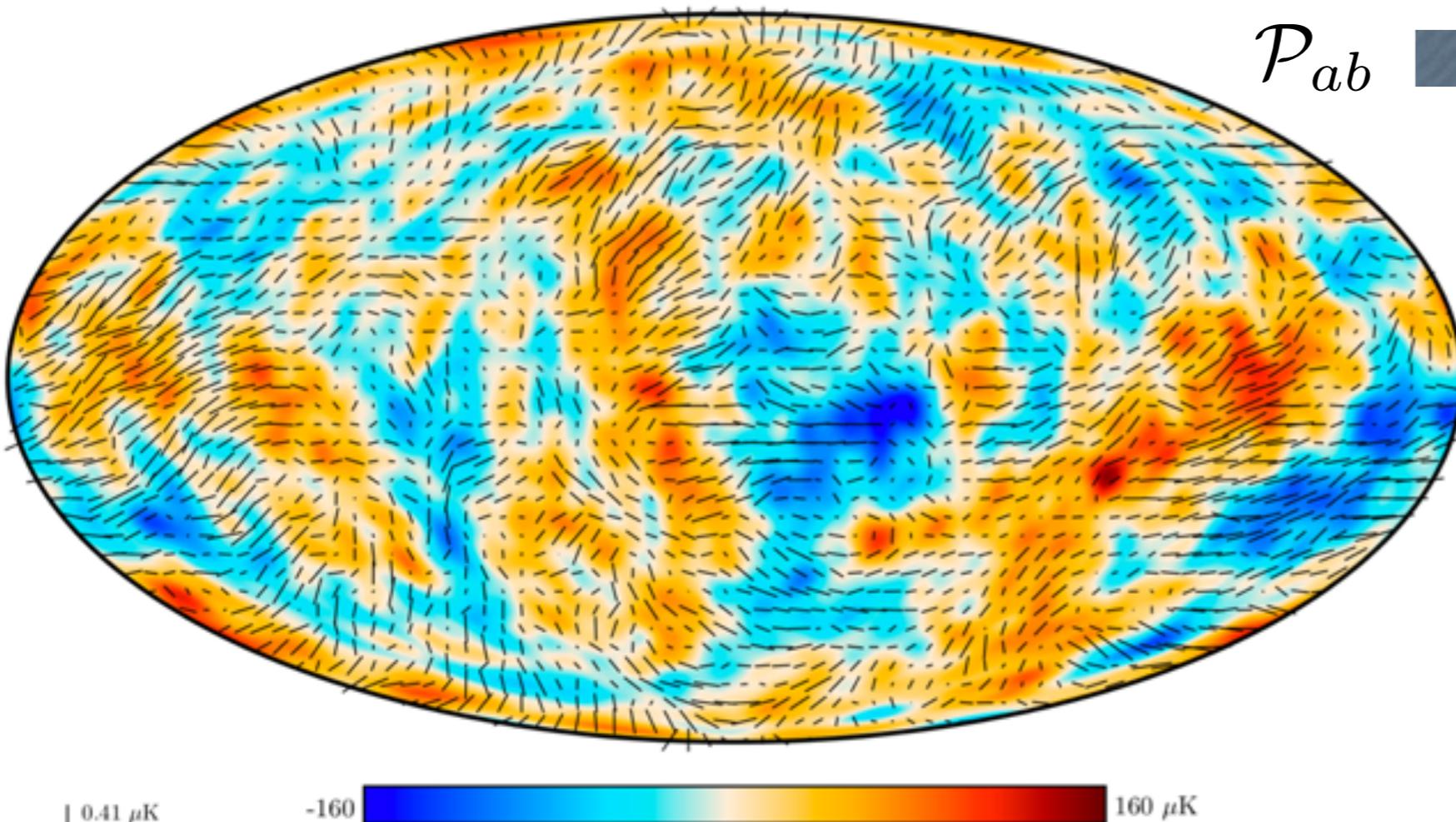


$$r \equiv \frac{\Delta_b^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon \simeq 0.1 \left[\frac{V}{(2 \times 10^{16} \text{ GeV})^4} \right]$$

$$\epsilon = 3 \frac{\dot{\phi}^2/2}{V + \dot{\phi}^2/2} \simeq \frac{M_{\text{Pl}}^2}{2} \left(\frac{V'}{V} \right)^2$$

Come la misuro?

- Monopole term: 2.725 K blackbody $O(1)$
- Dipole term: 3.355 mK $O(10^{-3})$
- Anisotropy: 100 μK rms $O(10^{-4})$
- Tensor perturbations produce a background of primordial gravitational waves
 - E-mode polarization: 3 μK rms $O(10^{-6\div 7})$
 - B-mode polarization: <500 nK rms

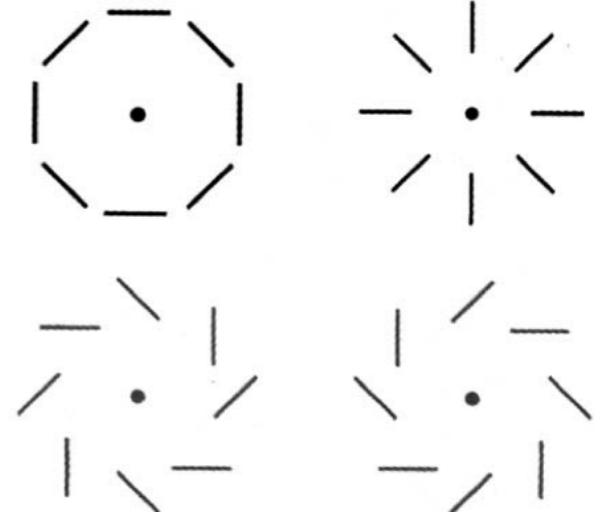


$$\mathcal{P}_{ab}$$

$$E \sim \partial_a \partial_b \mathcal{P}_{ab}$$

$$B \sim \epsilon_{ac} \partial_b \partial_c \mathcal{P}_{bc}$$

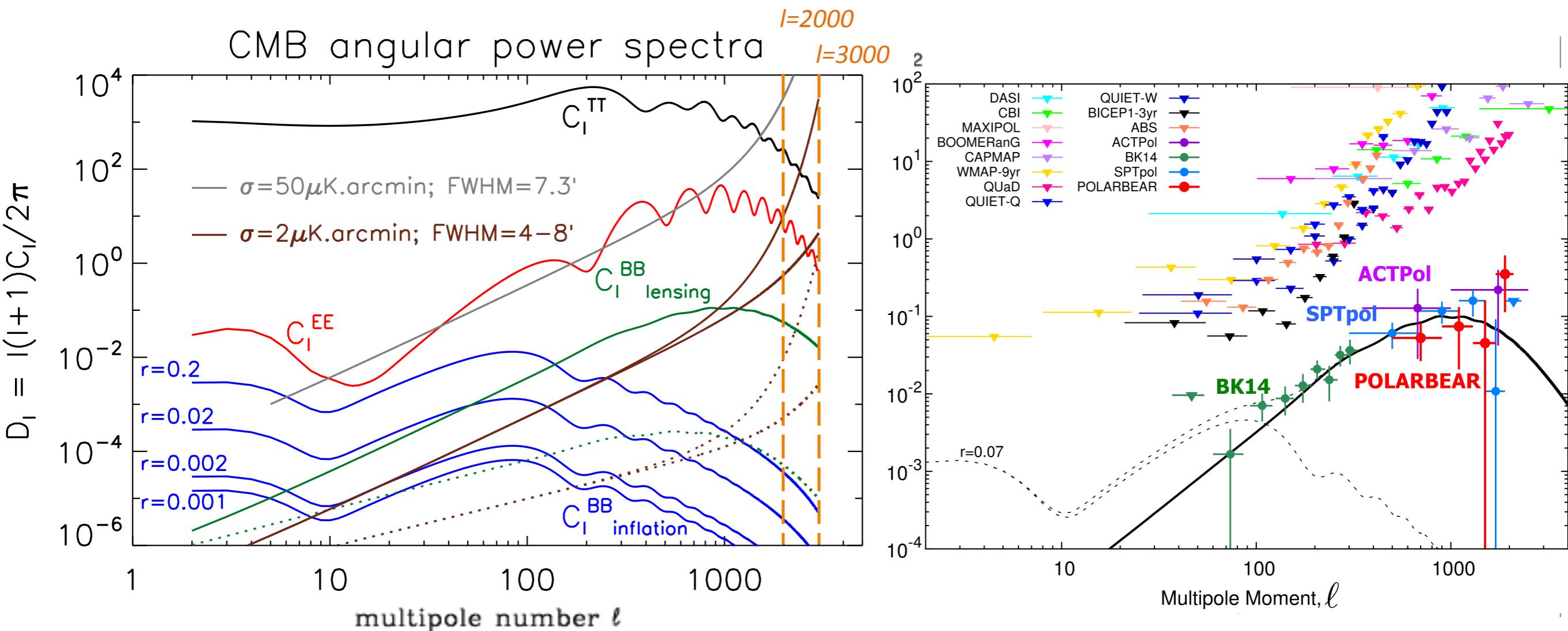
E-modes



B-modes

Come la misuro?

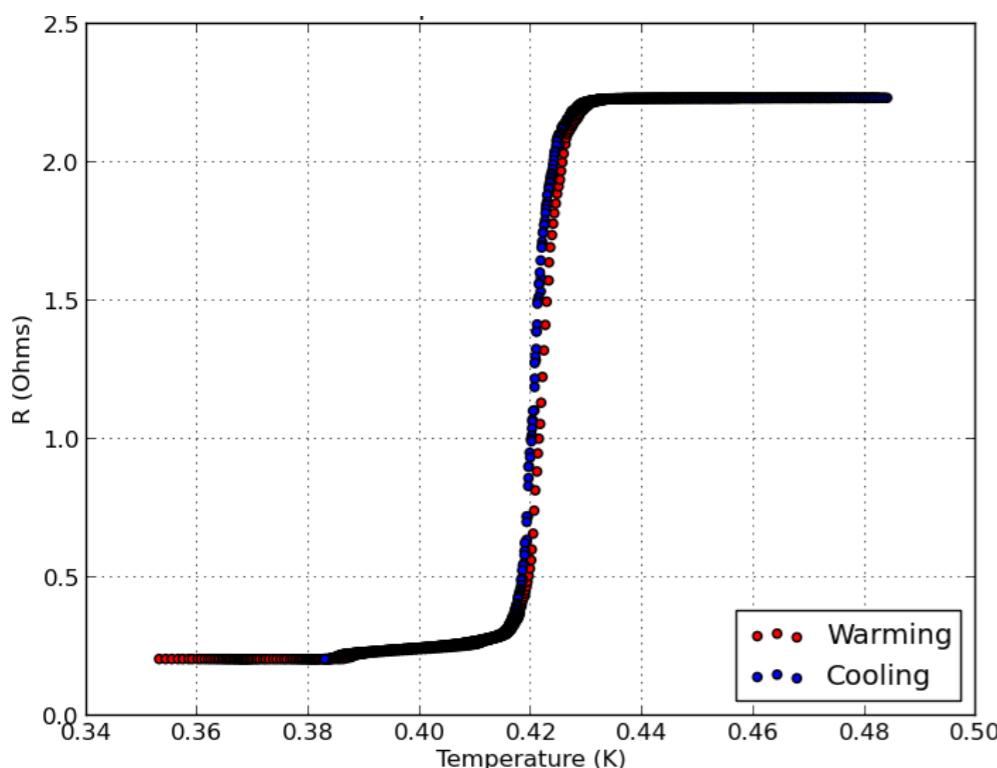
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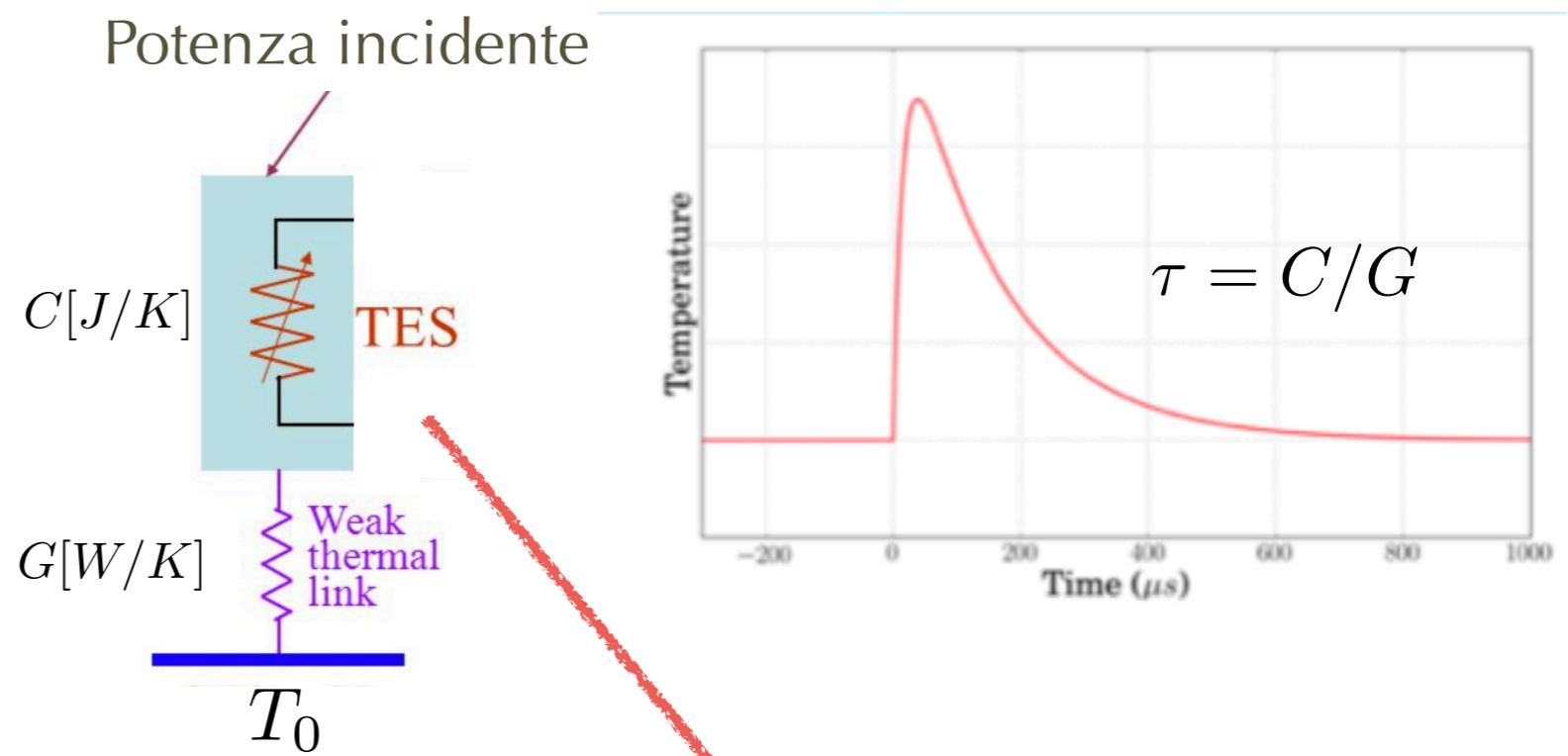
Transition-Edge Sensors

- “Termometri” che permettono di misurare piccolissime variazioni di temperatura
- Film superconduttori alla transizione di fase

steep $R(T)$



$$P_{\text{ott}} = C \frac{dT}{dt} + G (T - T_0)$$



$$\frac{10 \Omega}{1 \text{ mK}} = 10^4 \Omega/\text{K}$$

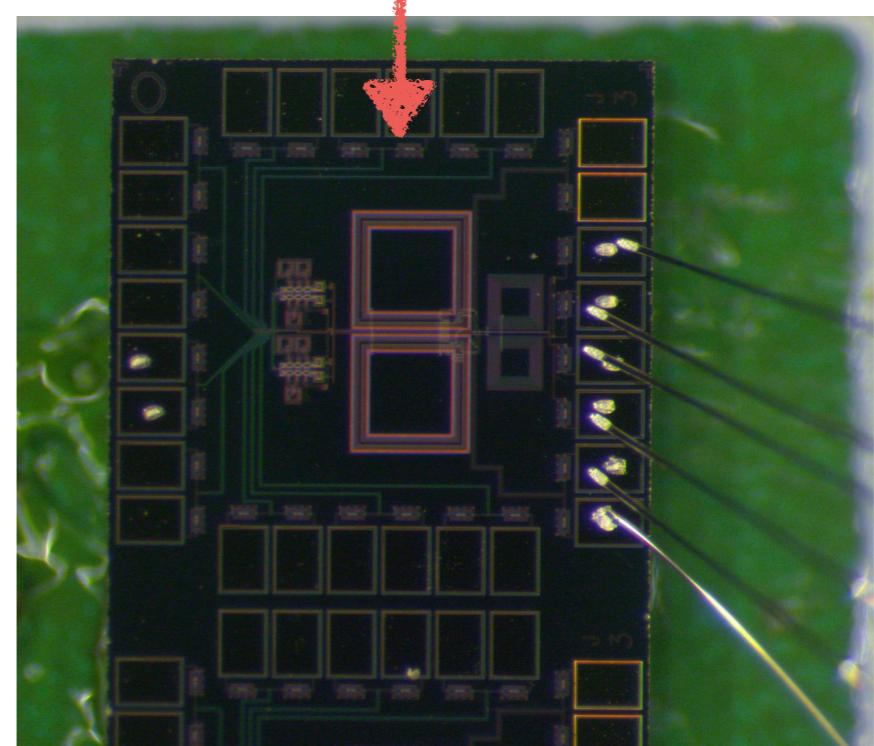
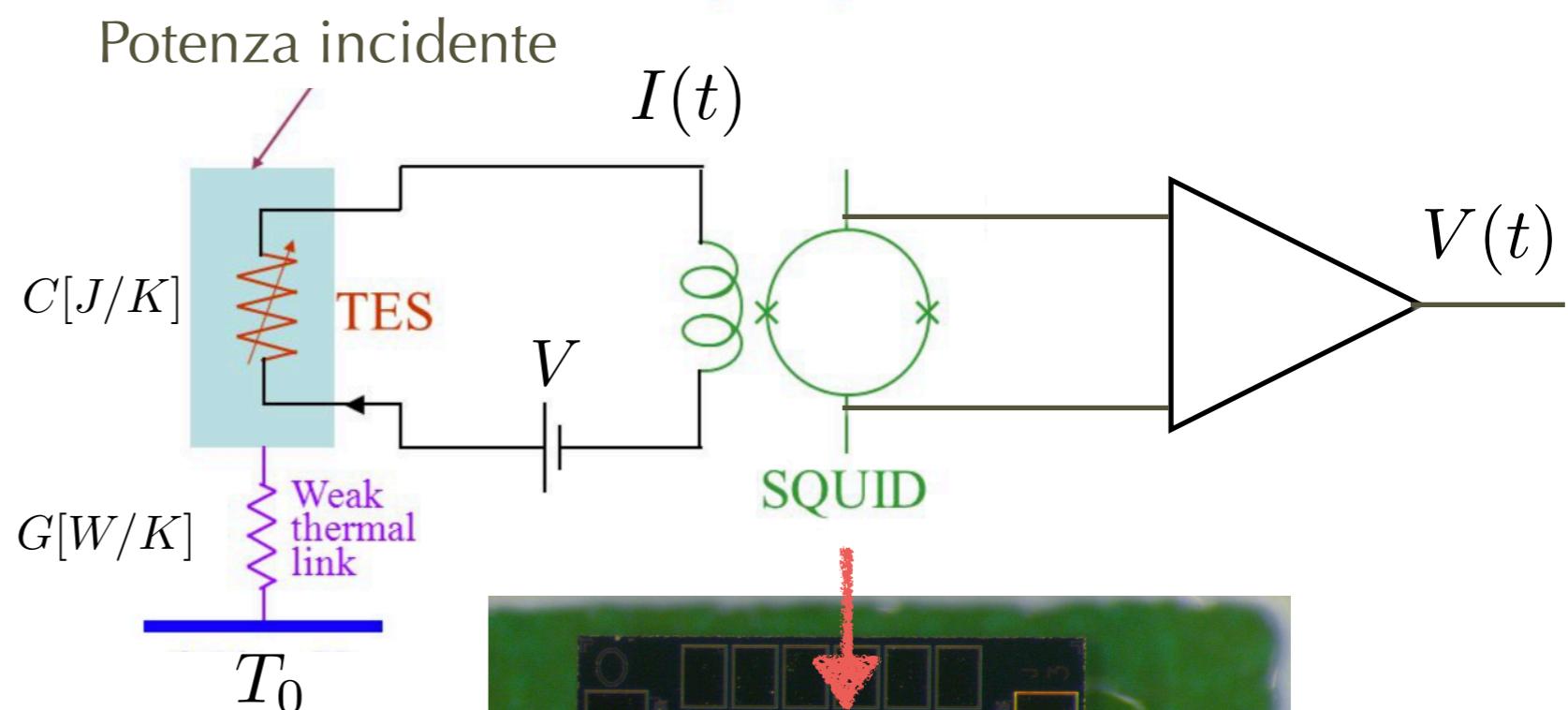
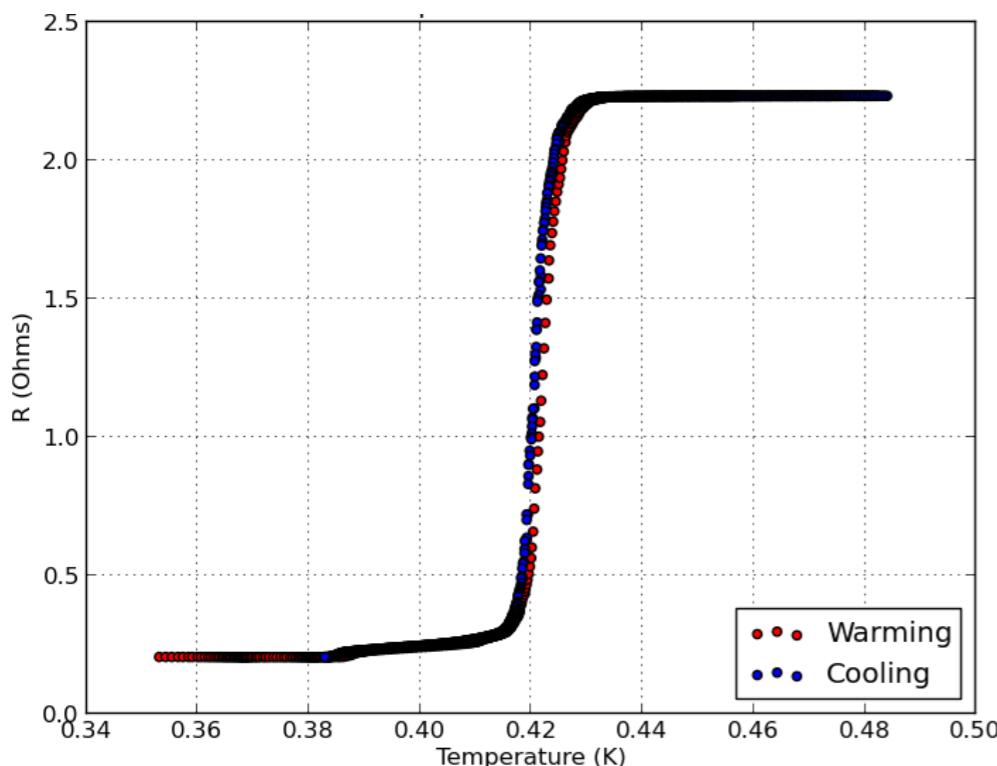
$$100 \text{ nK} \Rightarrow 1 \text{ m}\Omega$$



Transition-Edge Sensors

- “Termometri” che permettono di misurare piccolissime variazioni di temperatura
- Film superconduttori alla transizione di fase
- Voltage bias \Rightarrow read current through SQUID

$$P_{\text{ott}} + \frac{V^2}{R} = C \frac{dT}{dt} + G(T - T_0)$$

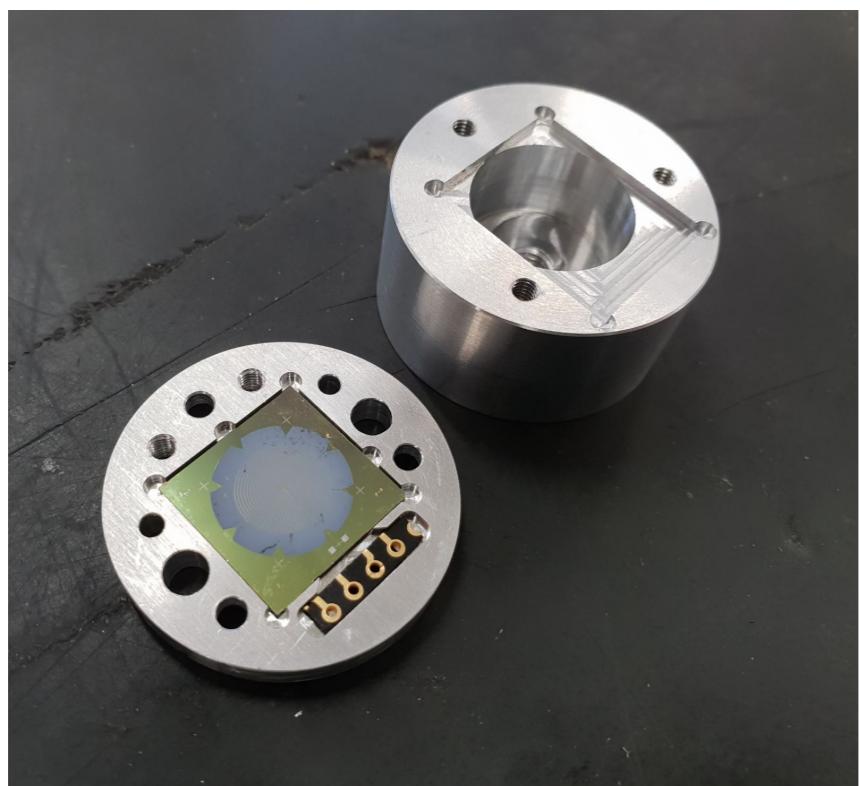
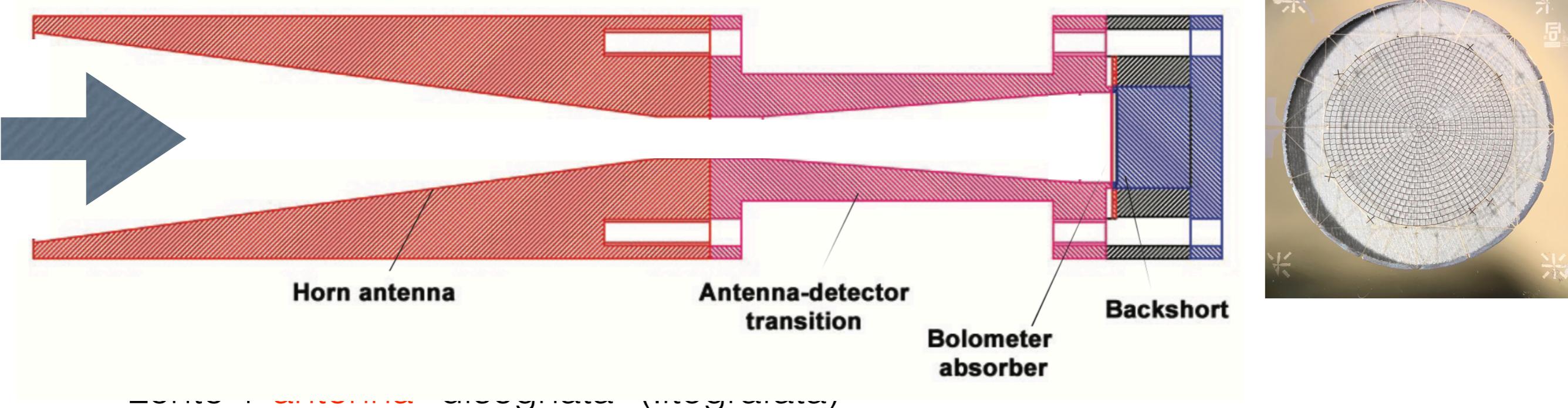


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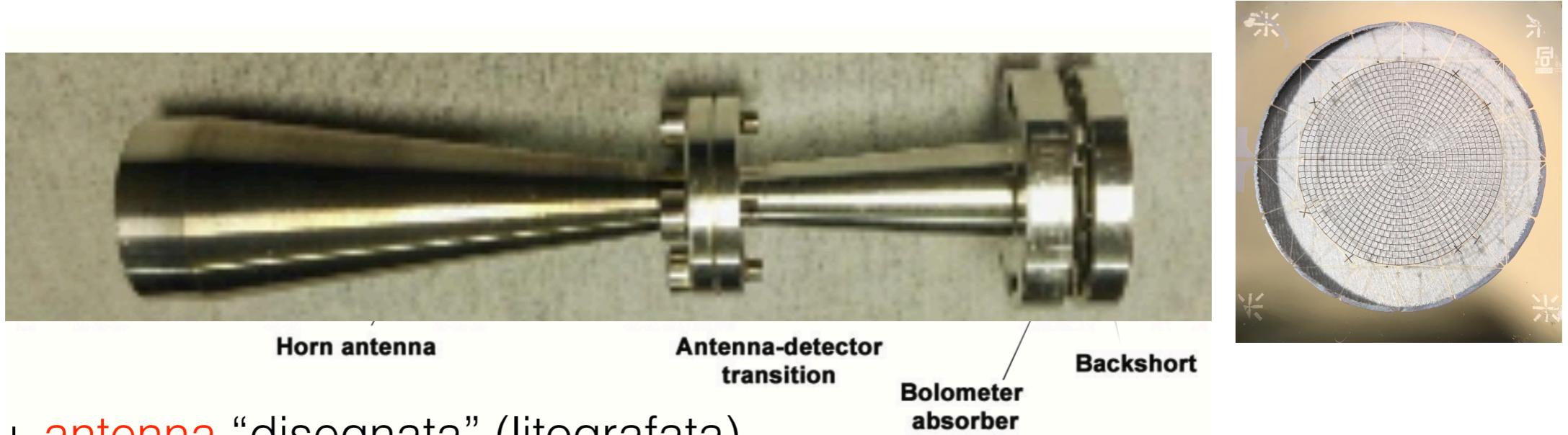
Assorbire le microonde

- Radiazione convogliata nella guida d'onda e dissipata sul bolometro nella cavità risonante

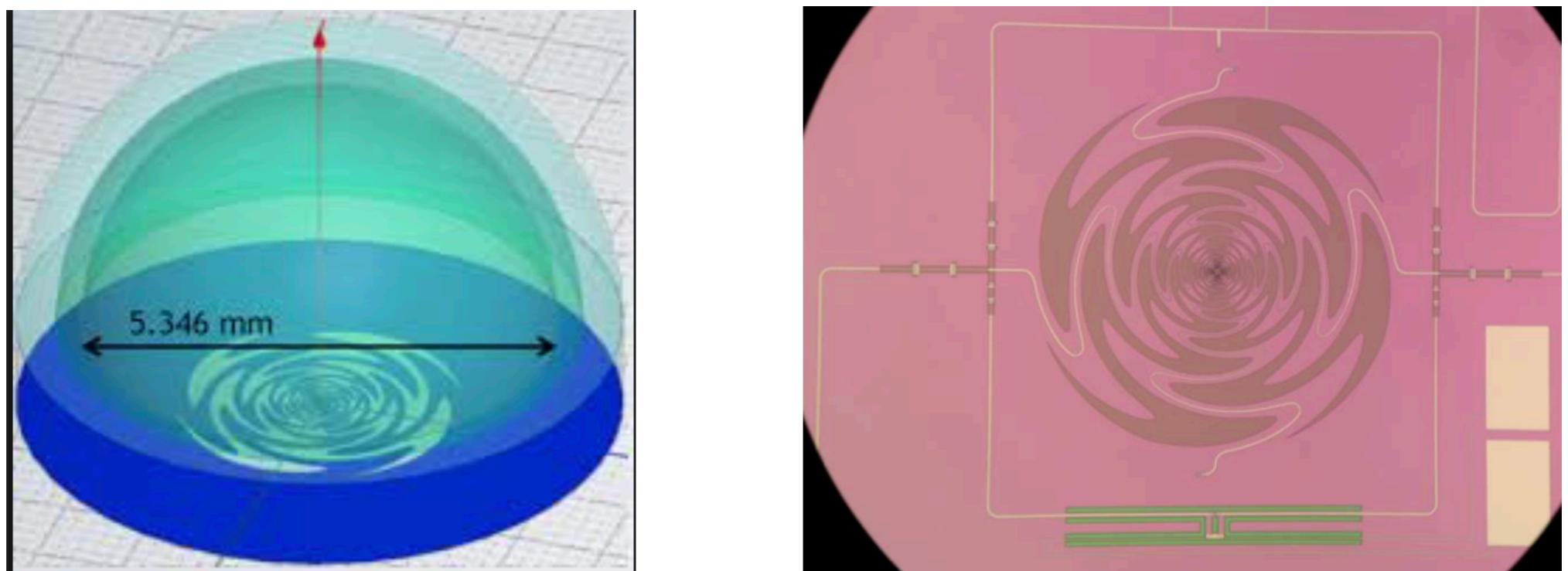


Assorbire le microonde

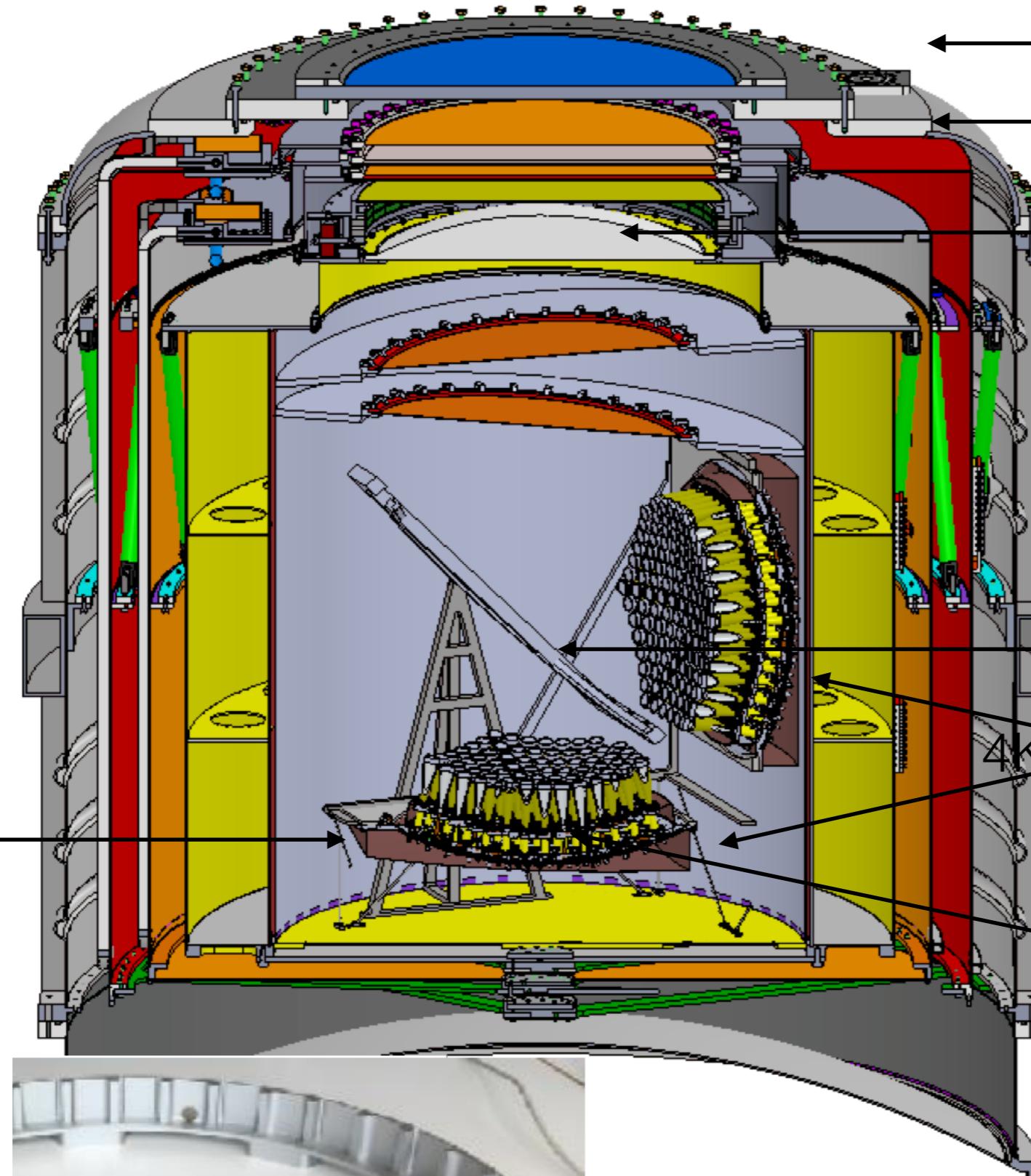
- Lunghezza d'onda $\lambda \sim 2\div 3$ mm
- “Horn” (guida d'onda più cavità risonante)



- Lente + antenna “disegnata” (litografata) (litografata)



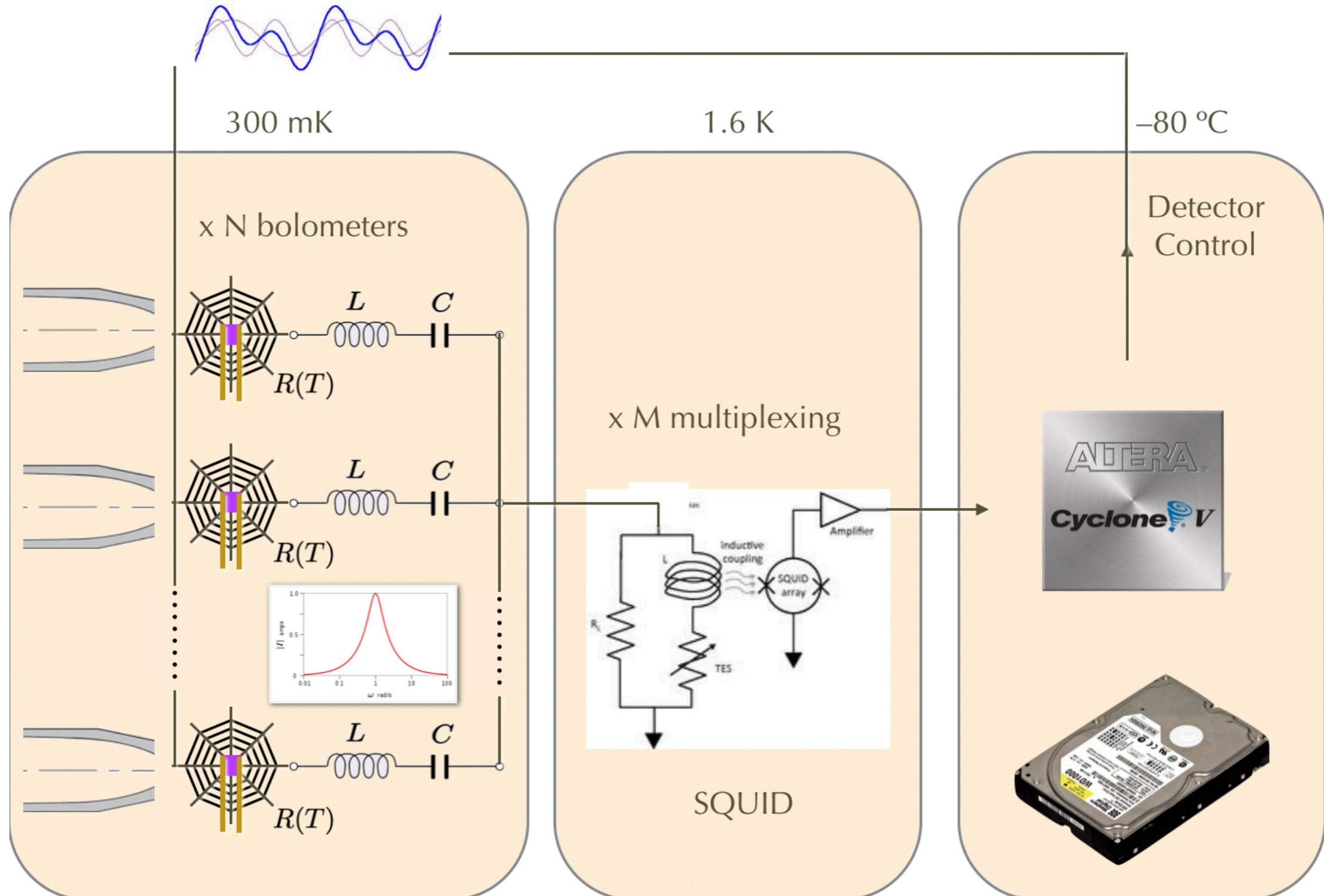
Tipico esperimento
LSPE (ASI/INFN)



- incoming radiation
- window
- filters
- polarization modulator
- polarizer grid
- focal planes
- 300mK
- detectors O(300)
at sub-K
temperatures

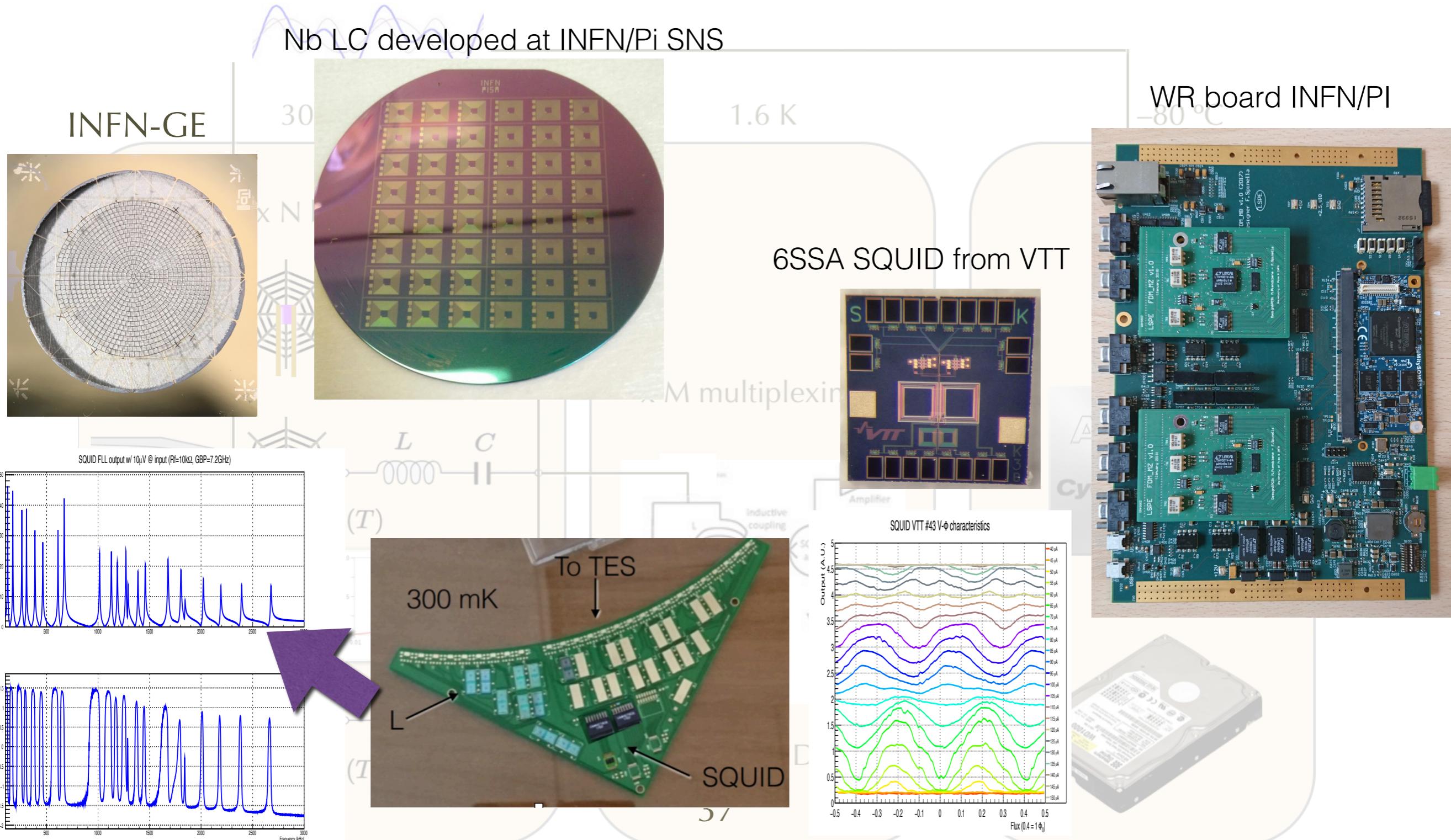
Multiplexed readout

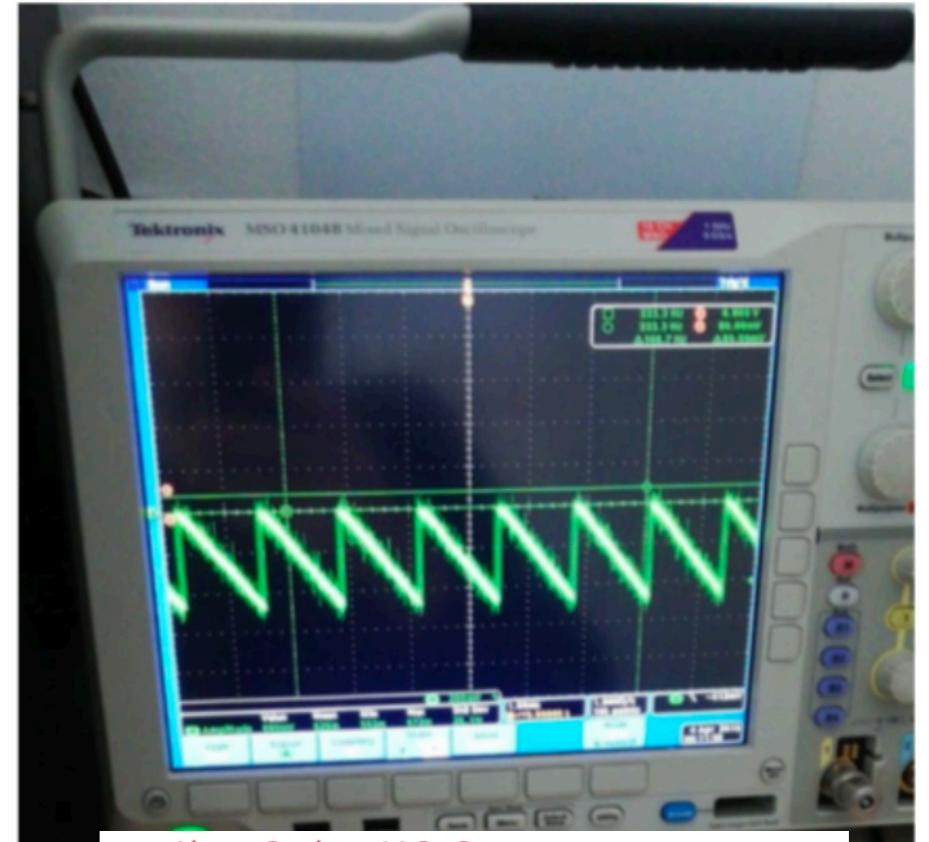
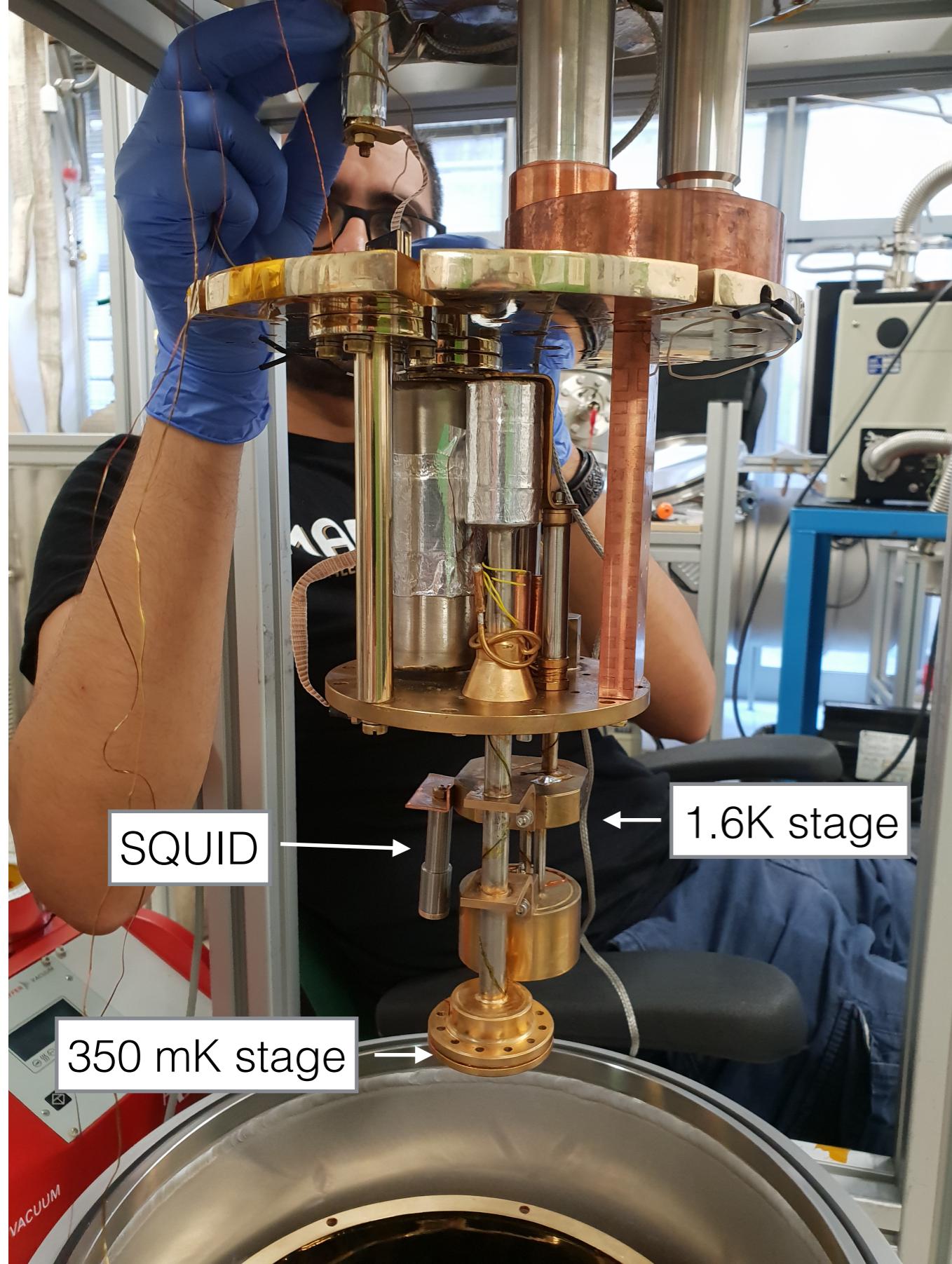
- Tiny **cooling power** requires reading **multiple sensors** with a single pair of wires
- Each detector is coupled to a **superconducting resonant circuit**
 - Frequency-domain multiplexing (**FDM**) \Rightarrow sum of sinusoids



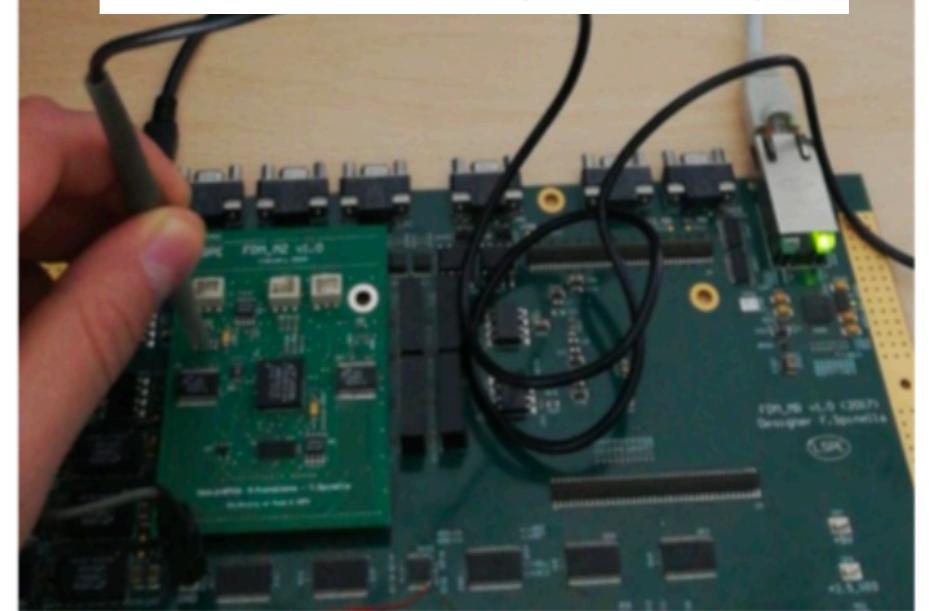
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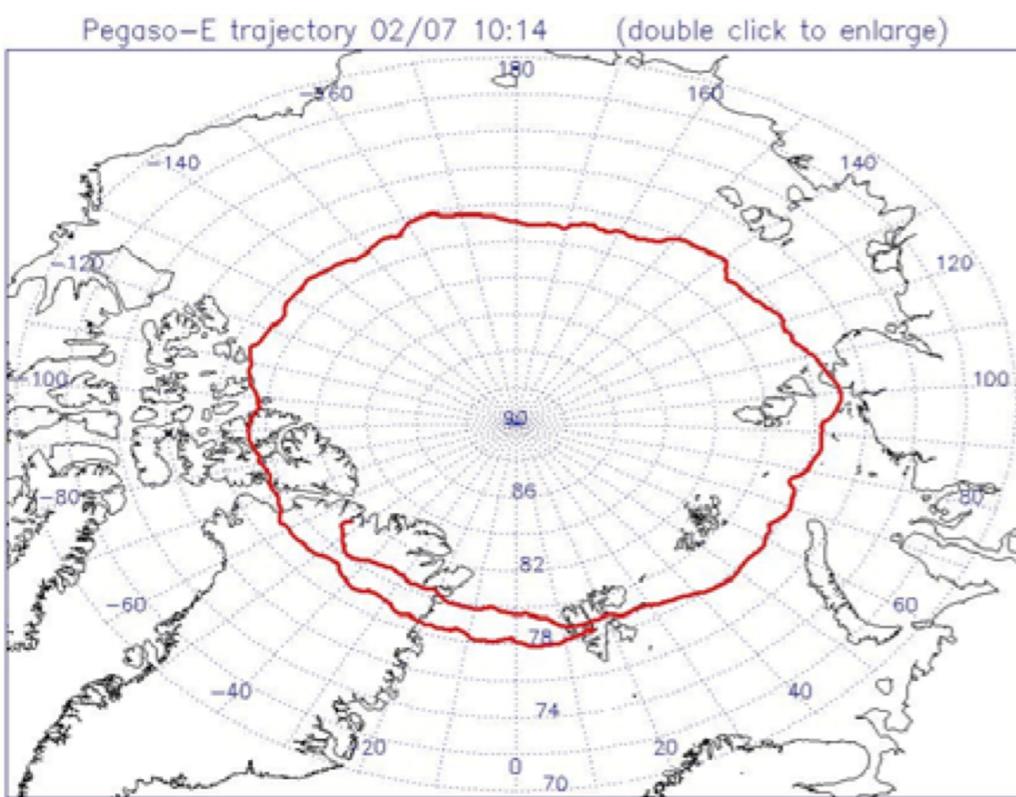


- Altera Cyclone V SoC
 - FPGA with 110'000 logic elements
 - 925 MHz dual-core micro-controller
- Mezzanine plug-ins for DAC and ADCs
 - 2 LTC1668 DACs (low noise, low power consumption)
 - 1 LTM9001-GA ADCs (16-bit, 25 MSPS)



LSPE

- Large Scale Polarization Explorer (ASI / INFN)
 - uno strumento per misurare la **polarizzazione di modo-B** della CMB
 - Vola su **pallone stratosferico** nella notte polare artica
 - 40km, -80°C , 15 gg di durata
 - Sensibilità alle grandi scale angolari. $r < 0.03$ @99%CL



Siti di misura

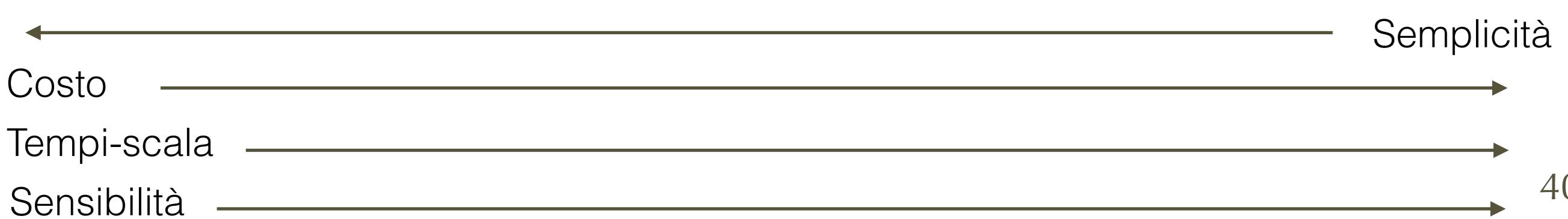
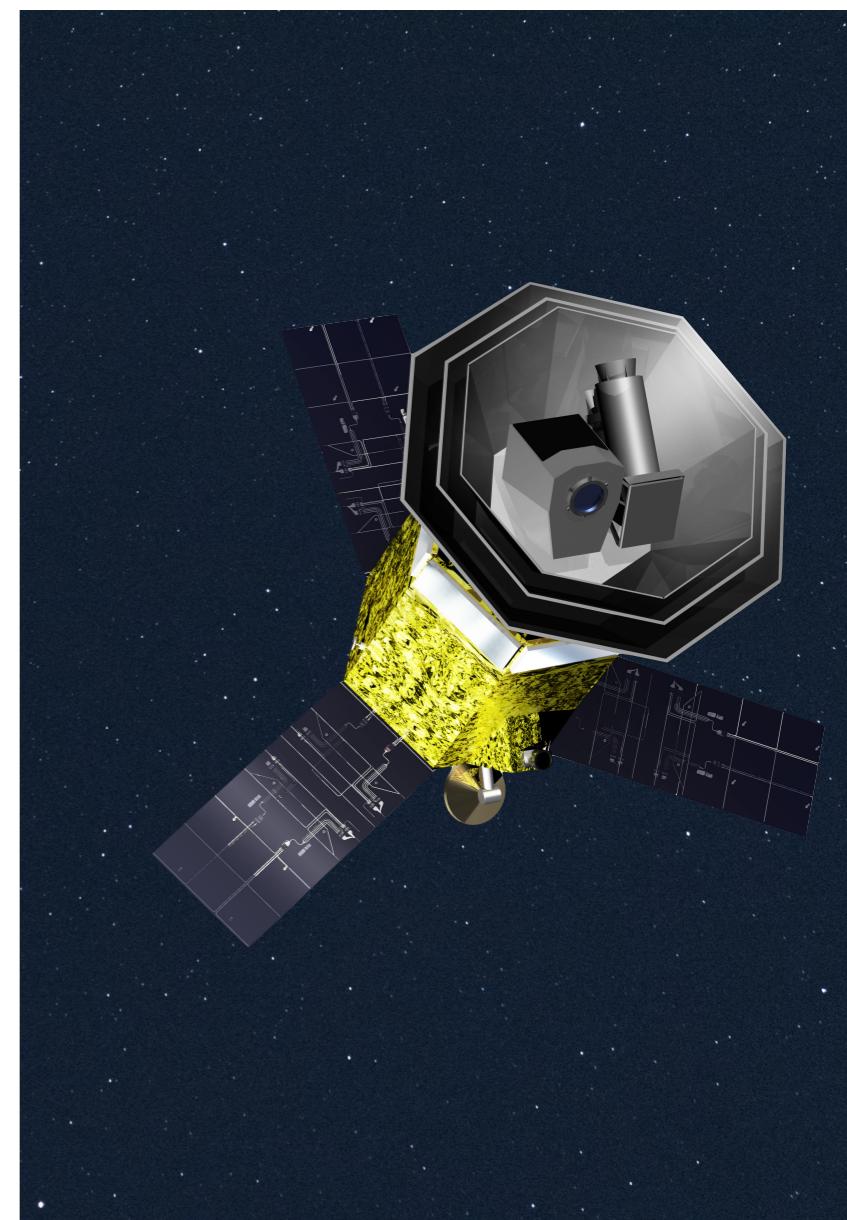
Terra



Pallone



Spazio



Siti di misura

Terra



2020

Pallone

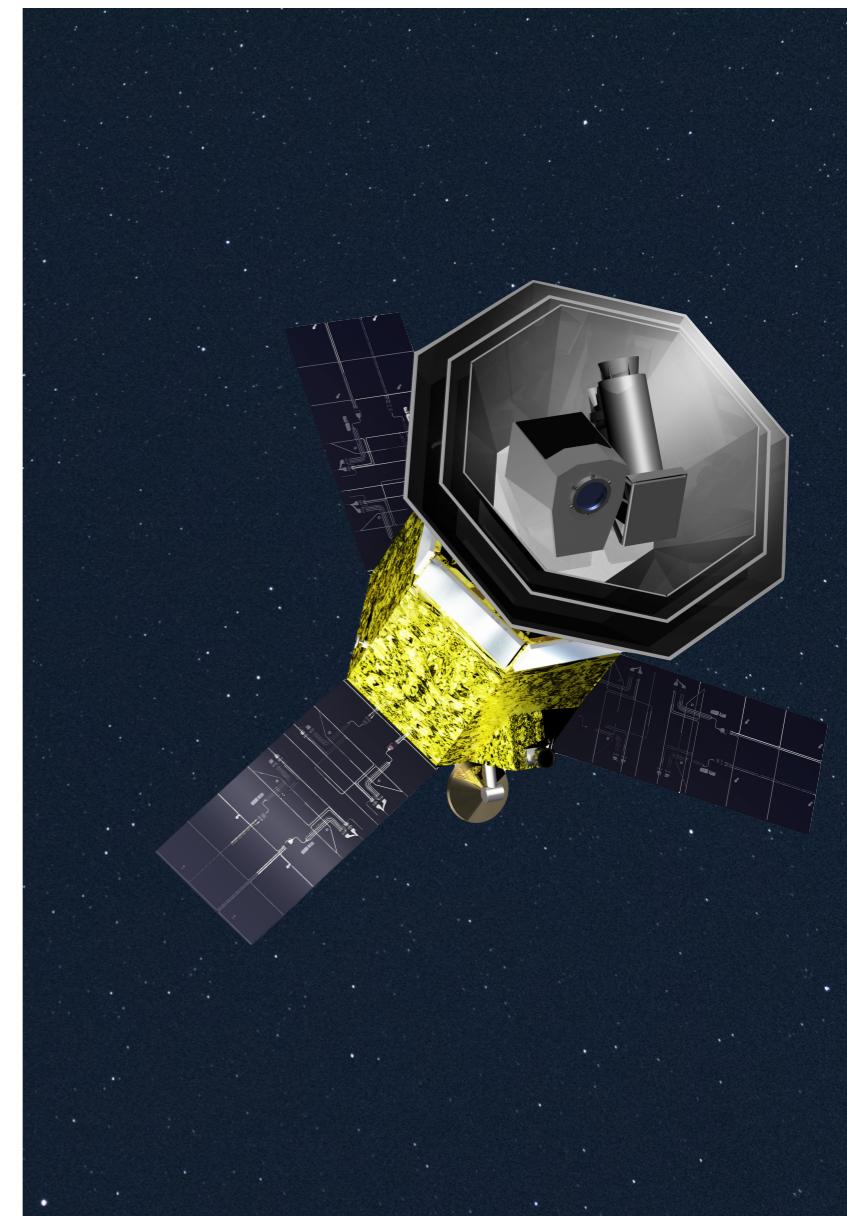


2020

LSPE/Swipe



Spazio



2028

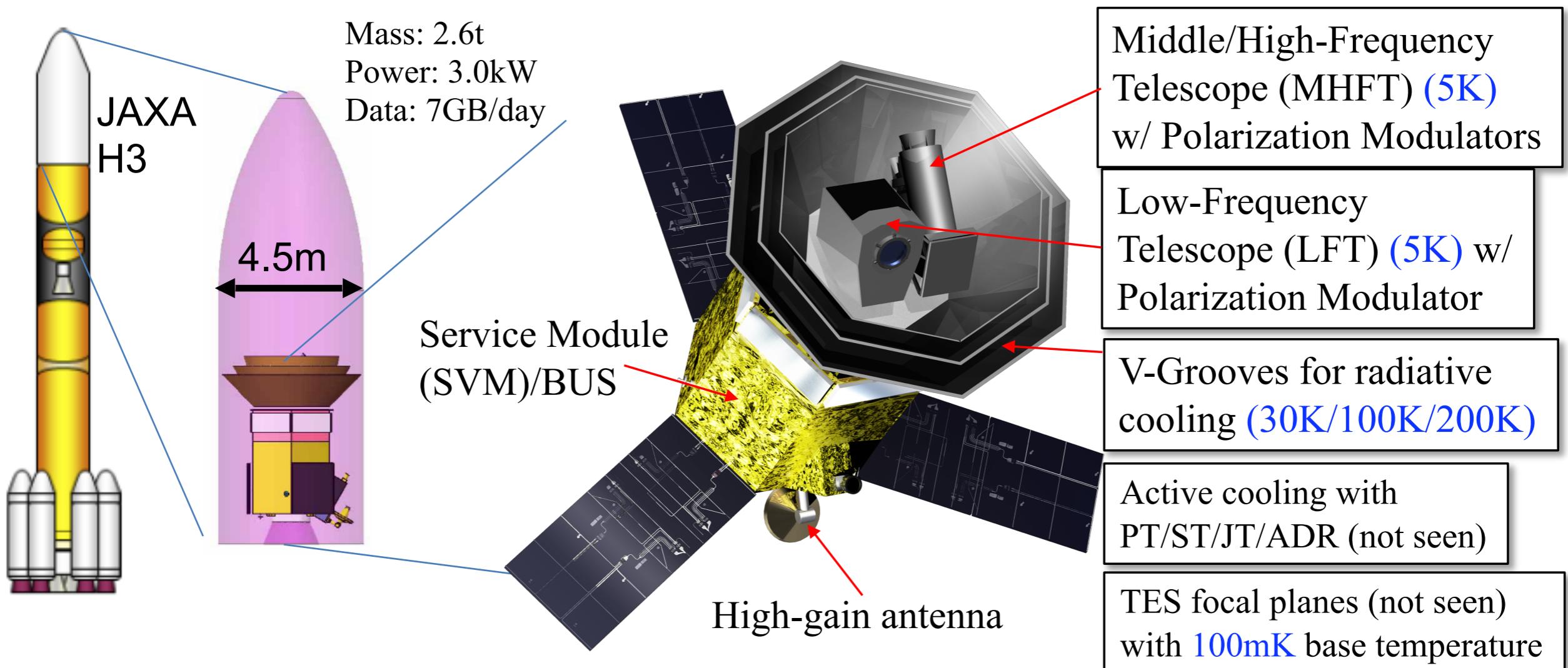
LiteBIRD

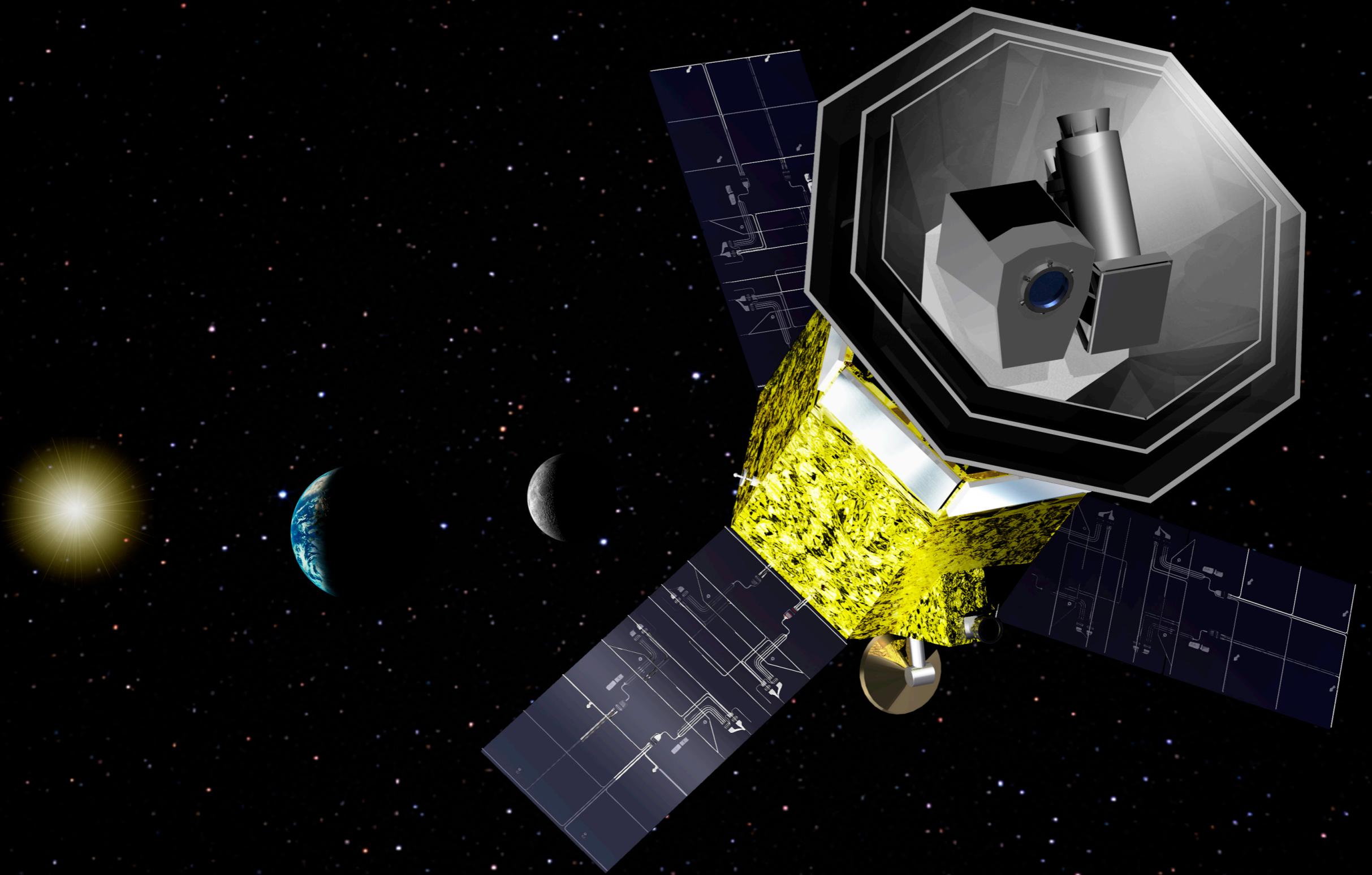


- Misura della mappa di polarizzazione nel futuro prossimo

LiteBIRD Overview

- Light satellite for B-modes from Inflation CMB Radiation Observation
- Just selected (May 2019) as the next JAXA's L-class mission
- Expected launch in 2028 with JAXA H3 rocket
 - LiteBIRD is the only CMB space mission that can be realized in 2020s
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (34–448 GHz, 15 bands) at 70–20 arcmin
- Mission δr (total uncertainty) < 0.001 (for $r=0$) with CMB B-mode observation





LiteBIRD mission instrument

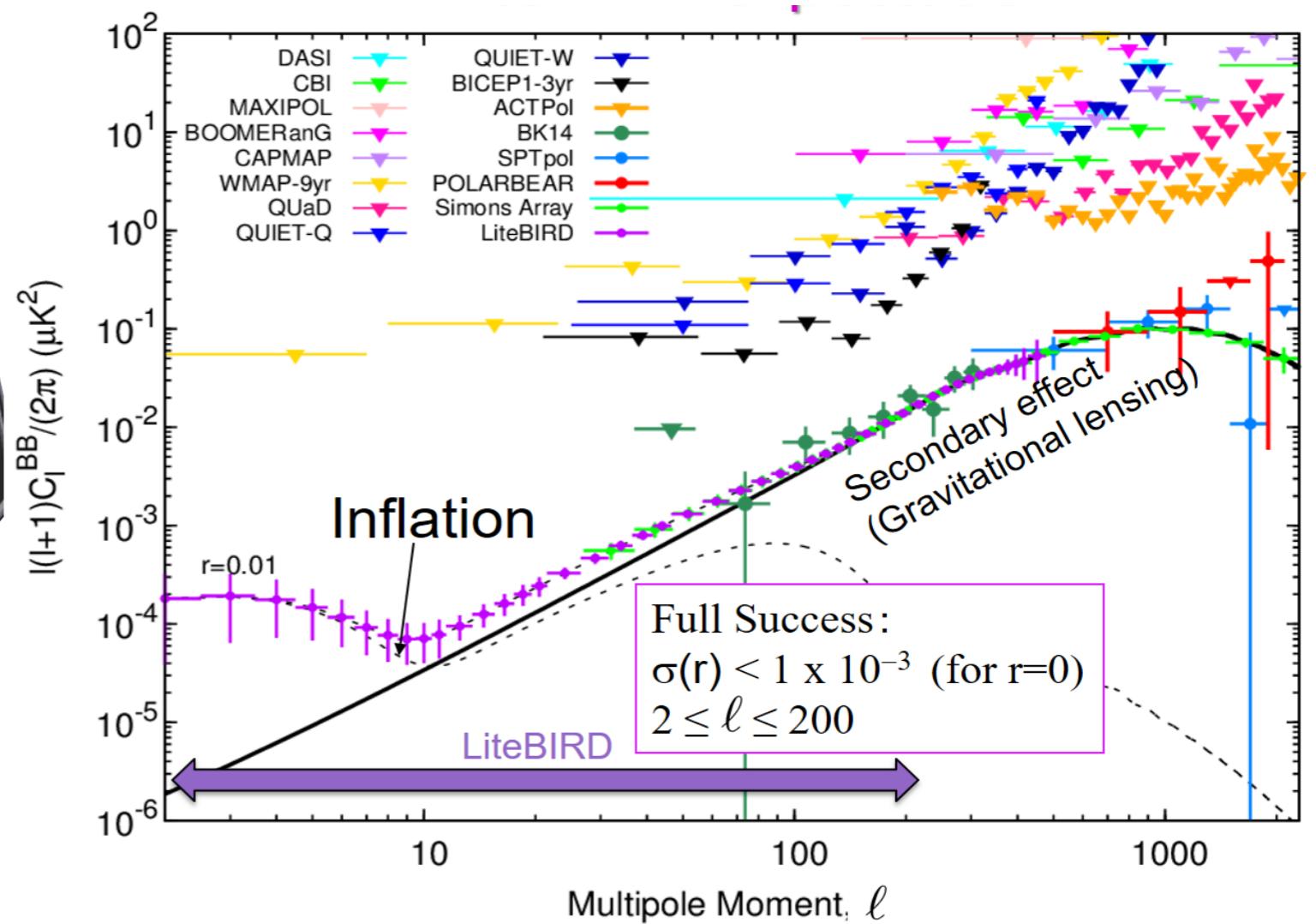
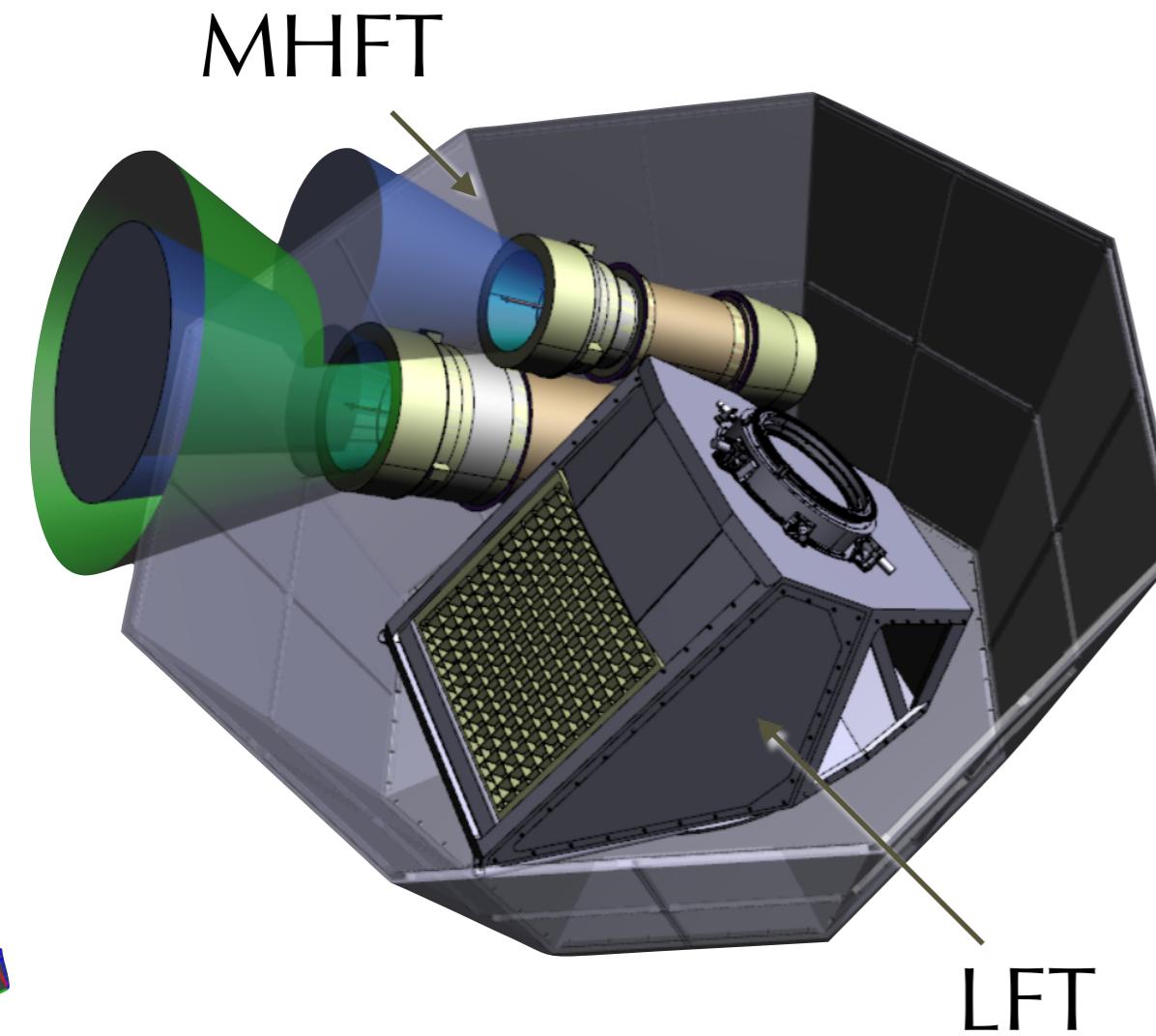
- Three features
 - Three telescopes w/ TES arrays (4732 detectors)
 - Polarization modulator for 1/f noise reduction
 - Cryogenic system for 0.1K base temperature

Full Success :

$$\delta r < 1 \times 10^{-3} \text{ (for } r=0\text{)}$$

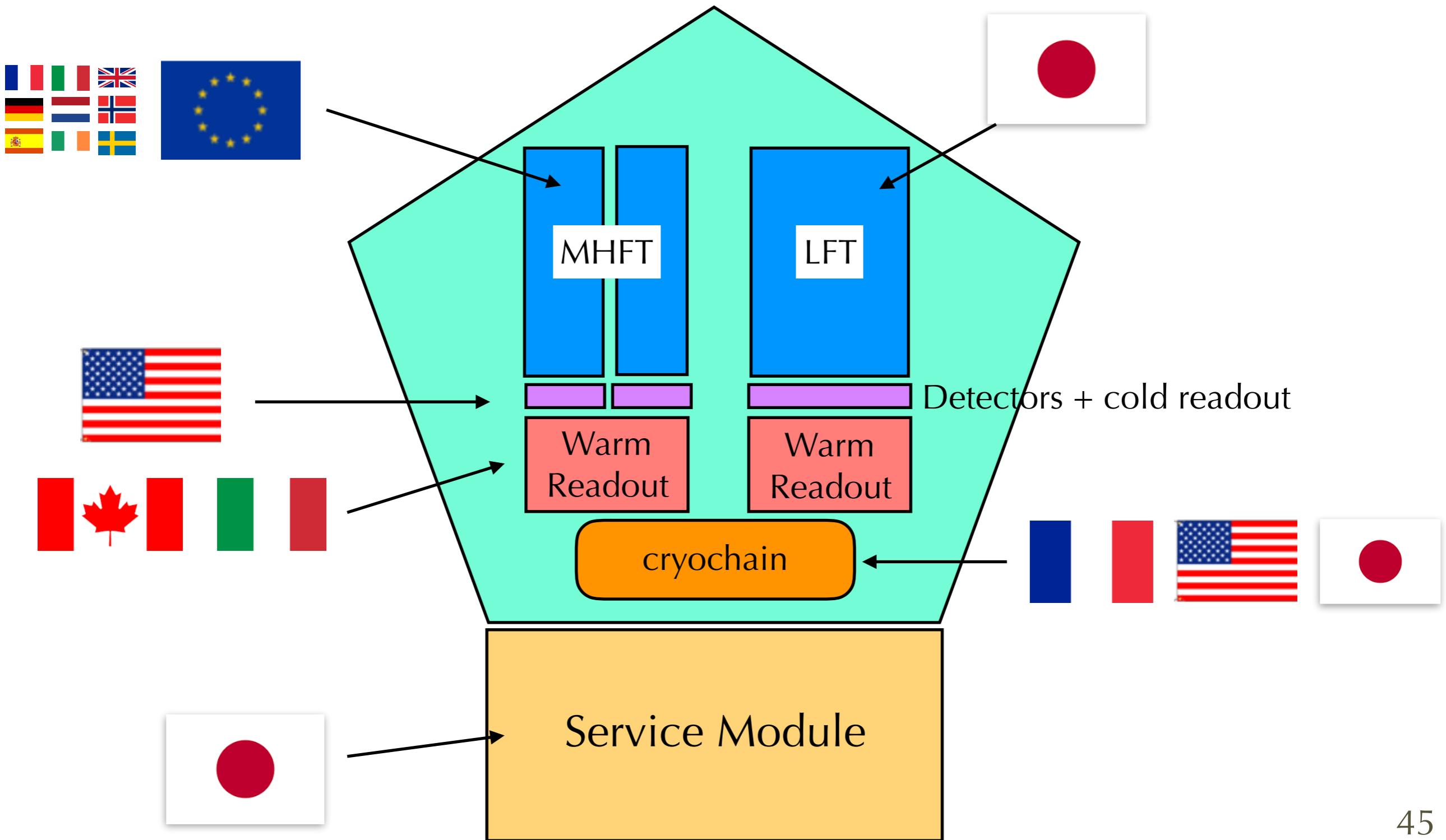
$$2 \leq \ell \leq 200$$

x70 sensitivity
w.r.t. present limit



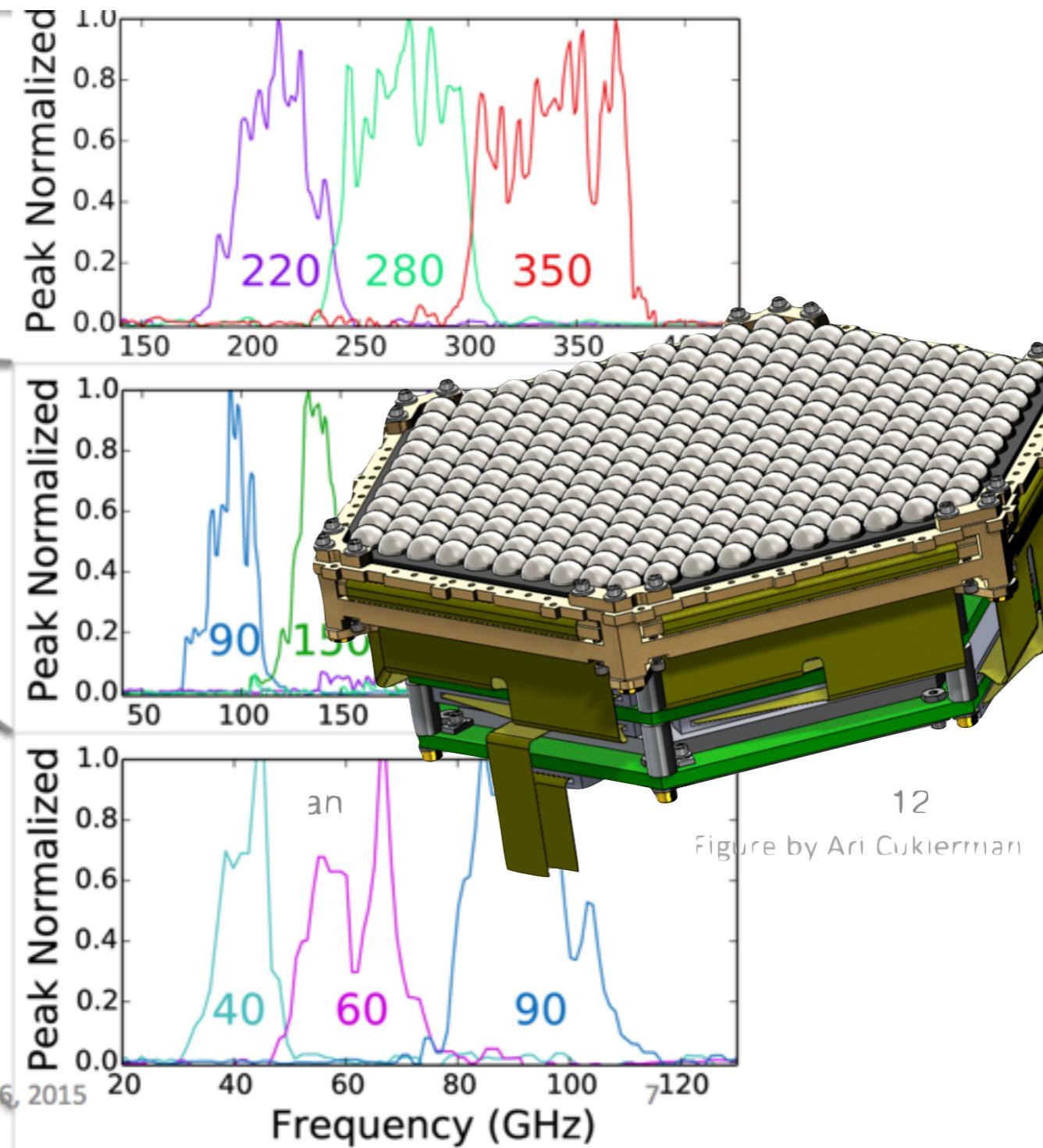
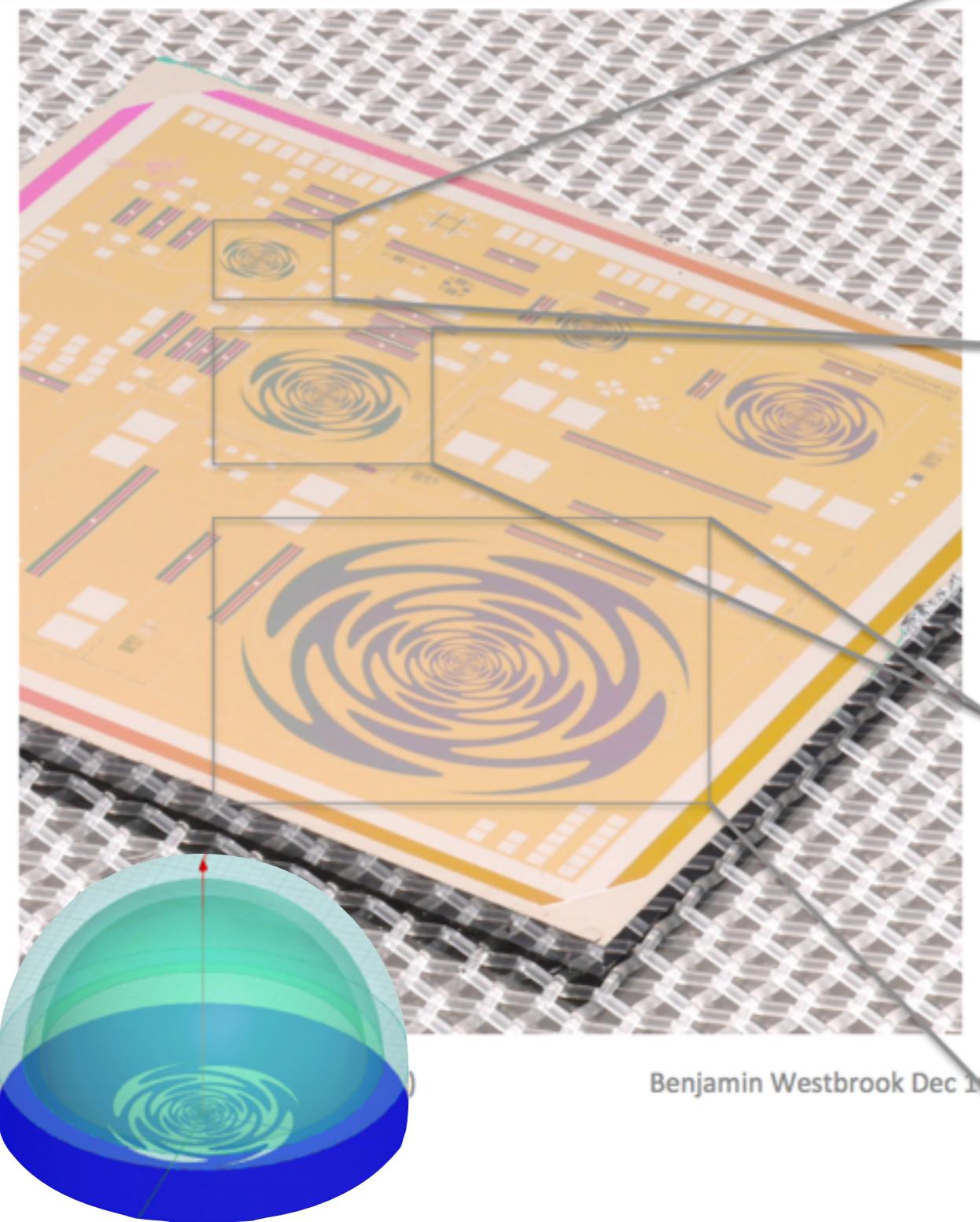
Task division

- JAXA led with strong U.S. (NASA), Canadian (CSA) and EU participation
- About 180 researchers, still growing, with CMB, x-ray, HEP, background
 - PI M.Hazumi (KEK &al), US PI A.Lee, Can PI M.Dobbs, EU PI L. Montier



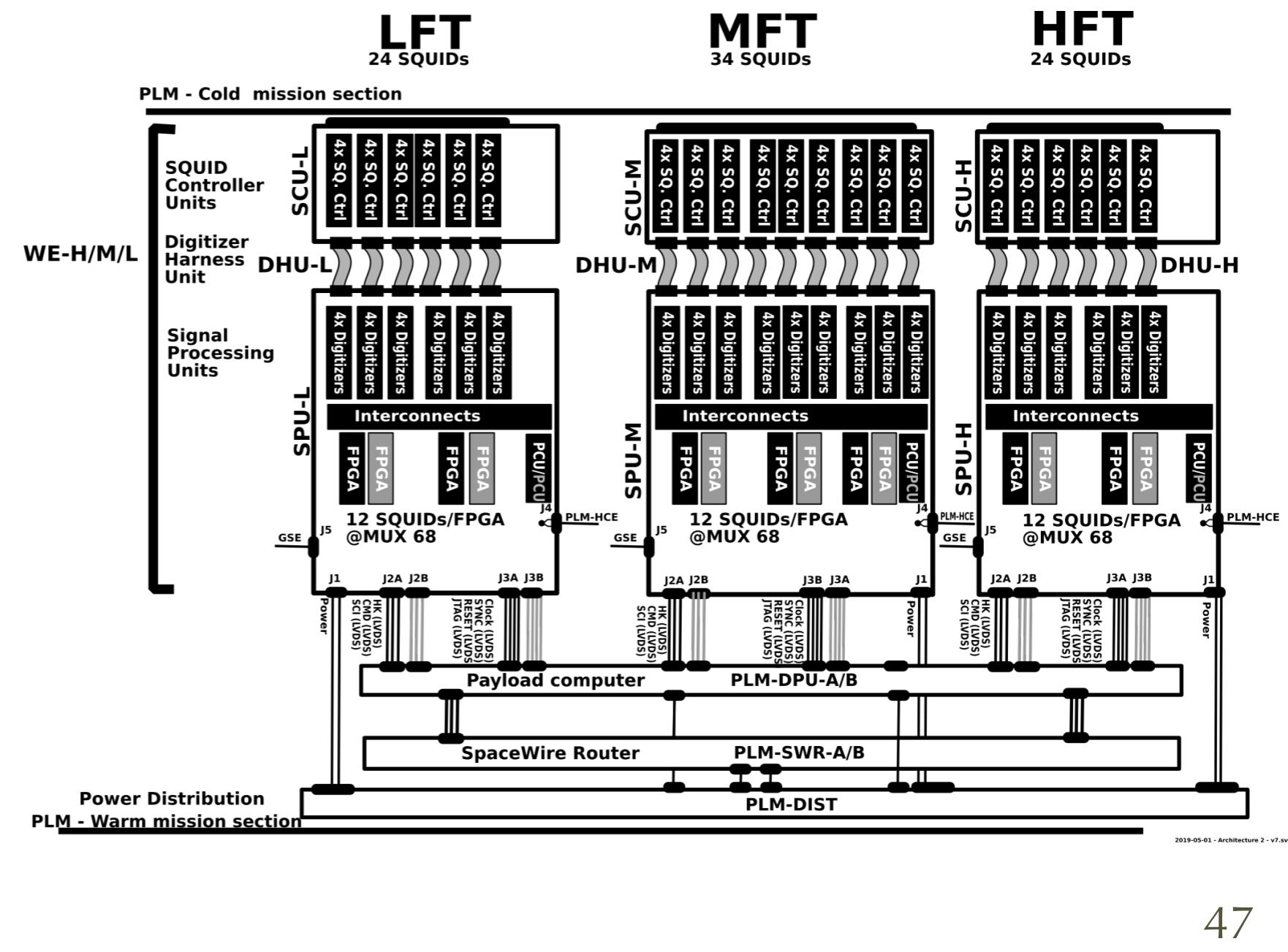
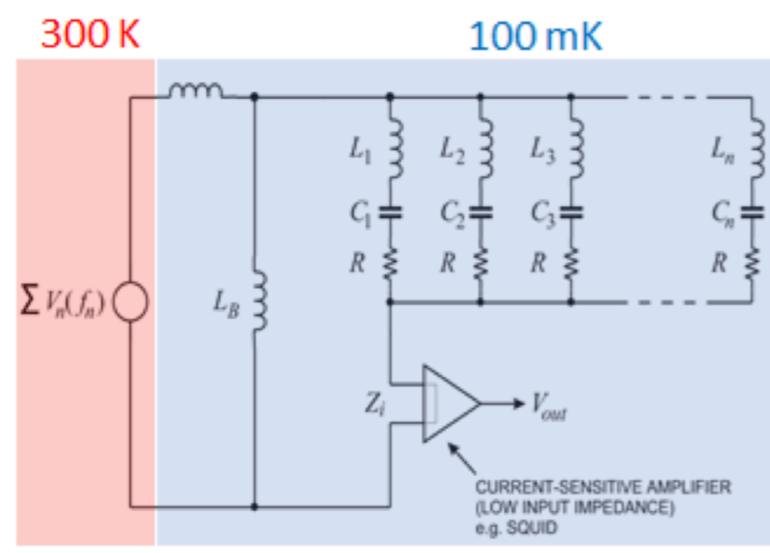
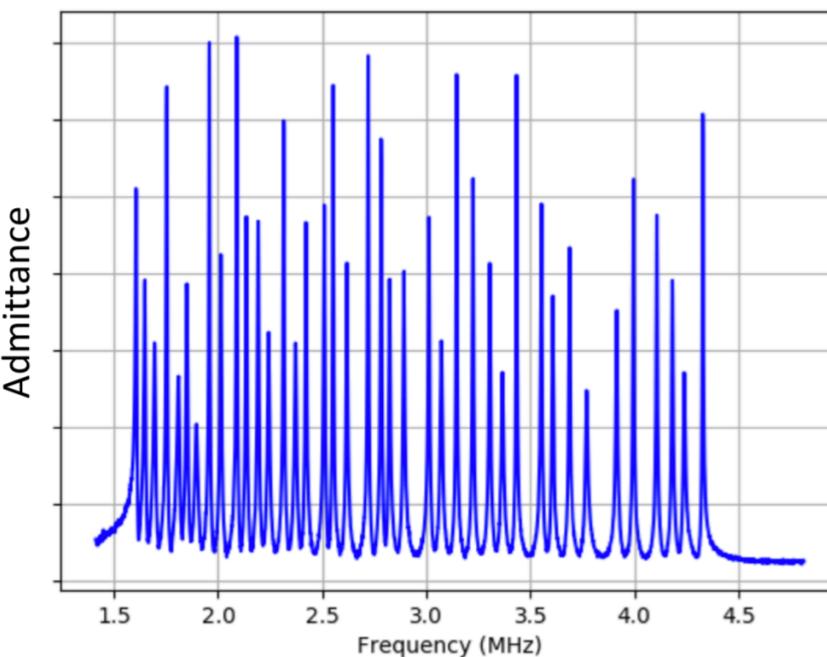
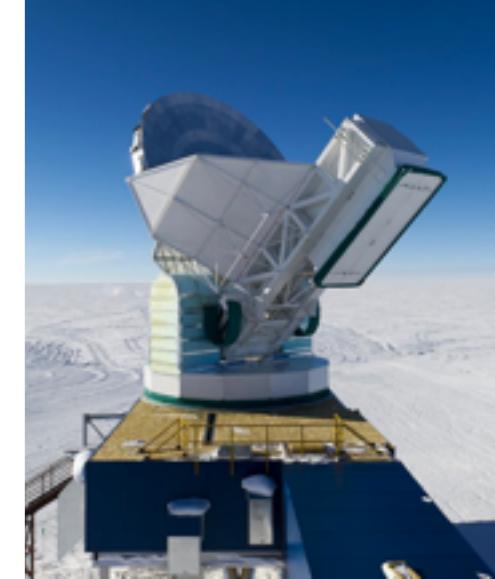
Low and mid-frequency arrays

- lenslet-coupled “trichroic pixel” = broadband sinuous antenna + filters + TES



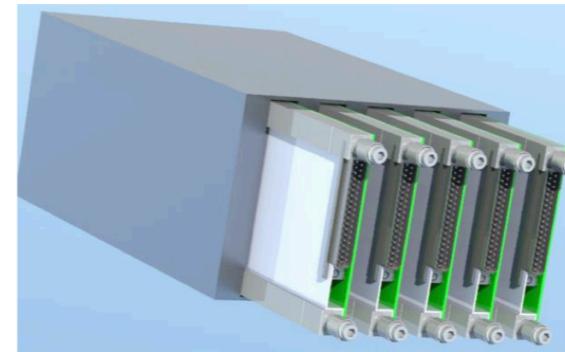
DfMUX readout

- Frequency Multiplexed **Readout** (FDM, same as LSPE)
 - USA: Cold components (LC boards + **SQUID**)
 - Canada (+INFN): **warm** electronics
- Based on system deployed for South Pole Telescope and POLARBEAR

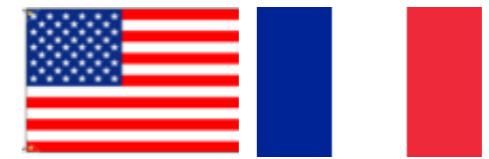


INFN Contribution

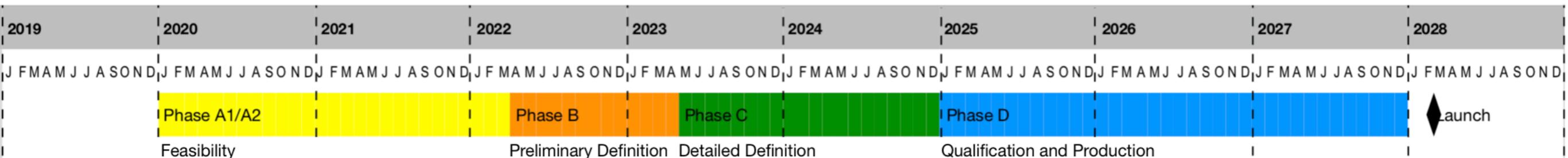
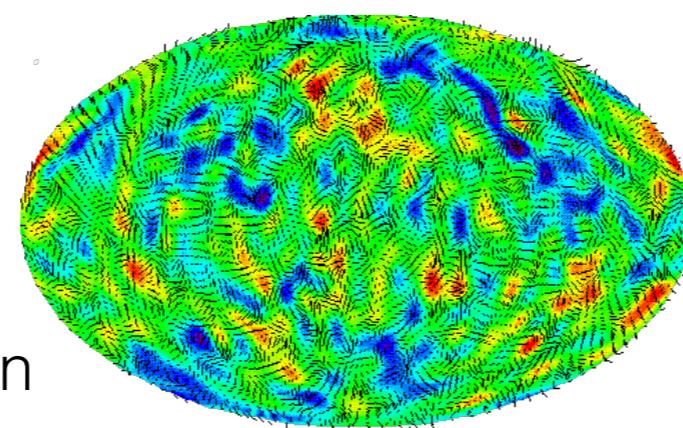
- Warm Readout Electronics
 - Flight qualification of selected components
 - SQUID control units (LFT + MHFT)
 - electronic boards
 - mechanics
 - thermal interfaces
 - (digital assembly DAC/ADC boards)



- Detector study
 - Study of CR impact on detectors
 - on-beam test of detectors



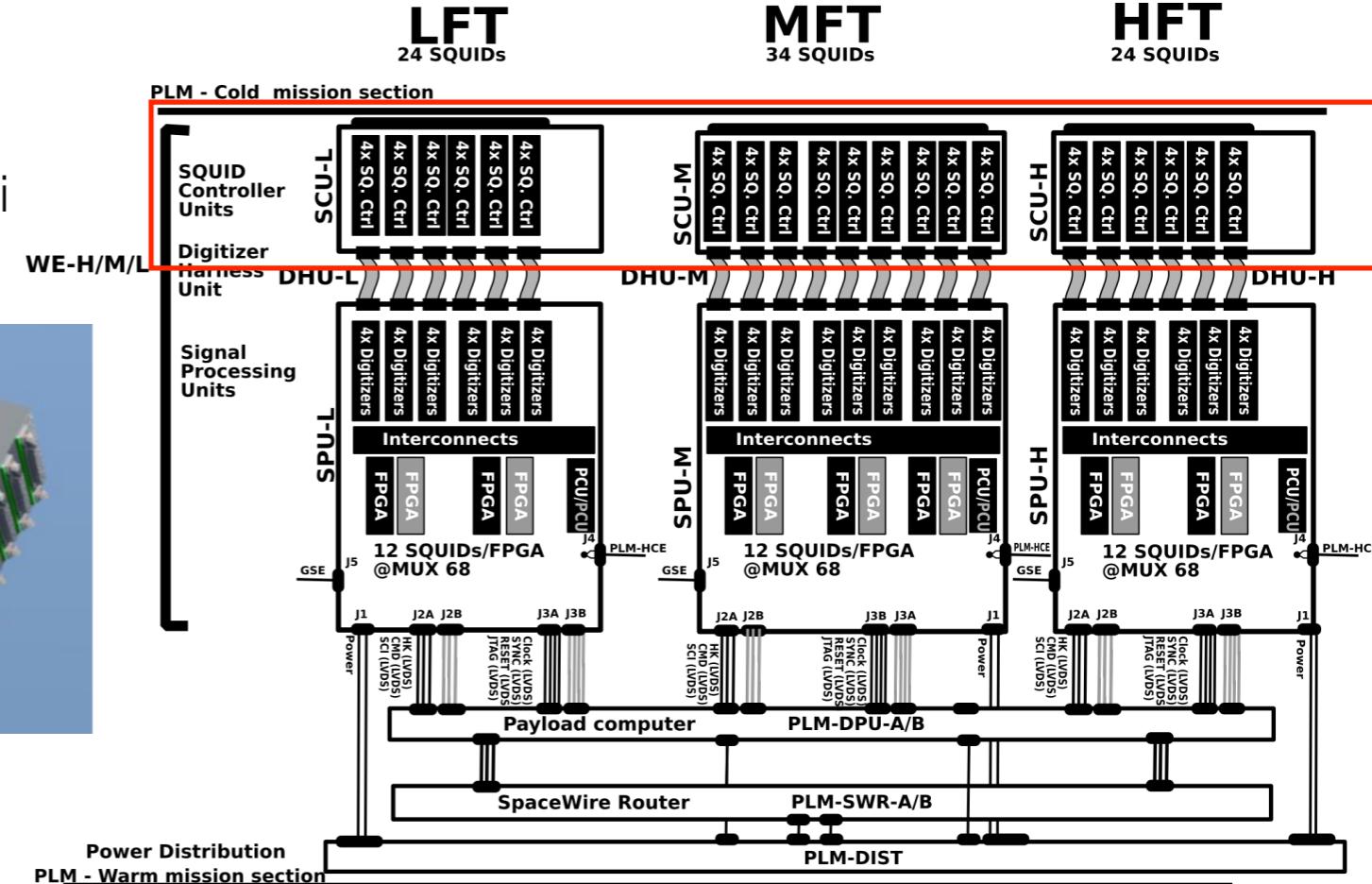
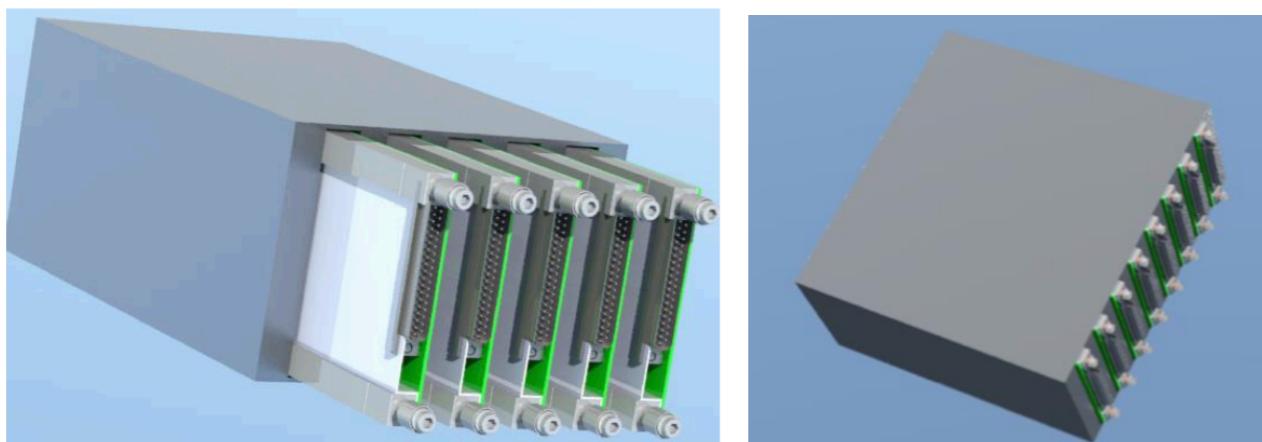
- Data Analysis
 - simulation
 - map making
 - CMB parameters extraction



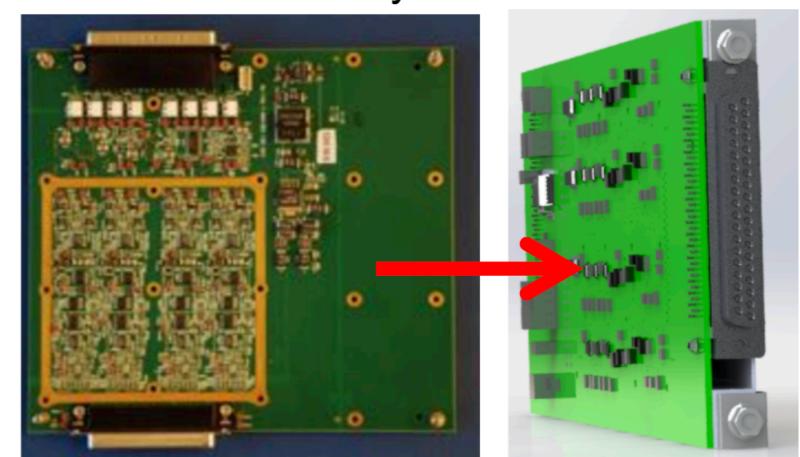
Il contributo INFN



- Il contributo INFN si inquadra nel contesto dell'**elettronica di readout** (Warm Readout electronics) :
 - Fornire le **SQUID control units** (per i tre telescopi LFT + MHFT)
 - schede elettroniche
 - meccanica di supporto
 - interfacce termiche
 - Flight **qualification** di componenti selezionati
 - qualificare per lo spazio il DAC LT1668



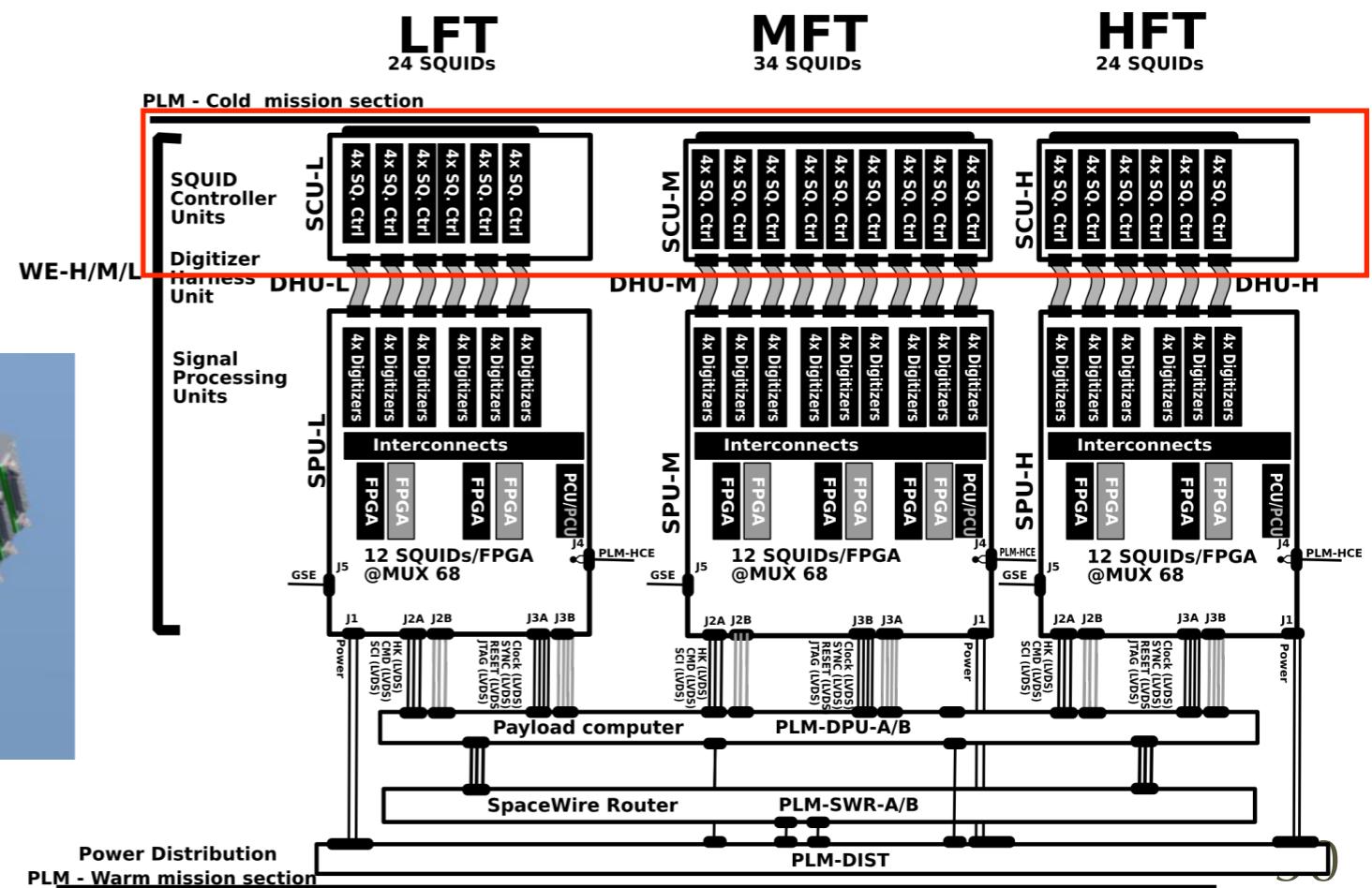
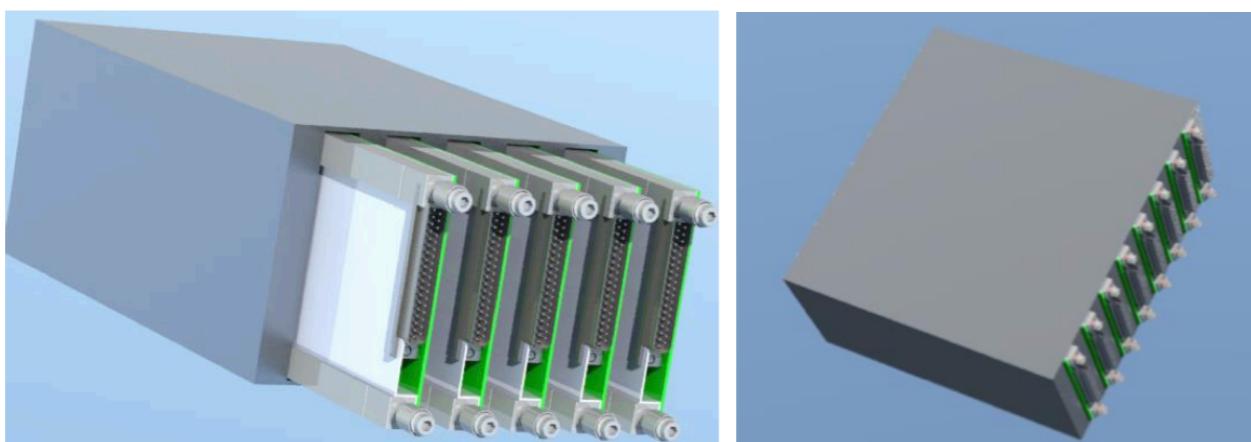
- Ulteriori contributi HW possibili
 - (**digital assembly DAC/ADC boards**)
 - DPU – in collaborazione con ASI
- In seconda battuta
 - studio della **risposta dei detector ai cosmici** (CR and/or beam tests)
 - In previsione dell'**analisi dati**
 - simulation
 - map making
 - CMB parameters extraction



SQUID readout units



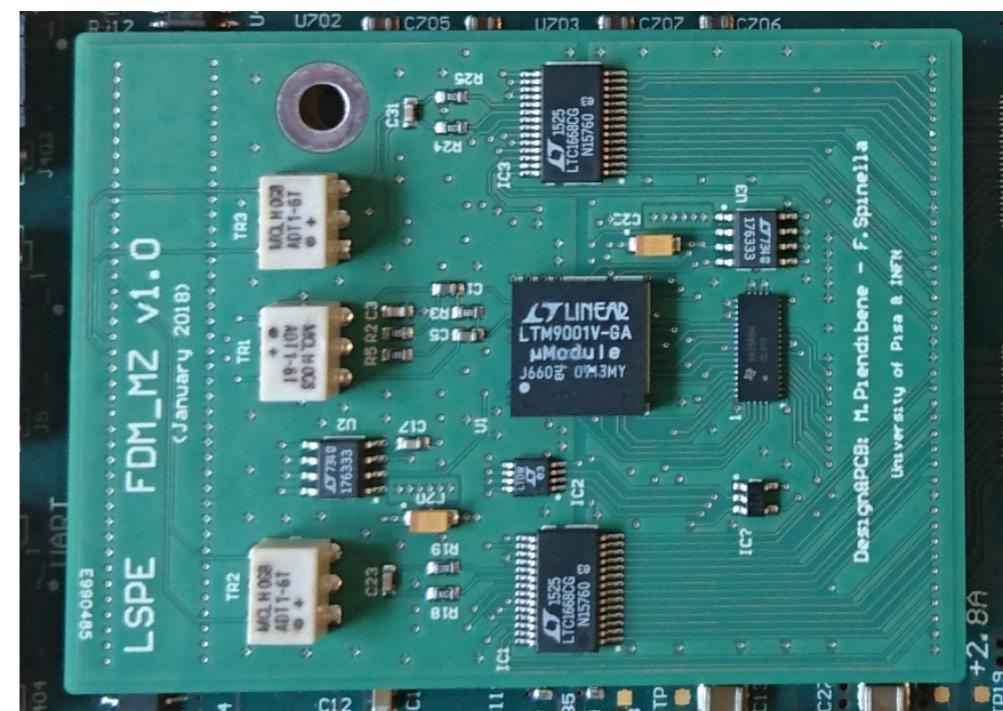
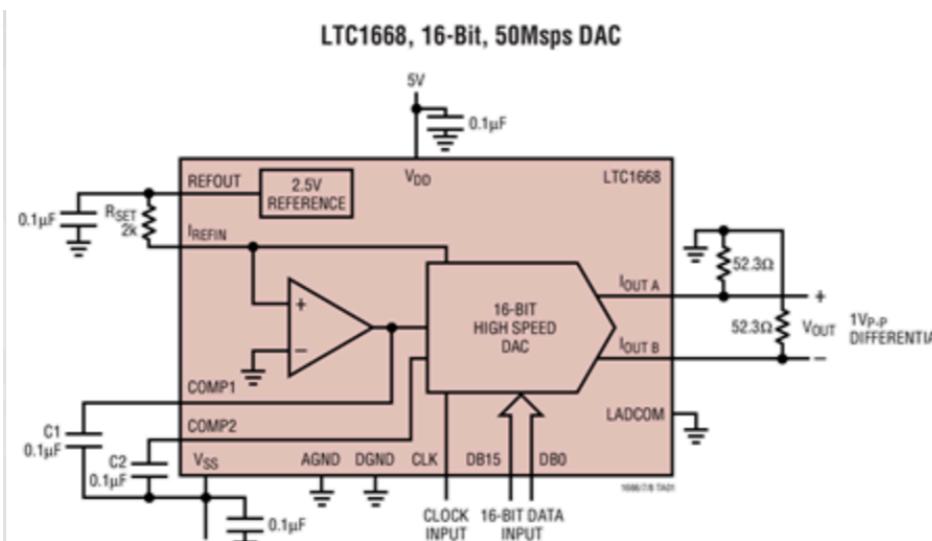
- Ci sono **4732 detectors** (multichroic TES) divisi su **3 piani focali**
 - LFT, MFT e HFT ognuno con una Signal Processing Unit (SPU)
- Una **Squid Control Unit** (SCU) per ogni SPU
 - LFT (**24 SQUIDS**), MFT (**34 SQUIDS**), HFT (**24 SQUIDS**)
- Fino ad 9 Squid Control Assembly (le boards) per ogni SCU
 - Le **Squid Control Boards** forniscono l'interfaccia fondamentale fra i rivelatori e il readout (4 SQUID/each)
- Partendo dall'attuale versione per SPT, le unità vanno
 - ridisegnate
 - testate a caldo
 - testate a freddo (SQUID @100mK)
 - Prodotti i DM, EQM e FM
 - Documentati

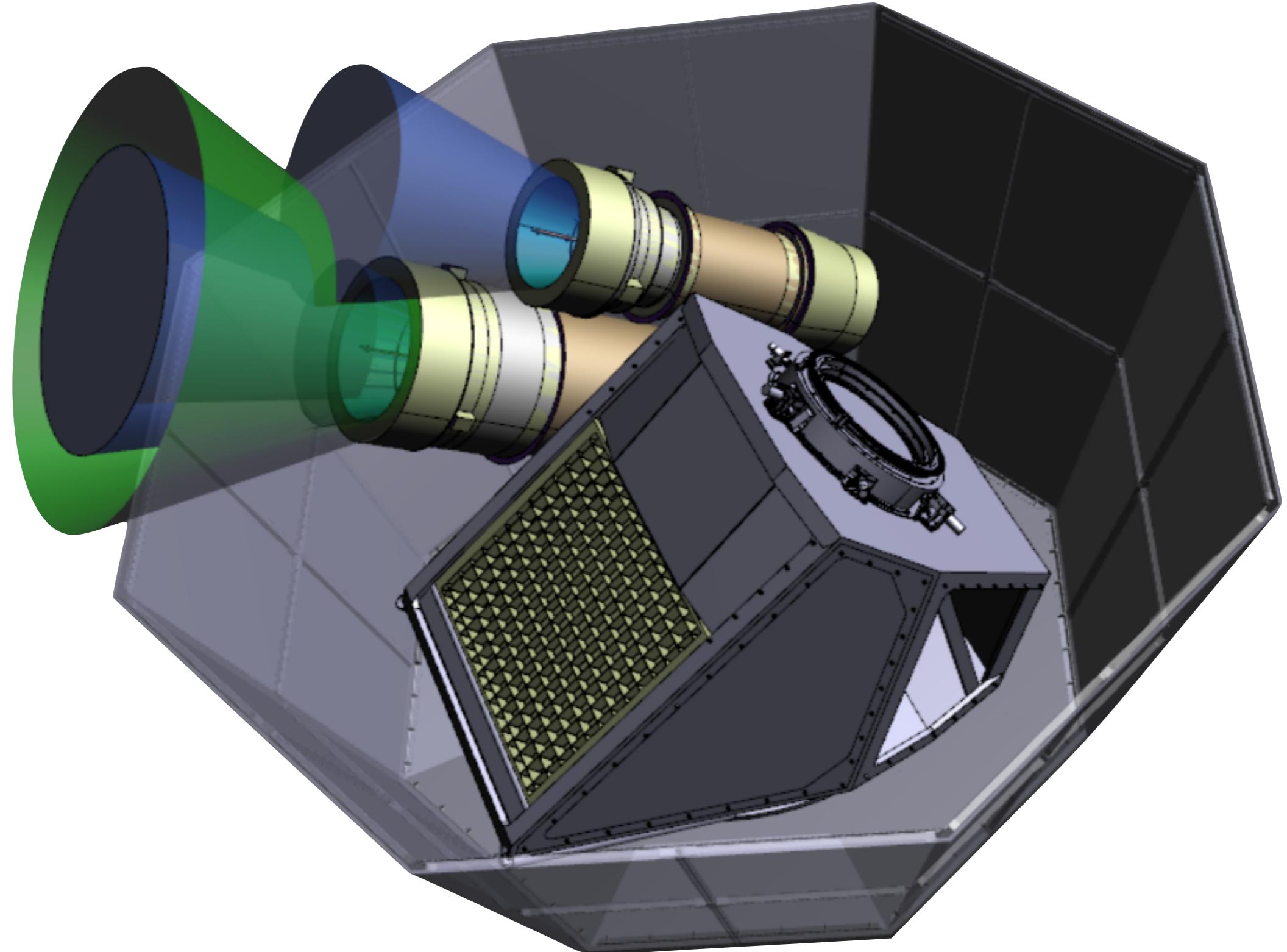
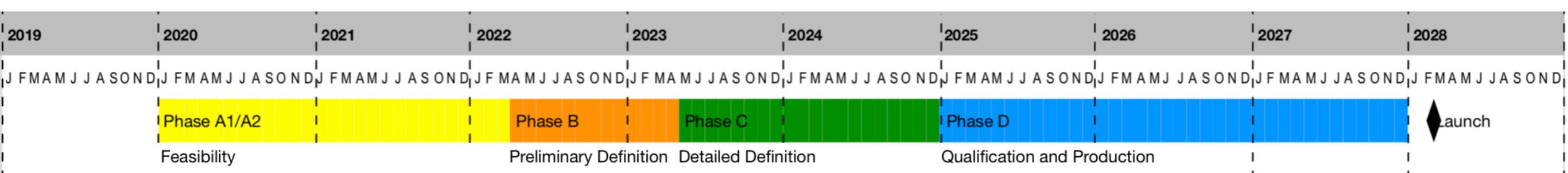


Flight qualification

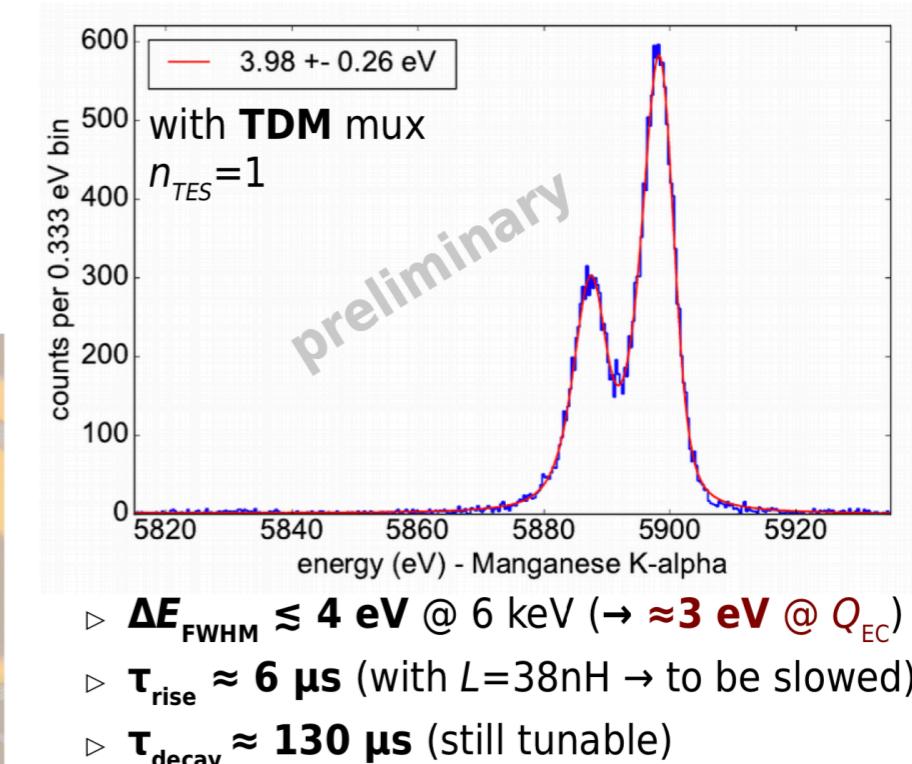
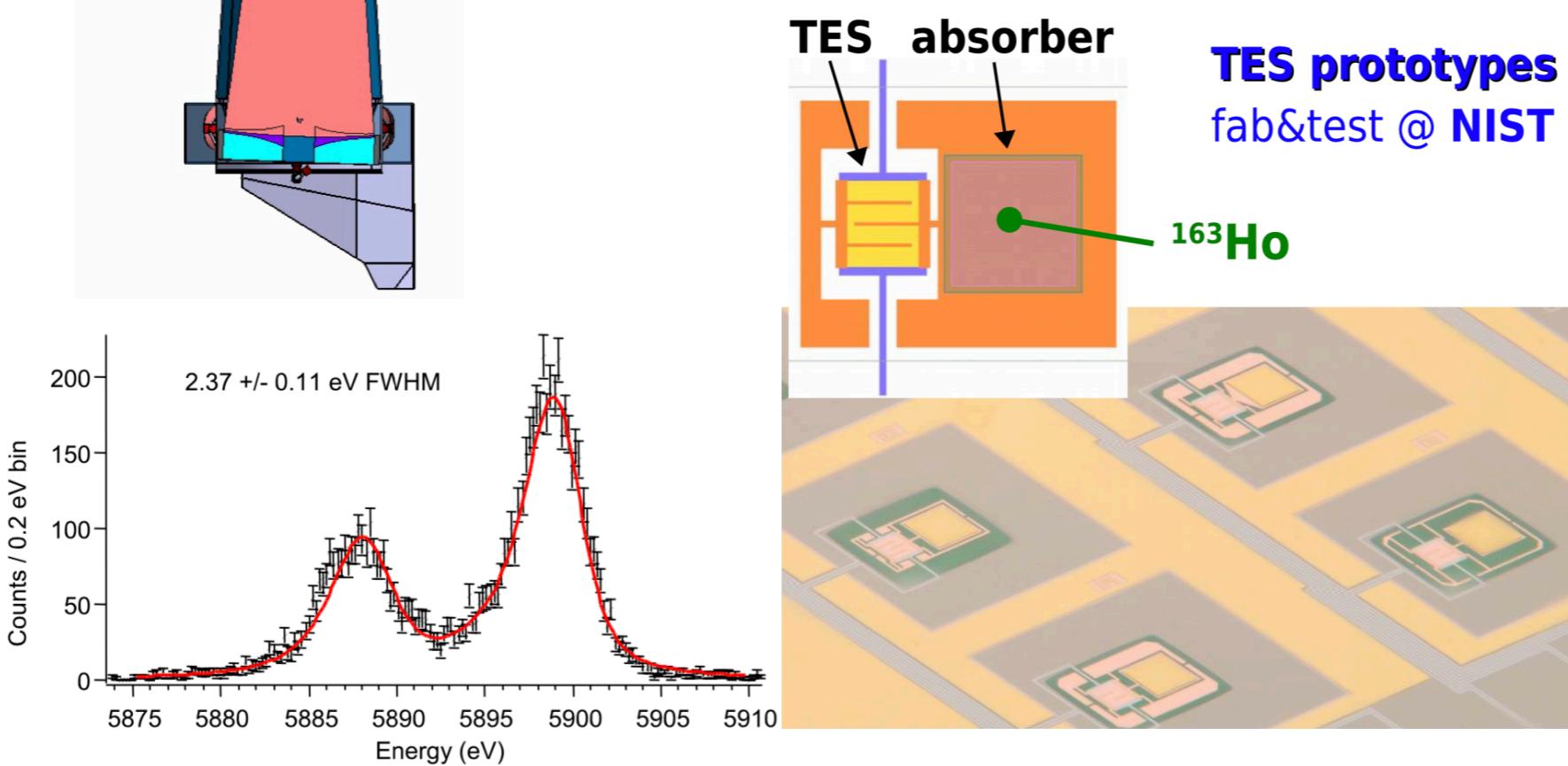
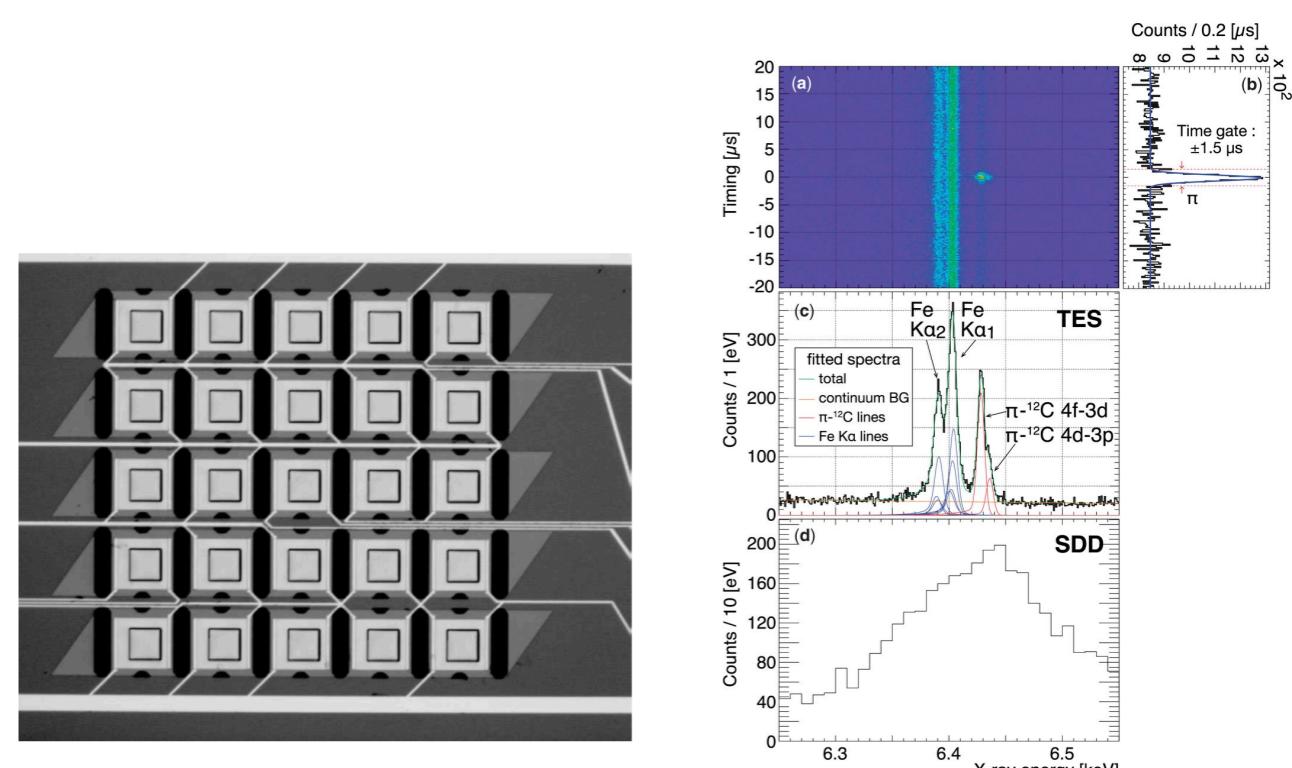
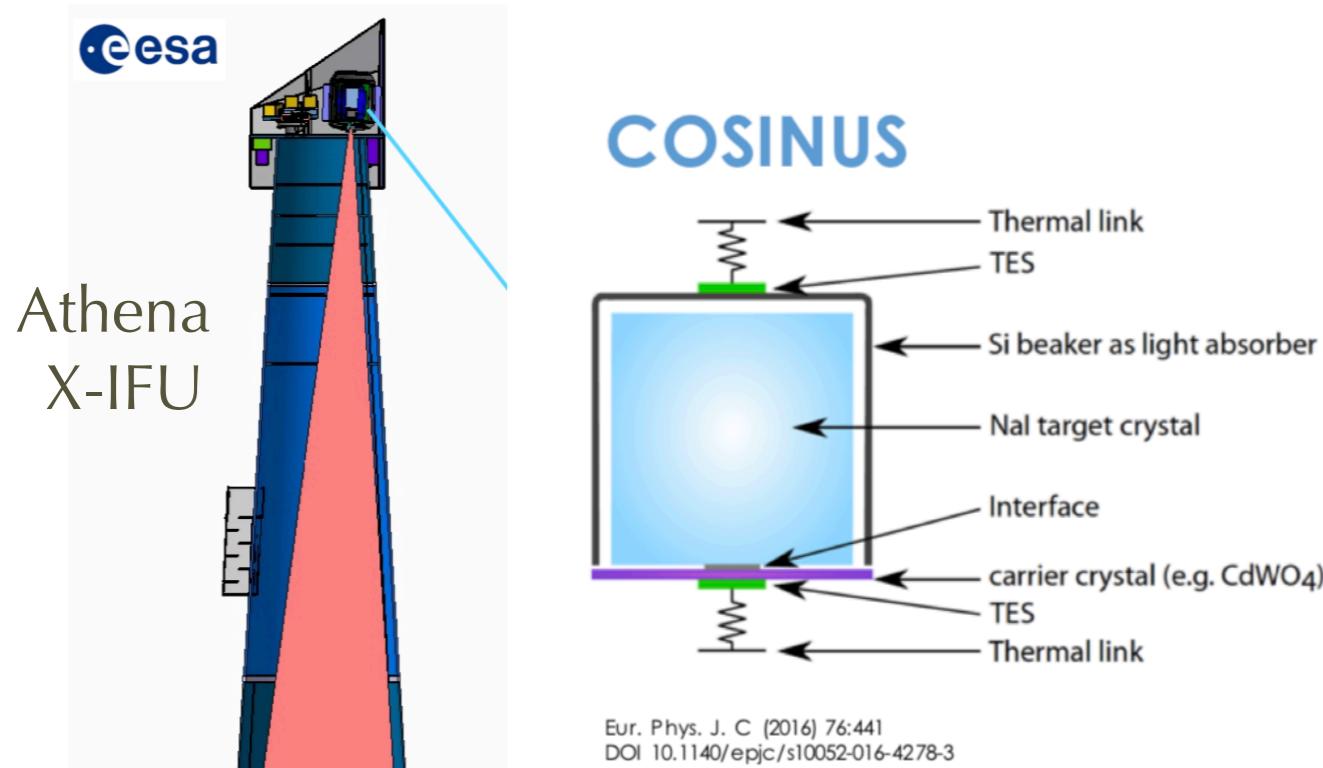


- The Digitizer Assembly (DA) uses the **AD768 DAC** to generate the carrier and noller signals. It was selected due to its low 1/f noise and its availability as a space qualified component.
 - However, this DAC is **power hungry**, and accounts for a non-negligible part of the WE power budget.
 - An alternate DAC, the **LT1668**, offers the same performance with at least half of the power consumption, but is not space qualified.
- LT1668 presently being **used in LSPE** warm readout
 - test fino a **30 krad** con particelle ionizzanti
 - acceptable system performance
 - 1/f noise & white noise
 - Linearity & monotonicity
 - Power consumption
 - Radiation behavior (transients, latch-ups etc.)



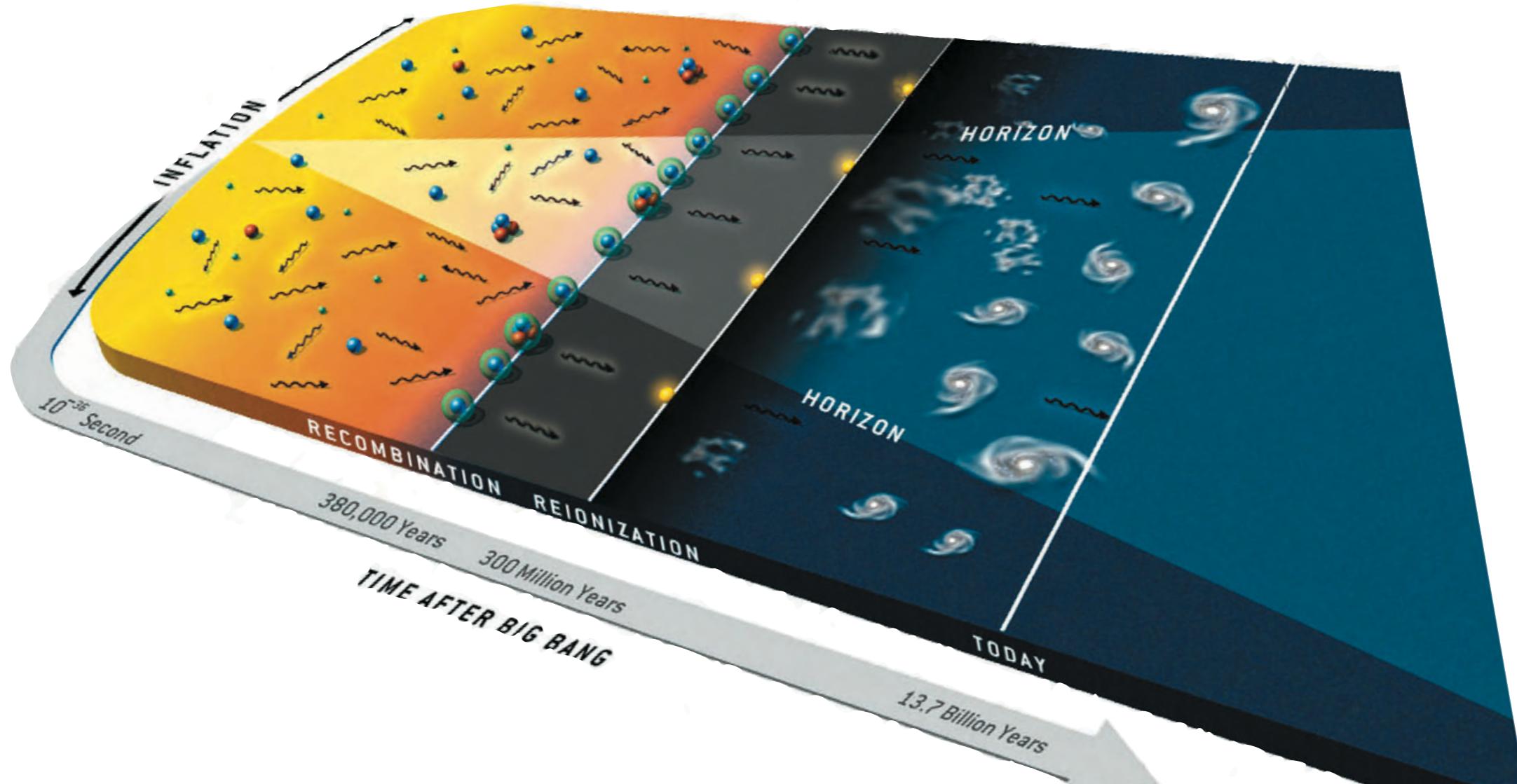


- Due to their intrinsic energy resolution usage in cutting-edge HEP research projects (x-rays, ν -masses, $0\nu2\beta$...)



Conclusione

- La CMB fornisce informazioni sui primi istanti di vita dell'universo
- La prossima sfida è la misura precisa della sua polarizzazione
 - tecnologia all'avanguardia
- LiteBIRD rappresenta l'unica occasione nel futuro prossimo per accedere a scale $10^{15\div 16}$ GeV
- Possibilità di misurare l'esistenza dei modi-B di polarizzazione della CMB
 - Prima misura degli aspetti quantistici della gravità
 - Avremo per la prima volta un *hint* sperimentale dell'"unificazione" della gravità con le altre forze fondamentali





GRAZIE