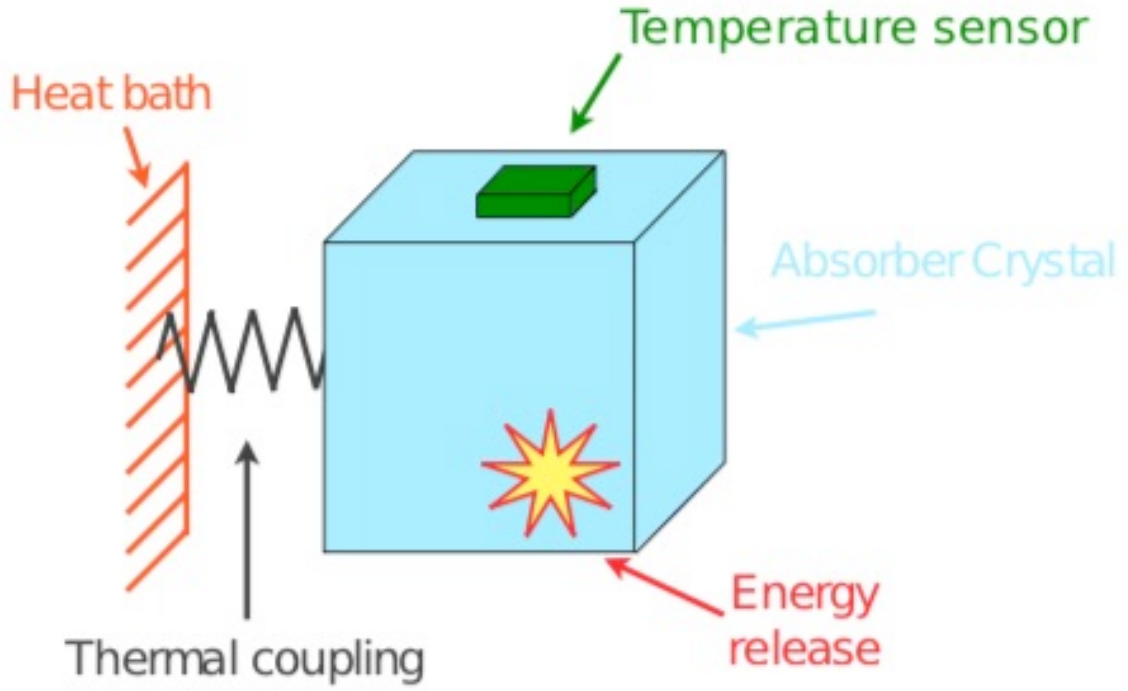
低温粒子探测器工作原理及声子热化



$$\Delta T(t) = \frac{E}{C} e^{-t/\tau} \quad \text{with} \quad \tau \equiv \frac{C}{G}$$

When a particle releases some energy in the absorber, phonons out of the thermodynamic equilibrium are produced (**athermal phonons**). These phonons degrade their energy via several interactions and reach a new thermal equilibrium distribution.

Bolometric detectors sensitive to **athermal phonons** are characterized by response times of the order of μs (**'fast' detectors**). Instead, if the temperature sensor response time is higher than the phonons thermalization time, **it will detect mainly the thermalized phonons, thus measuring the actual temperature of the absorber; in this case the device is a 'slow' detector and it acts as an ideal calorimeter.**

声子热化

将沉积的粒子能量转化为热声子的过程复杂，主要热化过程可以通过**核和电子通道**，即粒子通过与**原子核/电子的散射**与吸收体相互作用，进而将能量转换为声子；

- 与原子核散射
  - 产生声子（高能声子athermal phonon, μeV-meV）
  - 产生晶格缺陷(若最终未转化为声子)→影响能量分辨
- 与电子散射
  - 产生声子（高能声子athermal phonon, μeV-meV ）
  - 能量逃逸，比如荧光等

高能声子 → 衰变 → 低能声子 Thermal phonon

非常缓慢的过程

最后，声子平均自由程大于晶体尺寸，晶体表面/边沿反射

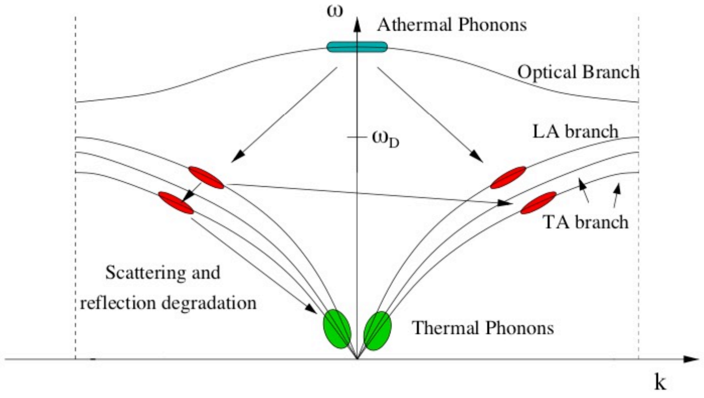


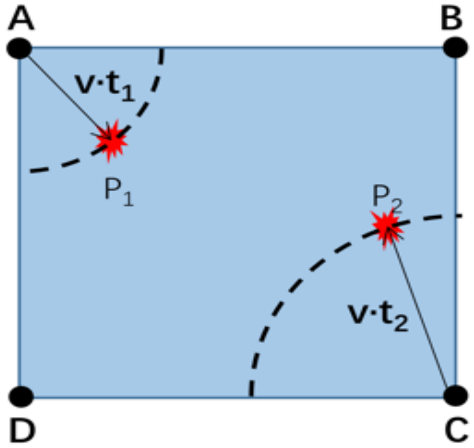
FIGURE 3.3: Athermal phonon thermalization model.

两种传感器

收集/感受声子的器件，热信号转化为电信号

TES，超导转变边沿传感器，快速传感器'fast' sensor (μs)，can detect athermal phonon

NTD，半导体辐照掺杂传感器，快速传感器'slow' sensor (ms)，only sensitive to thermalized phonons



$$v(t_1+t_2) < AC$$

⬇

Multi-site event

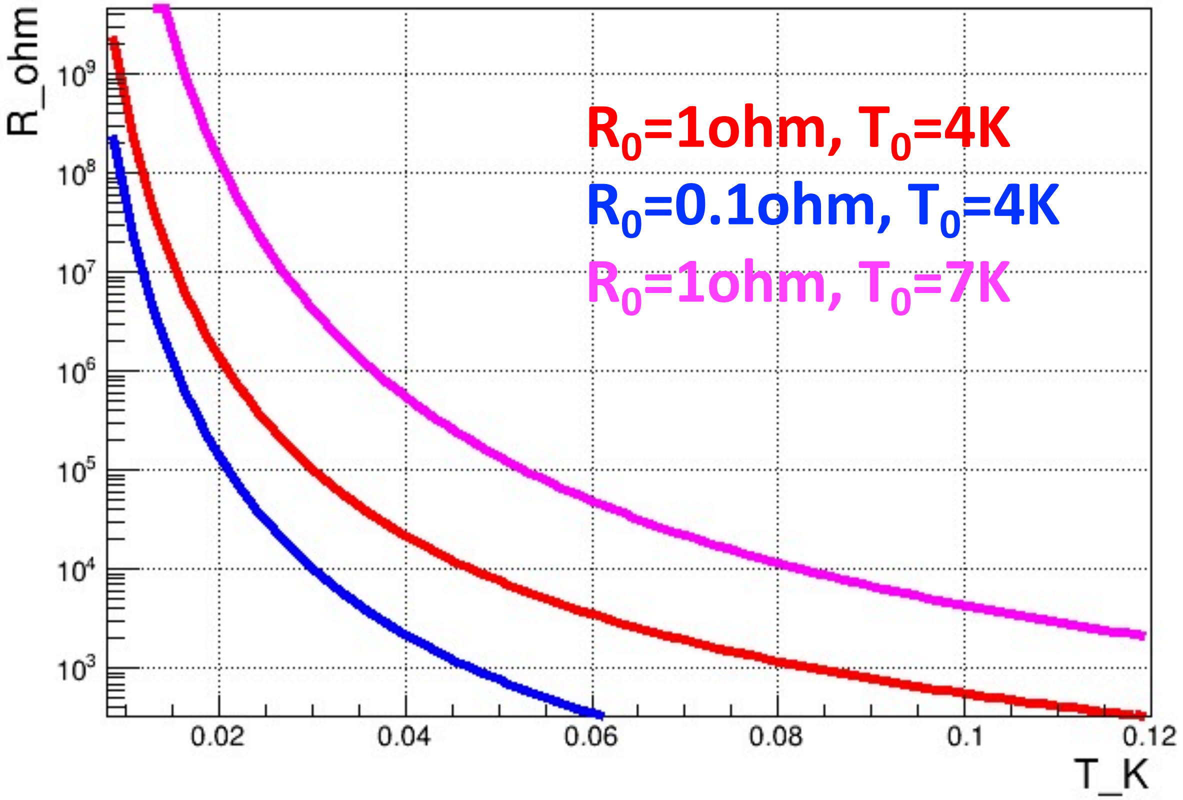
t0, light detector

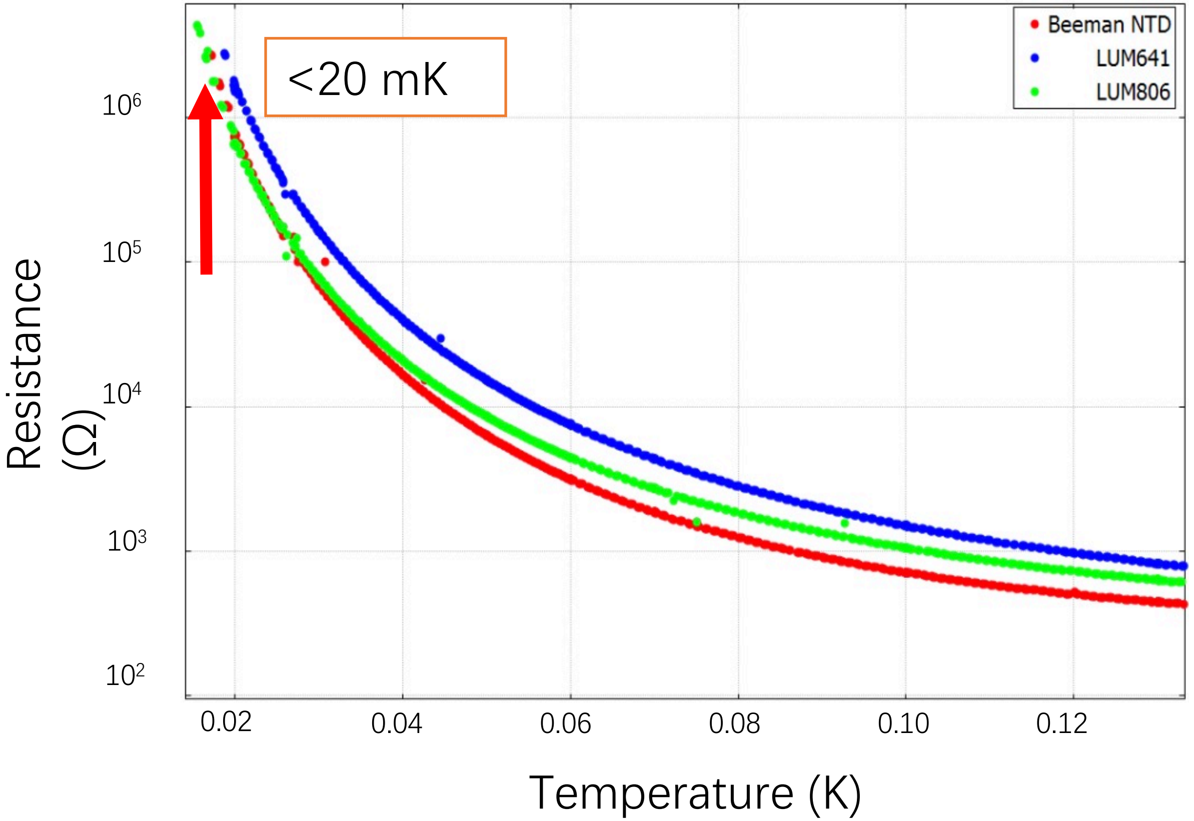
The basic idea is to utilize the different arrival times from the interaction point to different thermal sensors. **The phonon group velocity is usually few km/s.** If a time resolution around **~ 1us can be achieved, the position accuracy will be few millimeters**. In the following, we'll discuss the possibility in detail.

The characteristic velocity of phonons is the velocity of the sound vs; this is the **velocity with which "vibrations" or "phonons" move through the lattice**. Typical values for solids, in particular metals, are **vs = (3–5) × 10^5 cm s^{-1}.**

Pobell 2007 matter and methods at low temperature

NTD参数





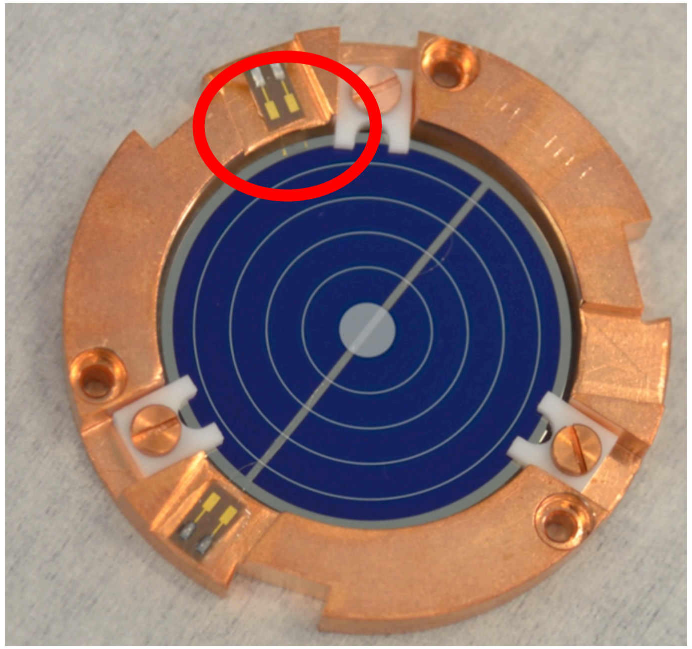
掺杂浓度

$$R = R_0 exp\left(\frac{T_0}{T}\right)^{\alpha}$$

Ge本征属性

其中，$\alpha = 0.5$

光探测器的小尺寸NTD-Ge



A small NTD, with a mass of 10 mg or less, will be glued on the Ge surface using the same gluing tools as the main Li2MoO4crystals. To minimize the 1/f noise in sliced NTDs faced over the CUPID-Mo commissioning, it will be necessary to perform a dedicated polishing of thermistors as done in CUPID-0. **The use of ∼ 1 mg NTDs would yield a faster response, further increase the signal amplitude, and reduce the baseline noise** [39, 89].

CUPID-preCDR

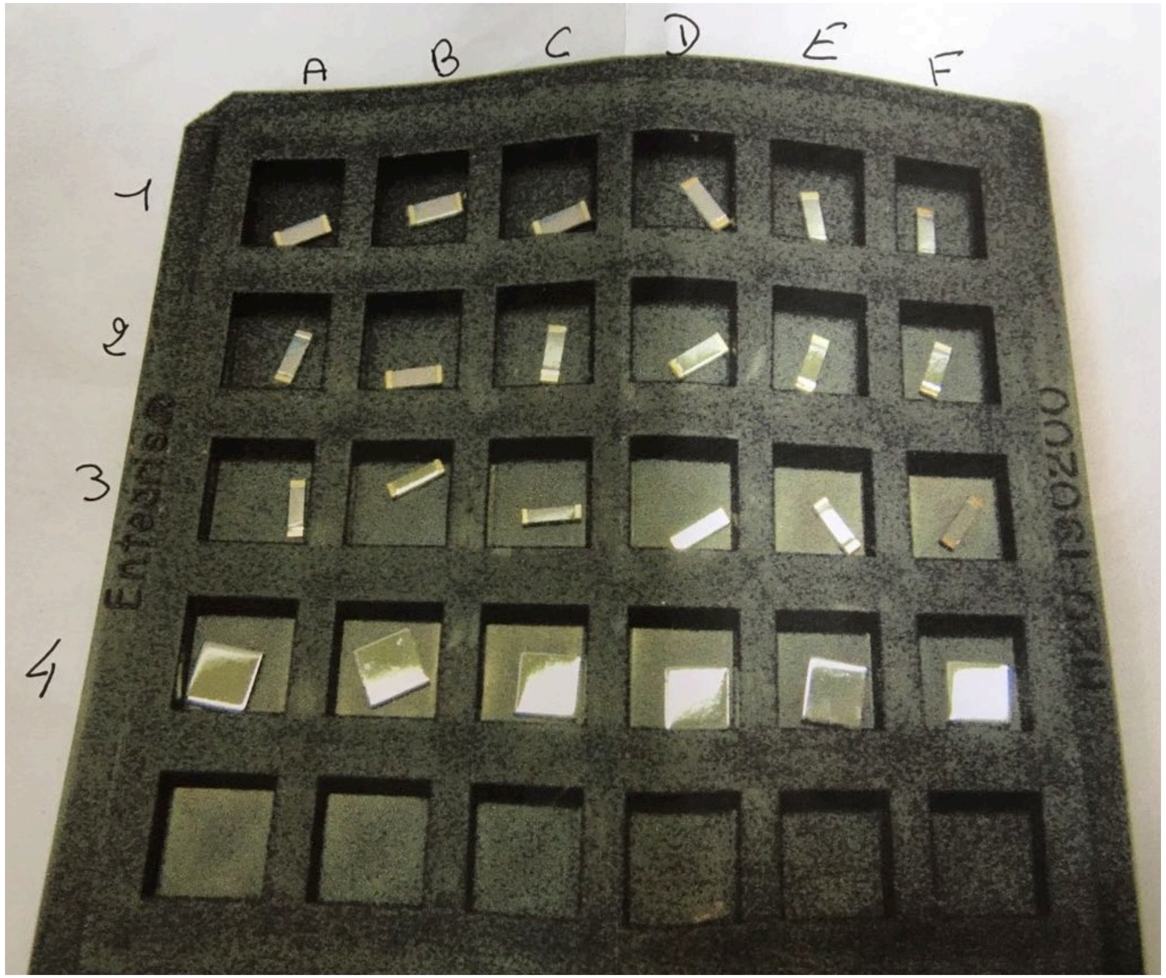
[39] The **reduced size** of both the absorber and the sensor of light detectors (see Tables 3, 4) **leads to lower heat capacities and therefore to higher sensitivities**, which are in the range ∼ 1–2 μV/keV for a good-performance detector.

$$\Delta T = \frac{\Delta E}{C(T)}, C(T) \propto T^3$$

As for the LDs, smaller NTDs are required to increase the sensitivity. In fact, the heat capacity of the Li_2MoO_4crystal dominates that of the NTD, while the opposite is true in the case of LDs, due to the small mass (∼1 g) of the Ge wafer. In this case, therefore, **the mass of the NTD plays an important role**. Based on the lessons learned in CUPID-0, CUPID-Mo, and related R&D, we plan to employ NTD sensor for the LDs with a mass of about 5-10 mg and the same contact distance as the NTDs for the heat channel, but the contact cross section modified accordingly.

CUPID-preCDR

REF:	Length (mm)	width (mm)	height (µm)	weight (mg)
A1	3.025	1.160	365	6
A2	3.020	0.890	345	5
A3	3.020	0.820	300	5
B1	3.040	1.120	425	5
B2	3.040	0.930	415	4
B3	3.040	0.810	420	4
C1	3.040	1.100	435	6
C2	3.040	0.905	435	5
C3	3.040	0.800	410	4
D1	3.050	0.980	370	5
D2	3.050	0.985	370	5
D3	3.050	0.920	360	4
E1	3.060	0.945	410	5
E2	3.060	0.945	395	5
E3	3.060	0.820	430	5
F1	3.060	0.925	400	6
F2	3.060	0.915	370	5
F3	3.060	0.870	335	4
A4	3	3	530	22
B4	3	3	405	18
C4	3	3	430	19
D4	3	3	465	22
E4	3	3	430	20
F4	3	3	560	22



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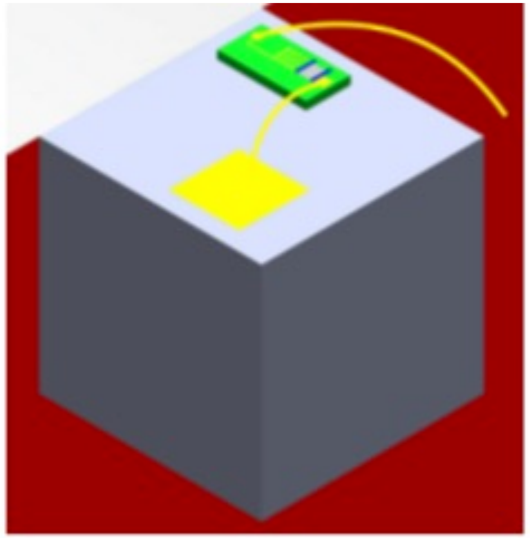
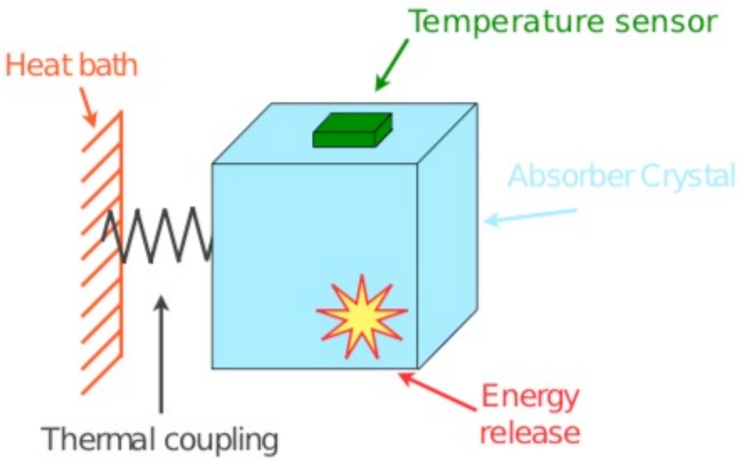


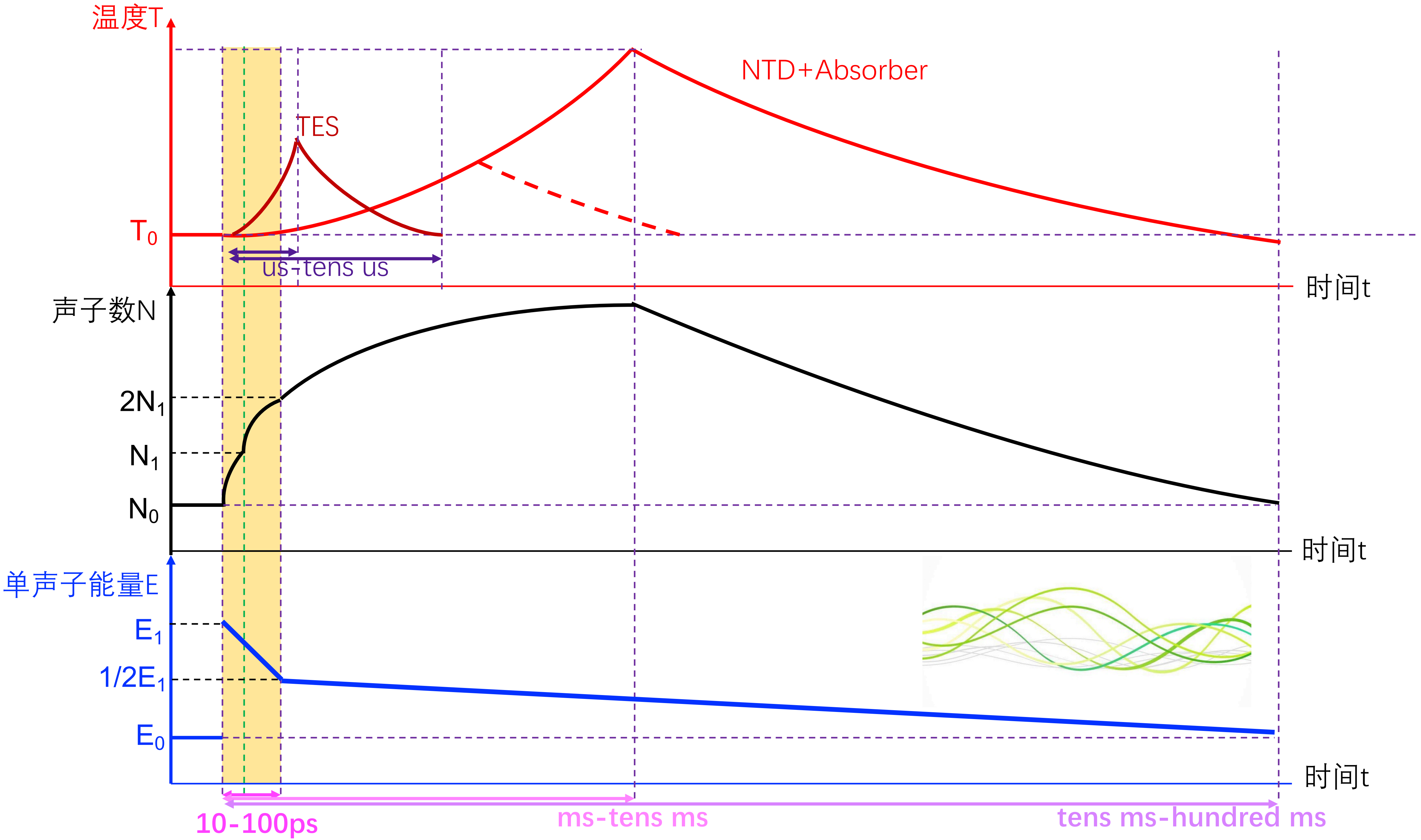
TES+吸收体



NTD+吸收体

$$C_{total}\frac{dT}{dt} = -K_W(T - T_b) + P(t)$$

T为吸收体温度，t为时间，K_w为热传导系数，T_b为低温恒温器温度，$P(t)$是能量沉积，瞬时完成，冷却时为0。



温度T
NTD+Absorber
TES
T_0
us-tens us
时间t
声子数N
$2N_1$
N_1
N_0
时间t
单声子能量E
E_1
$1/2E_1$
E_0
时间t
10-100ps
ms-tens ms
tens ms-hundred ms