Cryogenic Calorimeters: Principles and Applications

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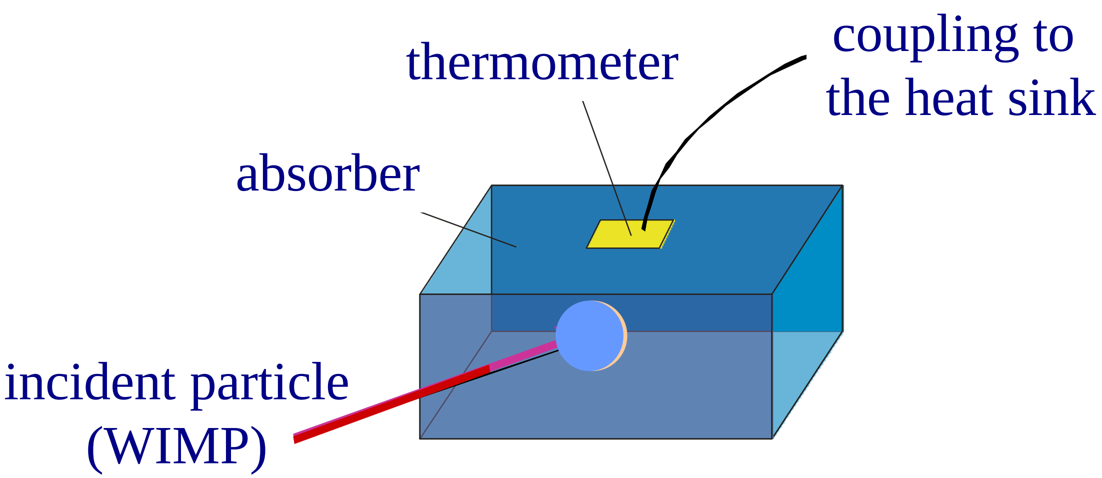
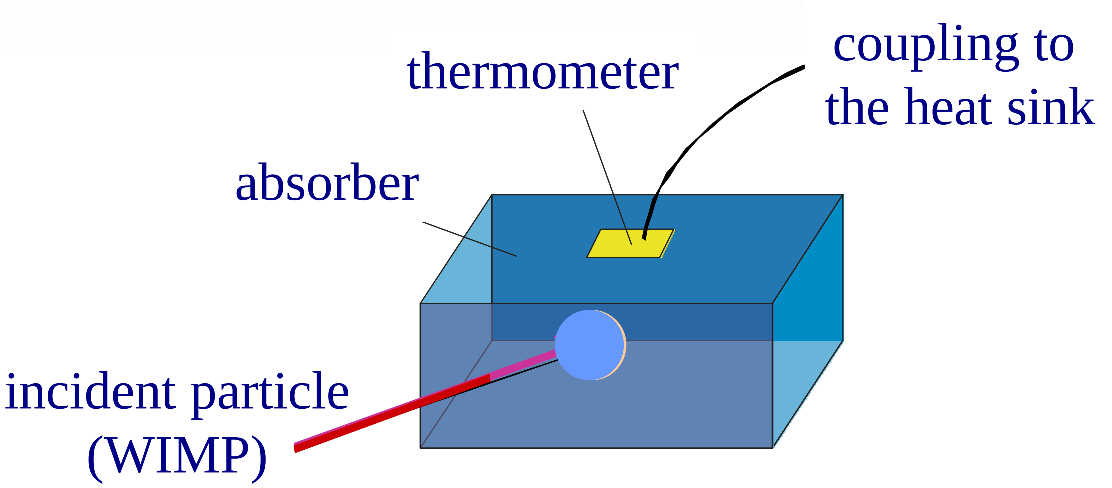


Principle
Sensitivity - Resolution
Advantages - Applications

Basic Concept

absorption of energy due to
incident particle or radiation
causes a rise in temperature

$$\Delta T \propto E/C$$



very low temperature
=> high sensitivity, since C is small

types of thermometers: Superconducting phase transition thermometers (SPT)
NTD - Ge thermistors (highly doped semiconductors), ...

History of Cryogenic Particle Detection

1935 suggestion of low temperaturecalorimetry for particle detection
Simon

1949 alpha particles with phase transition thermometers
Andrews et al.

1974 danger of cosmic rays for low temperature experiments...
Niinikoski

1984 suggestion to measurelow energy neutrinos by
coherent scattering with cryogenic detectors
Drukier, Stodolsky

1984 suggestion for double beta decay experiments
Fiorini, Niinikoski

1987 first conference on
Low **T**emperatur **D**etector for Neutrinos and Dark Matter, Munich
since then LTD's: Annecy, Gran Sasso, Oxford, Berkeley,
Beatenberg (Switzerland), Munich,
Dalfsen (Netherland), ...Madison

Last proceedings in *Special Issue of Nucl.Instr. & Meth. A, Vol.444, # 1,2*

Motivations

solar neutrino detection (inverse beta decay)
target nuclei of interest can be incorporated

free choice of detector material

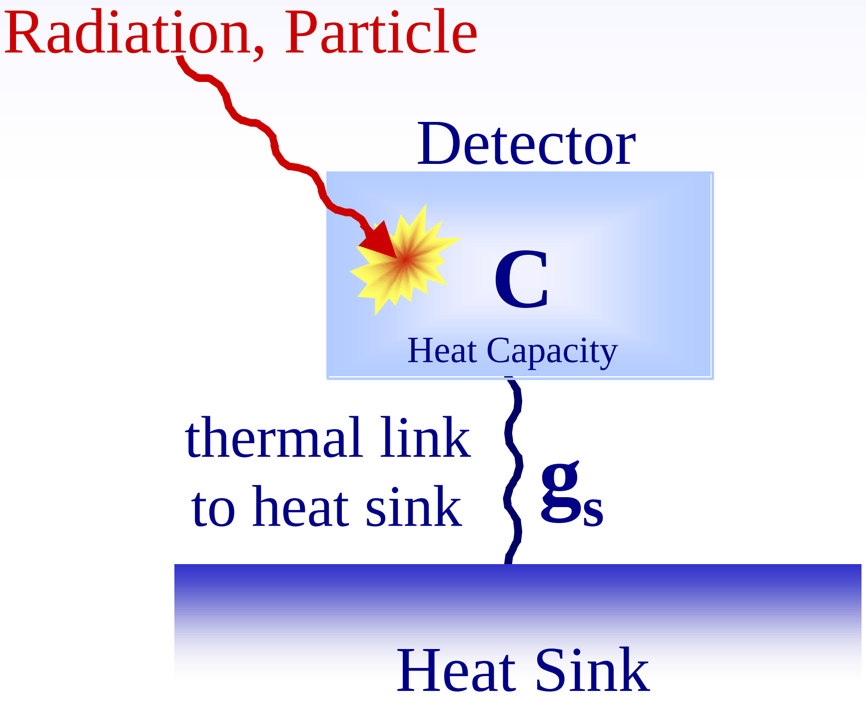
WIMP detection, choherent neutrino scattering

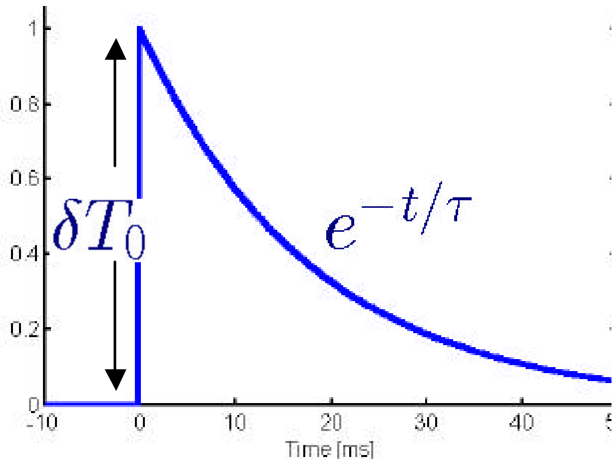
sensitivity to nuclear recoils

double beta decay, beta endpoint spectroscopy

source = detector
high energy resolution

Simplest Shape of the Signal





initial temperature rise

$$\delta T_0 = \frac{E}{C}$$

relaxation to equilibrium through thermal link

shape of the temperature signal

$$\delta T(t) = \frac{E}{C}\, e^{-t/\tau}$$

$$\tau = C/g_s$$

Heat Capacity

	T-dependence	material	heat capacity @25mK	temperature rise for 6keV @ 25mK
phonons	$C_{ph} \propto \left(\frac{T}{\Theta_D}\right)^3$	Saphir 1cm³	5.5pJ/K = **34keV/mK**	170µK
electrons	$C_e = \gamma T$	Gold 1cm³	1.7mJ/K= **10TeV/mK**	5.6 10^{-7} µK
		Gold (300µm x 300µm x 1µm)	170pJ/K = **1MeV/mK**	5.6 µK

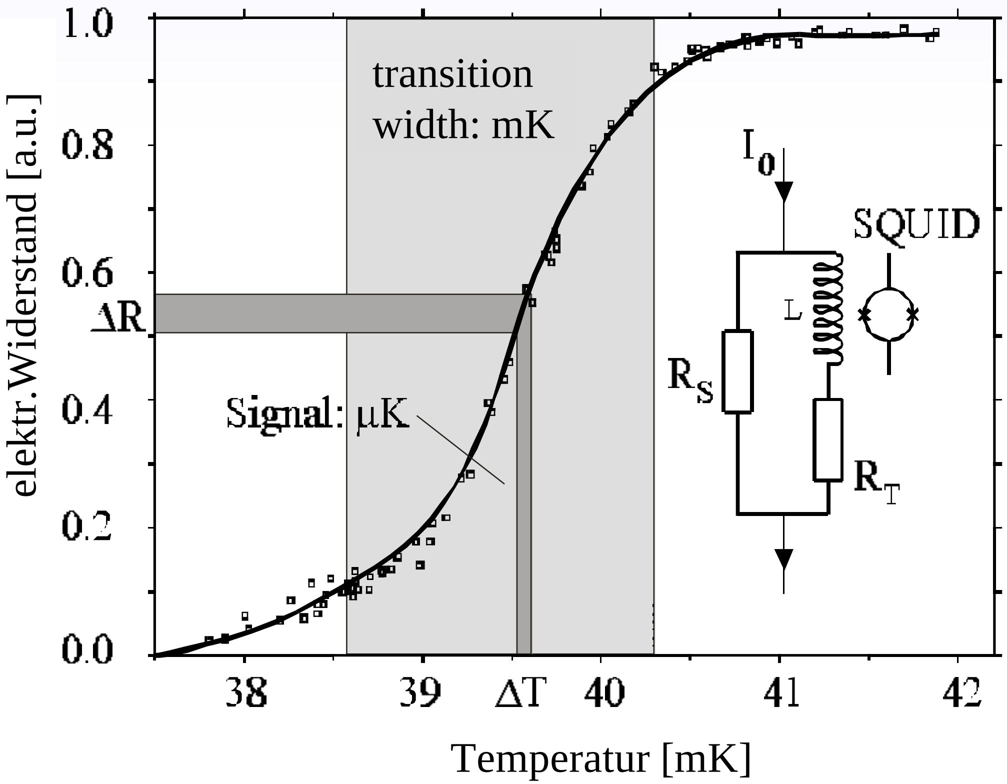
=> small detectors $\approx$ 0.1mm² x 1µm

=> low temperatures 10 - 100 mK

metals <=> dielectrics

small *large*

Phase Transition Thermometer



superconducting thin film
at the phase transition

materials:
W
T_c = 15mK
Ir/Au double layers
T_c = (20-110)mK
...

small change in temperature
=> large change in resistance

read out by a SQUID

sensitivity

$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

Doped Semiconductor Thermistors

implanting dopands e.g. P or As into Si wafers

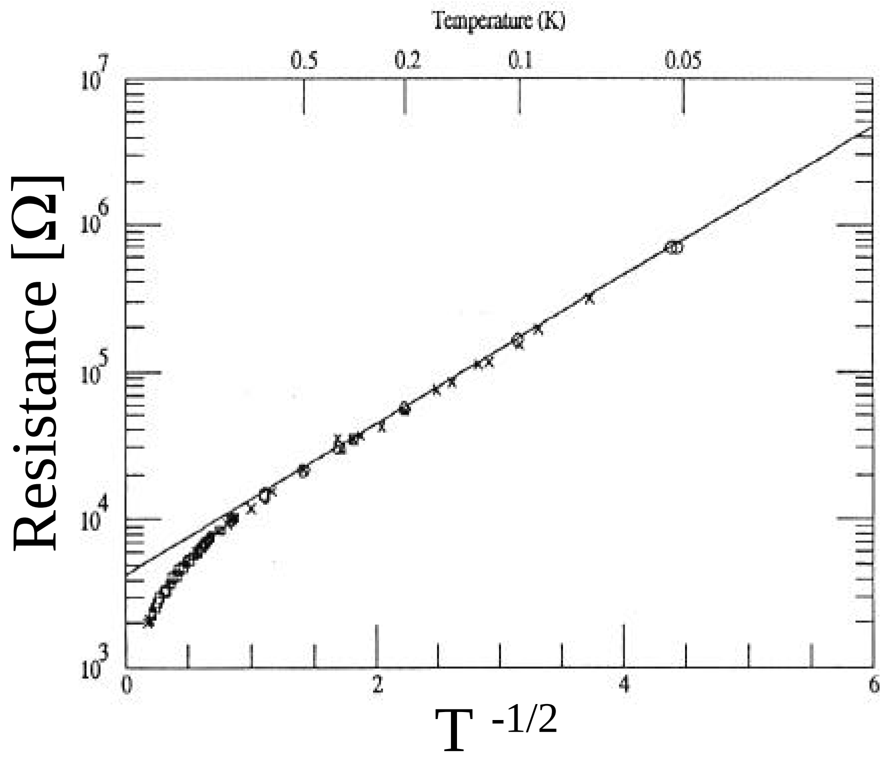
or

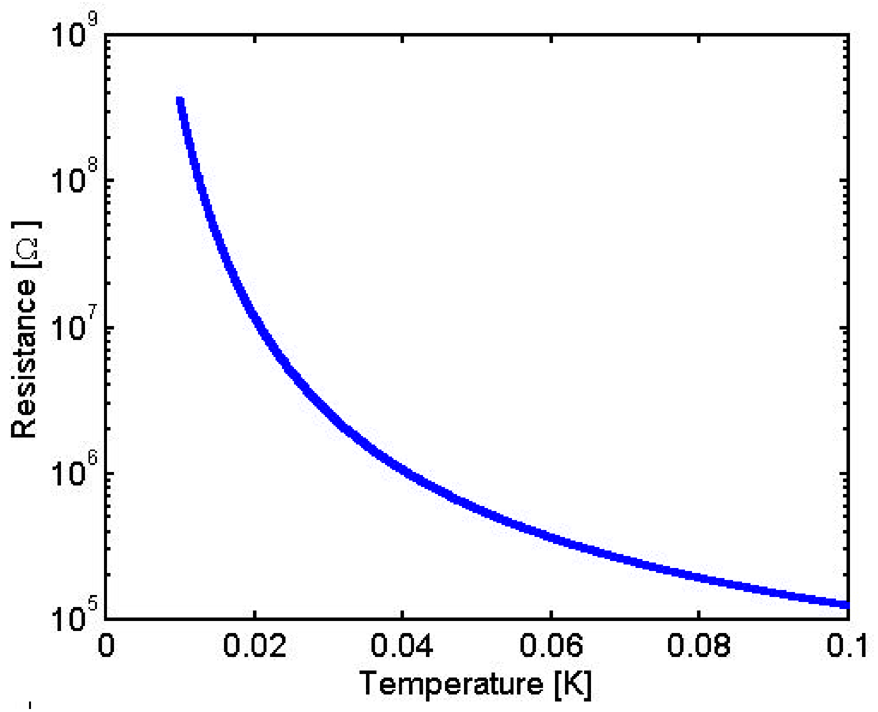
NTD Thermistors (uniform doping concentration by
irradiation of Ge to thermal neutrons,
Neutron **T**ransmutation **D**oping)

phonon assisted variable range hopping conduction
(carriers are localized at impurities and are aided
in tunneling by phonons)

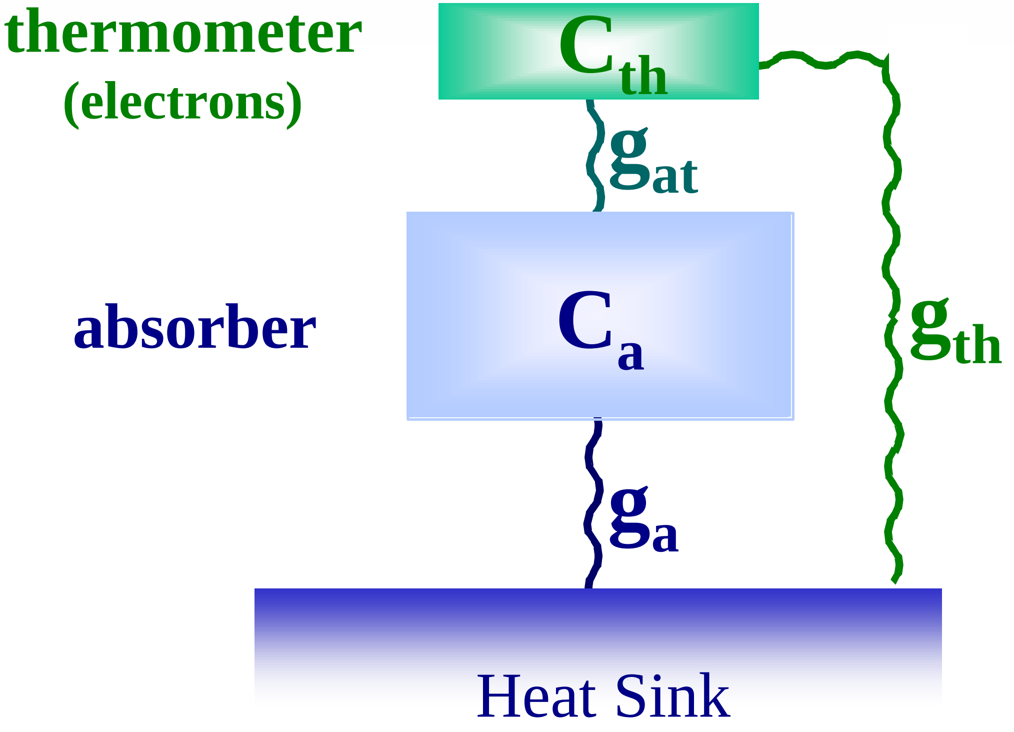
strong T dependence of resistance $R = R_o e^{\sqrt{T_o/T}}$

Doped Semiconductor Thermistors





Calorimetry - Bolometry



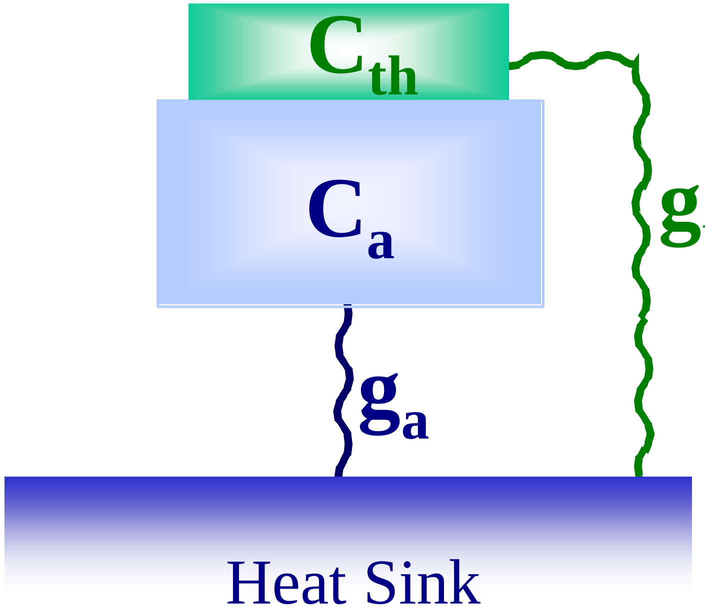
g_{at}: • contact resistance thermometer - absorber $\sim T^3$

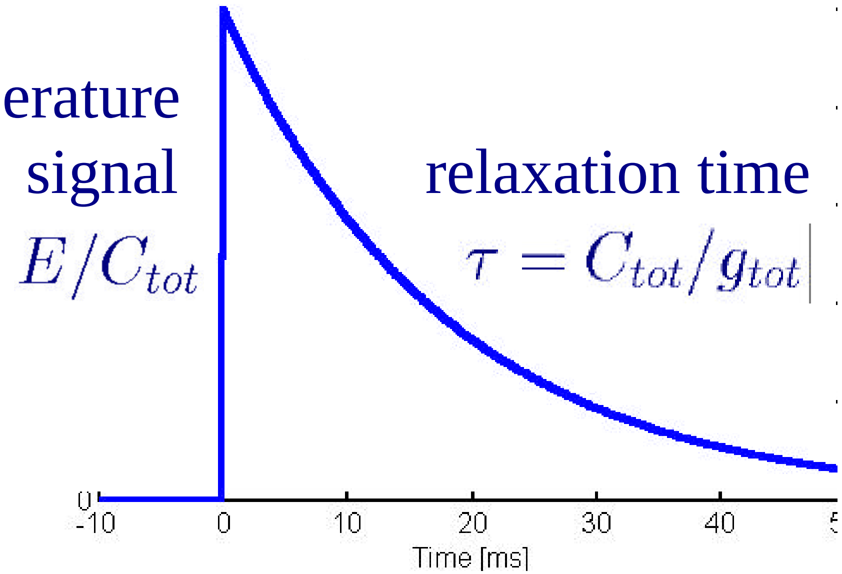
• electron-phonon coupling $\sim T^5$

resistance therm. - absorber

low for high / high for low frequency phonons

g_{at} large - T high (e.g. 100mK)

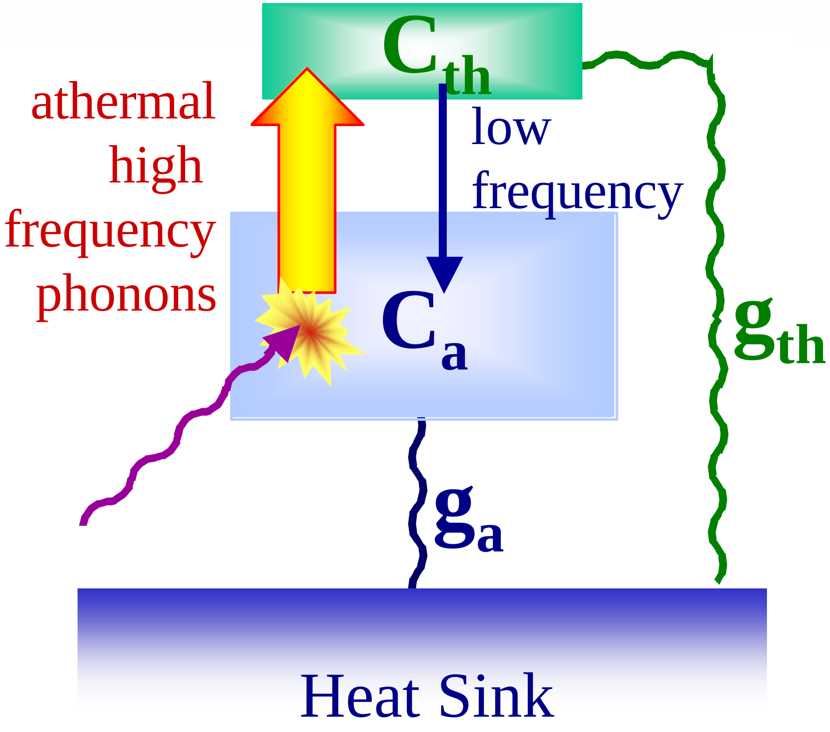


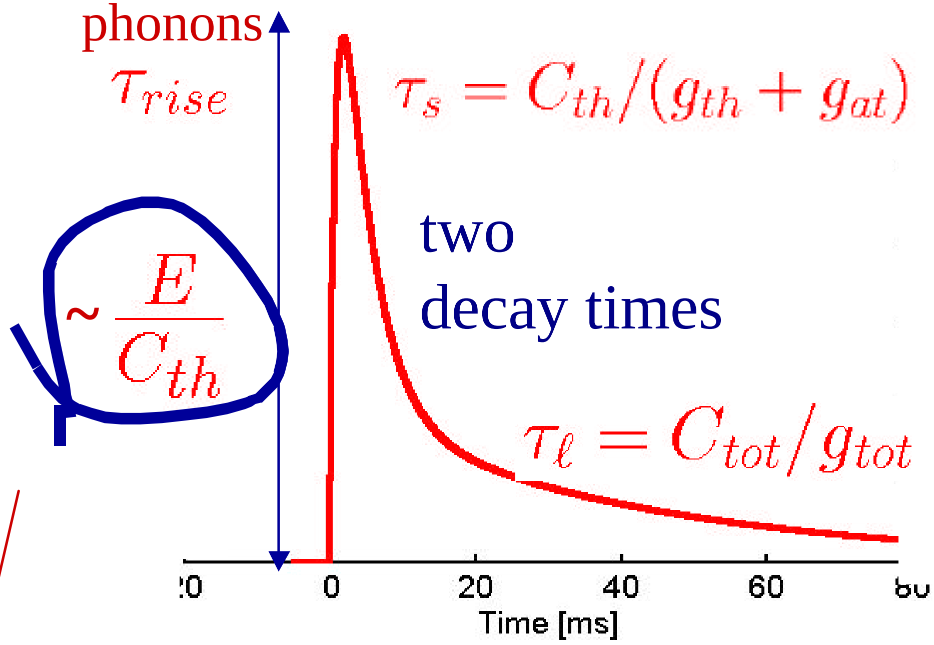


$C_{tot} = C_a + C_{th}$ $g_{tot} = g_a + g_{th}$

it's calorimetry

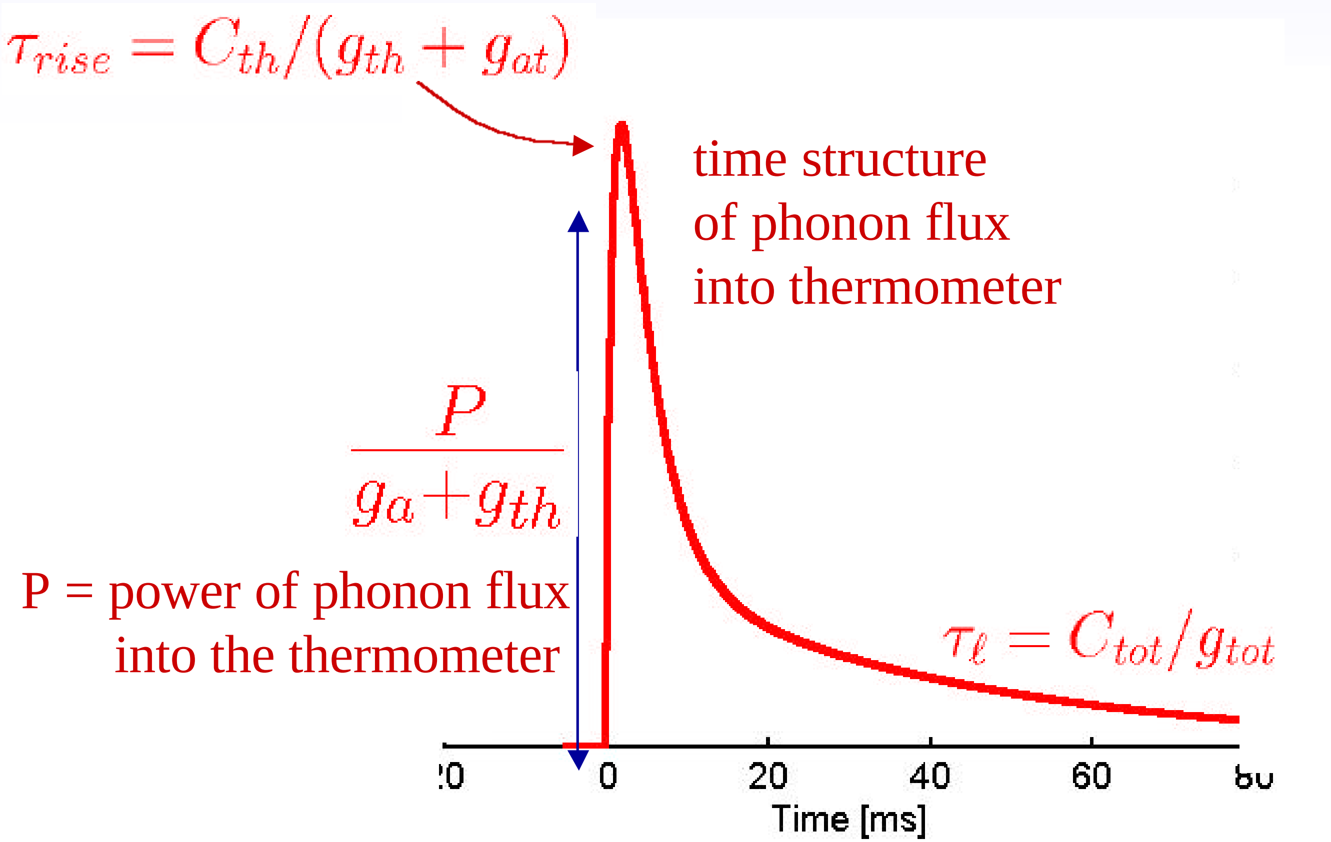
g_{at} small (high for low / low for high frequency) - T low (e.g. 15mK)





large absorbers possible !!!

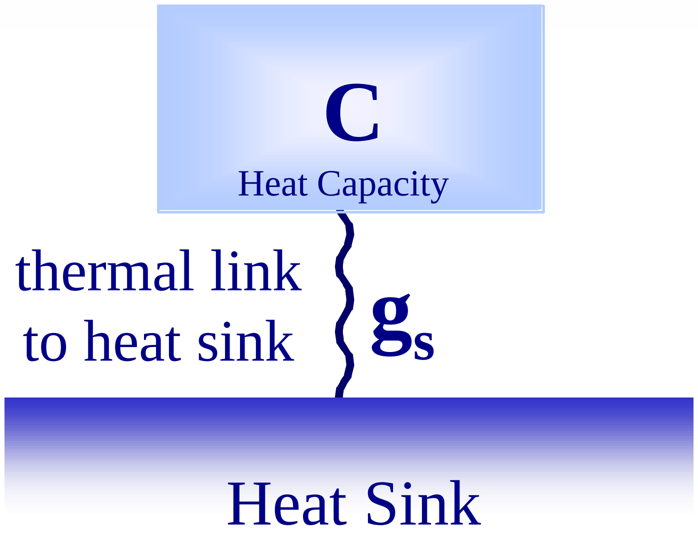
Relaxation Time of Thermometer < Phonon Collection Time



fast signal **is bolometry** (for the phonons)

(later it's calorimetry again)

Sensitivity - Energy Resolution



statistical fluctuations of energy content in C due to random transport of energy through g_s

=> noise spectrum

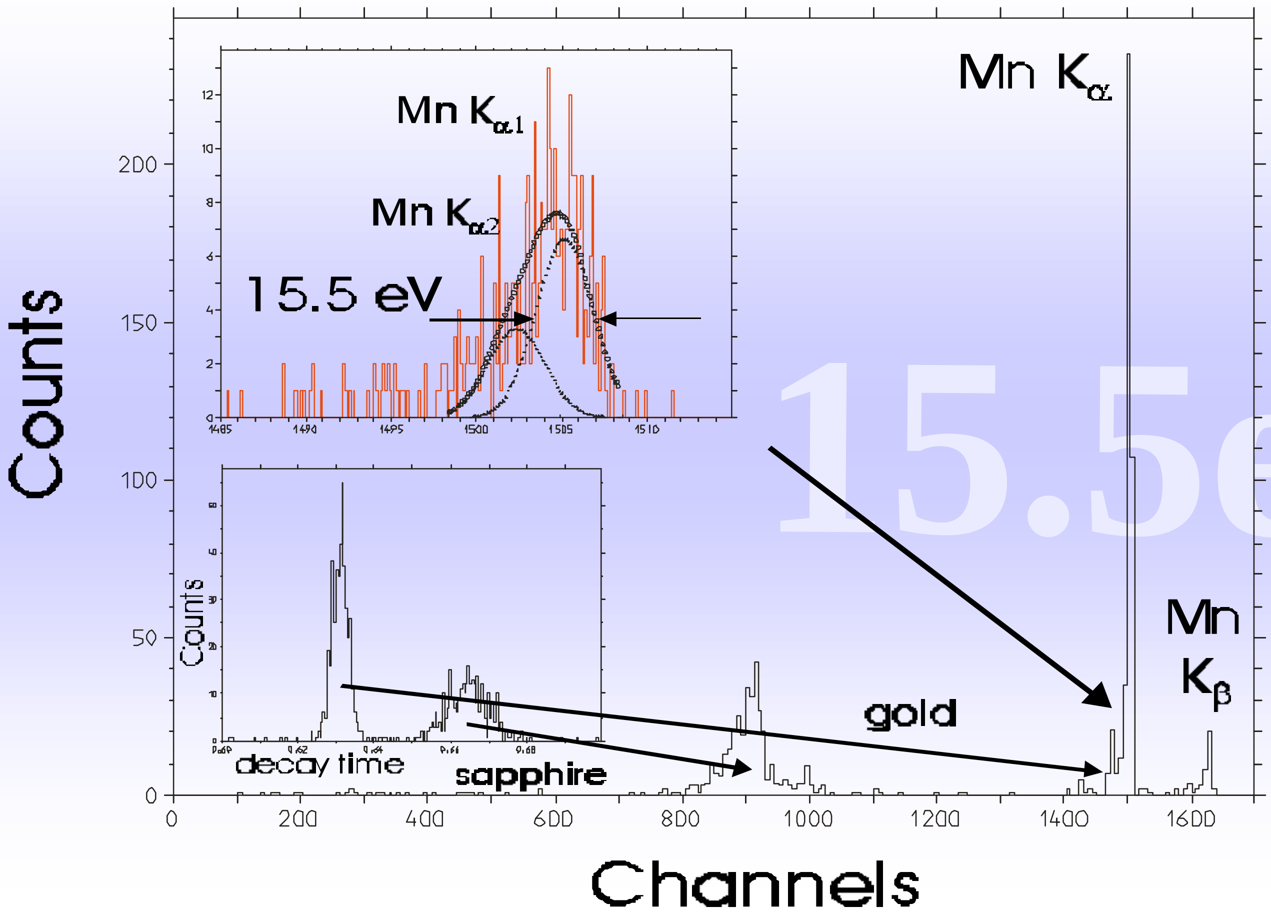
$$\frac{4k_B T g_s^2}{1+\omega^2\tau^2}$$

rms of energy content as ‘limit‘of energy resolution

$\delta E^2 = 4kT^2C$ $\underset{\text{measurement}}{=>}$ $\delta Signal \approx \sqrt{4kT^2C/\alpha}$

Mikrokalorimeter:

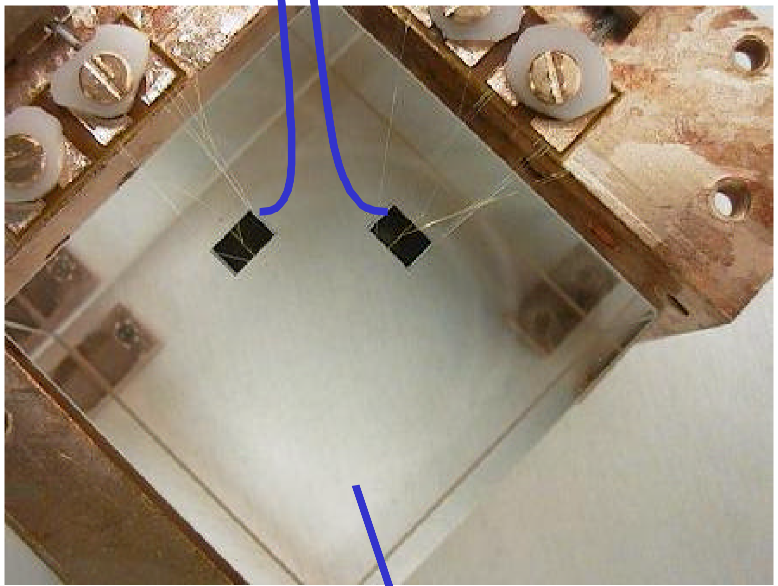
Gold (300μm x 300μm x 1μm) + Phase Transition Thermometer



$$2.35\sqrt{4kTC^2} = 35eV \longrightarrow 1/\sqrt{\alpha}$$ thermometer sensitivity

CRESST Calorimeter

Tungsten Thermometer
Tc 15mK



Sapphire- Absorber
250gr, 4cm x 4cm x 4cm

energy threshold, a few 100eV !

$$2.35\sqrt{4kTC^2} = 52eV \longrightarrow ???$$

Other Contributions to Energy Resolution -Band Gap

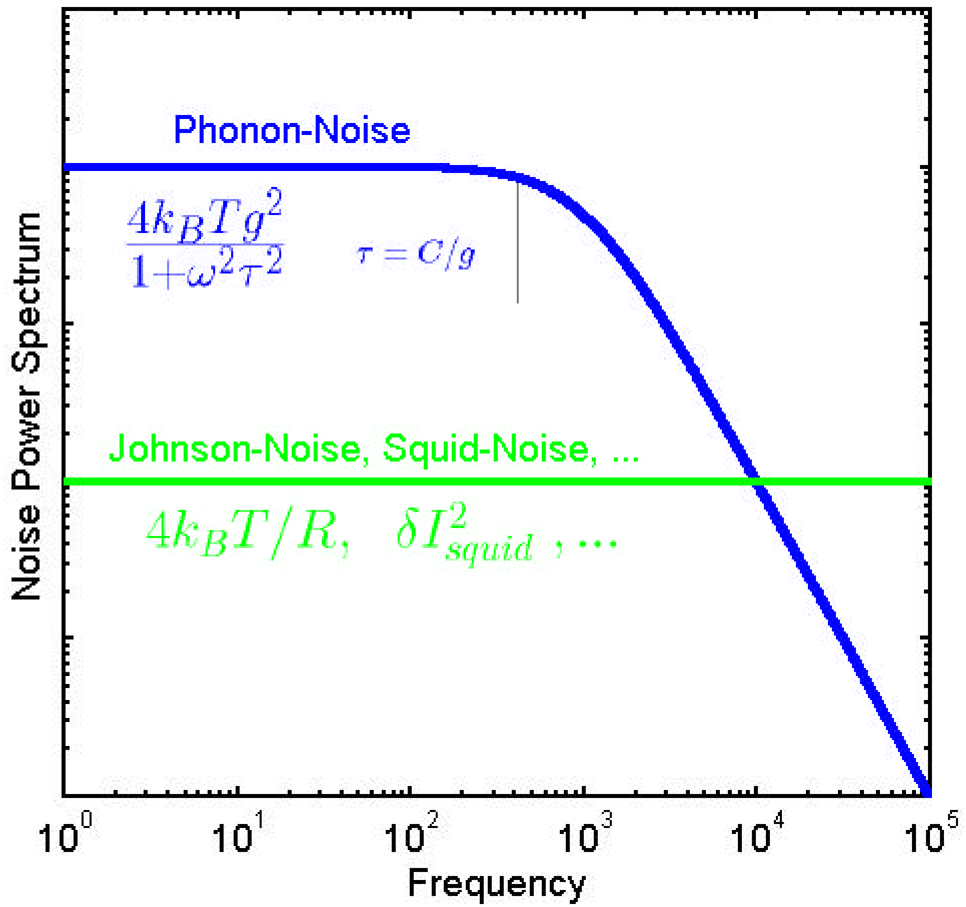
Statistical Limit: $\frac{\Delta E}{E} \propto 1/\sqrt{N}$; $N = E/\varepsilon$

Detector Material	effective excitation energy ε	number of excitations @ 1.5keV	energy resolution FWHM @ 6keV
Dielectric	10-20eV	75-150	≈ 100 - 200 eV
Semiconductor	3eV	500	≈ 30 eV
Superconductor	10^{-3} eV	> 10^6	< 1.5 eV

if excitations do not thermalize in a reasonable time => statistics

Other Contributions to Energy Resolution -Electronic Noise

- Johnson noise of thermometer resistance
- noise of preamplifier (SQUID, FET, ...)
- ...



Size - Sensitivity - Material

large detectors

dielectrics
to get low C

reduced resolution

high resolution

metals
to avoid bandgap

small detectors

Cryogenic Calorimeter: Advantages

very sensitive,
also to nuclear recoils

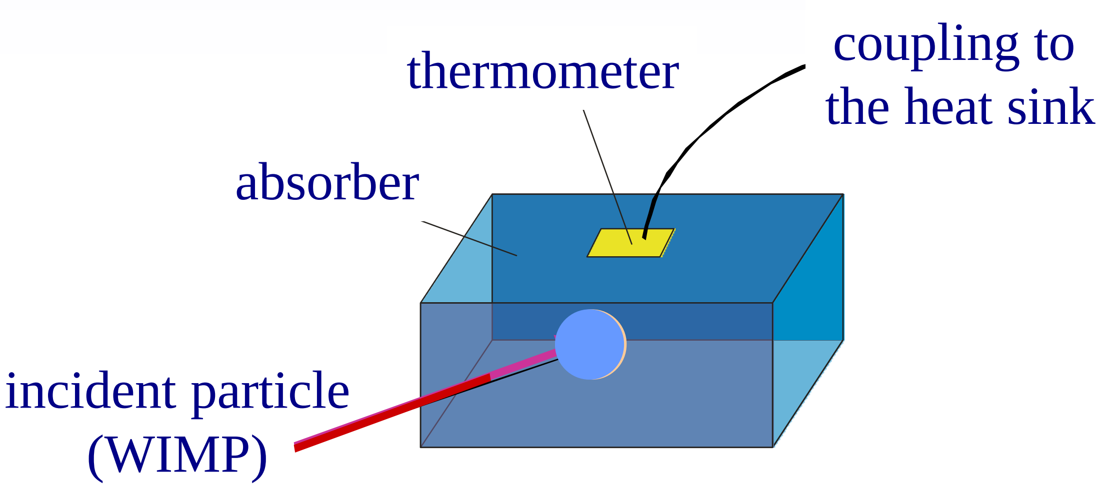
low energy threshold

high energy resolution

large variety of possible
target nuclei

very radiation hard

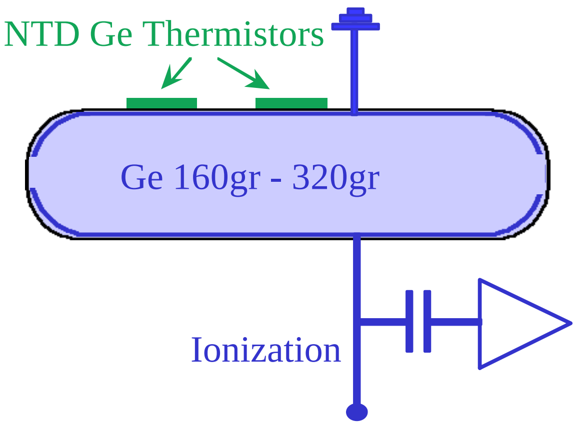
can be combined with other detection
methods (ionisation, szintillation)



$$\Delta T \propto E / C_{Thermometer}$$

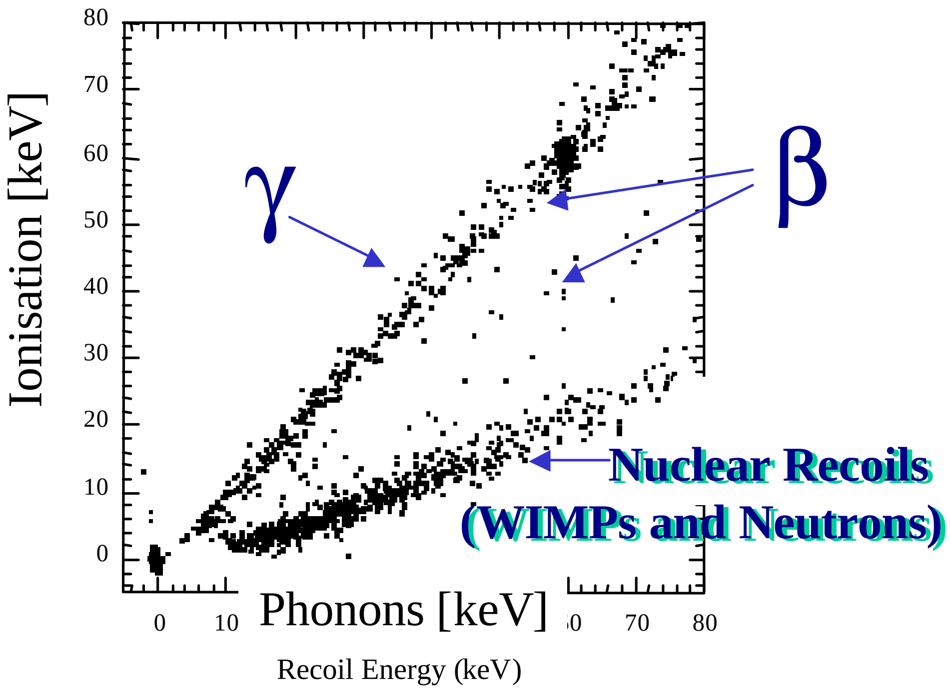
Discrimination: Photons ↔ Nuclear Recoils

Simultaneous Measurement of Phonons and Ionisation



signal (nuclear recoils) and dominant background (γ and β) can be distinguished

CDMS and EDELWEISS Particle Dark Matter Searches



Low Temperature Detectors

Mikrocalorimeter
Cryogenic-Calorimeter
Superconducting Tunneling Junctions
Magnetic Bolometers,
...

high energy resolution
(keV X-Ray: 10 x better than SiLi)

low energy threshold

free choice of detector material
(detector = source)

radiation hard

Microanalysis

Element-Analysis (low Z, PIXE)
Fluorescence-Analysis (XRF)
X-Ray Microscopes
X-Ray Emission in SEM

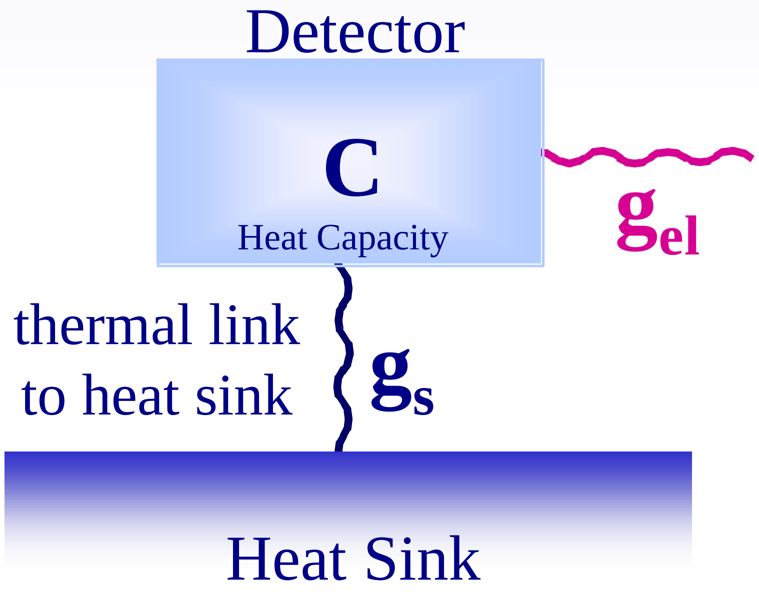
Optical- and X-Ray Astrophysics

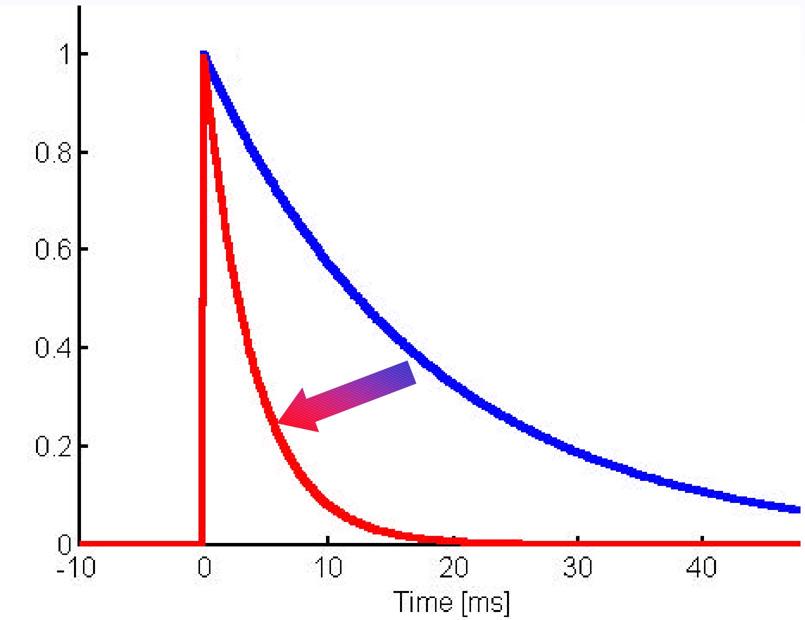
Next Generation after CCD
Energy-, Time- and Position-Resolution for single Photons

Particle-Astrophysics

Nuclear Recoils / Dark Matter
Neutrinophysics
β–decay und 2β-decay
Heavy Ion Physcis

Heating Power by Measurement





if thermometer is voltage biased

$$P_{el} = U^2 / R_{thermometer}$$

if $T \nearrow$ => $R_{thermometer} \nearrow$

(phase transition thermometer)

=> $P_{el} \searrow$

speeds up relaxation to equilibrium

relaxation time $\tau = \frac{C}{g_s + g_{el}}$

$$g_{el} = -\frac{\delta P_{el}}{\delta T}$$