The low Side of the Dark Side

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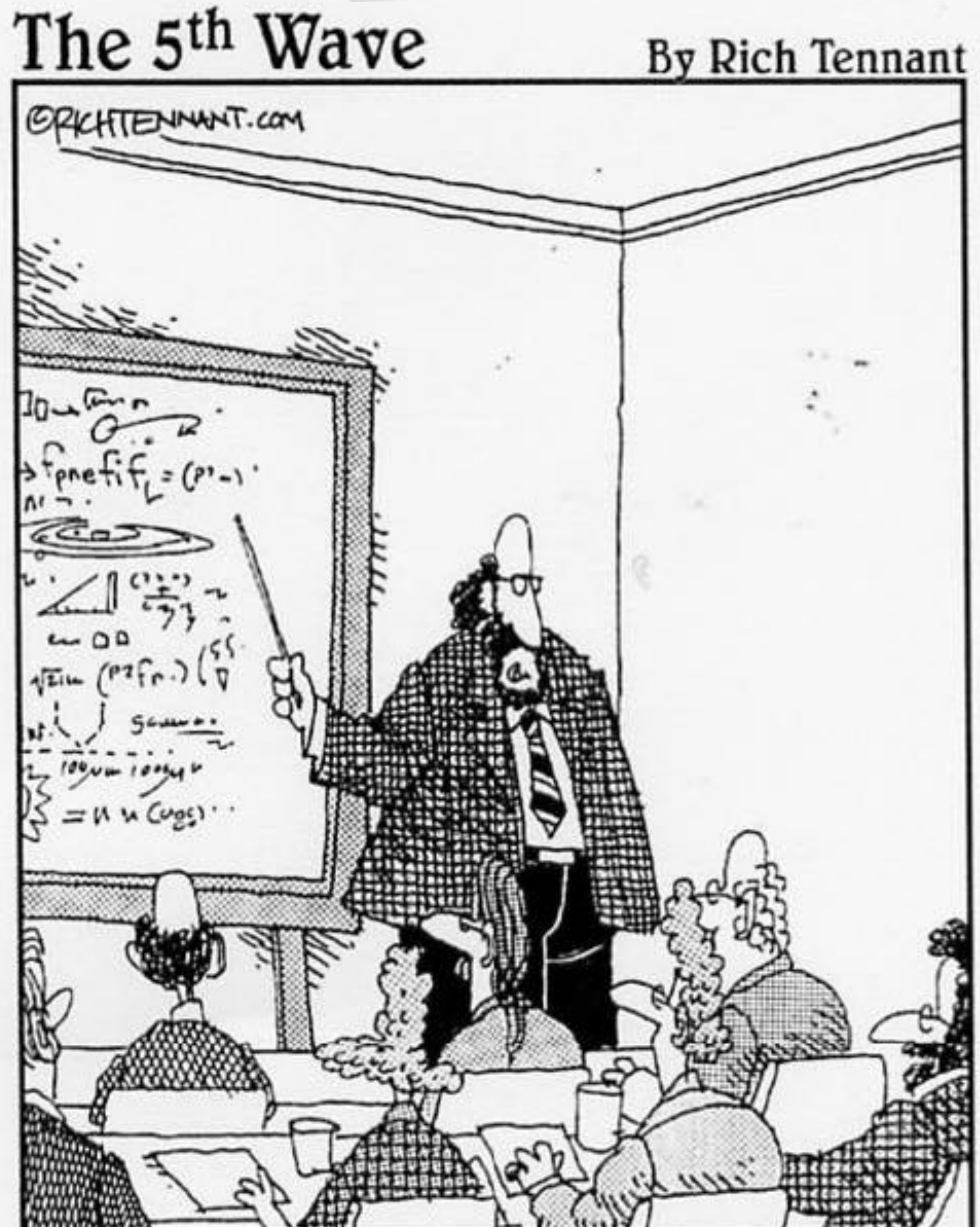
Content

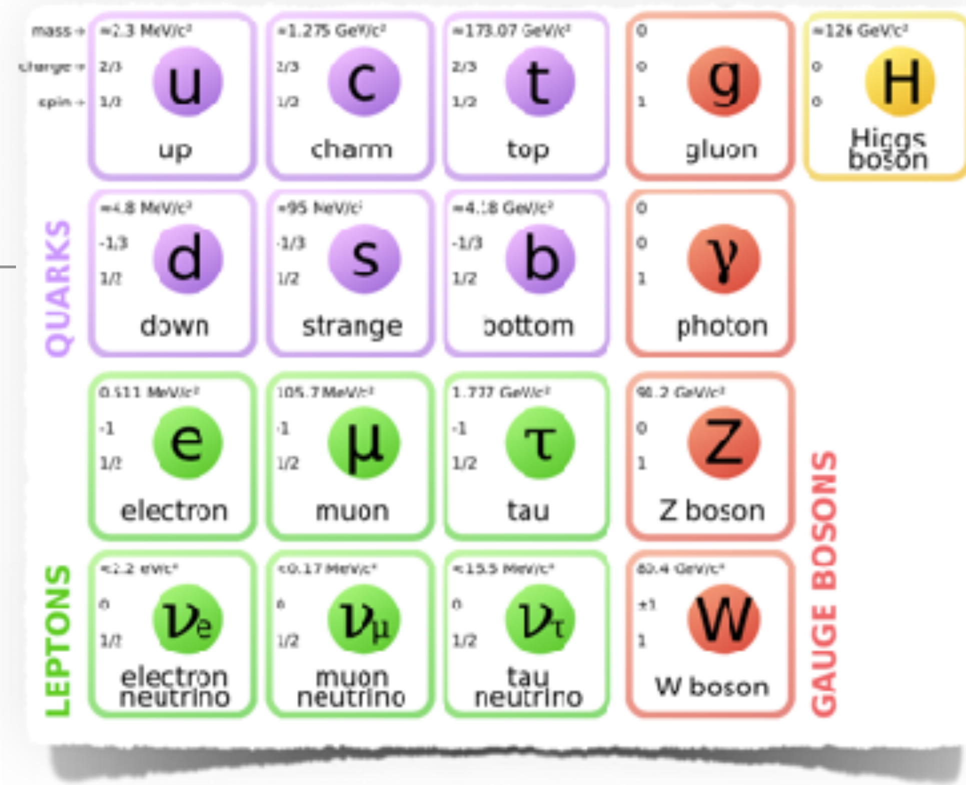
- Dark Matter and alternatives to the WIMP paradigm
- Dark Matter searches with the CRESST experiment
- new ideas for low mass Dark Matter searches

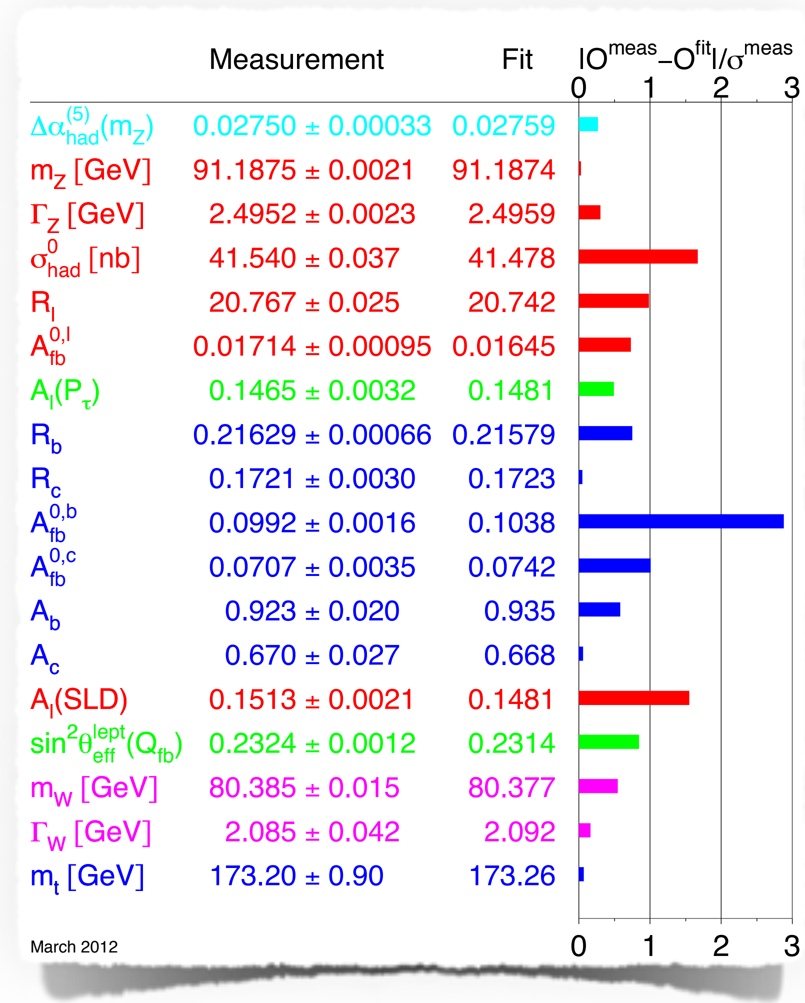


"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

The Standard Model of Particle Physics

- the Standard Model of Particle Physics describes successfully all phenomena observed at nano-nano scales
- with the Higgs boson all particles of the Standard Model have been observed
    - the observed Higgs Boson has the quantum numbers of the Standard Model Higgs
- **the Standard Model is expected to be the low energy limit of an even more fundamental theory**

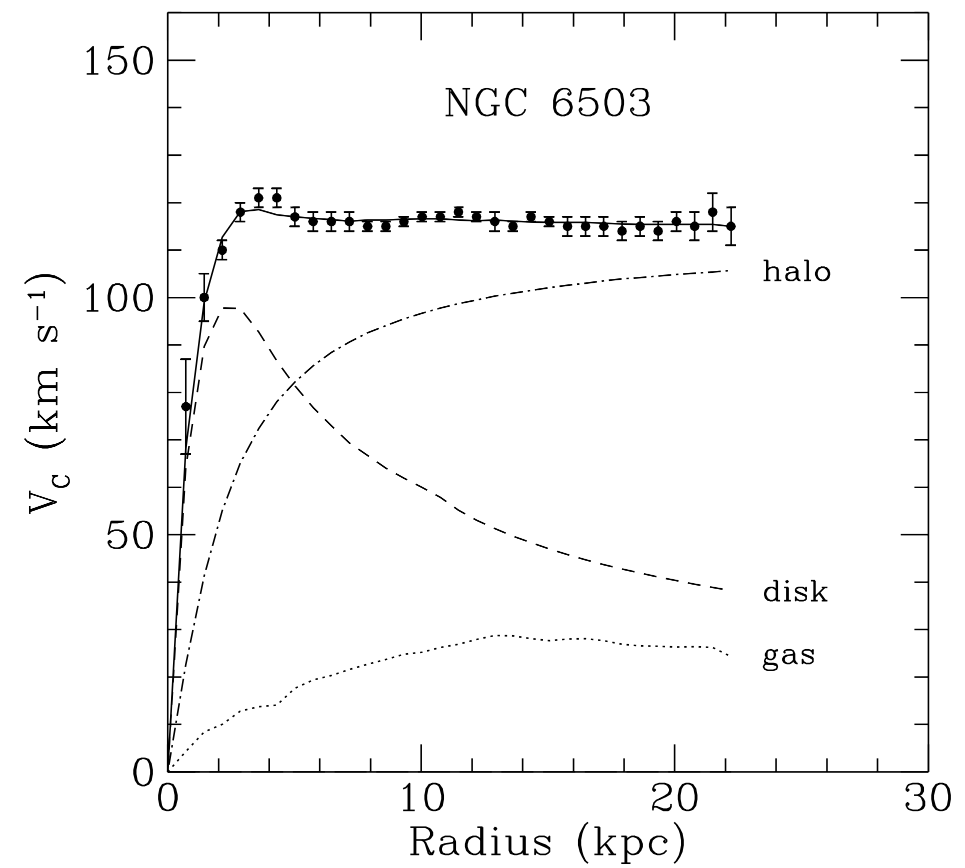




The Standard Modell: Shortcomings

- several observations on astrophysical scales can not be explained with particles or forces from the Standard Model of Particle Physics
- the Standard Model of Particle Physics
  - does not explain gravity
  - not enough CP-violation to explain the observed baryon asymmetry
  - **no “Dark Matter” particle candidate**

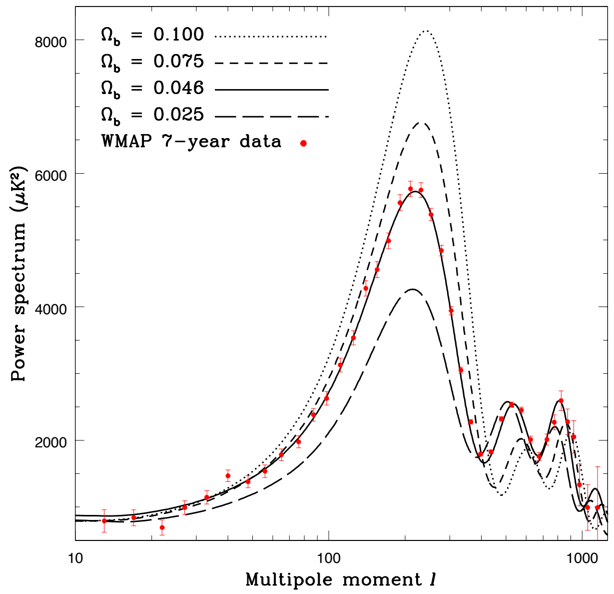
Rubin ‘80s



expectations from newtonian dynamics: $v(r) = \sqrt{G\frac{m(r)}{r}}$

More evidence for Dark Matter

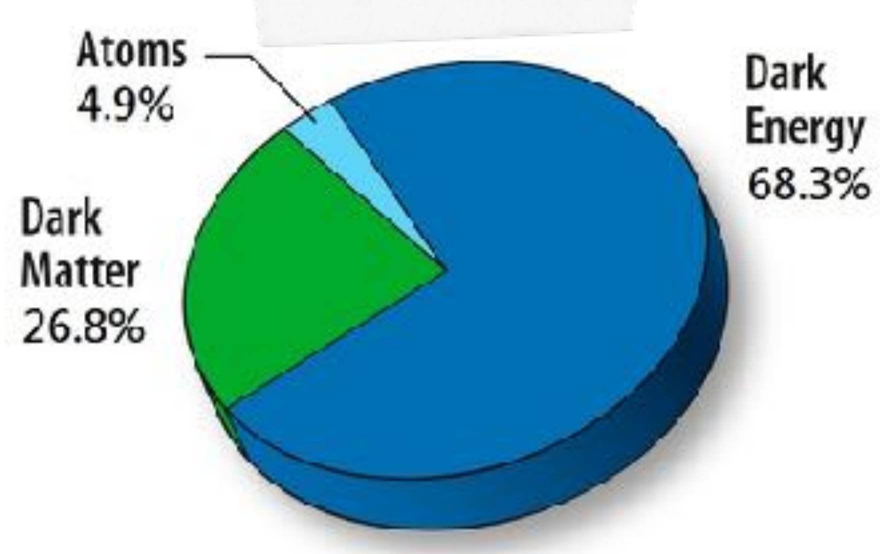
- **rotation curves of galaxies**
  - arms of spiral galaxies rotate faster than anticipated
- **gravitational lensing**
  - light of distant galaxies is bended by gravitational potential
- **temperature fluctuations of microwave background**
  - acoustic oscillations depend on baryonic density
- **bullet cluster**
  - collision-less penetration of two massive galaxies
- **structure formation**
  - observed present-day structure requires Dark Matter

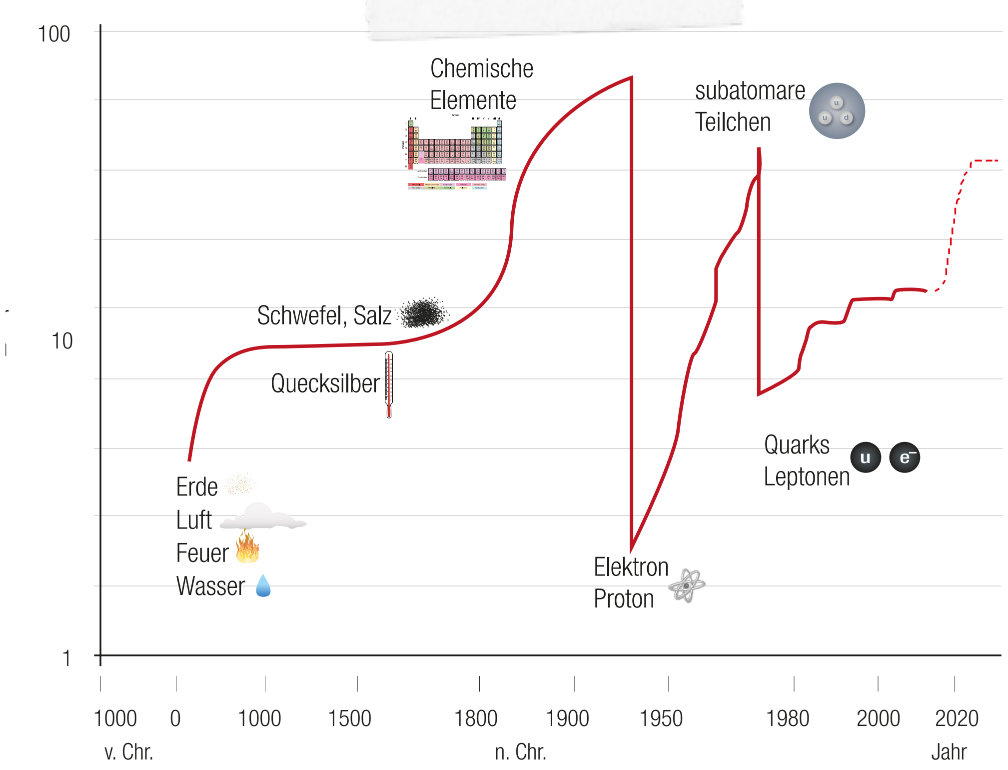


all observations are based on gravitational pull of Dark Matter on visible matter

The Standard Model cannot explain Dark Matter

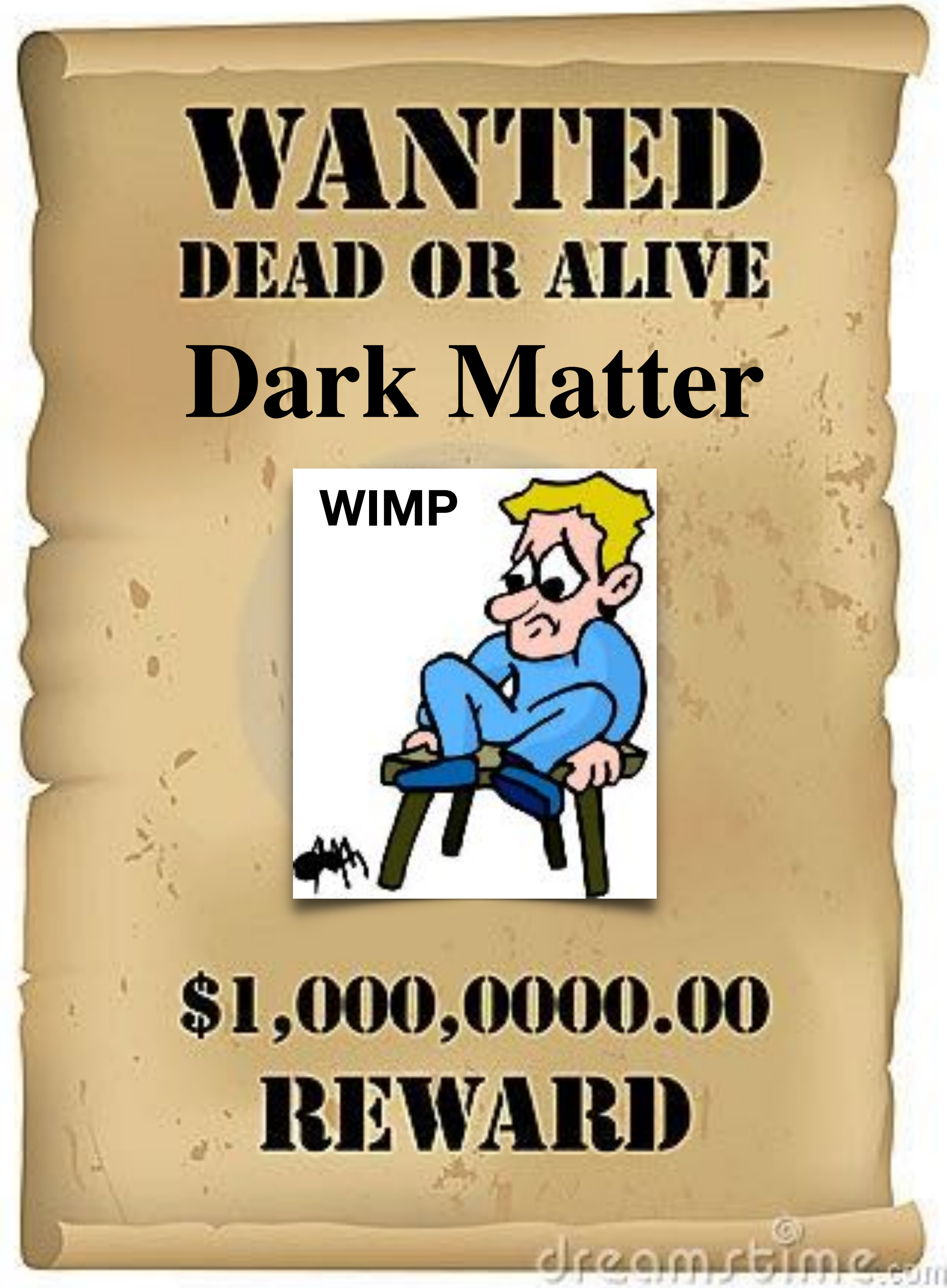
- Dark Matter: the missing mass problem of the 21st century
  - **about five times more Dark Matter than baryonic Matter**
- particle physics point of view: explain observations with new particles and forces
- **search for new particles, new forces, new symmetries**





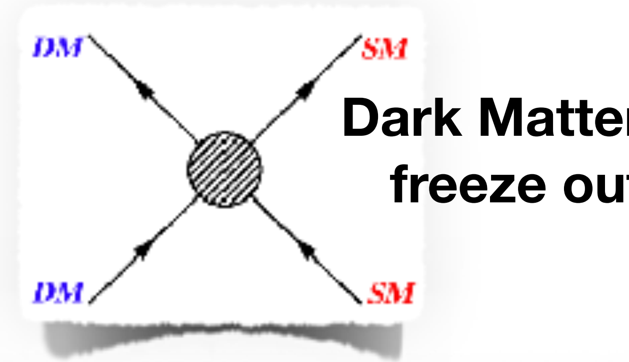
Profile of a Dark Matter Candidate

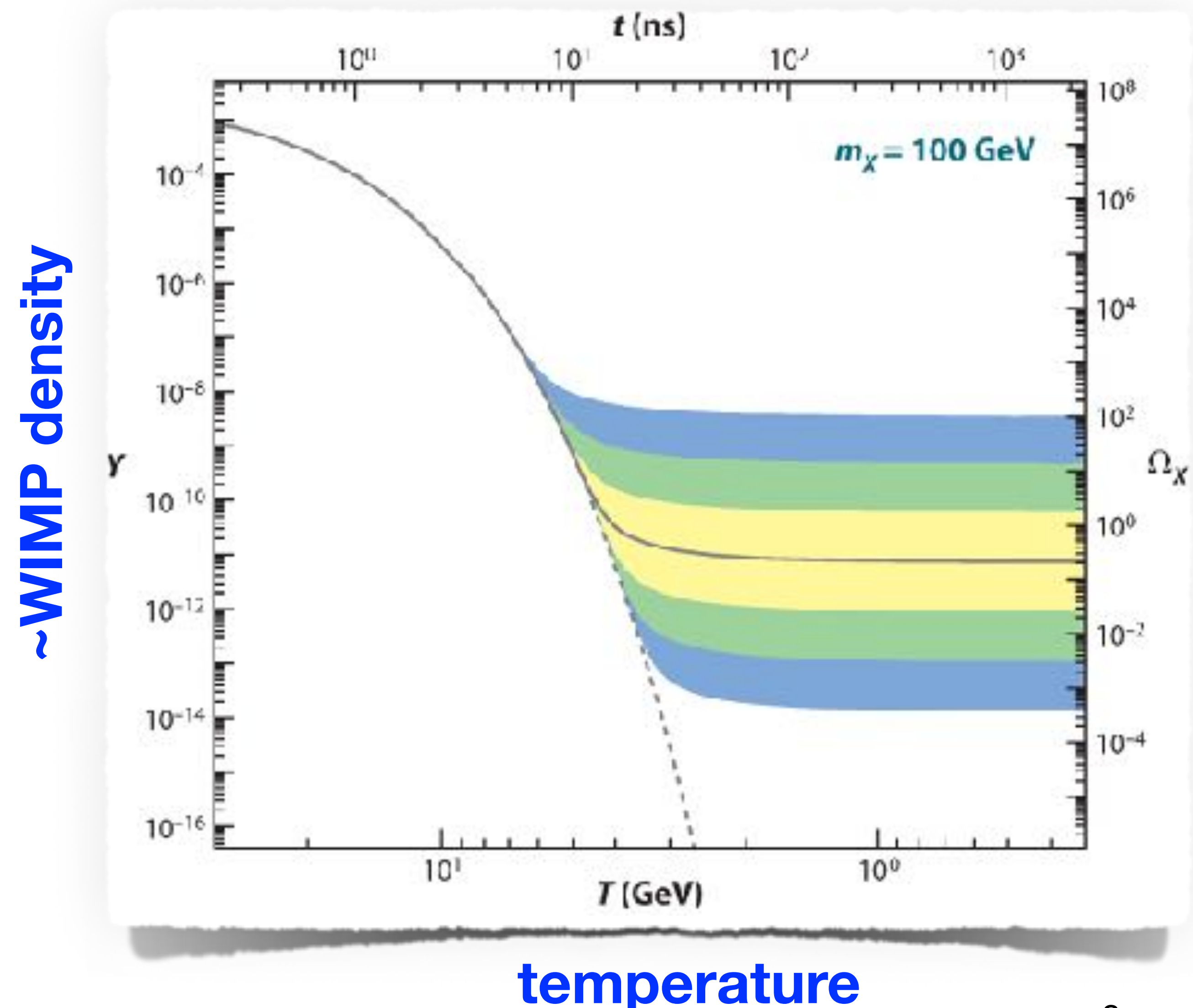
- massive particle
- non-luminous, i.e. electrically neutral
- non-baryonic
- cold, i.e. non-relativistic
- stable with respect to the lifetime of the universe
- only weakly (or less) interacting with ordinary matter



The best Candidate? The WIMP miracle!

- WIMPs are produced in the early hot phase of the universe
- in thermal equilibrium until universe cools down
- survivors are known as “thermic relics”
- “weak” cross-section and mass scale returns relic density consistent with Dark Matter content
- mass range **~ 2 GeV to 120 TeV**
- **⇒“WIMP miracle”**



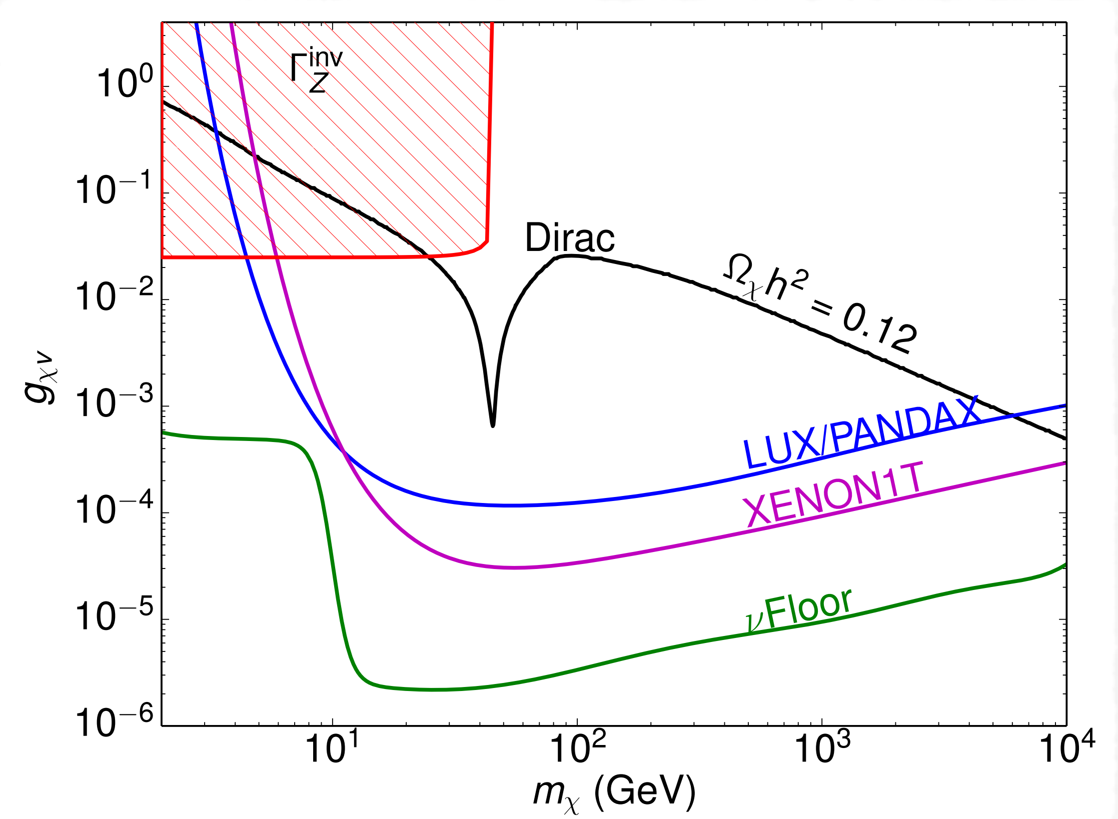


Lee and Weinberg -1977

Dark Matter versus Dark Sector

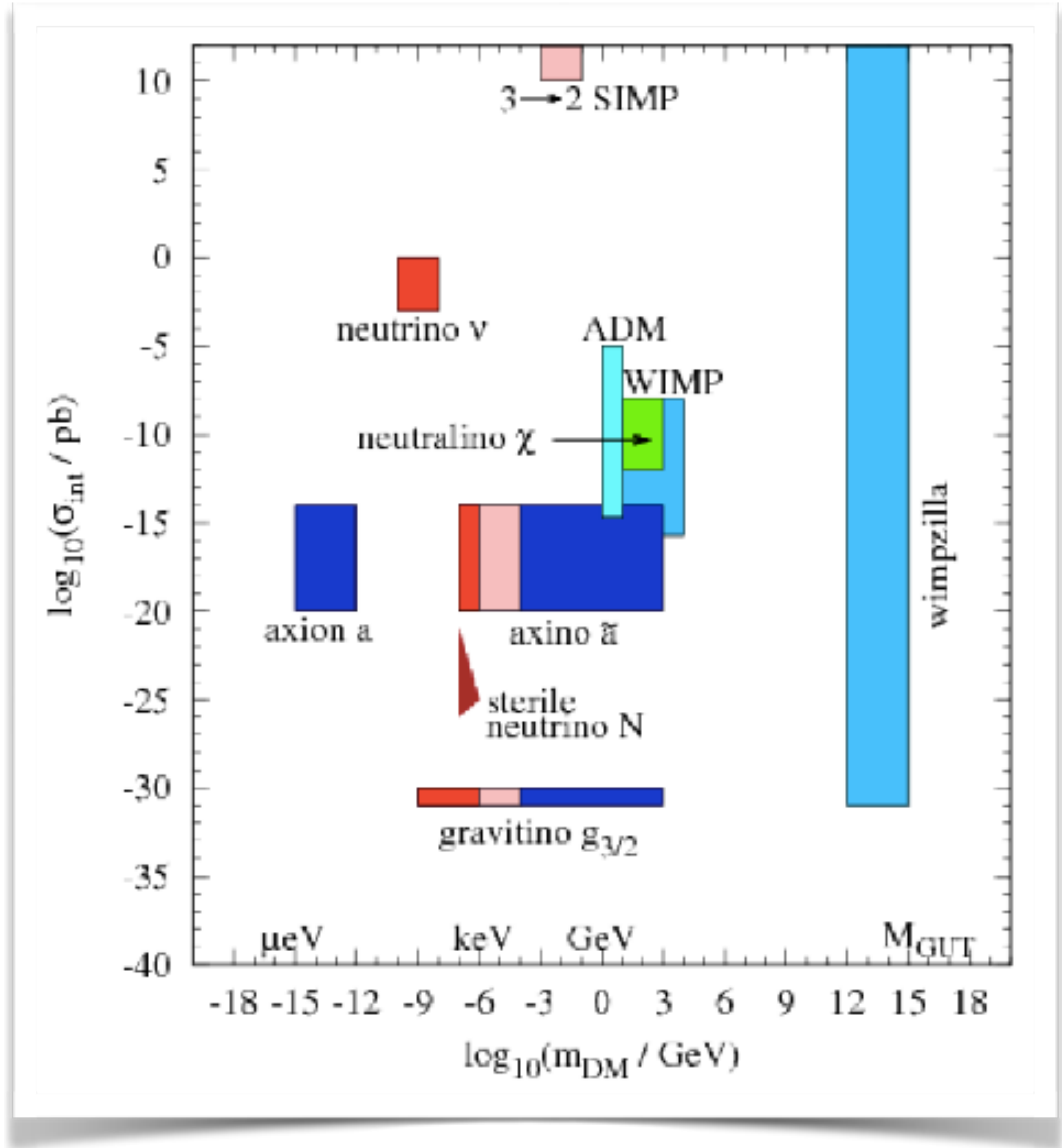
- so-called "WIMP" miracle predicts dark matter WIMP mass between 2 GeV and 120 TeV
    - dark matter particle weakly interacting with matter
      $<\sigma_{WIMP} \cdot v> \sim \mathbf{G_F^2} \cdot m_X^2 \sim 1/\Omega_X$
      → **lower bound** on m_X from prohibiting over-closure of the universe
- coupling to Z and H almost ruled out
- new force coupling matter to dark matter
  → **Dark Sector**

arXiv:1609.09079



Unraveling the Particle Character of Dark Matter

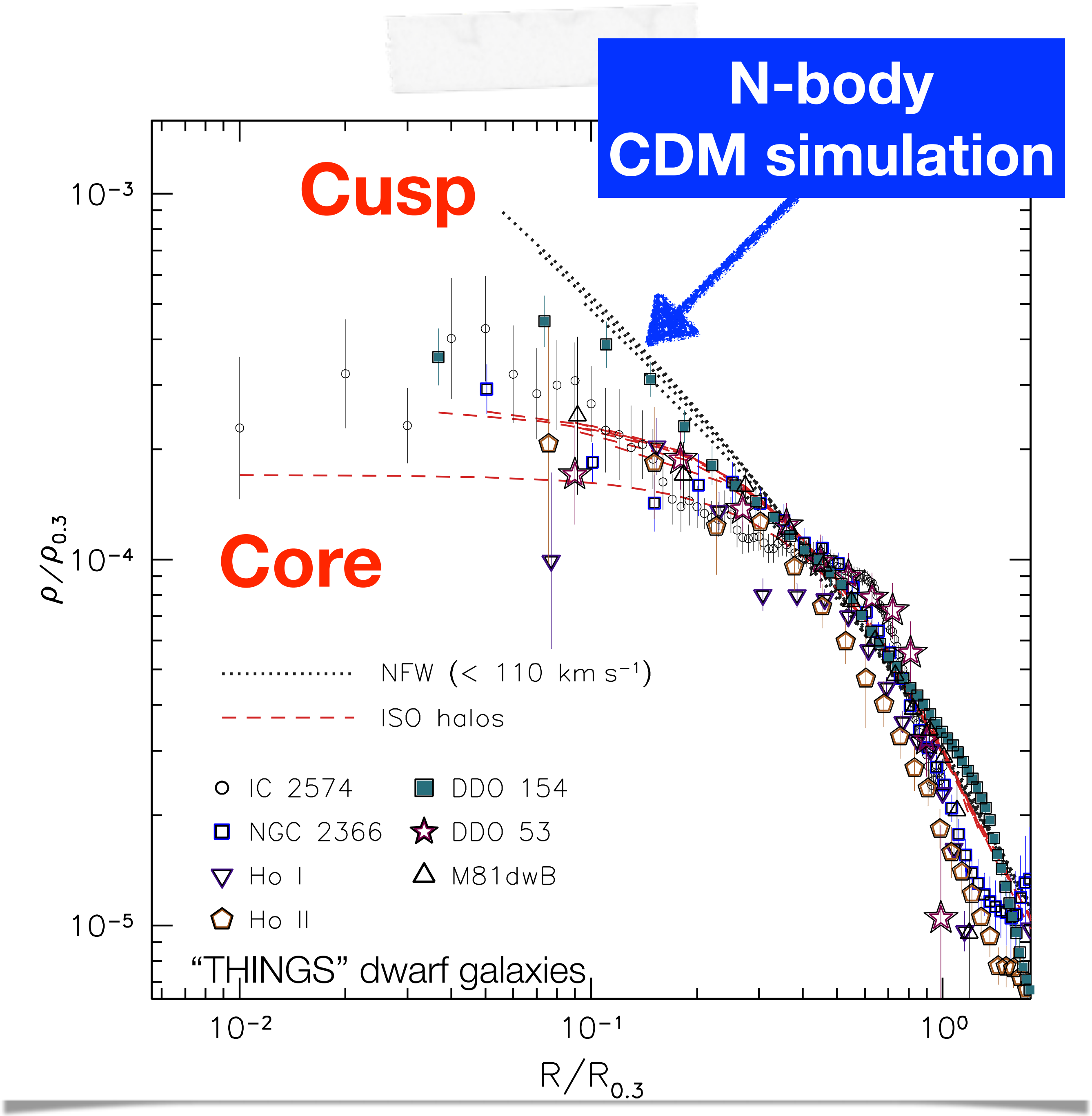
- variety of Dark Matter particle candidates with large range of mass and χ-N cross section
- Standard Model particles (e.g. neutrinos) cannot act as Dark Matter candidates
- WIMP only one candidate out of a range of theoretical motivated Dark Matter candidates



arxiv:1407.0017

Light Dark Matter

Dark Matter - Small Structure Problems

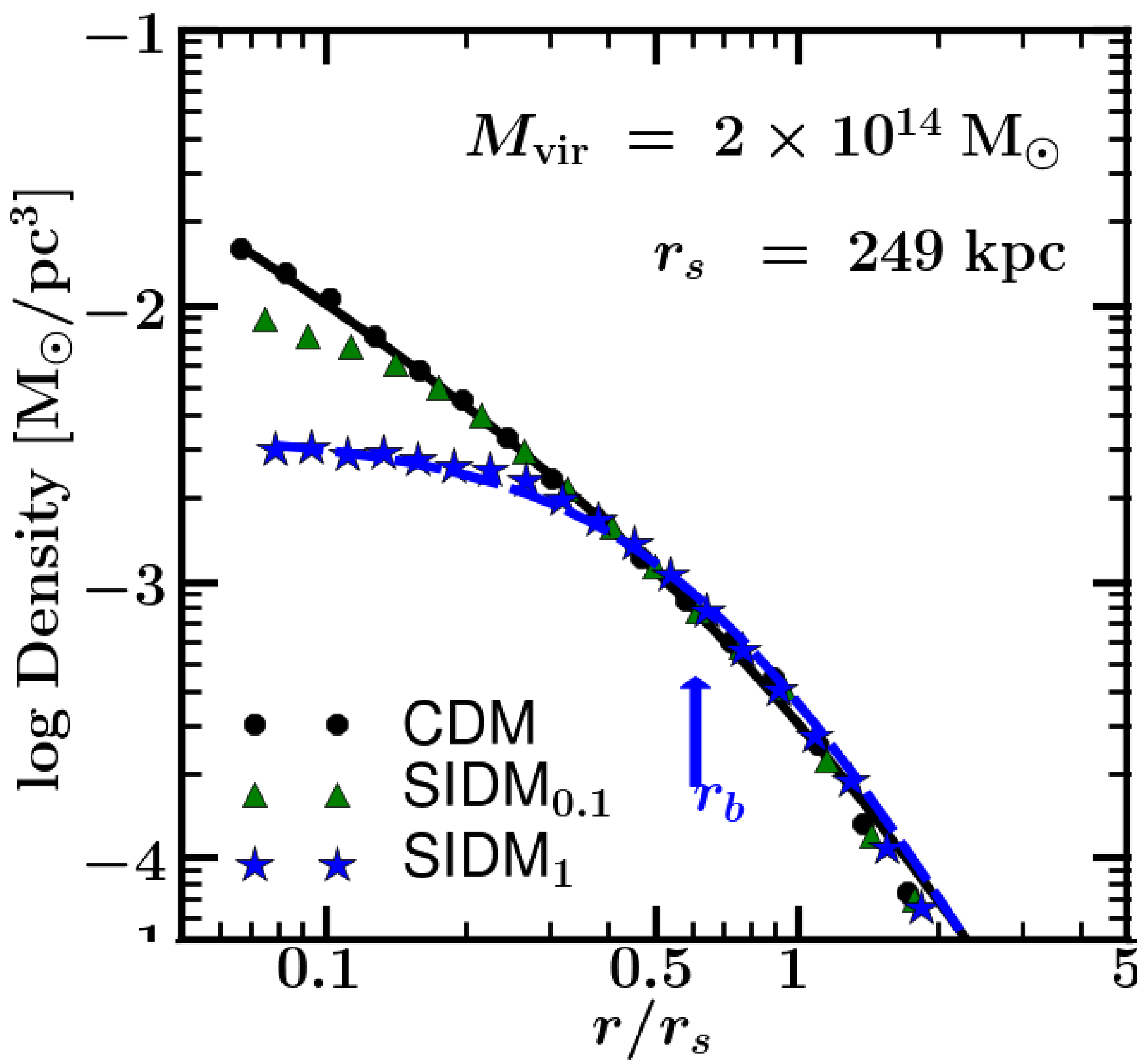


arXiv:1011.0899

- simulations based on Cold Dark Matter assumption can not reproduce all observations
- long-standing **core-versus-cusp problem**
- reduced Dark Matter density at center of halo

Self Interacting Dark Matter I

arXiv:1208.3025

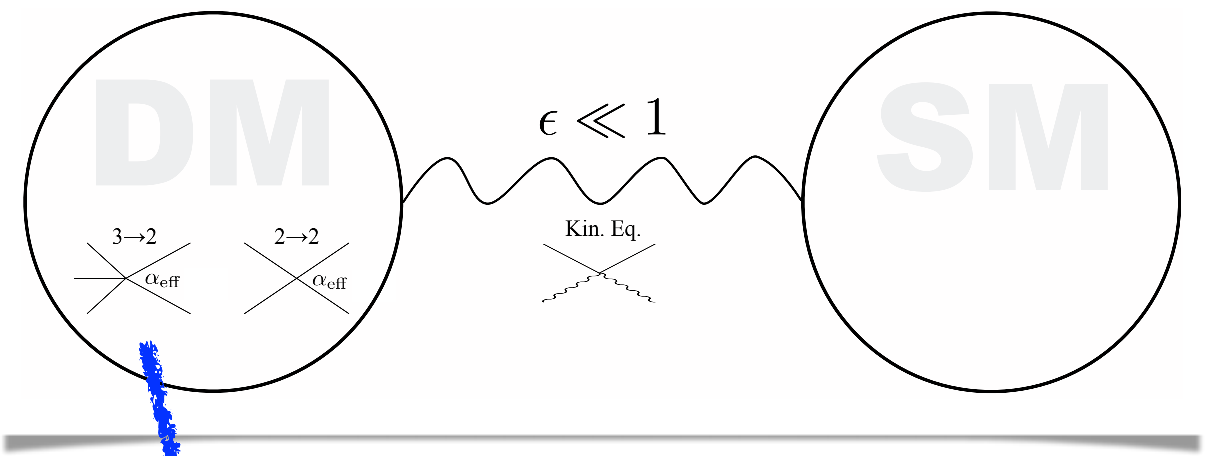


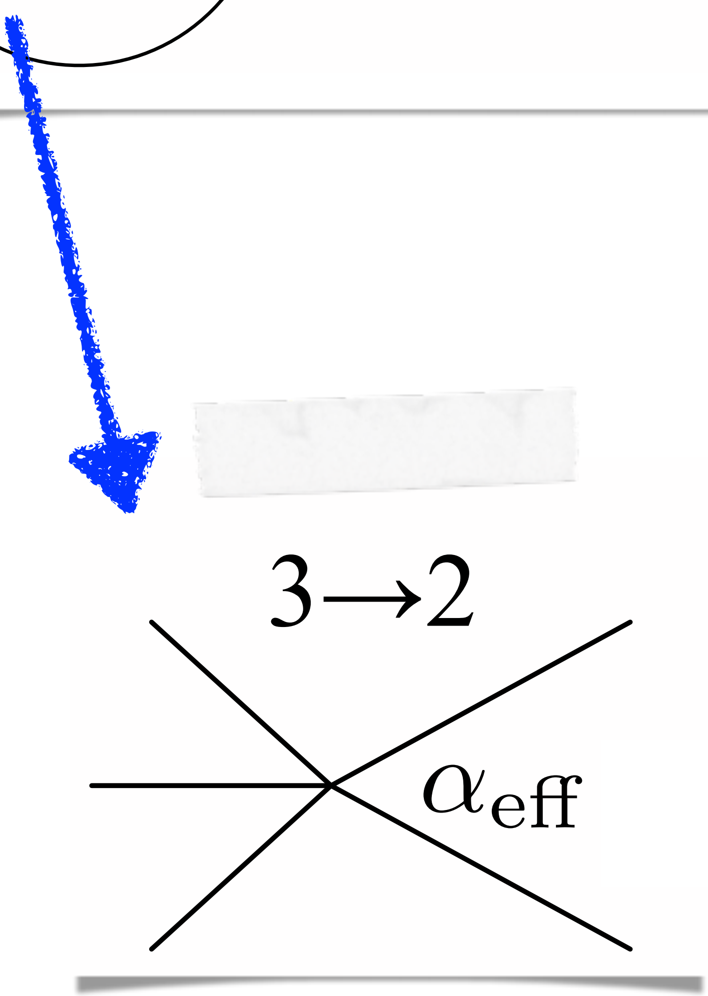
SIDM: self interacting Dark Matter

- N-body simulation assumes collision-less Dark Matter particles
  - gravitational interaction only
- **strong self-interaction** between Dark Matter particles reduces density at the centre of the galaxy

Self Interacting Dark Matter II

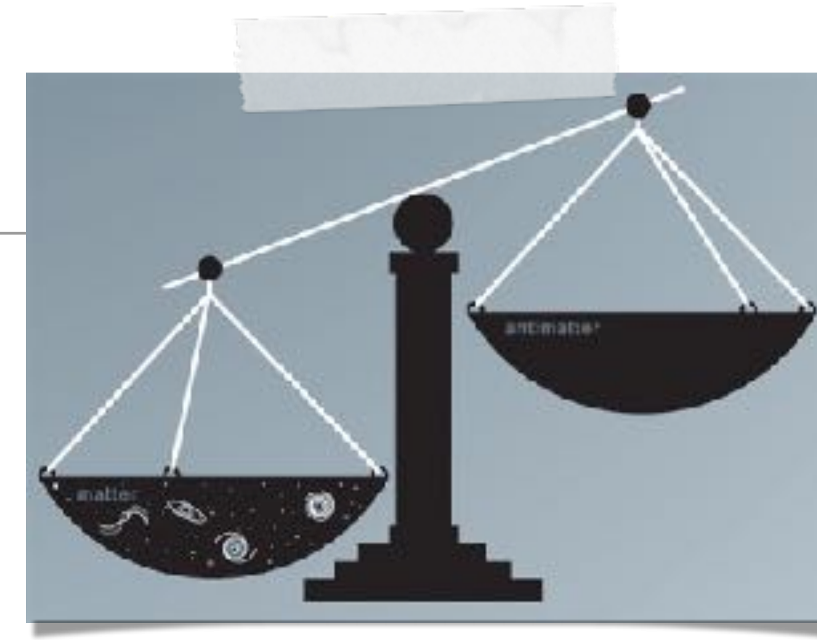
arXiv:1402.5143





- observations are consistent with a self-interaction $\sigma_{scatter}/M_{DM} \approx 0.1$ - 1 barn/GeV
- **freeze out** mechanism via 3→2 SIMP processes reproduces observed Dark Matter relic density
    - for large range of couplings 2→2 freeze out process is subdominant
    - sizeable 2→2 self-interaction
- **expected Dark Matter mass scale ~ 100 MeV**

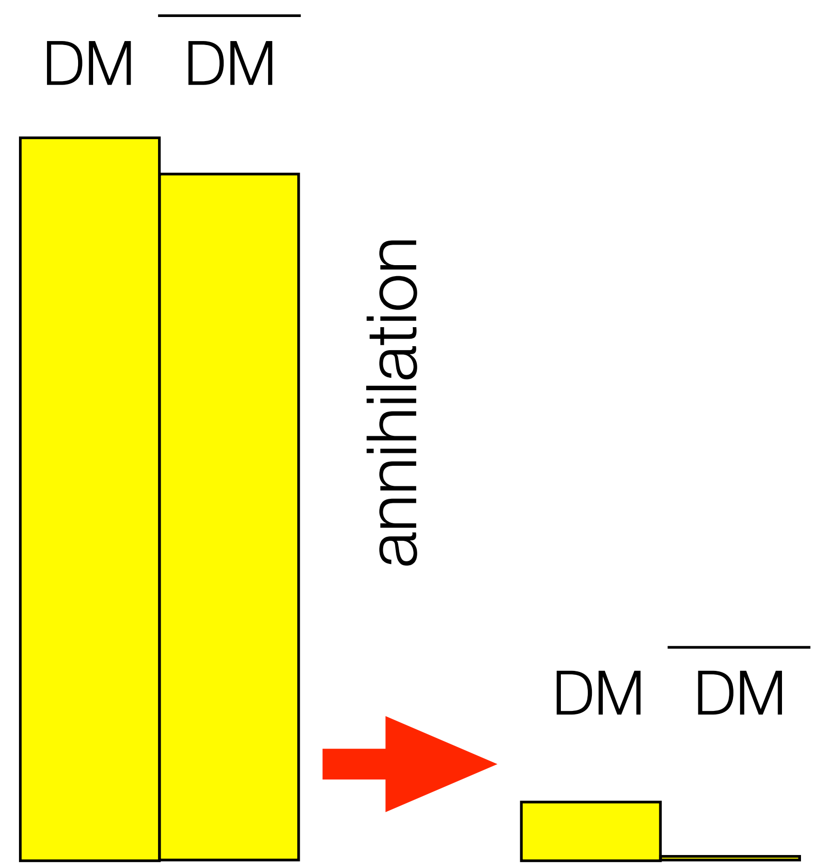
Asymmetric Dark Matter



- DM density $\boldsymbol{\rho_{DM}}$ **~ 5** x baryon density $\boldsymbol{\rho_B}$
- large matter anti-matter asymmetry
  - DM density coupled to freeze out mechanism → **WIMP miracle**

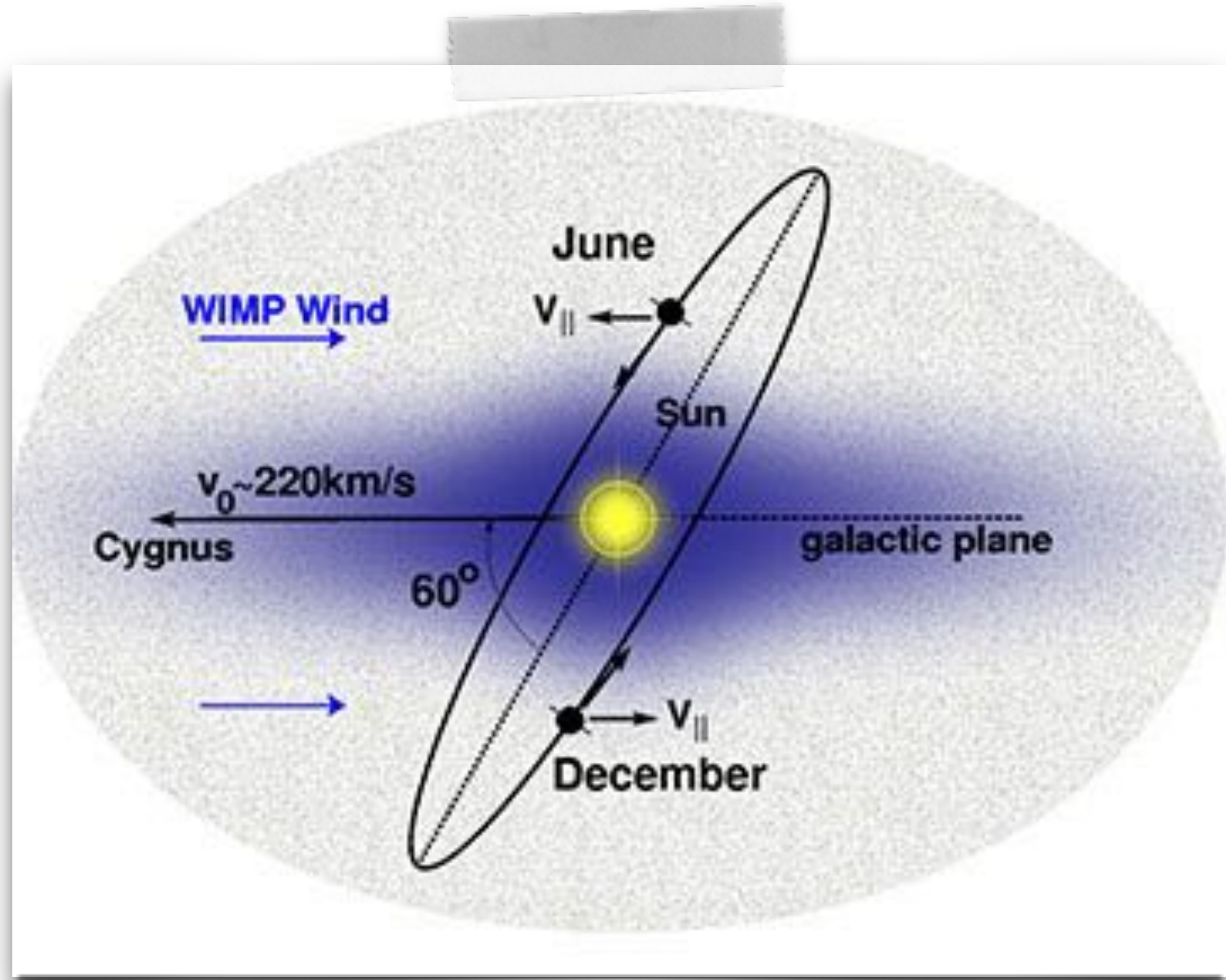
no relation!

  - baryon density related to CP violation and baryon number violation
- asymmetric Dark Matter models relate Dark Matter and Baryon asymmetry
  - $\mathbf{M_{DM}}$ ~ 5 M_B ~ 5 M_{proton} **~ 5 GeV**



Astrophysical Parameters - Distribution of Dark Matter

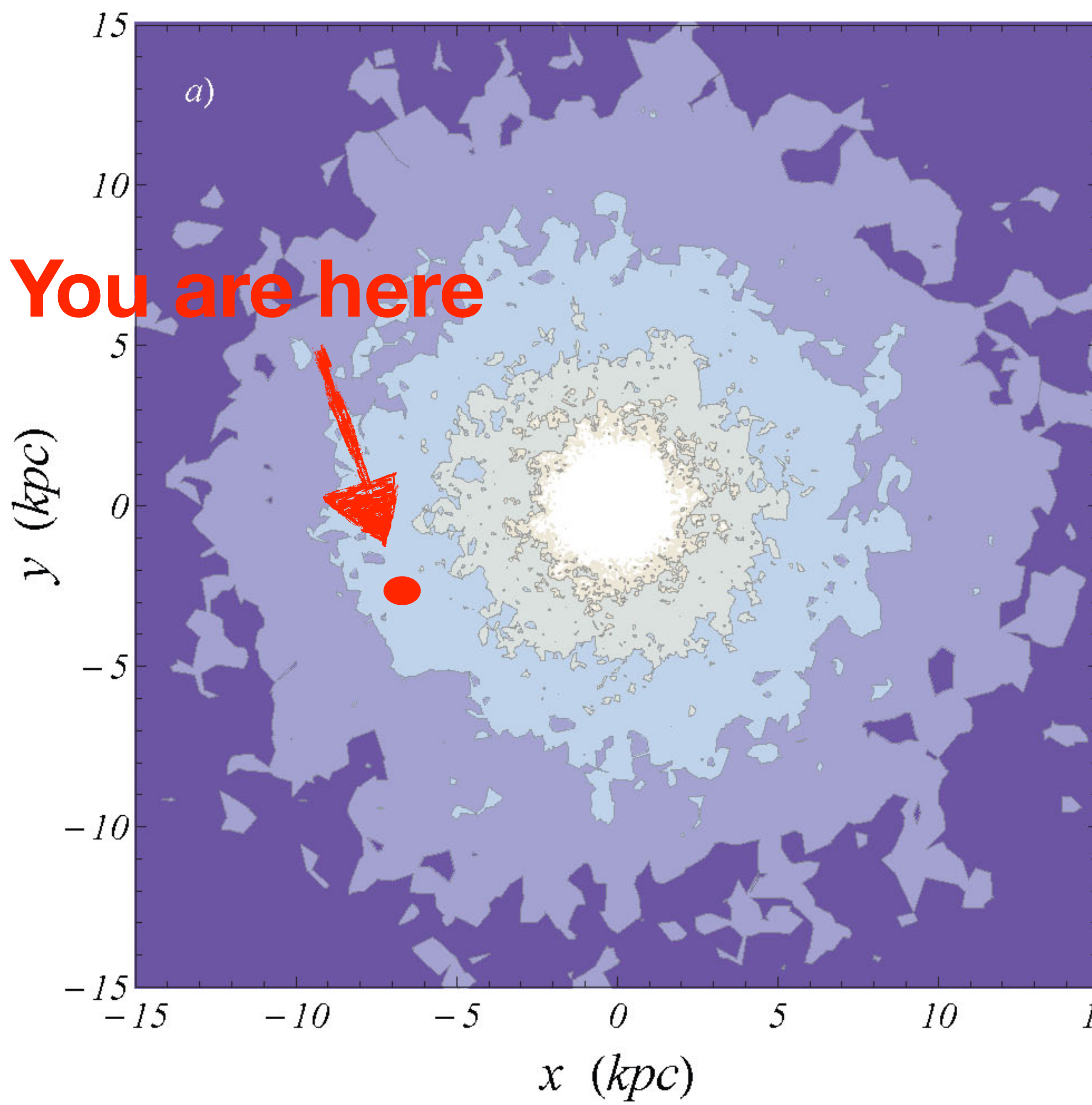
- velocity of dark matter in the halo follows Maxwell-Boltzmann distribution
  - most probable DM velocity ~220 km/s
  - escape velocity for DM to escape halo about 540 km/s
  - ~5-10 % variation originating from path of earth around sun



Astrophysical Parameters - Distribution of Dark Matter

- Dark Matter distribution in Milky Way from simulation
- local Dark Matter density ~0.3 GeV/cm^3
- dark Matter flux on earth **~10^7 /cm^2 s for M_{DM} = 1 GeV**

arxiv 0909.2028



contours correspond to {0,1,0.3.,1.0,3.0} GeV/cm^3

Intermission - Recapitulation

- unambiguous observation of Dark Matter
  - observations based on gravitational measurements only
- new particles from physics beyond the Standard Model offer candidates for particle interpretation of Dark Matter
  - weak (or less) interaction with baryonic matter expected
- various models predict candidates for explaining Dark Matter
  - WIMPs - mass range above 2 GeV
  - low mass Dark Matter - mass range in the GeV / sub-GeV region

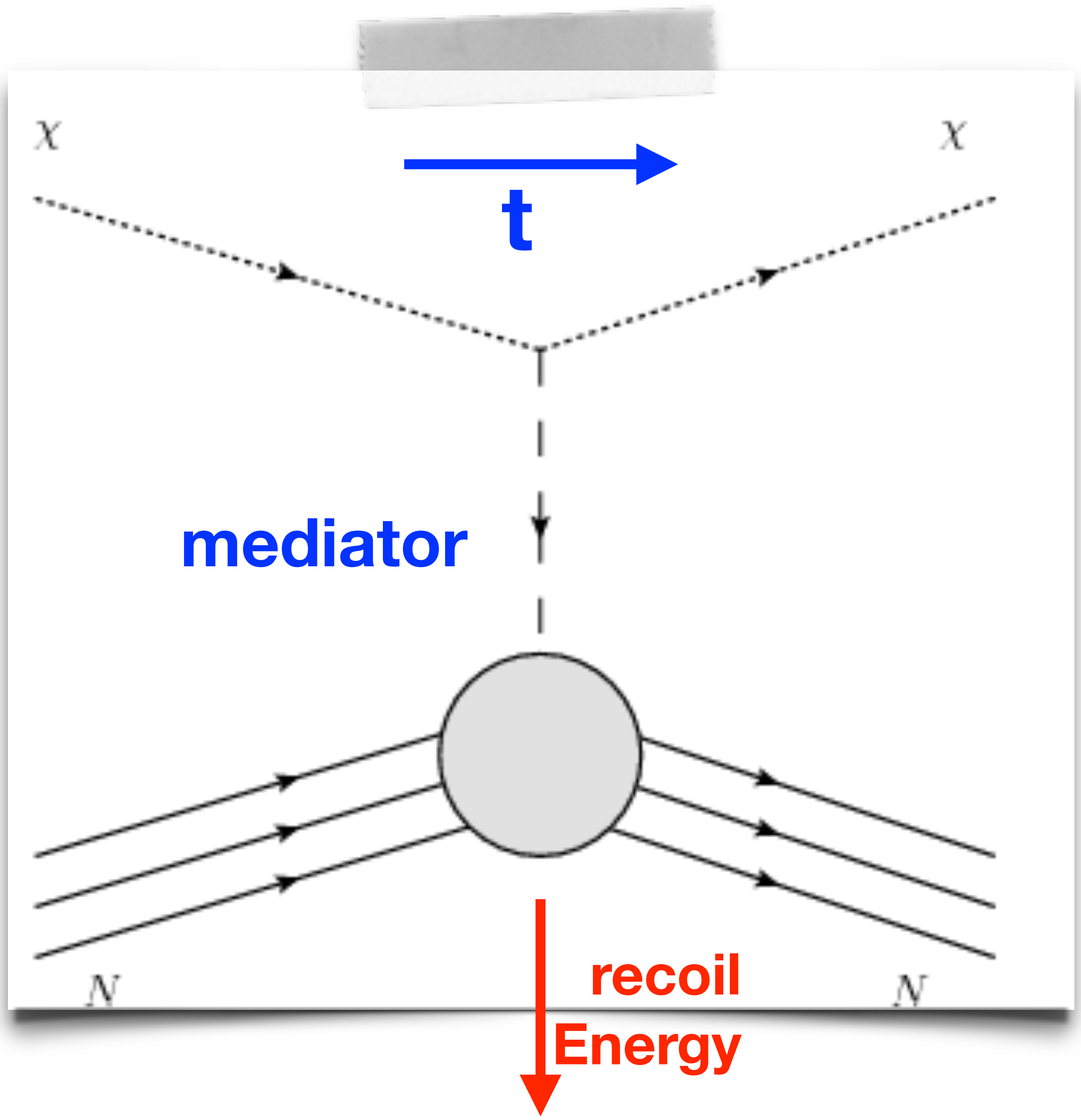
Direct Detection of Dark Matter

Direct Detection of Dark Matter - Basic Principle

- weakly interacting massive particles scatter elastically with baryonic dark matter

  1. recoil of nucleus leads to
  2. deposition of energy followed by
  3. measurement of deposited energy

- exact interaction rate and size of deposited energy (=mass of Dark Matter particle) unknown



Direct Detection - Event Rate

- differential event rate for WIMP nucleon scattering

ρ_0: WIMP density in the Milky Way

f(v): WIMP speed distribution

$d\sigma/dE_R$: WIMP-nucleus elastic scattering

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v\, f(v)\, \frac{d\sigma_{W\,N}}{dE_R}(v, E_R)\, dv$$

m_N : nucleon mass
m_χ: WIMP mass

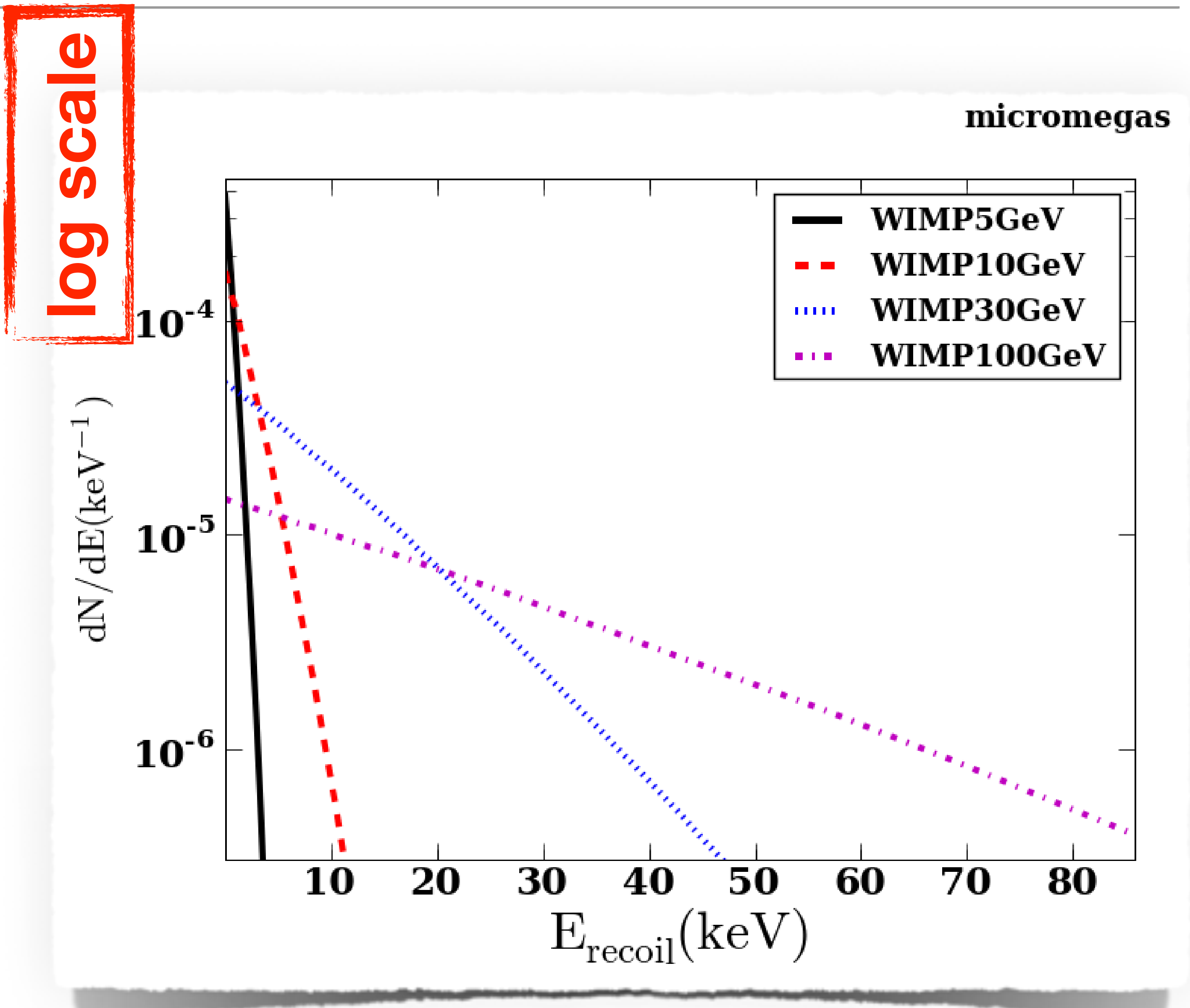
- recoil energy between eV and tens of keV

Direct Detection - Event Rate

- differential event rate decreases exponentially with recoil energy

$$\frac{dR}{dE_R} = \left(\frac{dR_0}{dE_R}\right)_0 F^2(E_R)\,\exp(-E_R/E_c)$$

- low detection threshold for WIMP-nucleon scattering crucial

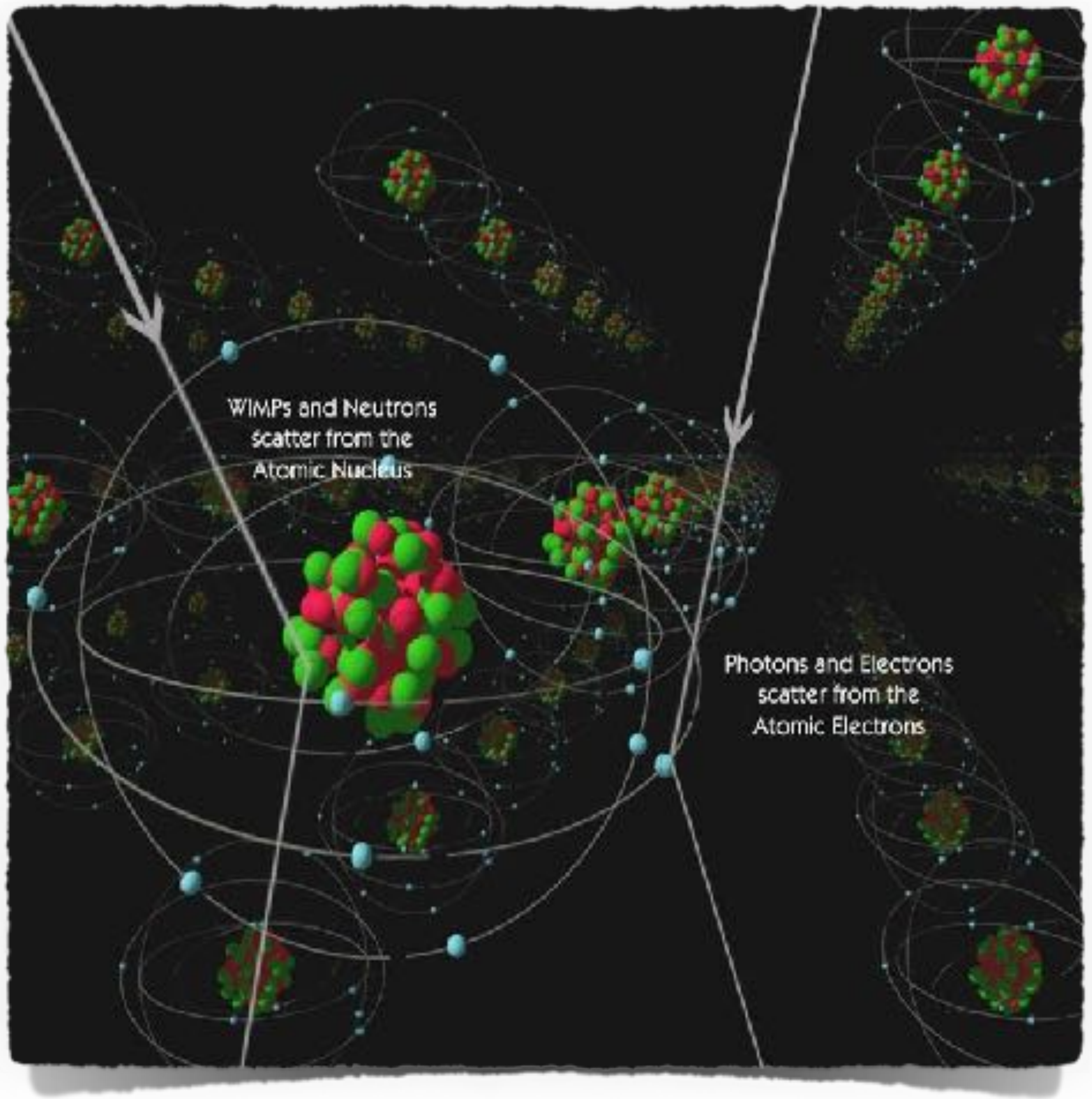


WIMP - ^{78}Ge nucleon scattering

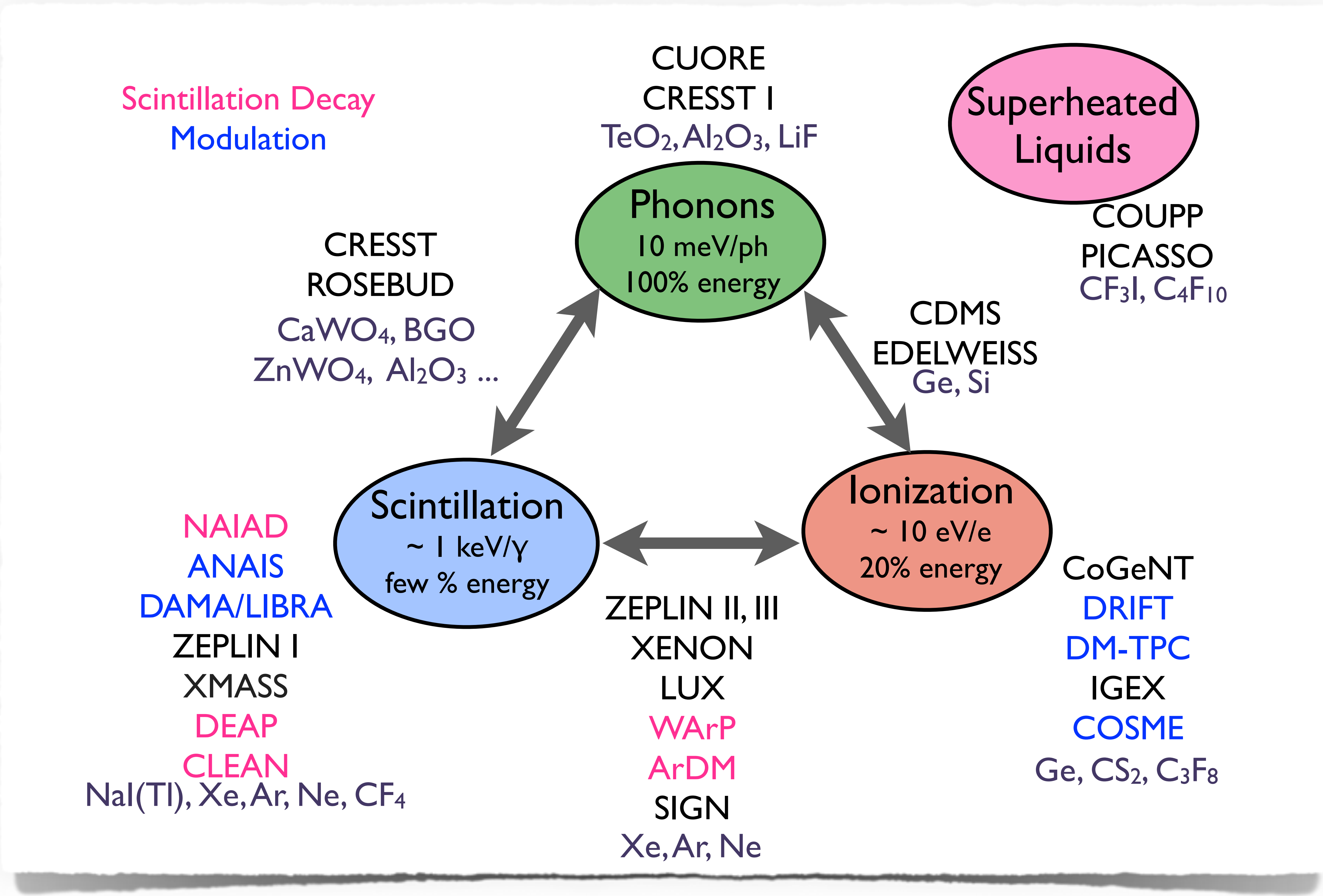
How to search for Dark Matter?

Recipe for a Direct Dark Matter Search Experiment

- experimental challenges for measuring elastic Dark Matter-nucleus scattering:
  - **low energy threshold:** very small energy transfers (O(100 eV)); differential event rate decreases exponentially
  - **low background:** small interaction rate (O(events/kg year))
- **sensitivity to small energy deposition in a low background environment**



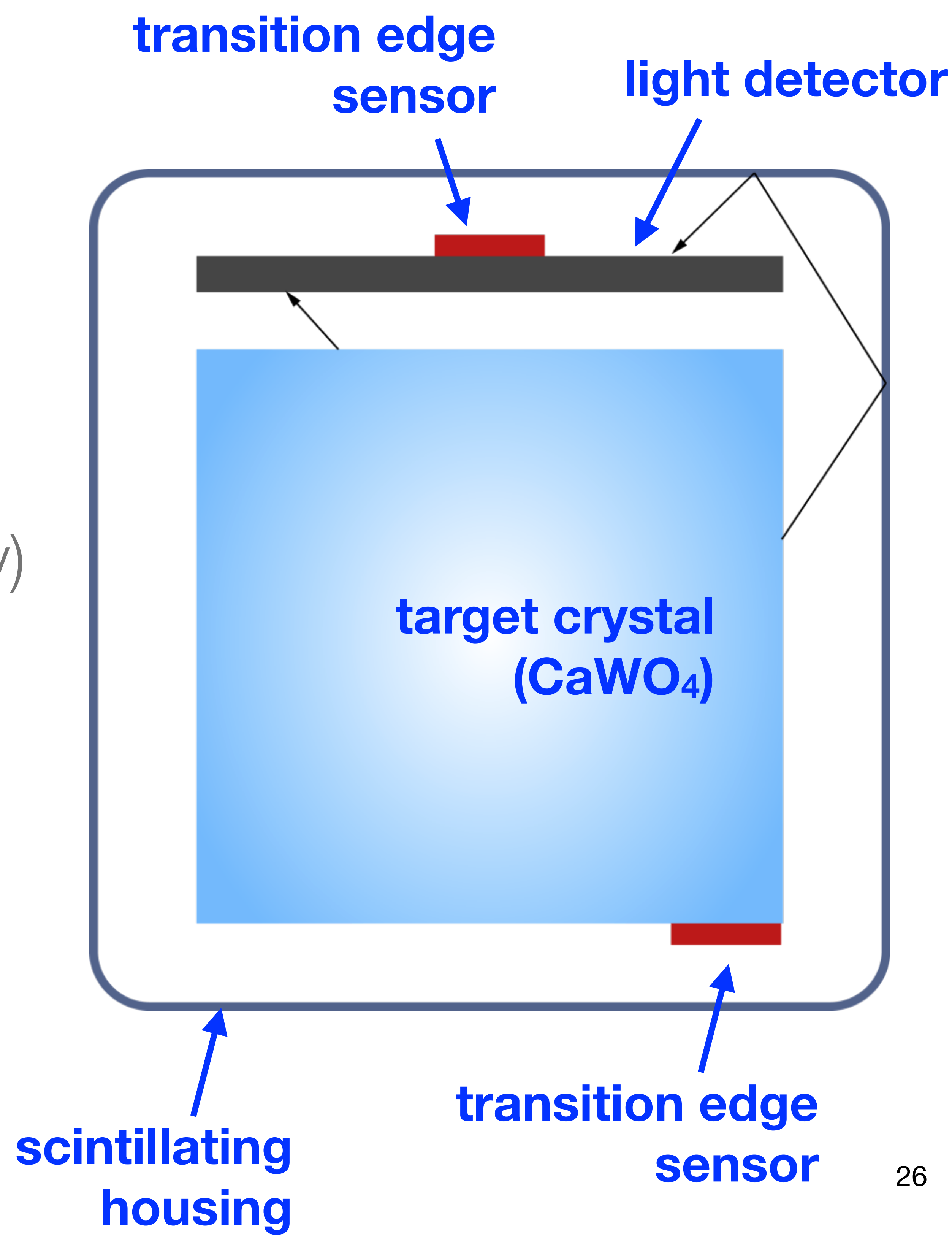
Measurement of Recoil Energy deposited by Scattering



CRESST - Detection Principle I

simultaneous read-out of two signals

- **phonon channel:** particle independent measurement of deposited energy (= nuclear recoil energy)
- **(scintillation) light:** different response for signal and background events for background rejection ("quenching")



CRESST - Detection Principle II

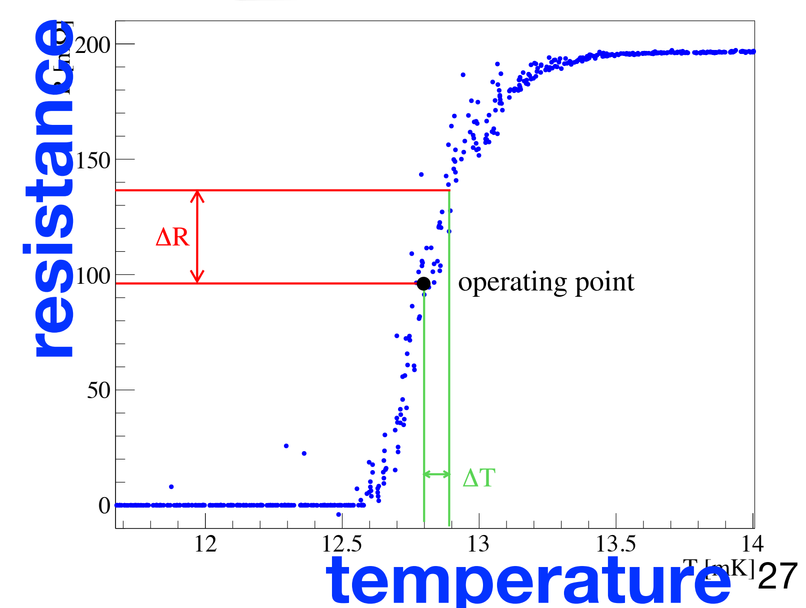
- experiment operated at cryogenic temperature (~15 mK)
- nuclear recoil will deposit energy in the crystal leading to a temperature rise proportional to energy

$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

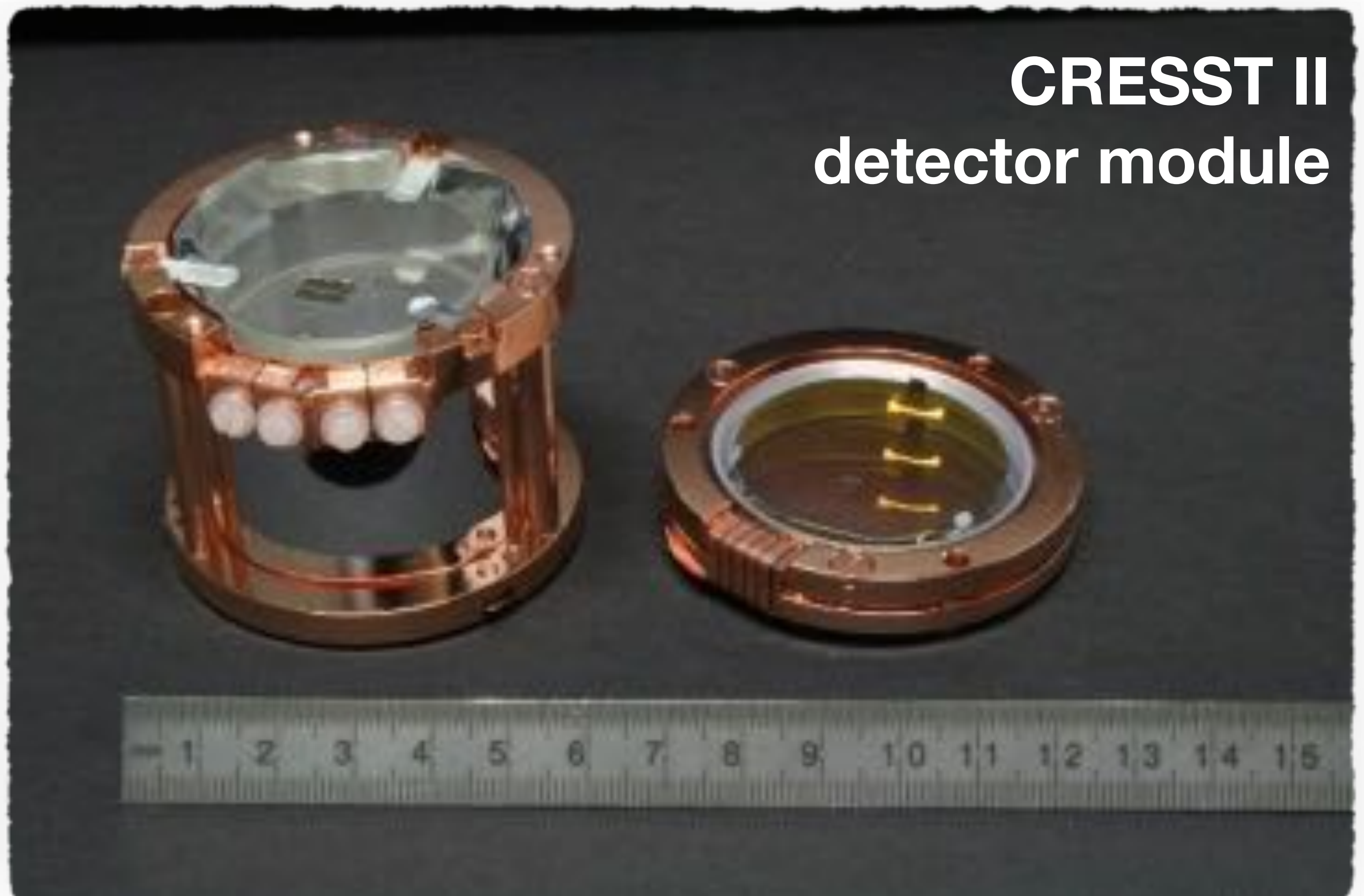
$$c \propto (T/\theta_D)^3$$

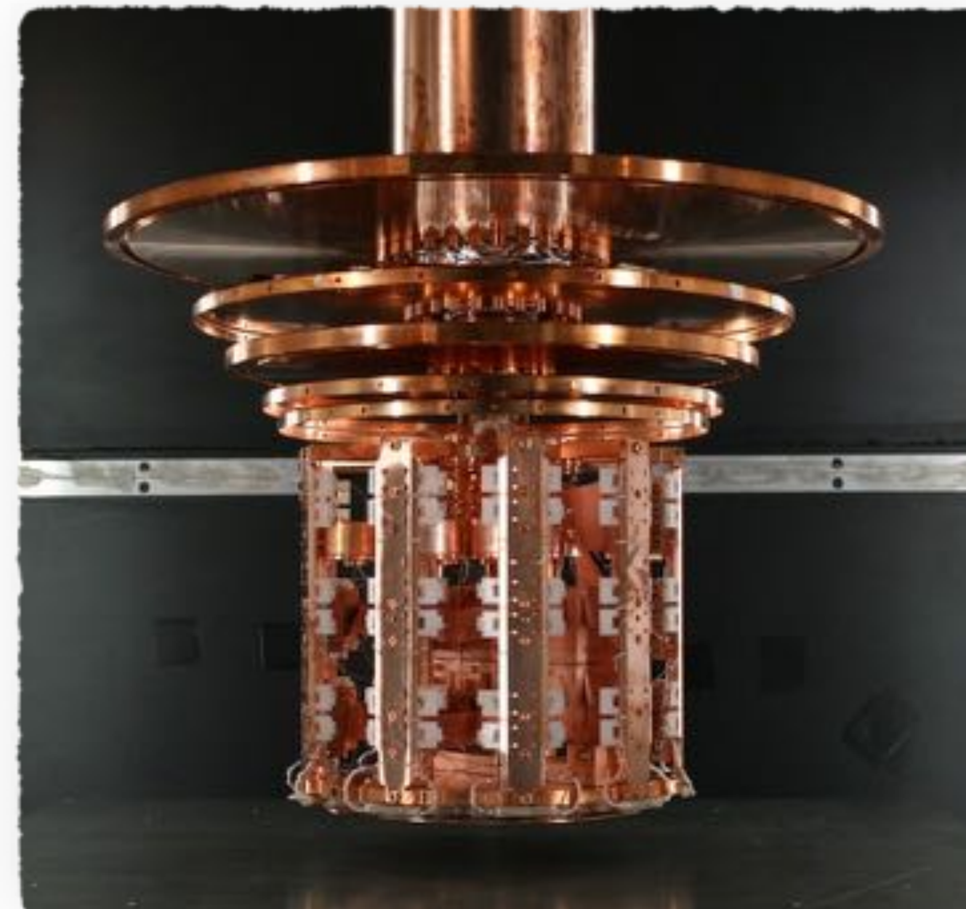
Θ_D:Debye temperature

- detection of small energy depositions requires very small heat capacity C
- detection of temperature rise with superconductor operated at the phase transition from normal to superconducting



CRESST - Detector Module



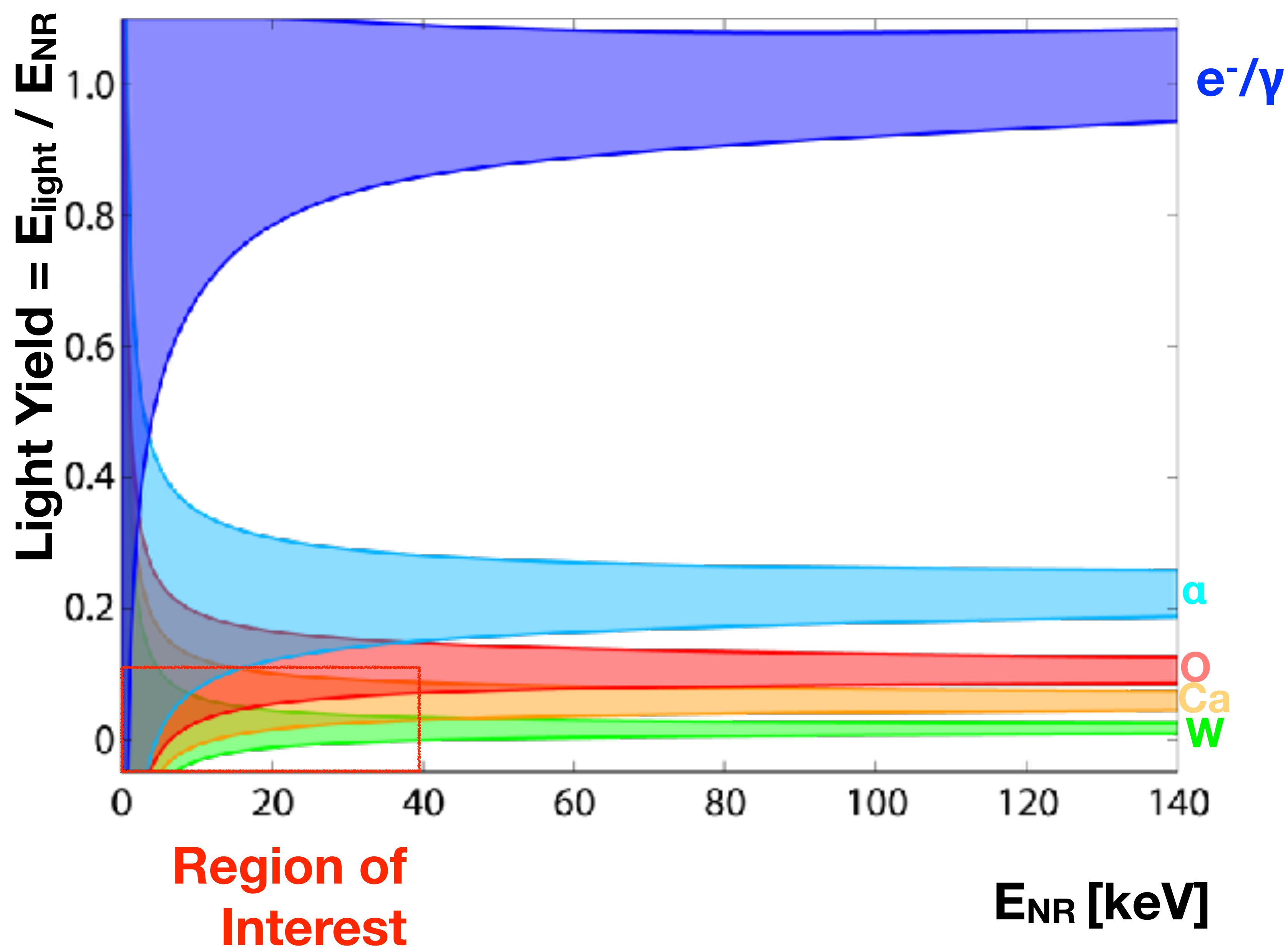


- $CaWO_4$ crystal placed inside fully scintillating and reflective housing
- modules operated in shielded cryostat in the Laboratori Nazionali del Gran Sasso (Italy) at 3600 mwe

Data Taking and Results

Signal-Background Separation

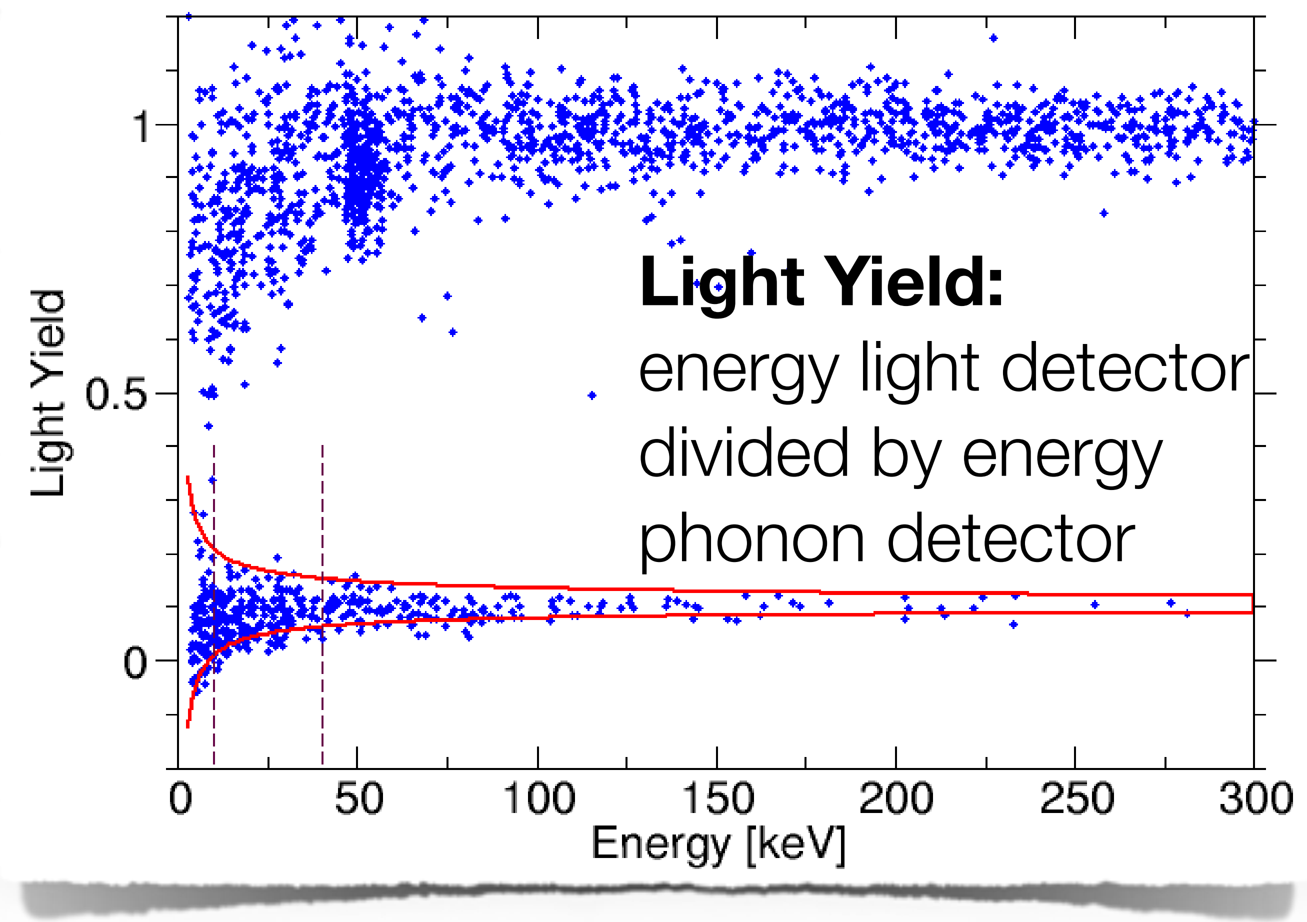
- simultaneous readout of light and phonon channel allows background reduction
- less scintillation light from dark matter-nucleus scattering (“Quenching”)
    - clear separation between signal and background at large E_{NR}
    - **significant overlap of bands at low energies (= low mass dark matter)**



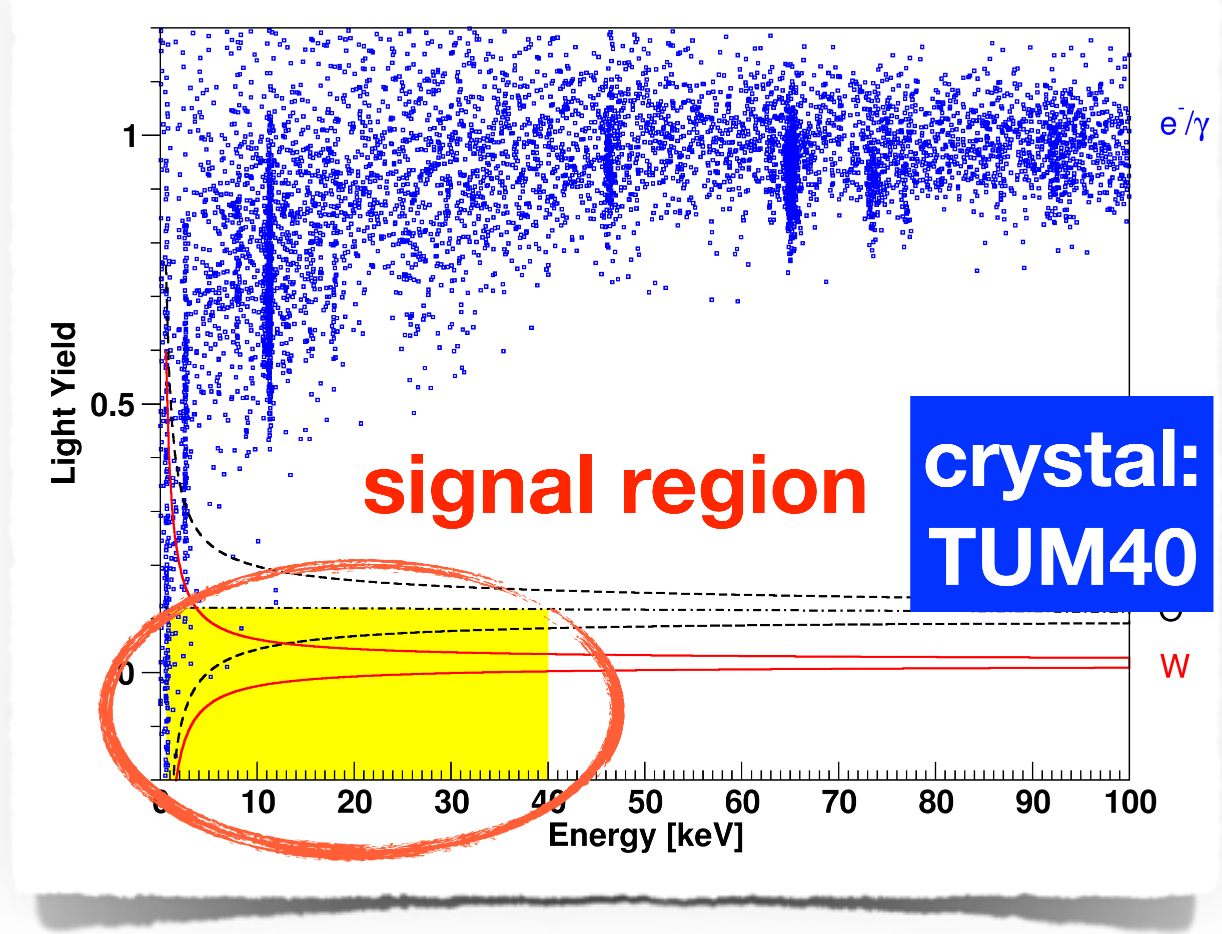
Signal-Background Separation - Data

Eur.Phys.J. C74 (2014) 12, 3184
arxiv 1407.3146

neutron calibration



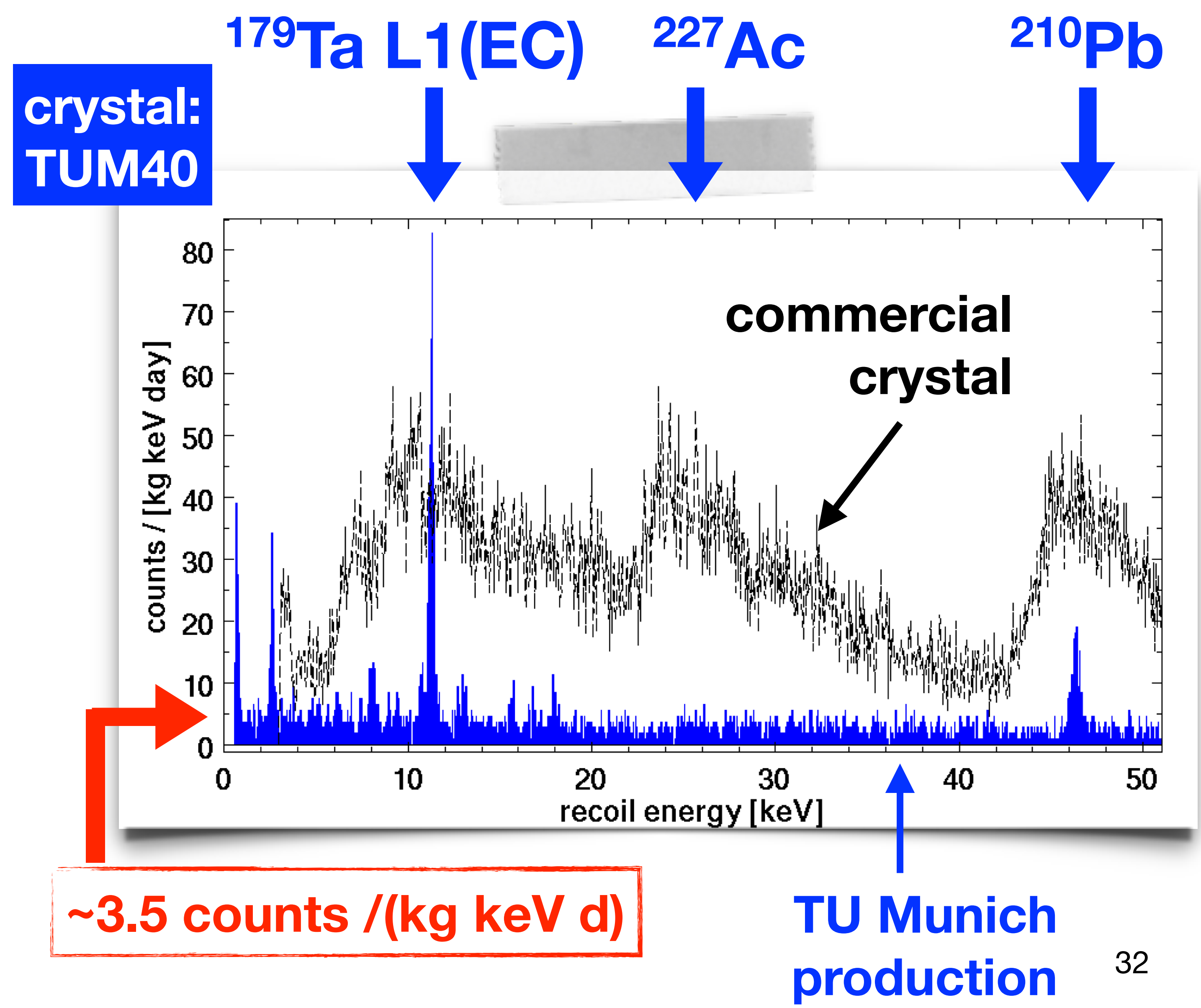
measurement



- signal region identified in light yield / energy space
- **reduction and understanding of intrinsic background crucial for low mass Dark Matter searches**

Crystal Intrinsic Background

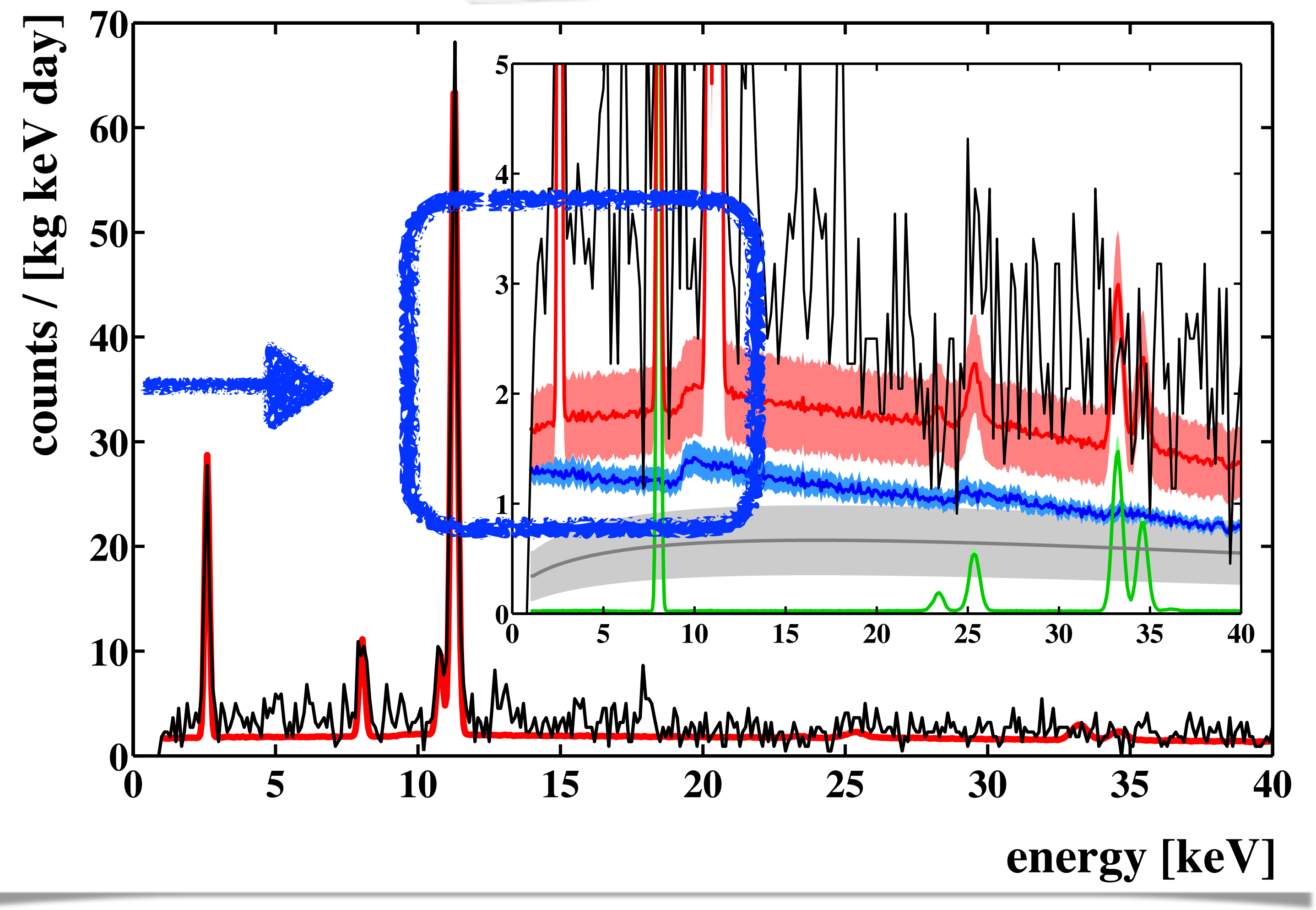
- experimental sensitivity limited by background
    - CRESST dominated by crystal-intrinsic radioactive contaminations
- **improve radio purity**
- in-house production of $CaWO_4$ crystals improves radio purity significantly



Background Simulation of CRESST

- understanding of background crucial
- simulation of 11 most prominent isotopes
- crystal only simulation
- **data cannot be explained completely by simulation**

JCAP, 2015(06), 030



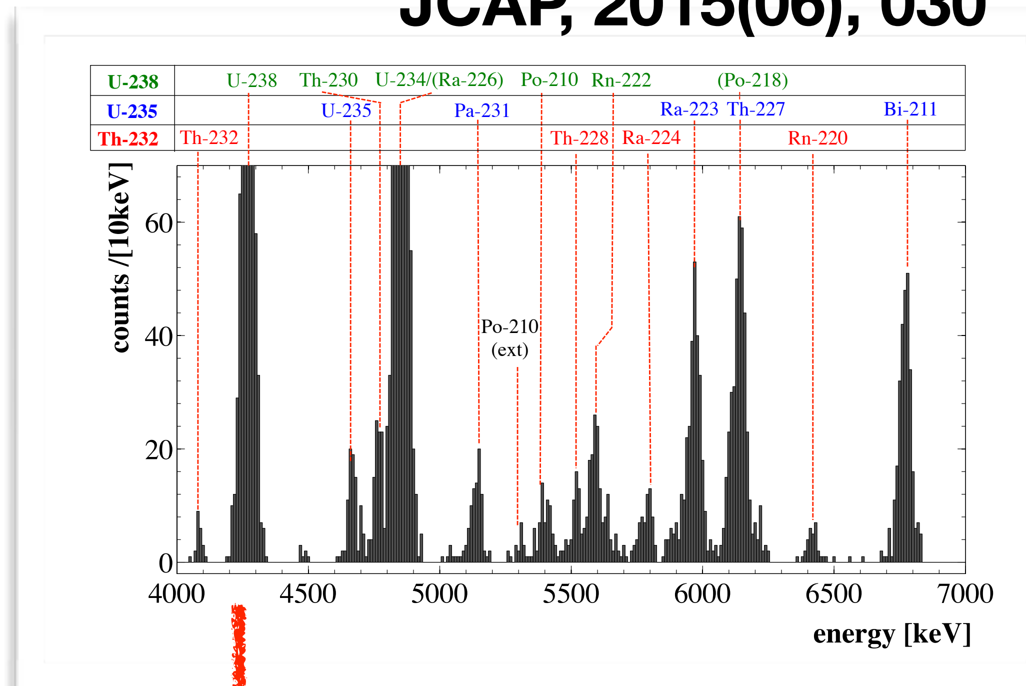
green: external gamma radiation
gray: external betas
blue: intrinsic β/γ radiation from natural decay chains
red: sum + cosmogenic activation

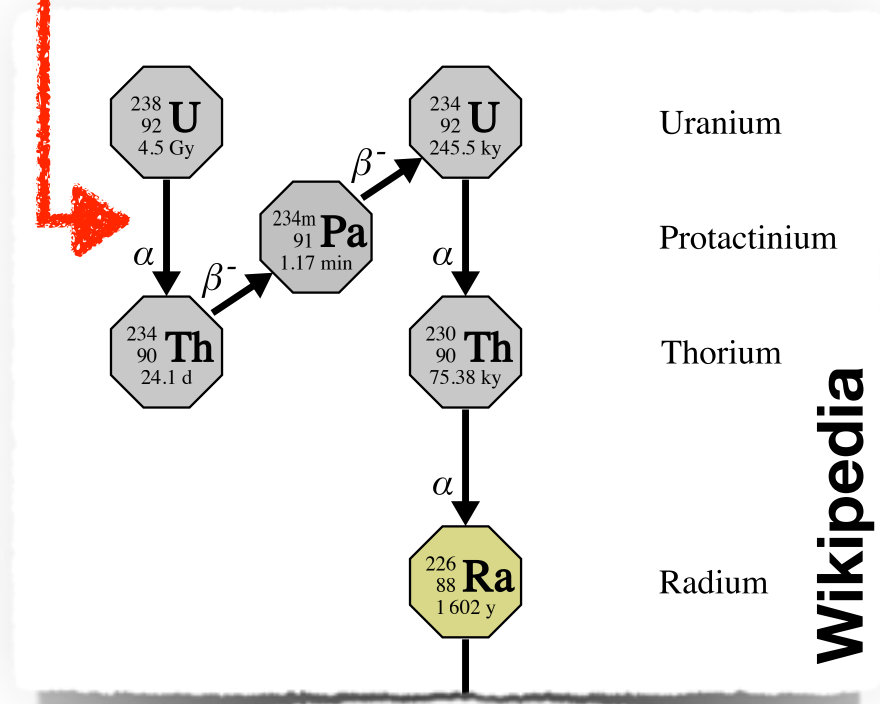
crystal: TUM40

Background Simulation of CRESST - Method I

- Geant4 based simulation to estimate intrinsic background
- use α-activity as input:
  - identification of decay / isotope
  - measured activity reflects size of contamination
- determine energy spectrum of isotope decay and scale it accordingly to the measured activity

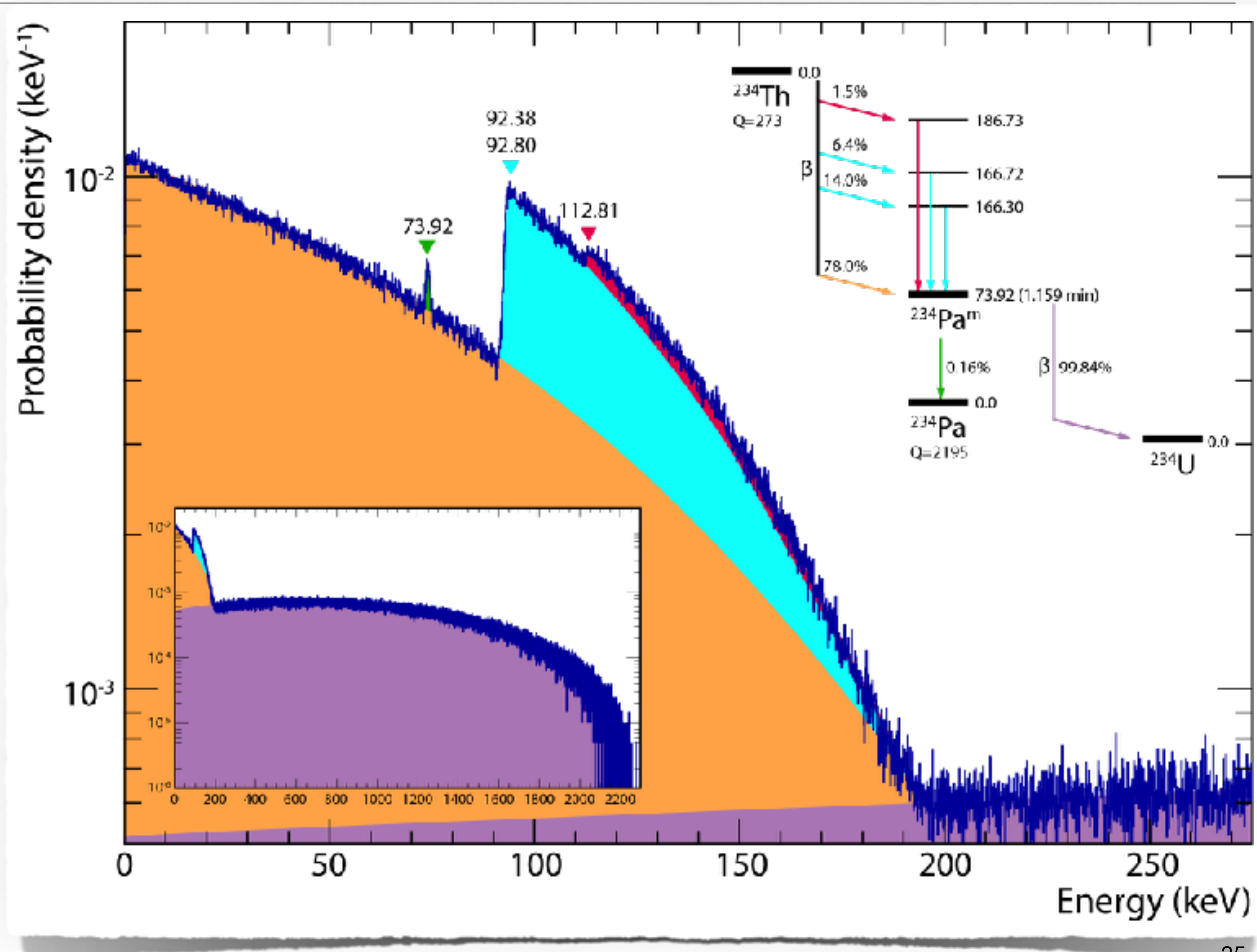
JCAP, 2015(06), 030



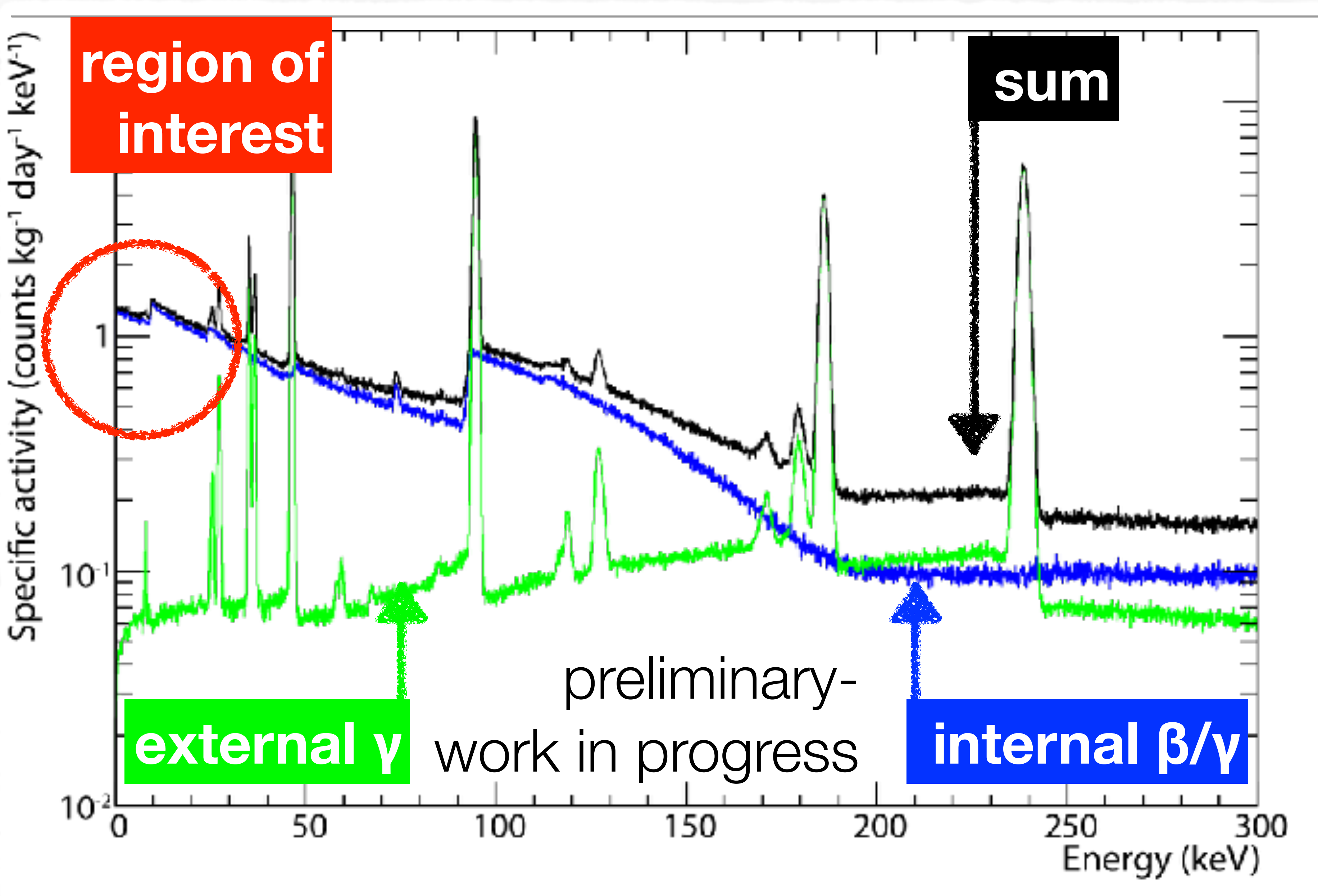


Background Simulation of CRESST - Method II

energy spectrum of simulated ^{234}Th decay with Giant



Background Simulation of CRESST

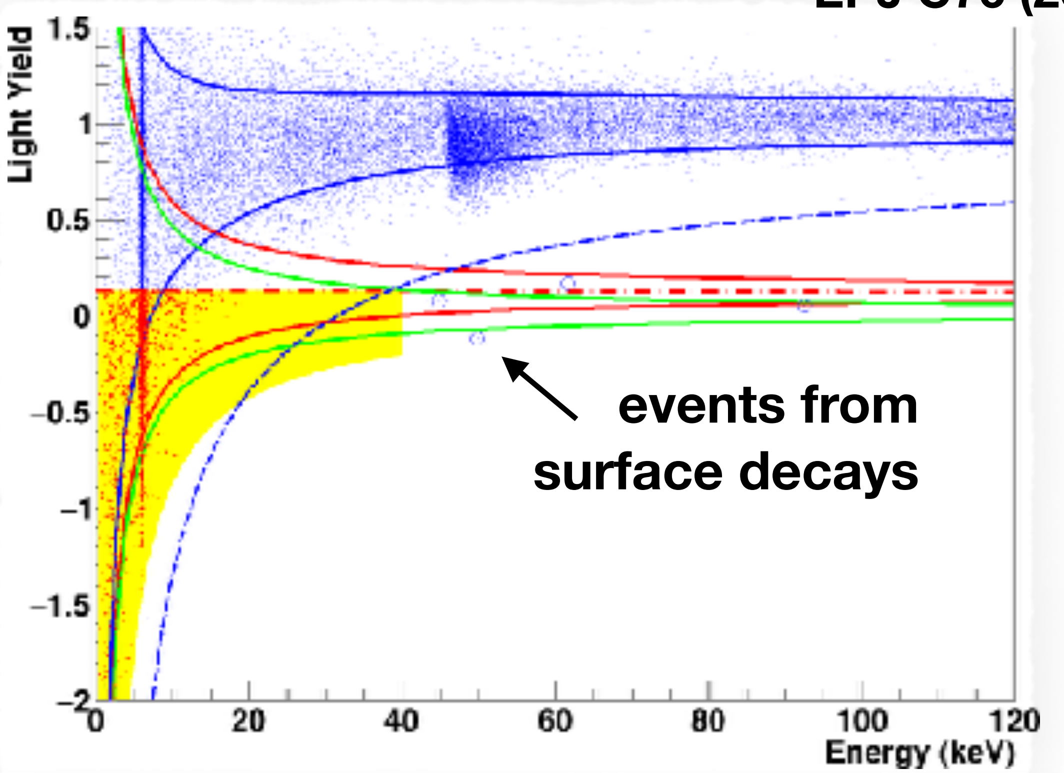


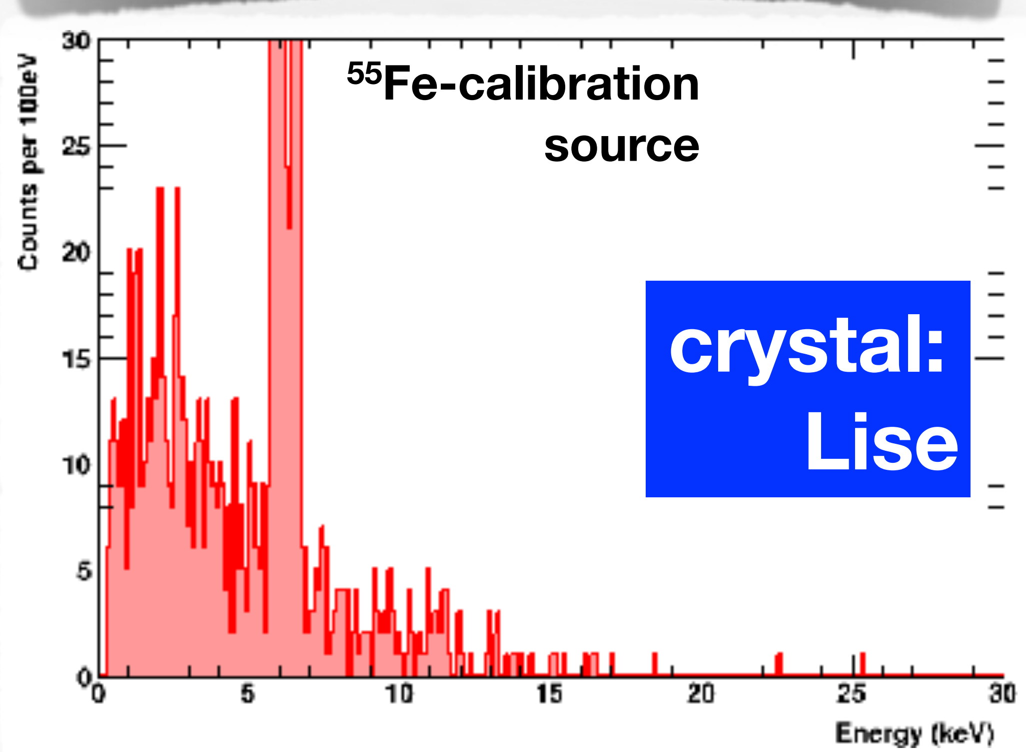
- internal background of 45 isotopes
- include simulation of detector module

- working towards better understanding of background for $CaWO_4$-based low background measurements

Dark Matter searches with CRESST

EPJ C76 (2016) 25



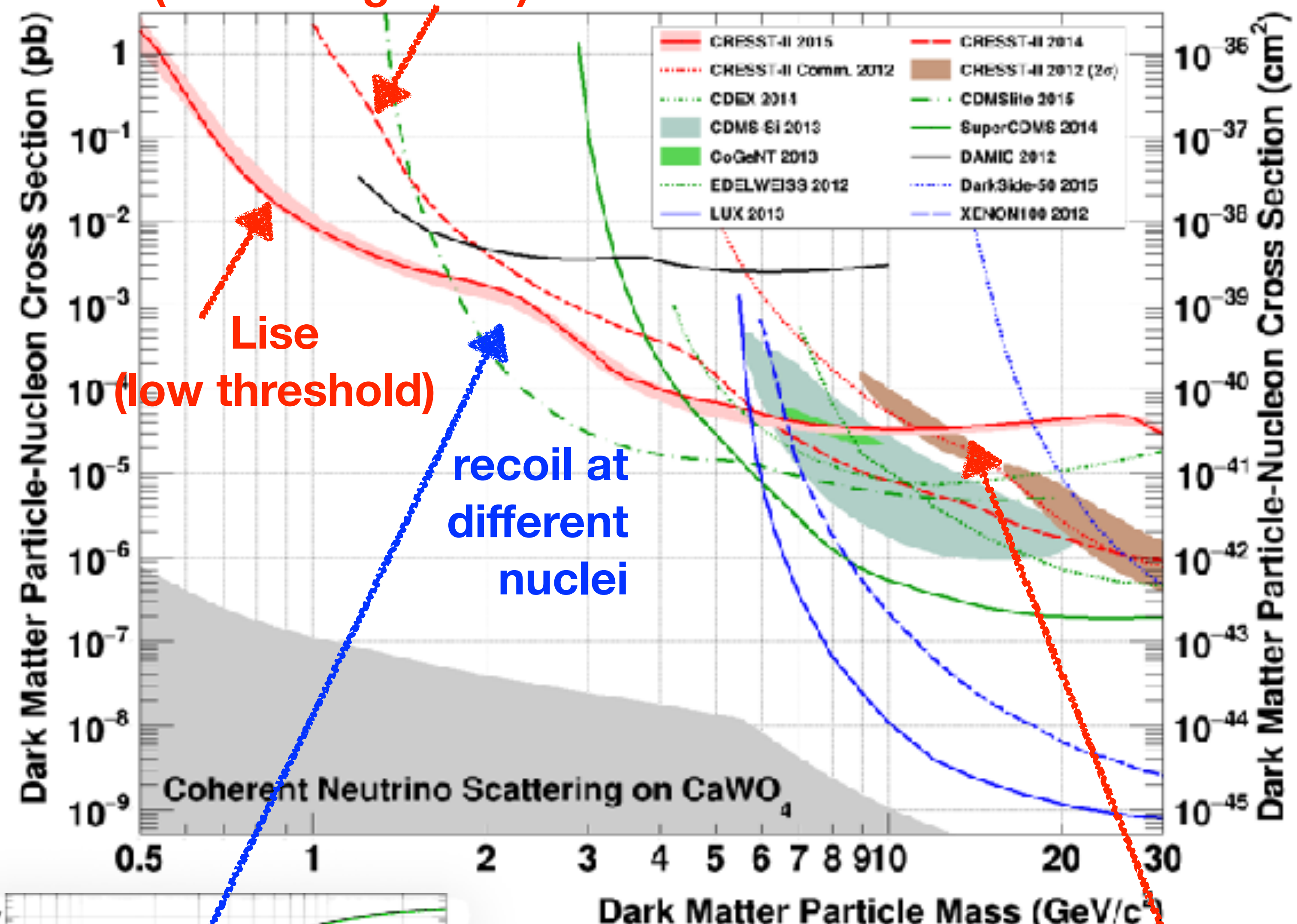


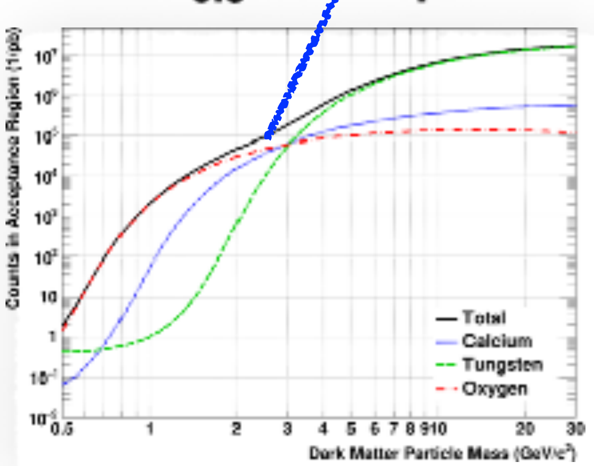
- data collected with a single detector module
  - commercial crystal with higher intrinsic e-/γ-background
  - trigger threshold of 300 eV
- interpretation of data using standard astrophysical assumptions
- limit set with Yellin’s optimum interval method (conservative limit)

CRESST II limit for low mass dark matter

TUM 40
(low background)

EPJ C76 (2016) 25





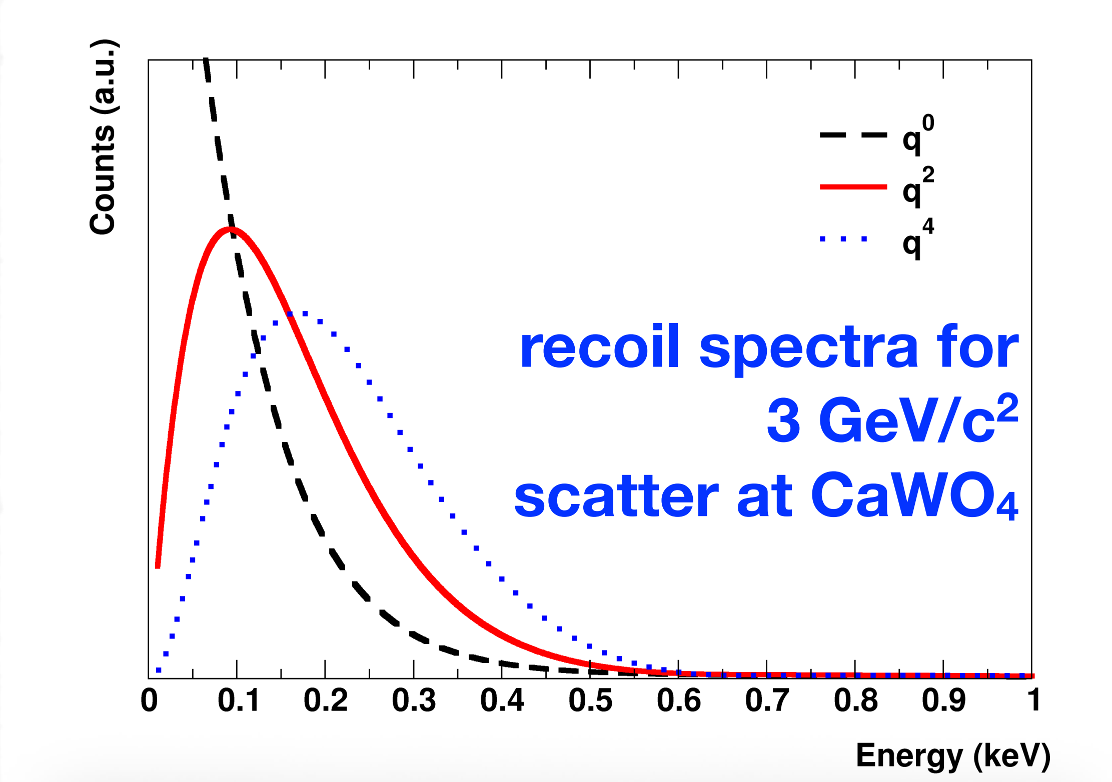
expected number of counts for $\sigma_{\chi\text{-}n}$=1pb in the acceptance region

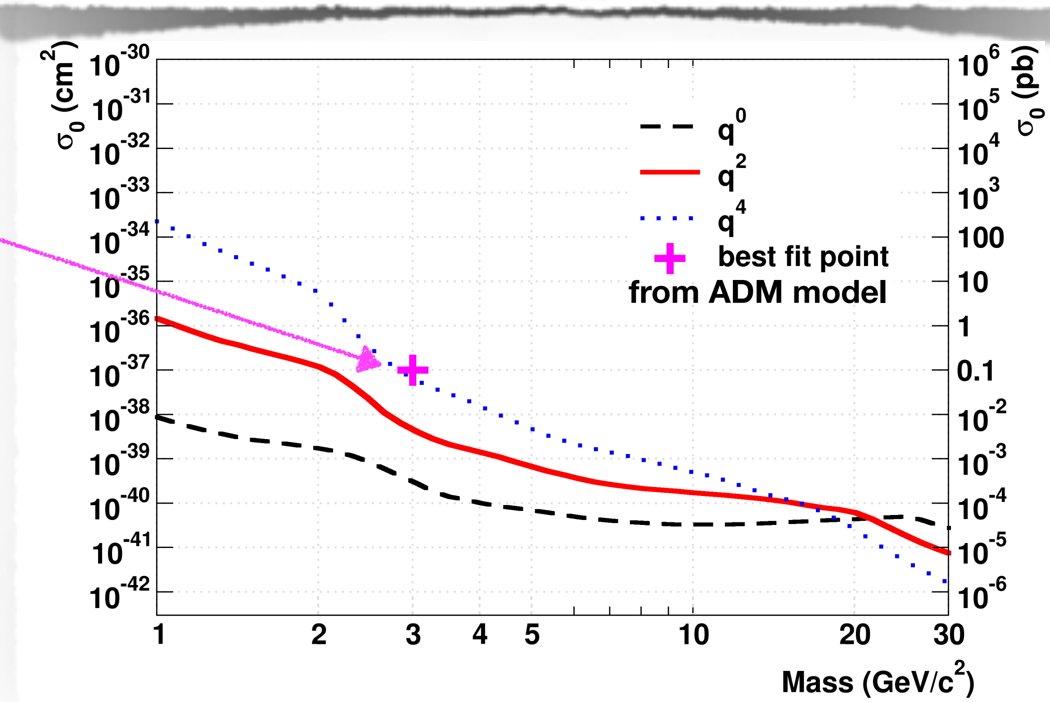
reduced sensitivity due to surface ^{55}Fe

- energy threshold and background conditions have impact to different mass regions
- **best limit in mass region between 0.5 GeV/c^2 and 1.6 GeV/c^2**

Momentum Dependent Cross-Section

- disagreement between helio-seismological data and solar models (Phys. Rev. Lett. 114, (2015) 081302)
- momentum dependent asymmetric dark matter (ADM) can resolve problem
    - preferred dark matter mass of 3 GeV/c^2 and $\sigma_{\chi\text{-}n}=10^{-37}$ cm^2
- reinterpretation of CRESST data assuming momentum dependent cross-section (Angloher et al., PRL 117 (2016) 021303) rules out the proposed best fit point





Search for Dark Photons

Dark Photons as Dark Matter Candidates

- Dark Matter candidate through U'(1) Standard Model allowed extension → **Dark Photon**

- coupling to the Standard Model U(1) symmetry
via kinetic mixing term κ
  - $\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} V_{\mu\nu}^2 - \kappa/2\, F_{\mu\nu} V^{\mu\nu} + m_V^2/2\, V_\mu V^\mu$

- relic abundance of dark photons from inflationary perturbations can account for Dark Matter relic density
  - $\Omega_V \approx 0.3 \sqrt{(m_V/1\ \mathrm{keV})}\, (H_{inf}/10^{12}\ \mathrm{GeV})^2$

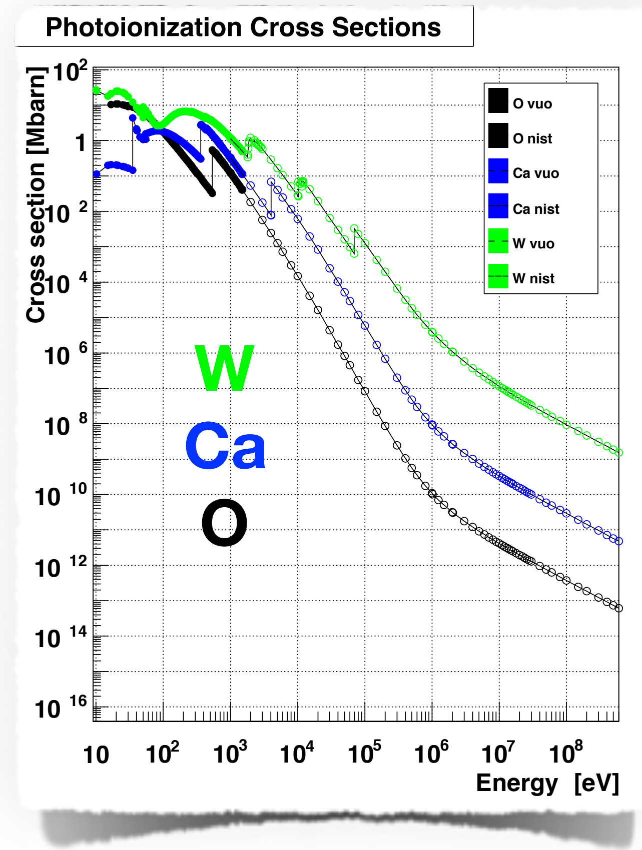
arXiv:1504.02102

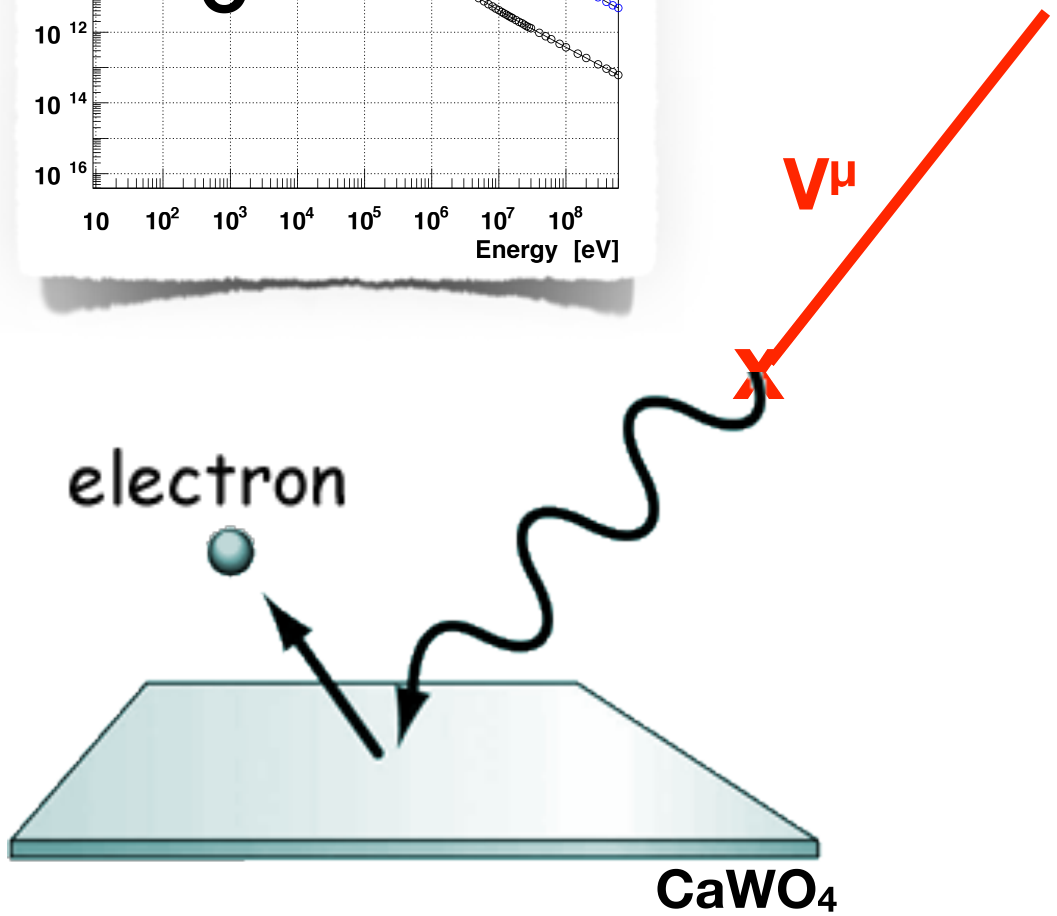
H_{inf}: Hubble scale at inflation

- possible parameter space for kinematic mixing term κ experimentally not excluded

Detection Principle of Dark Photons

- dark photons couple with eκ to charged particles
  - ‘photoelectric effect’ leads to deposition of total energy in the crystal
    - **total absorption - no elastic scattering!**
  - expected cross-section for Dark Photons: $\sigma_V(E_V=m_V)v_V \simeq \kappa^2 \sigma_\gamma(\omega=m_V)c$
  - expected rate per ≃ $\rho_{DM}/m_V c^2 \cdot \kappa^2 \sigma_\gamma(\omega=m_V)c$

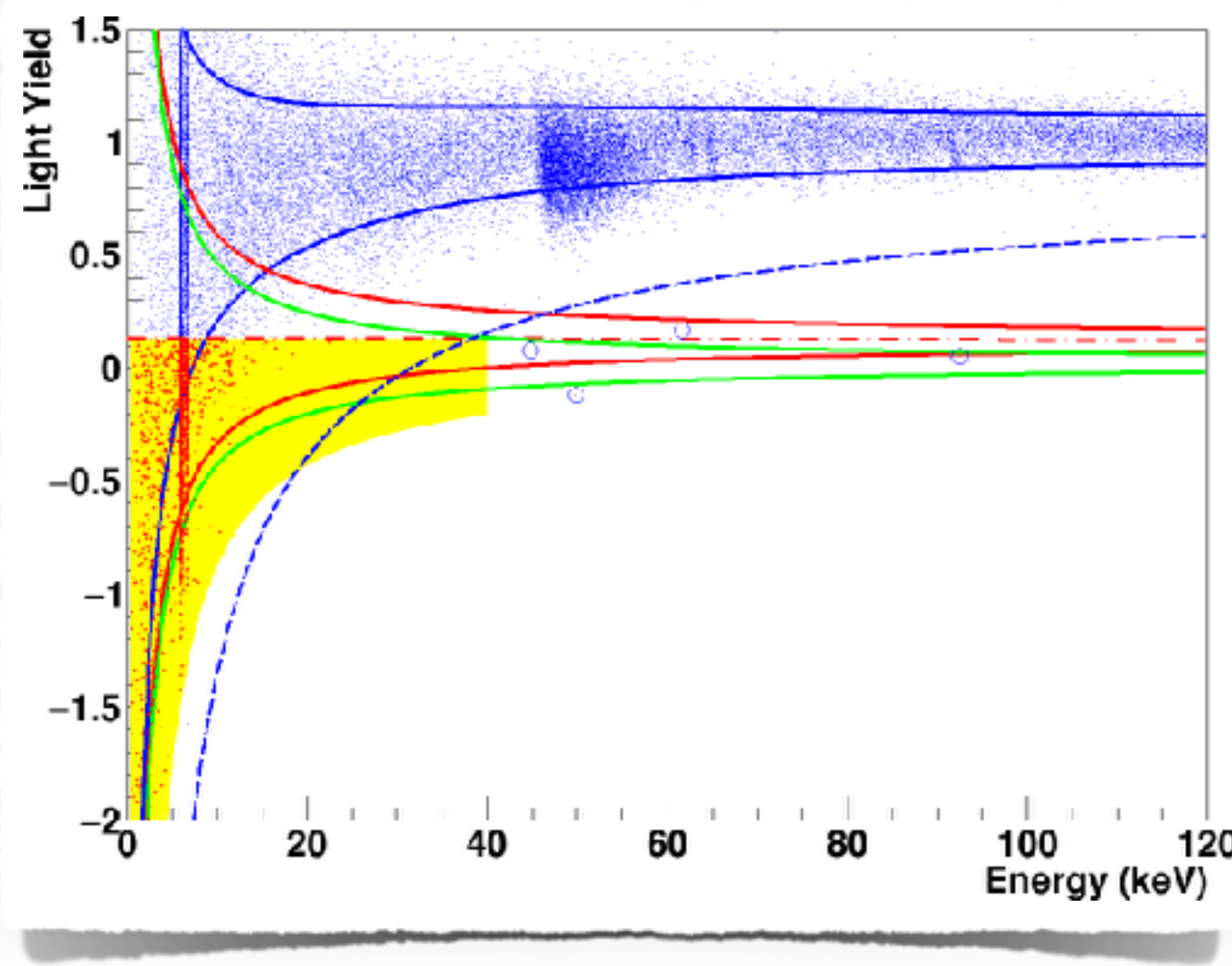




Detection of Dark Photons with CRESST

NEW

- data collected with the Lise detector
  - $E_{thr} \approx 300$ eV
- signal expected in the electron band
- search for mono-energetic peak at dark photon mass

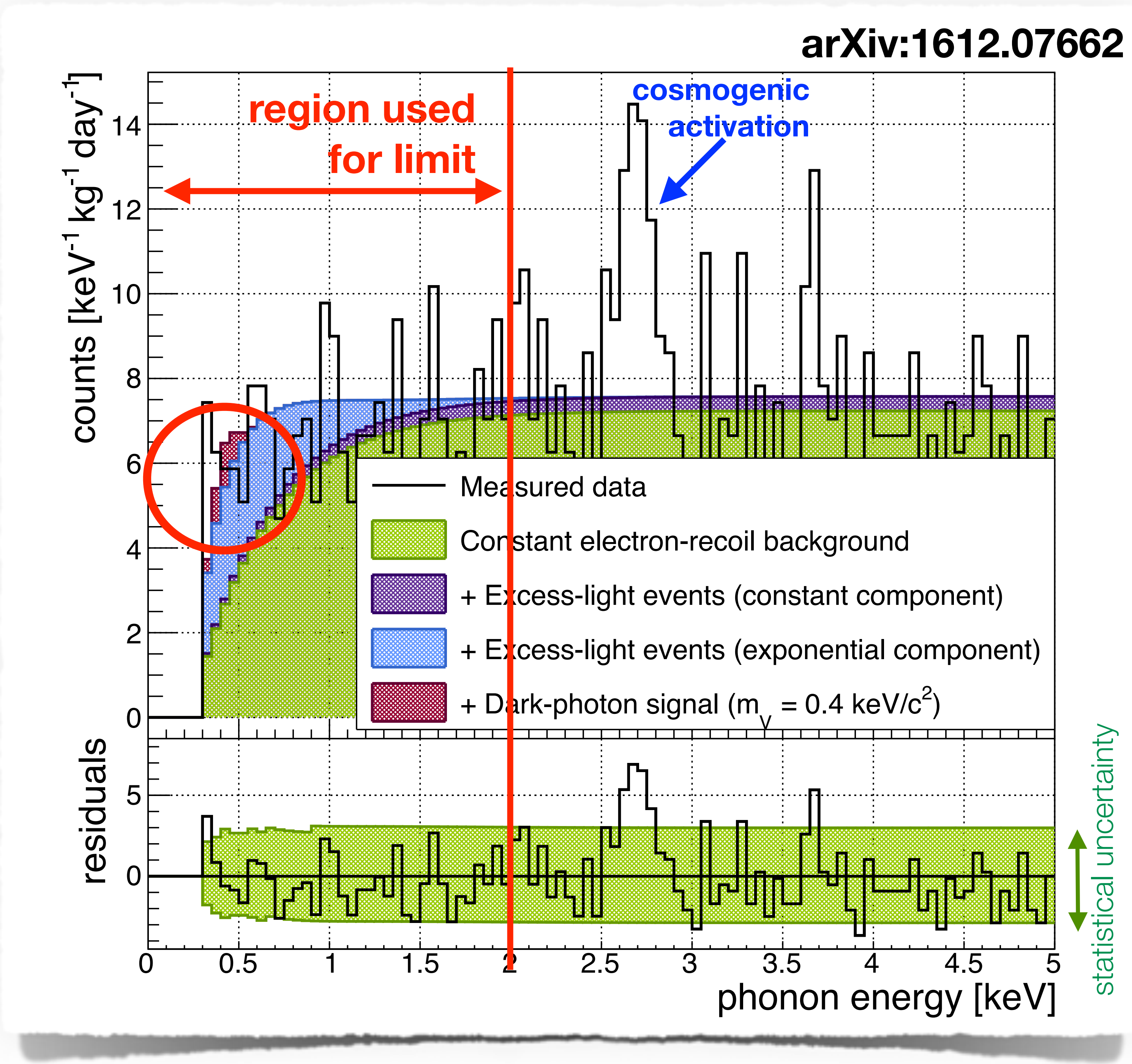


Dark Photons
(photoelectric effect)

Dark Matter
(nuclear recoil)

- focus on dark photons with $m_V < 2$ keV

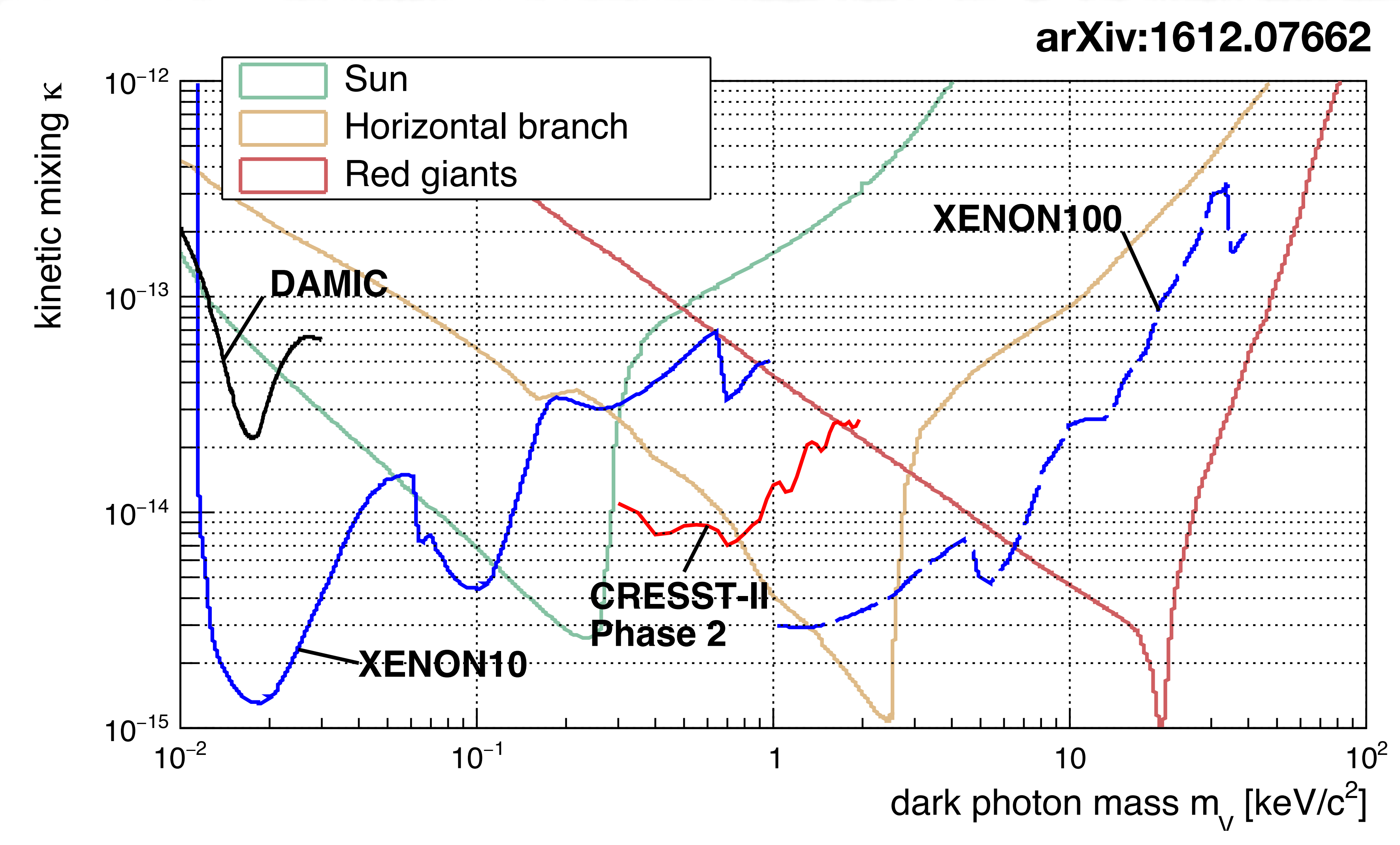
Detection of Dark Photons with CRESST



- empirical background model with several components
  - constant electron recoil background
  - excess-light events (electrons originating from outside detector module → light from scintillating foil)
- Dark Photon signal with assuming detector resolution (~60 eV to ~100 eV)

Detection of Dark Photons with CRESST

- deposited energy corresponds directly to the Dark Photon mass
- performance determined by background and detector resolution

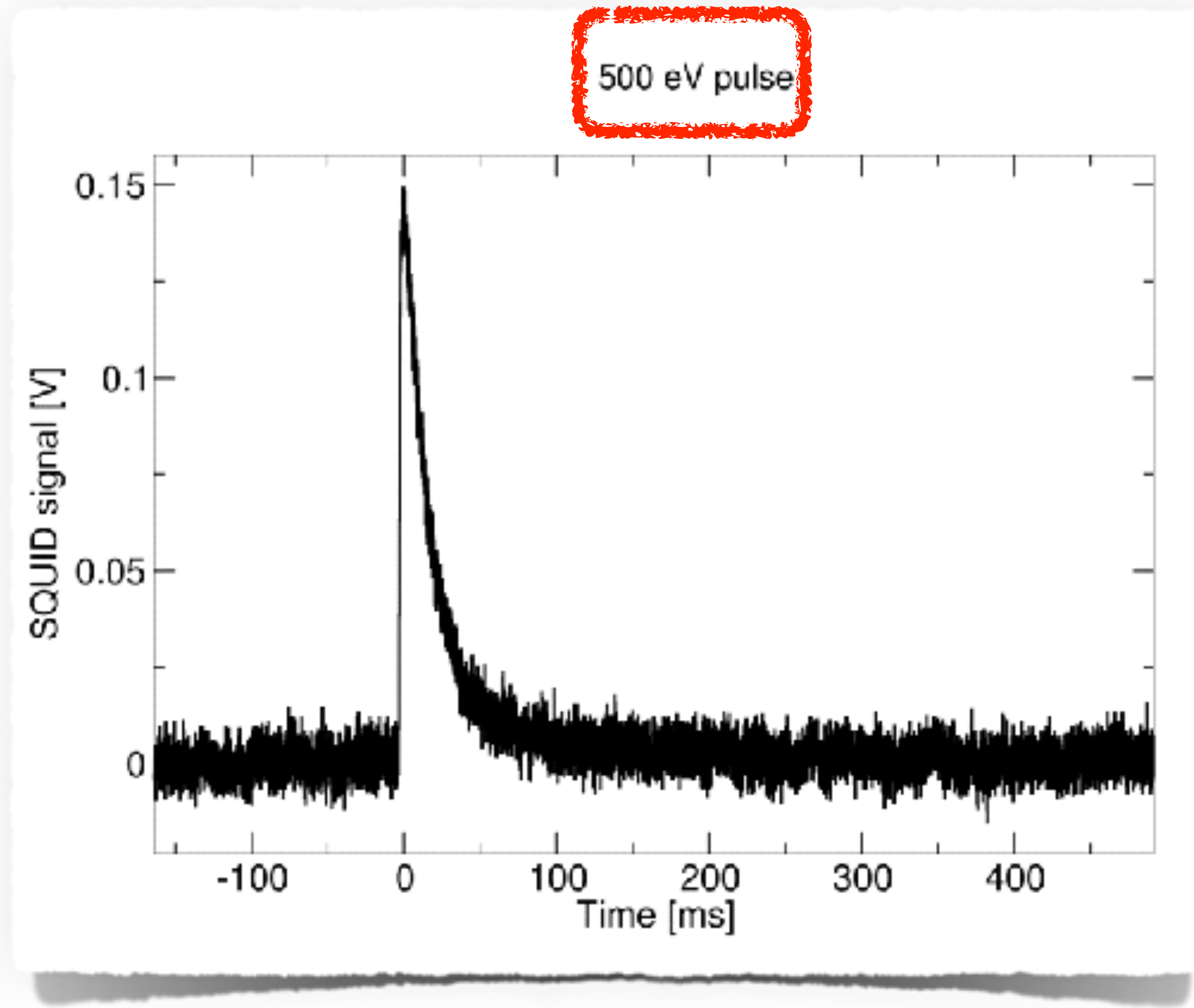


best limit for Dark Photons between 300 and 800 eV

Outlook for CRESST III

CRESST III - current status

- 10 modules installed in cryostat at LNGS
- cryostat reached operation temperature
- goal for detection threshold of 100 eV achieved
- performance studies currently ongoing

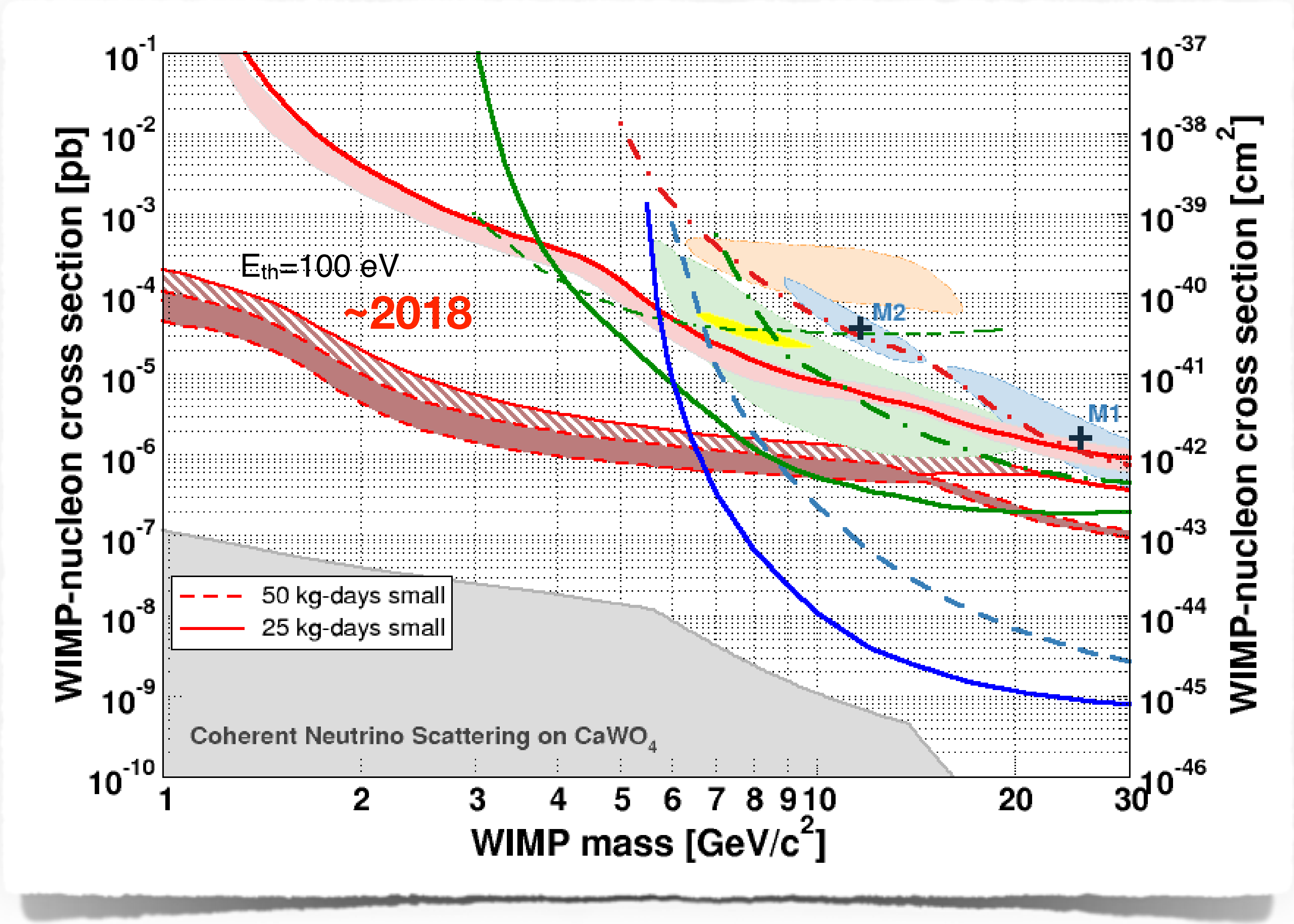


CRESST III - expected sensitivity

- expect to reach $\sigma_{\chi\text{-n}} \sim 10^{-40}$ cm^2 for 1 GeV/c^2 dark matter particles
- detector R&D program for improved radio purity ongoing
- to increase exposure upgrade of read out system planned

arXiv 1503.08065

CRESST III projections



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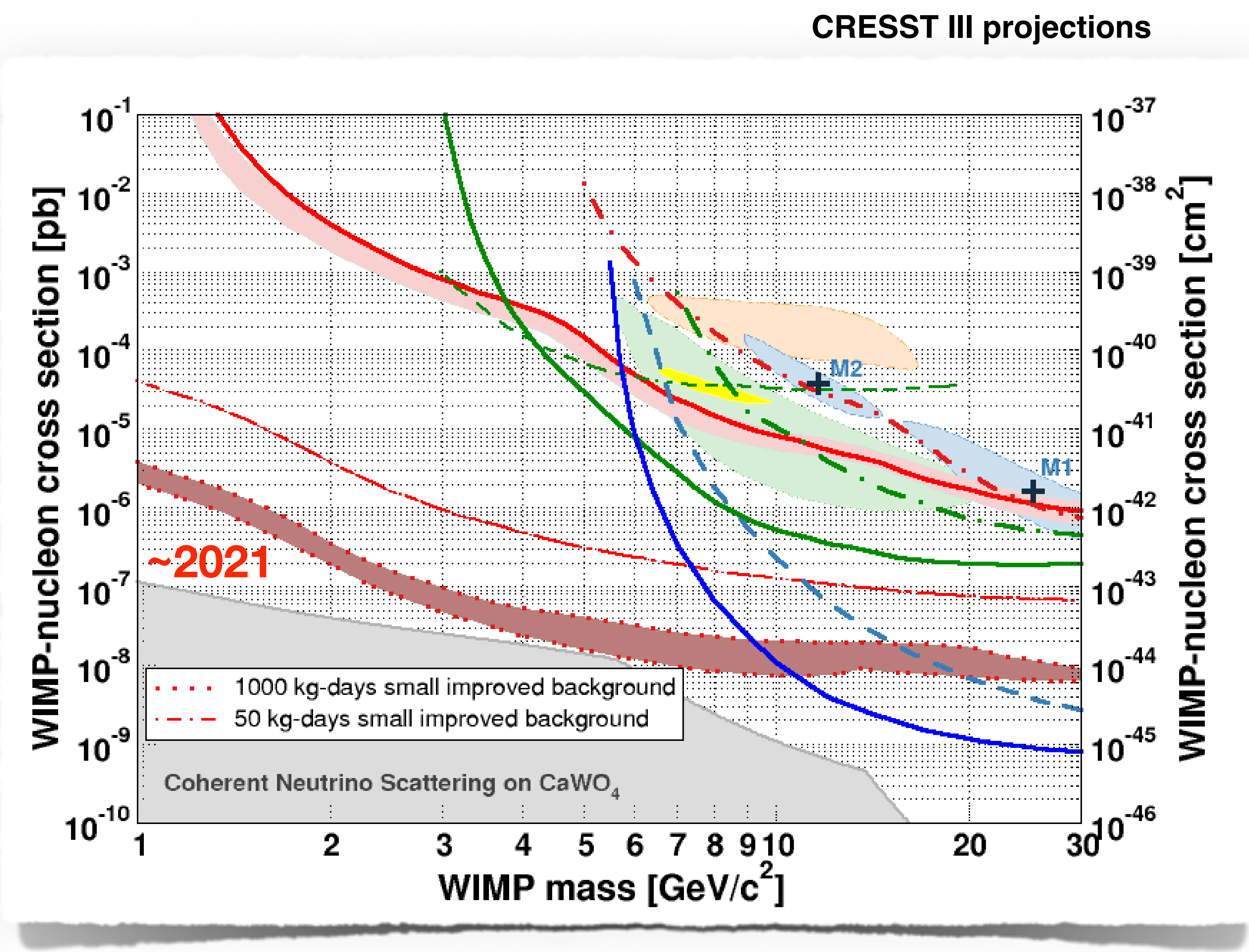


Towards even lighter Dark Matter mass scales

Physics of the Dark Sector

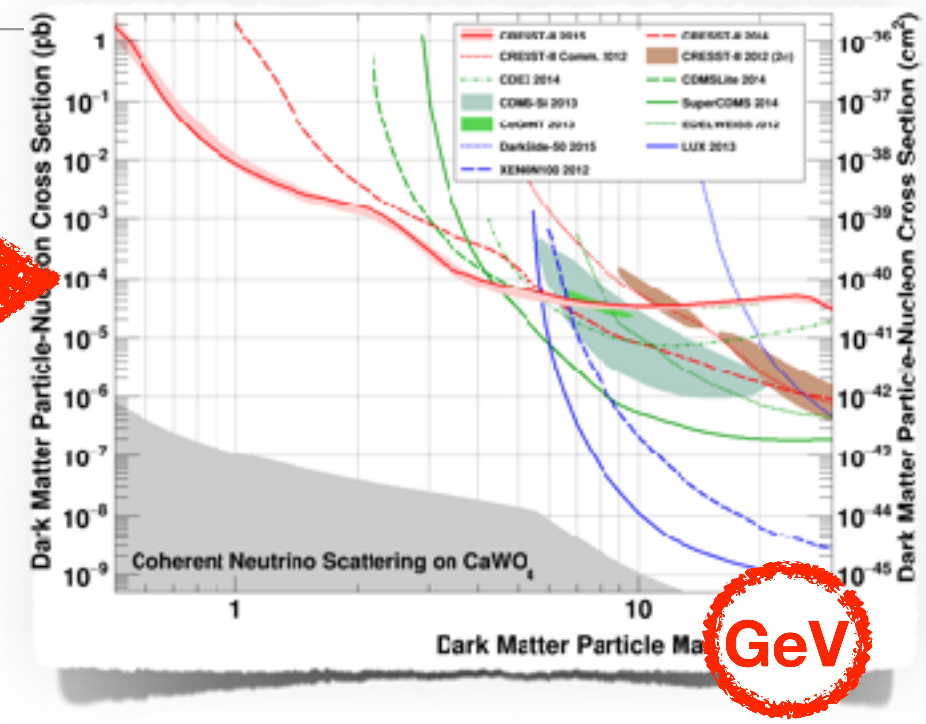
- new forces / new mediators relax the theoretical lower bound on dark matter masses
  → **sub-GeV dark matter**

- dark matter searches based on dark matter nucleon **elastic scattering**

- energy deposition from recoil:
  $E_{NR} \simeq 2\mu_{X,N}^2 \cdot v_X^2/m_N$
  → for 100 MeV m_X ~ 1 eV E_{NR}*

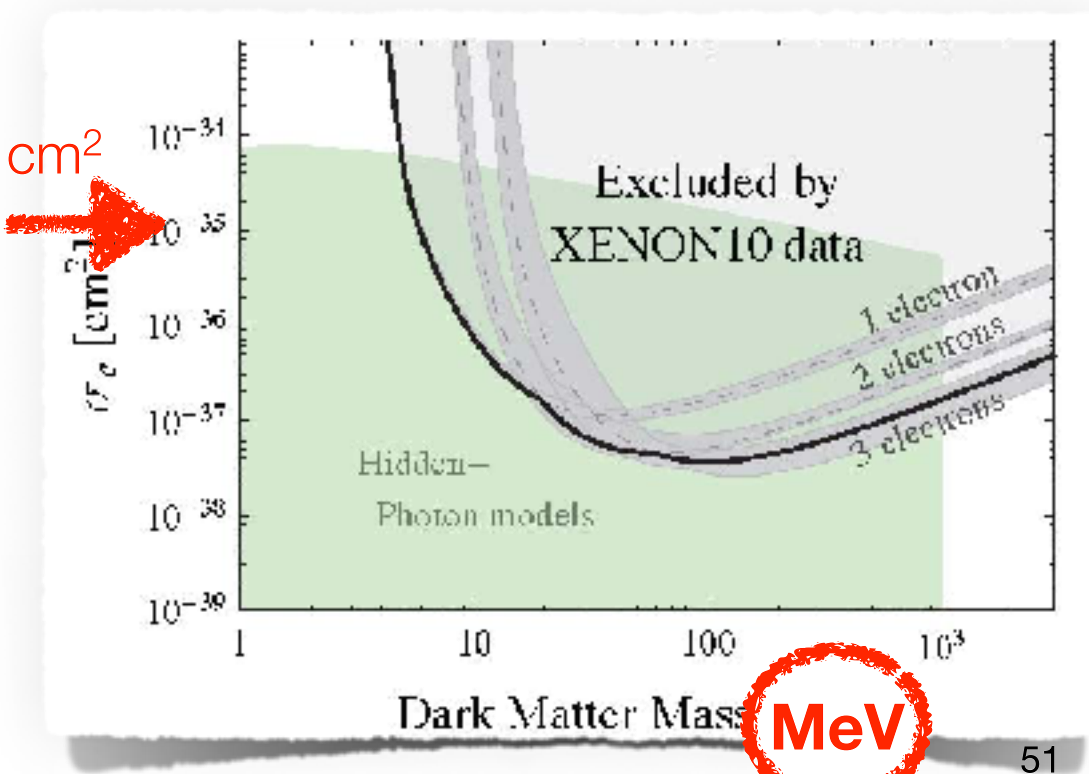
arXiv:1509.01515

10^{-40} cm^2



arXiv:1206.2644

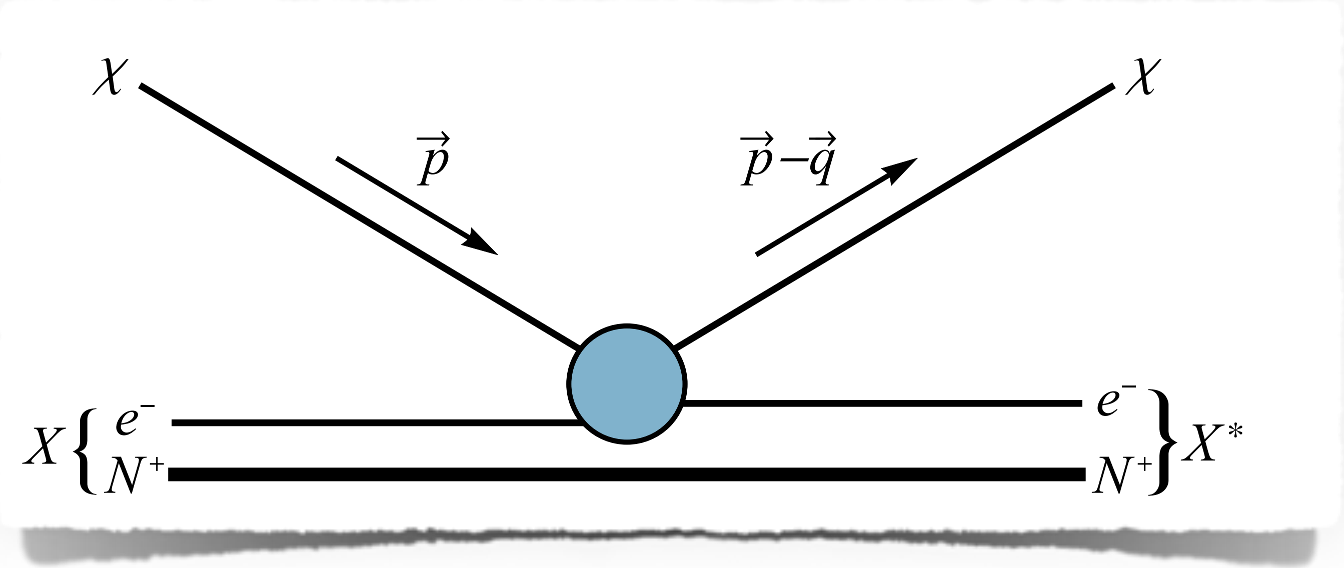
10^{-35} cm^2



* for silicon

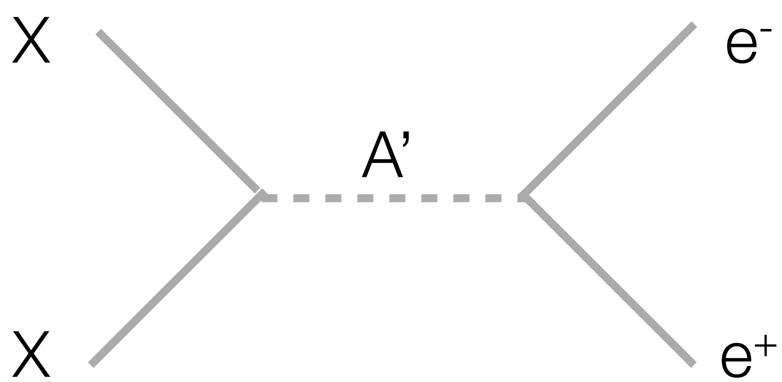
Detection techniques for light Dark Matter

- dark matter detection using ionisation signal from **Dark Matter-electron** scattering



- inelastic nature of scattering and increased energy transfer possible due to lightness of electron
- detection of small ionisation signals allow to probe Dark Matter particles down to ~ 1 MeV

Physics of the Dark Sector - concrete example

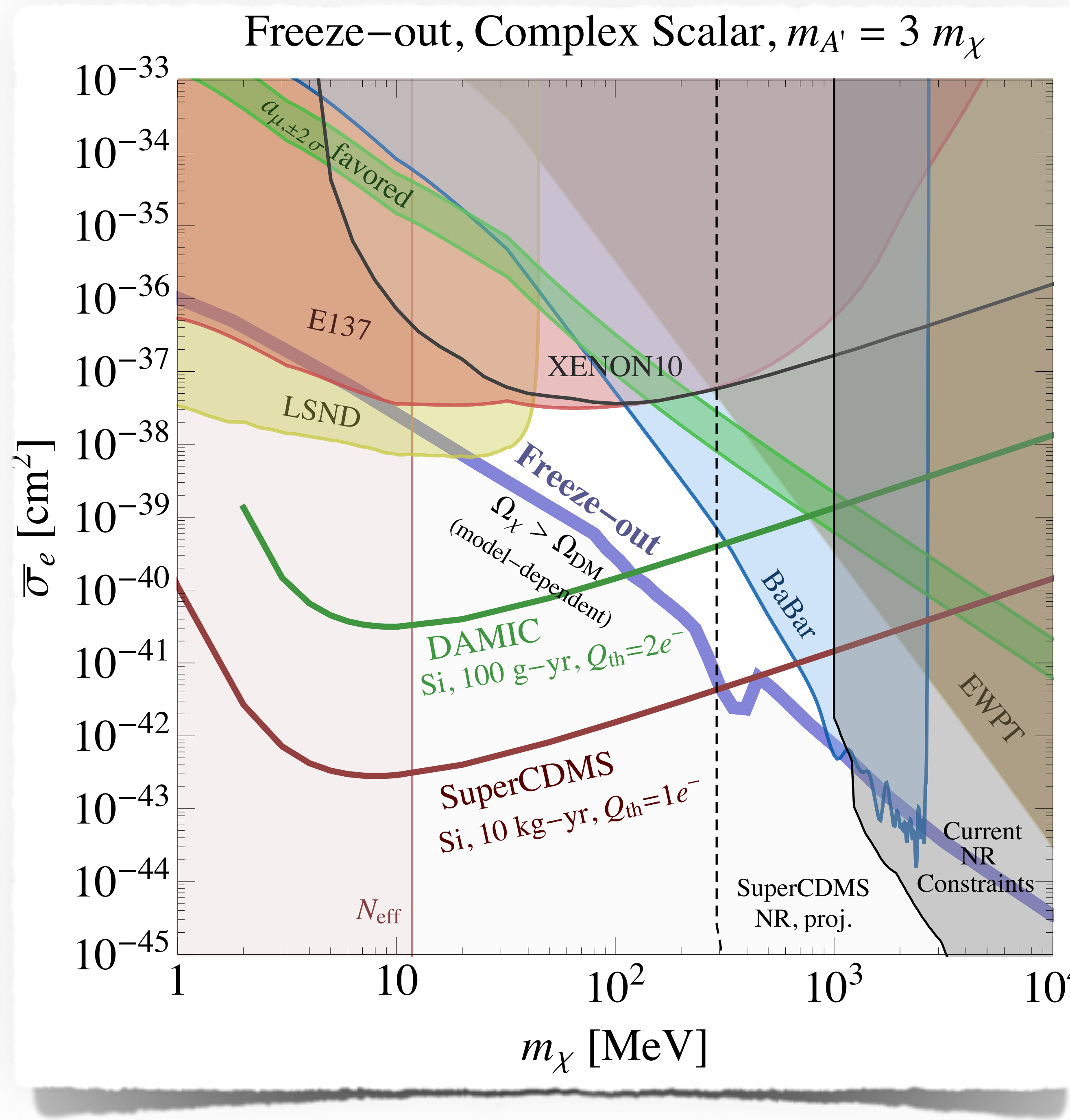


*

$m_{A'} > 3\, m_\chi$

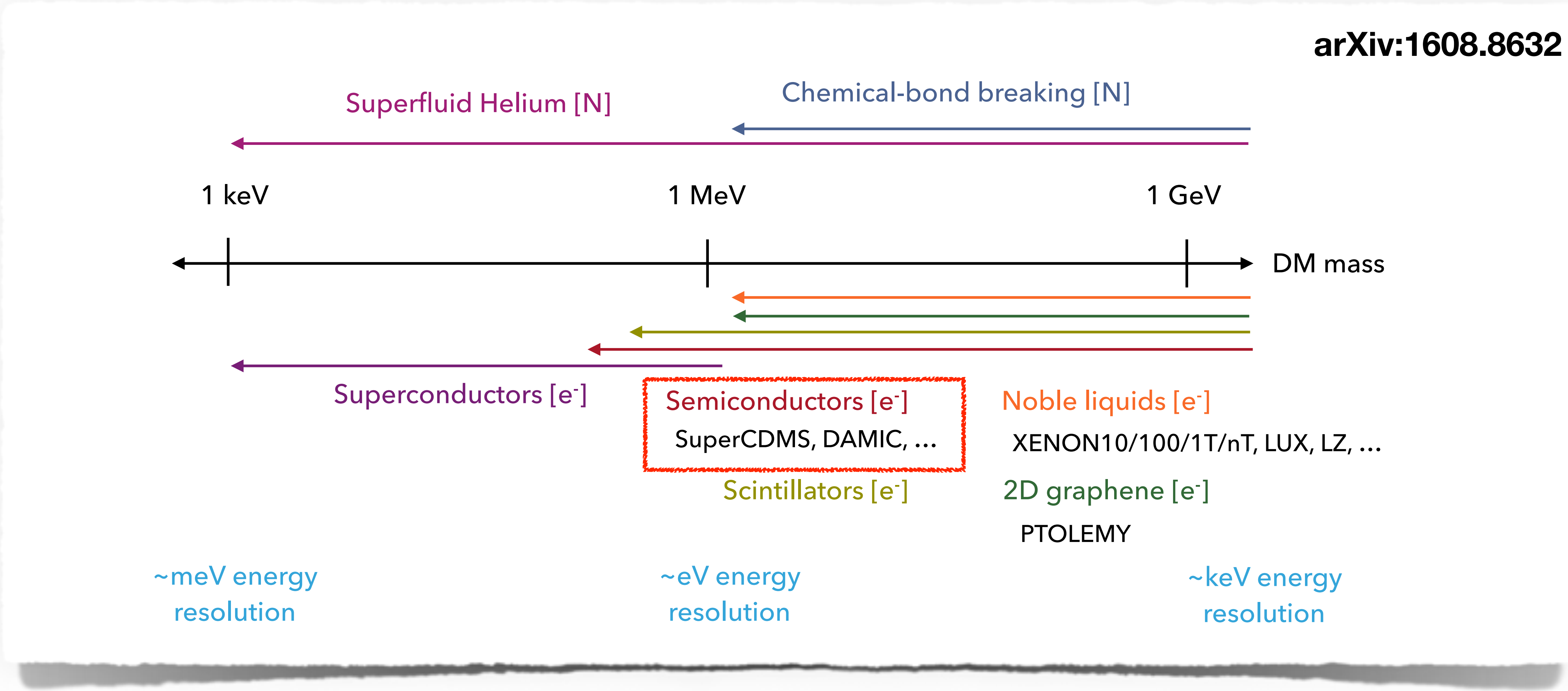
- simple model with freeze-out via vector portal to light complex dark matter
- experimentally unexplored region in the mass region above ~10 MeV

arXiv:1509.01598



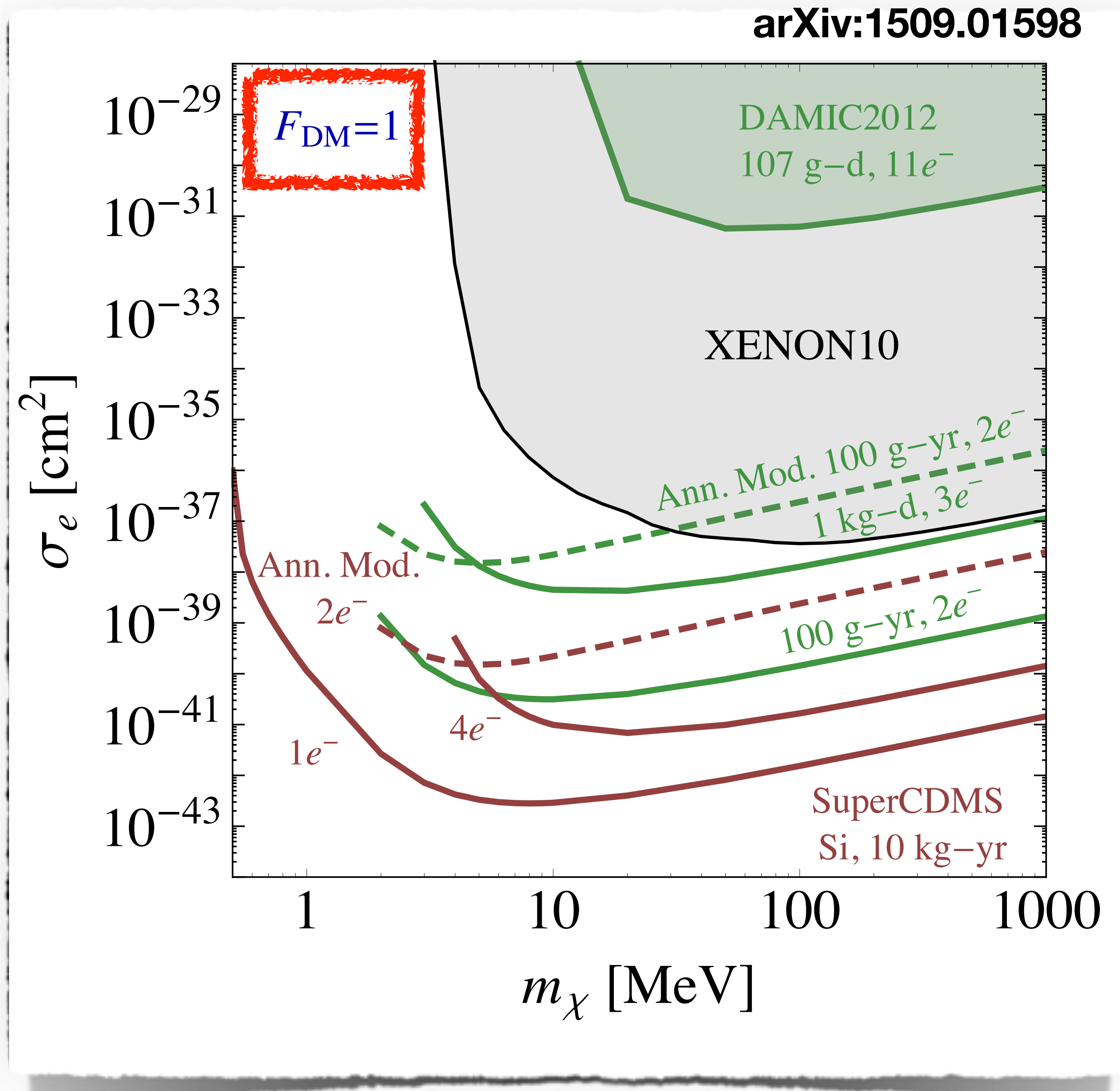
*cannot solve small-scale structure problems: arXiv:1612.00845

Detection techniques for light Dark Matter



- band gap of silicon ~ eV order of magnitude smaller compared to Xe
- expected reach for Dark Matter $m_X \gtrsim 250$ keV · (ΔE_B/1eV)
- sensitivity depends crucially on detector specific backgrounds (e.g. “dark counts”)

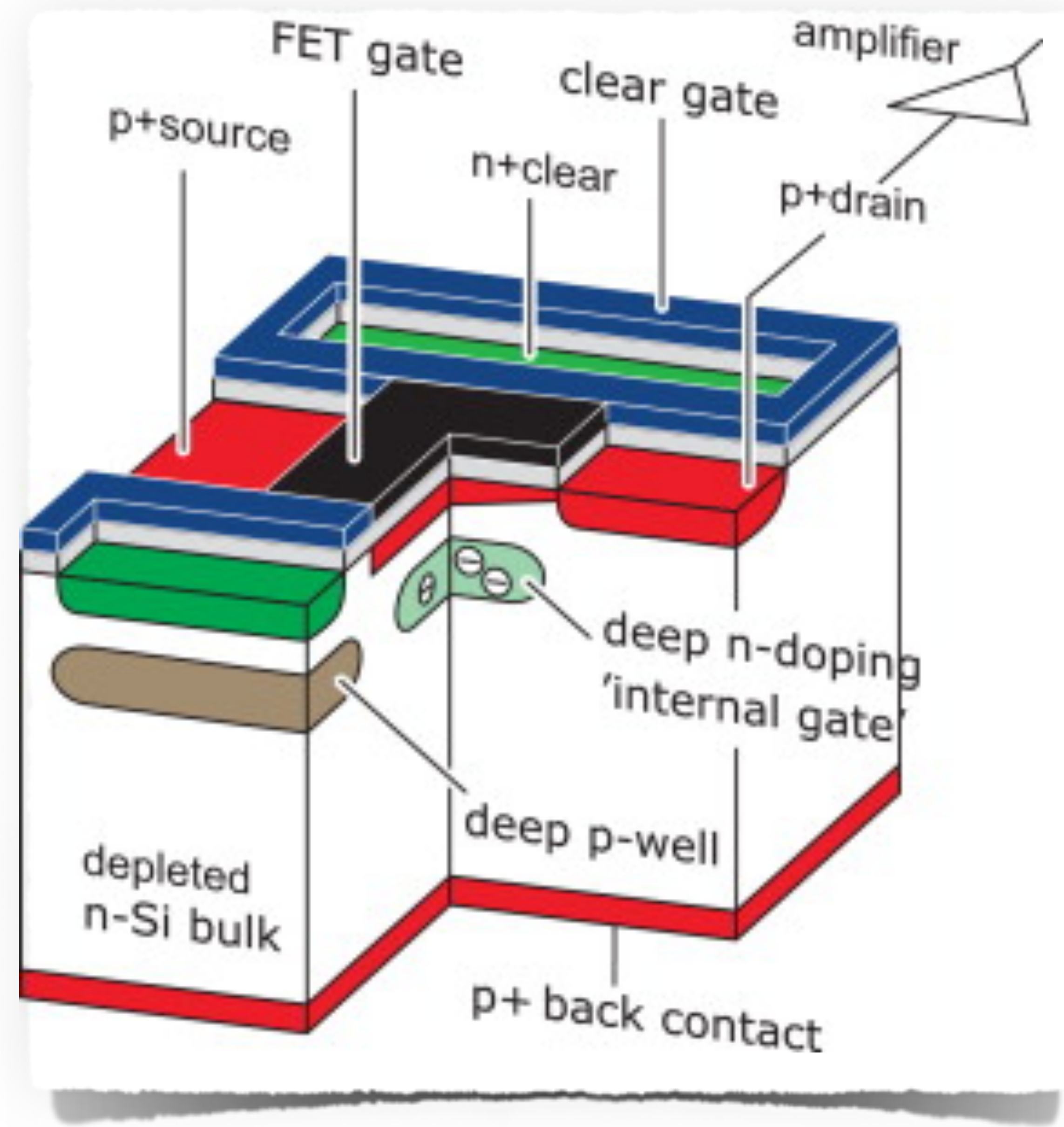
Detection techniques for light Dark Matter



- Dark Matter scatters on bound electrons in dense media
  - relation between energy deposition and momentum transfer differs to nuclear scattering
  - parametrised with a momentum dependent form factor F_{DM}
- **detection of single (two) electrons with low noise**

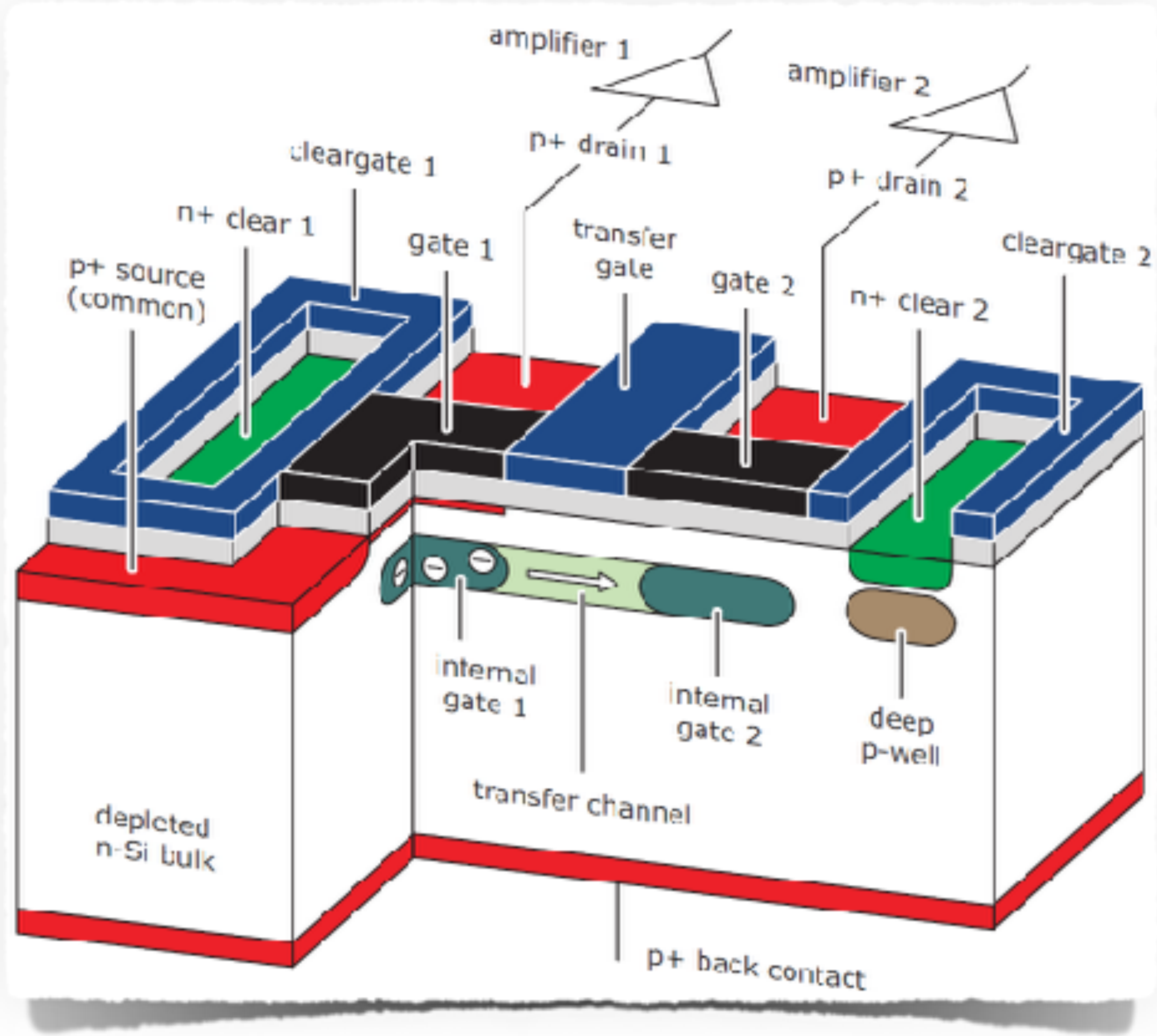
DEPFET detector as sub-GeV Dark Matter detector

- DEPFET: depleted field effect detector
  - charge collection in an internal gate
  - collected charge modulates current in FET
- known and applied detector concept, e.g. for Belle II
  - focus previously on energy measurement and spatial resolution
- **noise performance limited by 1/f noise**



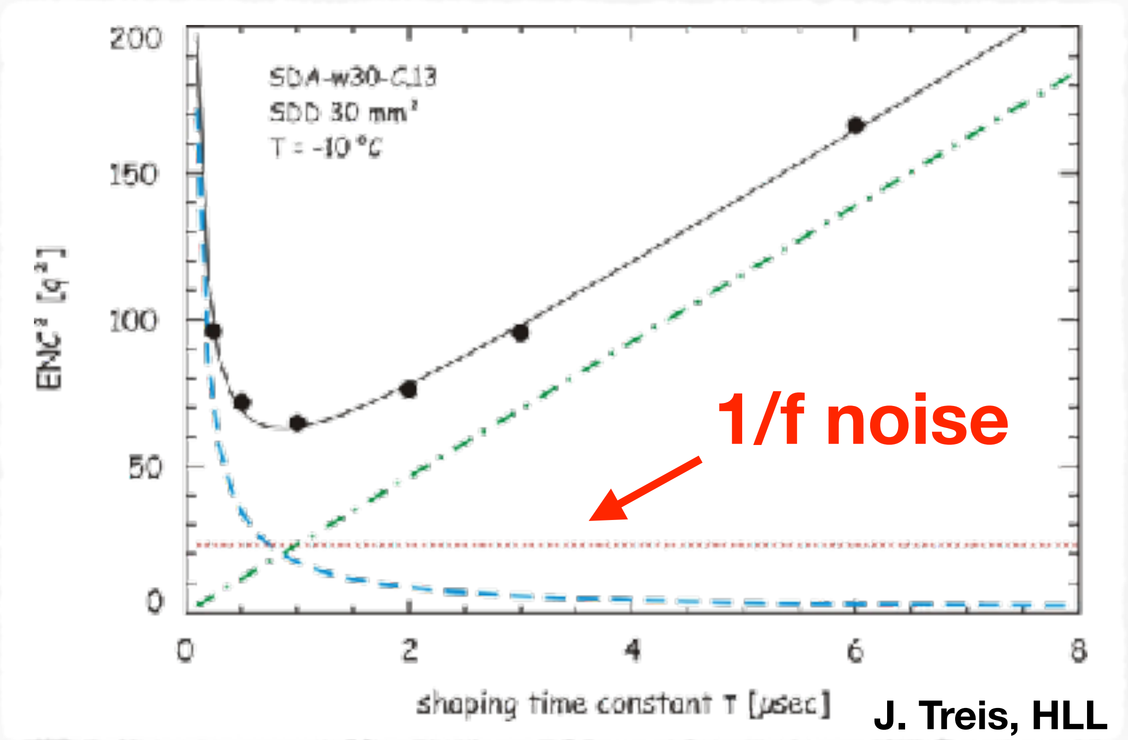
DEPFET detector as sub-GeV Dark Matter detector

- 1/f noise limit can be further reduced by using repetitive non-destructive readout (RNDR)
- charge transfer between sub-pixels in a “super-pixel” allow statistically independent measurements
- **effective noise can be reduced to $\sigma_{eff} \approx \sigma/\sqrt{N}$**

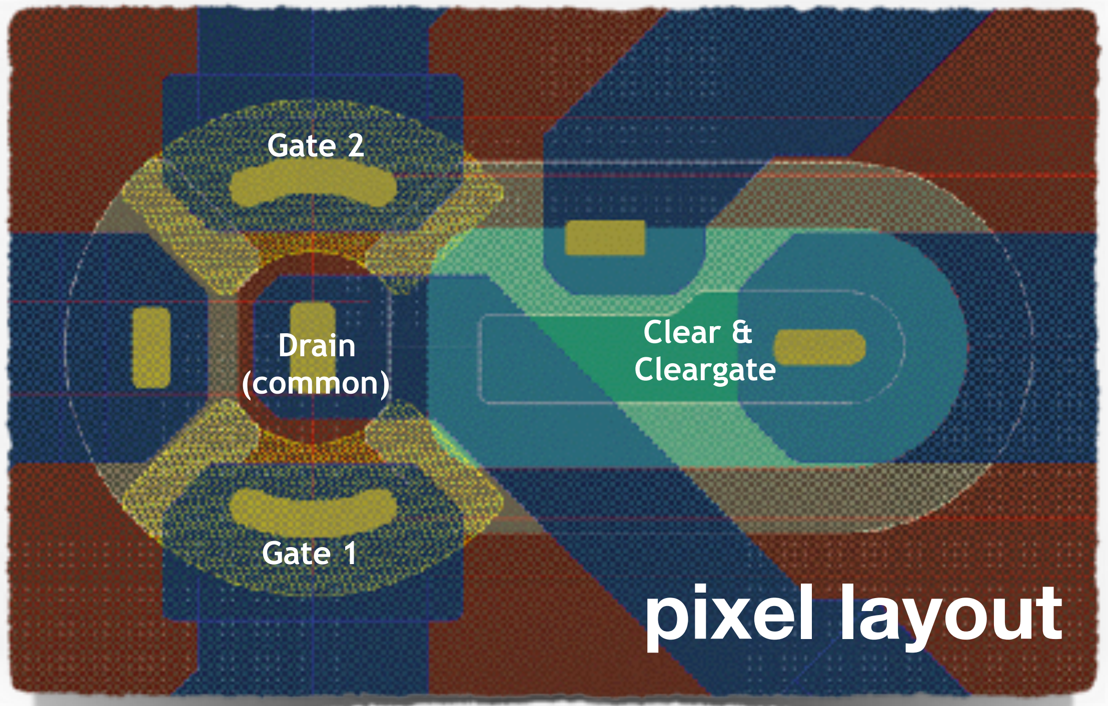


DEPFET-RNDR Prototypes

- proof-of-principle for DEPFET-RNDR demonstrated (Wölfel et al., NIMA 566 (2006) 536)
- DEPFET-RNDR prototype sensors are available
- 450 µm thickness, in principle up to 850 (1000?) µm possible
- “target mass” about 13 g / module

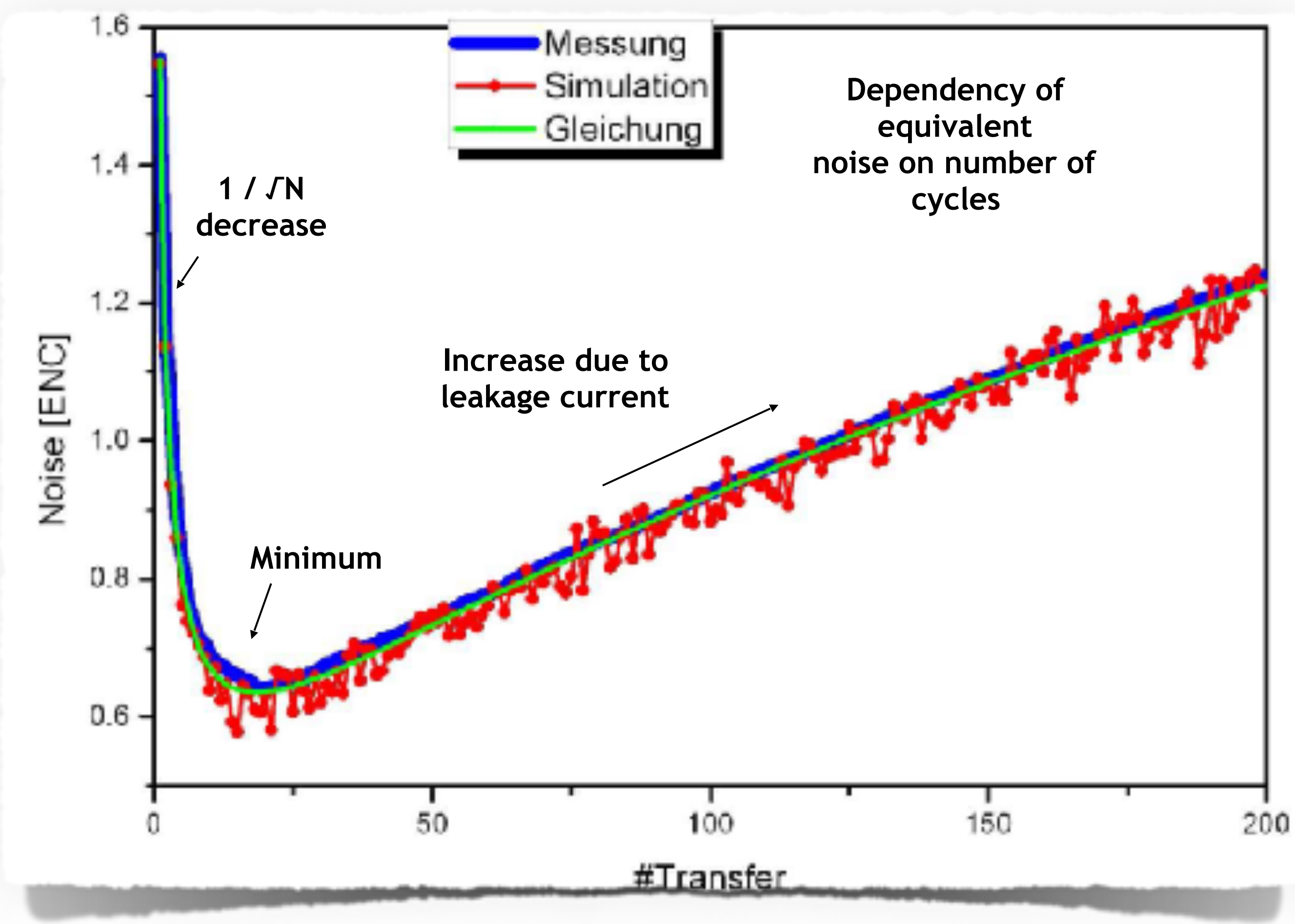


J. Treis, HLL



Measured Performance for DEPFET-RNDR

J. Treis, HLL



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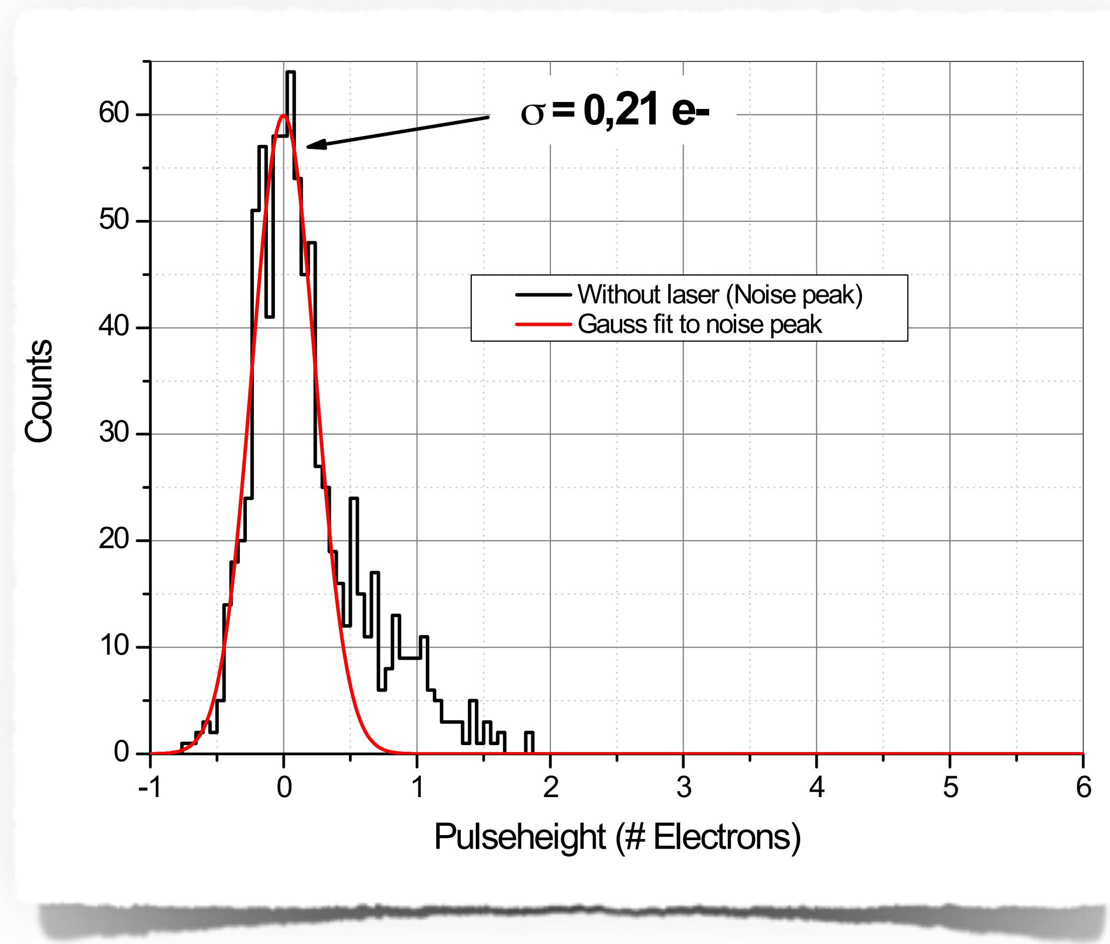
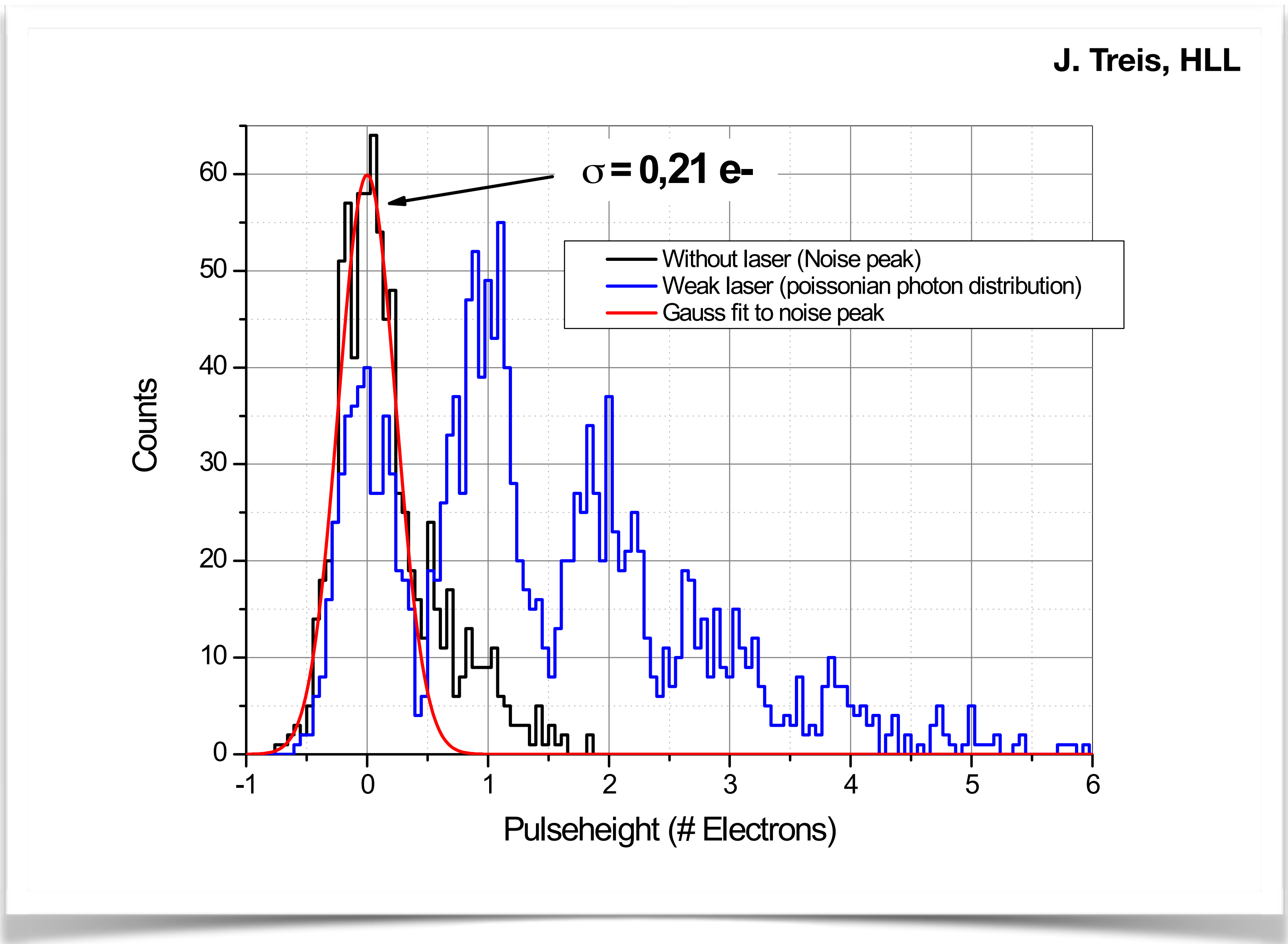


- noise performance as a function of readout cycles measured and reproduced by simulation

- **noise performance of σ=0,21 e^- achieved**

Measured Performance of DEPFET-RNDR



- measurement of single electrons with 5σ separation possible
- discrimination of number of electrons possible
- gated operation (switch off charge collection during readout) under investigation
  - reduction of noise increase with #transfers due to leakage currents

➜ extensive R&D project for Dark Matter searches with DEPFET started

Summary

- the Standard Model of particle physics is an effective theory
    - some astro physical observations cannot be explained → **Dark Matter**
- new particle(s) could explain Dark Matter
    - several new theoretical models (strongly interacting Dark Matter, asymmetric Dark Matter, Dark Photons,…) predict new particles **in the sub-GeV region**
- key experimental technique: **energy detection threshold**
- **CRESST** aims for best Dark Matter limit in the ~300 MeV - 3 GeV region
- **DEPFET-RNDR** aims for the best Dark Matter limit in the ~1 - 100 MeV region