



# Dark Matter Searches

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# Structure

## I. Introduction

- Dark Matter
- WIMPs

## II. Detection

- Philosophy & Methods
- Direct Detection

## III. Detectors

- Scintillators
- Bolometer
- Liquid Noble Gas Detectors

## IV. Ton scale experiments

## V. Summary



# Structure

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# I. Introduction

## Dark Matter



- 1933 Fritz Zwicky:  
„Missing Mass Problem“
  - mass-to-light ratio of Coma Cluster is not in equilibrium



# I. Introduction

## Dark Matter



- 1933 Fritz Zwicky:  
„Missing Mass Problem“
  - mass-to-light ratio of Coma Cluster is not in equilibrium
- for 40 years not much happened with this information...

...since the 1970's science became interested in DM



# I. Introduction

## Dark Matter

- Evidence for the existence of Dark Matter



# I. Introduction

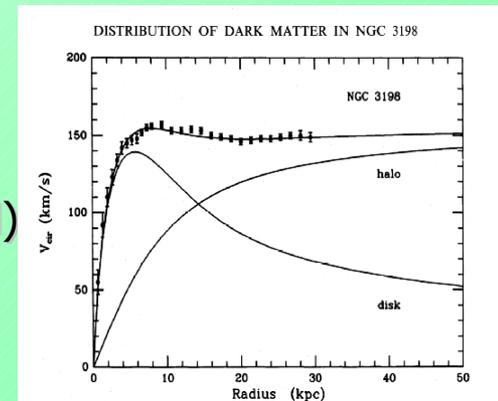
## Dark Matter

- Evidence for the existence of Dark Matter
  - Galaxy Scale
  - Galaxy Cluster Scale



# I. Introduction Dark Matter

- Evidence for the existence of Dark Matter
  - Galaxy Scale
    - rotational  $v = \text{const.}$  (not  $\sim 1/r$  as expected)
  - Galaxy Cluster Scale





# I. Introduction Dark Matter

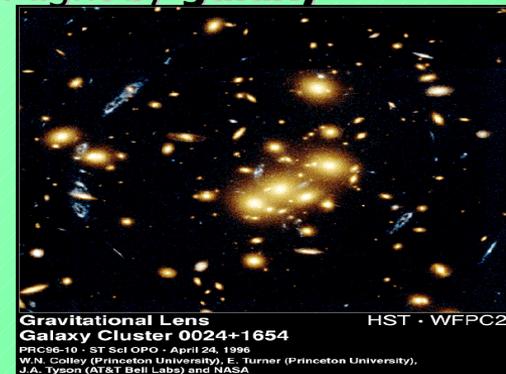
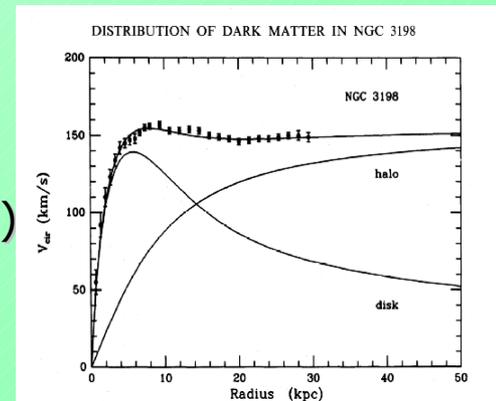
- Evidence for the existence of Dark Matter

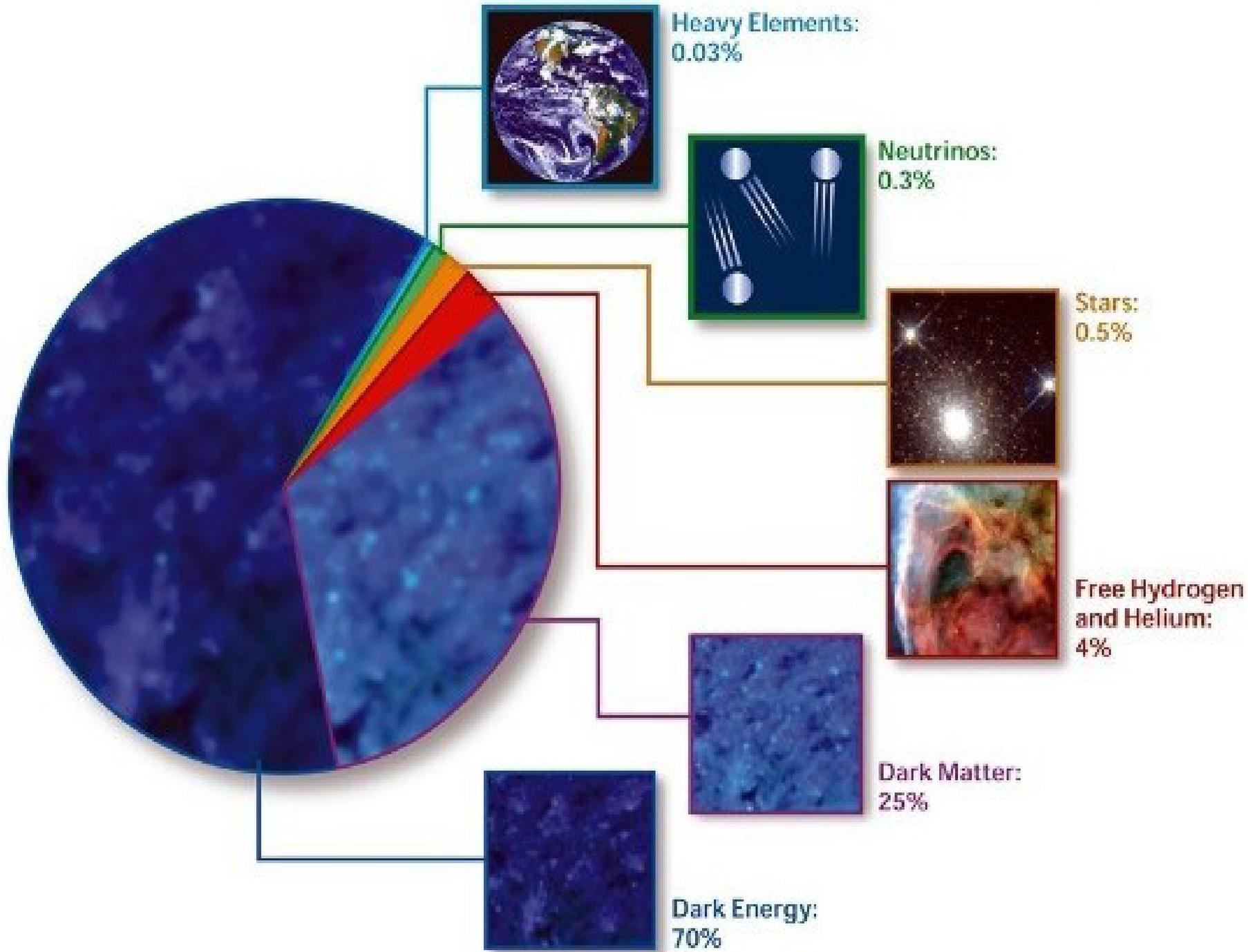
- Galaxy Scale

- rotational  $v = \text{const.}$  (not  $\sim 1/r$  as expected)

- Galaxy Cluster Scale

- Gravitational Lensing (Analysis of bending of light by **galaxy clusters** reveals **more mass** than visible)







# I. Introduction

## Dark Matter

- Today we need Dark Matter to explain
  - gravitational motion of Galaxies
  - the structure of the universe and
  - the fate of the universe



# I. Introduction

## Dark Matter

- Today we need Dark Matter to explain
  - gravitational motion of Galaxies
  - the structure of the universe and
  - the fate of the universe

*Dr Bruce H. Morgan: „Mother Nature is having a double laugh. She has hidden most of the matter in the universe, and hidden it in a form that can't be seen.“*



# I. Introduction

## Dark Matter

- Two main categories are considered as possible candidates for Cold Dark Matter

MACHOs

WIMPs



# I. Introduction

## Dark Matter

- Two main categories are considered as possible candidates for Cold Dark Matter

MACHOs



WIMPs





# I. Introduction

## Dark Matter



- **MACHOs**

- Massive Astroph Compact Halo Objects

- **WIMPs**

- Weakly Interacting Massive Particles

Detection



# I. Introduction Dark Matter



- **MACHOs**

- Massive Astroph Compact Halo Objects
- Baryonic
- big objects: small stars to supermassive Blackholes

- **WIMPs**

- Weakly Interacting Massive Particles
- non-Baryonic
- subatomic particles

Detection



# I. Introduction Dark Matter



- **MACHOs**

- Massive Astroph Compact Halo Objects
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- big objects: small stars to supermassive Blackholes
- Astronomy
- Galaxy Scale

- **WIMPs**

- Weakly Interacting Massive Particles
- non-Baryonic
- subatomic particles
- Particle Physics
- Universe

Detection



# I. Introduction Dark Matter



- **MACHOs**

- Massive Astroph Compact Halo Objects
- Baryonic
- big objects: small stars to supermassive Blackholes
- Astronomy
- Galaxy Scale
- Hubble Space Teleskop & Gravitational Lensis
  - => MACHOs exist, but cannot explain most of the Dark Matter

## Detection

- **WIMPs**

- Weakly Interacting Massive Particles
- non-Baryonic
- subatomic particles
- Particle Physics
- Universe
- following slides...



# I. Introduction

## WIMPs

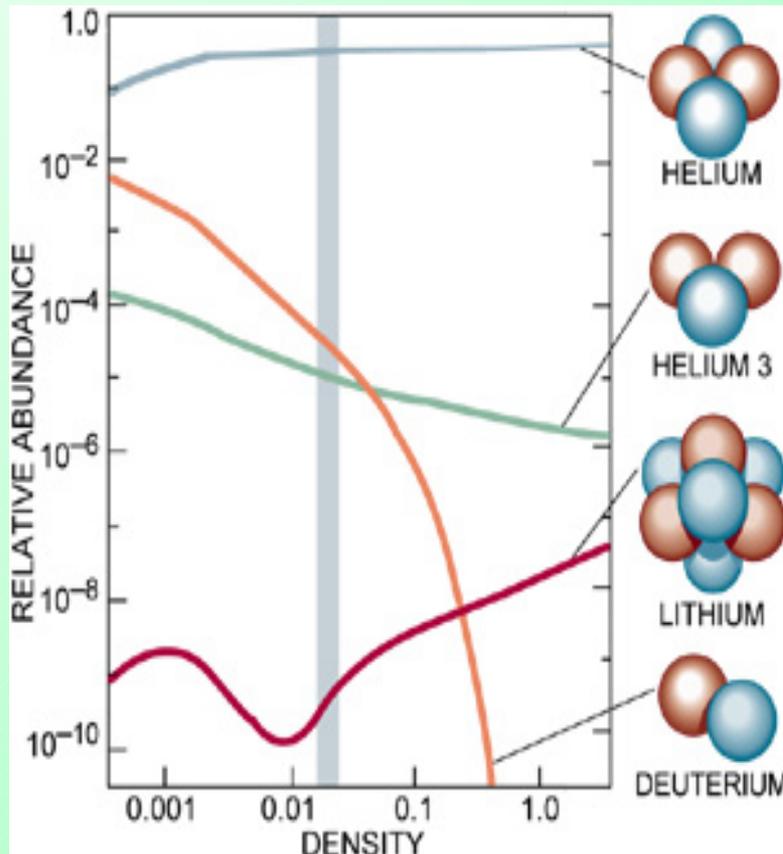
- Majority of Dark Matter is not baryonic:



# I. Introduction

## WIMPs

- Majority of Dark Matter is not baryonic:
  - Big Bang Nucleosynthesis

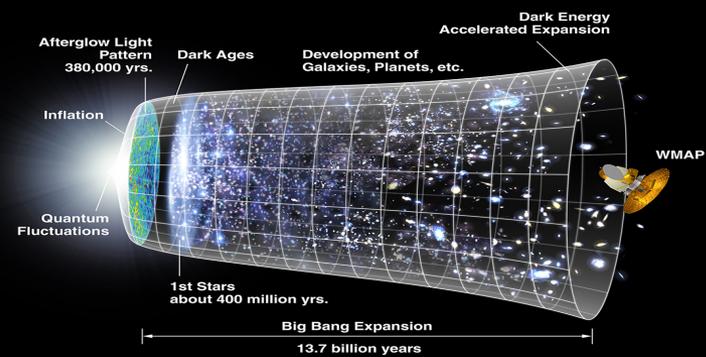
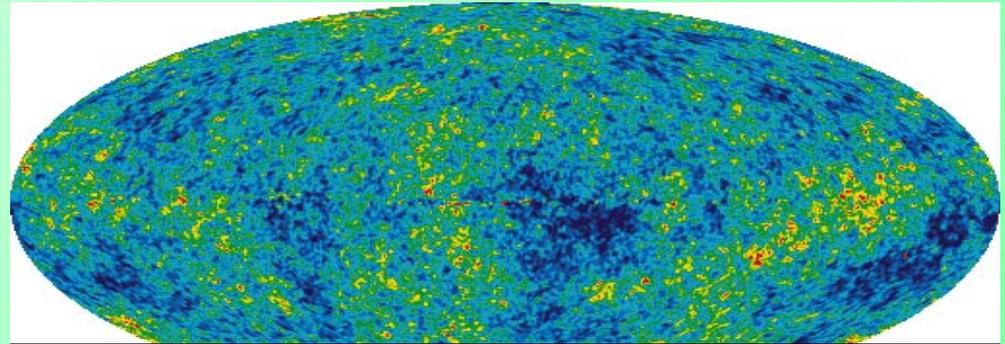
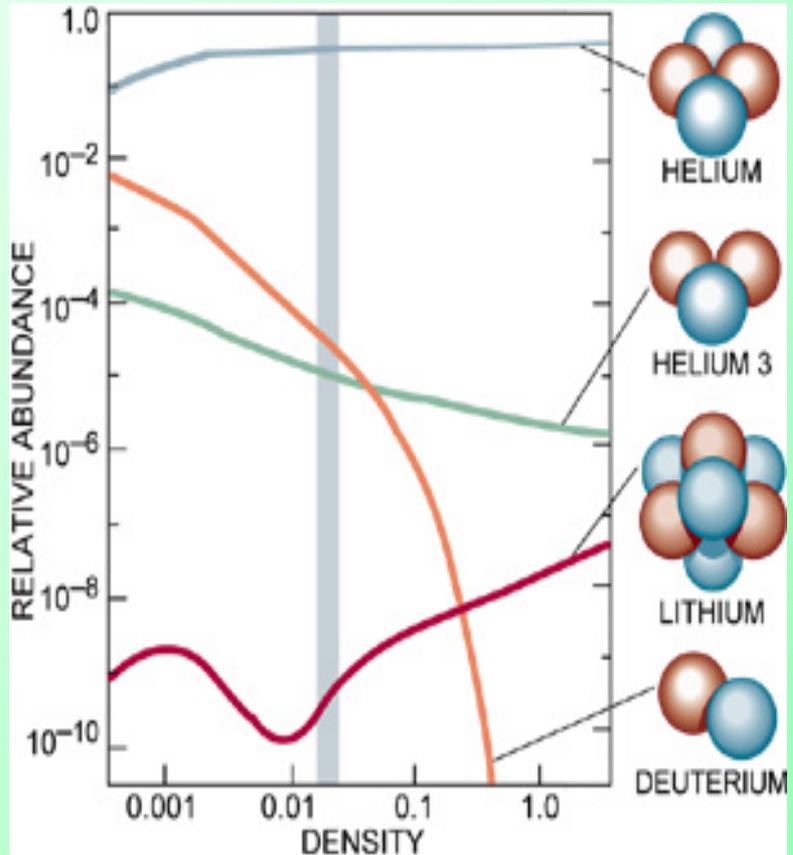




# I. Introduction WIMPs

- Majority of Dark Matter is not baryonic:

– Big Bang Nucleosynthesis & – WMAP





# I. Introduction

## WIMPs

- SUSY
  - new fundamental space-time symmetry:
    - translate fermions into bosons -> superpartner
    - same quantum numbers, differ in spin by  $1/2$



# I. Introduction

## WIMPs

- SUSY

- new fundamental space-time symmetry:
  - translate fermions into bosons -> superpartner
  - same quantum numbers, differ in spin by 1/2
- to prevent proton decay a discrete symmetry (**R-parity**) is imposed
  - $\rightarrow R = (-1)^{3B+L+2S}$
  - $\rightarrow R = 1$  for SM particles,  $R = -1$  for SUSY particles



# I. Introduction

## WIMPs

- SUSY
  - new fundamental space-time symmetry:
    - translate fermions into bosons -> superpartner
    - same quantum numbers, differ in spin by 1/2
  - to prevent proton decay a discrete symmetry (**R-parity**) is imposed
    - $\rightarrow R = (-1)^{3B+L+2S}$
    - $\rightarrow R = 1$  for SM particles,  $R = -1$  for SUSY particles
  - the lightest SUSY particle is stable and likely becomes a dark matter candidate

$$\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0$$



# I. Introduction

## WIMPs

- WIMP characteristics
  - only interact through weak nuclear force and gravity



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  - large mass (several GeV - TeV)
    - » slow moving -> cold



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    - » slow moving -> cold
  - no interaction with em and strong nuclear force
    - » invisible for usual (em) observations



# I. Introduction

## WIMPs

- WIMP characteristics
  - only interact through weak nuclear force and gravity
  - large mass (several GeV - TeV)
    - » slow moving -> cold
  - no interaction with em and strong nuclear force
    - » invisible for usual (em) observations
  - simulations universe with CDM -> galaxy distributions similar to really observed



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## II. Detection

- Philosophy & Methods
- Direct Detection

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## II. Detection Methods

- Indirect Detection
  - WIMPs interact with solar protons and Helium nuclei  
=>WIMP is “captured” by the sun
  - WIMPs begin to annihilate



## II. Detection Methods

- Indirect Detection

- WIMPs interact with solar protons and Helium nuclei  
=>WIMP is “captured” by the sun
- WIMPs begin to annihilate  
-> propagation of information carriers





## II. Detection Methods

- Indirect Detection
  - Neutrinos (GeV)
    - » Superkamiokande, IceCube
  - Gammas
    - » GLAST satellite
  - Positrons/Antiprotons
    - » Pamela, AMS-02



## II. Detection Methods

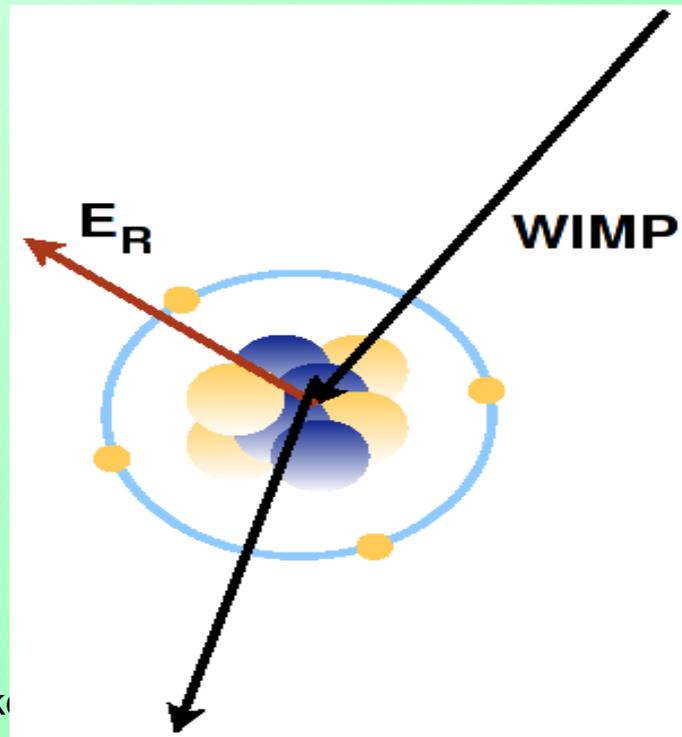
- Accelerators
  - WIMPs -> expected to be produced at LHC, Fermilab
  - rapid decays of heavier supersymmetric partner particles
  
  - ATLAS/CMS, COUPP



## II. Detection

# Direct Detection

- Theory of the possibility to detect WIMPs:
  - WIMPs pass through ordinary matter
  - > rare WIMP interaction can take place





## II. Detection

# Direct Detection

- expected WIMP event rate  $1 - 10^{-6}$  [event/(kg d)]
- Strategy:



## II. Detection

# Direct Detection

- expected WIMP event rate  $1 - 10^{-6}$  [event/(kg d)]
- Strategy:
  - find very **sensitive systems**
  - scale them up to **large volumes**
    - => follow the lessons learned from neutrino discovery



## II. Detection

# Direct Detection

- expected WIMP event rate  $1 - 10^{-6}$  [event/(kg d)]
- Strategy:
  - find very **sensitive systems**
  - scale them up to **large volumes**
    - => follow the lessons learned from neutrino discovery
  - elastic scattering of WIMP with target nuclei
  - energy transferred -> resulting nuclear recoil



## II. Detection

# Direct Detection

- WIMP signatures
  - WIMP interactions in detector should be
    - nuclear recoils and single scatters
  - Spectral shape
    - recoil spectrum should fall with energy



## II. Detection

# Direct Detection

- WIMP signatures
- WIMP interactions in detector should be
  - nuclear recoils and single scatters
- Spectral shape
  - recoil spectrum should fall with energy
- Dependence on material
  - test different target material
- Annual flux modulation ( $\sim 3\%$ )
- Diurnal direction modulation ( $\sim 7\%$ )



## II. Detection

# Direct Detection

- Core Requirements for WIMP detectors
  - **low energy threshold**
    - »
  - **high mass**
  - **low background**



## II. Detection

# Direct Detection

- Core Requirements for WIMP detectors
  - **low energy threshold**
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- Core Requirements for WIMP detectors
  - **low energy threshold**
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    - » high target mass ( $\sim$  ton-scale)
    - » high atomic mass of target nuclei ( $A$ )
  - **low background**



## II. Detection

# Direct Detection

- Core Requirements for WIMP detectors
  - **low energy threshold**
    - » expected recoil energy less than 100 keV
  - **high mass**
    - » high target mass ( $\sim$  ton-scale)
    - » high atomic mass of target nuclei ( $A$ )
  - **low background**
    - » gamma & neutron shield
    - » low radioactivity of detector materials
    - » deep underground (shield cosmic muons)



## II. Detection

# Direct Detection

- Core Requirements for WIMP detectors
  - **good background discrimination**

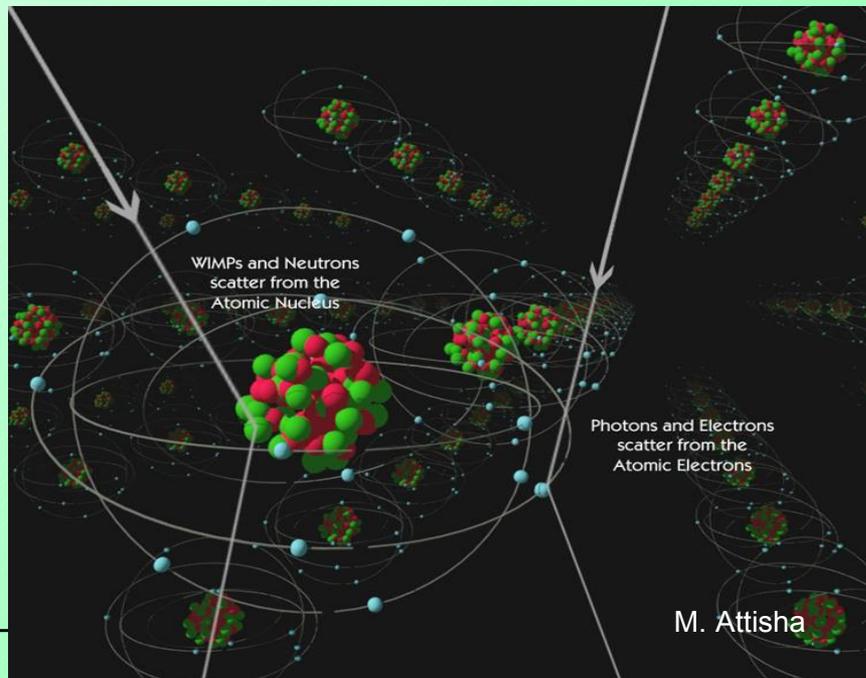


## II. Detection

# Direct Detection

- Core Requirements for WIMP detectors
  - **good background discrimination**

» reject e-recoils, while maintaining high sensitivity to nuclear recoils





## II. Detection

# Direct Detection

- Only few technologies can make use of this physics
  - Cryogenic detectors
  - Noble liquid gas detectors
  - Specific Scintillator detectors



## II. Detection

# Direct Detection

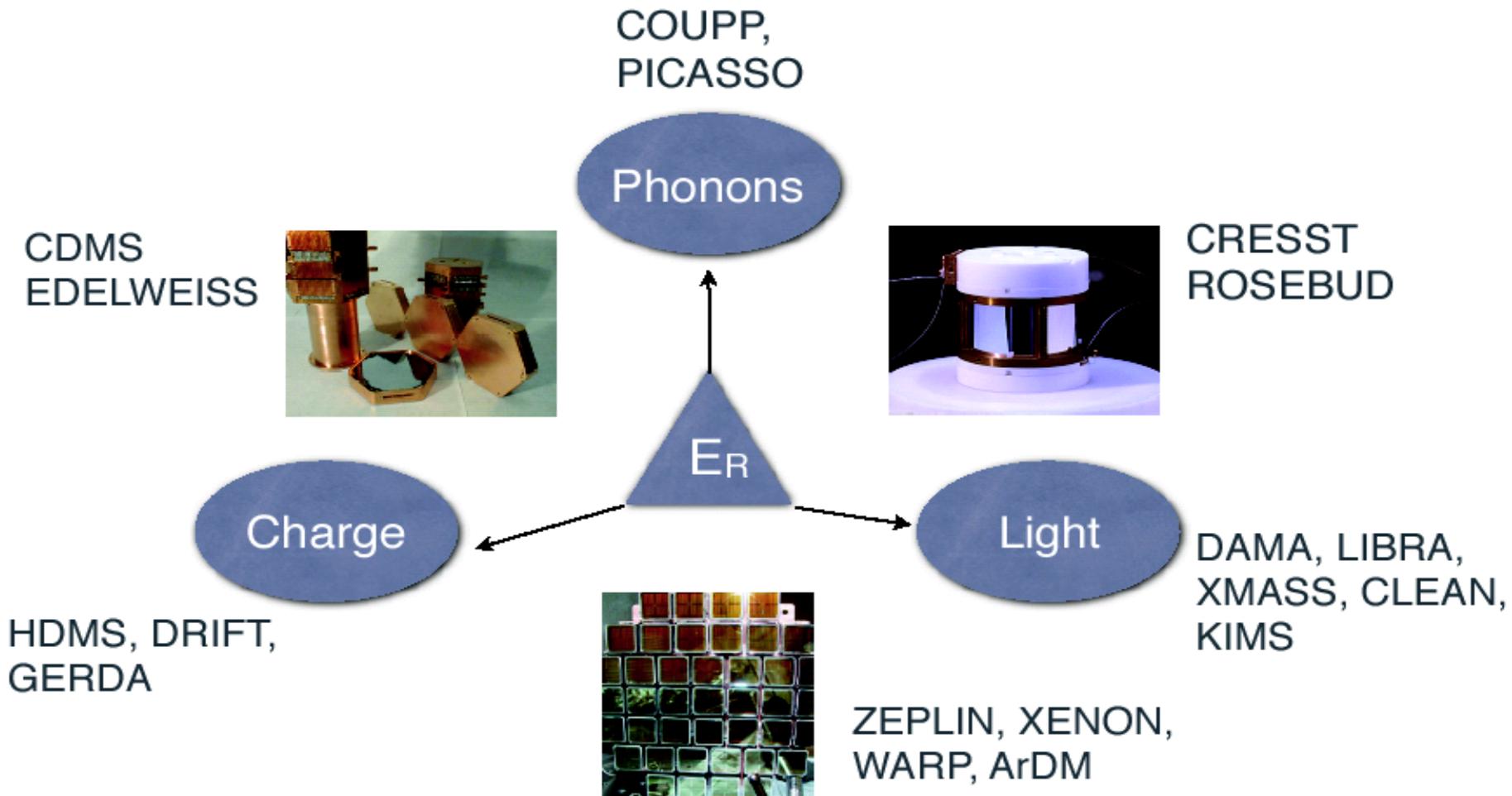
- Only few technologies can make use of this physics
  - Cryogenic detectors
    - » Ge, Si,  $\text{CaWO}_4$
  - Noble liquid gas detectors
    - » Xe, Ar
  - Specific Scintillator detectors
    - » NaI(Tl), CsI(Tl)



## II. Detection

# Direct Detection

- Only few technologies can make use of this physics

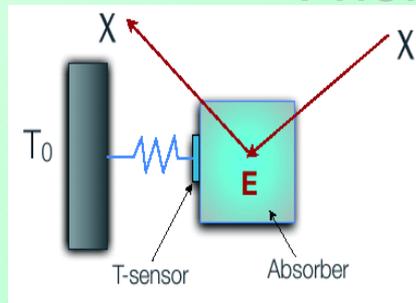




## II. Detection

# Direct Detection

- Techniques
  - Phonon collection



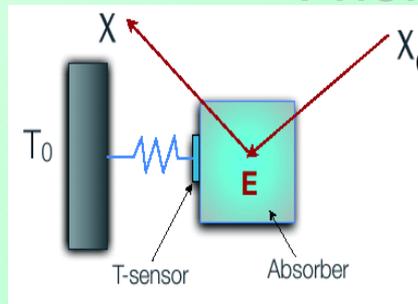
deposited Energy  $E$   
produces heat  $\Delta T$



# II. Detection

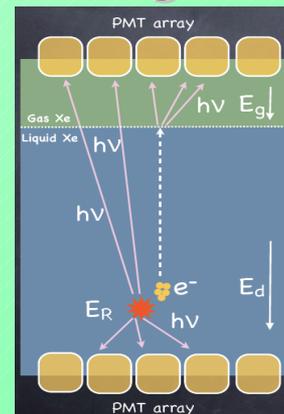
## Direct Detection

- Techniques
  - Phonon collection



deposited Energy  $E$   
produces heat  $\Delta T$

### Light collection



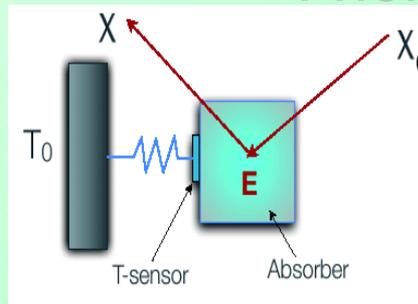
deposited Energy  
activates target  
-> photon emission



# II. Detection

## Direct Detection

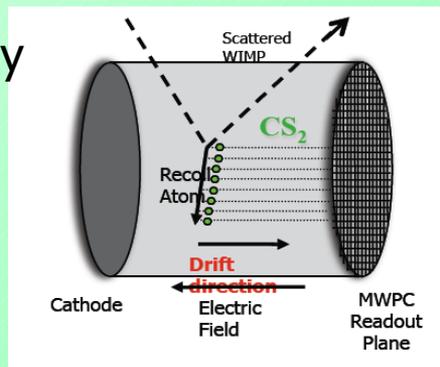
- Techniques
  - Phonon collection



deposited Energy  $E$   
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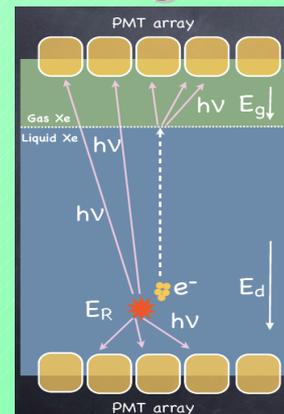
### Ionisation

deposited Energy  
ionises target  
-> charge



### Light collection

deposited Energy  
activates target  
-> photon emission





# Structure

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- WIMPs

## II. Detection

- Philosophy & Methods
- Direct Detection

## III. Detectors

- Scintillators
- Bolometer
- Liquid Noble Gas Detectors

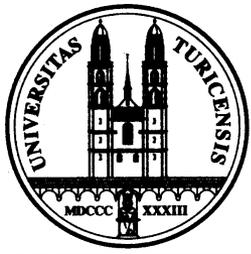
## IV. Ton scale experiments

## V. Summary



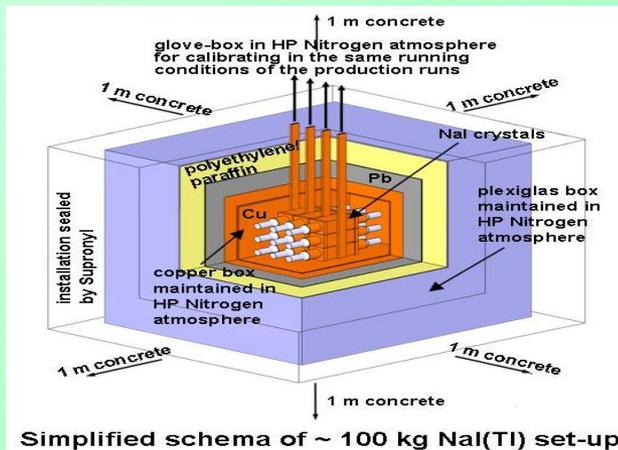
# III. Detectors Scintillators

- DAMA/LIBRA at Gran Sasso Laboratory
  - DArk MATter/Large sodium Iodide Bulk for RAre processes



# III. Detectors Scintillators

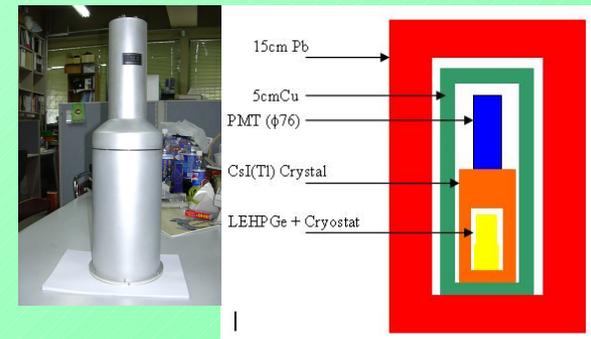
- DAMA/LIBRA at Gran Sasso Laboratory
  - DARK MATter/Large sodium Iodide Bulk for RARE processes
    - target-detector mass:  $\sim 250$  kg highly radiopure NaI(Tl)
    - single phase detector  $\rightarrow$  Light collection
    - looking for annual modulation of measured signal
    - first results: confirm previous DAMA results





# III. Detectors Scintillators

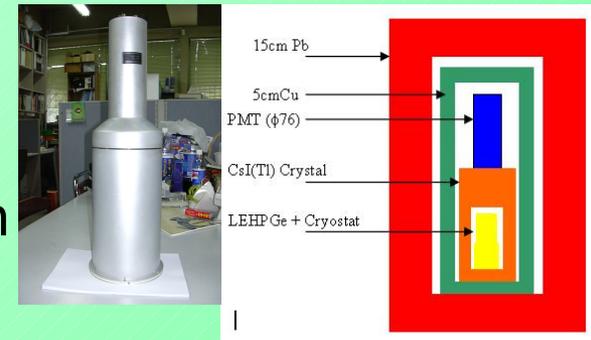
- KIMS (Yangyang Underground Lab South Korea)
  - Korean Invisible Mass Search





# III. Detectors Scintillators

- KIMS (Yangyang Underground Lab South Korea)
  - Korean Invisible Mass Search
    - CsI(Tl) crystals  $8 \times 8 \times 30 \text{ cm}^3$  (8.7 kg)
    - single phase detector -> Light collection
    - good pulse shape discrimination

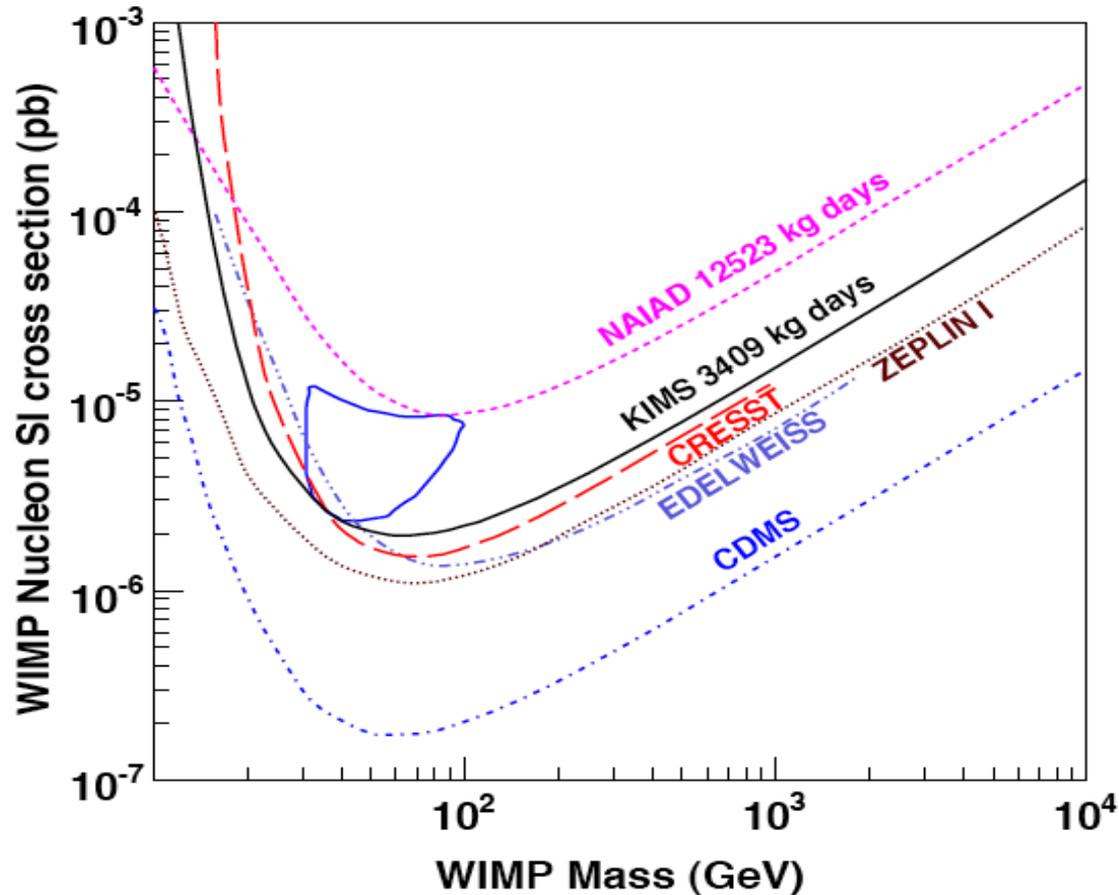




# III. Detectors Scintillators

- KIMS (Yangyang Underground Lab South Korea)

– Kc





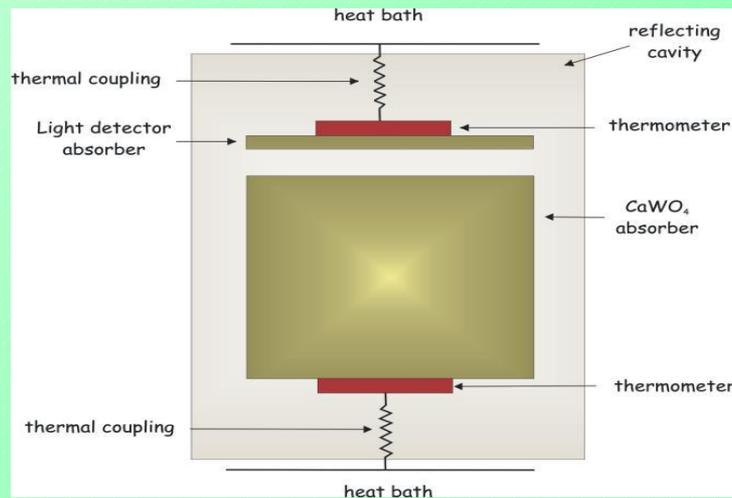
# III. Detectors Bolometer

- CRESST at Gran Sasso Laboratory
  - Cryogenic Rare Event Search with Superconducting Thermometer



# III. Detectors Bolometer

- CRESST at Gran Sasso Laboratory
  - Cryogenic Rare Event Search with Superconducting Thermometer
    - $\text{CaWO}_4$  Crystals:  $\varnothing = 4 \text{ cm}$ ,  $h = 4 \text{ cm}$ ,  $m = 300 \text{ g}$
    - $T_c = 8 - 15 \text{ mK}$
    - Dual phase detector -> Szintillation & Heat





# III. Detectors Bolometer

- CDMS at Soudan Mine
  - Cryogenic Dark Matter Search

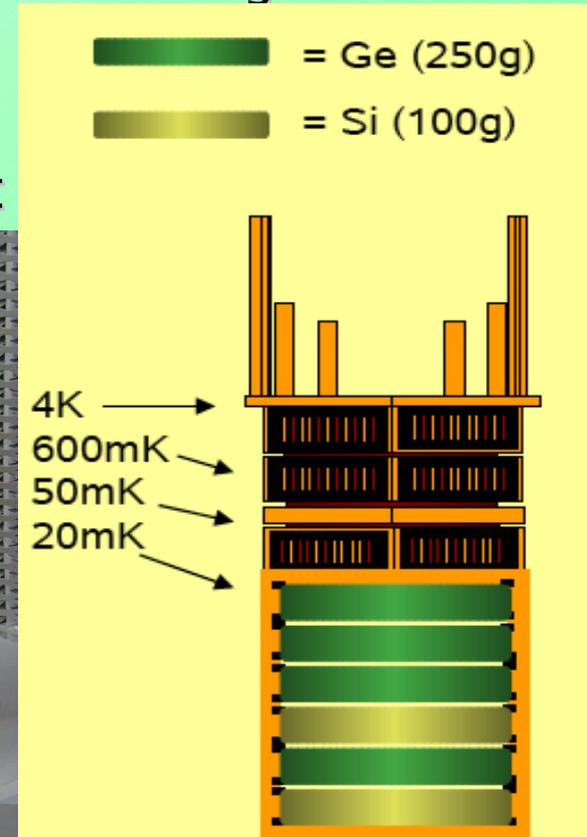


# III. Detectors Bolometer

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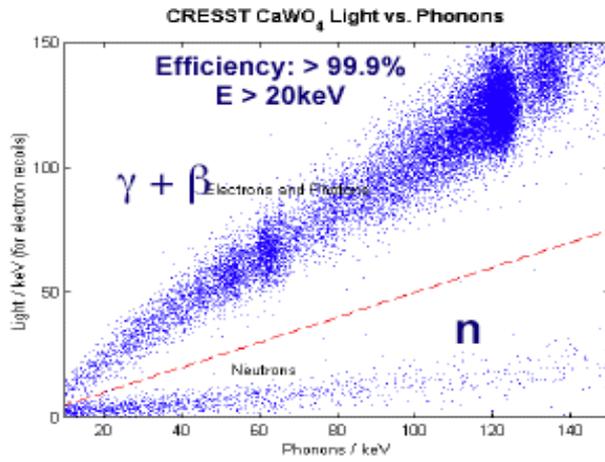
- Cryogenic Dark Matter Search

- Ge & Si Crystals:  $\varnothing = 7$  cm,  $h = 1$  cm,  $m = 250$  g
    - $T_c \sim 20$  mK; 5 Tower (6 detect. each)
    - Dual phase detector -> charge & heat

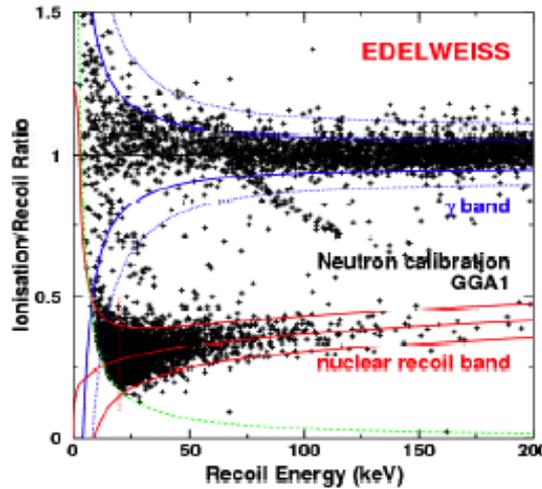




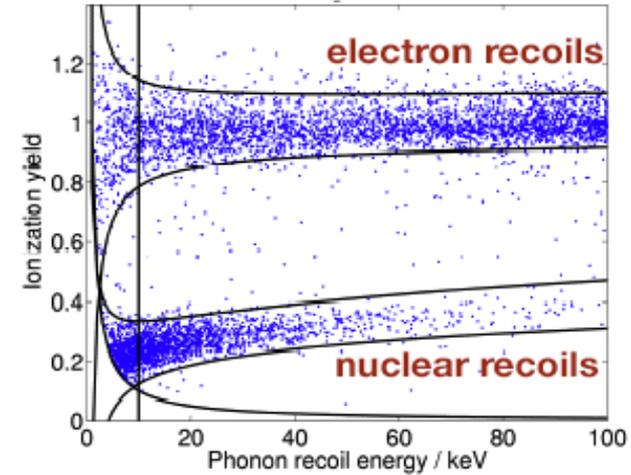
# III. Detectors Bolometer



**CRESST**



**EDLWEISS**



**CDMS**



# III. Detectors Bolometer

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LanguageLevel:2

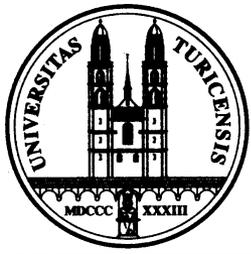
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# III. Detectors

## Liquid Noble Gas Detectors

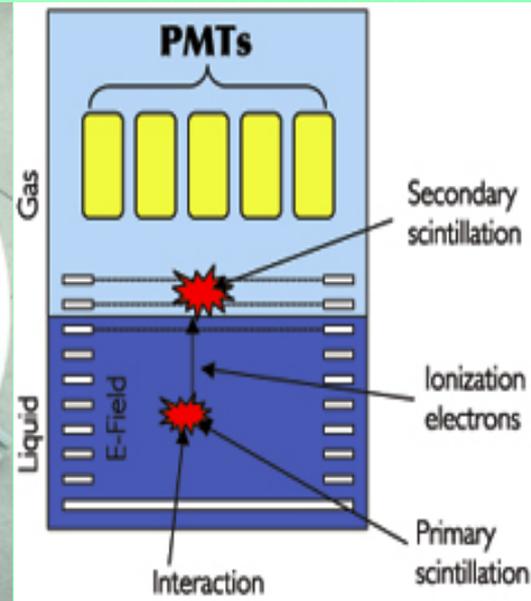
- WARP at Gran Sasso Laboratory
  - WIMP Argon Program



# III. Detectors

## Liquid Noble Gas Detectors

- WARP at Gran Sasso Laboratory
  - WIMP Argon Program
    - Dual Phase Detector -> Charge & Light collection
    - 100 l of liquid Argon

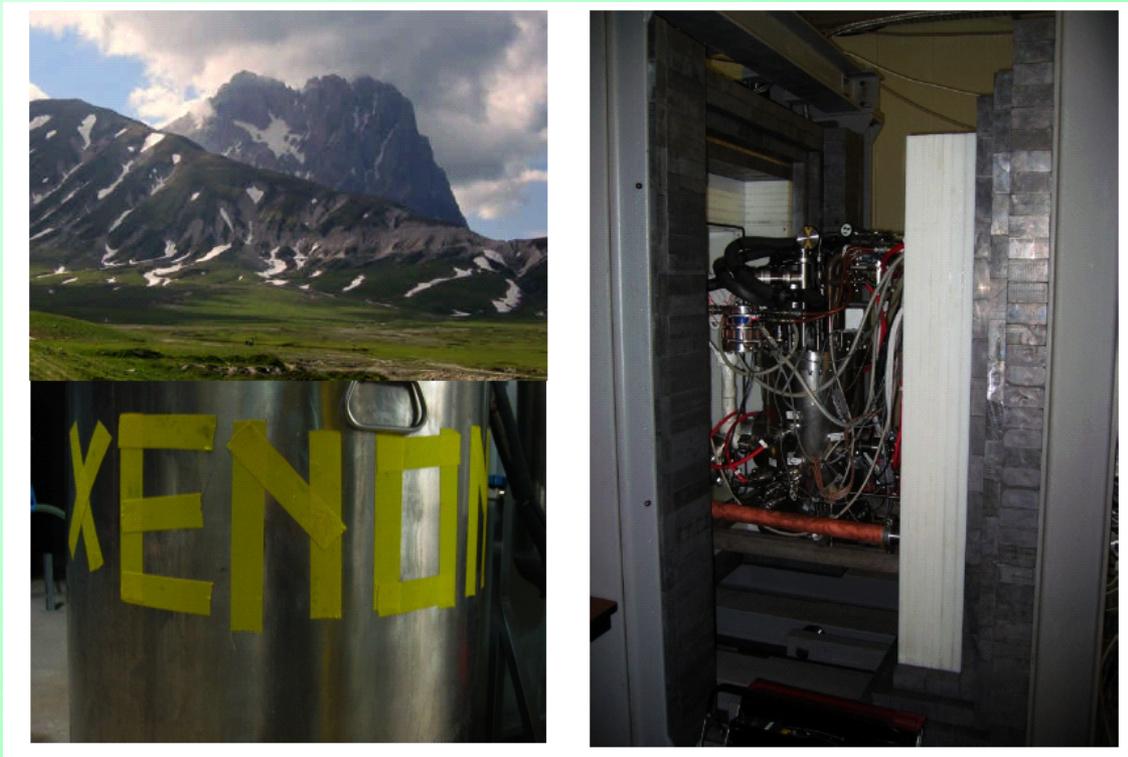




# III. Detectors

## Liquid Noble Gas Detectors

- XENON at Gran Sasso Laboratory
  - Dual Phase Detector -> Charge & Light collection
  - 150 kg of liquid Xenon





# III. Detectors

## Liquid Noble Gas Detectors

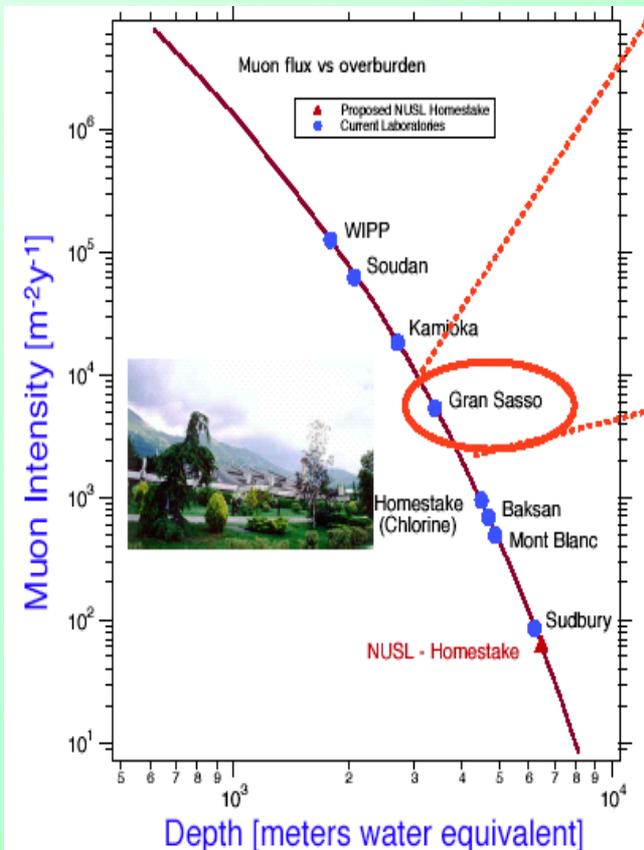
- XENON
- Abruzzi, Italy
- Depth 3800 mwe



# III. Detectors

## Liquid Noble Gas Detectors

- XENON
- Abruzzi, Italy
- Depth 3800 mwe

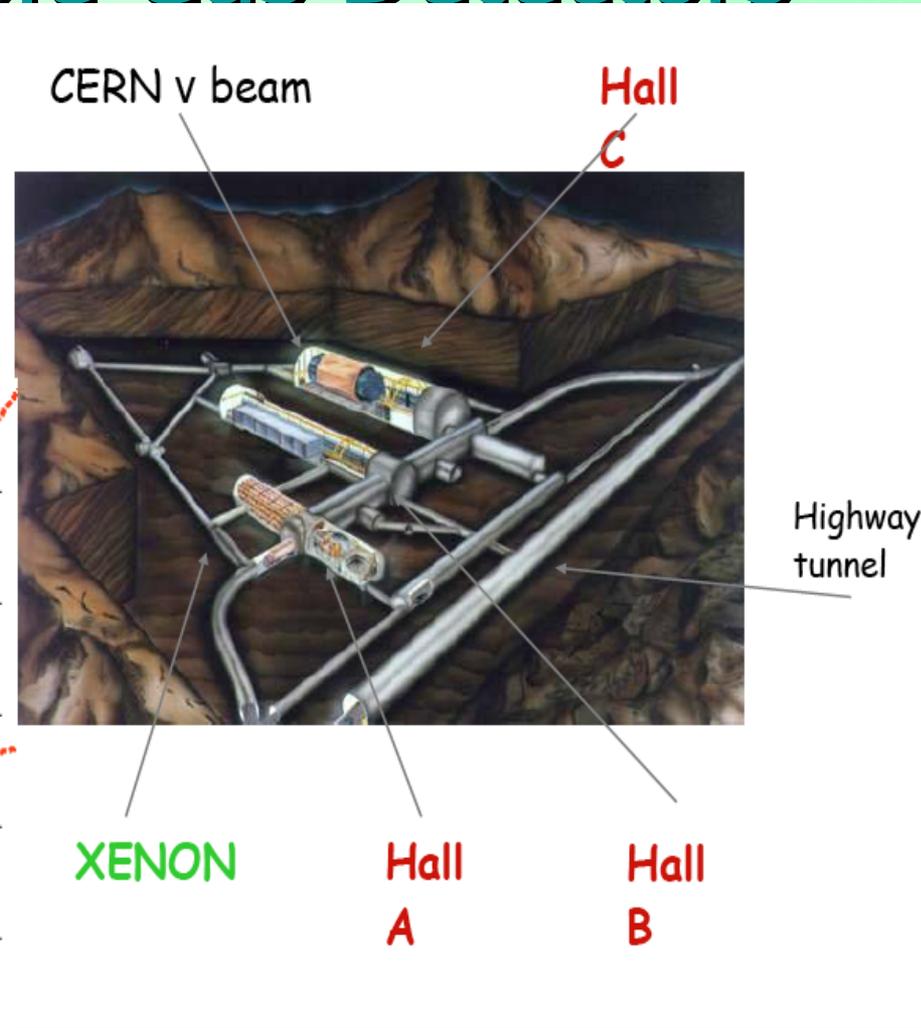
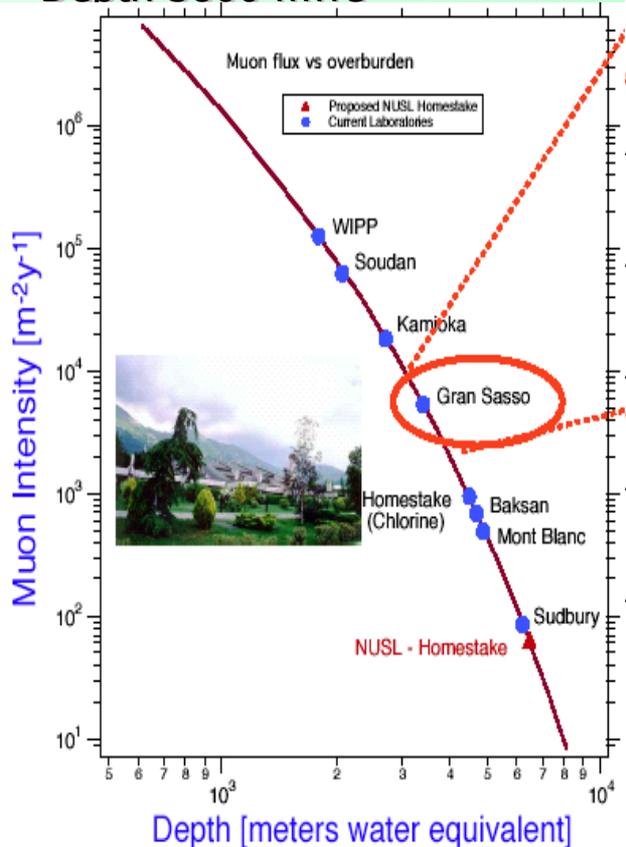




# III. Detectors

## Liquid Noble Gas Detectors

- XENON
- Abruzzi, Italy
- Depth 3800 mwe

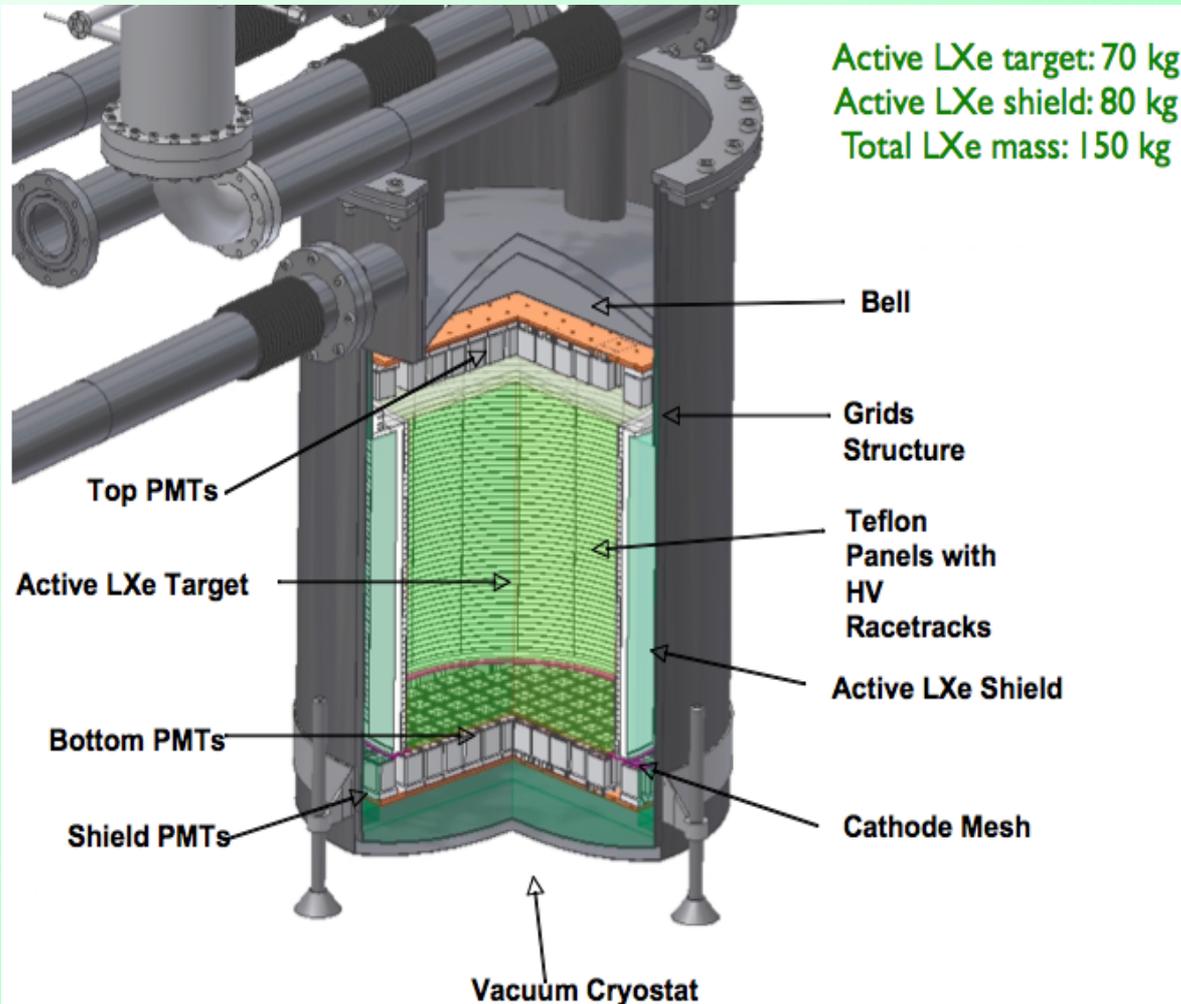




# III. Detectors

## Liquid Noble Gas Detectors

- XENON100 main detector features



**242 Photomultiplier Tubes  
in Total:**

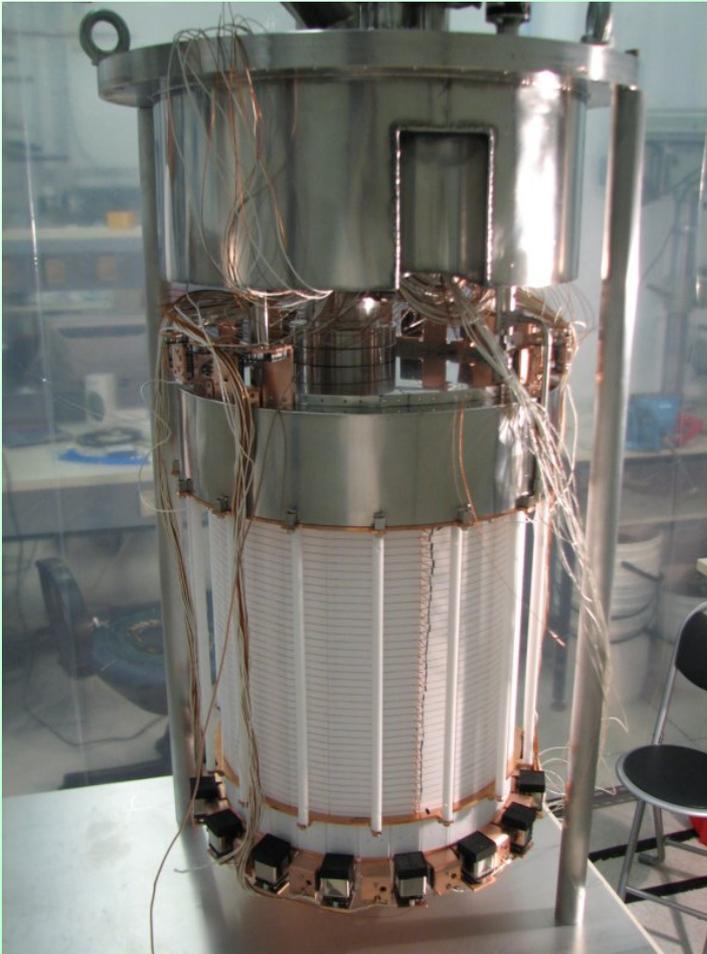
**98 in the top PMT array  
80 in the bottom array  
64 in the veto (top/bottom)**



# III. Detectors

## Liquid Noble Gas Detectors

- XENON100



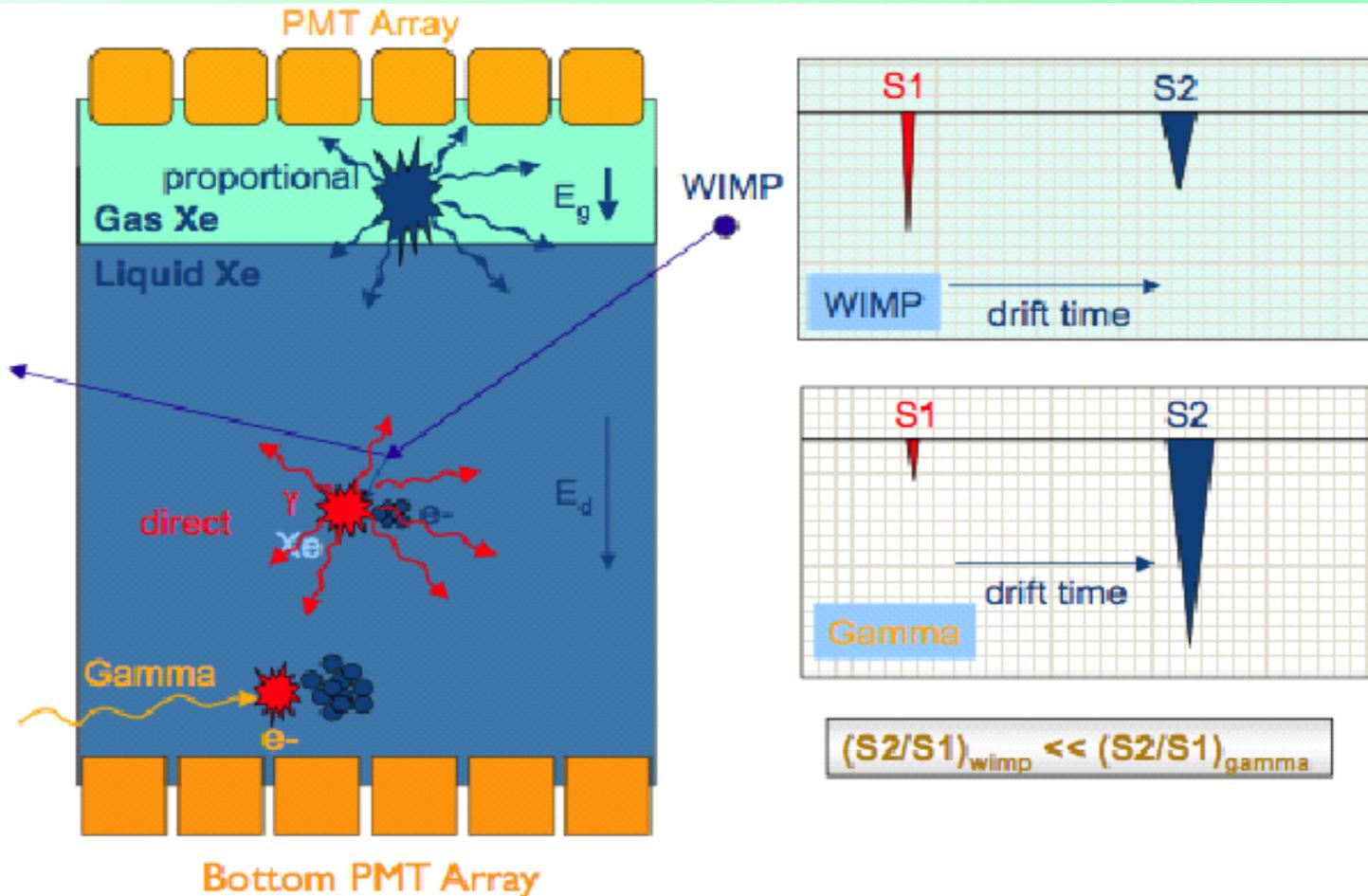
new  
detector put  
into Xenon10  
shield:  
20 cm lead  
20 cm poly  
5 cm copper



# III. Detectors

## Liquid Noble Gas Detectors

- XENON100: Event Discrimination





# III. Detectors

## Liquid Noble Gas Detectors

- XENON100
  - first measurements will start soon
  - expect results end of this year



# III. Detectors

## Liquid Noble Gas Detectors

- XENON100
  - first measurements will start soon
  - expect results end of this year
- **Expect to test cross section of  $9 \times 10^{-45} \text{ cm}^2$  (at 100 GeV WIMP mass)**



# Recent limits on WIMP-nucleon cross-sections

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Creator:MATLAB, The Mathworks, Inc. Vers  
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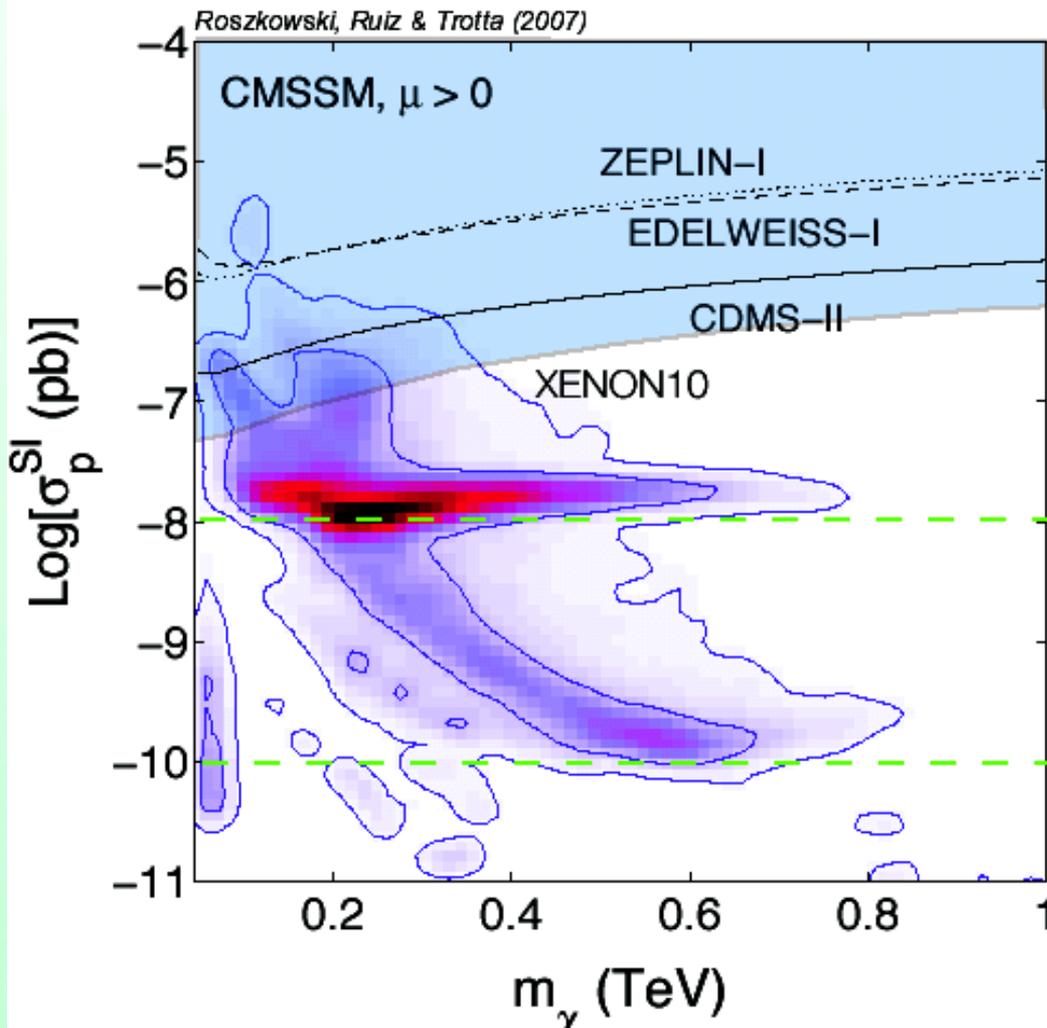


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# IV. Tonscale Experiments



excluded by XENON10  
(2007)

1 event/kg/yr

CDMS-II, XENON10+, COUPP,  
CRESST-II, EDELWEISS-II, ZEPLIN-III, ...

1 event/t/yr

SuperCDMS1t, WARP1t, ArDM  
XENON1t, EURECA, ELIXIR, XMASS, ...



# Structure

- I. Introduction
  - Dark Matter
  - WIMPs
- II. Detection
  - Philosophy & Methods
  - Direct Detection
- III. Detectors
  - Scintillators
  - Bolometer
  - Liquid Noble Gas Detectors
- IV. Ton scale experiments
- V. **Summary**



# V. Summary

- Majority of matter in universe is non-baryonic
- WIMPs are one of the best motivated candidates



# V. Summary

- Majority of matter in universe is non-baryonic
- WIMPs are one of the best motivated candidates
- Several experiments all over the world putting effort in the discovery of the lightest SS particle
- not yet detected...

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Creator:MATLAB, The Mathworks, Inc. Vers  
CreationDate:07/16/2008 12:44:53  
LanguageLevel:2

Title:output/graph\_30687\_legend.eps  
Creator:MATLAB, The Mathworks, Inc. Vers  
CreationDate:07/16/2008 12:44:54  
LanguageLevel:2



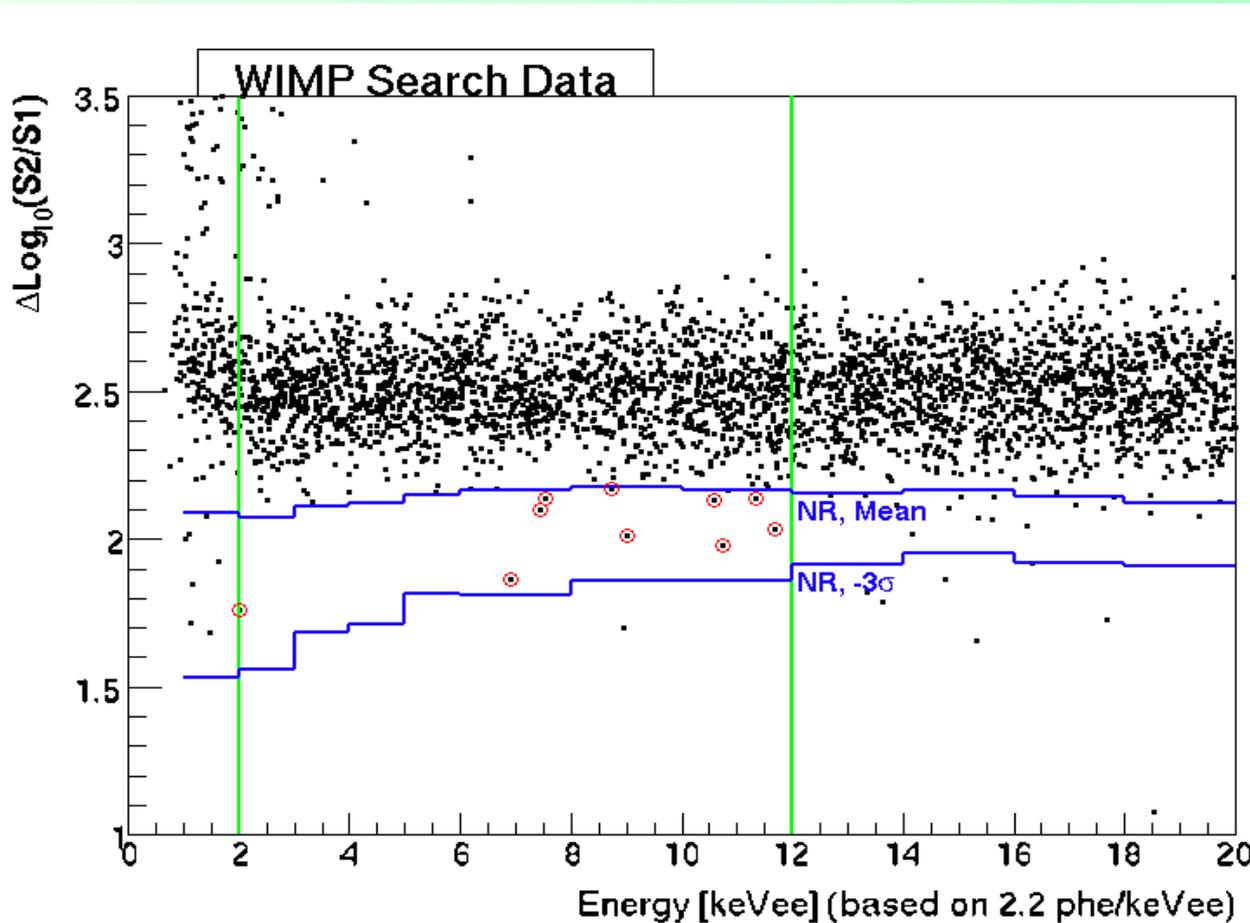
# Backup

- Results of Xenon10
- How to determine WIMPs and not background



# III. Detectors Results XENON10

- WIMP-Search-Run 24/08/06 – 14/02/07 : 136 kg-days



exposure

10 events in  
WIMP-Search  
window after all  
cuts  
( $\sim 7$  statistical  
leakage,  
expected from  
gammaband )



# Backup

- How to distinguish between WIMPs and background
  - 1. Earth orbital motion around sun implies an expected seasonal modulation in recoil spectrum
  - 2. Because of the galactical orbital motion, we would expect the direction of WIMP events dominantly opposite to our direction of motion



# I. Introduction

## WIMPs

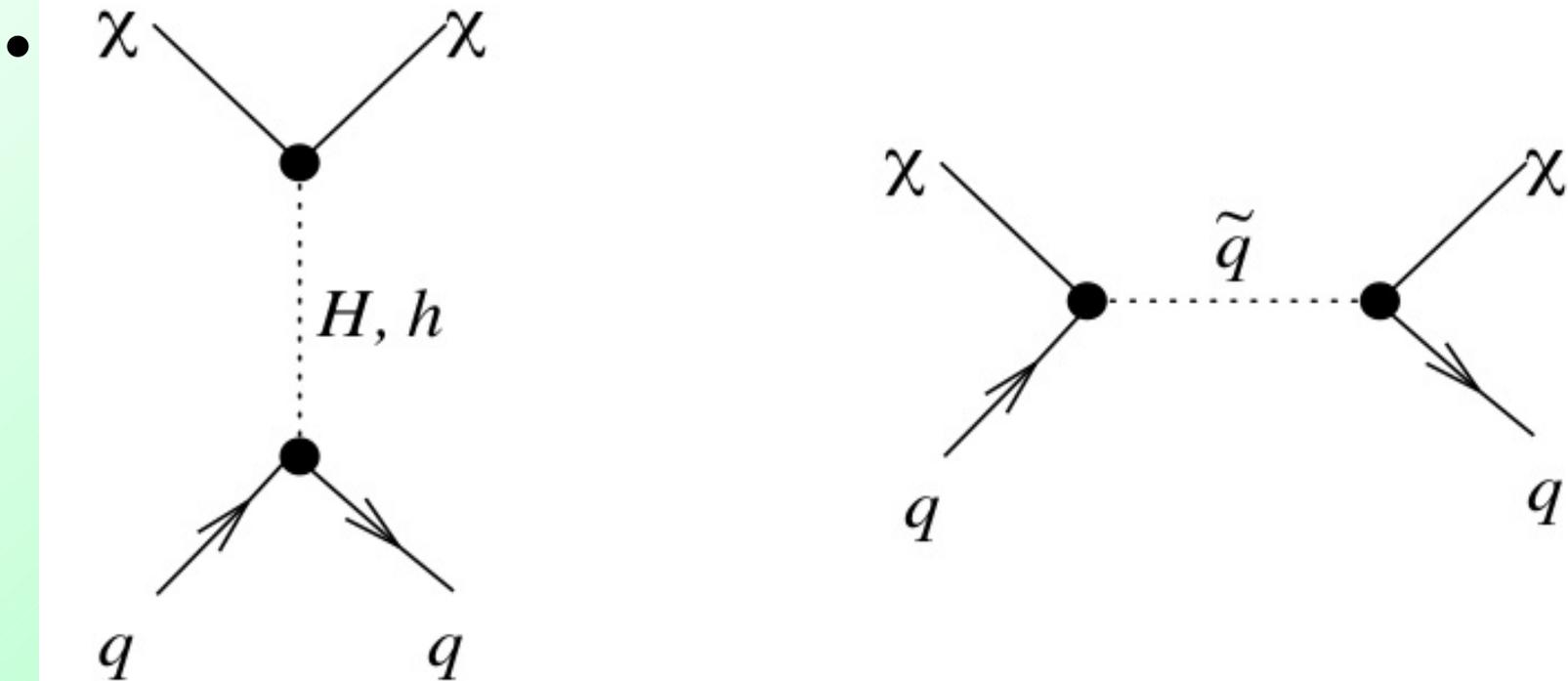


Figure 20. Feynman diagrams contributing to the scalar elastic-scattering amplitude of a neutralino from quarks.