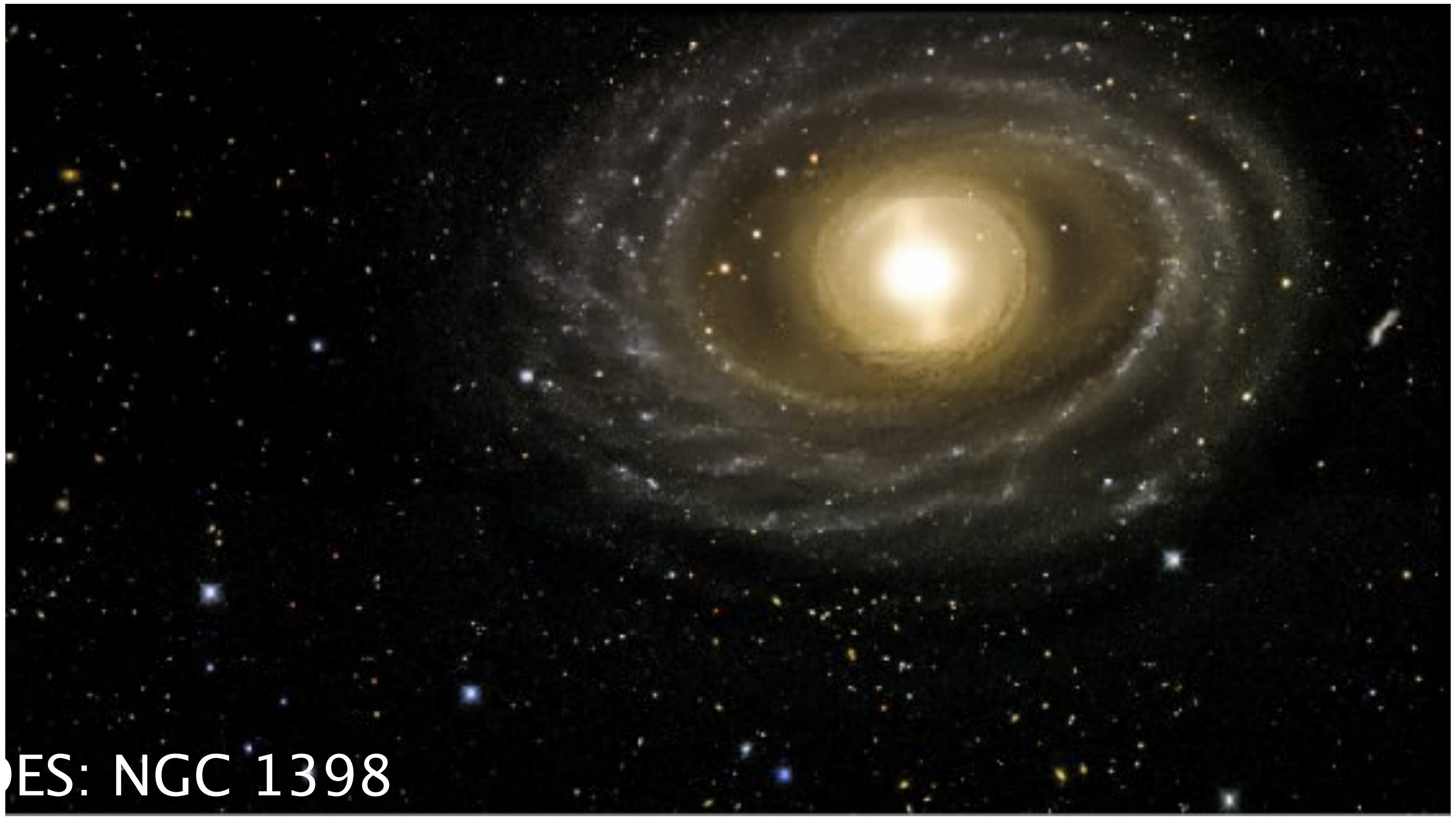
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Lecture 1
Dark Matter Direct Detection: Signals and Backgrounds

December 2, 2017

XIV ICFA School on Instrumentation in Elementary Particle Physics
La Havana,Cuba

Elena Aprile
Columbia University


ES: NGC 1398

Outline of Lecture 1

- **WIMP direct detection**

  kinematics of the elastic WIMP-nucleus scattering

  cross sections, differential rates, expected rates in a detector

- **WIMP signatures and Backgrounds**

  time dependance of the rate, directional dependance

  background sources, background discrimination

References and Additional Readings

- *Rate/Signal Definition*

J. D. Lewin and P. F. Smith, Astropart. Phys. 6, (1996) 87.

F. Donato, N. Fornengo, and S. Scopel, Astropart. Phys. 9,(1998) 247.

- *Backgrounds and more*

G. Heusser, Ann. Rev. Nucl. Part. Sci., 45, (1995) 543.

R. J. Gaiskell, Ann. Rev. Nucl. Part. Sci., 54, (2004) 315.

- *Detectors and experimental methods*

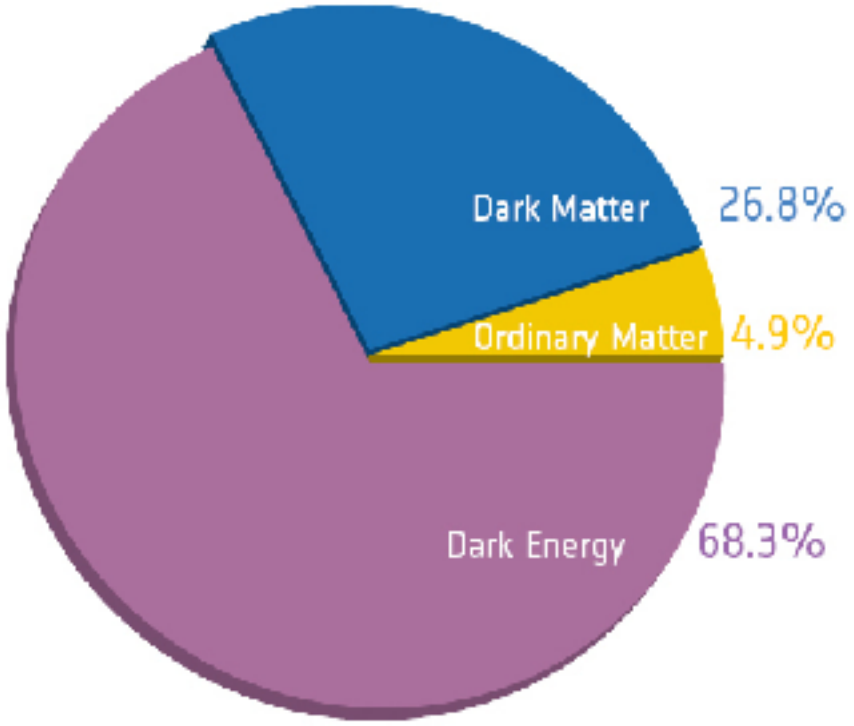
W. R. Leo, *Techniques for nuclear and particle physics experiments*, Springer, (1994)

G. F. Knoll, *Radiation Detection and Measurement*, Wiley, (2000).

- *LXe Detectors and Applications*

E. Aprile and T. Doke, Review of Modern Physics (2010).

Most of the matter in the Universe is non-baryonic



- Planck data reveals that its contents include ~ 5% atoms, the building blocks of stars and planets.
- Dark matter comprises ~27% of the universe. This matter, different from atoms, does not emit or absorb light. It has only been detected indirectly by its gravity.
- 68% of the universe, is composed of "dark energy", that acts as a sort of an anti-gravity. This energy, distinct from dark matter, is responsible for the present-day acceleration of the Universe expansion.

$$\Omega_\chi \equiv \frac{\rho_\chi}{\rho_c}$$ density parameter

$$\rho_c \equiv \frac{3H_0^2}{8\pi G} = 9.47 \times 10^{-27}\,\mathrm{kg\,m^{-3}}$$

critical density: the geometry of the Universe is flat

$$\rho_c \simeq 6\,\mathrm{H-atoms\,m^{-3}}$$

http://xxx.lanl.gov/abs/1502.01589

➡ Total matter density: $\Omega_m = 0.315 \pm 0.013$

➡ Density of baryons: $\Omega_b = 0.0449 \pm 0.0028$

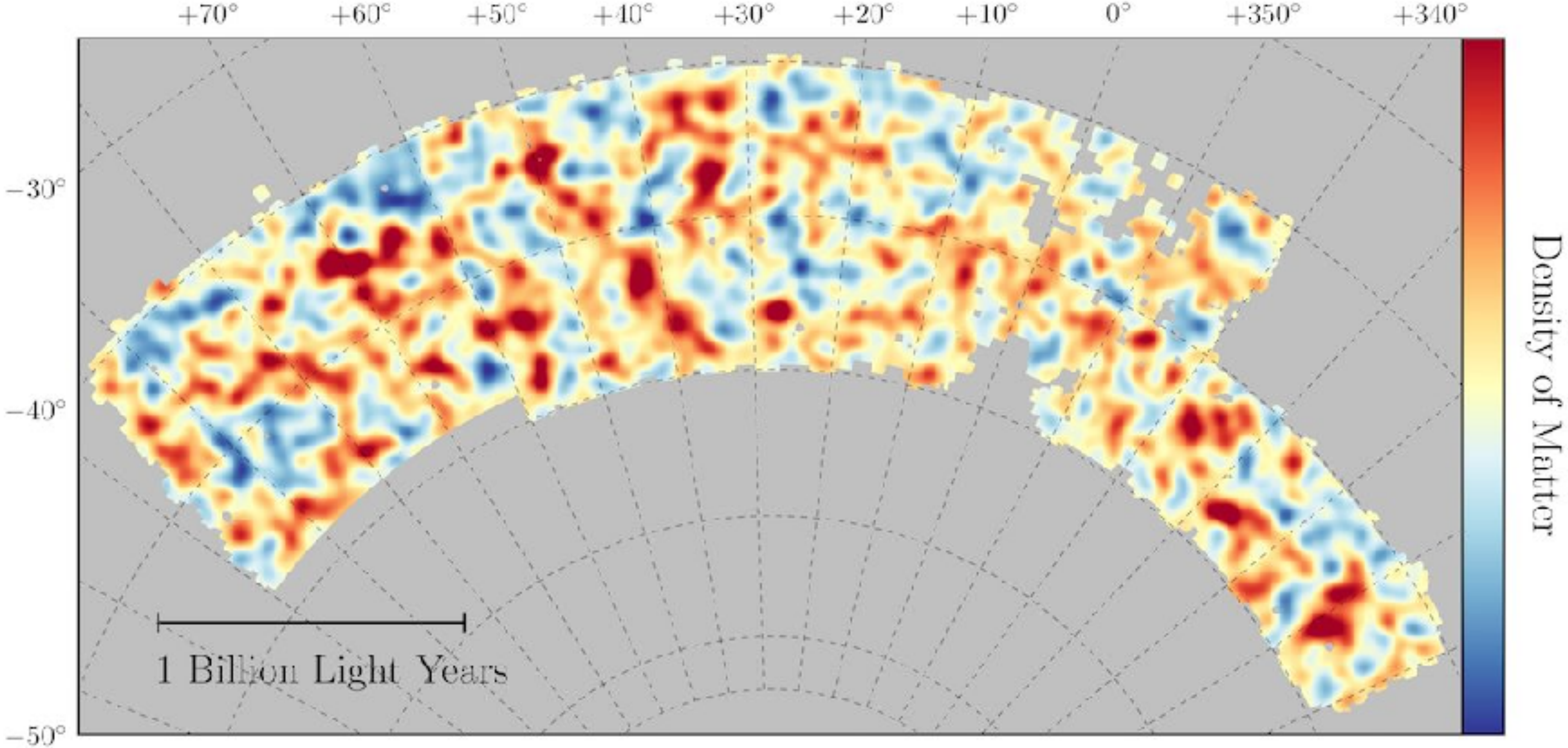
➡ Energy density of the vacuum: $\Omega_\Lambda = 0.685 \pm 0.013$

➡ Hubble constant: $H_0 = (67.31 \pm 0.96)$ km/s/Mpc

H_0 = current expansion rate

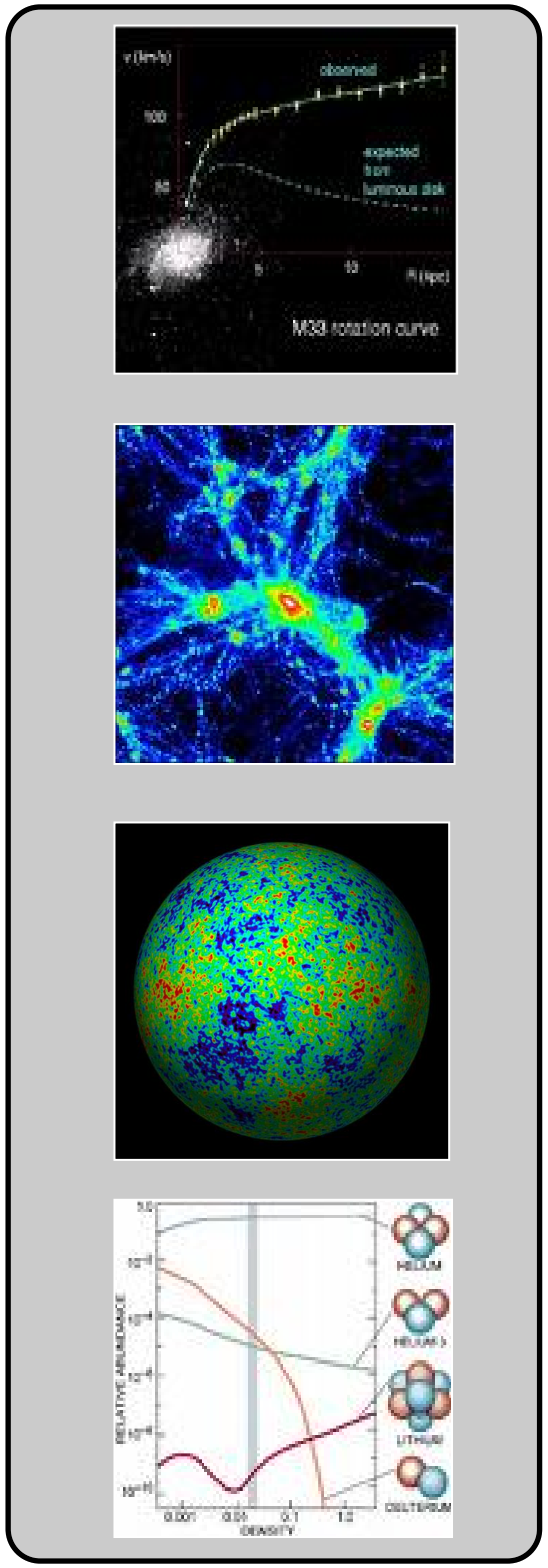
Dark Matter Distribution from the Dark Energy Survey

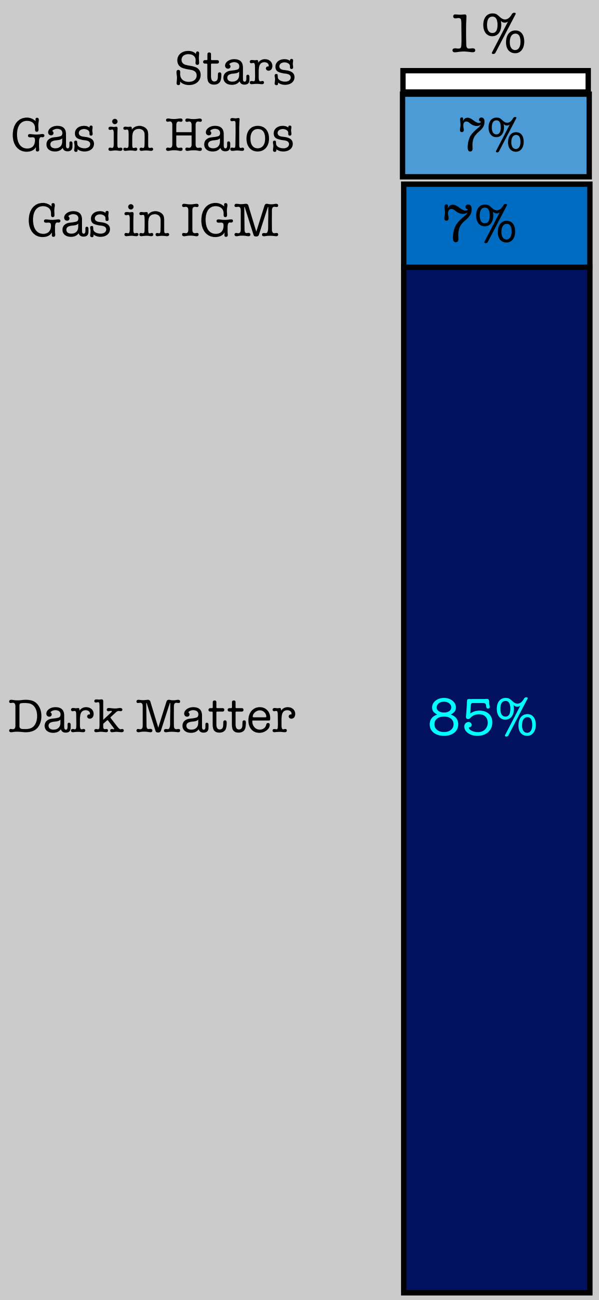
https://www.darkenergysurvey.org/des-year-1-cosmology-results-papers/

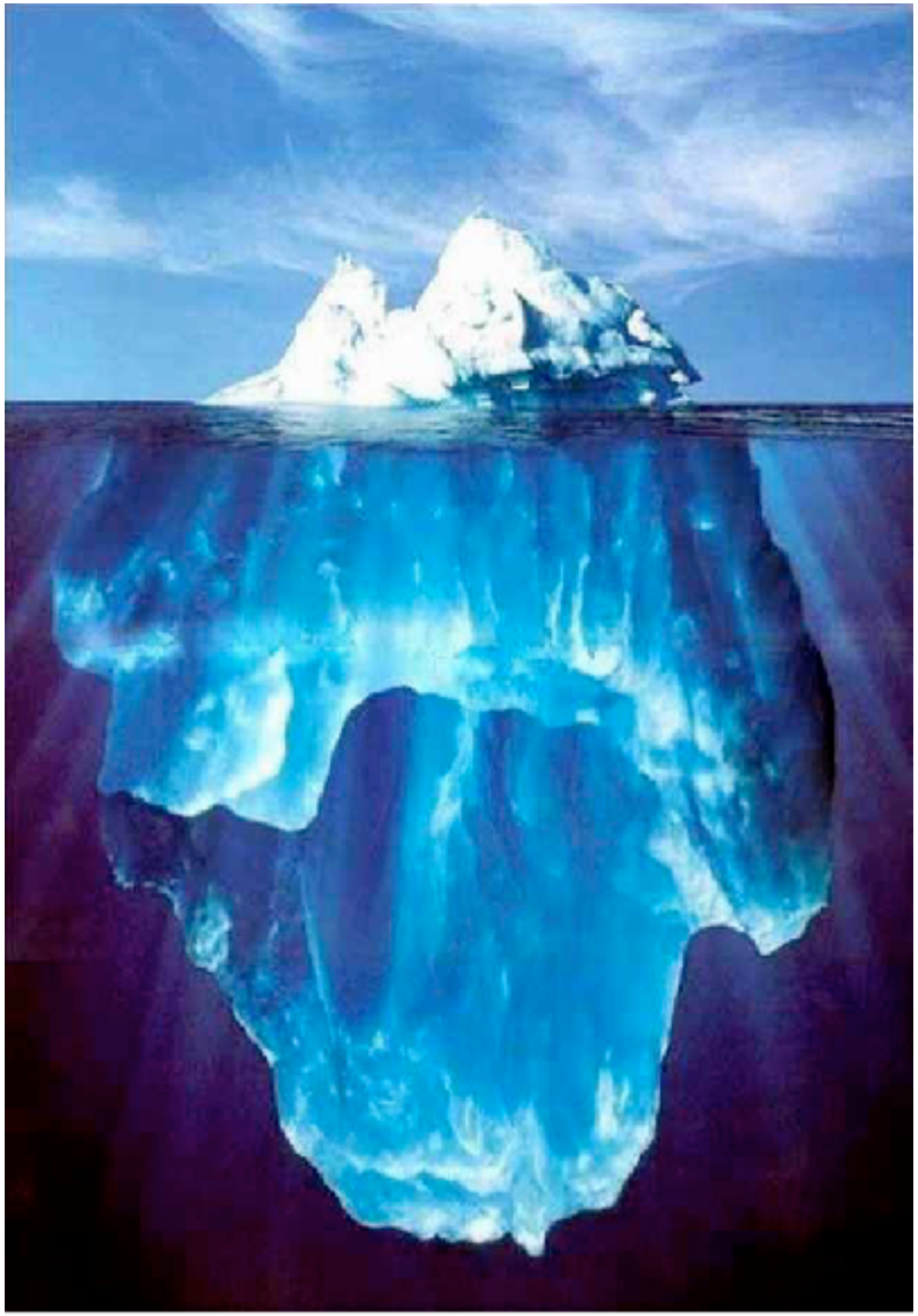


Map of dark matter made from gravitational lensing measurements of 26 million galaxies in the Dark Energy Survey. The map covers about 1/30th of the entire sky and spans several billion light-years in extent. Red regions have more dark matter than average, blue regions less dark matter.

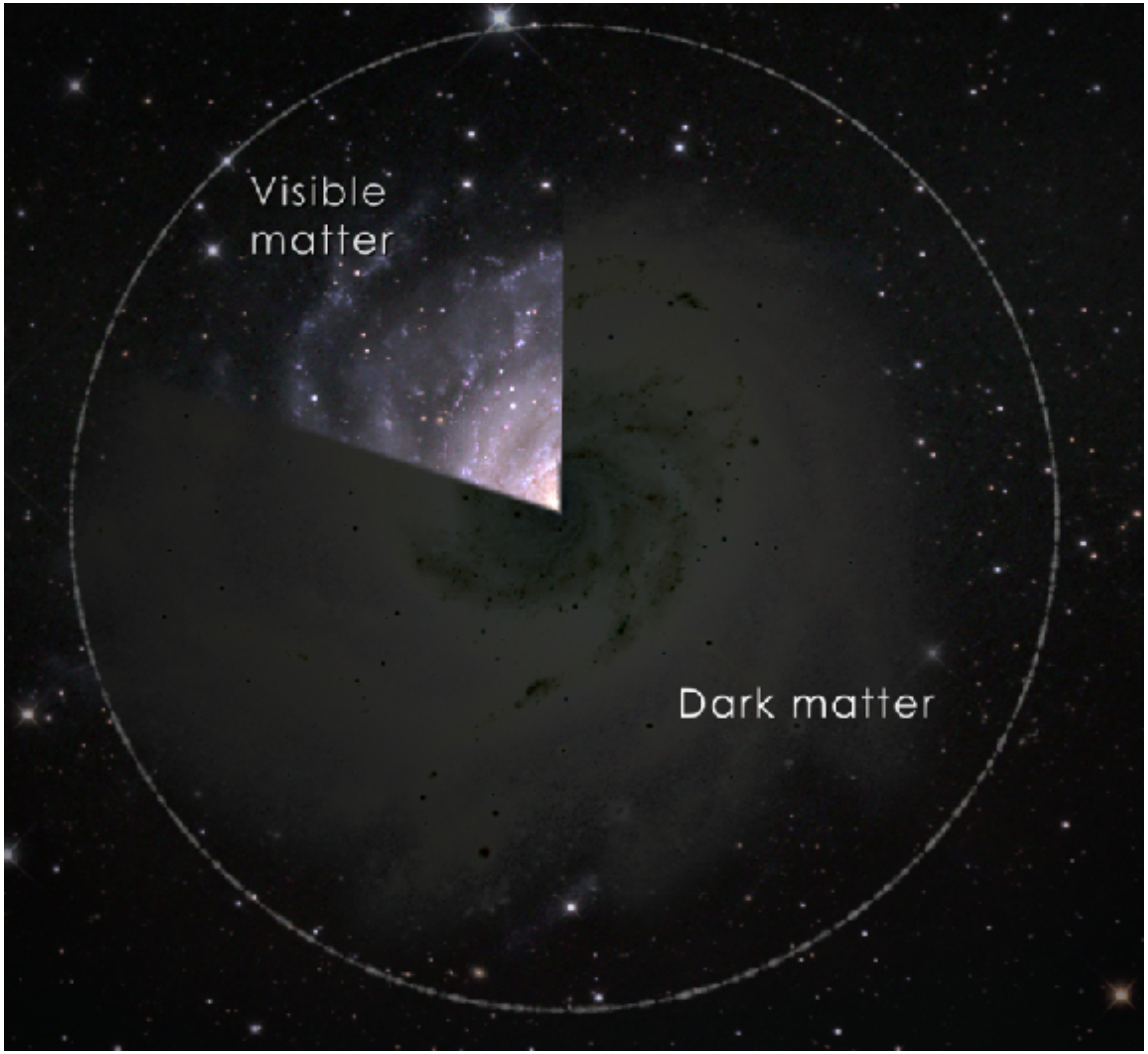
What we see is only the tip of the iceberg!





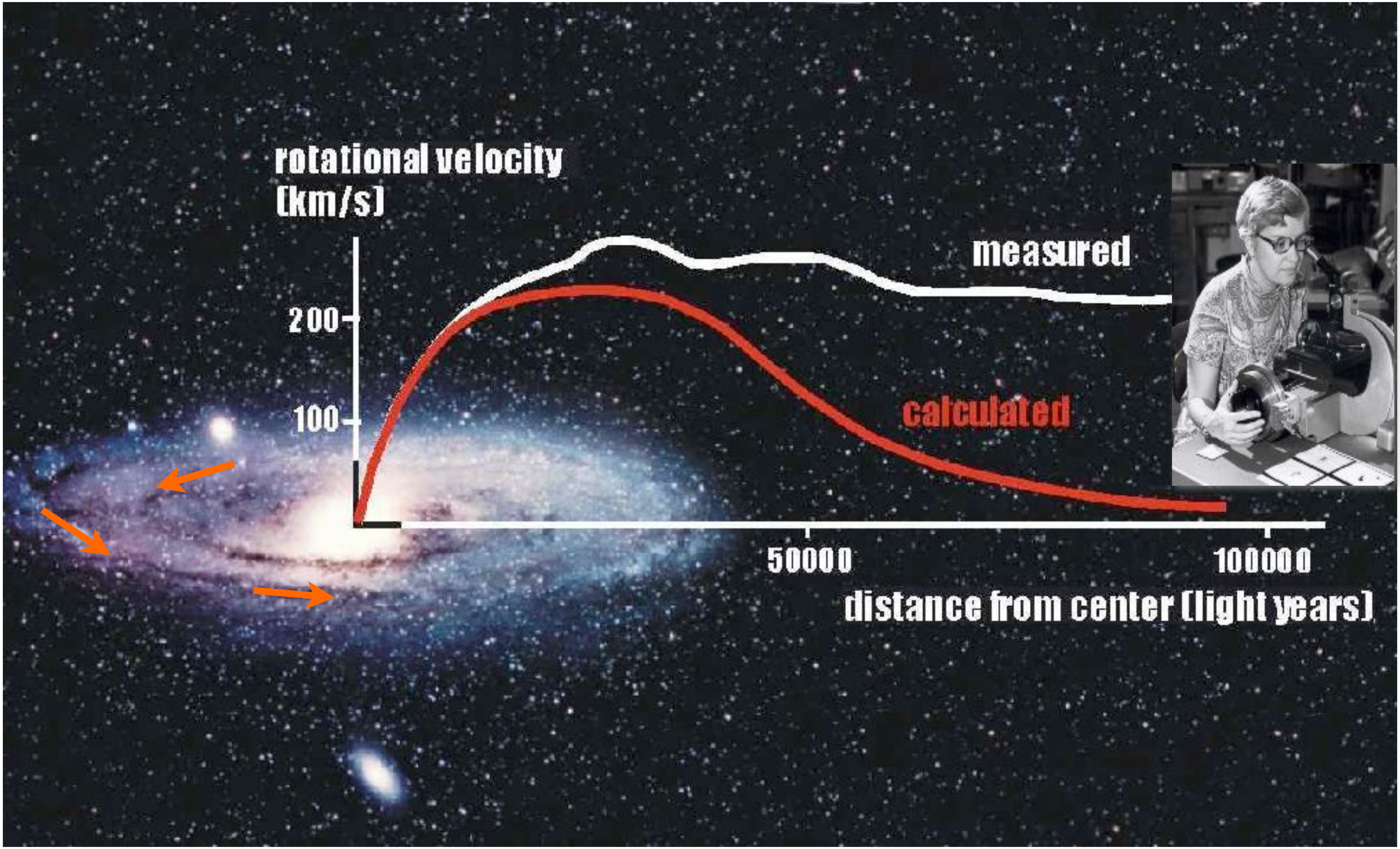


If 85% of the matter in the Universe is invisible how do we know it is there?



http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?

Evidence for Dark Matter from Galactic Rotation Curves



www.universetoday.com

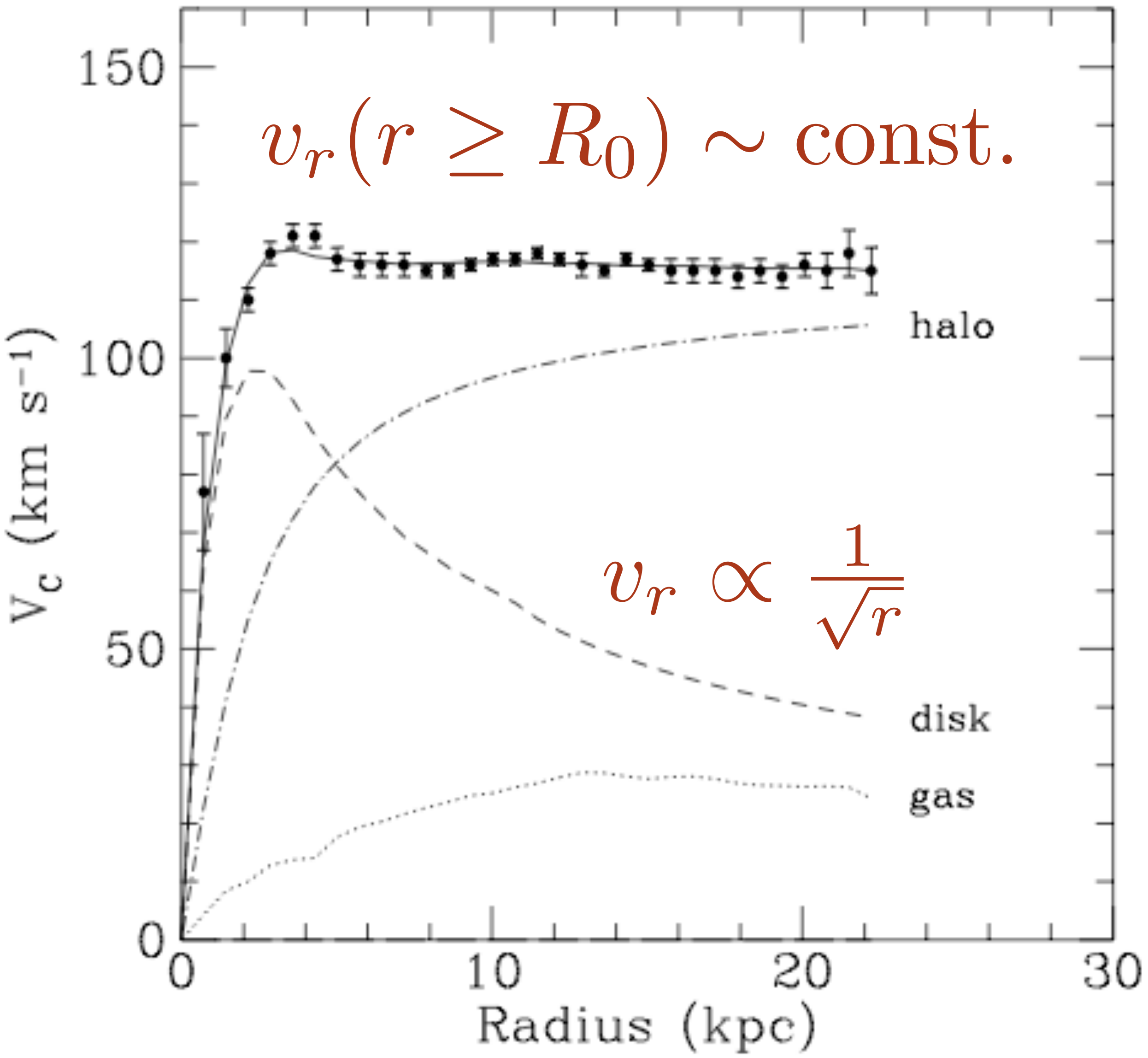
Galactic Rotation Curve

- **Expectations:** from centrifugal force = gravitational attraction **(M_r = total mass interior to r)**

$$\frac{mv_r^2}{2} = G\frac{M_r m}{r^2}$$

$$v_r^2 = G\frac{M_r}{r}$$

$$v_r = \sqrt{\frac{GM_r}{r}}$$



$$v_r(r \geq R_0) \sim \text{const.}$$

$$v_r \propto \frac{1}{\sqrt{r}}$$

- **Observations:**

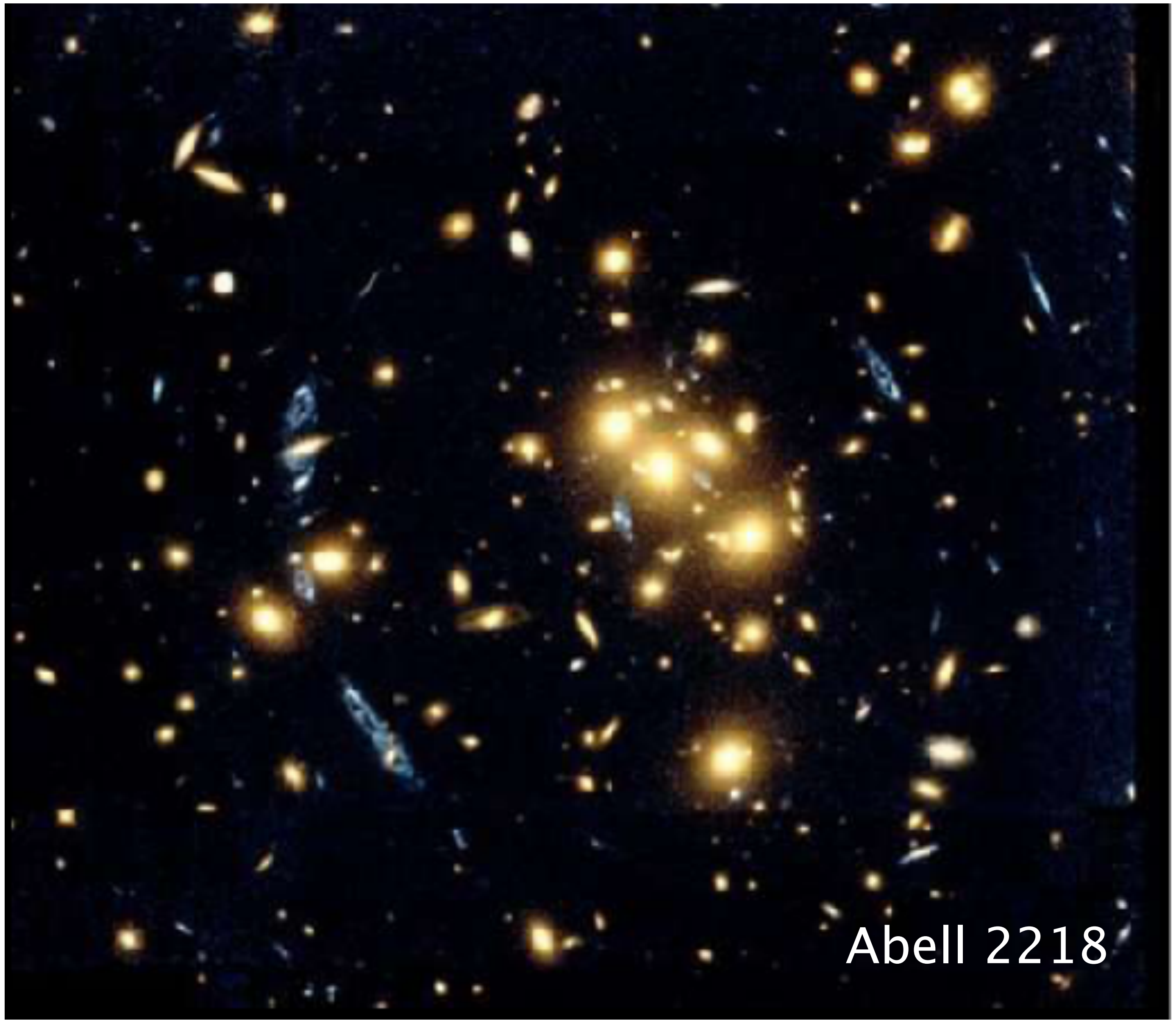
$$v_r(r \geq R_0) \approx \text{const.}$$

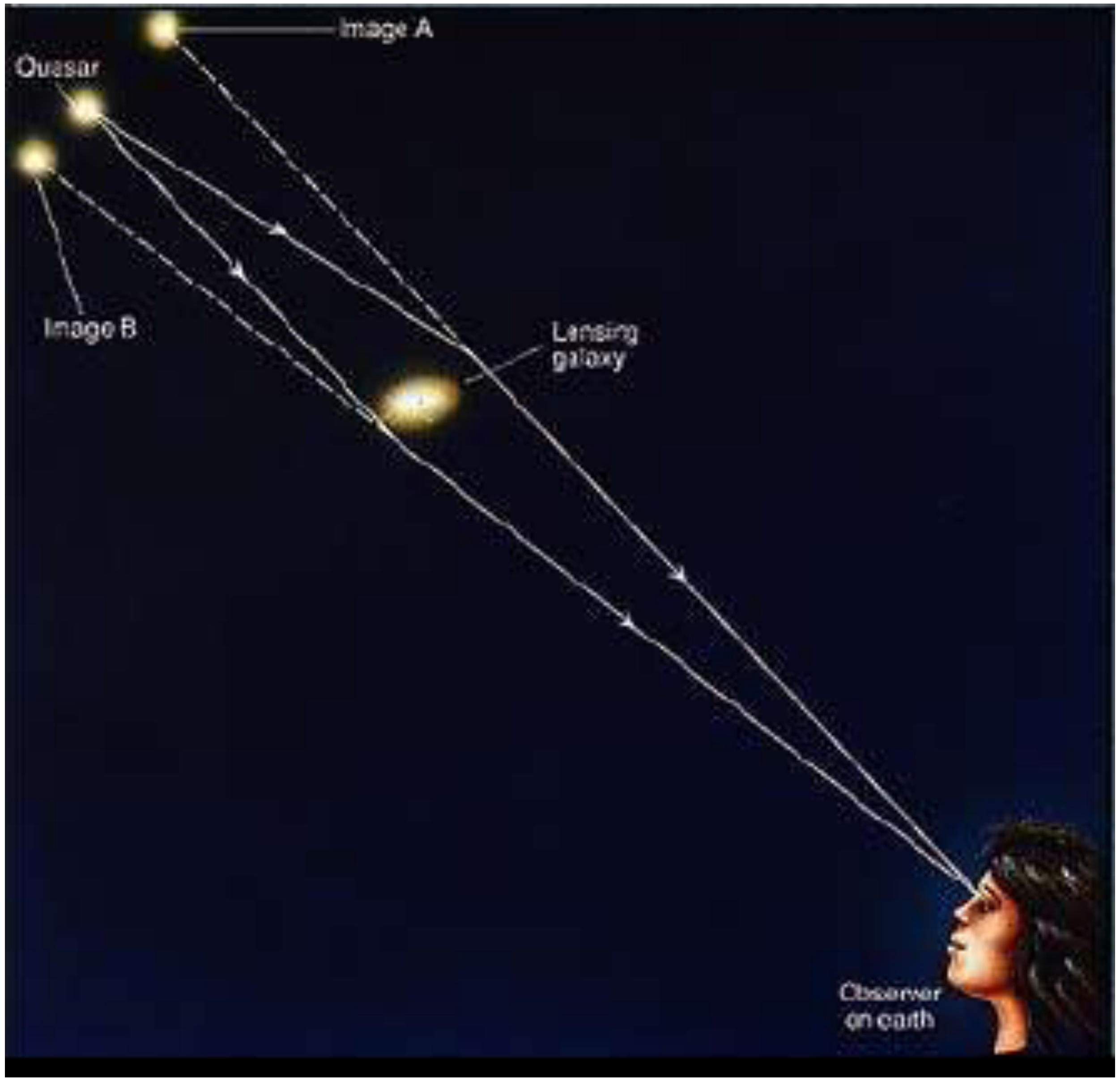
$$\Longrightarrow M_r \propto r$$

=> a non-visible mass component, which increases linearly with radius, must exist

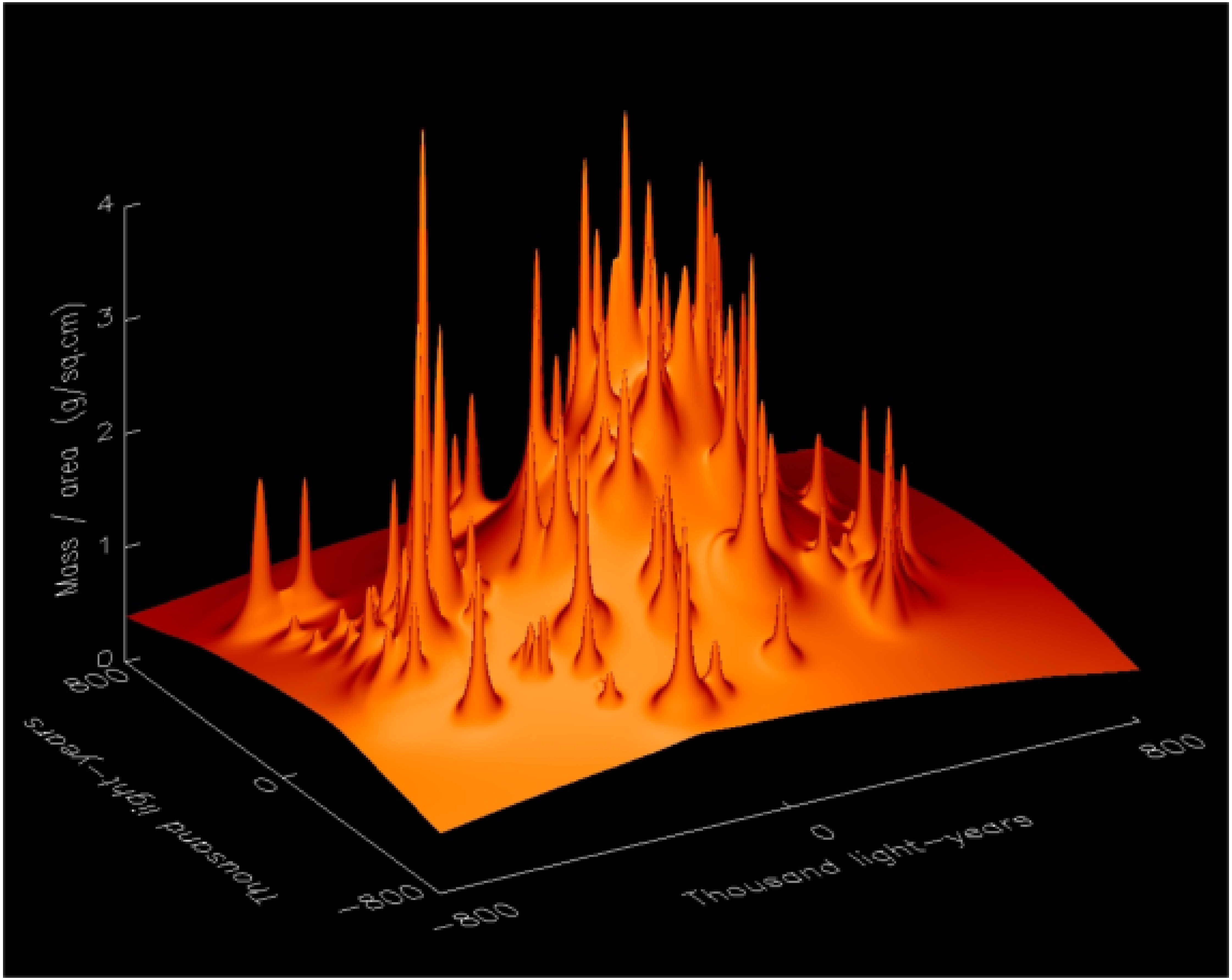
Evidence for Dark Matter from Gravitational Lensing

The gravitational field of a galaxy (or cluster of galaxies) deflects light. The more mass, the greater deflection



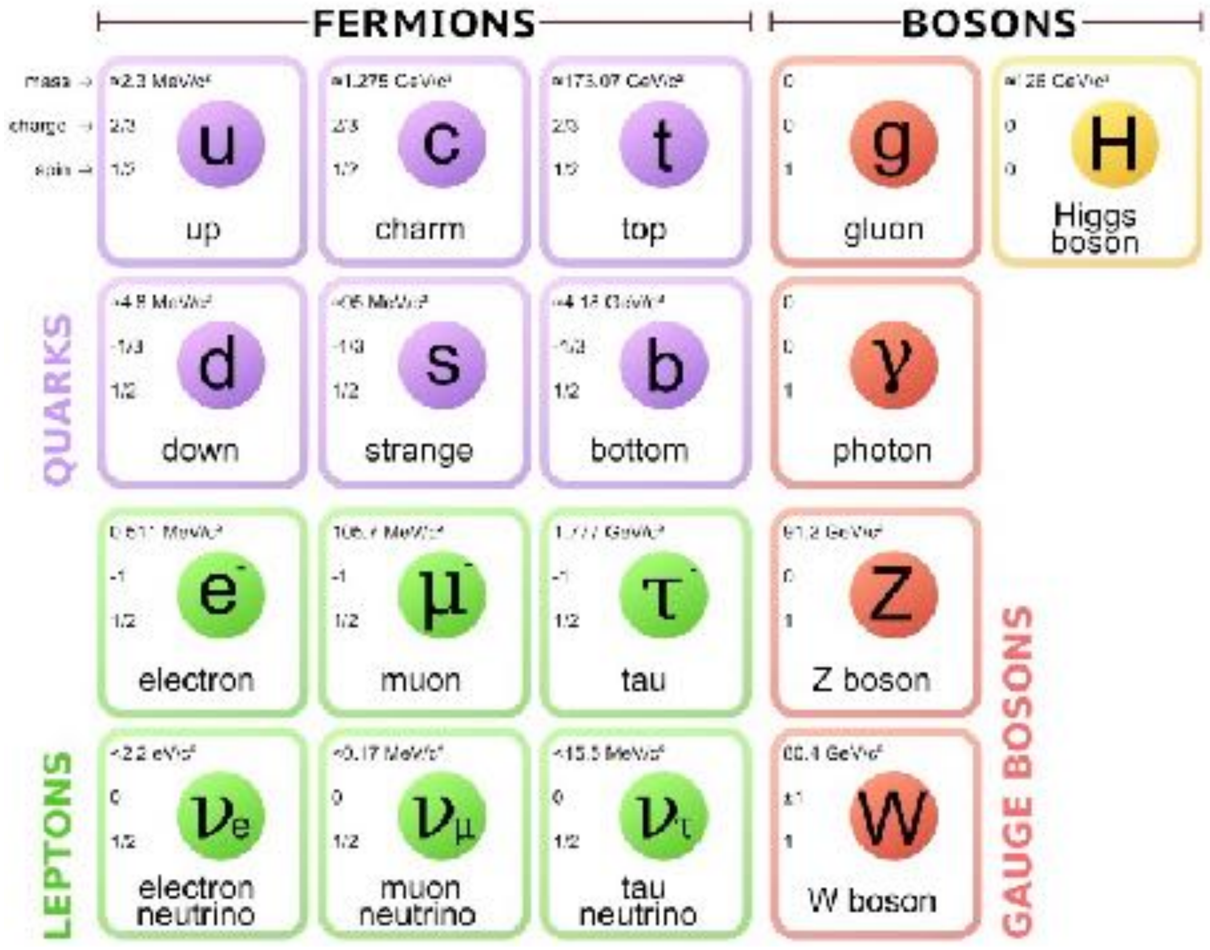


Mass reconstruction of the cluster. Note the large, smooth distribution of the invisible matter



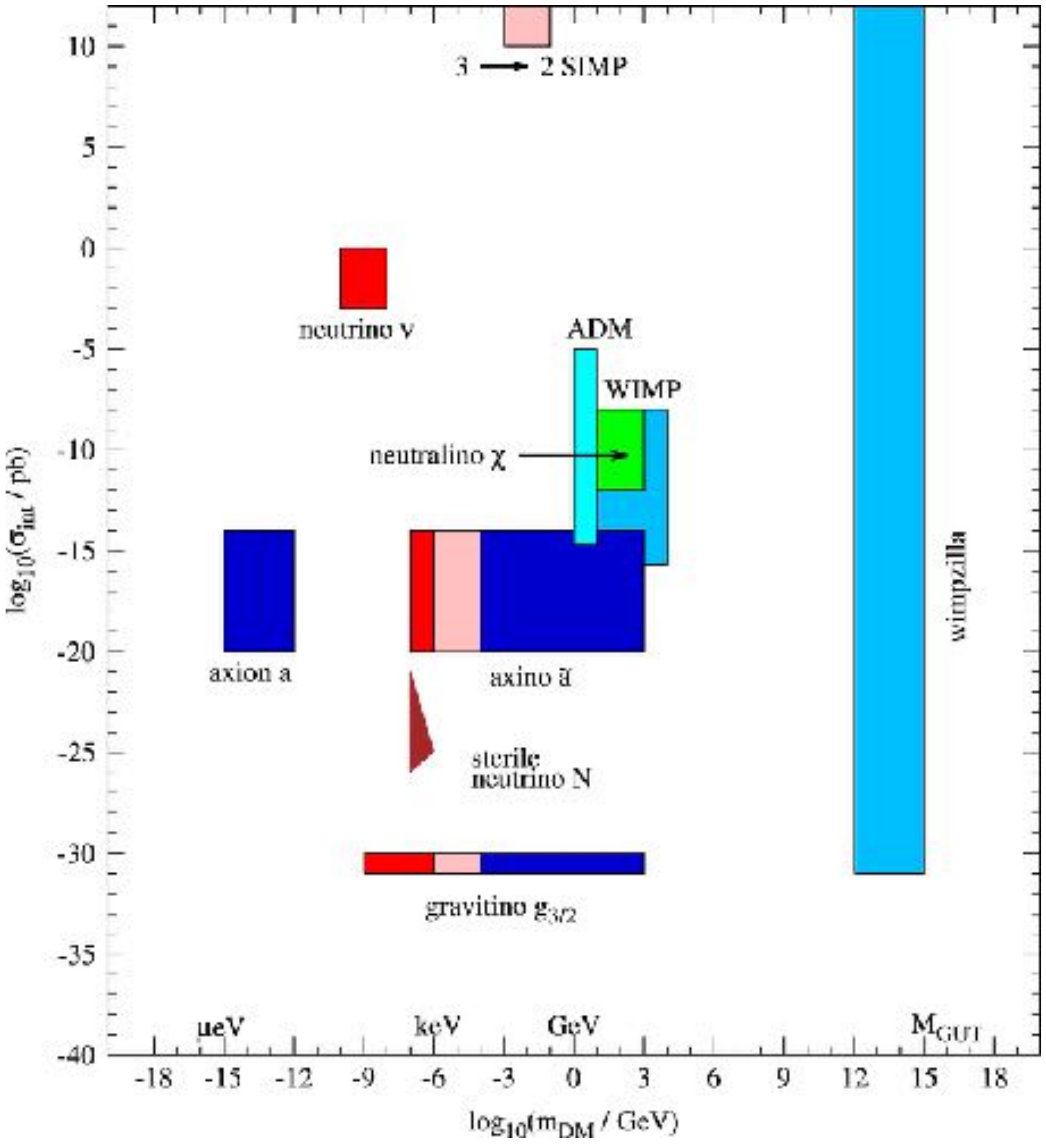
What do we know about Dark Matter?

- We know how much there is
- We know it is cold
- We know it is neutral
- We know it is non-baryonic
- We know it is stable



-> No Standard Model Particle

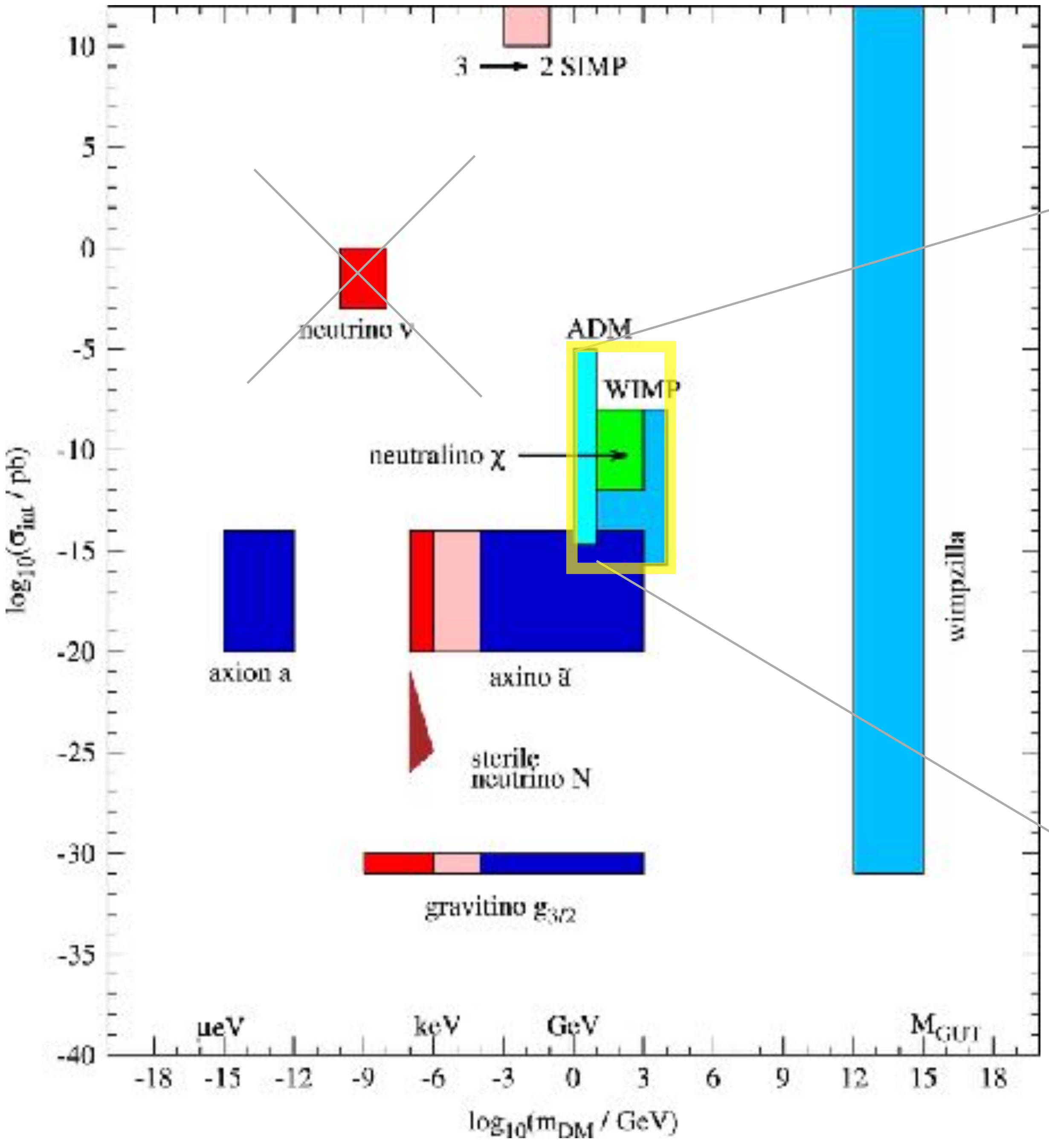
Dark Matter Candidates



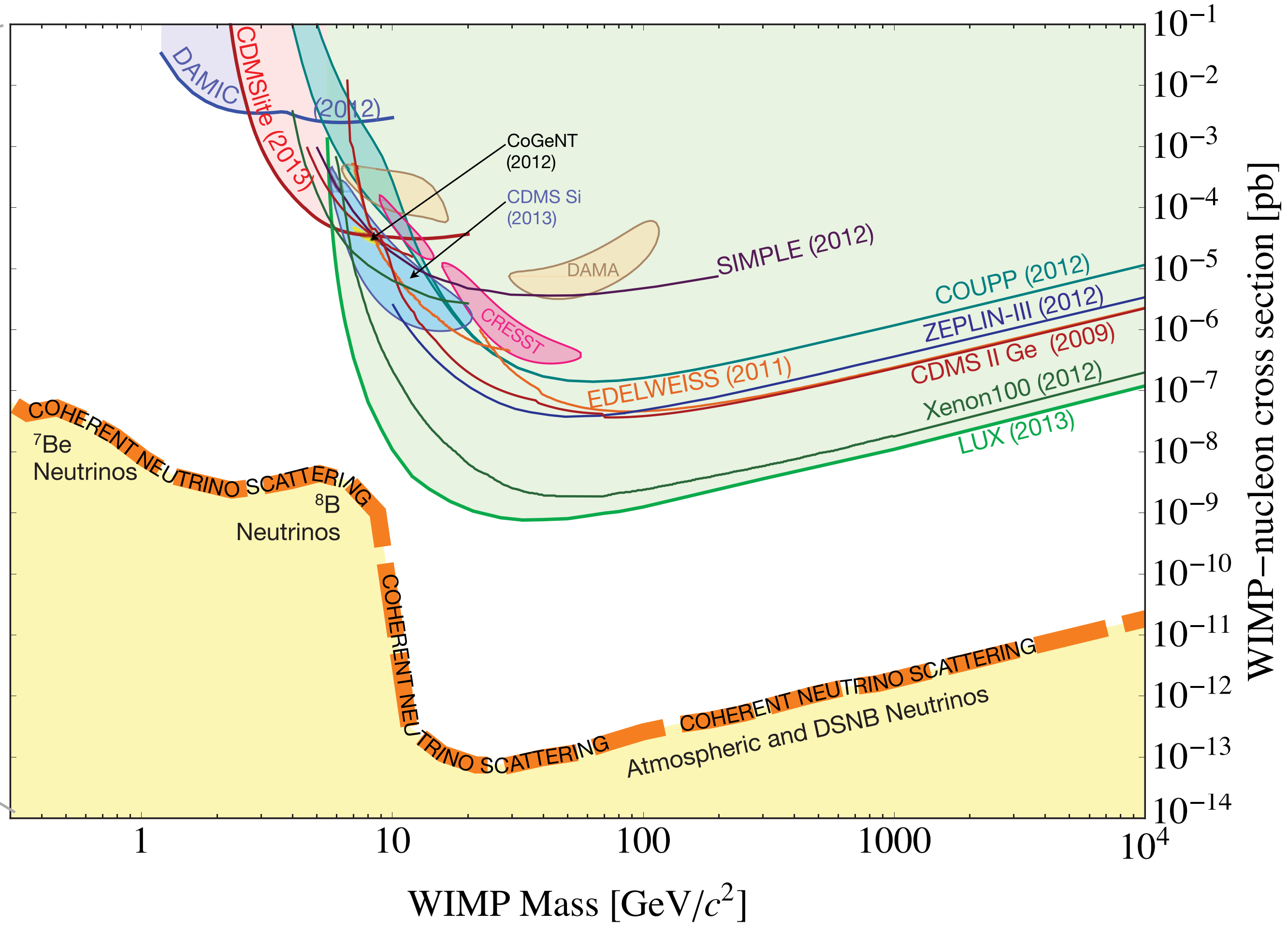
H. Baer et al., Phys. Rept. 555, 2014

- **Masses & interaction cross sections span an enormous range**
- Most dark matter experiments optimized to search for WIMPs
- However also searches for axions, ALPs, SuperWIMPs, etc

Dark Matter Candidates



WIMP direct searches



H. Baer et al., Phys. Rept. 555, 2014

How to detect Weakly Interacting Massive Particles

Direct detection

nuclear recoils from elastic scattering

dependance on A, J; annual modulation, directionality

local density and v-distribution

Indirect detection

high-energy neutrinos, gammas, charged CRs

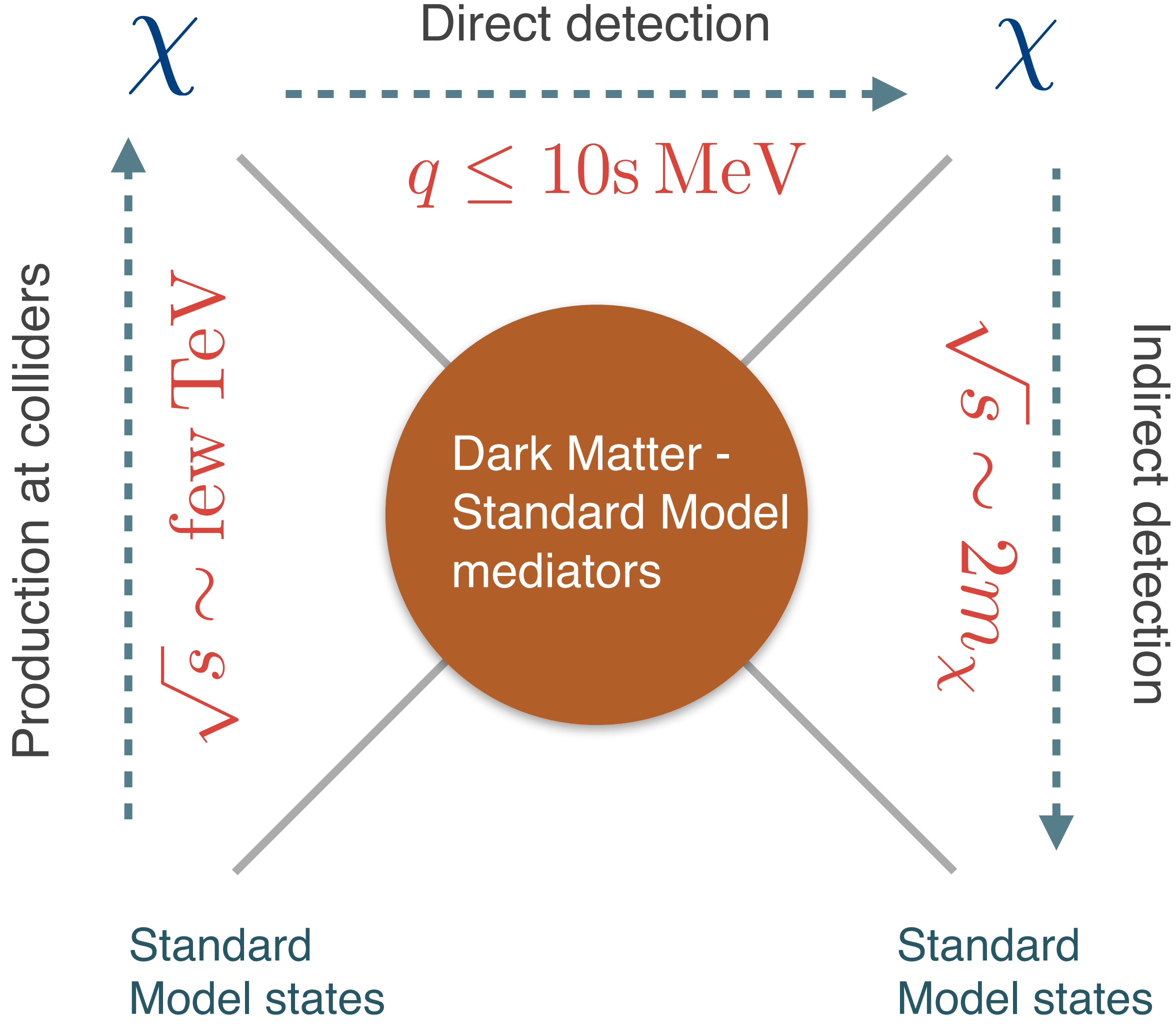
look at over-dense regions in the sky

astrophysics backgrounds difficult

Accelerator searches

missing E_T, mono-‘objects’, etc

can it establish that the new particle is the DM?



χ

Direct detection

χ

$q \leq 10\text{s MeV}$

Production at colliders

$\sqrt{s} \sim \text{few TeV}$

Dark Matter - Standard Model mediators

$\sqrt{s} \sim 2m_\chi$

Indirect detection

Standard Model states

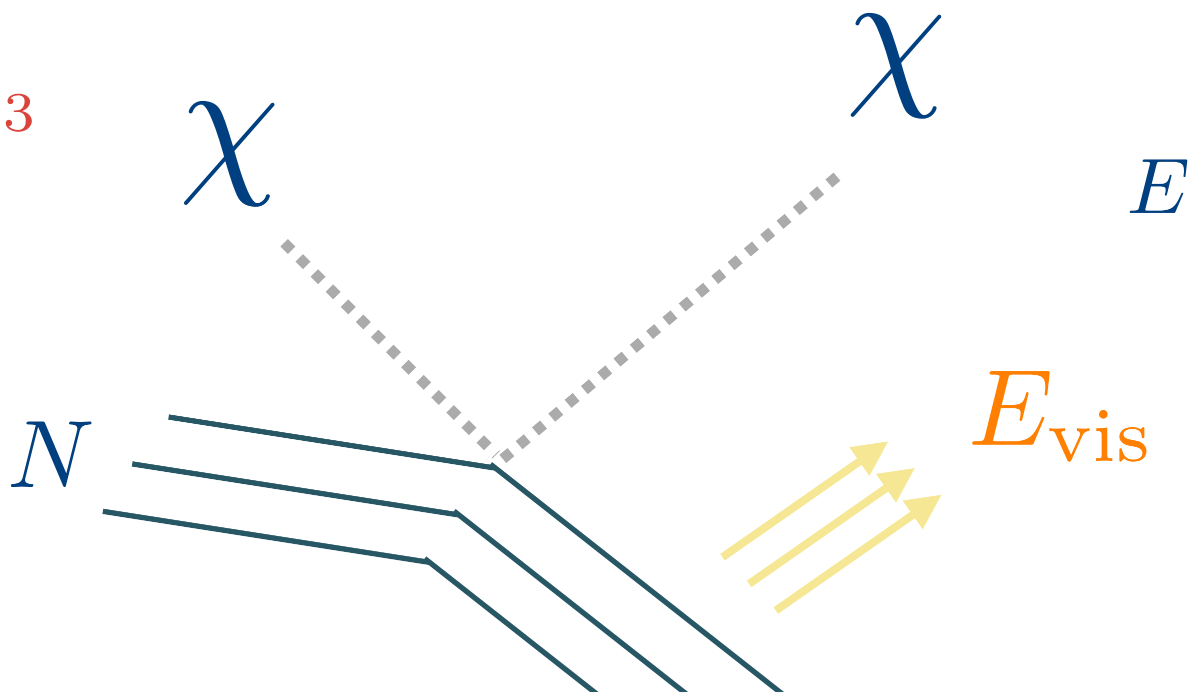
Standard Model states

Direct detection

Collisions of invisibles particles with atomic nuclei

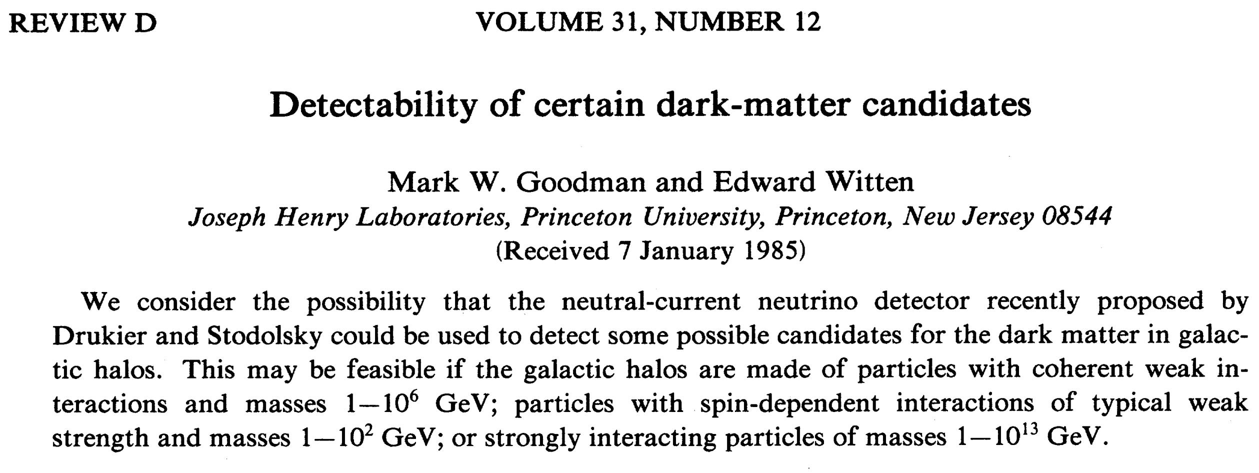
=> E_{vis} (q ~ tens of MeV):

$v/c \sim 0.75 \times 10^{-3}$



$$E_R = \frac{q^2}{2m_N} < 30\,\mathrm{keV}$$

Observable: kinetic energy of the recoiling nucleus


REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Expected Rates in a Detector

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Detector physics

N_N, E_{th}

Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$

- **Minimum velocity = the velocity that is required to produce a recoil of energy E_R**

$$v_{min} = \sqrt{\frac{2E_R}{r \cdot m_\chi}} = \sqrt{\frac{E_R m_N}{2\mu^2}} = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_R}{2m_N}}$$

Expected Rates in a Detector

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$m_W, d\sigma/dE_R$

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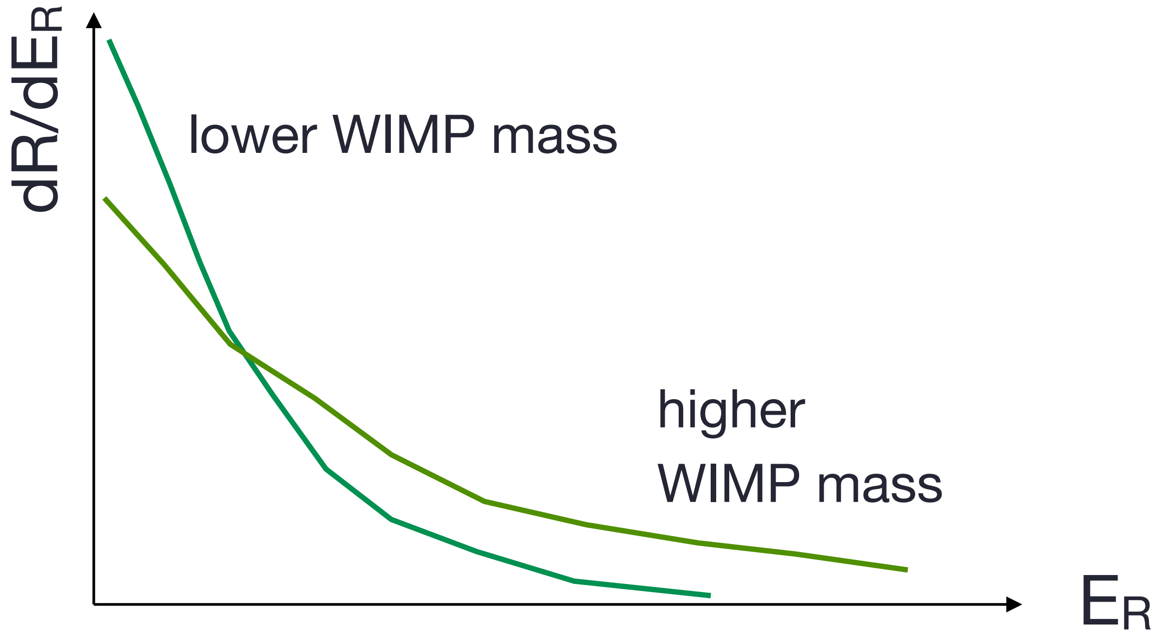
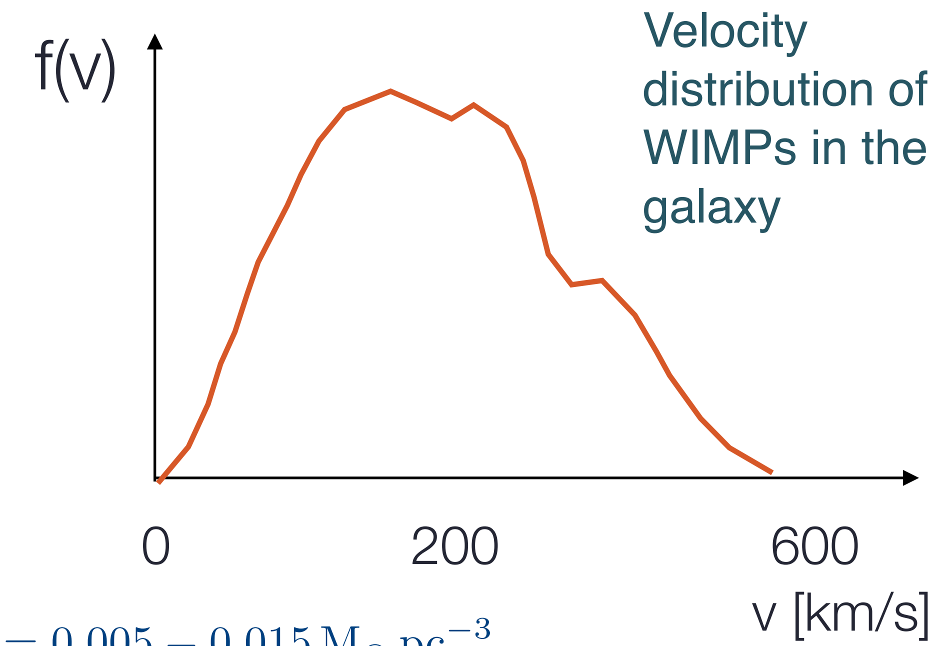
$\rho_0, f(v)$





Velocity distribution of WIMPs in the galaxy

$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$

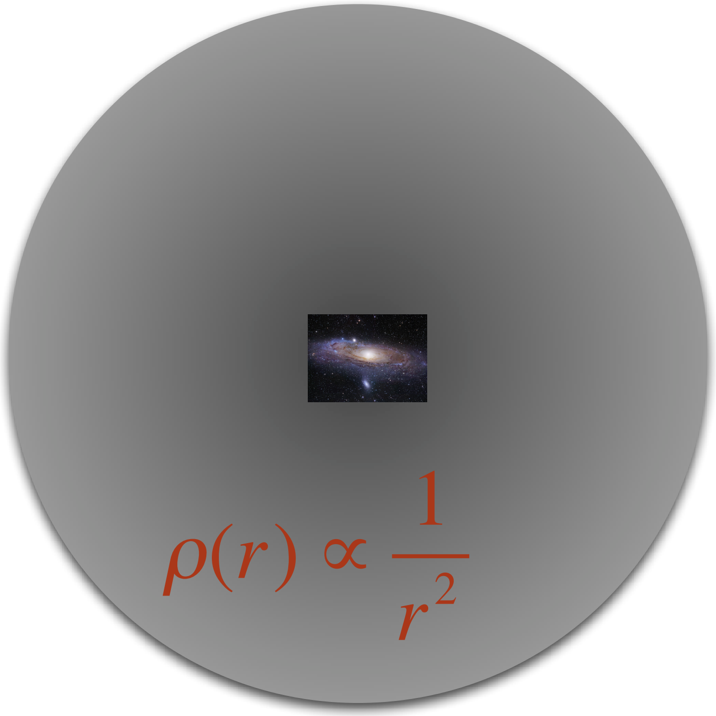
The Standard Halo Model

- **The standard parameter values used for the SHM are the following:**

- local density

$$\rho_0 \equiv \rho(R_0) = 0.3\,\mathrm{GeV\,cm^{-3}}$$

$$\rho_0 = 0.008 M_{\odot} \mathrm{pc}^{-3} = 5 \times 10^{-25} \mathrm{g\,cm^{-3}}$$



$$\rho(r) \propto \frac{1}{r^2}$$

- local circular speed

$$v_{\mathrm{c}} = 220\,\mathrm{km\,s^{-1}}$$

- local escape speed

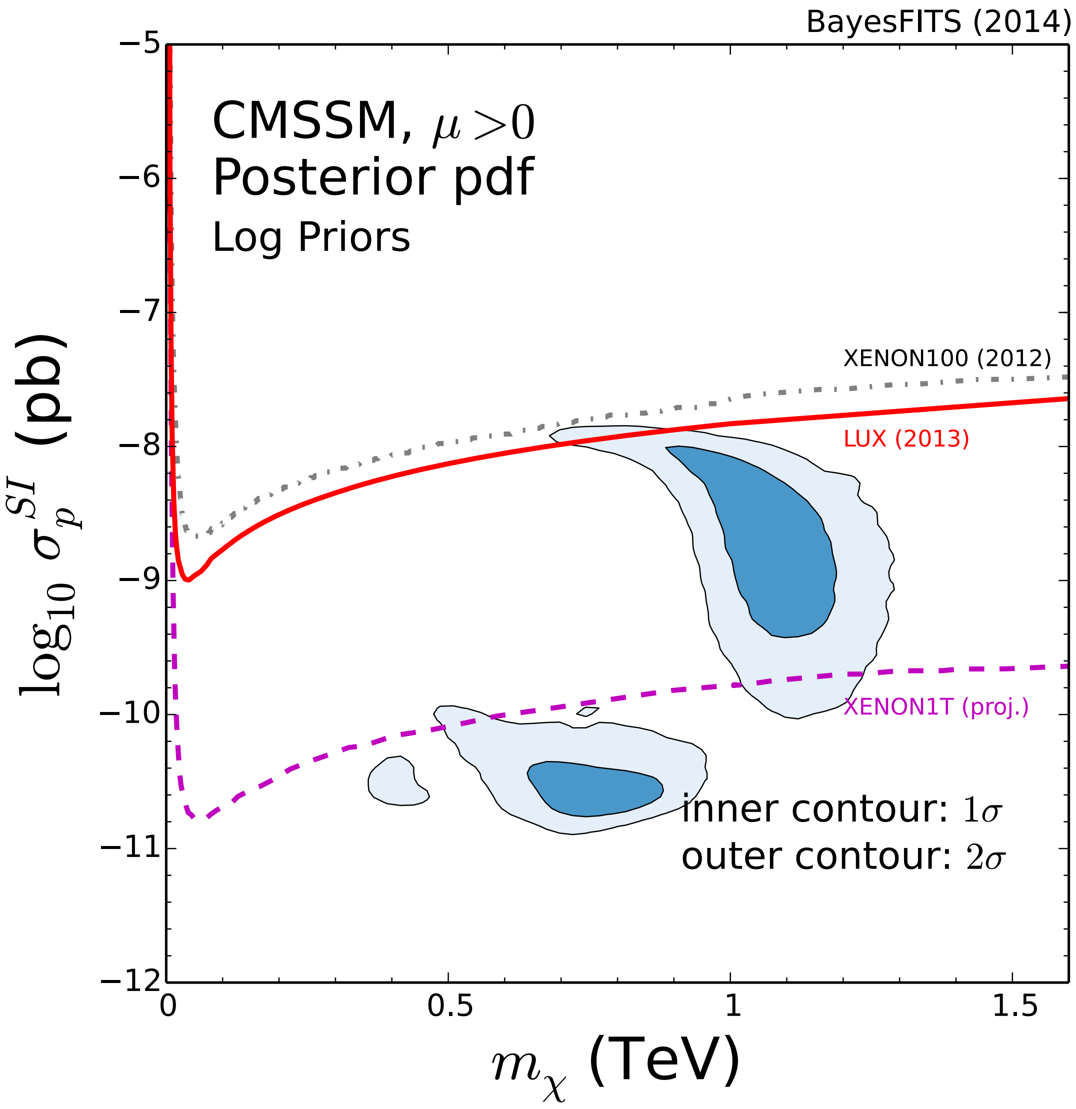
$$v_{\mathrm{esc}} = 544\,\mathrm{km\,s^{-1}}$$

- The escape speed is the speed required to escape the local gravitational field of the MW, and the local escape speed is estimated from the speeds of high velocity stars
- The RAVE survey has measured:

$$498\,\mathrm{km\,s^{-1}} < v_{esc} < 608\,\mathrm{km\,s^{-1}}$$

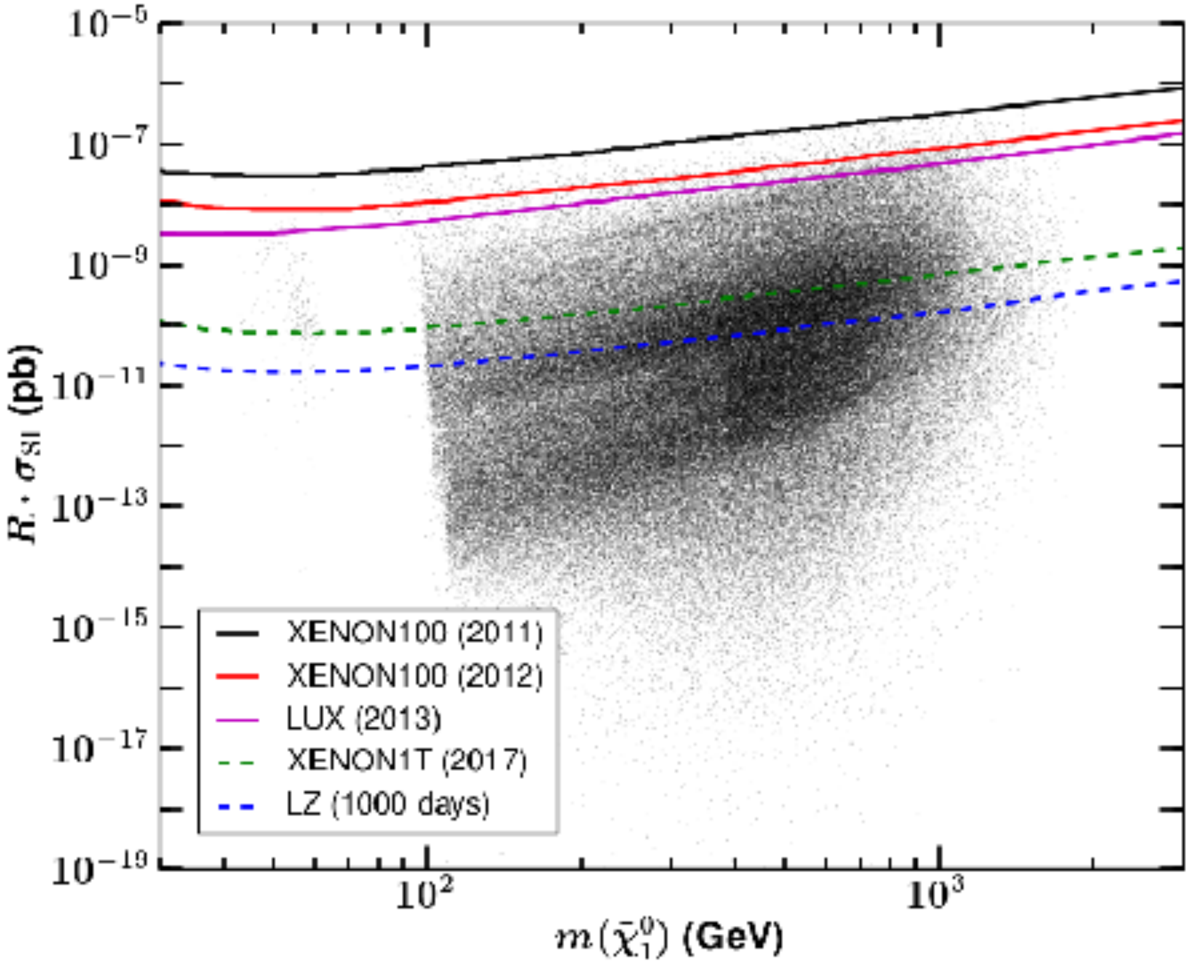
SUSY Predictions: 2 examples

CMSSM



L. Rozkowski, Stockholm 2015

pMSSM

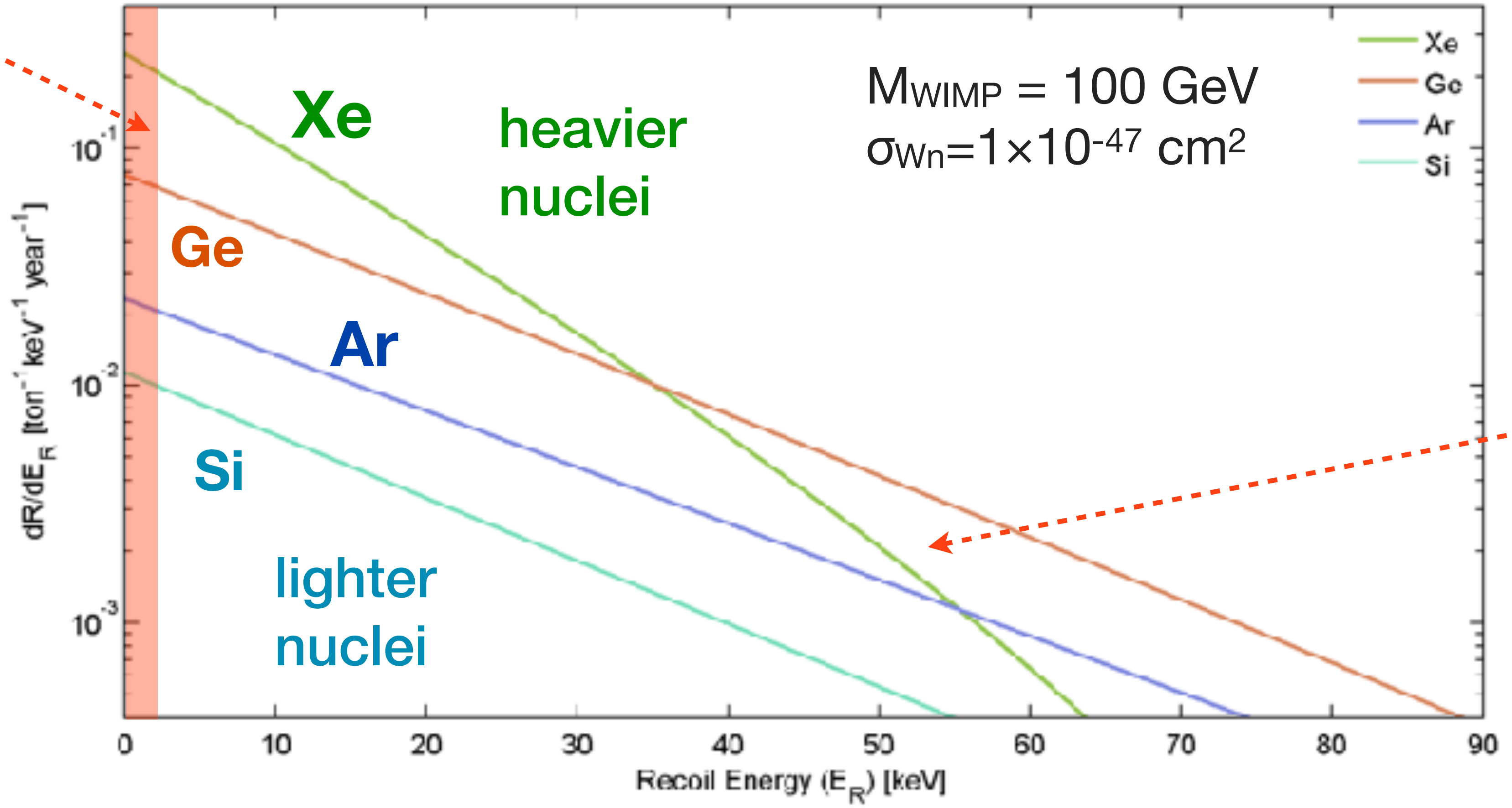


M. Cahill-Rowley, Phys.Rev. D91 (2015) 055011

Expected interaction rates

$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}}\left[\frac{A}{100}\times\frac{\sigma_{WN}}{10^{-38}\,\mathrm{cm}^2}\times\frac{\langle v\rangle}{220\,\mathrm{km\,s^{-1}}}\times\frac{\rho_0}{0.3\,\mathrm{GeV cm^{-3}}}\right]$$

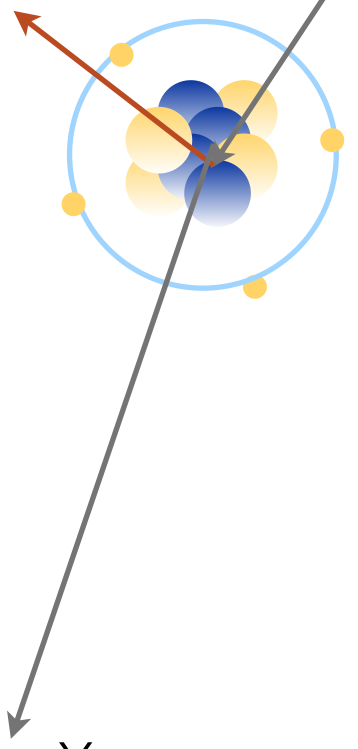
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$



$F^2(E_R)$

Detection of WIMPs: Signal and Backgrounds

Signal (WIMPs)



Recoiling nucleus

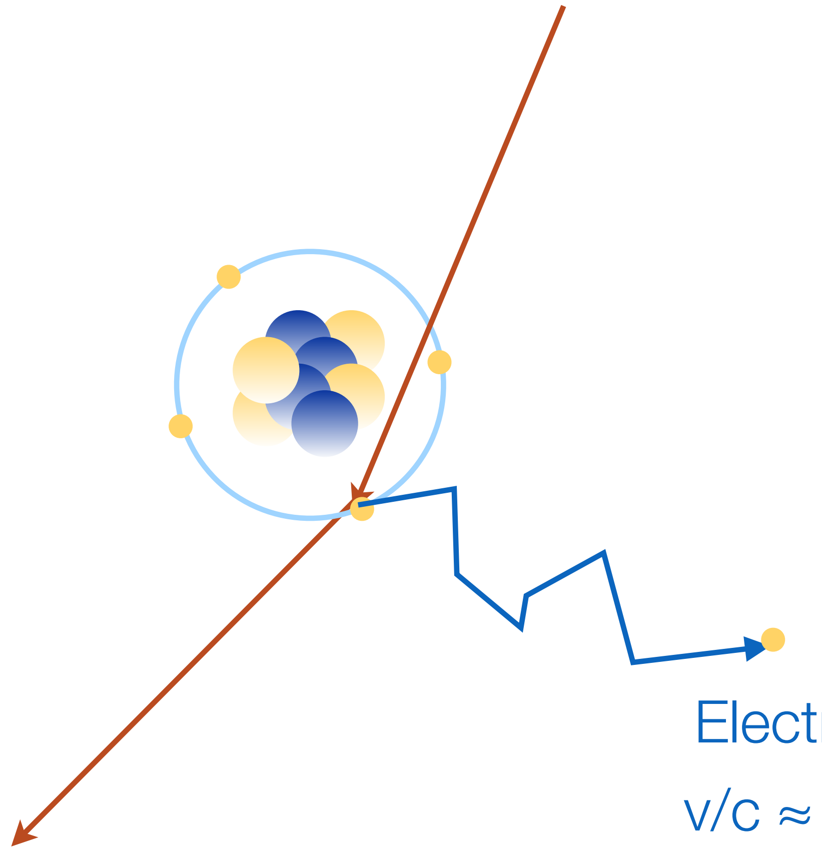
$v/c \approx 7 \times 10^{-4}$

$E_R \approx 10$ keV

X

X

Background (gamma-, beta-radiation)



gamma

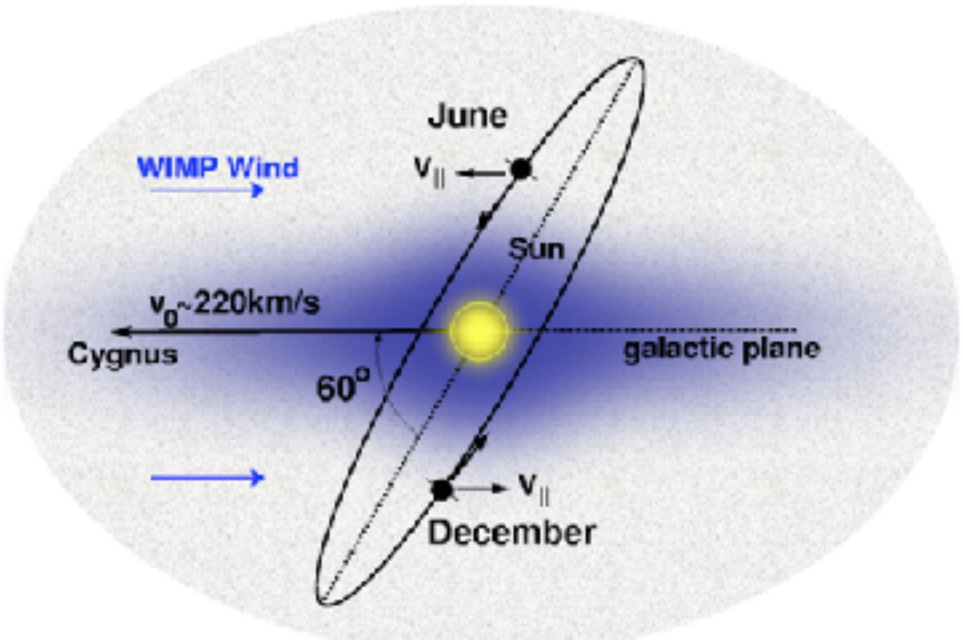
Electron

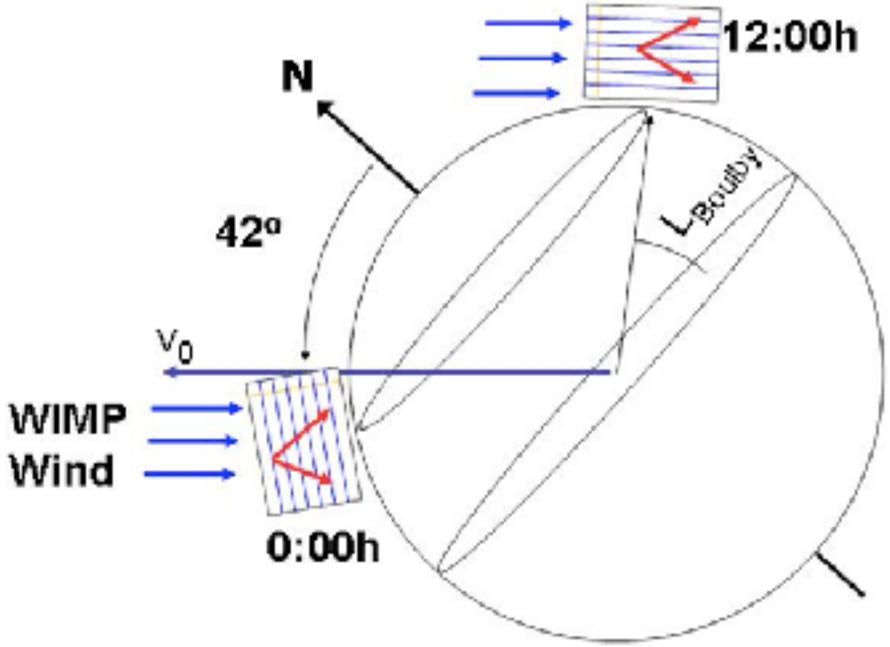
$v/c \approx 0.3$

gamma

WIMP Signatures

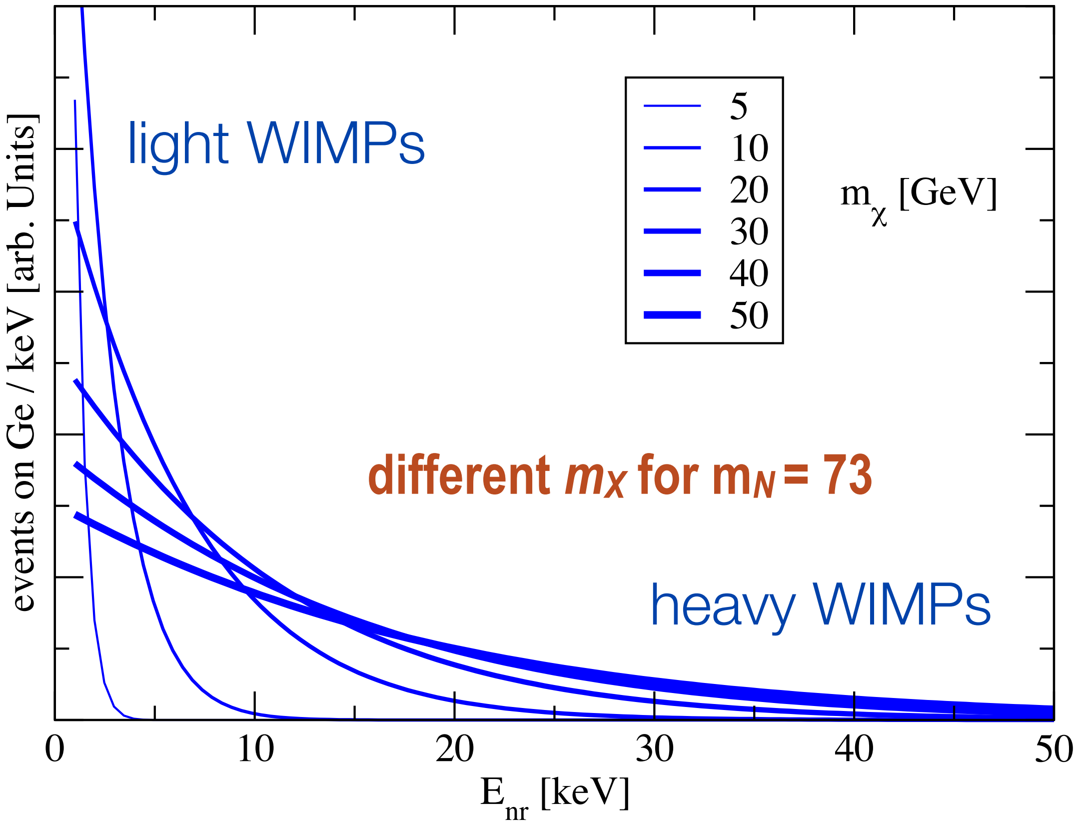
- Nuclear recoils: single scatters with uniform distribution in target volume
- A^2 & $F^2(Q)$ Dependence: we have seen that recoil rate is energy dependent due to kinematics and WIMP velocity distribution. Hence we can test consistency of signal with different targets (SI and SD)
- Annual Modulation: Earth annual rotation around Sun: orbital velocity has a component that is anti-parallel to WIMP wind in summer and parallel to it in winter. So apparent WIMP velocity (and hence the rate) will increase (decrease) with season: rate modulation with a period of 1 year and phase ~2 June; small effect (few %) among other effects which also have seasonal dependence
- Diurnal Direction Modulation: Earth rotation about its axis, oriented at angle w/respect to WIMP "wind" , change the signal direction by 90 degree every 12 hrs. ~30% effect.

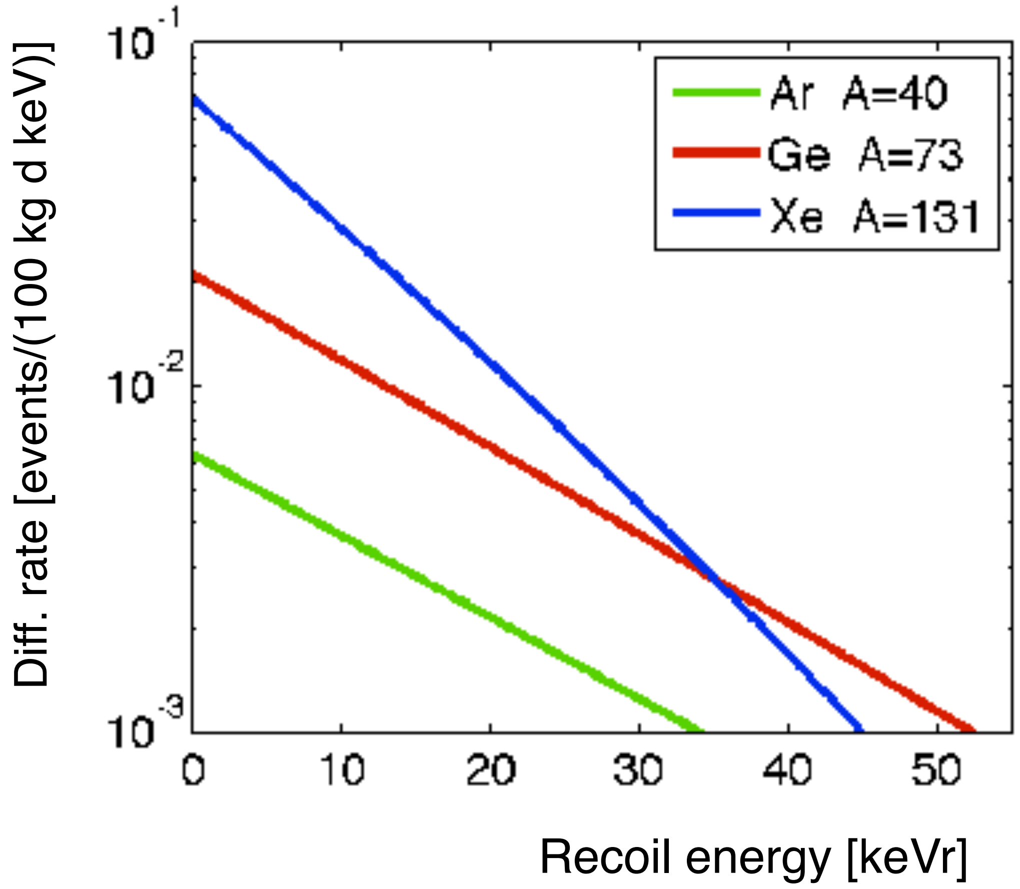




Summary: Signal Characteristics of a WIMP

- A^2 - dependence of rates
- coherence loss (for $q \sim \mu v \sim 1/r_n \sim 200$ MeV)
- relative rates, for instance in Ge/Si, Ar/Xe,...
- dependance on WIMP mass
- time dependence of the signal (annual, diurnal)





M_{WIMP} = 100 GeV
$\sigma_{WN}=1\times10^{-44}$ cm^2

(Standard halo model
with ρ= 0.3 GeV/cm^3)

Backgrounds in Dark Matter Detectors

- Radioactivity of surroundings
- Radioactivity of detector and shield materials
- Cosmic rays and secondary reactions

- Remember: activity of a source
- **Do you know?**

$$A = \frac{dN}{dt} = -\lambda N$$

N = number of radioactive nuclei
λ = decay constant, $T_{1/2} = \ln 2/\lambda = \ln 2\ \tau$
[A] = Bq = 1 decay/s (1Ci = 3.7×10^{10} decays/s = A [1g pure ^{226}Ra])

1. how much radioactivity (in Bq) is in your body? where from?

1. 4000 Bq from ^{14}C, 4000 Bq from ^{40}K (e^- + 400 1.4 MeV γ + 8000 ν_e)

2. how many radon atoms escape per 1 m^2 of ground, per s?

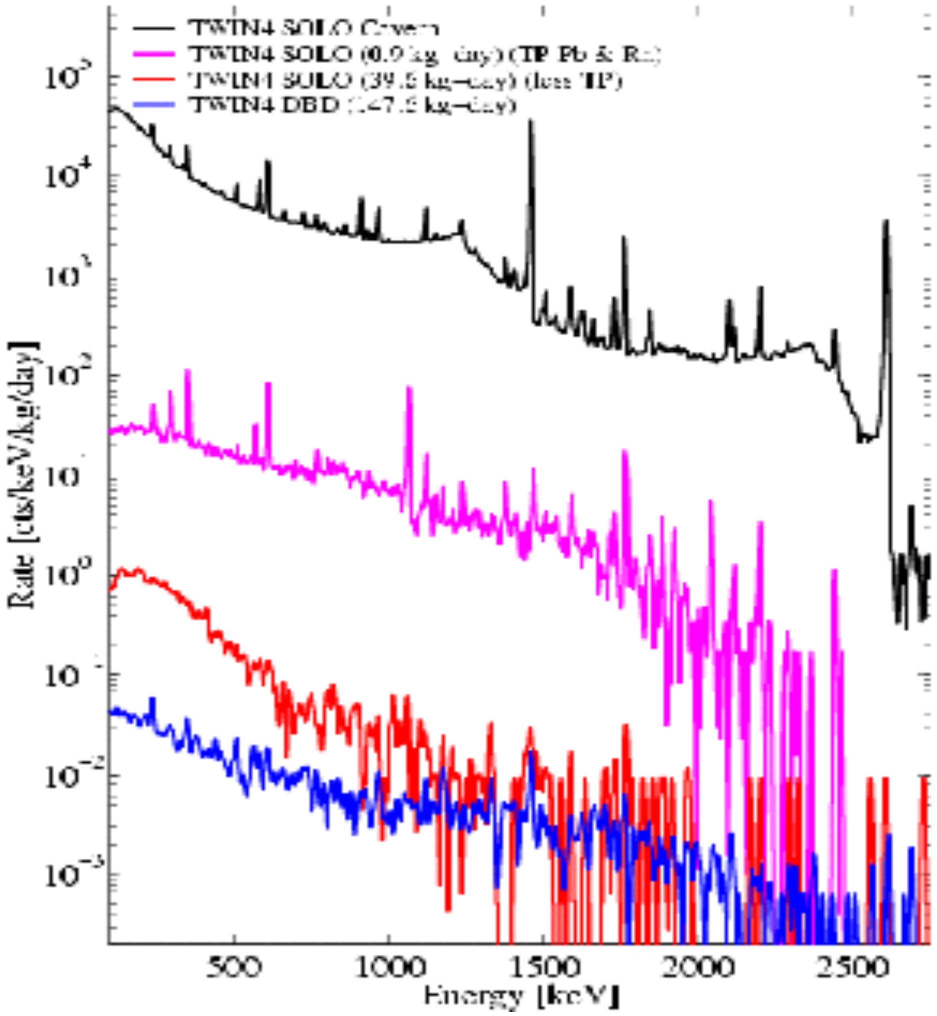
2. 7000 atoms/m^2 s

3. how many plutonium atoms you find in 1 kg of soil?

3. 10 millions (transmutation of ^{238}U by fast CR neutrons), soil: 1 - 3 mg U per kg

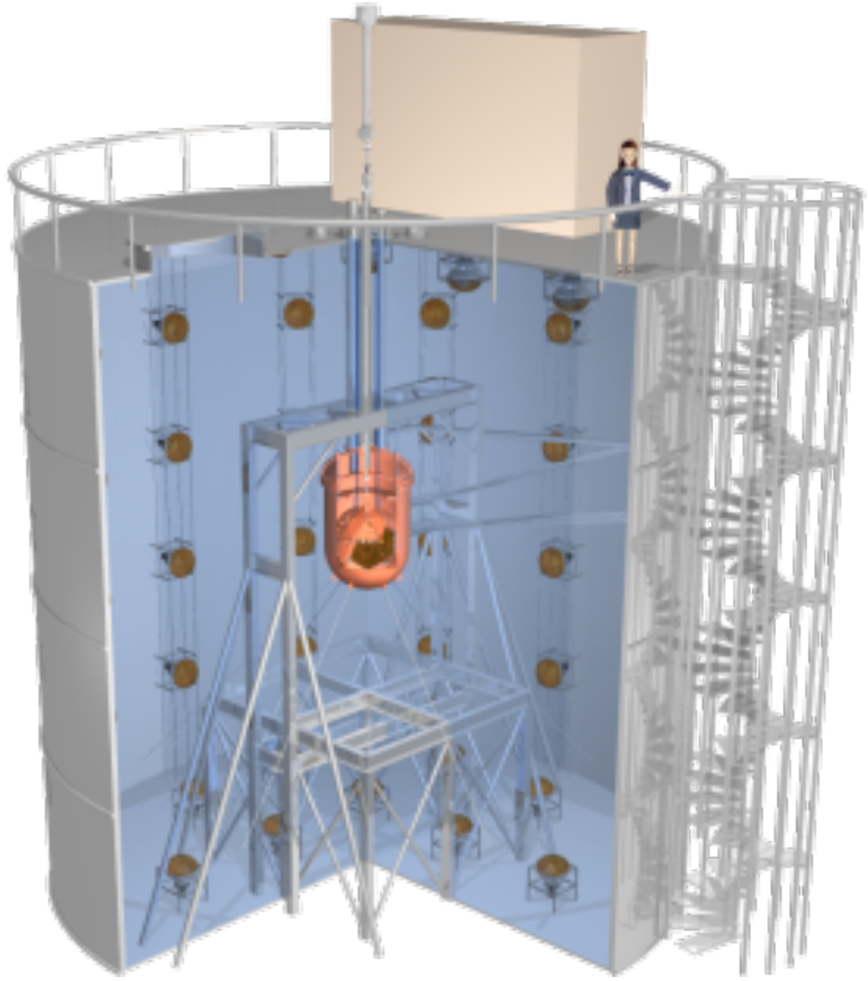
Backgrounds in Dark Matter Detectors

- External, natural radioactivity: ^{238}U, ^{238}Th, ^{40}K decays in rock and concrete walls of the laboratory => mostly gammas and neutrons from (α,n) and fission reactions
- Radon decays in air
  - ➡ passive shields: Pb against the gammas, polyethylene/water against neutrons
  - ➡ active shields: large water Cherenkov detectors or scintillators for gammas and neutrons



Ge detector underground, no shield

Ge detector underground, Pb shield and purge for Rn



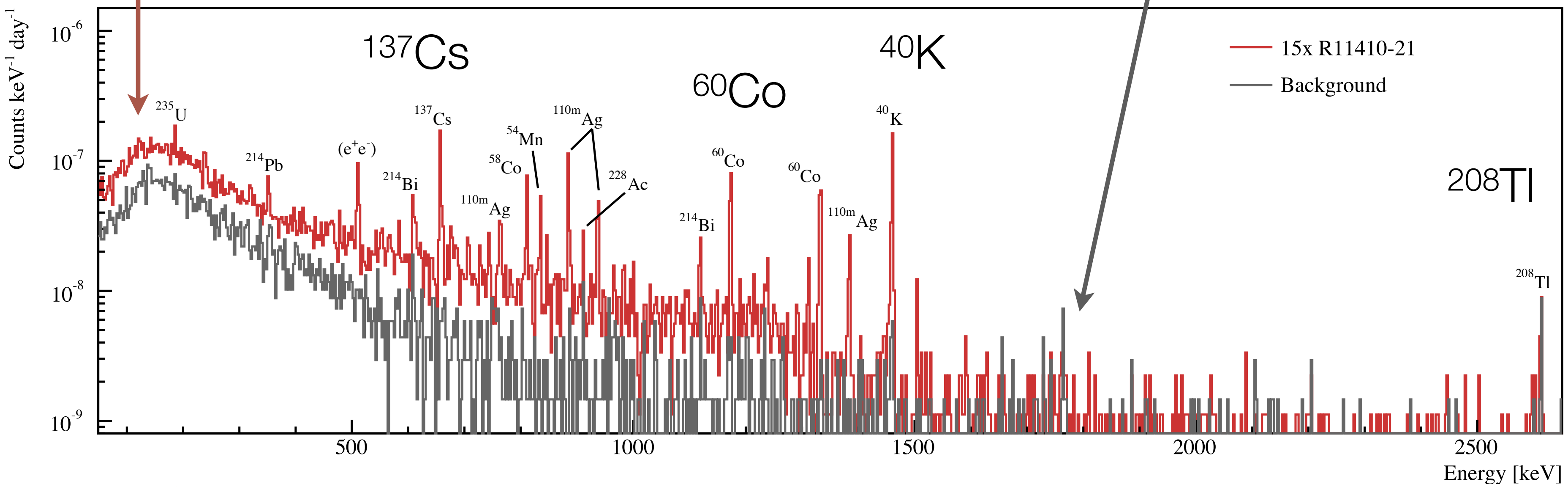
Backgrounds in Dark Matter Detectors

- **Internal radioactivity:**
- ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ... decays in the detector materials, target medium and shields
- Ultra-pure Ge spectrometers (as well as other methods) are used to screen the materials before using them in a detector, down to parts-per-billion (ppb) (or lower) levels

PMT sample

^{226}Ra/^{228}Th: ~1 mBq/PMT

HPGe detector background



^{137}Cs

^{60}Co

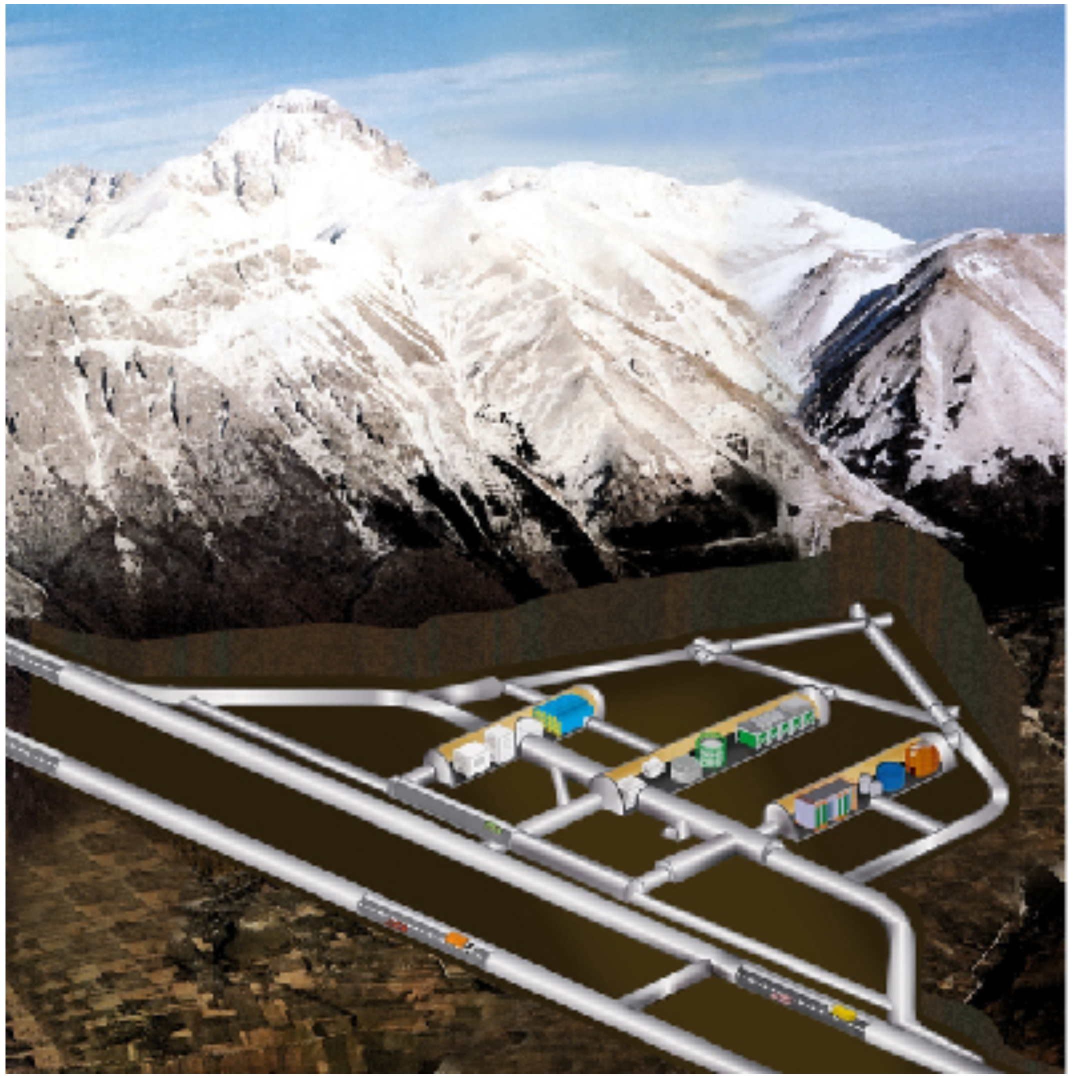
^{40}K

^{208}Tl

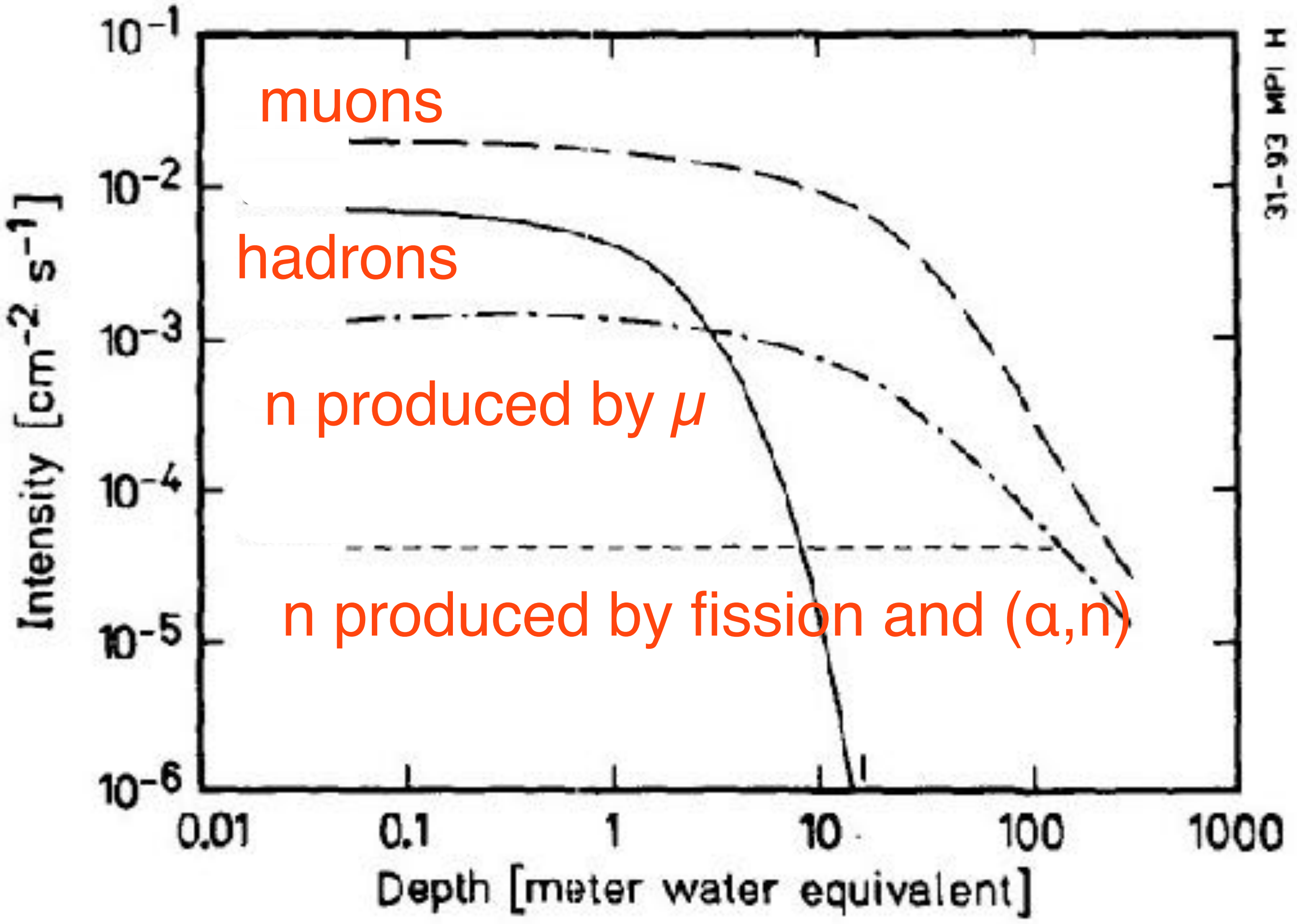
XENON collaboration, arXiv:1503.07698v1

Backgrounds in Dark Matter Detectors

- Cosmic rays and secondary/tertiary particles: go underground
- Hadronic component (n, p): reduced by few meter water equivalent (m w. e.)



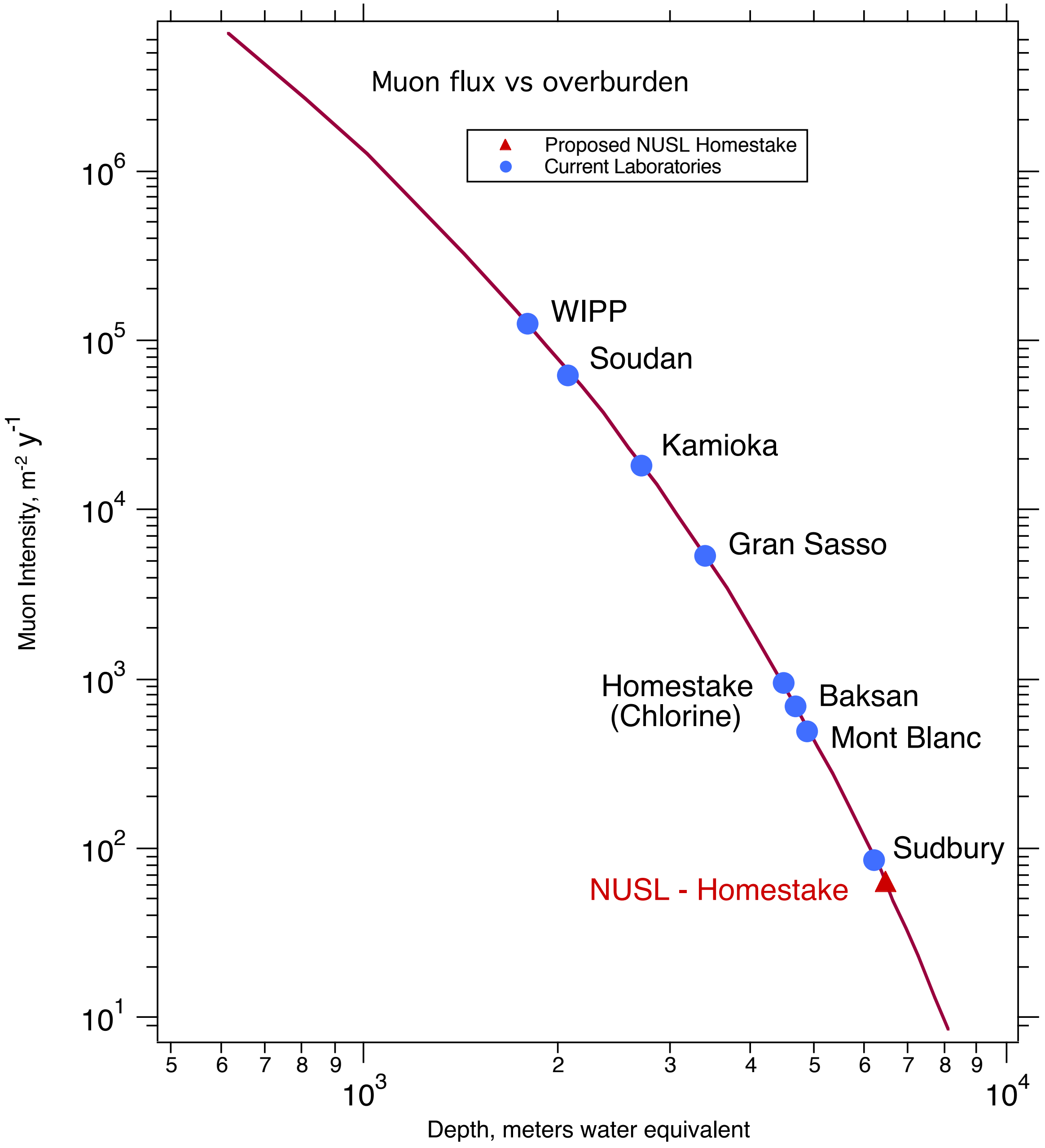
Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth
Gerd Heusser, 1995

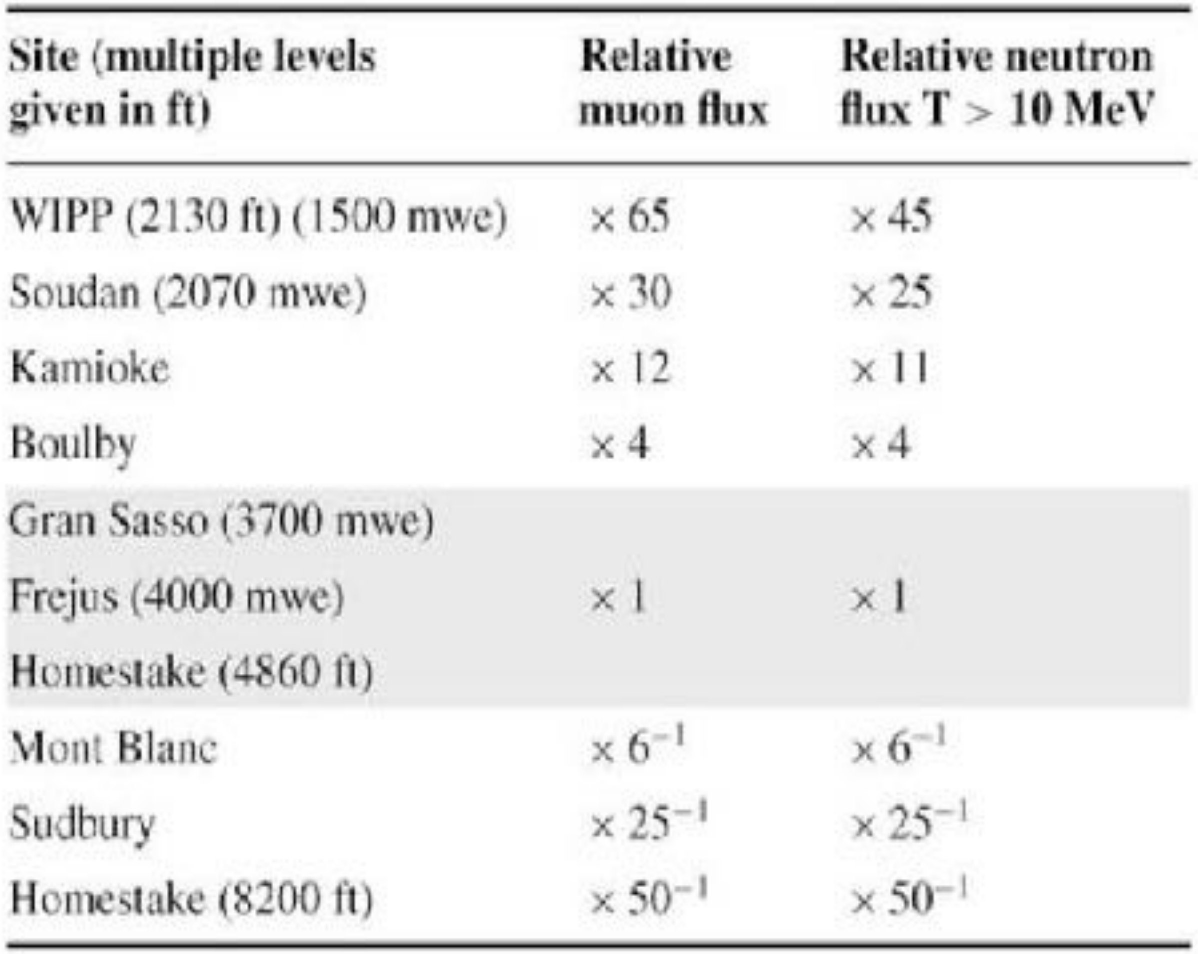


Backgrounds in Dark Matter Detectors

- **Most problematic:** muons and muon induced neutrons

➡ **go deep underground**, several laboratories, worldwide



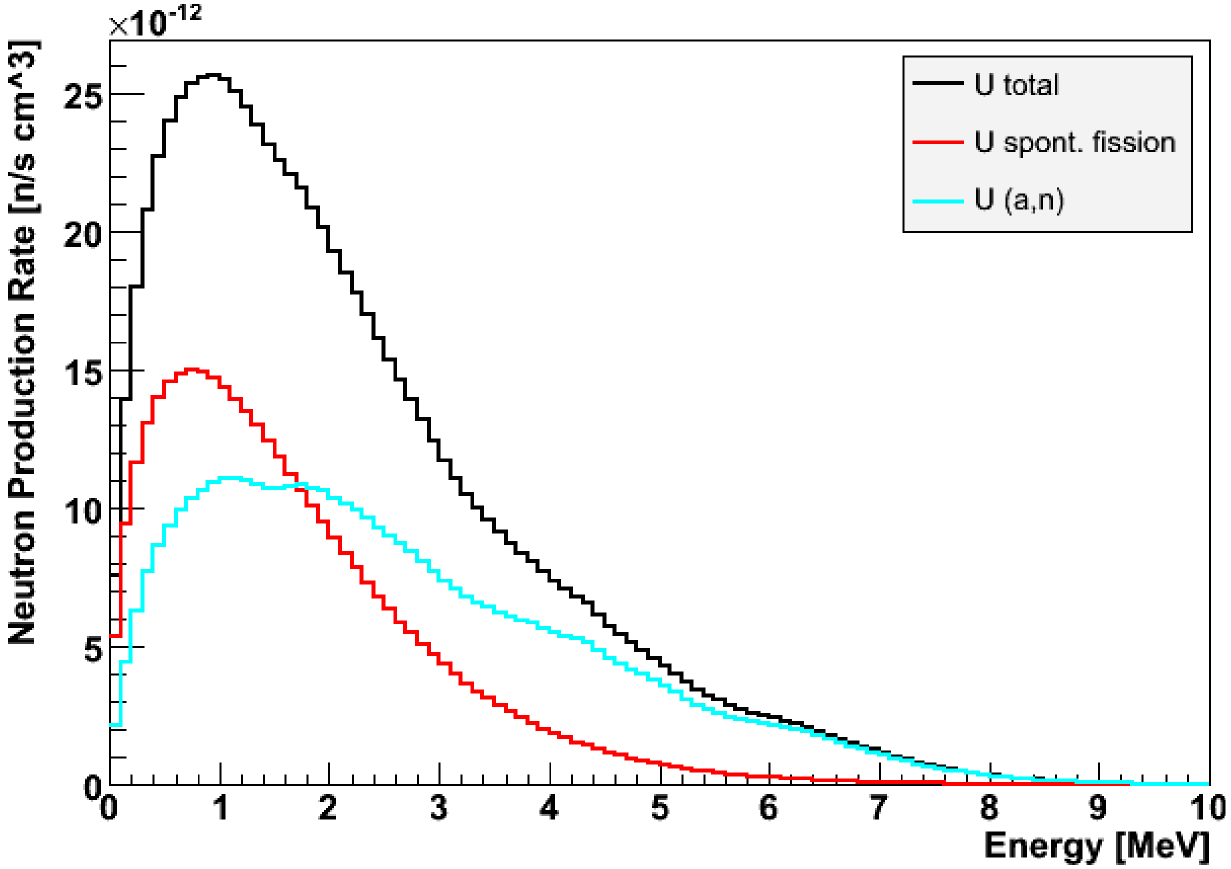


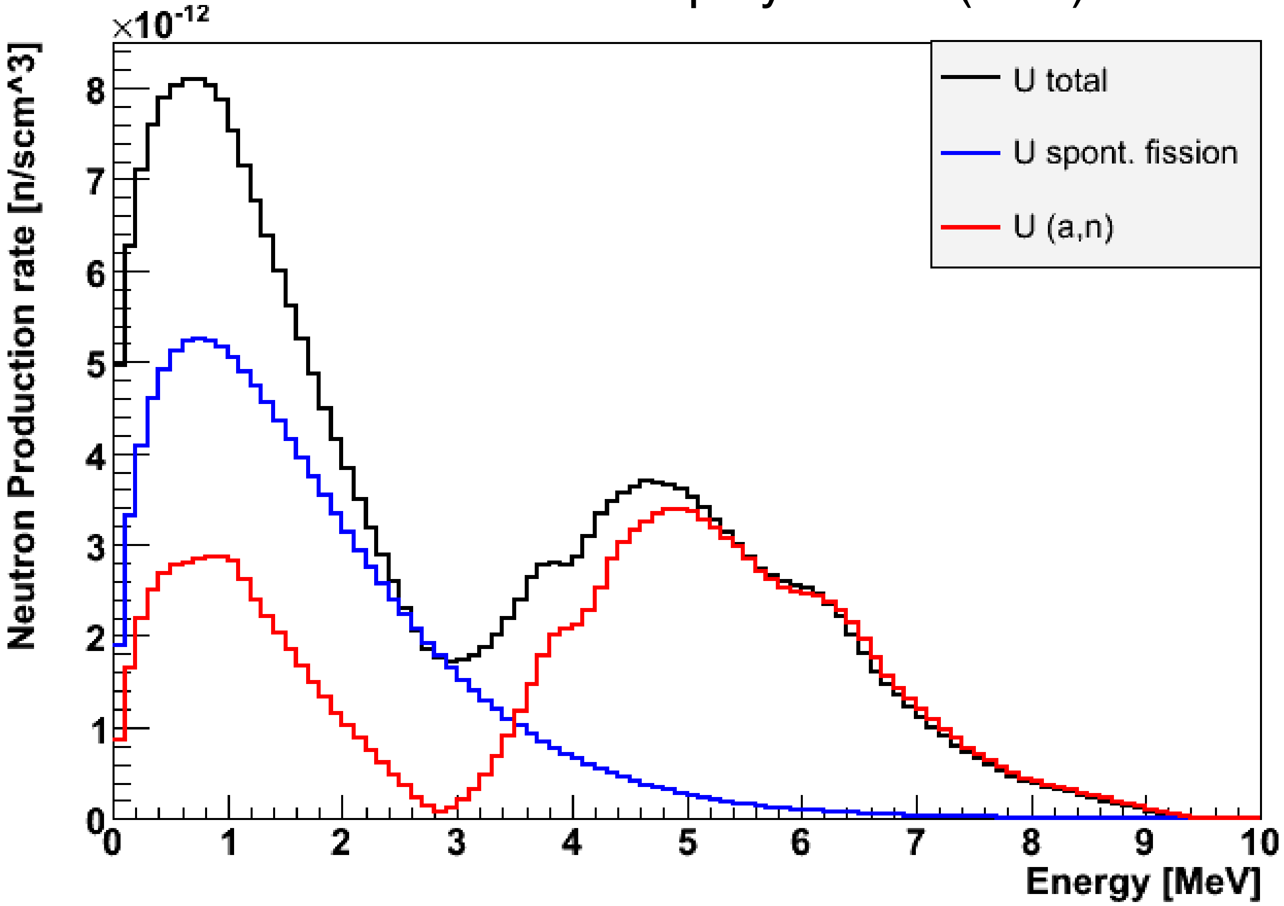
Site (multiple levels given in ft)	Relative muon flux	Relative neutron flux T > 10 MeV
WIPP (2130 ft) (1500 mwe)	× 65	× 45
Soudan (2070 mwe)	× 30	× 25
Kamioke	× 12	× 11
Boulby	× 4	× 4
Gran Sasso (3700 mwe)	× 1	× 1
Frejus (4000 mwe)		
Homestake (4860 ft)		
Mont Blanc	× 6^{-1}	× 6^{-1}
Sudbury	× 25^{-1}	× 25^{-1}
Homestake (8200 ft)	× 50^{-1}	× 50^{-1}

compiled by: R. Gaitskell

Backgrounds in Dark Matter Detectors

- **MeV neutrons can mimic WIMPs** by elastically scattering from the target nuclei
  - ➡the rates of neutrons from detector materials and rock are calculated taking into account the exact material composition, the α energies and cross sections for (α,n) and fission reactions and the measured U/Th contents

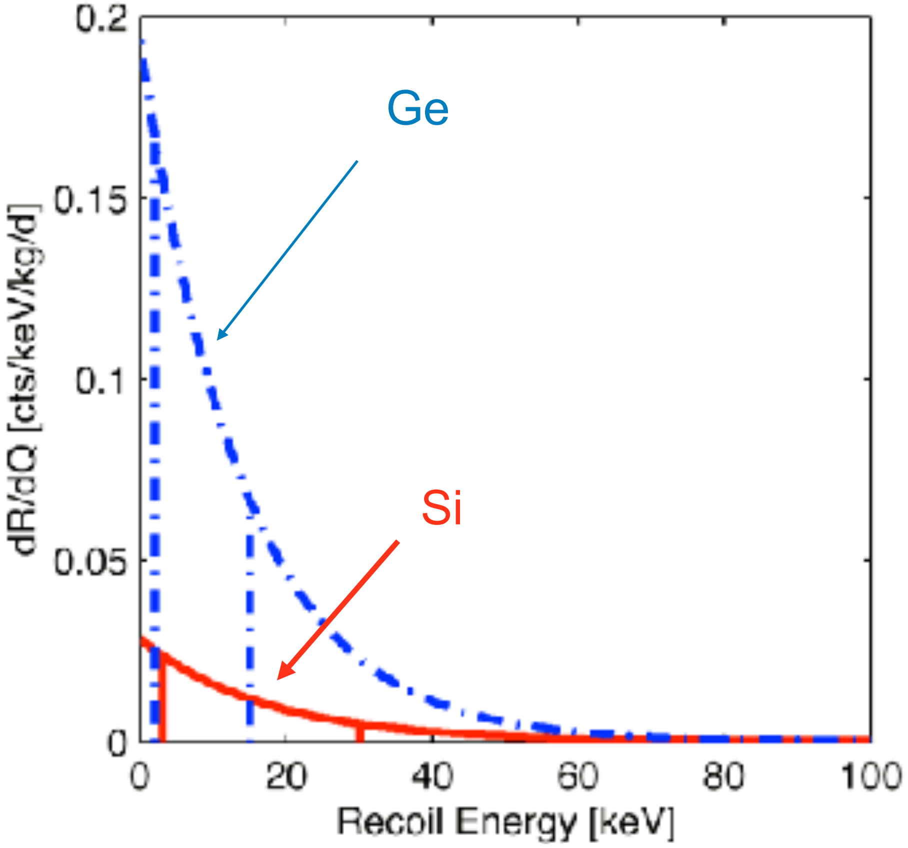

neutrons from rock (^{238}U)


neutrons from poly shield (^{238}U)

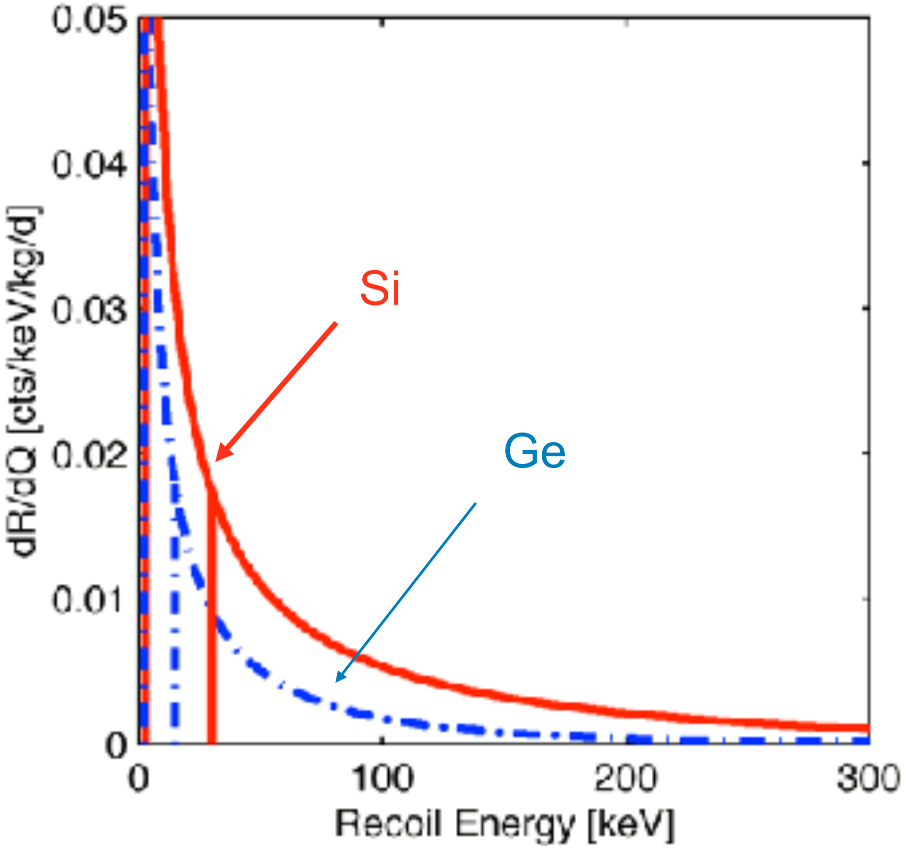
Neutrons: how can we distinguish them from WIMPs?

- ➡ mean free path of few cm (neutrons) versus 10^{10} m (WIMP)
- ➡ if n-capture => distinctive signature
- ➡ material dependence of differential recoil spectrum
- ➡ time dependence of WIMP signal (if neutron background is measured to be constant in time)

WIMP SI signal ~ A^2



WIMPs, M_χ = 40 GeV

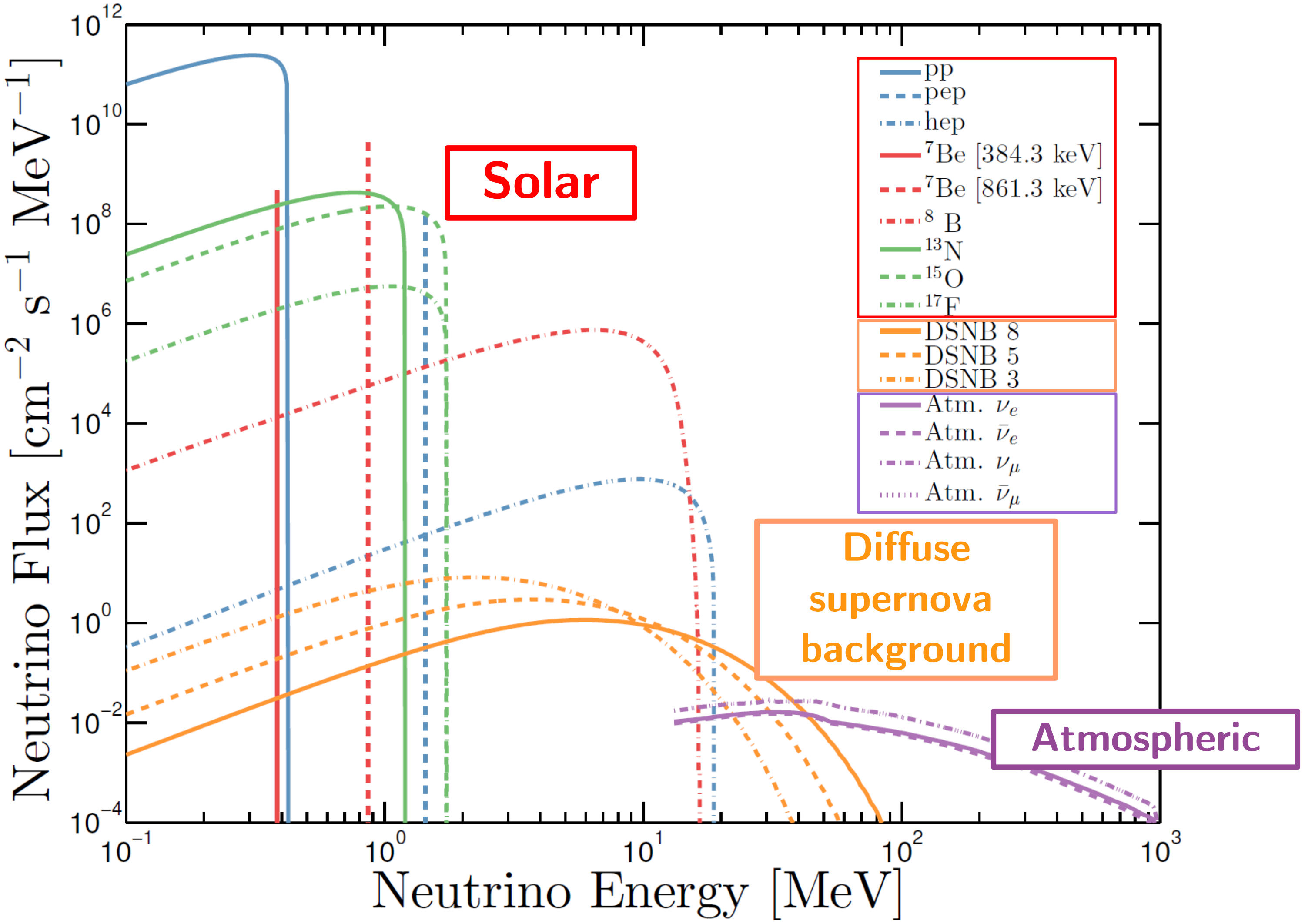


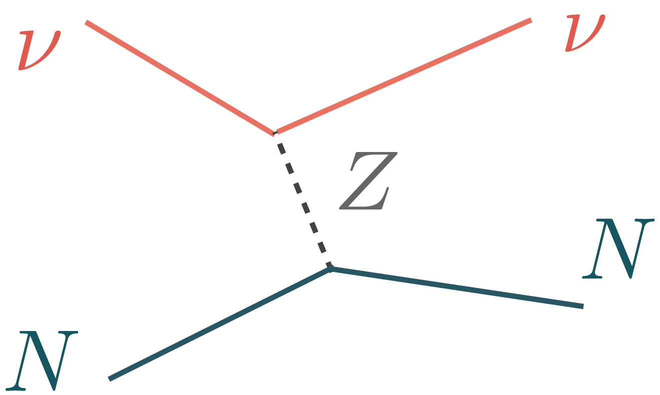
Background neutrons

Neutrino backgrounds

- Neutrino-electron and neutrino-nucleus scatters

$$\nu + e^- \longrightarrow \nu + e^-$$





$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_\omega^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F_{SI}^2(E_r)$$

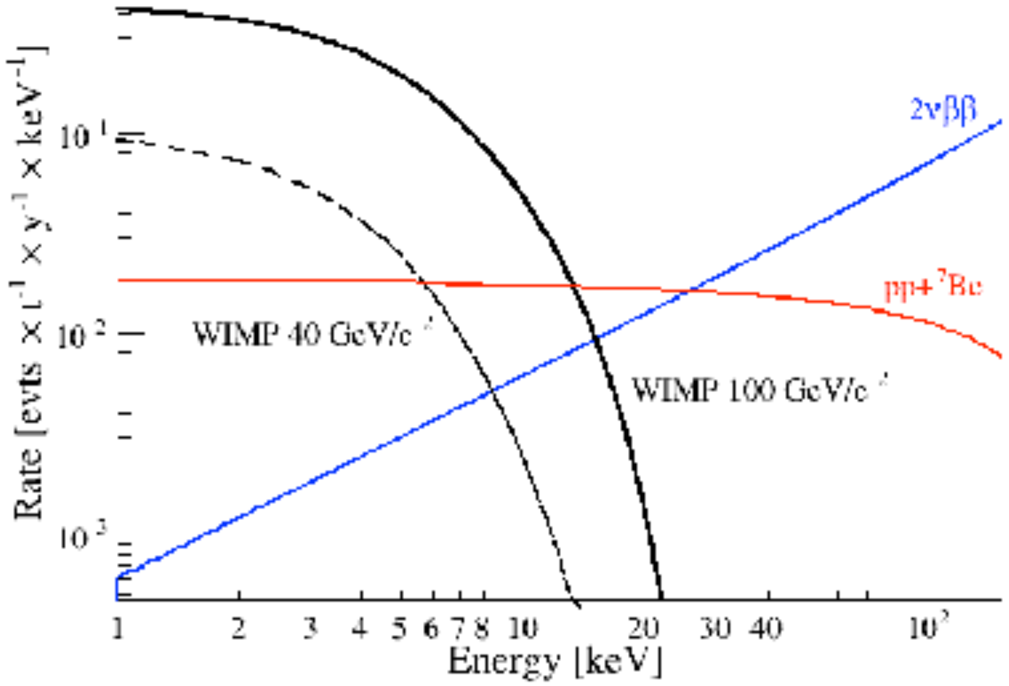
$$Q_\omega = N - (1 - 4\sin^2\theta_\omega)Z$$

F. Ruppin et al., 1408.3581, PRD 90, 2015

Neutrino-electron scatters

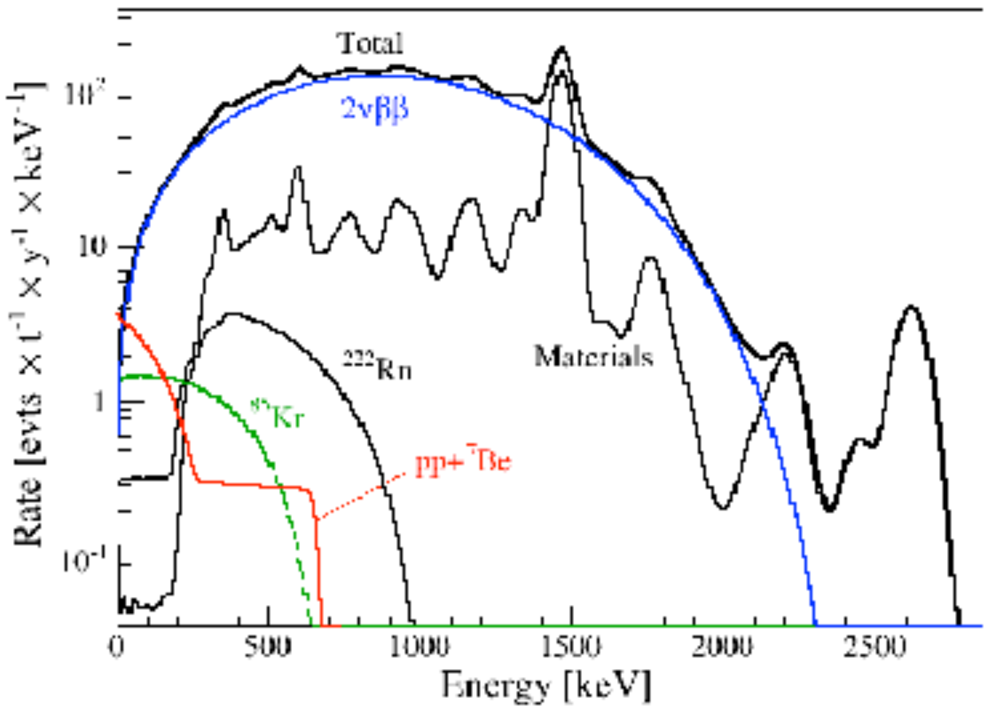
- Will generate electron recoils, uniformly distributed in the detector
- In spite of various background discrimination techniques, such events can potentially “leak” into the signal region
- Example (in liquid xenon) for spectra expected from WIMPs and solar neutrinos

After discrimination (99.5%)



$$\nu + e^- \to \nu + e^-$$

Before discrimination

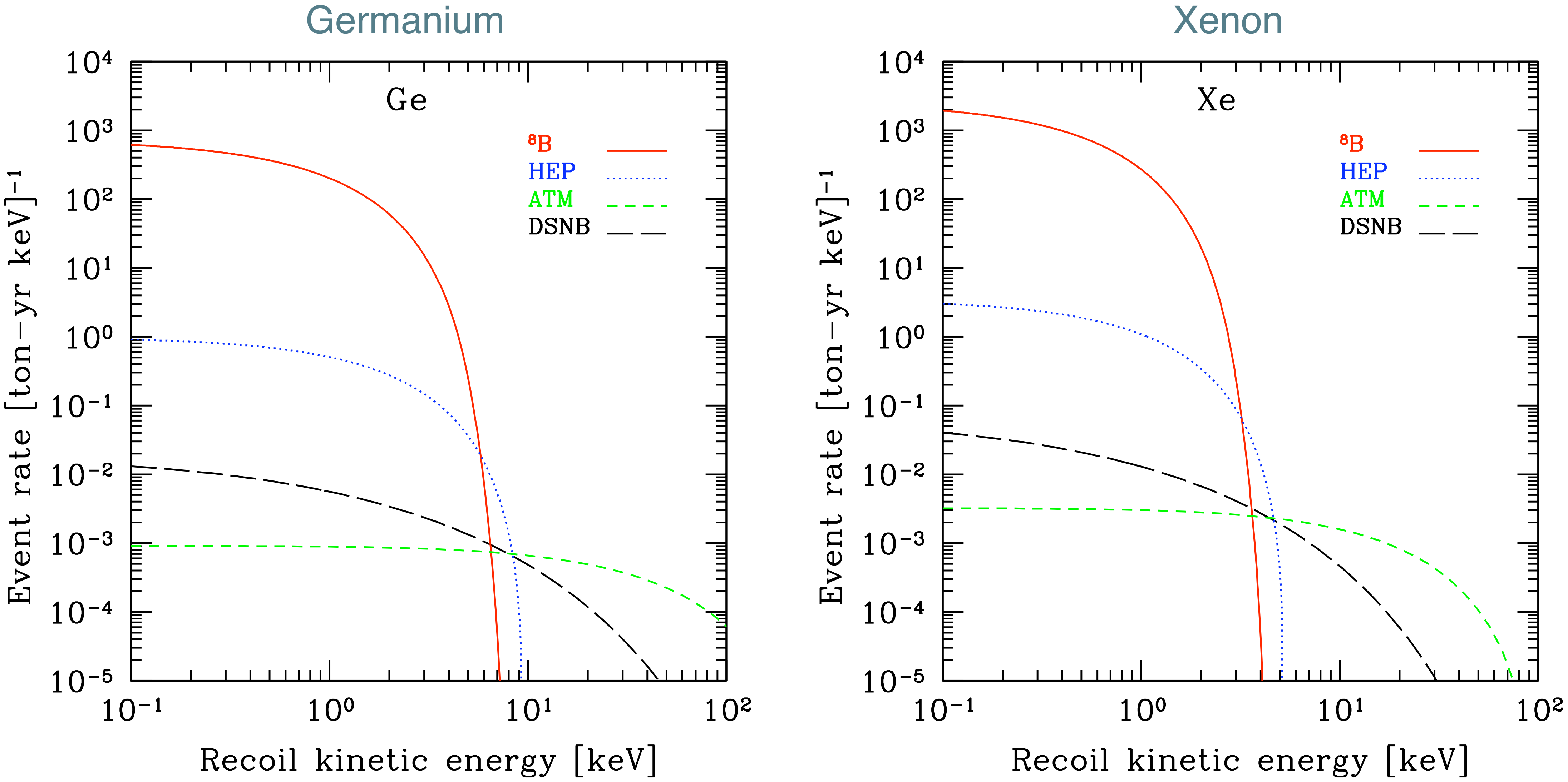


LB et al., JCAP01 (2014) 044

Neutrino-nucleus scatters

- ^{8}B neutrinos dominate: serious background if the WIMP-nucleon cross section < 10^{-10} pb
- But: energy of nuclear recoils: <4 keV (heavy targets, Xe, I etc) to <30 keV in light targets (F, C)
- Non-^{8}B neutrinos: impact on WIMP detectors at much lower WIMP-nucleon cross sections

L. E. Strigari, New J. Phys. 11 (2009) 105011



Germanium

Xenon

Detector strategies

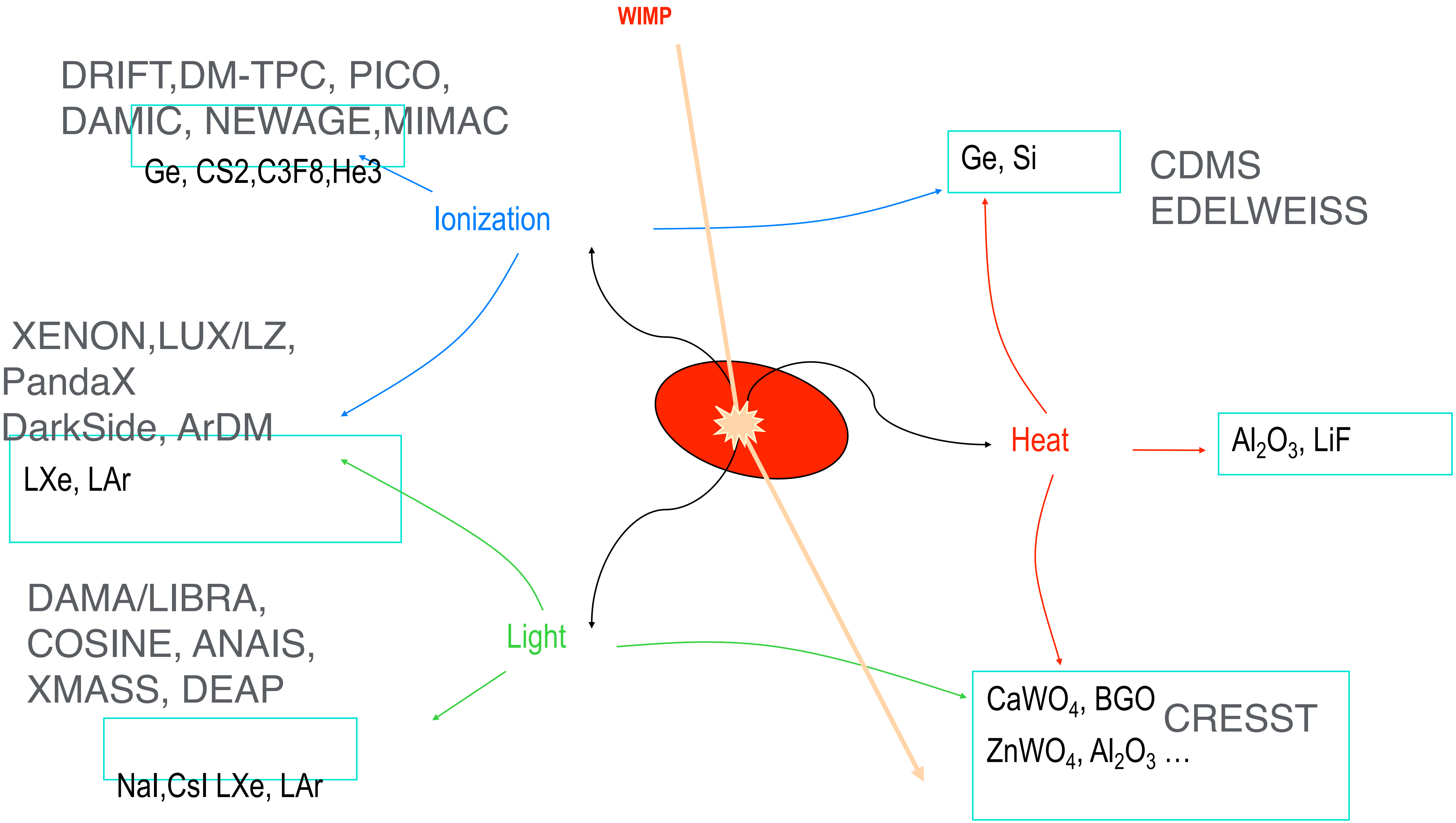
Aggressively reduce the absolute background & pulse shape analysis	Background reduction by pulse shape analysis and/or self-shielding	Background rejection based on simultaneous detection of two signals	Other detector strategies
State of the art: (primary goal is $0\nu\beta\beta$ decay): Past experiments: Heidelberg-Moscow HDMS IGEX Current and near-future projects: GERDA MAJORANA	Large mass, simple detectors: NaI (DAMA/LIBRA, ANAIS, SABRE, DM-Ice) CsI (KIMS) Large liquid noble gas detectors: XMASS, CLEAN, DEAP-3600	**Charge/phonon** (CDMS, EDELWEISS, SuperCDMS) **Light/phonon** (CRESST) **Charge/light** (XENON, LUX-LZ, PandaX DarkSide)	Large bubble chambers - insensitive to electromagnetic background: COUPP, PICASSO, SIMPLE, PICO Low-pressure gas detectors, sensitive to the direction of the nuclear recoil: DRIFT, DMTPC, NEWAGE, MIMAC,DAMIC

In addition:

→ reject multiple scattered events and events close to detector boundaries

→ look for an annual and a diurnal modulation in the event rate

Direct Detection Experiments



WIMP

DRIFT,DM-TPC, PICO,
DAMIC, NEWAGE,MIMAC

Ge, CS2,C3F8,He3

Ionization

Ge, Si

CDMS
EDELWEISS

XENON,LUX/LZ,
PandaX
DarkSide, ArDM

LXe, LAr

Heat

Al_2O_3, LiF

DAMA/LIBRA,
COSINE, ANAIS,
XMASS, DEAP

Light

NaI,CsI LXe, LAr

$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 …

CRESST