# Detection of Dark Matter
# Science Cases and Challenges

**Katsushi Arisaka**

***University of California, Los Angeles***
***Department of Physics and Astronomy***

arisaka@physics.ucla.edu

# UCLA DM2012 Conference

Agenda Contact

UCLA Dark Matter 2012

Tenth Symposium on Sources and Detection of Dark Matter and Dark Energy in the Universe
Marina del Rey Marriott February 22-24, 2012

## UCLA Dark Matter 2012

*The UCLA Department of Physics and Astronomy will host its tenth Dark Matter and Dark Energy conference in Marina del Rey. The symposium provides a scientific forum for the latest discussions in the field. The $595 registration fee covers your admission to the meeting, breakfast and lunch on Thursday and Friday, a reception on February 22 and a banquet on February 23.*

Preliminary topics include:

- Status of measurements of the equation of state of dark energy and new experiments
- The search for missing energy events at the LHC and implications for dark matter search
- Theoretical calculations on all forms of dark matter (SUSY, axions, sterile neutrinos, etc.)
- Status of the indirect search for dark matter
- Status of the direct search for dark matter in detectors around the world
- The low-mass wimp search region
- The next generation of very large dark matter detectors
- New underground laboratories for dark matter search

## Advisory committee

Elena Aprile (Columbia), Elliott Bloom (Stanford), David Cline (UCLA), Juan I. Collar (University of Chicago), Katherine Freese (University of Michigan), Ana Heras (ESA/ESTEC), Rene Ong (UCLA), Joel Primack (UCSC), Leszek Roszkowski (University of Sheffield, UK and SINS, Poland), Bernard Sadoulet (UC Berkeley), Ina Sarcevic (University of Arizona), Max Tegmark (Massachussetts Institute of Technology), Ned Wright (UCLA).

## Links

Los Angeles International Airport

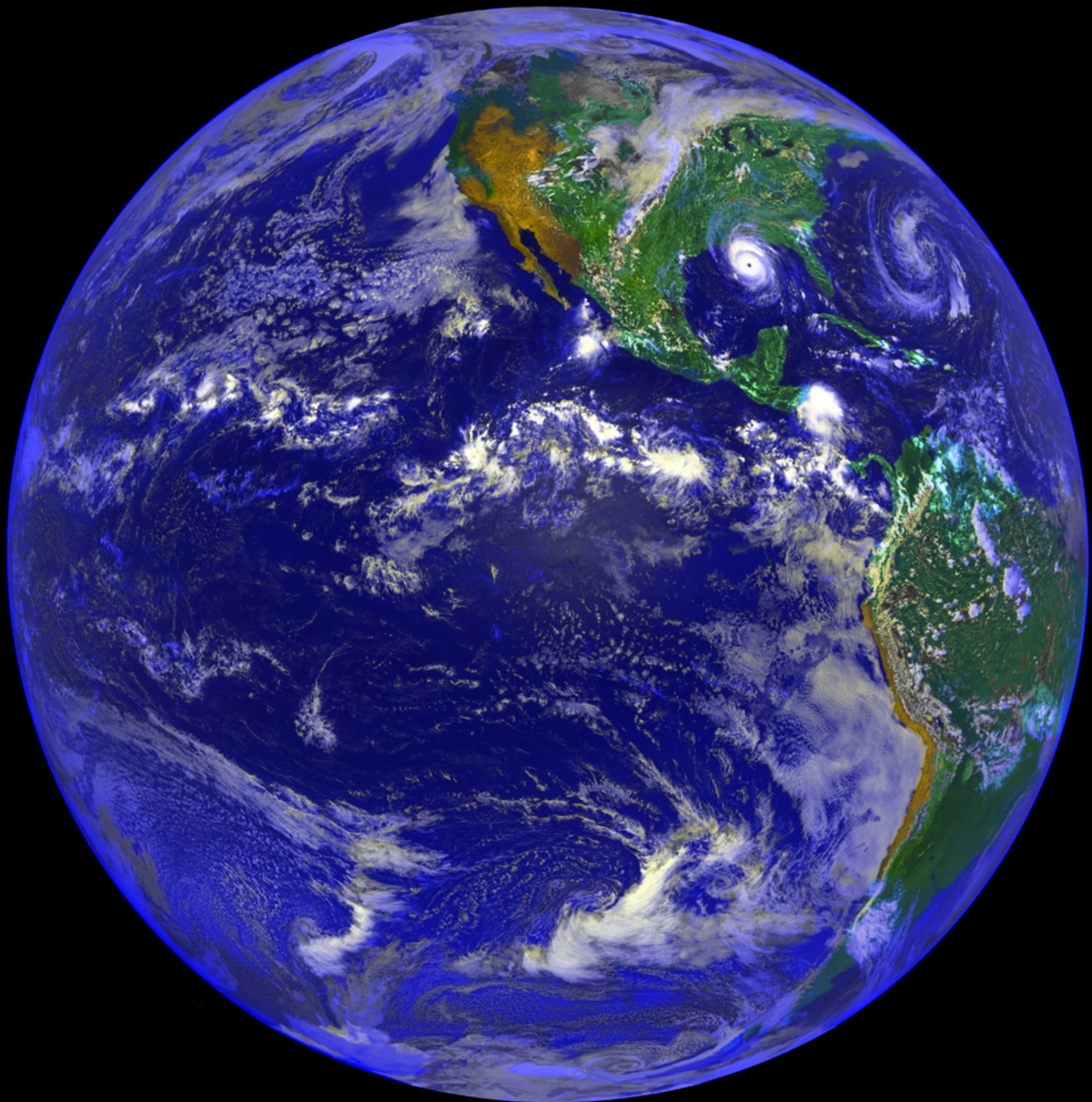
Local transportation

Marina del Rey weather

UCLA Physics and Astronomy

# Talk Outline

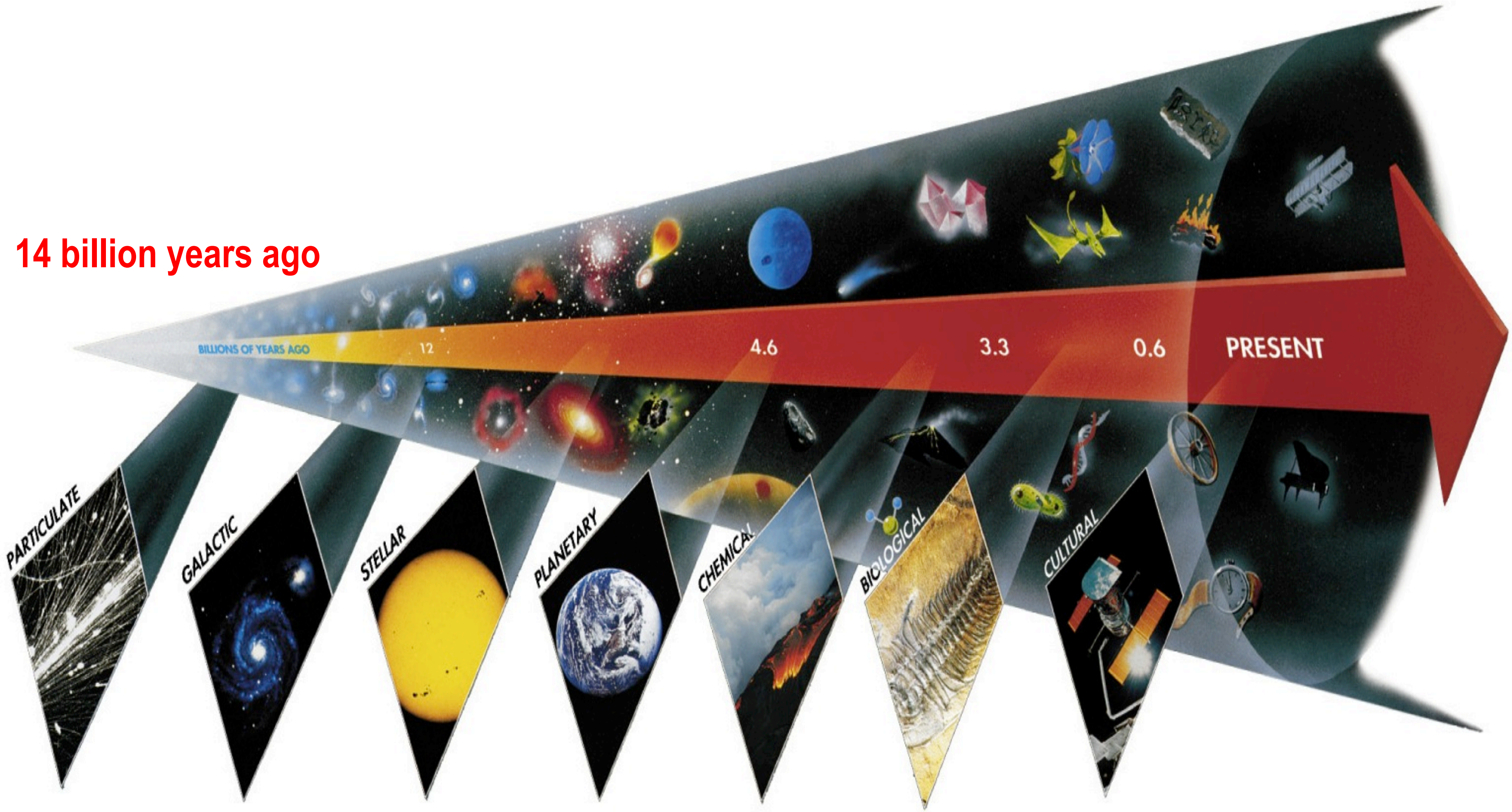
- **Scientific Cases**
  - Origin of the Universe and Mass
- **Detection Methods**
  - Noble Liquid and TPC
  - XENON100 and 1T
- **Sensitivities**
  - SUSY, Extra Dimensions…
  - Comparison with LHC, Indirect searches
- **Ultimate G3 Observatory**
  - Xenon vs. Argon
  - Technological challenges



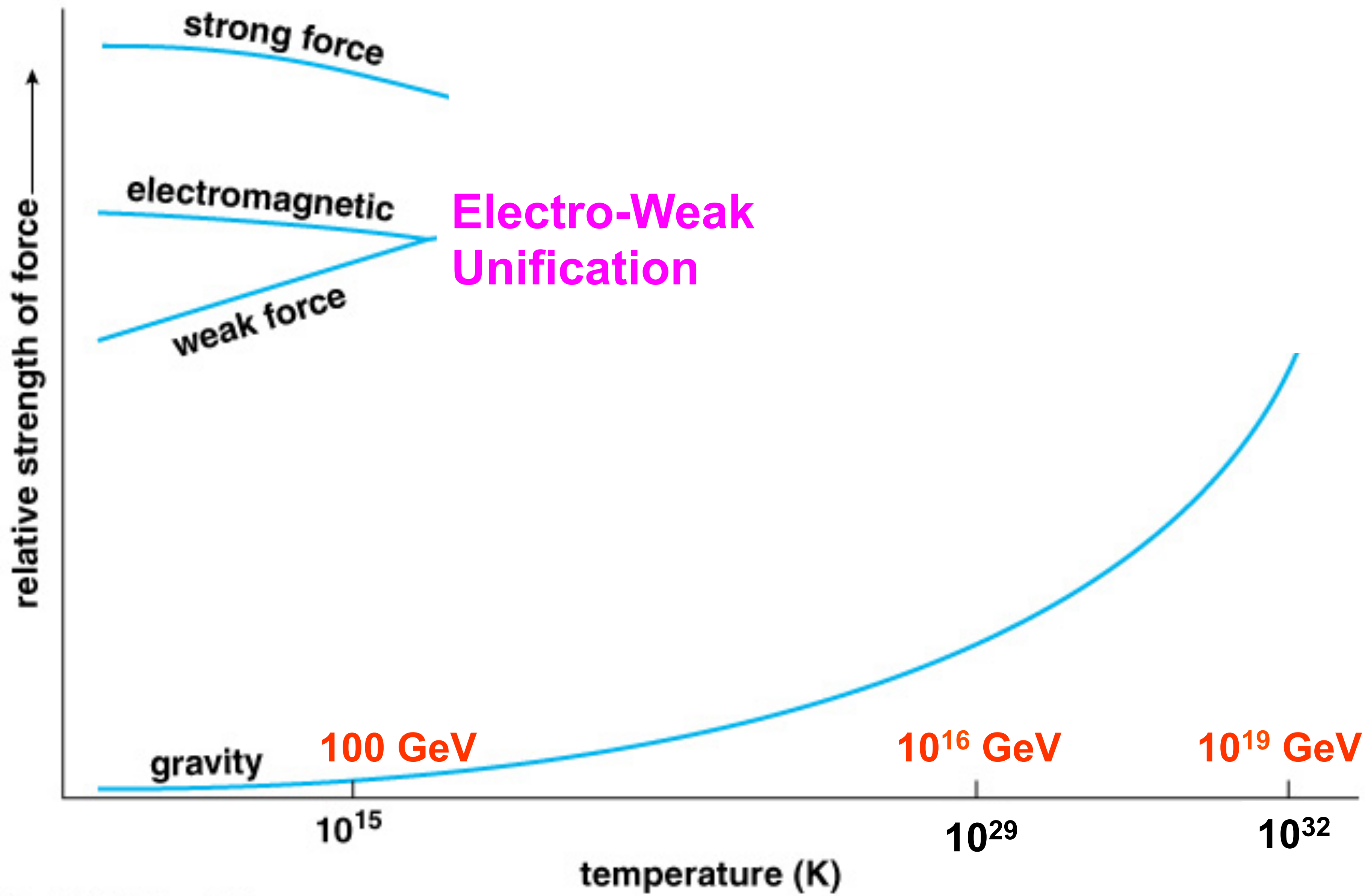
# Why are we here?

# Seven Phases of Cosmic Evolution

14 billion years ago



# Unification of Forces



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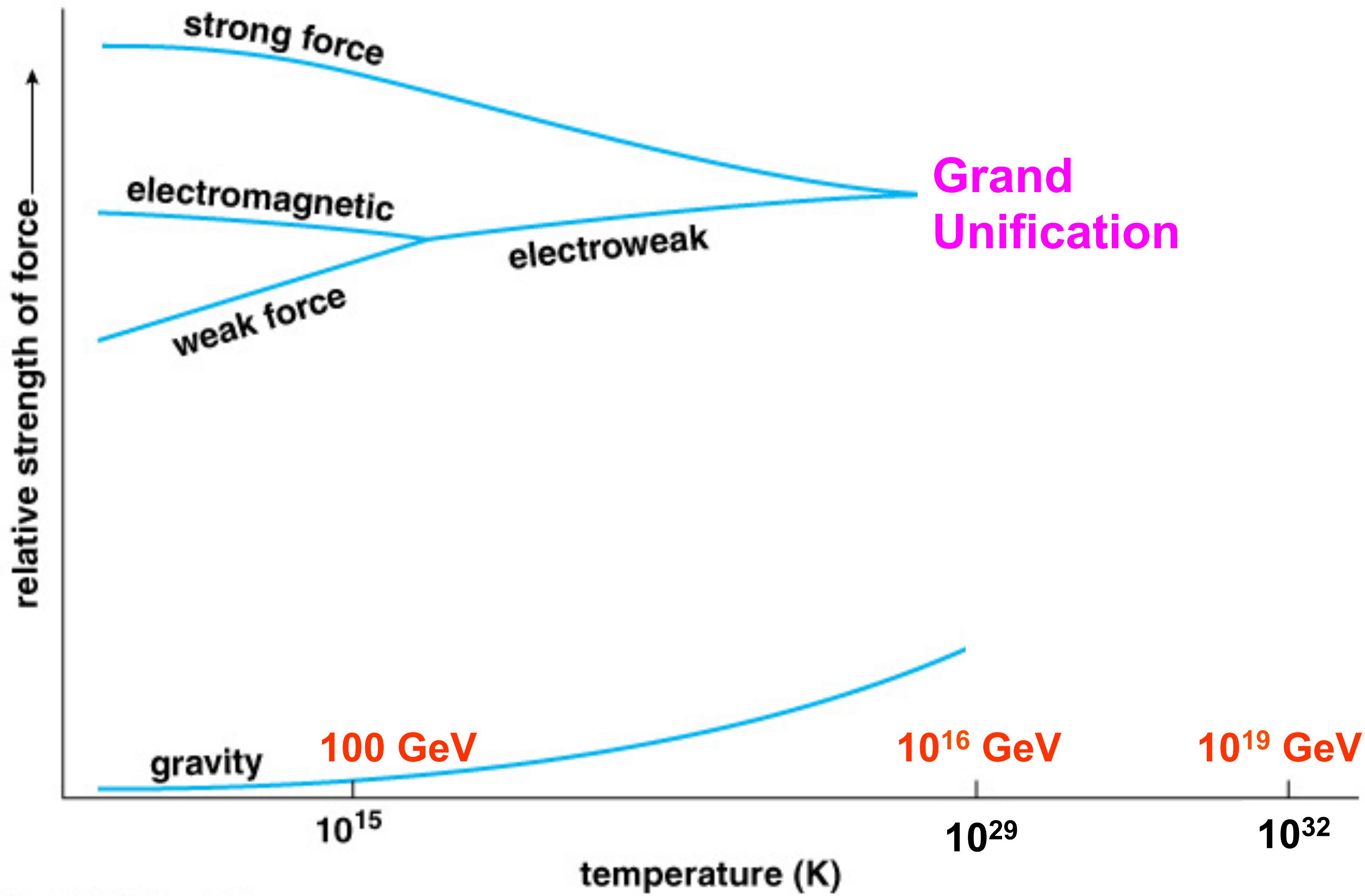

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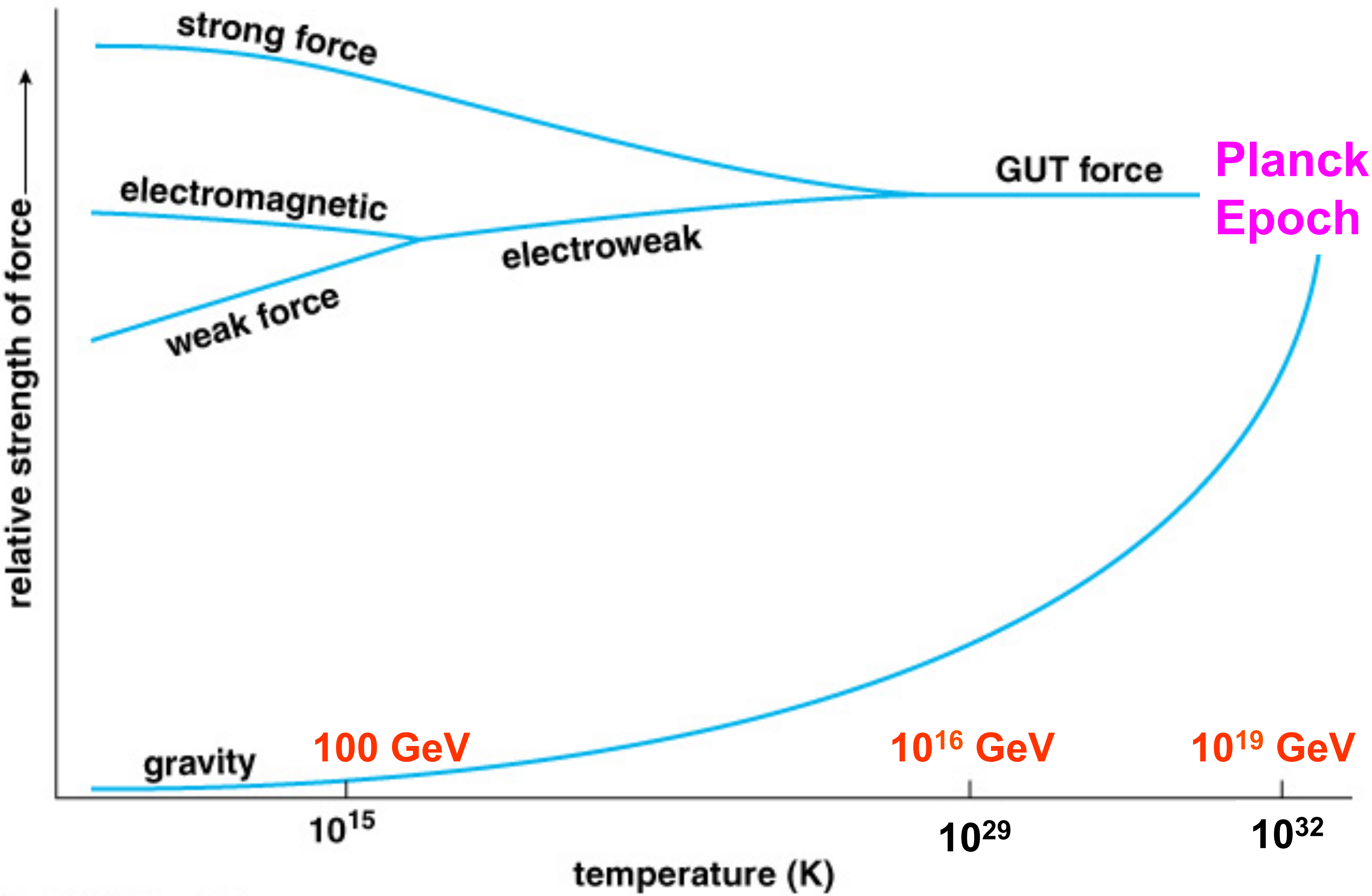


# Physicists' View of Early Universe

**Fiat lux**

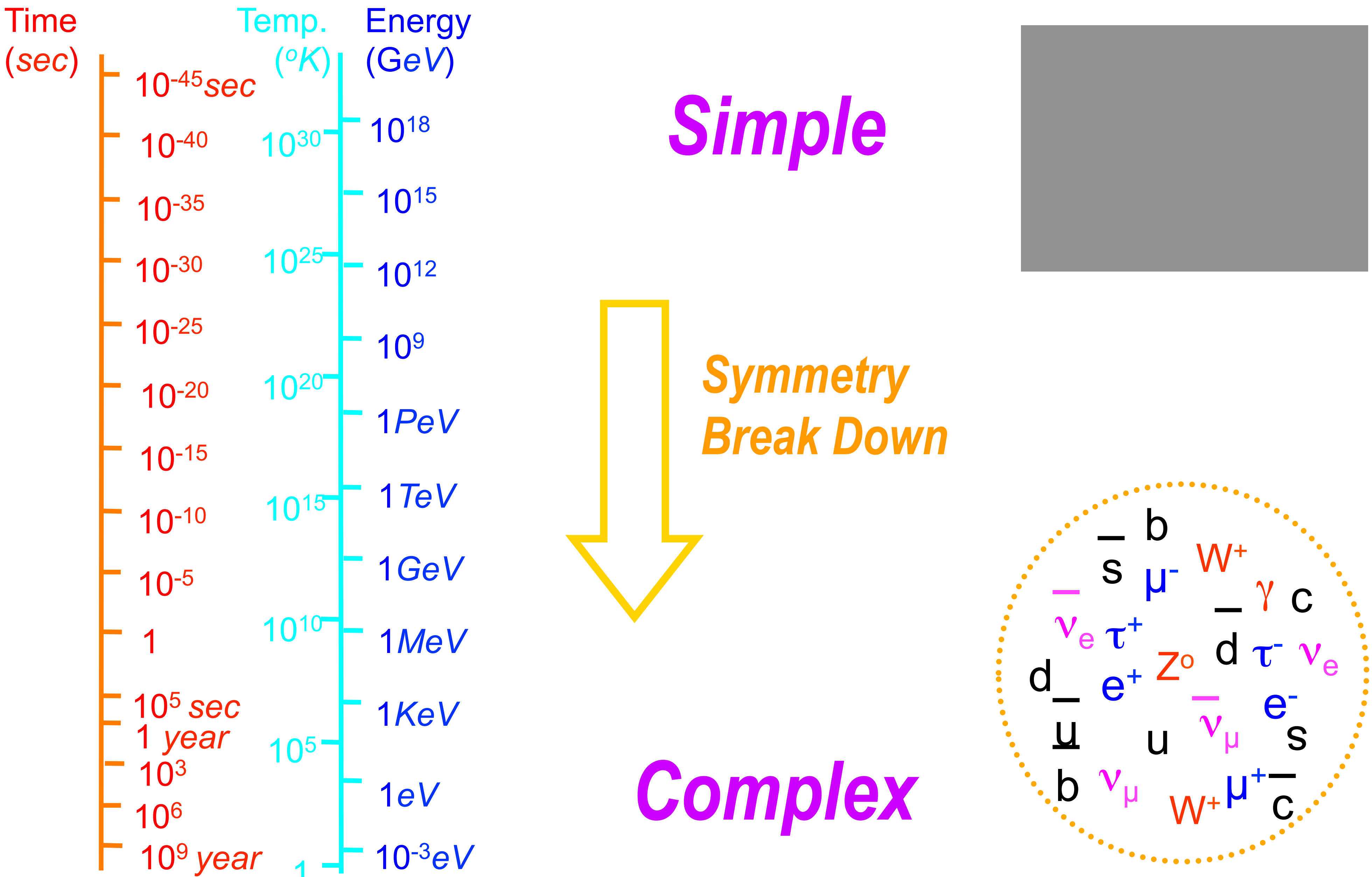
**Let there be light**

# Physicists' View of Early Universe

**Lorentz Invariance**

**Local Gauge Invariance**

# Symmetry Breaking



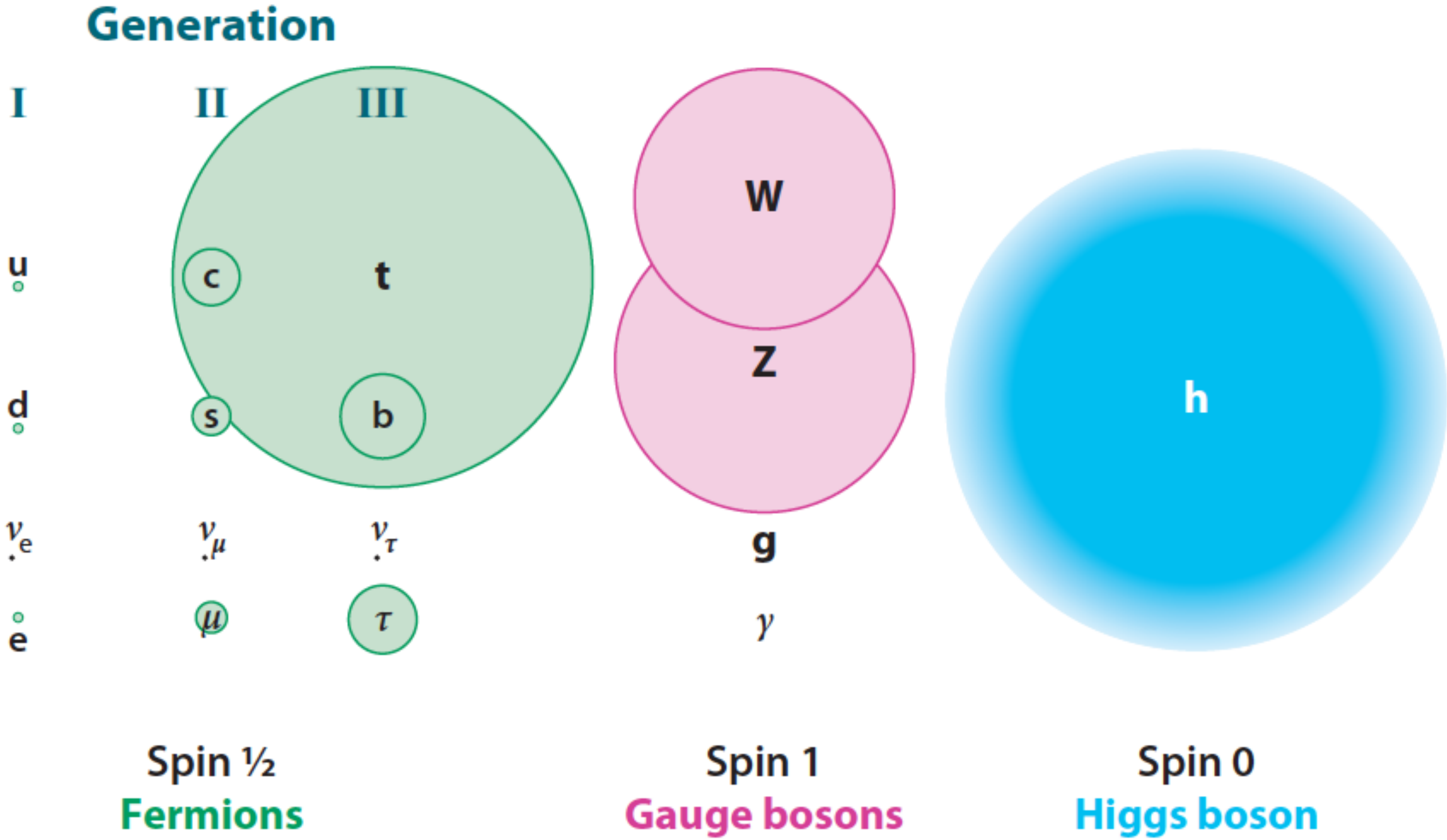
# The Beginning (at T = 0)

- **Everything was the same ↔ Perfect symmetry.**
  - **All the particles are the same as photons.**
  - **All four forces are the same.**

- **The Universe was <u>10 dimension</u>.**

| | | | |
|---|---|---|---|
| 3 | | Space | → *Flattened* |
| 1 | | Time | |
| 6 | 3 | Strong Force | *Compacitified* |
| | 2 | Weak | |
| | 1 | Electro-Magnetic | |

# Mass of Particles (at T = 0.1 ns)



# Mystery of the Mass (since 1970)

1) How to create mass from energy?

**Energy → Mass**

While maintaining the initial symmetry

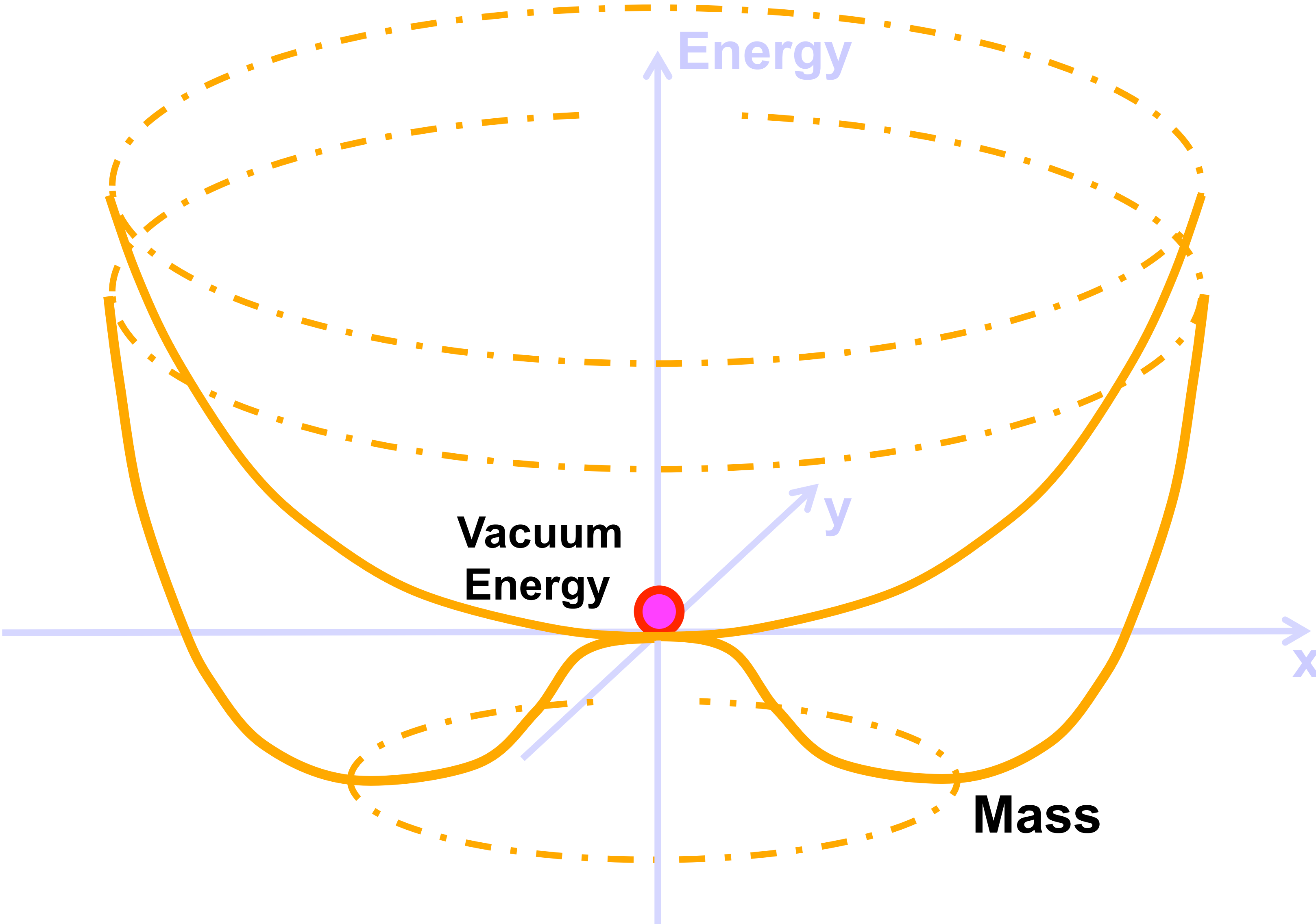
Spontaneous Symmetry Breaking

2) **Particle mass << Plank Mass**

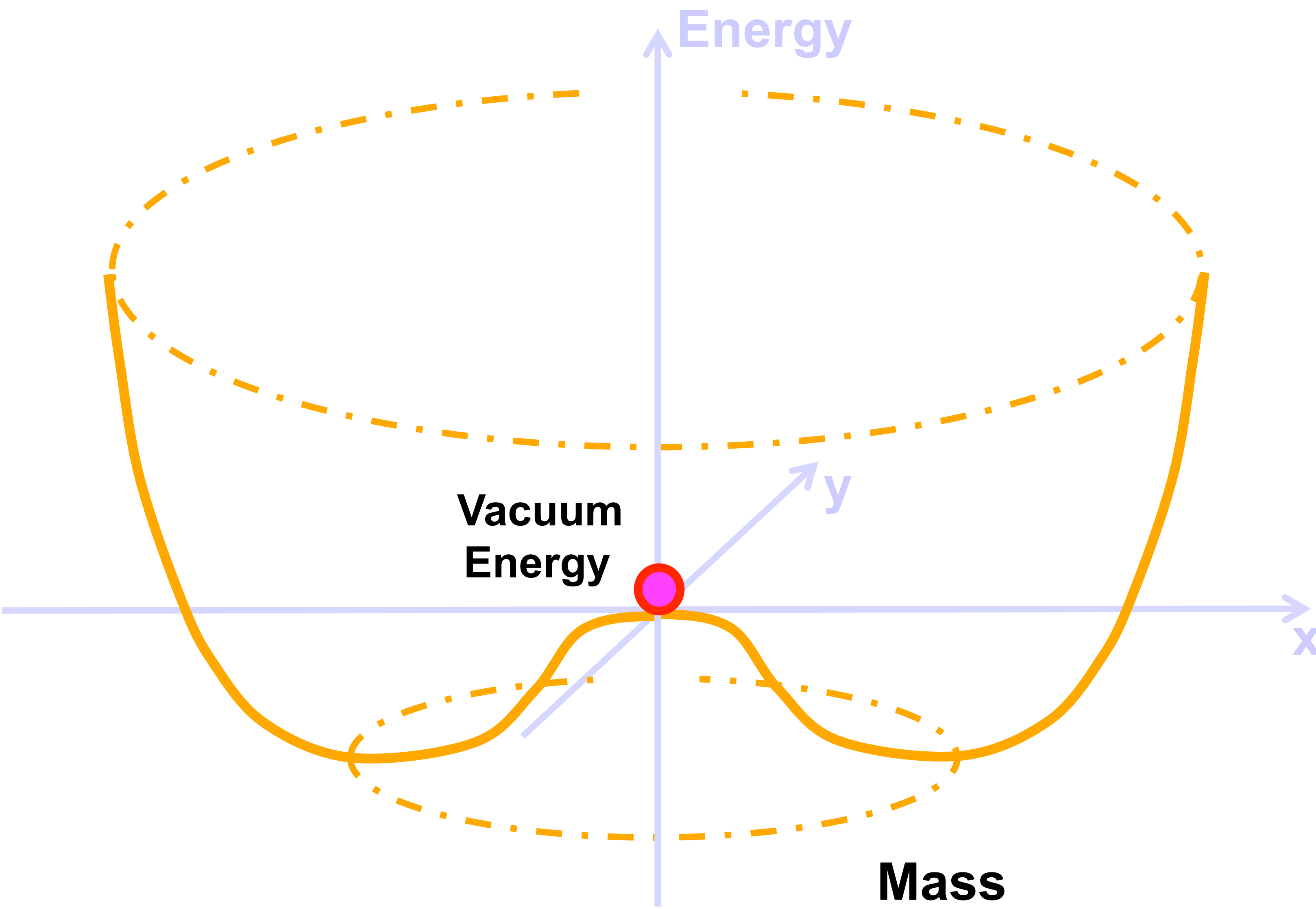
MeV – GeV $10^{19}$ GeV

3) Why so many particles (Generations) with different masses?

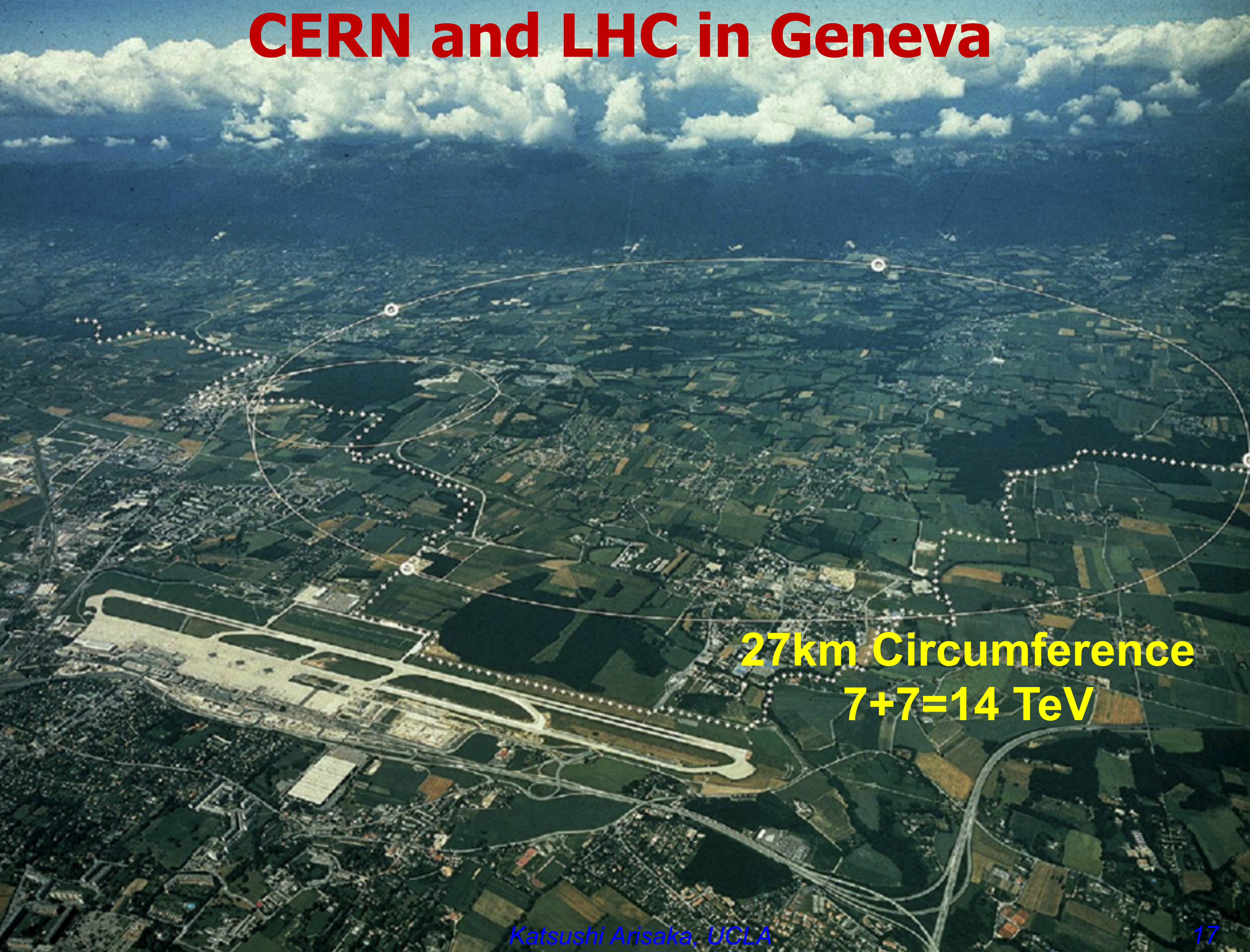
# Spontaneous Symmetry Breaking
# - Higgs Mechanism -



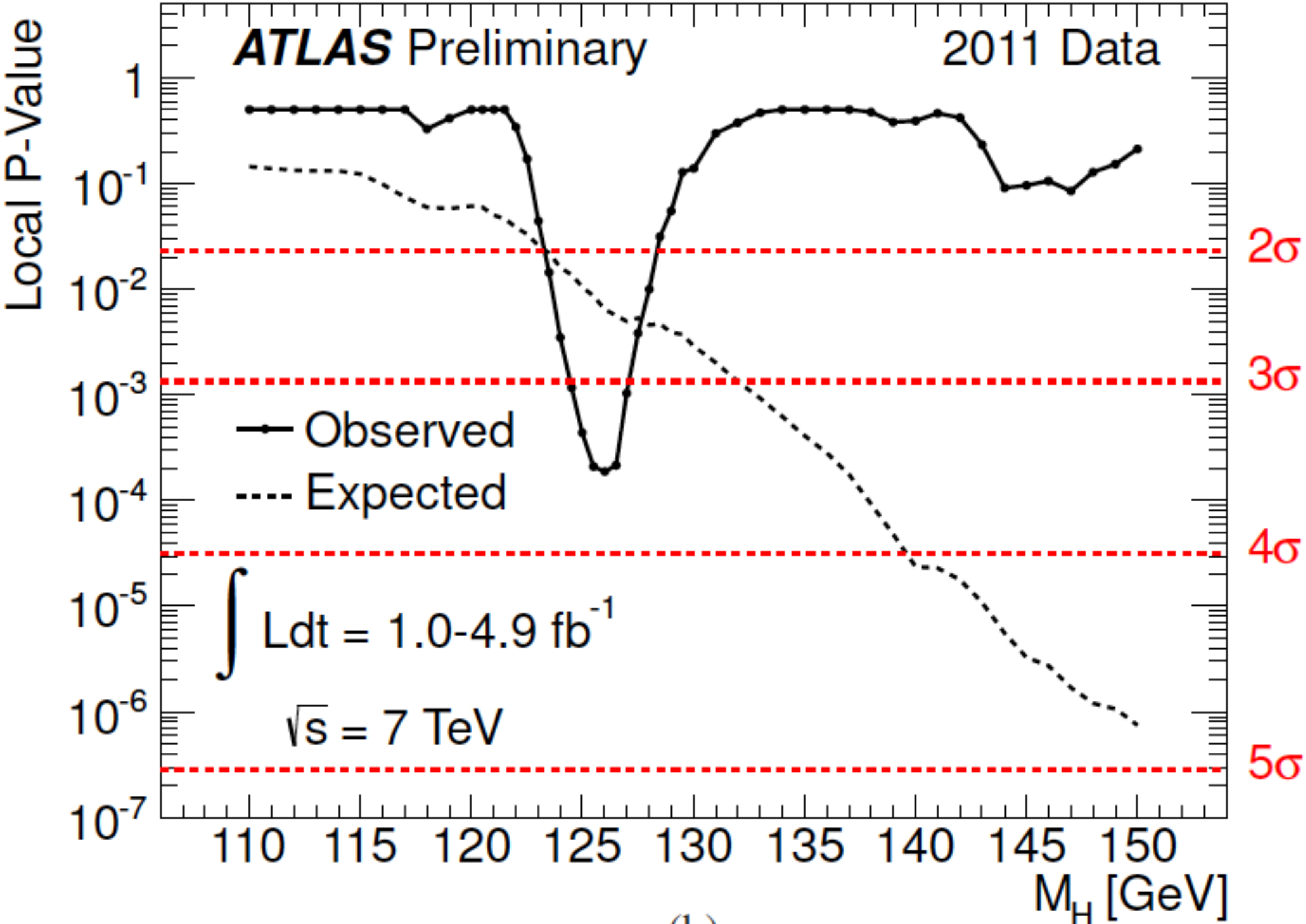
# Spontaneous Symmetry Breaking - Higgs Mechanism -



# CERN and LHC in Geneva



# ATLAS Higgs Results

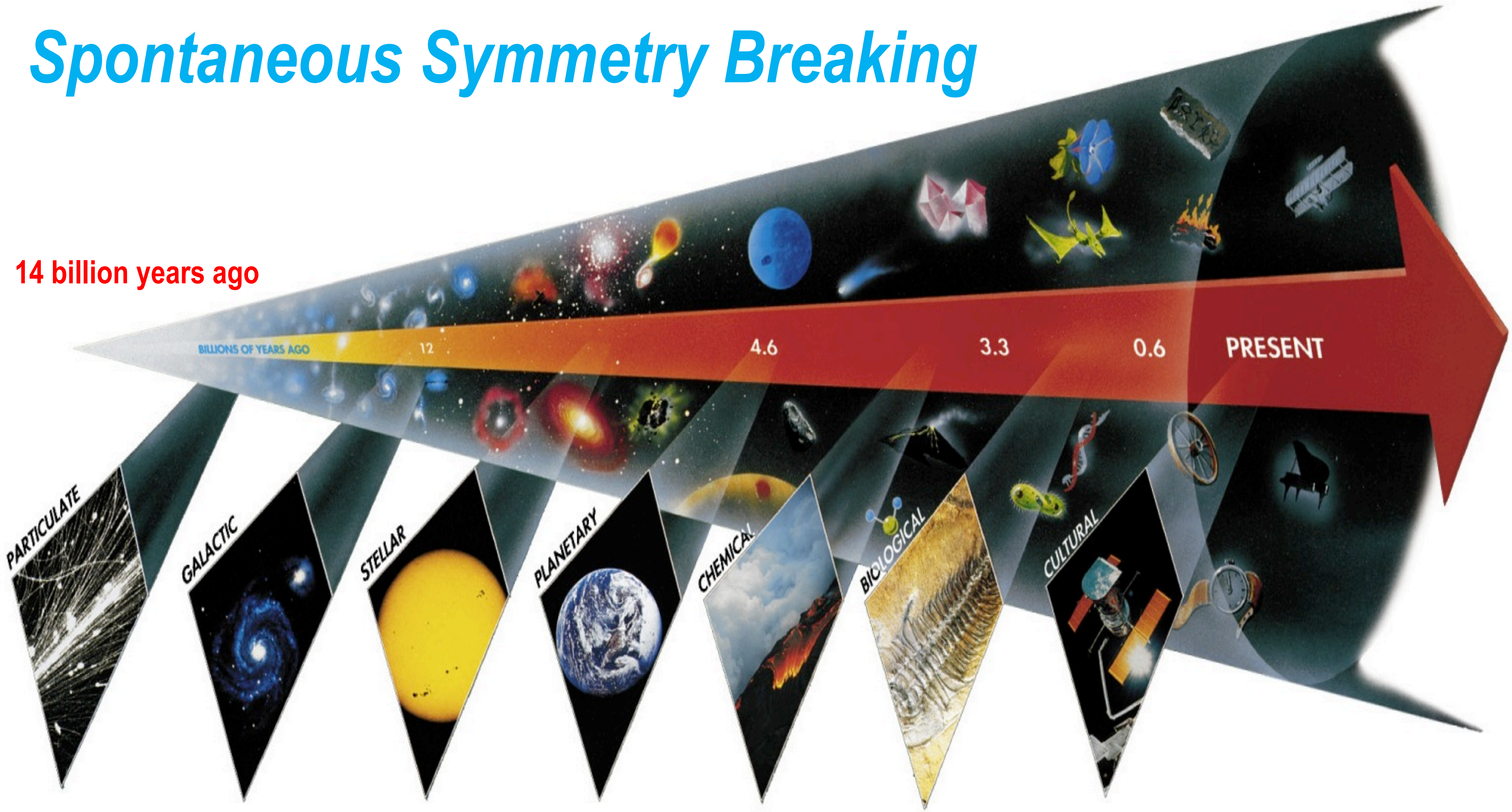



(b)

# Seven Phases of Cosmic Evolution

## *Spontaneous Symmetry Breaking*

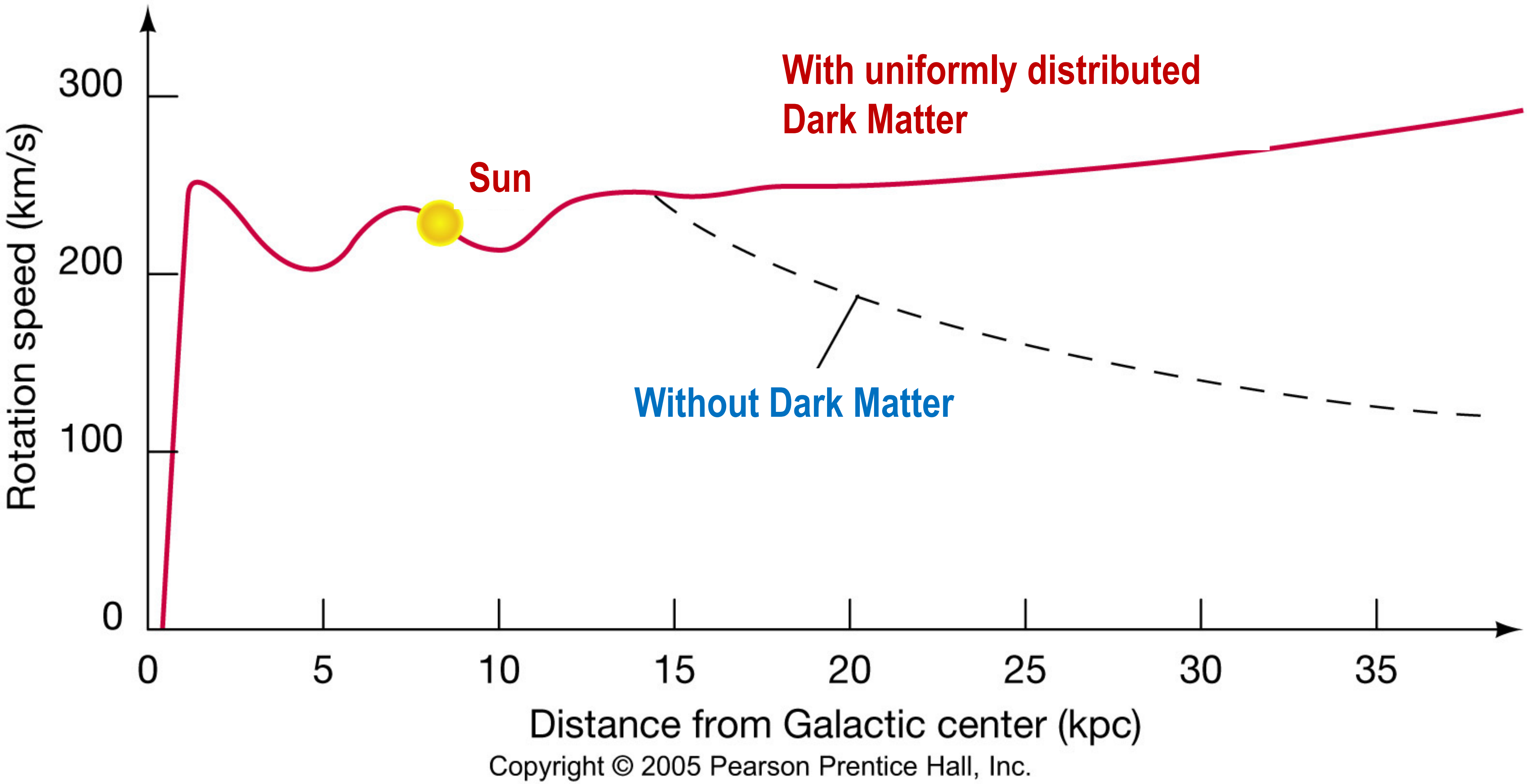
14 billion years ago



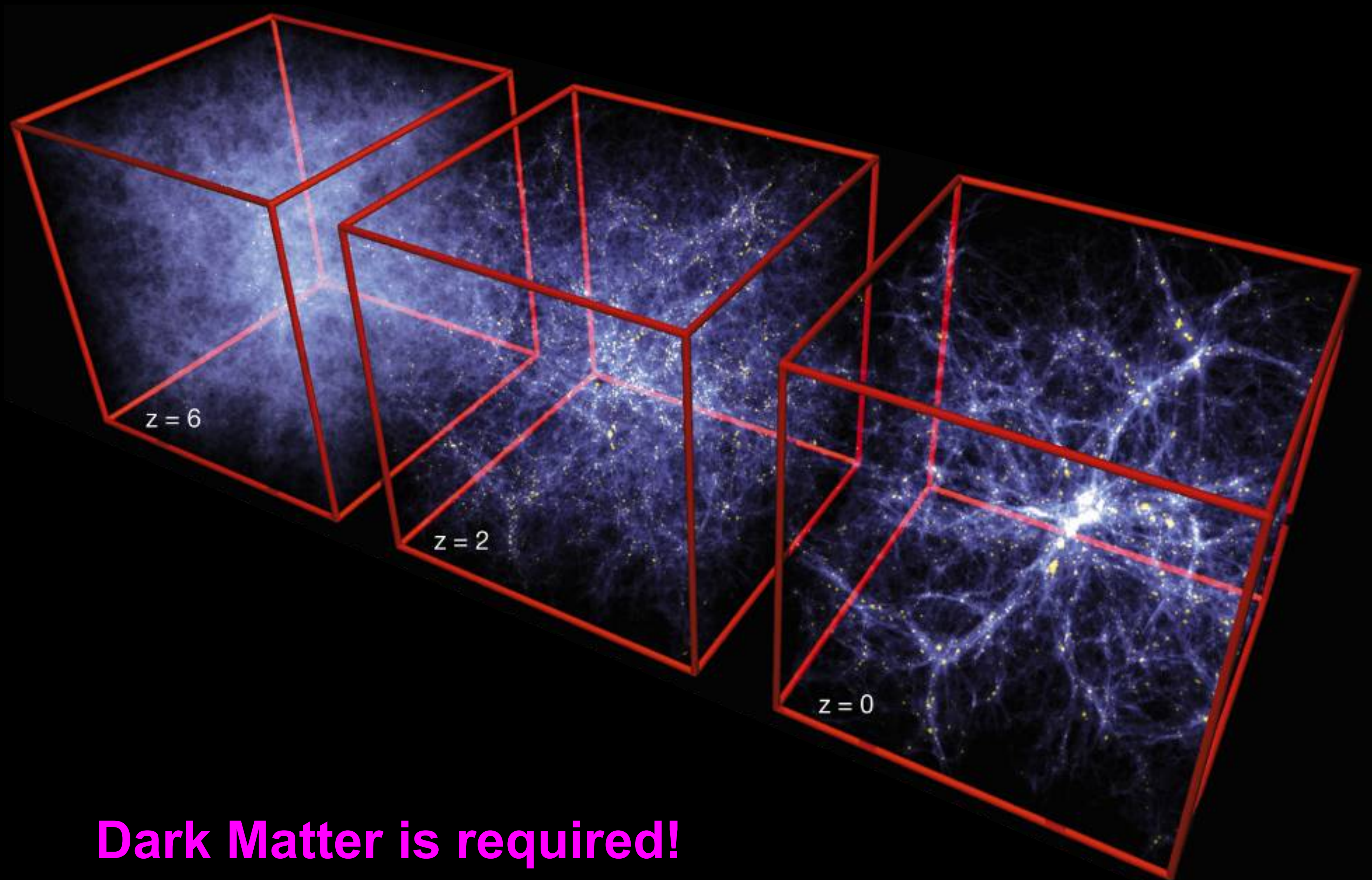

Origin of Particles

Origin of Structure

# Rotational Velocity of Galaxies

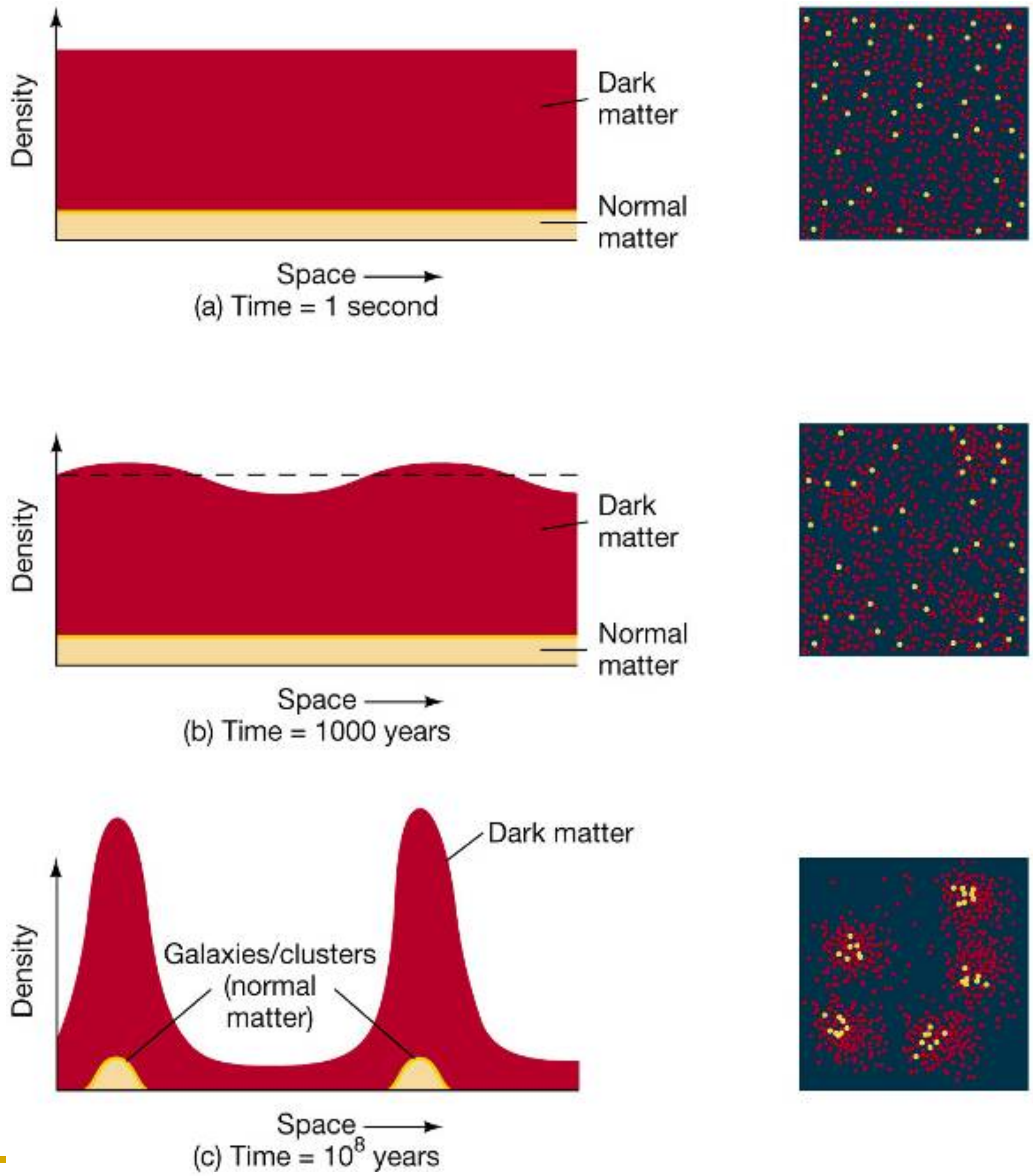


# Formation of Structure in the Universe



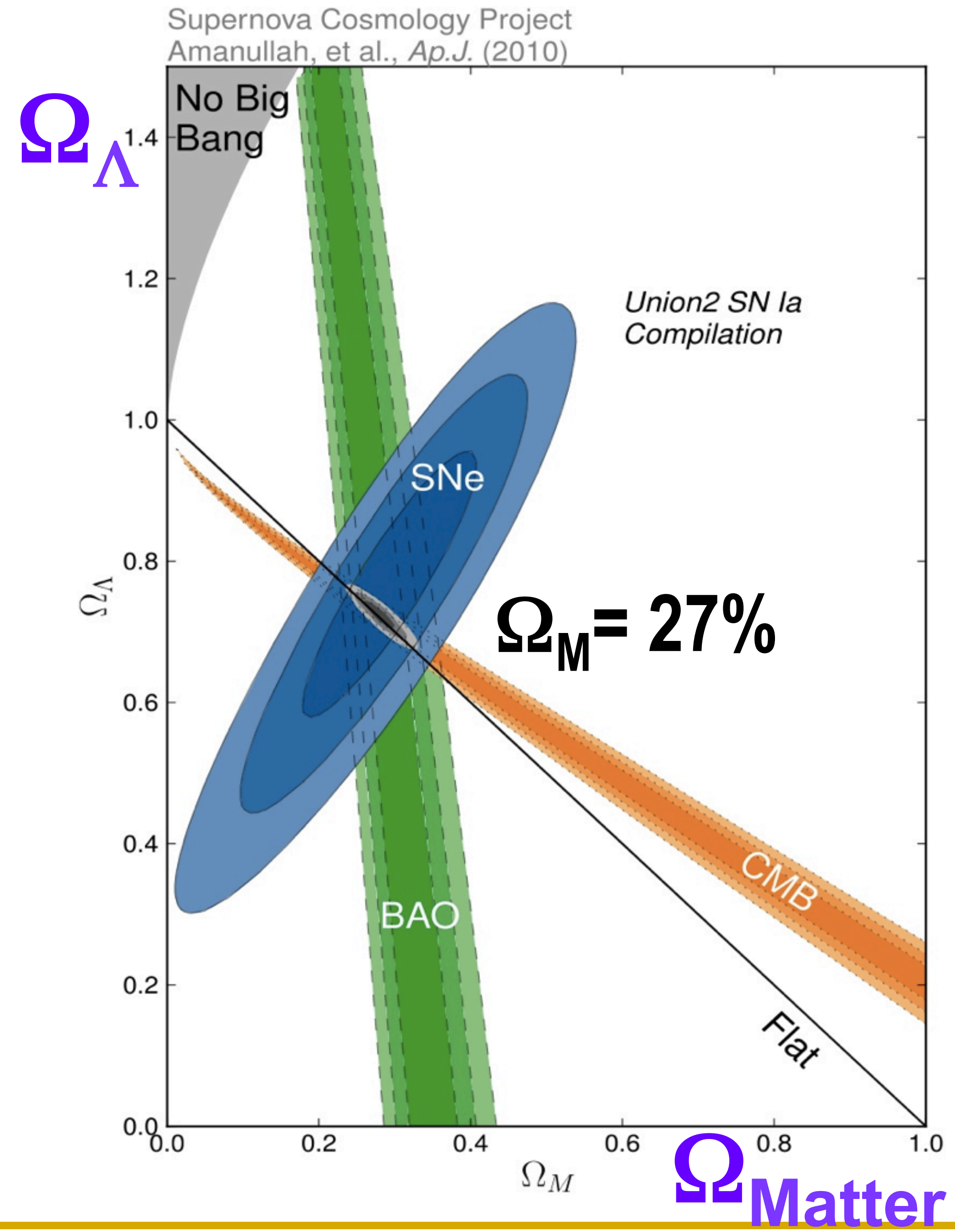

**Dark Matter is required!**

# Evolution of Large Structure

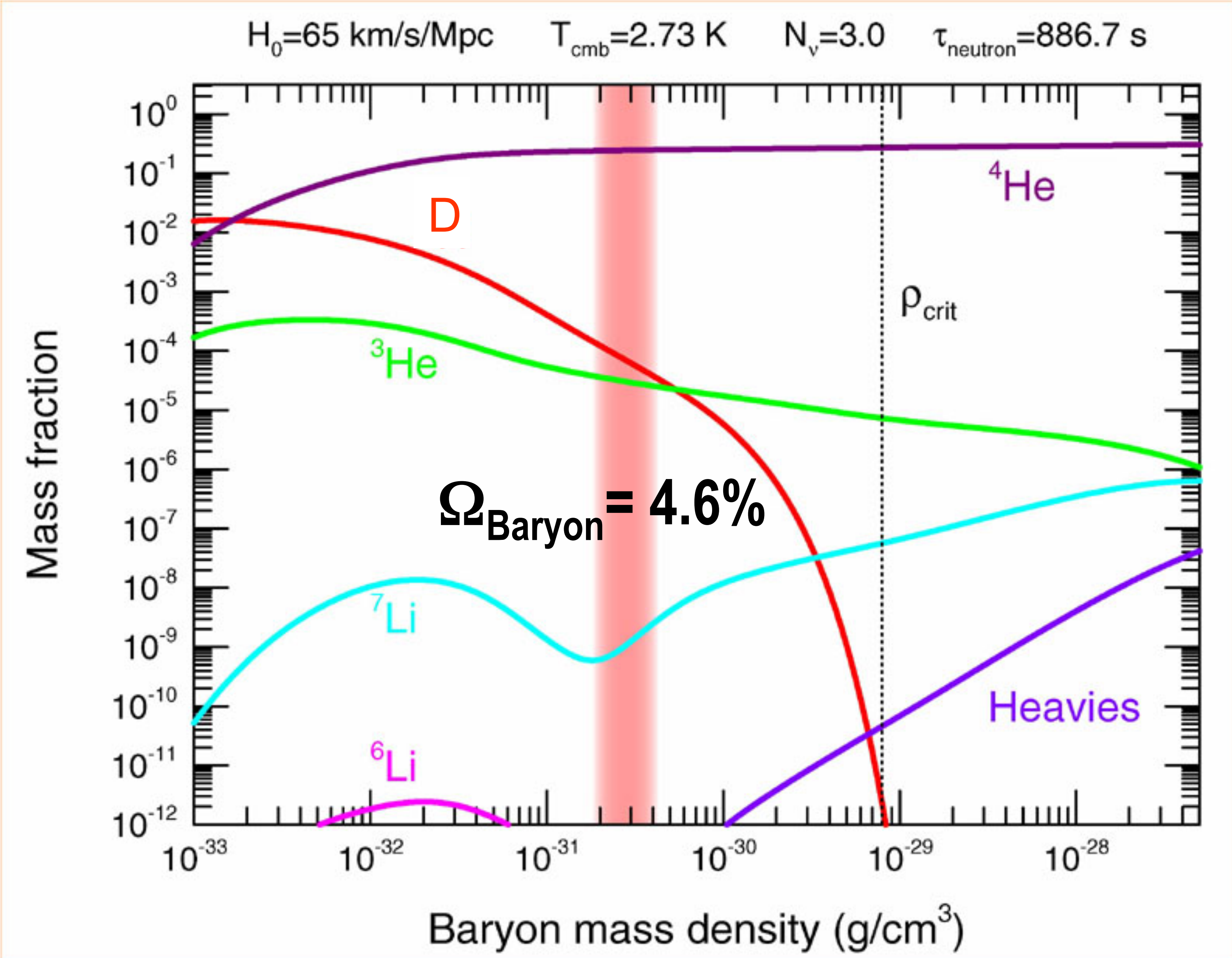


# Density of Our Universe

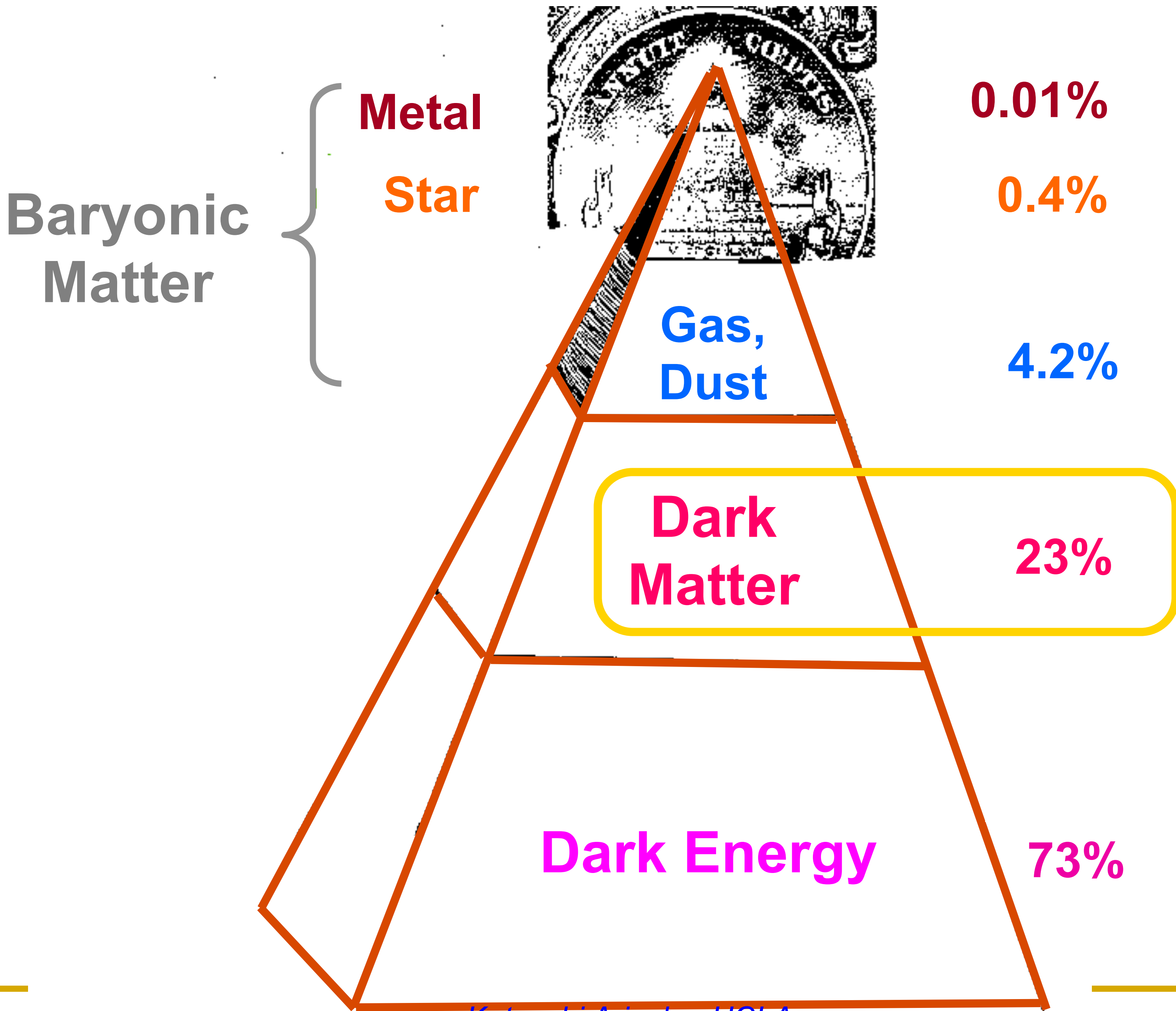
- $\Omega_{Total} = \Omega_{\Lambda} + \Omega_{Matter}$
  $= 1.0$
- **Universe is Flat.**
  $\Rightarrow$ Inflation
- **73% is Dark Energy.**
  $\Rightarrow$ Accelerating



# Abundance vs. Density



# Cosmic Pyramid



# WIMP Miracle

$$\Omega_X = \frac{m_X n_0}{\rho_c} = \frac{m_X T_0^3}{\rho_c}\frac{n_0}{T_0^3} \sim \frac{m_X T_0^3}{\rho_c}\frac{n_f}{T_f^3} \sim \frac{x_f T_0^3}{\rho_c M_{\rm Pl}}\langle\sigma_A v\rangle^{-1}$$

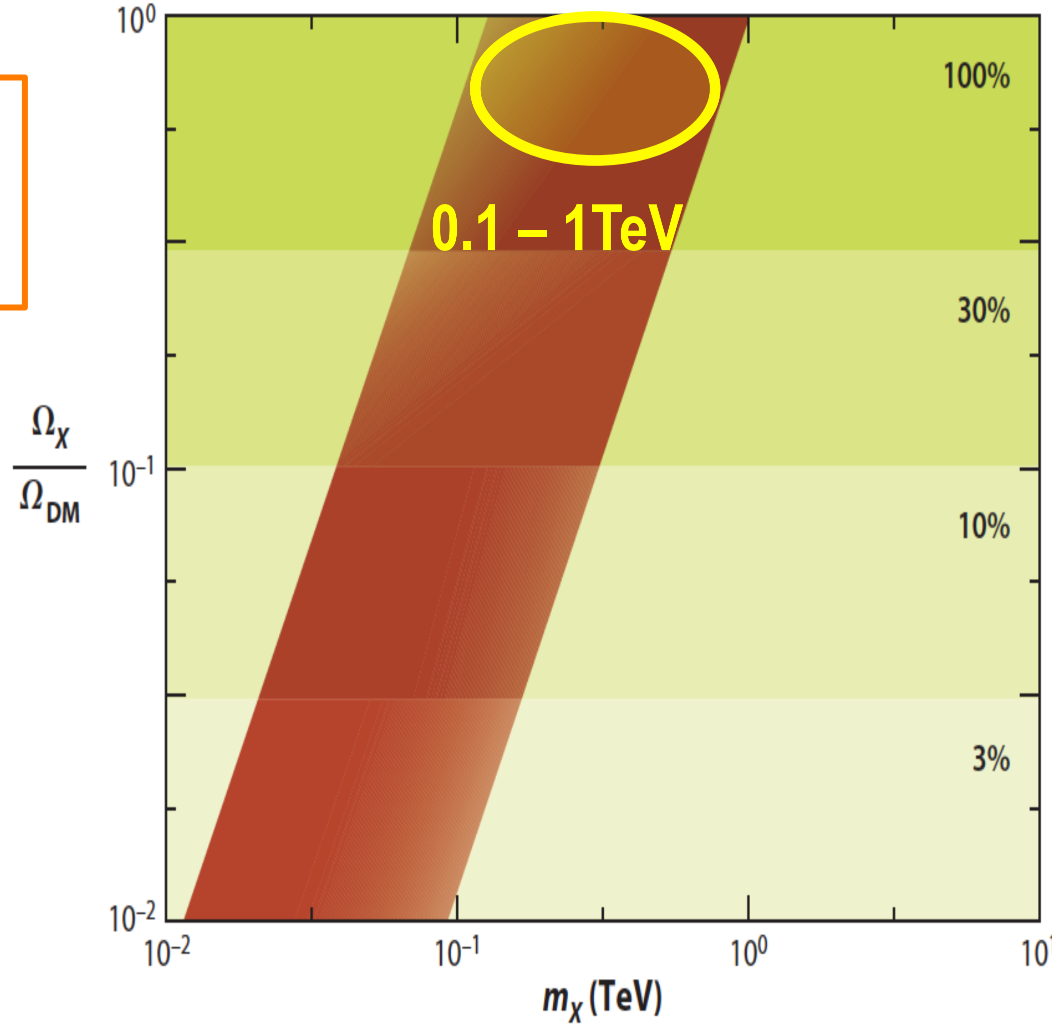
$$\sigma_A v = k\frac{g_{\rm weak}^4}{16\pi^2 m_X^2}(1 \text{ or } v^2)$$

⇓

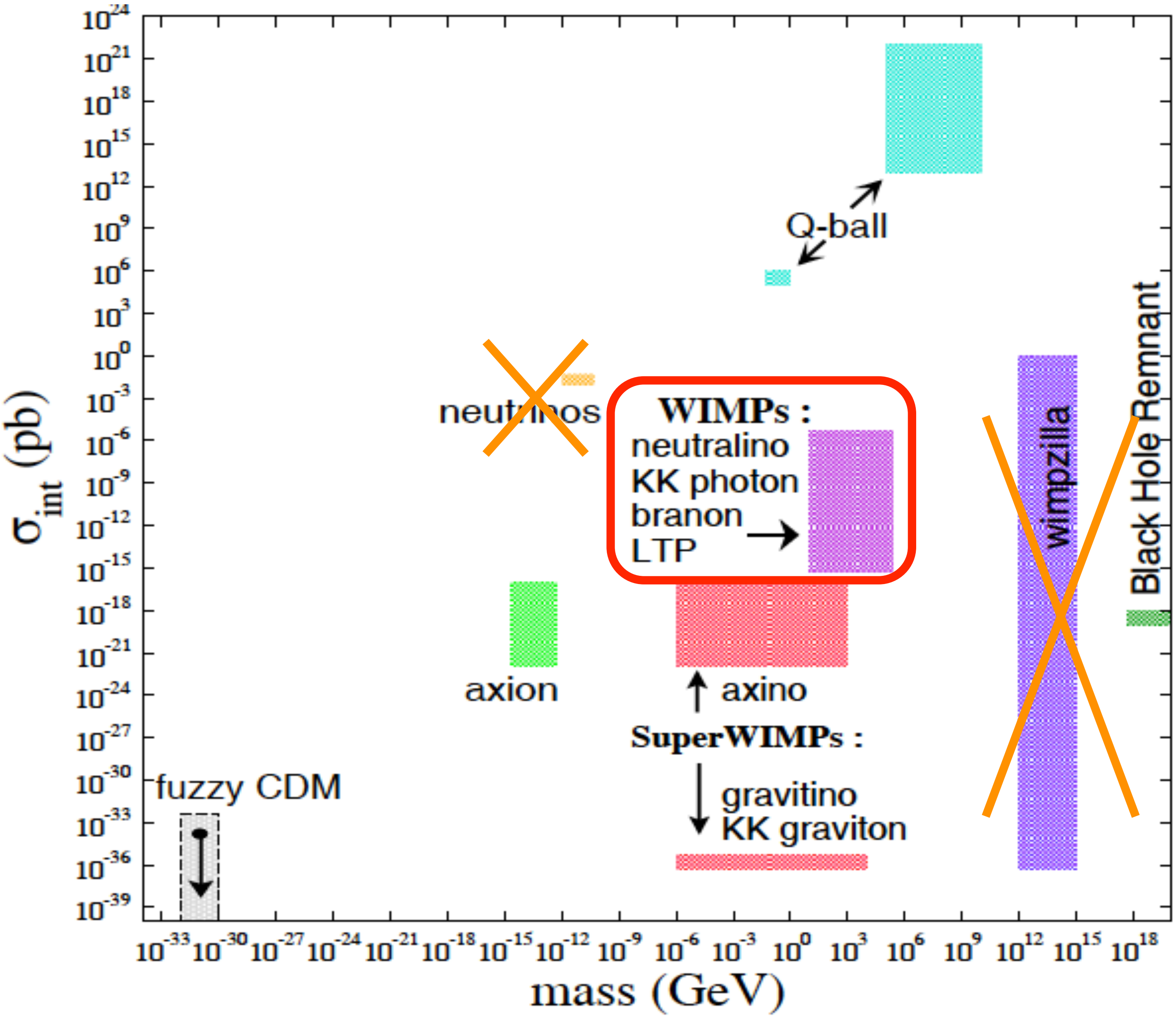
$$\Omega_X \propto M_X^2$$

$M_X \sim 0.1\text{-}1\,TeV$

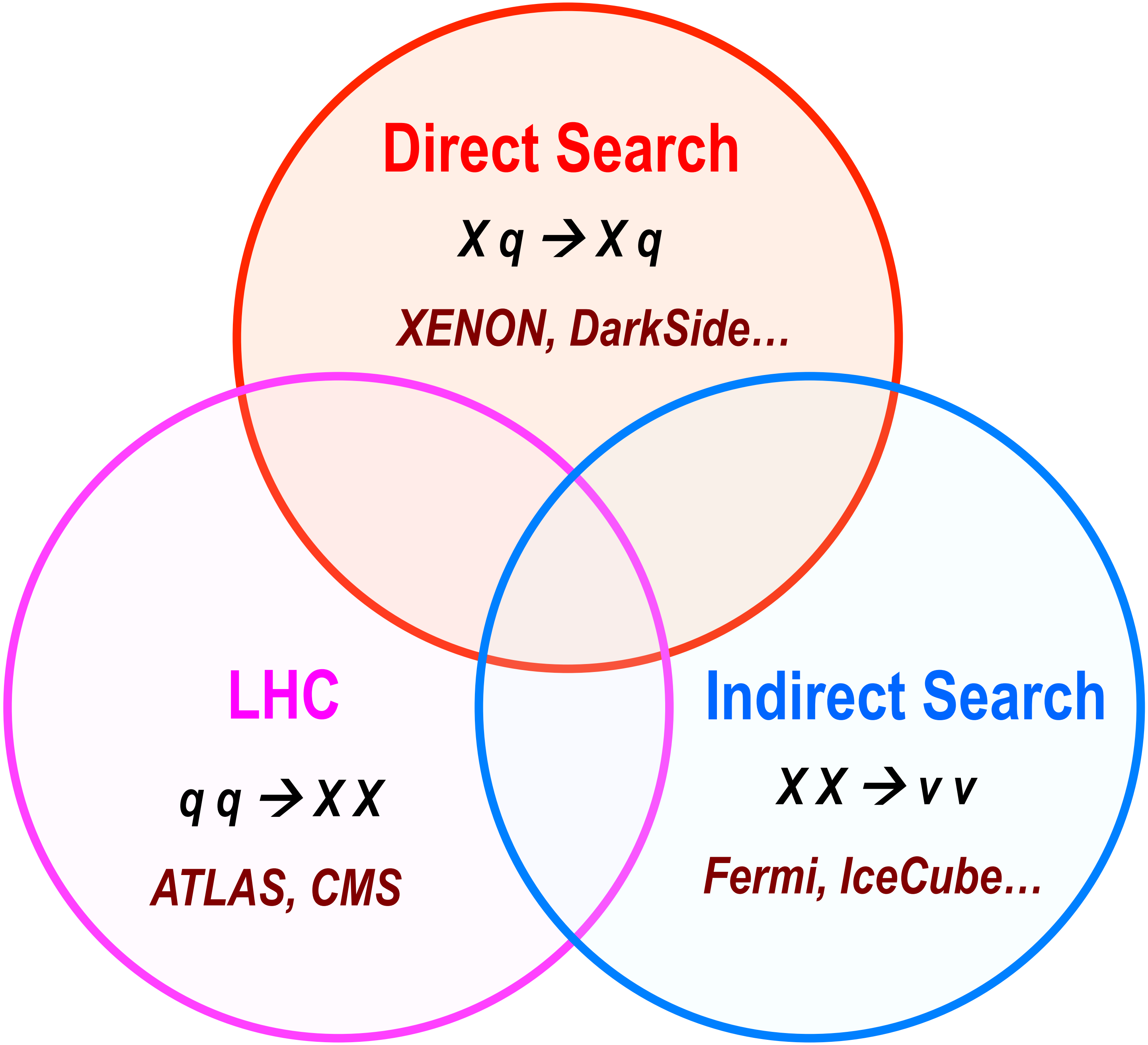
$\sigma_A \sim pb$



# What is Dark Matter?

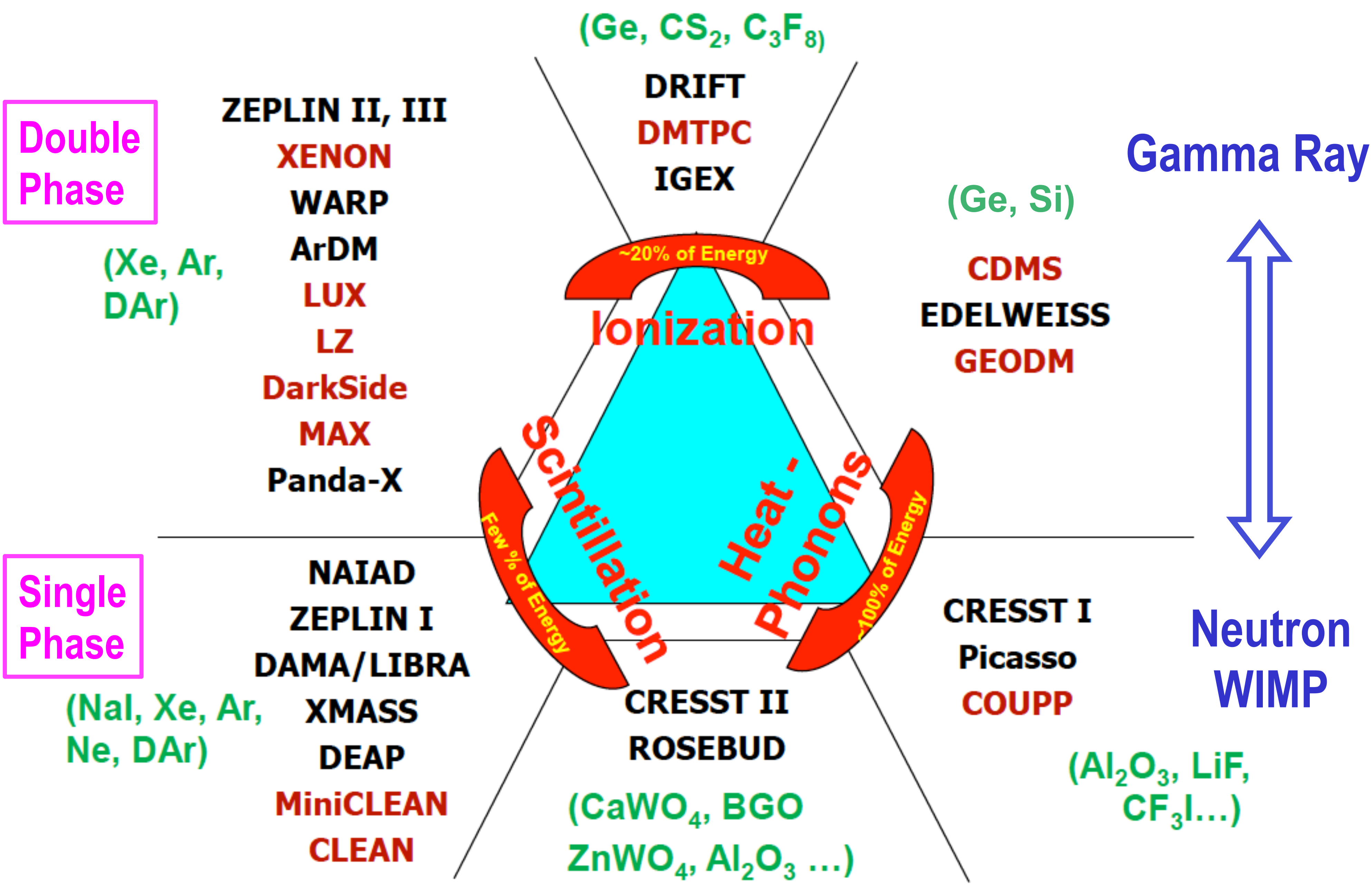


# How to approach dark matter?

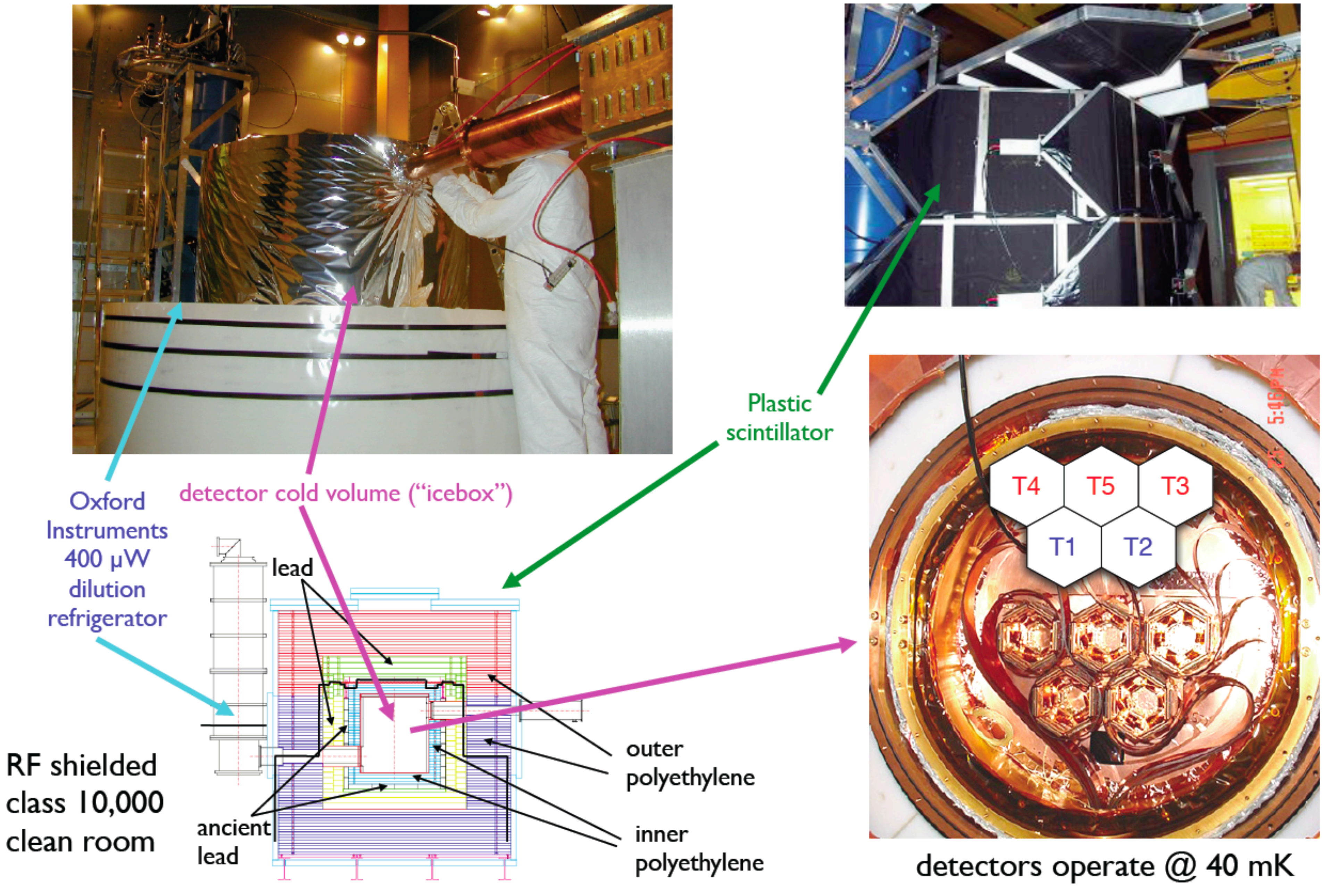


# Direct Detection Methods

# Detection Technique

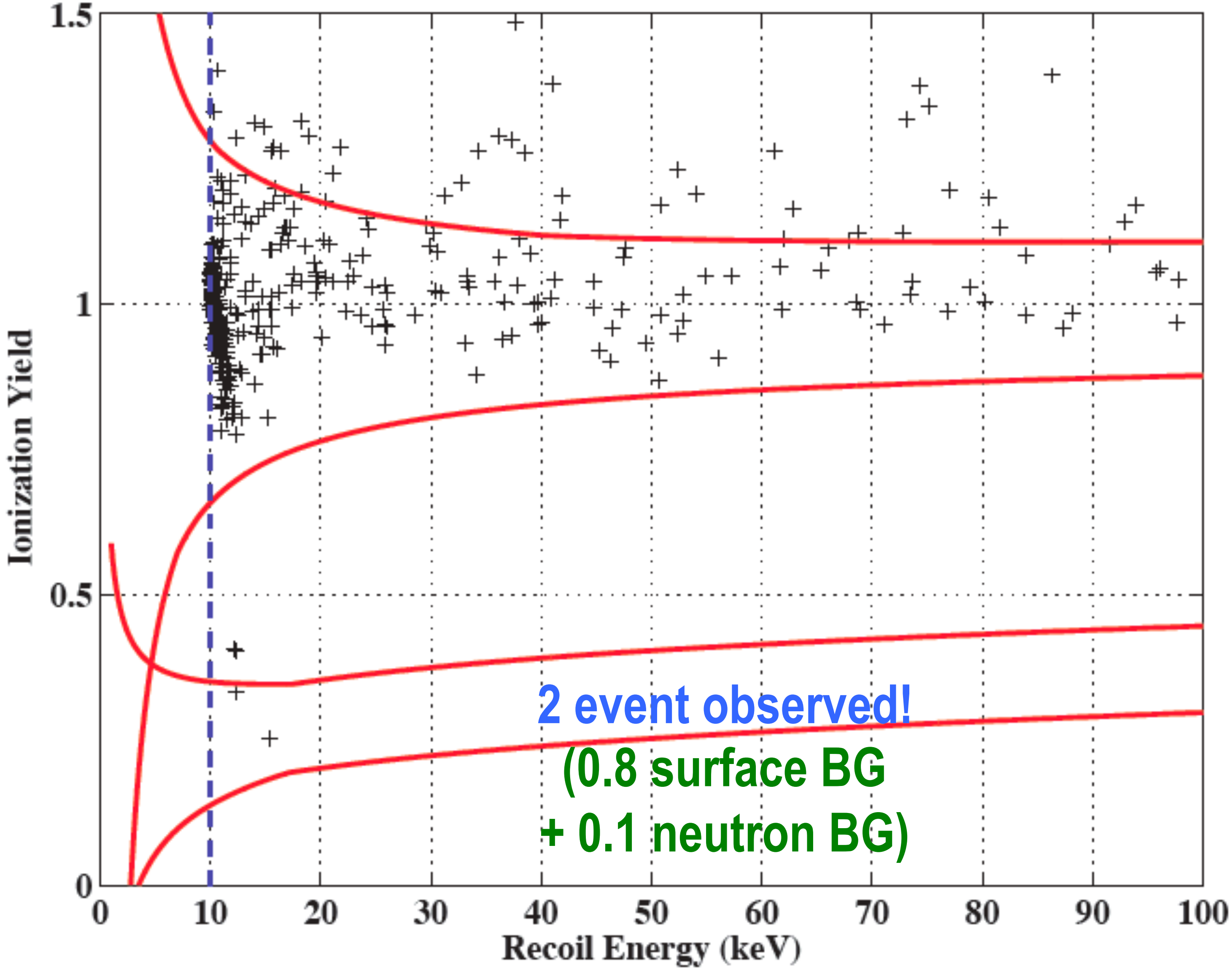


# CDMS-II in Soudan



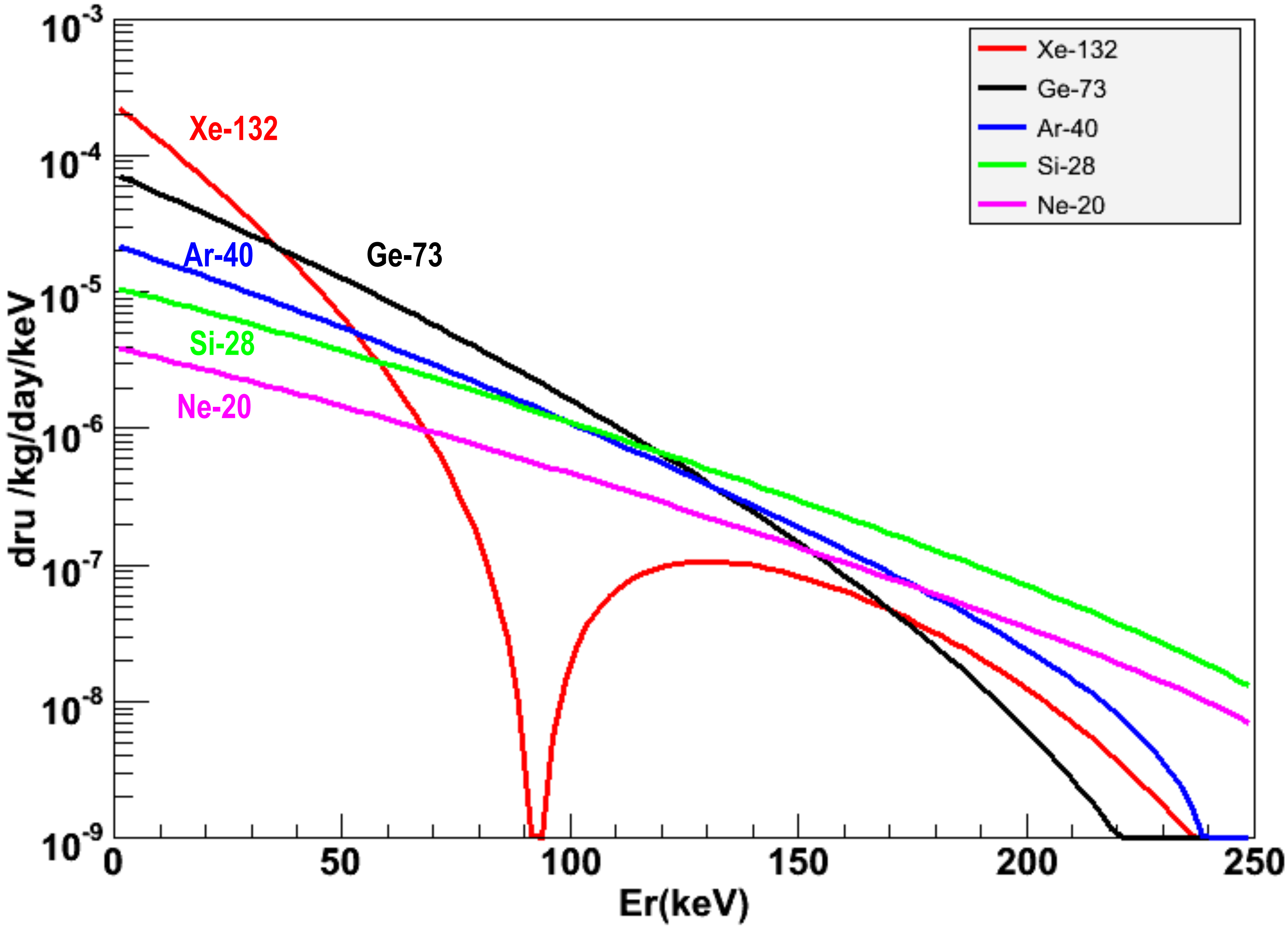
# CDMS-II New Results

194 kg-days exposure = 4.4 kg x 139 day x 0.33 (eff.)



# Target Mass Dependence of WIMP Cross Section

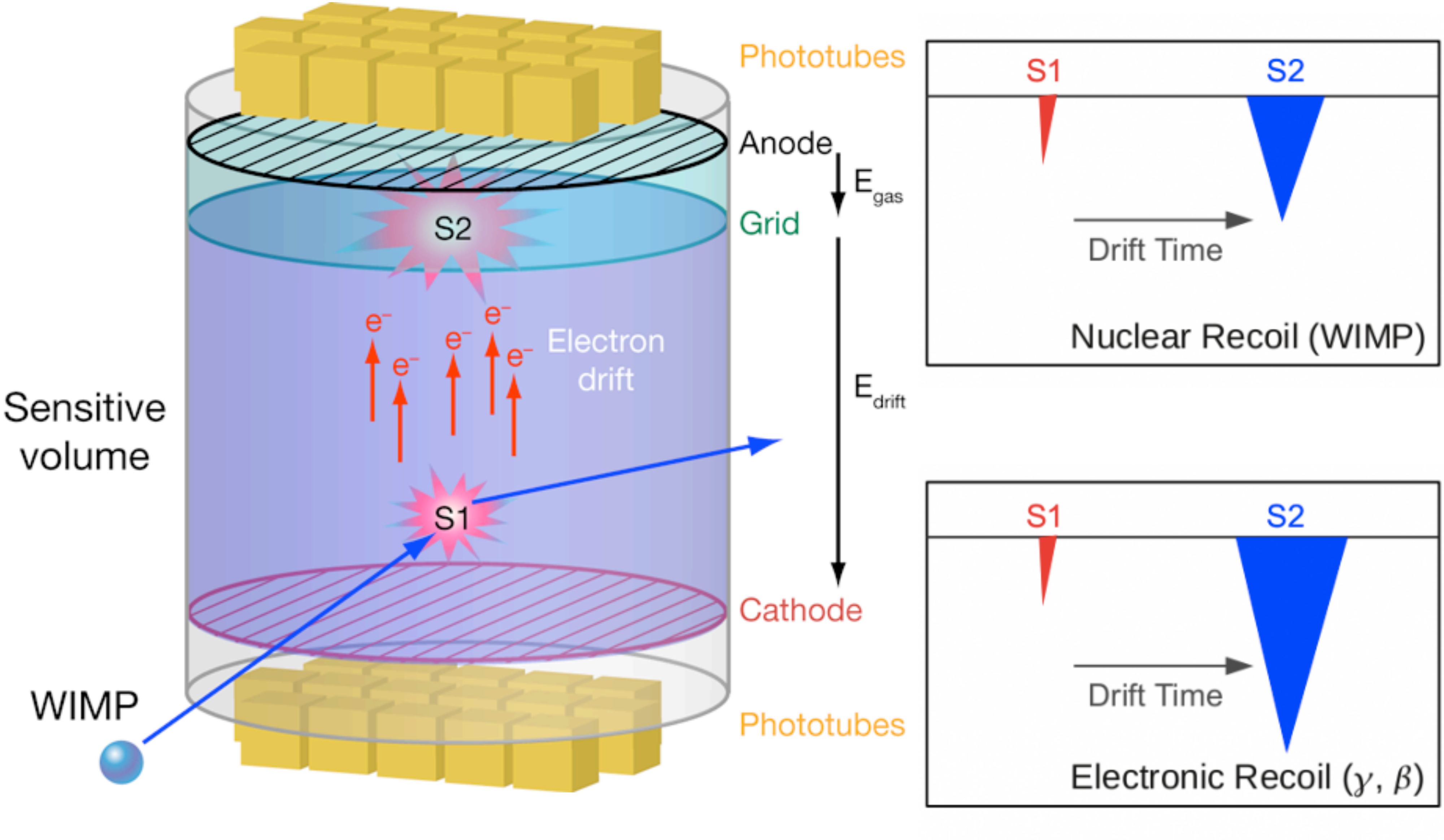
cross section $10^{-44}$ $cm^2$ , WIMP mass 100 GeV



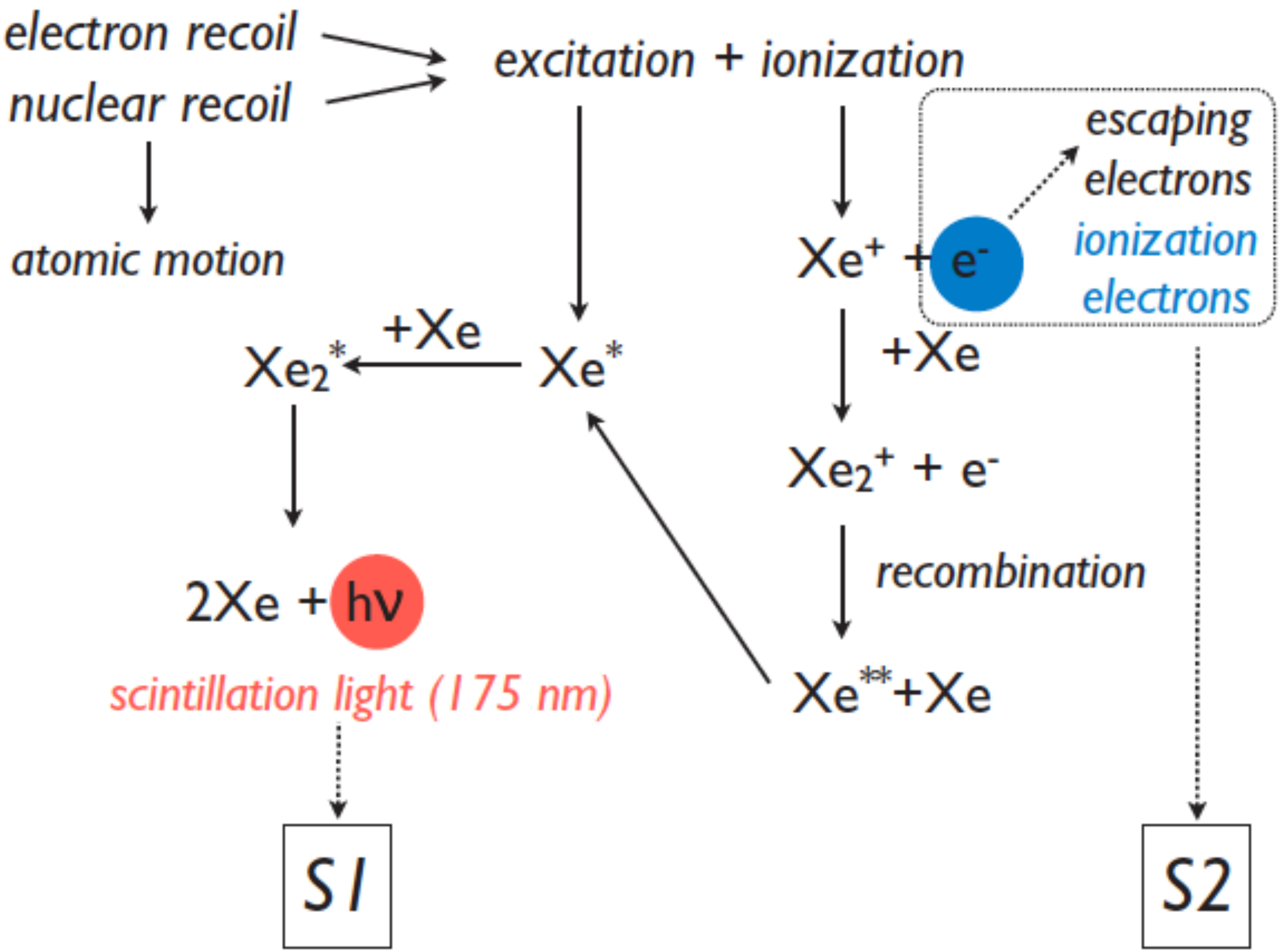
# Properties of Noble Liqud

| | Unit | Neon | Argon | Xenon |
|---|---|---|---|---|
| *Z* | | 10 | 18 | 54 |
| *A* | | 20 | 40 | ~132 |
| *Liquid Density* | *g/cc* | 1.21 | 1.4 | 3.06 |
| *Energy Loss (dE/dX)* | *MeV/cm* | 1.4 | 2.1 | 3.8 |
| *Radiation Length* | *cm* | 24 | 14 | 2.8 |
| *Collision Length* | *cm* | 80 | 80 | 34 |
| *Boiling Temperature* | *°K* | 27.1 | 87.3 | 165 |
| *Scintillation Wavelength* | *nm* | 85 | 125 | 178 |
| *Scintillation* | *photon/keV* | 30 | 40 | 46 |
| *Ionization* | *e-/keV* | 46 | 42 | 64 |
| *Decay time (Fast Component)* | *nsec* | 19 | 7 | 4 |
| *Decay time (Slow Component)* | *nsec* | 1500 | 1600 | 26 |
| *Isotope* | | No | $^{39}$Ar (1 Bq/kg) | $^{136}$Xe |
| *Price* | *$ /ton* | $90k | ~$2k | ~$1M |
| *Single Phase Experiments* | | CLEAN | DEAP/CLEAN | XMASS |
| *Double Phase Experiments* | | | WARP, ArDM, DarkSide, MAX | ZEPLIN, XENON, MAX LUX, LZD |

# Double-Phase Noble Liquids

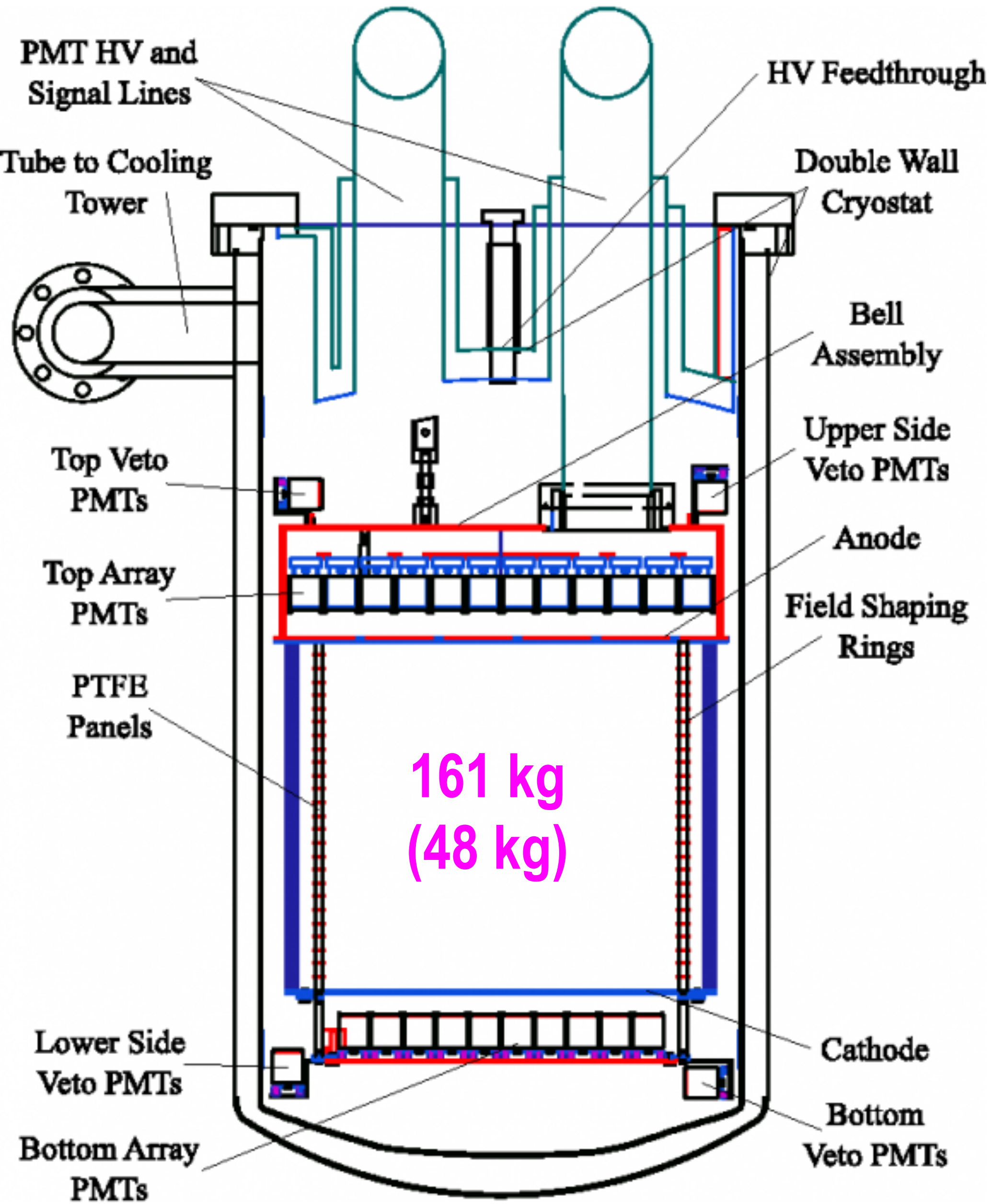


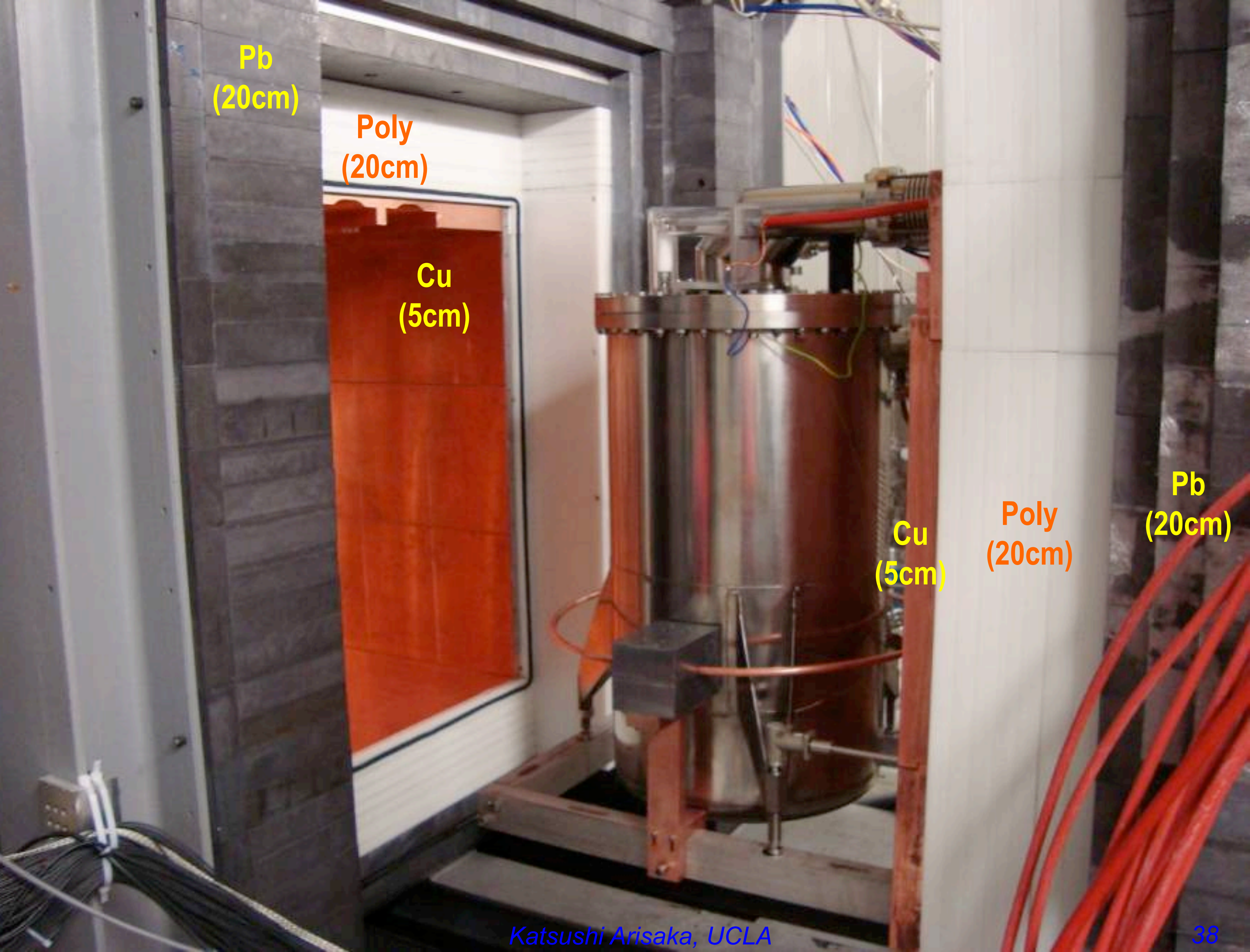
# S1 and S2




Manzur 2010

# XENON100 Detector

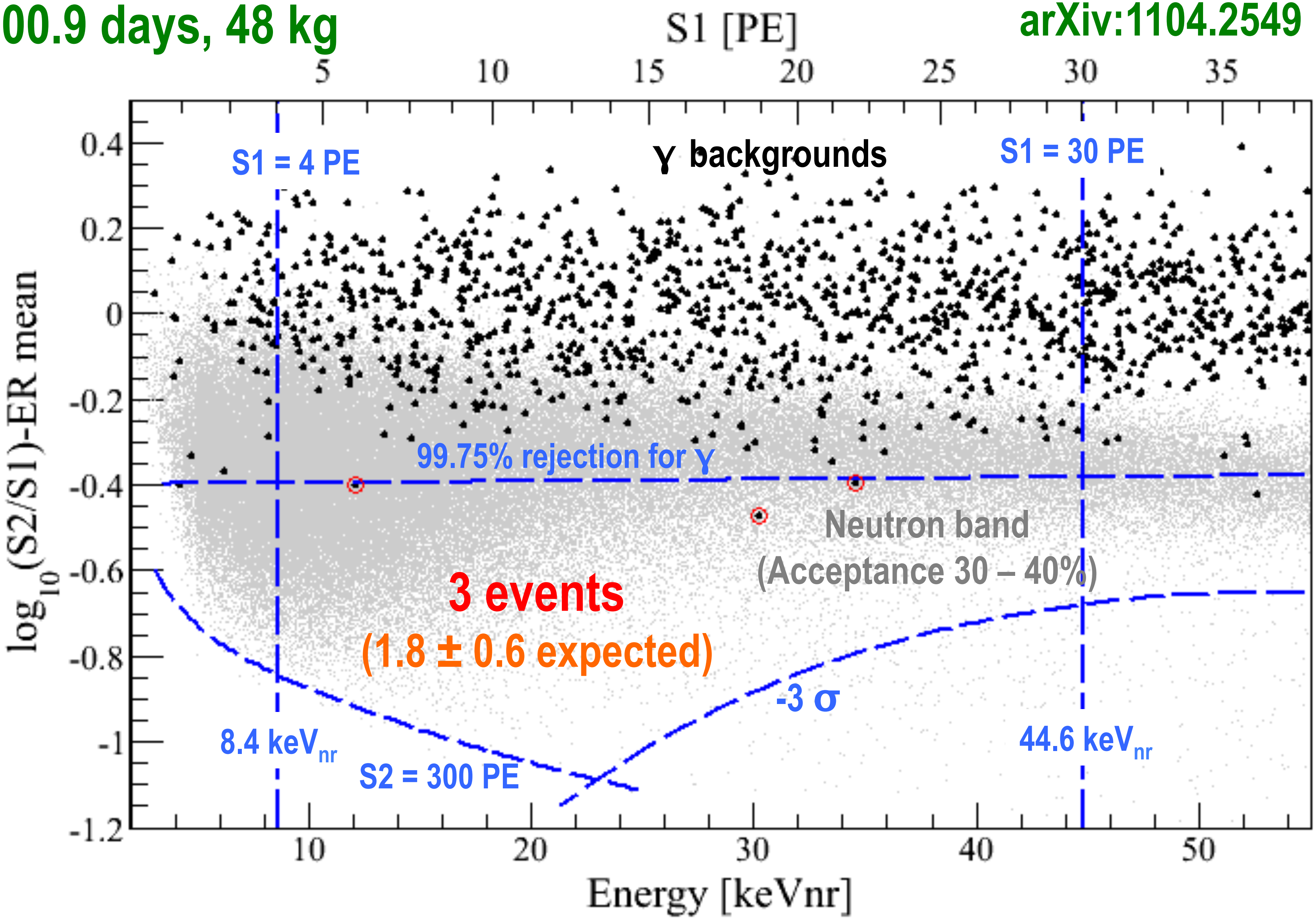




Pb
(20cm)
Poly
(20cm)
Cu
(5cm)
Cu
(5cm)
Poly
(20cm)
Pb
(20cm)

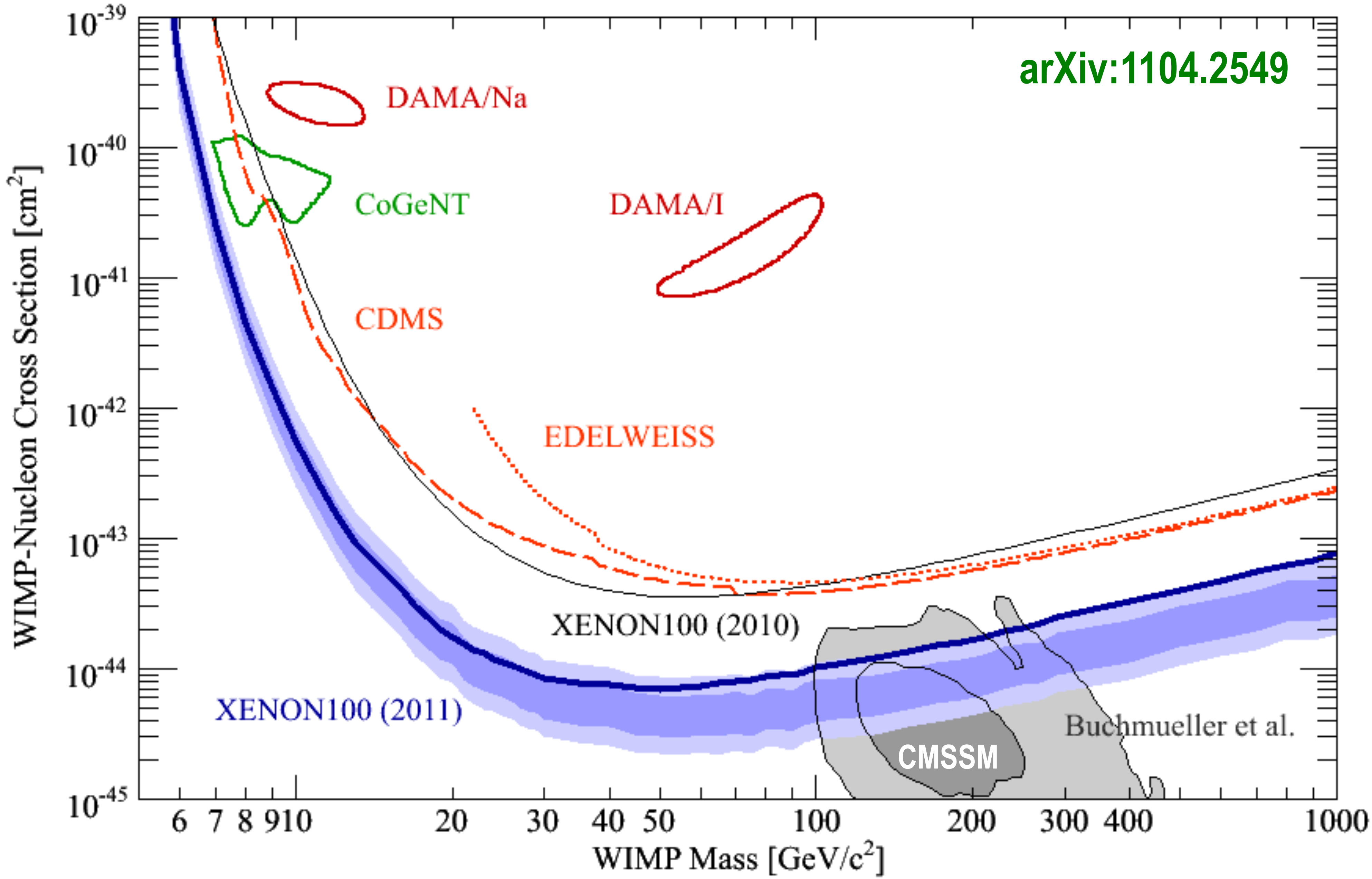
# Log(S2/S1) vs. Energy

100.9 days, 48 kg

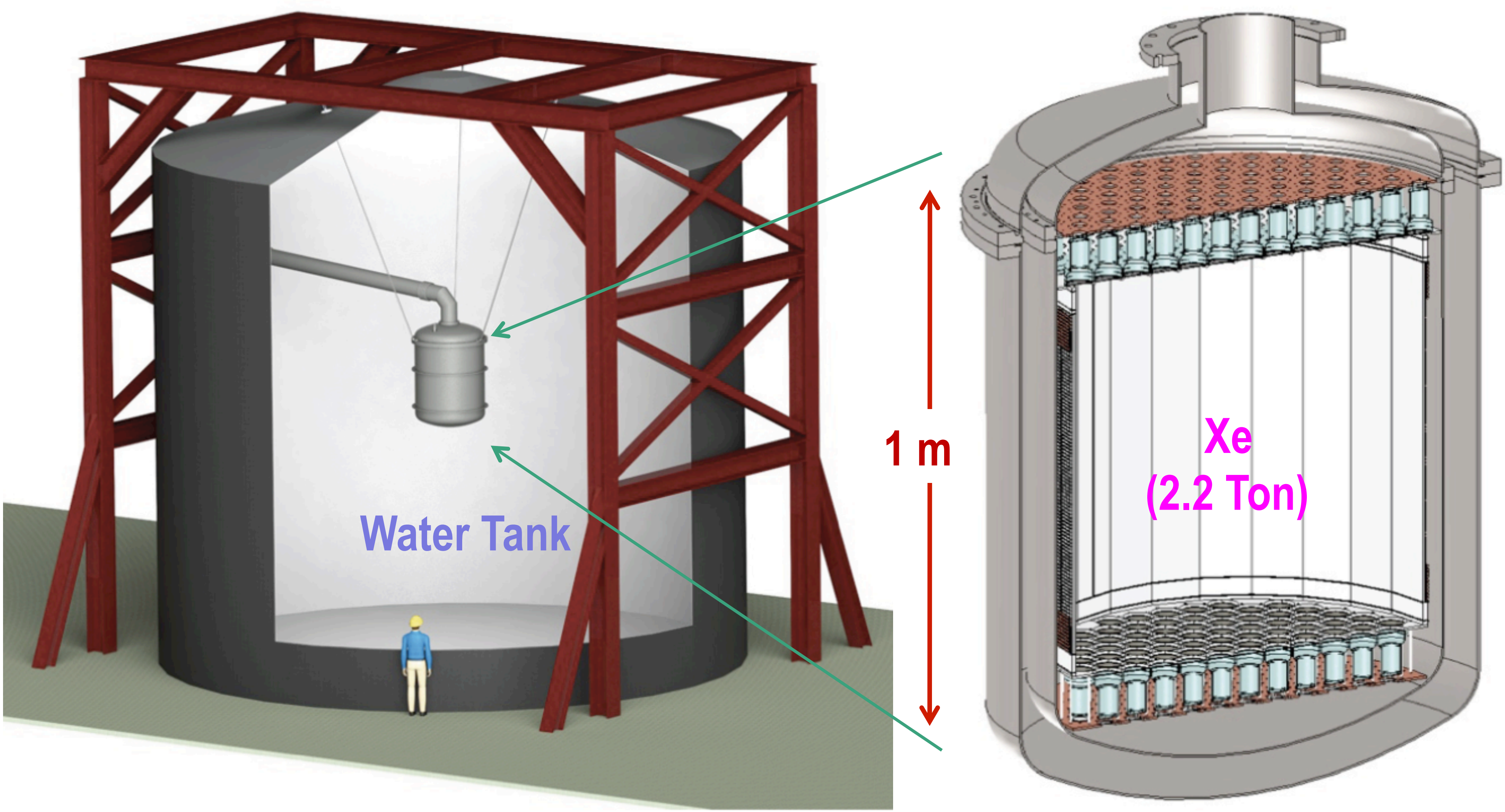
arXiv:1104.2549



# 90% CL Limits of SI Cross Section (April, 2011)

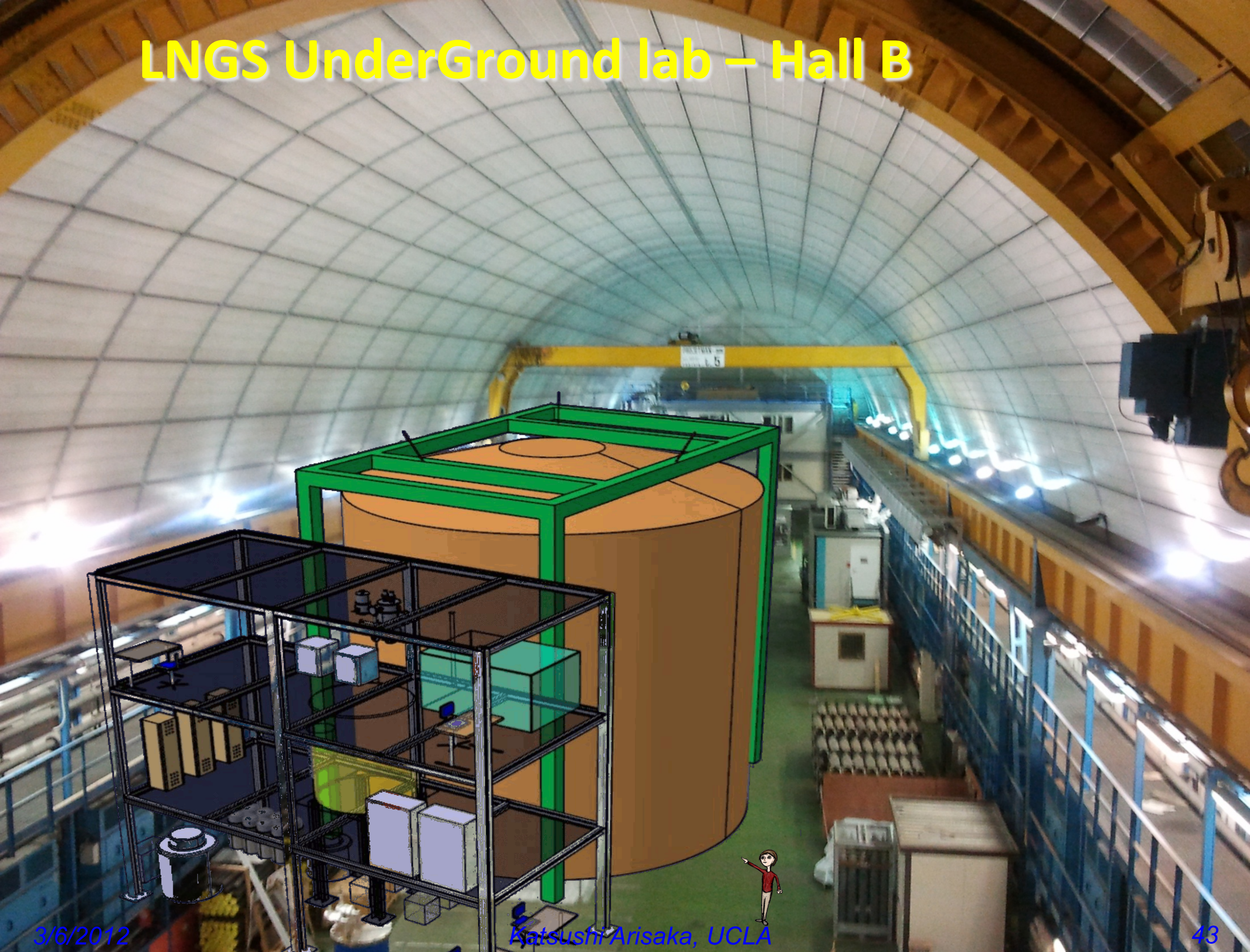


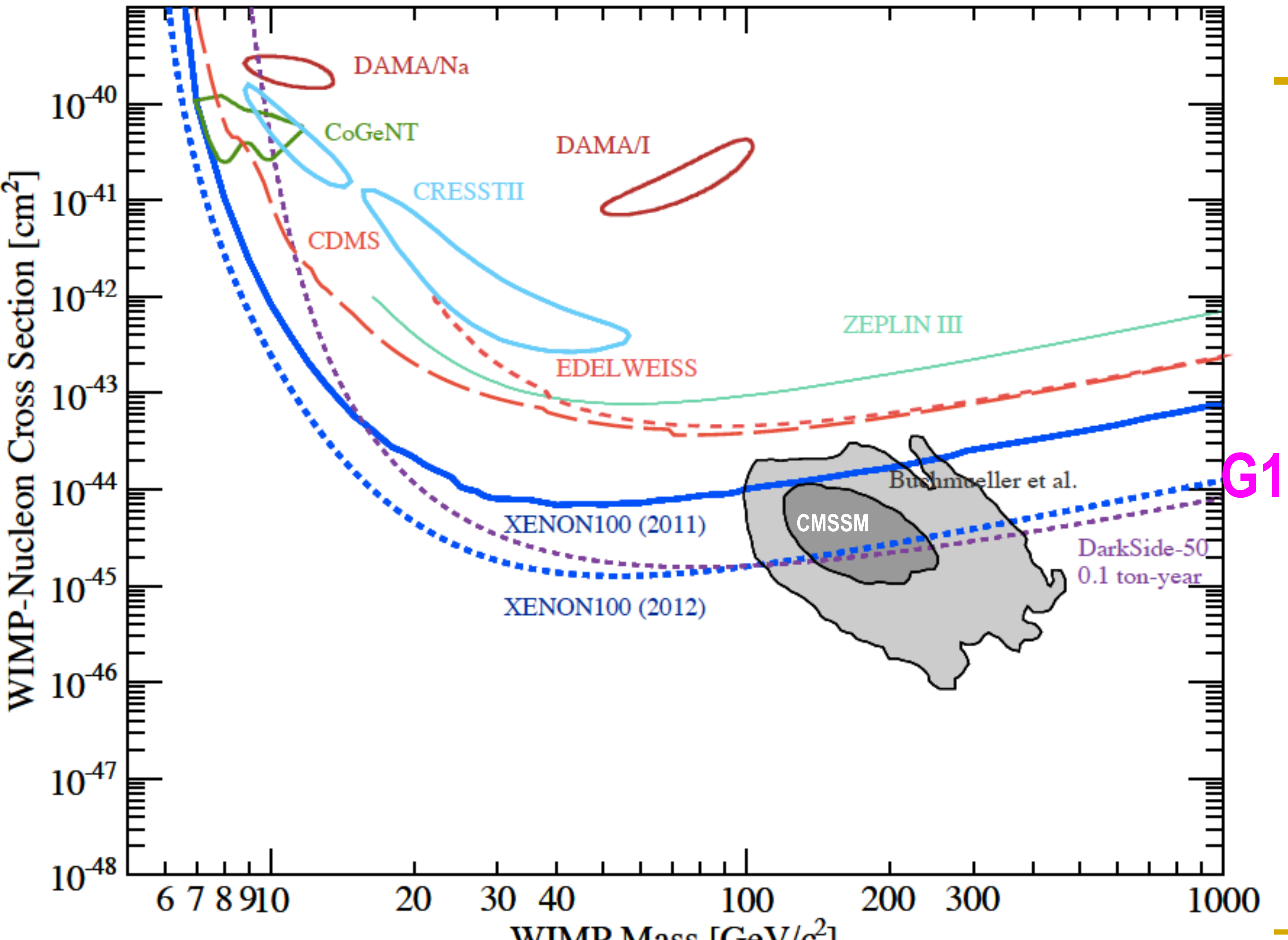
# XENON1T (G2) at LNGS

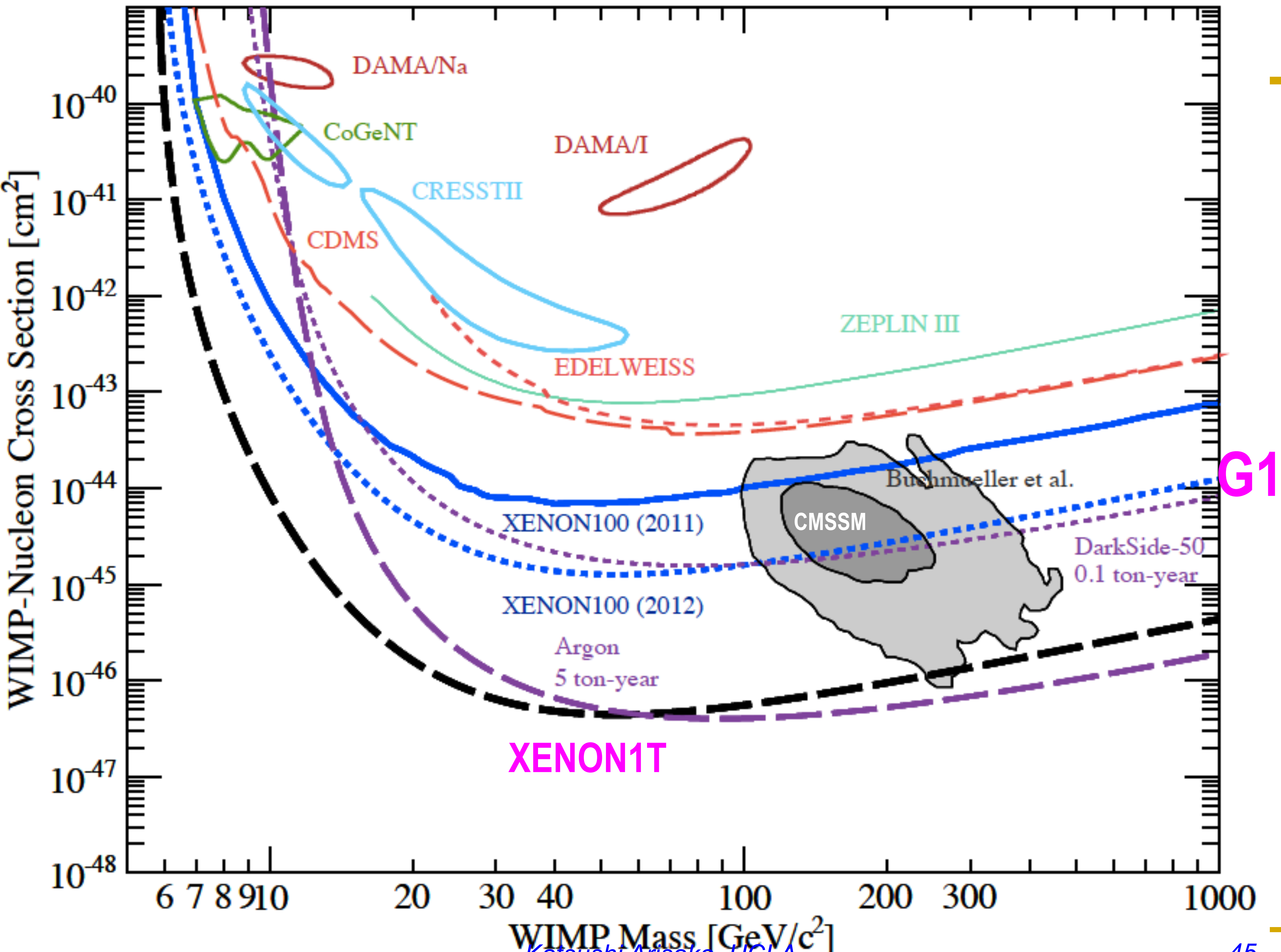


# LNGS UnderGround lab – Hall B

# LNGS UnderGround lab – Hall B



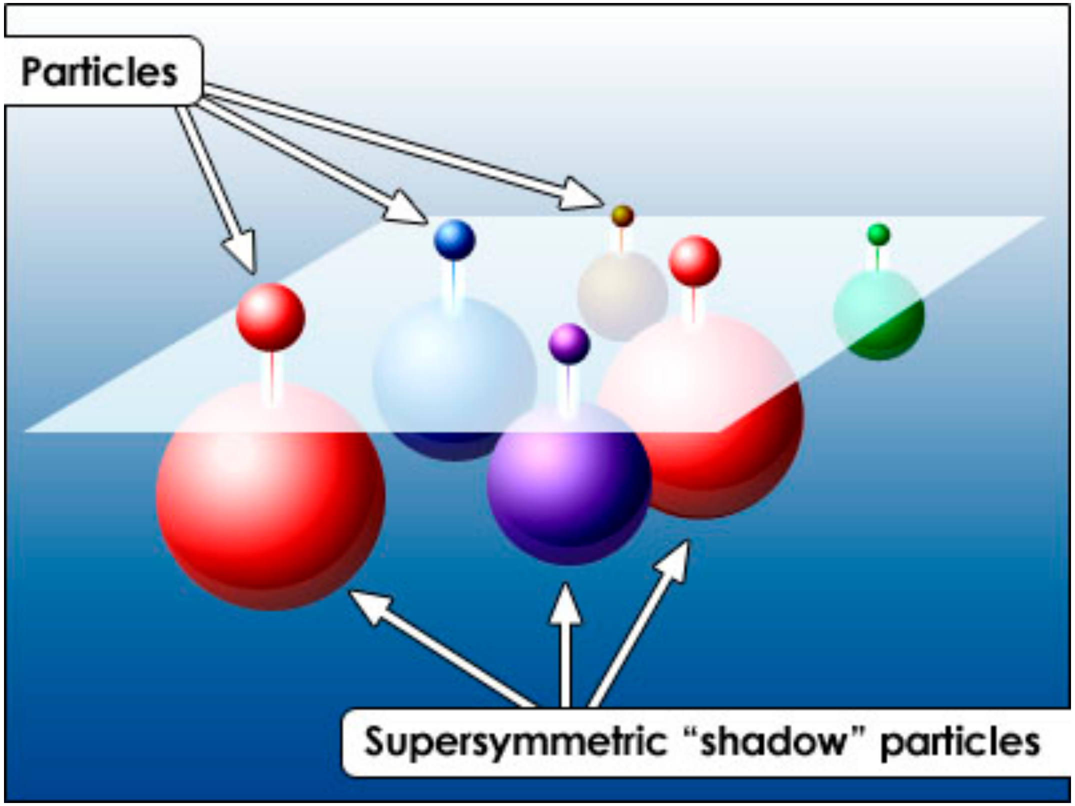

DAMA/Na
CoGeNT
DAMA/I
CRESSTII
CDMS
ZEPLIN III
EDELWEISS
G1
Buchmueller et al.
CMSSM
XENON100 (2011)
DarkSide-50
0.1 ton-year
XENON100 (2012)
WIMP-Nucleon Cross Section [cm²]
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
6 7 8 9 10
20
30 40
100
200 300
1000
WIMP Mass [GeV/c²]



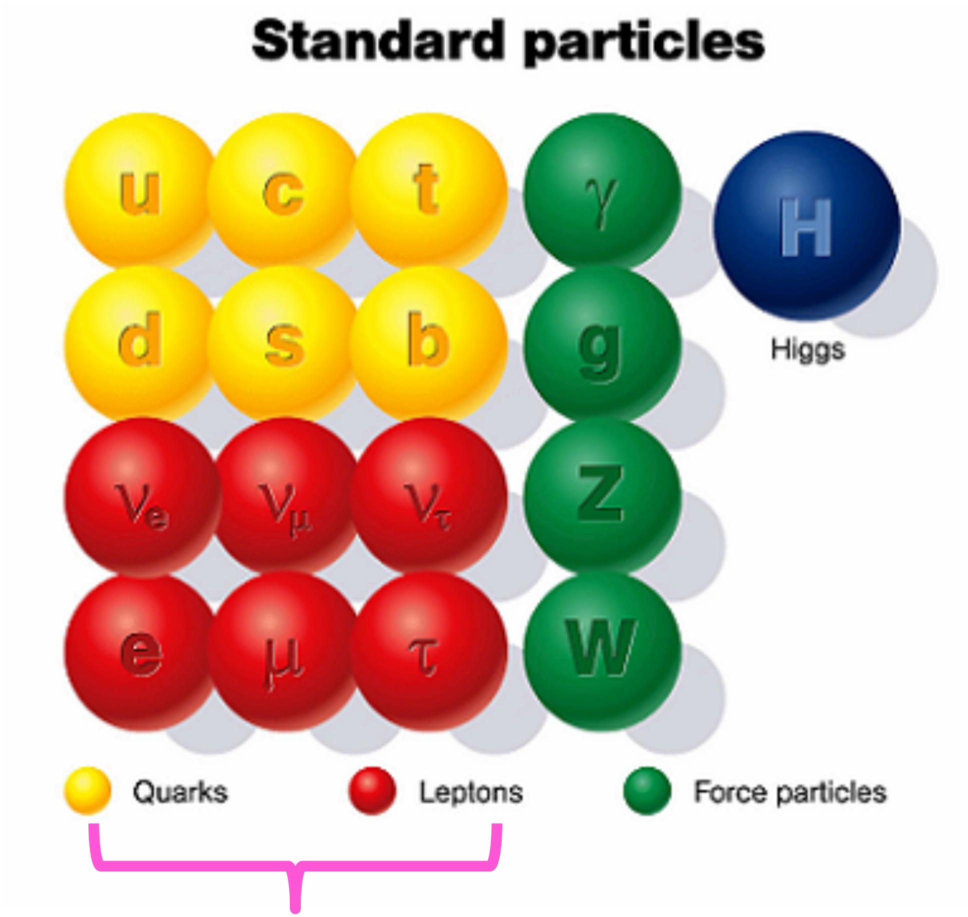
DAMA/Na
CoGeNT
DAMA/I
CRESSTII
CDMS
ZEPLIN III
EDELWEISS
Buchmueller et al.
CMSSM
G1
XENON100 (2011)
XENON100 (2012)
DarkSide-50
0.1 ton-year
Argon
5 ton-year
XENON1T
WIMP-Nucleon Cross Section [cm$^2$]
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
$10^{-46}$
$10^{-47}$
$10^{-48}$
6 7 8 9 10 20 30 40 100 200 300 1000
WIMP Mass [GeV/c$^2$]

# SUSY and
# Extra Dimensions

# SUSY Neutralino

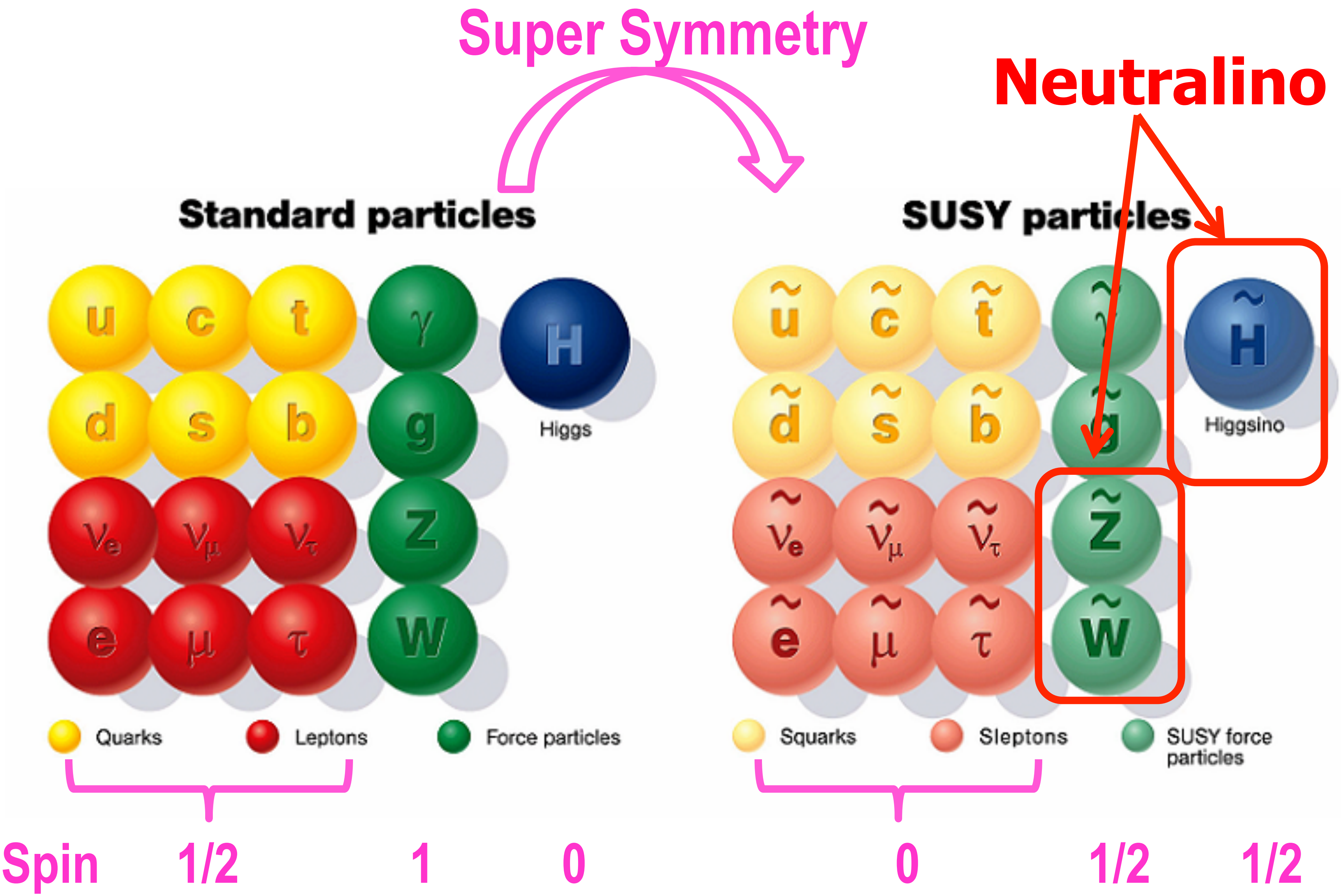


# SUSY Particles and Neutralino




Spin 1/2 1 0

# SUSY Particles and Neutralino



# Hierarchy Problem

## Higgs mass

$m_h^2 = m_{h\,0}^2 + \Delta m_h^2$, where $m_{h\,0}^2$ is the tree-level mass, and

**SM :**

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2} \int^{\Lambda} \frac{d^4 p}{p^2} \sim \frac{\lambda^2}{16\pi^2} \boxed{\Lambda^2}$$

**SUSY :**

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2} \int^{\Lambda} \frac{d^4 p}{p^2}\bigg|_{\mathrm{SM}} - \frac{\lambda^2}{16\pi^2} \int^{\Lambda} \frac{d^4 p}{p^2}\bigg|_{\mathrm{SUSY}}$$

$$\sim \frac{\lambda^2}{16\pi^2} (m_{\mathrm{SUSY}}^2 - m_{\mathrm{SM}}^2) \boxed{\ln \frac{\Lambda}{m_{\mathrm{SUSY}}}}$$

**or : new physics at the energy scale of Λ ~ 1 TeV**

# MSSM: > 100 parameters

Minimal Flavour Violation: 13 parameters

(+ 6 violating CP)

SU(5) unification: 7 parameters

NUHM2: 6 parameters

NUHM1 = SO(10): 5 parameters

CMSSM: 4 parameters

mSUGRA: 3 parameters

String?

John Ellis

# Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- 2 Higgs doublets, coupling $\mu$, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  Scalar masses $m_0$, gaugino masses $m_{1/2}$,
  trilinear soft couplings $A_\lambda$, bilinear soft coupling $B_\mu$
- Often assume universality:
  Single $m_0$, single $m_{1/2}$, single $A_\lambda, B_\mu$: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity also predicts gravitino mass
  $m_{3/2} = m_0, B_\mu = A_\lambda - m_0$
- No-scale supergravity: $m_0 = A_\lambda = B_\mu$

John Ellis

# Mass Spectra at the best fit points (before LHC)

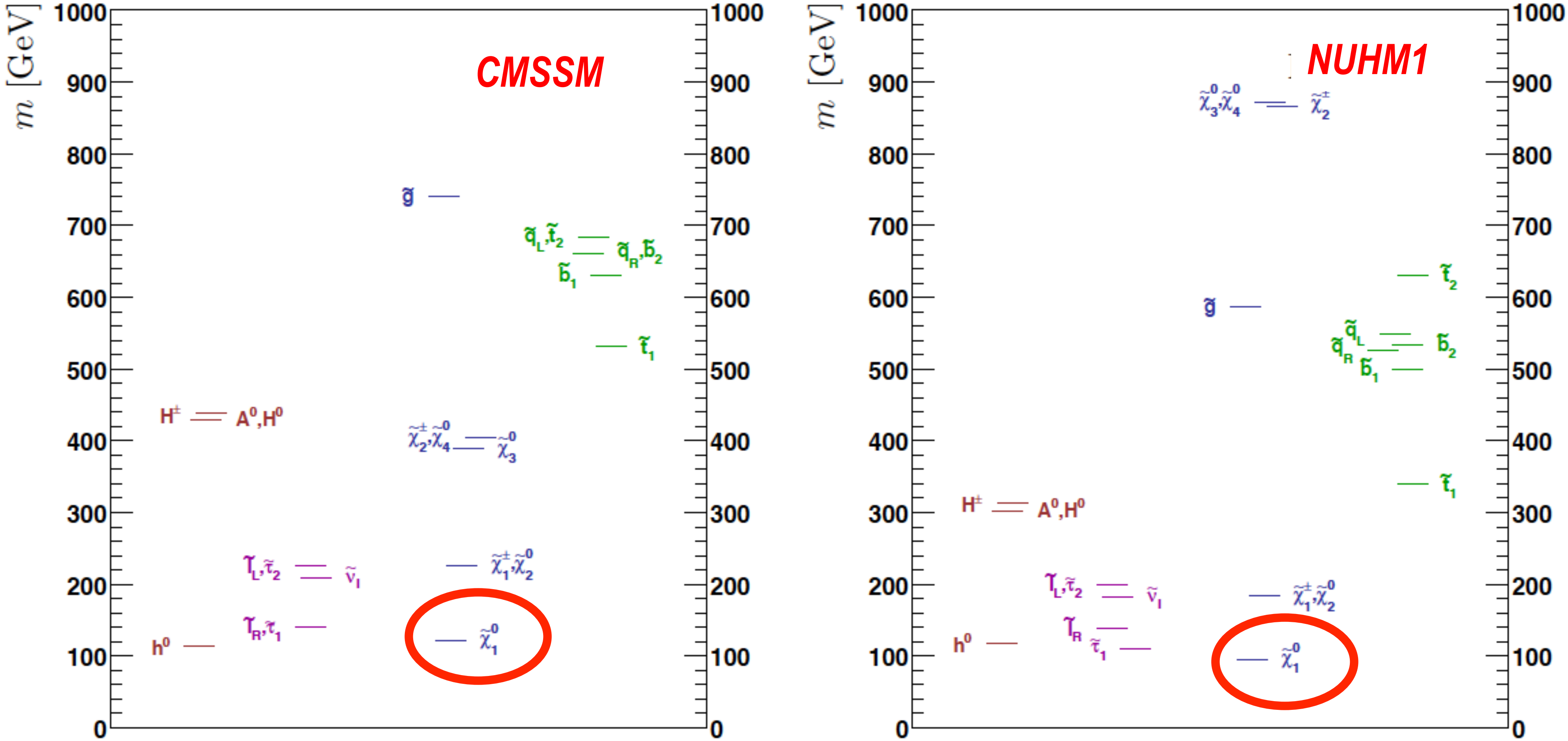
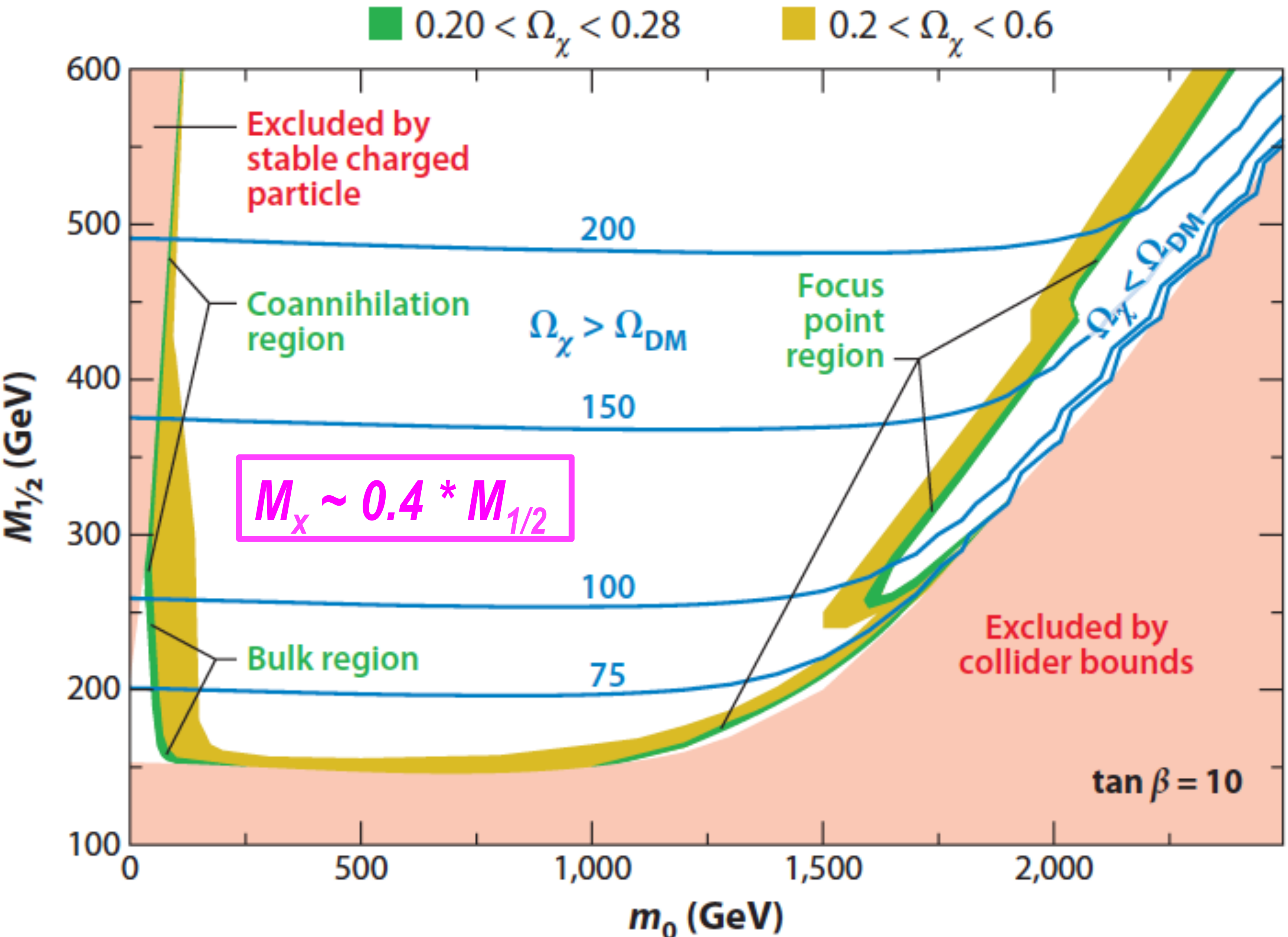



Figure 2. The spectra at the best-fit points: left — in the CMSSM with $m_0 = 60$ GeV, $m_{1/2} = 310$ GeV, $A_0 = 240$ GeV, $\tan\beta = 11$, and right — in the NUHM1 with $m_0 = 100$ GeV, $m_{1/2} = 240$ GeV, $A_0 = -930$ GeV, $\tan\beta = 7$, $m_H^2 = -6.9 \times 10^5$ GeV$^2$ and $\mu = 870$ GeV.

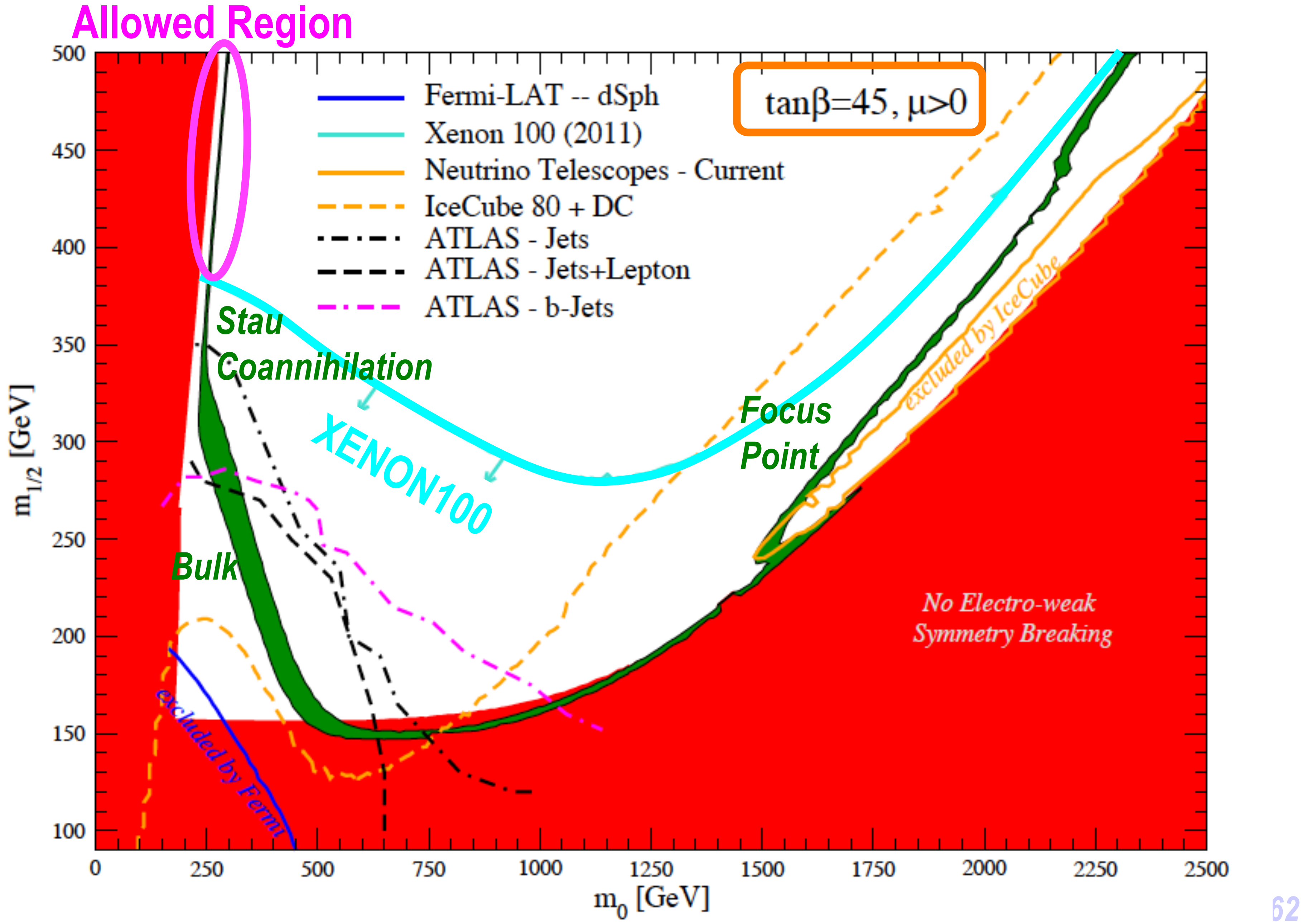
*Buchmueller et al arXiv: 0808.4218*

# mSUGRA $m_{1/2}$ vs. $m_0$

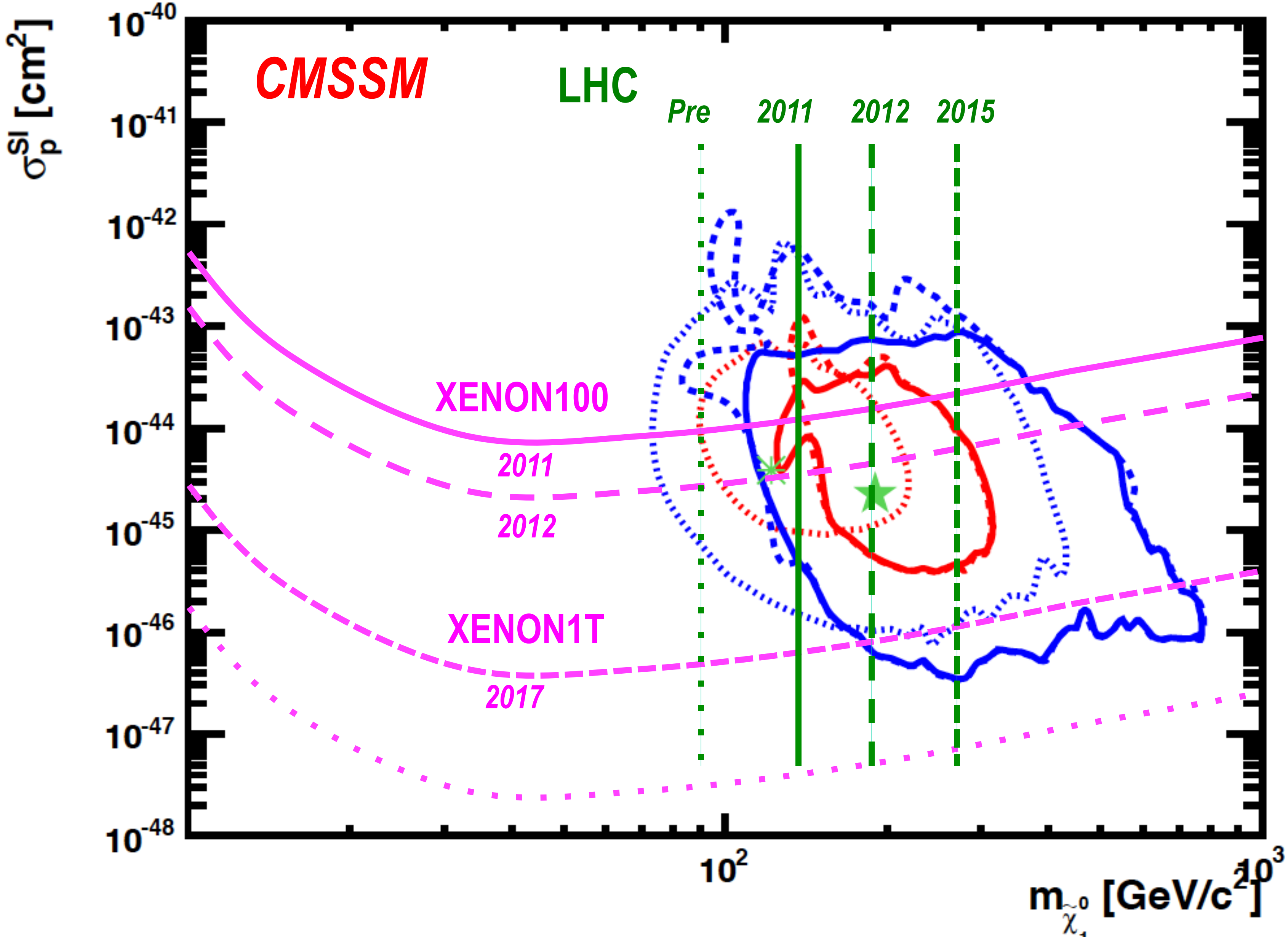



*Feng Ann. Rev. Astro. Astrophys. 2010.48:495-545*

# CMSSM $m_{1/2}$ vs. $m_0$

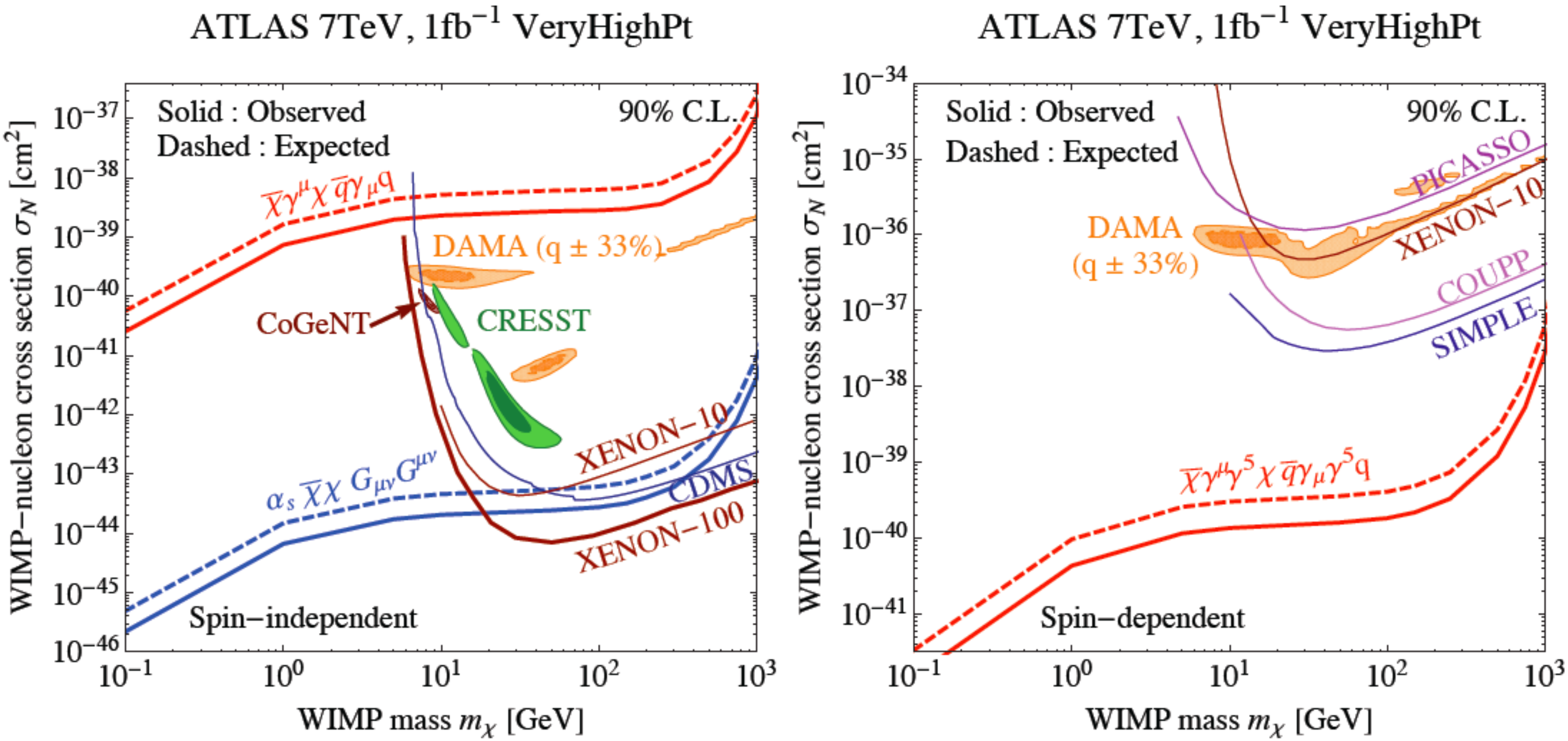


# SI Cross Section vs. Mass



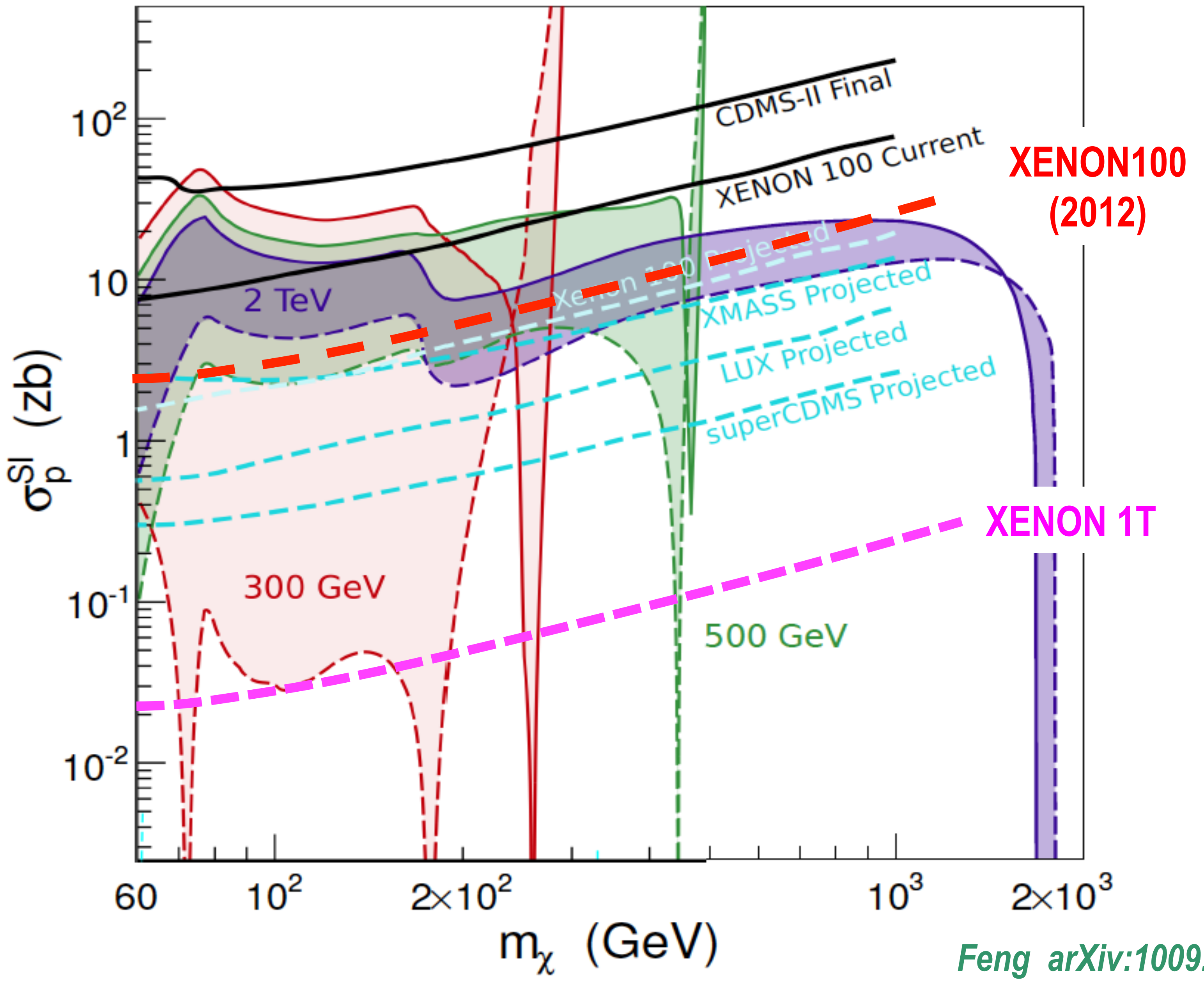

Buchmueller et al arXiv:1106.2529

# Limit from Mono-jet analysis



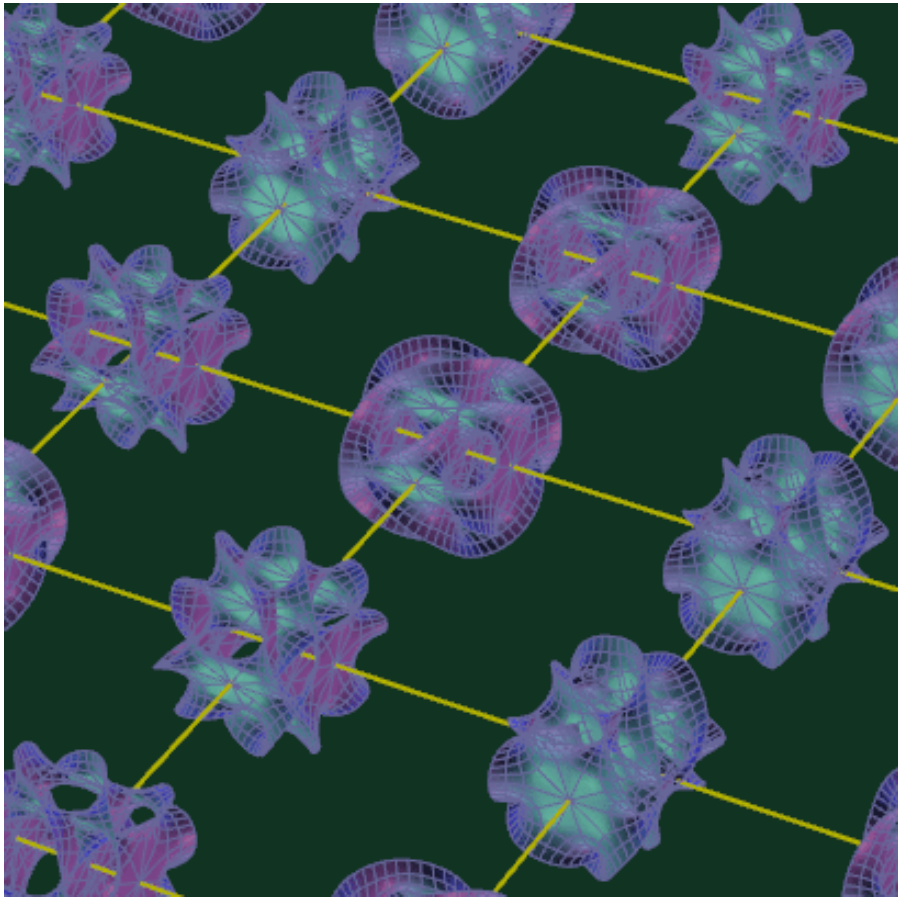

*Fox et al arXiv:11094398*

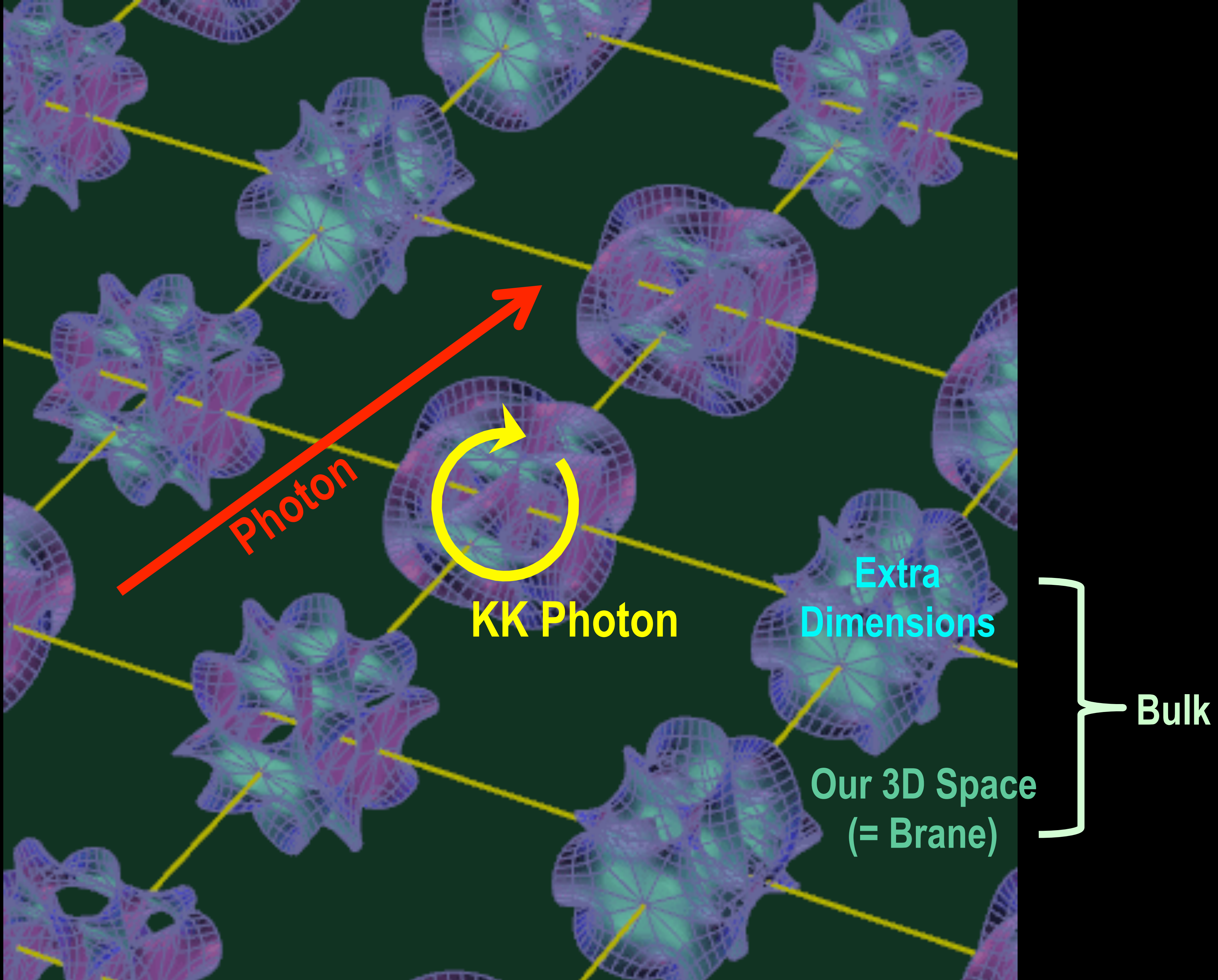
# Sfermion Mass Dependence




*Feng arXiv:1009.3934v2*

# KK particles in Extra Dimensions




Photon
KK Photon
Extra Dimensions
Our 3D Space (= Brane)
Bulk

# Origin of Mass in Extra Dimensions

$$E = mc^2 \rightarrow \boxed{m = E/c^2}$$

- **Mass can be generated as kinetic energy in extra dimensions.**
  - Origin on mass
  - Dark matter is running in the extra dimensions
- **Gravity can escape into the extra dimensions.**
  - Why gravity is so small
  - Origin of dark energy

# Mass Spectrum of the first KK level

## Similar to the SUSY mass spectrum

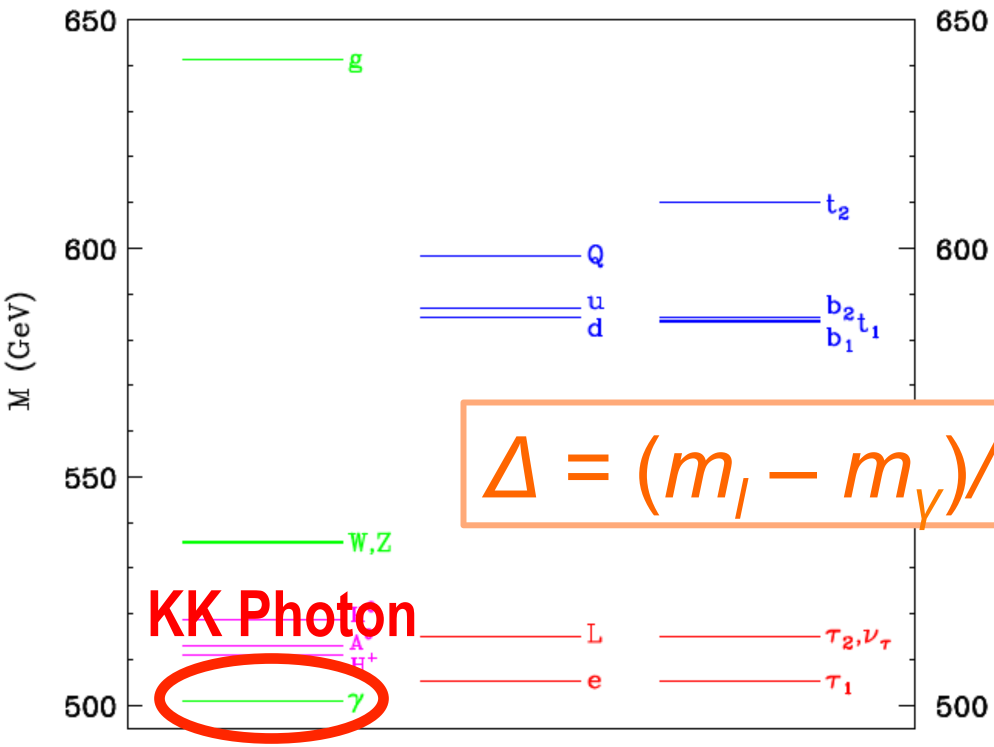



FIG. 1: *One-loop corrected mass spectrum of the first KK level in MUEDs for $R^{-1} = 500$ GeV, $\Lambda R = 20$ and $m_h = 120$ GeV.*

$$\Delta = (m_l - m_\gamma)/m_\gamma$$

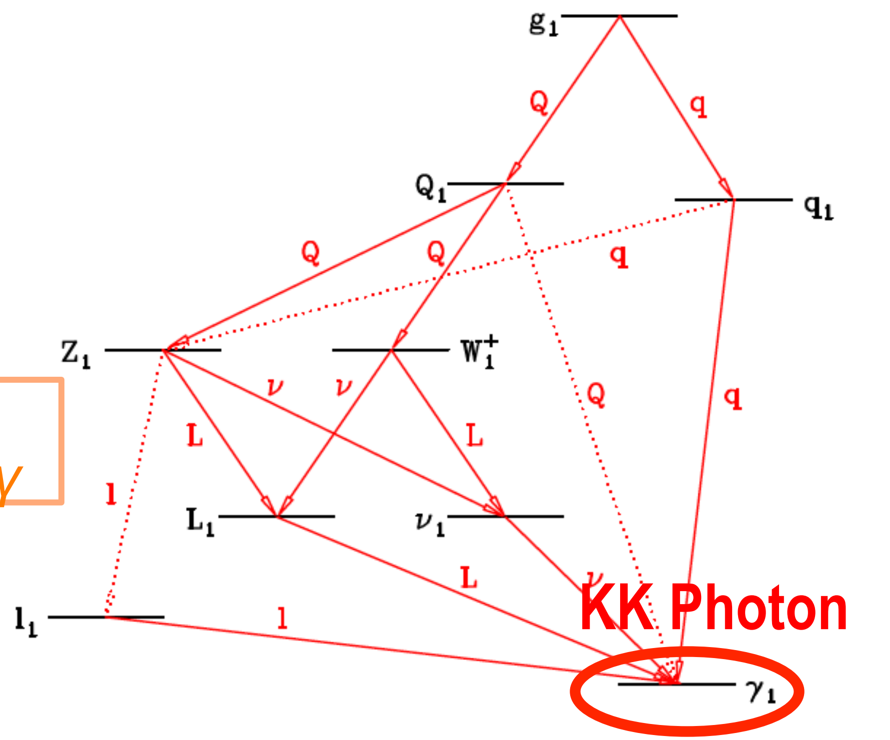
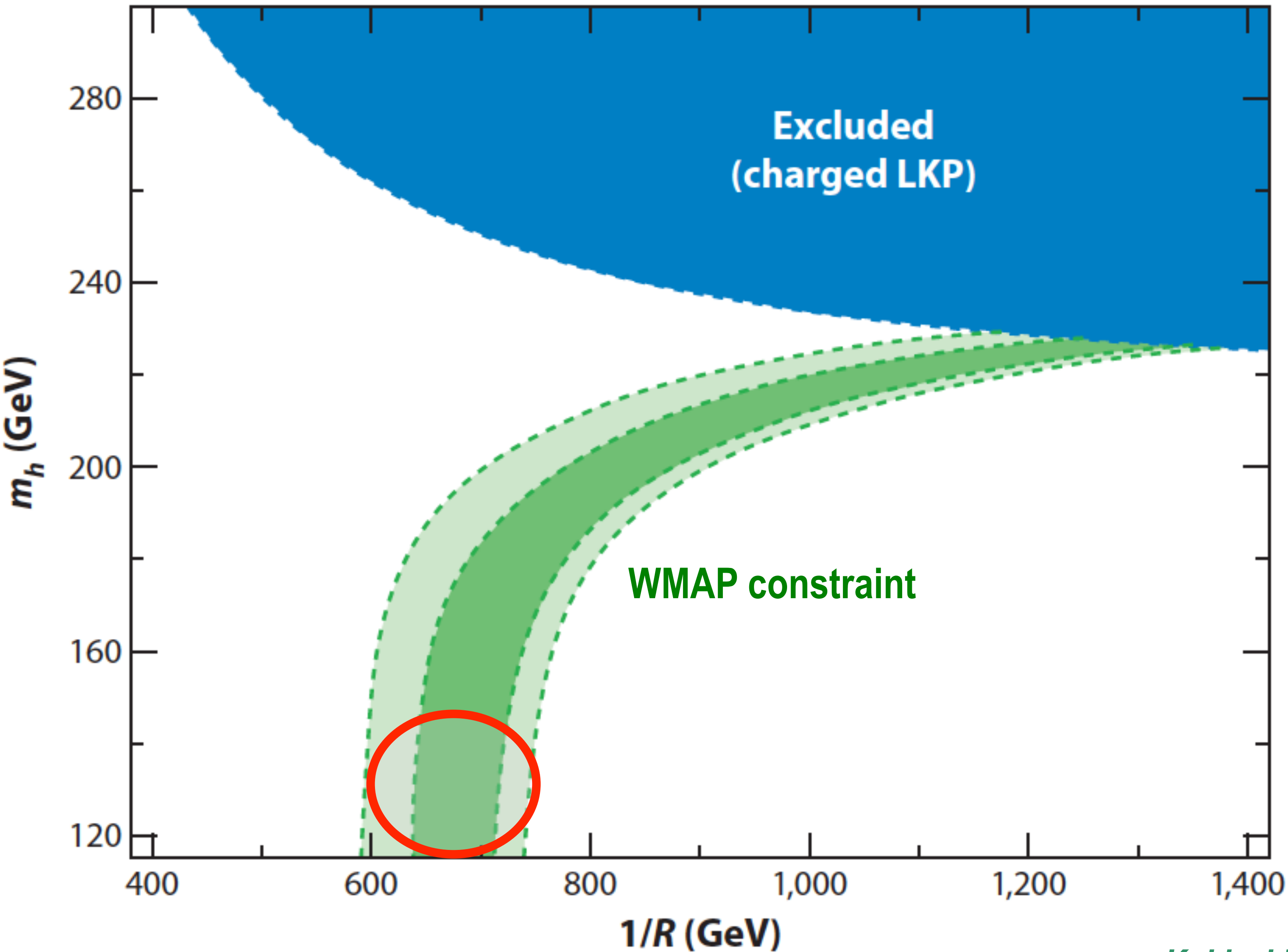



FIG. 3: *Qualitative sketch of the level 1 KK spectroscopy depicting the dominant (solid) and rare (dotted) transitions and the resulting decay product.*

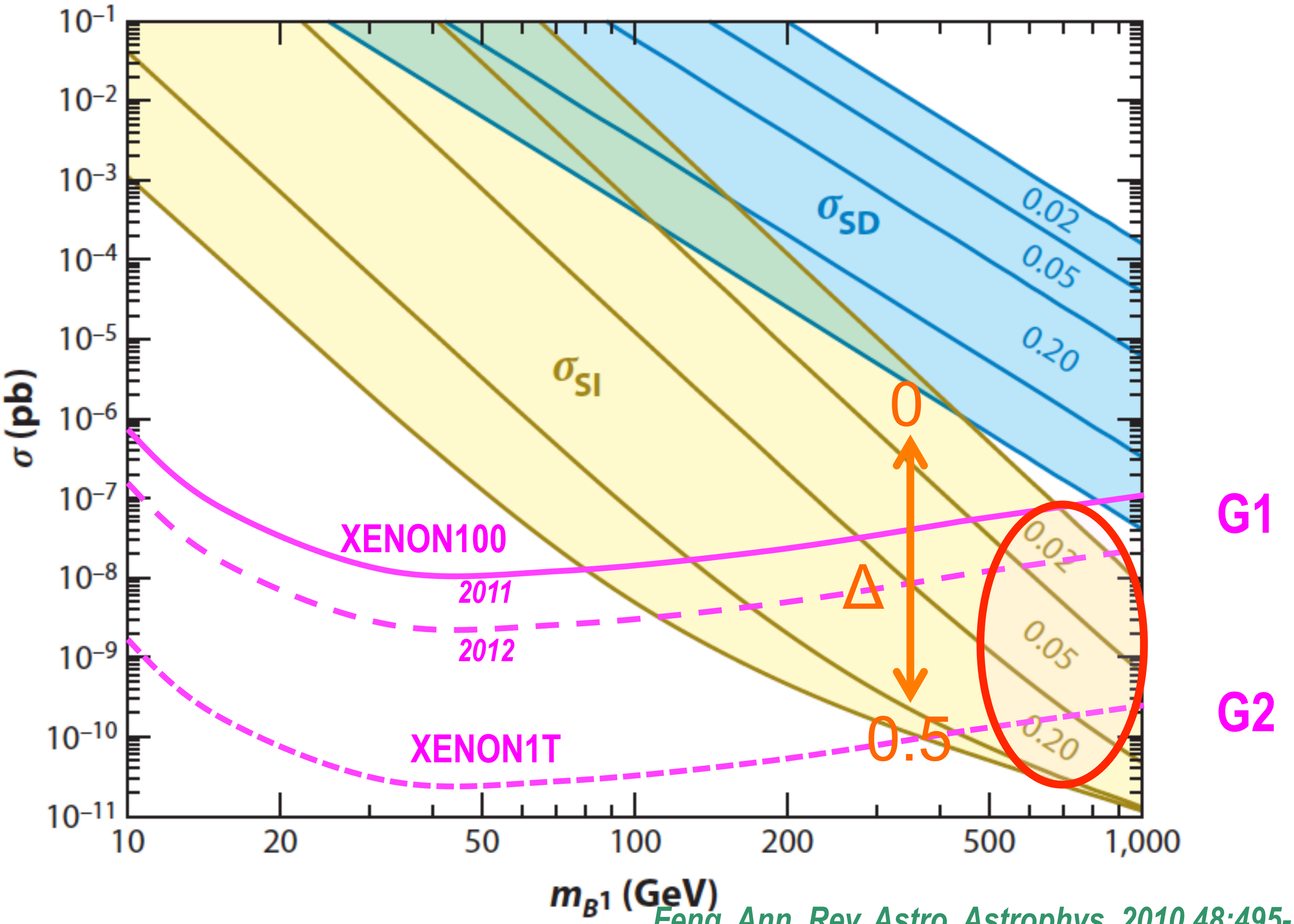
Cheng 2002 arXiv:hep-ph/0205314v1

# Allowed Region of Minimum Universal Extra Dimensions



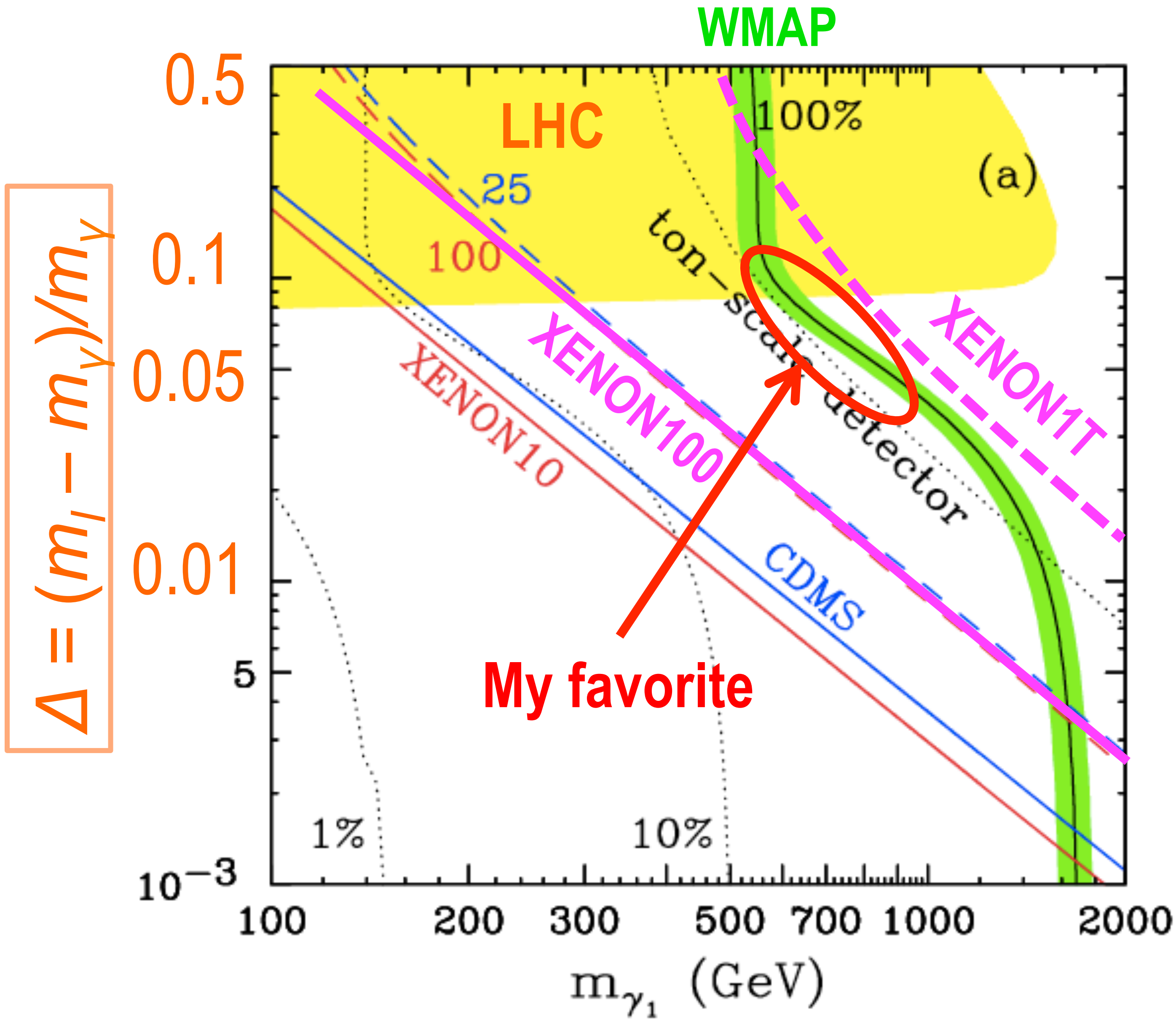

*Kakizaki 2006*

# Predicted Cross Section of Kaluza-Klein Dark Matter




*Feng Ann. Rev. Astro. Astrophys. 2010.48:495-545*

# Sensitivity to KK particles




*Arrenberg 2008*

# Summary on "Science Cases"

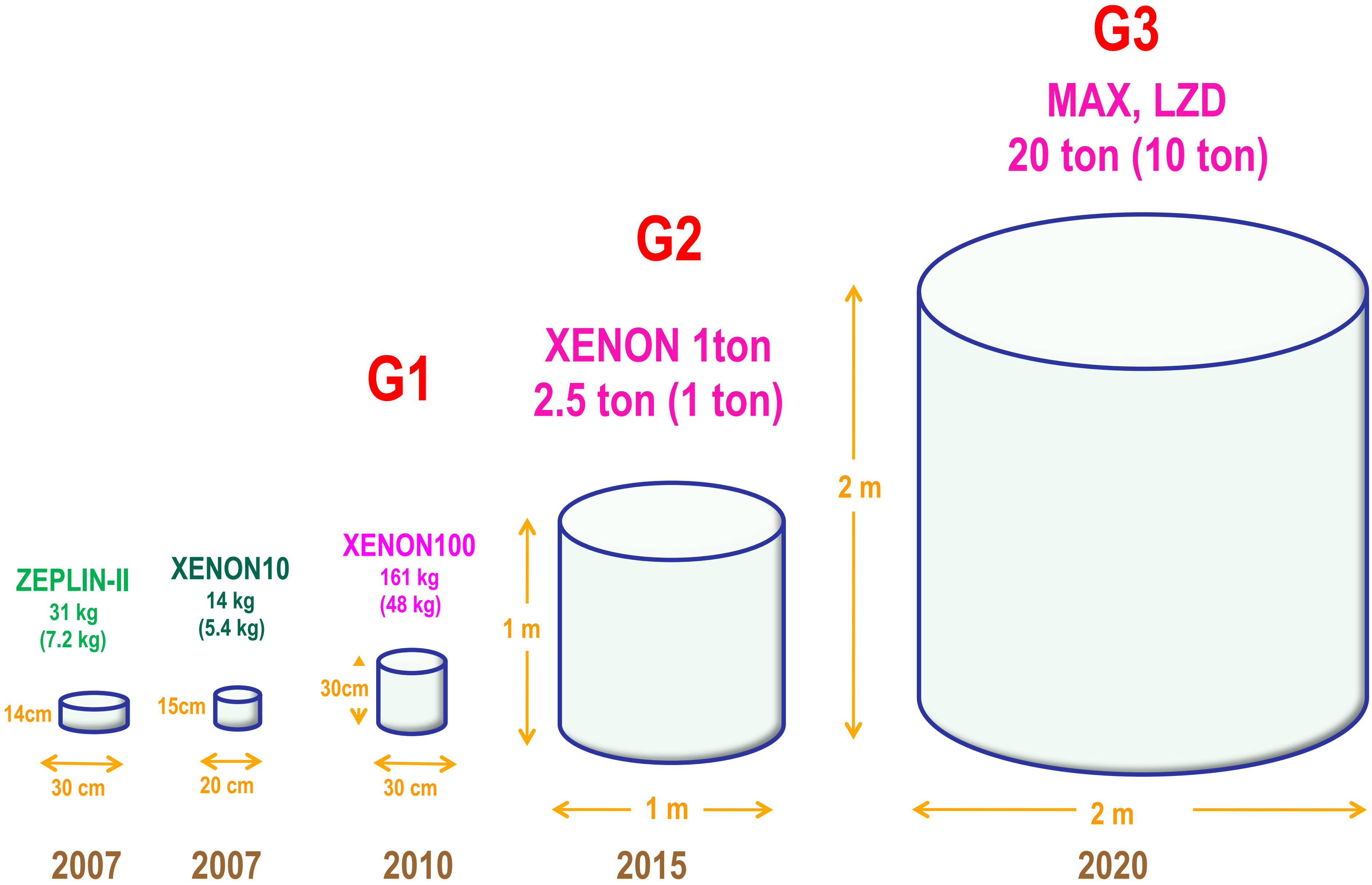
- XENON program (~$10M) is timely and competitive to LHC (~$10B)
  - XENON100 ~ Current LHC
  - XENON1T ~ Future LHC
- If new physics at 100 – 1000 GeV (as it should be), LHC and/or XENON1T will discover WIMPs.
  - SUSY - Neutralino
  - Extra Dimensions – KK photon
- By combining LHC and XENON1T, we have a better chance to untangle large parameter spaces.

# G2 & G3 Detectors

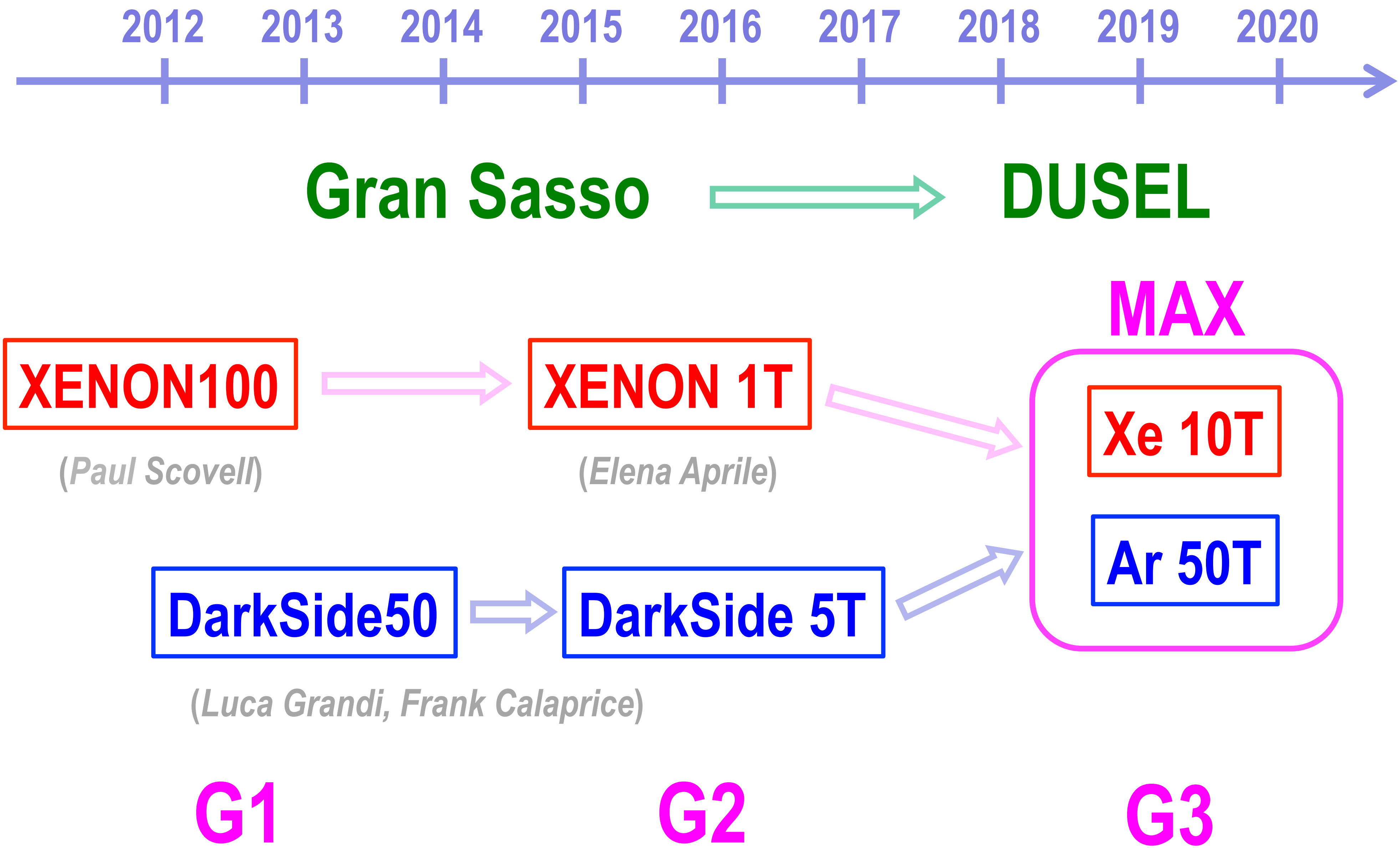
# G2 and G3 facilities defined by PASAG (2009)

| | G1 | G2 | G3 |
|---|---|---|---|
| Sensitivity | < $10^{-44}$ $cm^2$ | < $10^{-46}$ $cm^2$ | < $10^{-47}$ $cm^2$ |
| Target Mass | 10 – 100 kg | ~ 1 Ton | ~ 10 Ton |
| Cost | $1M – 5M | $10 – 20M | ~ $100M |

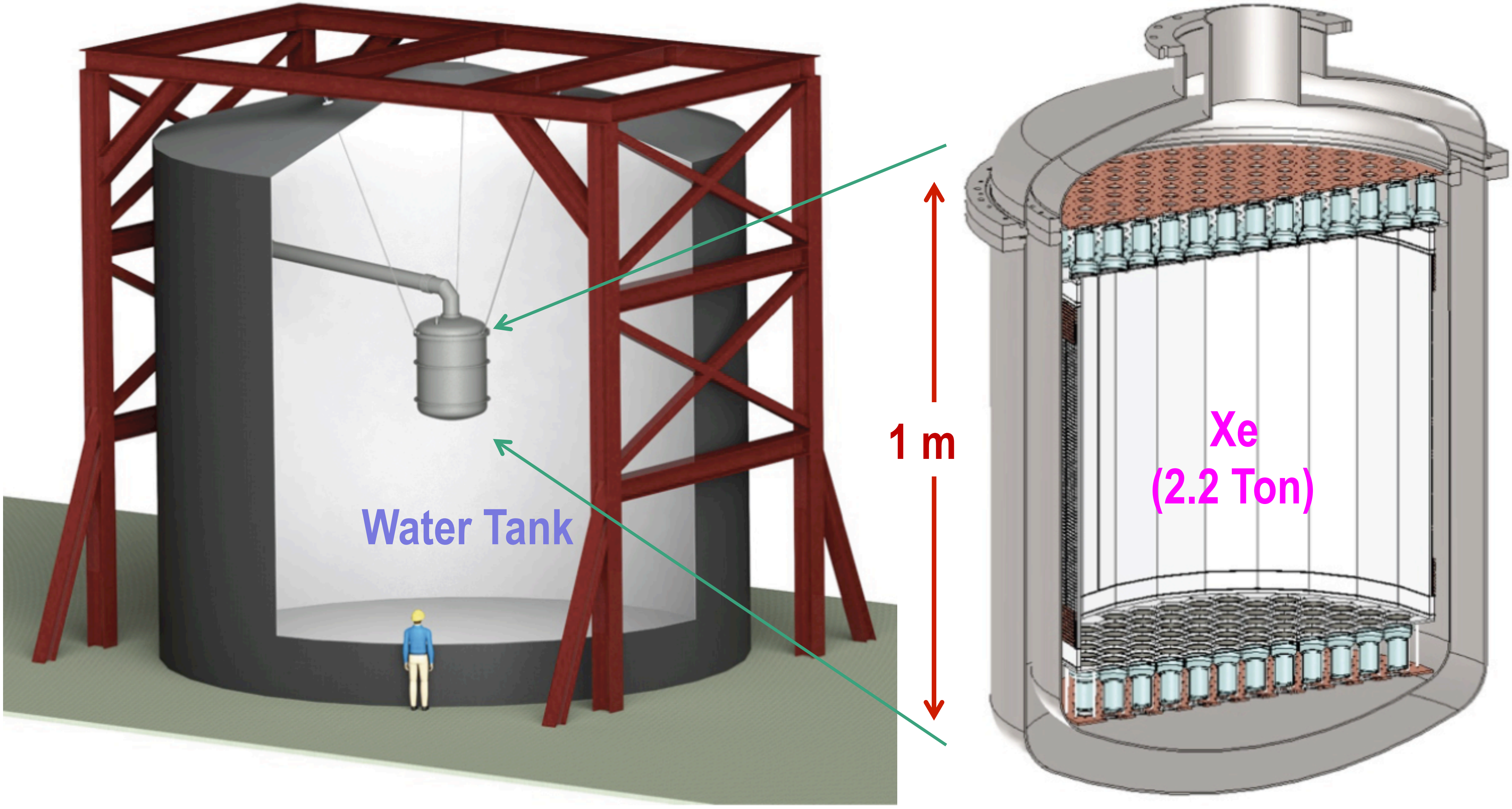
# Comparison of Xenon Detector Size



# Roadmap to MAX

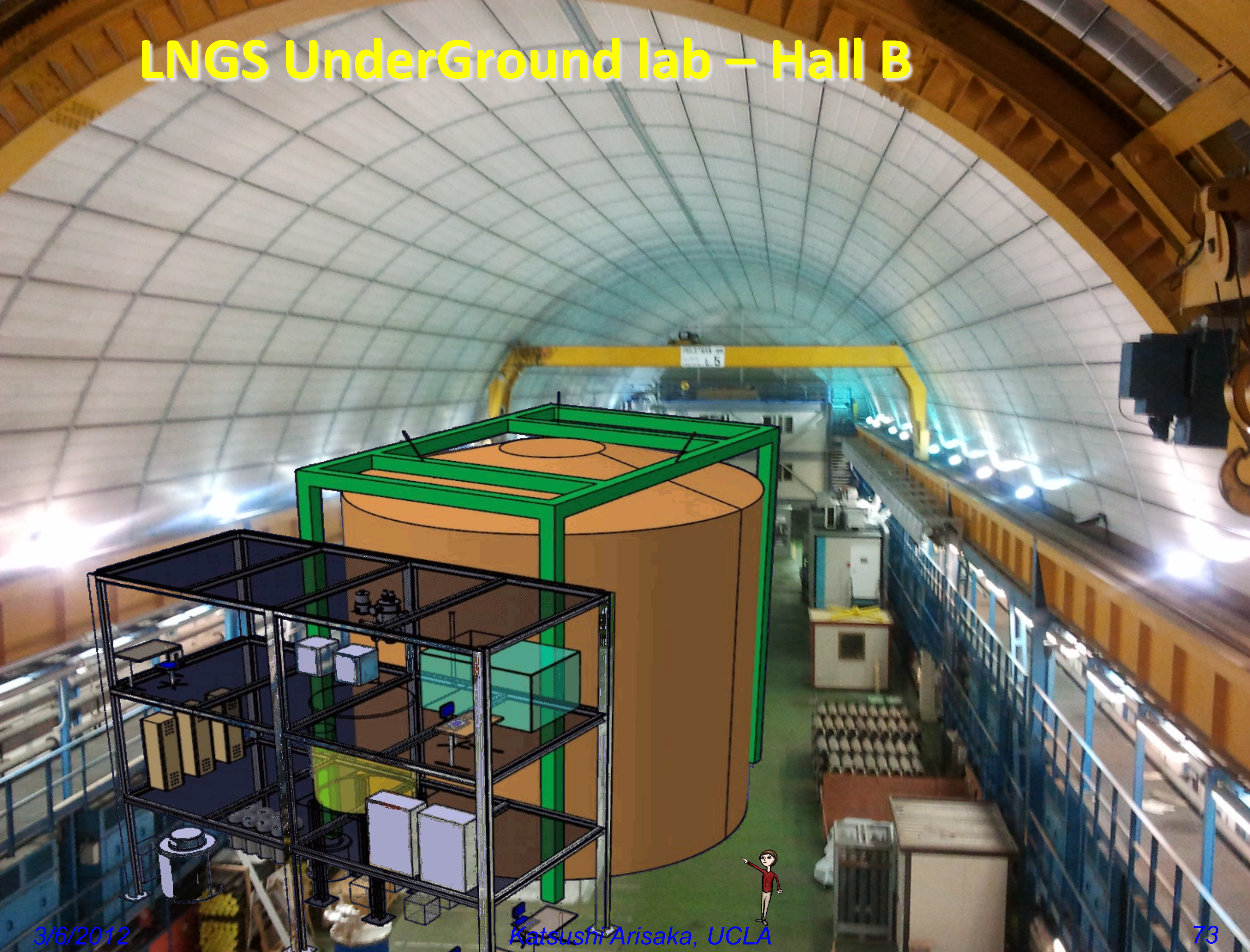


# XENON1T (G2) at LNGS

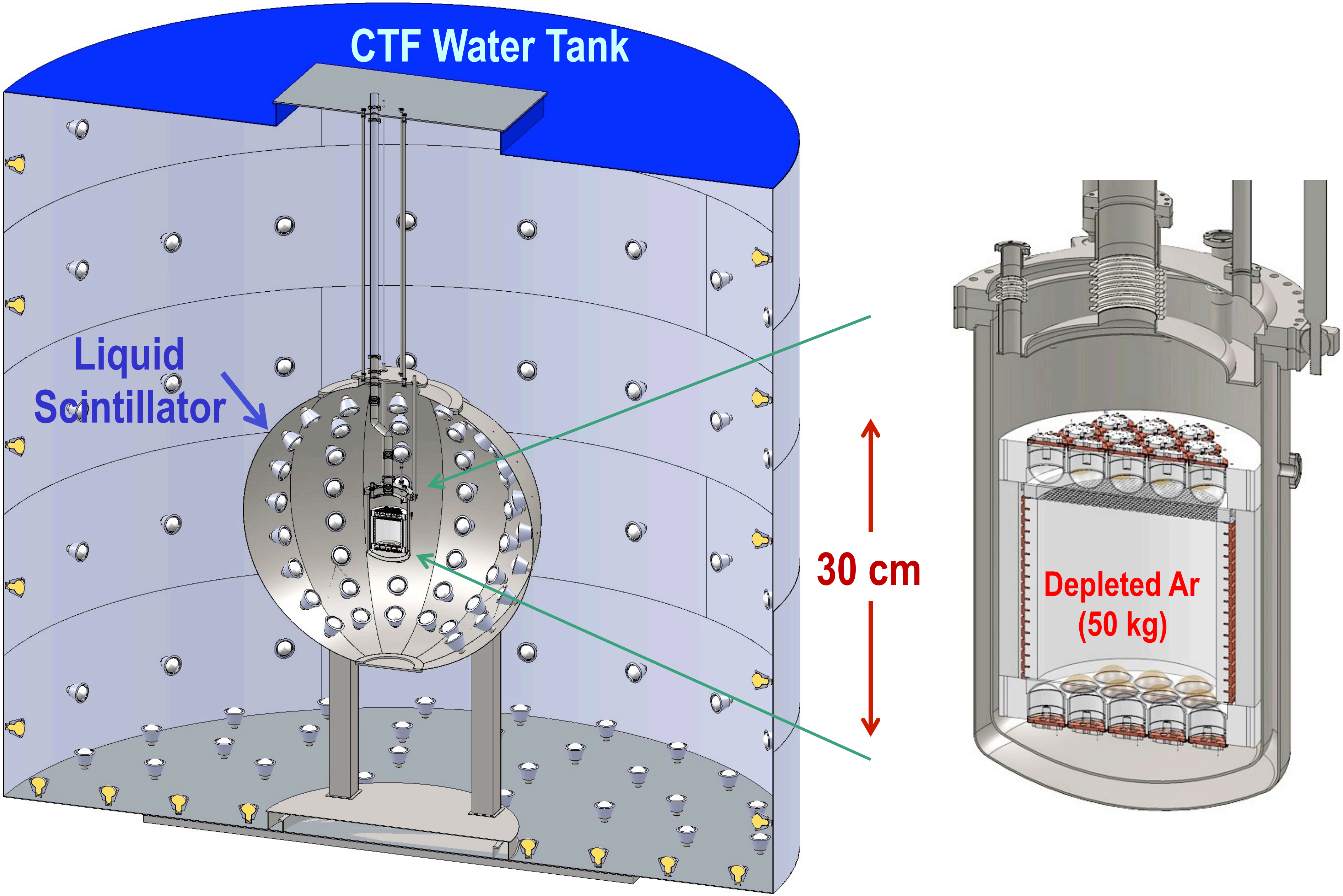


# LNGS UnderGround lab – Hall B

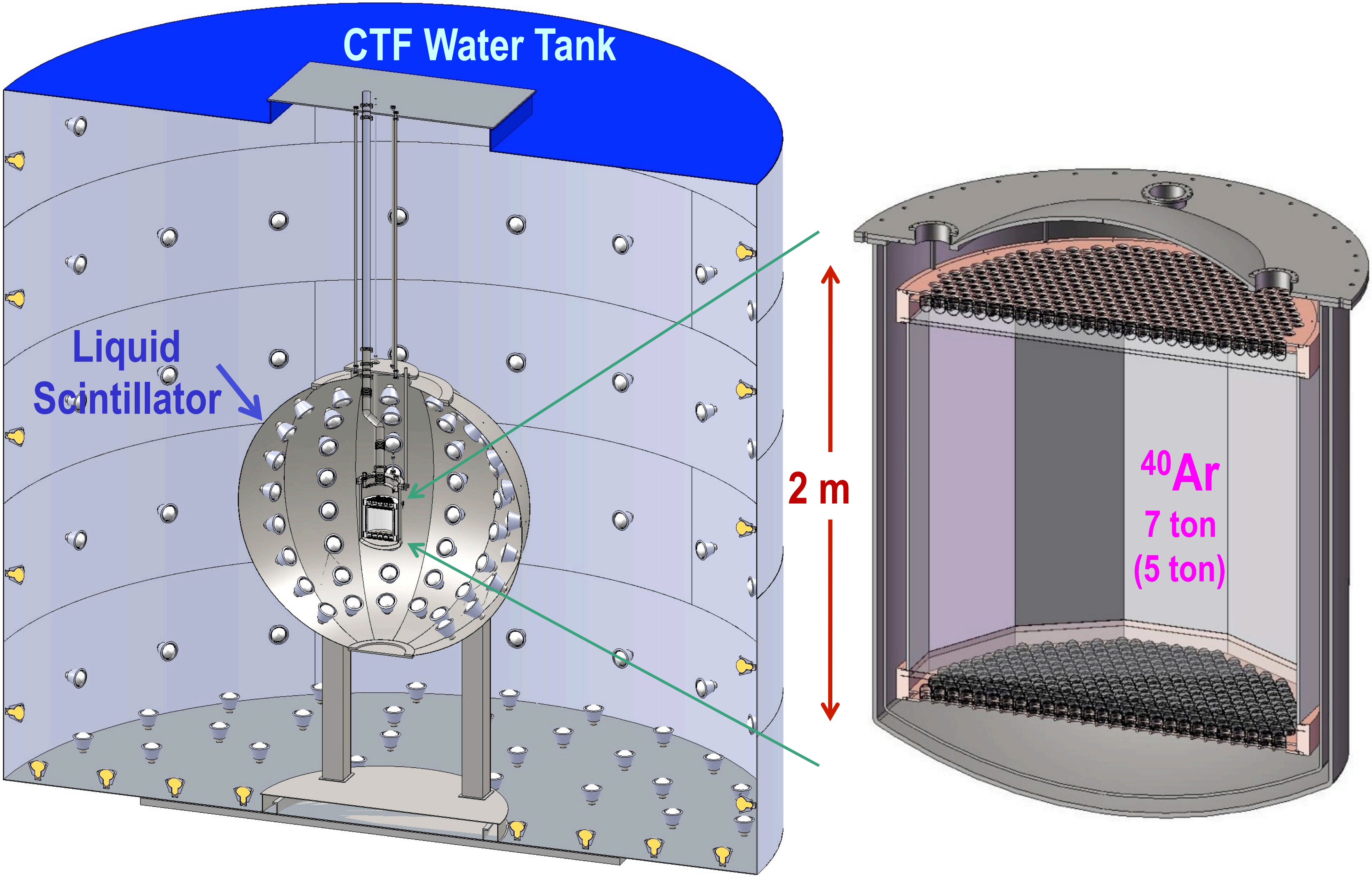
# LNGS UnderGround lab – Hall B



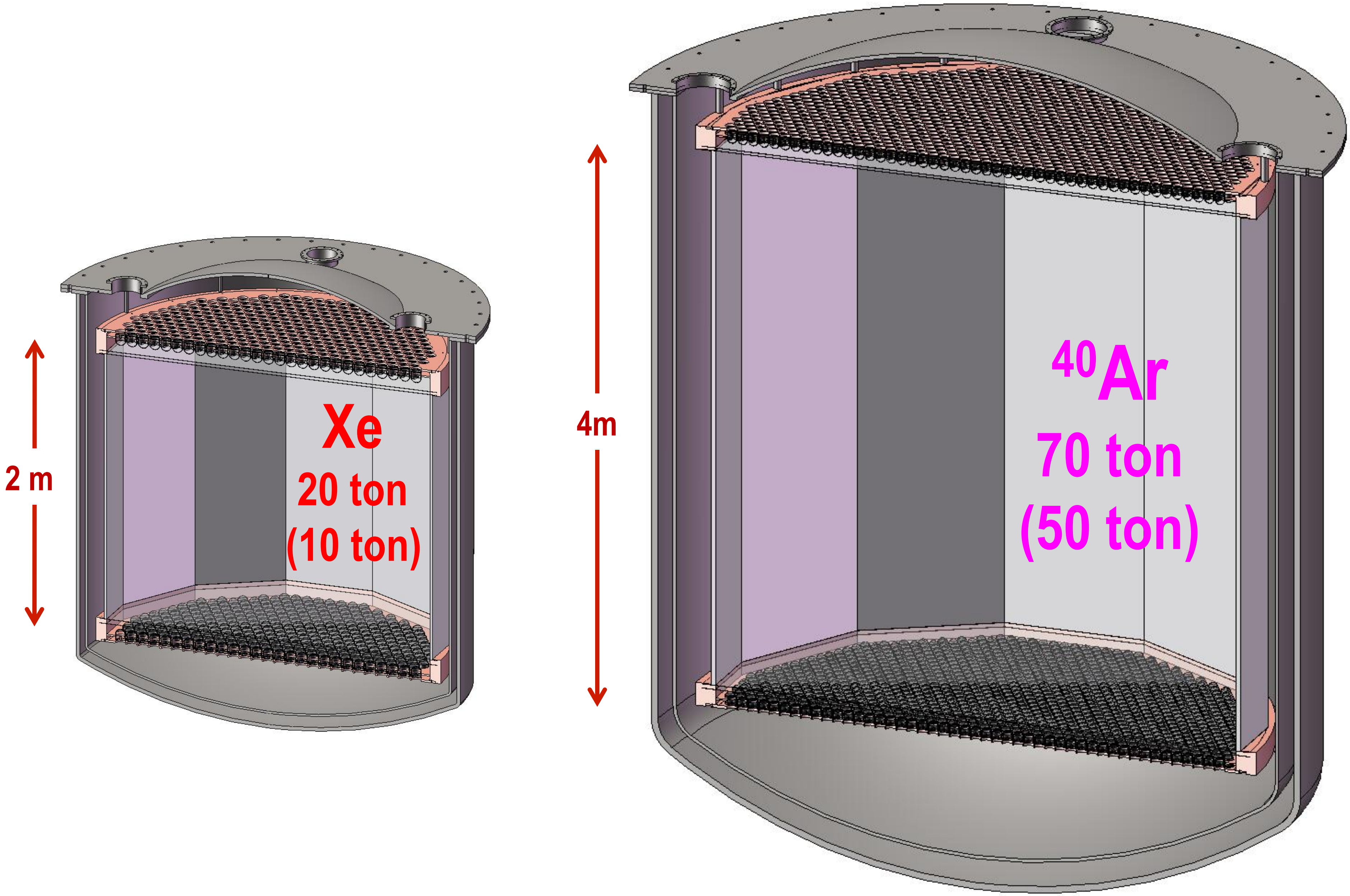
# DarkSide 50 (G1) at LNGS



# DarkSide 5T (G2) at LNGS

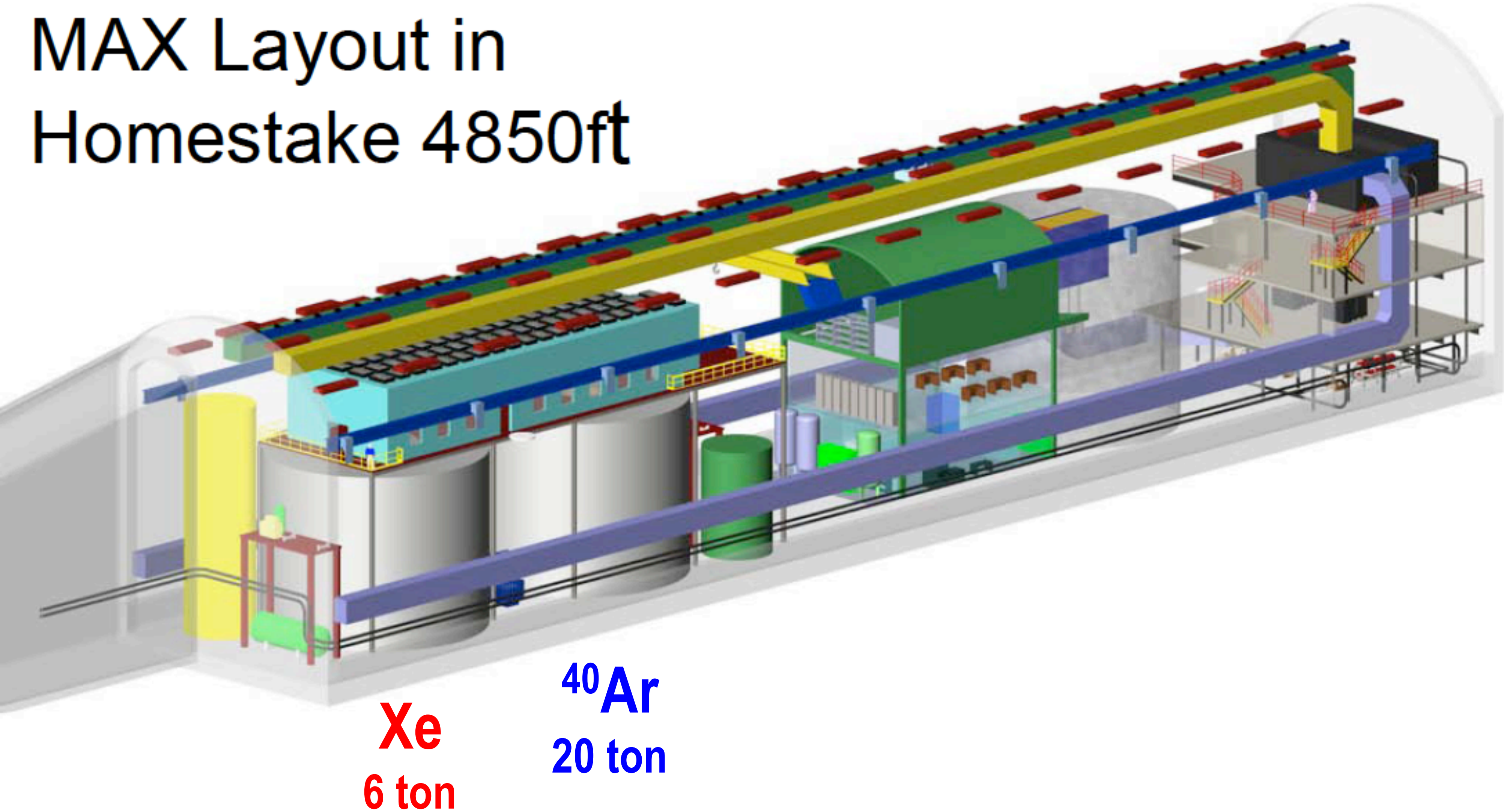


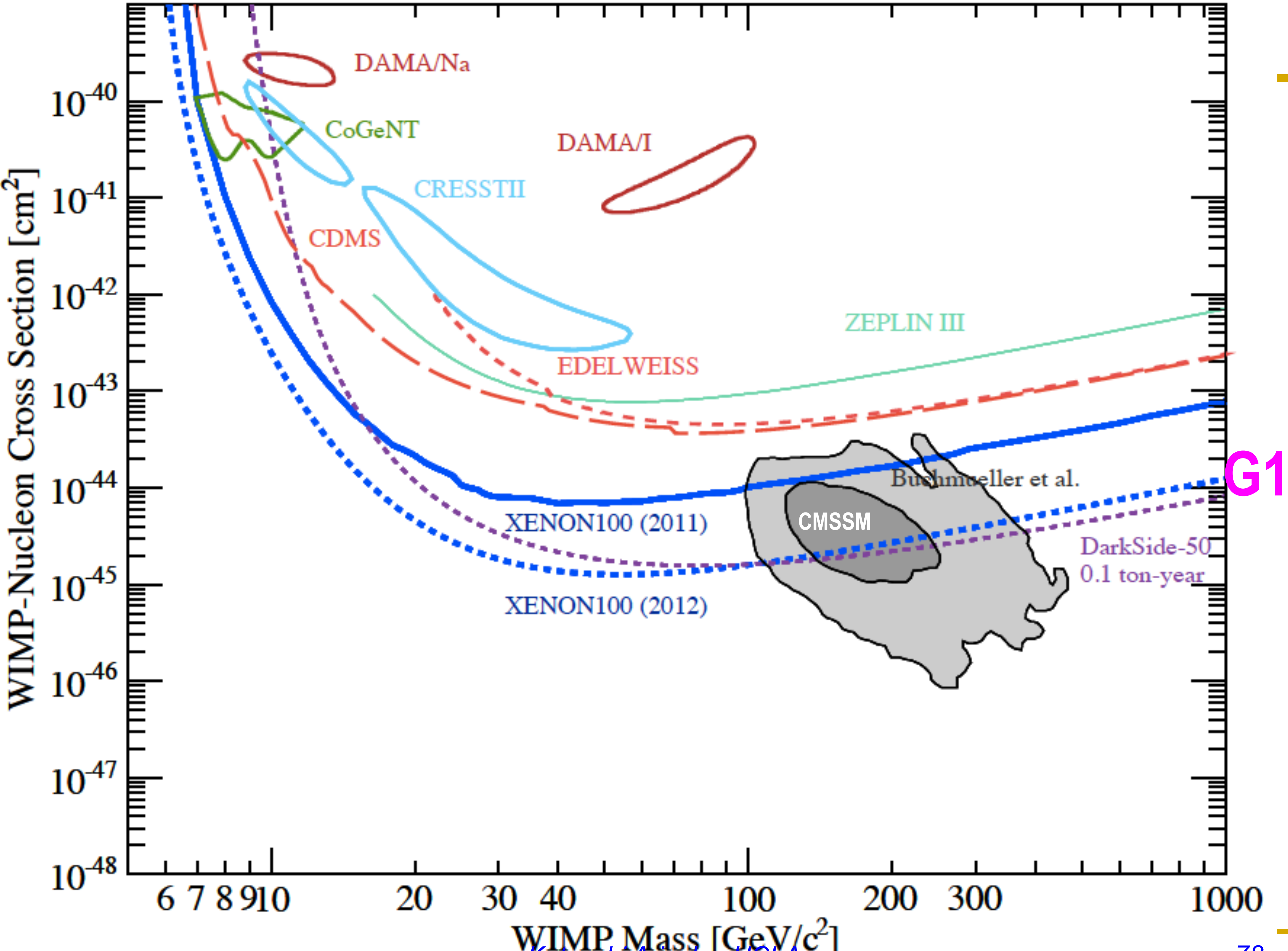
# MAX G3 Detector (at DUSEL)



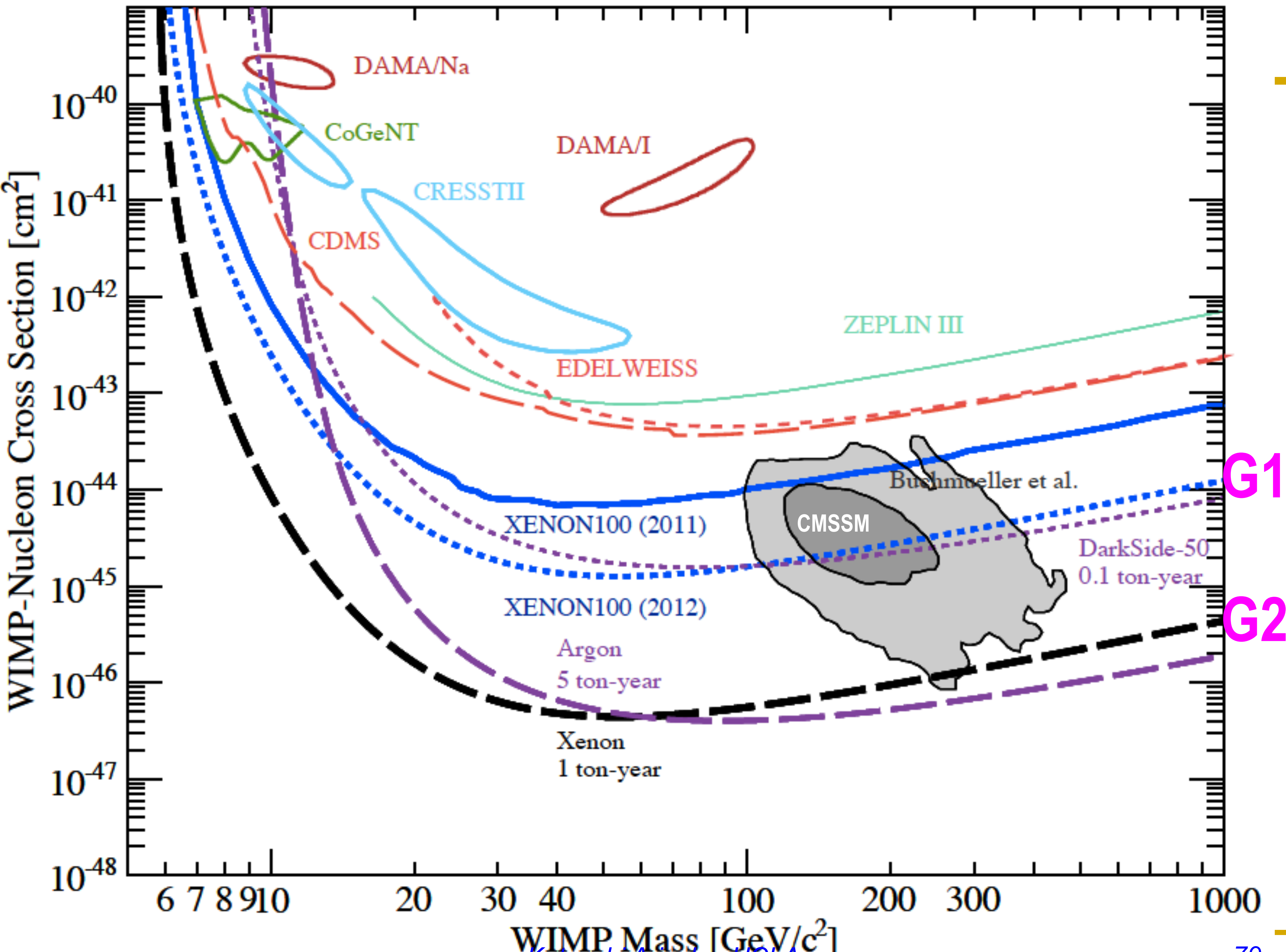
# MAX (G3) (at DUSEL)

MAX Layout in Homestake 4850ft





DAMA/Na
CoGeNT
DAMA/I
CRESSTII
CDMS
ZEPLIN III
EDELWEISS
Buchmueller et al.
CMSSM
XENON100 (2011)
XENON100 (2012)
DarkSide-50
0.1 ton-year
G1
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
$10^{-46}$
$10^{-47}$
$10^{-48}$
WIMP-Nucleon Cross Section [cm$^2$]
6 7 8 9 10 20 30 40 100 200 300 1000
WIMP Mass [GeV/c$^2$]



DAMA/Na
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Argon
5 ton-year
Xenon
1 ton-year
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6 7 8 9 10
20
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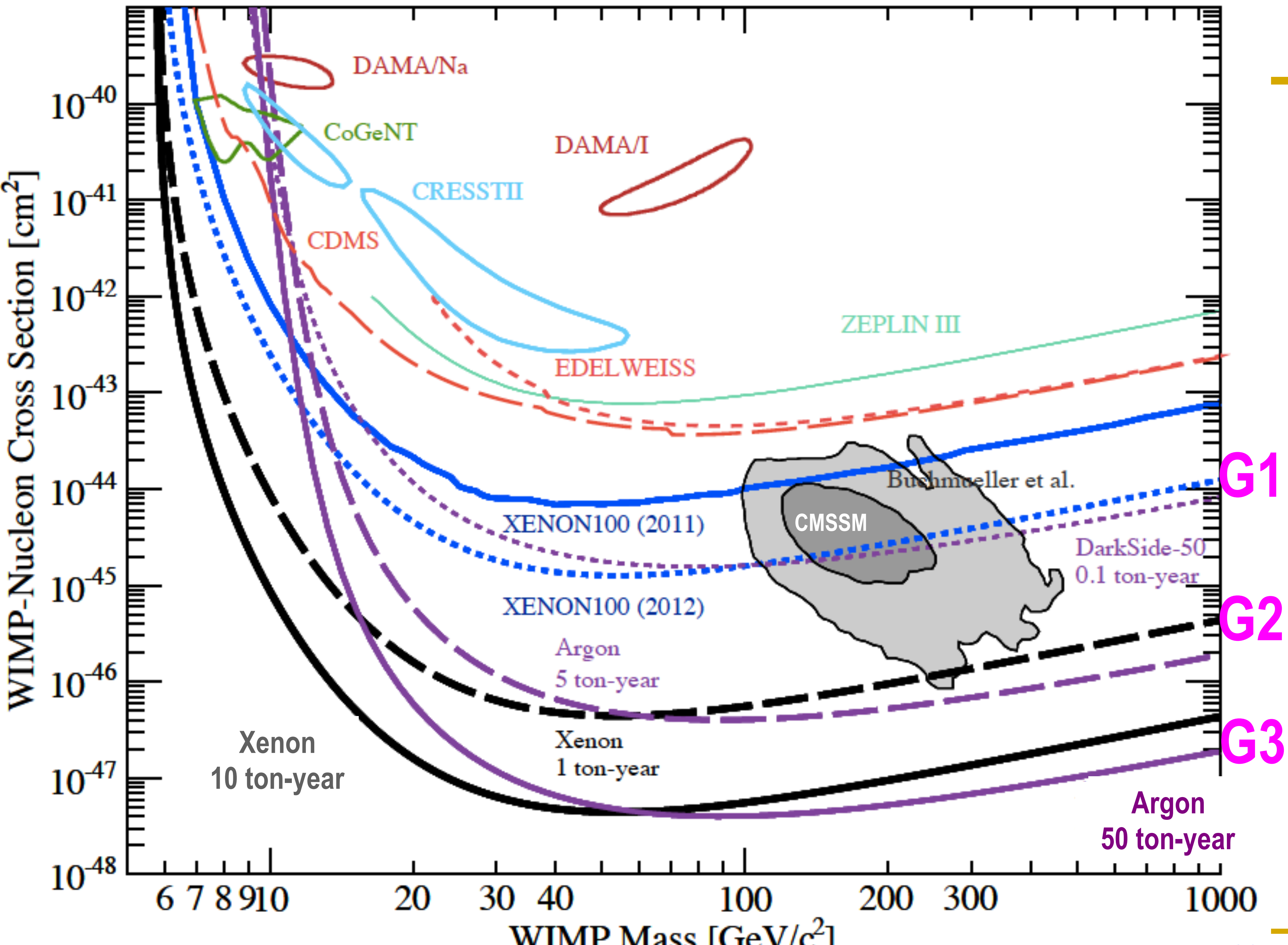
100
200 300
1000



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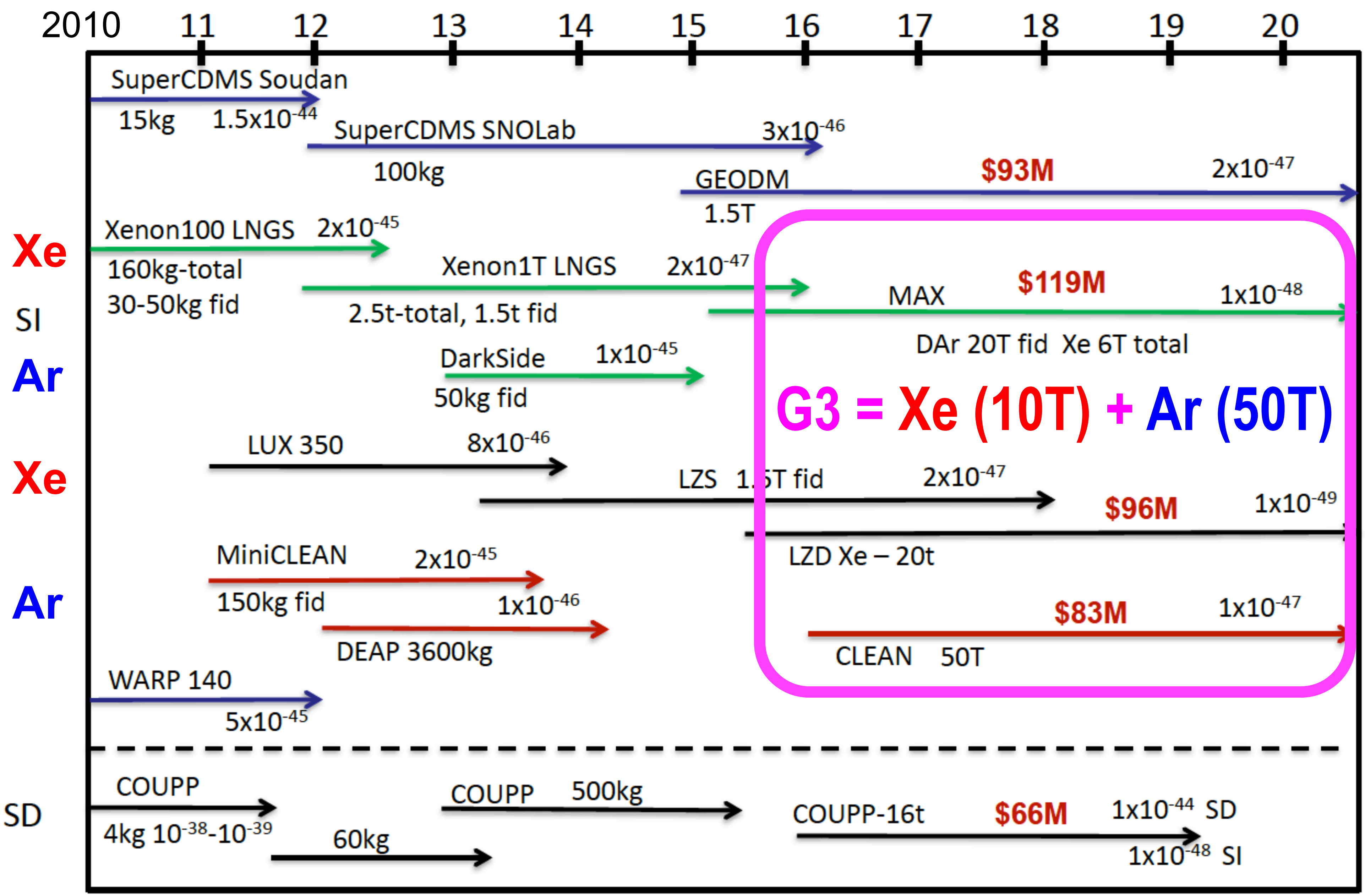
6 7 8 9 10 20 30 40 100 200 300 1000

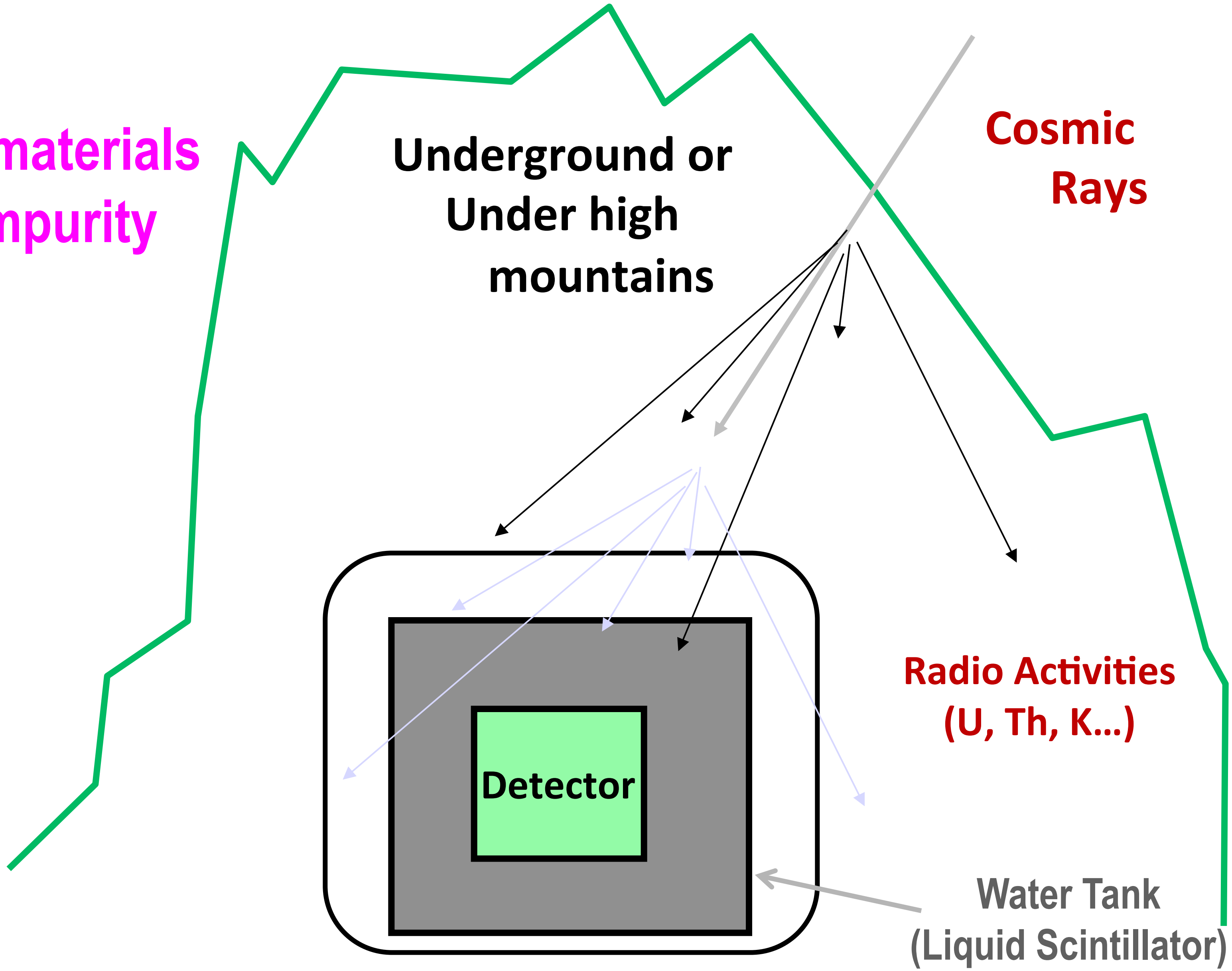
# US Dark Matter Programs



# Technological Challenges

# Where backgrounds come from?

- External
- Detector materials
- Internal impurity

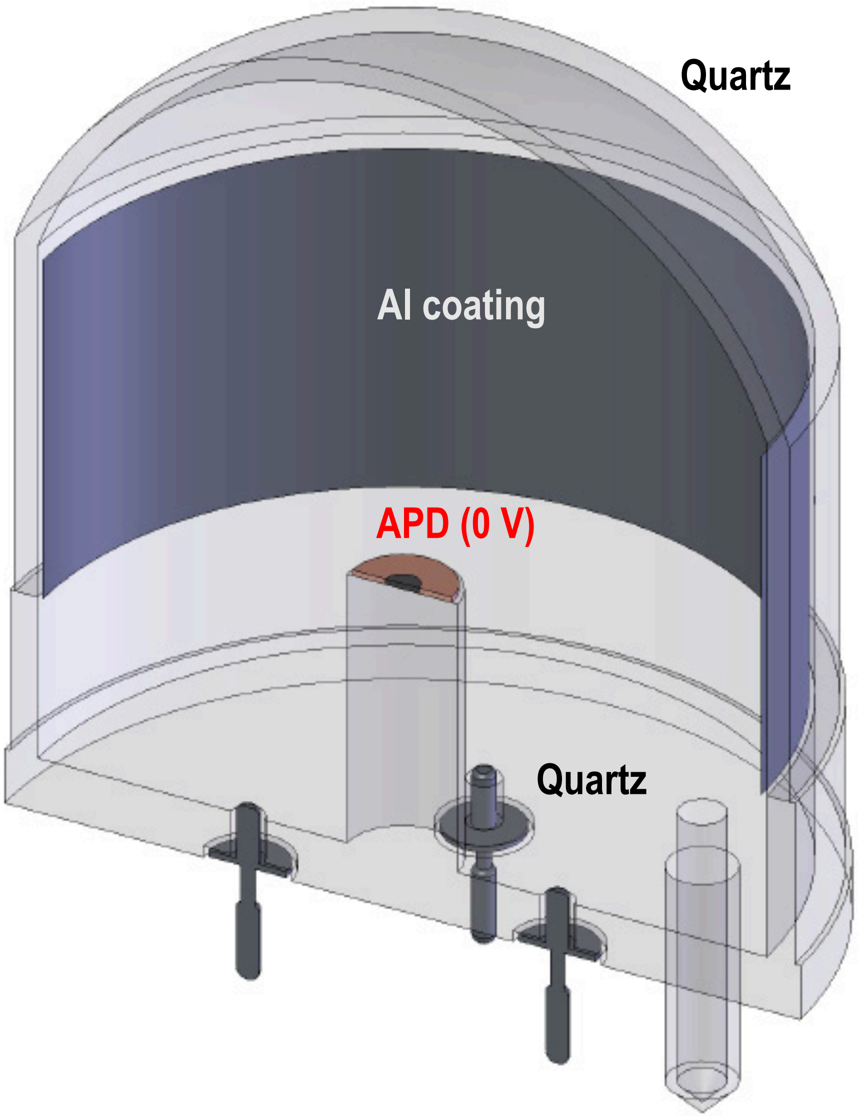


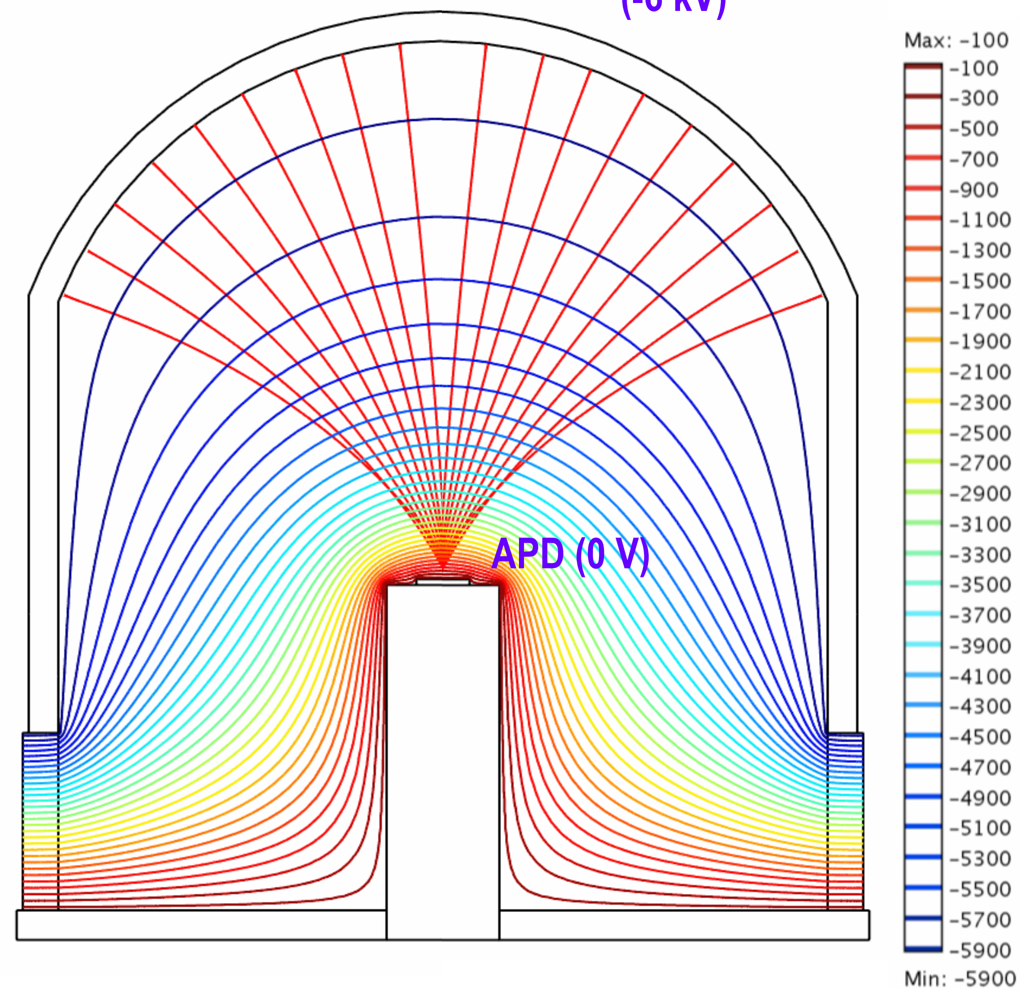
# Technological Challenges

- **External Backgrounds**
  - Deep underground – DUSEL 4850 ft
  - > 5 m water shielding – Water Tank (15 m)
- **Detector Materials**
  - Photon Detectors – QUPID
  - Cryostat – Titanium
  - Others – Copper, PTFE…
- **Purity of Liquid Xe/Ar**
  - Radon (< 0.3 mBq / ton)
  - $^{39}Ar$ (> 100 depletion) – Depleted Ar
  - $^{85}K$ (< 0.2 ppt in Xe) – 1 event / 10 ton-year
- **Physics Backgrounds in Xe**
  - pp-chain solar neutrinos – 1 event / 10 ton-year
  - 2v Double beta decays from $^{136}Xe$ – 1 event / 10 ton-year
- **Neutron Active Veto**
  - Boron doped Liquid Scintillator

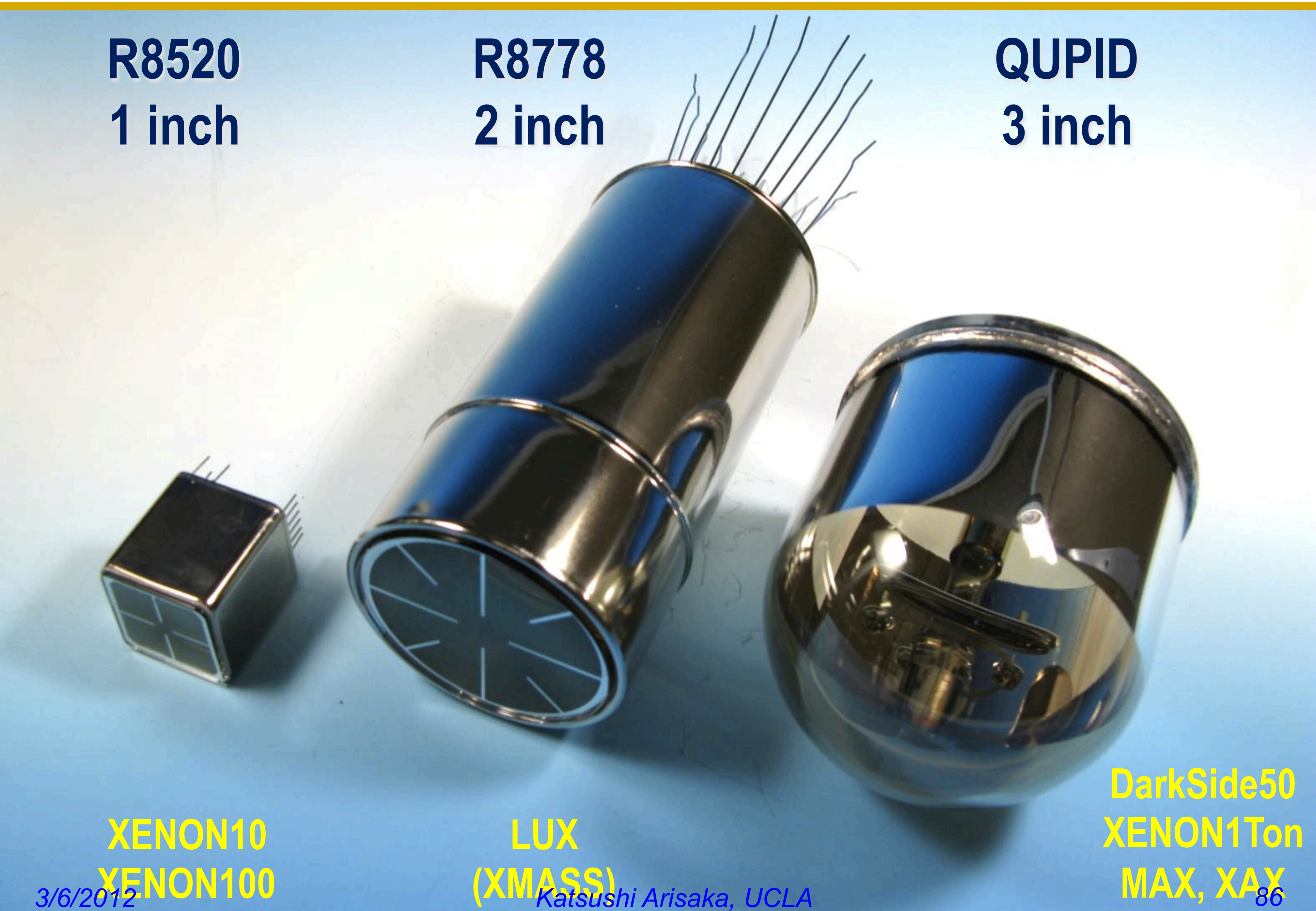
# QUPID (QUartz Photon Intensifying Detector)

arXiv:1103.3689



# Comparison of Low-radioactive Photon Detectors from Hamamatsu

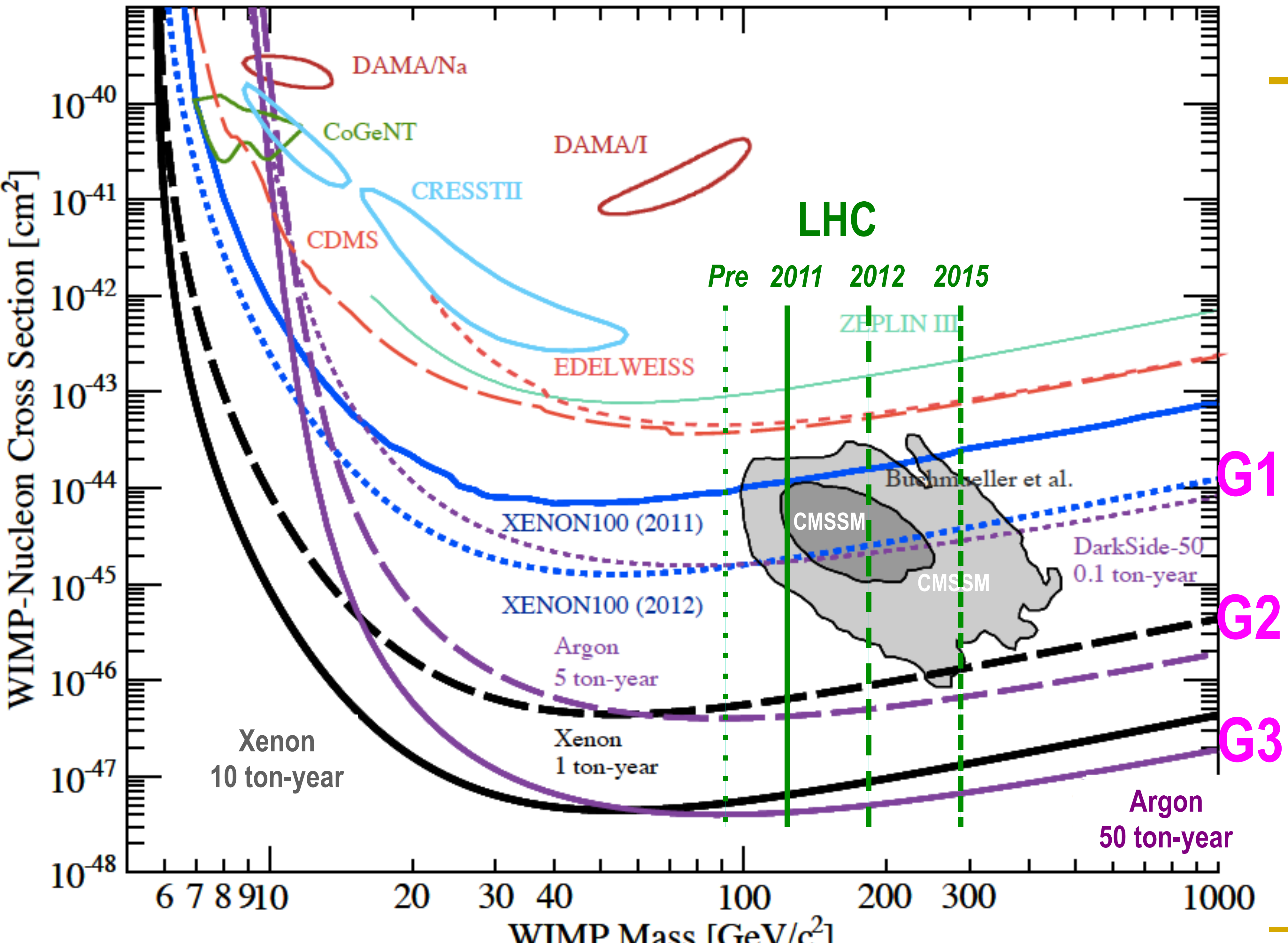


# 7 QUPID with Holder

**Tested in both Xe and Ar at UCLA**
**Ready for DarkSide 10**


# Princeton Prototype Plant for Depleted Argon:

# Summary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6 7 8 9 10 20 30 40 100 200 300 1000
WIMP Mass [GeV/c$^2$]

# Conclusions

- **Science cases**
  - Stronger than ever - SUSY, Extra Dimensions…
  - Competitive and complementary to LHC
  - Extremely timely
- **Technical challenges**
  - Xe-G1 (100 kg) well demonstrated by XENON100
  - New photon detector (QUPID) developed
  - Radioactivity ($^{39}Ar$, $^{85}Kr$, Rn) major challenges
- **Future directions**
  - G2 : XENON 1T and DarkSide 50 / 5T at Gran Sasso.
  - G3 : MAX + LZD (Xe 10T + Ar 50T) at DUSEL

# Detection of Cosmic Radiation