The Ultimate Dark Matter Observatory: Science Cases and Challenges

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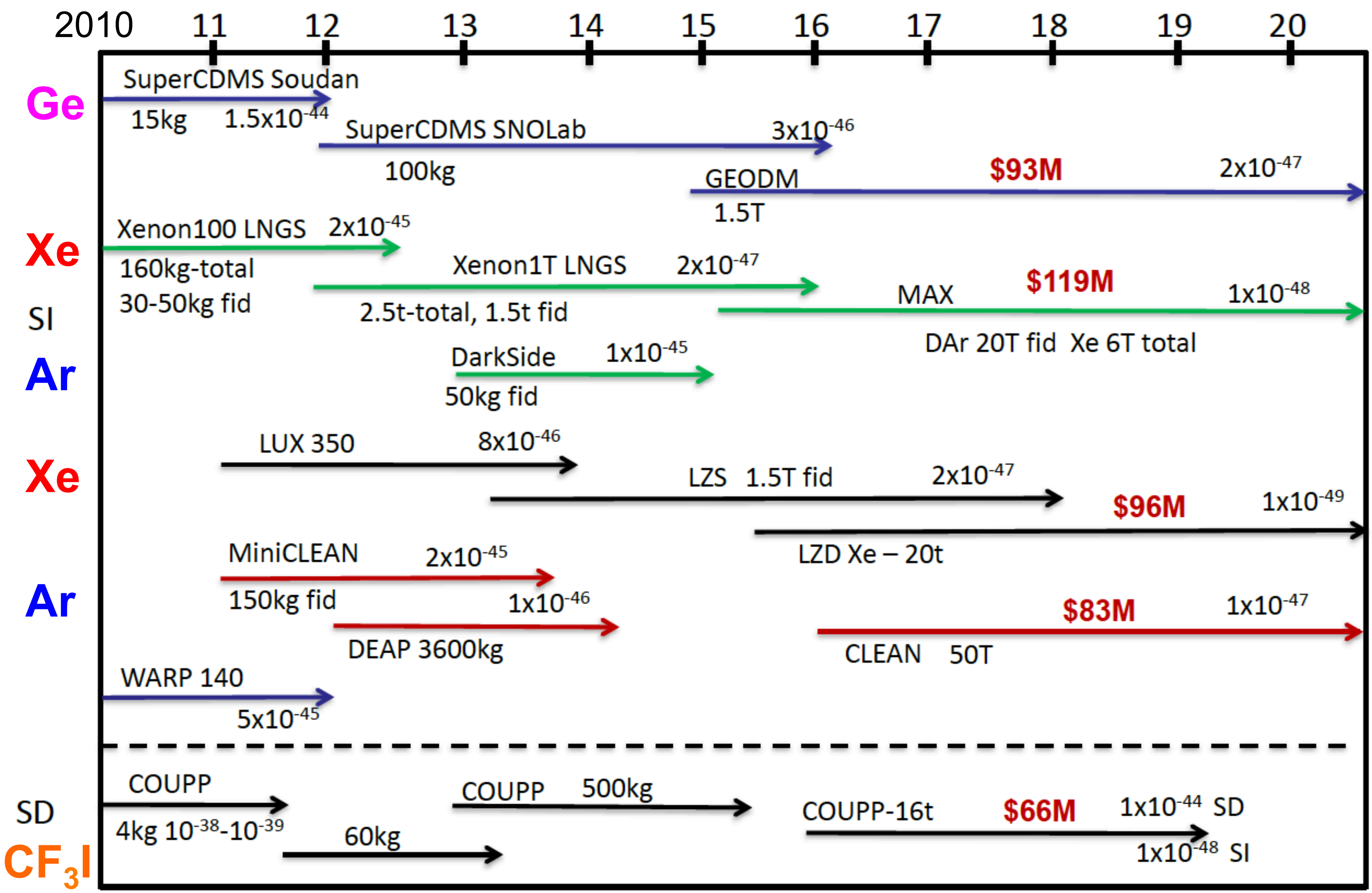
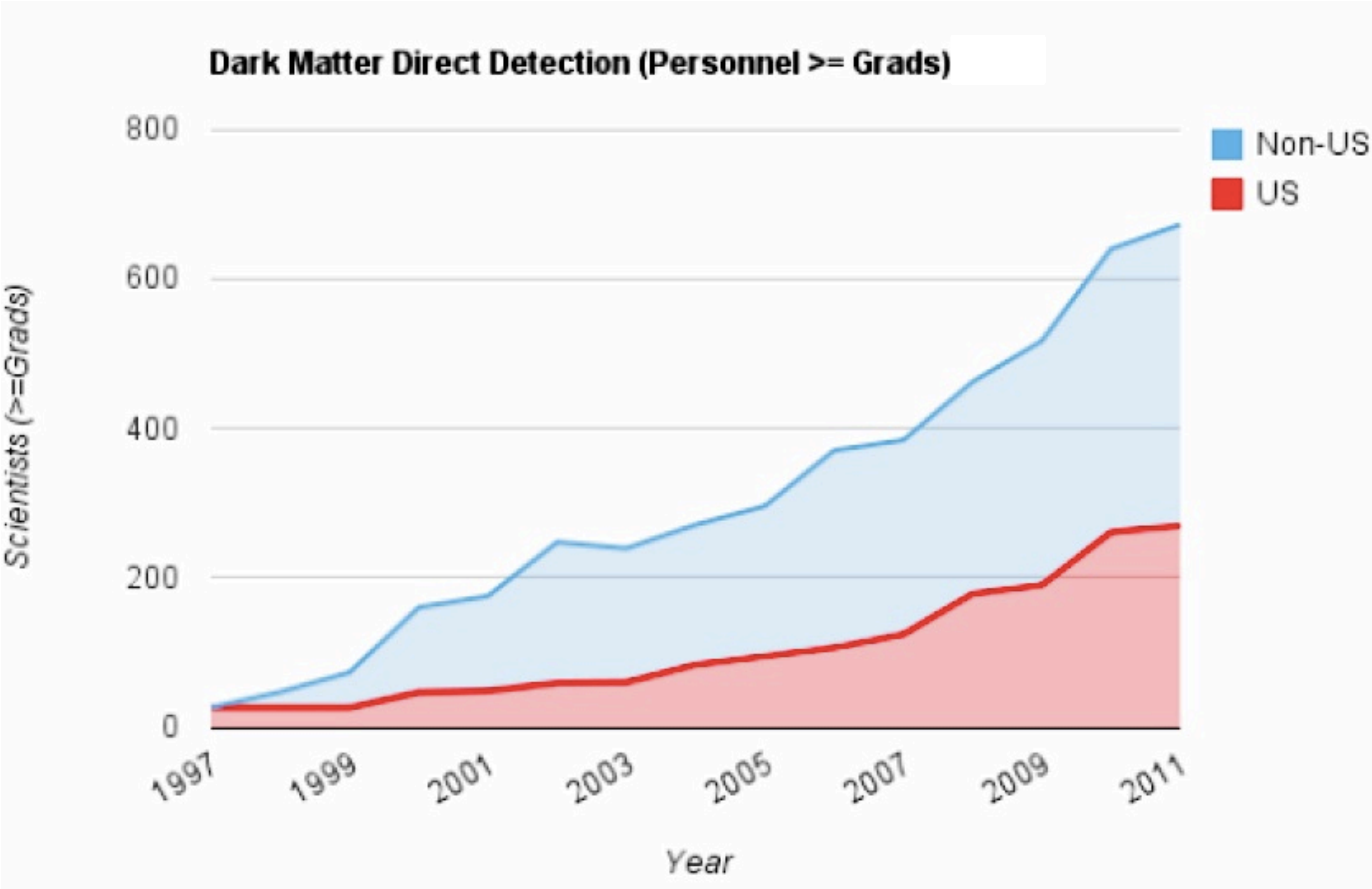
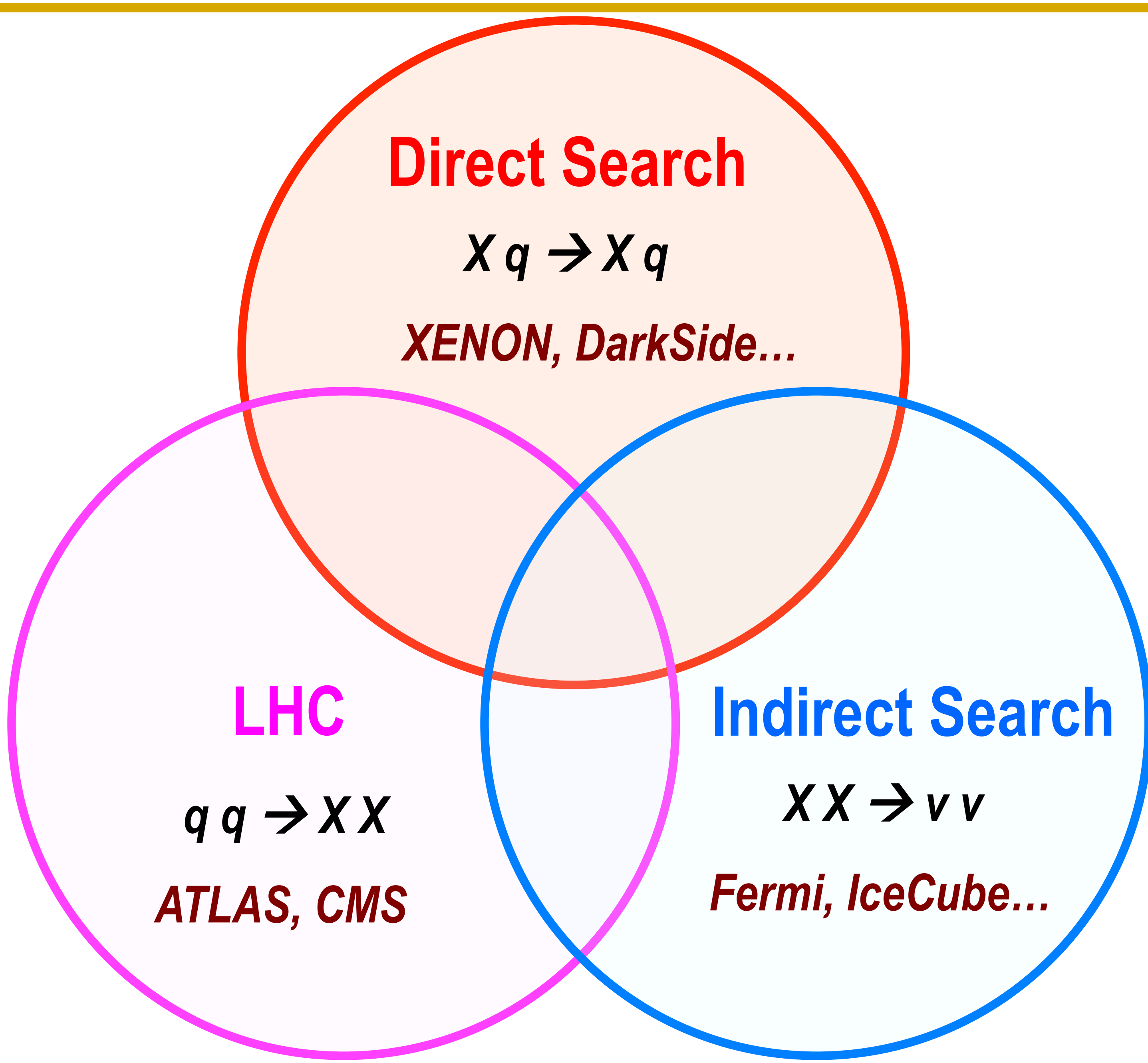
US Dark Matter Programs



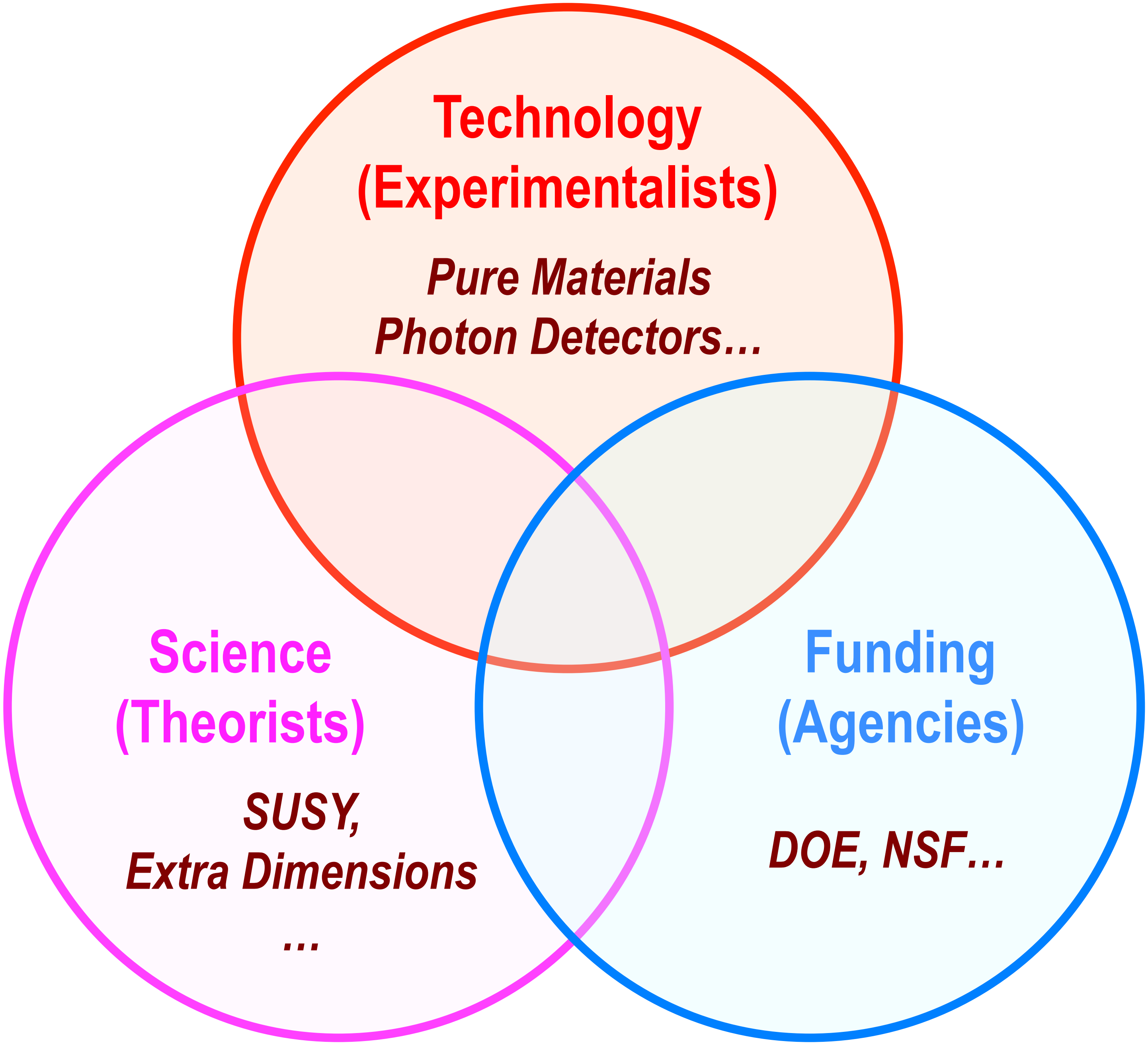
Growth of Direct Detection Community



How to approach dark matter?

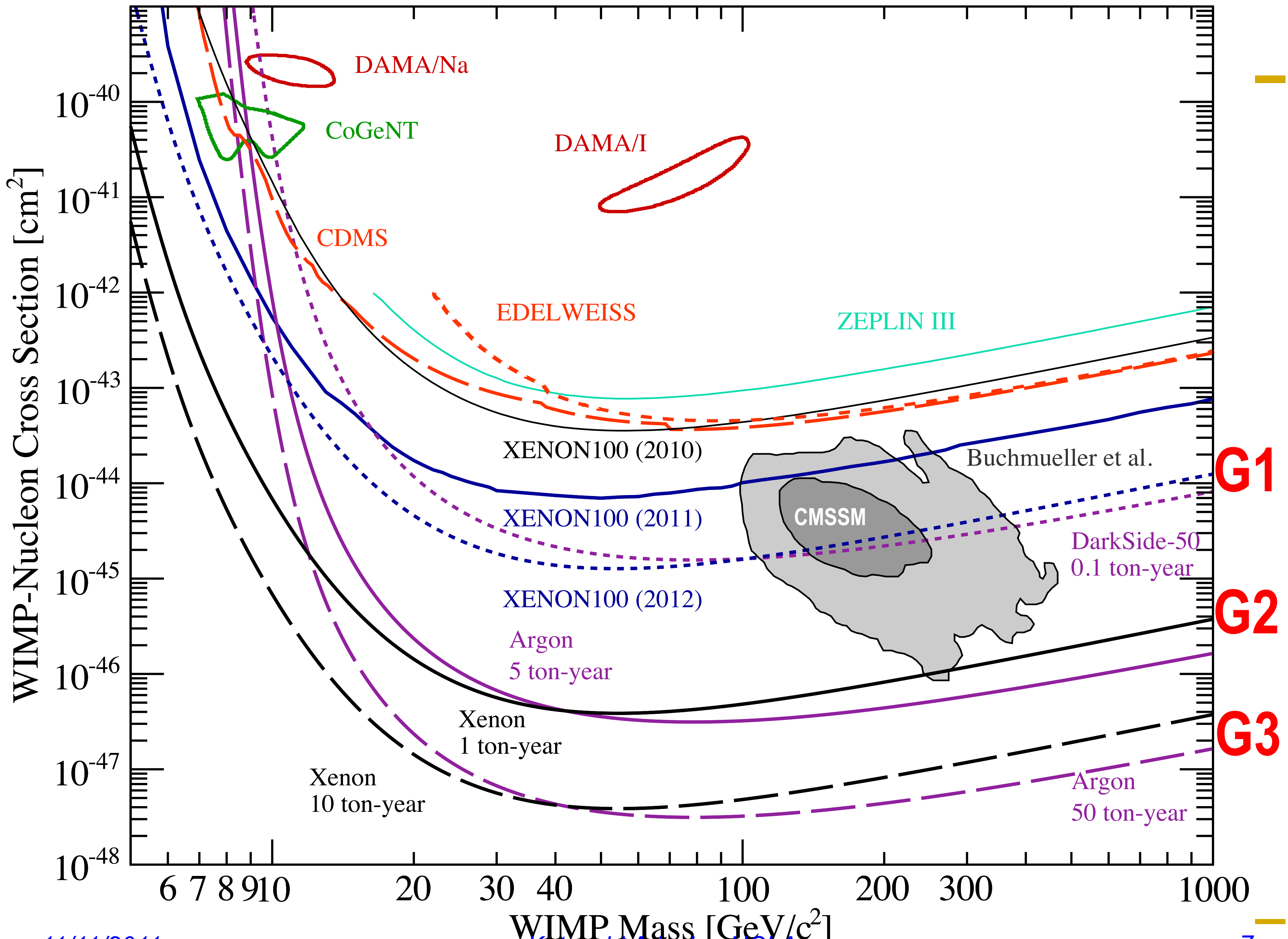


How to approach dark matter?



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
  - Neutrino Physics



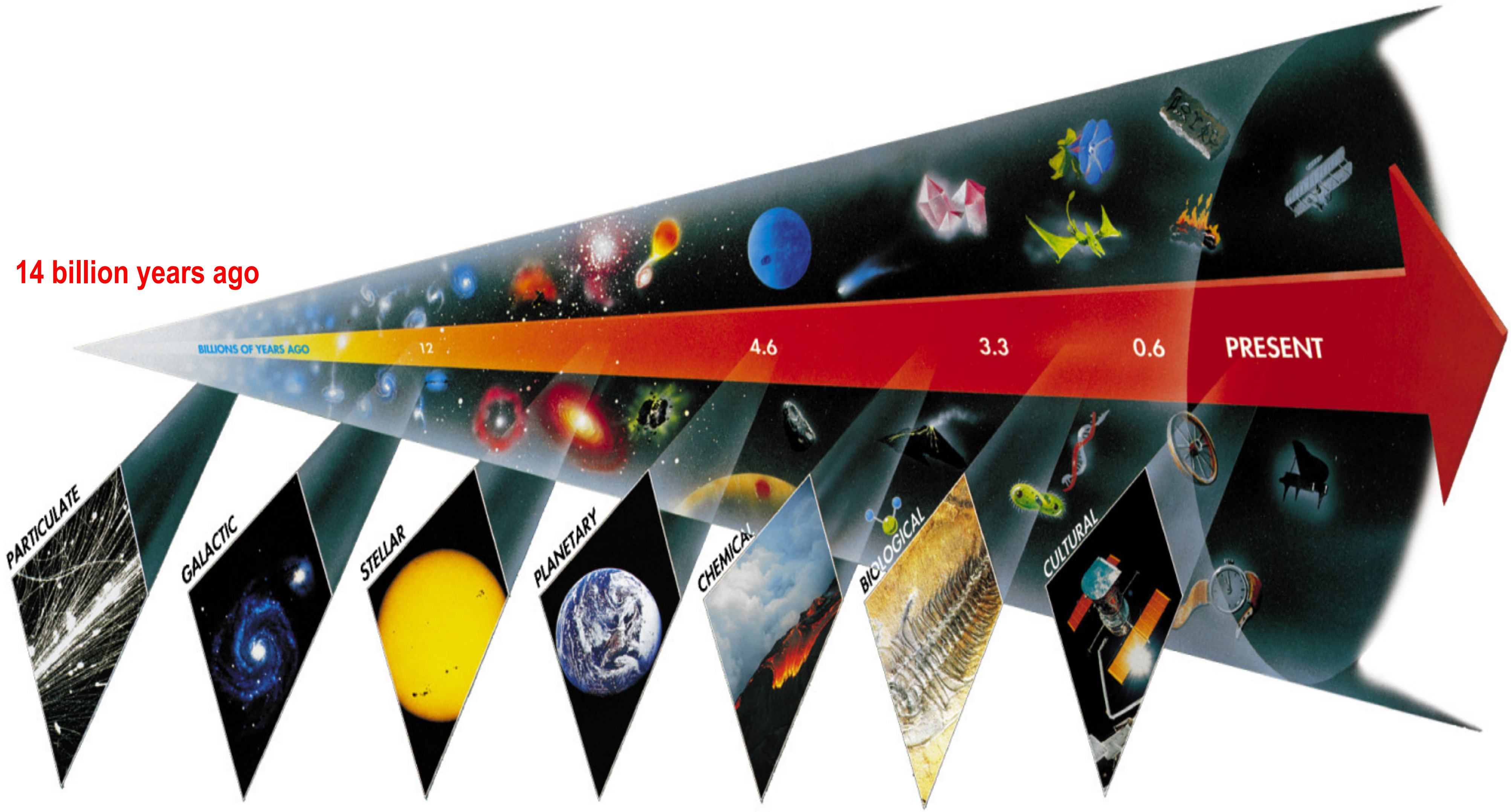
DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
ZEPLIN III
XENON100 (2010)
Buchmueller et al.
CMSSM
XENON100 (2011)
DarkSide-50
0.1 ton-year
XENON100 (2012)
Argon
5 ton-year
Xenon
1 ton-year
Xenon
10 ton-year
Argon
50 ton-year
G1
G2
G3
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
6 7 8 9 10 20 30 40 100 200 300 1000

Scientific Cases

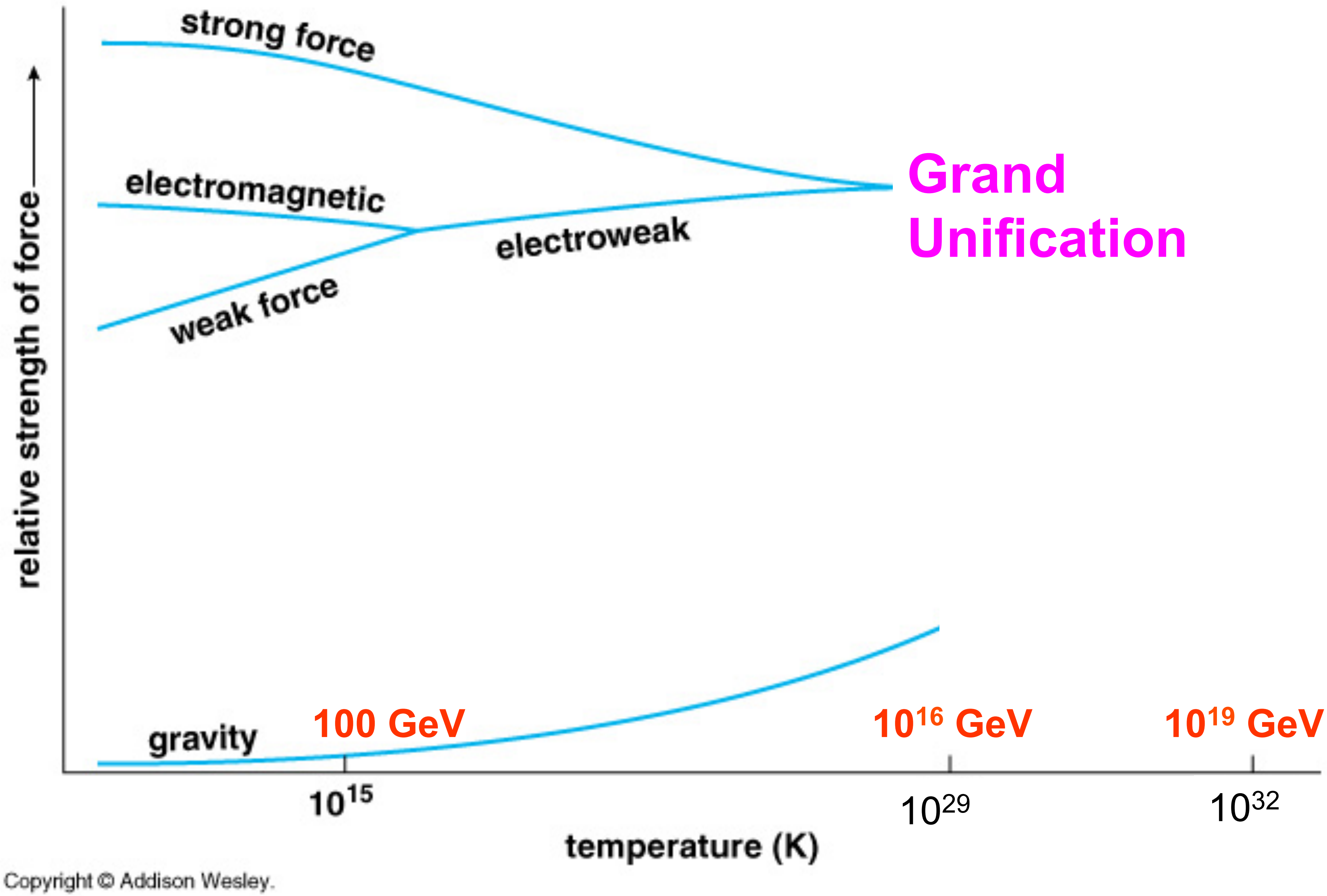
Why are we here?

Seven Phases of Cosmic Evolution

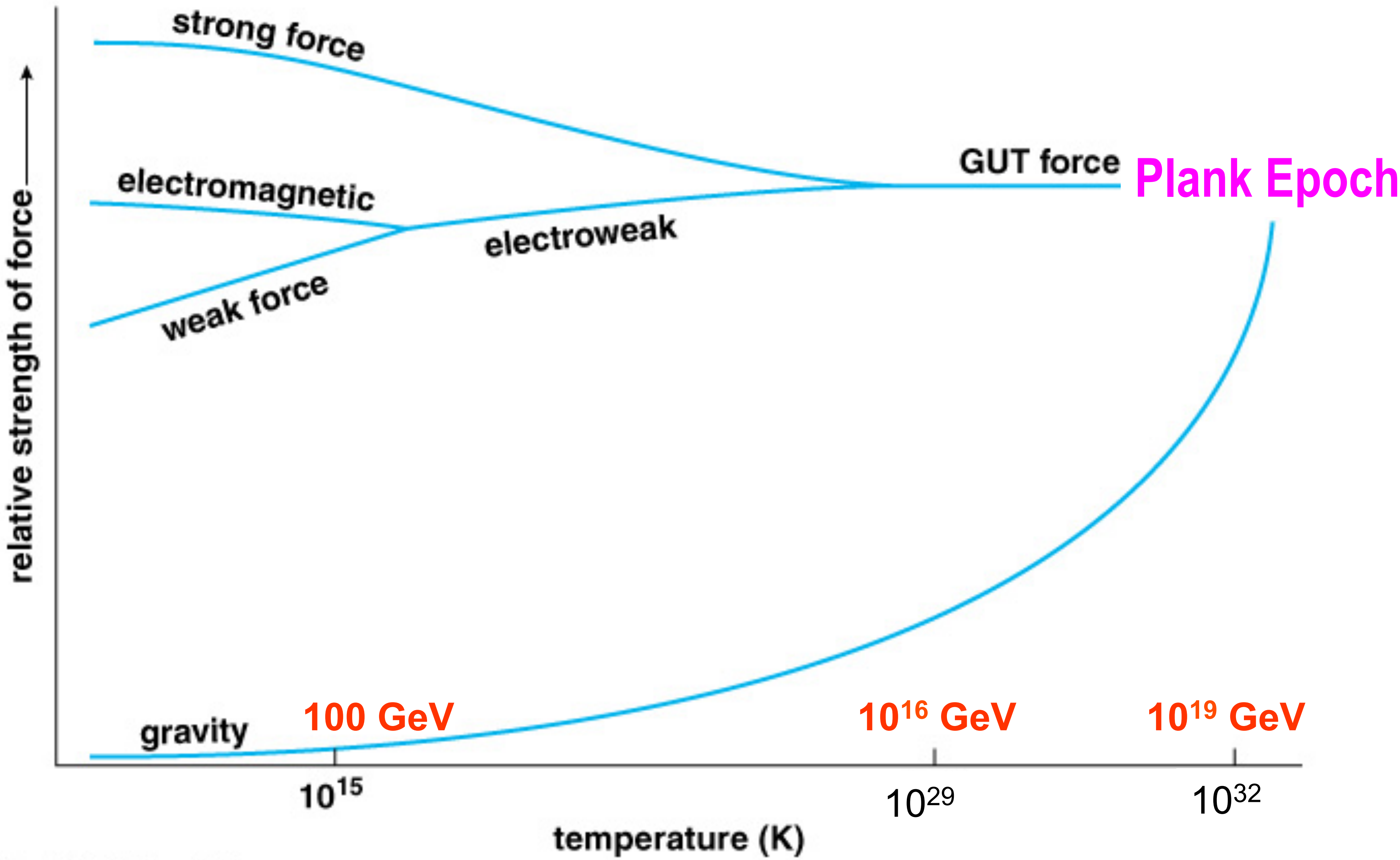
14 billion years ago



Unification of Forces



Unification of Forces



Physicists' View of Early Universe

Fiat lux

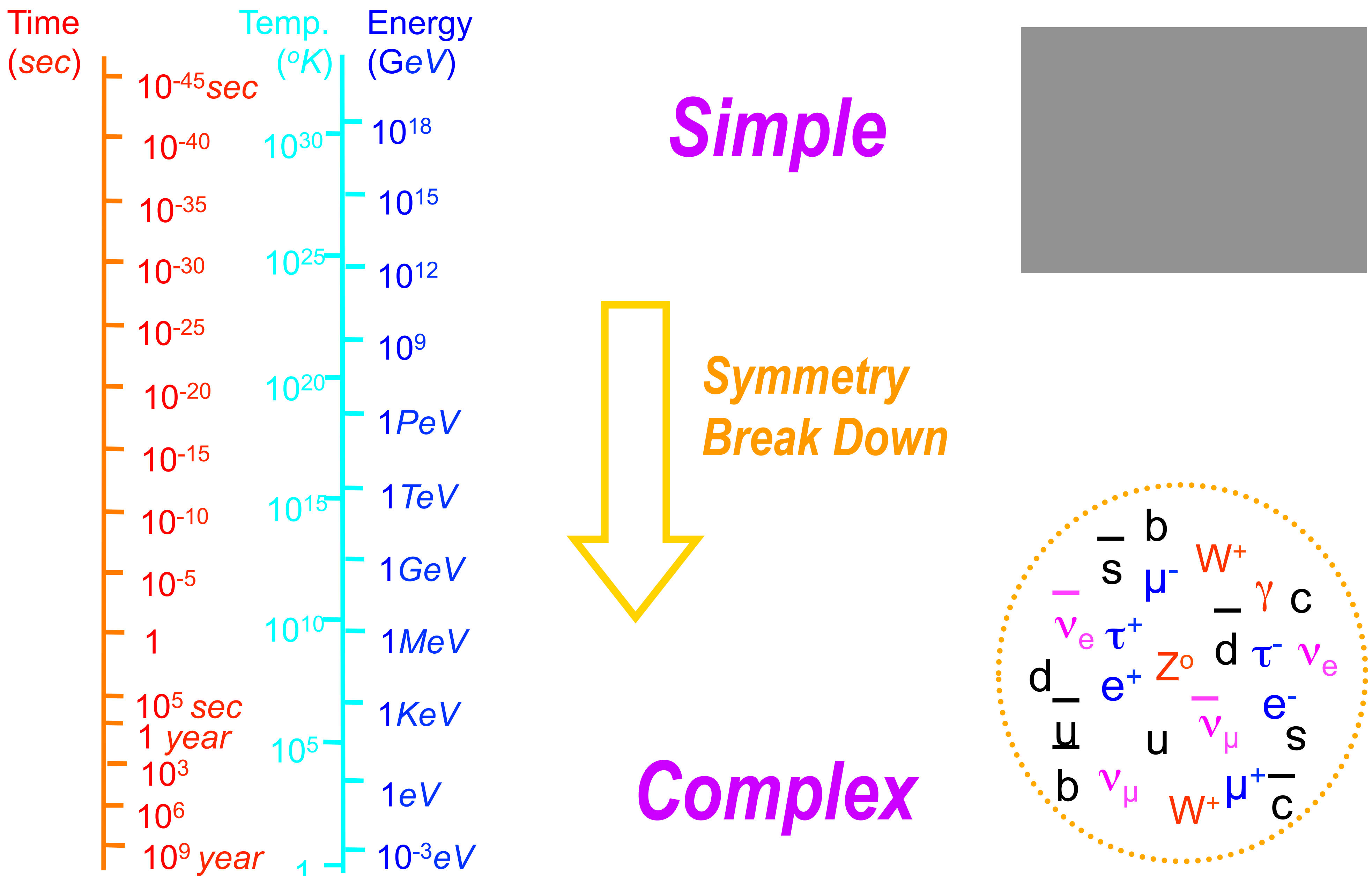
Let there be light

Physicists' View of Early Universe

Lorentz Invariance

Local Gauge Invariance

Symmetry Breaking



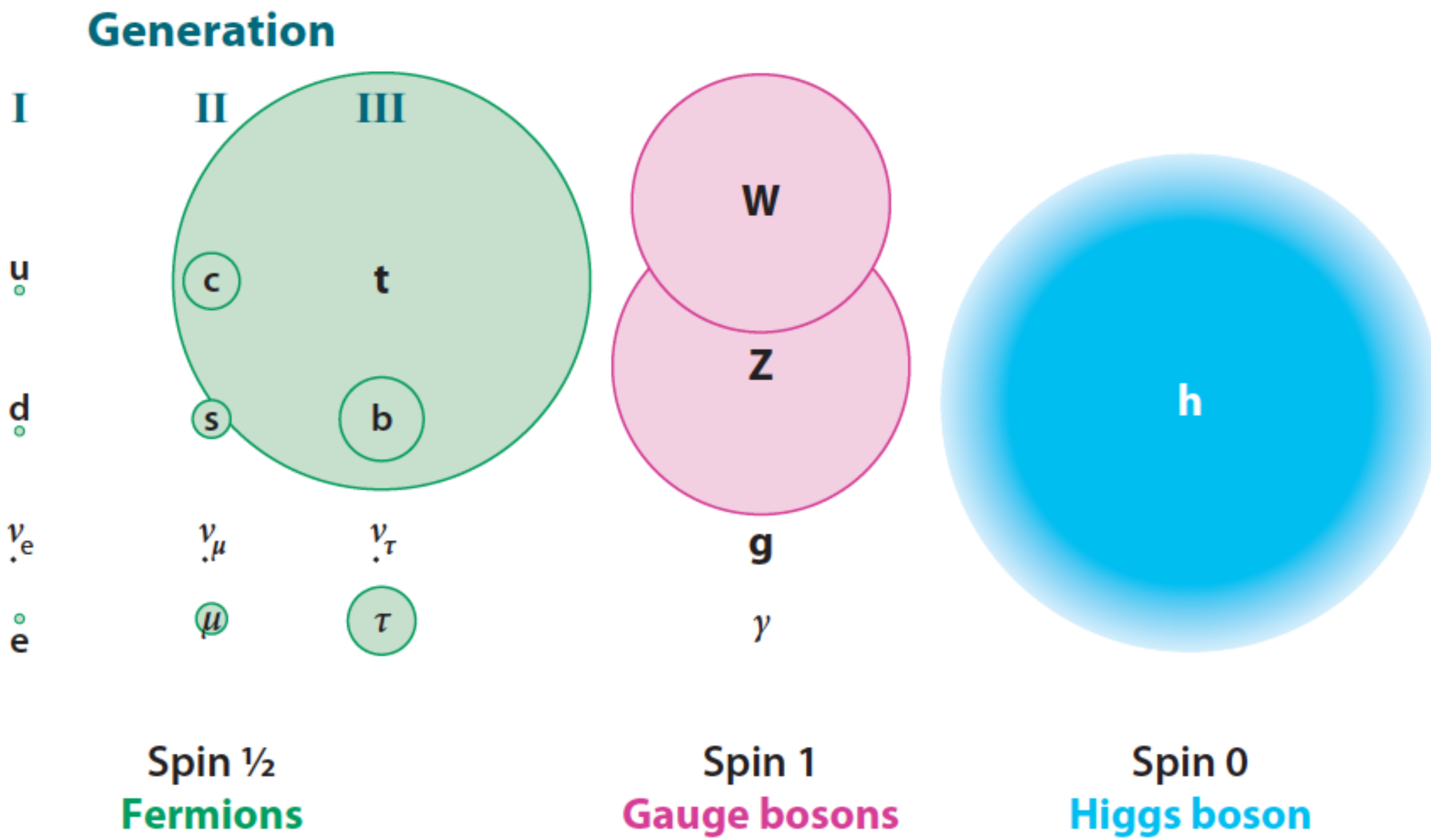
The Beginning

- 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



Mystery of the Mass (since 1970)

1) How to create mass from energy?

Energy → Mass

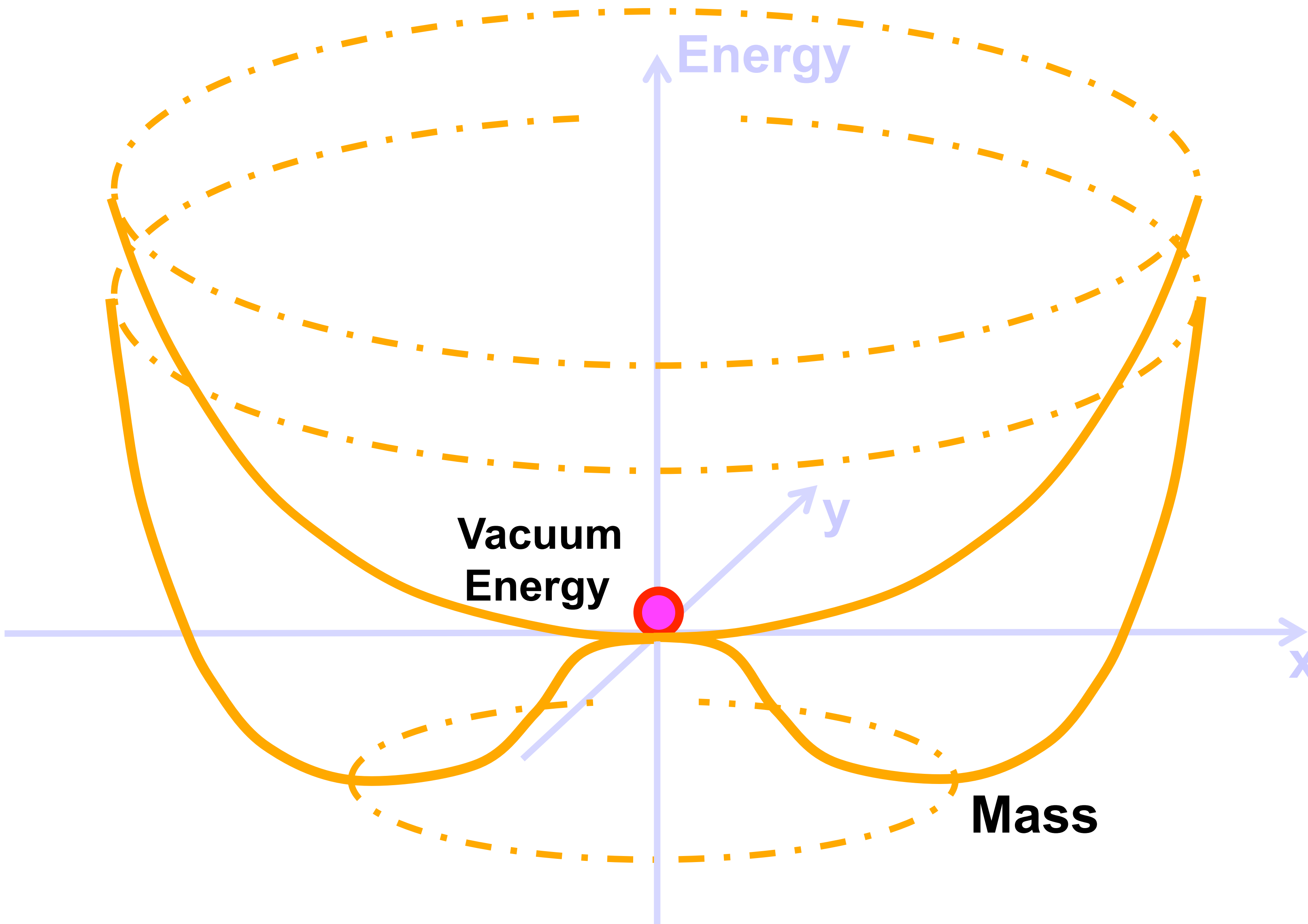
While maintaining the initial symmetry
Spontaneous Symmetry Breaking

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

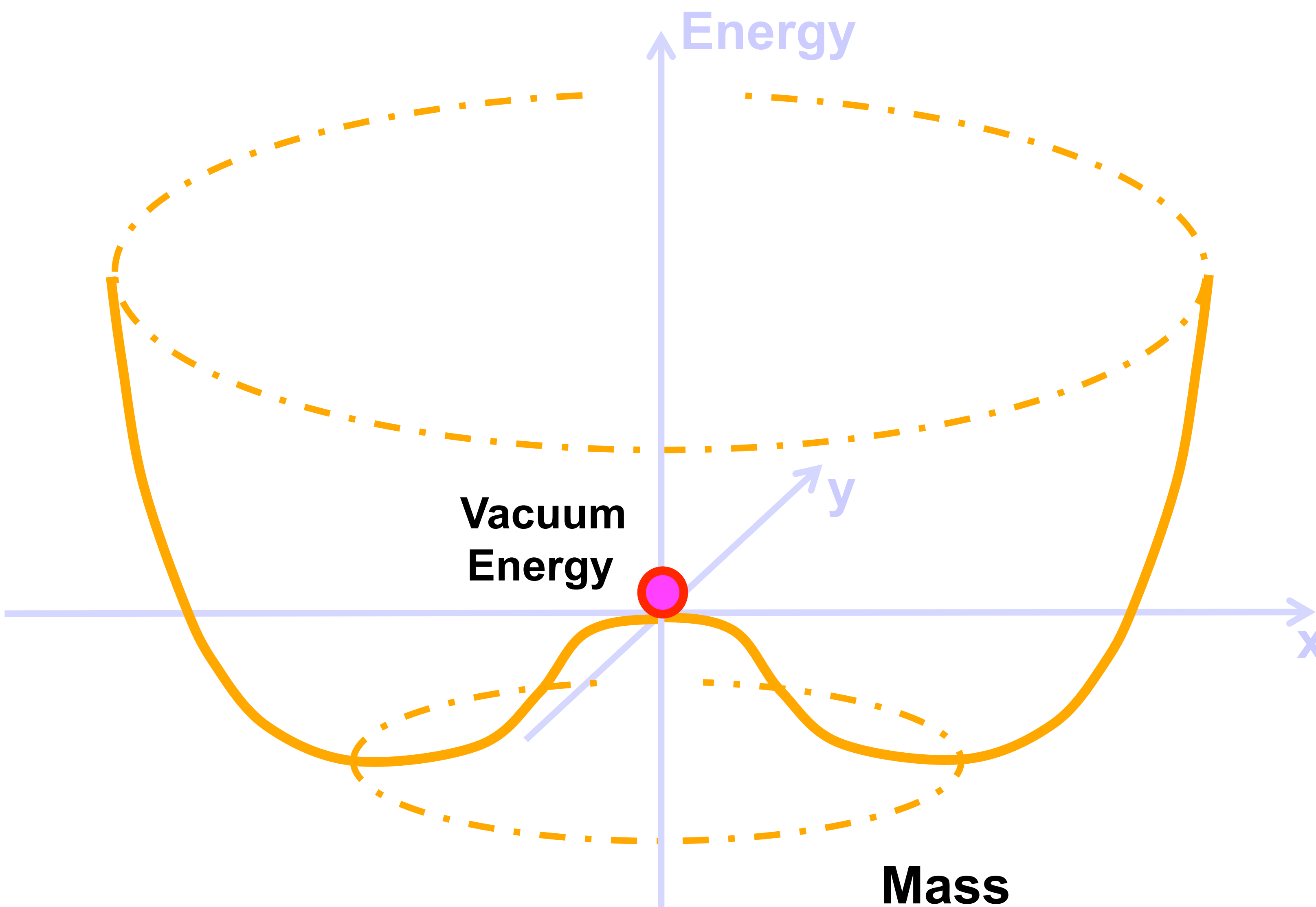
MeV – GeV 10^{19} GeV

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

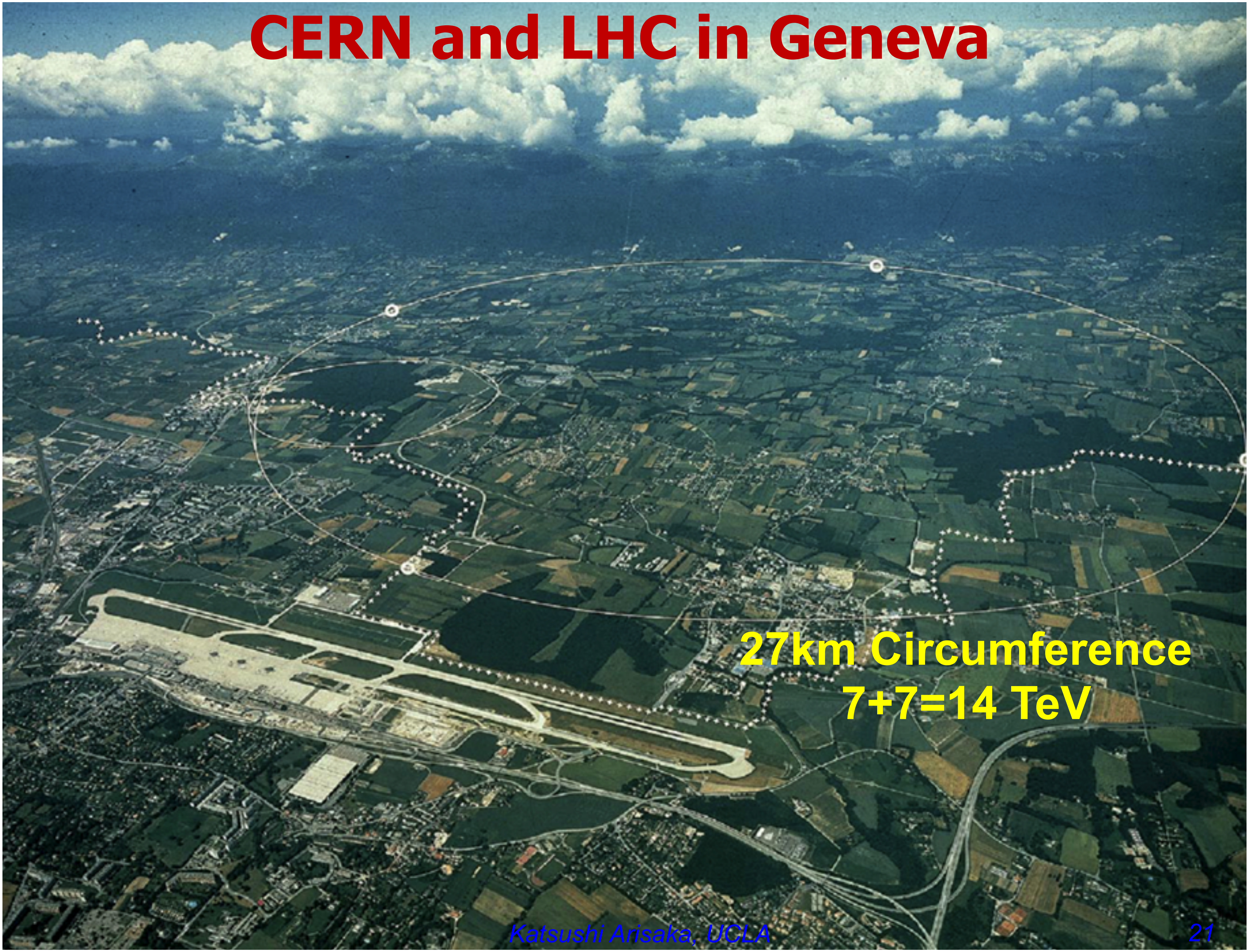
Spontaneous Symmetry Breaking
- Higgs Mechanism -



Spontaneous Symmetry Breaking
- Higgs Mechanism -



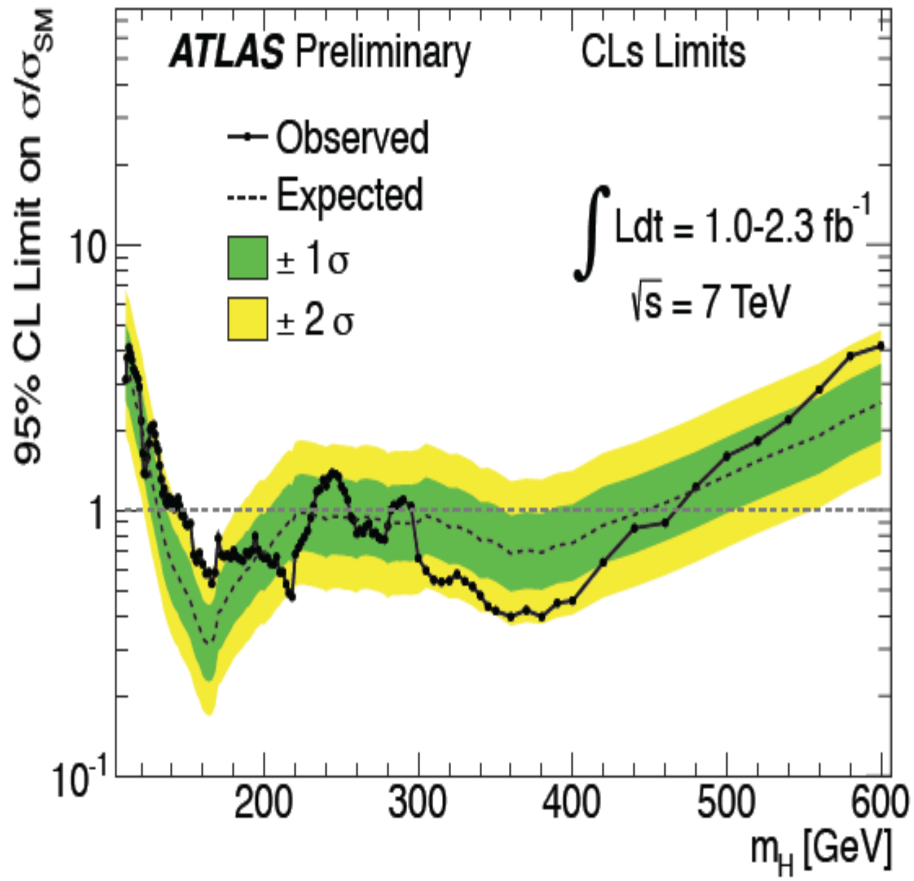
CERN and LHC in Geneva



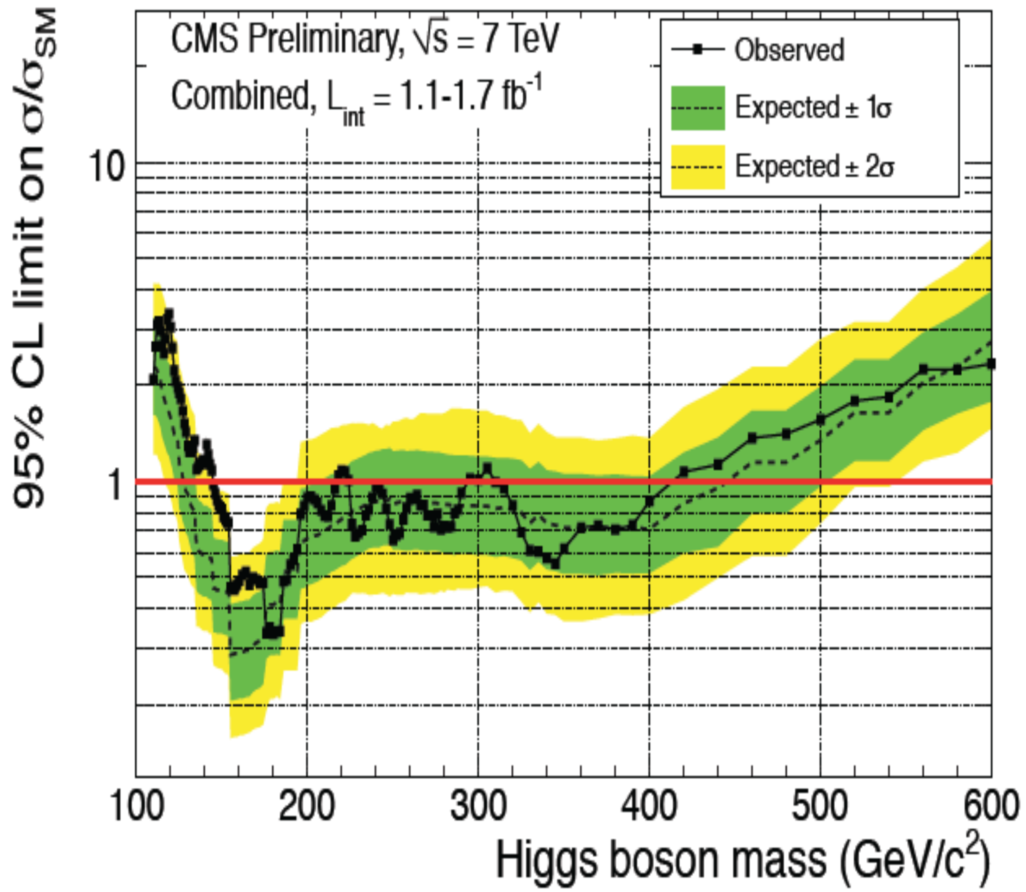
LHC Higgs search results

Results from the LHC Higgs Cross Section WG by R. Tanaka

ATL-PHYS-PUB-2011-135

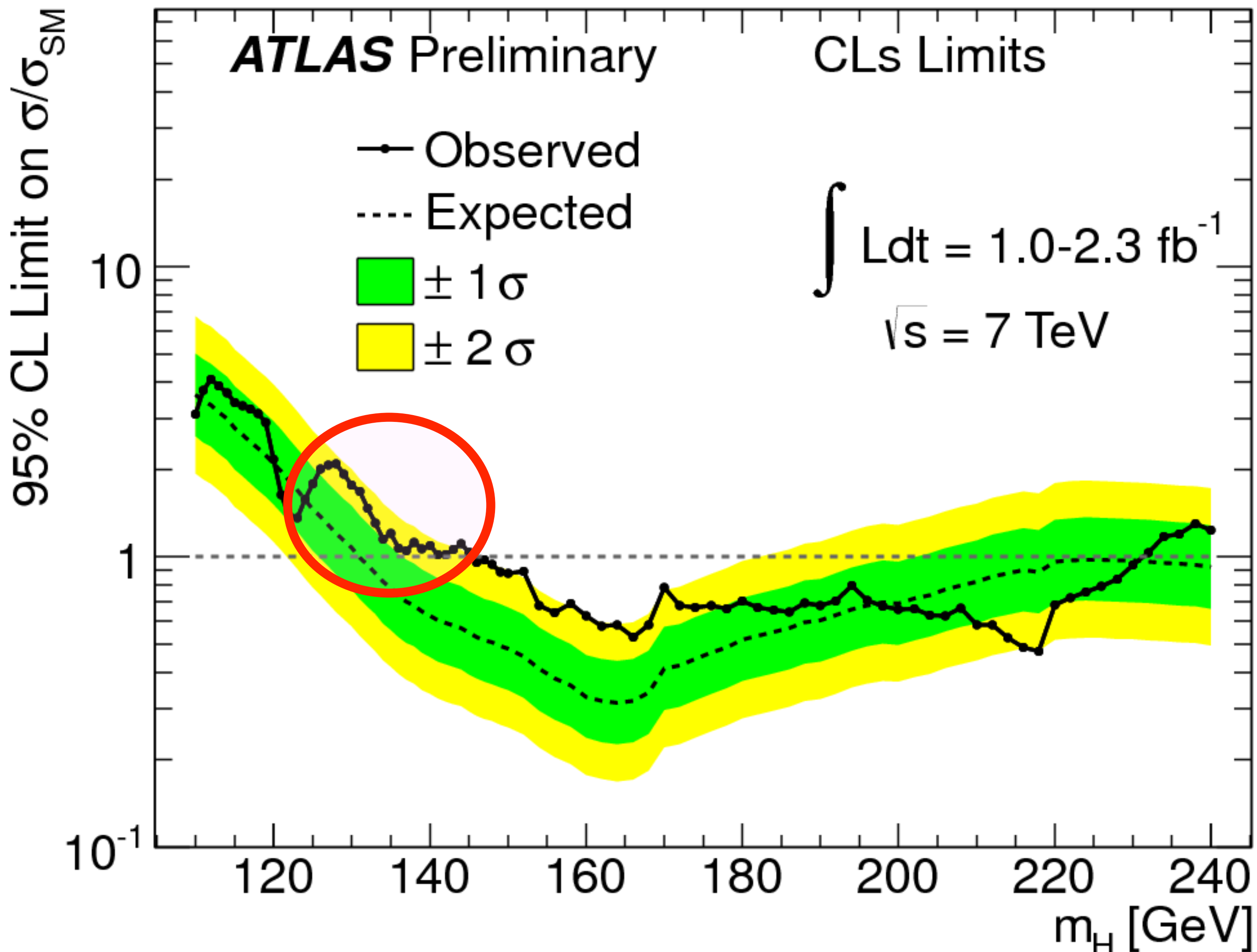


CMS-PAS-HIG-11-022



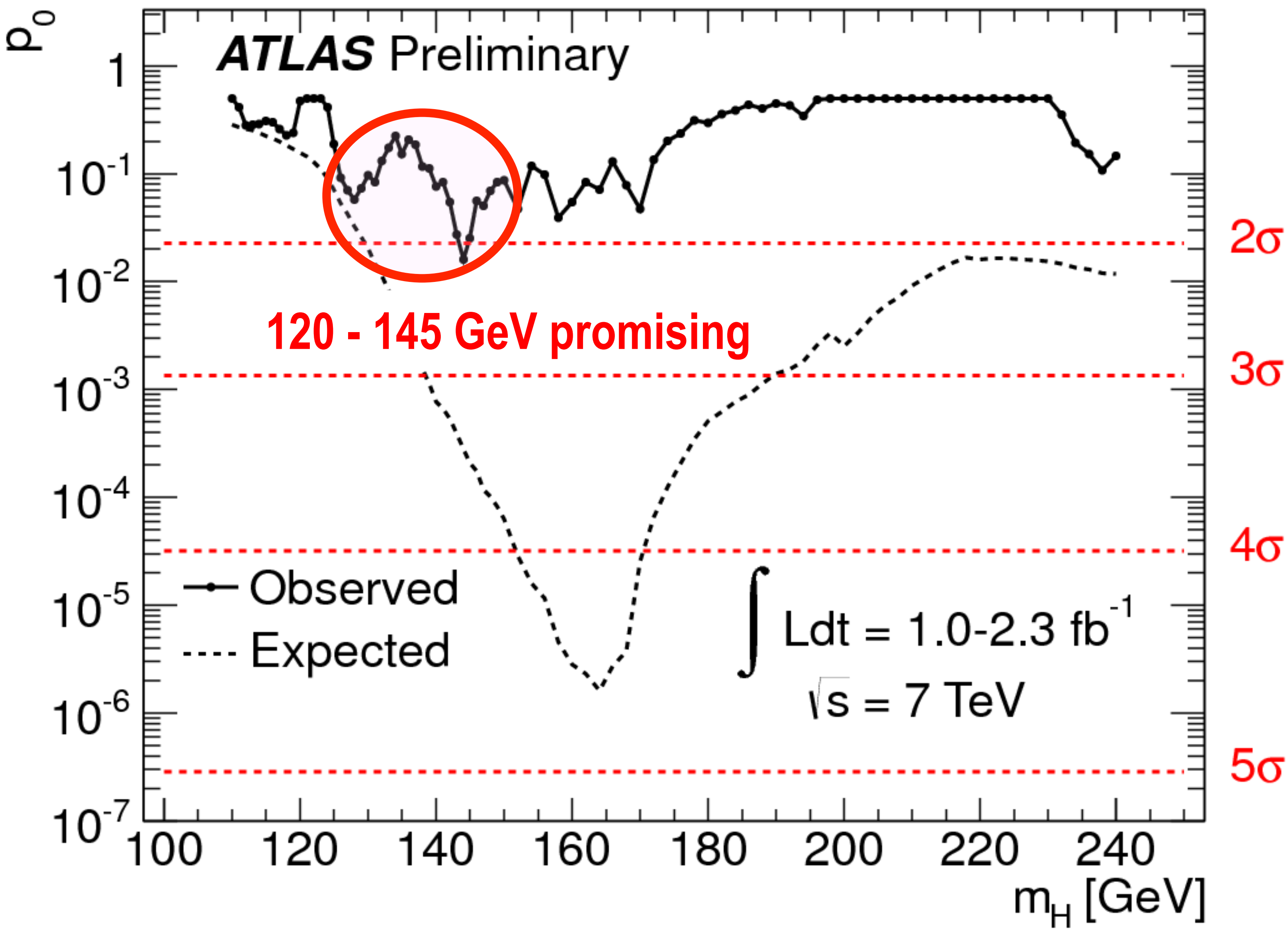
145 - 466 GeV excluded.

LHC Higgs search results

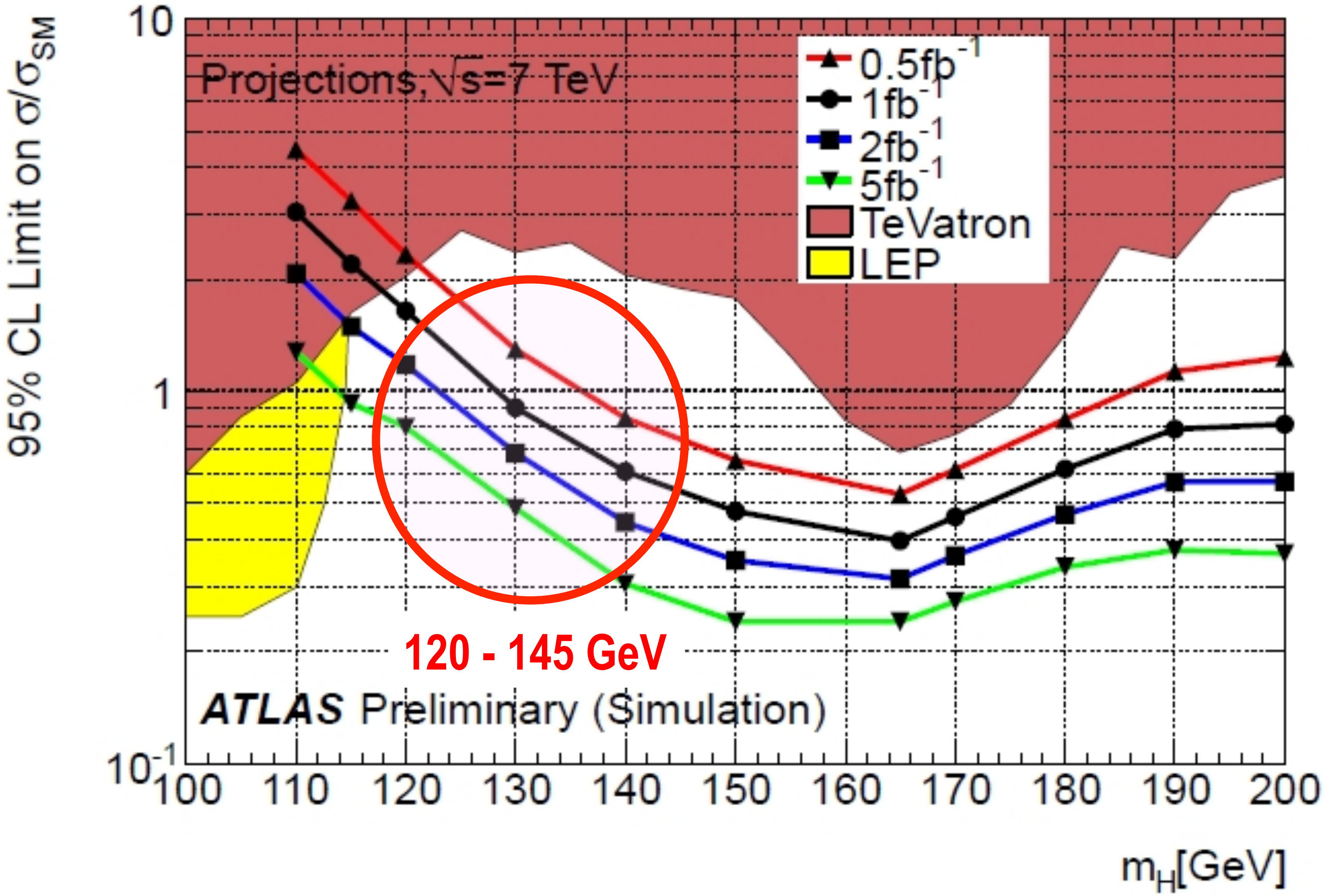


120 - 145 GeV promising

LHC Higgs search results



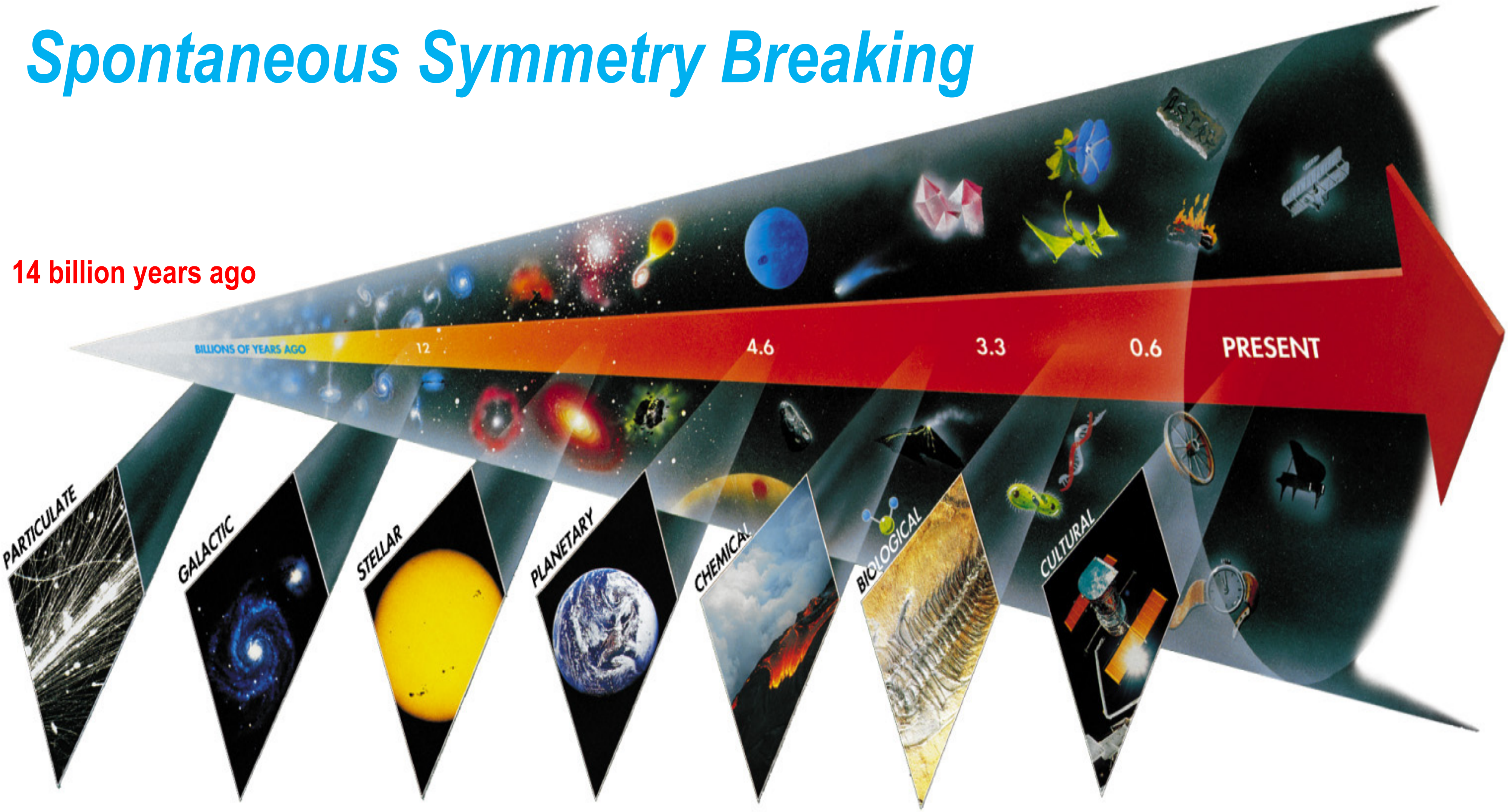
Predicted Sensitivity to Higgs



Seven Phases of Cosmic Evolution

Spontaneous Symmetry Breaking

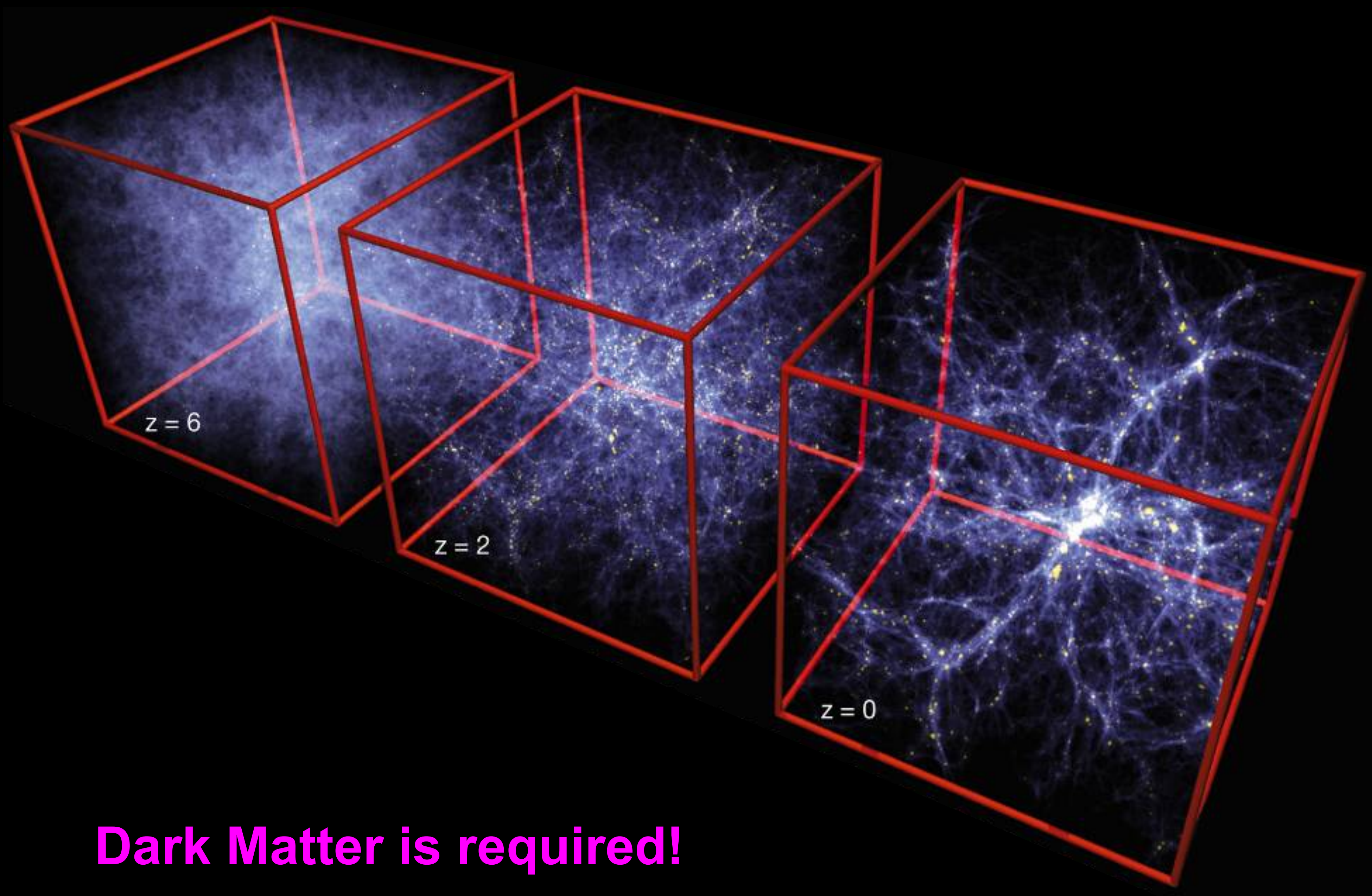
14 billion years ago



Origin of Particles

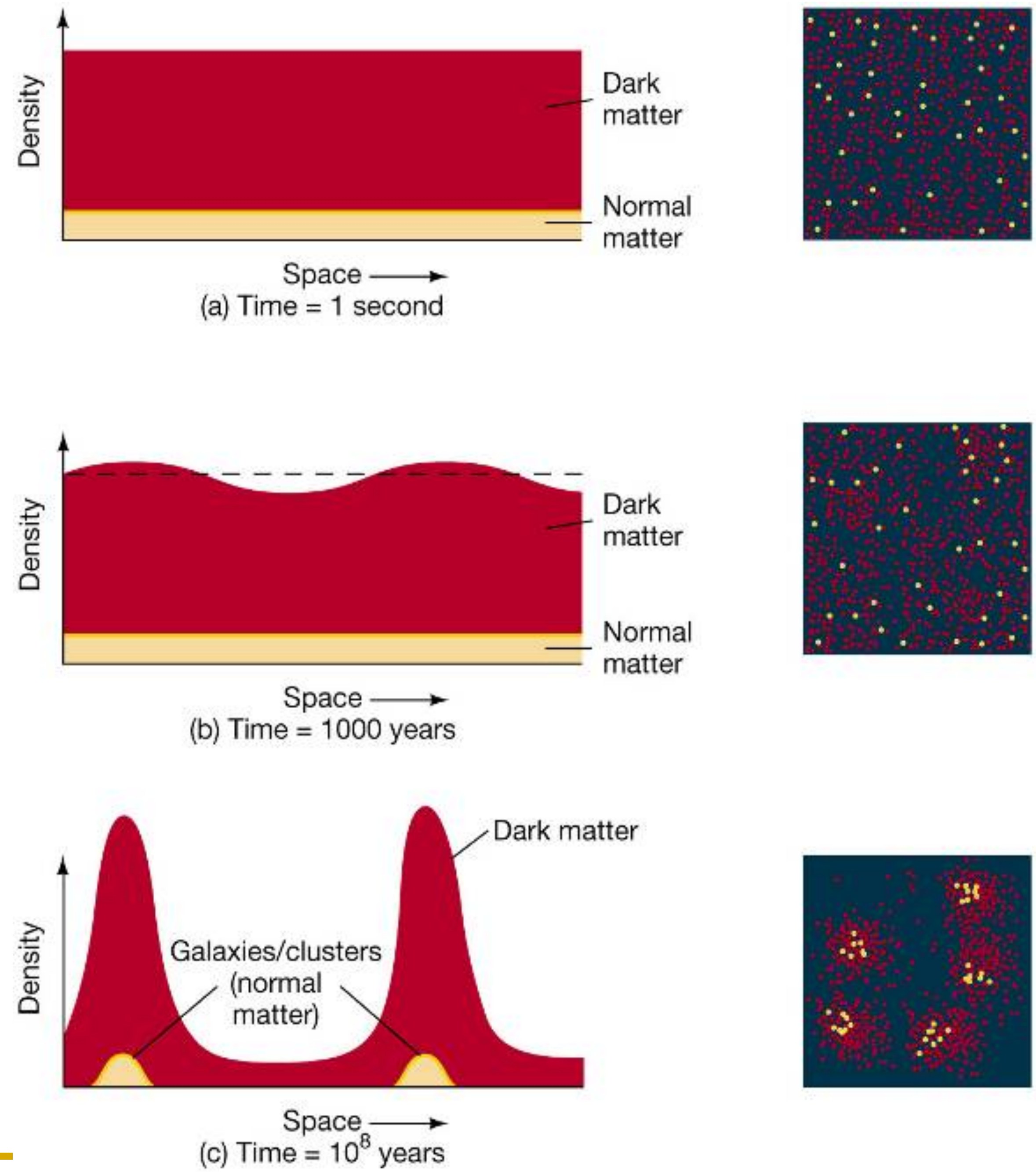
Origin of Structure

Formation of Structure in the Universe



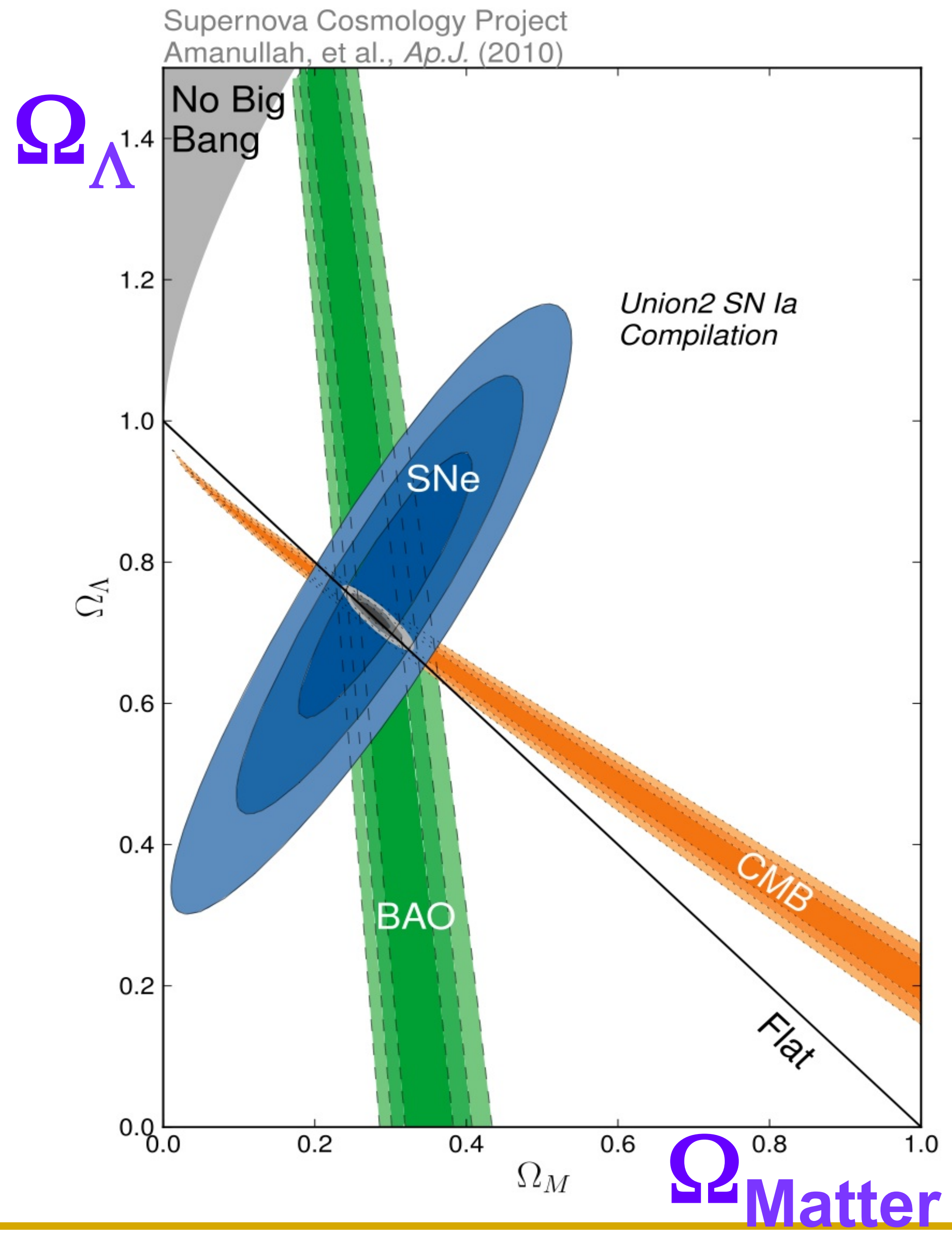
Dark Matter is required!

Evolution of Large Structure

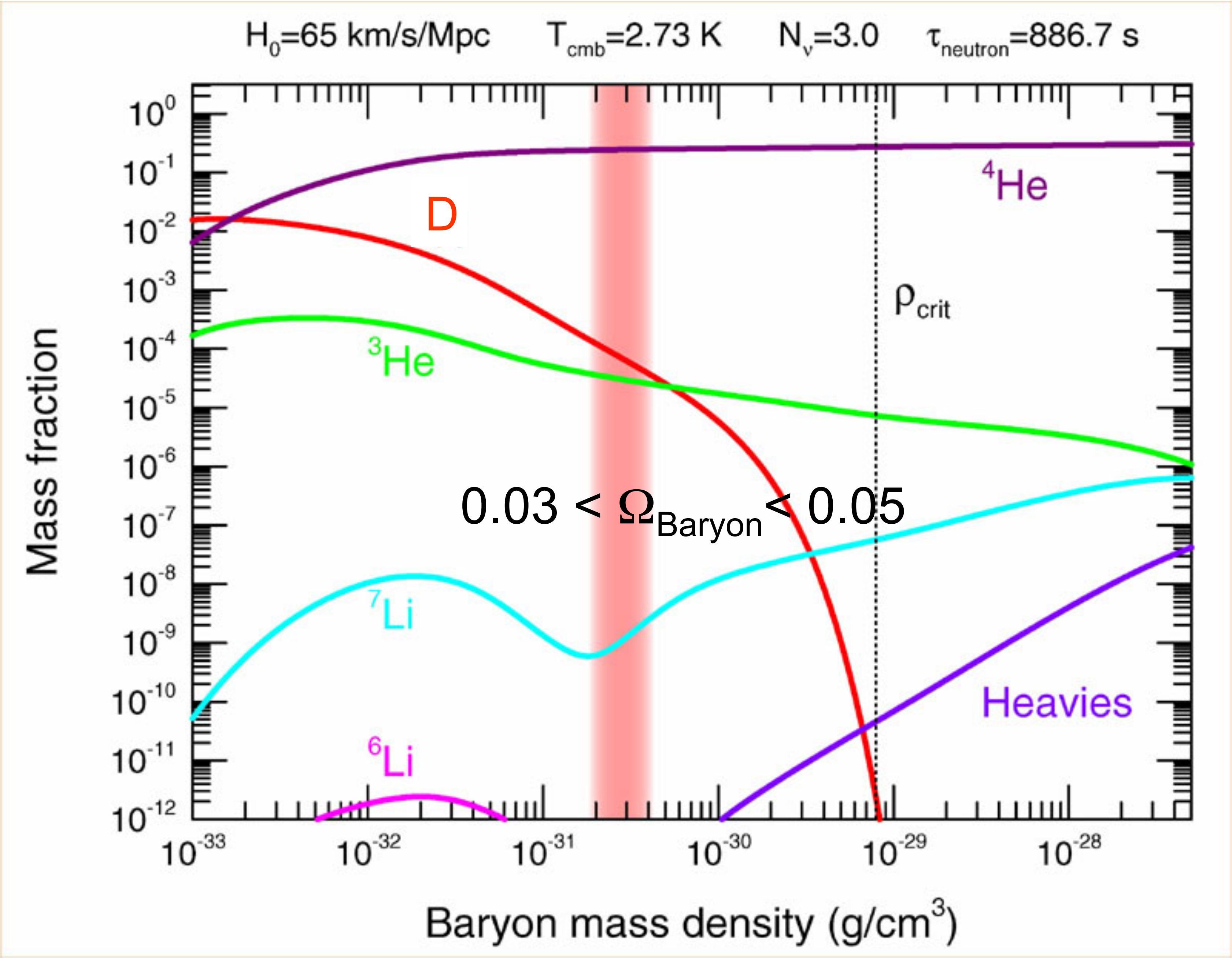


Density of Our Universe

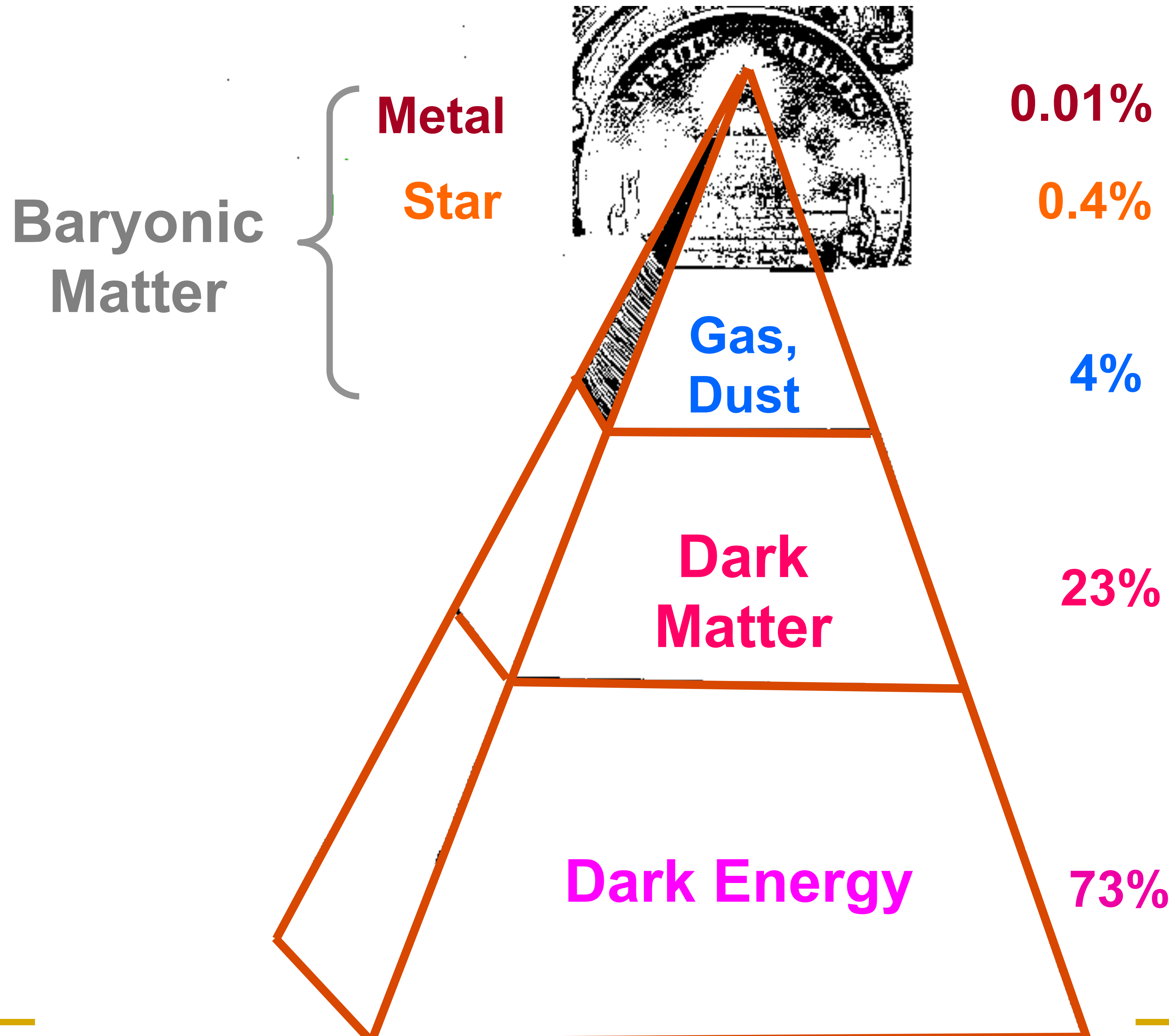
- $\Omega_{Total} = \Omega_{\Lambda} + \Omega_{Matter} = 1.0$
- Universe is Flat.
  ⇒ Inflation
- 74% is Dark Energy.
  ⇒ Accelerating



Abundance vs. Density



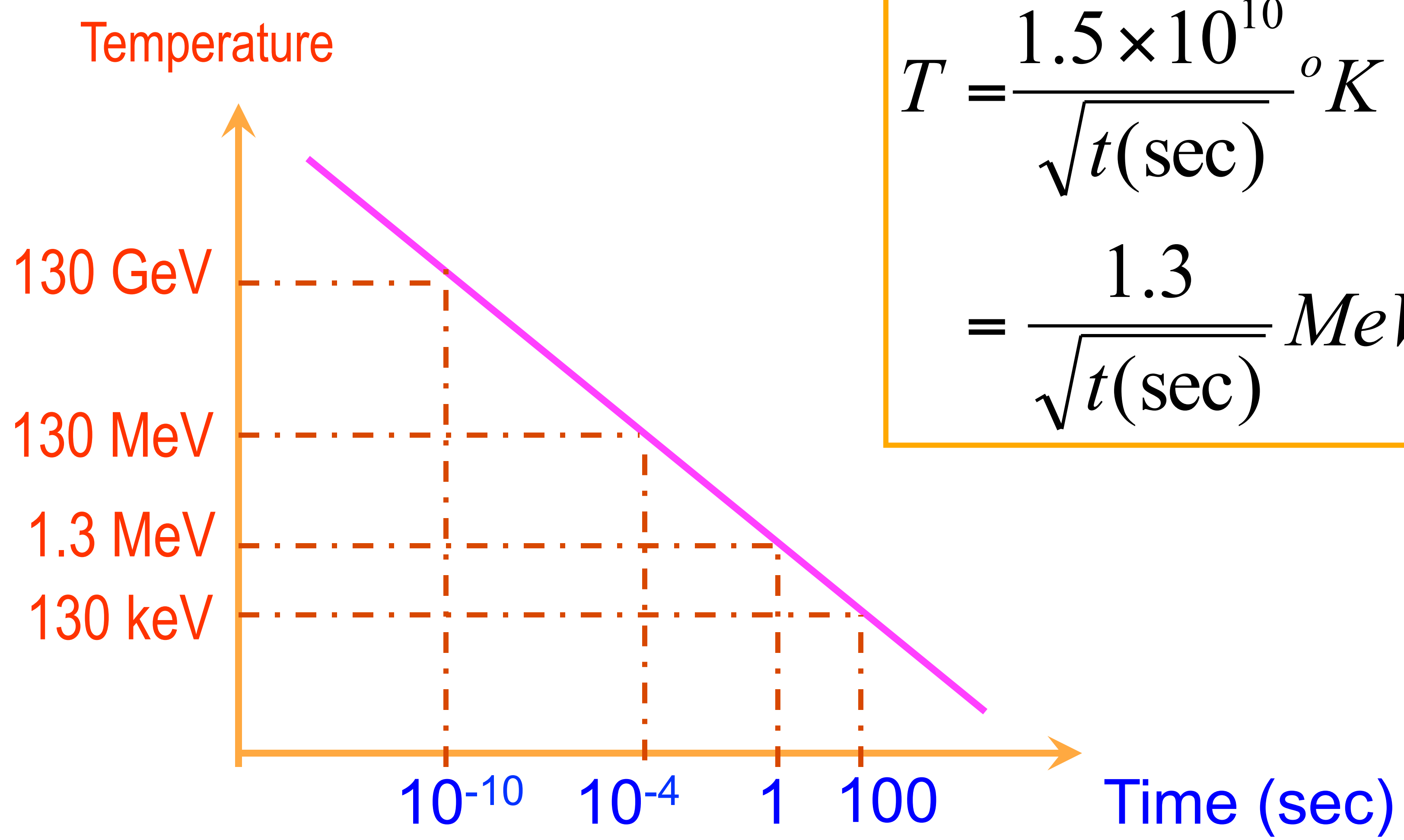
Cosmic Pyramid



Relation between Temperature and Time

T: Temperature
t : time

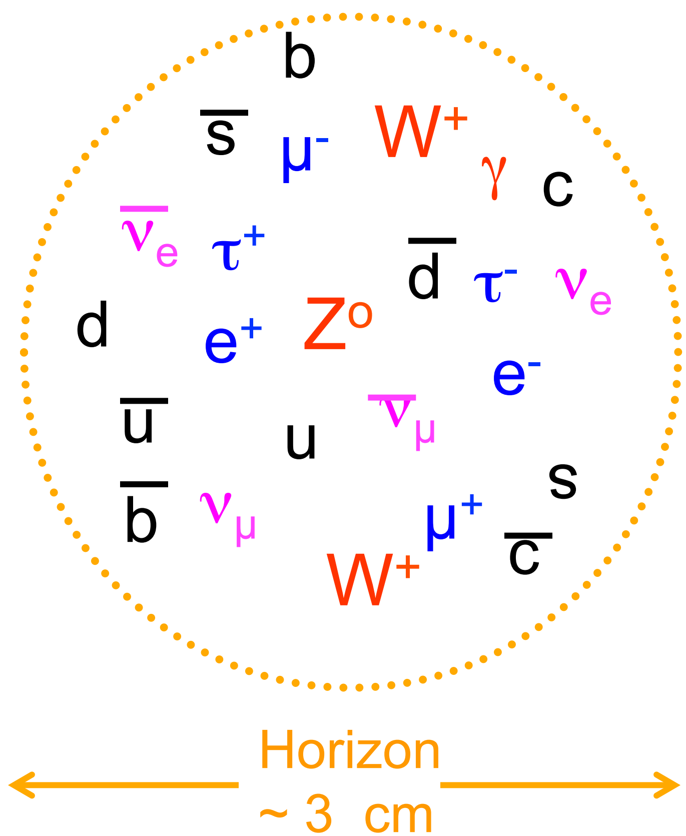
$$T = \frac{1.5 \times 10^{10}}{\sqrt{t(\text{sec})}} {}^{o}K$$
$$= \frac{1.3}{\sqrt{t(\text{sec})}} MeV$$



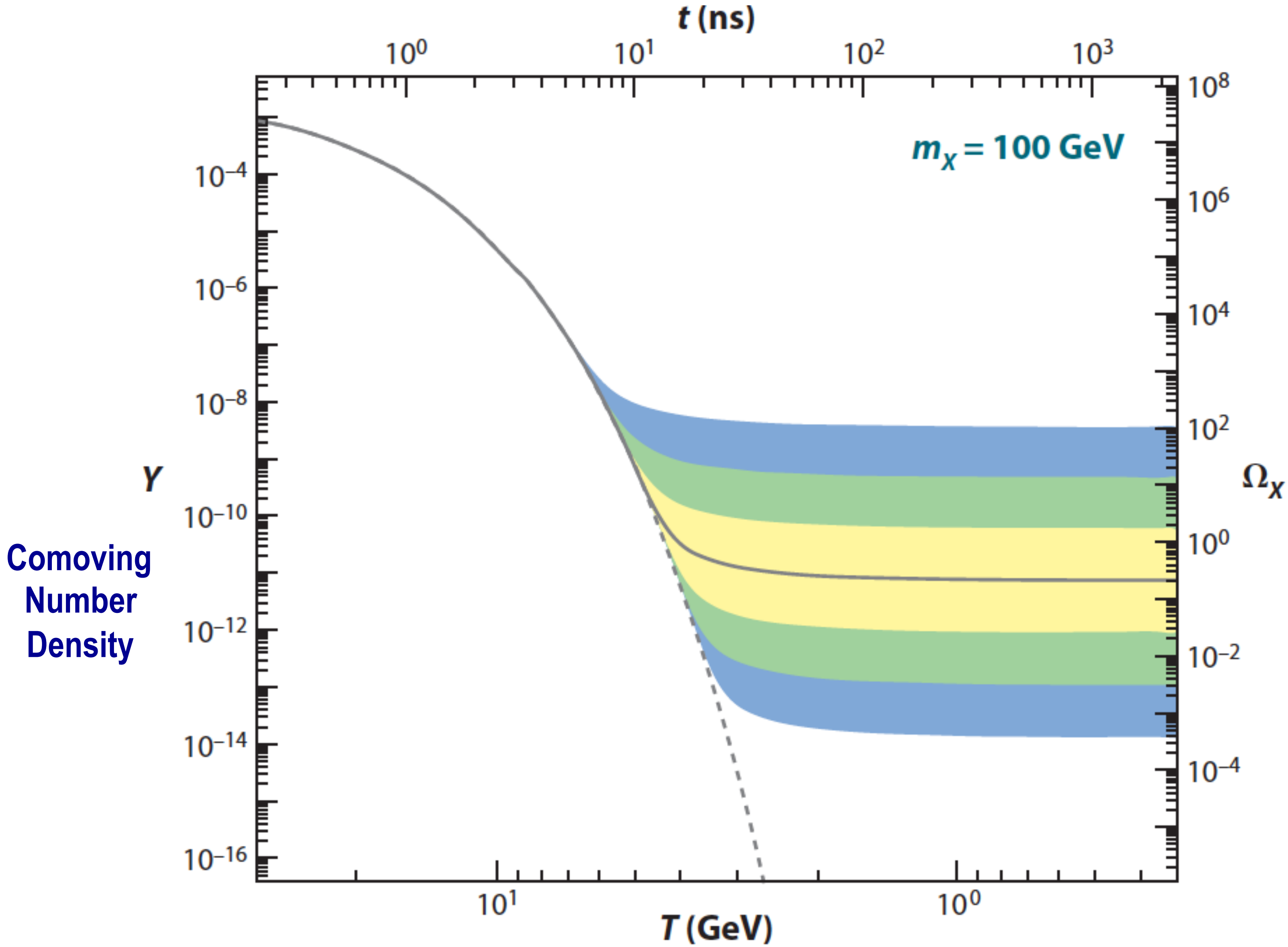
Time = 10^{-10} sec, Temp.= 10^{15} °K (~100 GeV)

➢ Electro-weak Unification

- Electro-Magnetic force = Weak force
- The highest energy we can study by the accelerators



Relic Density vs. Time



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

WIMP Miracle

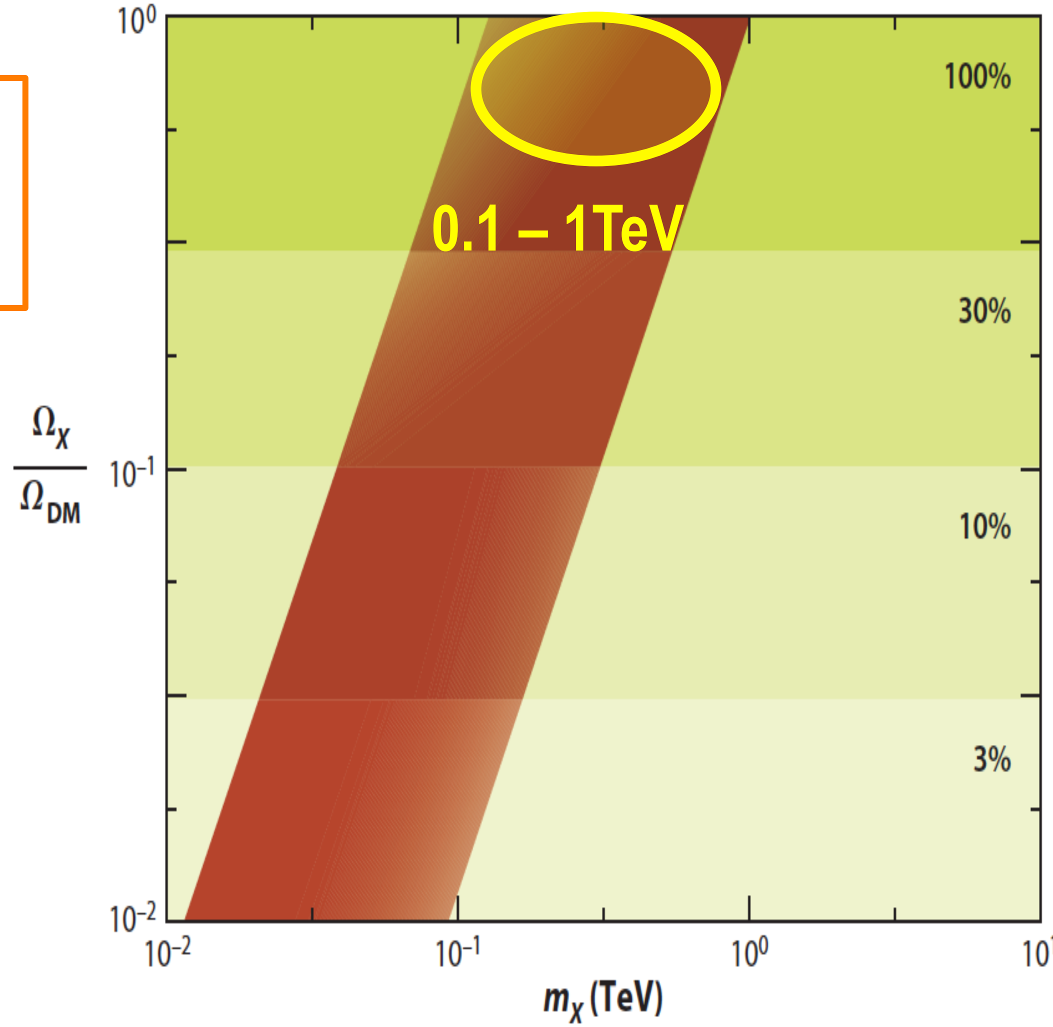
$$\Omega_X = \frac{m_X n_0}{\rho_c} = \frac{m_X T_0^3}{\rho_c}\frac{n_0}{T_0^3} \sim \frac{m_X T_0^3}{\rho_c}\frac{n_f}{T_f^3} \sim \frac{x_f T_0^3}{\rho_c M_{\text{Pl}}}\langle \sigma_A v\rangle^{-1}$$

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

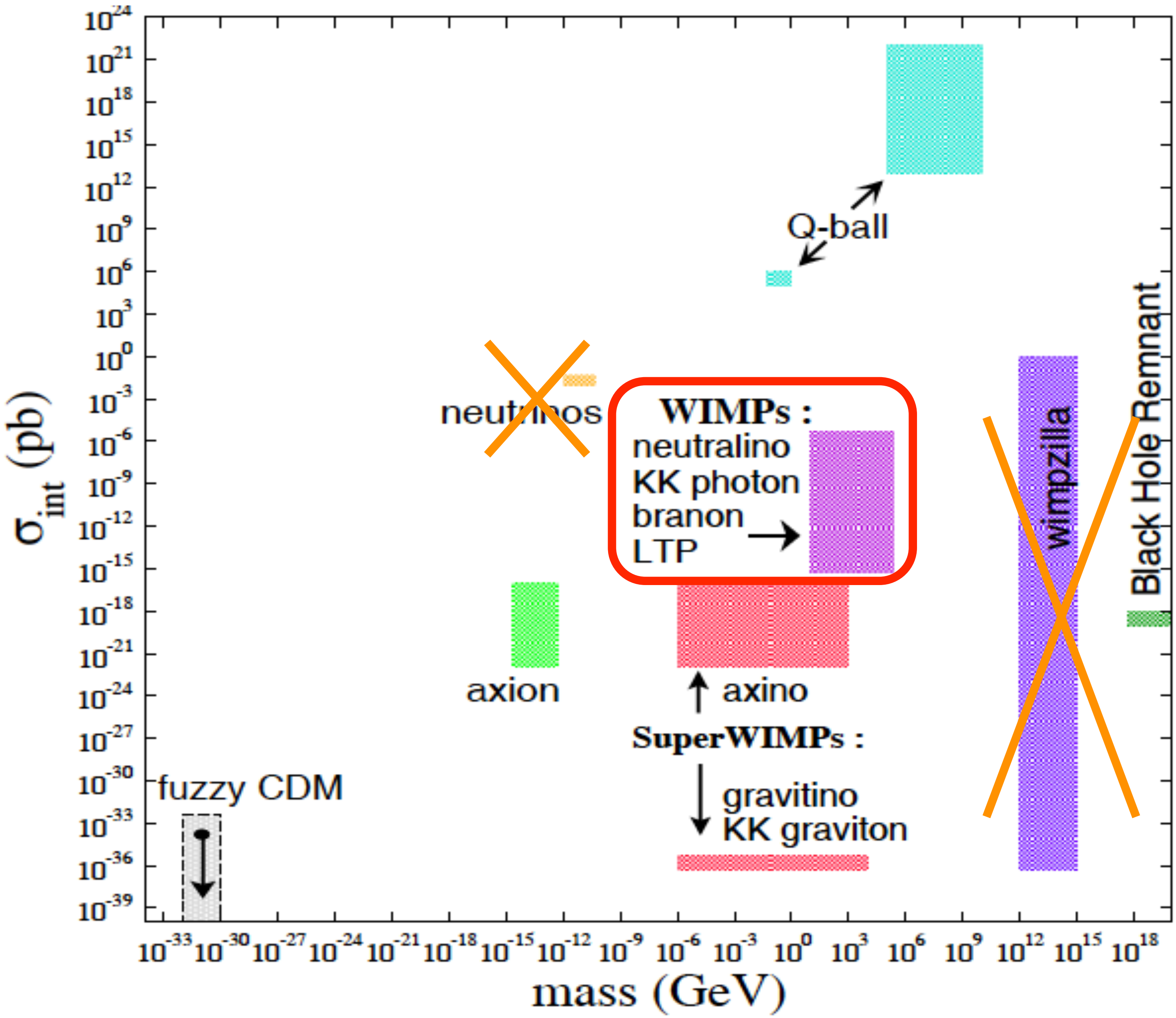
⇩

$$\Omega_X \propto M_X^2$$

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

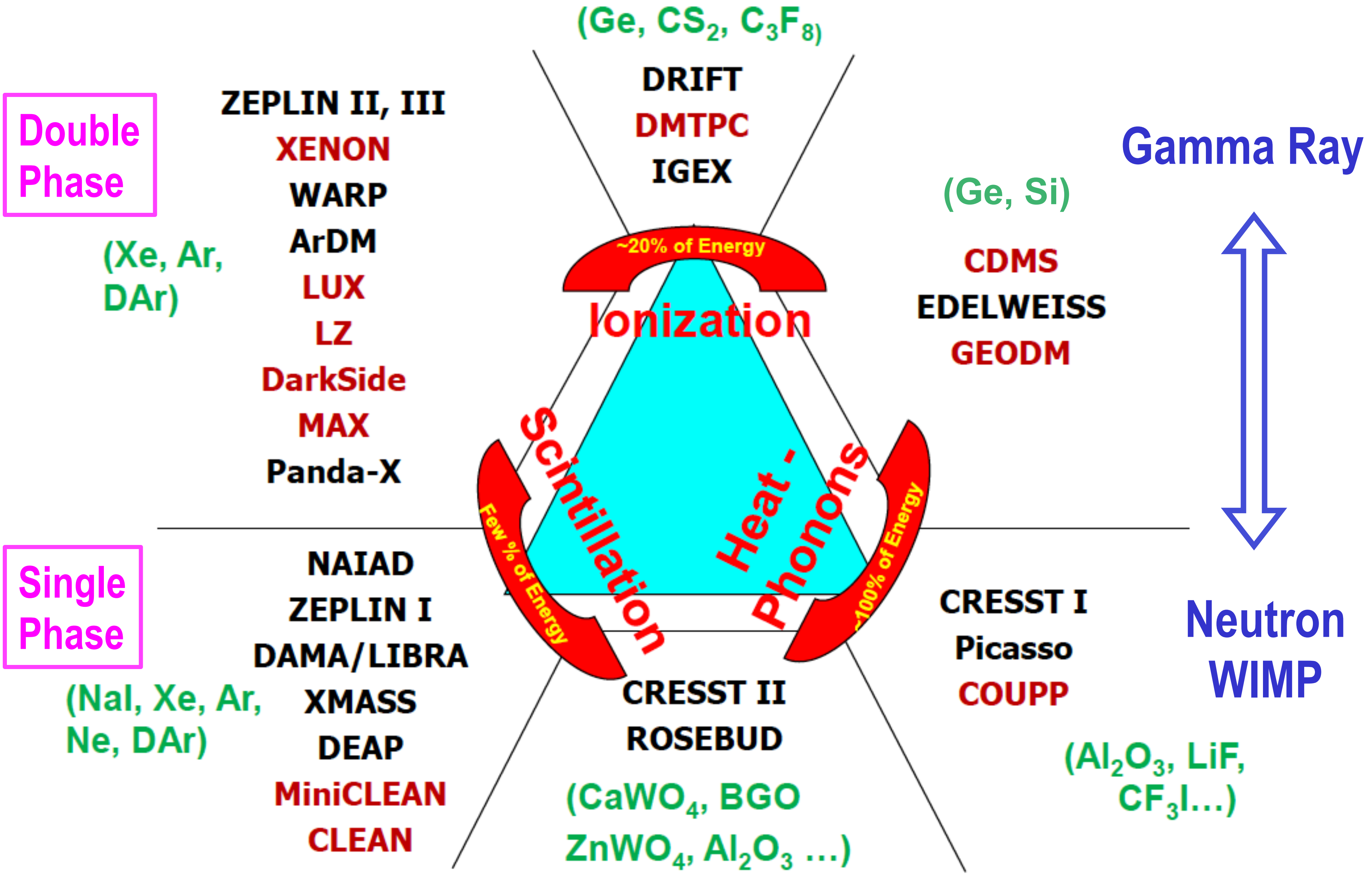


What is Dark Matter?



Detection Methods

Detection Technique

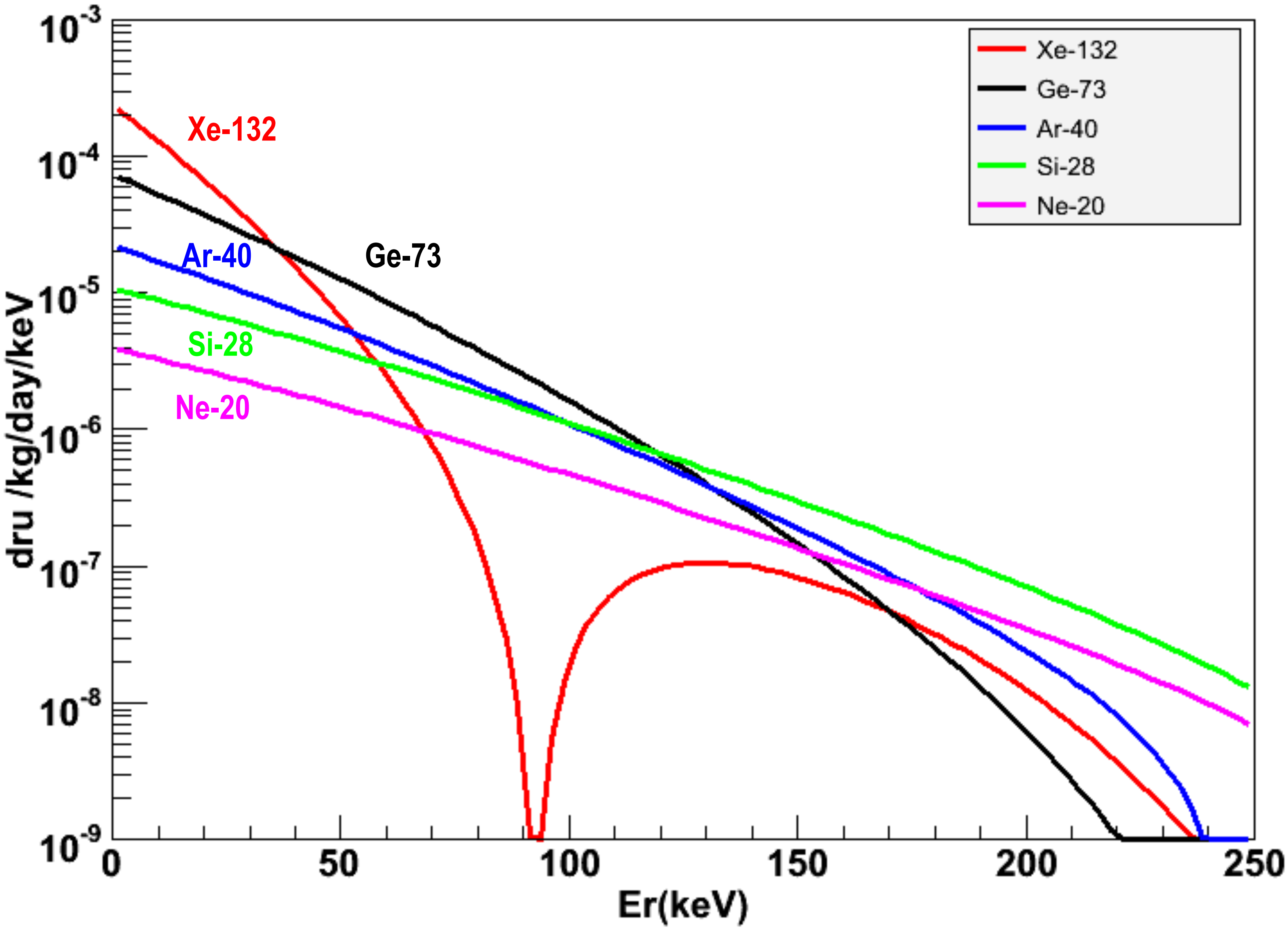


Properties of Noble Liqud

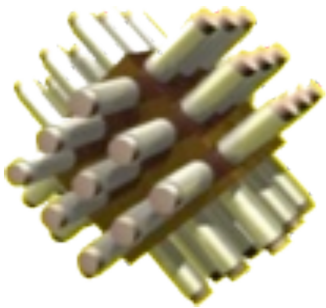
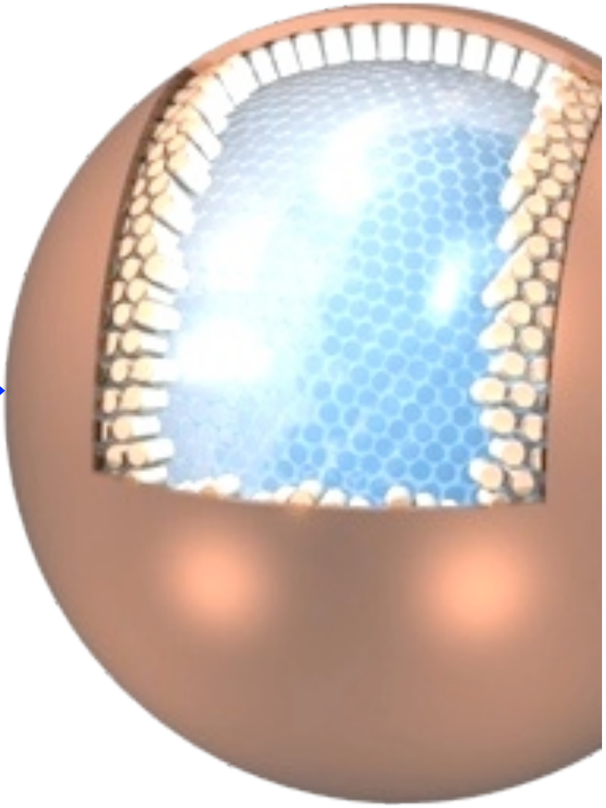
	Unit	Neon	Argon	Xenon
Z		10	18	54
A		20	40	~132
Liquid Density	*g/cc*	1.21	1.4	3.06
Energy Loss (dE/dX)	*MeV/cm*	1.4	2.1	3.8
Radiation Length	*cm*	24	14	2.8
Collision Length	*cm*	80	80	34
Boiling Temperature	*°K*	27.1	87.3	165
Scintillation Wavelength	*nm*	85	125	178
Scintillation	*photon/keV*	30	40	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

Target Mass Dependence of WIMP Cross Section

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

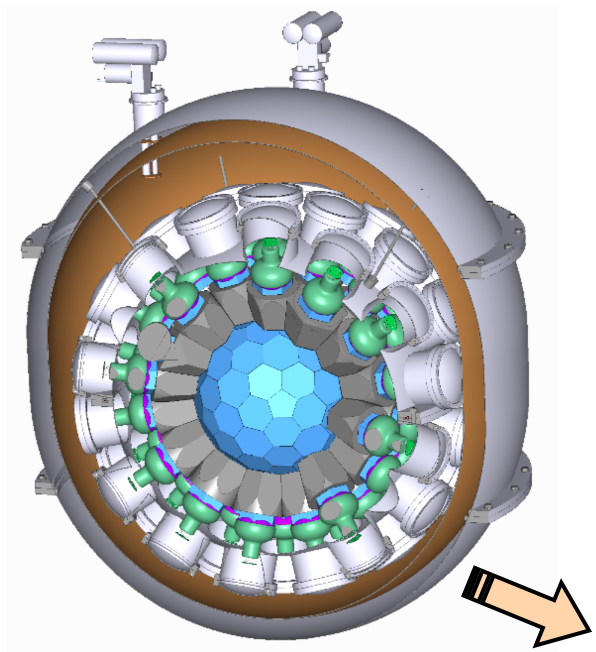


XMASS (Single Phase Xe)

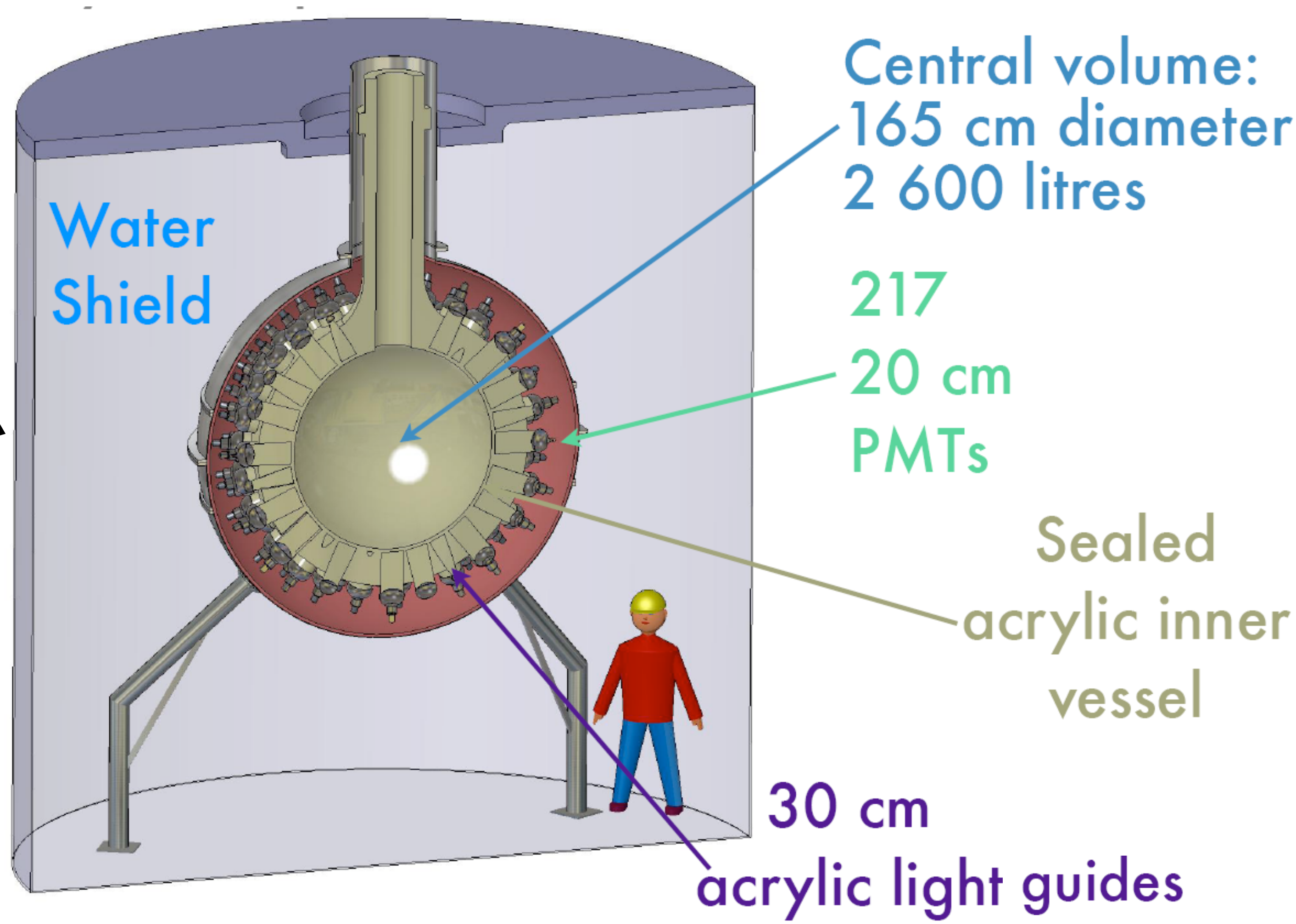
100kg Prototype (FV:30kg、30cm)	800kg Detector (FV:100kg、80cm)	20ton Detector (FV:10ton、2.5m)
		
R&D	Dark Matter	Solar neutrino Dark Matter
completed	2011 ～	Future

DEAP/CLEAN (Single Phase Ar/Ne)

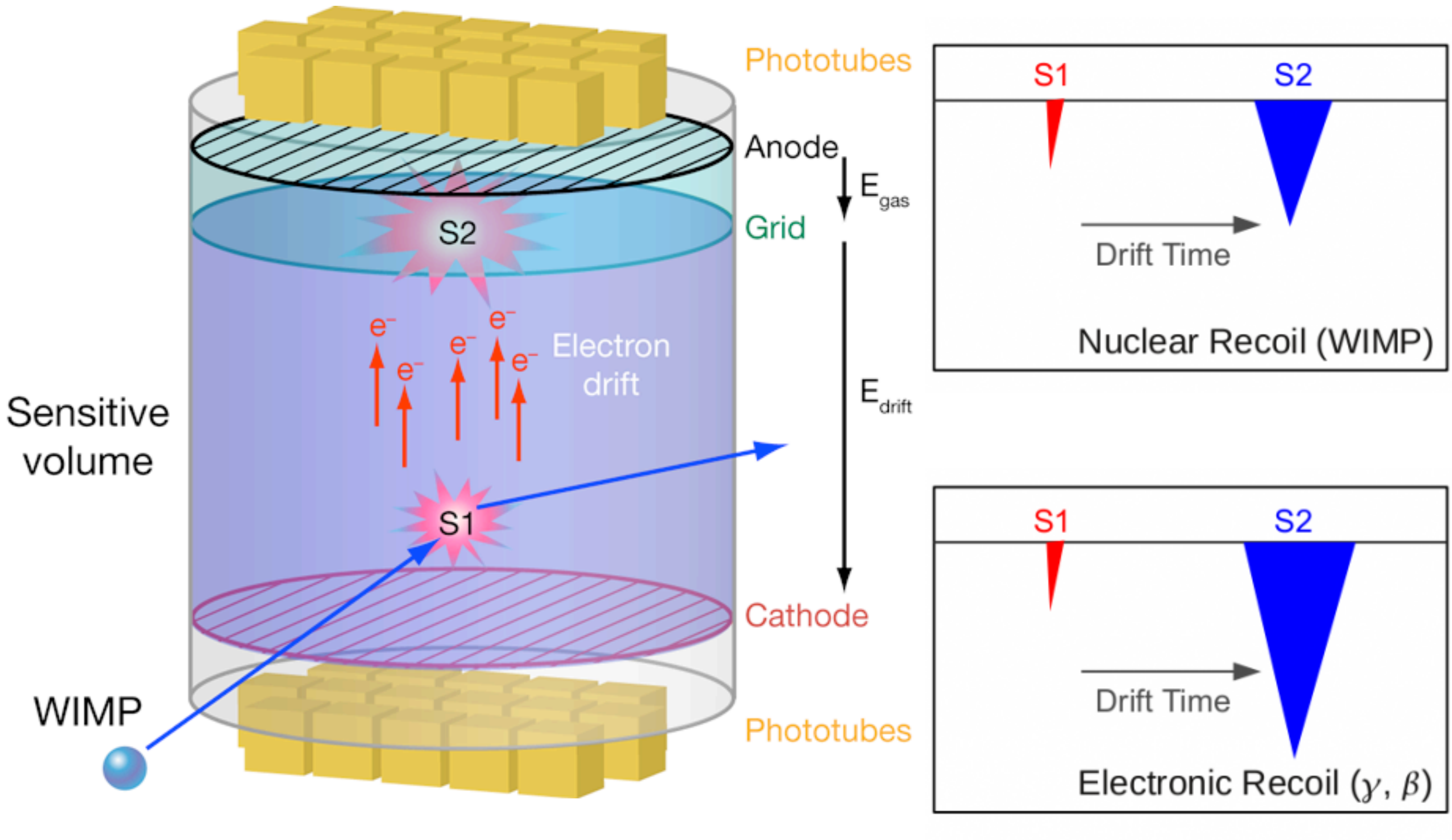
360 kg Mini-CLEAN



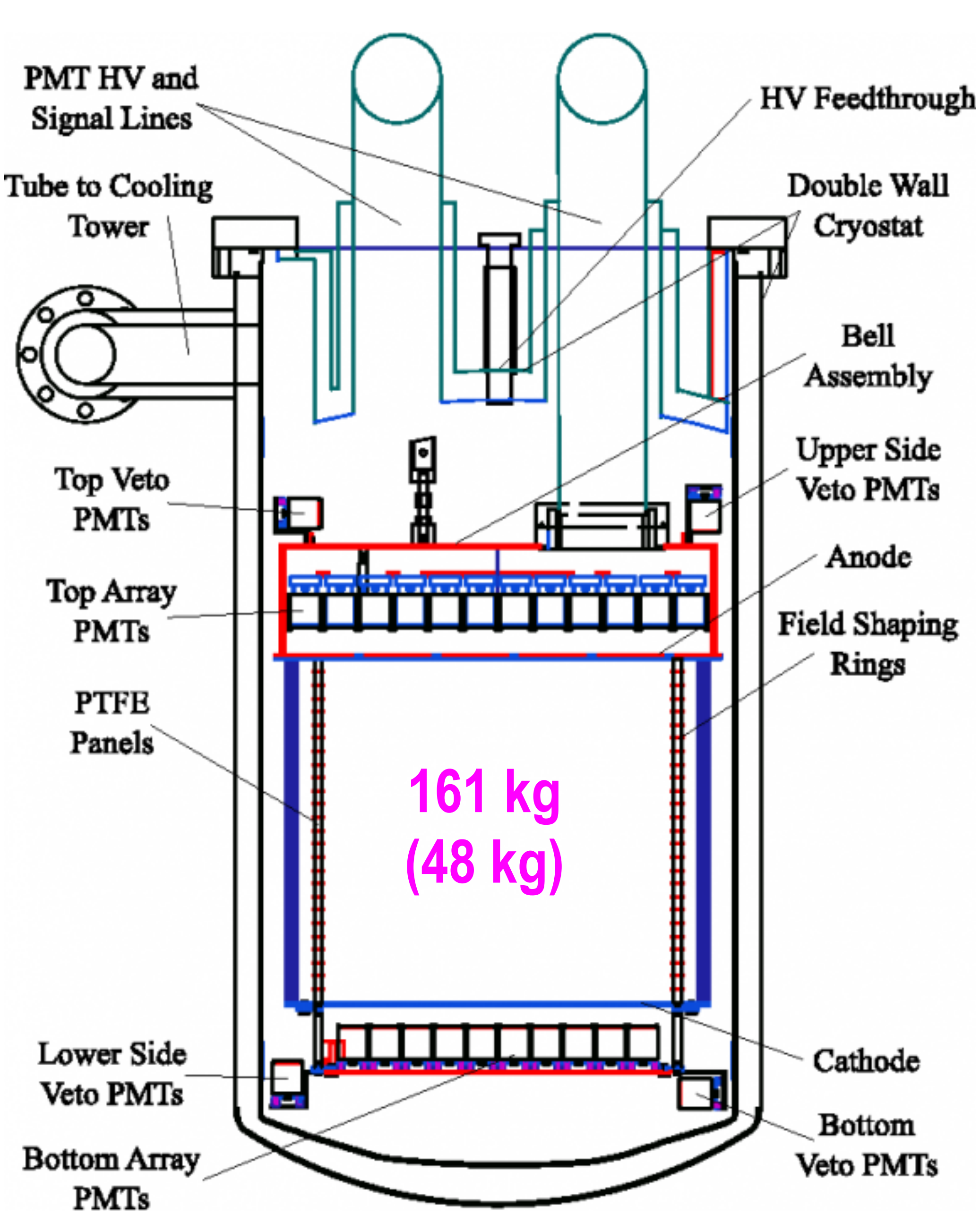
3.6 ton DEAP/CLEAN



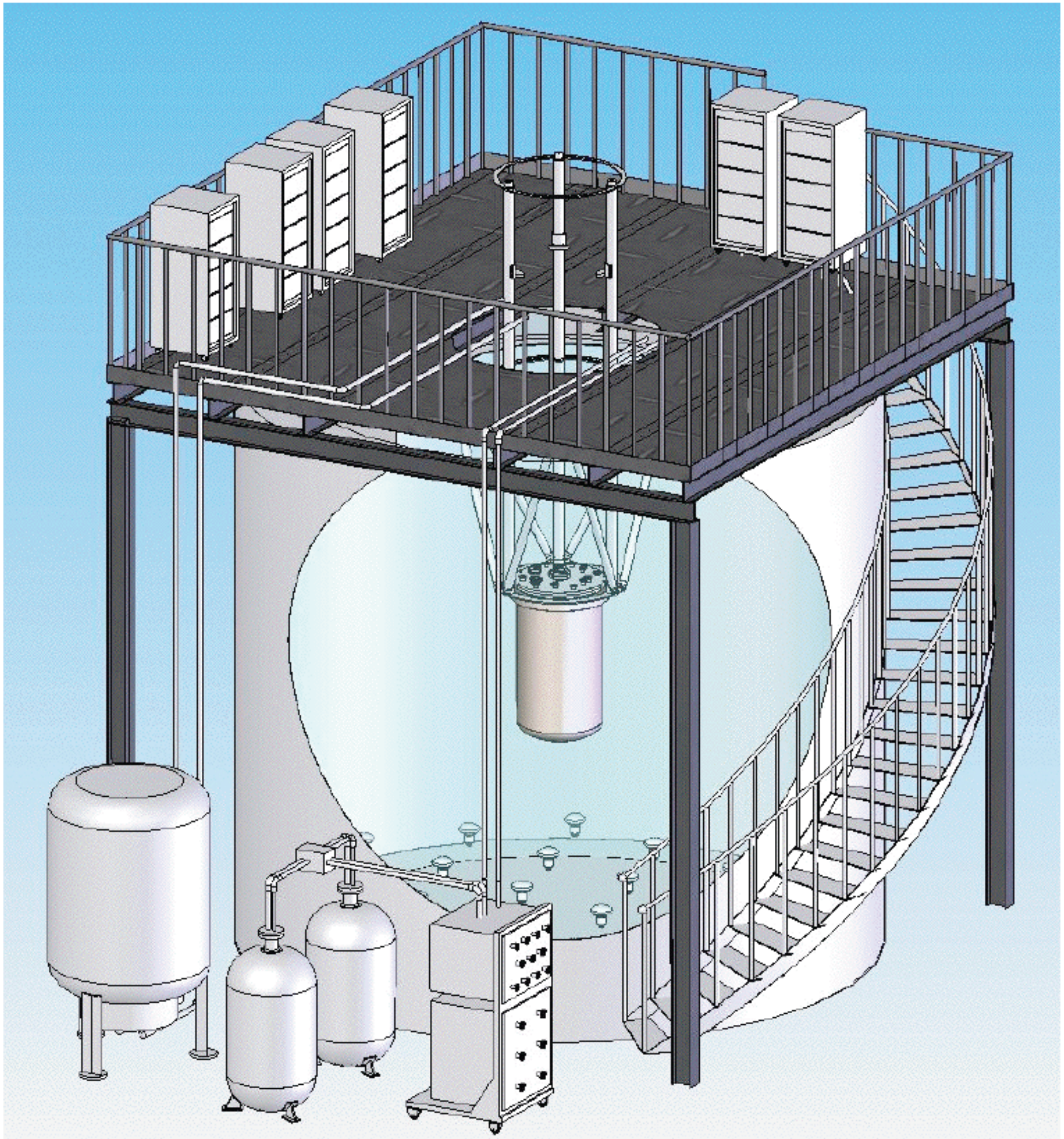
Double-Phase Noble Liquids

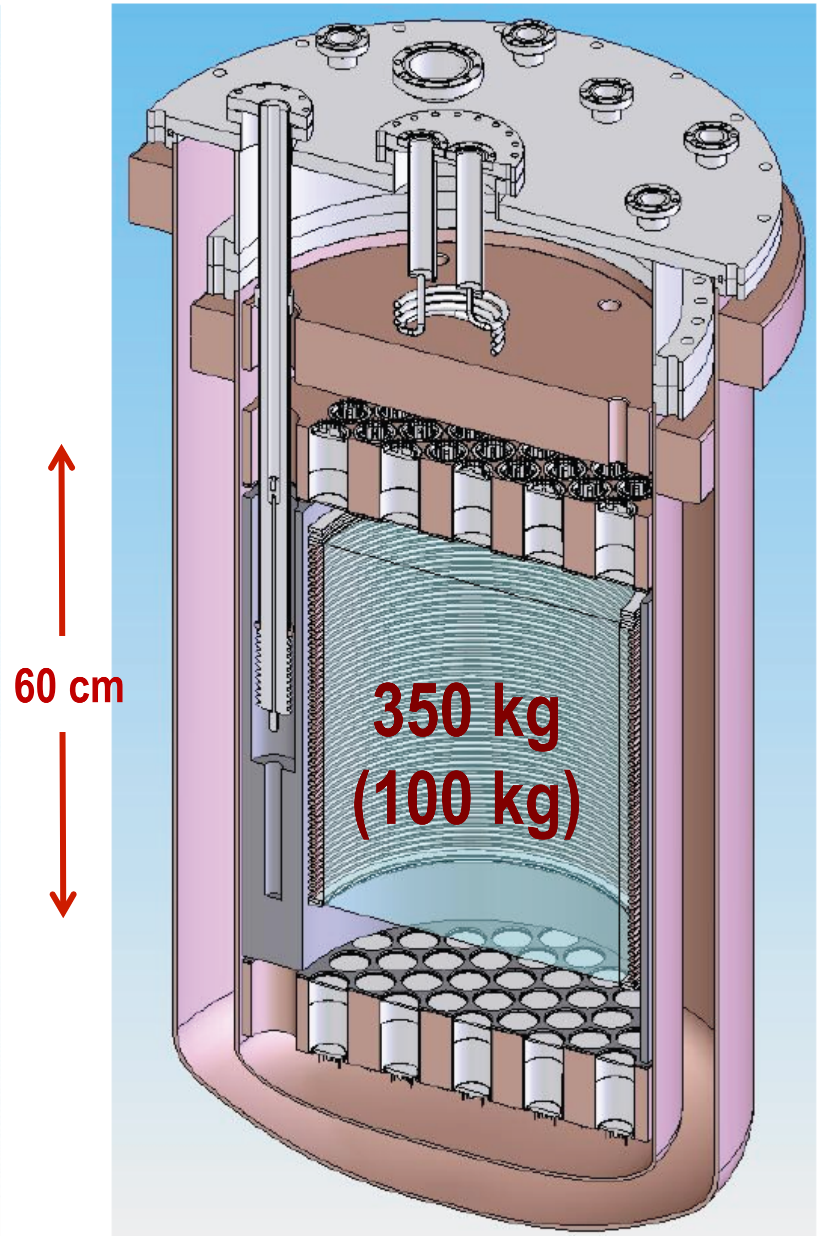


XENON100 Detector(Double phase Xenon)

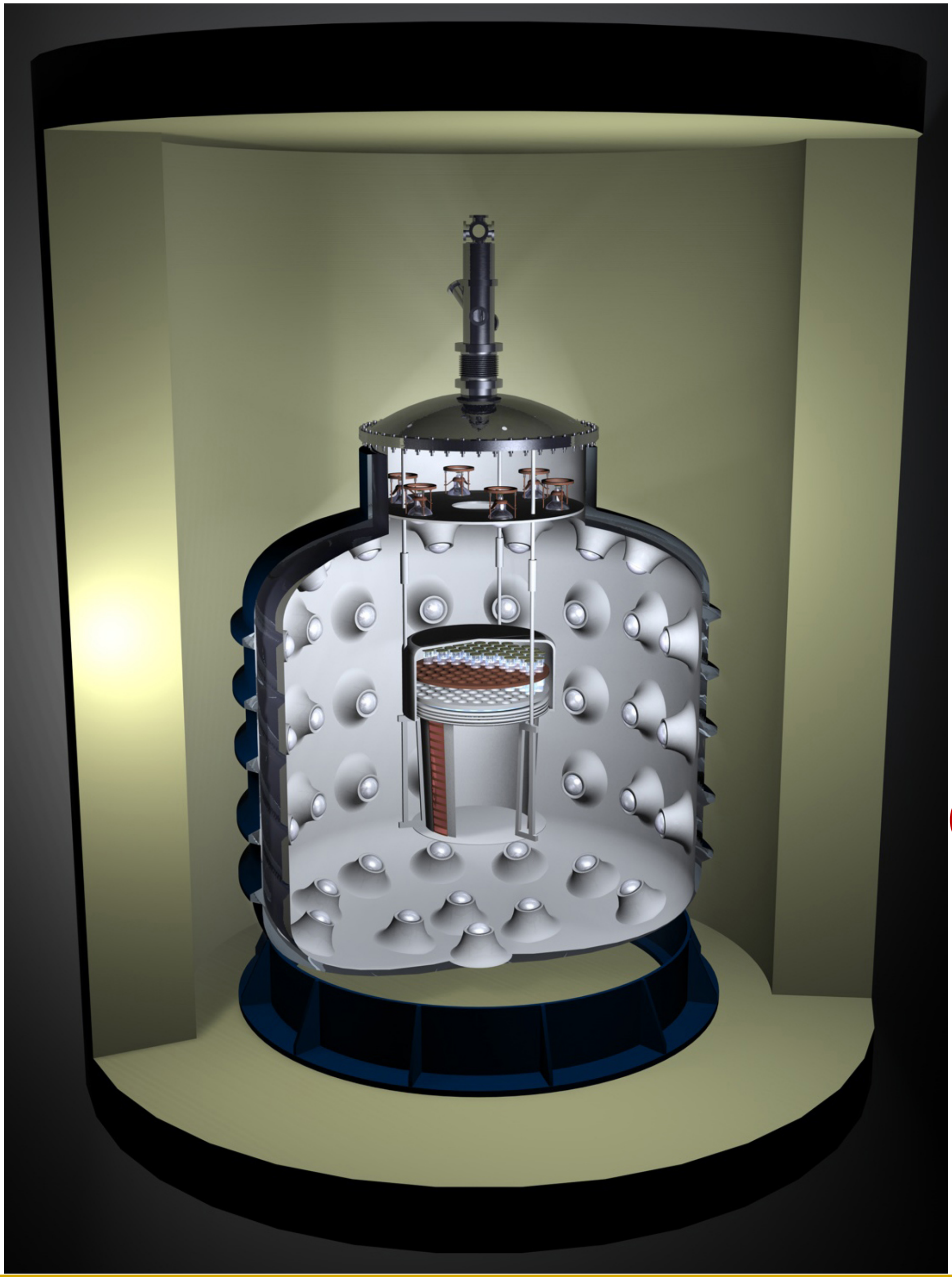


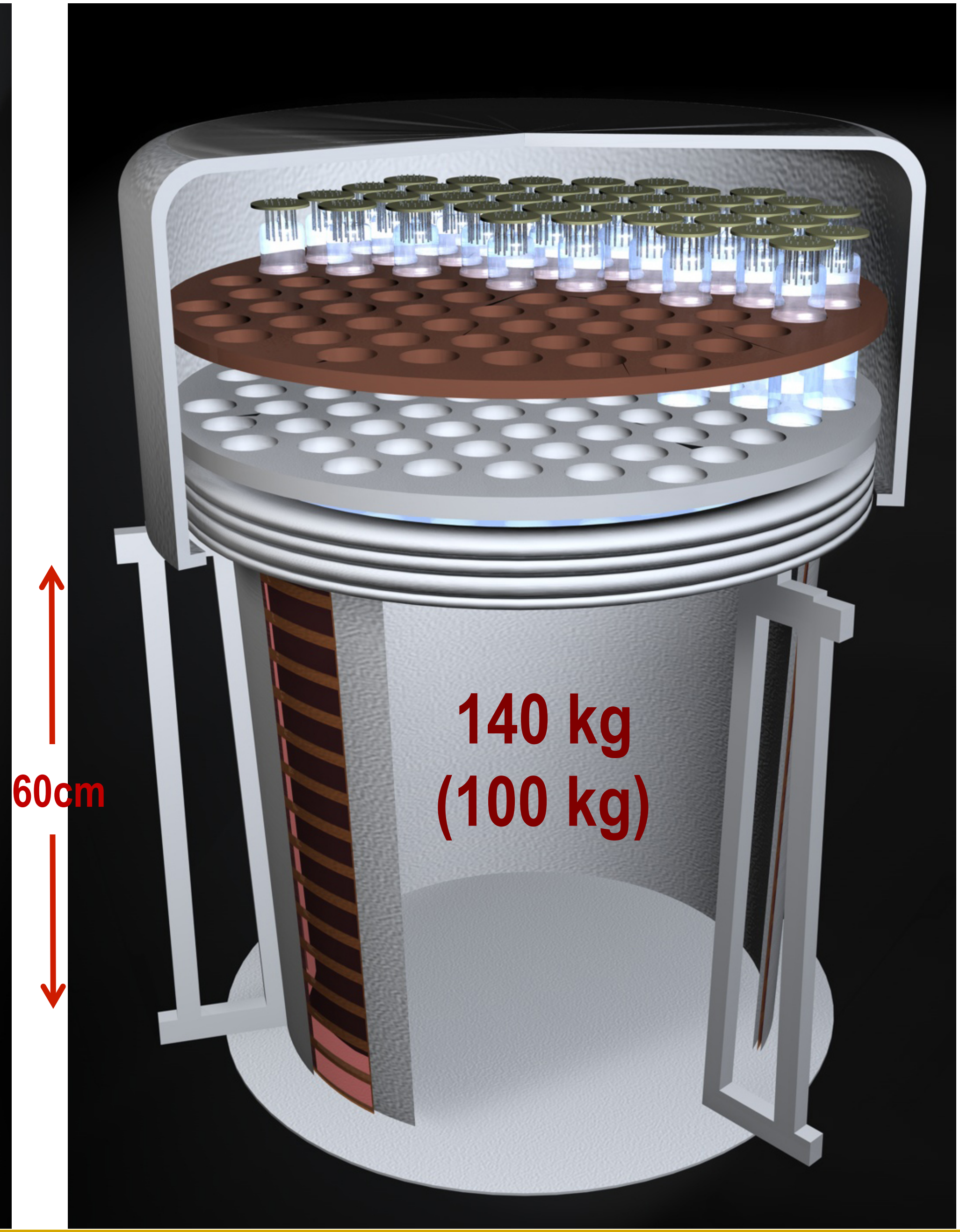
LUX 300 kg (Double phase Xenon)



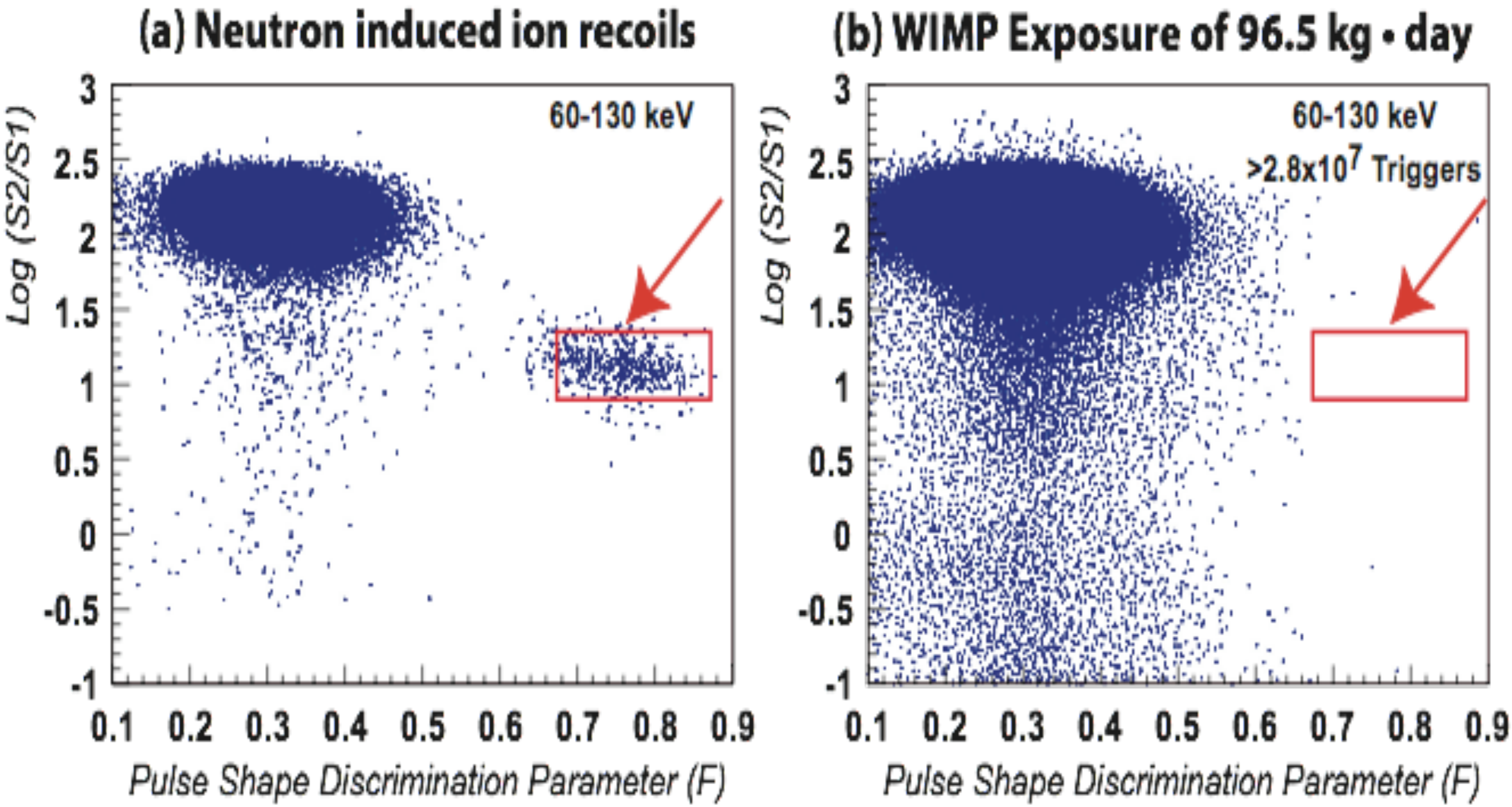


WARP 140 kg (Double Phase Argon)

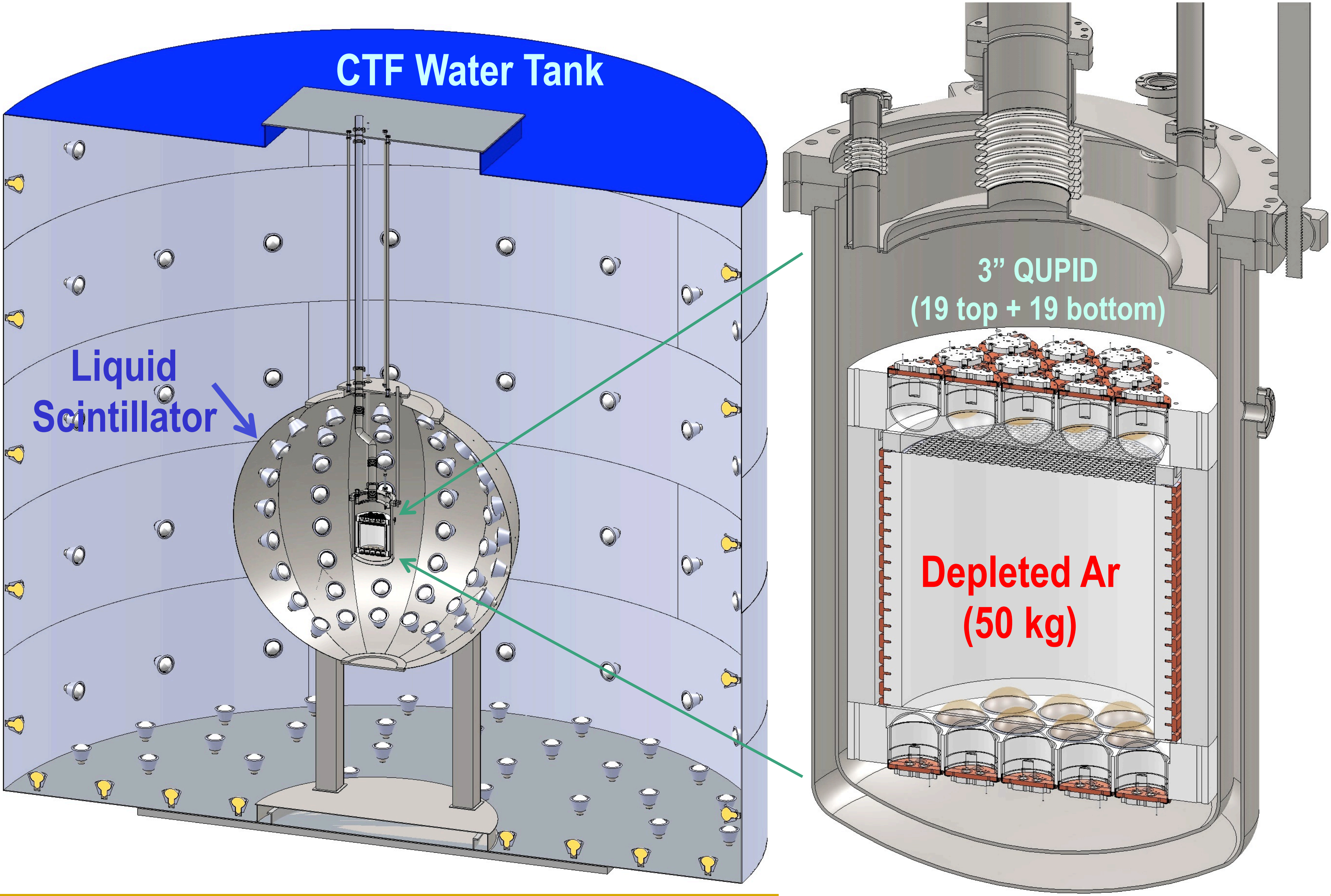




Pulse Shaping Discrimination by Ar



DarkSide 50 kg (Double phase Argon)



Comparison of G1 Experiments

Experiment Name	Location	Mass				Photon Detector				
		Target	Total	Fiducial	Phase	Type	Location	Size	Radioactivity	
			(kg)	(kg)				(inch)	(mBq / piece)	(mBq / cm^2)
XENON100	Gran Sasso	Xe	162	48	Double	R8520	Top/Bot.	1	1	0.2
XMASS	Kamioka	Xe	800	100	Single	R8778Hex	4π	2	5	0.2
LUX	DUSEL	Xe	350	100	Double	R8778	Top/Bot.	2	20	0.8
Mini-CLEAN	SNO	Ar	360	100	Single	8" PMT	4π	8	500	1.5
WARP	Gran Sasso	Ar	140	100	Double	3" PMT	Top	3	200	4.4
DarkSide 50	Gran Sasso	Ar	60	50	Double	3" QUPID	Top/Bot.	3	1	0.02

Single Phase vs. Double Phase

	Single Phase	Double Phase
HV for electron drift	Not required	Required (~1 kV/cm)
O_2 / H_2O impurity	Not critical	Critical
Energy threshold	20 PE	4 PE
Sensitivity for low mass WIMP	> 20 GeV	> 5 GeV
Position resolution	~ 10 cm	~ 2 mm
Gamma rejection by S2/S1	No	Yes (> 99.5%)
Neutron rejection by Multi-hit cut	No	Yes

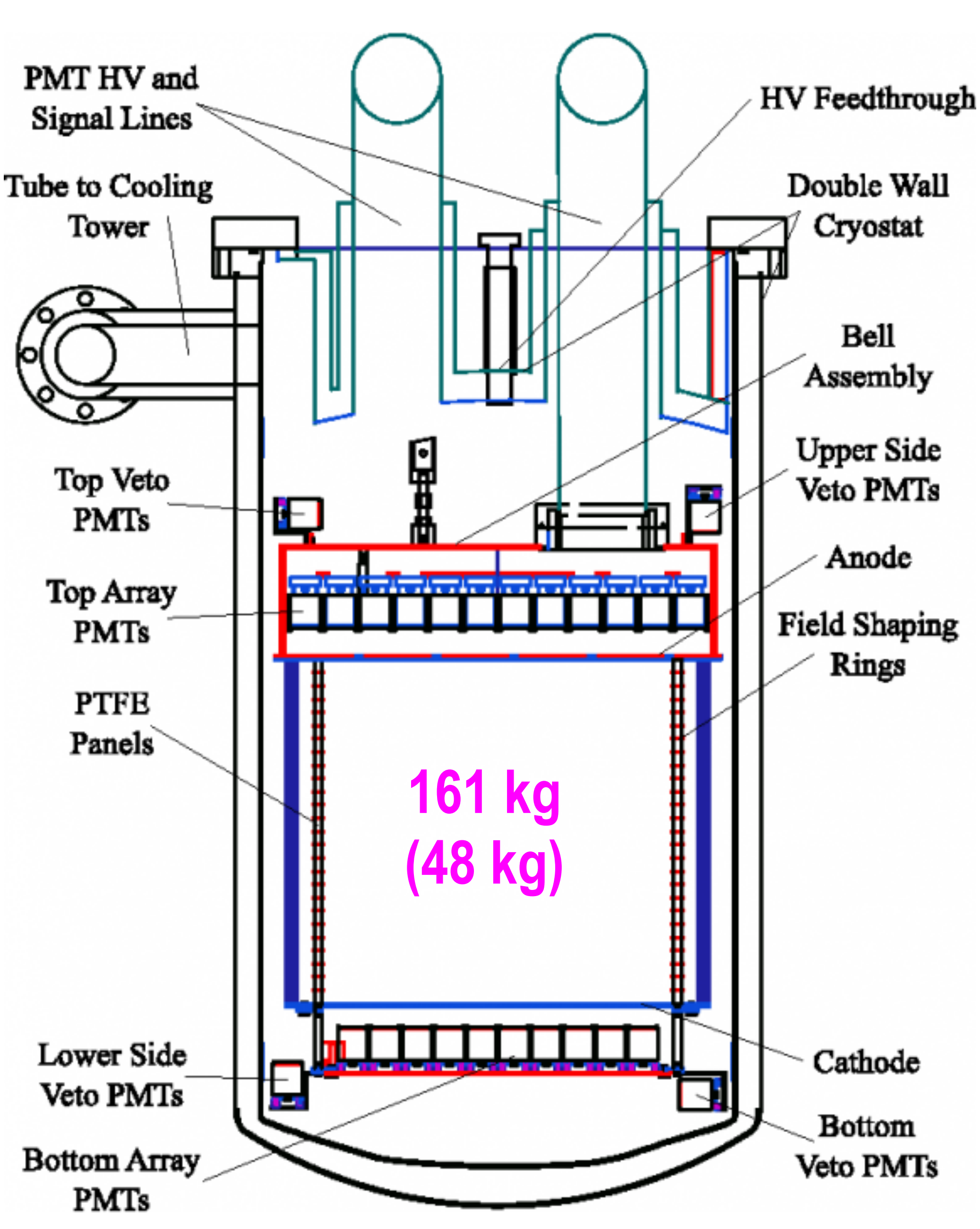
Summary on "Xenon vs. Argon"

- **Xenon**
  - 5 times more sensitive (per unit mass)
    - due to A^2 dependence.
  - Ideal for mass range of 10 – 100 GeV
    - Spectrum is independent from mass
  - Expensive
    - ~$1M / ton
  - Limited by
    - pp-chain solar neutrino : 0.1 event / ton-year
    - ^{136}Xe Double beta decay: 0.1 event / ton-year
    - ^{85}Kr : 1 ppt → 0.2 event / ton-year

- **Argon**
  - Free from gamma background
    - > 10^6 rejection by pulse shaping
  - Ideal for mass range of 20 – 200 GeV
    - Insensitive to low mass < 10 GeV
  - ^{39}Ar is the major source of radioactivity

XENON100
The 1st G1 Experiment

XENON100 Detector



XENON100 Detector

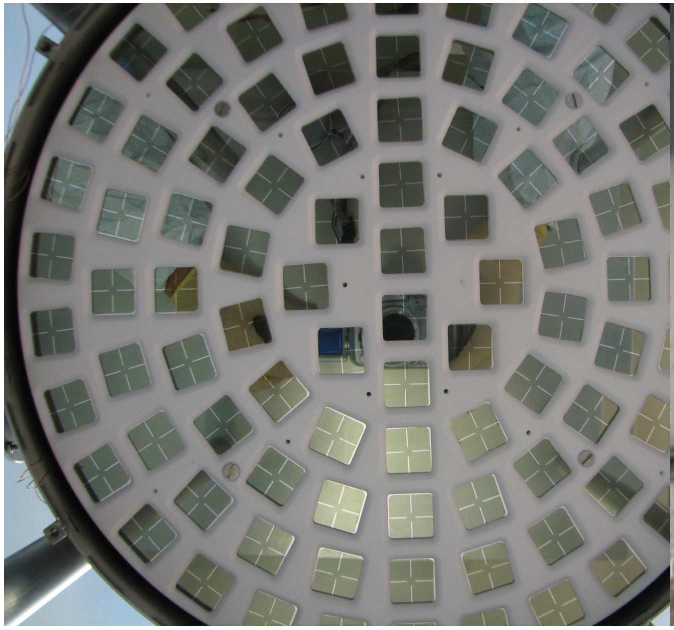
PMT Arrays

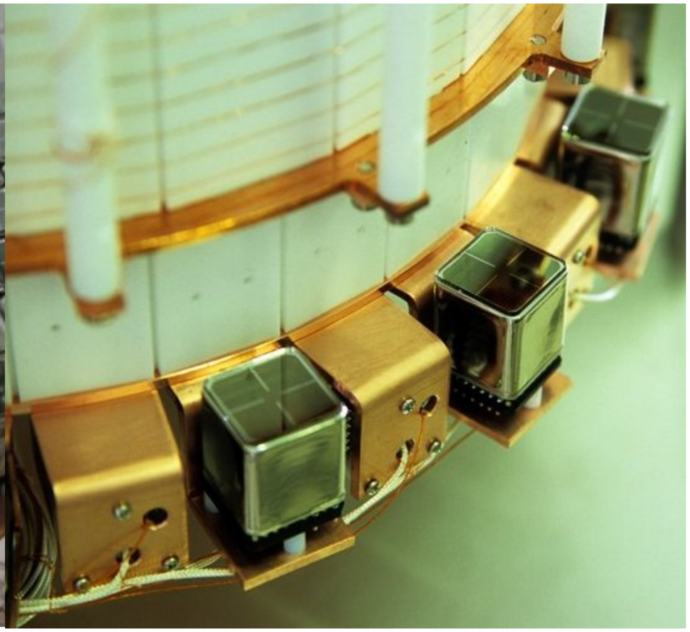
242 Hamamatsu R8520 PMTs

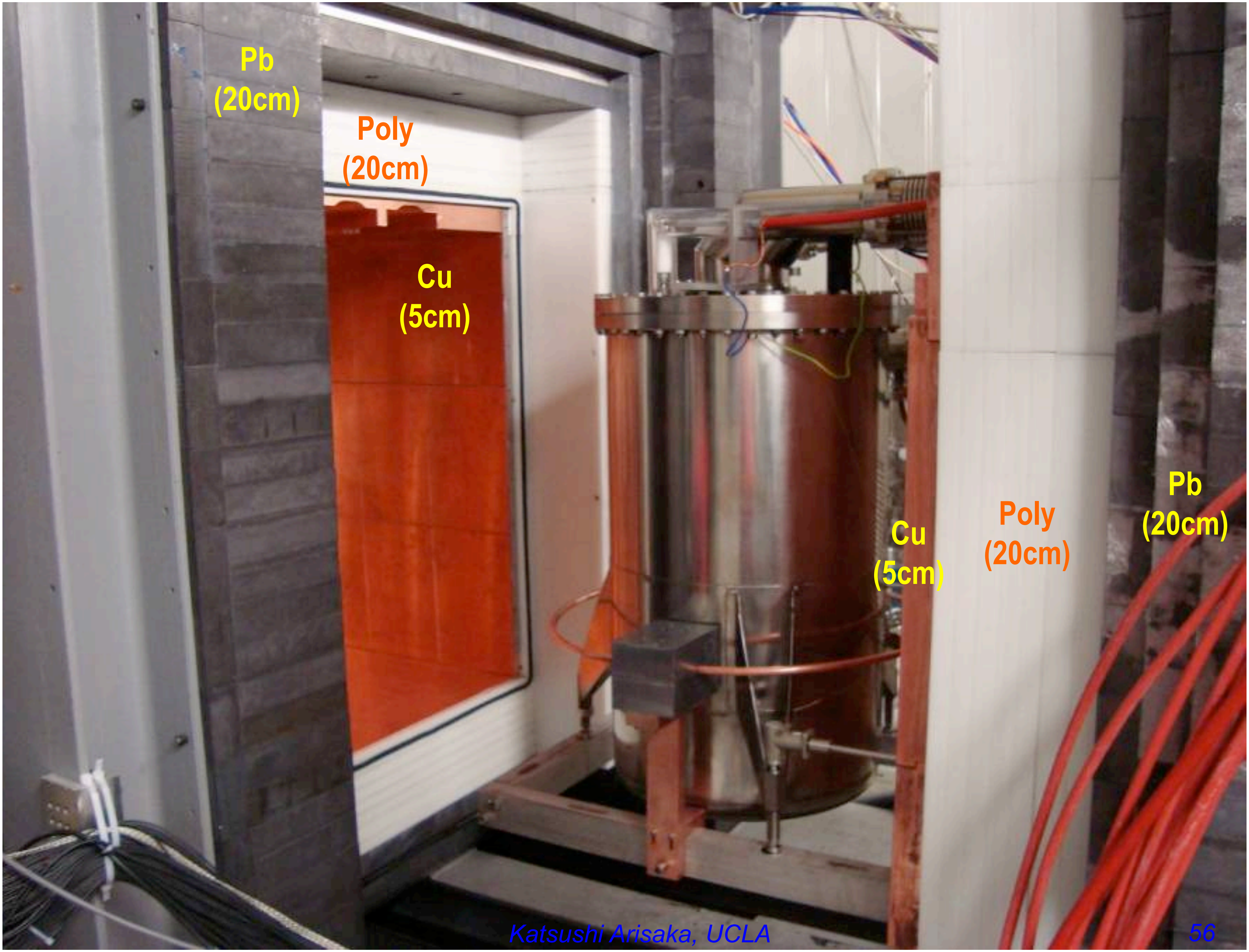
1"x1", optimized for response @ Xe scintillation light (178 nm)

Low radioactivity (~ <1 mBq/PMT)

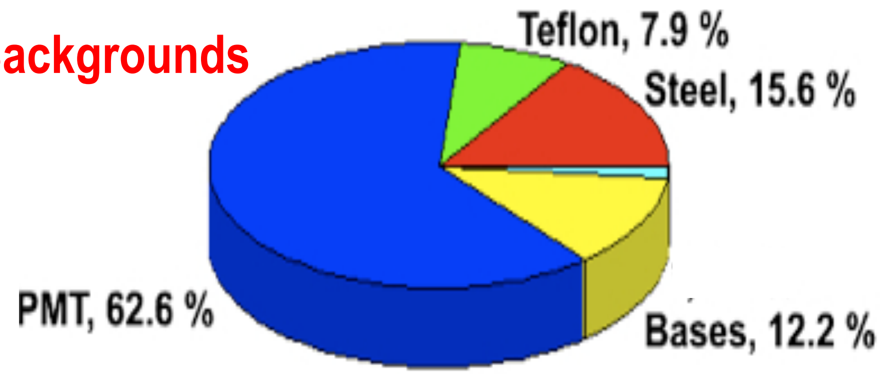
Top Array	Bottom Array	Active Veto
98 PMTs	80 PMTs	64 PMTs
~23% QE	~33% QE	~23% QE



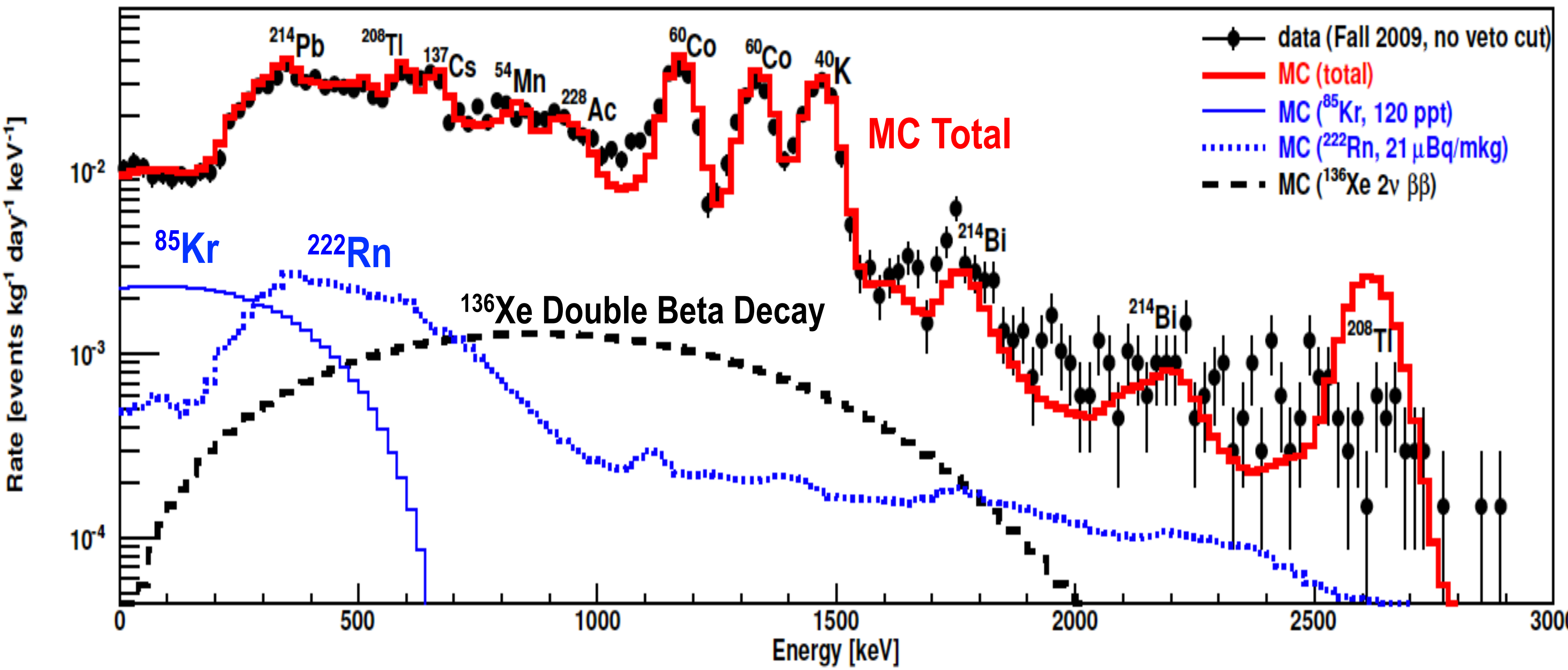



Pb
(20cm)
Poly
(20cm)
Cu
(5cm)
Cu
(5cm)
Poly
(20cm)
Pb
(20cm)

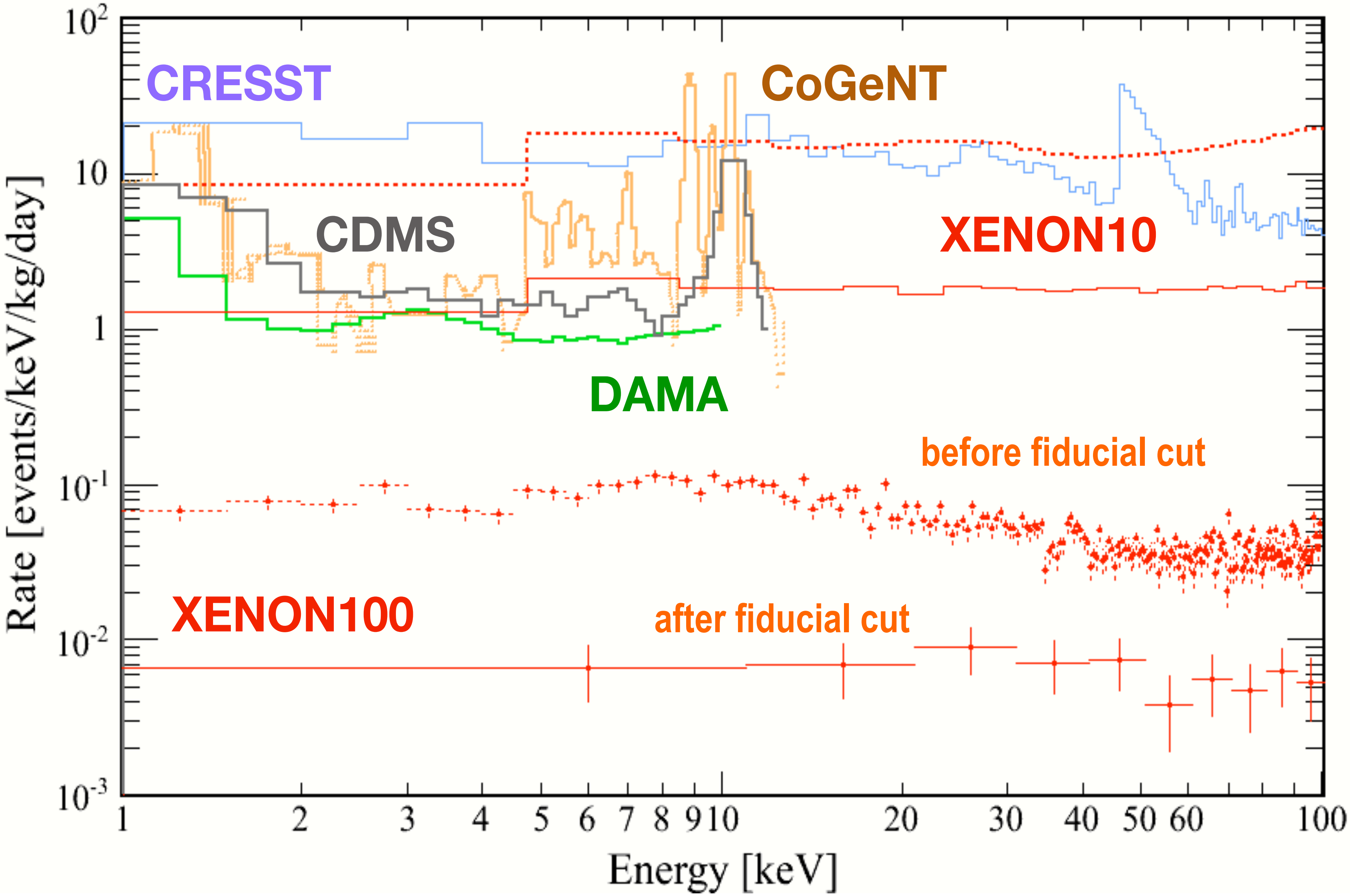
Energy Spectrum of Real Data vs. MC



arXiv:1101.3866



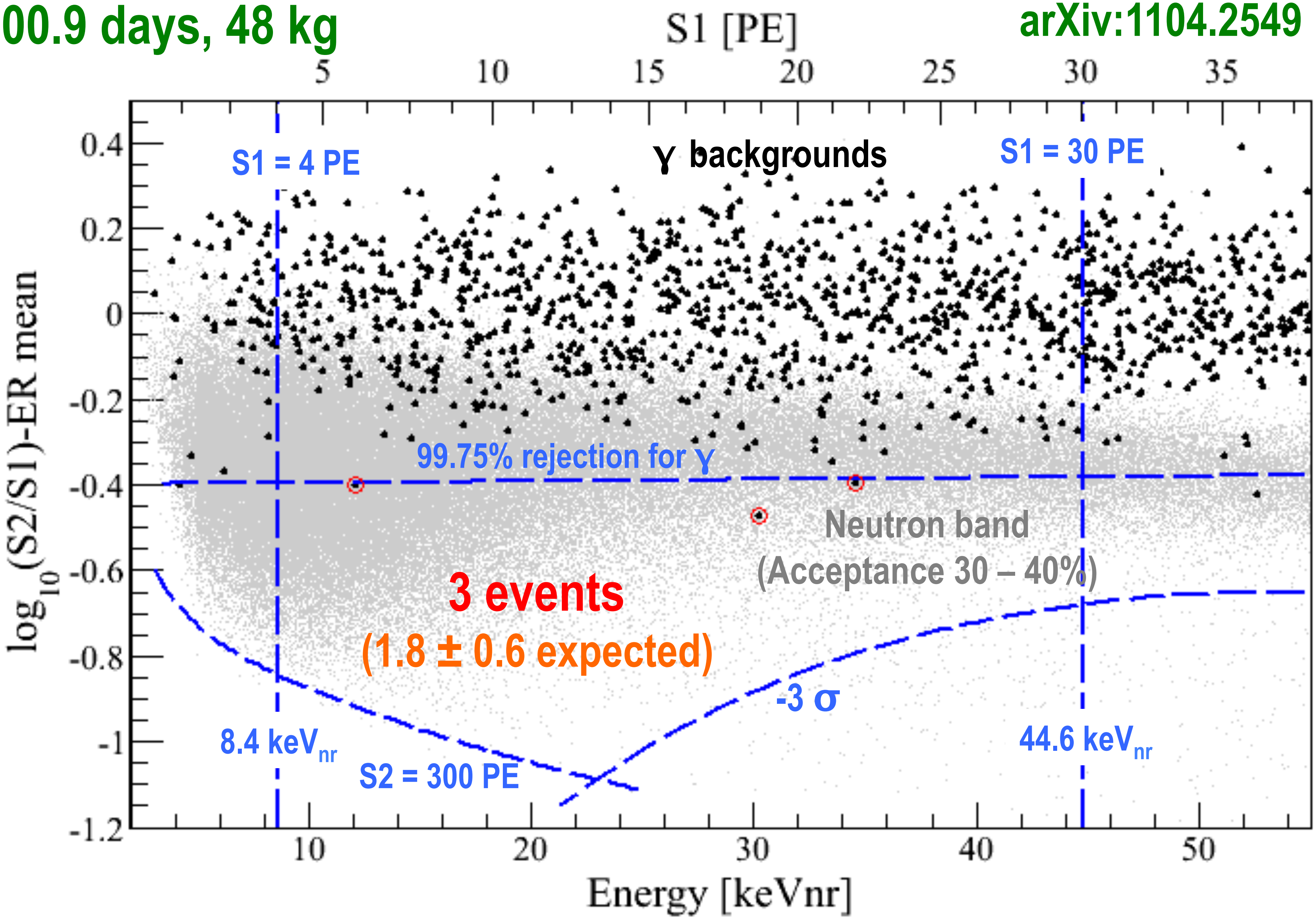
Level of Backgrounds (before S2/S1 cut)



Log(S2/S1) vs. Energy

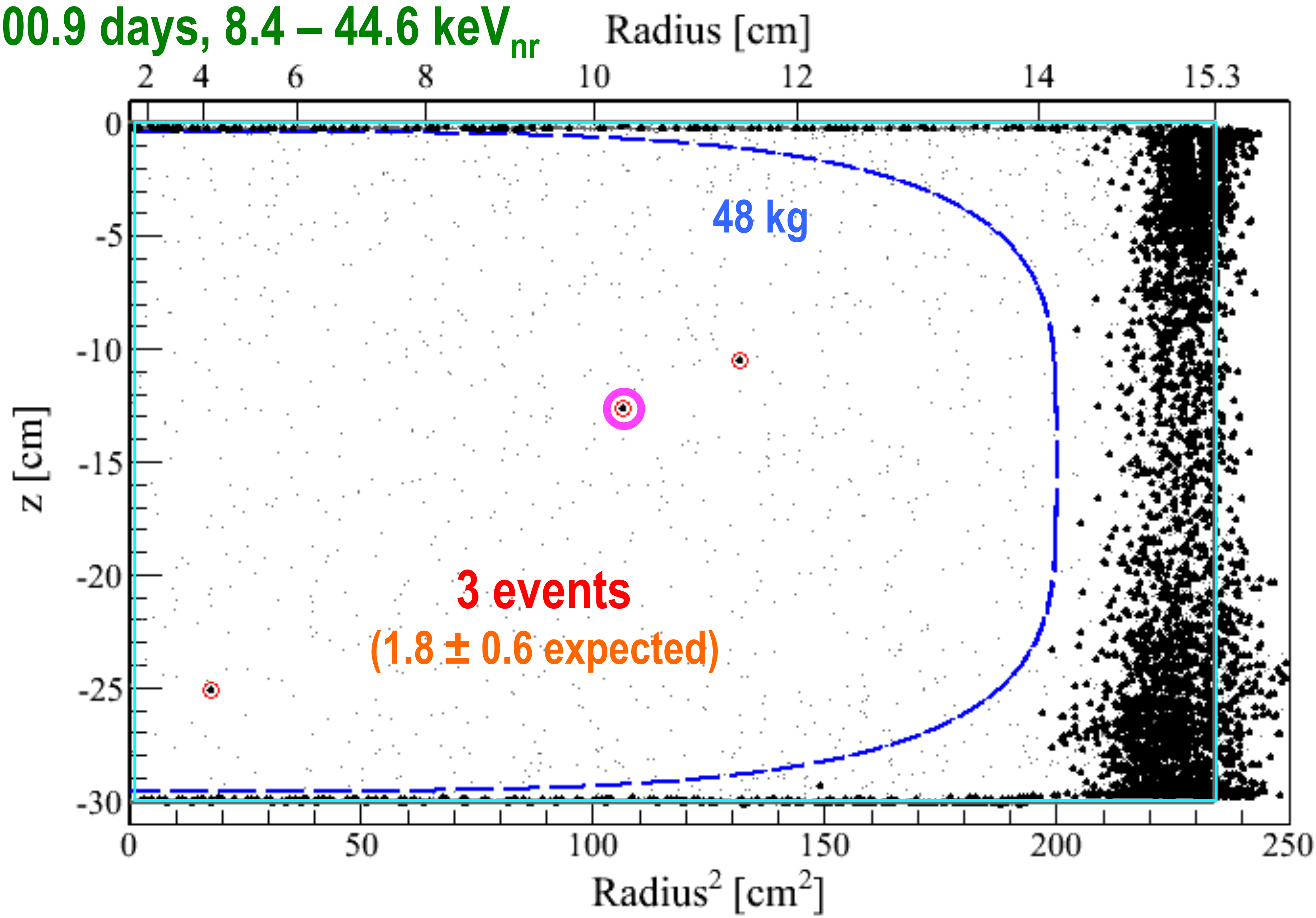
100.9 days, 48 kg

arXiv:1104.2549

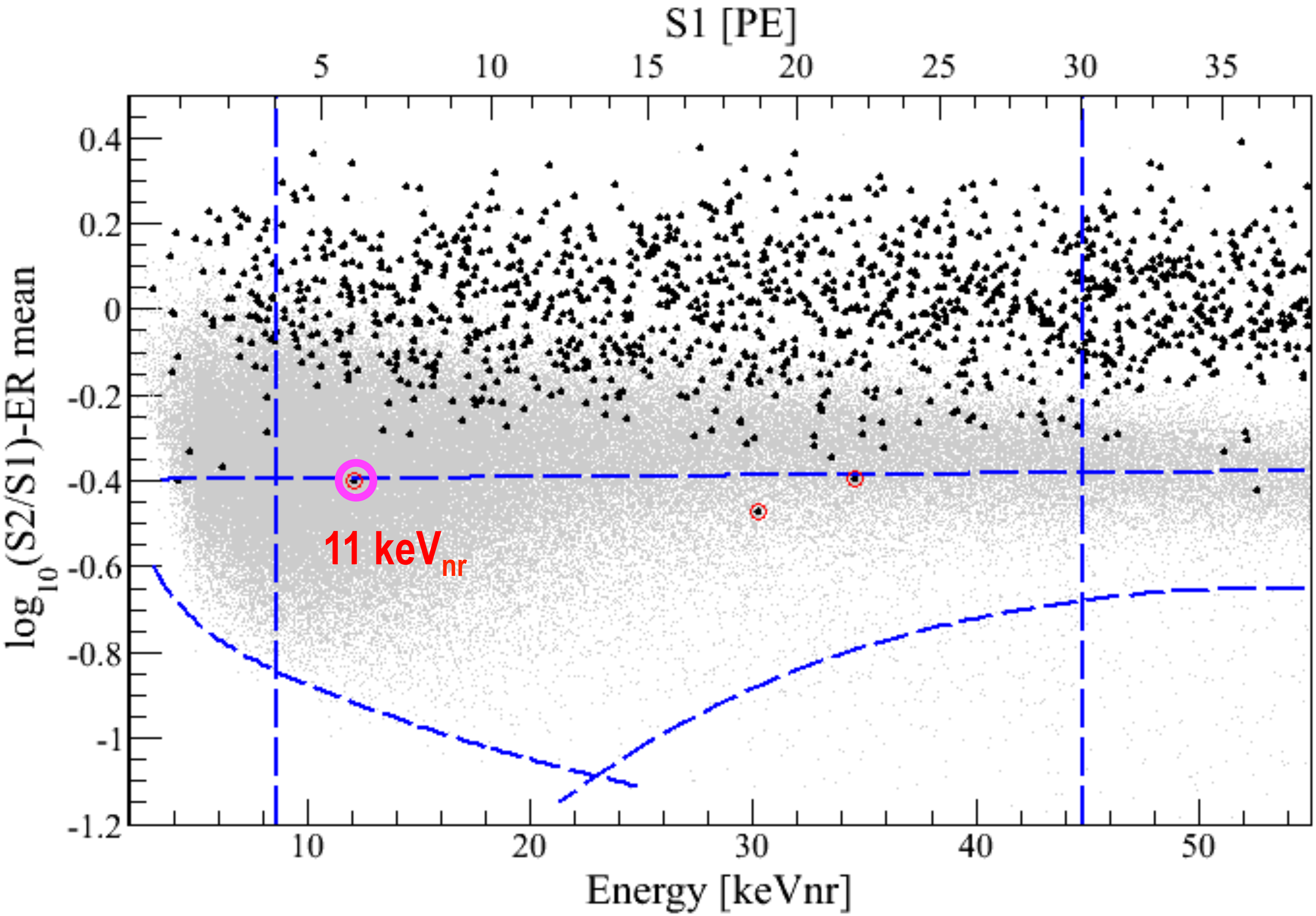


Event distribution in z vs. R^2

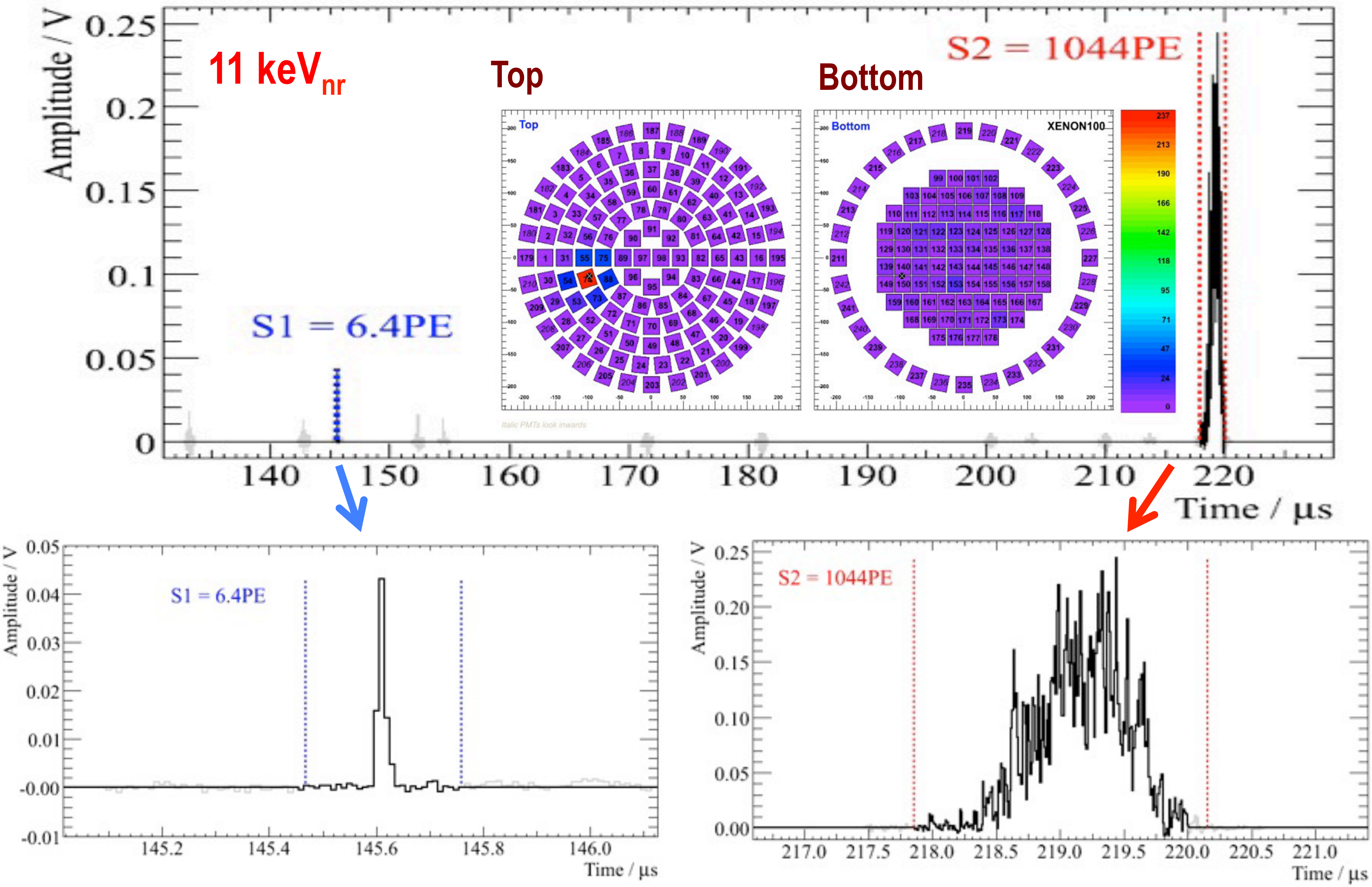
100.9 days, 8.4 – 44.6 keV_{nr}



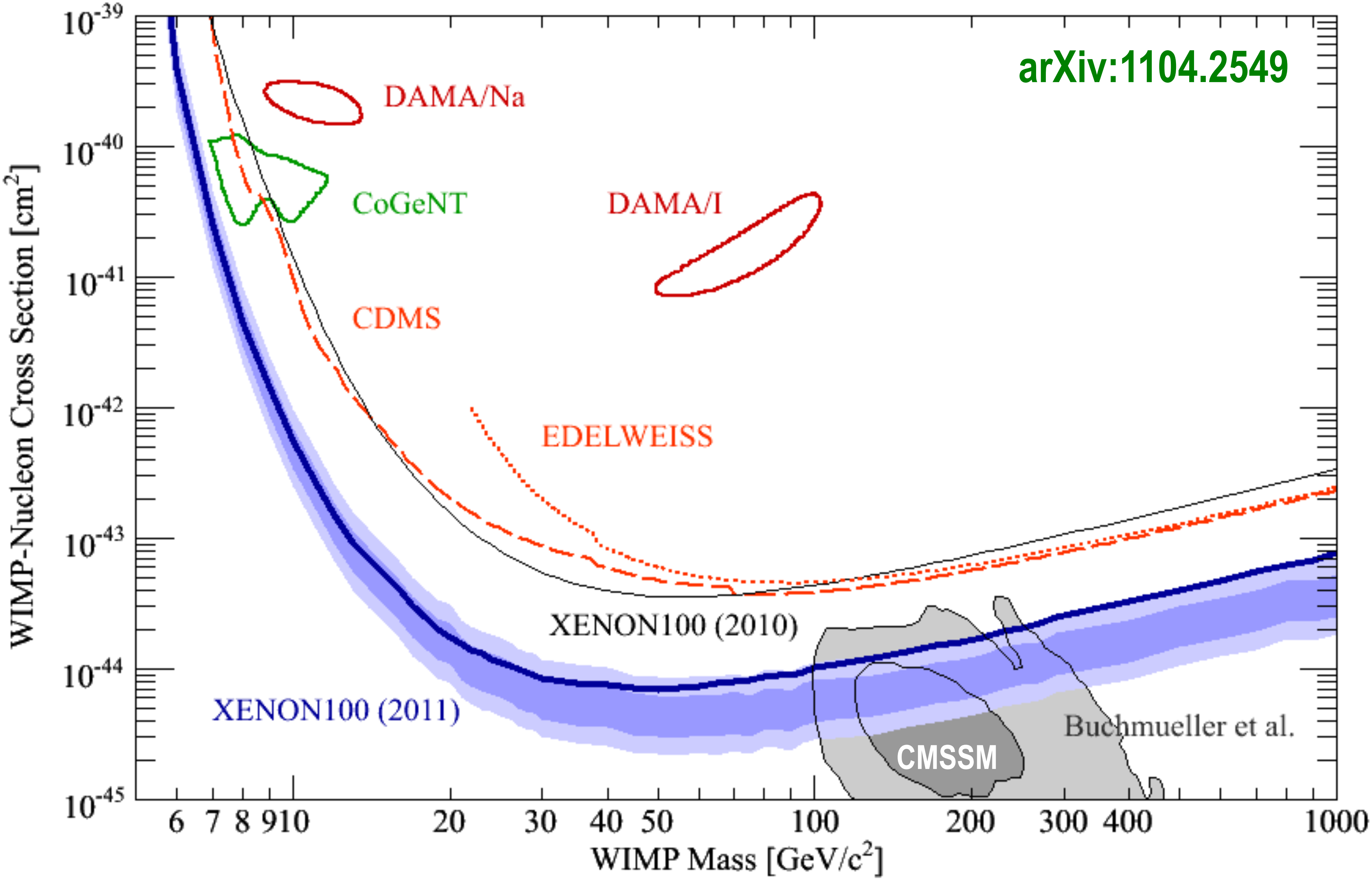
Log(S2/S1) vs. Energy



Single Scatter Nuclear Recoil Event Candidate



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



Summary of XENON100

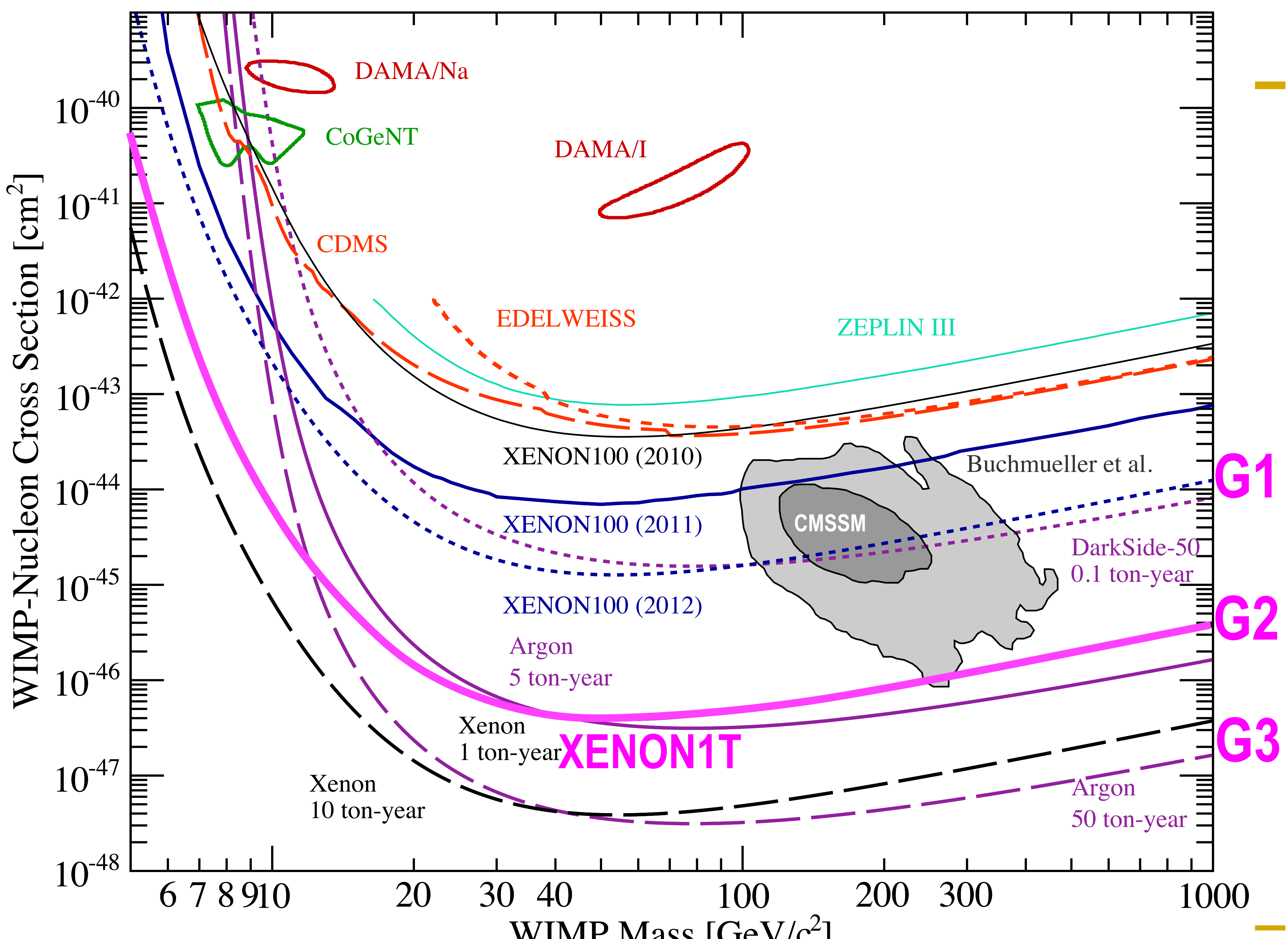
- Purity of Xenon has achieved the design goal.

	Actual	Goal	
Light Yield:	2.2	> 2	pe/keVee
Electron Drift Time:	400	> 300	μs
Krypton 85:	80	< 100	ppt
Radon:	1.1	< 2	Bq/m^3

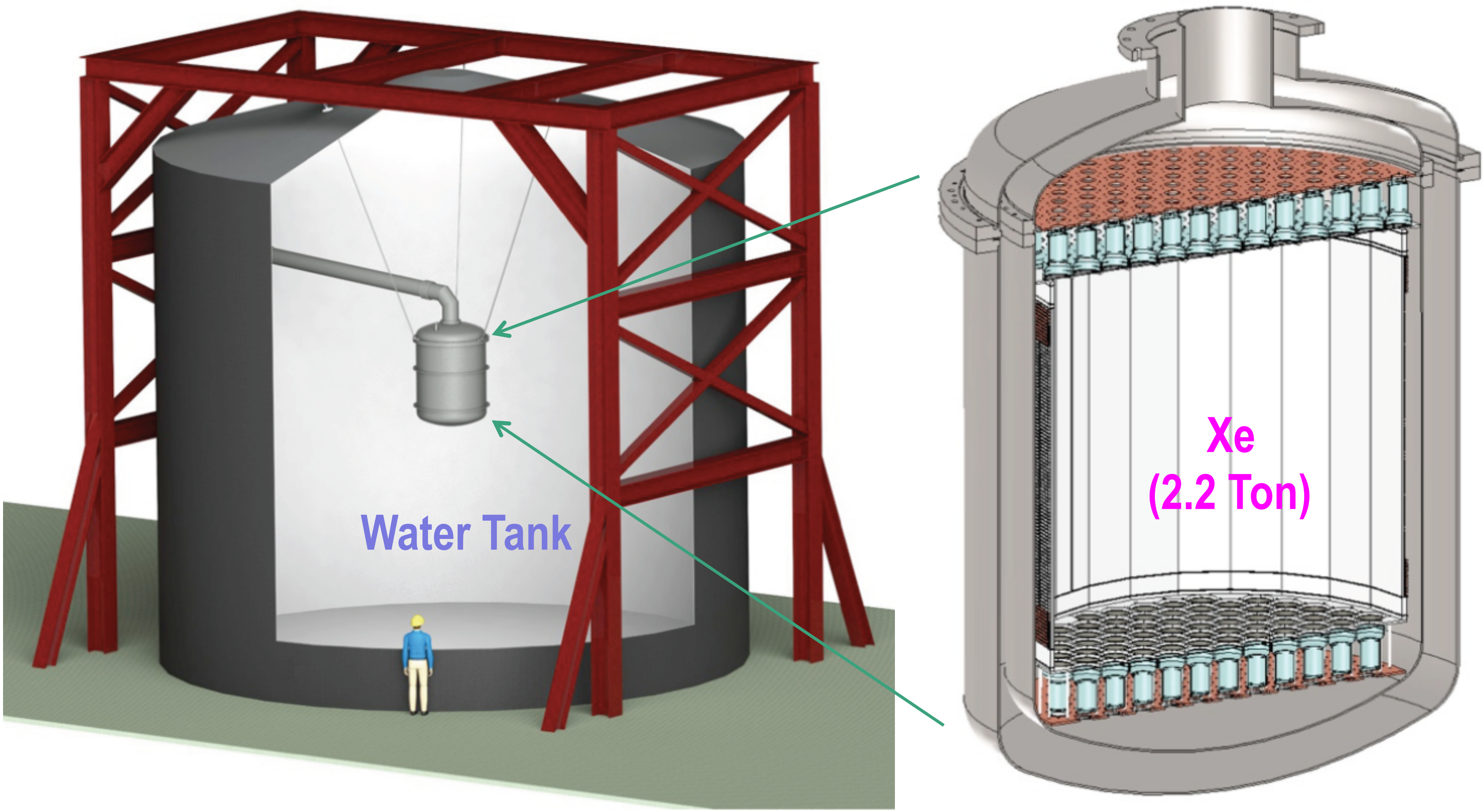
- 100 days of data published.
  - 3 event observed (1.8 +- 0.6 events expected)
    - Contaminated by ^{85}Kr at ~ 700 ppt → 1.1 events
  - < 7 x 10^{-45} cm^2 at 50 GeV arXiv:1104.2549
  - Low mass (7-10 GeV) WIMP unlikely.
  - Inelastic DM excluded. arXiv:1104.3121

- Data taking continues.
  - ^{85}Kr reduced to < 80 ppt
  - < 2 x 10^{-45} cm^2 by the end of 2011 expected.

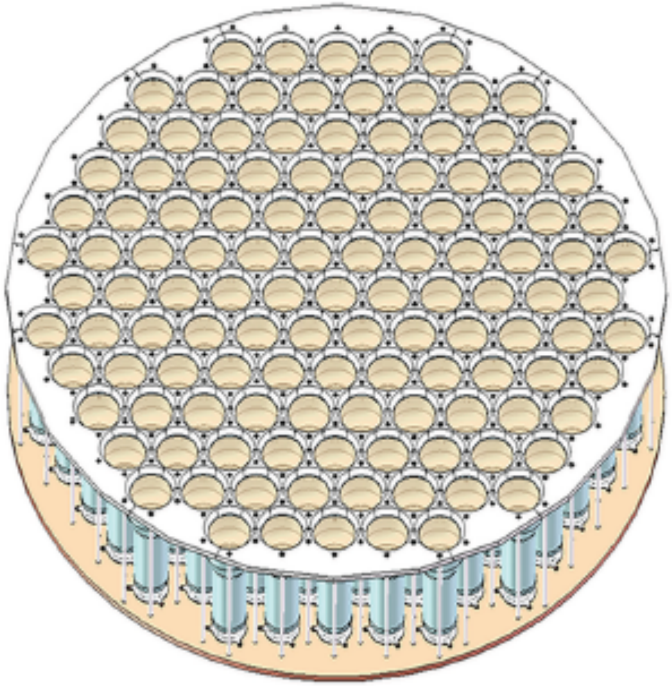
XENON1T
The 1st G2 Experiment

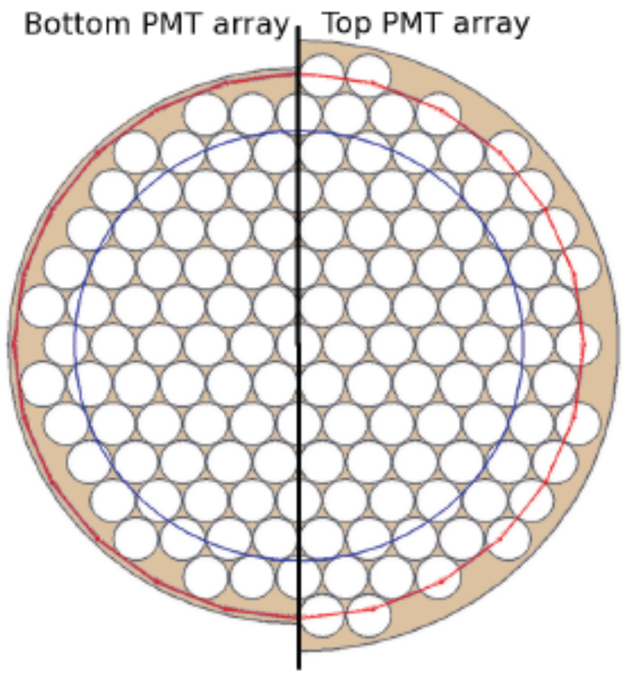

DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
ZEPLIN III
XENON100 (2010)
XENON100 (2011)
XENON100 (2012)
Buchmueller et al.
CMSSM
DarkSide-50
0.1 ton-year
Argon
5 ton-year
Xenon
1 ton-year
XENON1T
Xenon
10 ton-year
Argon
50 ton-year
G1
G2
G3
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-40}
10^{-41}
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

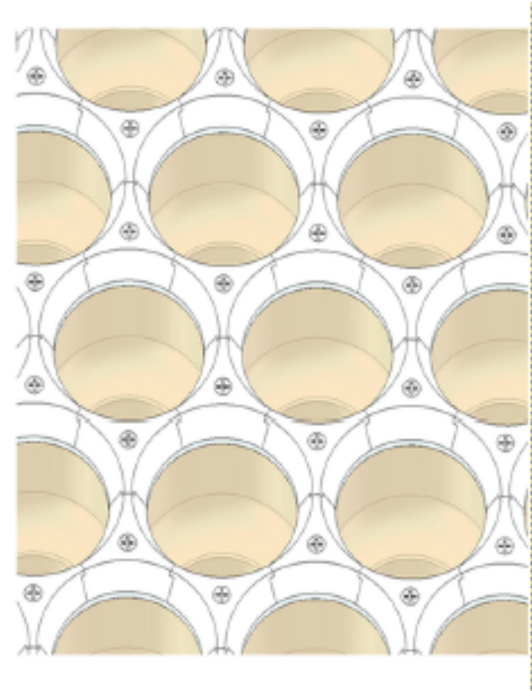
XENON1T (G2) at LNGS

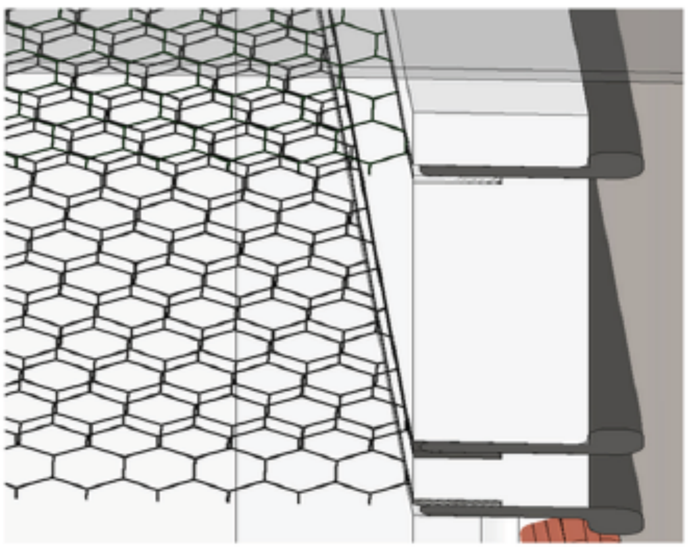


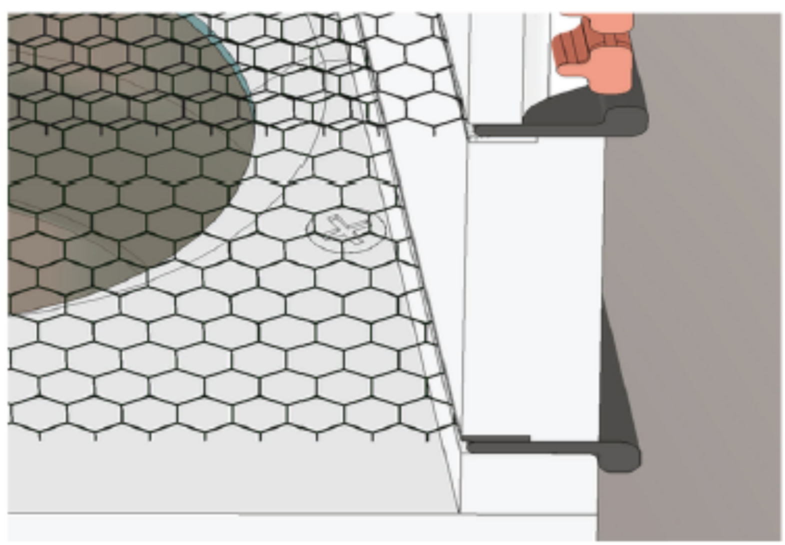
XENON1T Detector Structure



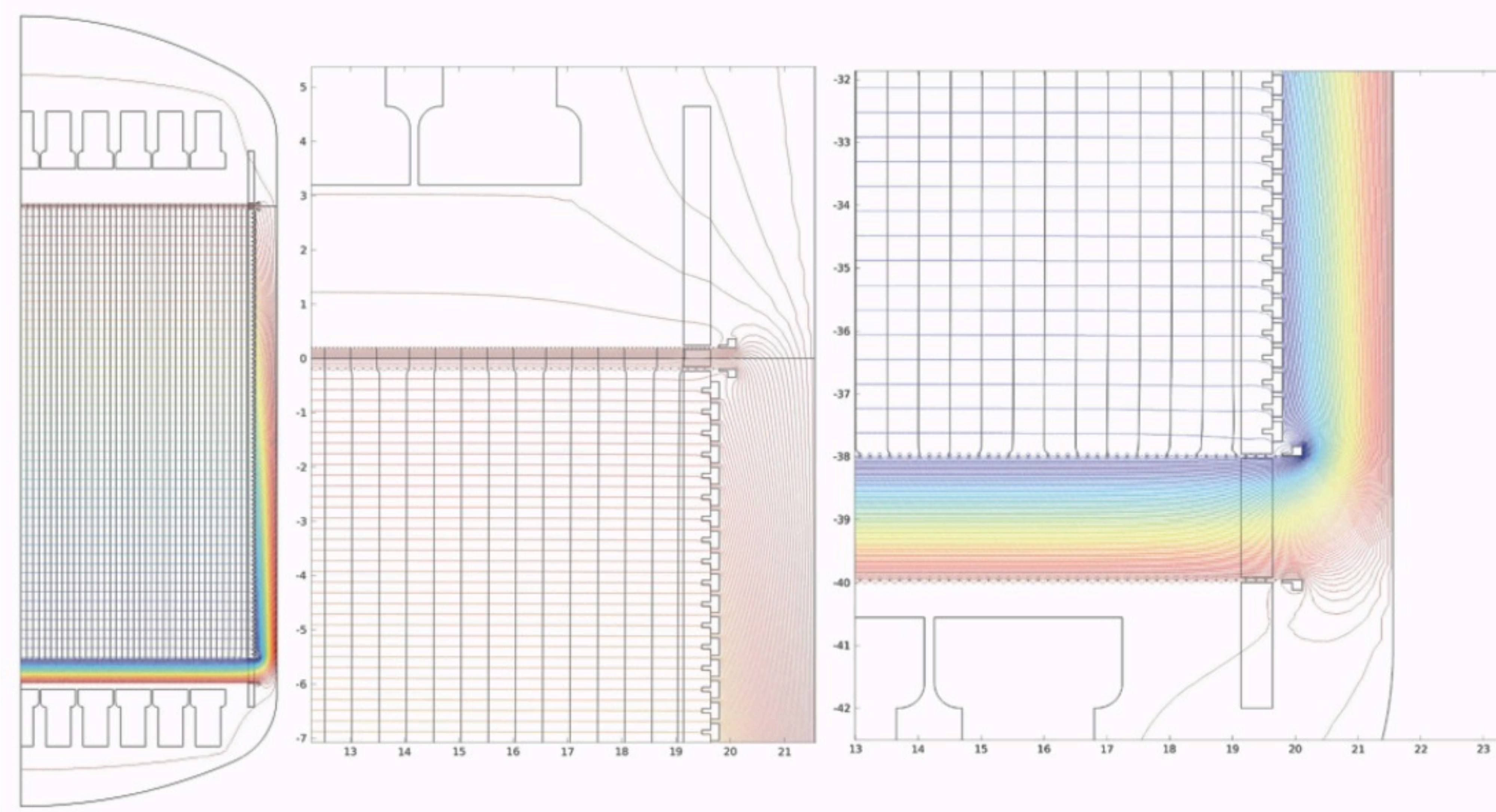








Electric Field of TPC

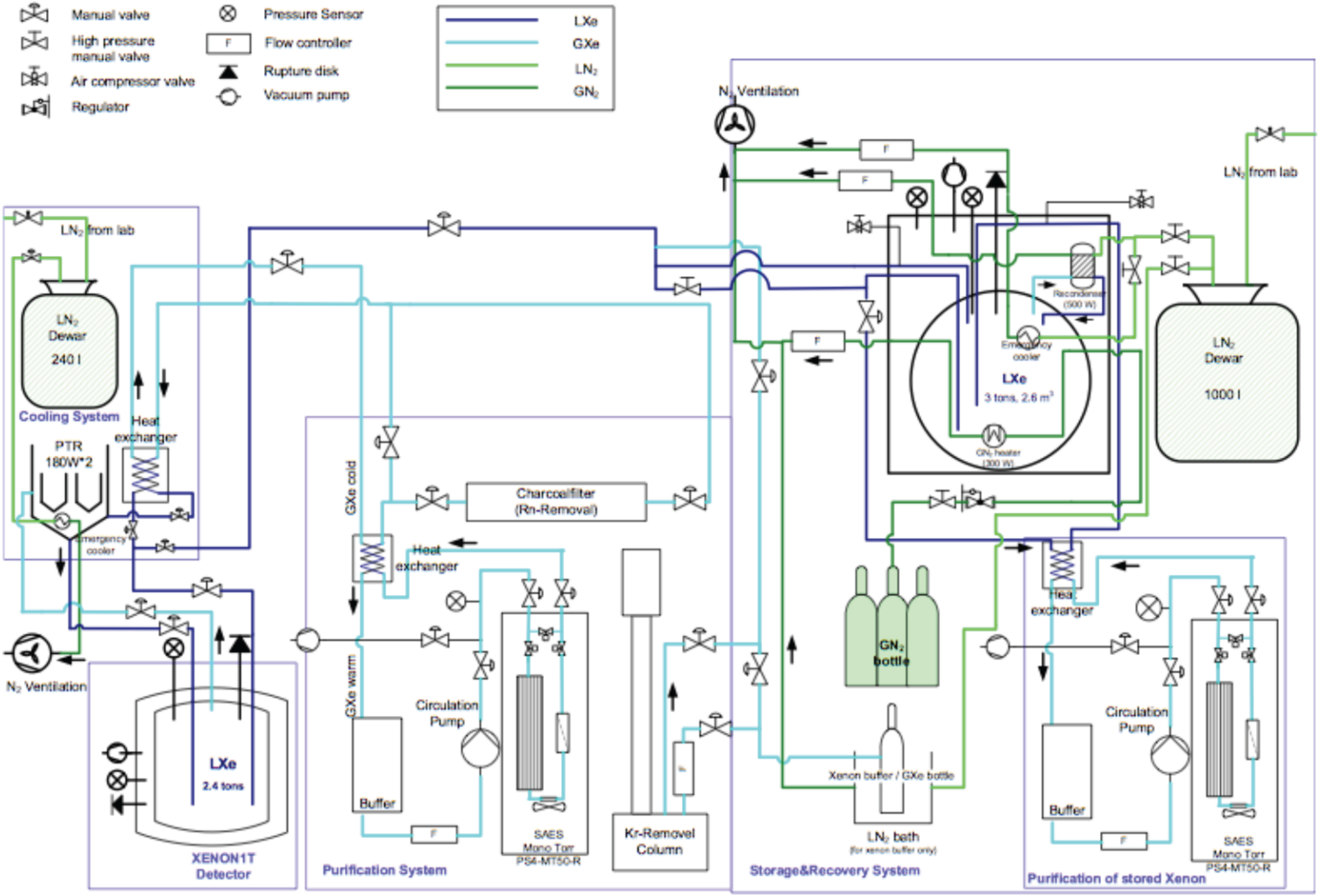


Key Parameters of XENON1T

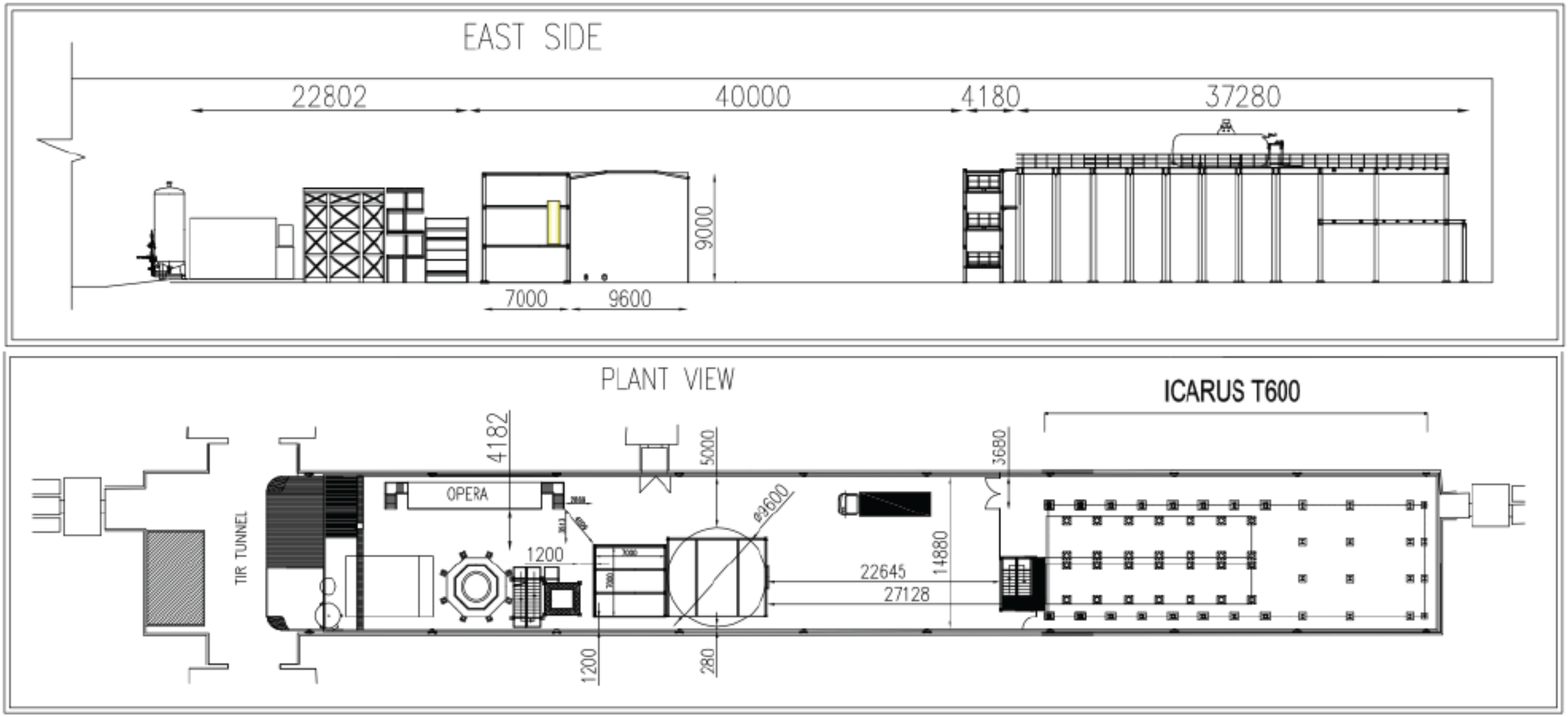
		XENON10	XENON100	XENON1T
Timing	Construction	2005 – 2006	2008 – 2009	2012 – 2014
	Data taking & Analysis	2006 – 2007	2009 – 2012	2015 – 2018
Detector TPC Size	Diameter (cm)	20	30	100
	Maximum Drift Length (cm)	15	30	100
	Operational Field (kV/cm)	0.73	0.53	1.00
	Maximum Drift Time (μs)	72	158	476
	Total Mass (kg)	15	161	2500
	Fiducial Mass (kg)	5.4	48	1100
Detector Material	Photon Detector	R8520 x 89	R8520 x 242	R11410 x 272
	Photon Detector Diameter (inch)	1	1	3
	Cryostat	Stainless Steel	Stainless Steel	Titanium
Detector Cooling	Cooling System	PTR	PTR	PTR
External Shielding		Poly (20cm) Lead (20cm)	Cu (5cm) Poly (20cm) Lead (20cm) Water	(Active Muon Veto) Water (4 m)
Operation and Sensitivity	Live Time (days)	58.6	100.9	730
	Exposure (kg $\times$ years)	0.37	4.02	880
	No. of observed events	10[a]	3[b]	-
	Sensitivity[c] (cm^2)	5×10^{-44}	7×10^{-45}	2×10^{-47}

[a] Observed number of events consistent with the 7 expected background events.
[b] Observed number of events consistent with the 1.8 expected background events.
[c] 90% CL at 50 GeV/c^2 WIMP mass.

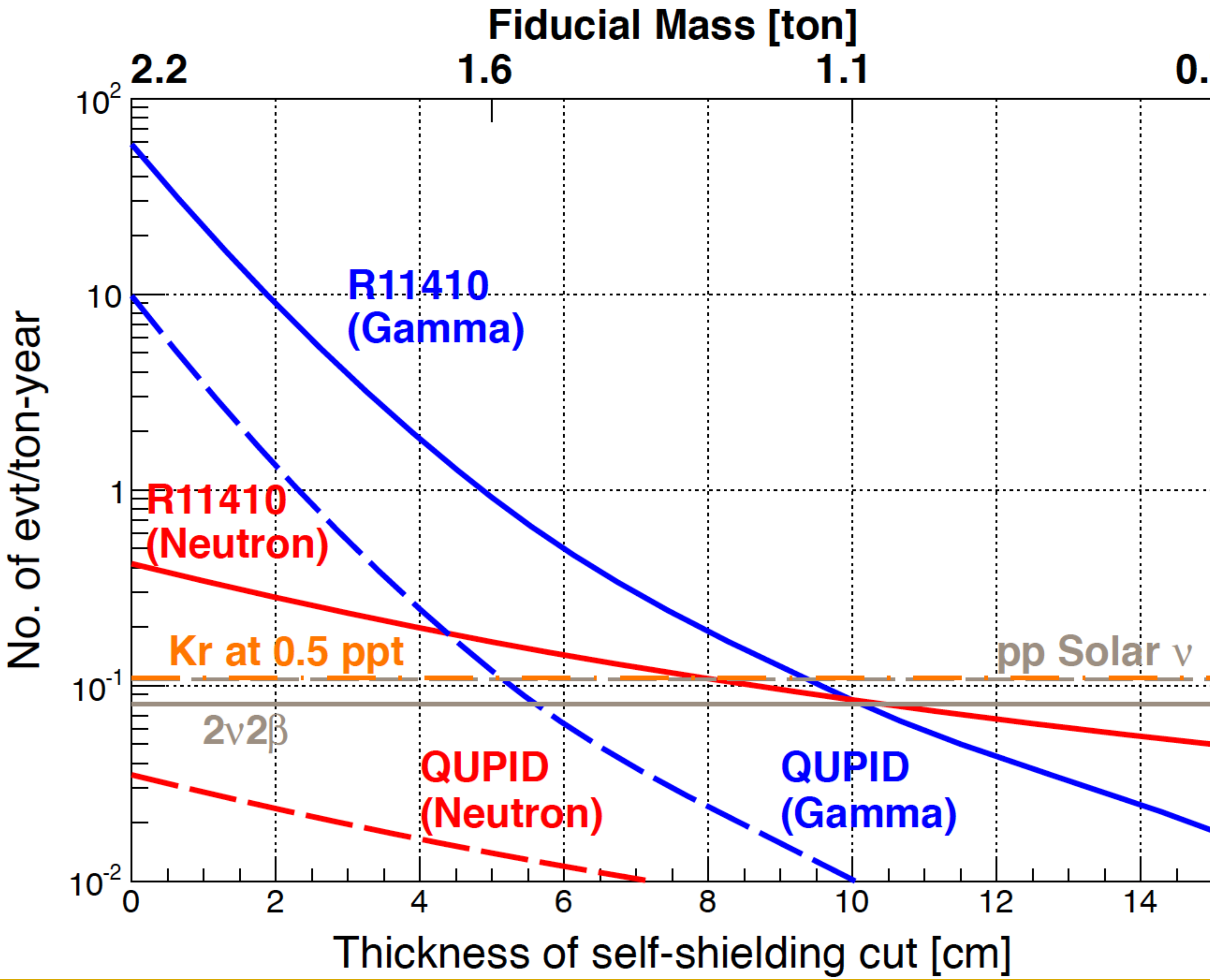
XENON1T Cryogenic System



XENON1T at LNGS Hall B



Expected Backgrounds vs. Self-shielding cut



Expected Backgrounds and Sensitivity

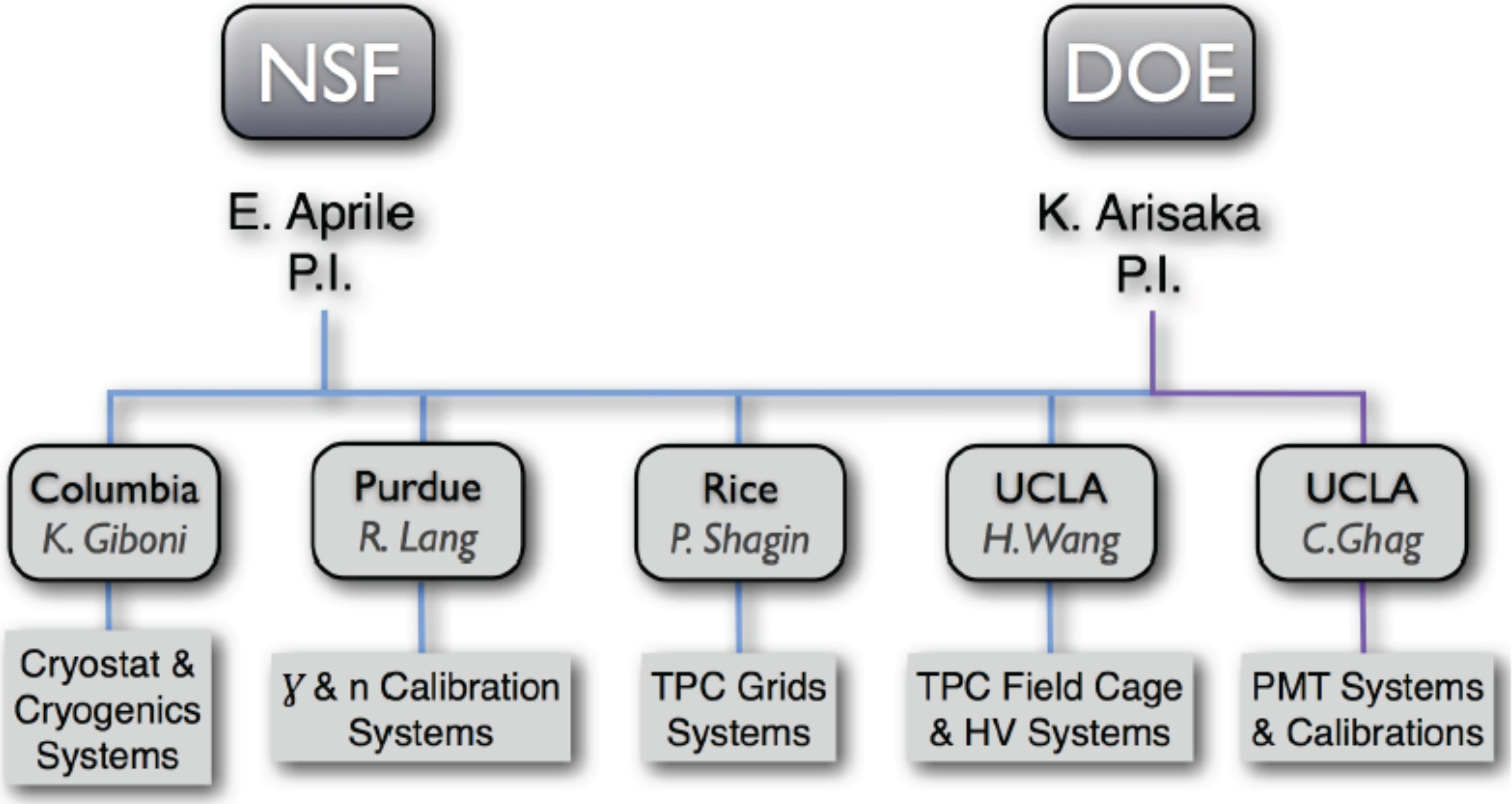
	XENON100				XENON1T	
Fiducial Mass	48 kg		30 kg		1.1 ton	
Background	ER	NR	ER	NR	ER	NR
Units	$[10^{-3}\,\mathrm{dru_{ee}}]$	$[10^{-7}\,\mathrm{dru_{nr}}]$	$[10^{-3}\,\mathrm{dru_{ee}}]$	$[10^{-7}\,\mathrm{dru_{nr}}]$	$[10^{-3}\,\mathrm{dru_{ee}}]$	$[10^{-7}\,\mathrm{dru_{nr}}]$
^{85}Kr	13.5	–	2.0	–	0.01	–
pp Solar neutrino	0.01	–	0.01	–	0.01	–
^{136}Xe $2\nu\beta\beta$	0.008	–	0.008	–	0.008	–
n from Rock and μ-induced	–	55	–	50	–	0.05
PMTs with bases	3.59	3.25	1.1	2.87	0.006	0.05
PTFE	0.02	6.99	0.01	5.04	0.0001	0.02
Cryostat	0.95	2.01	0.47	1.66	0.0002	0.0007
Total Bkg.	18.1	67	3.6	59	0.03	0.12
Total ER Bkg. after S2/S1 cut	0.045		0.009		< 0.0001	
Run Time	100 days		200 days		730 days	
Raw Exposure	13 kg-year		16 kg-year		2.2 ton-year	
Expected number of Bkg. events	1.8 ± 0.6	0.1 ± 0.1	0.6	0.1	0.8	0.2
Number of Observed events	3		N/A		N/A	
SI $\sigma_{\chi-p}$ reach	$7 \times 10^{-45}\,\mathrm{cm}^2$ (April 2011)		$2 \times 10^{-45}\,\mathrm{cm}^2$ (2012)		$2 \times 10^{-47}\,\mathrm{cm}^2$ (2017)	

XENON1T – Responsibility and Cost

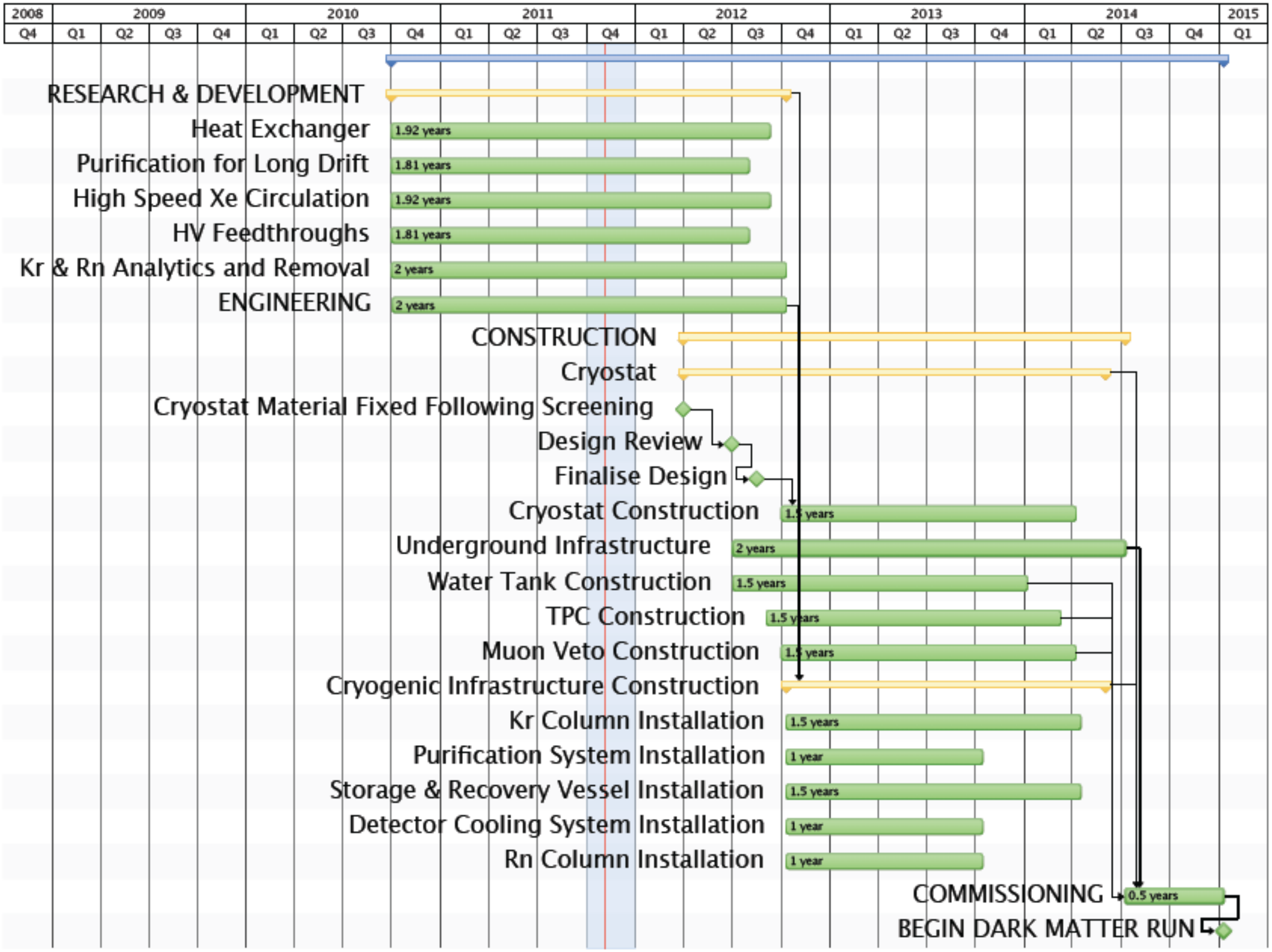
Item	Primary Institution Responsibility	Secondary US Institution Responsibility	US Funds Already Secured	Non-US Funds Secured and Proposed	US Funds Requested	Total Capital Costs
Photomultiplier Tubes[a]	UCLA	Columbia	0.07	0.41	1.57	2.05
Cryostat/Cryogenics Plant	Columbia	UCLA	0.10	–	1	1.1
Electronics/DAQ/Computing	Zurich	Columbia	0.50	0.10	–	0.6
Water Shield	Weizmann	–	–	0.5	–	0.5
Cherenkov Muon Veto	Bologna, Mainz	–	–	0.65	–	0.65
LNGS Infrastructure (Water Plants, AC, Electrical Systems)	LNGS	Columbia Rice, Purdue UCLA	–	0.55	0.15	0.7
Purification & Cryogenic Distillation Plants	Muenster	Columbia Purdue	0.1	0.6	–	0.7
Xenon Gas (2.5 ton)	Columbia	Rice	1.25	1.25	–	2.5
LXe Storage/Recovery Vessel	SubaTech	–	–	0.8	–	0.8
Internal TPC & PMT Support Structures[a]	UCLA	Rice Columbia	–	0.04	0.52	0.56
Slow Control	Coimbra, Weizmann	–	–	0.05	–	0.05
Calibration	Purdue	–	0.05	–	0.1	0.15
Material Screening	MPIK, Zurich	UCLA	–	0.27	0.07	0.34
Cryostat Support & Platform	Nikhef	Columbia	–	0.25	–	0.25
			2.07	5.47	3.41	10.95

DOE + NSF

XENON1T – US Responsibility

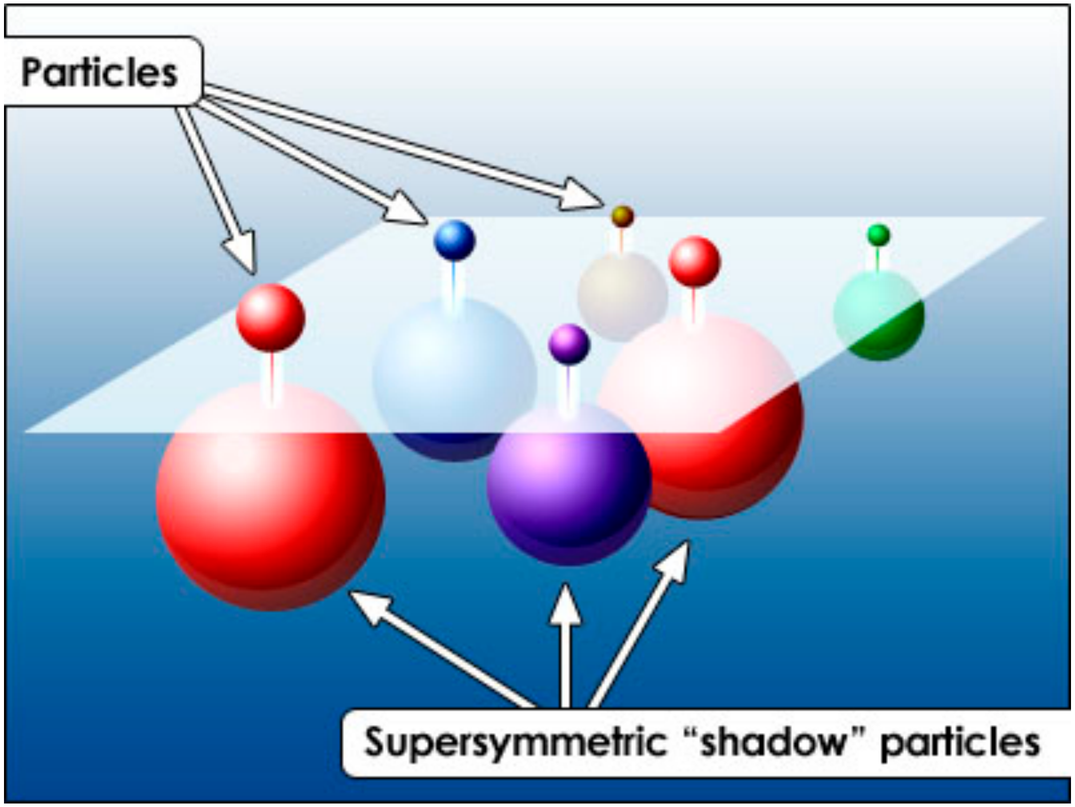


XENON1T – Schedule

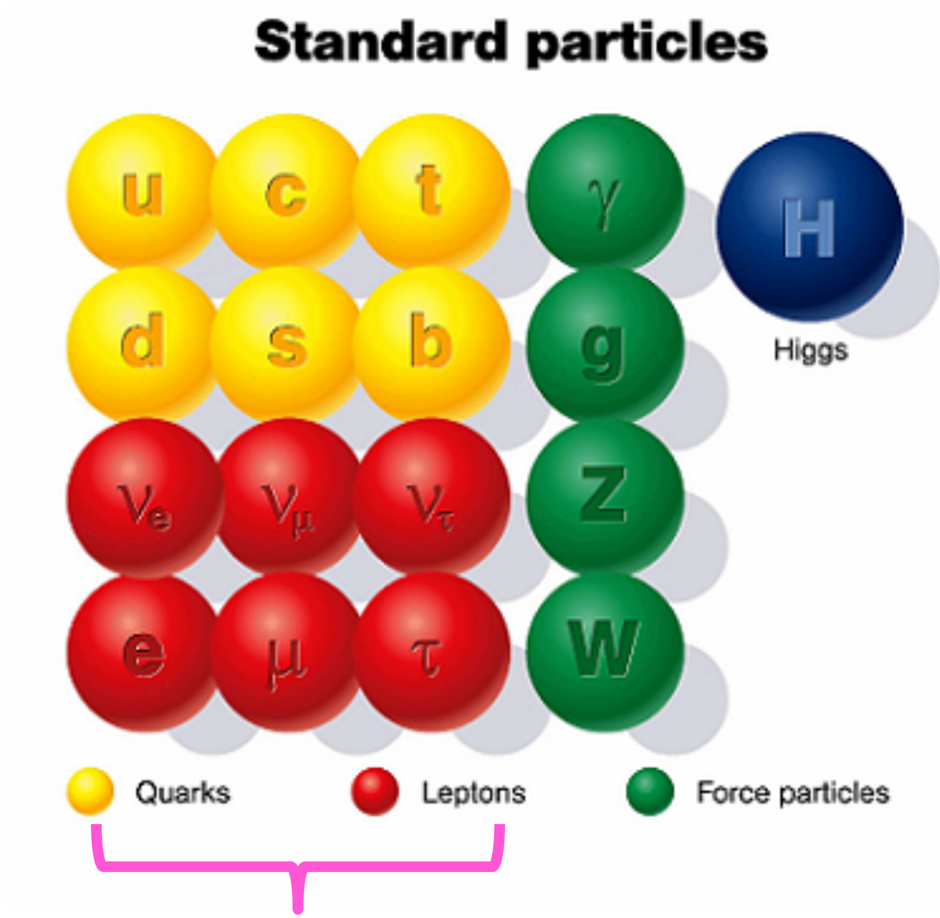


SUSY and Extra Dimensions

SUSY Neutralino

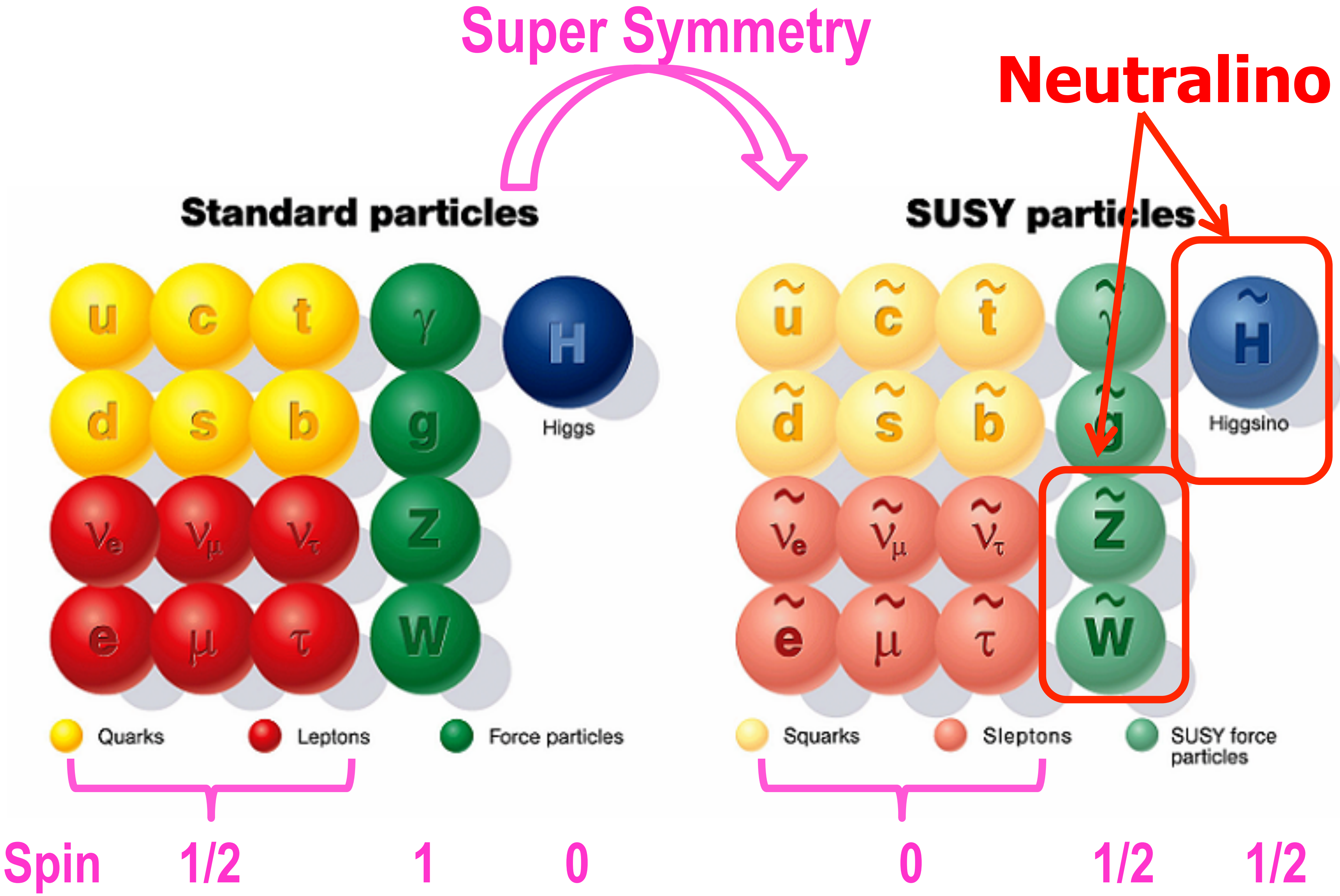


SUSY Particles and Neutralino



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

Minimal Supersymmetric Extension of Standard Model (MSSM)

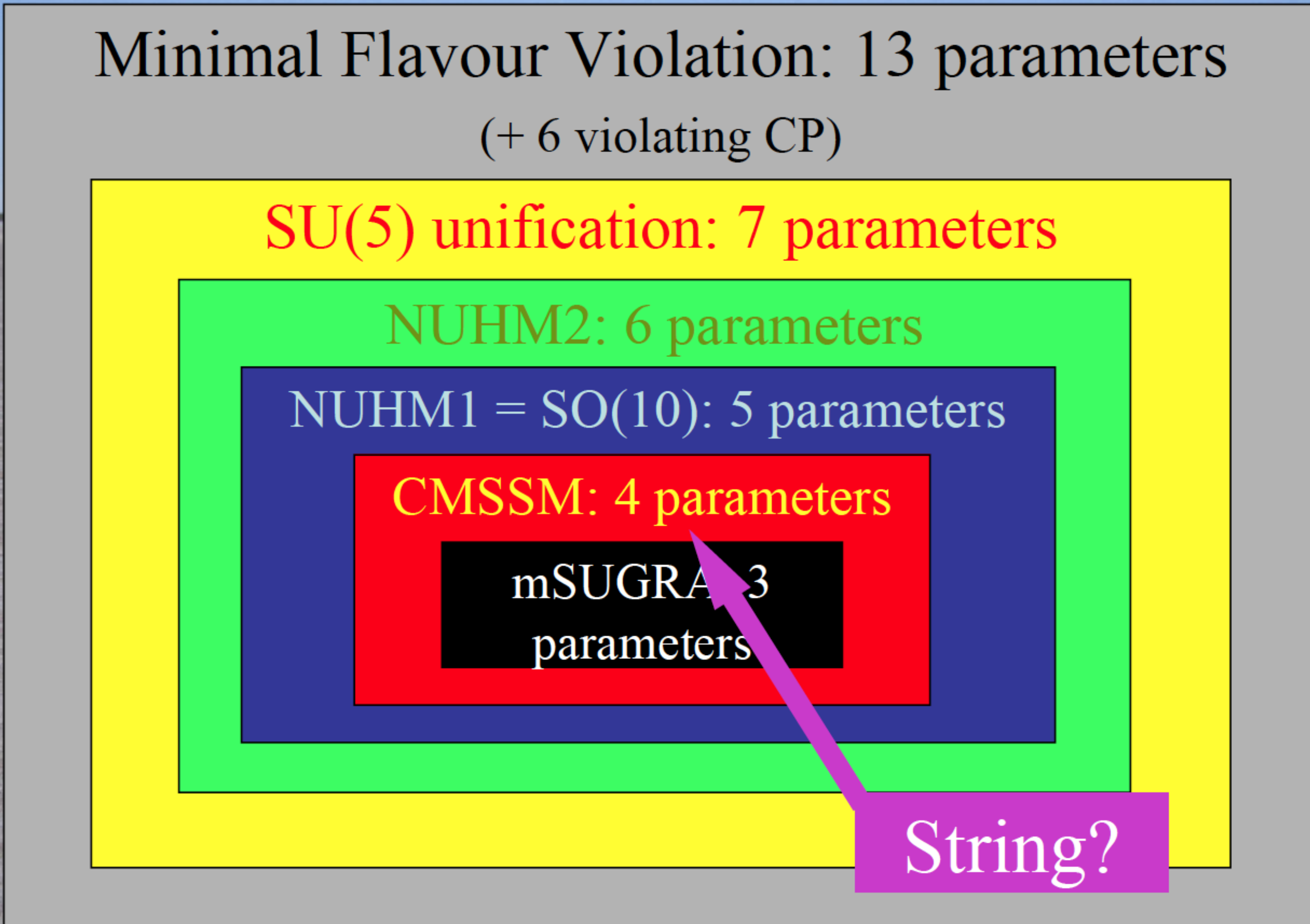
- Particles + spartners

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

- 2 Higgs doublets, coupling μ, 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_λ, bilinear soft coupling B_μ
- Often assume universality:
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: 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

MSSM: > 100 parameters



Mass Spectra at the best fit points (before LHC)

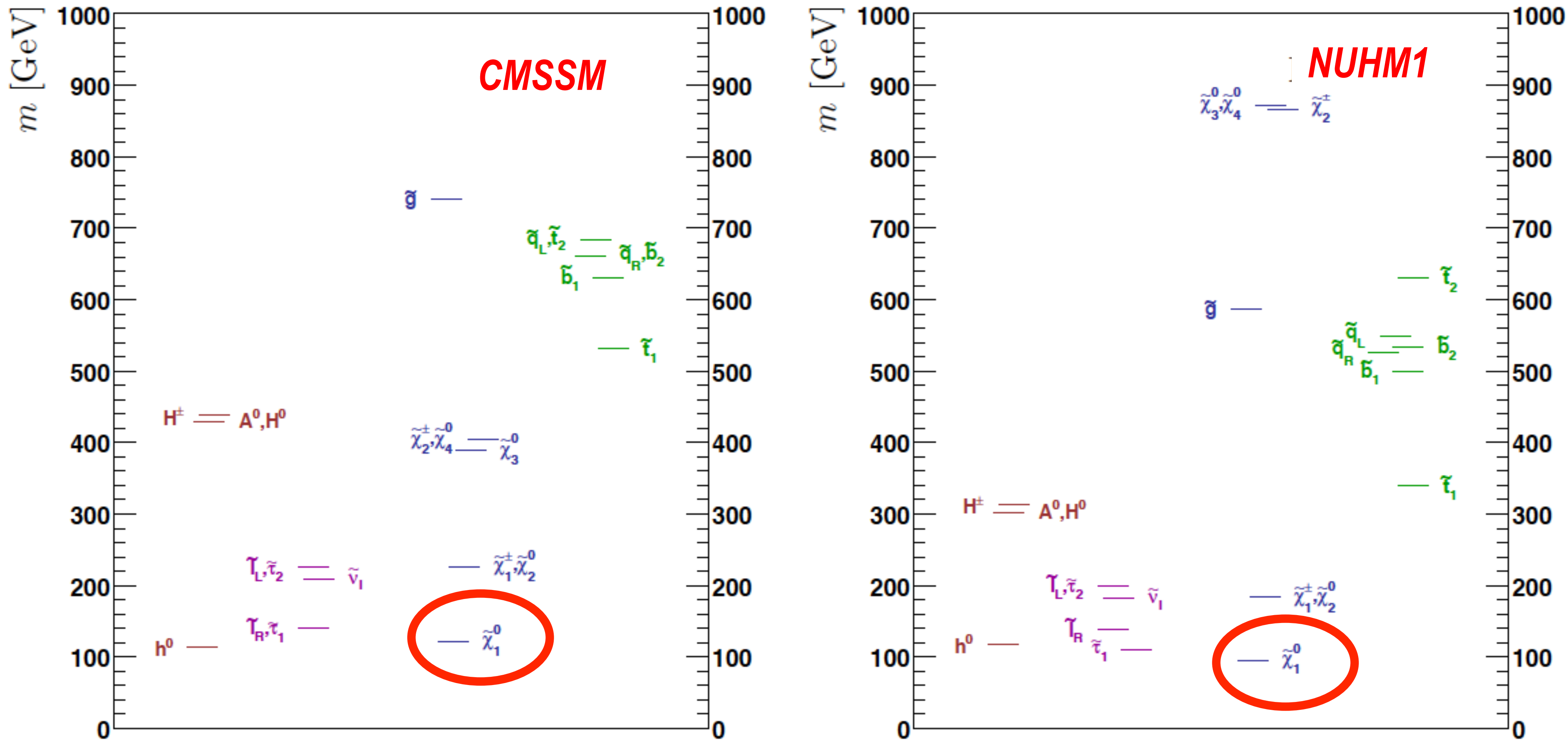
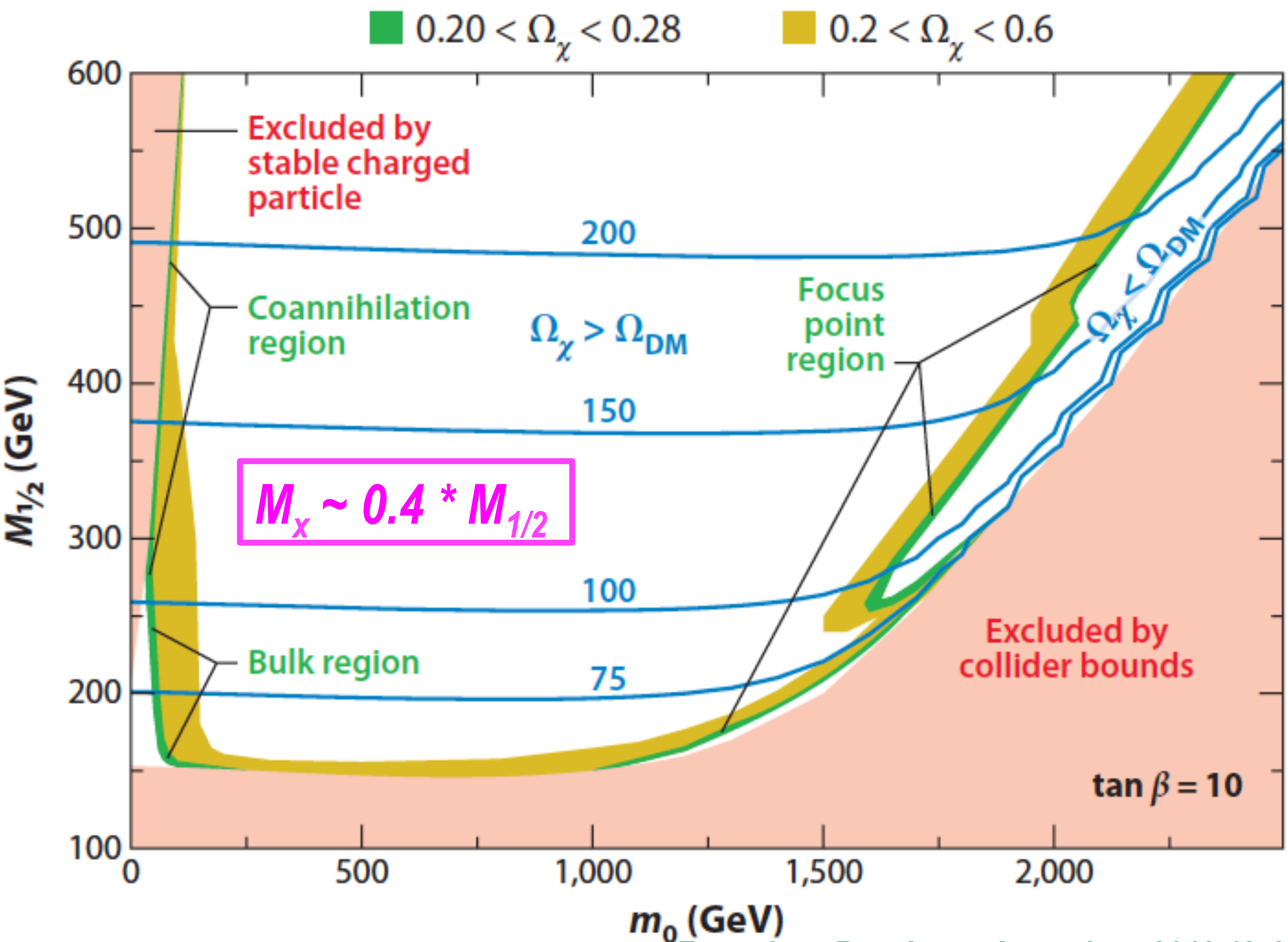


Figure 2. The spectra at the best-fit points: left — in the CMSSM with $m_0 = 60$ GeV, $m_{1/2} = 310$ GeV, $A_0 = 240$ GeV, $\tan\beta = 11$, and right — in the NUHM1 with $m_0 = 100$ GeV, $m_{1/2} = 240$ GeV, $A_0 = -930$ GeV, $\tan\beta = 7$, $m_H^2 = -6.9 \times 10^5$ GeV^2 and $\mu = 870$ GeV.

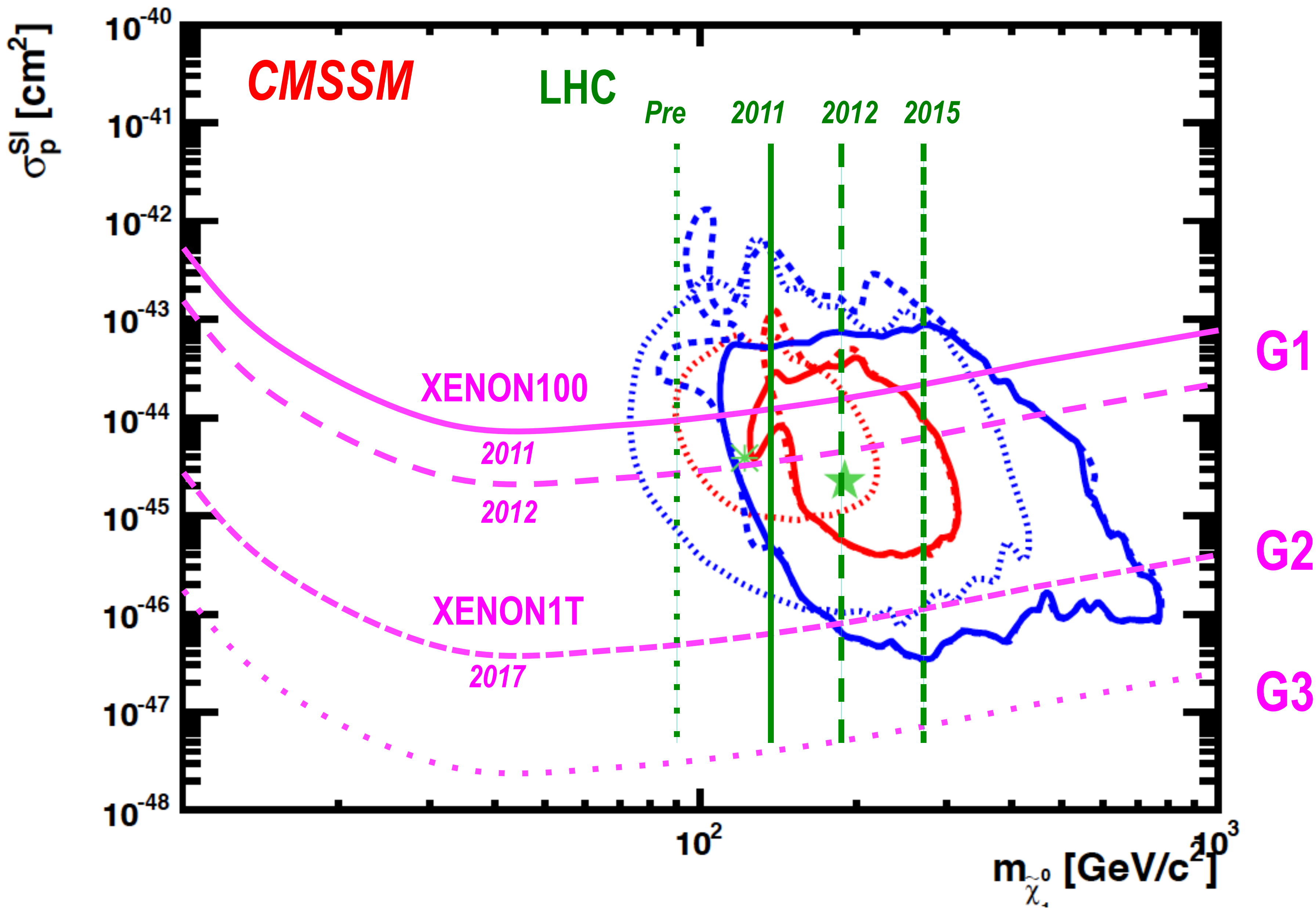
Buchmueller et al arXiv: 0808.4218

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



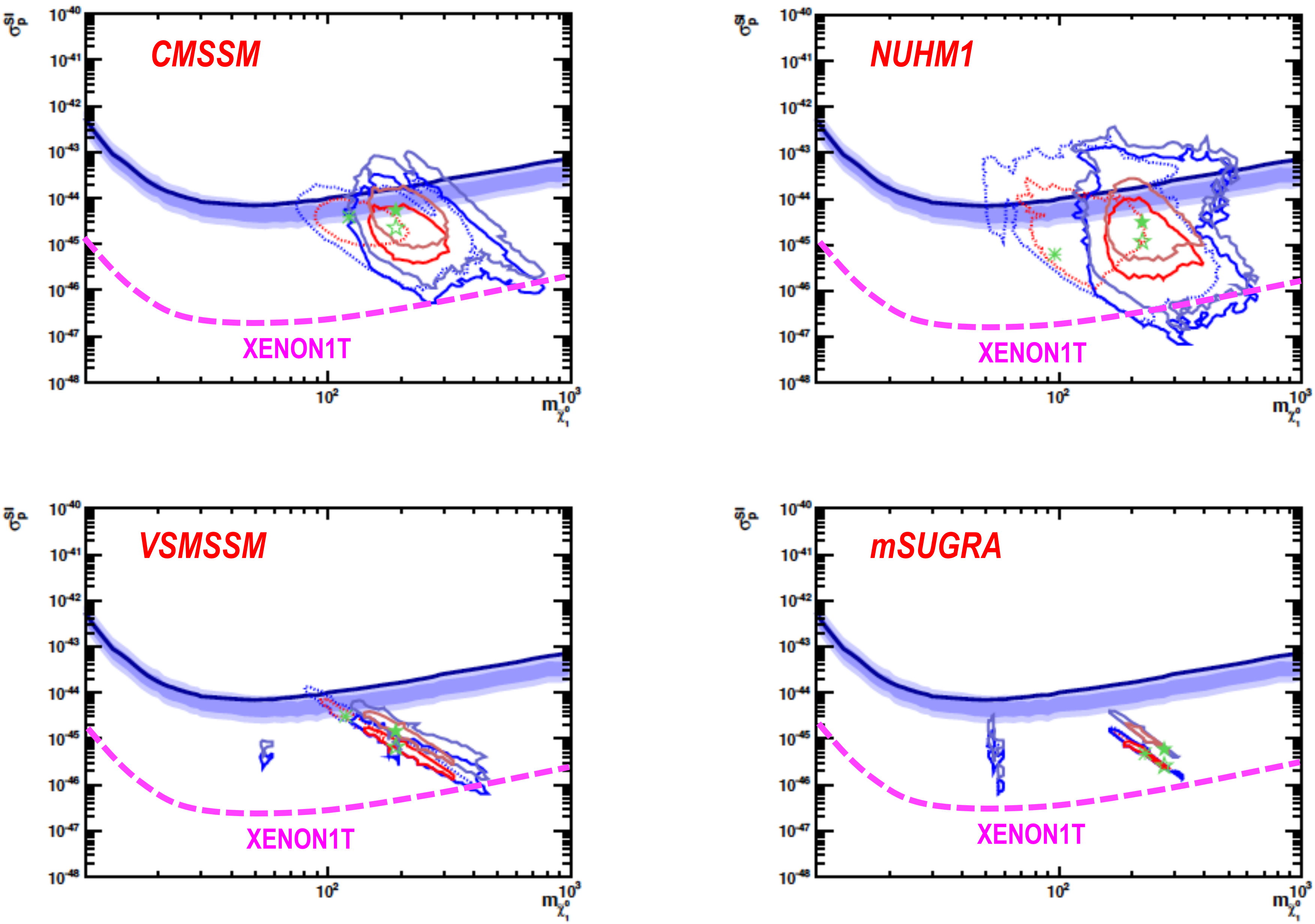
Feng Ann. Rev. Astro. Astrophys. 2010.48:495-545

SI Cross Section vs. Mass



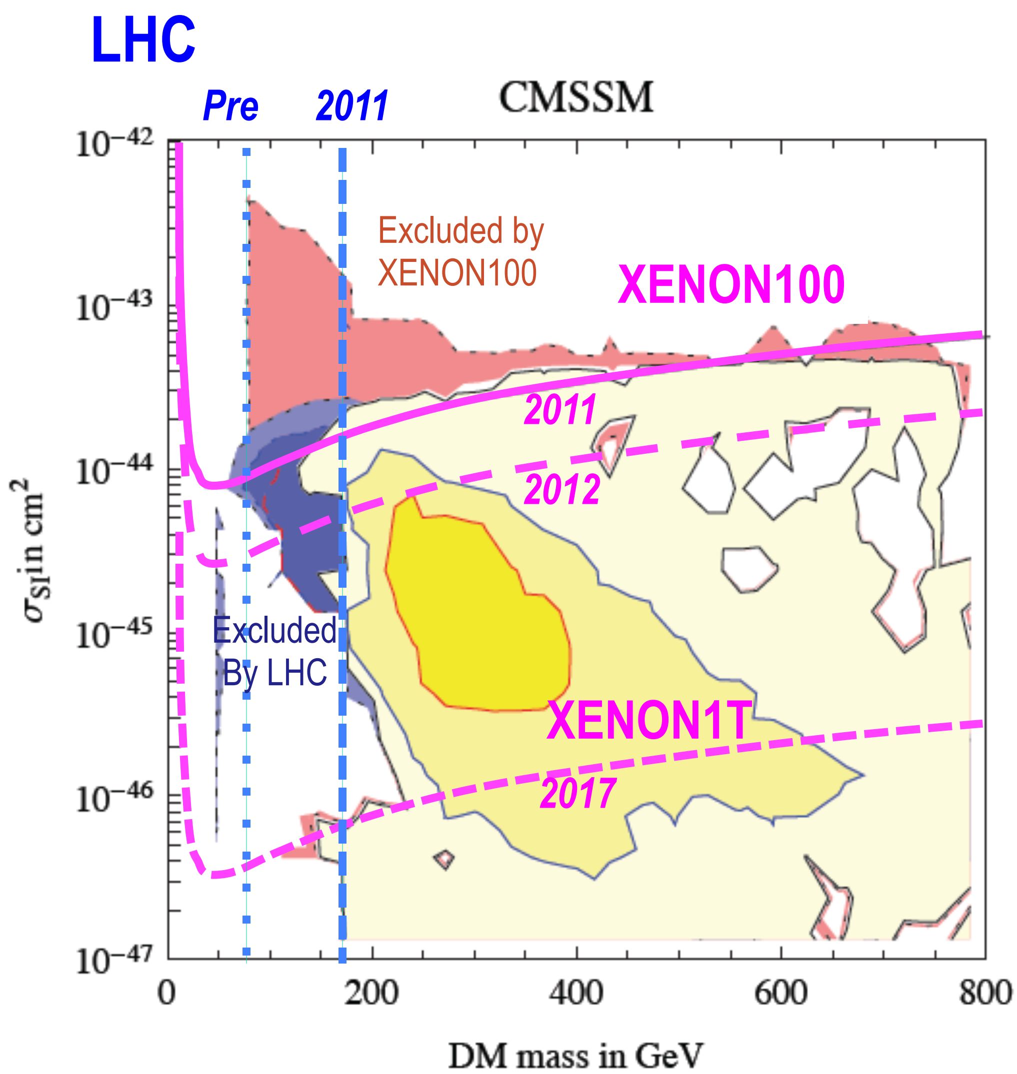
Buchmueller et al arXiv:1106.2529

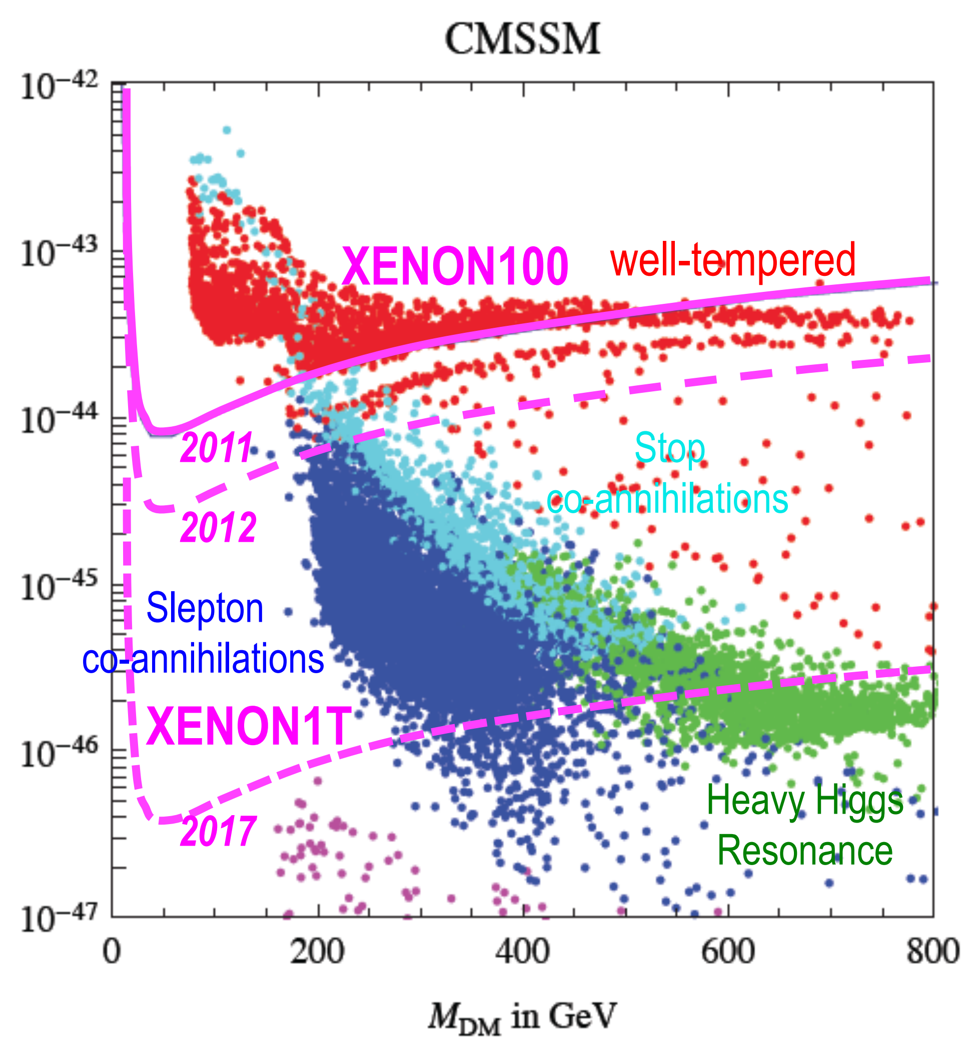
SI Cross Section vs. Mass



Buchmueller et al arXiv:1106.2529

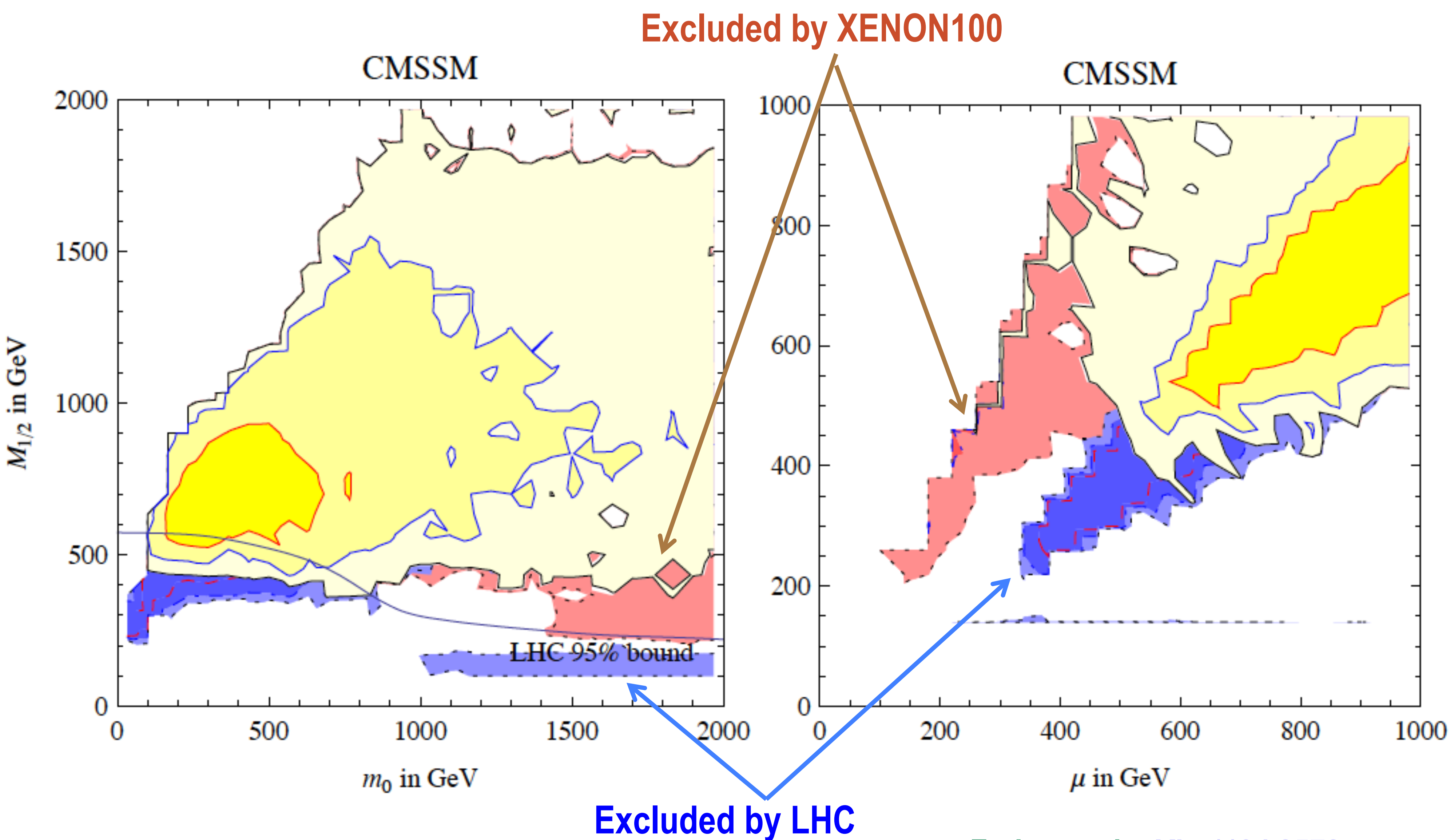
SI Cross Section vs. Mass





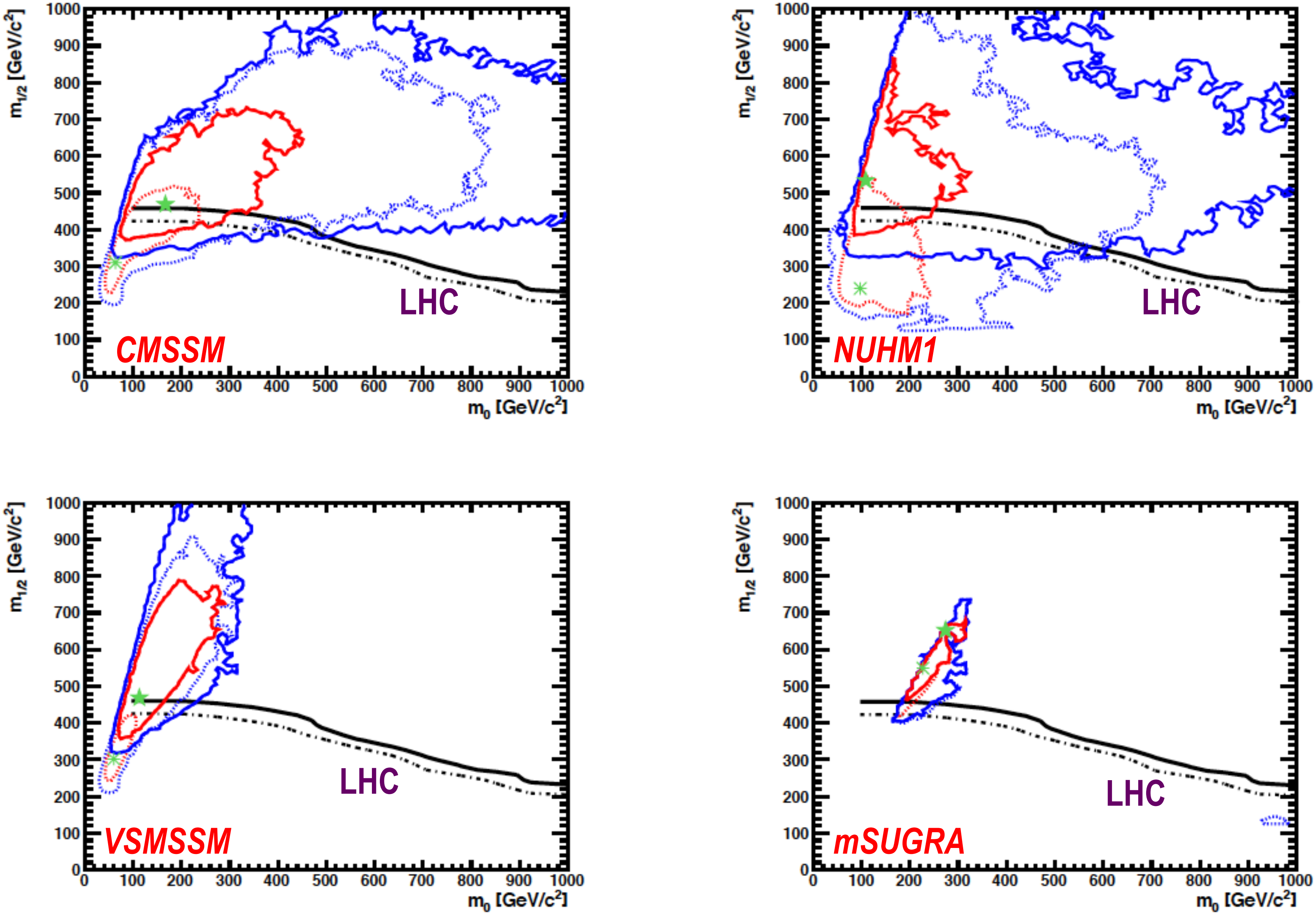
Ferina et al arXiv:1104.3573

$M_{1/2}$ vs. M_0 & μ



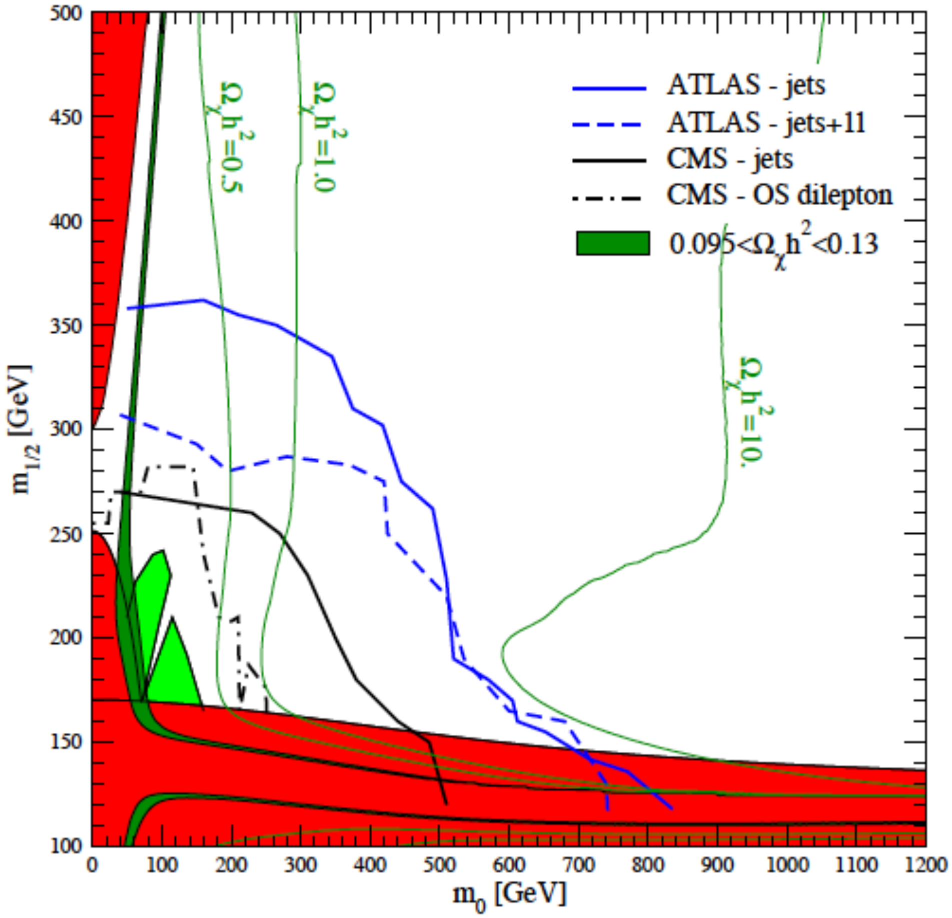
Ferina et al arXiv:1104.3573

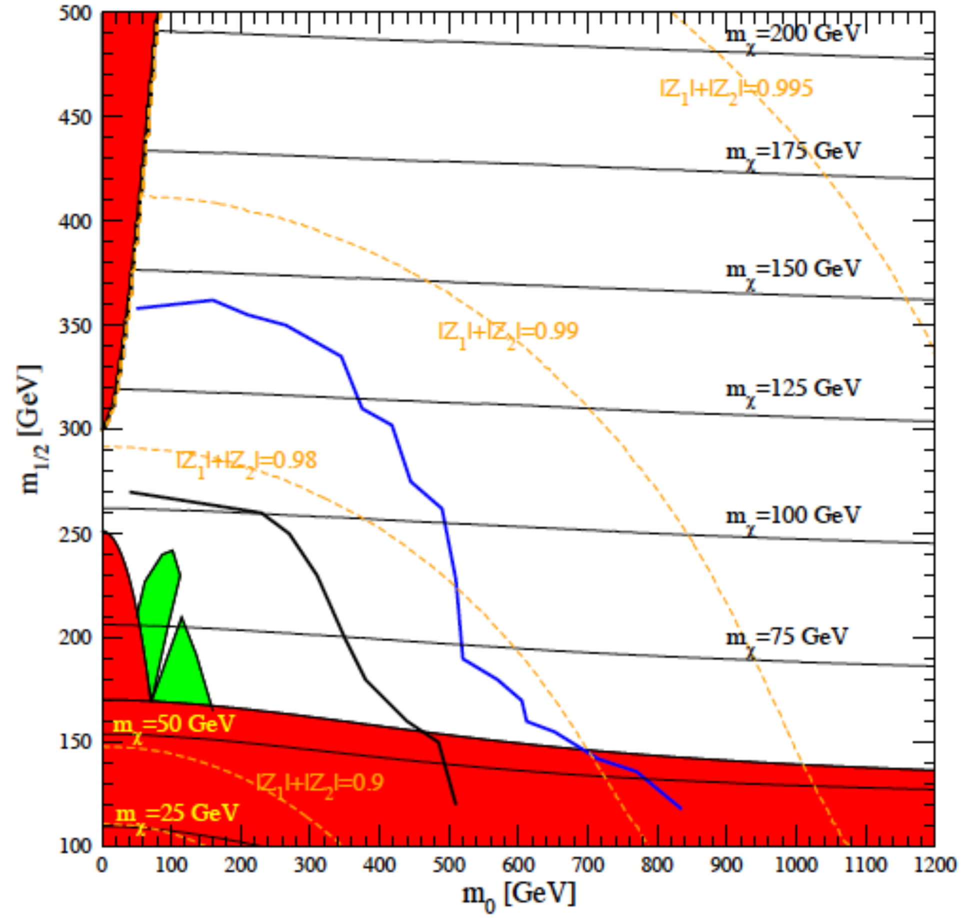
$M_{1/2}$ vs. M_0



Buchmueller et al arXiv:1106.2529

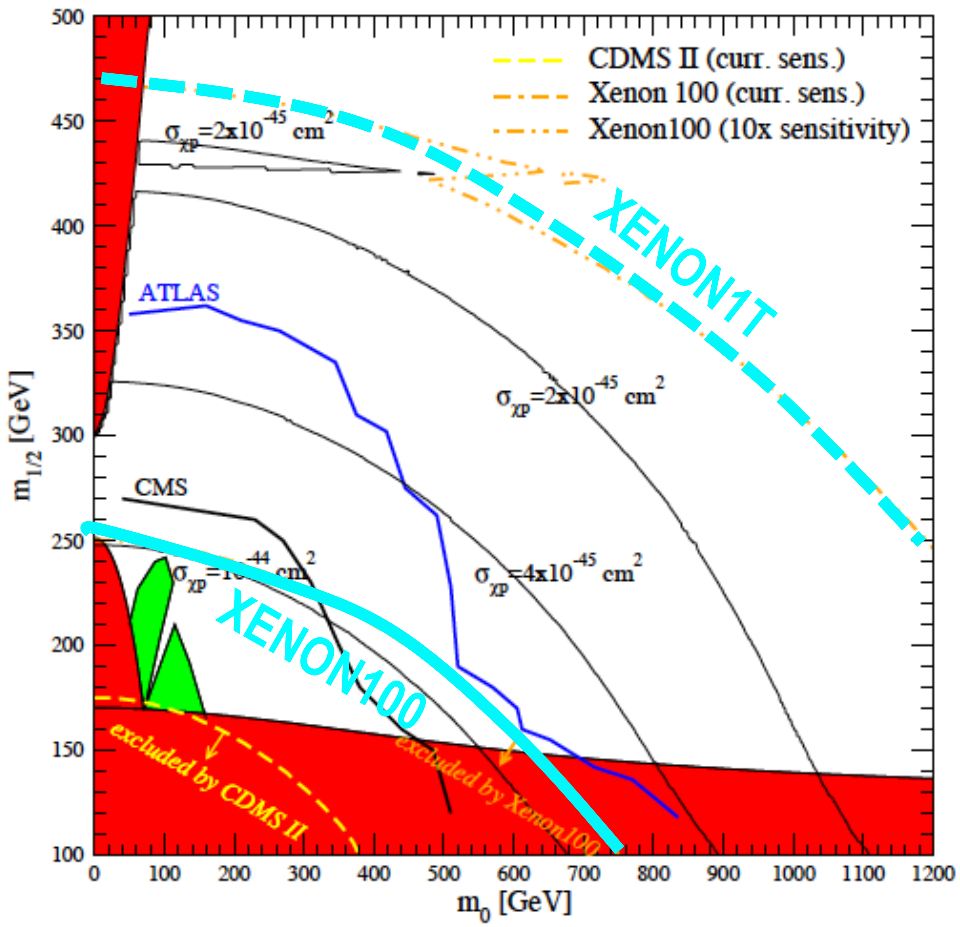
CMSSM $m_{1/2}$ vs. m_0

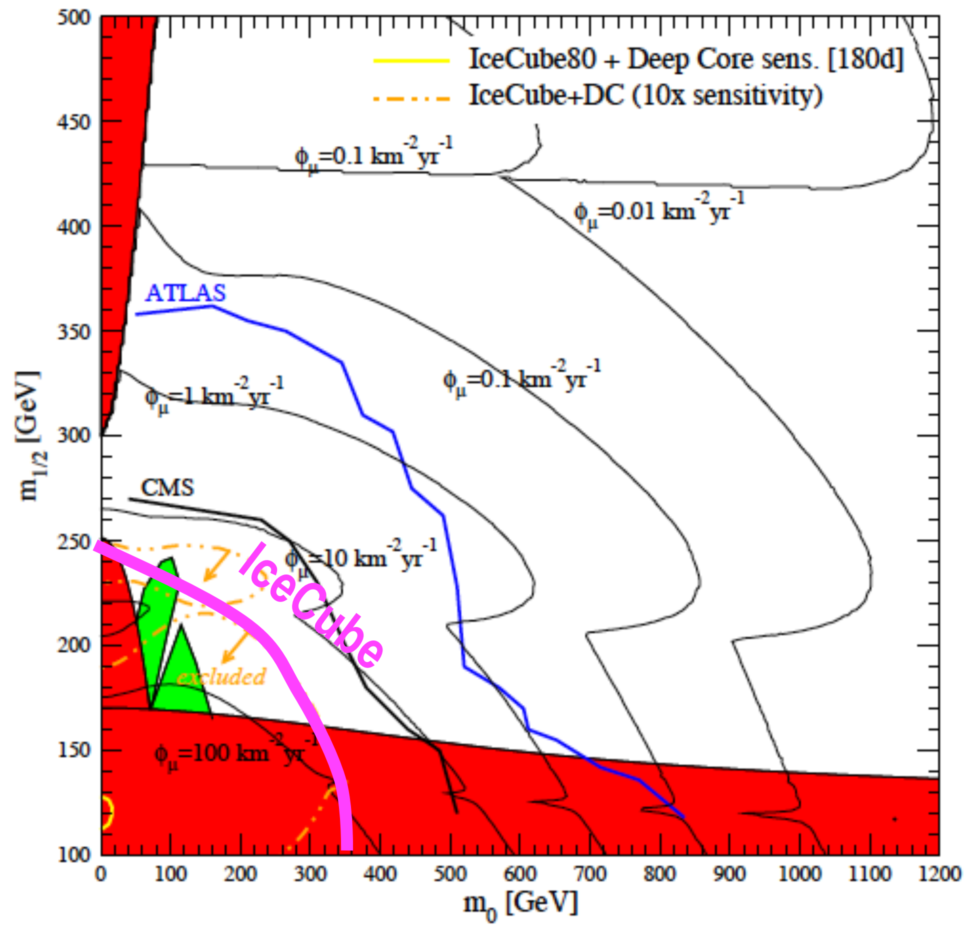




Profumo arXiv:1105.5162

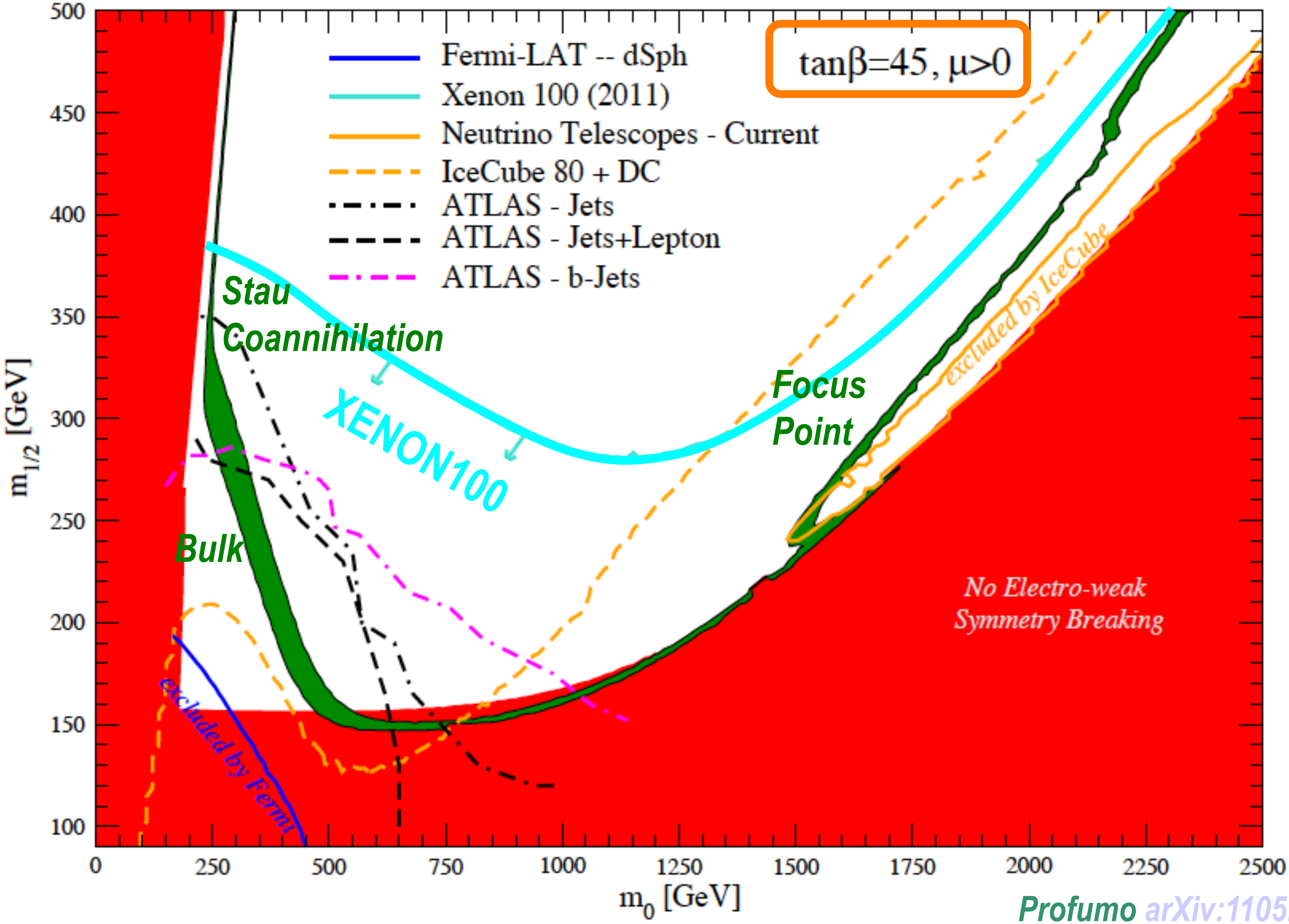
CMSSM $m_{1/2}$ vs. m_0





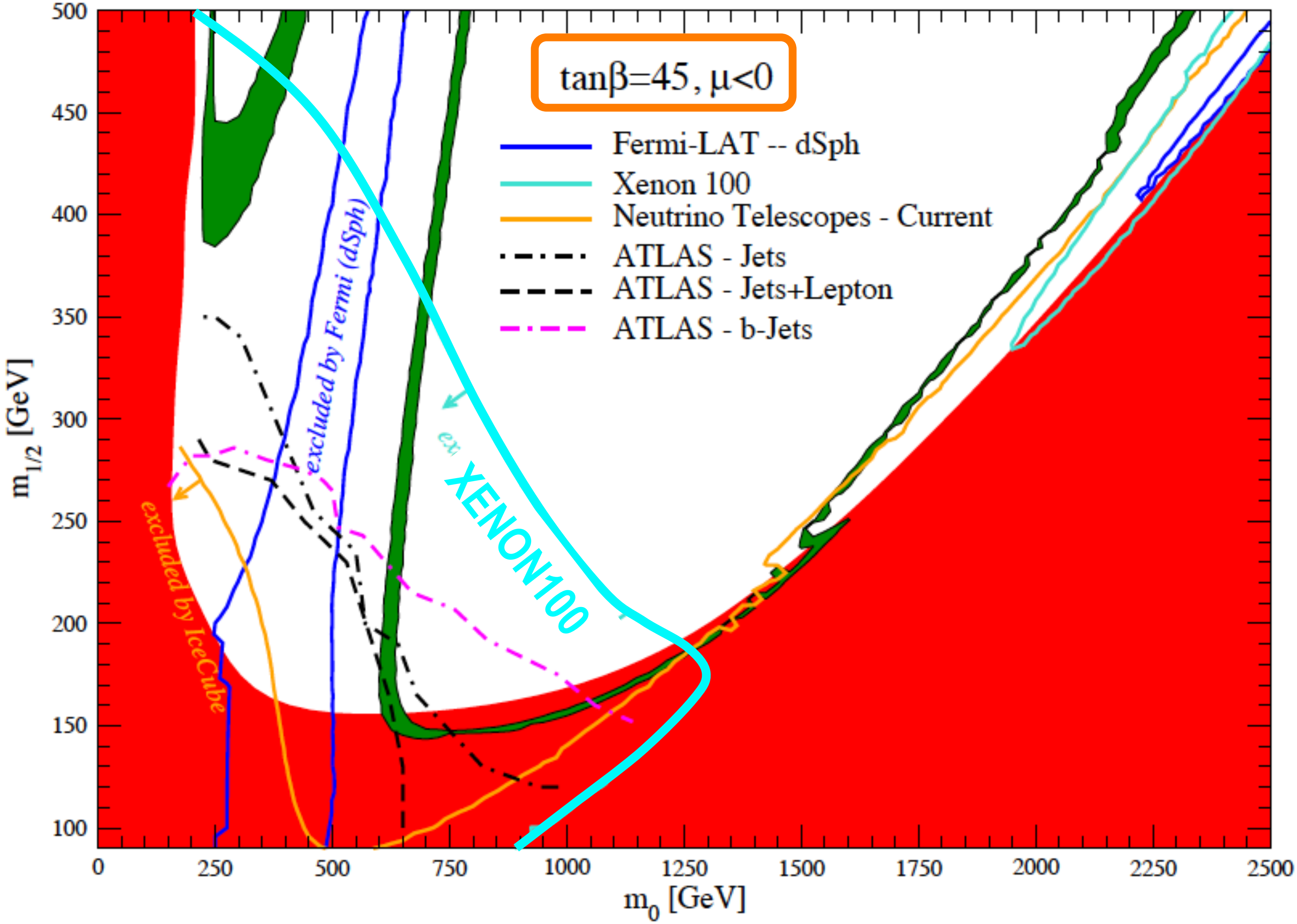
Profumo arXiv:1105.5162

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

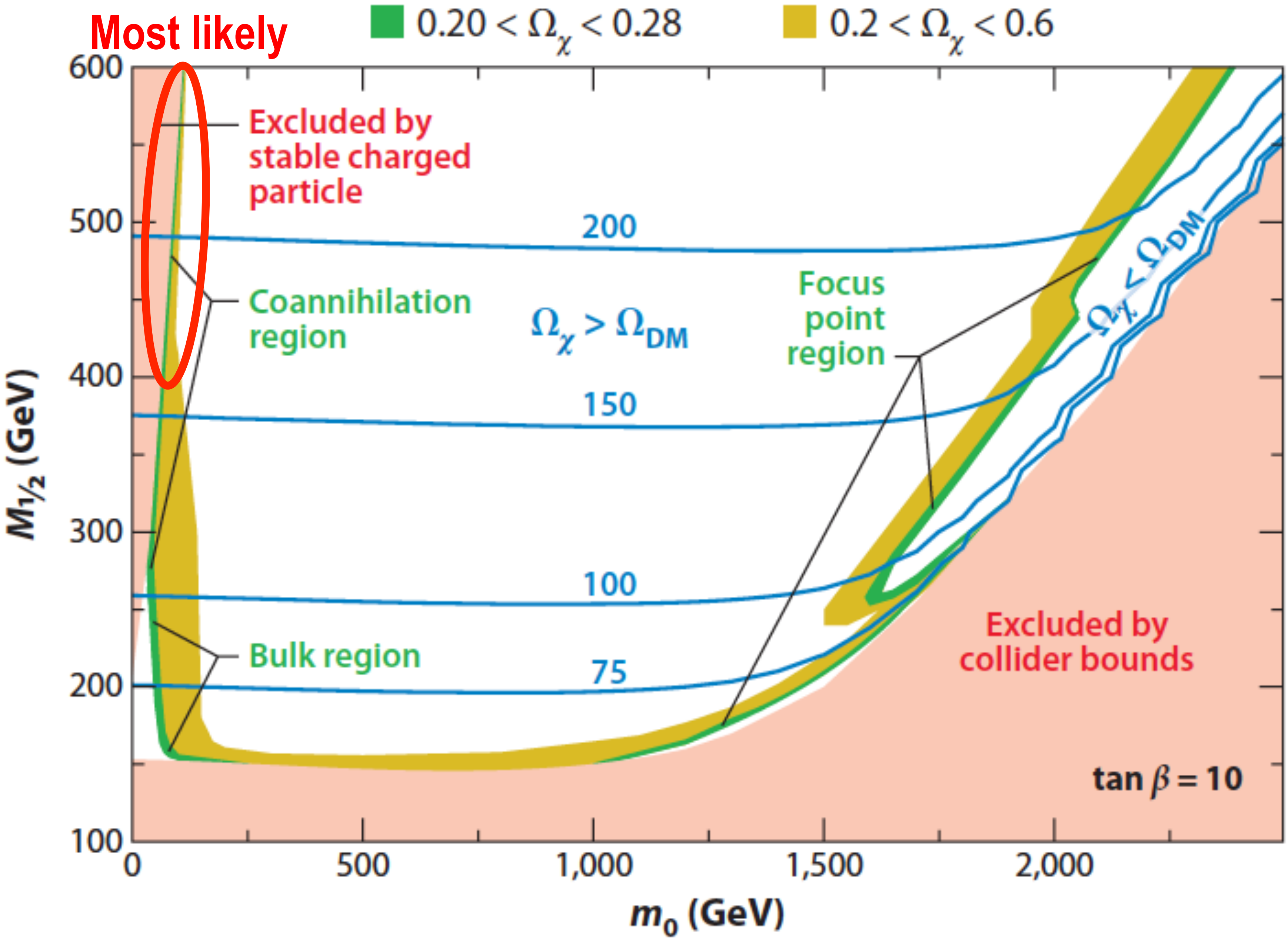


Profumo arXiv:1105.5162

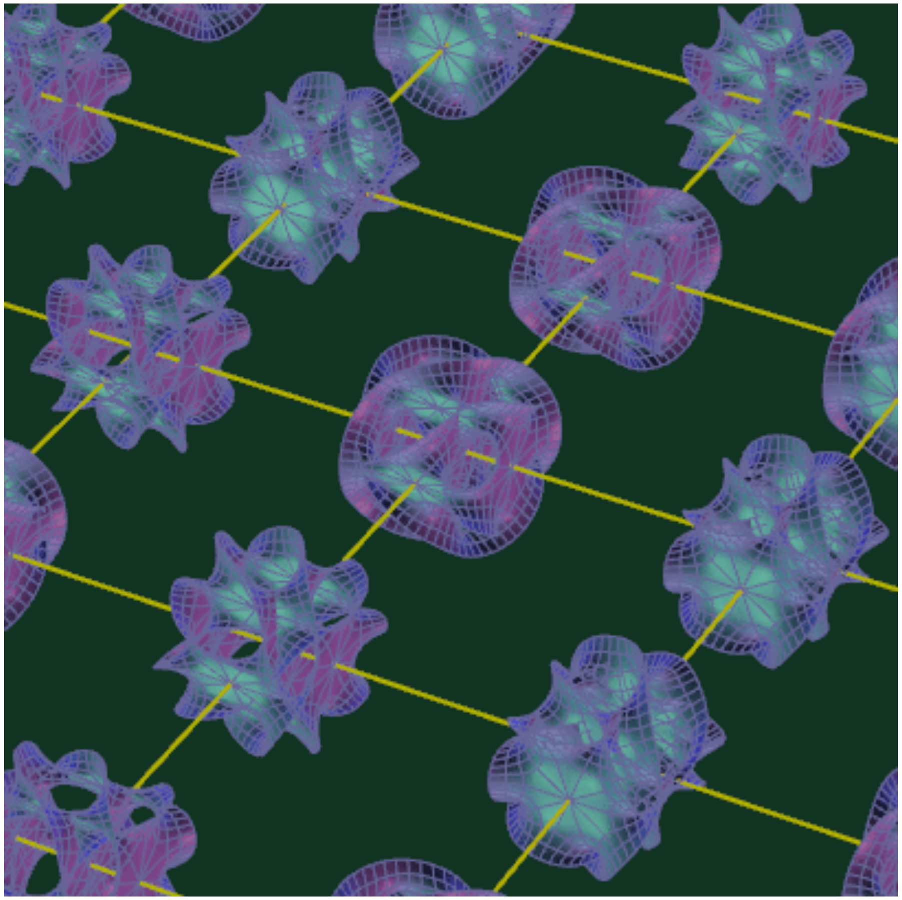
CMSSM $m_{1/2}$ vs. m_0

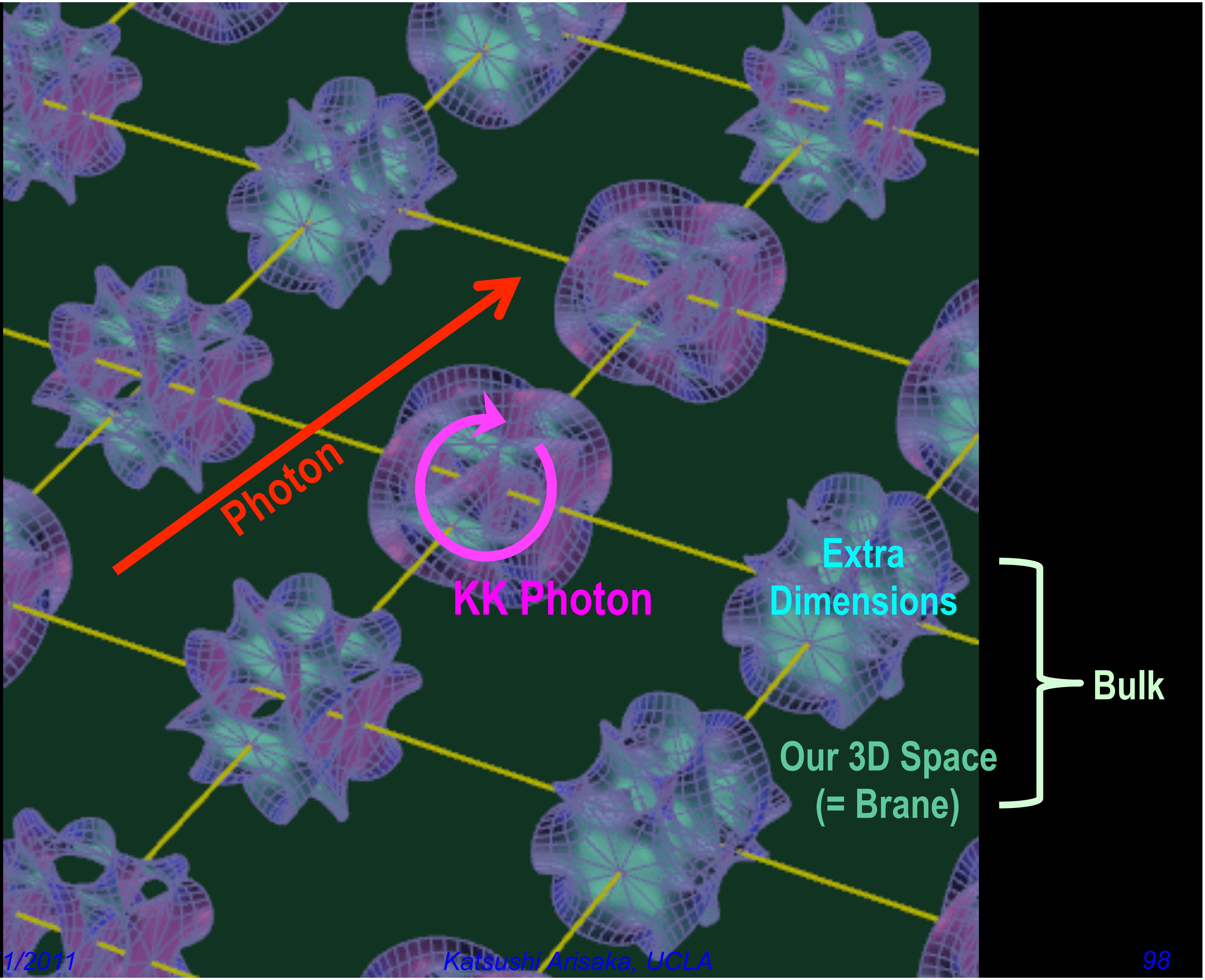


mSUGRA $m_{1/2}$ vs. m_0



KK particles in Extra Dimensions





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

Origin of Mass in Extra Dimensions

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

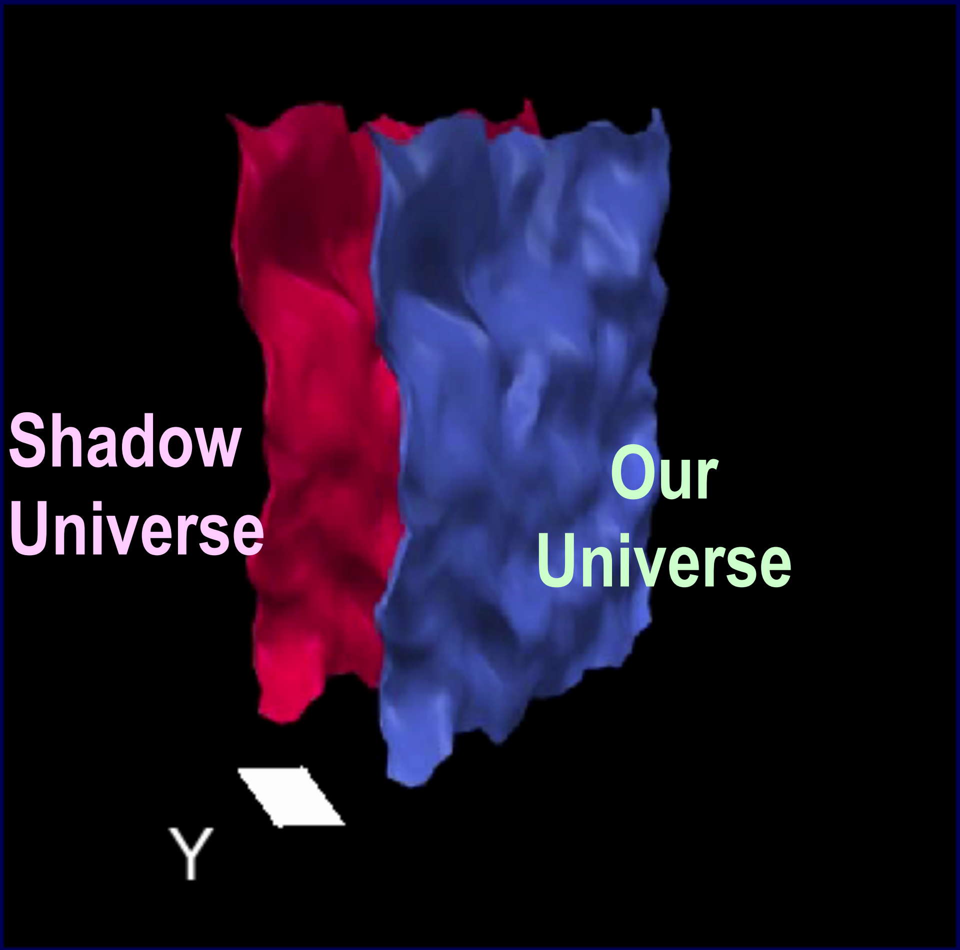
- **Mass can be generated as kinetic energy in extra dimensions.**
  - Origin on mass
  - Dark matter is running in the extra dimensions
- **Gravity can escape into the extra dimensions.**
  - Why gravity is so small
  - Origin of dark energy

Paul Steinhardt

Cyclic Model

- “bang”
- radiation
- matter
- dark energy
- “contraction”
- “crunch”

M theory



Mass Spectrum of the first KK level

Similar to the SUSY mass spectrum

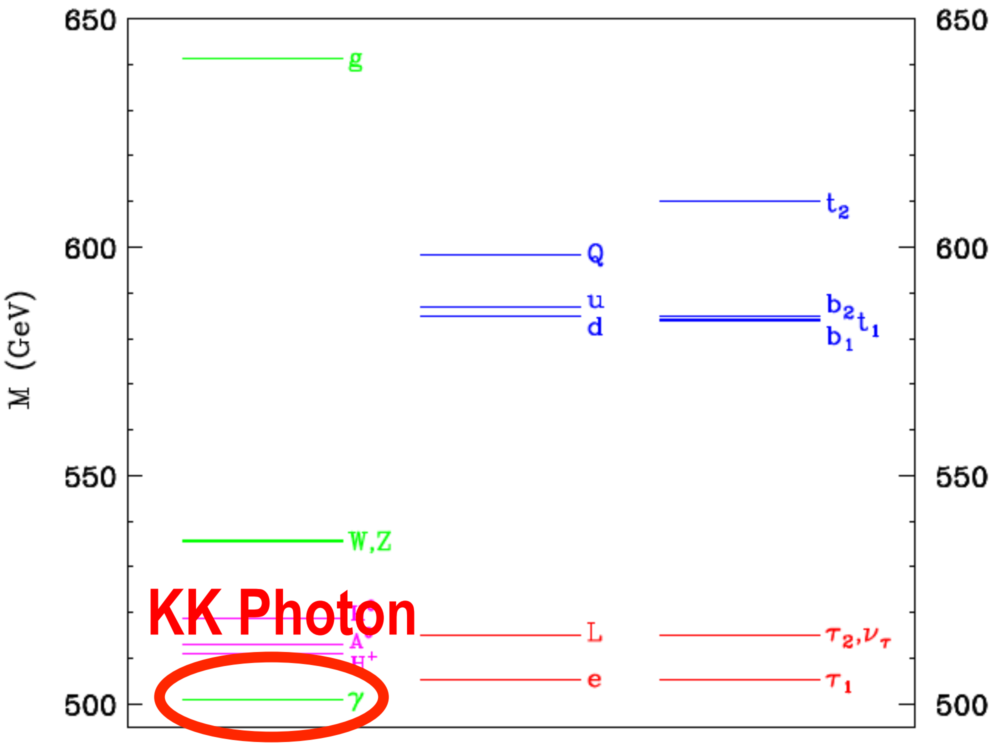


FIG. 1: *One-loop corrected mass spectrum of the first KK level in MUEDs for* $R^{-1} = 500$ *GeV*, $\Lambda R = 20$ *and* $m_h = 120$ *GeV.*

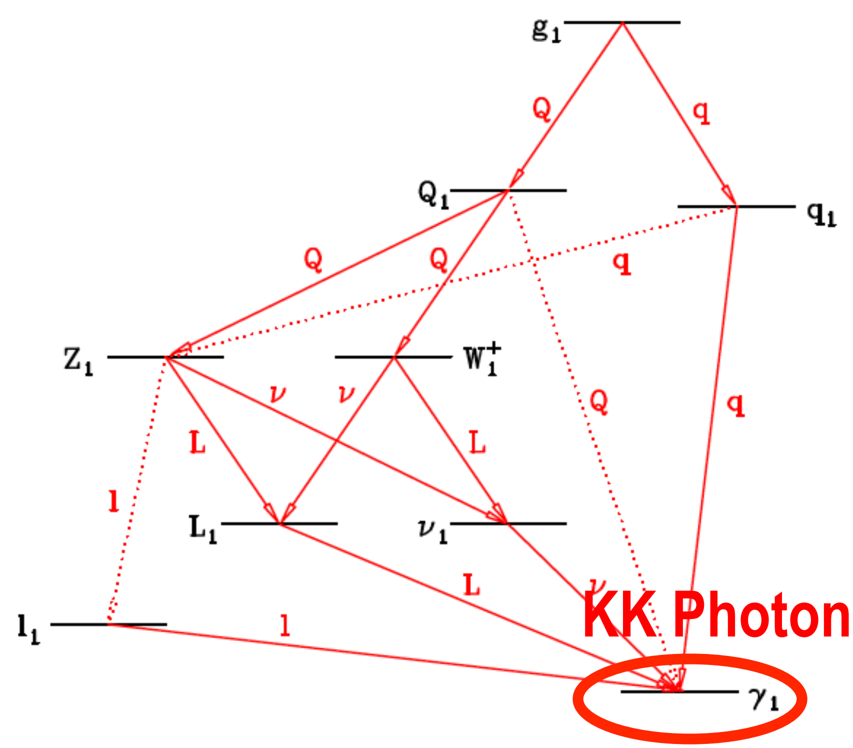
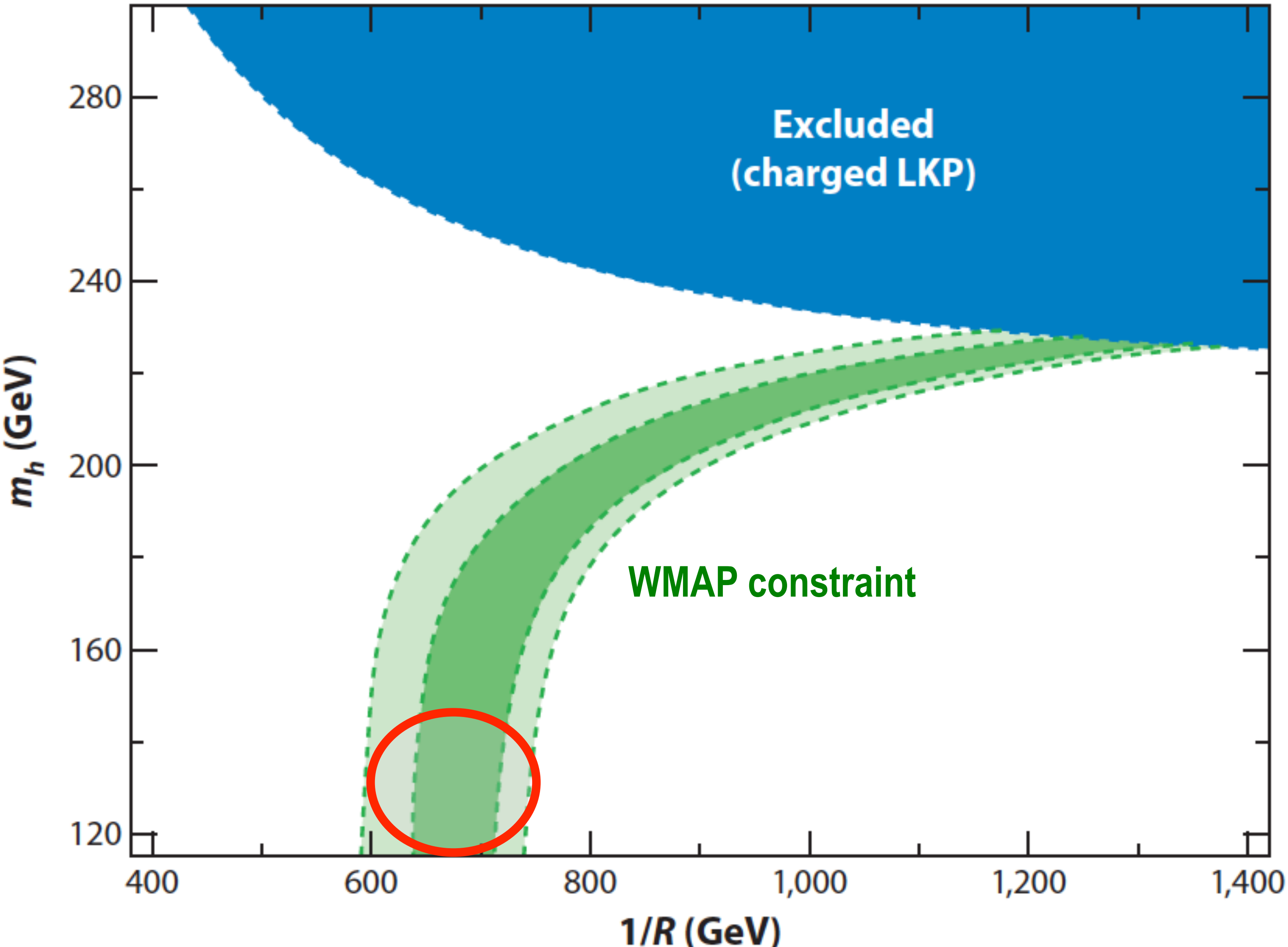


FIG. 3: *Qualitative sketch of the level 1 KK spectroscopy depicting the dominant (solid) and rare (dotted) transitions and the resulting decay product.*

Cheng 2002 arXiv:hep-ph/0205314v1

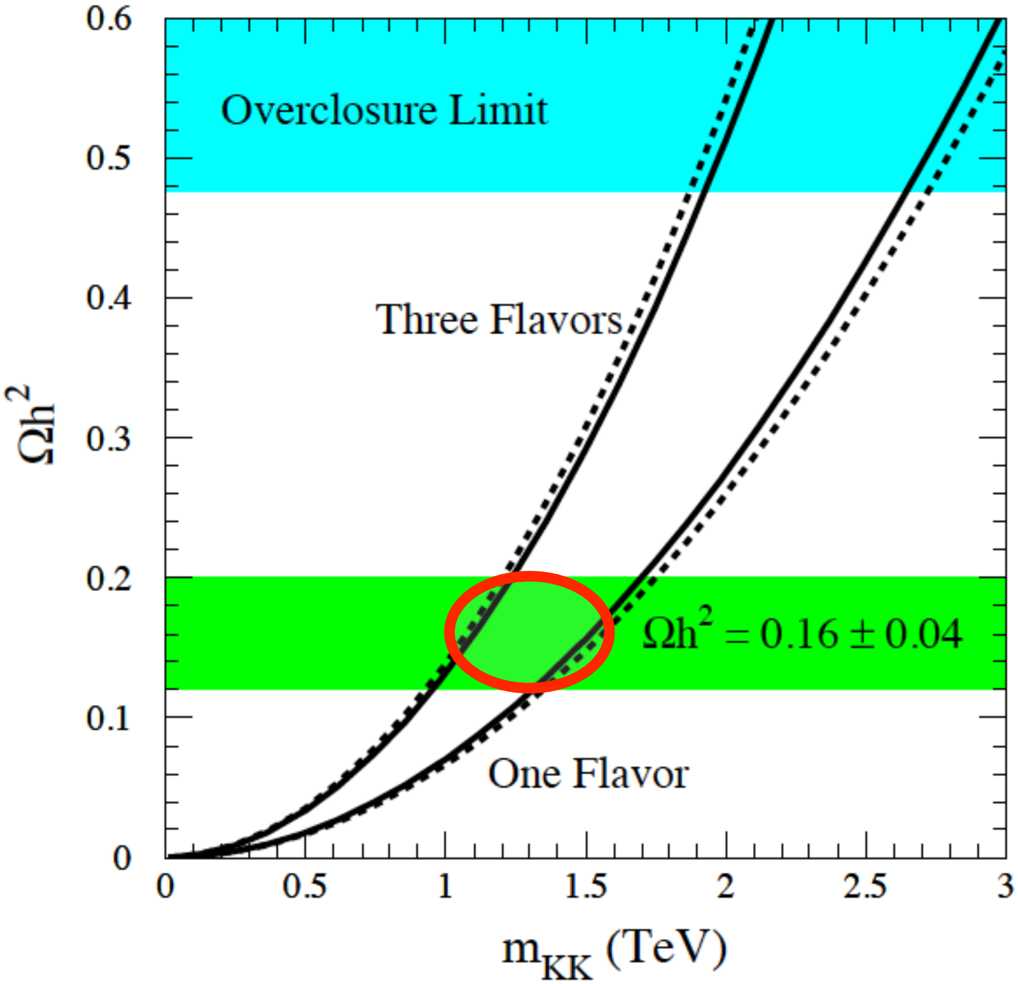
Allowed Region of Minimum Universal Extra Dimensions



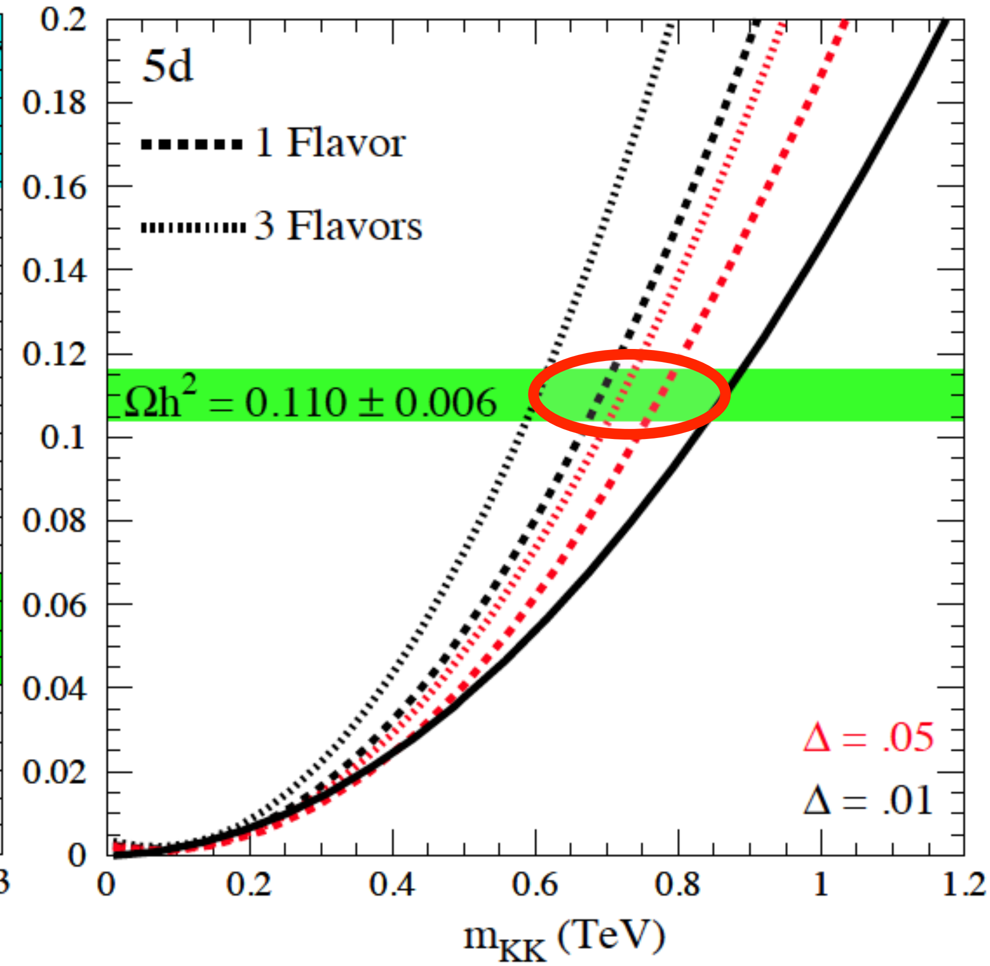
Kakizaki 2006

Ωh^2 vs. m_{KK}

$\nu^{(1)}$

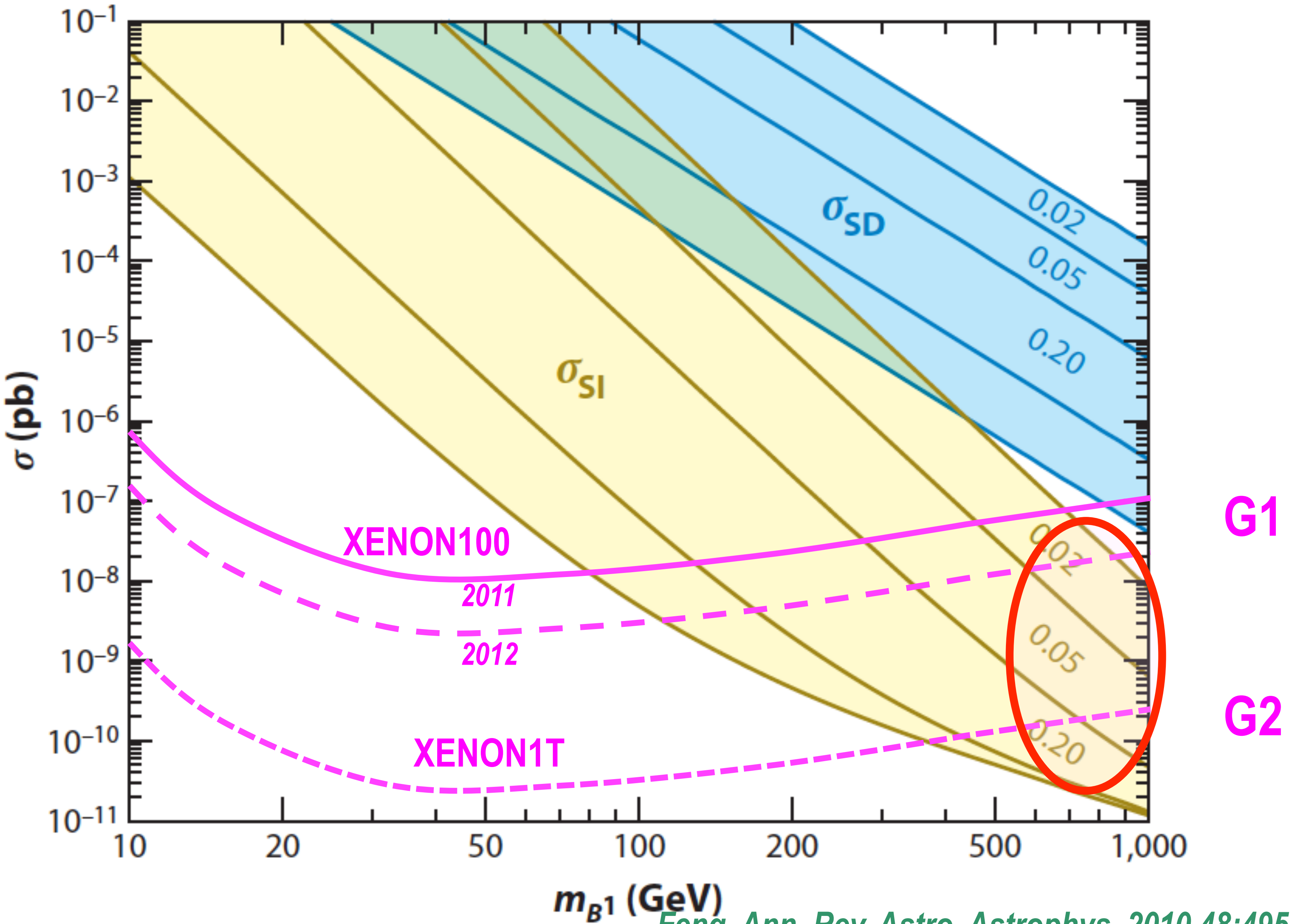


$B^{(1)}$



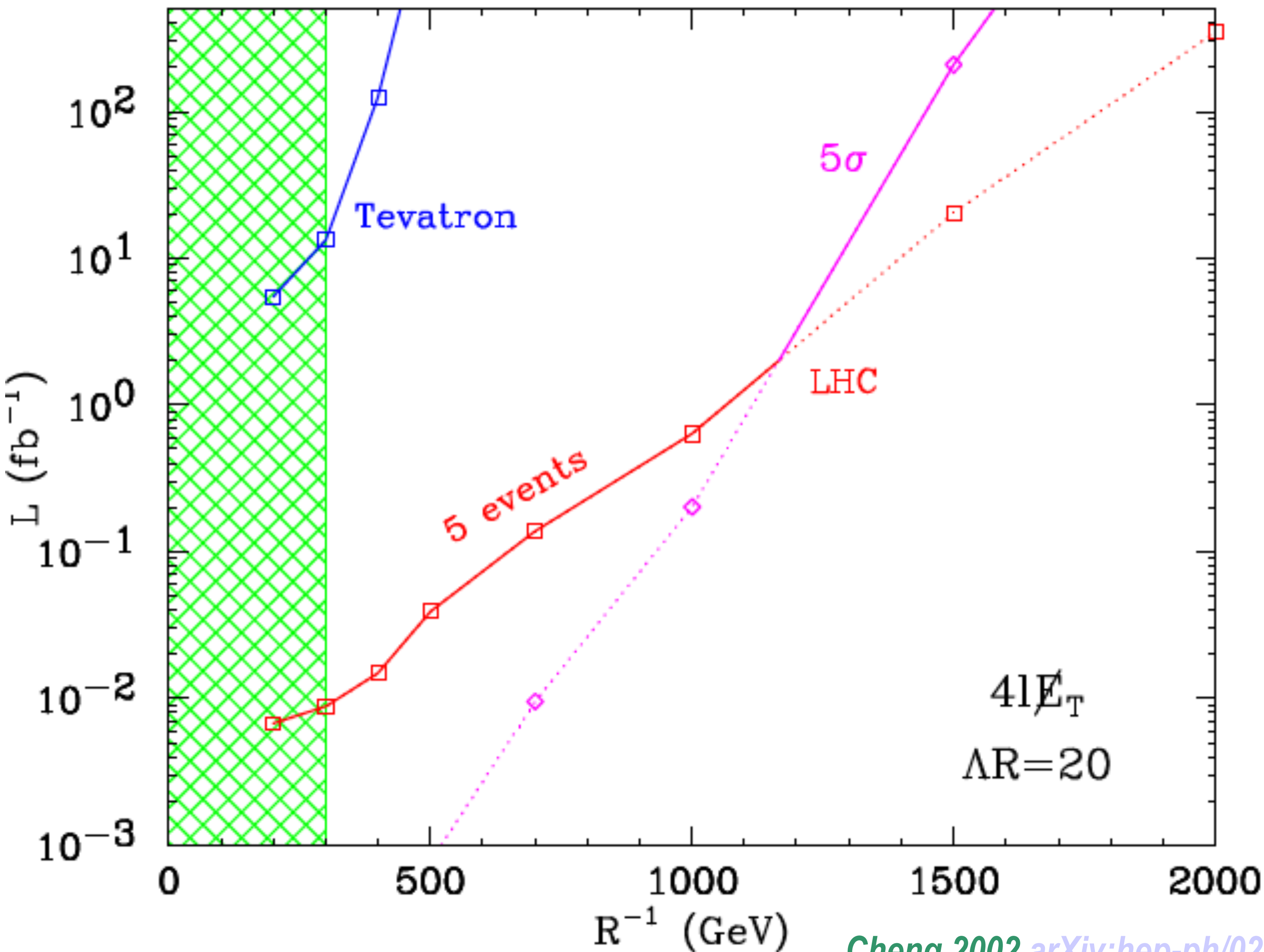
Berone et al Phys. Rep. 2005

Predicted Cross Section of Kaluza-Klein Dark Matter



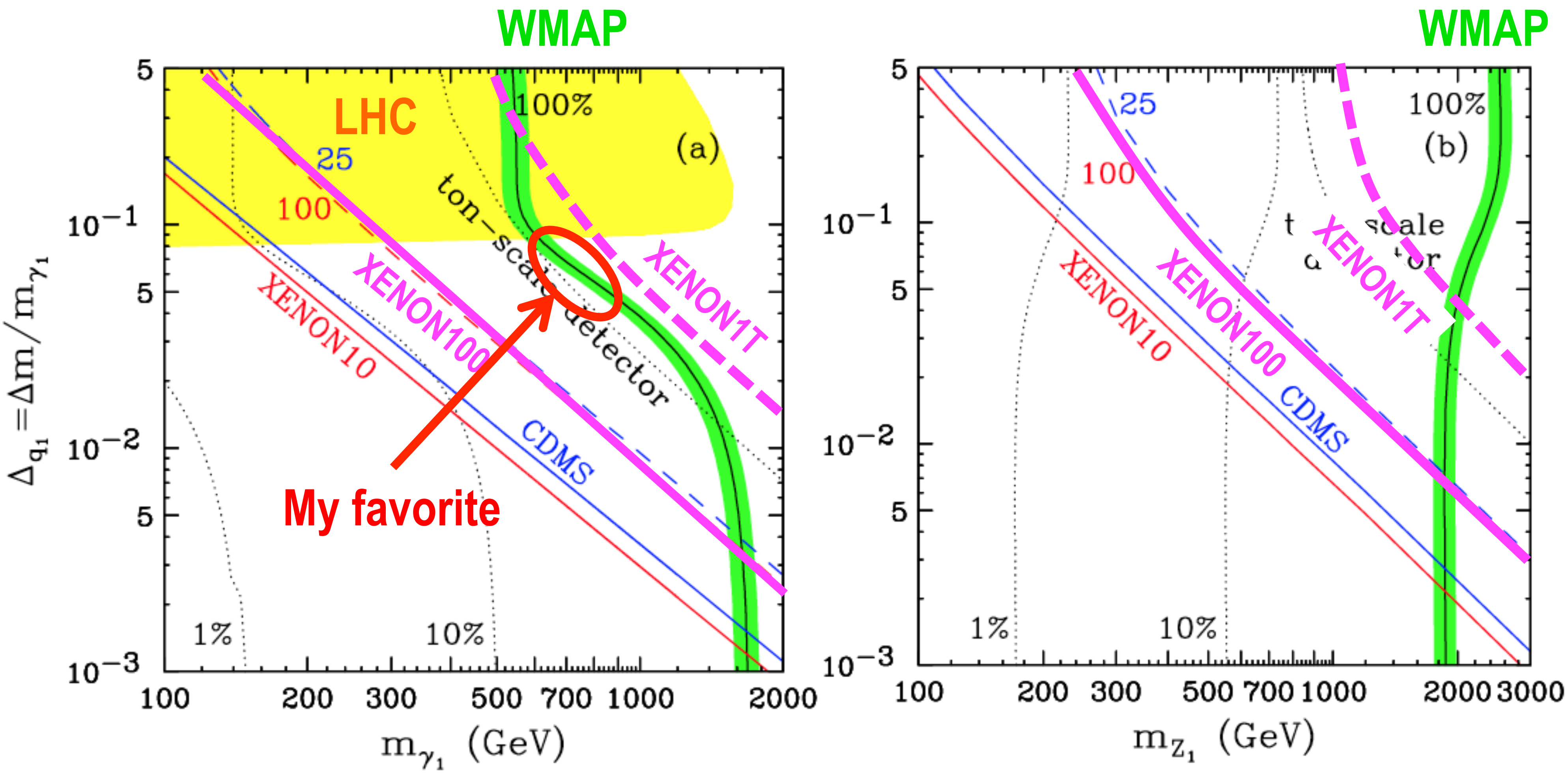
Feng Ann. Rev. Astro. Astrophys. 2010.48:495-545

Discovery Potential by LHC



Cheng 2002 arXiv:hep-ph/0205314v1

Sensitivity to KK particles

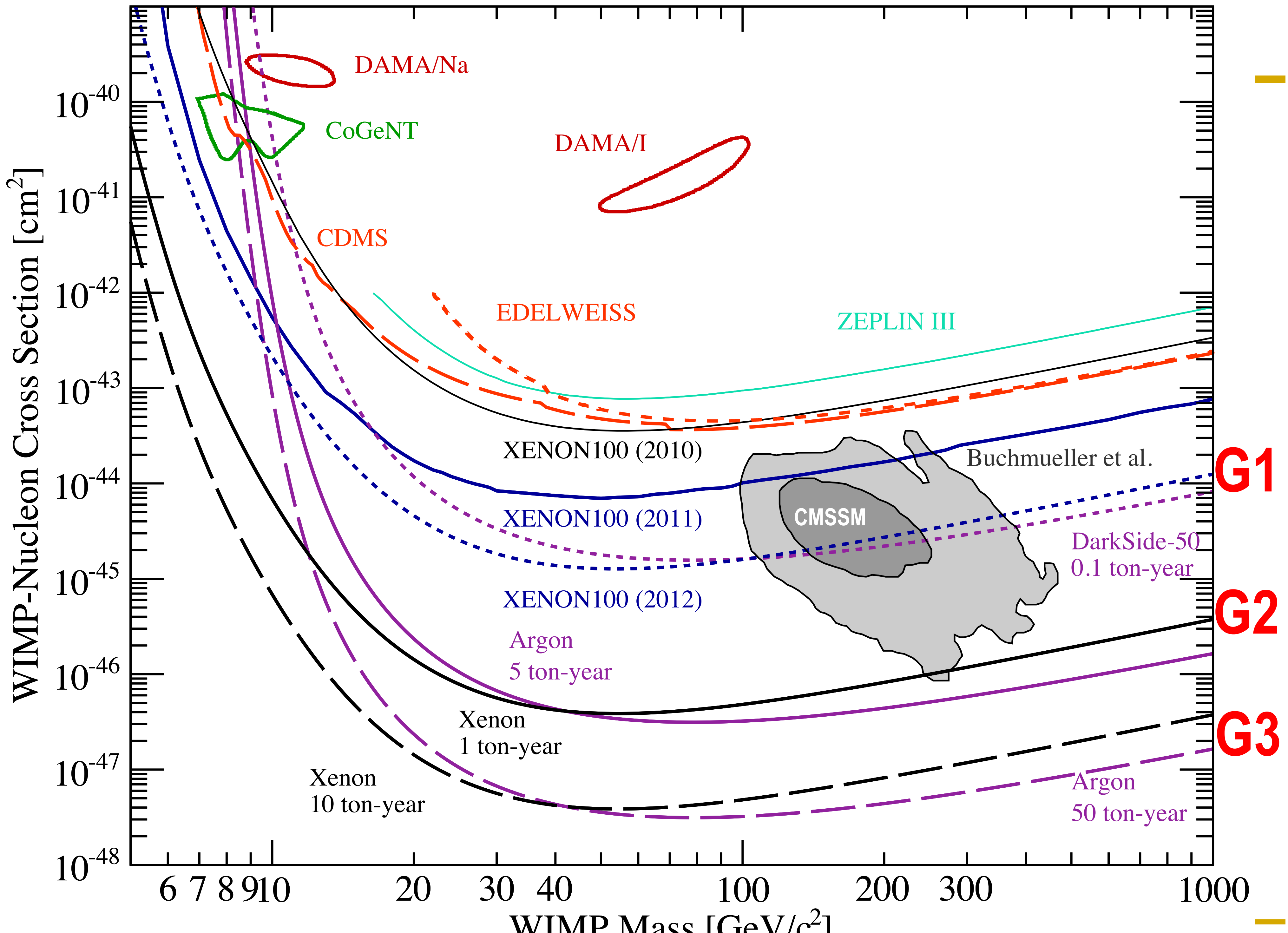


Arrenberg 2008

Summary on "Science Cases"

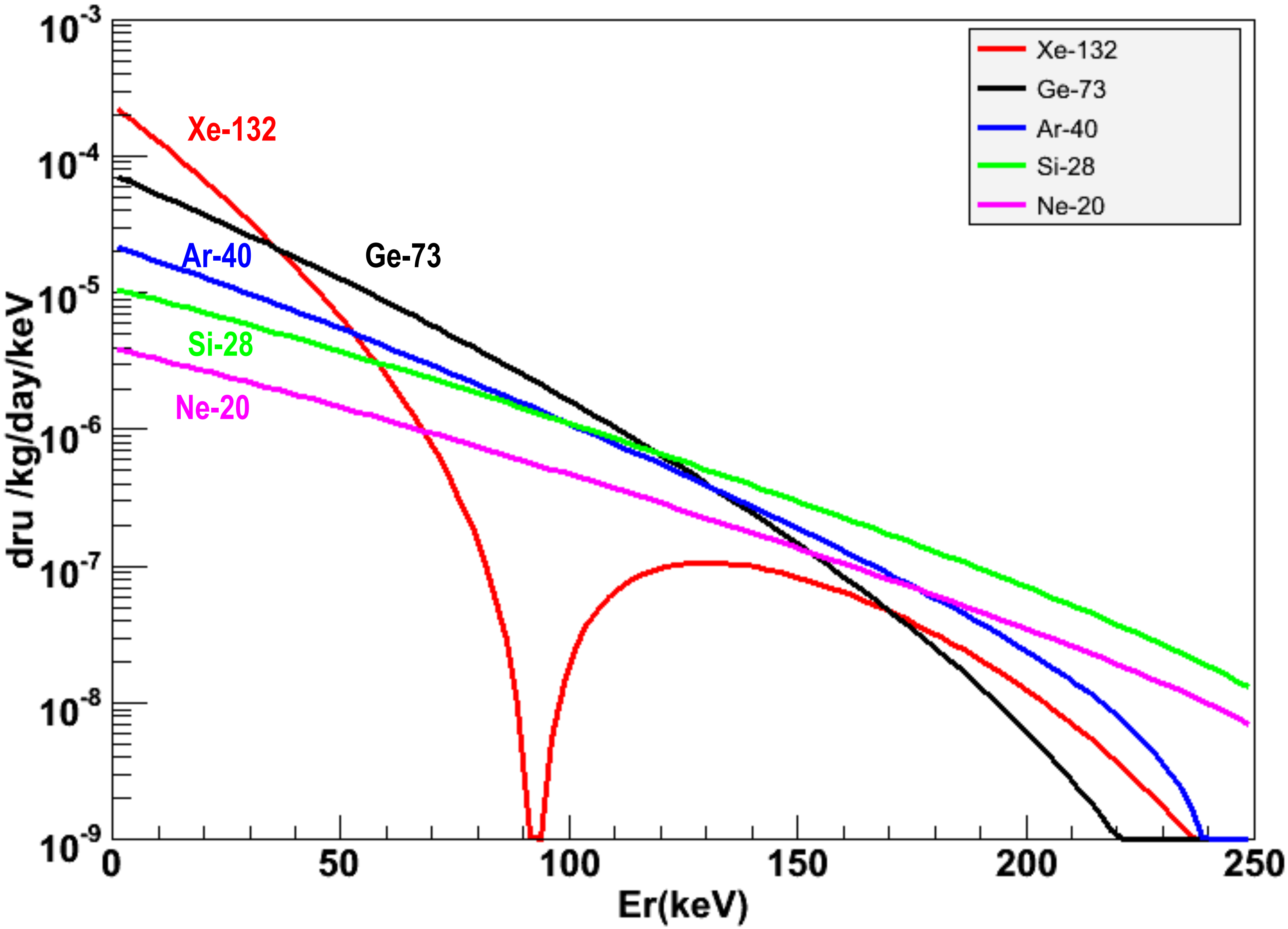
- XENON program (~$10M) is extremely timely and competitive to LHC (~$10B)
  - XENON100 ~ Current LHC
  - XENON1T ~ Future LHC
- If new physics at 100 – 1000 GeV (as it should be), both LHC and XENON1T will discover WIMPs.
  - SUSY - Neutralino
  - Extra Dimensions – KK particles
- By combining LHC and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

Ultimate Detectors

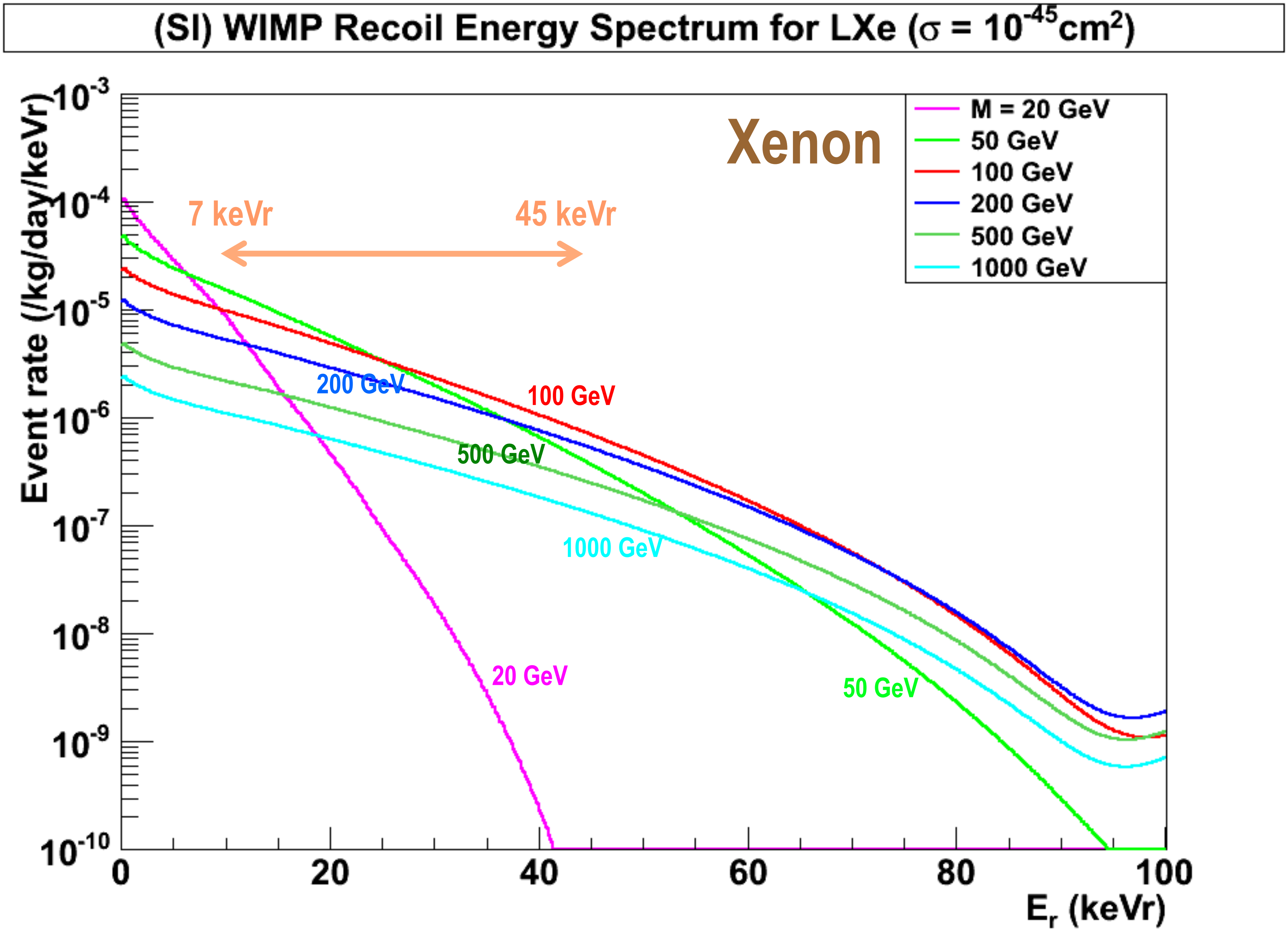

WIMP-Nucleon Cross Section [cm^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
6 7 8 9 10 20 30 40 100 200 300 1000
WIMP Mass [GeV/c^2]
DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
ZEPLIN III
XENON100 (2010)
XENON100 (2011)
XENON100 (2012)
Buchmueller et al.
CMSSM
DarkSide-50
0.1 ton-year
Argon
5 ton-year
Xenon
1 ton-year
Xenon
10 ton-year
Argon
50 ton-year
G1
G2
G3

Target Mass Dependence of WIMP Cross Section

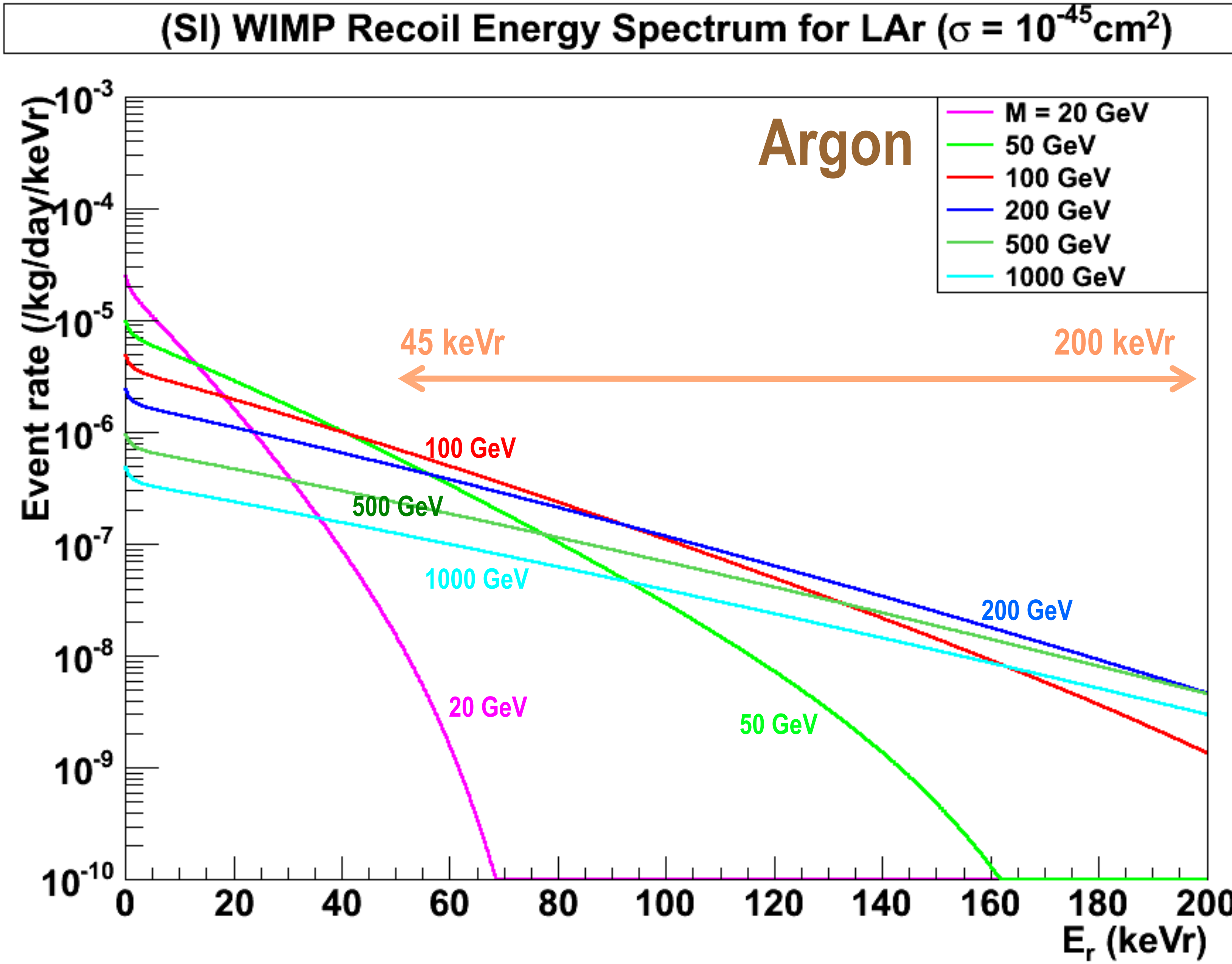
cross section 10^{-44} cm^2 , WIMP mass 100 GeV

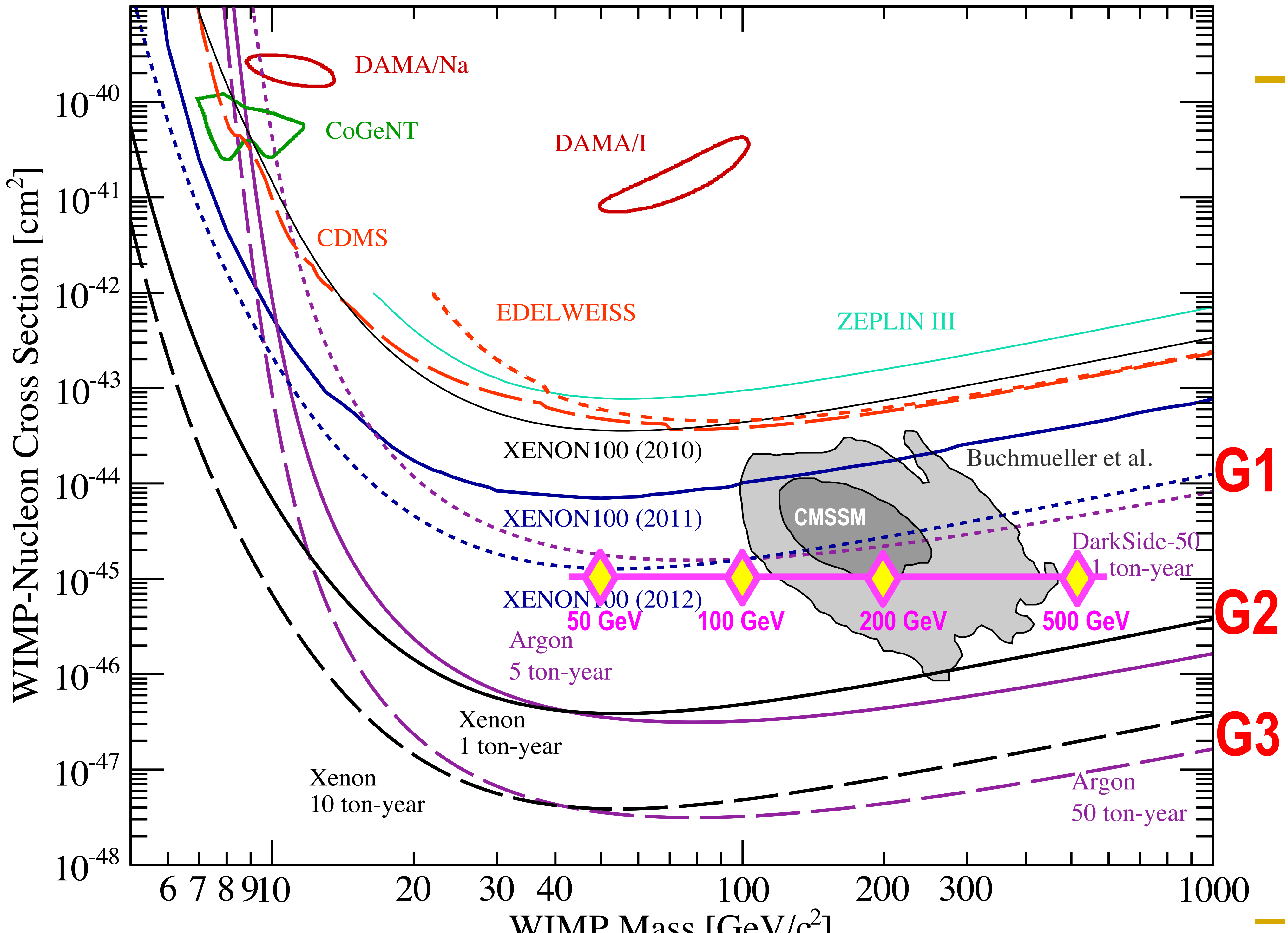


(SI) WIMP Energy Spectrum for LXe
(Cross Section = $10^{-45}cm^2$)



(SI) WIMP Energy Spectrum for LAr
(Cross Section = $10^{-45}cm^2$)





DAMA/Na
CoGeNT
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CDMS
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XENON100 (2010)
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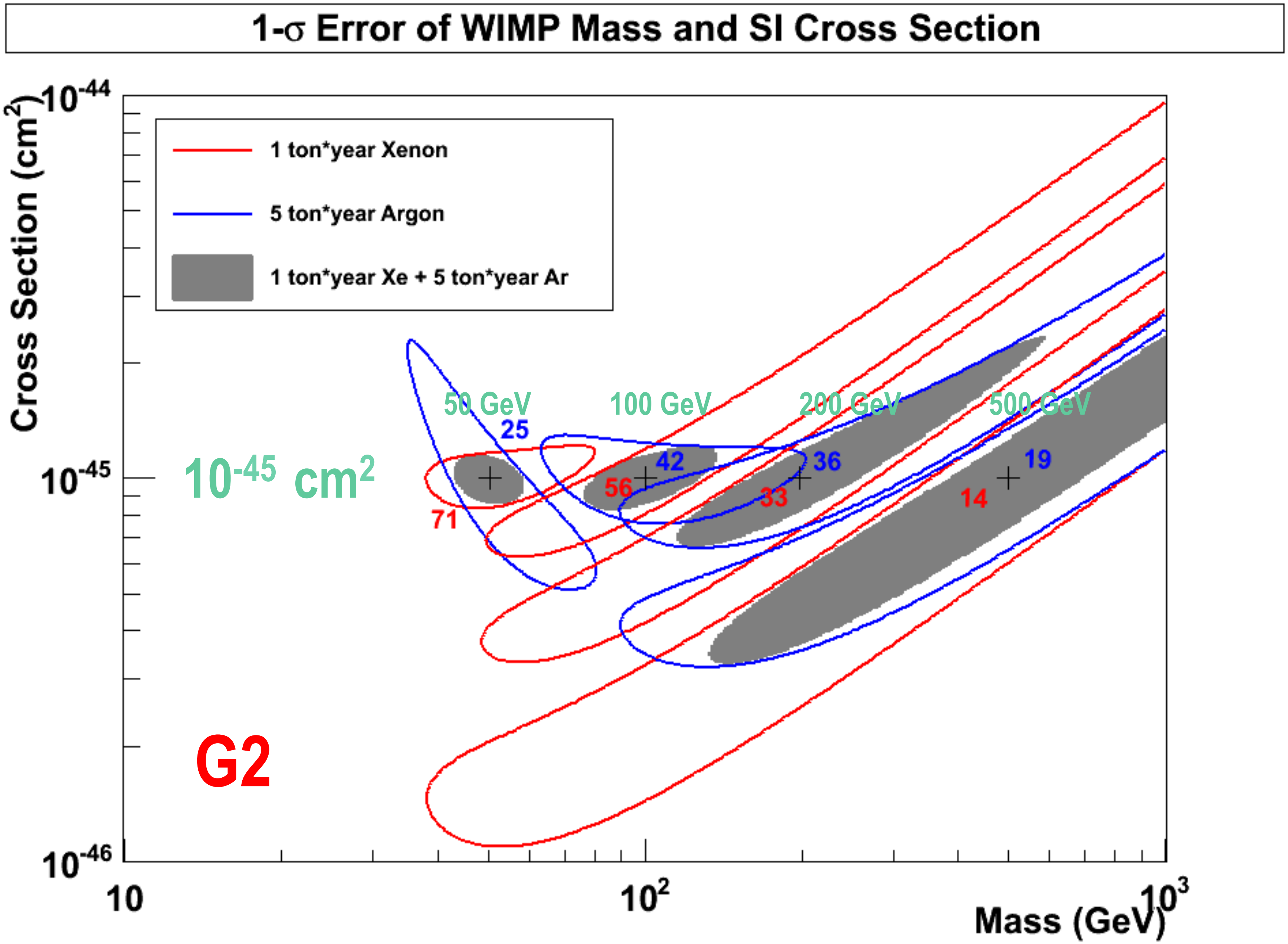
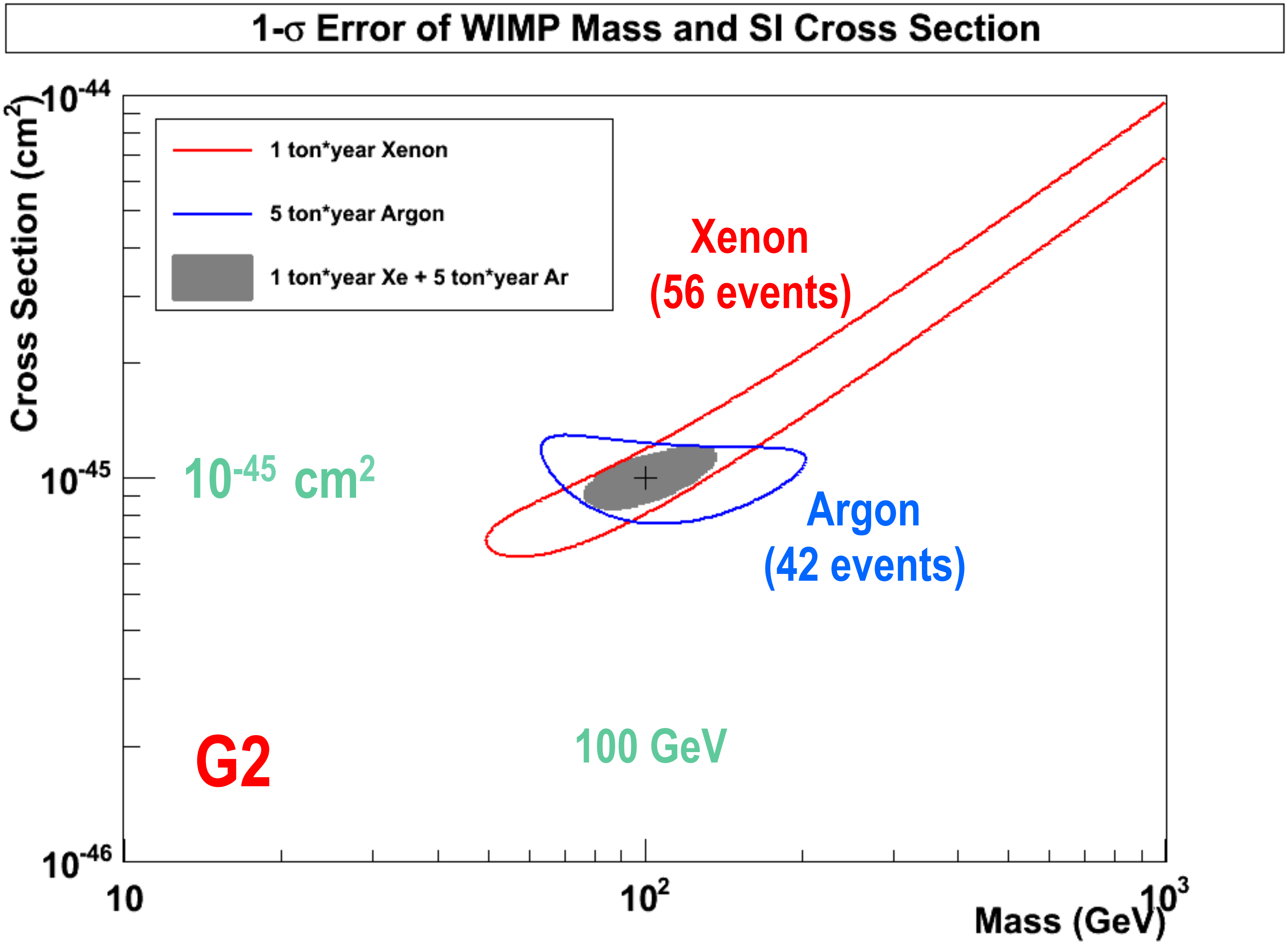
CMSSM
DarkSide-50
1 ton-year
50 GeV
100 GeV
200 GeV
500 GeV
Argon
5 ton-year
Xenon
1 ton-year
Xenon
10 ton-year
Argon
50 ton-year
G1
G2
G3
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
6 7 8 9 10 20 30 40 100 200 300 1000

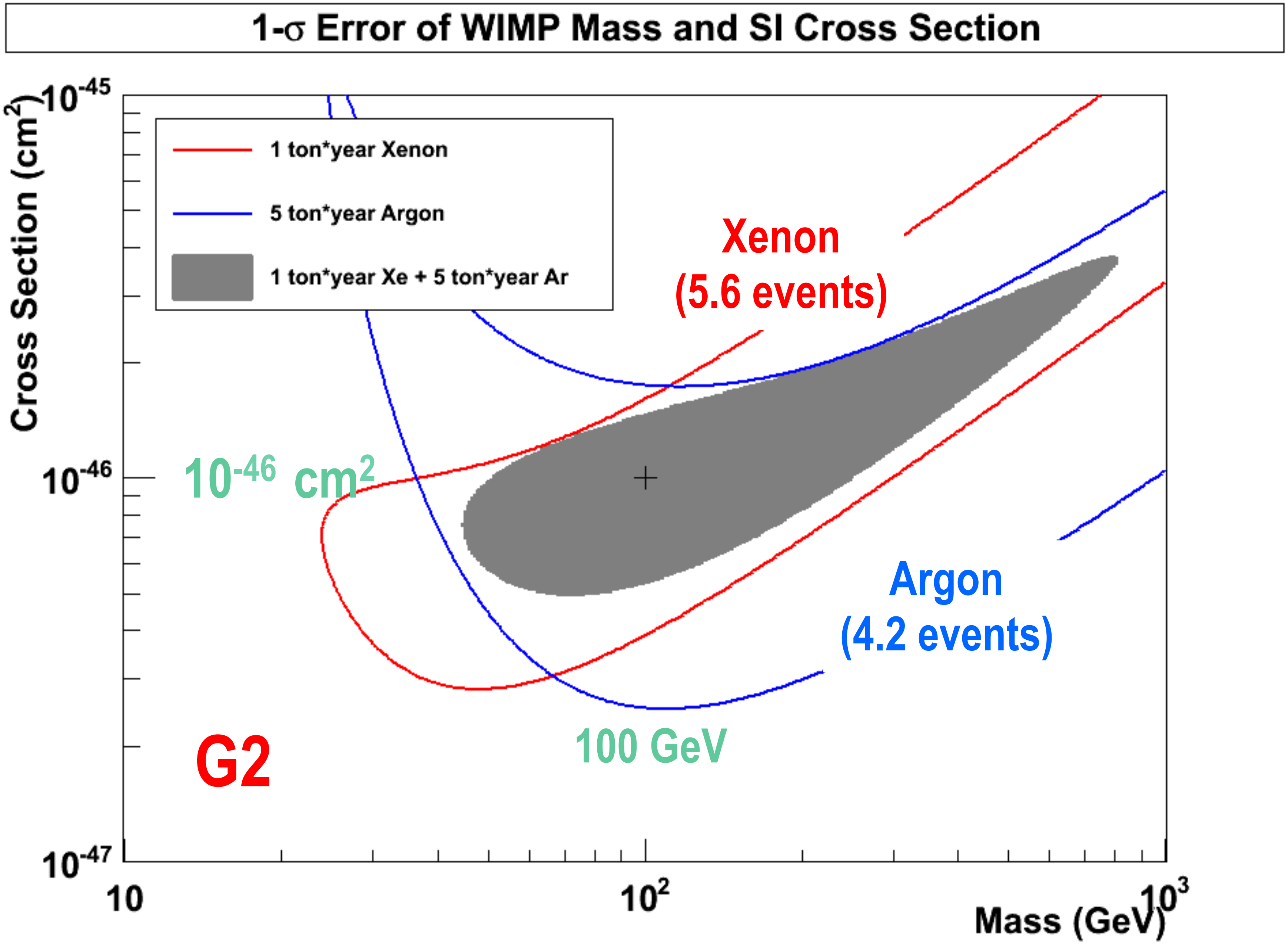
1-σ Error of WIMP Mass vs SI Cross Section
(1 ton*year Xe and 5 ton*year Ar)



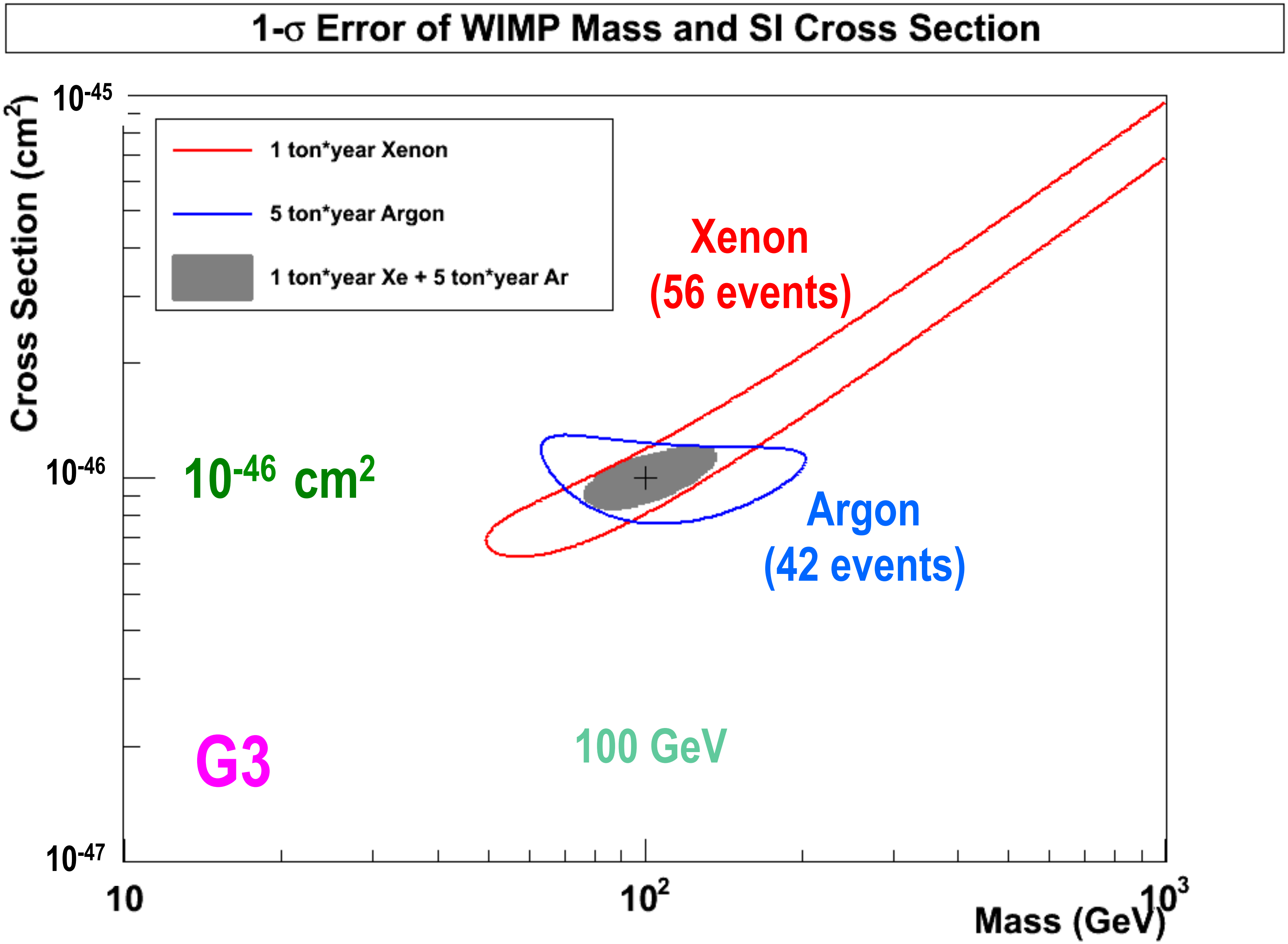
1-σ Error of WIMP Mass vs SI Cross Section
(1 ton*year Xe and 5 ton*year Ar)



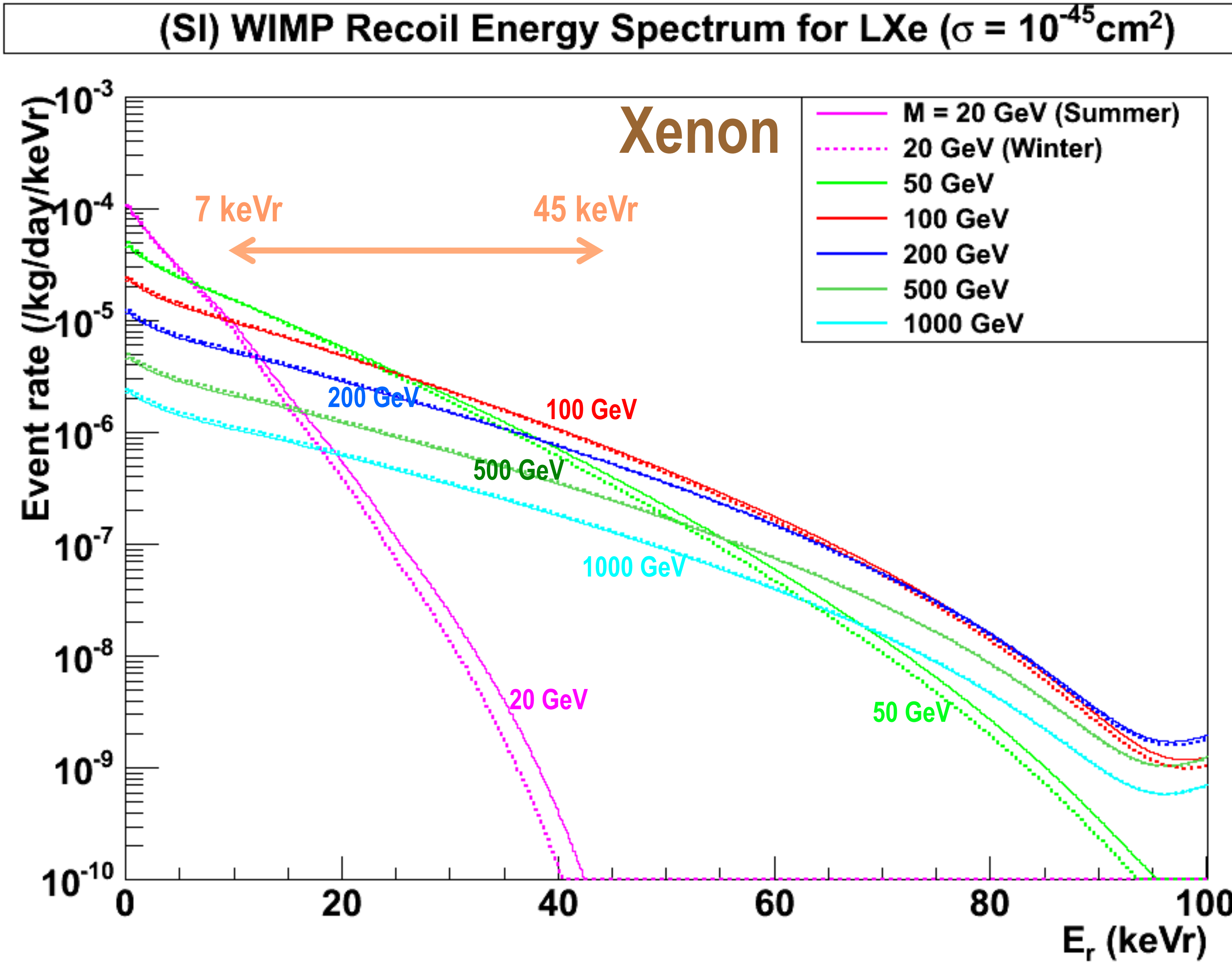
1-σ Error of WIMP Mass vs SI Cross Section
(1 ton*year Xe and 5 ton*year Ar)



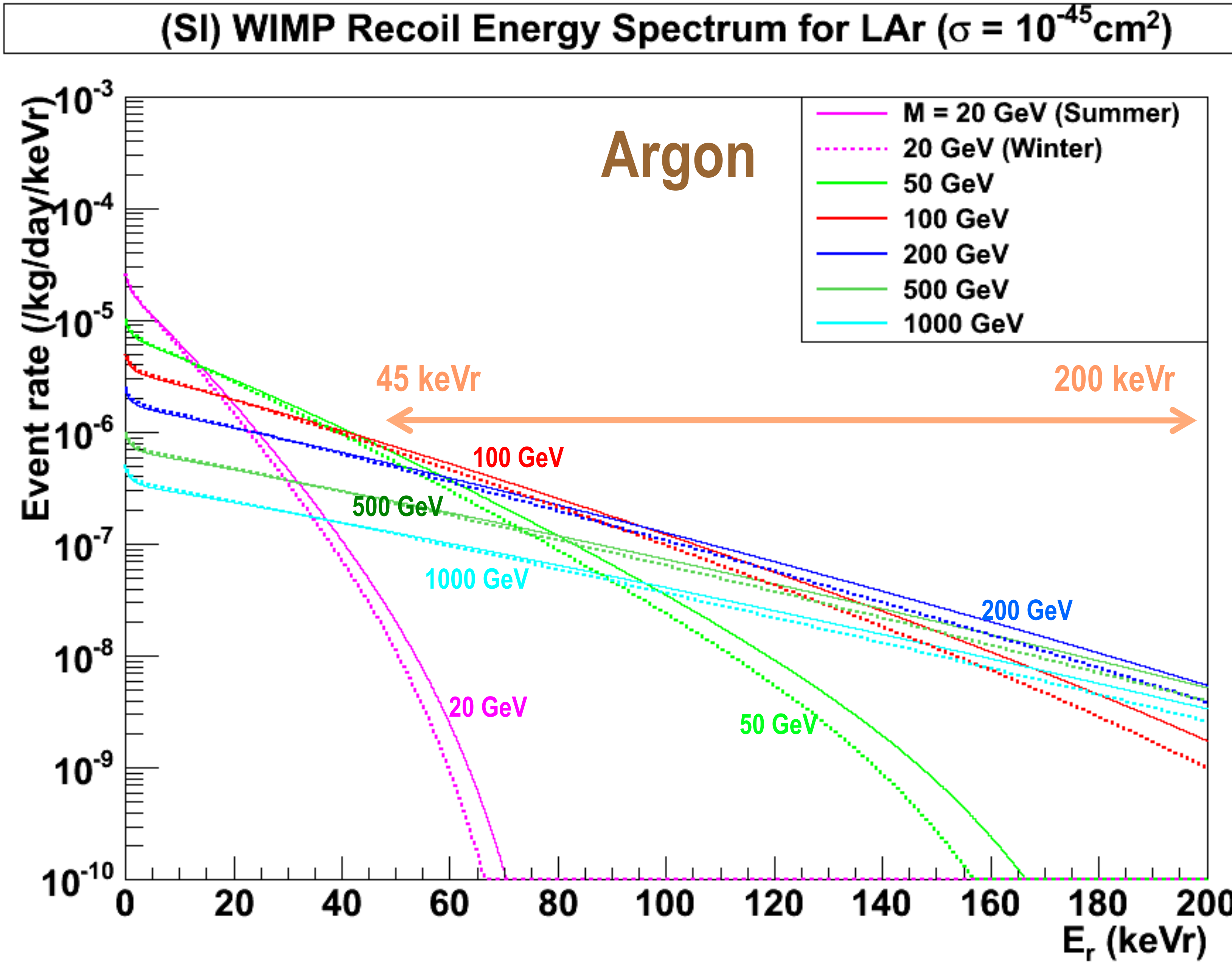
1-σ Error of WIMP Mass vs SI Cross Section (10 ton*year Xe and 50 ton*year Ar)



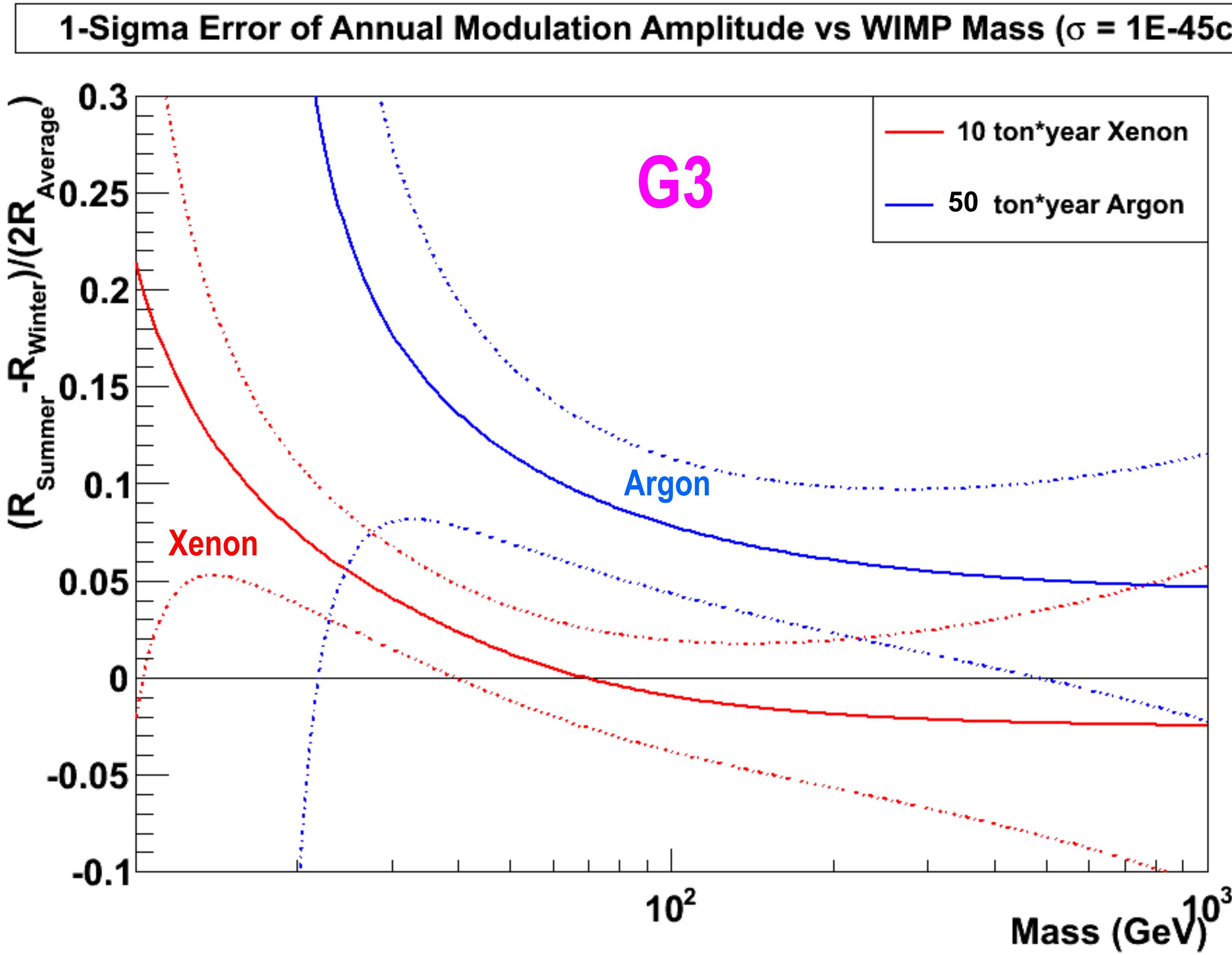
(SI) WIMP Energy Spectrum for LXe
(Cross Section = $10^{-45}cm^2$)



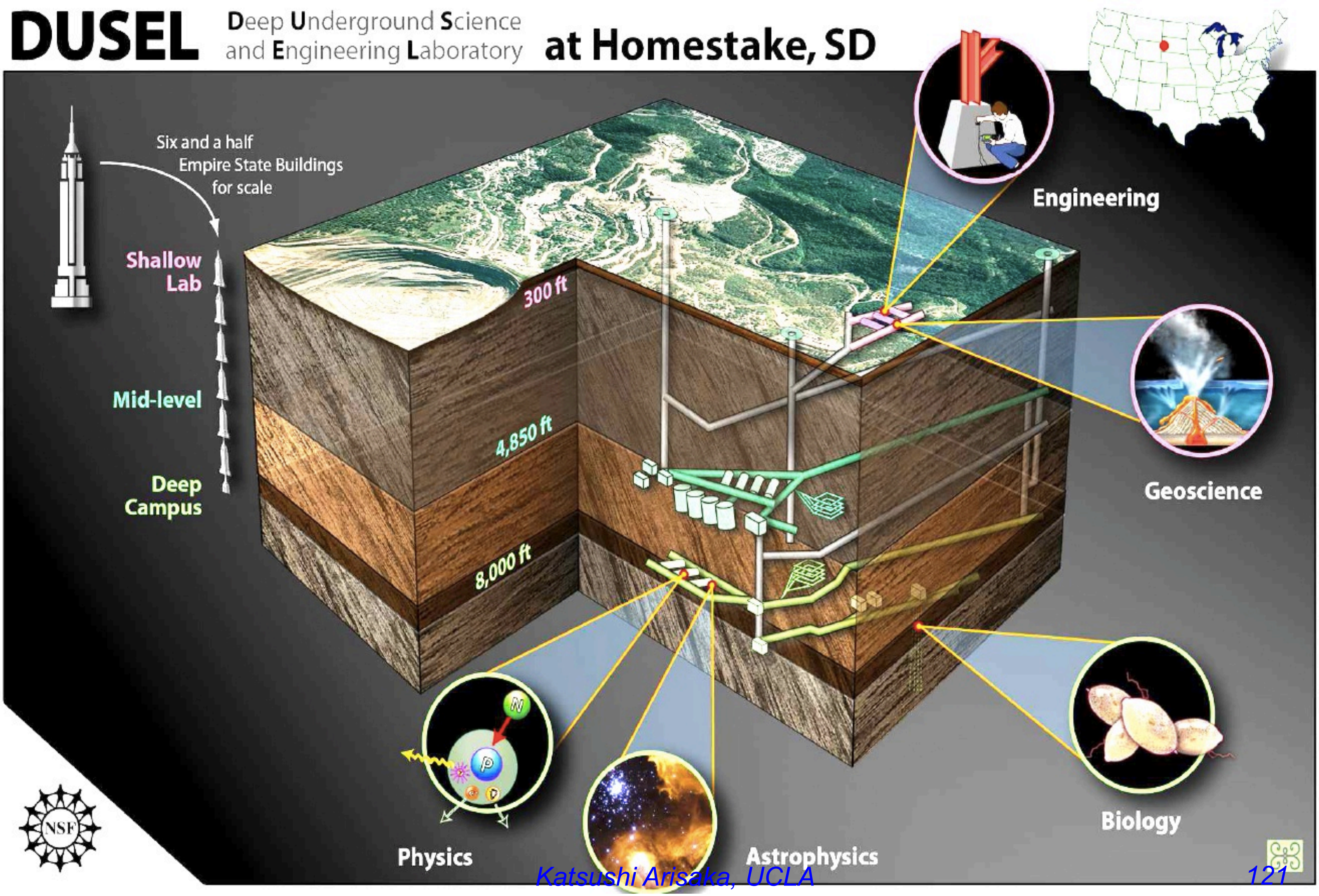
(SI) WIMP Energy Spectrum for LAr
(Cross Section = $10^{-45}cm^2$)



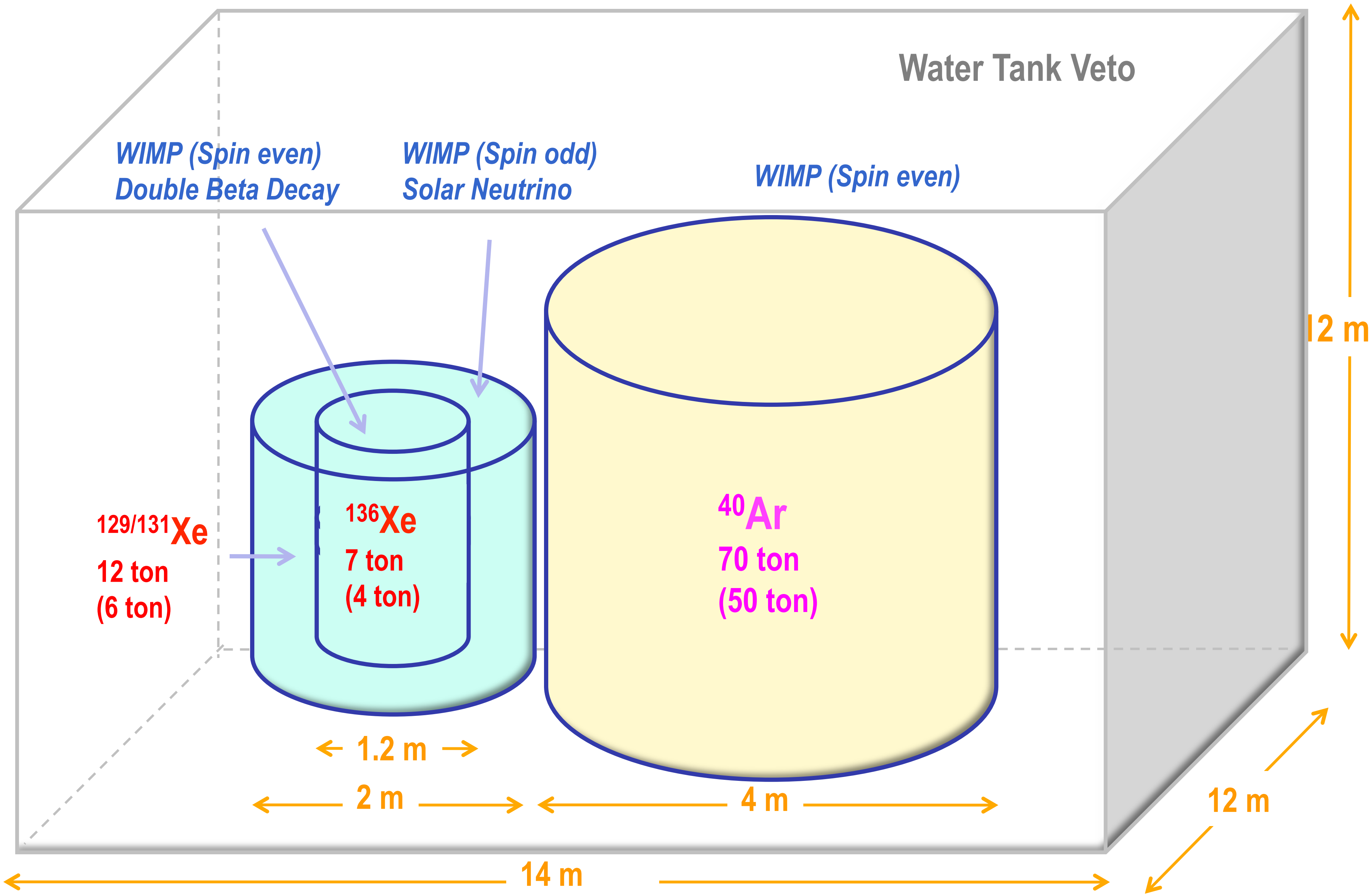
$\pm 1\sigma$ Error of Annual Modulation Amplitude vs WIMP Mass
(10 ton*year Xe and 50 ton*year Ar, Cross Section = $10^{-45}cm^2$)



DUSEL at Homestake, started in 2007



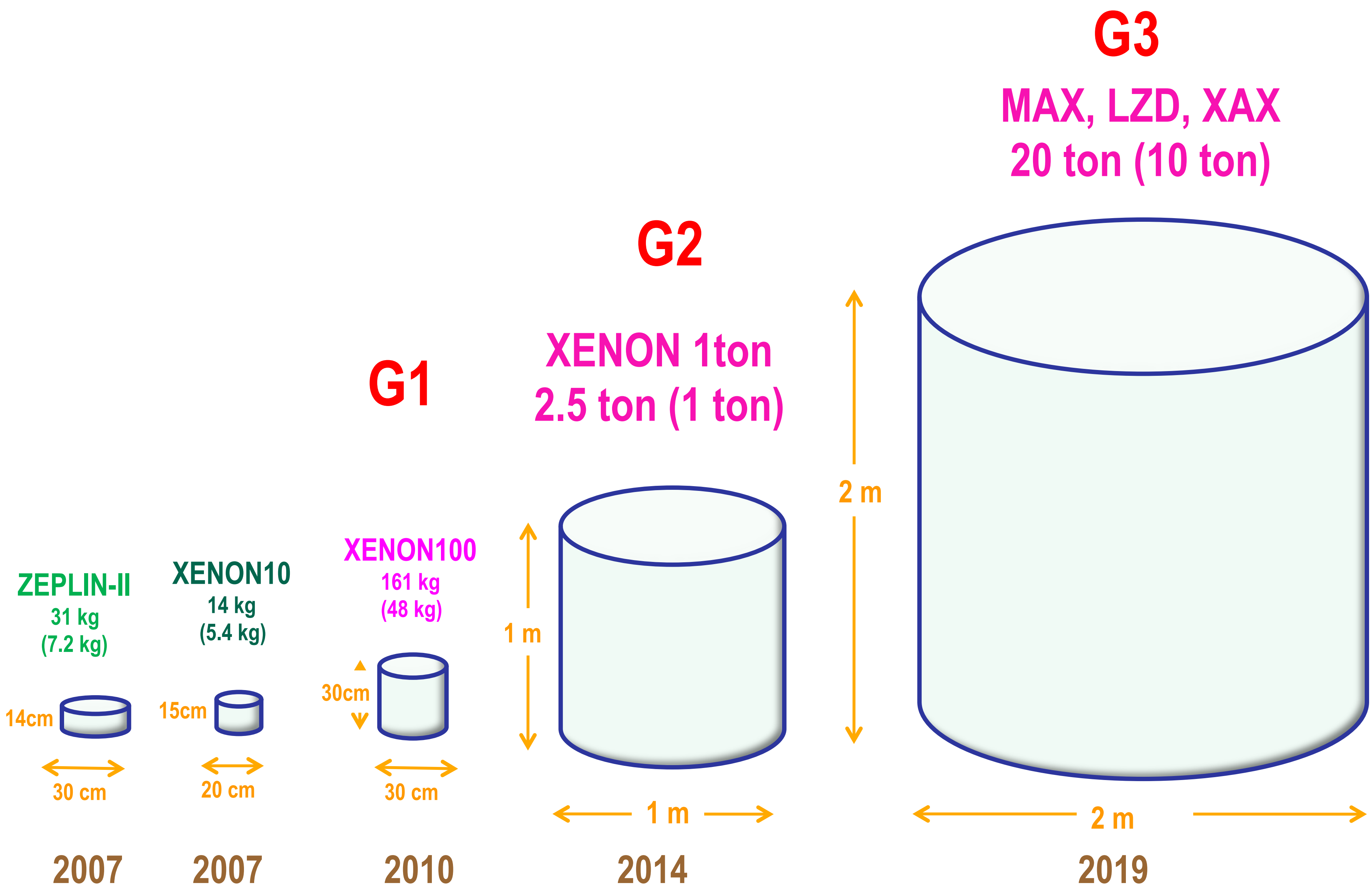
XAX (Xenon-Argon-Xenon) arXiv:0808.3968



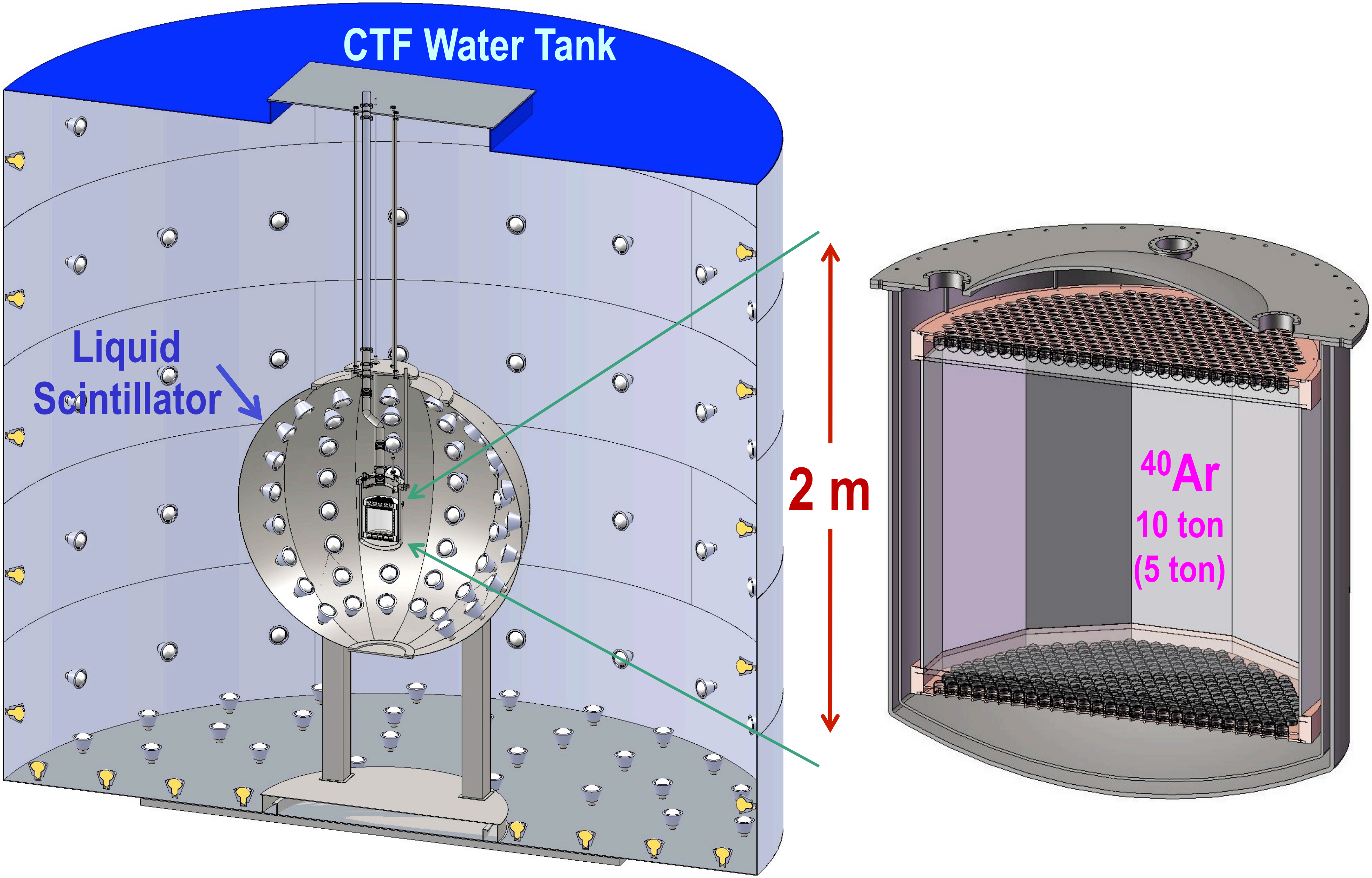
G2 and G3 facilities defined by PASAG (2009)

	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

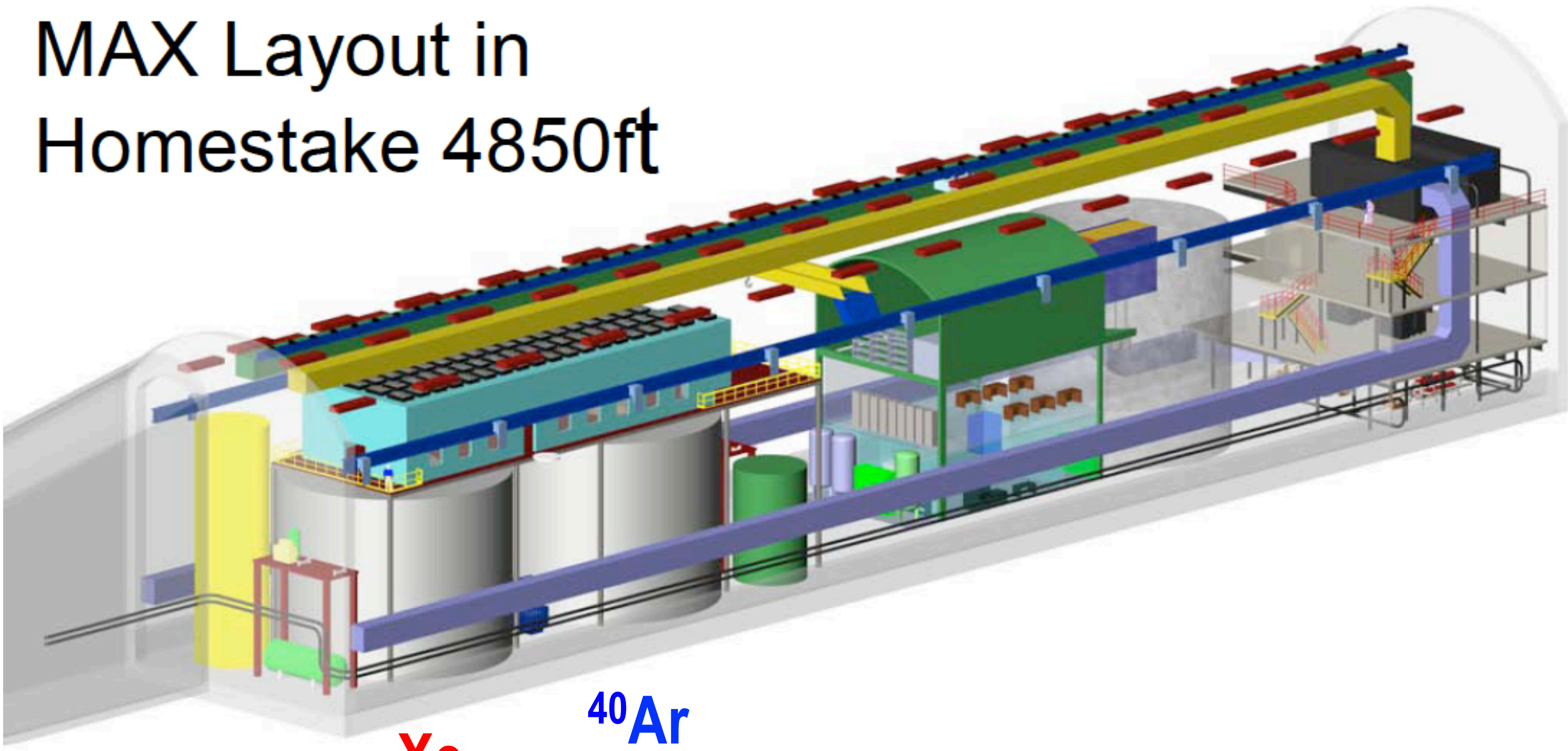
Comparison of Xenon Detector Size



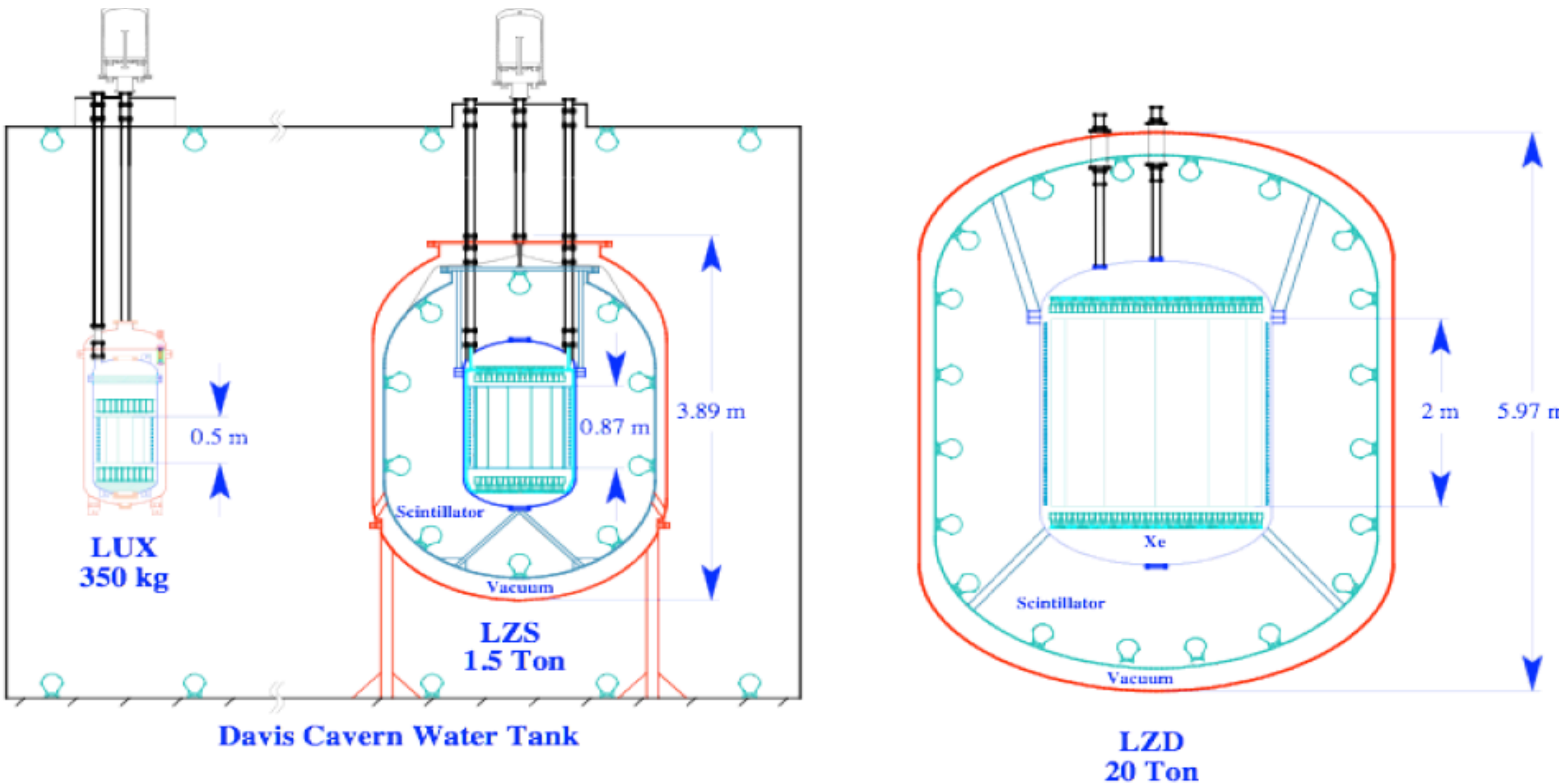
DarkSide 5T (G2) at LNGS



MAX (G3) (at DUSEL)

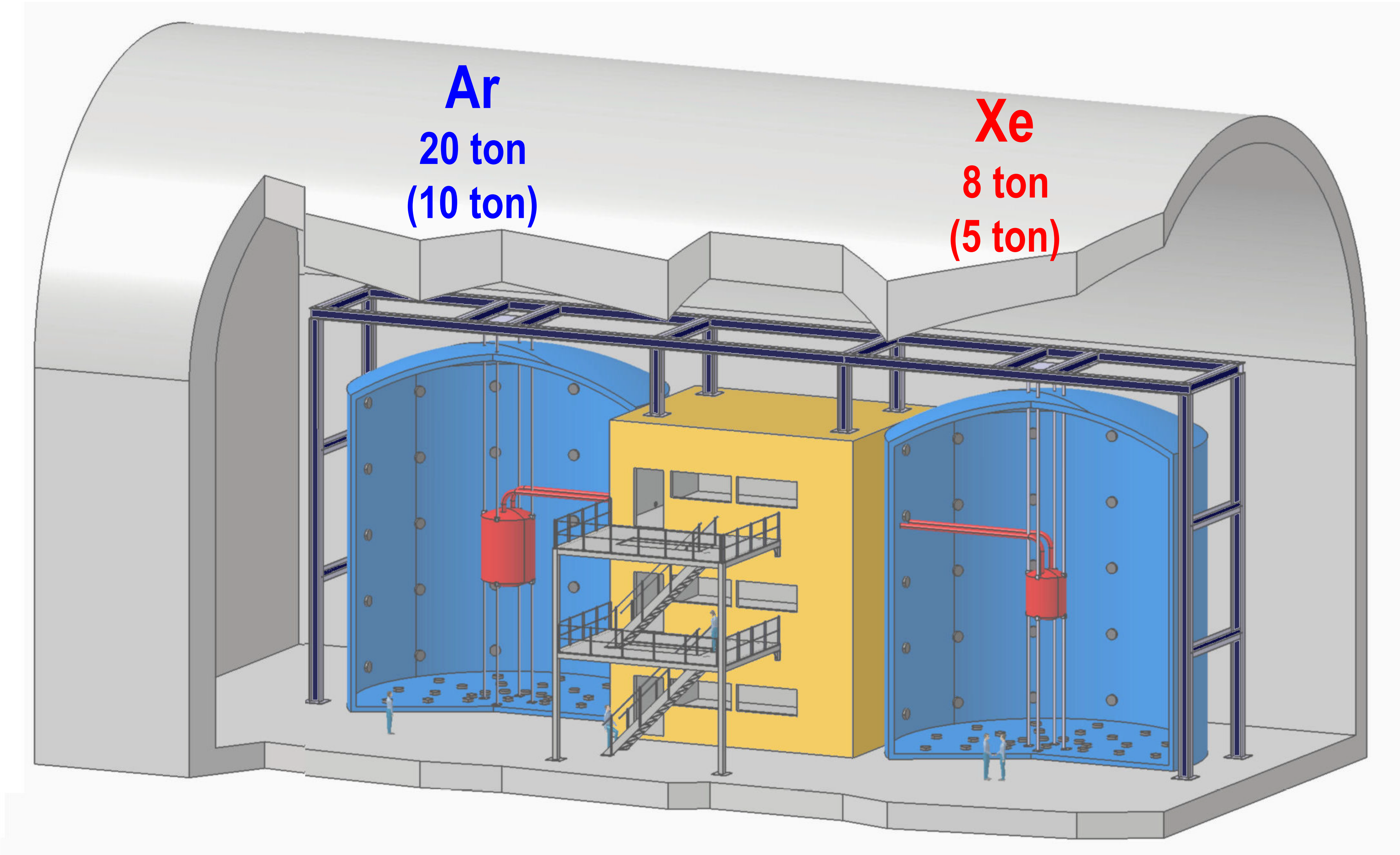


LUX and LZD (at DUSEL)

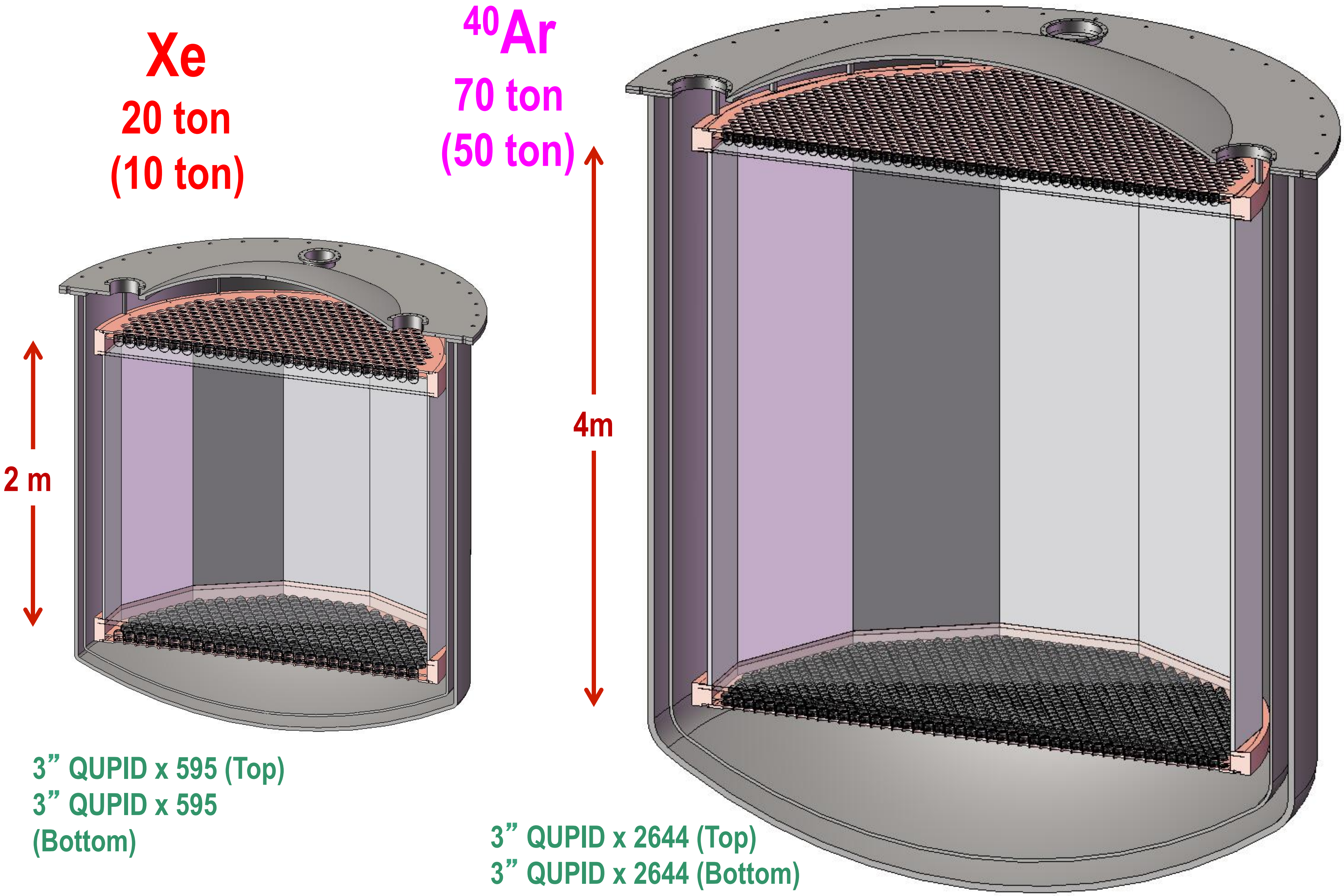


G1 G2 G3

DARWIN in Europe (LNGS?)

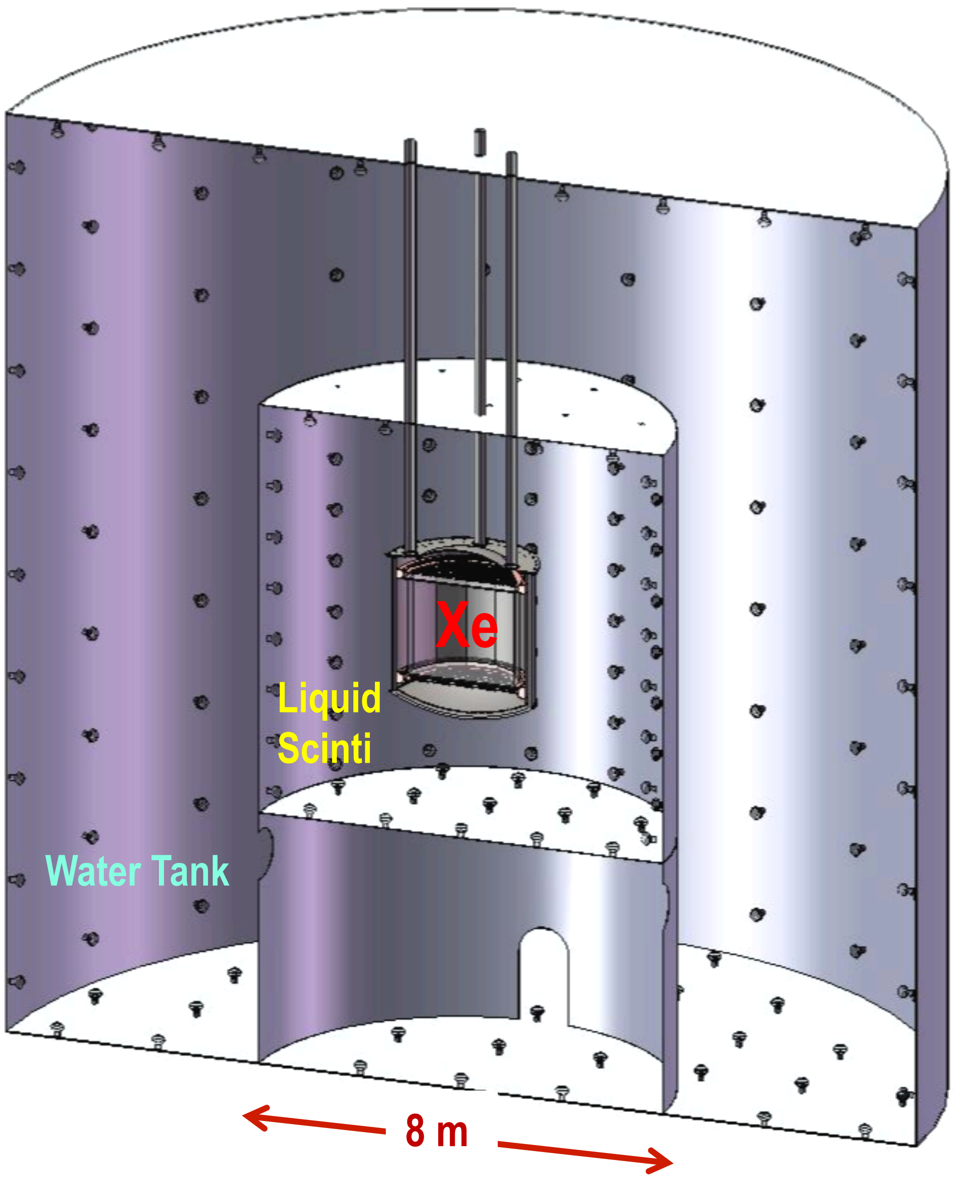


MAX+LZD = “Ultimate G3” Detector (at DUSEL)

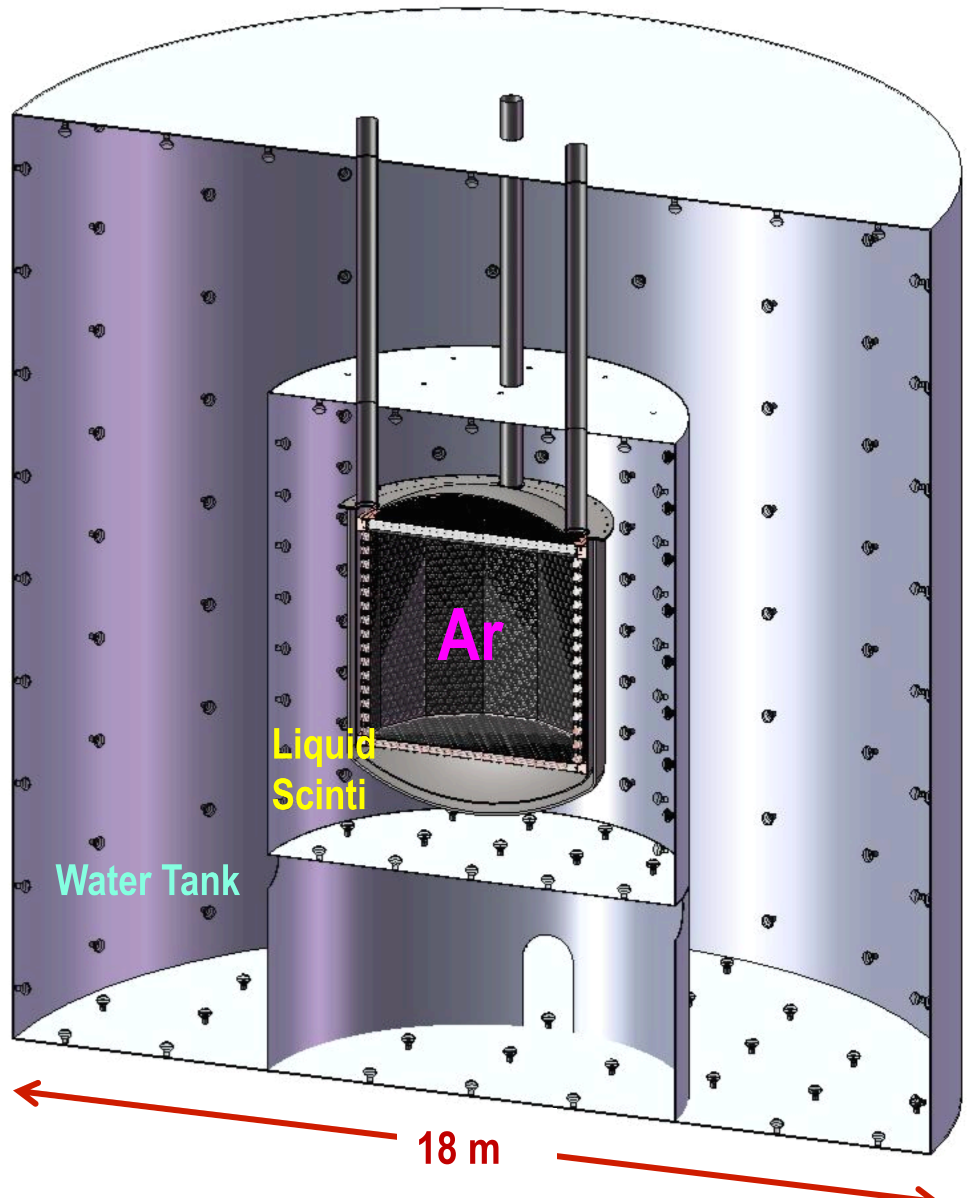


MAX+LZD = "Ultimate G3" Detector (at DUSEL)

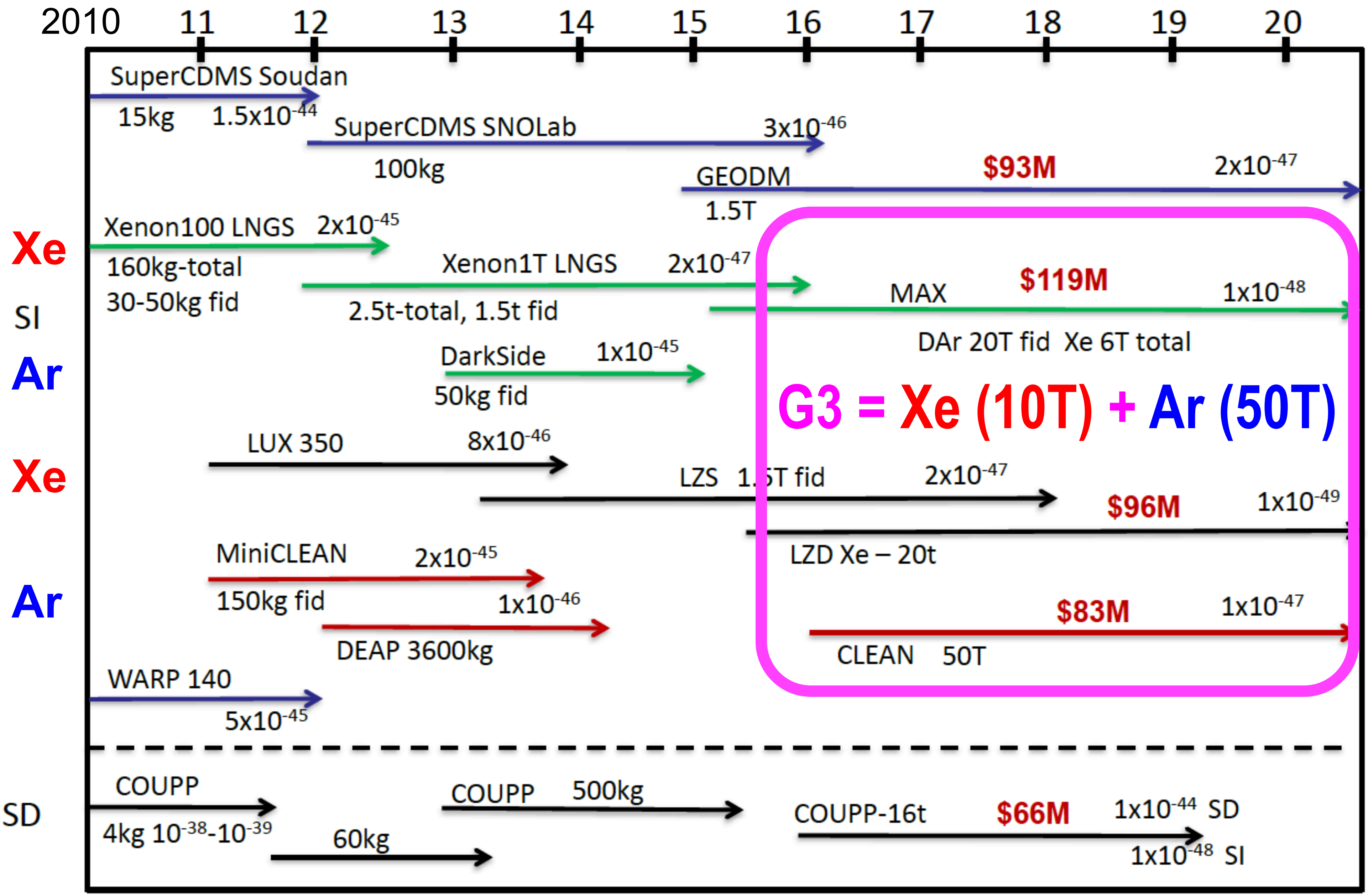
Xe 20 ton (10 ton)



^{40}Ar 70 ton (50 ton)



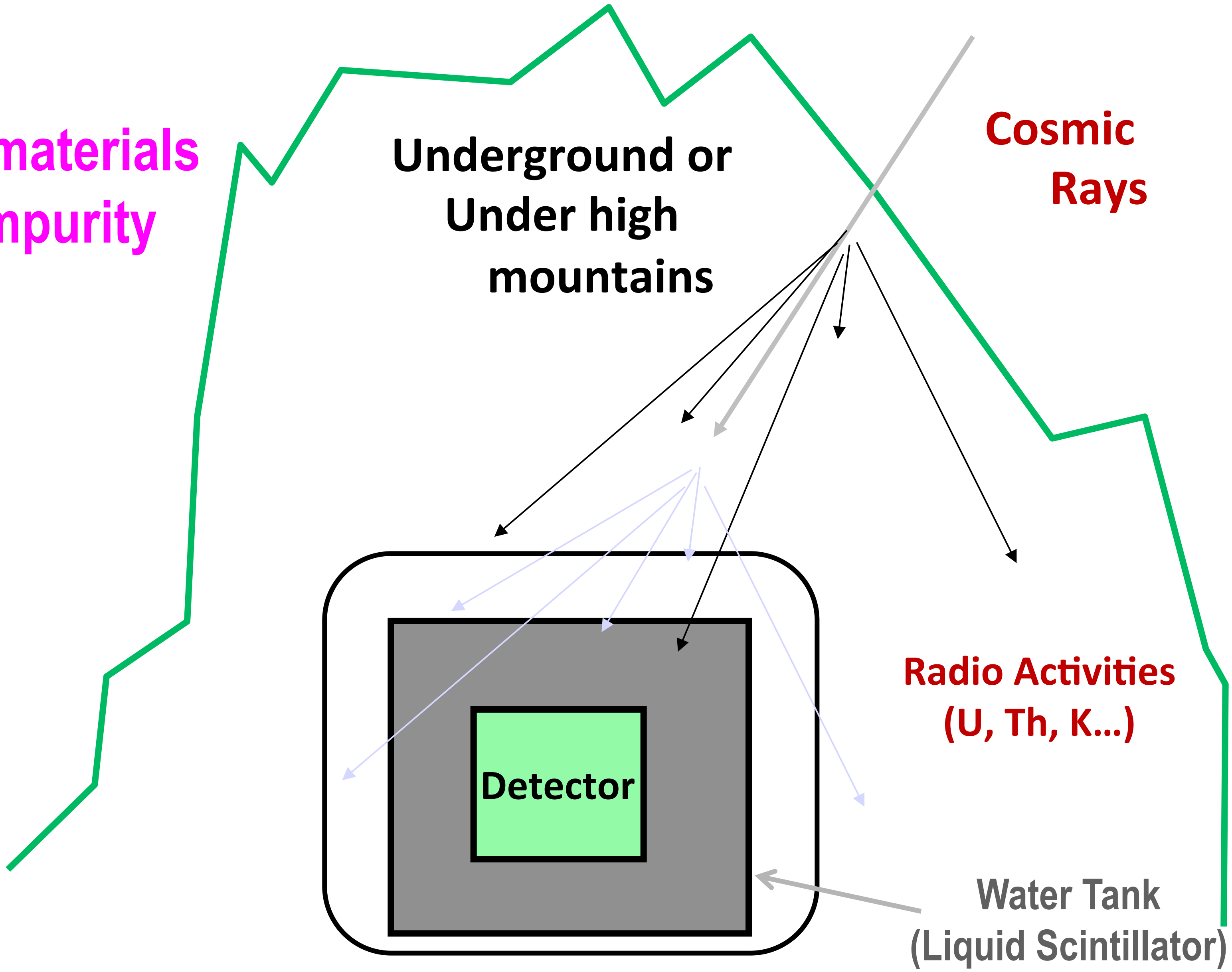
US Dark Matter Programs



Technological Challenges

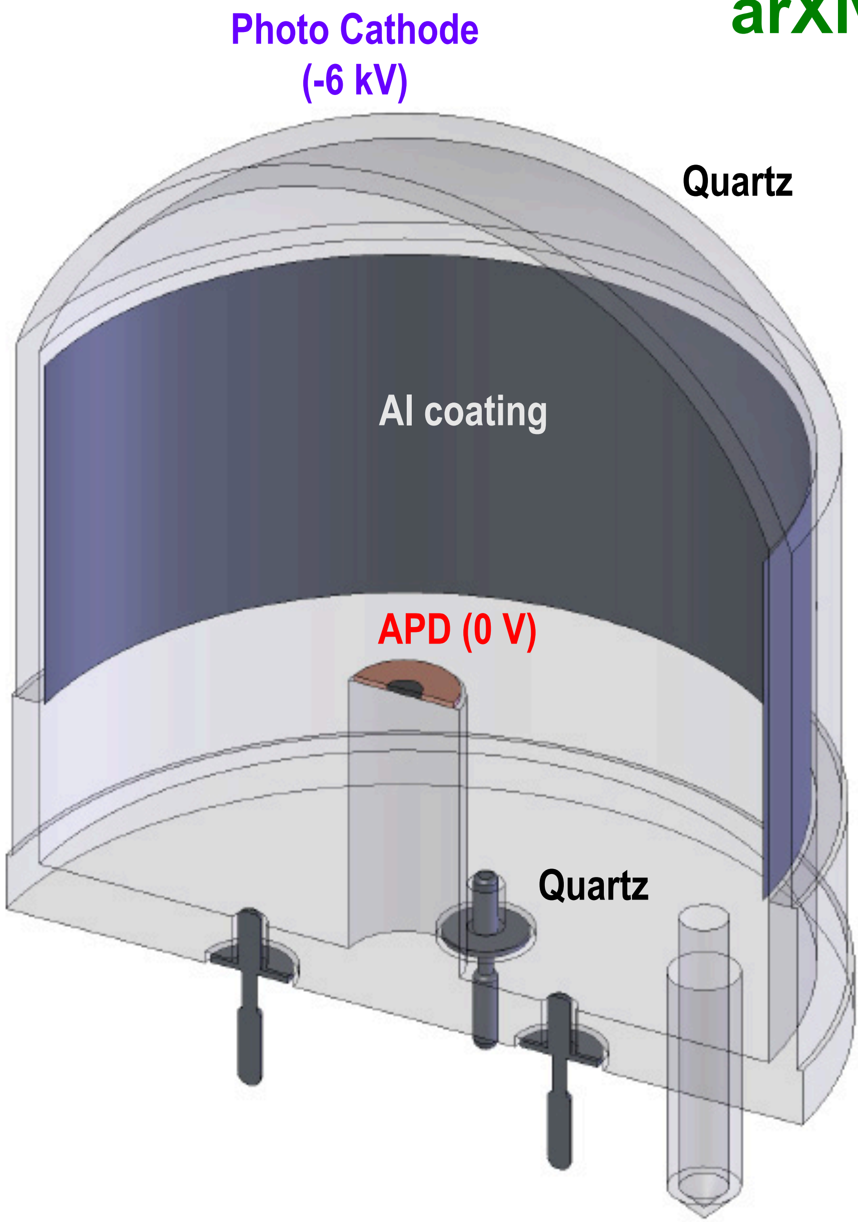
Where backgrounds come from?

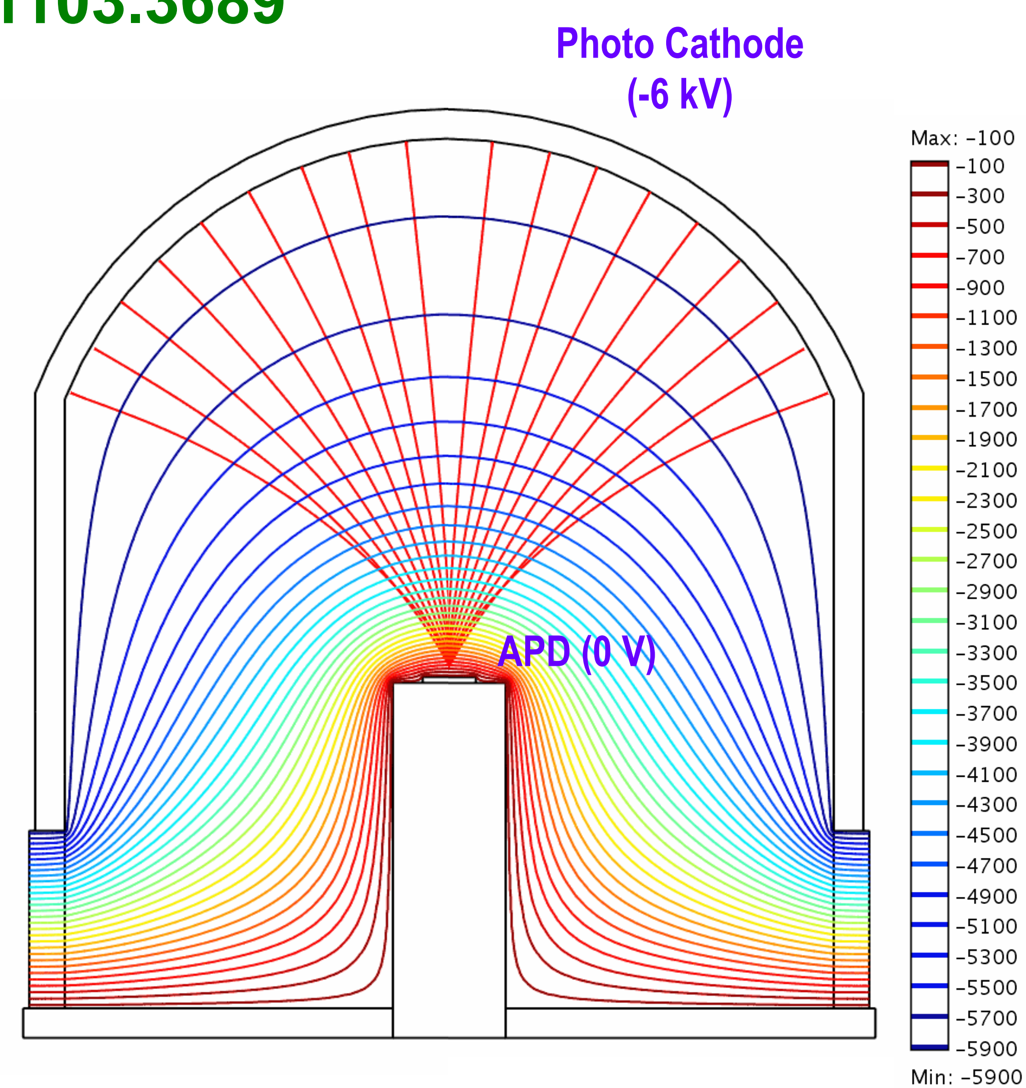
- External
- Detector materials
- Internal impurity



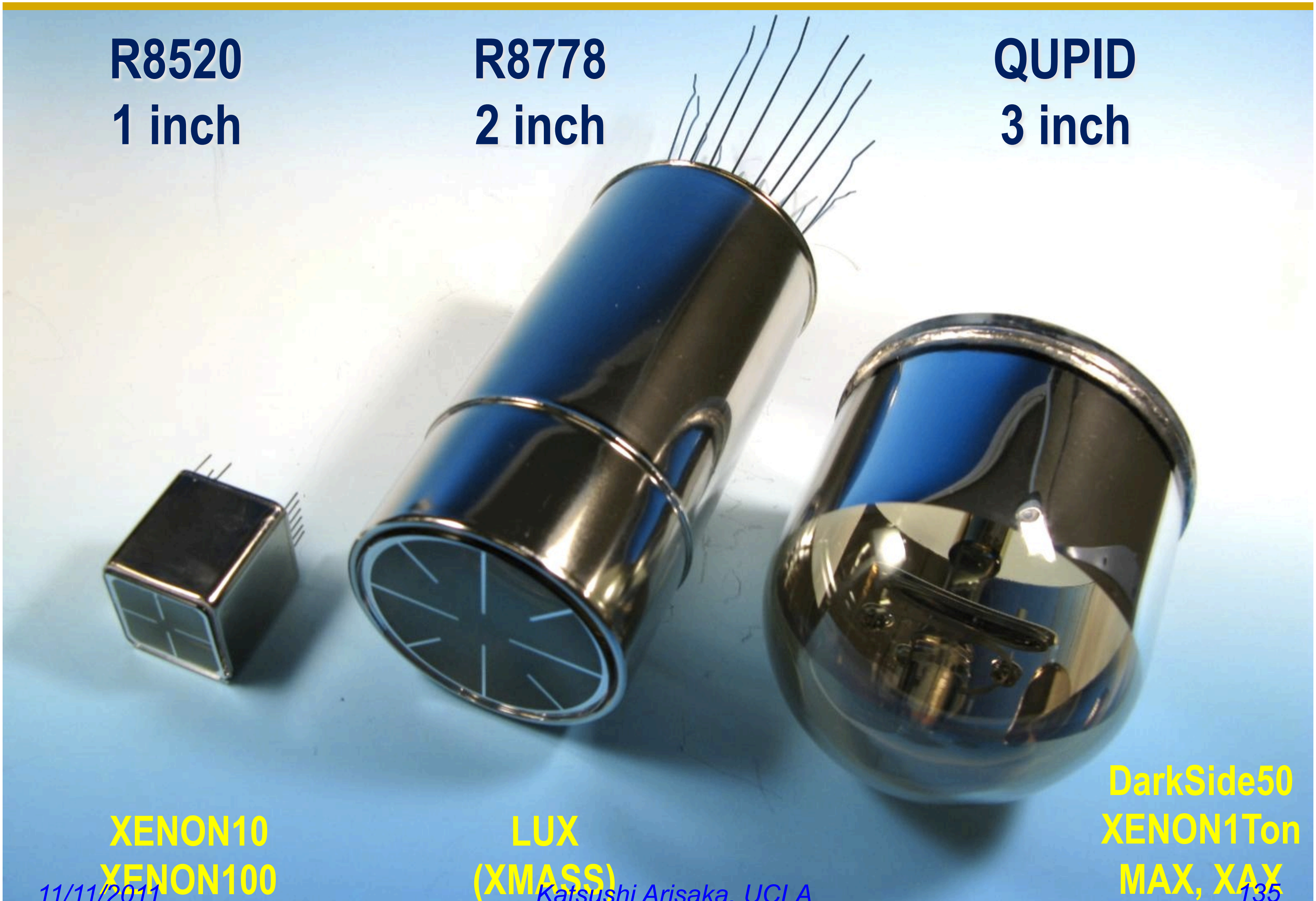
QUPID (QUartz Photon Intensifying Detector)

arXiv:1103.3689

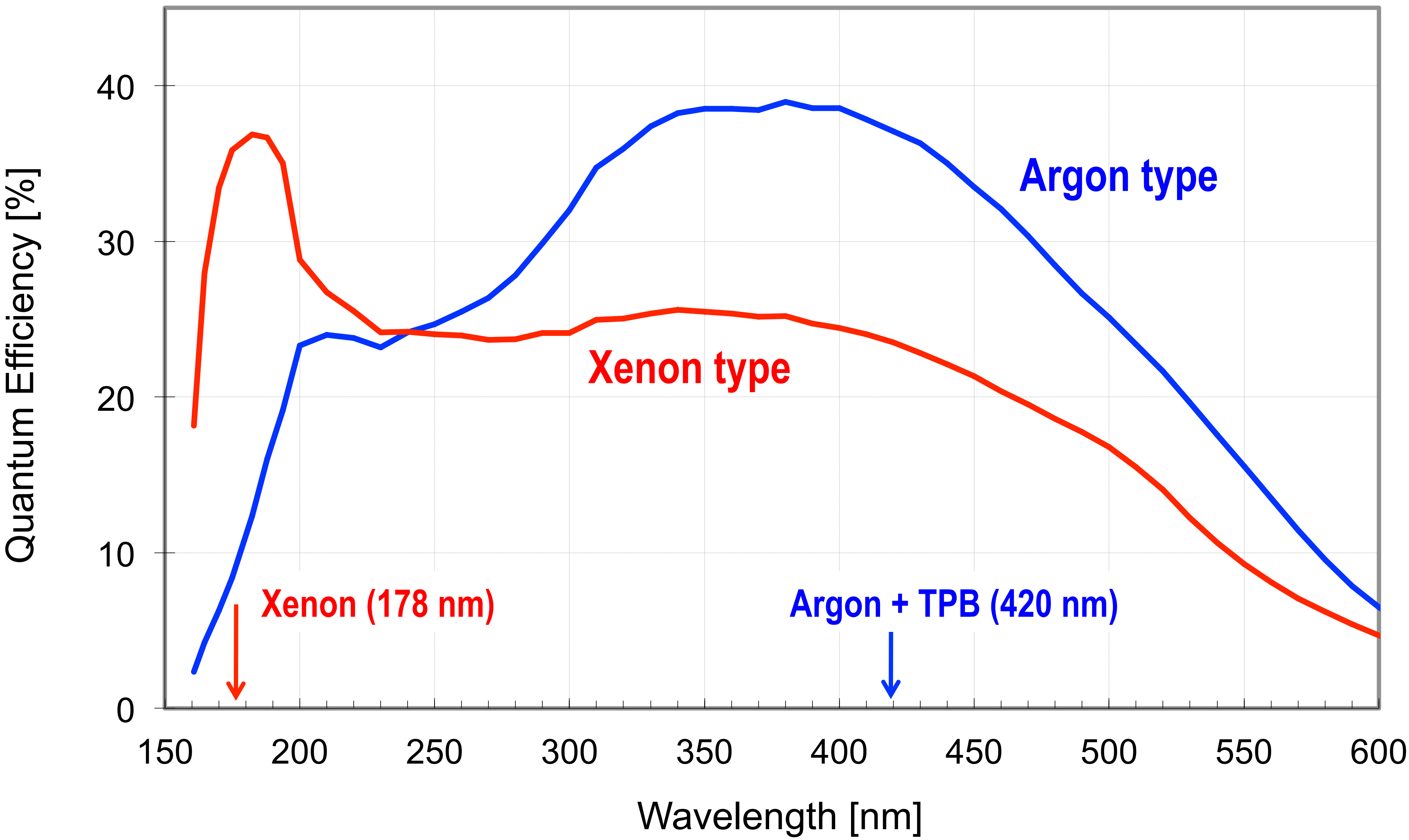




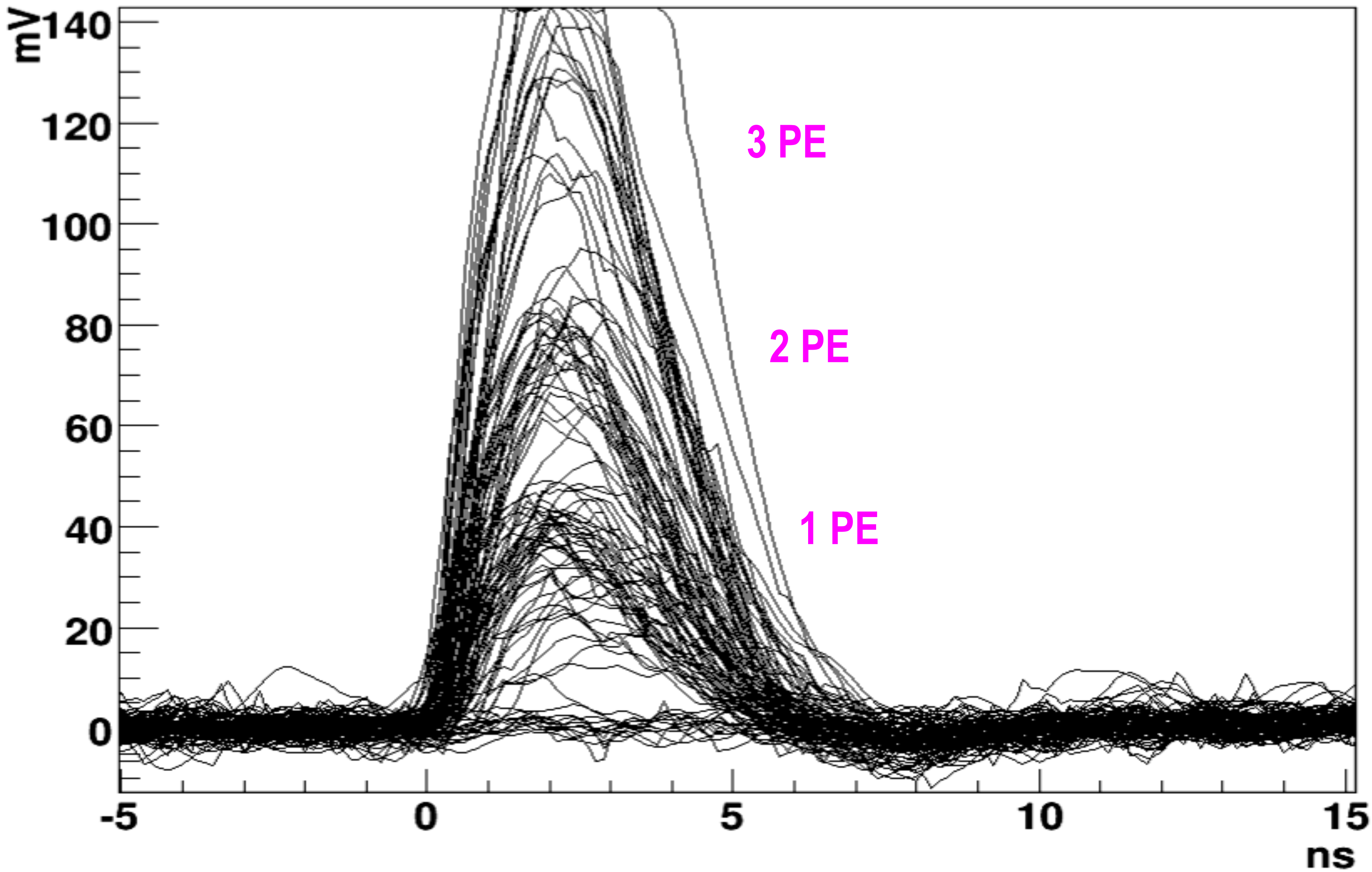
Comparison of Low-radioactive Photon Detectors from Hamamatsu



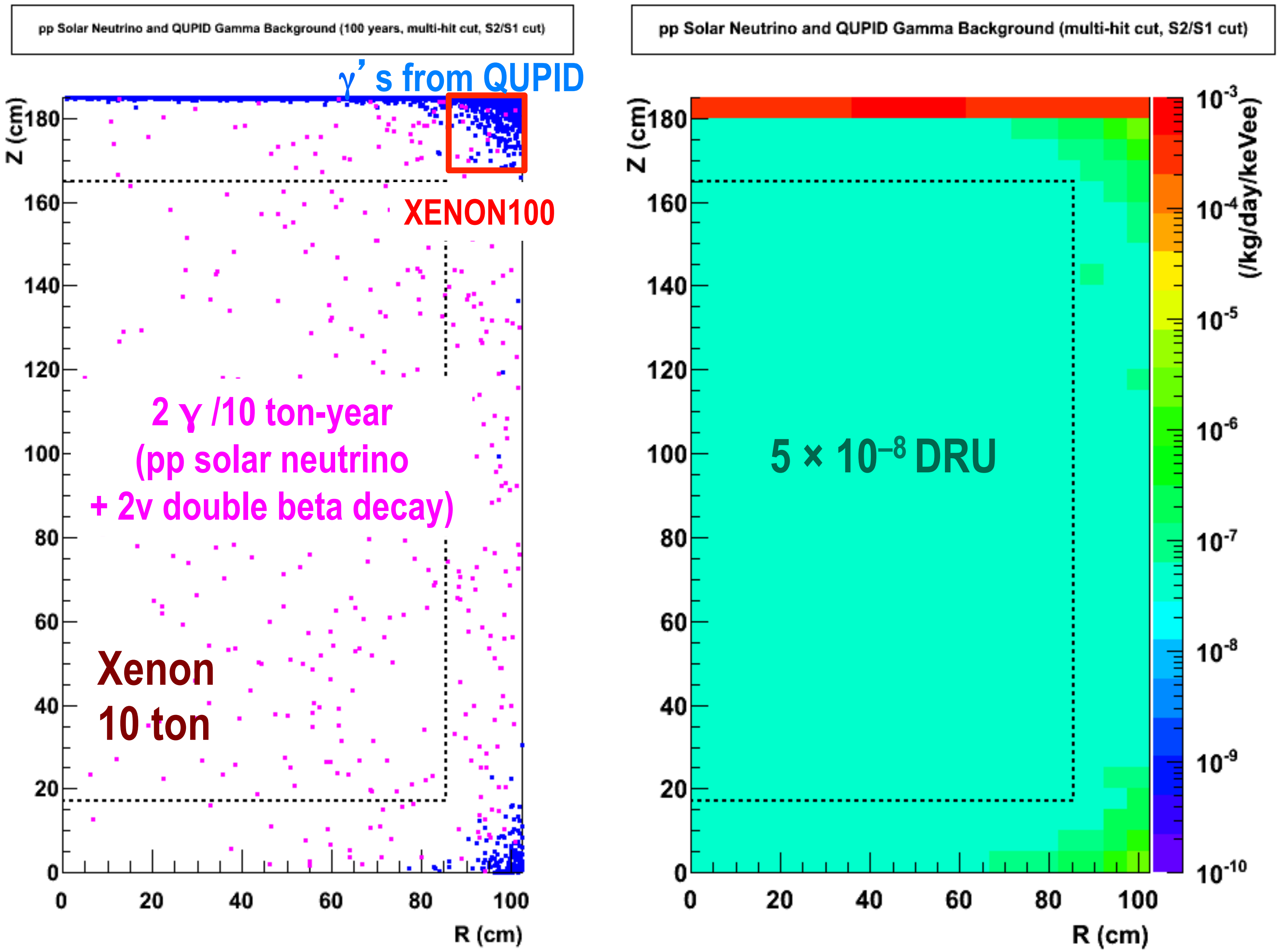
QE of two types of QUPID



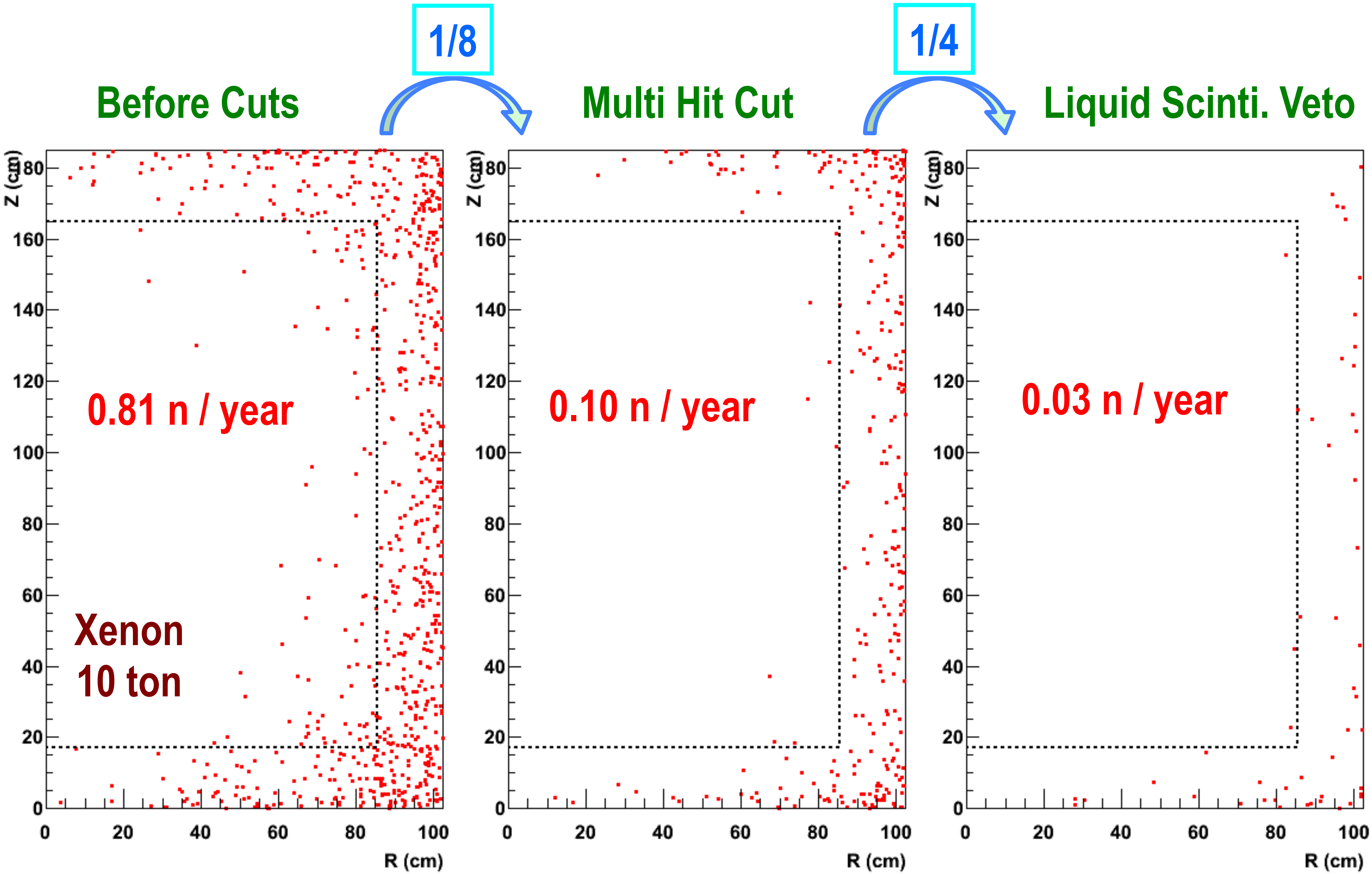
1, 2 and 3 PE Distribution with 2m cable



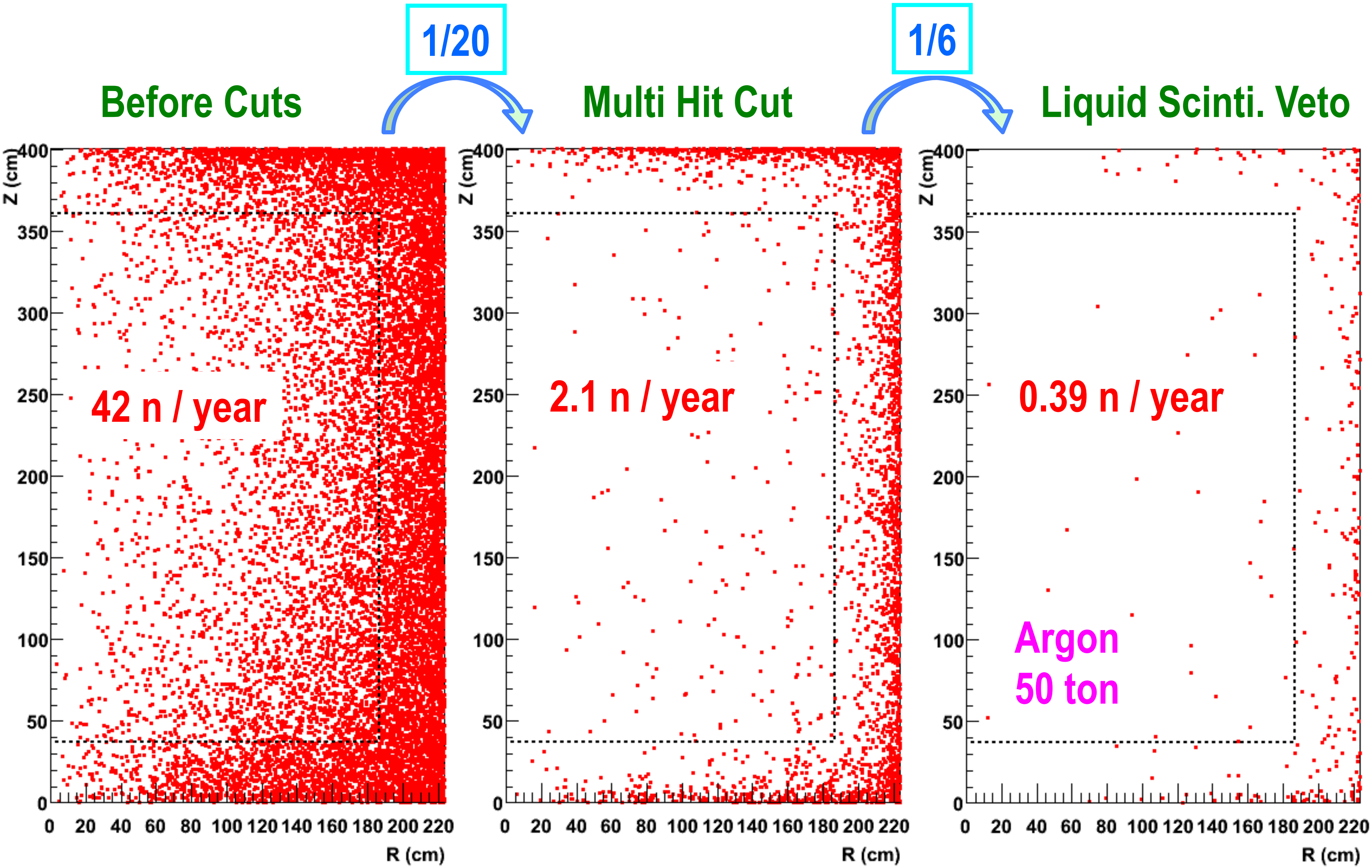
Expected Background from Gammas and pp Solar Neutrinos
(100 Year, Multi-hit Cut, S2/S1 Cut)

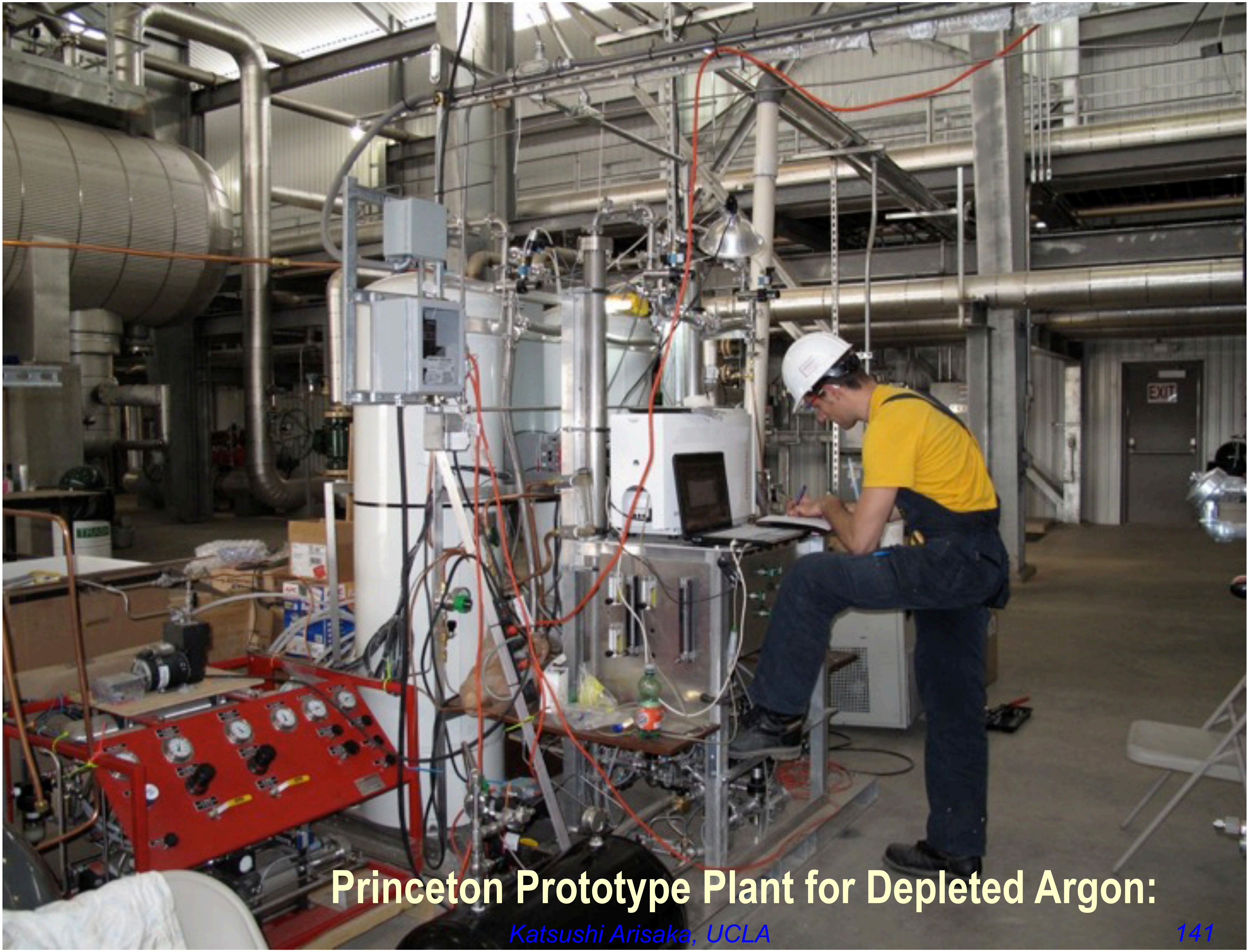


Xe 10 ton Neutron Background (100 Years)



Ar 50 ton Neutron Background (100 Years)





Princeton Prototype Plant for Depleted Argon:

Technological Challenges

- **External Backgrounds**
  - Deep underground – LNGS, SNOLab, DUSEL
  - 4 m water shielding
- **Detector Materials**
  - Photon detectors – QUPID
  - Cryostat – Titanium
  - Others – Copper, PTFE
- **Purity of Liquid Xe/Ar**
  - Radon
  - ^{85}K (0.5 ppt in Xe) – 1 event / 10 ton-year
  - ^{39}Ar (in Ar) – Depleted Ar from underground
- **Physics Backgrounds (in Xe)**
  - pp-chain solar neutrinos – 1 event / 10 ton-year
  - Double beta decays from ^{136}Xe – 1 event / 10 ton-year
- **Neutron Vetos**
  - B (or Gd) doped Liquid Scintillator

Some Remarks

- **Xenon is optimum up to 1 Ton scale**
  - Largest discovery potential
  - Background ~ 1 / ton-year
  - Good sensitivity to low mass WIMP

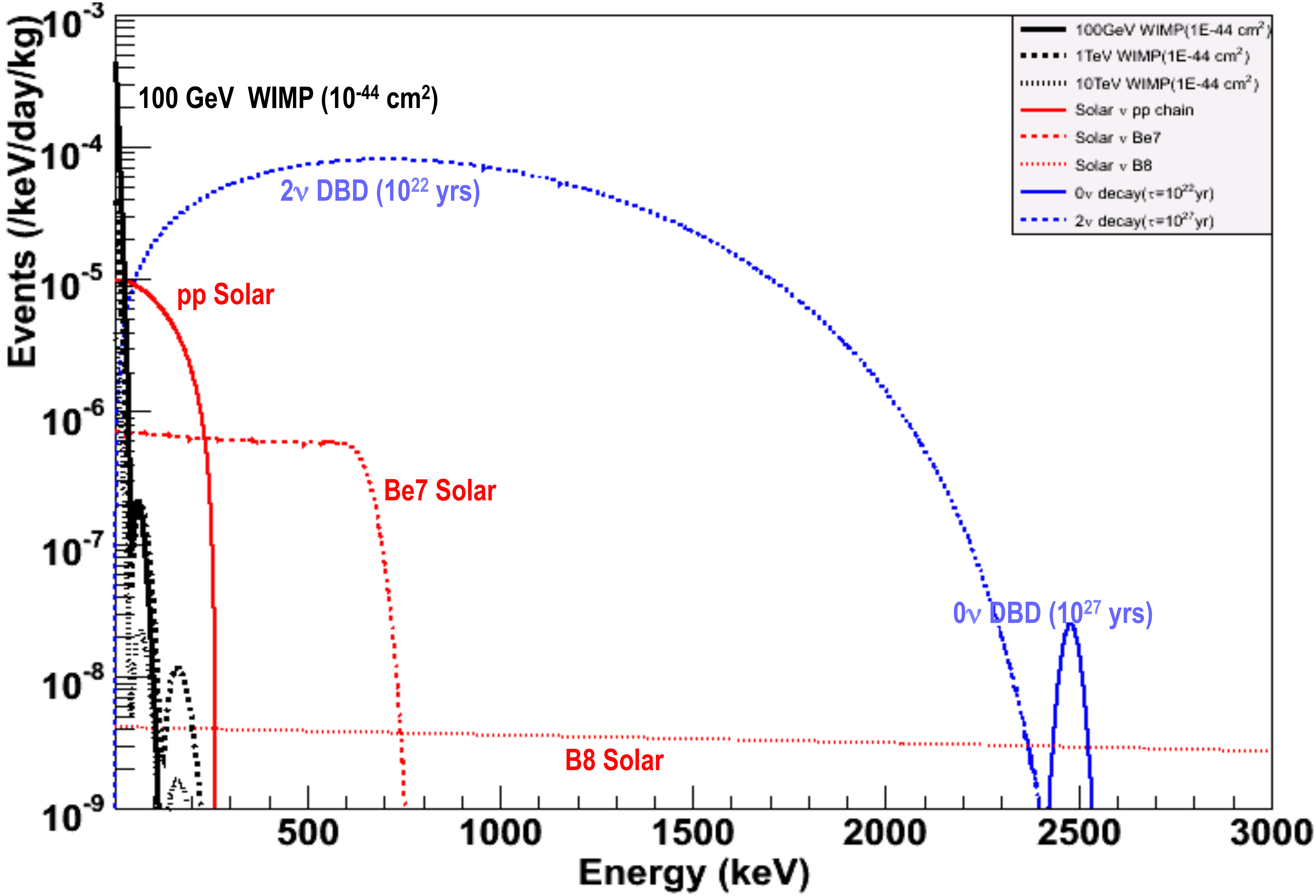
- **At > 10 ton scale, Argon is more appealing**
  - No gamma ray backgrounds
  - Mass determination up to 200 GeV
  - Large annual modulation

Neutrino Physics

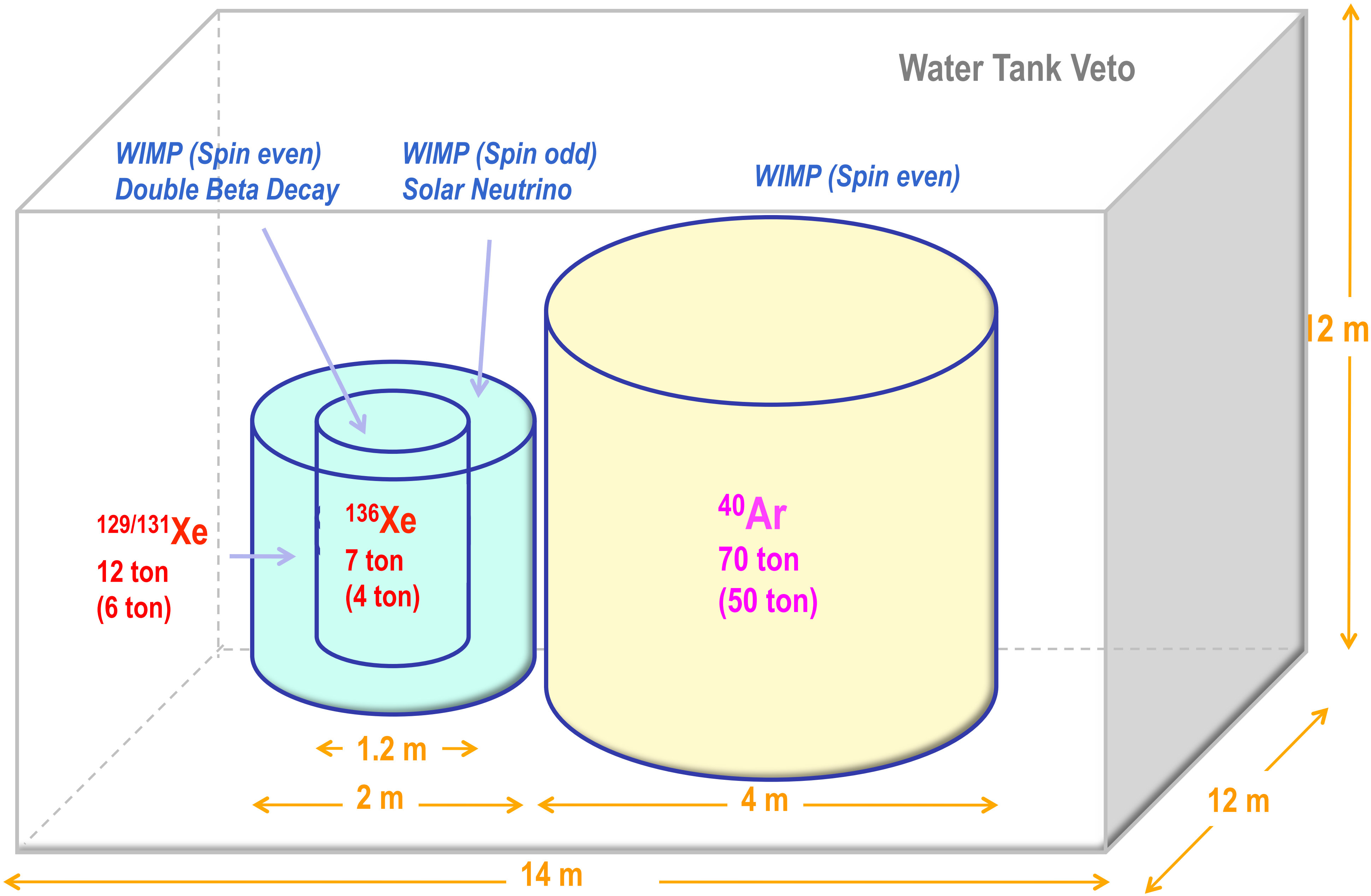
- Neutrinoless Double Beta Decay
- pp-chain Solar Neutrino
- Supernova Neutrino

Energy Spectrum (Natural Xe)

arXiv:0808.3968

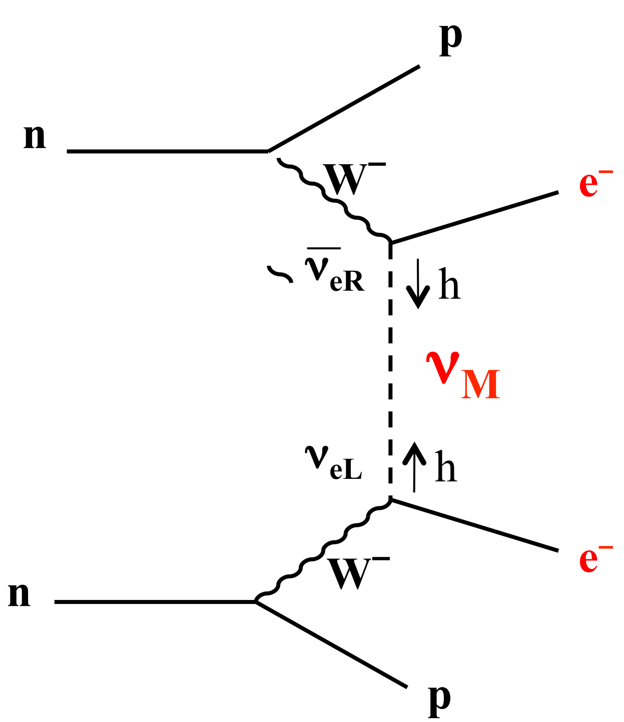


XAX (Xenon-Argon-Xenon) arXiv:0808.3968



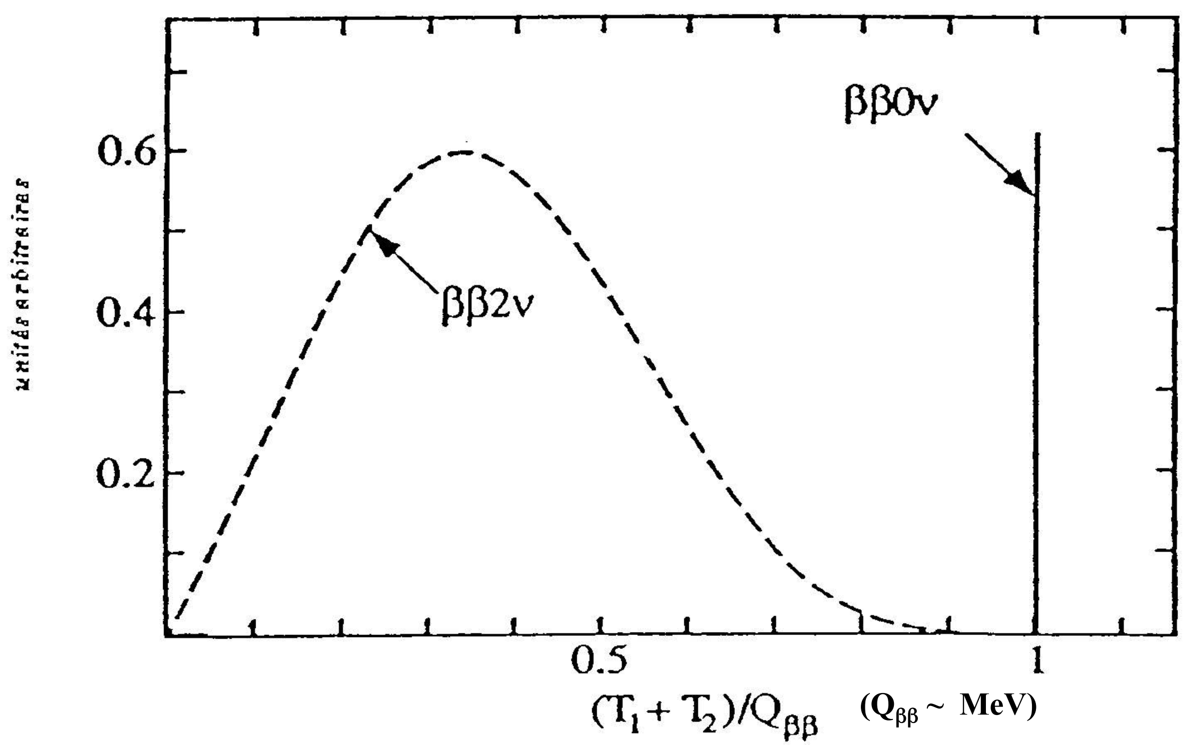
Double Beta $\beta\beta(0\nu)$ Decay

$\beta\beta(0\nu)$: $2n \rightarrow 2p + 2e^-$

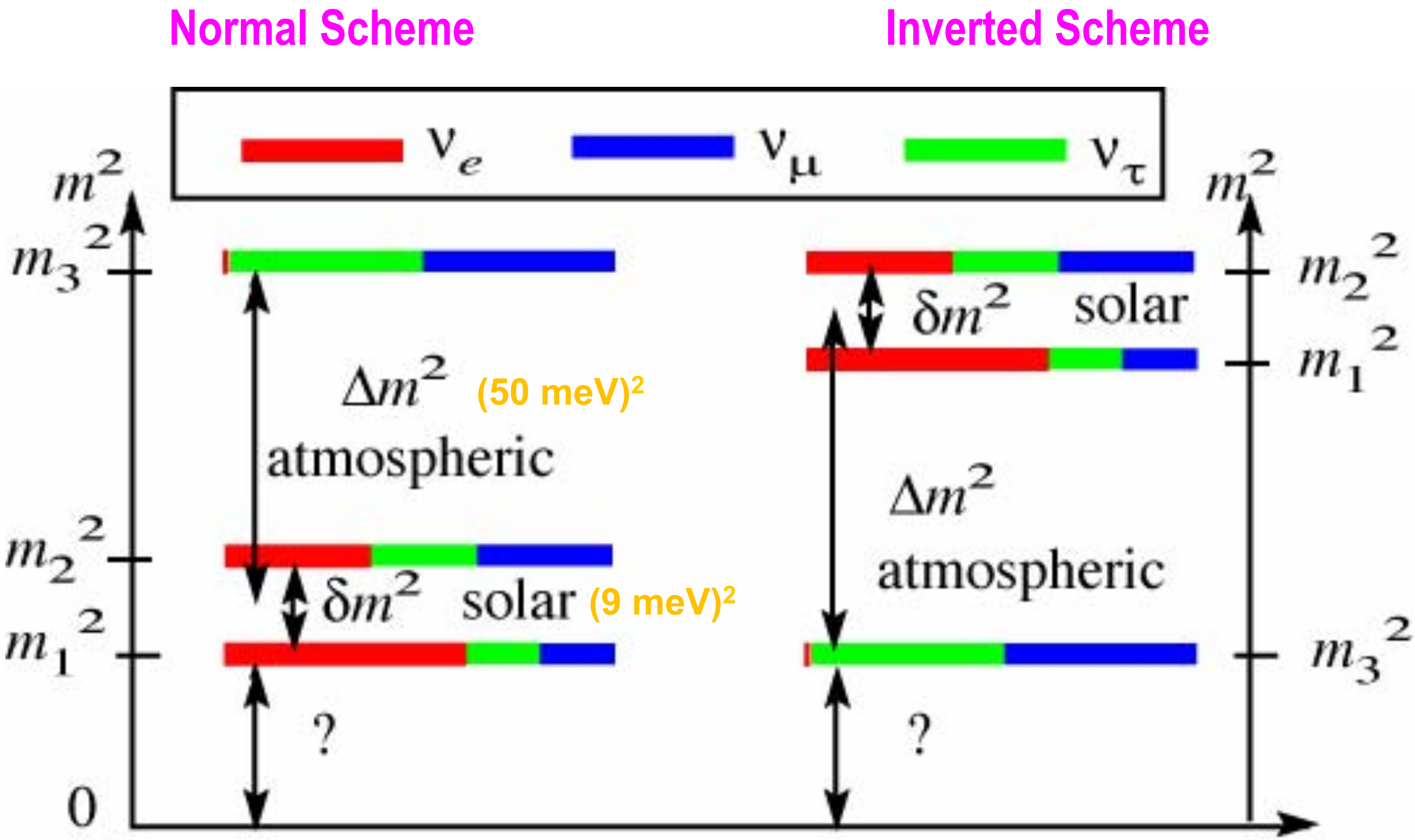


$\Delta L = 2$ Process

- Majorana Neutrino $\nu = \bar{\nu}$
- Right-handed current in weak interaction
- Majoron emission
- SUSY particle exchange

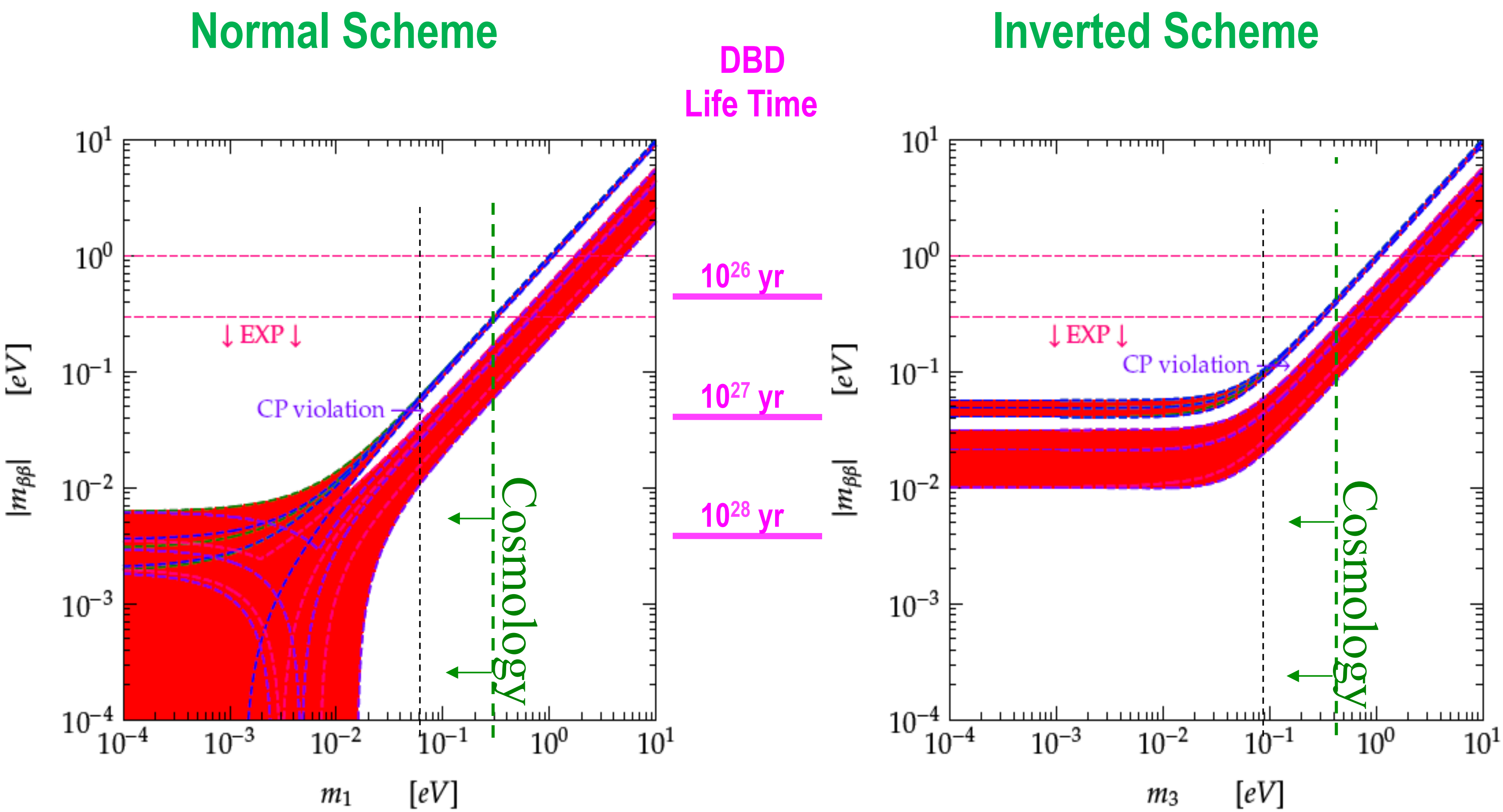


Neutrino Mass Differences



Laurent SIMARD, LAL - Orsay

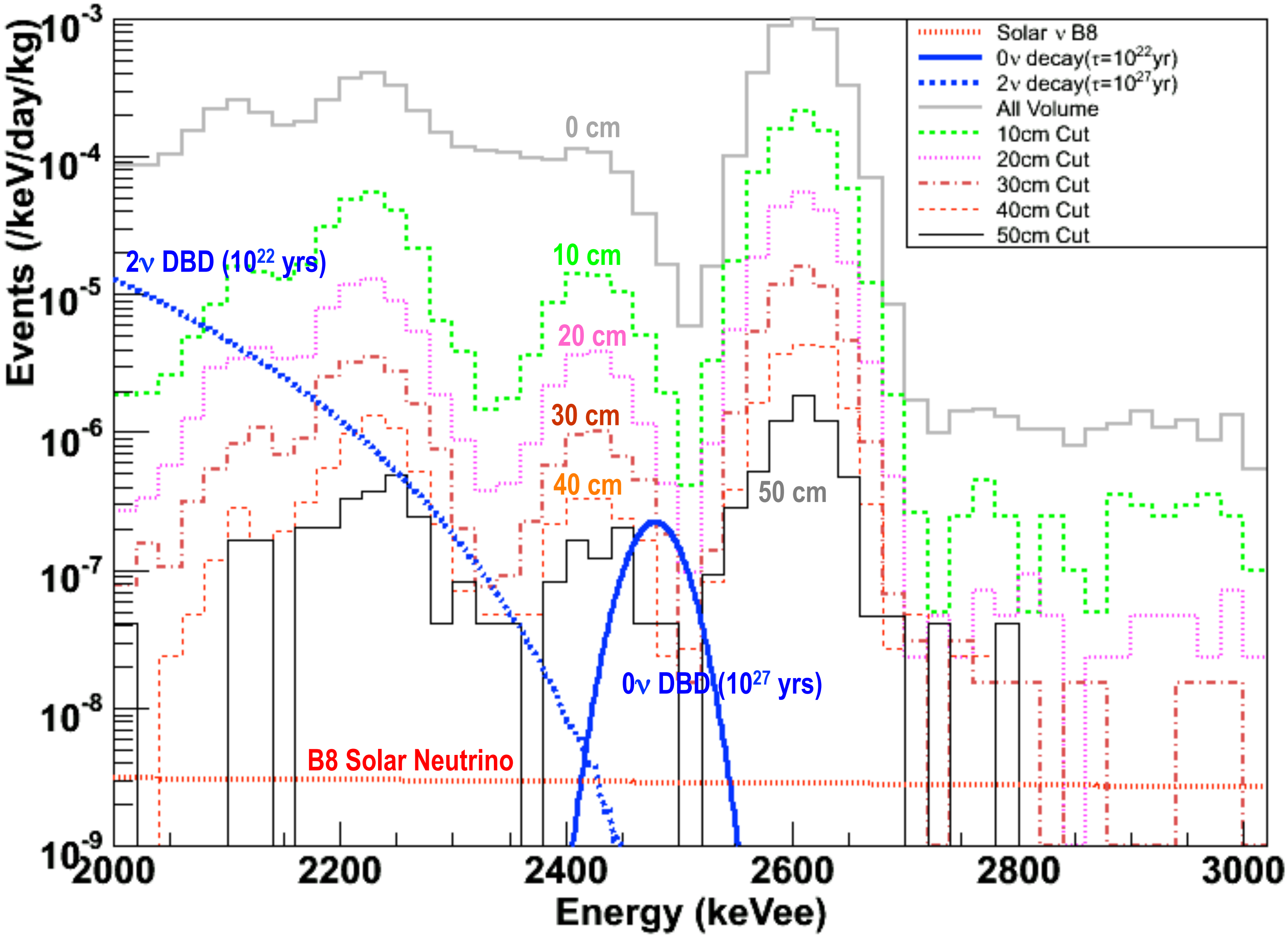
Sensitivity of Neutrinoless Double Beta Decay to Neutrino Mass



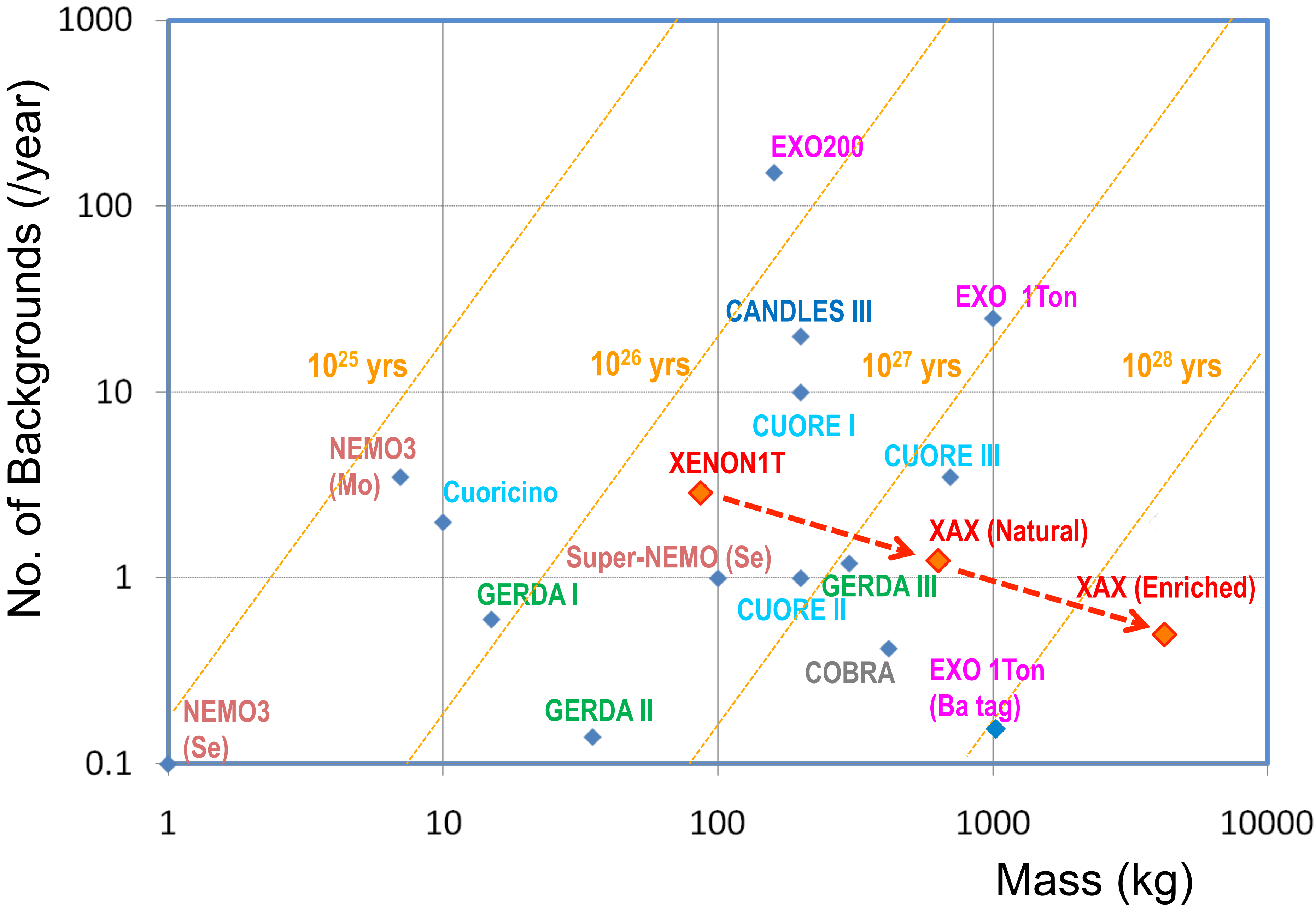
(Figure from C. Giunti)

Laurent SIMARD, LAL - Orsay

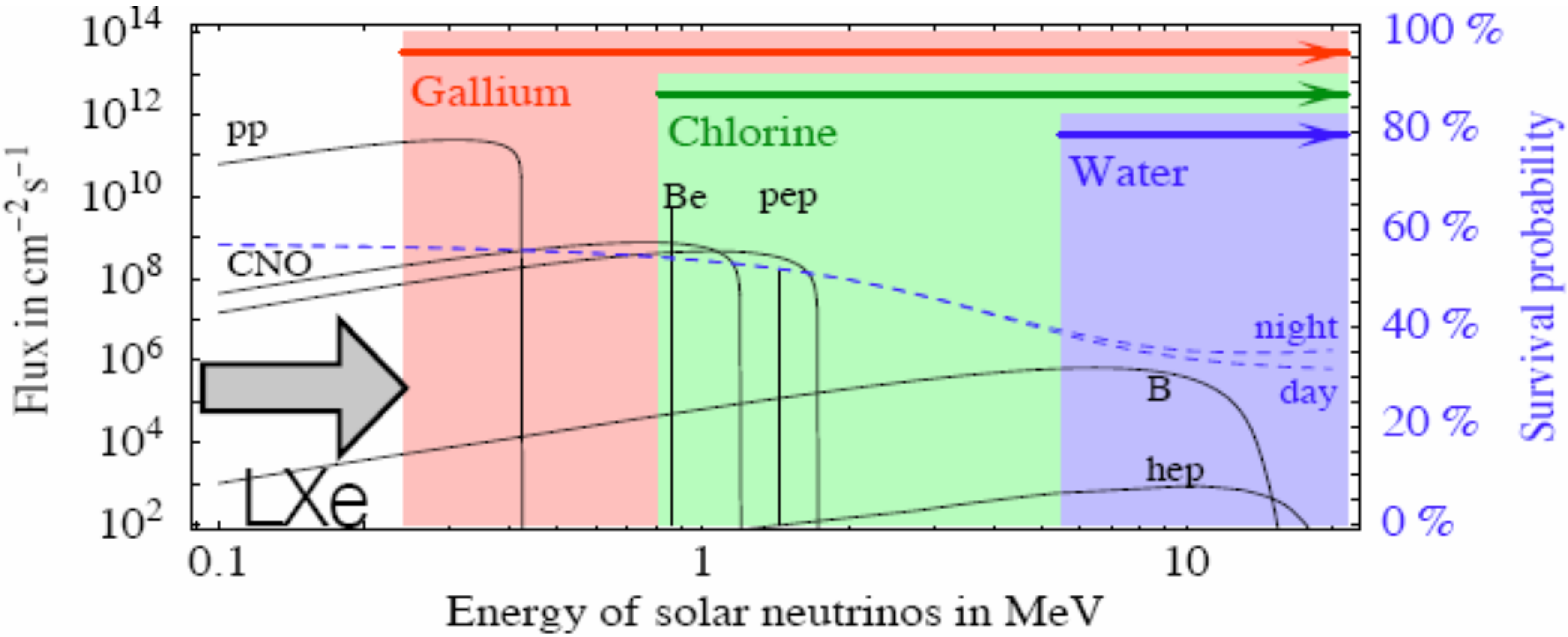
^{136}Xe Double Beta Decay and Gamma Background
(1 mBq / QUPID, 2m Xenon Detector)



Double Beta Decay Experiments



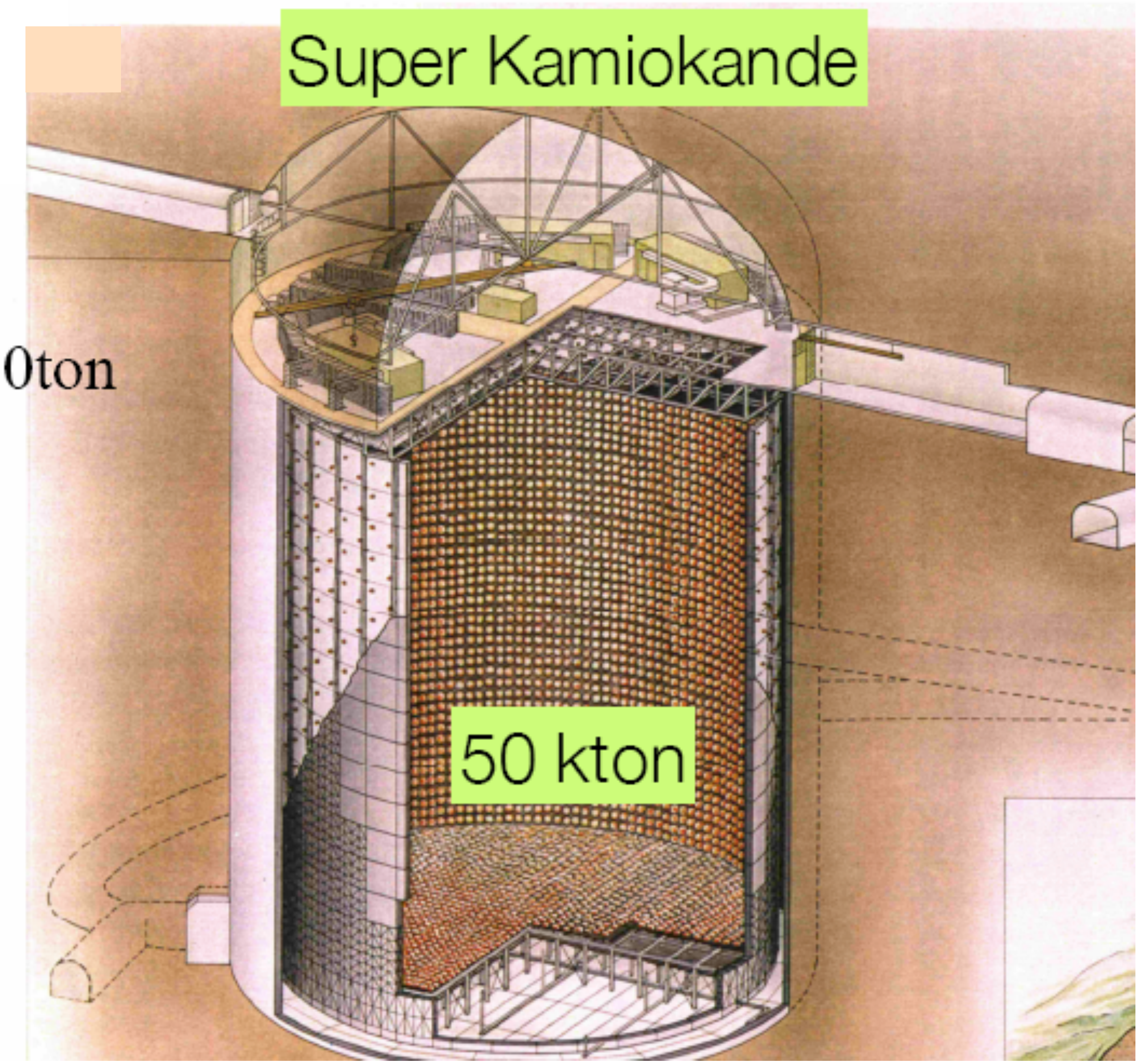
Solar Neutrino (by XMASS group)



- Motivation
  - ➡99% of solar neutrinos are from pp chain
  - ➡Measurement of θ_{12} with ~1% precision
  - ➡confirmation LMA solution

M. Nakahata

Sular Neutrino Detection



10pp /5 ^{7}Be events/day/10ton

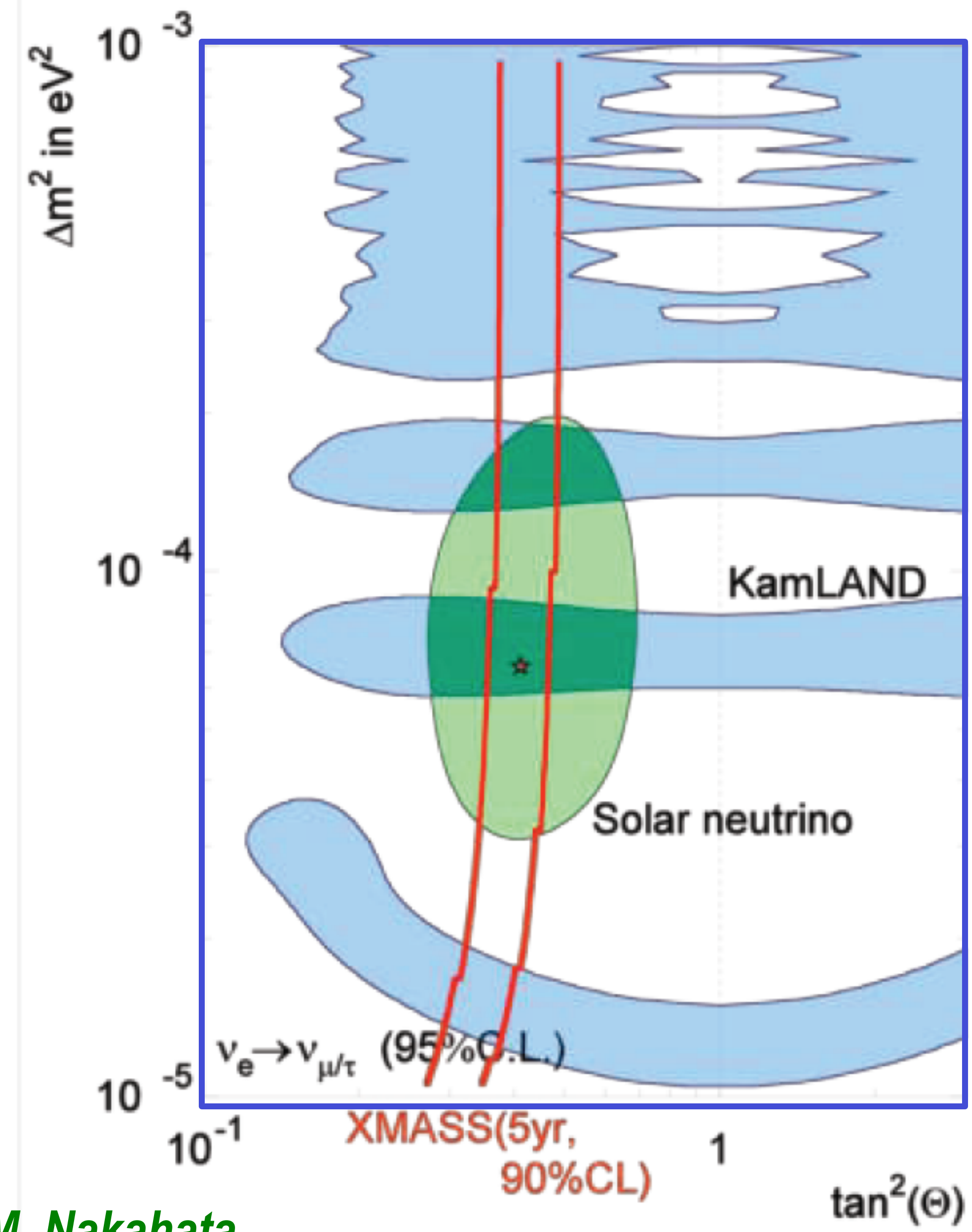
SK 13 events/day

10 ton LXe

0 =

M. Yamashita

Solar Neutrino Study by XMASS Group



- Expected region using pp neutrinos (90 % C.L.) :
  - 10 ton Liq. Xe
  - νe scattering
  - 5 years data
  - Statistical error and SSM prediction error(1%)
- Accuracy of mixing angle: $\sin^2 2\theta = 0.77 \pm 0.03$(stat.+SSM)

KamLAND and pp solar neutrinos will determine precise oscillation parameters

M. Nakahata

Horowitz, Coakley, Mckinsey 2003

PHYSICAL REVIEW D **68**, 023005 (2003)

Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

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K. J. Coakley
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D. N. McKinsey
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(Received 5 February 2003; published 28 July 2003)

Development of large mass detectors for low-energy neutrinos and dark matter may allow supernova detection via neutrino-nucleus elastic scattering. An elastic-scattering detector could observe a few, or more, events per ton for a galactic supernova at 10 kpc (3.1×10^{20} m). This large yield, a factor of at least 20 greater than that for existing light-water detectors, arises because of the very large coherent cross section and the sensitivity to all flavors of neutrinos and antineutrinos. An elastic scattering detector can provide important information on the flux and spectrum of ν_μ and ν_τ from supernovae. We consider many detectors and a range of target materials from ^{4}He to ^{208}Pb. Monte Carlo simulations of low-energy backgrounds are presented for the liquid-neon-based Cryogenic Low Energy Astrophysics with Noble gases detector. The simulated background is much smaller than the expected signal from a galactic supernova.

DOI: 10.1103/PhysRevD.68.023005 PACS number(s): 97.60.Bw, 95.85.Ry

Neutrinos from a Supernova

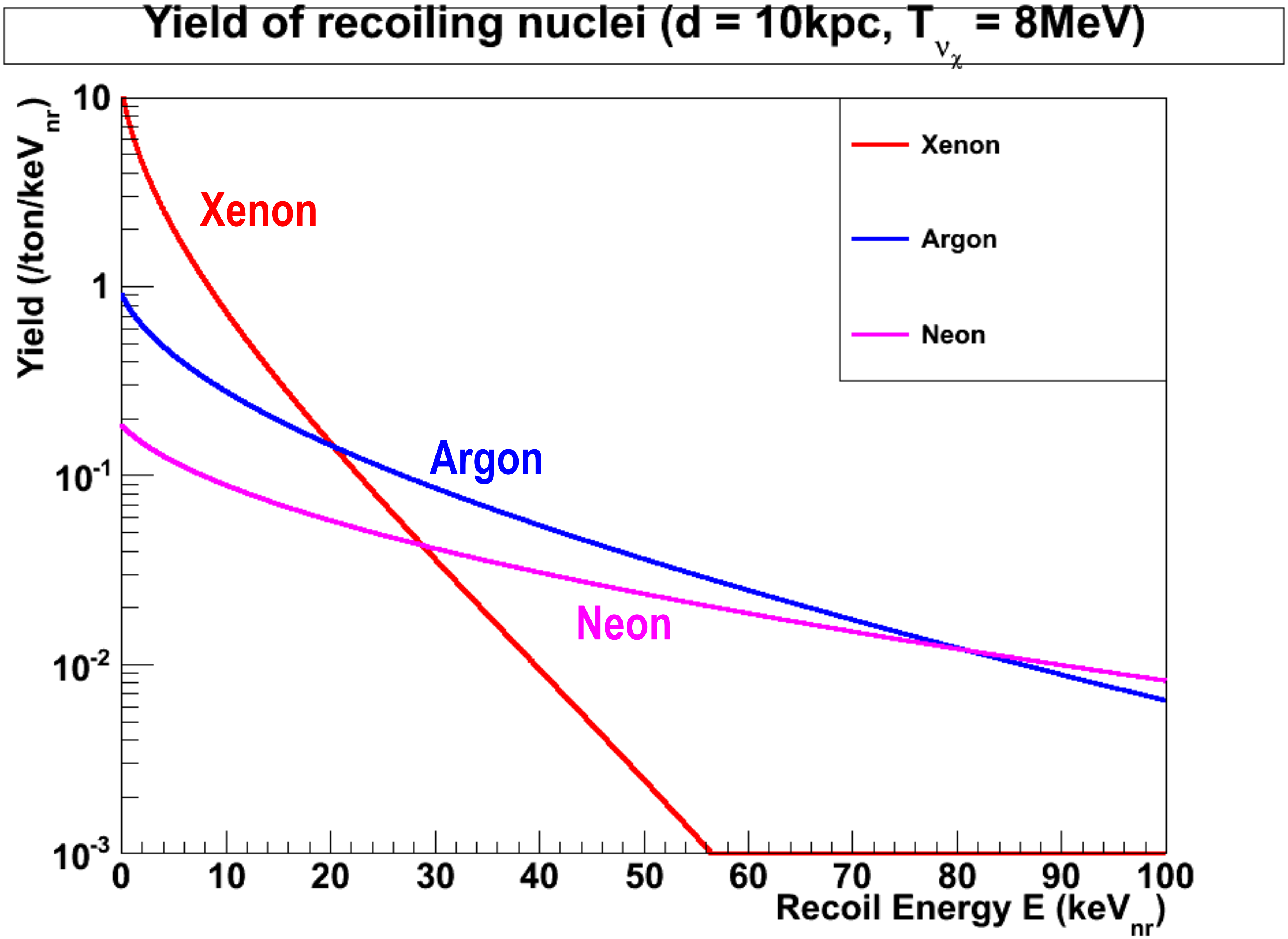
➢ Assumptions:

- 10 kpc away.
- Total energy radiated in neutrinos = $3*10^{53}$ ergs
- Equal partition of energy among the 6 neutrinos

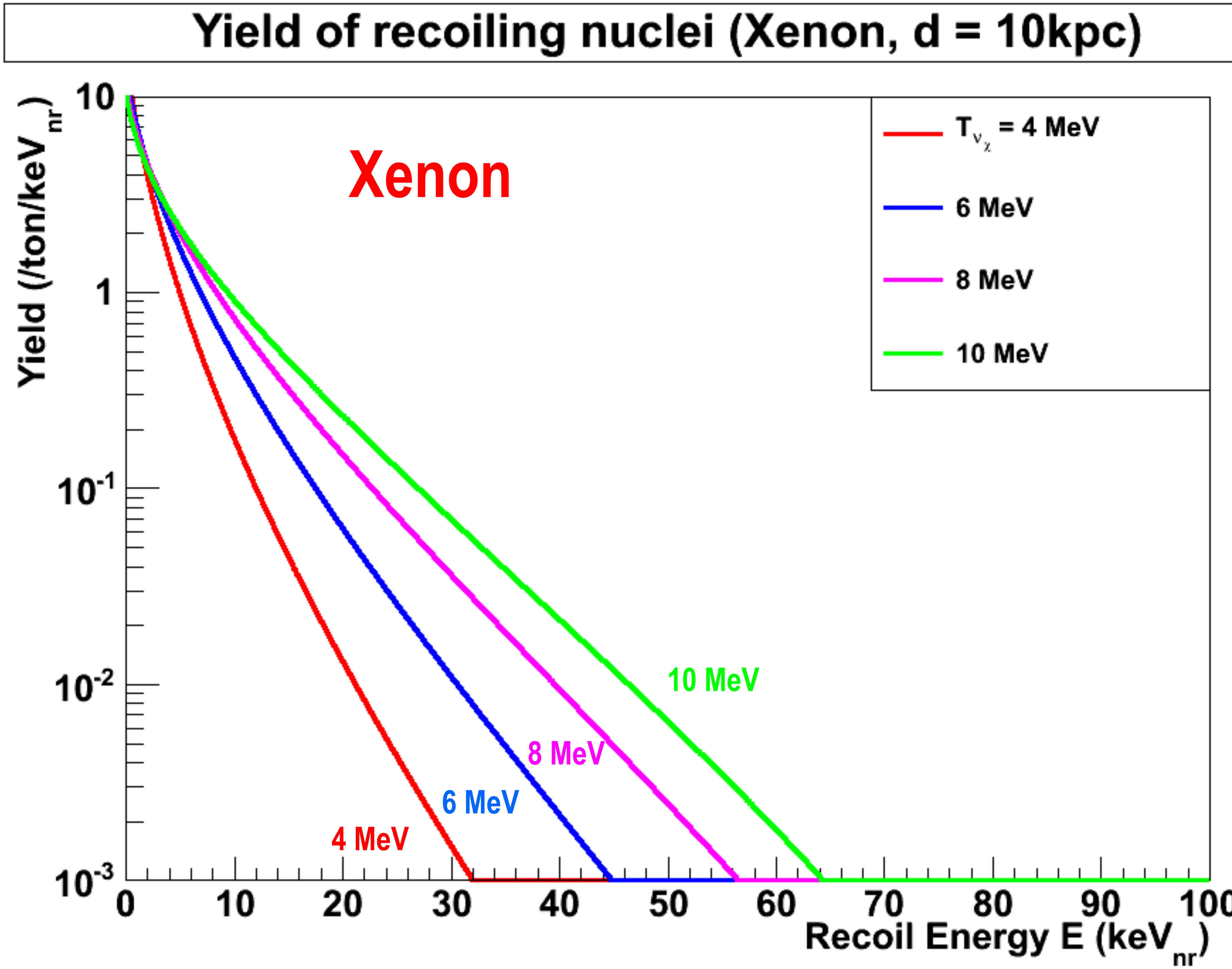
➢ Temperatures of neutrinos:

- ν_e — $k_BT = 3.5$ MeV
- $\bar{\nu}_e$ — $k_BT = 5$ MeV
- $\nu_\chi \ (\chi = \mu, \bar{\mu}, \tau, and\ \bar{\tau})$ — $k_BT = 6\sim8$ MeV

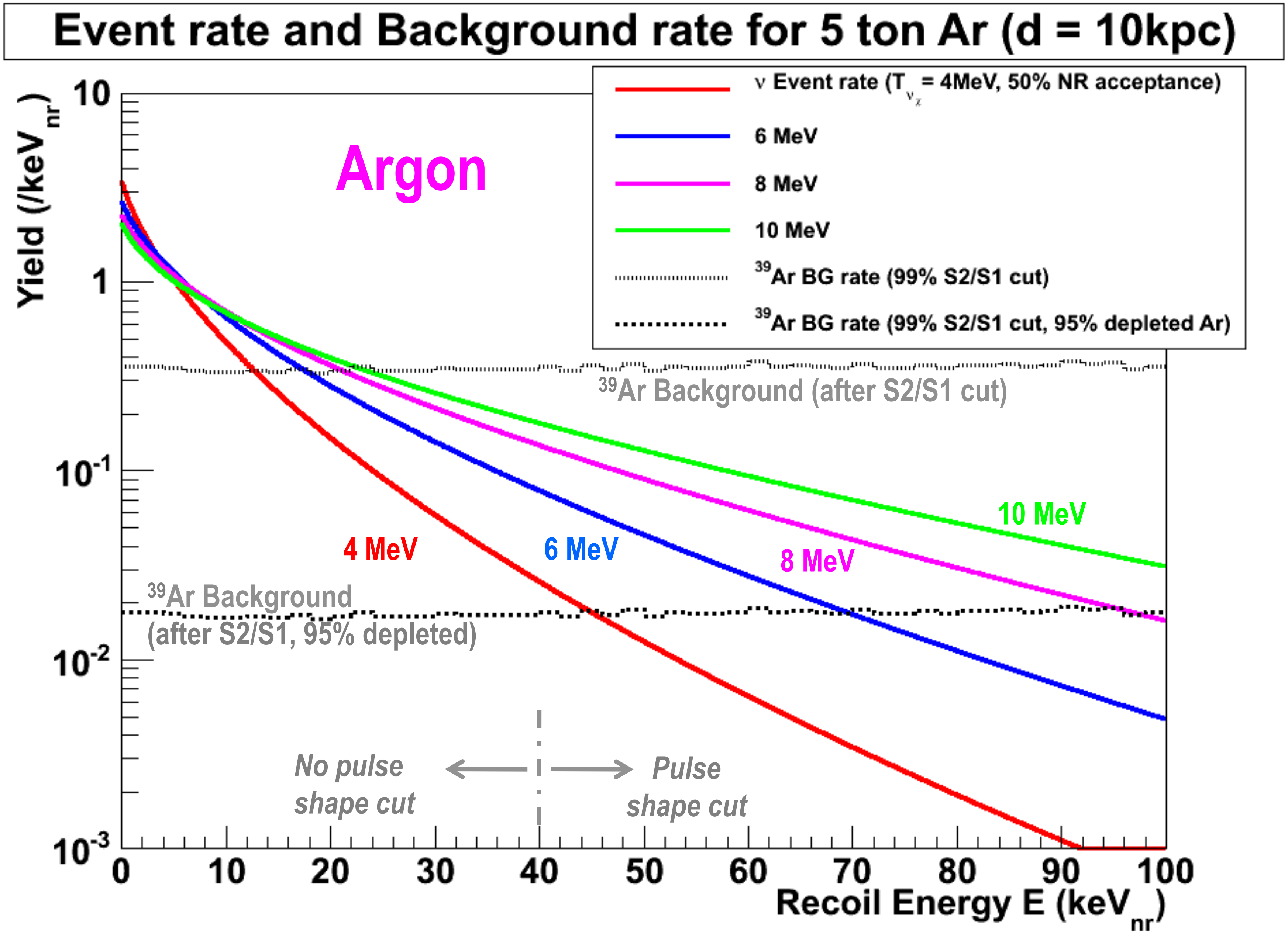
Energy Spectrum of SN Nuclei Scattering



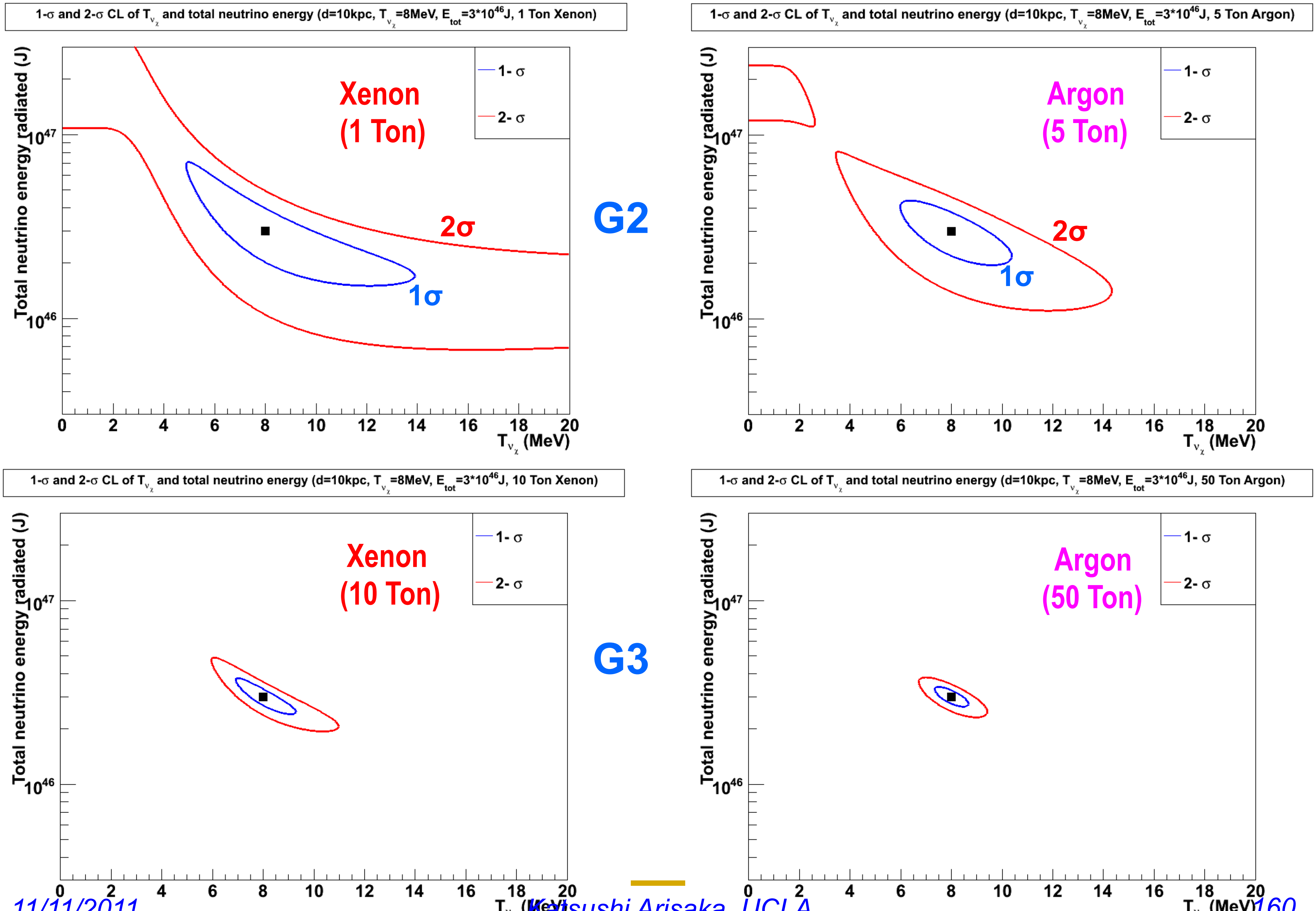
Temperature Dependence of Energy Spectrum



Temperature Dependence of Energy Spectrum

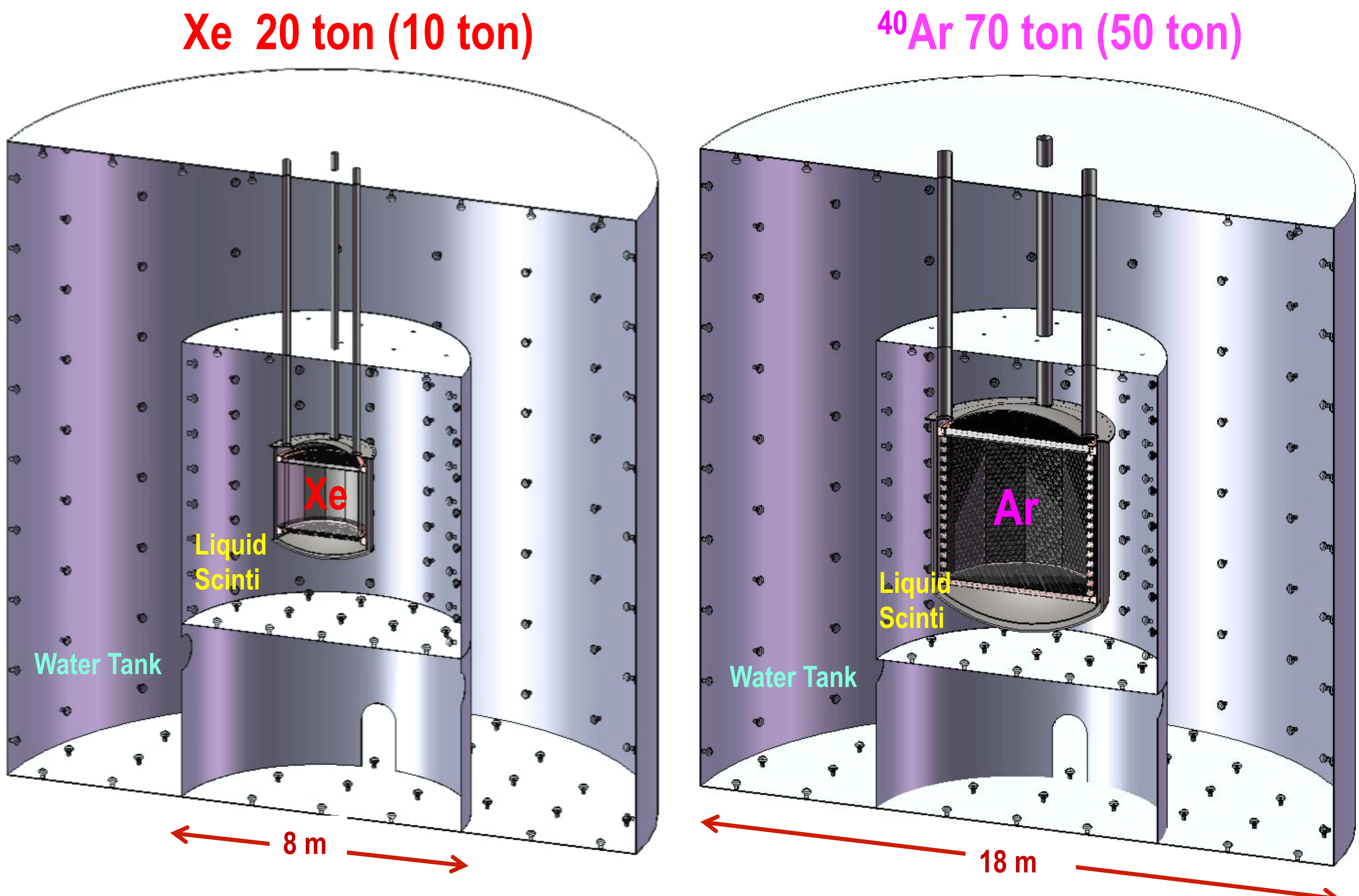


Estimate of Total Energy vs. Temperature

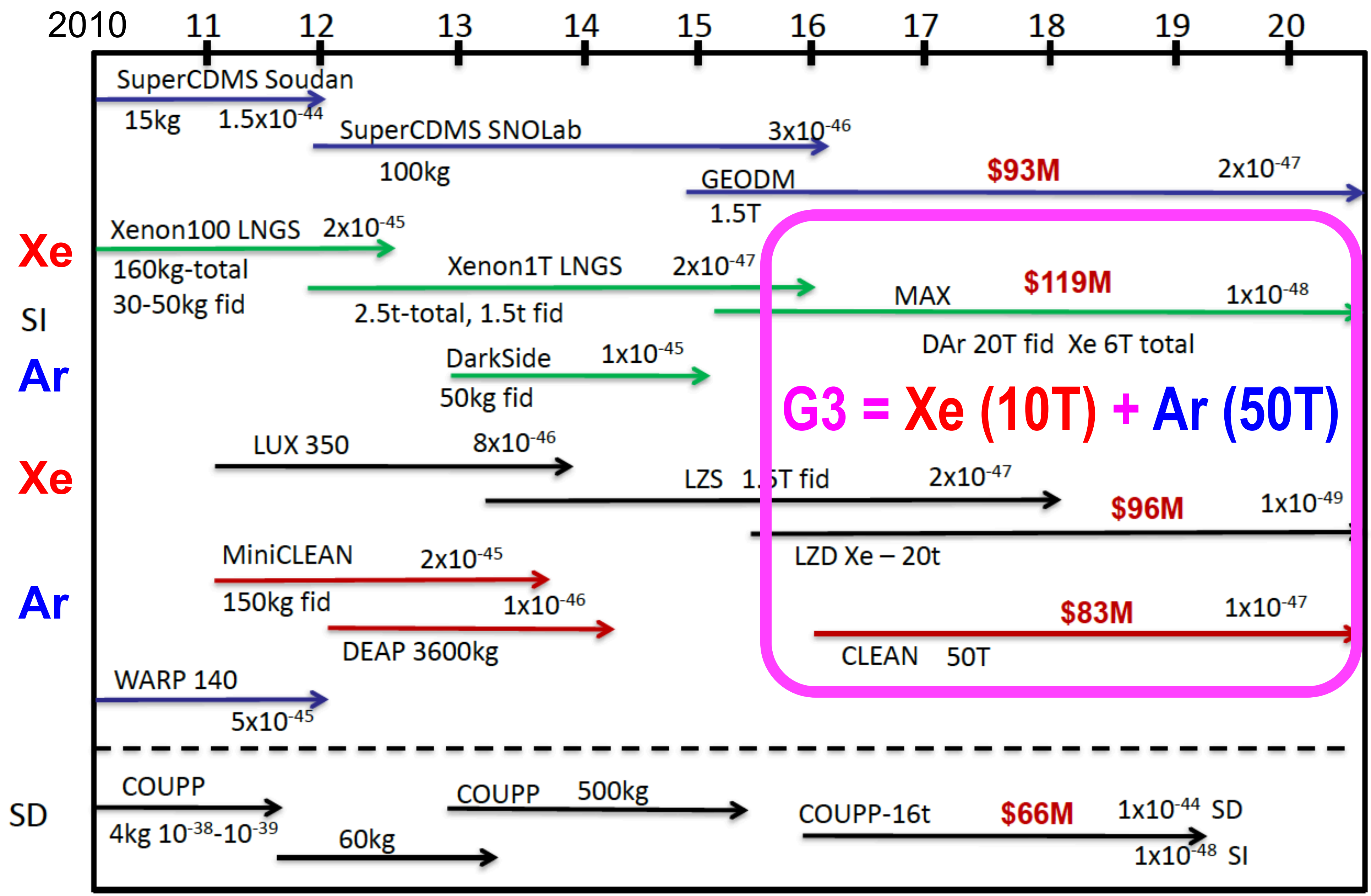


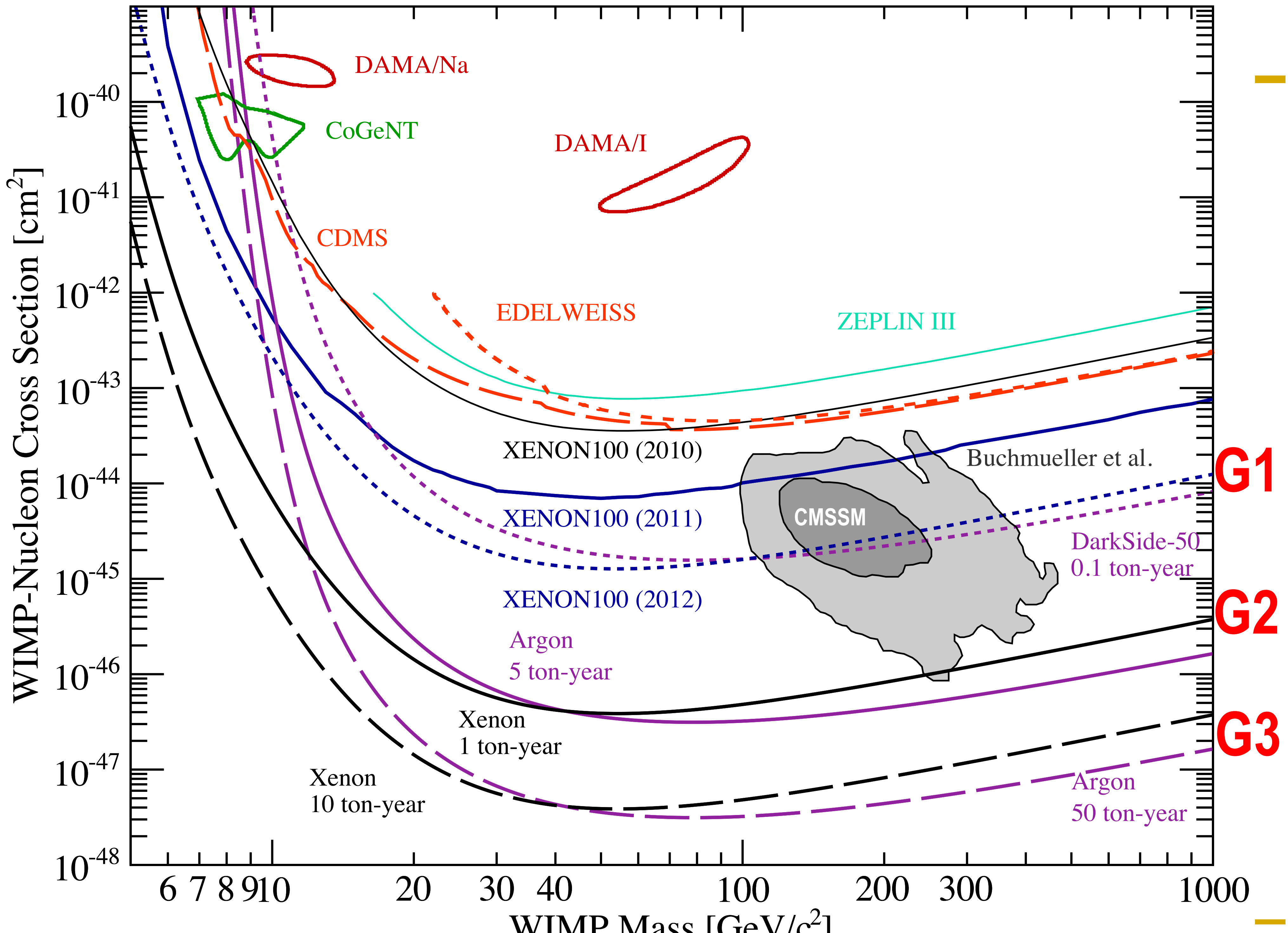
Summary

"Ultimate G3" Detector (at DUSEL)



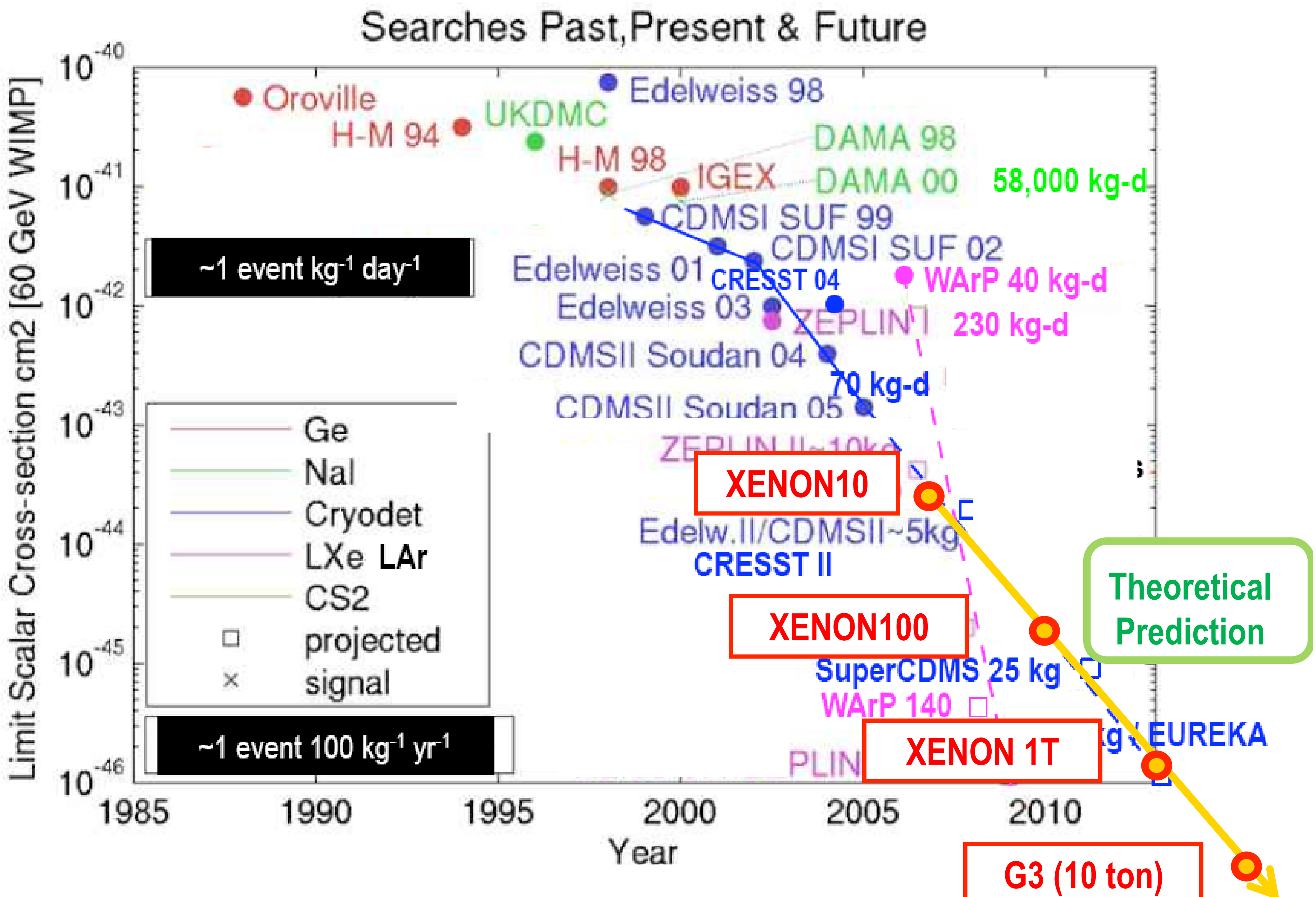
US Dark Matter Programs



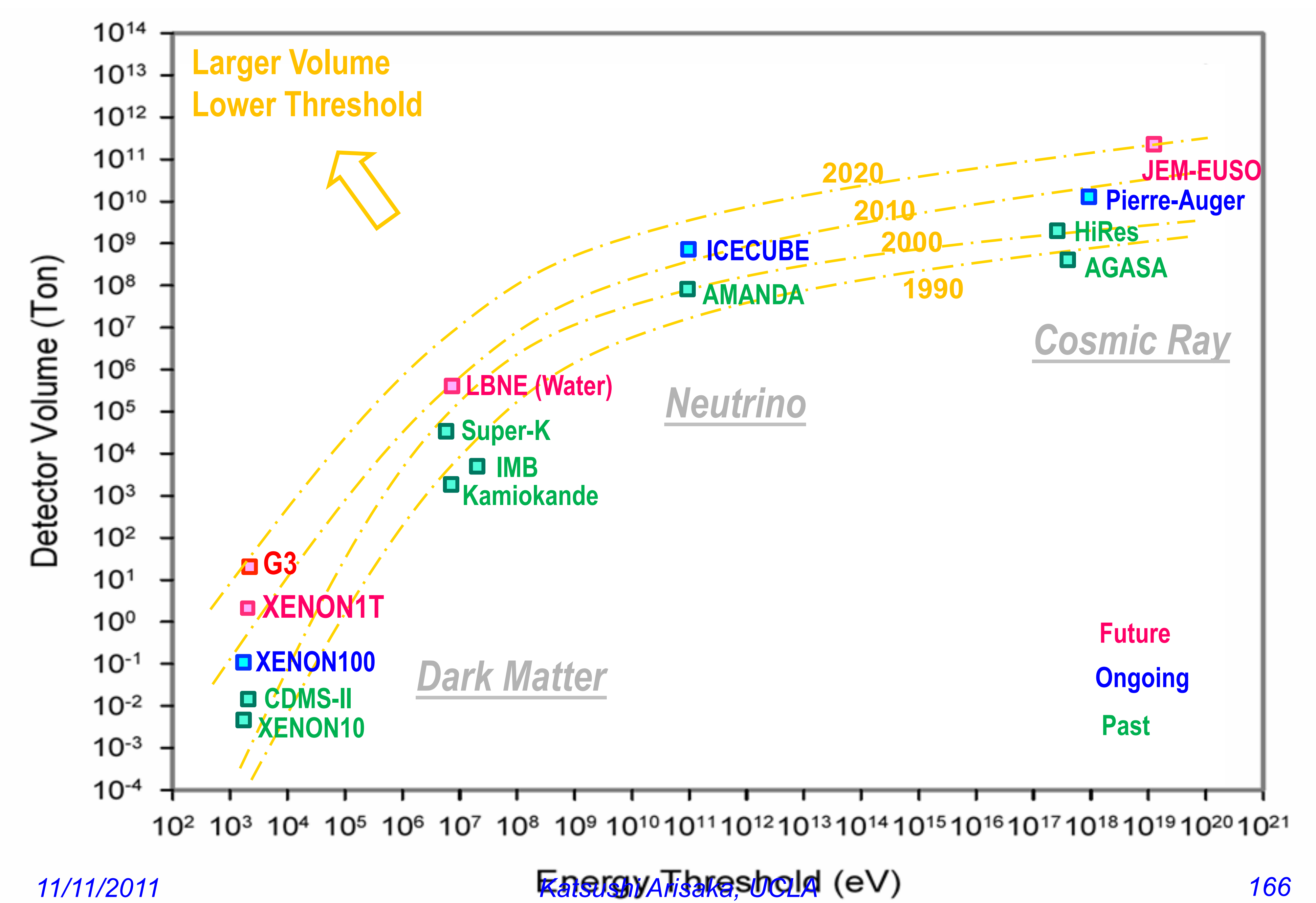


DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
ZEPLIN III
XENON100 (2010)
XENON100 (2011)
XENON100 (2012)
Buchmueller et al.
CMSSM
DarkSide-50
0.1 ton-year
Argon
5 ton-year
Xenon
1 ton-year
Xenon
10 ton-year
Argon
50 ton-year
G1
G2
G3
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^-46
10^-47
10^-48
6
7
8
9
10
20
30
40
100
200
300
1000

Dark Matter Experiments



Detection of Cosmic Radiation



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

Katsushi's Speculations

- **2012 LHC (ATLAS+CMS) announces**
  - 120 GeV Higgs (at 3σ)
- **2016 XENON1T announces**
  - Observation of 5 WIMP signals (> 200 GeV)
- **2021 G3 (Xe+Ar) and LHC jointly confirm**
  - Extra Dimensions
  - WIMP = 600 GeV KK Photon (Δ = 5%)
  - No SUSY
  - Katsushi happily retires at age 65.