UNIVERSIDAD AUTONOMA DE MADRID

Identifying $\bar{\nu}_e$ with Super-Kamiokande:

GADZOOKS!,

status and some of its current challenges

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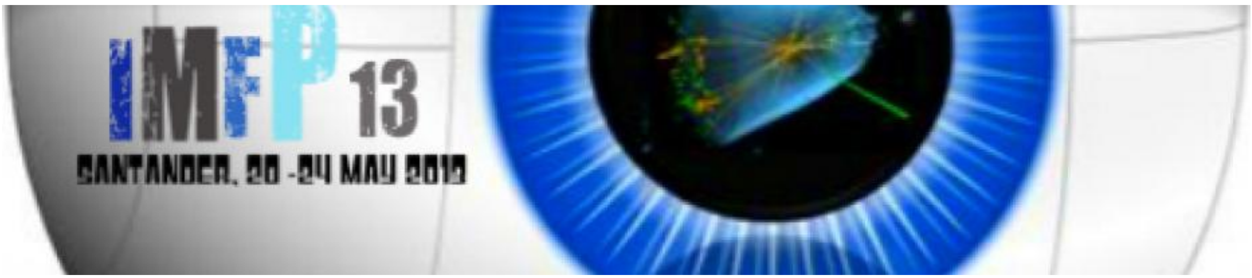
IMFP13, Santander, Spain

May 22nd, 2013



Outline

- Why ? What ? How ? Who ?
  - physics new research paradigms
  - The GADZOOKS! Project
  - EGADS
  - EGADS members
  - Status / Schedule
- Some backgrounds in GADZOOKS!
  - γs and neutrons from radioactive contamination
  - βs from radioactive contamination
- Summary/Conclusions

Why ? (I) *the current Super-Kamiokande experiment*

- SK is a 50 kTon water Cherenkov detector in the Kamioka Mine, Japan
- SK was built for proton decay and neutrino physics searches in 1996
- SK detects neutrinos coming from Sun, cosmic rays, nuclear reactors …
- Major achievements:
  - Kamiokande, its predecessor: neutrinos from Supernova explosion (SN1987A)
  - Oscillations from atmospheric neutrinos → neutrinos are massive
  - Neutrinos coming from the Sun → Solar neutrino problem
  - Best proton decay bounds
- Reasons of success: WC technology
- Important reactions are the CCQE scattering of the incoming ν with nucleons in water

$\nu_\alpha + n \rightarrow l_\alpha + p$	$\bar{\nu}_\alpha + p \rightarrow \bar{l}_\alpha + n$

- Nowadays, SK cannot distinguish (efficiently) ν from $\bar{\nu}$ because it is not able to detect either neutrons nor protons (the latter at low energy)
- **This distinction would be of most importance for deeper study of ν properties → try neutron tagging**

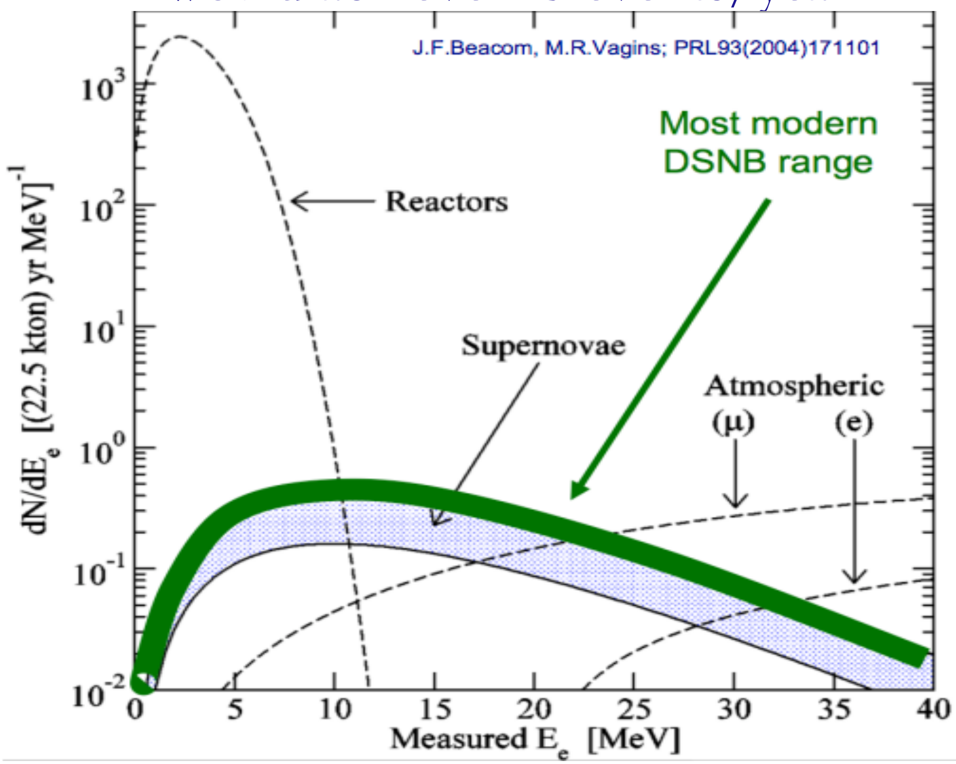
Why ? (IIa)

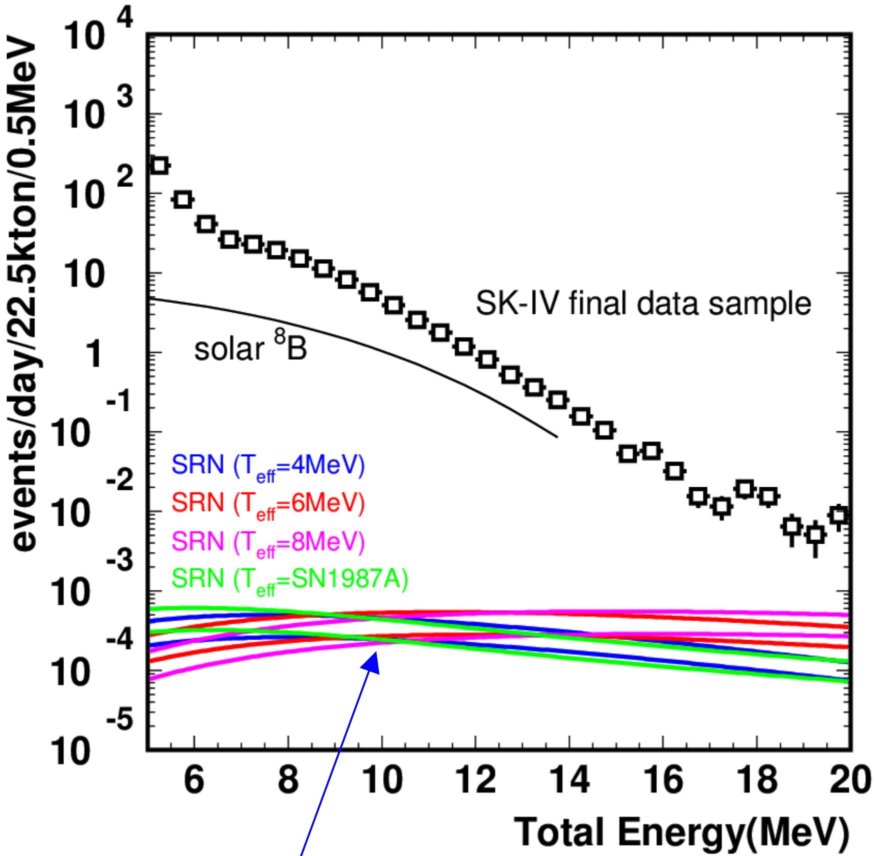
new physics research paradigms

➢ Diffuse Supernova Neutrino Background (DSNB):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- this observation is limited by current background
- with neutron tagging, SK would achieve ~5 events/year

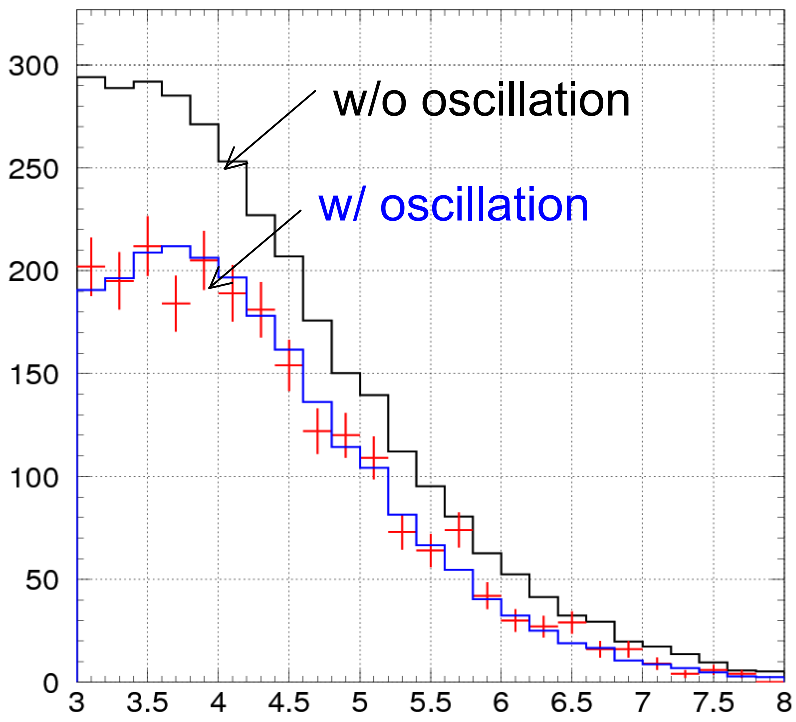


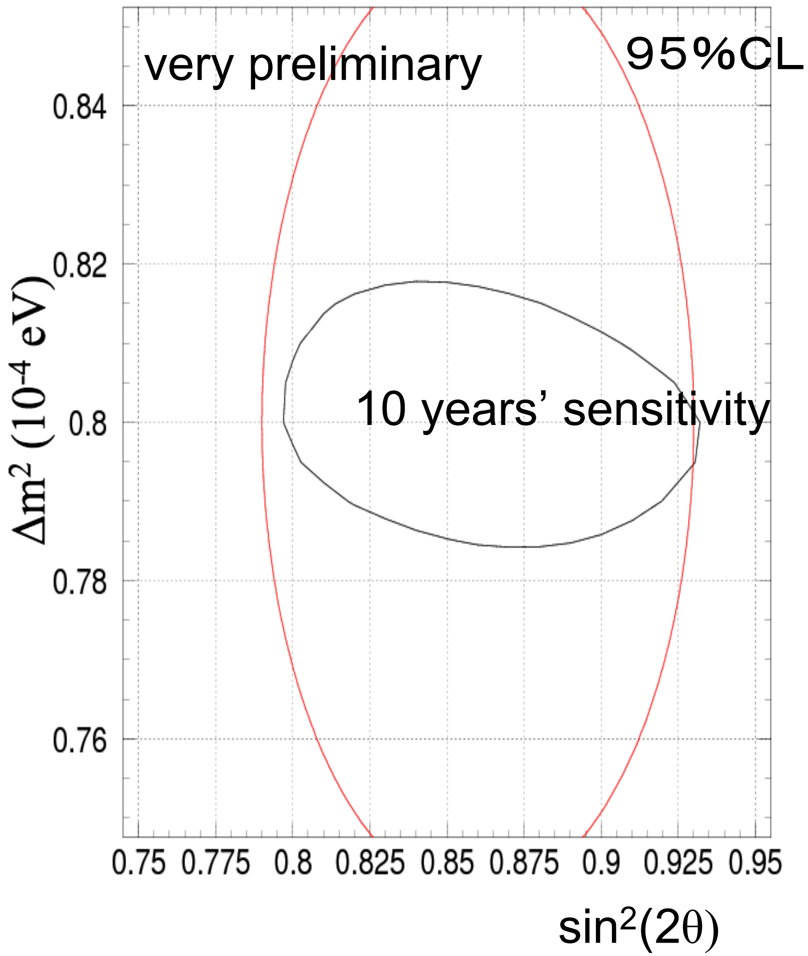


SRN predictions

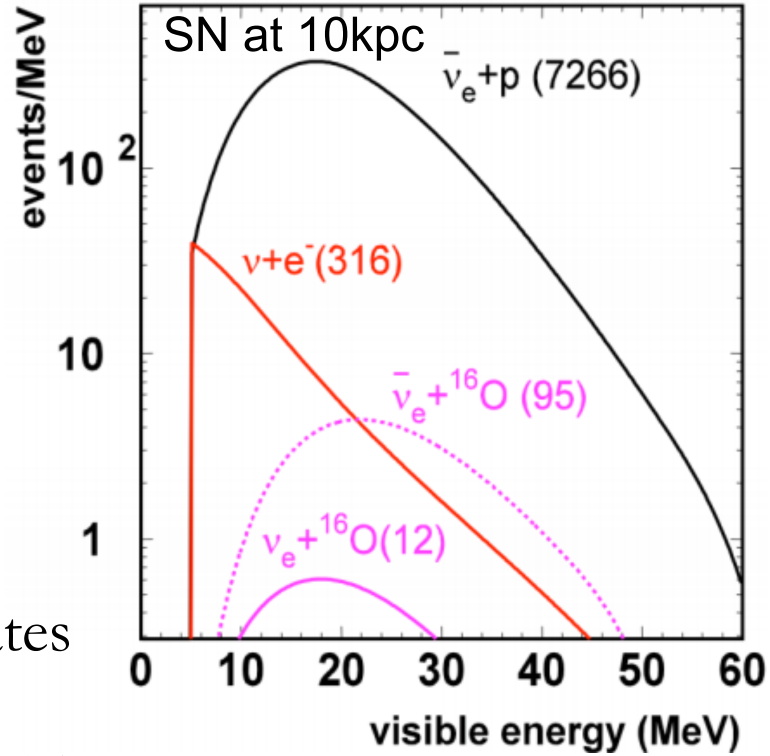
Why ? (IIb) *new physics research paradigms*

- Improve sensitivity to solar sector oscillation parameters (Δm_{12} & $\sin^2\theta_{12}$)
  - ⇨ neutron tagging would increase substantially the rate compared to the KamLAND reactor





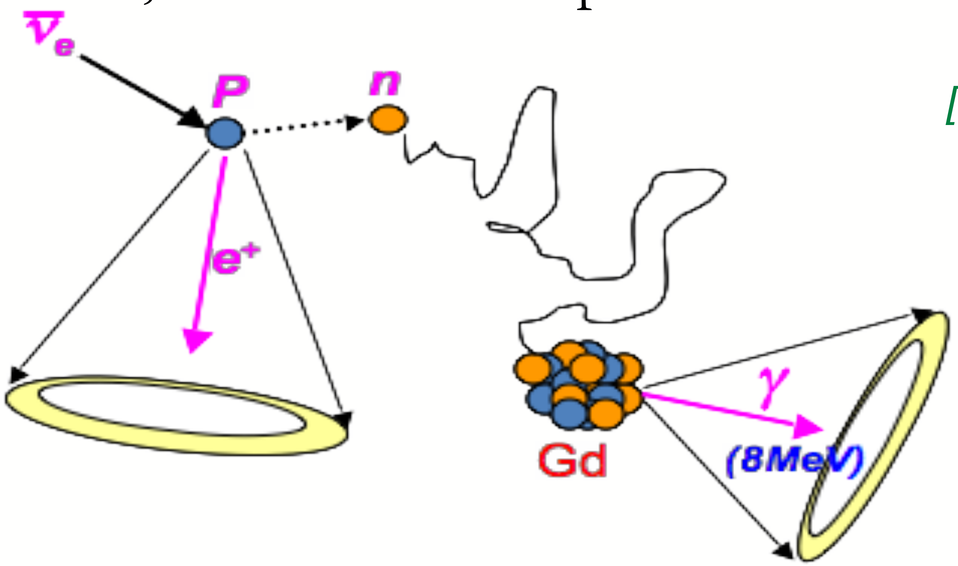
Why ? (IIc) *new physics research paradigms*



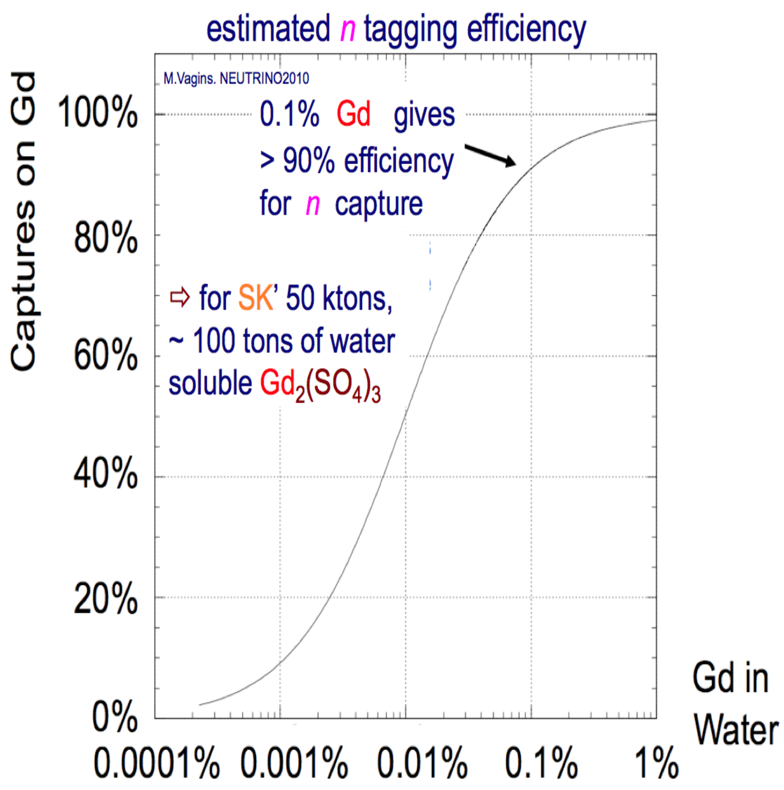
- Much more detailed measurement of nearby Supernovae explosion
- proton decay:
  no neutron should be present in the event
- Sensitivity to "wrong sign" ν_e production from Sun
- Gain information on the hadronic final states of νs interactions in the detector
- Maybe distinction between $\bar{\nu}$s and νs from T2K
- Improvement of identification of $\bar{\nu}$ over ν in the atmospheric sector (~GeV) is being studied

Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!

- **neutron tagging** in Super Kamiokande
- **Gad**olinium has the greatest **n** capture cross section of all stable nuclei
- When **Gd** captures a thermalized **n**, it emits a γ cascade of **8 MeV** (scatters an **e** by Compton scattering)
- Then, the inverse beta process:



[Beacom and Vagins PRL93,171101 (2004)]

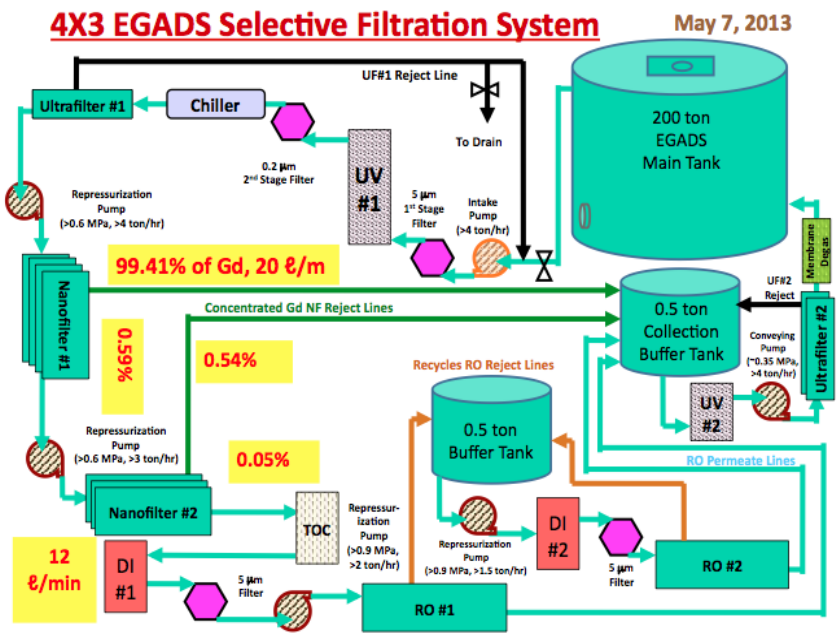


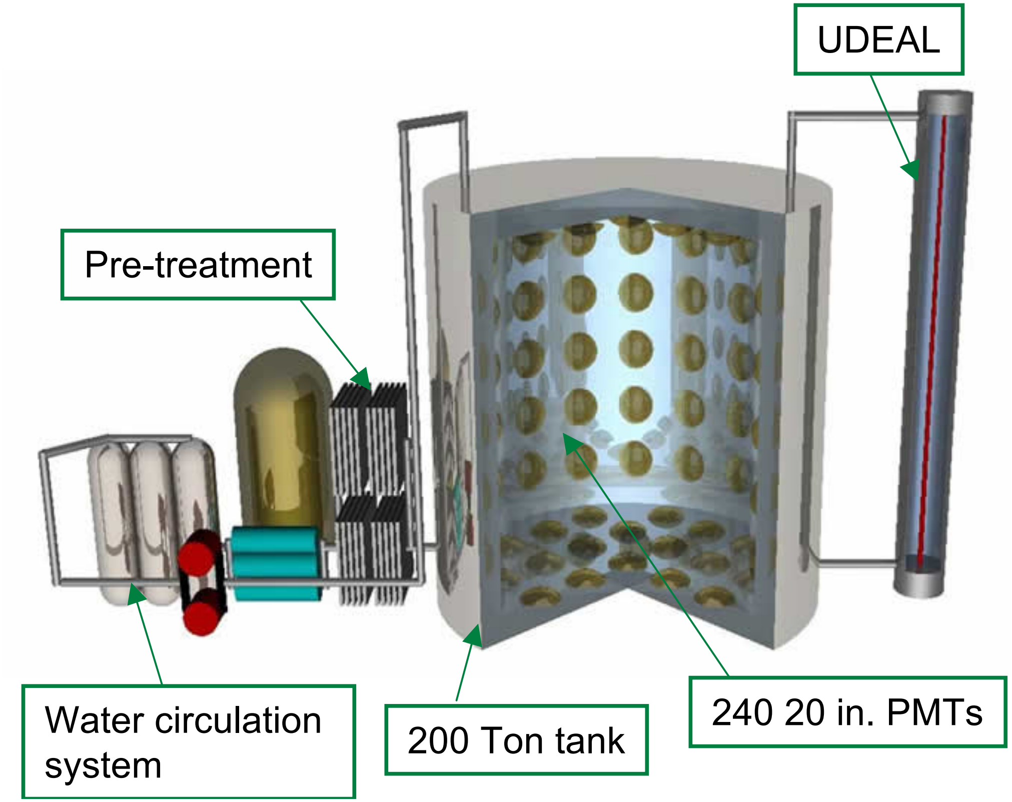
- A **Gd** dissolvable compound in WC detectors would improve its performance hugely by space-time delayed coincidence
- $Gd_2(SO_4)_3$: no corrosion, excellent solubility and and small light attenuation

How ? (Ia)

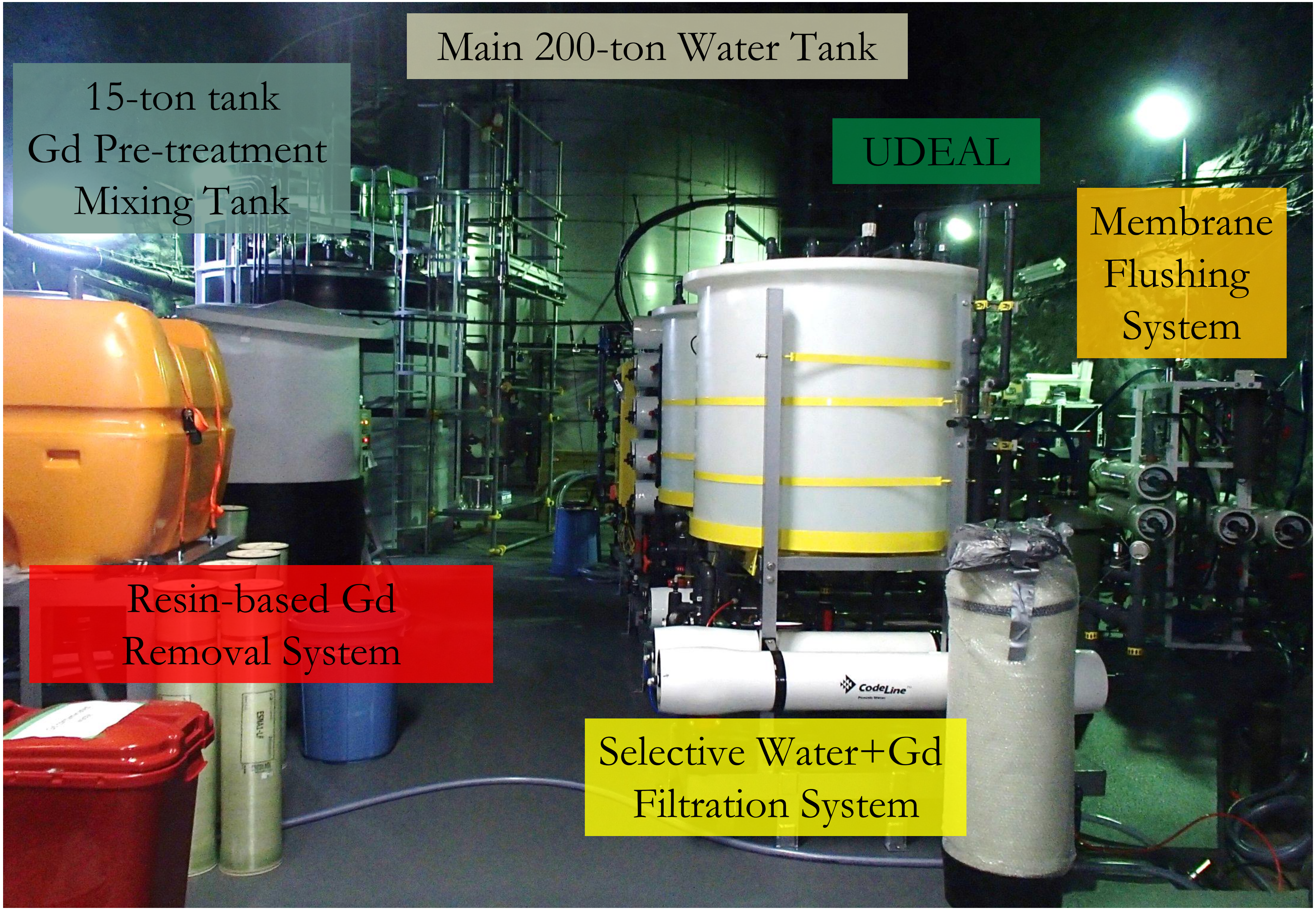
*EGADS (**E**valuating **G**adolinium's **A**ction on **D**etector **S**ystems)*

- Selective filtration system (brand new technology developed at UCI)
- Gd compound "cleaning" and dissolving → pre-treatment system circulation thorough resins (AJ4400 to remove U, Th)
- Water transparency control → UDEAL (**U**nderground **D**evice **E**valuating **A**ttenuation **L**ength)
- Gd uniformity along volume control → AAS (**A**tomic **A**bsorption **S**pectrometer)
- Gd removal





How ? (Ib)


Main 200-ton Water Tank
15-ton tank
Gd Pre-treatment
Mixing Tank
UDEAL
Membrane
Flushing
System
Resin-based Gd
Removal System
Selective Water+Gd
Filtration System
CodeLine

How ? (IIa) *status / schedule*

- What we have done
  - Selective filtration system; excellent water purity, excellent no-rejection of Gd
  - Fully automated monitoring of water transparency
  - PMT pre-calibration
  - Dissolved $Gd_2(SO_4)_3$ up to 0.2% concentration in 200-ton tank; good water transparency; good uniformity in concentration; no strange effects

How ? (IIb) *possible timelines*

EGADS

2012-2013: 200-ton Tank Gd run

2013: PMT installation

2013: 200-ton Tank pure water data-taking

2013 - : 200-ton Tank Gd data-taking

2014: Electronics upgrade

2014 - : Nearby Galactic Supernova sensitivity

- While the EGADS R&D works will completed within the next two years, the precise schedule for adding Gd to SK must still be discussed and agreed upon within the SK Collaboration

Who?

EGADS members

- Kamioka Observatory. ICRR Univ. of Tokyo
  - Y.Kishimoto, ***M.Nakahata***, H.Sekiya, A.Takeda, T.Yokozawa
- Okayama University
  - H.Ishino, A.Kibayashi, Y.Koshio, T.Mori, T.Yano, M.Sakuda, Y.Yamada
- Kobe University
  - Y.Takeuchi
- Univ. of Autonoma Madrid
  - P. Fernández, L. Labarga
- Univ. of California, Irvine
  - G. Carminati, W. Kropp, A. Renshaw, M. Smy, P. Weatherly, J. Griskevich
- Kavli IPMU Univ. of Tokyo
  - L.Marti , ***M.Vagins***

Backgrounds in GADZOOKS!

- an important source of background comes from the radioactive contamination of the materials; of clear relevance is that in the Gd…

- Three main types of background events (details in next slides)
  - 1γ + 1**n** events in the **S**pontaneous **F**ission of the ^{238}**U** isotope
  - 1**e** and 1**e** + γ from *β* decay of ^{214}Bi and ^{208}Tl
  - events with **n**eutrons produced in SF and (α,**n**) reactions on ^{18}O and ^{17}O scattering, the α coming from the radioactive α decays

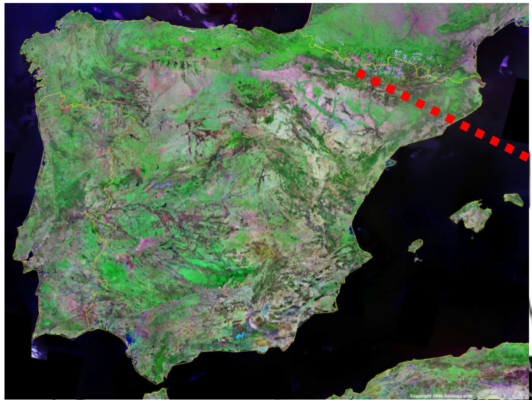
- We are studying thoroughly the above backgrounds:
  - their intensity given the measured radio-activities
  - their impact on the new physics measurements
  - their impact in the "regular" SK measurements

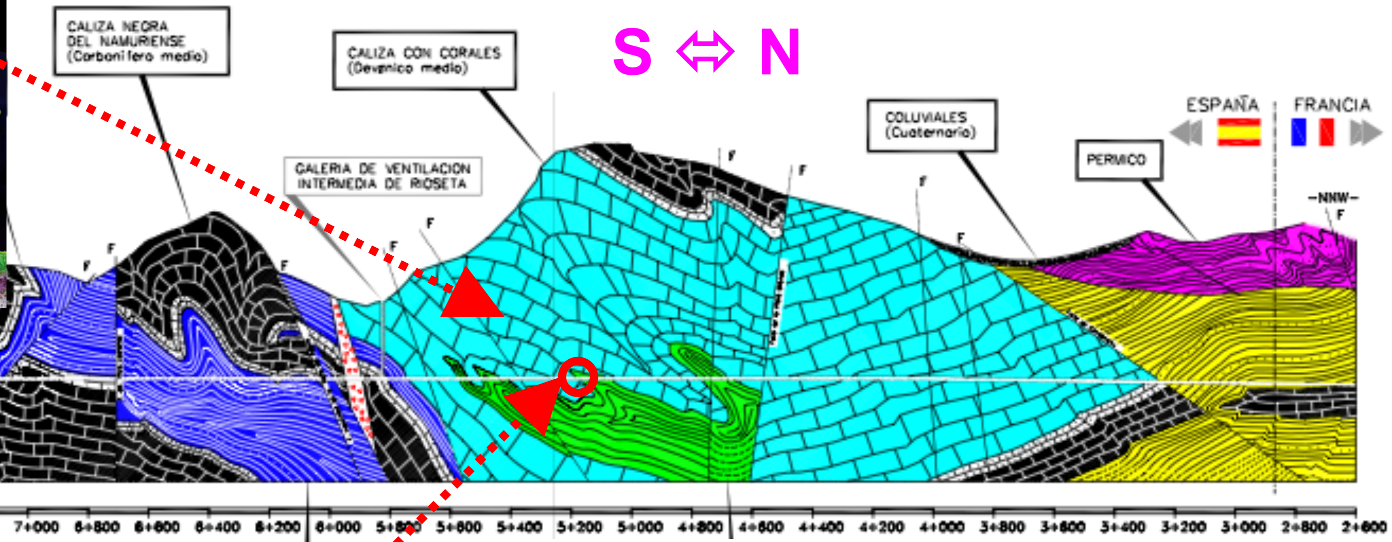
details follow …

- An official experiment at the LSC (Canfranc Underground Lab.), EXP-06-2009, carries out the complete campaign of radioactivity measurements for GADZOOKS! using HPGe detectors

Measurements done mostly with *HpGe* detectors at the *LSC*

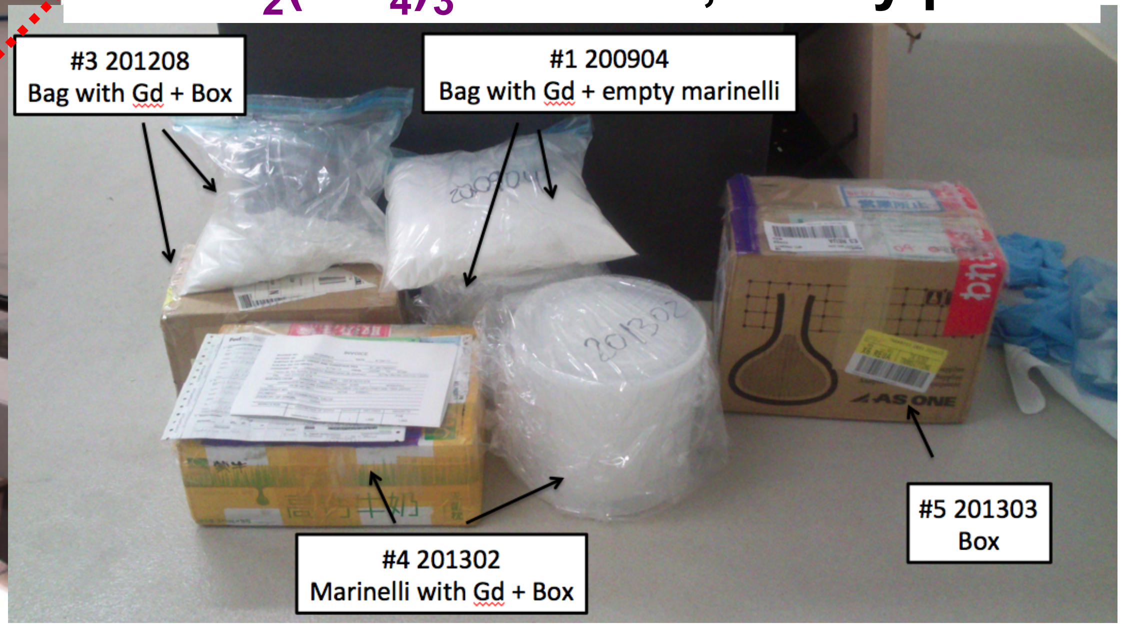
[Canfranc Underground Laboratory]





HpGe detector farm @ LSC

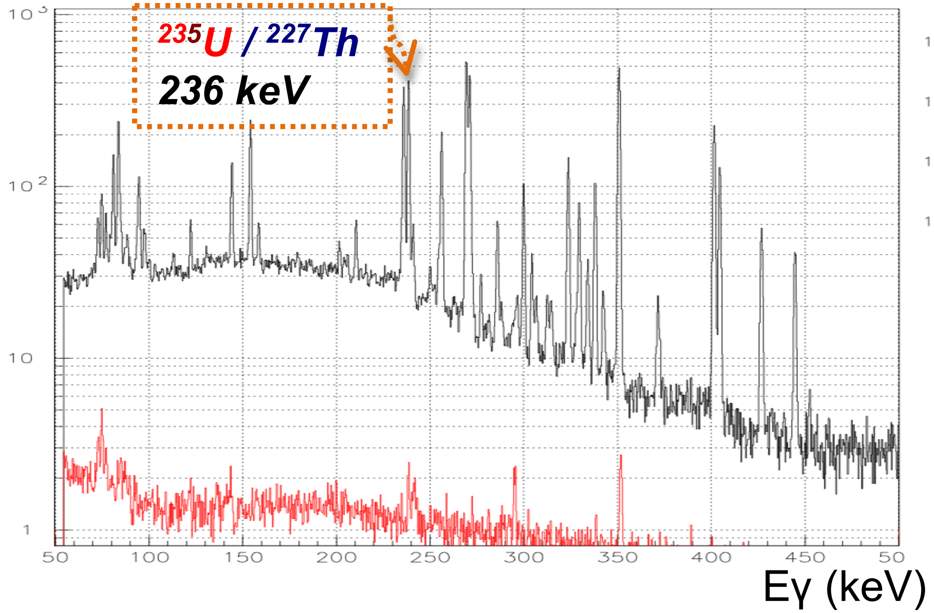
$Gd_2(SO_4)_3$ batches; family photo

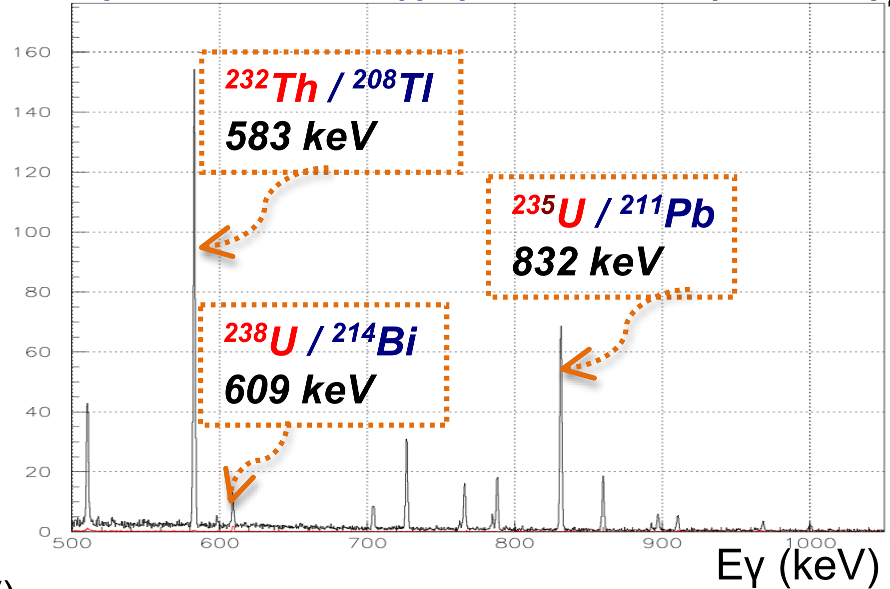


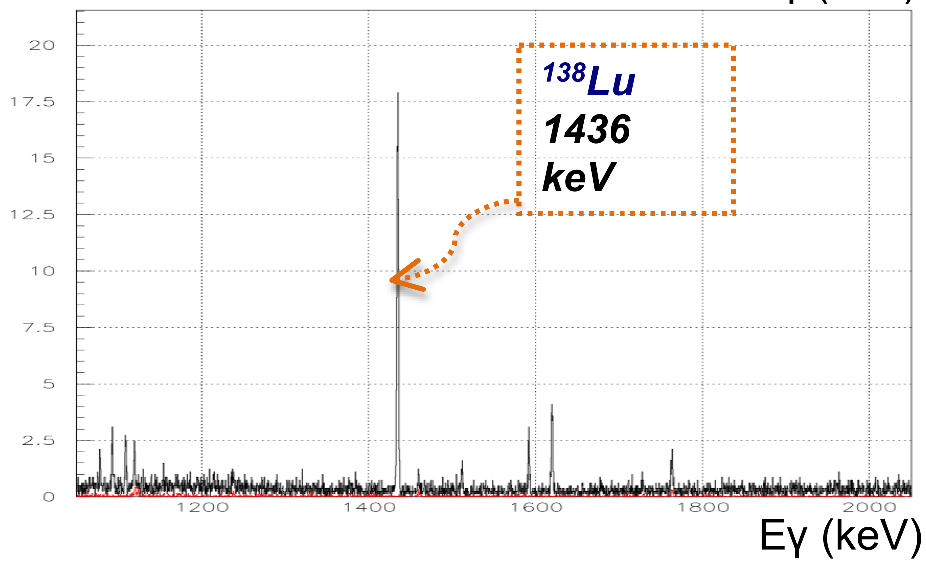
FOR ILLUSTRATION: batch to be used at instrumented EGADS

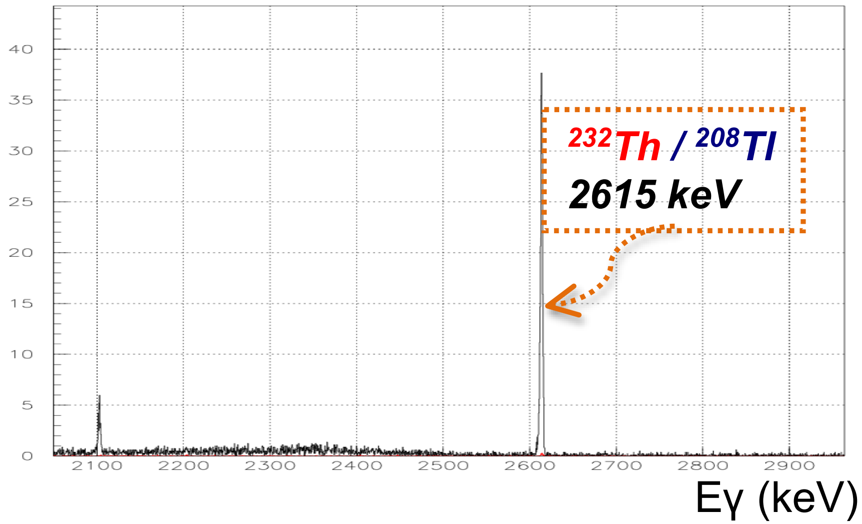
γ spectrum from ***radioactive decays:***

black is Gd sample **red** is bkg. [counts/day/kev/kg]





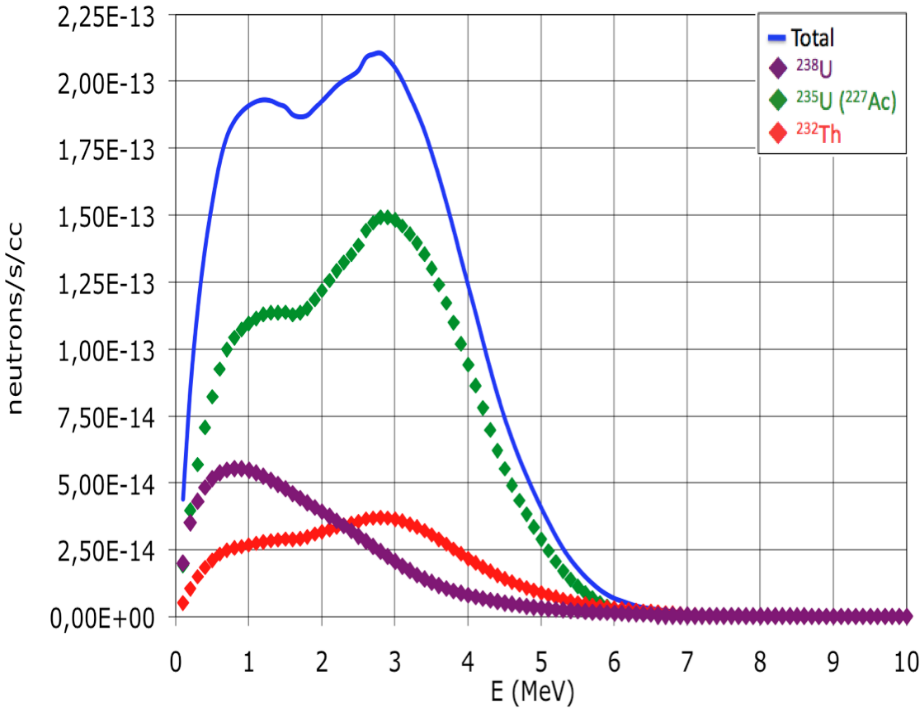


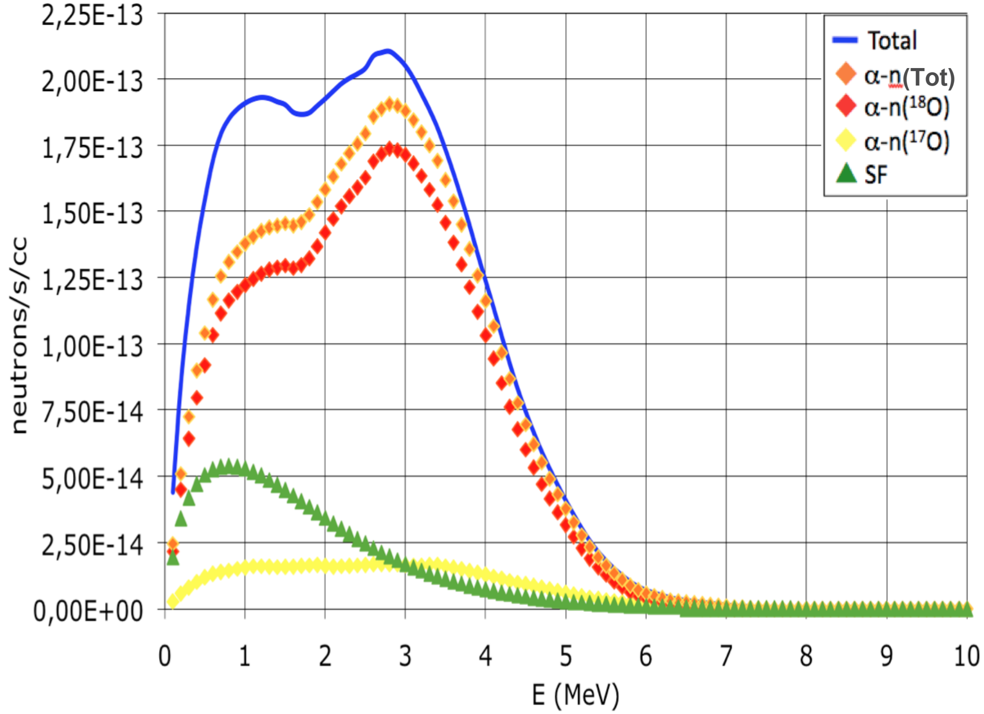


Background in GADZOOKS!

γ_s and Neutrons from radioactive contamination

- **n**eutron production processes are **(α,n)** reactions and **SF**





- **(α,n)** reactions with **^{18}O** are dominant to produce **n**

Background in GADZOOKS! *neutrons*

- **(α,n)** reactions with **^{18}O**
  - **α** particles are emitted with ~6 MeV
  - Low **n**eutron separation energy of **^{22}Ne** and **^{21}Ne**

$$^{18}O+^{4}\alpha(\sim 6MeV)\rightarrow^{22}Ne^{*}(\sim 15MeV)\rightarrow^{20}Ne+2^{1}n(\sim 2.5MeV)$$

  - **^{18}O** and a are in the fundamental states 0^{+}, the same as **^{22}Ne**

    =>No angular momentum transition (i.e. photons)

    =>All **n**eutrons come in pairs and no *γ*s are emitted
- Similarly occurs with **^{17}O** case, but
  - Angular momentum change between **^{21}Ne**$_{5/2}$ and **^{19}Ne**$_{3/2}$ ⇨ 0.4 MeV *γ*
  - **^{19}Ne** decays to **^{19}F** by emitting 1.5 MeV *β*

$$^{17}O+^{4}\alpha(\sim 6MeV)\rightarrow^{21}Ne^{*}\rightarrow^{19}F+2^{1}n(\sim 2.6MeV)+\gamma(0.4MeV)+\beta(1.5MeV)$$

Final state from **(α,n)** reactions are distinguishable from inverse beta
… But produce many **n**eutrons

Background in GADZOOKS!

[1γ + 1n] events

- ^{238}**U** the greatest contribution to **SF**
  - emits neutrons and photons
  - Fraction of **SF** in ^{238}**U** is $5 \cdot 10^{-7}$
  - Probability of a γ ray from ^{238}**U SF** with a given energy is $P(E)=0.7e^{-E/1.4}$
  - Probability of *1***n** per fission is *28%*

(E_γ small dependence with **n** multiplicity (ν))

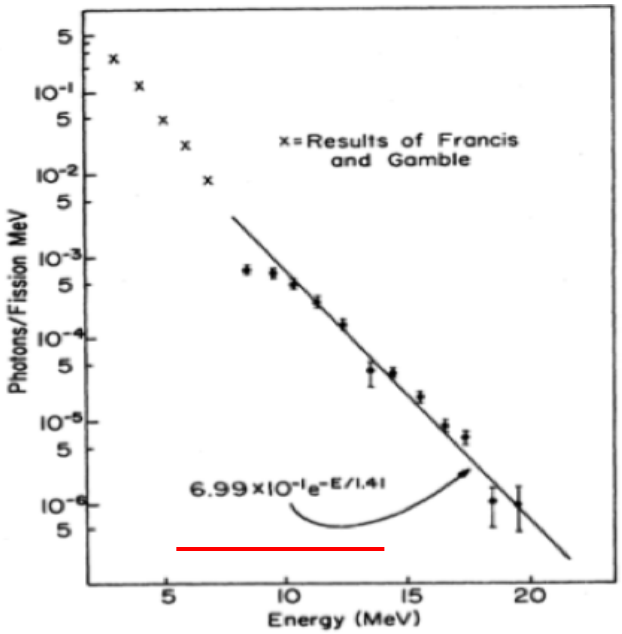
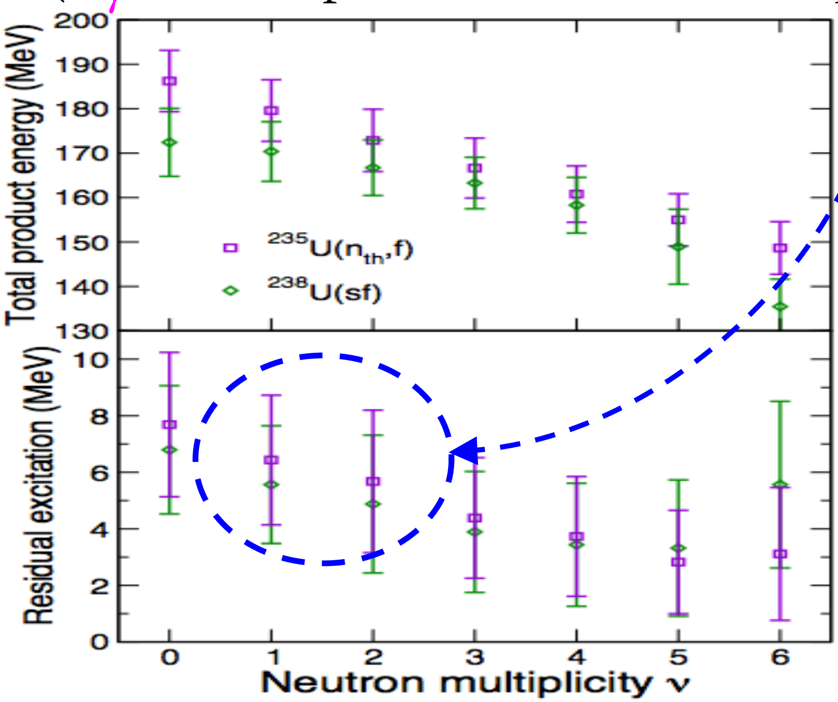
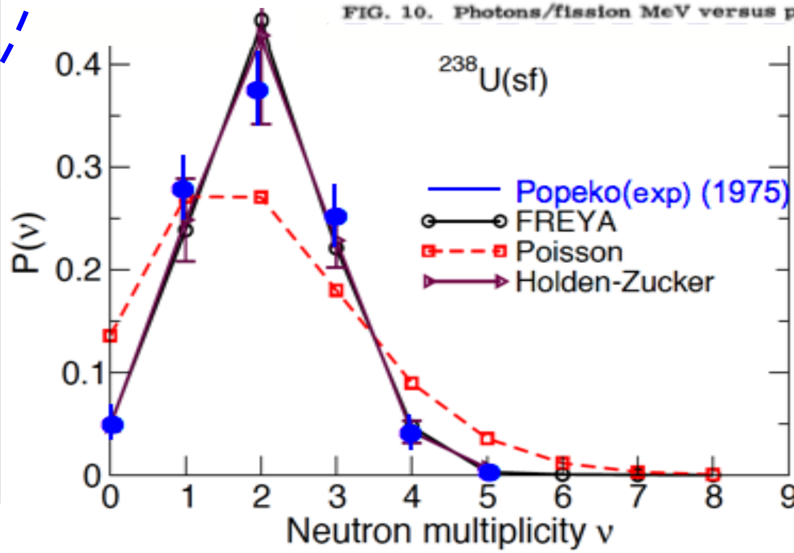


FIG. 10. Photons/fission MeV versus photon energy.





[R. Vogt and J. Randrup, Phys.Rev.C 84, 044621 (2011)]

[A.G.Popeko, V.I.Smirnov, G.M.Ter-Akopyan, B.V.Fefilov,JNuclPhys 24 1976 473, Sov. J. Nucl. Phys. 24 1976 245 (18/06/1975)]

[H. W. Sobel et al, Phys.Rev.C 7, 4 (1973)]

Background in GADZOOKS! *[1γ + 1n] events*

- taking Eγ>13.5 *MeV* (this means an **e⁻** of ~10 MeV), we estimate the background due to **^{238}U SF**
- considering 1 mBq of **^{238}U**

  → **5 ·10^{-7} SF** per **^{238}U** decay

  → **6 ·10^{-5}** γs/Fission [Eγ > 13.5 MeV]

  → 22.5 ·10^{6} kg in SK fiducial volume:

  - 1 mBq of **^{238}U**:

    ⇨ 214 prompt-γs/year in SK-fv with Eγ > 13.5 MeV

  - in 28% of **SF** **^{238}U** only 1 neutron is produced, thus

    ⇨ 6 [γ + **n**] events/year

  - AJ4400 reduces the amount of **^{238}U** by a factor 100

    ⇨ 0.06 [γ + **n**] events/year After AJ4400 processing

- For ilustration, take the current **$Gd_2(SO_4)_3$** batch at EGADS:
  - 30 mBq/kg = 2.4 ·10^{-9} g(^{238}U)/g(Gd)

    ⇨ <**2** [γ + **n**] events/year with AJ4400

- Signal estimates from SRN are ~**5** events/year

Background in GADZOOKS!

βs and γs from radioactive contamination

- Other elements of radioactive chains decay by emitting ***β***s
  - Some elements emit *β*s with sufficiently high energy accompanied by *γ*s
    - ^{232}Th → … → ^{228}Ra → … → **^{208}Tl** → E_{β}^{max}= 5.00 MeV +
      - γ 277 keV 6%
      - γ 511 keV 23%
      - γ 583 keV 84%
      - γ 861 keV 12%
      - γ 2615 keV 99%
    - ^{238}U → … → ^{226}Ra → ^{222}Rn → … → **^{214}Bi** → E_{β}^{max} = 3.26 MeV +
      - γ 609 keV 46%
      - γ 1120 keV 15%
      - γ 1765 keV 16%
  - To achieve **4.0 MeV** solar neutrino analysis in 0.2%Gd+H_2O SK, the following radioactivity levels would be needed
    - **< 0.35 mBq/kg [^{238}U]**
    - **< 0.35 mBq/kg [^{232}Th]**
  - we also need to remove the **Ra** from Gd compound
    - Selective resins, such as DOWEX RSC , are one commercially available solution

Summary / conclusions

- Neutron tagging would improve dramatically the sensitivity of SK
- Gd very good candidate to do the job
- $Gd_2(SO_4)_3$ best compound in terms of solubility and corrosion
- Tests done with $Gd_2(SO_4)_3$ show
  - no Gd rejection due to the selective filtration system: success!
  - very good water transparency
  - solution uniformity very good
- Studied backgrounds from radioactive contamination
  - (α,**n**) produce many **n** but no high energy γs
  - background from ^{238}U **S**pontaneous **F**ission implies that we must reduce U contamination in Gd salt. AJ4400 resin removes U with high enough efficiency
  - βs and γs from ^{208}Tl and ^{214}Bi implies we must reduce Ra levels. We are going to test resins to remove Ra, e.g. DOWEX RSC

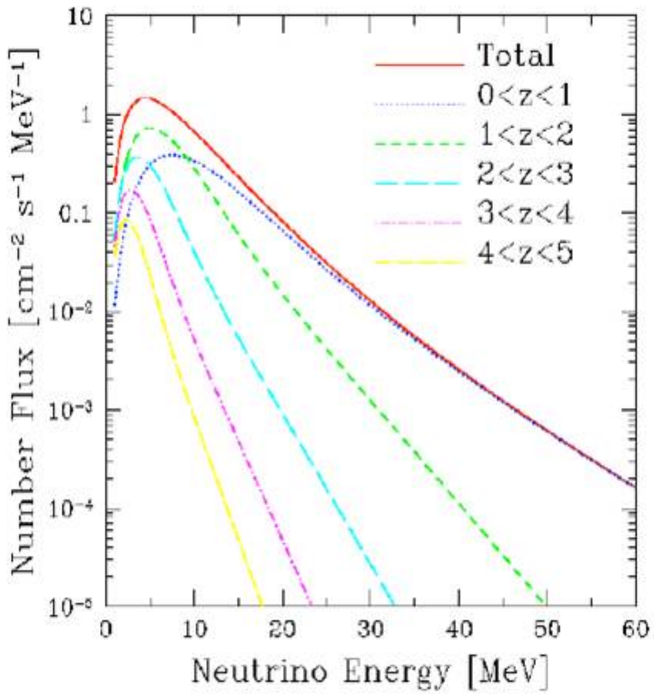
THANKS!!

ありがとうございます

Backup slides

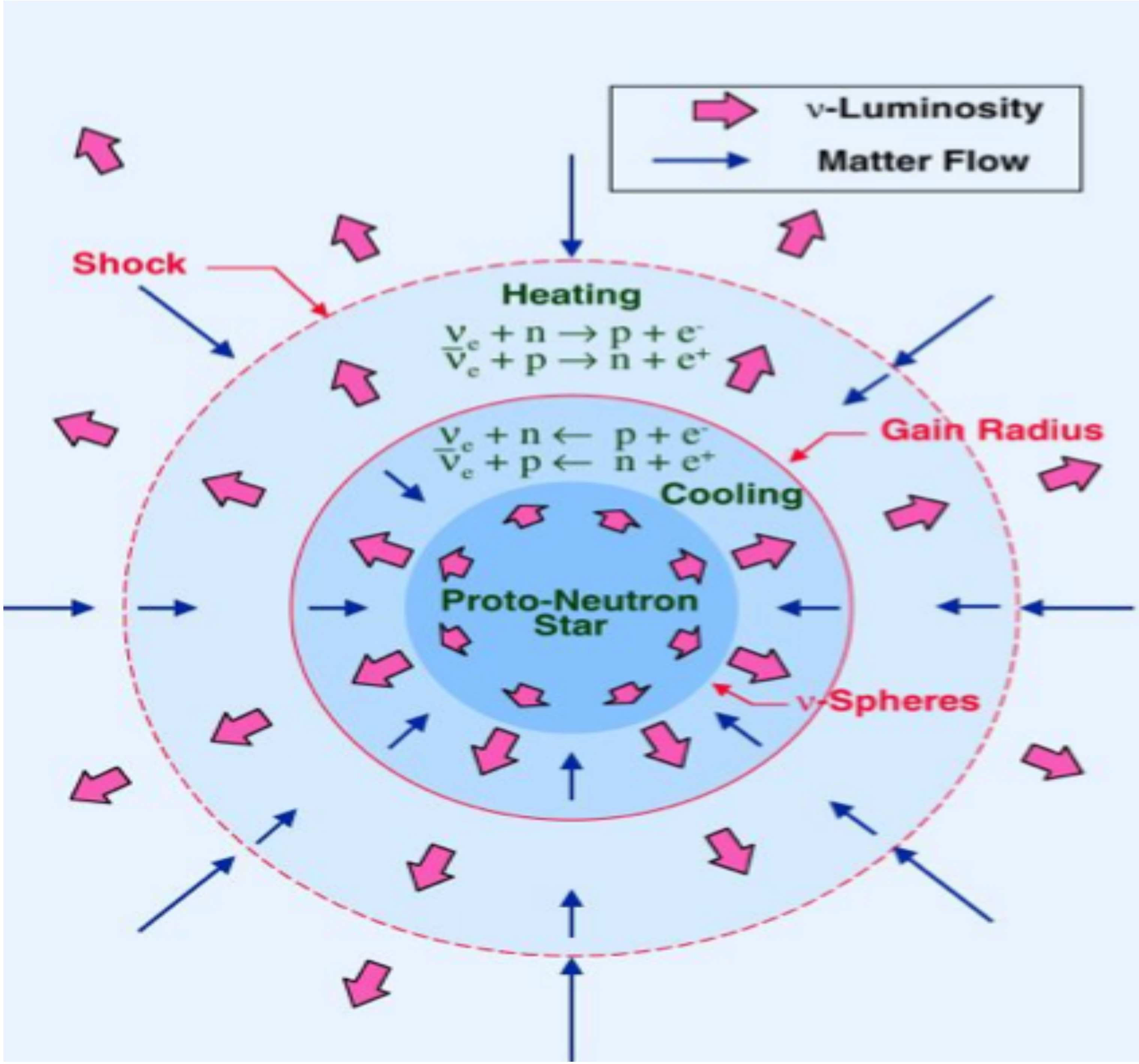
Supernova relic neutrinos

There are about 10^{20} stars in the universe.
(~10^{10} galaxies and ~10^{10} stars/galaxy)
About 0.3% stars end their life by supernova explosion.
So, about 10^{17} supernova explosions have happened from the beginning of the universe. Neutrinos from those supernova explosions are called supernova relic neutrinos (SRN).



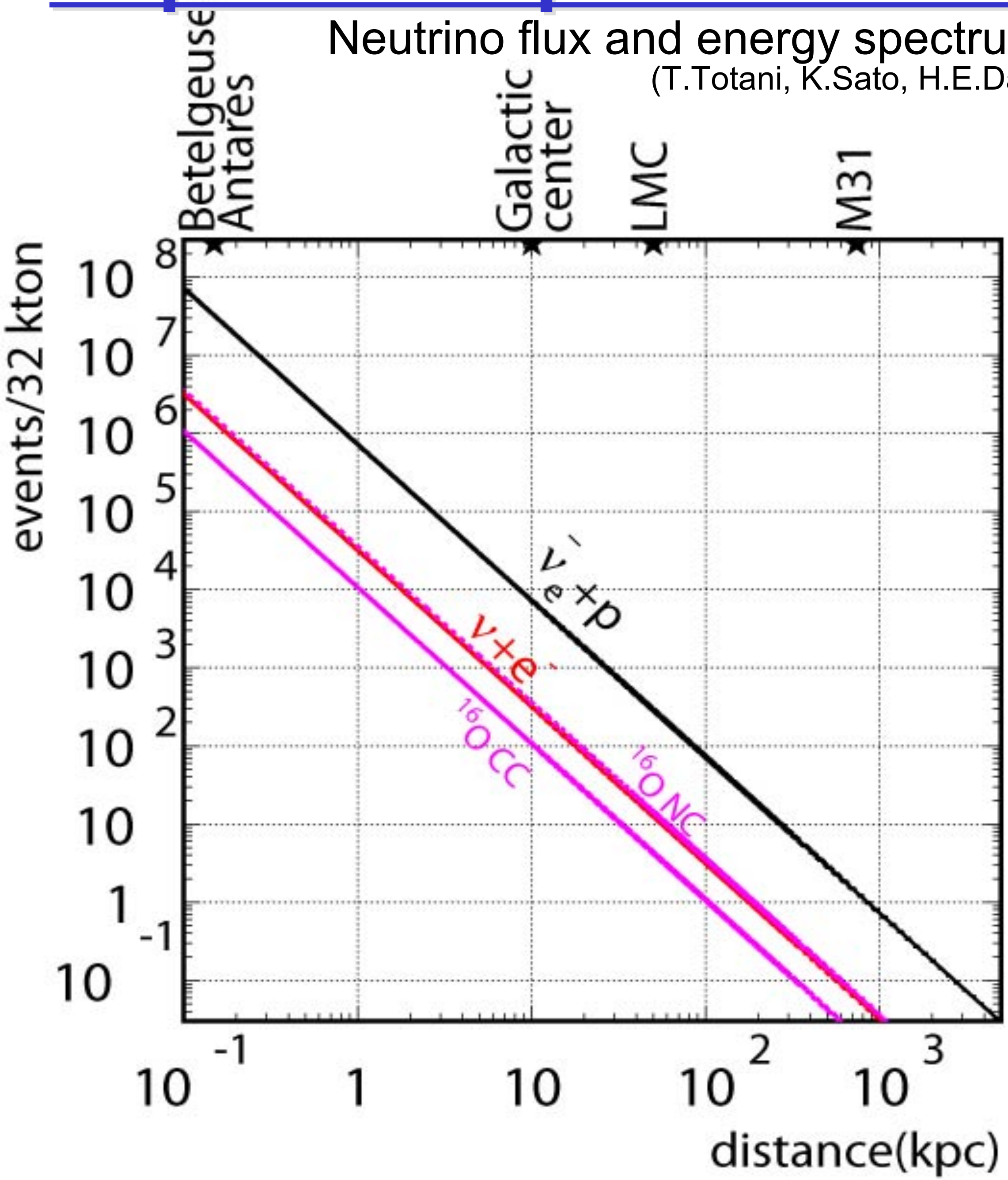
Expected energy spectrum of SRN
(a theoretical calculation)
SRN spectrum will tell us the history of massive stars.

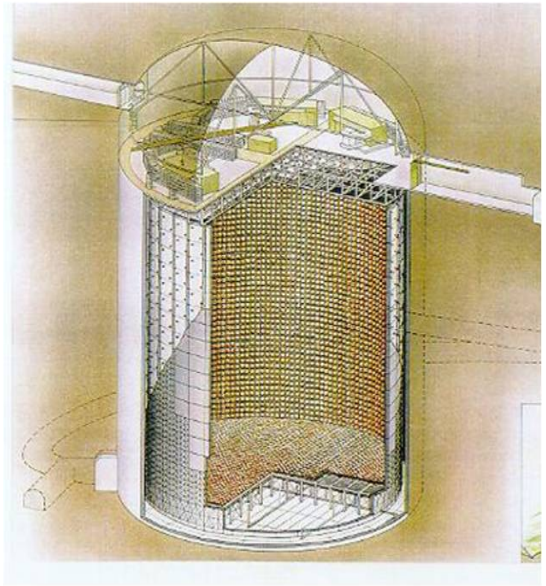
$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{max}} R_{SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$


ν-Luminosity
Matter Flow
Shock
Heating
$\nu_e + n \rightarrow p + e^-$
$\bar{\nu}_e + p \rightarrow n + e^+$
Gain Radius
$\nu_e + n \leftarrow p + e^-$
$\bar{\nu}_e + p \leftarrow n + e^+$
Cooling
Proto-Neutron Star
ν-Spheres

Super-K: Expected number of events

Neutrino flux and energy spectrum from Livermore simulation
(T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))



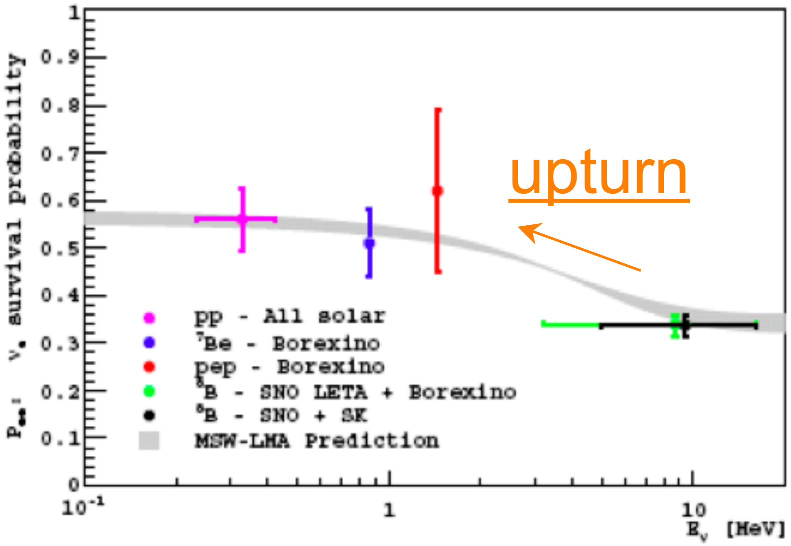


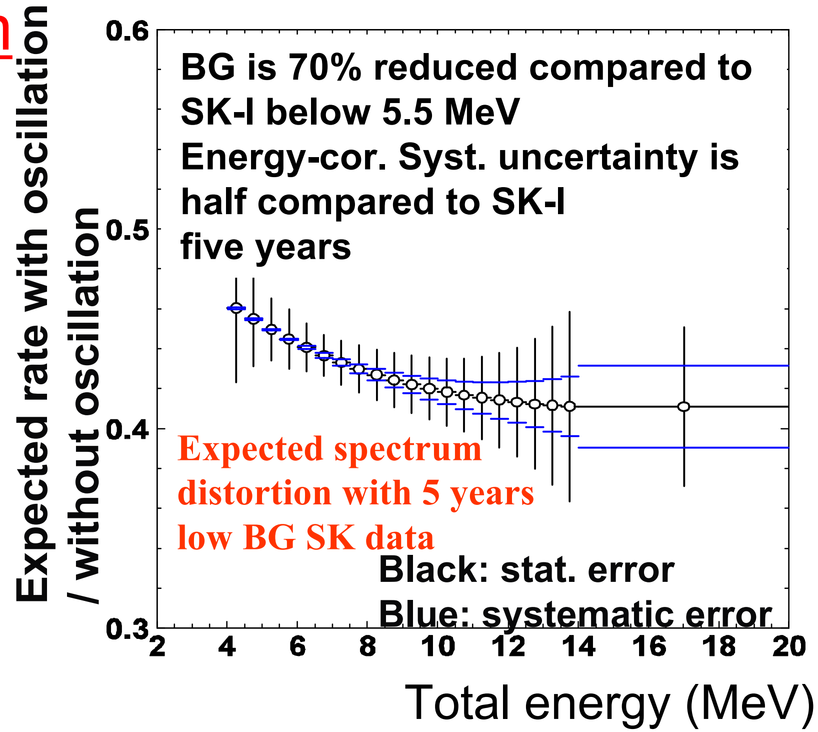
~7,300 $\overline{\nu}_e$+p events
~300 ν+e events
~360 ^{16}O NC γ events
~100 ^{16}O CC events
(with 5MeV thr.)

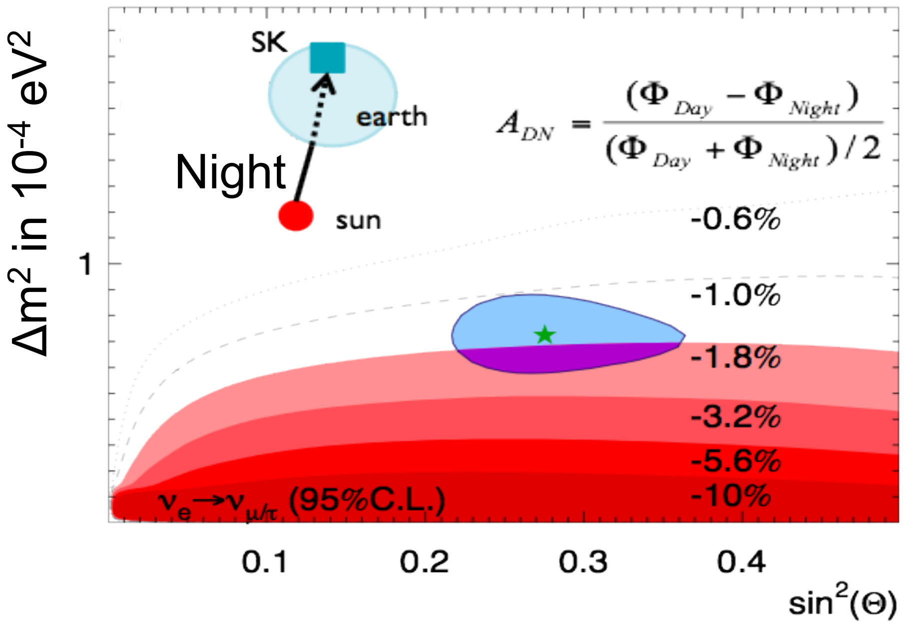
for 10 kpc supernova

Current targets at SK

Precise measurement of ^{8}B spectrum







Day/night difference

Direct measurement of matter effect

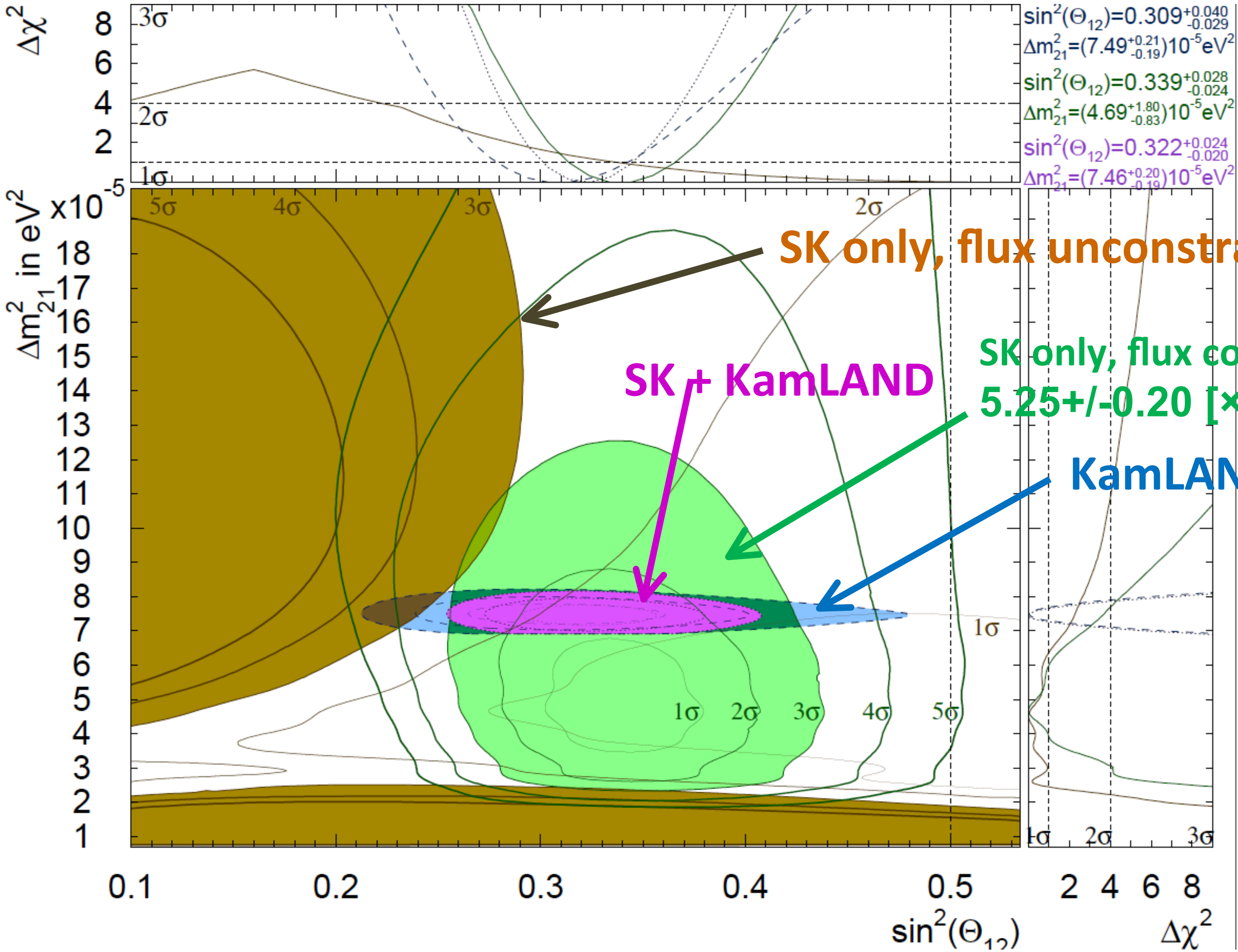
SK only : θ_{12} - Δm_{21}^2

- $\sin^2\theta_{13}$ is fixed at 0.025

Filled area: 3σ

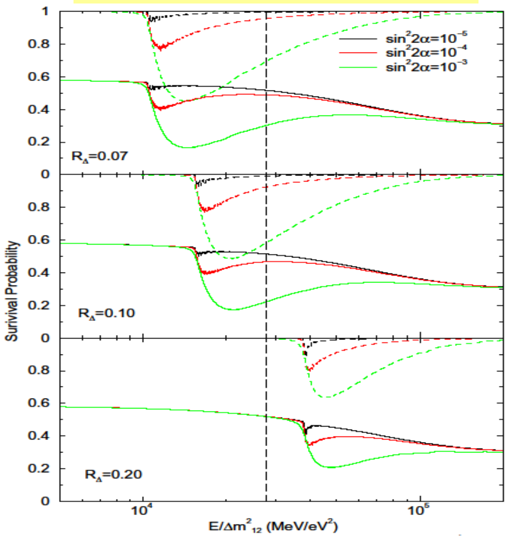
May 2012

Preliminary



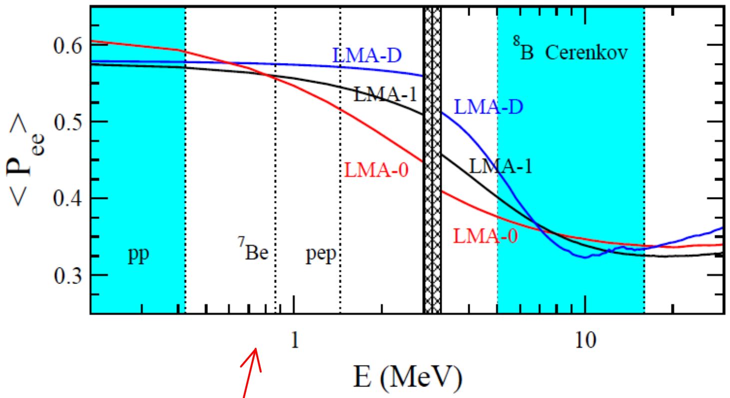
Models which predict non-upturn

Sterile neutrino



$$R_\Delta \equiv \frac{\Delta m^2_{01}}{\Delta m^2_{21}}$$

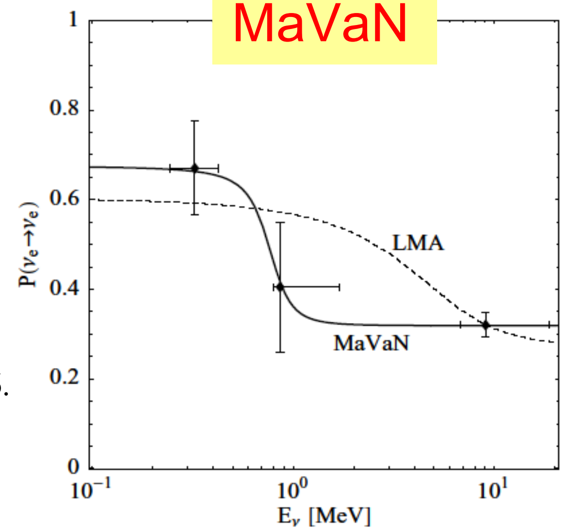
Holanda and Smirnov, Phys.Rev.D69(2004)113002. (hep-ph/0307266)



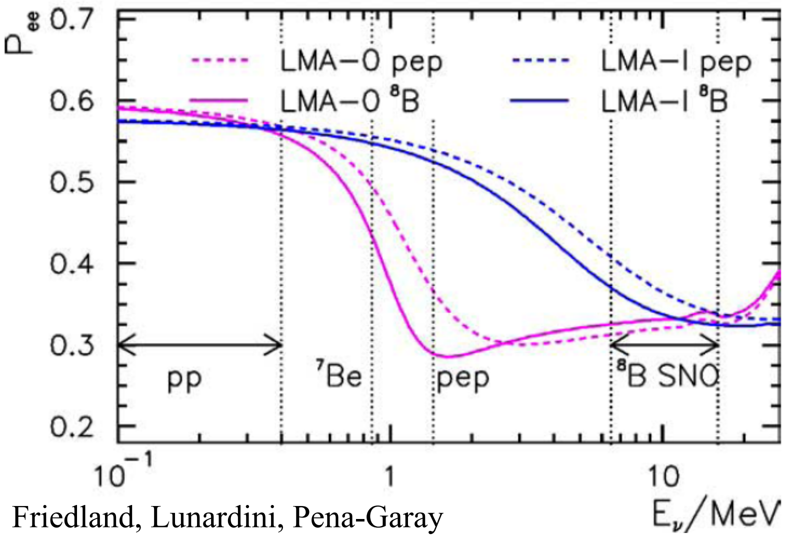
Miranda, Tortola and Valle, JHEP 0610:008,2006. (hep-ph/0406280)

Non standard Interaction

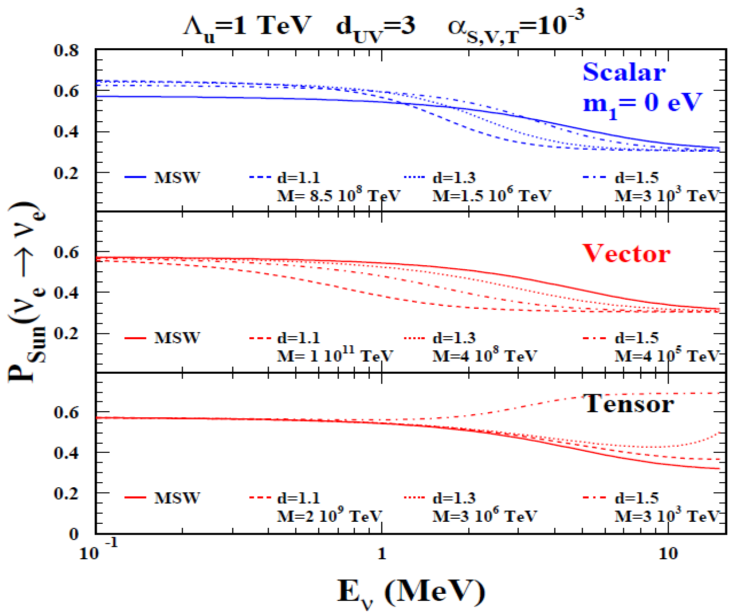
MaVaN



Barger, Huber and Marfatia, Phys.Rev.Lett.95:211802,2005 (hep-ph/0502196)



Friedland, Lunardini, Pena-Garay PLB594(2004)347(hep-ph/0402266)



Gonzalez-Garcia,Holanda,Zukanovich ,Funchal, JCAP 0806:019,2008. (hep-ph/0803.1180)

Unparticle

Day-Night variation *Preliminary* May 2012

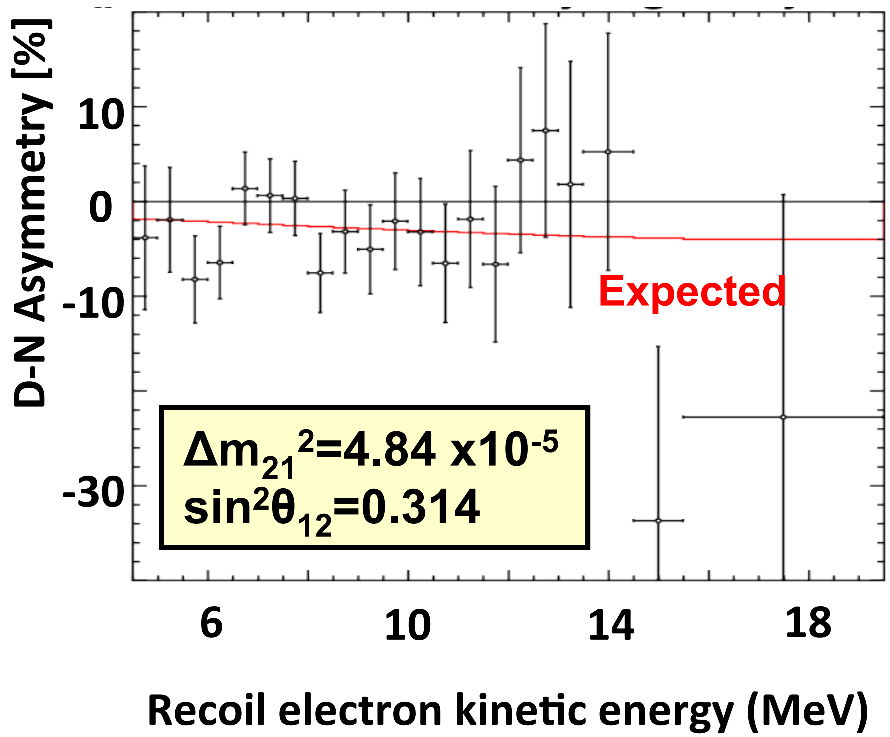
- Un-binned Day-Night analysis (PRD69, 011104) is applied in each SK phase, then obtained Day-Night asymmetry values (=A_{DN}) from fitted Day-Night amplitude parameter.
  - Consider energy and zenith angle dependence of event rate variation.

$$A_{DN} = \frac{\text{Day flux} - \text{Night flux}}{0.5\,(\text{Day flux} + \text{Night flux})}$$

	A_{DN} (±stat.±sys.)
SK-I	-2.0±1.7±1.0 %
SK-II	-4.3±3.8±1.0 %
SK-III	-4.3±2.7±0.7 %
SK-IV	-2.8±1.9±0.7 %
SK combined	-2.8±1.1±0.5 %

Day-Night asymmetry consistent with zero @ 2.3 σ

SK combined D-N asymmetry values



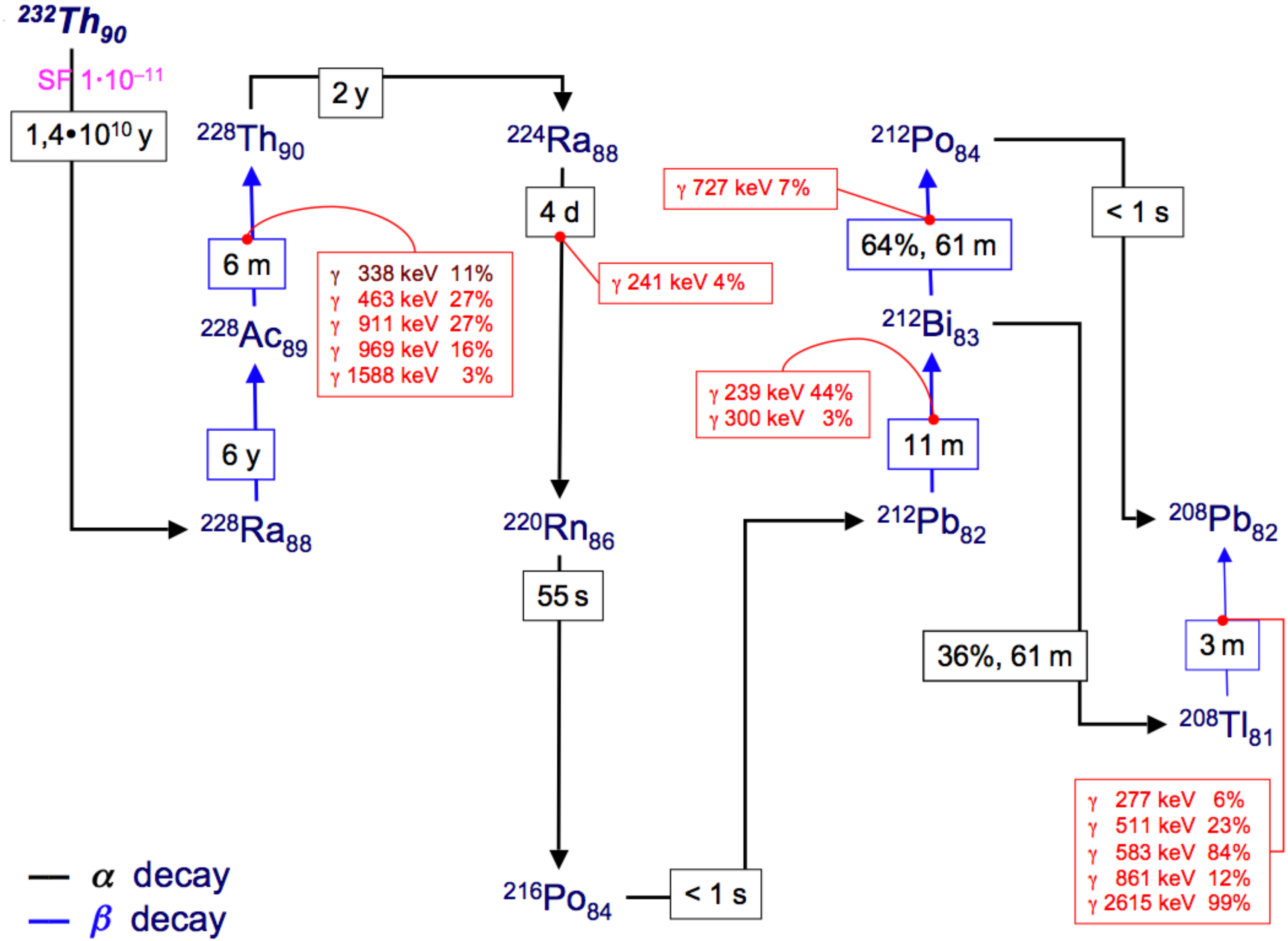
Radioactivity in $Gd_2(SO_4)_3$ batches measured in Canfranc [***mBq/Kg***, limits are ***@ 95%***

Chain	Longest lived parent in sub-chain	Gd200904 Stanford (to SLC)	Gd201008 Stanford (at EGADS now)	Gd201208 Beijing jinghonganxin 0,8kg	Gd201302 Changshu 2kg	Gd201303 Beijing jinghonganxin 2kg (50+450kg)
^{238}U	^{238}U	51 ± 21	< 33	292± 67	74 ± 28	242± 60
	^{226}Ra	8 ± 1	2,8 ± 0,6	74± 2	13± 1	13 ± 2
^{232}Th	^{228}Ra	11 ± 2	270 ±	1099± 12	205 ± 6	21 ± 3
	^{228}Th	29 ± 3	86 ± 5	504± 6	127 ± 3	374 ± 6
^{235}U	^{235}U	< 32	< 32	< 112	< 25	< 25
	$^{227}Ac/^{227}Th$	214 ± 10	1700 ± 20	2956 ± 30	1423 ± 21	1750 ± 42
Others	^{40}K	29 ± 5	12 ± 3 (*)	101 ± 10	60 ± 7	18 ± 8
	^{138}La	8 ± 1	<	683 ± 15	3 ± 1	42 ± 3
	^{176}Lu	80 ± 8	21 ± 2	566 ± 6	12 ± 1	8 ± 2

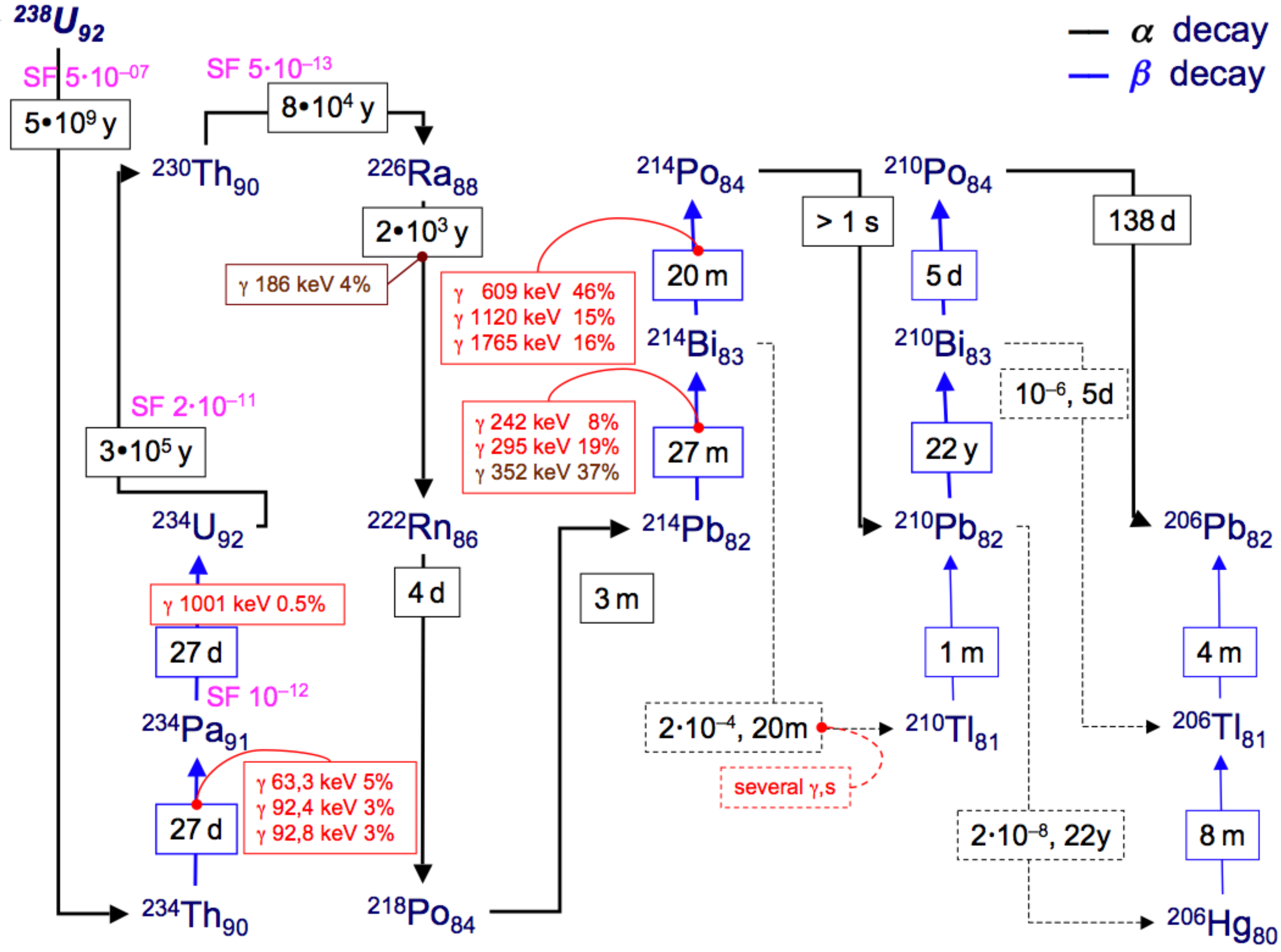
preliminary

→ →

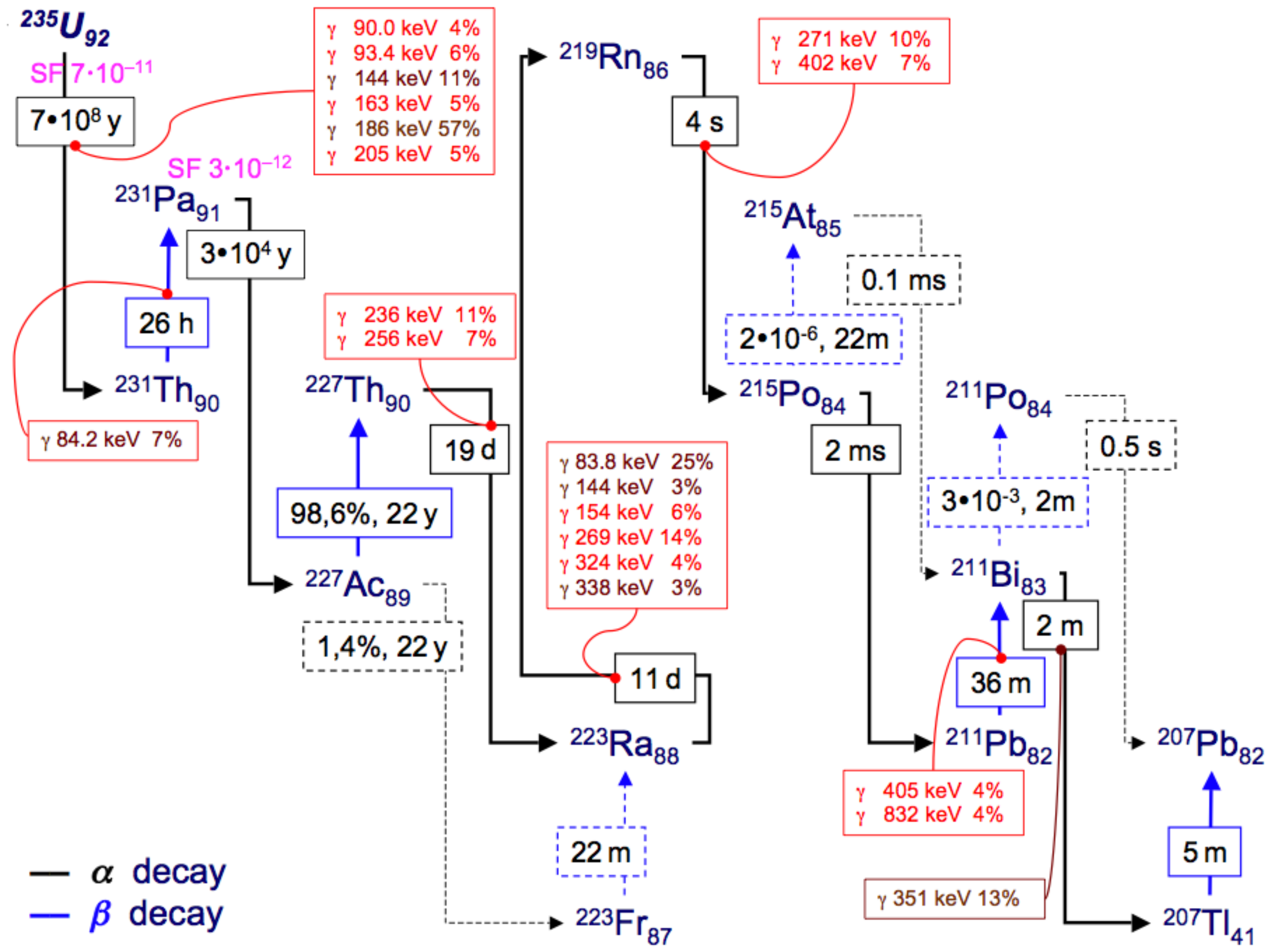
Far too high !



232Th90
SF 1·10−11
1,4•10^10 y
2 y
228Th90
224Ra88
212Po84
γ 727 keV 7%
< 1 s
64%, 61 m
6 m
4 d
γ 241 keV 4%
γ 338 keV 11%
γ 463 keV 27%
γ 911 keV 27%
γ 969 keV 16%
γ 1588 keV 3%
228Ac89
212Bi83
γ 239 keV 44%
γ 300 keV 3%
11 m
6 y
228Ra88
220Rn86
212Pb82
208Pb82
55 s
3 m
36%, 61 m
208Tl81
γ 277 keV 6%
γ 511 keV 23%
γ 583 keV 84%
γ 861 keV 12%
γ 2615 keV 99%
α decay
β decay
216Po84
< 1 s



238U92
α decay
β decay
SF 5·10−07
5•10⁹ y
SF 5·10−13
8•10⁴ y
230Th90
226Ra88
2•10³ y
γ 186 keV 4%
214Po84
> 1 s
210Po84
138 d
γ 609 keV 46%
γ 1120 keV 15%
γ 1765 keV 16%
20 m
5 d
214Bi83
210Bi83
10−6, 5d
γ 242 keV 8%
γ 295 keV 19%
γ 352 keV 37%
27 m
22 y
SF 2·10−11
3•10⁵ y
234U92
222Rn86
214Pb82
210Pb82
206Pb82
4 d
3 m
γ 1001 keV 0.5%
27 d
1 m
4 m
SF 10−12
234Pa91
2·10−4, 20m
210Tl81
206Tl81
several γ,s
γ 63,3 keV 5%
γ 92,4 keV 3%
γ 92,8 keV 3%
27 d
2·10−8, 22y
8 m
234Th90
218Po84
206Hg80



$^{235}U_{92}$
SF 7·10⁻¹¹
7•10⁸ y
γ 90.0 keV 4%
γ 93.4 keV 6%
γ 144 keV 11%
γ 163 keV 5%
γ 186 keV 57%
γ 205 keV 5%
SF 3·10⁻¹²
$^{231}Pa_{91}$
3•10⁴ y
26 h
$^{231}Th_{90}$
γ 84.2 keV 7%
γ 236 keV 11%
γ 256 keV 7%
$^{227}Th_{90}$
19 d
98,6%, 22 y
$^{227}Ac_{89}$
1,4%, 22 y
$^{219}Rn_{86}$
4 s
γ 271 keV 10%
γ 402 keV 7%
γ 83.8 keV 25%
γ 144 keV 3%
γ 154 keV 6%
γ 269 keV 14%
γ 324 keV 4%
γ 338 keV 3%
11 d
$^{223}Ra_{88}$
22 m
$^{223}Fr_{87}$
$^{215}At_{85}$
0.1 ms
2•10⁻⁶, 22m
$^{215}Po_{84}$
2 ms
$^{211}Po_{84}$
0.5 s
3•10⁻³, 2m
$^{211}Bi_{83}$
2 m
36 m
$^{211}Pb_{82}$
γ 405 keV 4%
γ 832 keV 4%
γ 351 keV 13%
$^{207}Pb_{82}$
5 m
$^{207}Tl_{41}$
α decay
β decay