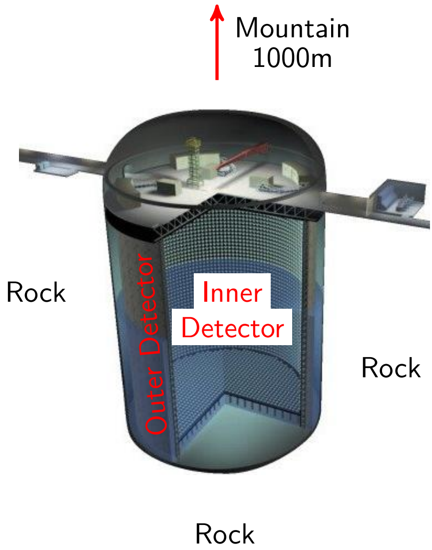
Super-Kamiokande
The Gadolinium Era

Sonia El Hedri

GDR Neutrinos 2019

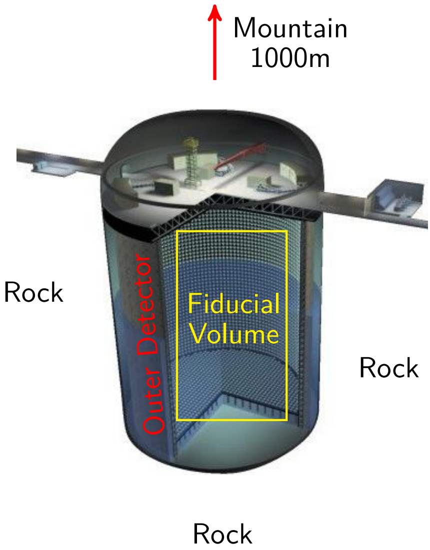
30 octobre 2019

Super-Kamiokande Cheat Sheet

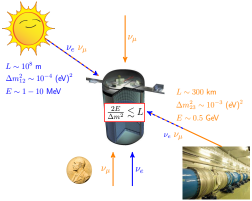


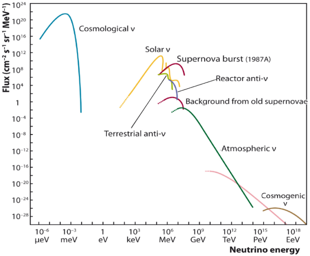
- Kamioka Mine, Japan
- Two parts :
  Outer Detector (veto)
  Inner Detector
- Surrounding radioactivity
  $\Rightarrow$ Fiducial Volume 22.5 ktons
- Water constantly recirculated and purified
- 11456 ID PMTs : 50 cm, 3 ns resolution
- Energy coverage : 4 MeV to 1 TeV

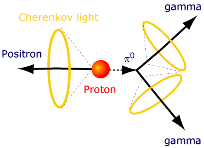
Super-Kamiokande Cheat Sheet



- Kamioka Mine, Japan
- Two parts :
  Outer Detector (veto)
  Inner Detector
- Surrounding radioactivity
  $\Rightarrow$ Fiducial Volume 22.5 ktons
- Water constantly recirculated and purified
- 11456 ID PMTs : 50 cm, 3 ns resolution
- Energy coverage : 4 MeV to 1 TeV







Oscillations

Atmospheric neutrinos
Solar parameters
ν_μ disappearance
θ_{13} measurement
CP violation
...

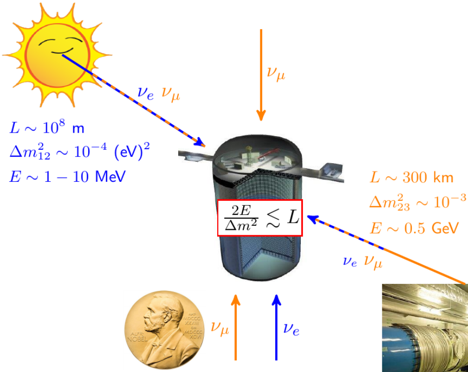
Astrophysics

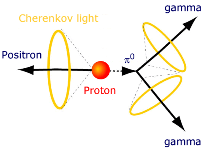
Solar neutrinos
Supernova burst(s)
Supernova relics (DSNB)
Blazars ?

New Physics

Proton decay
Dark Matter
...

Physics potential



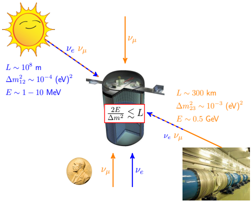


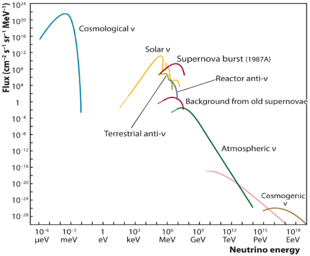
New Physics

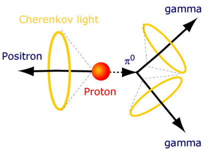
ν_μ disappearance
θ_{13} measurement
CP violation
...

Supernova burst(s)
Supernova relics (DSNB)
Blazars ?

Proton decay
Dark Matter
...







Oscillations

Atmospheric neutrinos
Solar parameters
ν_μ disappearance
θ_{13} measurement
CP violation
...

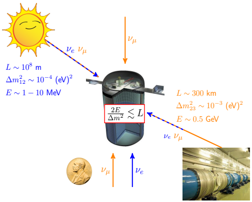
Astrophysics

Solar neutrinos
Supernova burst(s)
Supernova relics (DSNB)
Blazars ?

New Physics

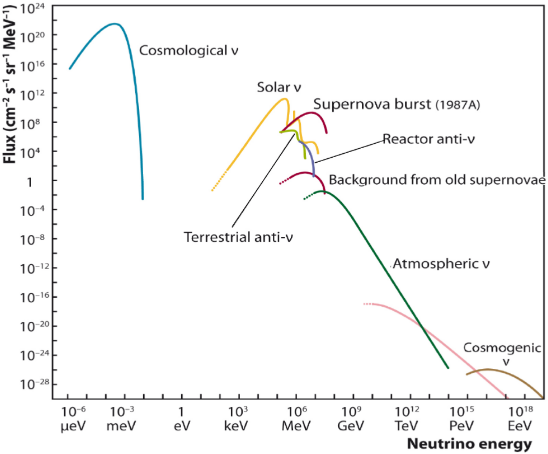
Proton decay
Dark Matter
...

Physics potential



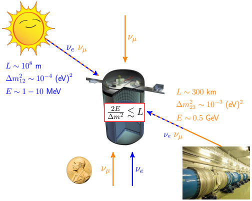
Oscillations

Atmospheric neutrinos
Solar parameters
ν_μ disappearance
θ_{13} measurement
CP violation
...



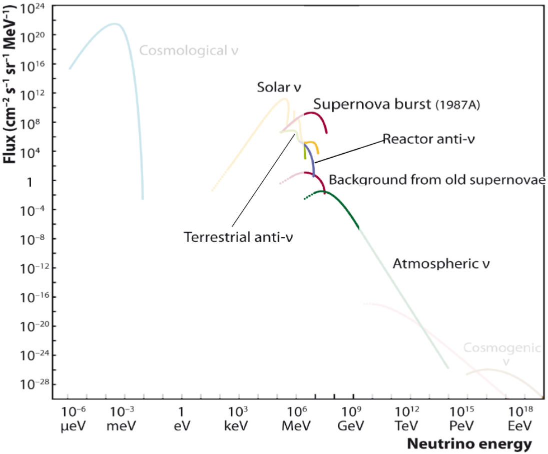
Blazars ?

Physics potential



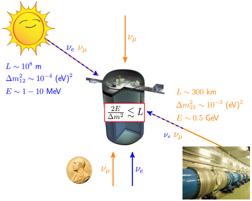
Oscillations

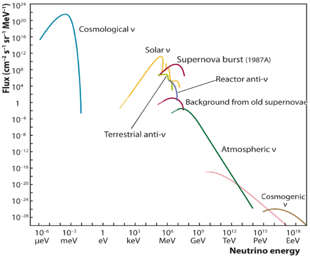
Atmospheric neutrinos
Solar parameters
ν_μ disappearance
θ_{13} measurement
CP violation
...

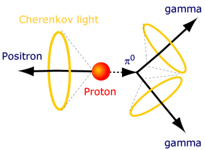


Blazars ?

Physics potential







Oscillations

Atmospheric neutrinos
Solar parameters
ν_μ disappearance
θ_{13} measurement
CP violation
...

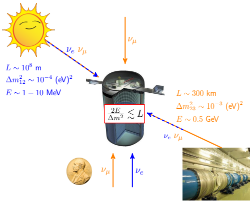
Astrophysics

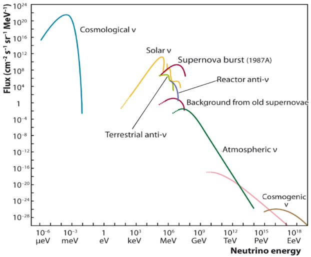
Solar neutrinos
Supernova burst(s)
Supernova relics (DSNB)
Blazars ?

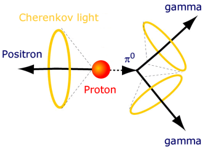
New Physics

Proton decay
Dark Matter
...

Physics potential



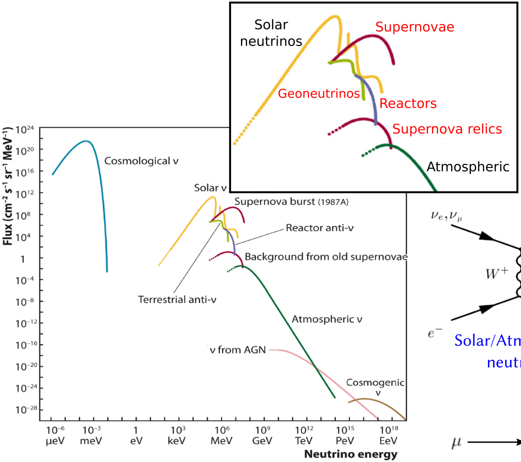




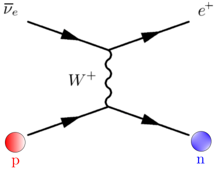
Oscillations	Astrophysics	New Physics
Atmospheric neutrinos	Solar neutrinos	Proton decay
Solar parameters	Supernova burst(s)	Dark Matter
ν_μ disappearance	Supernova relics (DSNB)	...
θ_{13} measurement	Blazars ?	
CP violation		
...		

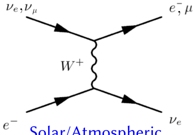
A myriad of new processes...but limited discriminating power !

On the importance of neutrons : low energies

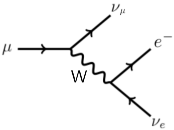


Inverse Beta Decay (IBD)

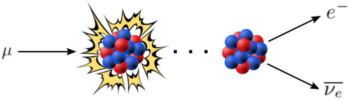




Solar/Atmospheric neutrinos



Muon decays

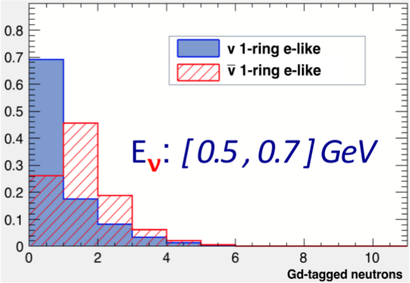


Spallation

On the importance of neutrons : high energies

ν-$\bar{\nu}$ discrimination

- Less efficient than at low energy
- Still works for CC interactions
- 80% tagging efficiency
  $\Rightarrow$ better sensitivity for δ_{CP}

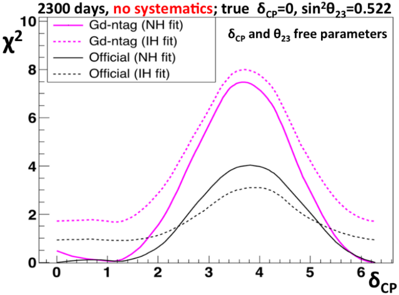


- **CC/NC separation** : reject NC for atmospheric oscillation analysis
- **Energy reconstruction** : neutral hadron production enhances neutron production
- **Proton decay** : neutron veto significantly reduces the atmospheric background

On the importance of neutrons : high energies

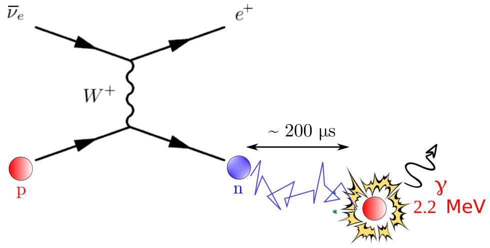
ν-$\bar{\nu}$ discrimination

- Less efficient than at low energy
- Still works for CC interactions
- 80% tagging efficiency
  $\Rightarrow$ better sensitivity for δ_{CP}



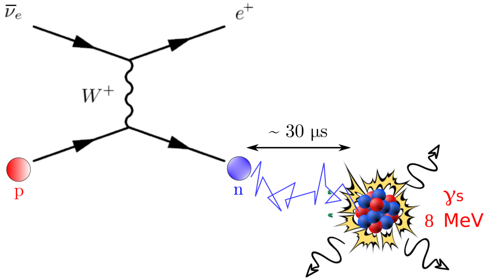
- **CC/NC separation** : reject NC for atmospheric oscillation analysis
- **Energy reconstruction** : neutral hadron production enhances neutron production
- **Proton decay** : neutron veto significantly reduces the atmospheric background

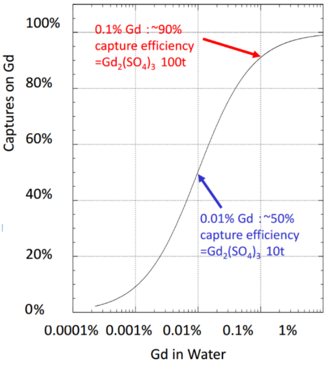
Neutron tagging...but how ?



- Tagging on hydrogen : large capture times, low energy signal $\Rightarrow$ look for coincidences
- Existing algorithm : 15% signal efficiency for 0.01% background acceptance
- Neutron capture significantly improved with Gadolinium
- 0.1% Gd $\Rightarrow$ capture probability

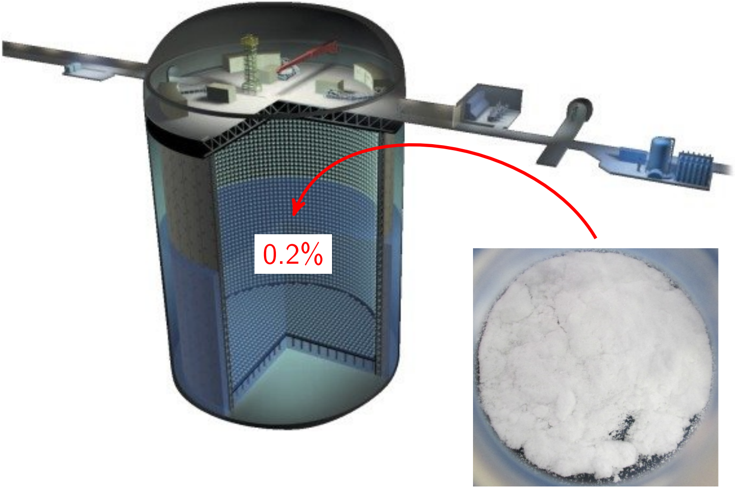
Neutron tagging...but how ?





- Tagging on hydrogen : large capture times, low energy signal $\Rightarrow$ look for coincidences
- Existing algorithm : 15% signal efficiency for 0.01% background acceptance
- Neutron capture significantly improved with Gadolinium
- 0.1% Gd $\Rightarrow$ capture probability

One spoonful of Gadolinium



Gadolinium Sulfate

Practical issues

- No reaction with the detector's components
- Preserves water transparency
- No additional radioactivity
- Environmental/security issues ?

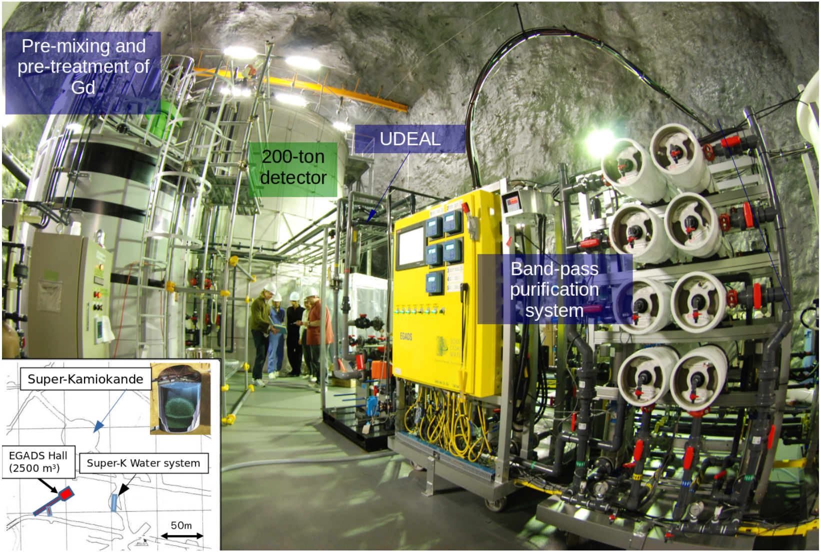
A SK replica : EGADS

Evaluating Gadolinium Action on Detector Systems

- Small scale replica of SK : 200T tank
- 15T tank for Gd mixing
- Dedicated water system
- UDEAL : laser system to measure water transparency

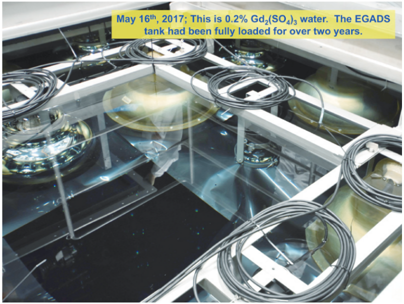
- Started in 2011 : empty tank + soak tests of Gd compounds
- April 2015 – September 2017 : run with 0.2% $(Gd)_2(SO_4)^3$

A SK replica : EGADS



Gd and the detector's components

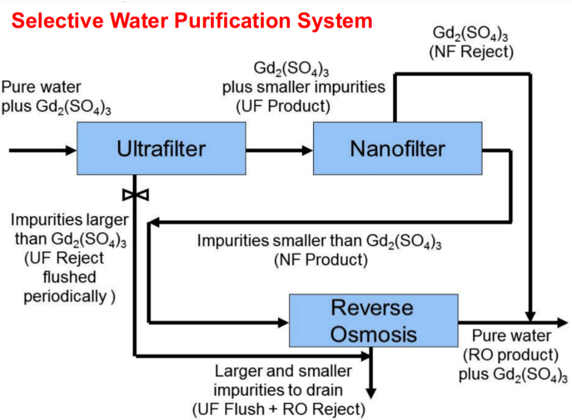
- Safest component : Gadolinium Sulfate $(Gd)_2(SO_4)^3$



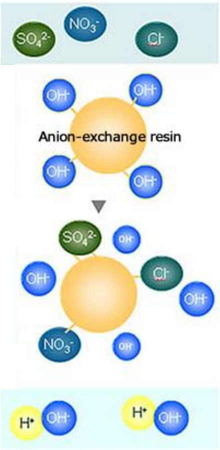
- After 2.5 years exposure to $(Gd)_2(SO_4)^3$: "Looks great !"

Water purification : How to keep Gadolinium ?

Band pass filter

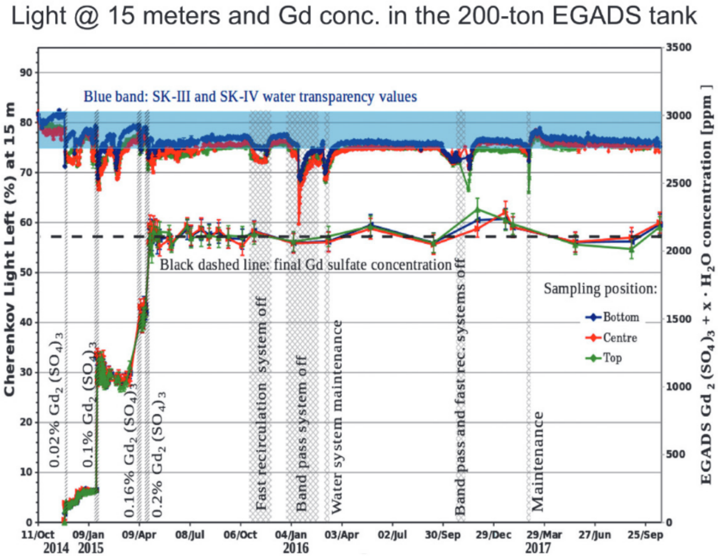


Fast recirculation
Ion-exchange resin



- Both systems (will) run in parallel in EGADS (SK-Gd)

Water Transparency and Gd concentration



Radioactive contamination and backgrounds

Backgrounds for solar and DSNB searches :

- Spontaneous fission : $^{238}U \rightarrow \gamma + n \sim 5$ evts/year
- Neutron production : $U \rightarrow n \sim 320$ evts/day
- β decay, γ emission : Th/Ra$\rightarrow \beta/\gamma + A \sim 3 \times 10^5$ evts/day

Need reductions by orders of magnitude :

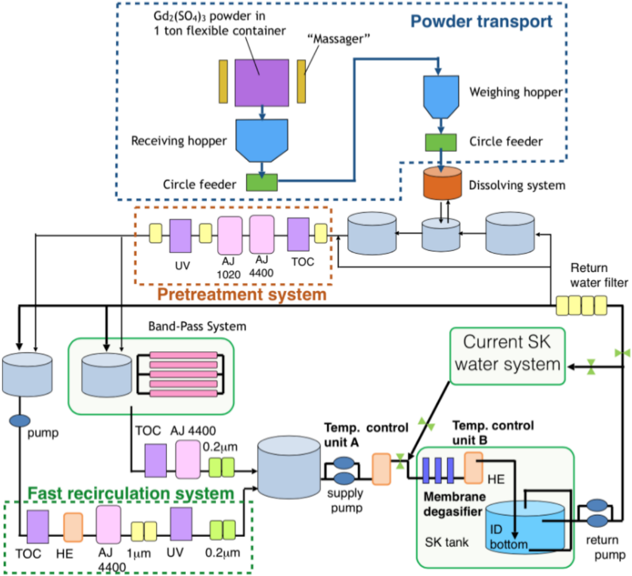
- Work with different compagnies on purification techniques
- Gd samples analyzed at Canfranc (LSC)/Boulby Mine/SK
- Gd pre-treatment : anion-exchange resins to remove U and Ra

Chain	Isotope	Typical	DSNB	Solar	A	B	C
^{238}U	^{238}U	50	<5	-	<0.04	<0.04	<0.04
	^{226}Ra	5	-	< 0.5	<0.2	<0.2	1
^{232}Th	^{232}Th	10	-	< 0.05	<0.02	<0.06	0.09
	^{228}Th	100	-	< 0.05	<0.3	<0.26	2
^{235}U	^{235}U	32	-	<3	<0.4	<0.3	<1.3
	^{227}Ac/^{227}Th	300	-	<3	<1.5	<1.2	<3.1

Practical issues

- No reaction with the detector's components
  Verified with $Gd_2(SO_4)^3$
- Preserves water transparency
  Within SK-III and IV levels
- No additional radioactivity
  Purification by companies, pre-treatment during recirculation
- Environmental/security issues ?
  System to extract Gd from water, work with local community

From EGADS to Super-K Gd



May-September 2018 : SK refurbishment

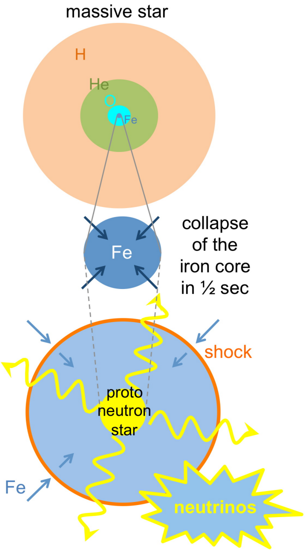
- Replaced 136 PMTs
- Leak repair : cover welding points with BioSeal and MineGuard coating
- Cleaning
- Recalibration
  December 2019-April 2020

SK-Gd : timeline and expectations

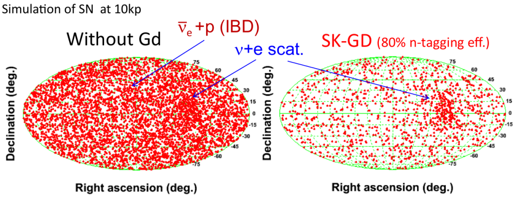
- October 2018 : New water system implemented for SK
  Fast Recirculation only for now, Band Pass will be added later
- September 2019 : 13T ultra-pure GdSO$_4$ delivered at Super-K
- Before march 2020 : dilution 0.02% $(\text{Gd})_2(\text{SO}_4)_3$
- End of 2020 (?) : dilution 0.2% $(\text{Gd})_2(\text{SO}_4)_3$ [nominal]
- 2020 – 2030 : data-taking
- Tests with AmBe source in EGADS
  $\Rightarrow$ 80%neutron$/2 \times 10^{-4}$ event^{-1} background efficiency

Physics prospects : supernova neutrinos

- SN type II : collapse of the core of a massive star ($> 8\ M_{\odot}$)
  $\Rightarrow$ Neutron star or black hole
- Mechanism still poorly understood : 3D simulations do not lead to explosions
- 99% of the energy of the supernovae $\Rightarrow$ 10^{57} neutrinos emitted in 10 seconds !
- Neutrino spectra track the core-collapse history
- Main detection channel in Super-K : inverse beta decay



Supernovae and multi-messenger



Supernova à 10 kpc :

- 7300 $\overline{\nu}_e$
- 300 ν_e (elastic)
- Arrive before the visible signal

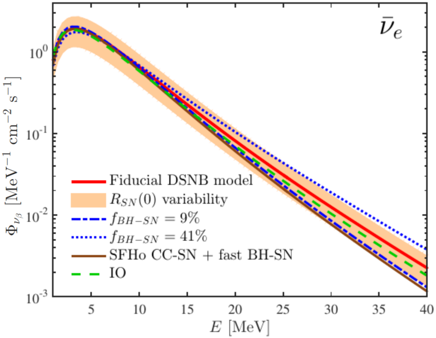
Alert system for other experiments :

- SNEWs : Super-Kamiokande, IceCUBE, KamLAND, LVD, Borexino, Daya Bay, HALO
- Warning for telescopes + analysis window for gravitational wave detectors
- Maybe pre-supernova neutrinos from Si burning ?
- **Gadolinium :** Isolate elastic interactions ν_e
  $\Rightarrow$ **pointing with 3° resolution**

But galactic supernovae are rare...

The Diffuse Supernova Neutrino Background (DSNB)

- Observable Universe : ~ 1 supernovae per second
- Past supernovae $\Rightarrow$ diffuse neutrino background
- All flavors of (anti)neutrinos

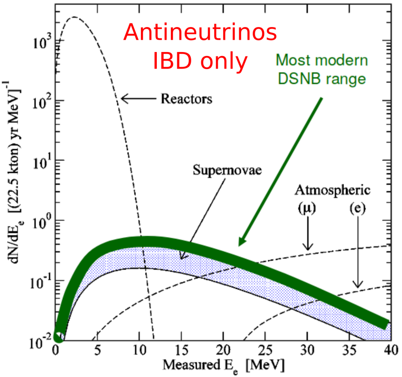


[Lunardini et al, JCAP 1207 (2012) 012]

$$\Phi = \int \left[\bar{\nu}_e \text{ emission (black hole fraction)} \right] \otimes \left[\text{Star formation} \right] \otimes \left[\text{Universe expansion} \right]$$

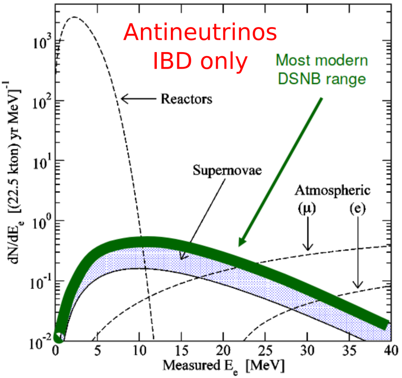
- **Weak signal** : 5 to 20 events/year

DSNB detection : current (Gd-less) status



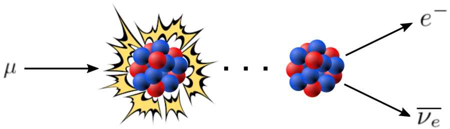
[Beacom and Vagins, Phys. Rev. Lett., 93 :171101, 2004]

DSNB detection : current (Gd-less) status



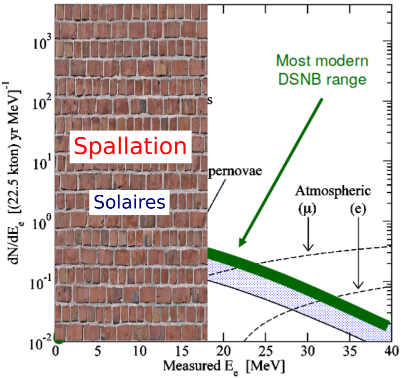
[Beacom and Vagins, Phys. Rev. Lett., 93 :171101, 2004]

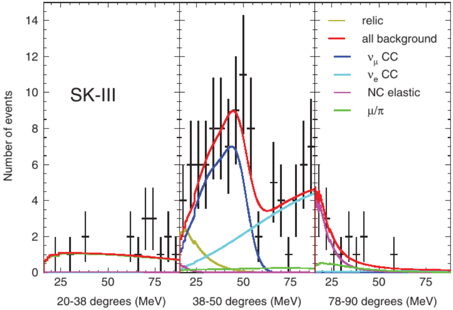
Spallation



$\mathcal{O}(10^4 - 10^5) \times$ signal

DSNB detection : current (Gd-less) status

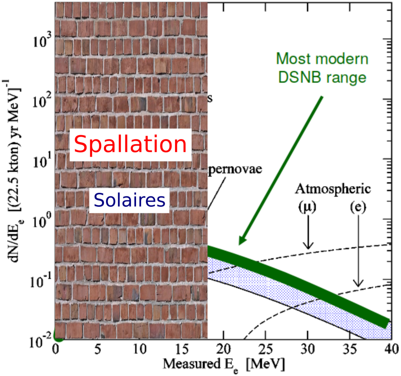


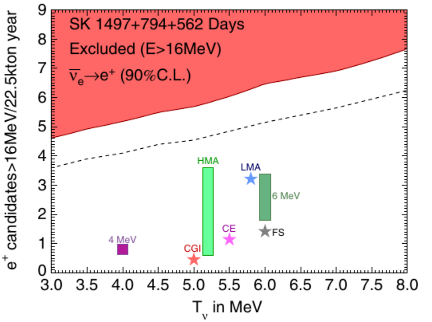


[Phys. Rev. D, 95 :052007, 2012]

- After spallation cuts : $\sim 10^5$ spallation/solar evts in [8-30] MeV
- Spectral analysis : $E = 17.3$ MeV threshold $\Rightarrow$ poor statistics...
- Neutron tagging : cut 75% of the signal for $E < 16$ MeV...

DSNB detection : current (Gd-less) status

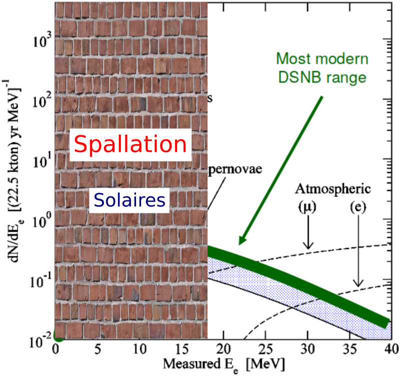


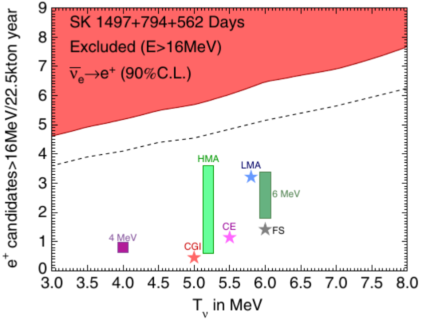


[Phys. Rev. D, 95 :052007, 2012]

- After spallation cuts : $\sim 10^5$ spallation/solar evts in [8-30] MeV
- Spectral analysis : $E = 17.3$ MeV threshold $\Rightarrow$ poor statistics...
- Neutron tagging : cut 75% of the signal for $E < 16$ MeV...

DSNB detection : current (Gd-less) status

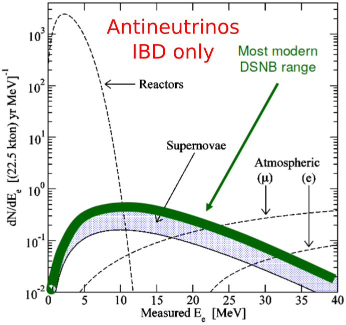


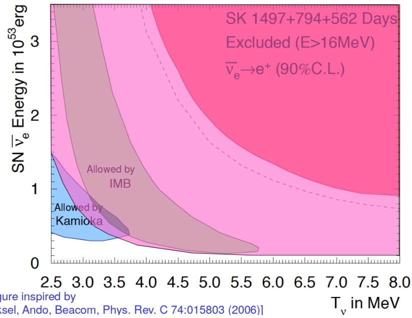


[Phys. Rev. D, 95 :052007, 2012]

- After spallation cuts : $\sim 10^5$ spallation/solar evts in [8-30] MeV
- Spectral analysis : $E = 17.3$ MeV threshold $\Rightarrow$ poor statistics...
- Neutron tagging : cut 75% of the signal for $E < 16$ MeV...
- Gadolinium is necessary for this analysis !

DSNB detection : the future





[Figure inspired by
Yuksel, Ando, Beacom, Phys. Rev. C 74:015803 (2006)]

- Prospects : explore regions favored by SN1987A
- New neutron tagging algorithm : understand Gd neutron capture signal, bring background acceptance below 10^{-4}
- Spallation reduction : tag secondaries from muon showers
- Data interpretation : pave the way to more precise measurements in HK !

Conclusion

- SK-Gd will start in a few months
- Key project for the next decade : our best chance to observe supernova relic neutrinos
- Analysis work for the next few years :
  - Understand Gd neutron capture signal
  - New neutron tagging algorithms
  - Understand the mechanisms of spallation
- SRN contains essential information on supernova mechanisms and the history of the Universe $\Rightarrow$ these must be disentangled !
- Prepare for a full spectrum analysis in Hyper-K ?