Hyper-Kamiokande proto-Collaboration

EUROPEAN PHYSICAL SOCIETY HEP2019

Astrophysical νs @ HyperK

David **Bravo-Berguño,** on behalf of the **HyperK protoCollab.**
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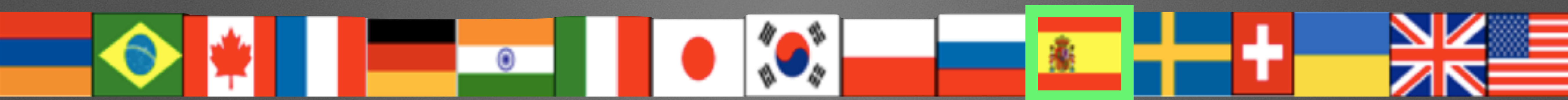
MARIE CURIE ACTIONS

H2020-MSCA-RISE-2014-GA641540, SKPLUS

Hyper-Kamiokande protoCollaboration

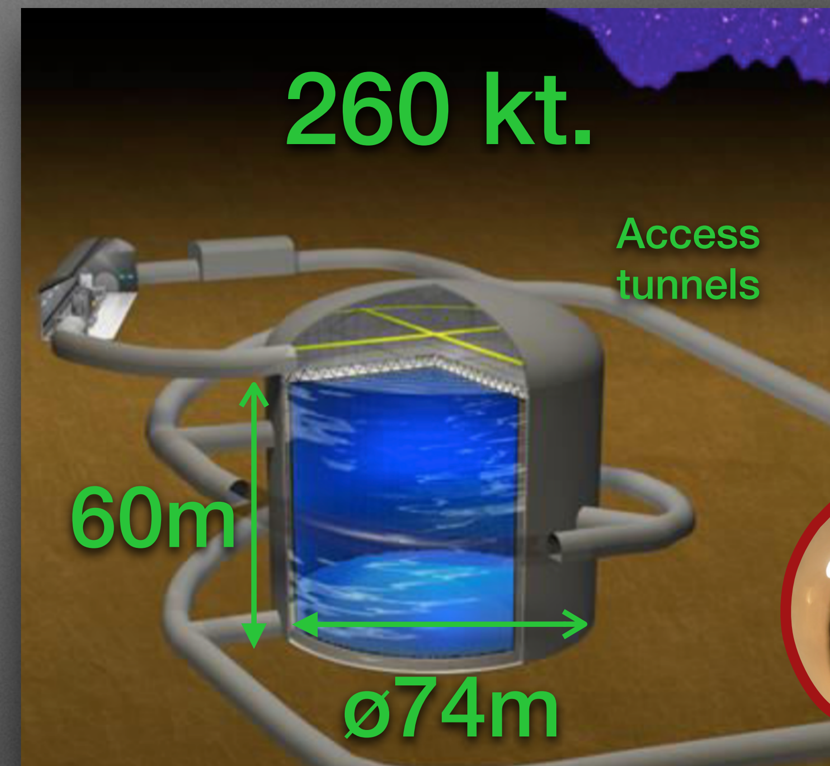
300+ member (proto)Collaboration, comprising 17 countries in Asia, Europe and the Americas, inscribed in 82 institutes (75% international)



March 2018 protoCollaboration meeting in UAM (Madrid, Spain)

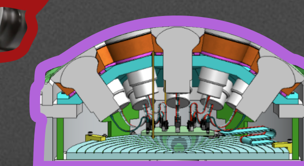
Hyper-Kamiokande project

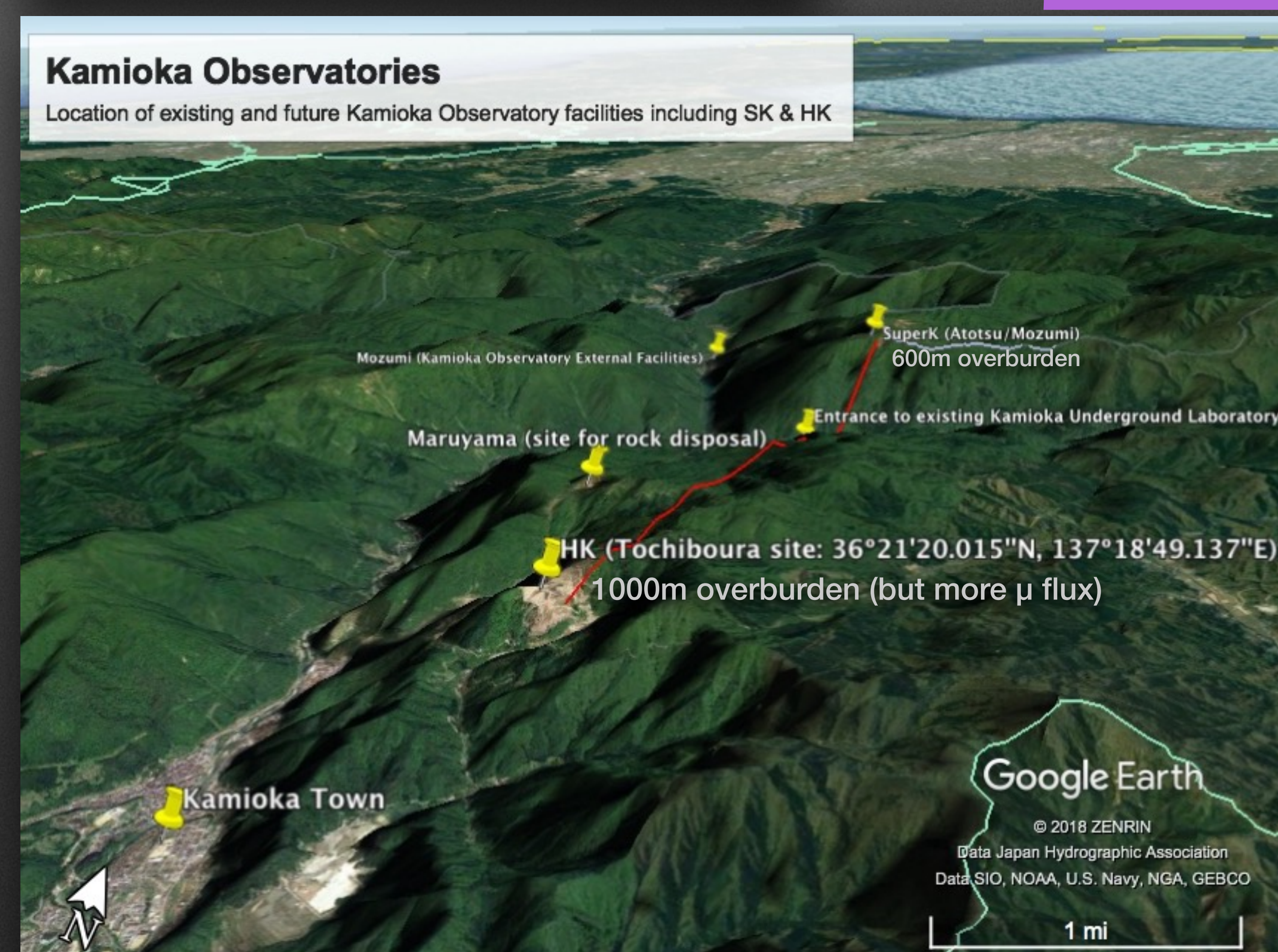
- UTokyo ratified funding to continue design and start construction next April, to **start DAQ in 2027**. One of MEXT's higher priority large-scale projects in Japan.
- Published Design Report last year. (arXiv: *phys.inst-det:1805.04163*)
- Several internal Technical Reports published.
- Intermediate Water Cherenkov Detector (IWCD) CDR released.
- Enlarged, improved version of SuperK (10x statistics!) aiming for low background, and therefore low threshold.
- Second tank under detailed consideration (preferred location in Korea: HKK).
- Same beam oscillation possibilities as with SuperK through J-PARC's T2HK(K) beam.



40% ID photocoverage

40,000 new 20" PMTs
or
50% 20" PMTs +
50% multiPMTs



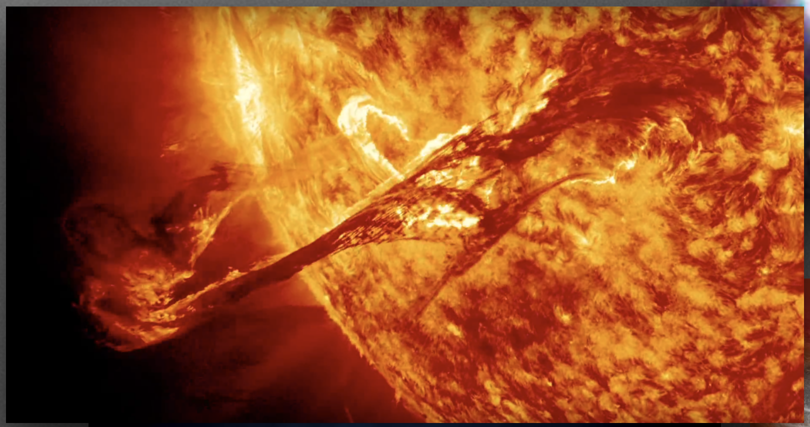


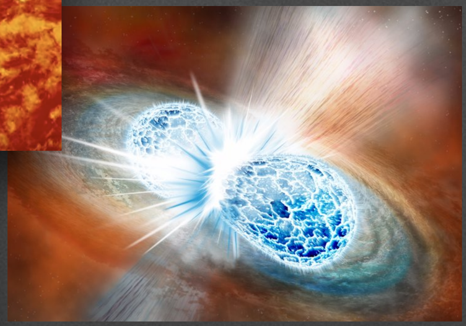
Hyper-Kamiokande's physics

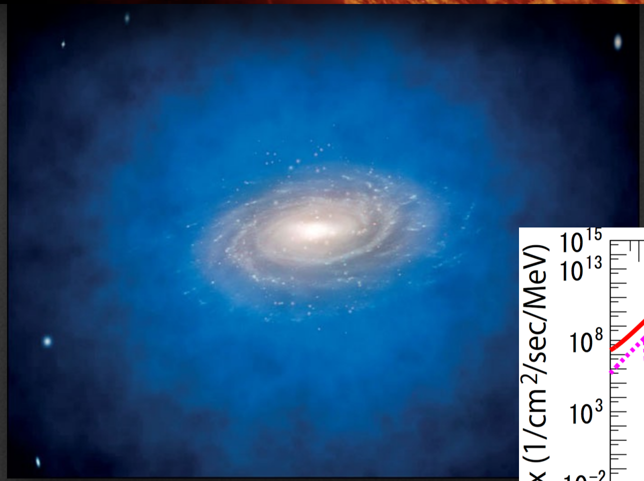
- Multipurpose detector with a wide breadth of physics reach; unparalleled projected sensitivity in many areas:

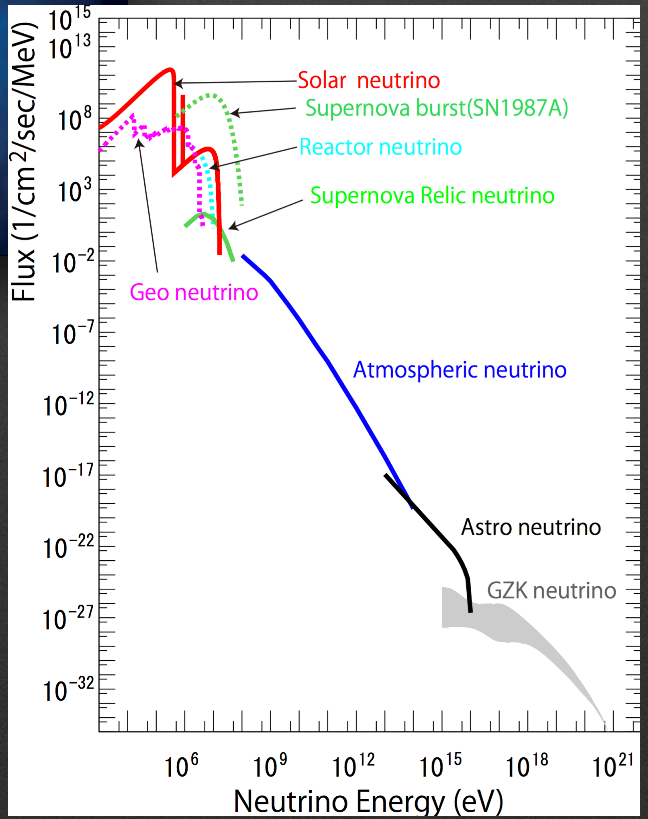
√ Neutrino oscillations (MH, δ_{CP}, PMNS)
- Long-baseline beam (T2HK)
- Atmospheric
- Solar

√ Neutrino astrophysics (*this talk*)









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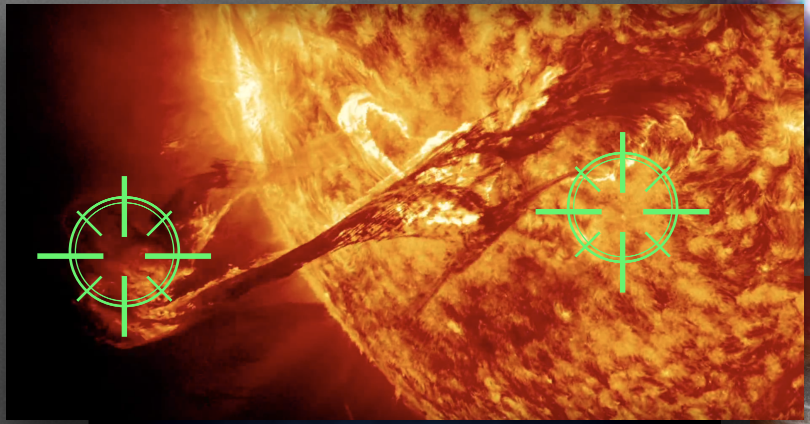
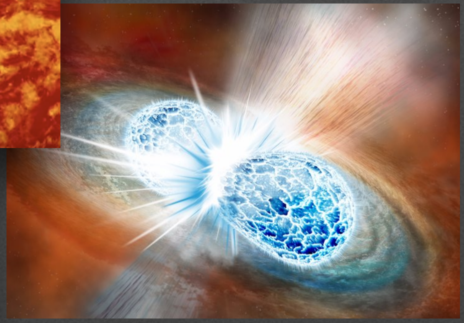
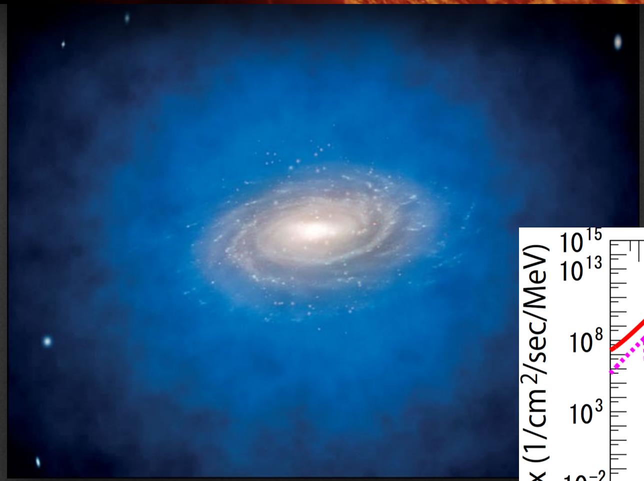
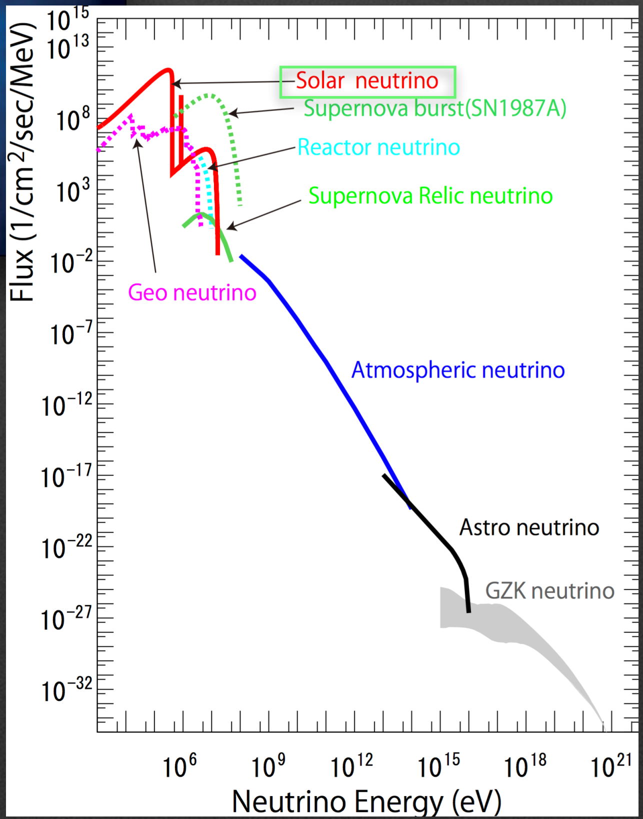

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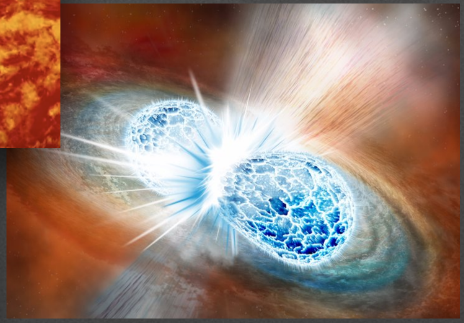

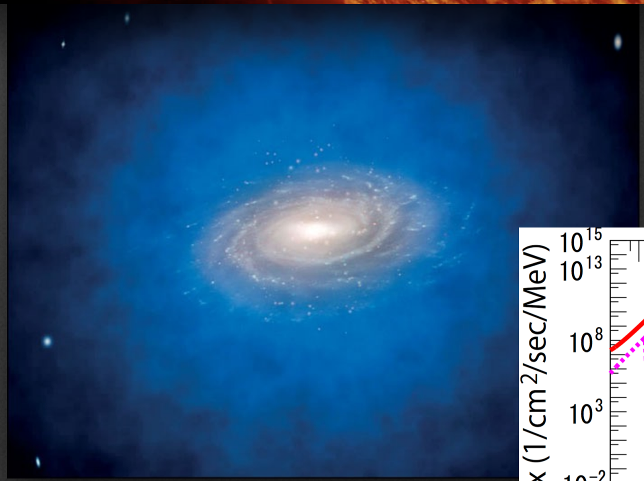

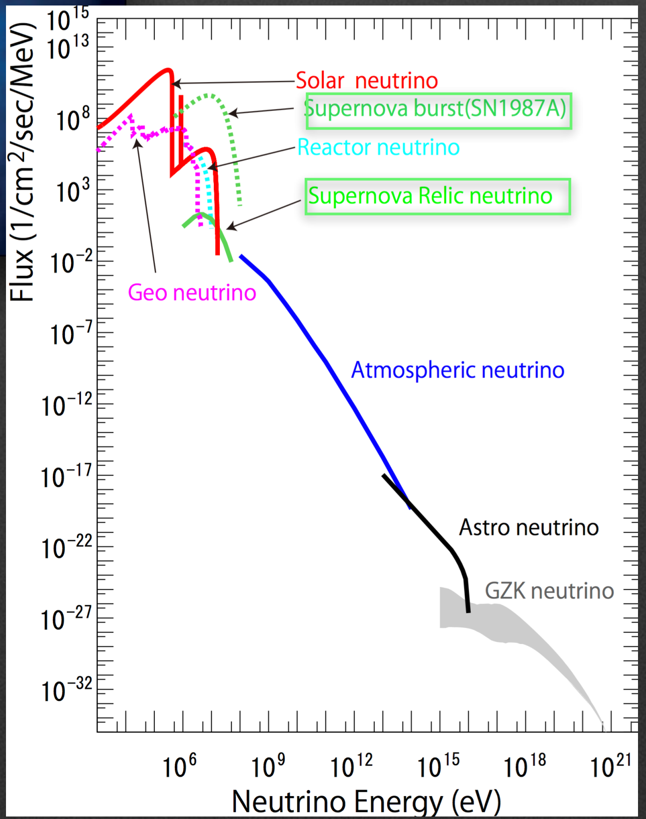

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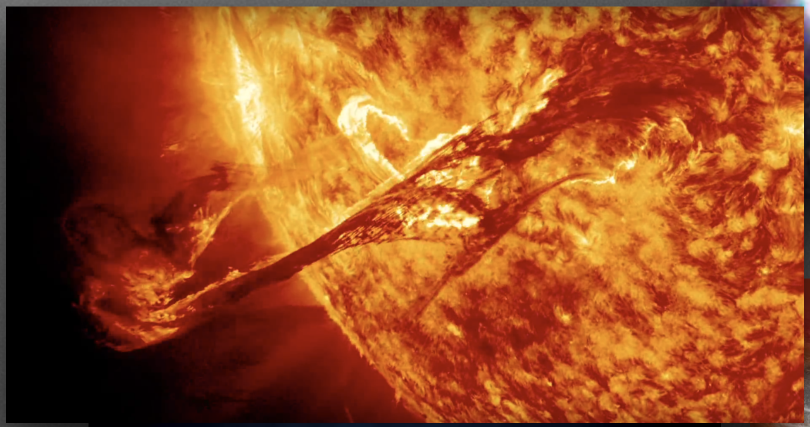
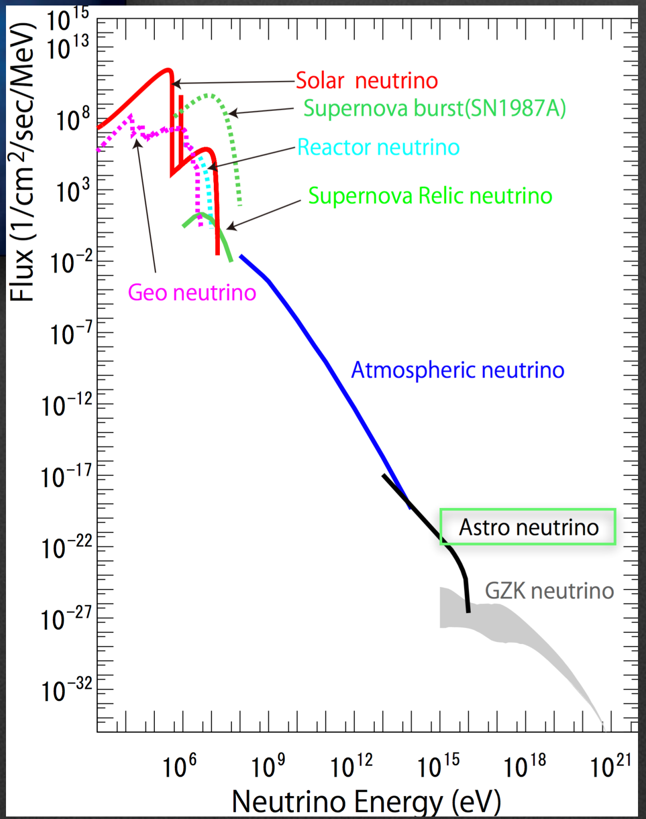
√ **Neutrino astrophysics** (*this talk*)
- Solar (spectrum and flare)
- Supernova (burst and DSNB)
- Dark matter searches
- Other sources (AGN, GRB, GW…)





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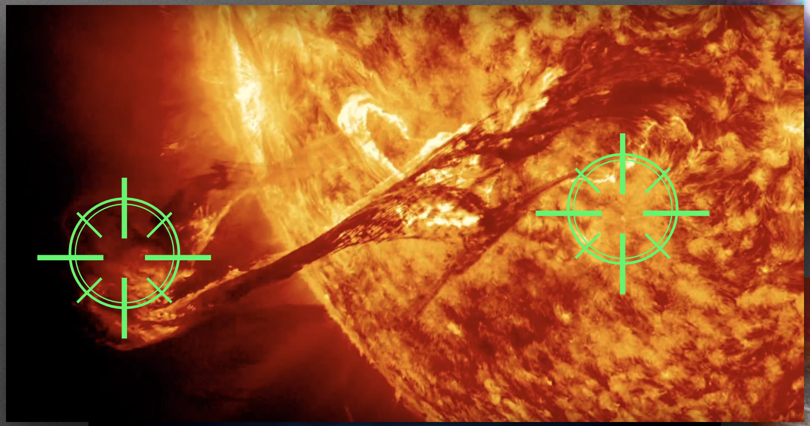
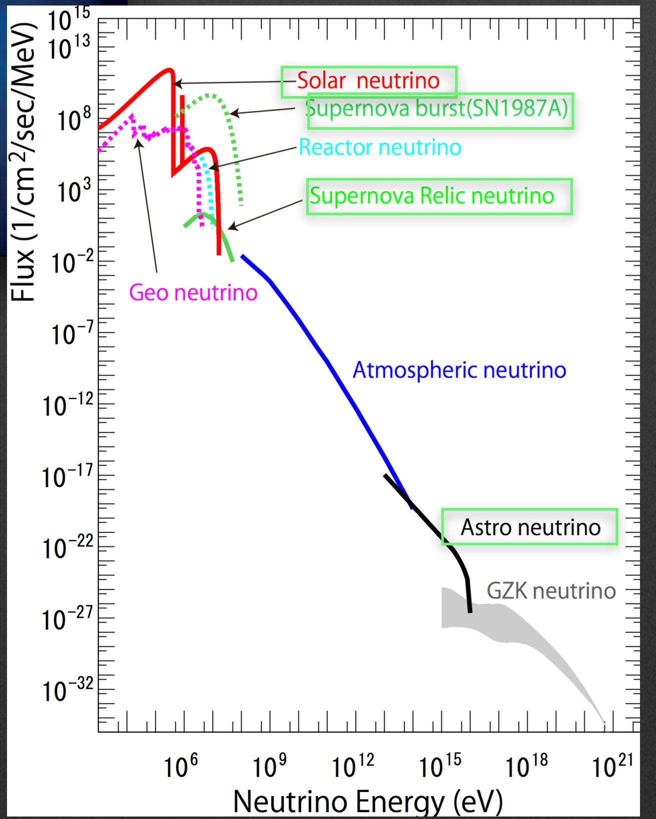
  √ Neutrino geophysics
  √ Nucleon decay

- For more on:
  - Nucleon decay searches and sensitivity with HK, see next talk!
  - Long-baseline beam neutrino physics, including sensitivity to neutrino CP violation (δ_{CP}), see tomorrow's talk and Near Detectors contribution at poster session!

Astrophysical neutrinos: HK aims

- Supernova neutrinos
  √ Pinpoint directionality & reach (~80k events for a 10 kpc SN; visible up to 4 Mpc)
  √ Neutronization burst
  √ Accretion phase
  √ Black hole formation
  √ Absolute neutrino mass
  √ Nucleosynthesis, SASI…
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How will HK achieve this?

- A superior energy resolution in a wide dynamic range is the critical factor in achieving HyperK's planned objectives.

- This will pair with the much enhanced statistics collection.

- Projected energy resolution relies on achieving high precision calibrations, as well as background suppression (esp. ^{222}Rn), in line with SuperK's SK-IV period (2009-18).

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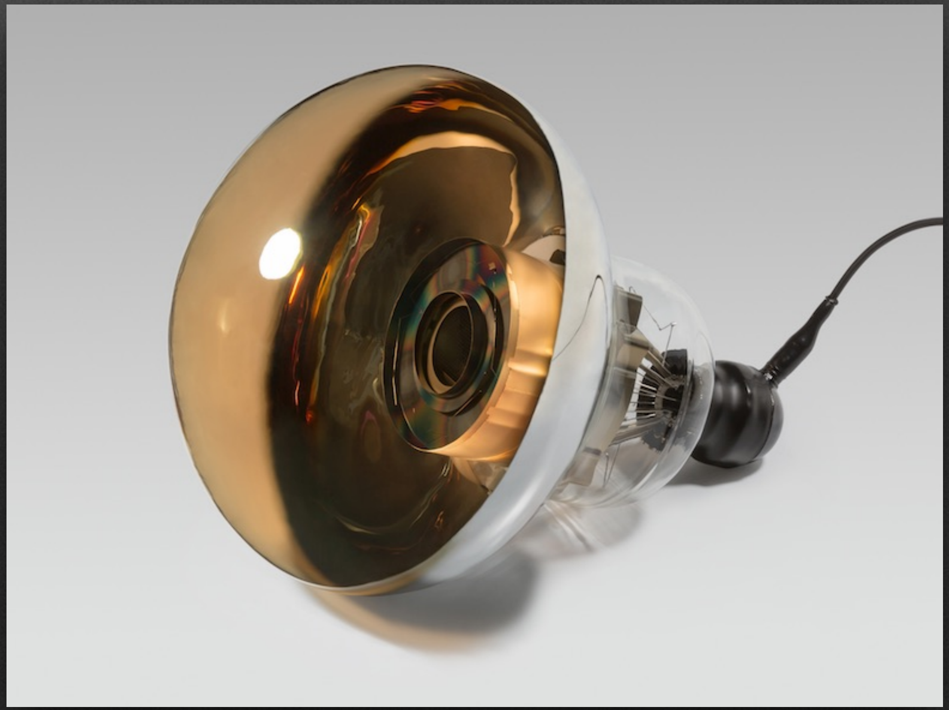
- NEW high-quantum-efficiency 50cm box-and-line (B&L) PMTs: **R12860-HQE**.
  - √ **Commonality** with SK's shape and dimensions
  - √ **~40% faster** time response
  - √ **+8% Q.E.** @ peak
  - √ Greater Sb-K-Cs **collection area and efficiency**
  - √ Improved SPE **resolution**
  - √ Linear response **resilience to saturation**

	HK	SK CM
Rise time	6.7 ns (SPE)	10.6 ns (SPE)
FWHM (w/o ringing)	13.0 ns	18.5 ns
Timing res.	2.6±0.1 ns	~5 ns
QE (peak)	30%	22%
Ph.cath. area	49.2 cm	46 cm
CE within ph.c.	87%	73%
Sigma res.	35%	50%
Output linearity	470 p.e.	250 p.e.(specs) 700 p.e.(measured)
Dark rate	~6 kHz (reducing)	4.2 Khz
Pressure rating	80 m	50 m



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  - √ Twice the **pressure bearing** resistance (neck redesign)
  - √ Order-of-magnitude reduction (^{40}K) in **background**
  - √ Improved **shockwave prevention PMT covers ->**
    - -> *Spanish contribution*
  - √ **Dark rate** reduction effort ongoing
  - √ Possibility to include **multi-PMT** modules (19 3" PMTs) for increased granularity, or **MCPs** for detection efficiency…

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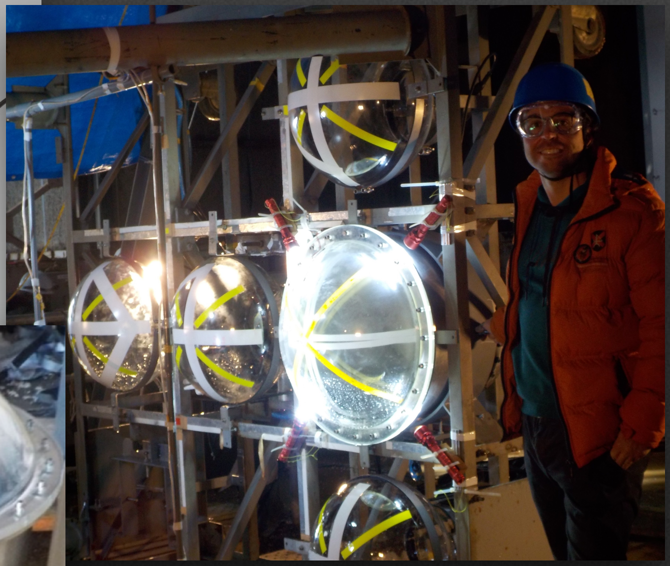
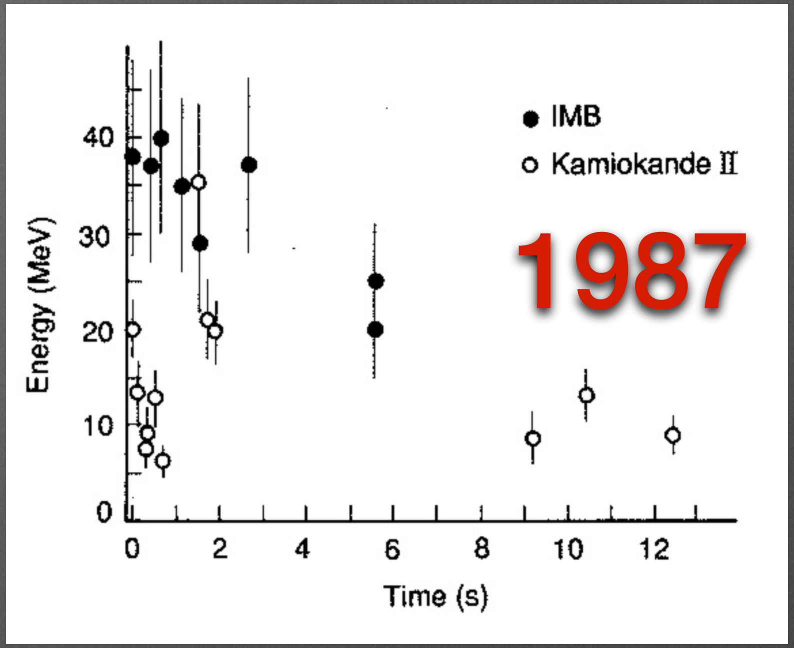


SuperNovae with HK

- 99% of released energy (~3·10^{53} erg) in core collapse SN expected to be carried out by neutrinos.

  √ 10^{51} erg in short e^{-} capture burst: ν_e (neutronization burst, ~10 ms)
  √ Majority of energy in accretion+cooling phase (≤1 s). All flavors & antinus.

- 25 SN neutrinos observed (ever!): SN1987A, mainly IBD, in KamiokaNDE II (12) + IMB (8) + Baksan (5).
  Want more!



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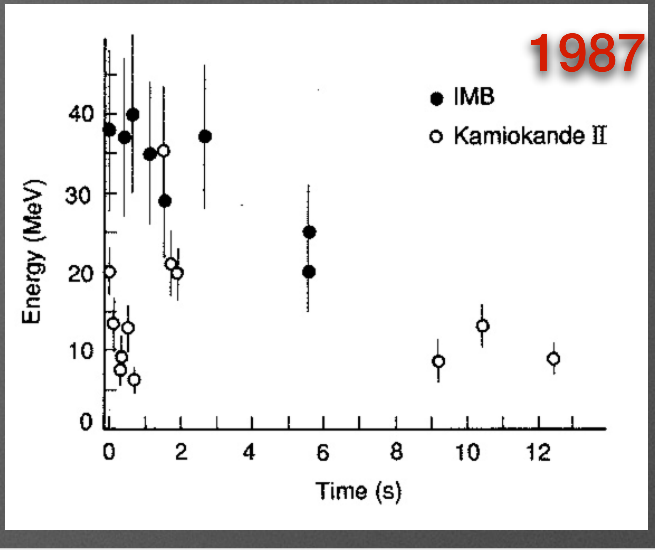

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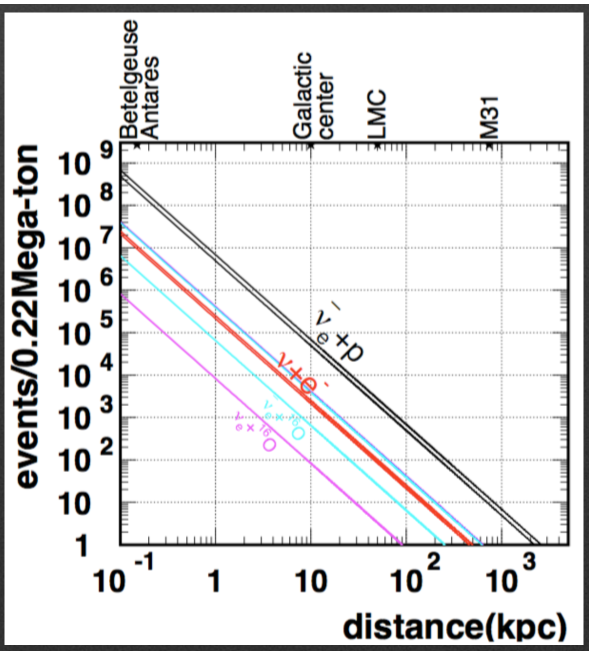
Neutrino source	Single Tank (220 kt Full Volume)
$\bar{\nu}_e + p$	49,000 - 68,000 events
$\nu + e^-$	2,100 - 2,500 events
$\nu_e + ^{16}O$ CC	80 - 4,100 events
$\bar{\nu}_e + ^{16}O$ CC	650 - 3,900 events
$\nu + e^-$ (Neutronization)	6 - 40 events
Total HK (1Tank) @ 10kpc	52,000 - 79,000 events

can still do 9-13 @ Andromeda;
2100-3200 for SN1987A-like distance

- HK will have a low threshold (3 MeV)
  Can reconstruct with 1°-1.3° accuracy (pinpoint)
  DAQ stable at >50 kHz.

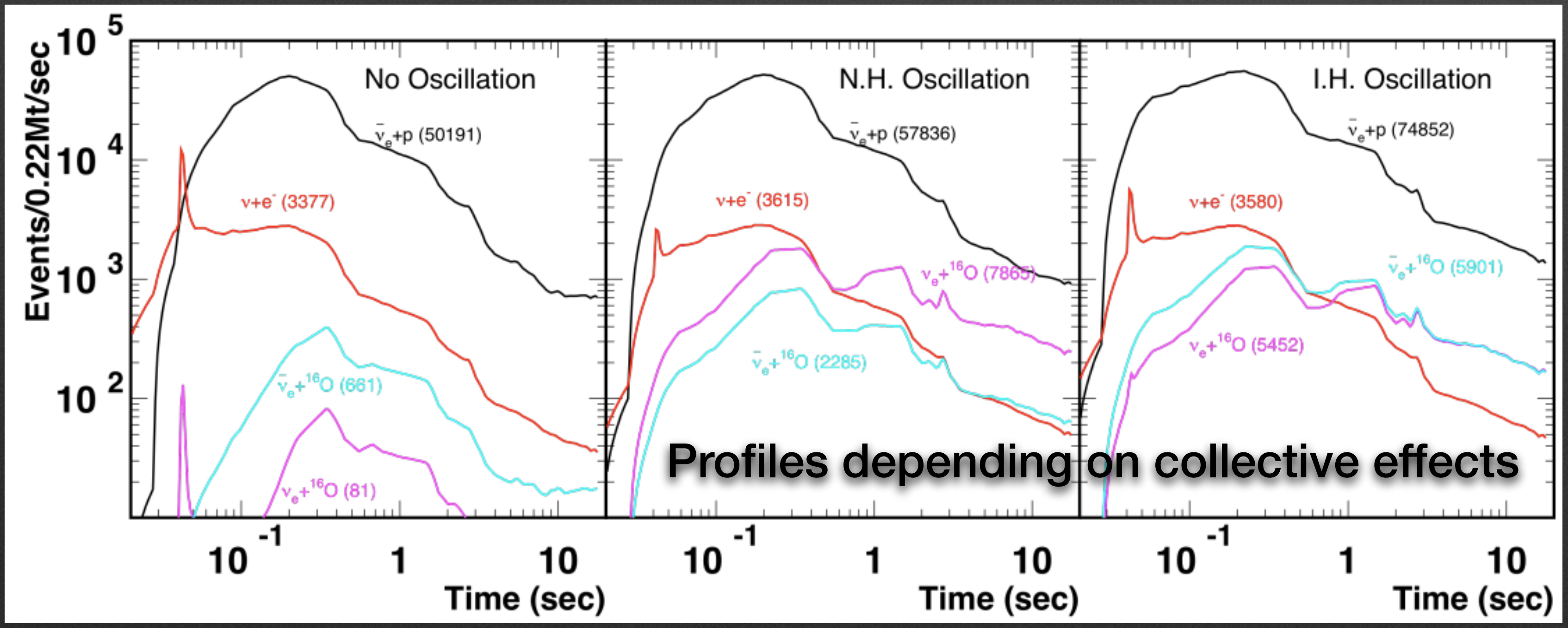
- Backgrounds negligible: full IV (instead of FV) of 220 kt (1 Tank)



- Superior sensitivity:
  √ FV 8-16x SK's -> Statistics!
  √ IBD possible (as opposed to just like ν_e LArTPCs)
  √ Event-by-event "low-E" recognition (as opposed to statistical, like ice arrays) -> Time-dependent E_{SN} spectrum.
  √ 3-6% detection probability of 4Mpc SN; 27-48% at 2 MPc -> with these sensitivities, SN signal every 3 y.

SuperNovae with HK: physics

√ Collective inter-neutrino effects: swap e-flavor spectra to μ,τ in energy intervals bound by sharp splits.
√ Shape of neutrino flux/energy within 1 ms: model downselect.
√ Sharp flux drop: direct observation of BH formation.
√ Sharp burst rise: absolute ν mass -> $\Delta t = 5.15ms(D/10kpc)(m/1ev)^2(E/10MeV)^{-2}$
Sensitivity to [0.5,1.3] eV, regardless of mass mechanism (Dirac/Maj.)
√ Electron neutrino temperature lower than μ,τ: nucleosynthesis.



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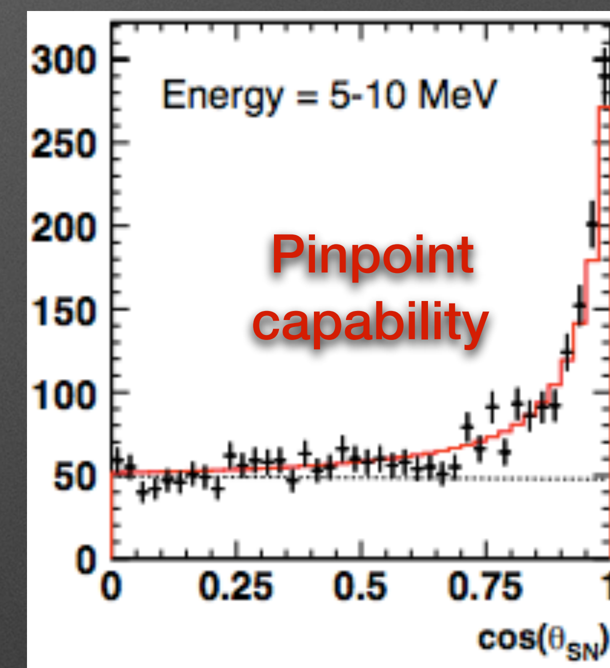
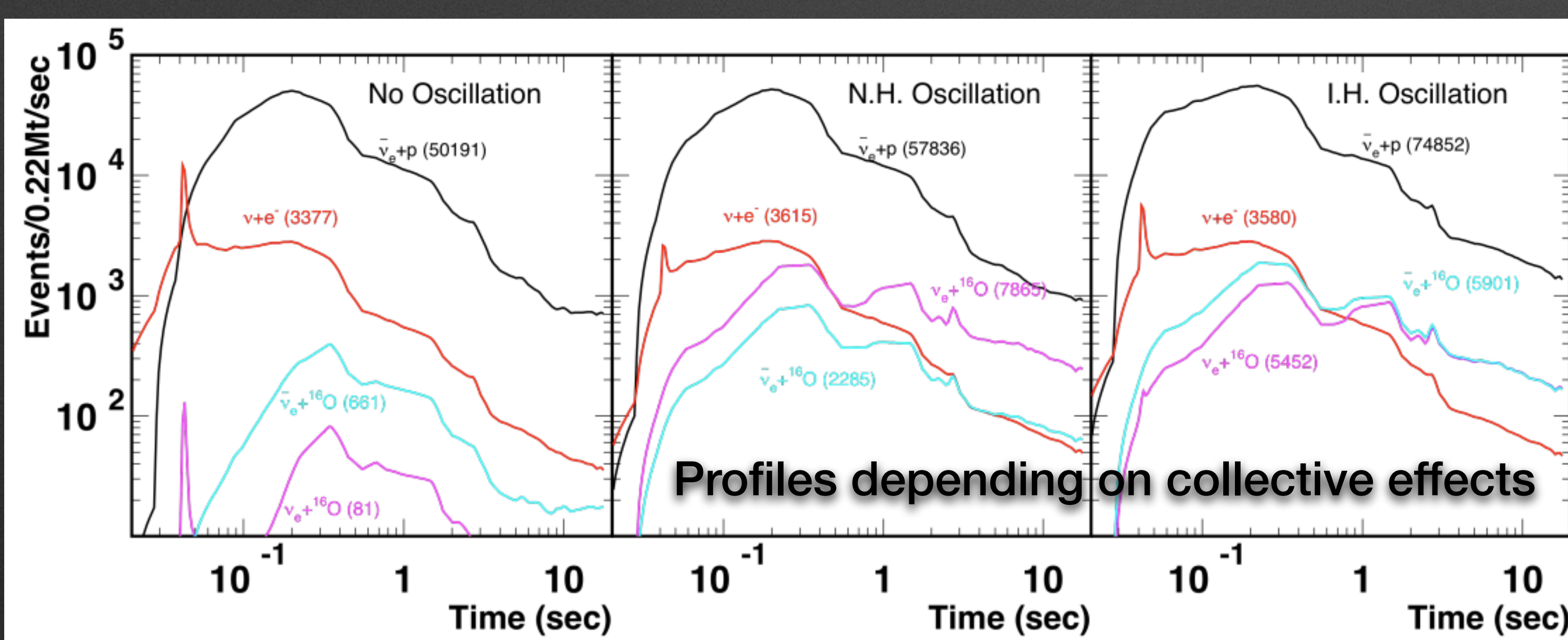
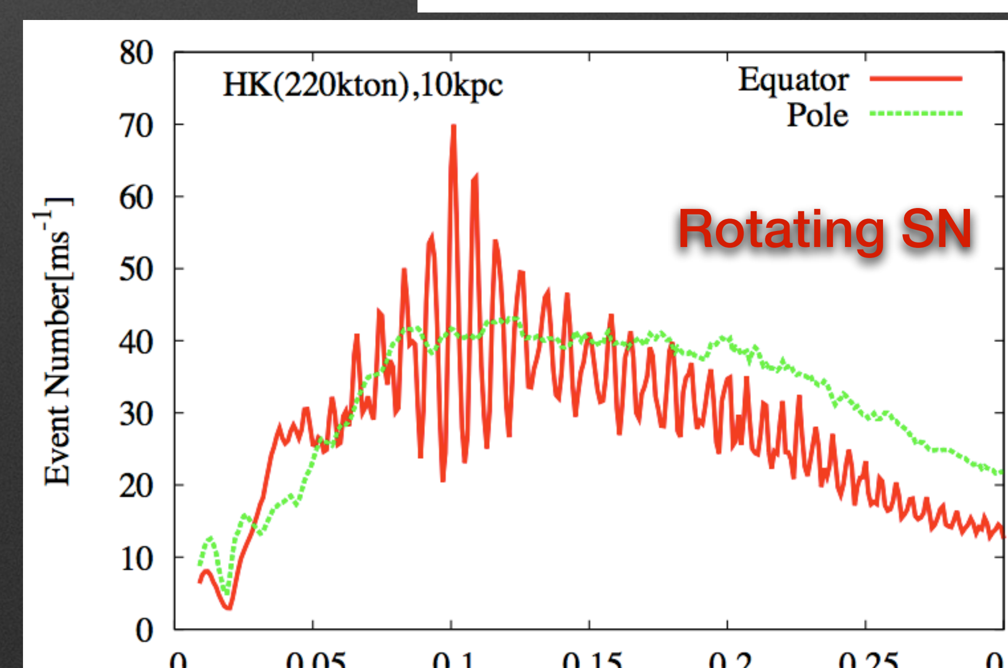
√ Electron neutrino temperature lower than μ,τ: nucleosynthesis.
√ Characteristic flux modulations within 15 kpc: are neutrinos driver of SN burst?
(Standing Accretion Shock Instability (SASI): controversial!)
√ Neutrino oscillation due to SN rotation.
√ Merged energy spectrum from extragalactic SN: reference spectrum
("DSNB w/o redshift").
√ Dim supernovae (threshold >10 MeV).
√ Shock breakout in interaction-powered SN:
Galactic CR acceleration by SN remnants.

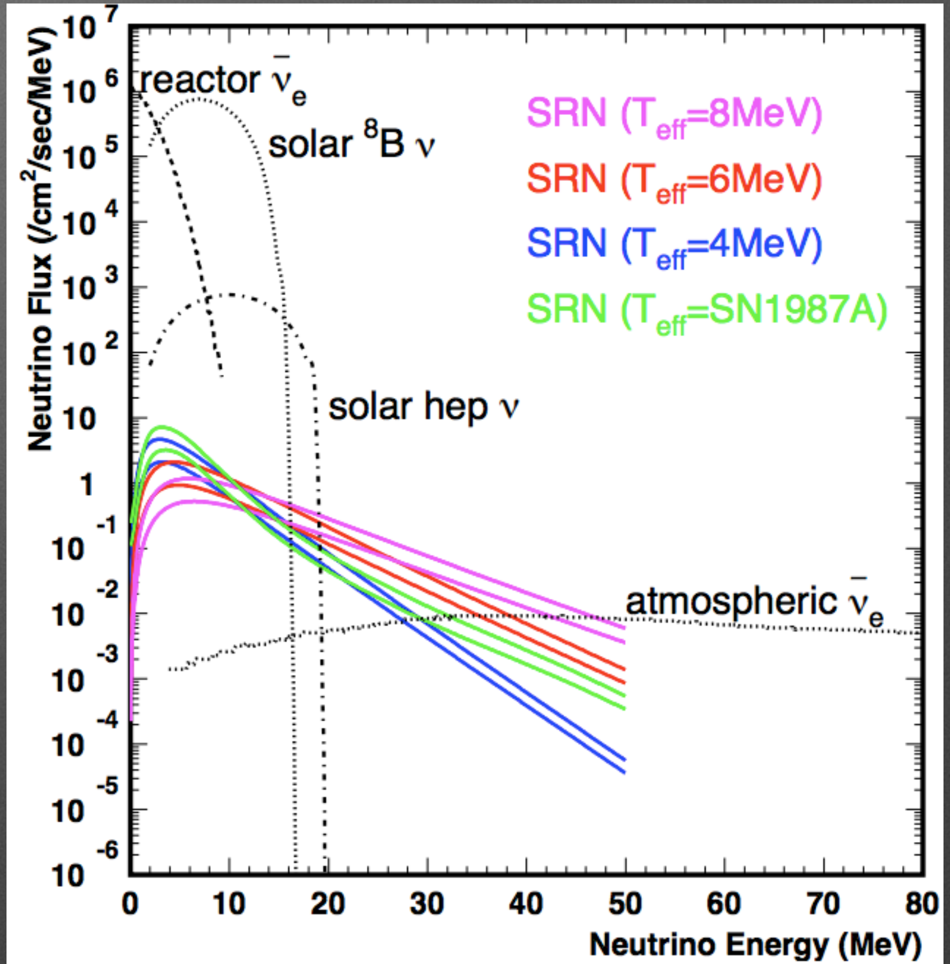


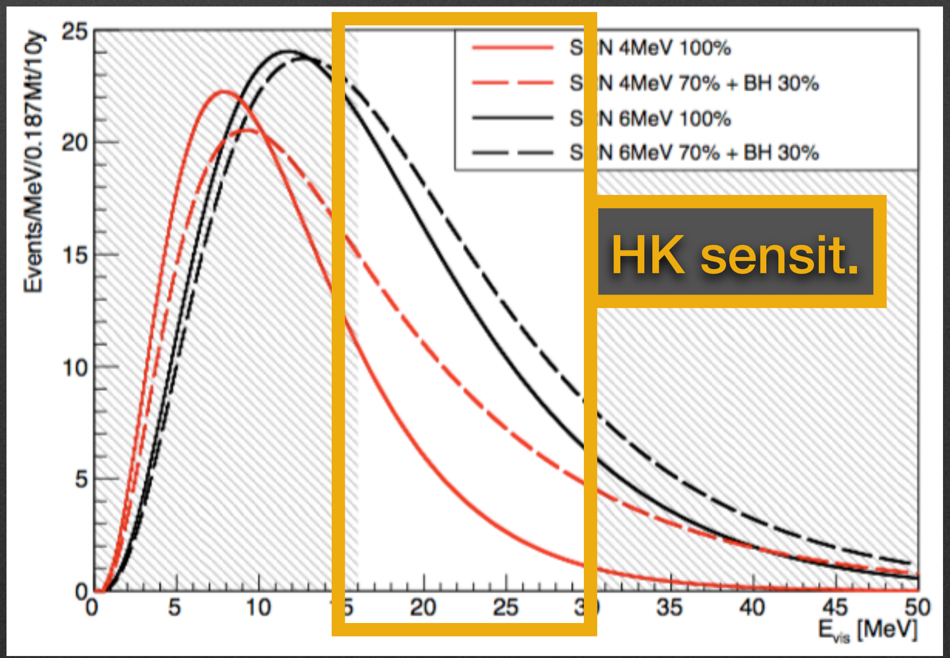




Diffuse Supernova Neutrino Background (SN relic)

- DSNB/SNR neutrinos are the neutrino background left over by all past supernovae. Theorized to constitute $\Phi \sim \mathcal{O}(10) cm^{-2} s^{-1}$
- Can tell history of heavy element synthesis since stellar formation commenced.
- Can in principle be discovered by current-generation experiments. Hopefully SK-Gd, currently obscured in pure-H_2O SK by spallation and low-E atmospherics.
- Megaton-scale needed to measure spectrum and characteristics: HyperK (~20 ev/y)
- Comparison with (optical) SN rate will give rate of failed explosions (optically-dark).





Supernovae with HK: neutron tag (+ digression on SK-Gd)

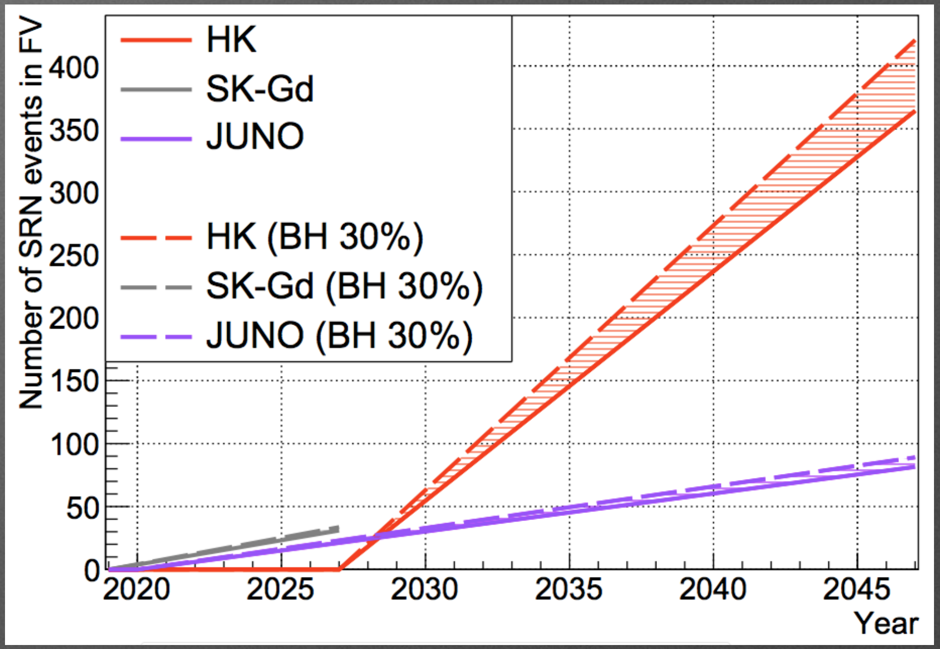
- Pre-SN (O-Si burning), SN burst pinpointing, DSNB + δ_{CP}, pdk… benefit from increased ν tagging efficiency. Antineutrinos generate more final-state neutrons in their interactions by charge exchange.

- Hydrogen tagging possible, but low efficiency (~50% w new HK PMTs)

- **0.1% $Gd_2(SO_4)_3$** (~500tonne, 90% neutron tag) for SRN ν:

  HyperK -> E~[16,30]MeV SuperK -> E~[10-20]MeV

  Limits dictated by spallation products (increased in HK wrt SK, but can be coincidence-rejected away) and atmospheric ν.



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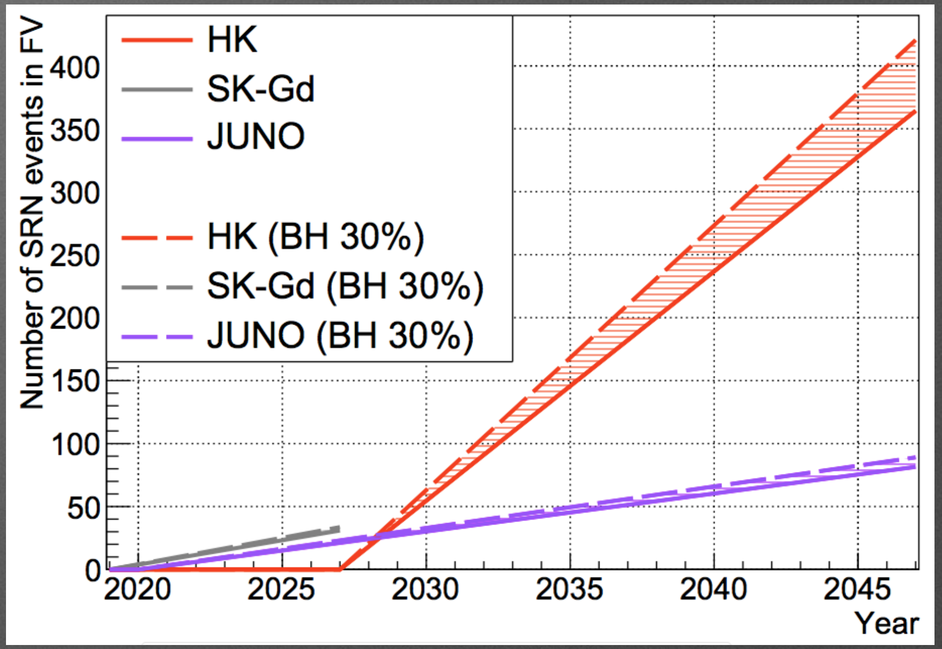


- Lower threshold (~10 MeV) to study SN bursts down to the epoch of z~1:

  √ Time correlation (30 μs)
  √ Vertex correlation (50 cm)
  √ Prompt=Cherenkov-like ; Delayed=isotropic

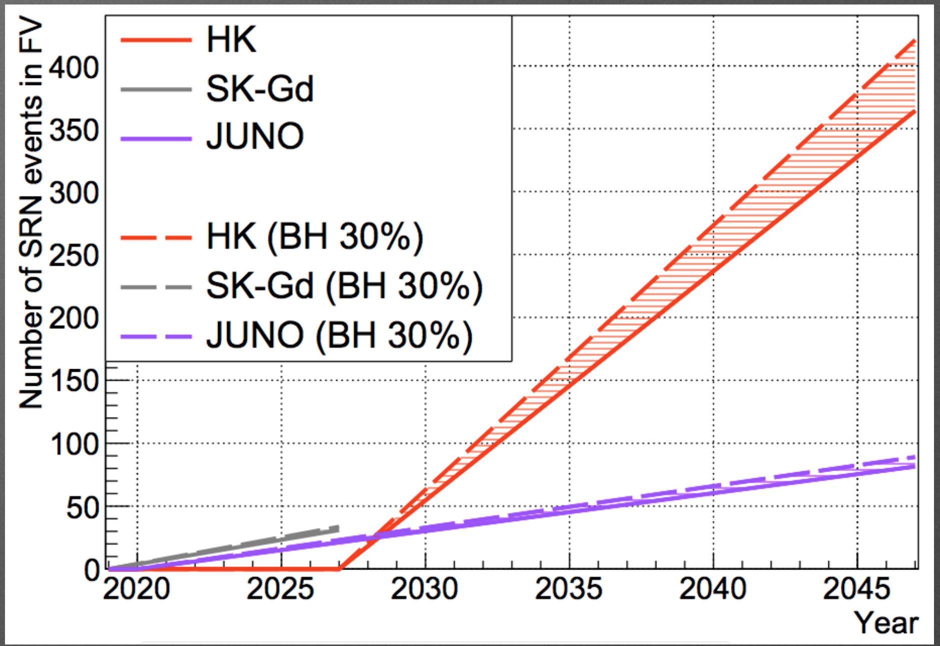
- Reduction of spallation backgrounds by **orders of magnitude.**
- Invisible μ backgrounds (decay-e from muons below Cherenkov thresholds produced by atmospheric ν) by **factor of 5x.**

Supernovae with HK: neutron tag (+ digression on SK-Gd)

- Pre-SN (O-Si burning), SN burst pinpointing, DSNB + δ_{CP}, pdk… benefit from increased ν tagging efficiency. Antineutrinos generate more final-state neutrons in their interactions by charge exchange.

- Hydrogen tagging possible, but low efficiency (~50% w new HK PMTs)

- **0.1% $Gd_2(SO_4)_3$** (~500tonne, 90% neutron tag) for SRN ν:
  HyperK -> E~[16,30]MeV SuperK -> E~[10-20]MeV
  Limits dictated by spallation products (increased in HK wrt SK, but can be coincidence-rejected away) and atmospheric ν.



- Lower threshold (~10 MeV) to study SN bursts down to the epoch of z~1:

  √ Time correlation (30 μs)
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- Reduction of spallation backgrounds by **orders of magnitude.**
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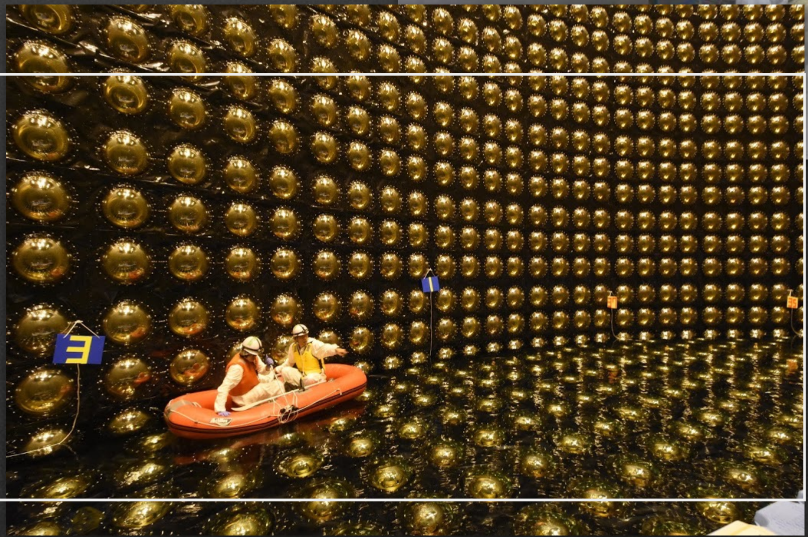
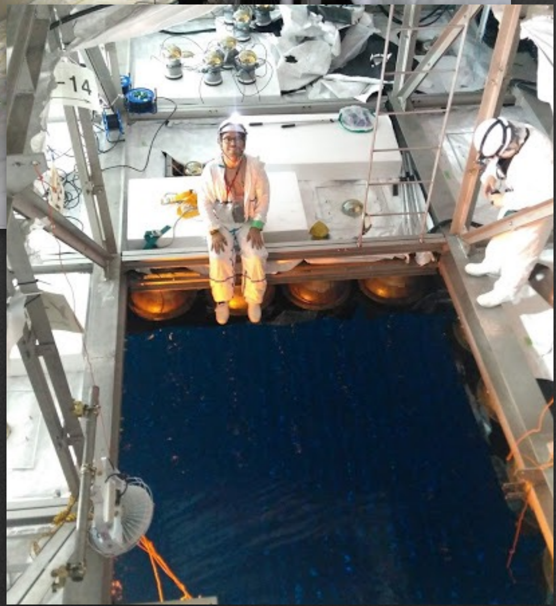
SuperK is gearing up to start (early) SK-Gd phase by the end of this year / early next.
√ Leak fixing (<<17 L/day) and refurbishment+upgrade work performed last summer.
√ Calibrations, new water system exercising and stabilization ongoing now (SK-V). Already close to SK-IV levels.

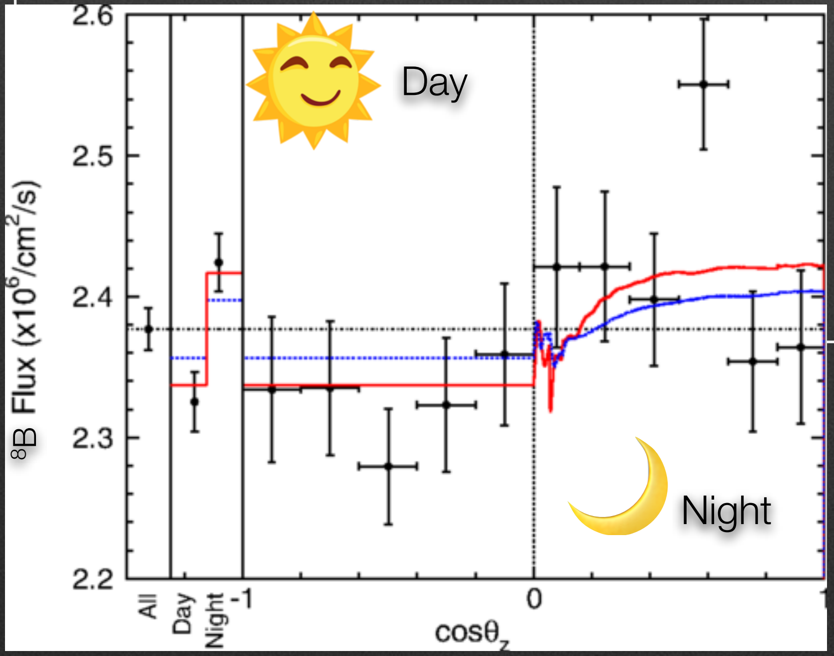




Solar neutrinos in HK

D/N asymmetry

- MSW matter effect -> enhanced solar ν flux at night (@ main ^{8}B energies).
- Aim to reduce 0.5->0.3% syst. thanks to energy thr., calibration & background shape.
- Paired with much higher statistics, can get **4σ** evidence in 2 years (no asymmetry) or 6 years (asymmetry from KL).
- Assumes SK's ^{222}Rn content in full FV (challenging but deemed workable).
- Spallation background larger *per se*, but can be reduced by 3x (vs SK-IV) because of photodetection efficiency.



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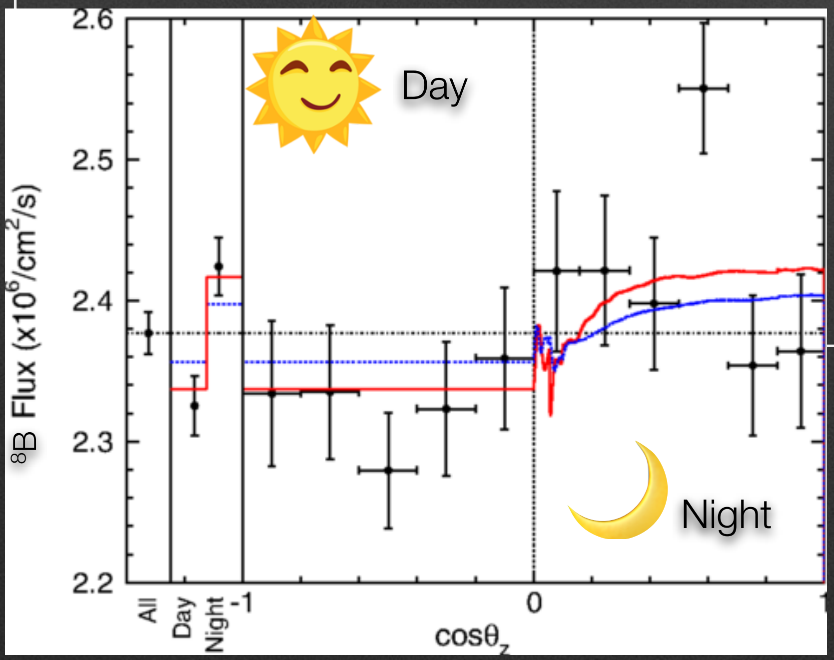
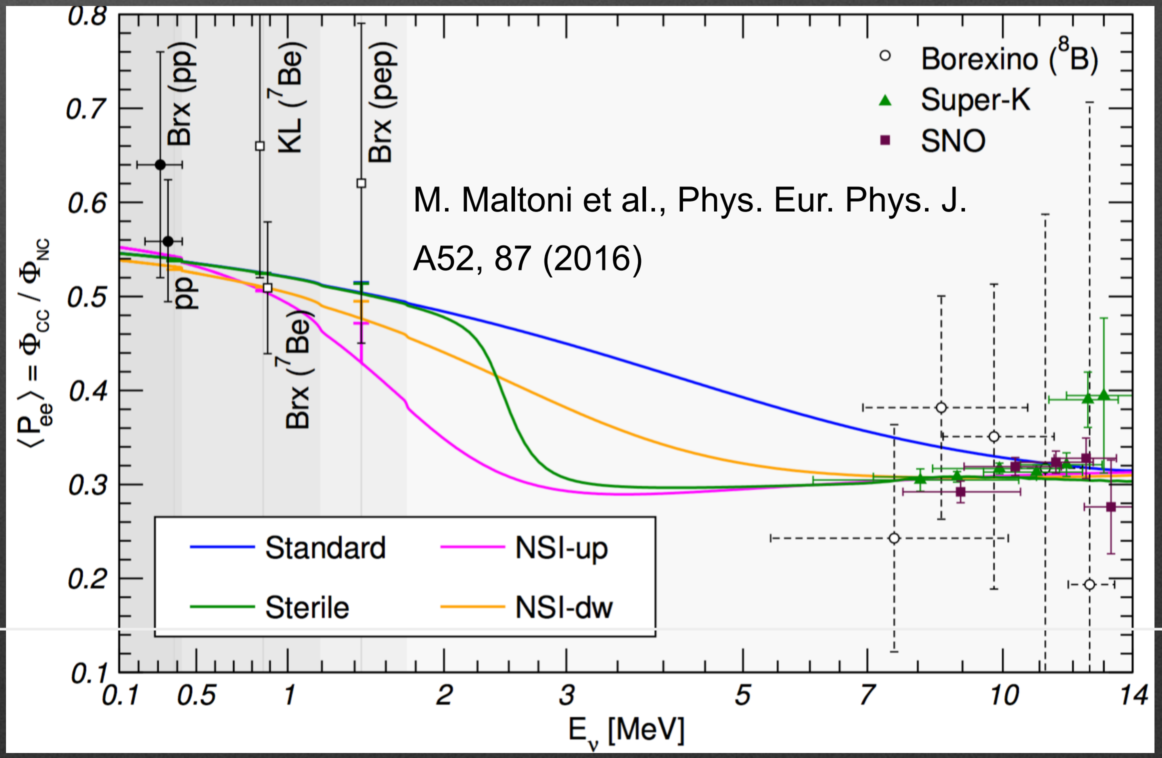


Upturn (P_{ee} transition region)

- Unprobed shape of survival probability between low-E (*pp, pep, ^{7}Be* <=> *vacuum-dominated*) and high-E solar ν (*^{8}B* <=> *matter enhanced*).
- Shape can reveal NSI, MaVaN, sterile neutrinos…
- Possible to measure thanks to better energy resolution and reduction of (higher than threshold, but possibly misreconstructed) backgrounds.



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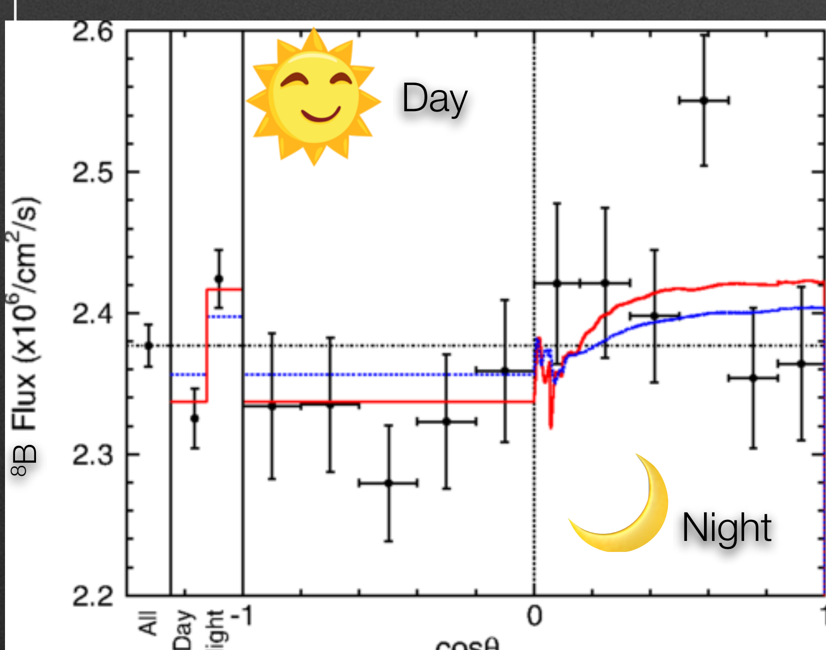

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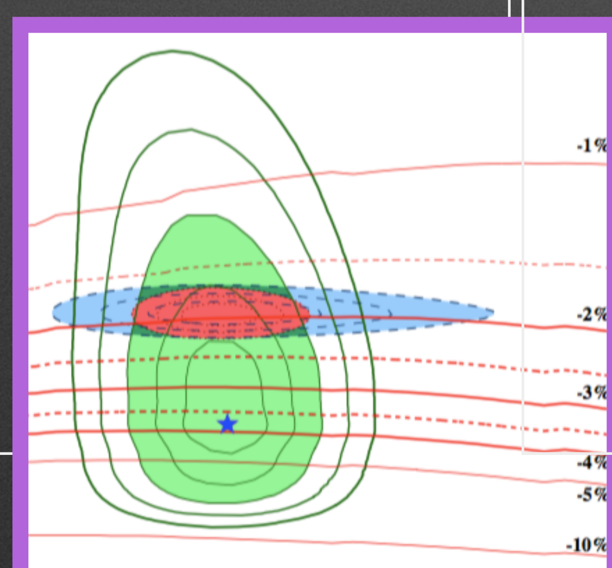
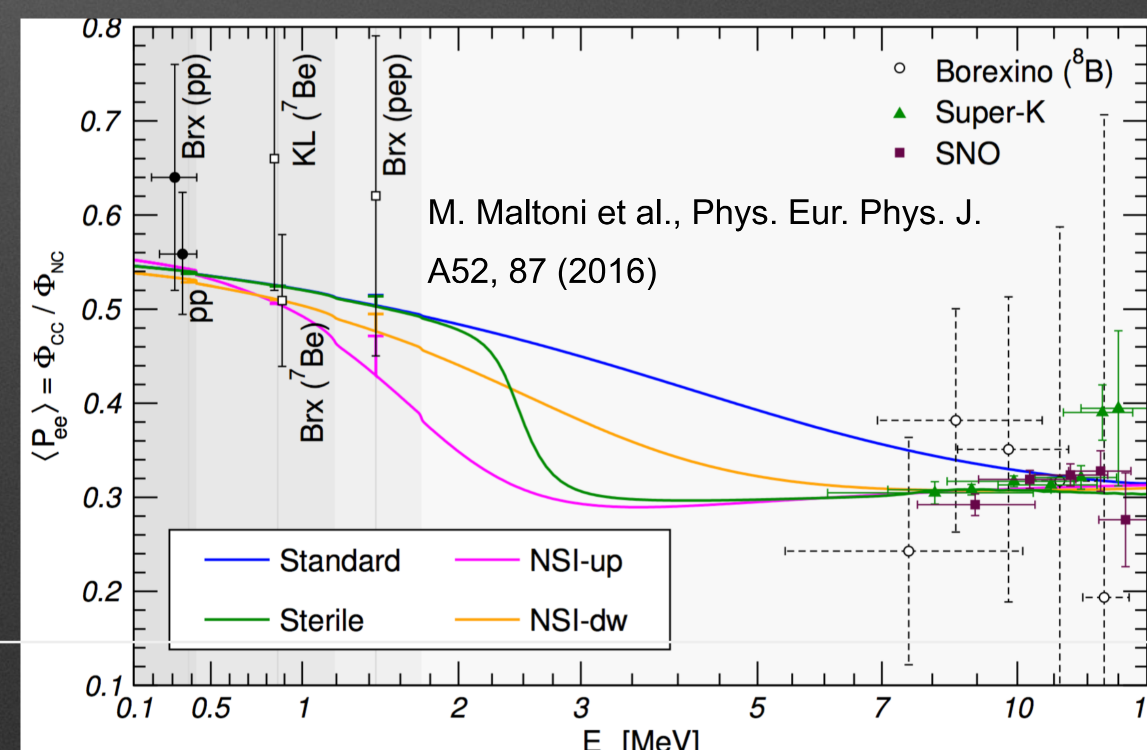


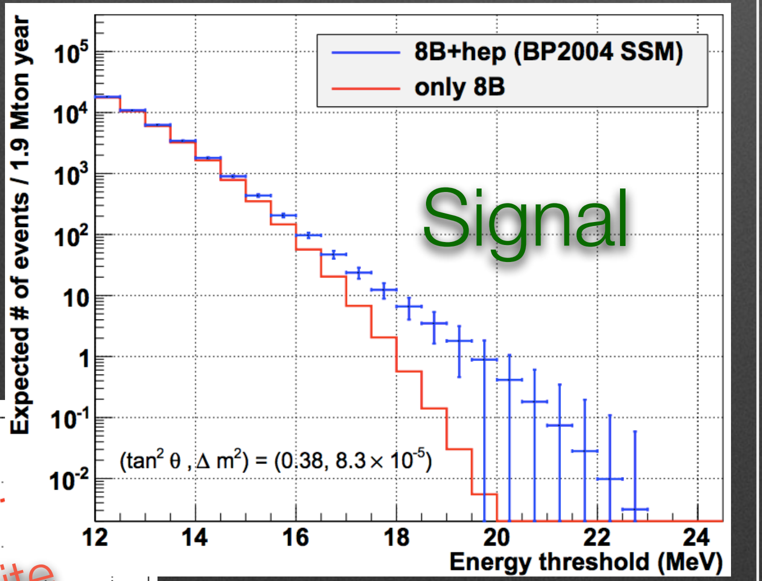


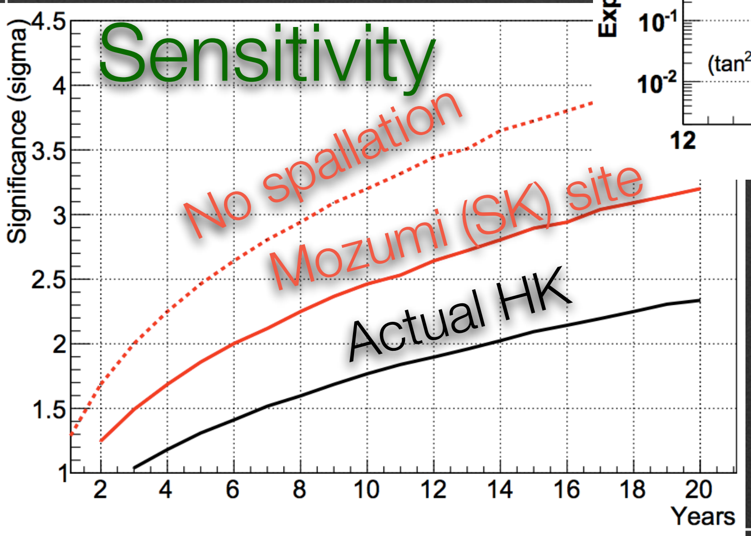
Together imply Δm^2_{12} tension (with KamLAND's antineutrino data, i.e. between ν and $\bar{\nu}$) that may be indicative of new physics, NSI…

Solar neutrinos in HK

hep neutrinos

- Smaller solar neutrino flux component. Comes from main *pp* chain; most externally-produced neutrino in chain.
- Hints that may be higher than expected by SSM (Winchester, PhD).
- Holds 2nd-most important key to solar metallicity problem (after CNO).
- Probe for NSI at ~18 MeV (possible enhancement).





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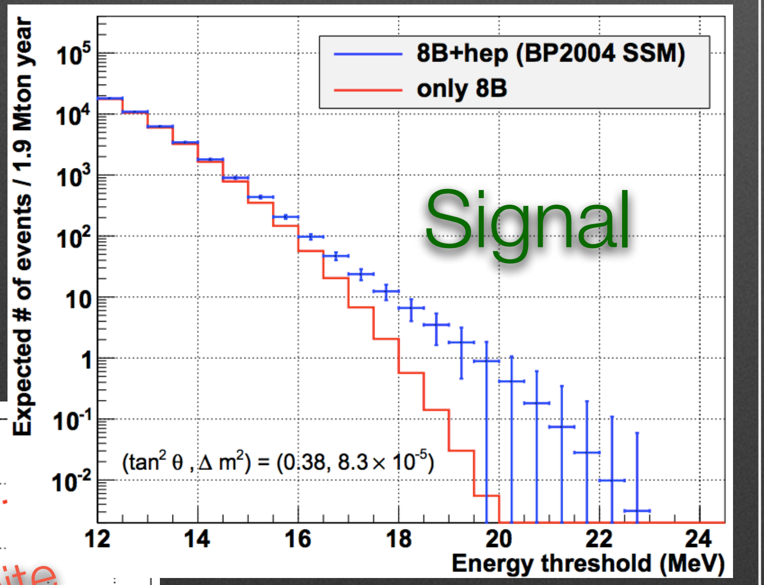

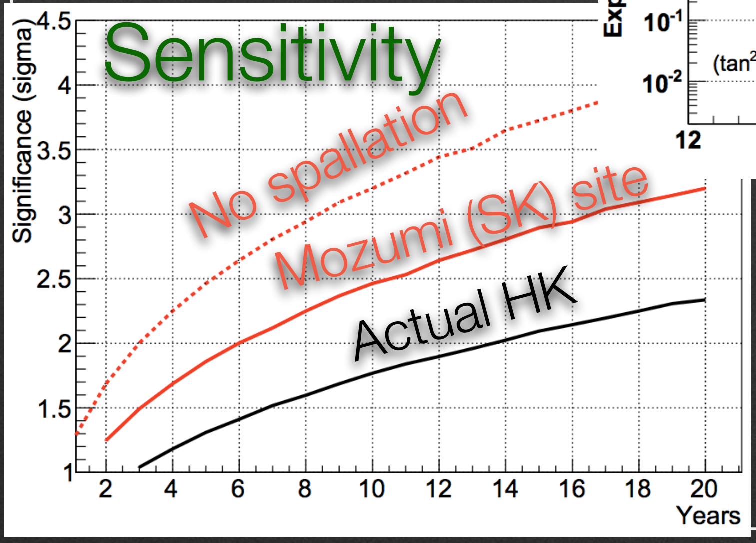

Solar variability

- Core temperatures influence directly ^{8}B production. Neutrinos give us a real-time probe of that process.
- Statistical power in HK means short-time variability analysis of Sun's core temperature.

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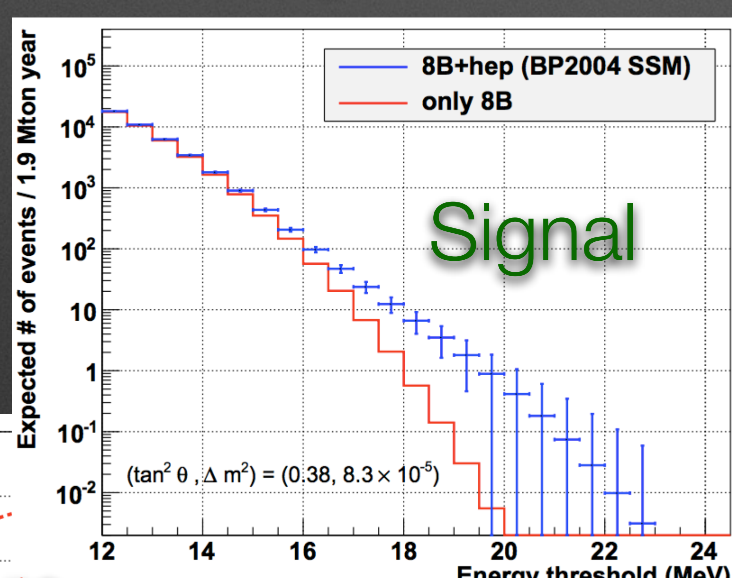

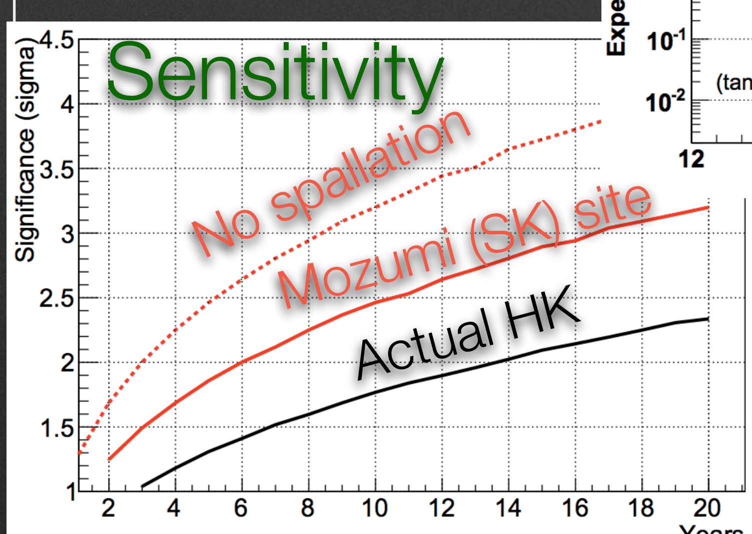

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Flares

- 10^{33} erg emitted over ~$\mathcal{O}$(10)min scale when magnetic reconnections occur.
- Protons can be accelerated ~10 GeV. Interactions in solar atmosphere can produce mesons that decay into neutrinos.
- 6-7 events can be expected in HK, but large uncertainties still exist for these estimates -> Discovery?

Multimessenger astronomy with HK

GRB jets & pulsar winds

- GRBs are most luminous (10^{52} erg/s) astrophysical phenomena: prompt ~MeV gamma rays.
- Relativistic jet, caused by a black hole's accretion disk (or magnetized neutron star), variable in the ~ms scale —> unsteady outflows <=> shock dissipation.
- UHE CRs come from them as recently proven (Fermi / IceCube, EHT…). TeV/PeV neutrinos emitted too.

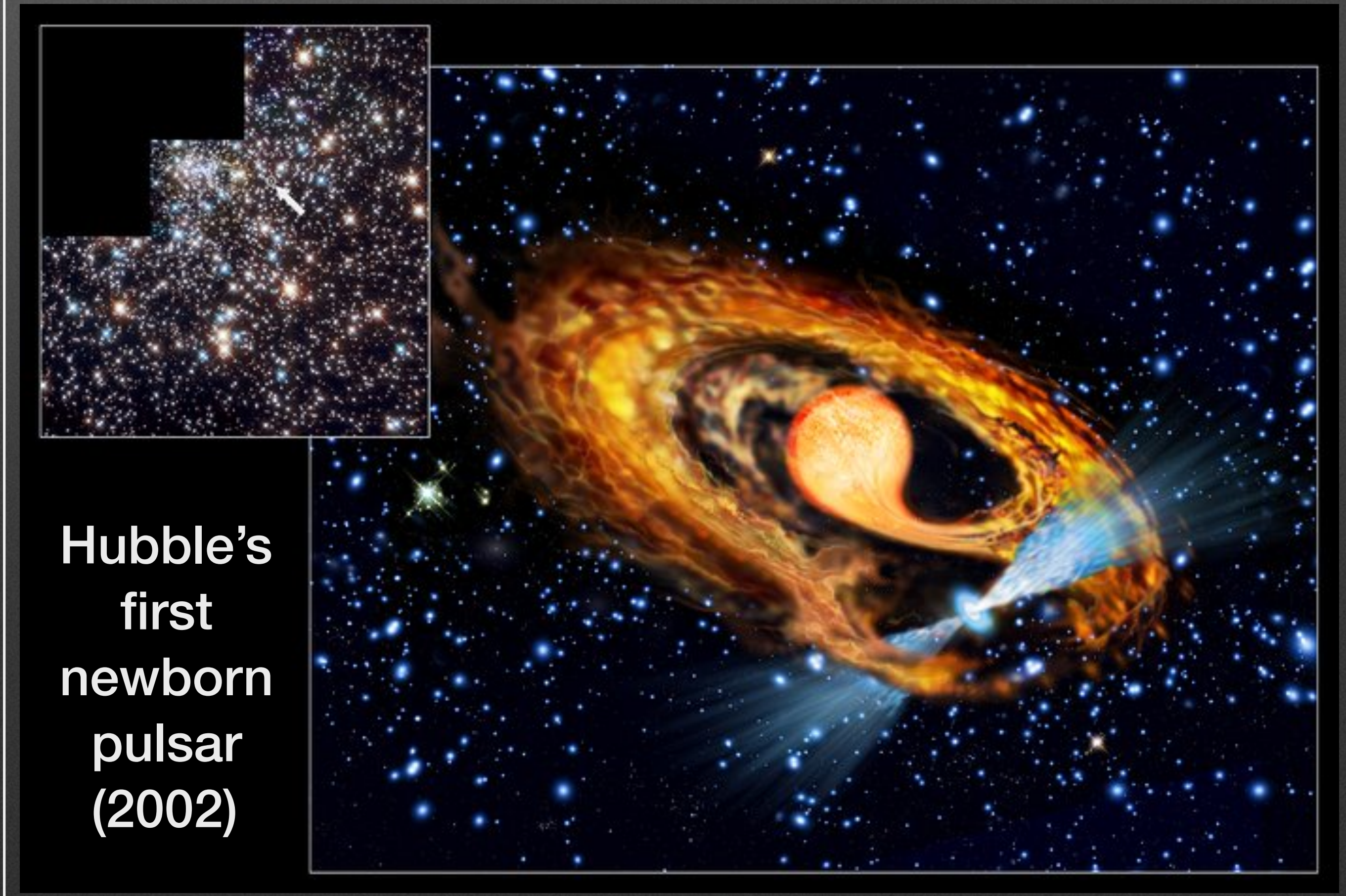
- Mechanism still debatable (low-E photon spectrum, inelastic nucleon-neutron collision…)
- GRB neutrino detection if <100 Mpc (can be, but unlikely).
- Trans-relativistic supernovae or low-luminosity GRBs ("choked jets") more plentiful.

- **How jets are accelerated, jet composition, connection between GRBs and energetic SN.**

- Outflows do not have to be jets: can be proto-neutron star winds (newborn pulsar) -> neutrino heating.
- 0.1-1 GeV neutrinos (20-30 events in HK @10kpc).
- Spatio-temporal coincidence to reduce atmospheric backgrounds crucial -> multimessenger at its best (information from other wavelengths).

Gravitational wave correlations

- As discovered by IceCube/LIGO, GW events can emit neutrinos (presumably only when at least a NS is involved)
- Models predict up to 10^{53} erg in neutrinos.
- HyperK will be able to detect thermal neutrinos from <10 kpc merger events.



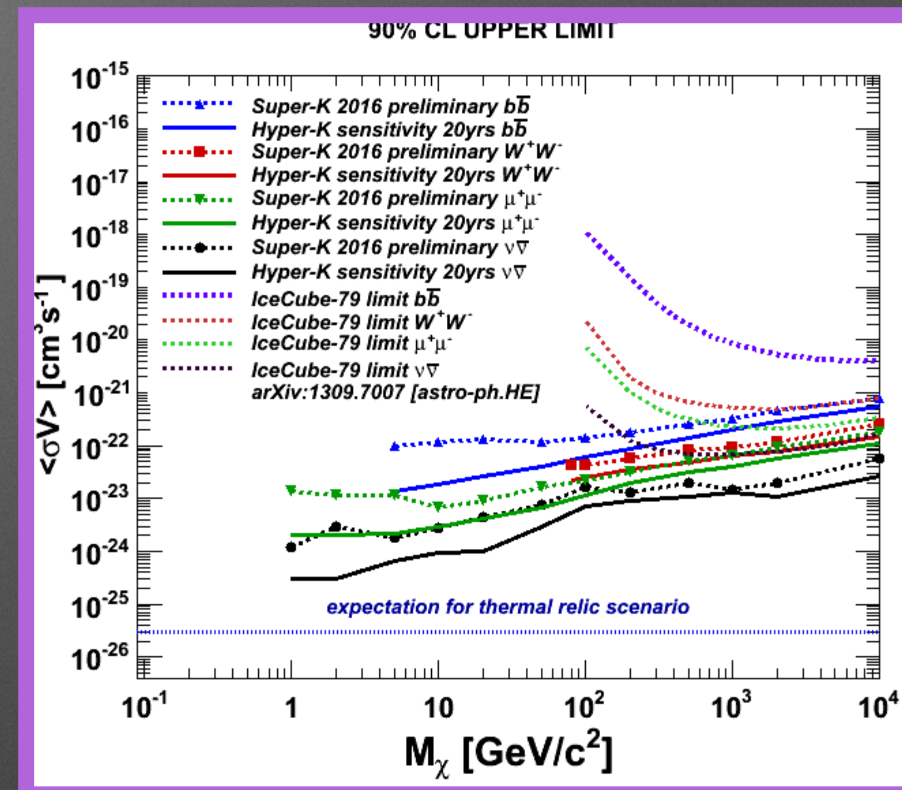
Hubble's first newborn pulsar (2002)

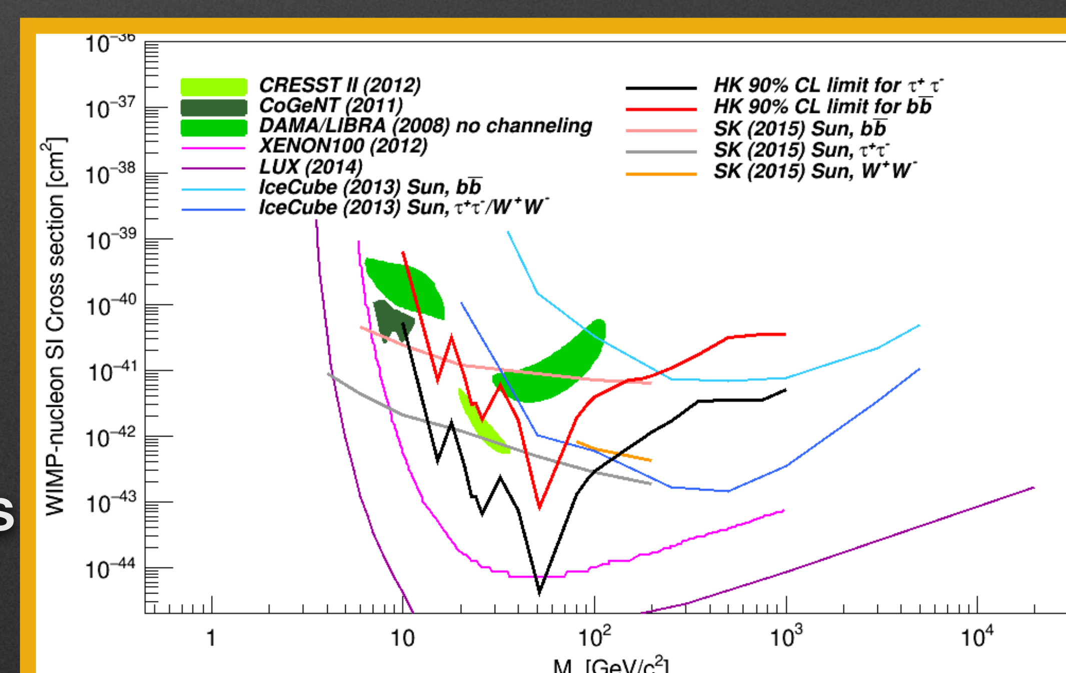
Dark Matter (WIMP) indirect searches with HK

- Self-annihilation of DM particles in gravitational wells can theoretically lead to SM pairs.

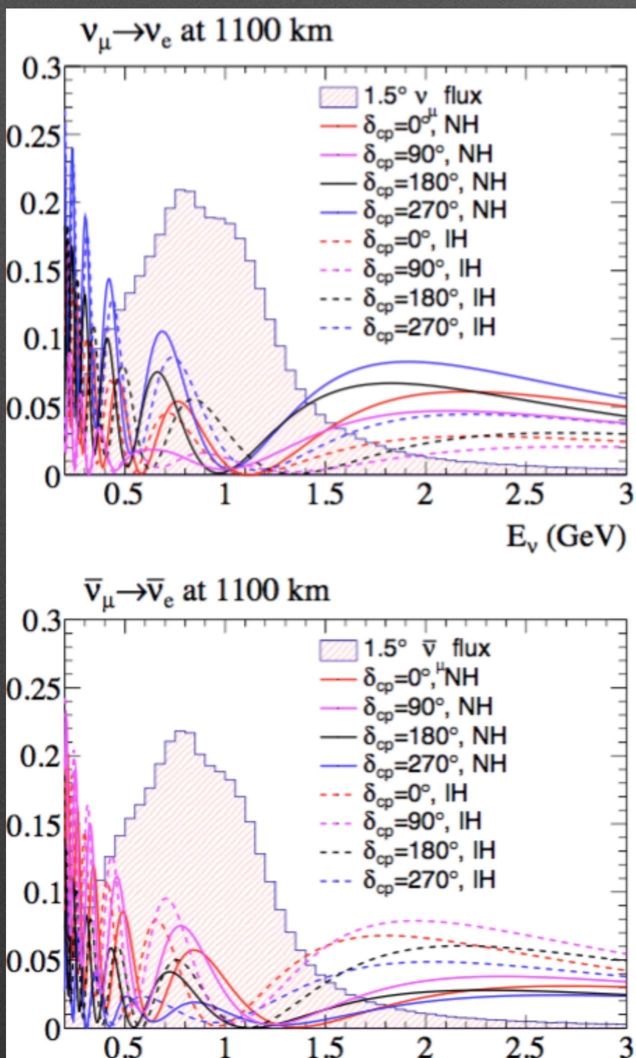
$$\chi\chi \rightarrow W^+W^-;\tau^+\tau^-;b\bar{b};\mu^+\mu^-;\nu\bar{\nu}$$

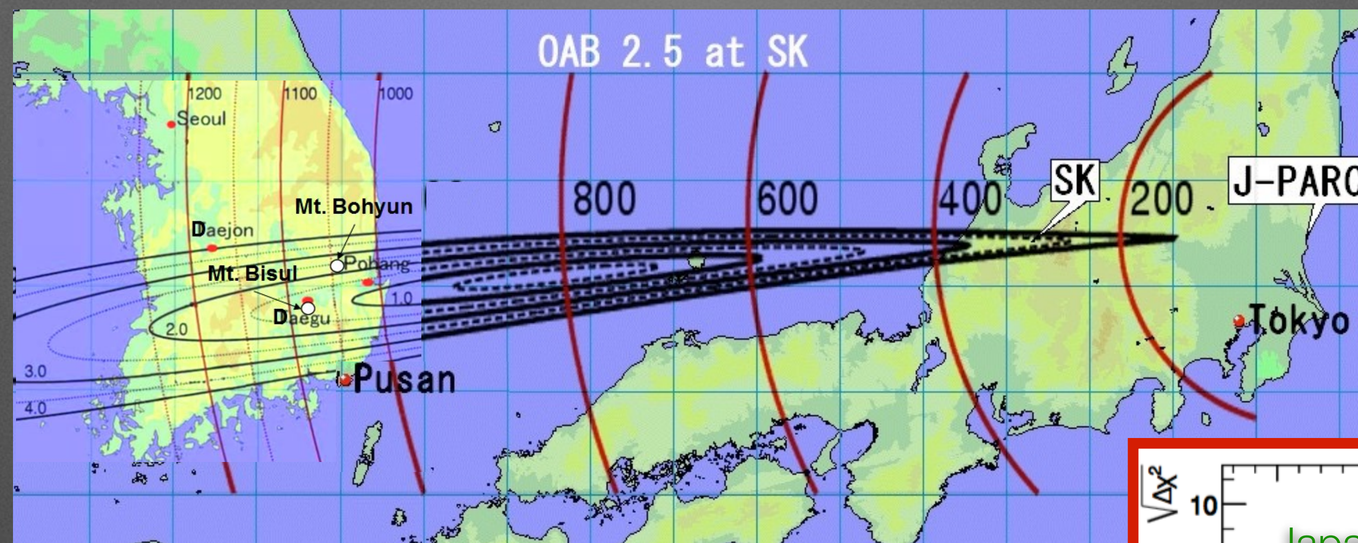
- Atmospheric neutrinos = background (signal = ν_e, ν_μ components)
- Angular distribution -> discern peak towards center of gravitational wells (Sun, Earth, galactic center…). Similar to discerning Sun in solar ν.
- Momentum distribution -> χ candidate mass (HK sensitive ≤100 GeV/c^2)
- Self-annihilation cross section sensitivity 3x-10x SK's.
- WIMP-nucleon scattering cross section (+ spin independent interactions) sensitivity through neutrinos coming from Earth's core (scattered & decayed χ)

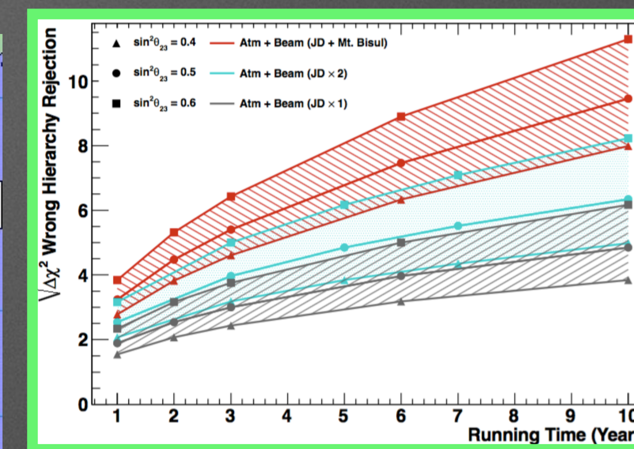


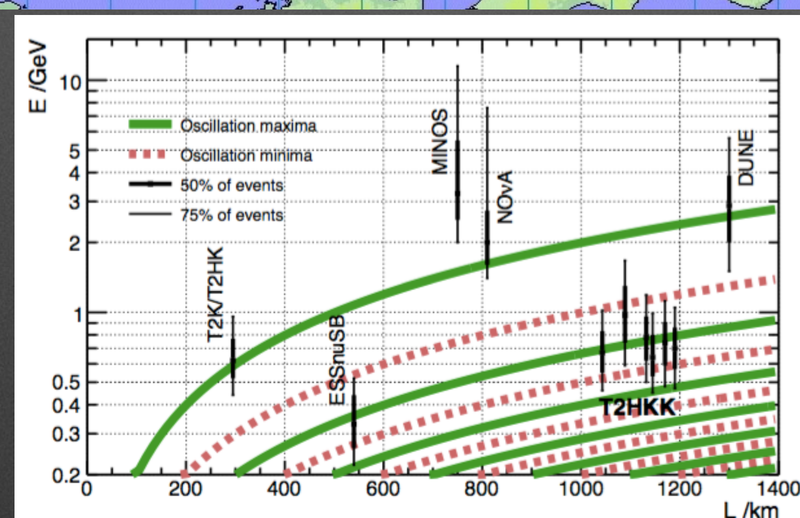


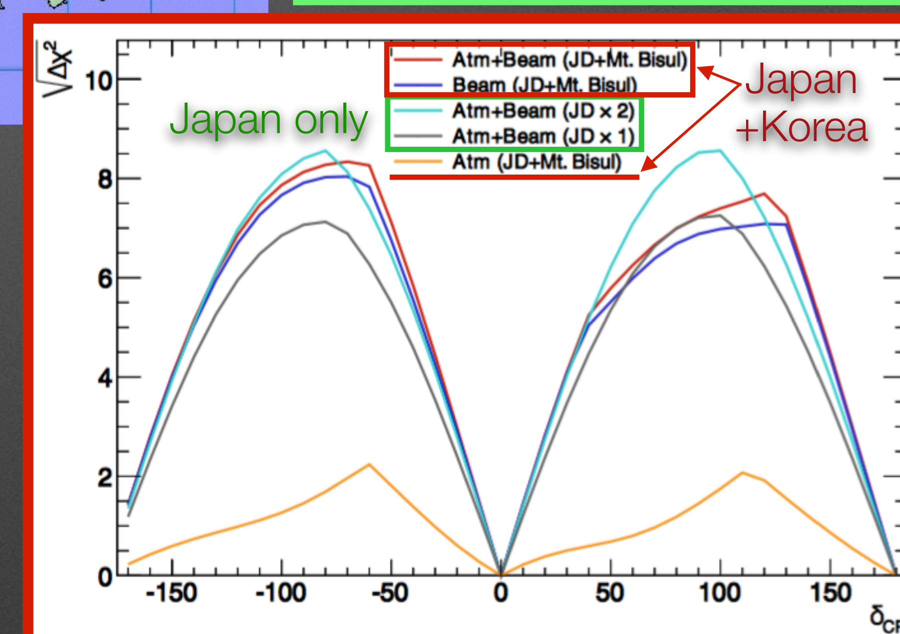
MOAR HK: HK-Korea and sensitivity reports











Sensitivity reports

Letter of Intent - arXiv:1109.3262

HK LBN - Prog. Theor. Exp. Phys. 053C02 (2015)

HK Design Report - arXiv:1805.04163 (public: May 9th'18)

Option for 2nd tank in Korea (HKK) - arXiv:1611.06118

Hyper-Kamiokande

Timeline and outlook

- Digging set to start in a few months (early JFY2020). It’s happening! Water filling in late ’26 / early ’27. DAQ start in late 2027.

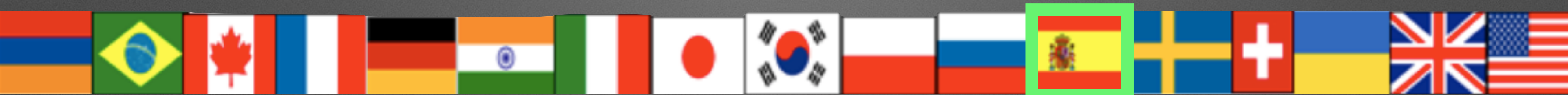
- Hyper-Kamiokande will be in the forefront of the neutrino oscillations, astroparticle physics and nucleon decay research, thanks to its unprecedented size, resolution and sensitivity.

- HyperK will expand frontiers of knowledge in particle astrophysics on:
  - √ Supernovae (core collapse, rotation, modulations, DSNB, pre-SN, trans-relativistic, dim, failed, interaction-powered, absolute neutrino mass, pinpoint location…)
  - √ Solar neutrinos (^{8}B spectrum, *hep*, flares, variability, temperature…)
  - √ Dark matter (self-annihilation, scattering, distribution, mass…)
  - √ GRBs, pulsars, GWs…

- Second tank (in Korea? <=> HKK) would extend the project’s sensitivity much further — under consideration.

HK proto-Collaboration (and myself) thank you for your attention.

Let's enjoy EPS'20 !



Questions, comments?

New collaborators?