Atmospheric Neutrino Oscillations with Super-Kamiokande

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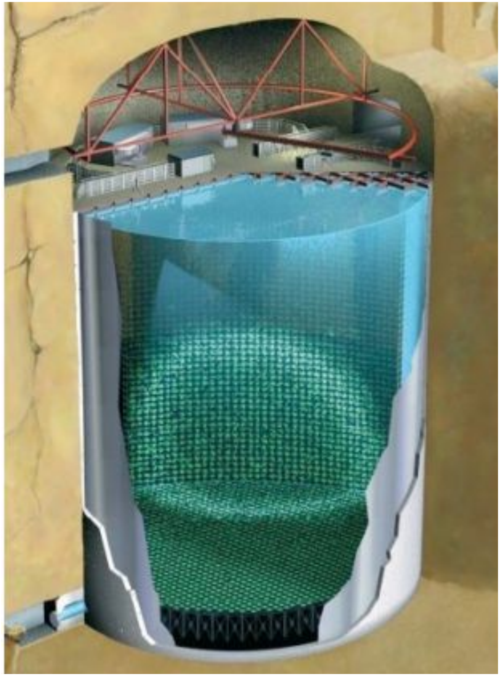
State of the Art Neutrino Observatory

Super-Kamiokande

- Experiment (Kamioka, Japan)
  - 22.5 kton fiducial volume
  - Overburden 1km rock
  - Inner (11k PMTs, 40% coverage) & outer (2k PMTs) detectors
  - **5 run periods** (~20 years of data)
    - **SK-I** (1996-2001)
    - **SK-II** (2003-2005): after accident, ½ PMT coverage
    - **SK-III** (2006-2008): restored PMT coverage
    - **SK-IV** (2008-2018): upgraded electronics
    - **SK-V** (2019-2020): after upgrade for SK-Gd
    - **SK-Gd** (2020-): **with gadolinium**

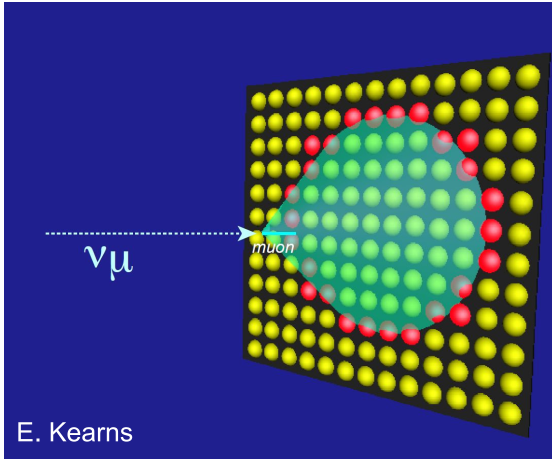


- Amazing multi-purpose physics laboratory (~10 - 10^4 MeV)

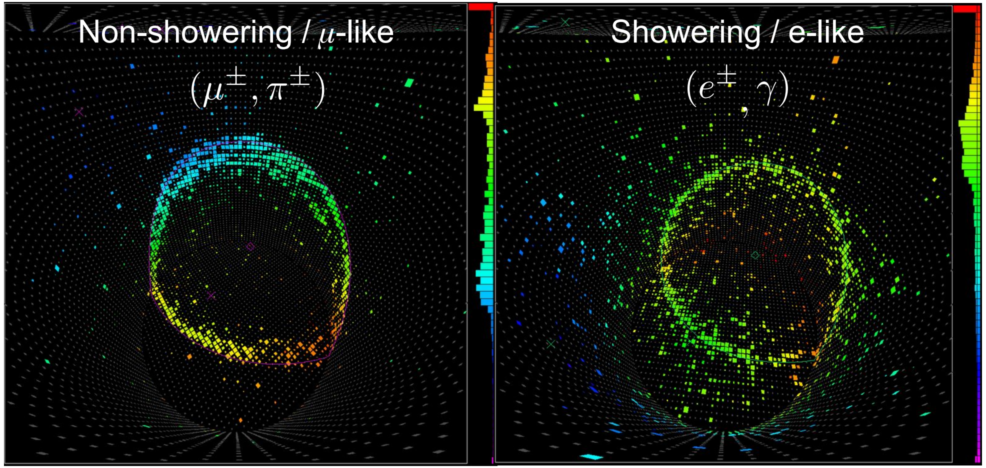
  → solar-ν, atmospheric-ν, supernovae-ν, DSNB, dark matter, proton decay, other baryon number violation, ν-astrophysics…

- Discovered neutrino oscillations 

Cherenkov Ring Imaging



(Super-K real data events from 1998)



- Cherenkov radiation
  - charged particle travels in medium faster than light → builds wave-front emission

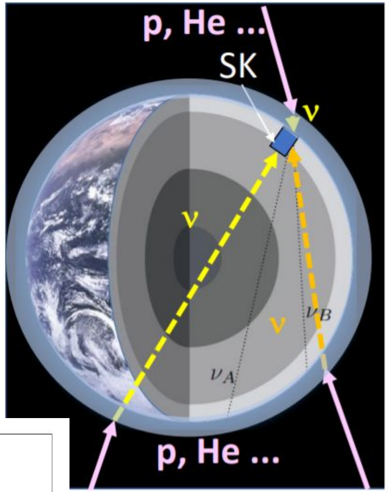
Exploring Atmospheric Neutrinos

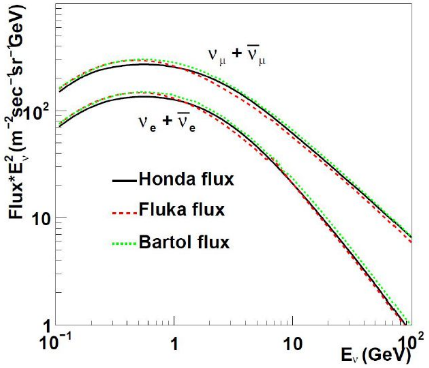
Atmospheric Neutrinos

- Cosmic ray interactions in atmosphere result in many ν's

- "*Atmospheric fixed target experiment*" is always ON

- ν propagation baseline: ~ O(10) - O(10^4) km





Atmospheric Neutrinos

- Earth matter (MSW) effects modify effective Hamiltonian and ν-propagation (for anti-ν, matter potential V → -V)

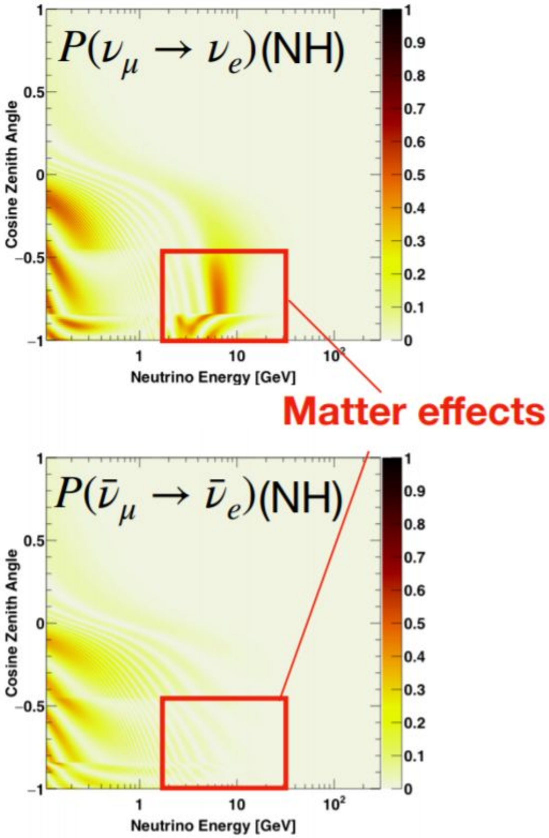
$$H_{\rm eff} = U_{\rm PMNS} M U^{\dagger}_{\rm PMNS} + \boxed{V_e}$$

- Change Normal Hierarchy (NH) → Inverted Hierarchy (IH), reverses matter effects of ν vs. anti-ν

- **Atmospheric neutrino oscillations are sensitive to:**
  $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$ and δcp

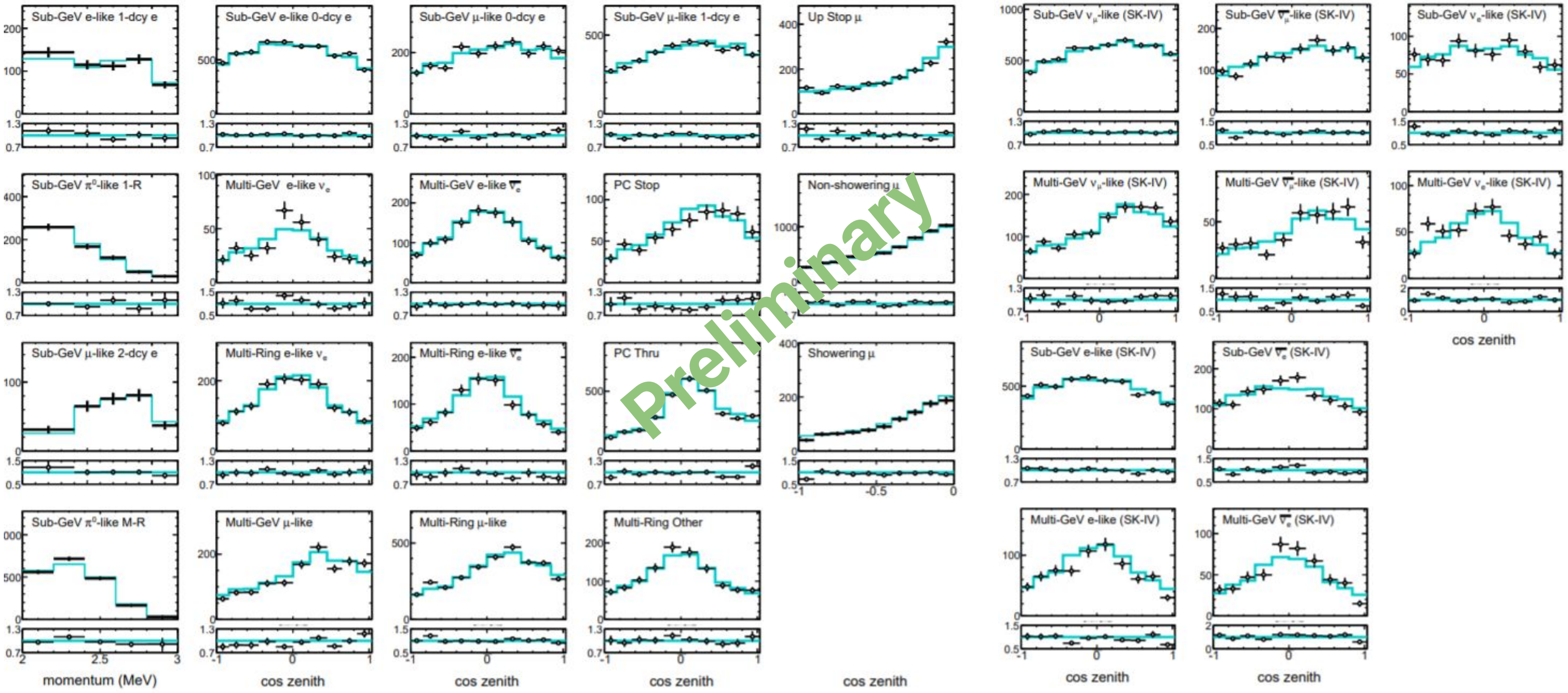
*** *SK also detected ν_τ from ν_μ oscillations* **[Abe+ (SK), *PRL*, 2012]**
(+ measured cross-section **[Li+ (SK), *PRD*, 2018]***)*

[Abe+ (SK), *PRD*, 2018]



SK Atmospheric Neutrino Analysis

- In-depth 3-flavor combined fit: >15 data samples + neutron separated samples (SK-IV), >150 systematics

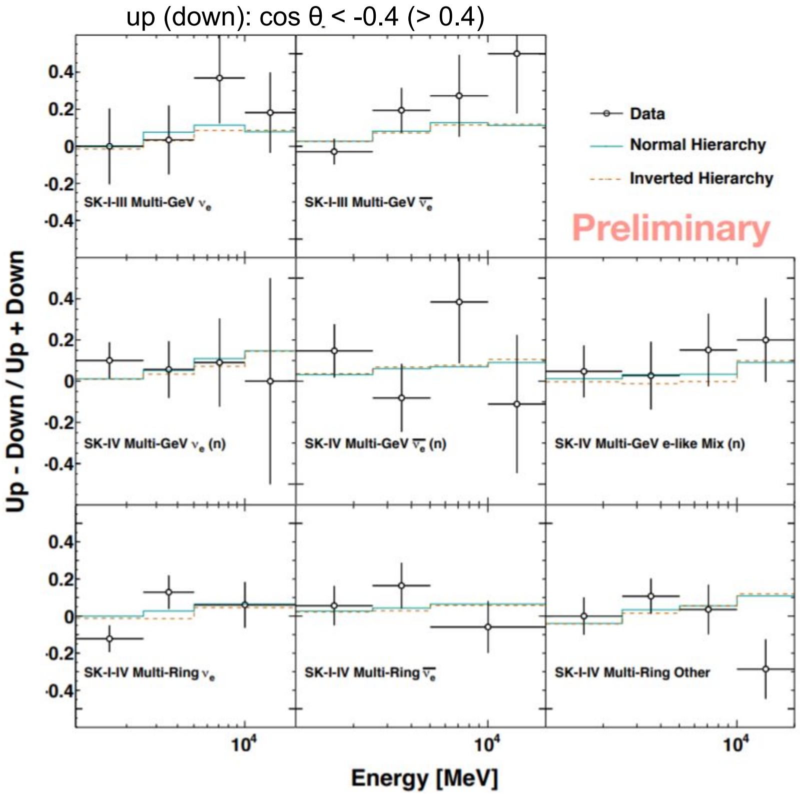


SK Atmospheric Neutrino Analysis

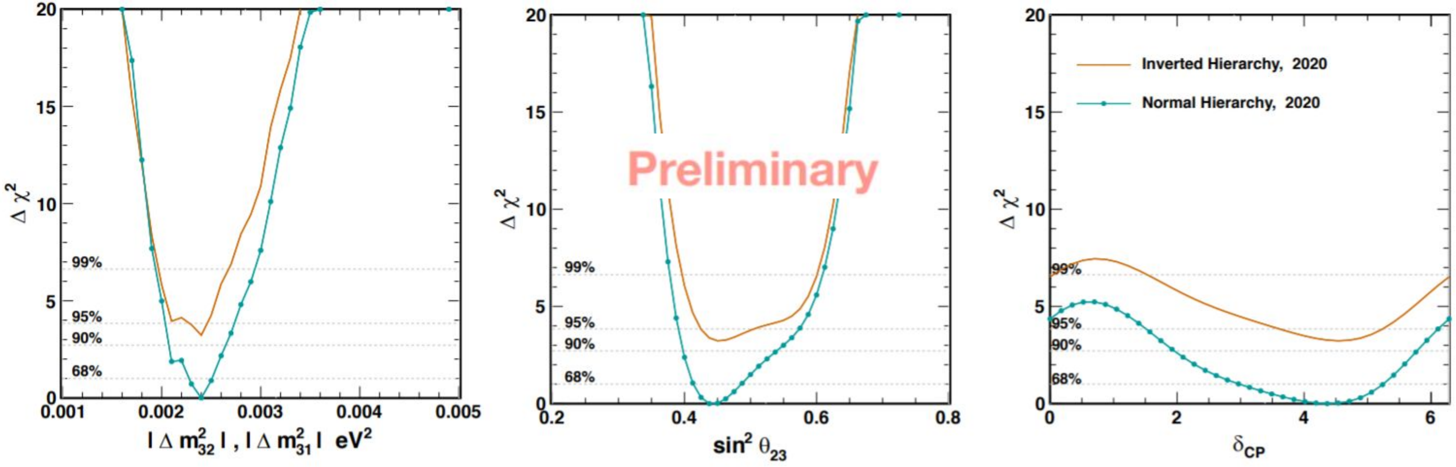
- Full SK I-IV livetime, exposure: 364.8 kton-yrs
  (SK 2018 published: 328 kton-yrs)

- Main improvements (vs. SK 2018 published):
  - neutron tagging (eff. ~ 25%) for ν/anti-ν separation
  - New BDT-based selection for multi-ring events → increased signal eff., sample purity

*** *previous results:* **[Abe+ (SK), *PRD*, 2018]**



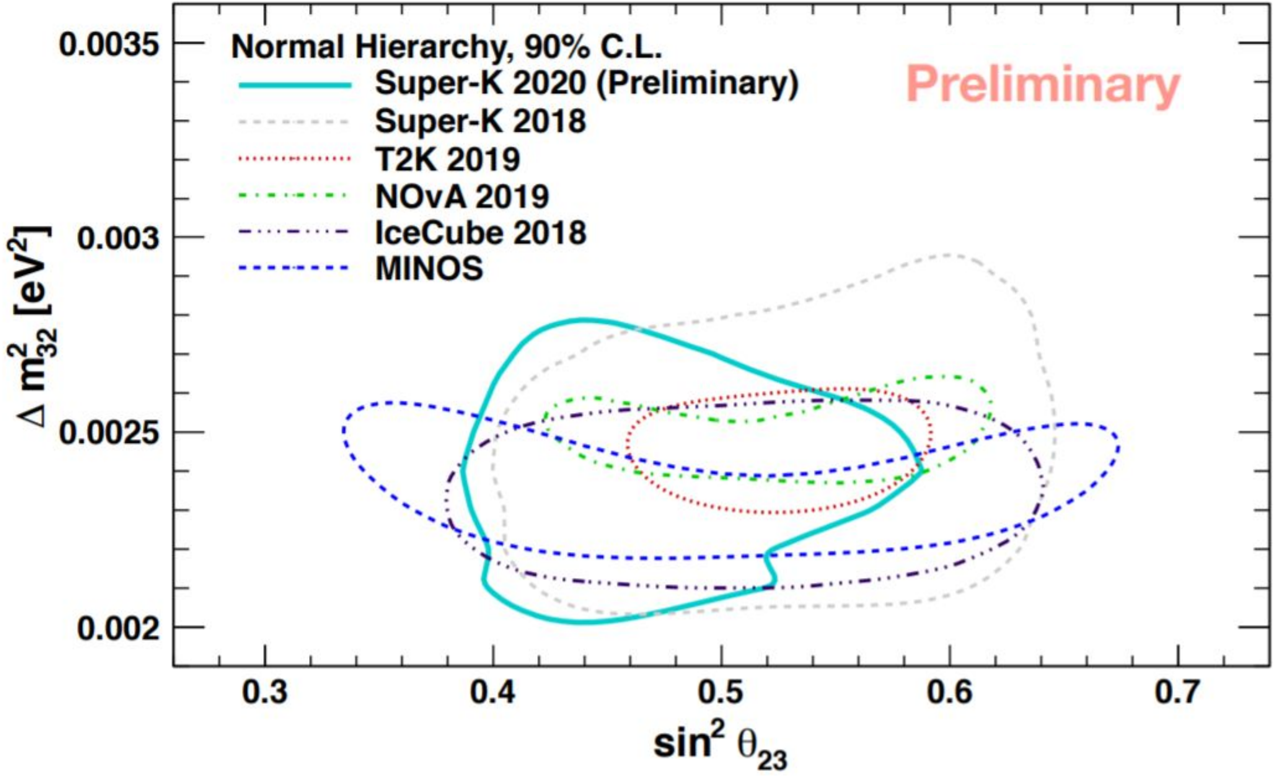
SK Atmospheric Neutrino Analysis



930 Bins	$\chi2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

- SK data ***disfavors*** **Inverted Hierarchy at 71.4-90.3% C.L.** (SK 2018 published: 81.9-96.1%)
- SK data ***prefers*** **1st θ_{23} octant** and **δcp ~ 3π/2**

SK Atmospheric Neutrino Analysis



Also Great Opportunities for BSM ...

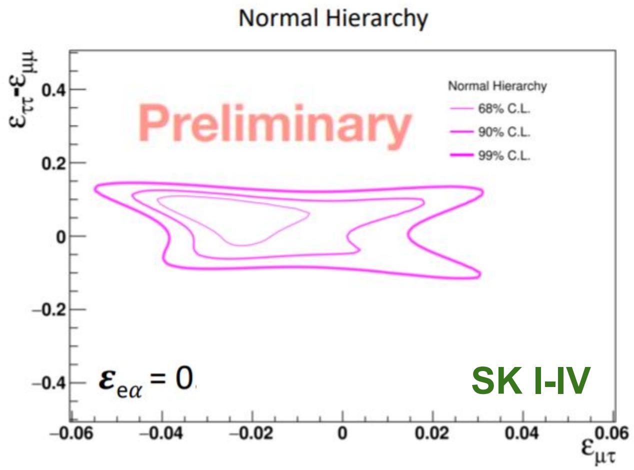
Non-standard Neutrino Interactions (NSI)

- BSM theories with extended gauge symmetry or particle content can result in non-standard ν-interactions (NSI)
  → affect ν-propagation in matter

- Parameterized via effective 4-fermion operators, will modify ν-Hamiltonian via (3x3) NSI matrix
  → different sensitivity to different entries

$$H_{\text{eff}} = U_{\text{PMNS}} M U^{\dagger}_{\text{PMNS}} + V_e + \boxed{V_{\text{NSI}}(\varepsilon_{\alpha\beta})}$$

- Fix oscillation parameters to SK best fit (no NSI)
  → fit new parameters



NEW (SK I-IV)
$$-4.5 \times 10^{-2} < \varepsilon_{\mu\tau} < 1.9 \times 10^{-2}$$
$$-5.1 \times 10^{-2} < \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} < 1.4 \times 10^{-1}$$

OLD (SK I-II)
$$|\varepsilon_{\mu\tau}| < 1.1 \times 10^{-2}$$
$$-4.9 \times 10^{-2} < \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} < 4.9 \times 10^{-2}$$

[Mitsuka+ (SK), *PRD*, 2011]

Very Bright Future Ahead with SK-Gd !

SK with Gadolinium (SK-Gd)

- **NOW:** adding Gd to SK (~0.2%) → **transform SK into powerful astro-particle detector**
  - greatly improve neutron tag efficiency: **20% on H → 90% on Gd**

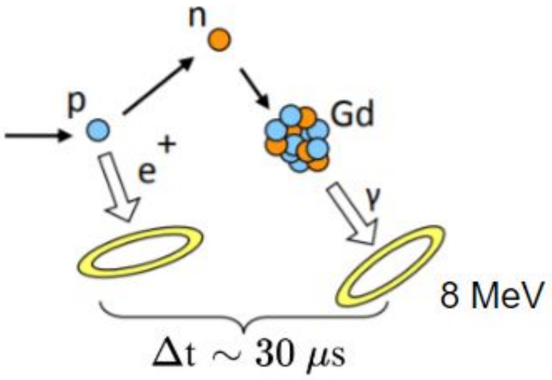
* see SK talk: *Lluis Marti-Margo*

*** *proposal* **[Beacom & Vagins, *PRL*, 2004]**

- Aim at first detection of diffuse supernova neutrino background (DSNB)

* see SK talk: *Sonia El-Hedri*

- Suppress atmospheric-ν background for proton decay
- Many benefits for atmospheric-ν analysis
  - ν/anti-ν separation
  - CC/NC separation
  - ν-energy reconstruction



Conclusions

- After ν-oscillation discovery, important to pin down fundamental oscillation parameters
- Super-K is the leading neutrino observatory and atmospheric neutrinos provide a fruitful arena for exploring oscillations
- New Super-K results (preliminary):
  - data disfavors Inverted Hierarchy at ~ 70-90% C.L.
  - data prefers 1st θ_{23} octant and δcp ~ $3\pi/2$
- Super-K can broadly explore BSM modifications of "*standard*" oscillations, such as NSI
  → no significant evidence
- Expect improved results with new exciting SK-Gd experiment !