Into the Future

with Large Underground Experiments

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The era of large underground experiments

- Exploration of neutrino physics and direct DM detection led by large experiments (Super-Kamiokande, Xenon1T ...)

- Further advances call upon even larger experiments
  - neutrino physics (δ_{cp}, mass hierarchy) → Hyper-K, DUNE
  - direct DM detection (probe WIMPs deeper) → DARWIN, Argo ...

Field leadership by many experts @ IPMU/U. Tokyo

experiment: Kajita, Nakahata, Moriyama, Martens, Vagins …

theory: Matsumoto, Ibe …

The era of large underground experiments

- These experiments constitute great sites of physics exploration beyond just their main target searches ...

Highlight their potential via 2 complimentary research programs

- **DM experiments as “neutrino telescopes”**
- **Neutrino detectors as “BSM laboratories”**

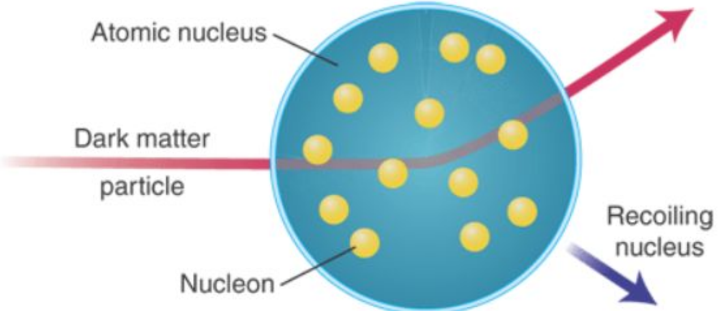
Part I

Dark Matter Detectors as Neutrino Telescopes

Direct DM detection experiments

- Look for particle DM interactions in detector → nuclear (and electron) recoils

- Typical setup:
    - heavy target material (A ~ 30-130)
    - low threshold (~ keV)
    - potentially scalable (Argon, Xenon)



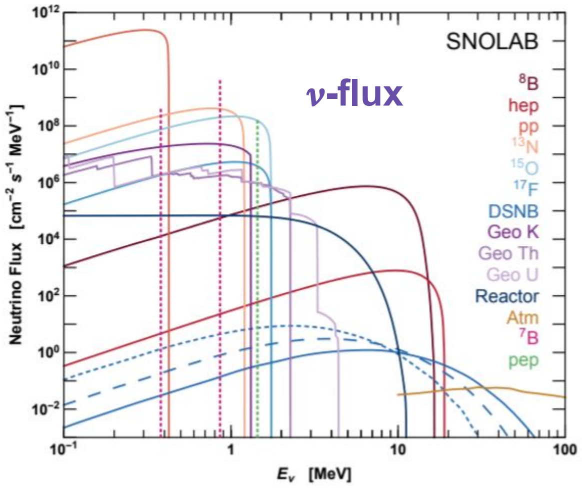
PRESTON HUEY/*SCIENCE*

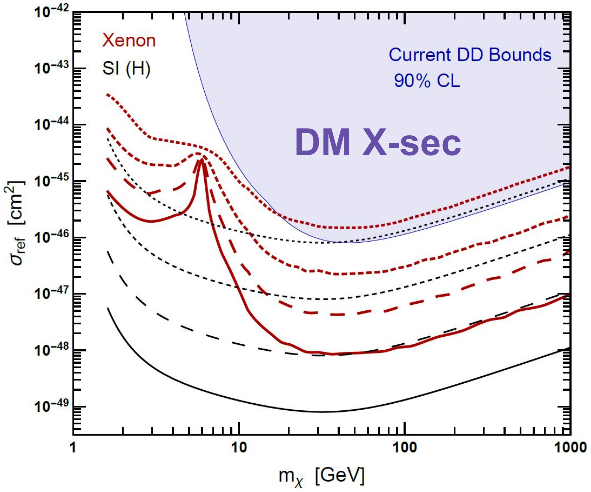
- Upcoming (Gen-2): ton-scale → future (Gen-3): multi-ton

(e.g. XENONnT O(10) ton - Martens, Moriyama)

Neutrino floor

- No convincing signs of DM → probe further (also other studies, e.g. light DM - Melia)
- Eventually will encounter irreducible neutrino-background: "neutrino floor"

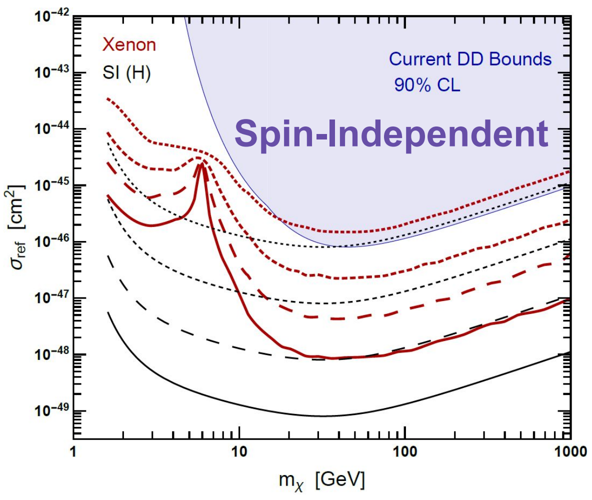


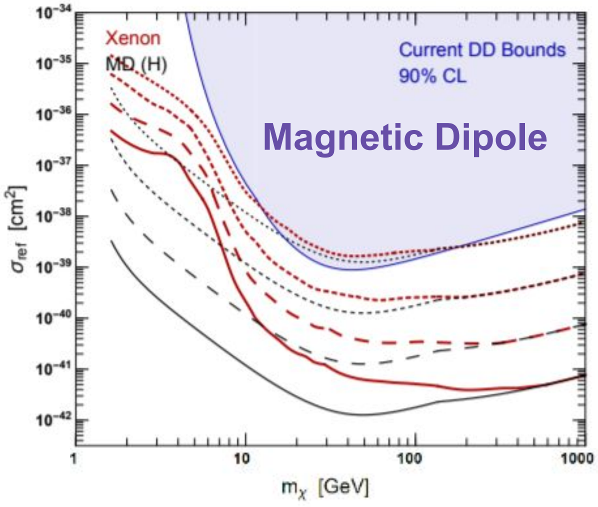


[Gelmini, VT, Witte, 2018]

Neutrino floor

- Results depend on DM interaction
- Can exploit target materials with different properties (e.g. spin, magnetic moment)





[Gelmini, VT, Witte, 2018]

DM detectors as neutrino telescopes

- Neutrinos will be seen in big DM experiments → **"effective neutrino telescopes"**

- Complementarity to dedicated neutrino experiments, which typically rely on Inverse Beta Decay ($\overline{\nu} + p \to e^{+} + n$)
  - enhanced coherent scattering ($\sigma \sim N^2$)
    → bypass IBD kinematic threshold of ~MeV
    → probe all ν's flavors
  - very low detector energy threshold

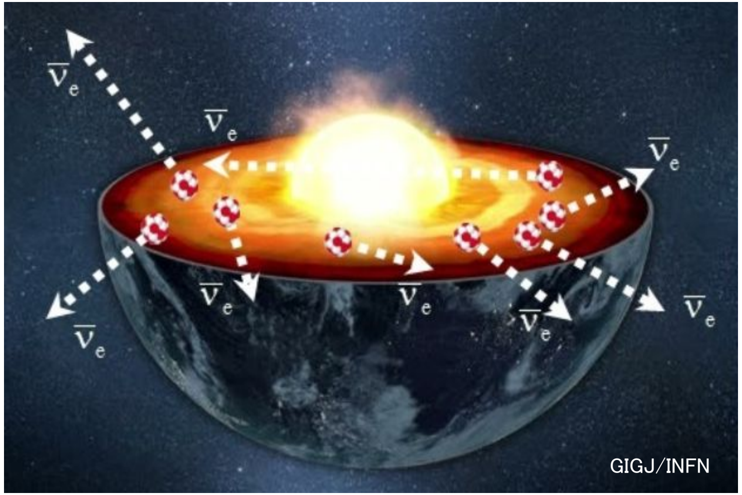
Exploring Earth formation with geoneutrinos

Geo-neutrinos

- Earth emits heat, is the origin primordial (from Earth formation) or radiogenic (nuclear reactions now)?

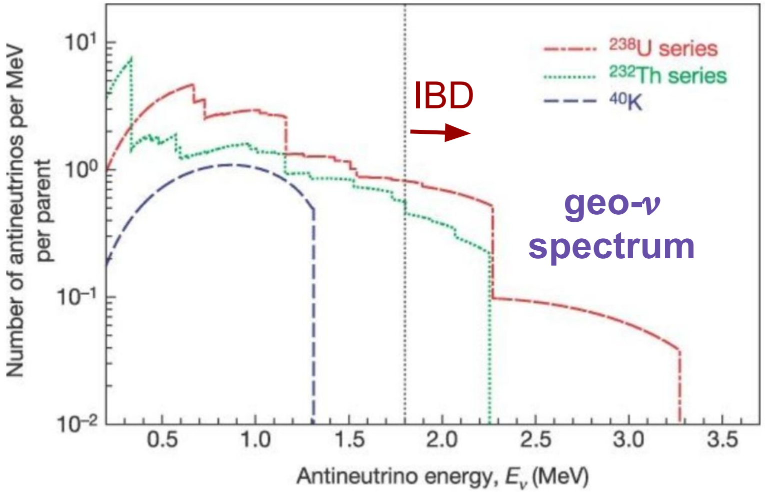
- Nuclear decays (^{238}U, ^{232}Th, ^{40}K) in Earth produce heat + **(geo-)neutrinos**

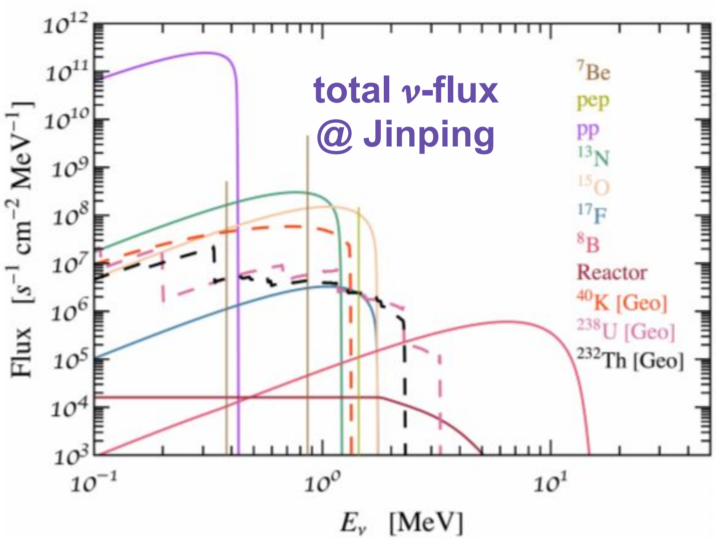
- Geo-neutrinos critical for geology
  - How Earth formed?
  - How Earth's magnetic field generated?



Geo-neutrinos

- First detection (with IBD) by KamLAND, 2005 [Araki+ (KamLAND), *Nature*, 2005] - Inoue

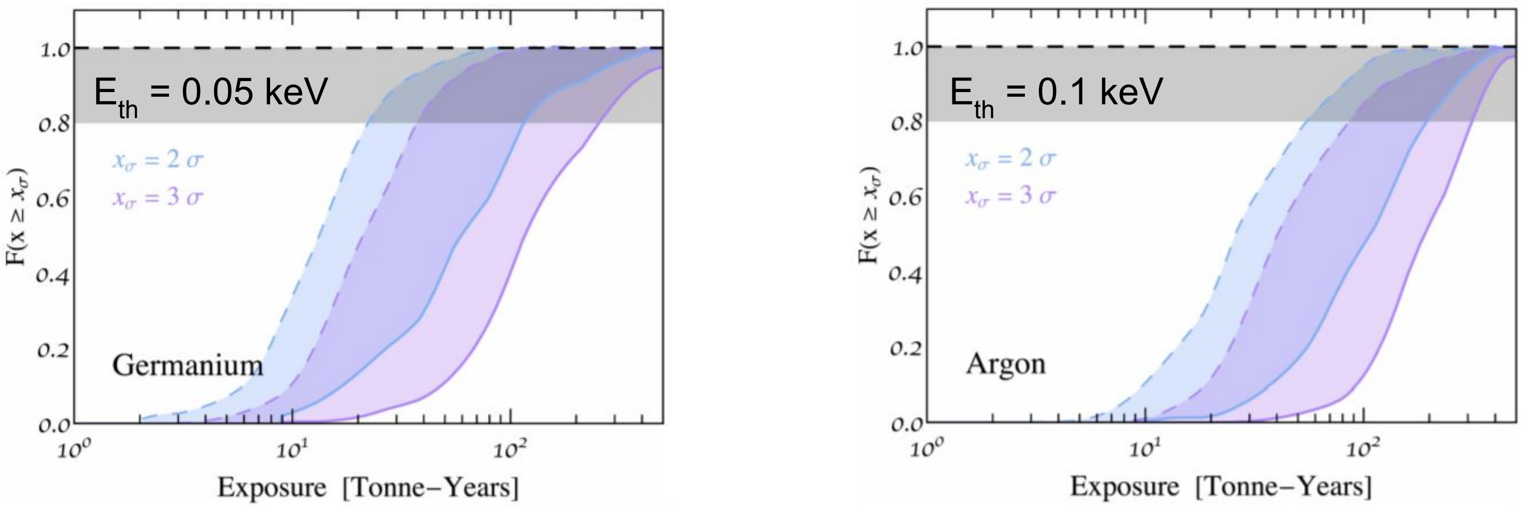




[Gelmini, VT, Witte, 2018]

Geo-neutrinos

- Low thresholds allow geo-ν's to be potentially visible in future DM detectors
- ^{40}K geo-ν fully invisible for IBD → **but possible in DM exp. via coherent scattering!**



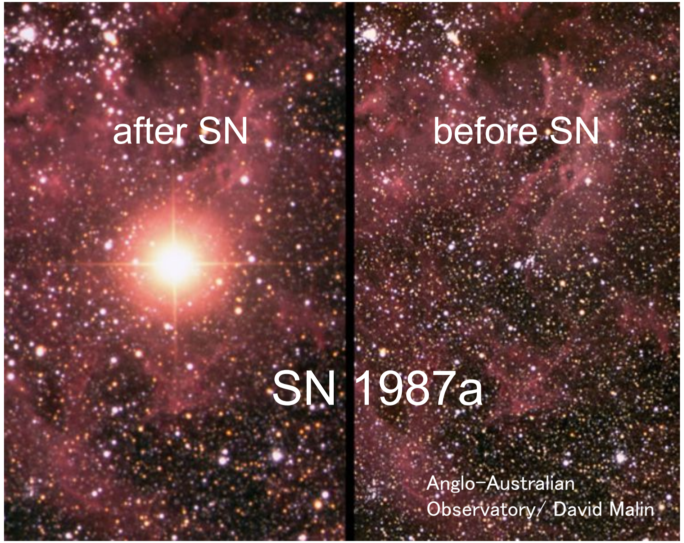
[Gelmini, VT, Witte, 2018]

Forecasting supernova with pre-SN neutrinos

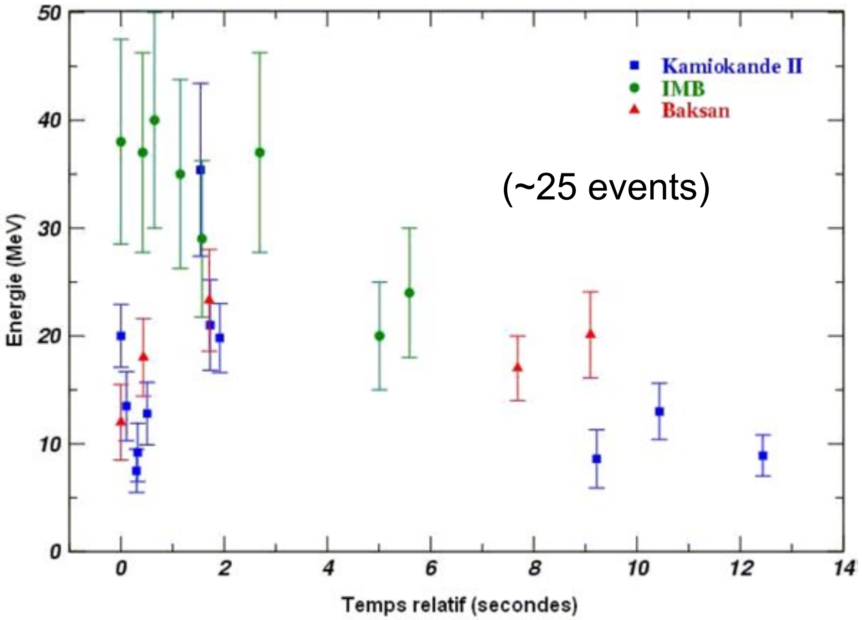
Historic neutrino astronomy breakthrough: SN 1987a

- Core-collapse SN: most energy released as neutrinos → mechanism confirmed by SN1987a

Optical



Neutrinos



- Many unknowns → **hunt for ν's from next Galactic SN (rate ~1/30 yrs) a major target**

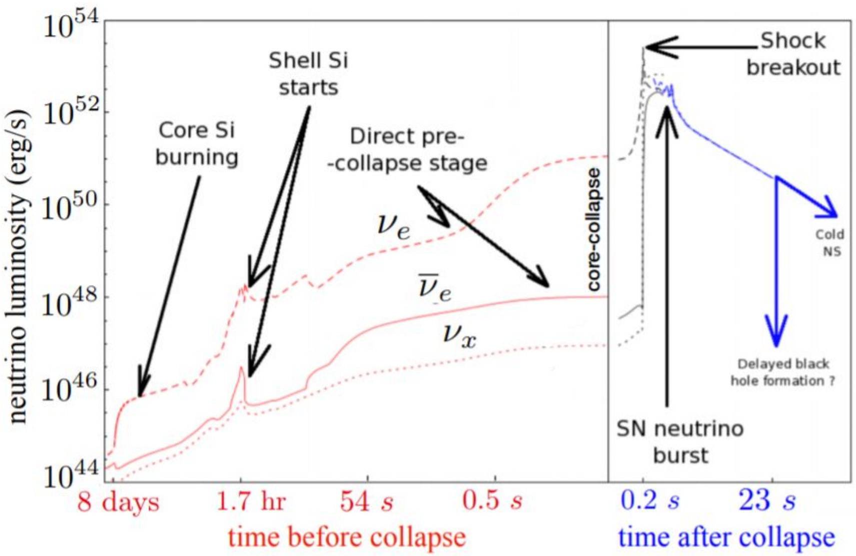
Pre-SN ν's

- Will easily see Galactic SN in large experiments (~10k events in SK) ***...but when?***

→ **pre-SN neutrinos:** probe final star evolution stages, supernova alarm

Super-K with Gadolinium (2020), will see O(100) pre-SN ν's within ~ day before SN explosion @ Betelgeuse (0.2 kpc)

Vagins

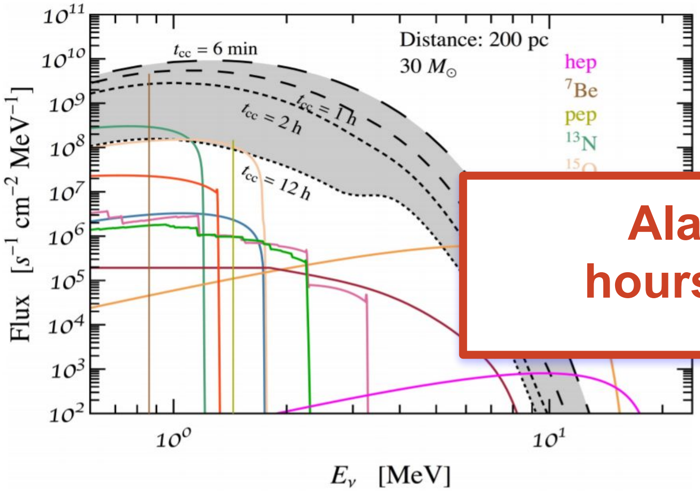


[Odrzywolek+, 2010]

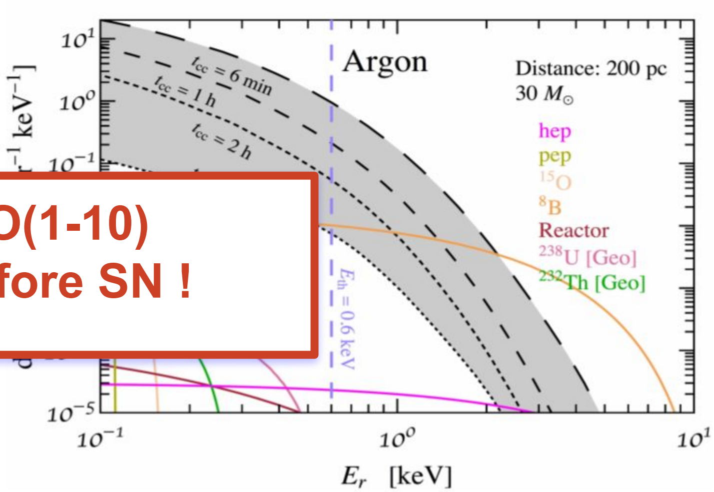
Pre-SN ν's

- Large DM experiments (Ar, Xe) can help → see all flavors, no oscillation effects

pre-SN ν-flux @ Betelgeuse



recoil spectra



Ar (300 t)

Alarm O(1-10) hours before SN !

[Raj, VT, Witte, 2019]

Part II

Large Neutrino Detectors as BSM Physics Laboratories

State-of-the-Art: Super-Kamiokande

2015
Nobel Prize
(ν-oscillations)

- Large water Cherenkov experiment
  - ~25 kton FV, ~20 years of data, ~10-10^4 MeV range

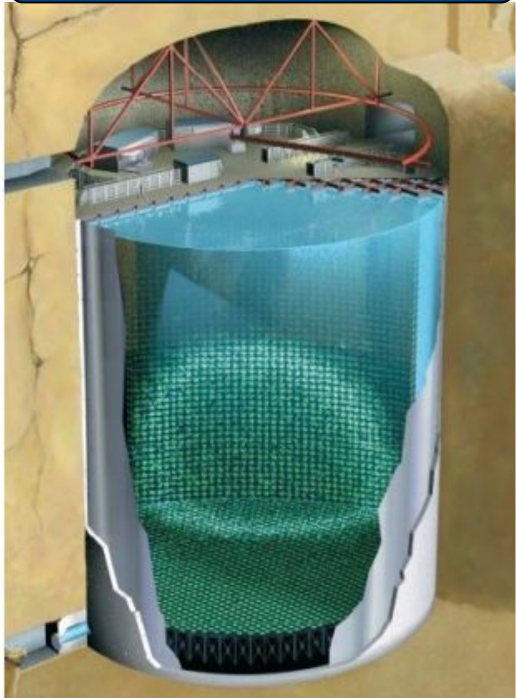
→ **huge success with leadership by U. Tokyo**

- Amazing for many neutrino topics
  - oscillations, supernova, solar-ν, neutrino astronomy....

- Great for physics beyond SM (nucleon decay, DM …)

→ much more BSM physics to explore !

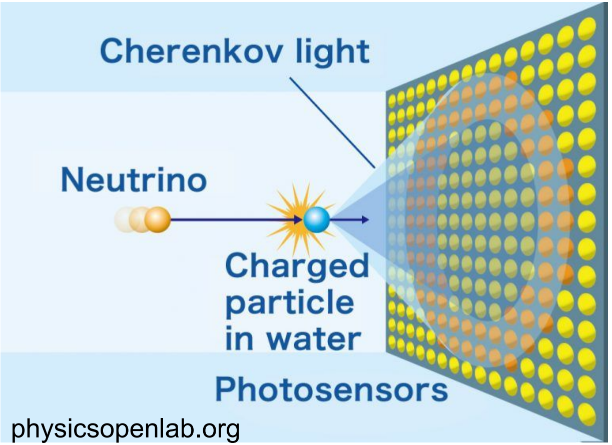
Super-Kamiokande (SK)

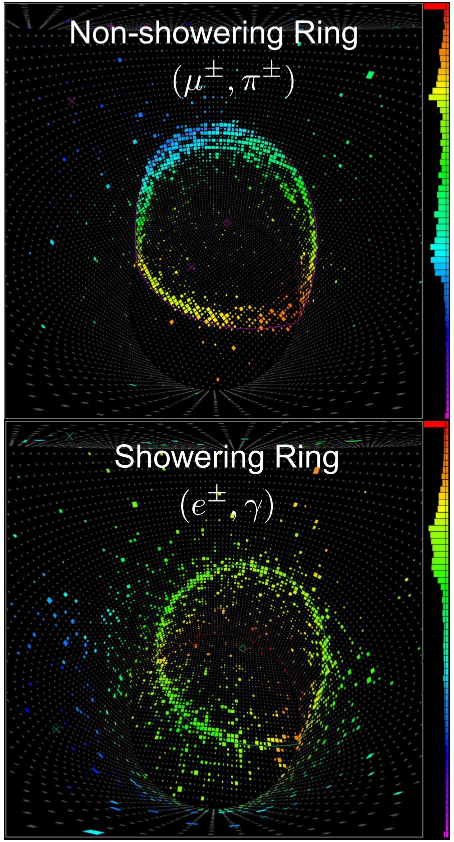


Very general detection technique

Cherenkov Radiation

... just need a not very slow charged particle !





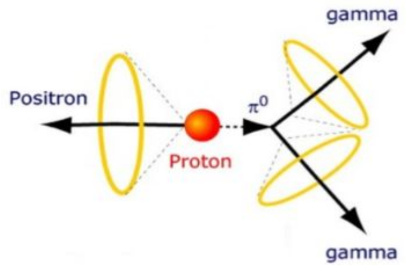
(real data events, 1998)

Testing models with baryon-number violation

Baryon-number violating processes

- Proton decay key prediction of Grand Unified Theories (Murayama, Yanagida, Ibe, Shirai…)
  → probe energies unreachable to accelerators

$$p \to e^+ \pi^0$$

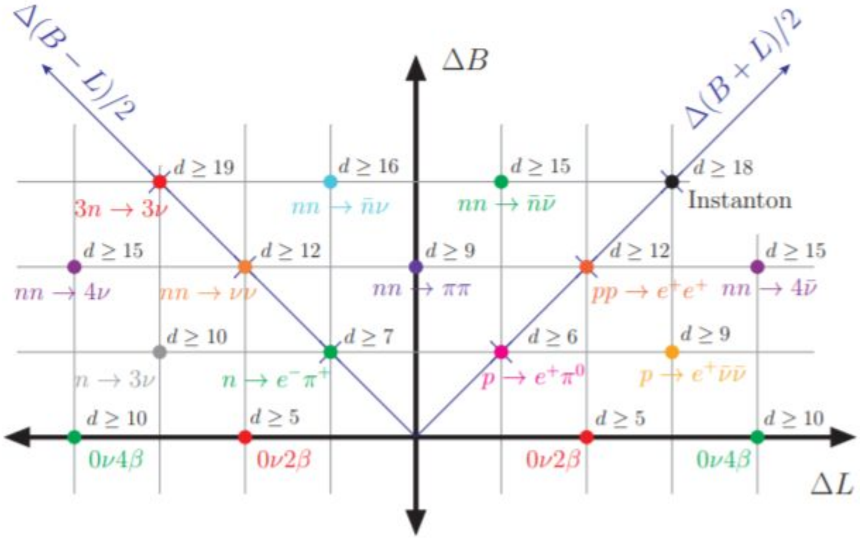


- Many searches performed, already ruled out minimal models
  - lifetime limits ($p \to e^+\pi^0$) pushing $>10^{34}$ yr [Abe+ (SK), 2016]

- Searches mainly focused on simplest 2-body nucleon decays, testing low-dimension effective operators

Baryon-number violating processes

- However, baryon number violation appears in many BSM theories beyond just GUTs
- High-dimension operators can dominate → **many different processes can be important**



[Heeck, VT, 2019]

Studies are far from exhaustive

- For 3-body processes, many never searched in any experiment before (even several 2-body remain...)

first 3-body SK search

→ [Takhistov+ (SK), PRL, 2014]

channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$p \to e^- + e^+ + e^+$	0	793 [62]
$p \to e^- + e^+ + \mu^+$	0	529 [62]
$p \to e^+ + e^+ + \mu^-$	0	529* [62]
$p \to e^- + \mu^+ + \mu^+$	0	6 [61] (359* [62])
$p \to e^+ + \mu^- + \mu^+$	0	359 [62]
$p \to \mu^- + \mu^+ + \mu^+$	0	675 [62]
$p \to e^+ + 2\nu$	0,2	170 [78]
$p \to \mu^+ + 2\nu$	0,2	220 [78]
$p \to e^- + 2\pi^+$	2	30 [59] (82* [62])
$p \to e^- + \pi^+ + \rho^+$	2	
$p \to e^- + K^+ + \pi^+$	2	75 [62]
$p \to e^+ + 2\gamma$	0	100 [79] (793* [62])
$p \to e^+ + \pi^- + \pi^+$	0	82 [62]
$p \to e^+ + \rho^- + \pi^+$	0	
$p \to e^+ + K^- + \pi^+$	0	75* [62]
$p \to e^+ + \pi^- + \rho^+$	0	
$p \to e^+ + \pi^- + K^+$	0	75* [62]
$p \to e^+ + 2\pi^0$	0	147 [62]
$p \to e^+ + \pi^0 + \eta$	0	
$p \to e^+ + \pi^0 + \rho^0$	0	
$p \to e^+ + \pi^0 + \omega$	0	
$p \to e^+ + \pi^0 + K^0$	0	
$p \to \mu^- + 2\pi^+$	2	17 [59] (133* [62])
$p \to \mu^- + K^+ + \pi^+$	2	245 [62]
$p \to \mu^+ + 2\gamma$	0	529* [62]
$p \to \mu^+ + \pi^- + \pi^+$	0	133 [62]
$p \to \mu^+ + K^- + \pi^+$	0	245* [62]
$p \to \mu^+ + \pi^- + K^+$	0	245* [62]
$p \to \mu^+ + 2\pi^0$	0	101 [62]
$p \to \mu^+ + \pi^0 + \eta$	0	
$p \to \mu^+ + \pi^0 + K^0$	0	
$p \to \nu + \pi^+ + \pi^0$	0,2	
$p \to \nu + \pi^+ + \eta$	0,2	
$p \to \nu + \pi^+ + \rho^0$	0,2	
$p \to \nu + \pi^+ + \omega$	0,2	
$p \to \nu + \pi^+ + K^0$	0,2	
$p \to \nu + \rho^+ + \pi^0$	0,2	
$p \to \nu + K^+ + \pi^0$	0,2	

channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [62]
$n \to \nu + e^- + \mu^+$	0,2	83 [62]
$n \to \nu + e^+ + \mu^-$	0,2	83* [62]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [62]
$n \to 3\nu$	0,2,4	0.58 [80]
$n \to e^- + \pi^+ + \pi^0$	2	29 [59] (52* [62])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [62]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [79]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	34 [59] (74* [62])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [62]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	257* [62]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

[Heeck, VT, 2019]

- Processes with $\Delta B > 1$ almost completely unexplored, even simplest channels

$nn \to e^+ + e^-$	2	4200 [69]
$nn \to e^+ + \mu^-$	2	4400 [69]
$nn \to \mu^+ + e^-$	2	4400 [69]
$nn \to \mu^+ + \mu^-$	2	4400 [69]
$nn \to e^+ + \tau^-$	2	
$nn \to \tau^+ + e^-$	2	
$nn \to 2\nu$	0,2,4	1.4 [80]
$nn \to 2\gamma$	2	4100 [69]
$nn \to \gamma + \pi^0$	2	
$nn \to \gamma + \eta$	2	
$nn \to \gamma + \rho^0$	2	
$nn \to \gamma + \omega$	2	
$nn \to \gamma + \eta'$	2	
$nn \to \gamma + K^0$	2	
$nn \to \gamma + K^{*,0}$	2	
$nn \to \gamma + D^0$	2	
$nn \to \gamma + \phi$	2	
$nn \to \pi^- + \pi^+$	2	0.7 [59] (72* [111])
$nn \to \pi^+ + \rho^-$	2	
$nn \to K^- + \pi^+$	2	
$nn \to K^{*,-} + \pi^+$	2	
$nn \to \pi^- + \rho^+$	2	
$nn \to K^+ + \pi^-$	2	
$nn \to K^{*,+} + \pi^-$	2	
$nn \to 2\pi^0$	2	404 [111]
$nn \to \eta + \pi^0$	2	
$nn \to \pi^0 + \rho^0$	2	
$nn \to \pi^0 + \omega$	2	
$nn \to \eta' + \pi^0$	2	
$nn \to K^0 + \pi^0$	2	
$nn \to K^{*,0} + \pi^0$	2	

channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170* [112]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	

channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$pn \to e^+ + \nu$	0,2	260 [27]
$pn \to \mu^+ + \nu$	0,2	200 [27]
$pn \to \tau^+ + \nu$	0,2	29 [27]
$pn \to \gamma + \pi^+$	2	
$pn \to \gamma + \rho^+$	2	
$pn \to \gamma + K^+$	2	
$pn \to \gamma + K^{*,+}$	2	
$pn \to \gamma + D^+$	2	
$pn \to \pi^+ + \pi^0$	2	170 [111]
$pn \to \eta + \pi^+$	2	
$pn \to \pi^+ + \rho^0$	2	
$pn \to \pi^+ + \omega$	2	
$pn \to \eta' + \pi^+$	2	
$pn \to K^0 + \pi^+$	2	
$pn \to K^{*,0} + \pi^+$	2	
$pn \to \pi^+ + \phi$	2	
$pn \to \pi^0 + \rho^+$	2	
$pn \to K^+ + \pi^0$	2	
$pn \to K^{*,+} + \pi^0$	2	
$pn \to \eta + \rho^+$	2	
$pn \to \eta + K^+$	2	
$pn \to \eta + K^{*,+}$	2	
$pn \to \rho^+ + \rho^0$	2	
$pn \to K^+ + \rho^0$	2	
$pn \to K^{*,+} + \rho^0$	2	
$pn \to \rho^+ + \omega$	2	
$pn \to \eta' + \rho^+$	2	
$pn \to K^0 + \rho^+$	2	
$pn \to K^{*,0} + \rho^+$	2	
$pn \to \rho^+ + \phi$	2	
$pn \to K^+ + \omega$	2	
$pn \to K^{*,+} + \omega$	2	
$pn \to \eta' + K^+$	2	
$pn \to \eta' + K^{*,+}$	2	
$pn \to K^+ + K^0$	2	
$pn \to K^+ + K^{*,0}$	2	
$pn \to K^+ + \phi$	2	
$pn \to K^{*,+} + K^0$	2	
$pn \to K^{*,+} + K^{*,0}$	2	

[Heeck, VT, 2019]

Inclusive and invisible searches

- Very many processes still to explore...

- Best limits obtained by exclusive (final state) searches
  → in future going to multi-body modes it will become impractical to search exhaustively

Inclusive searches (e.g. p → e^{+}+ *anything*) and **invisible searches** (e.g. neutron disappearance, n → *anything*) can provide model-independent handles on many processes simultaneously

[Heeck, VT, 2019]

Hunting for fractionally charged particles

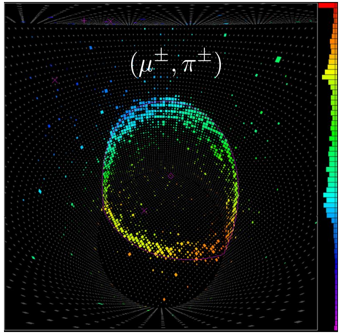
Fractionally charged particles

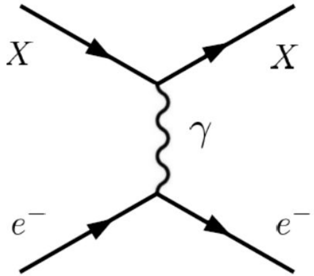
- Millicharge particles
  - arise in SM extensions with extra U(1)
  - test charge quantization
  - can contribute to DM
  - can be accelerated in astro-sources like regular cosmic rays

- Depending in charge, can see in Super-K as:

"faint muon"

($q \gtrsim 10^{-2}$)





electron scattering

($q \lesssim 10^{-2}$)

[Hu, Kusenko, VT, 2016]

Exploring cosmology with sterile neutrinos

Sterile neutrinos

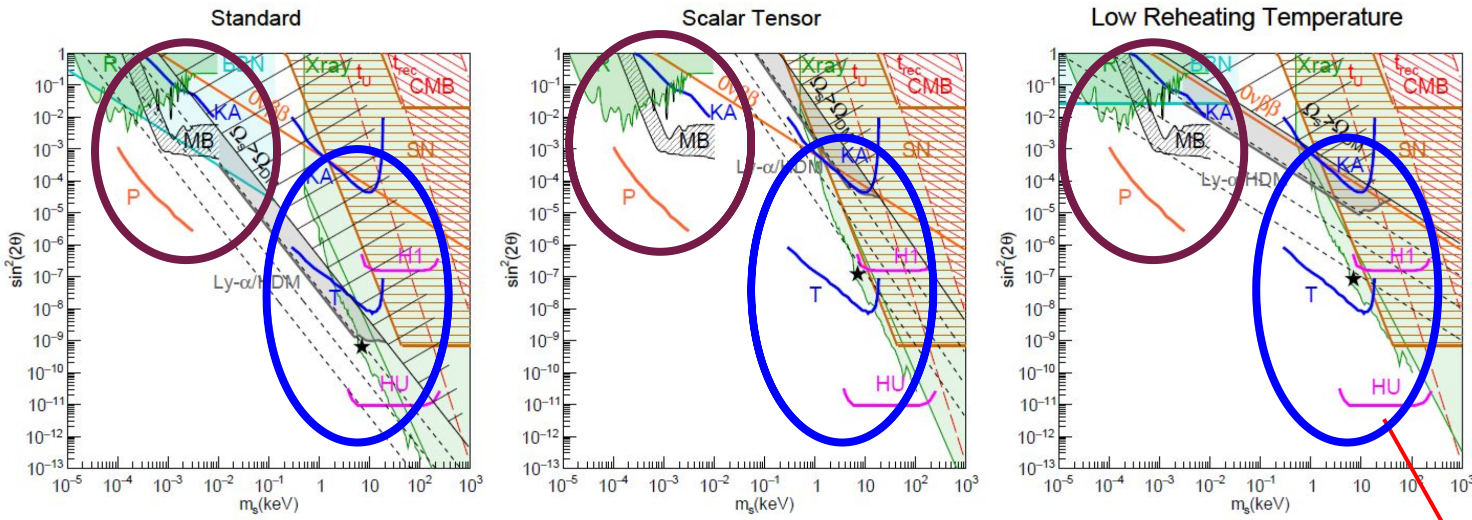
- In SM 3 massless weakly-interacting (active) neutrinos
  → oscillations imply mass, typical explanations add new **“sterile”** neutrinos
  (Murayama, Yanagida, Kusenko, Petcov...)

- Laboratory anomalies possibly hint at O(eV) sterile (e.g. MiniBooNE)

- O(keV) sterile could play role in DM and pulsar kicks [Fuller, Kusenko+, 2003]

Probing cosmology with sterile neutrinos

- In motivated models (e.g. moduli, extra-dim) cosmology can be different than usually assumed
  → steriles produced in early Universe are sensitive probes



Dodelson Widrow
(mix w/ ν_e)

→ can test 3.5 keV X-ray signal steriles in a lab
→ eV region can be unconstrained, cosmology bounds not robust

HUNTER @ UCLA

[Gelmini, Lu, VT, 2019 (short); Gelmini, Lu, VT, 2019 (long) x 2]

Heavy sterile neutrinos can also be interesting...

Hubble constant discrepancy

- **H0 -** parametrizes Universe expansion rate

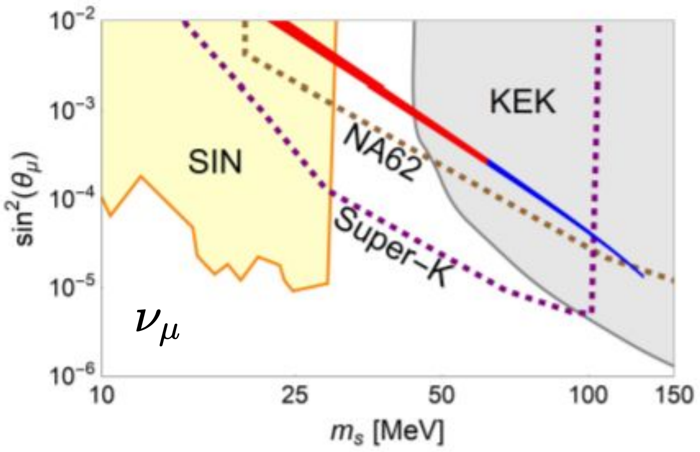
- H0 measurements inconsistent @ 4-sigma
  - local (independent of cosmology) → H0 = 74.03 +/- 1.42 km/s/Mpc
  - CMB → H0 = 67.66 +/- 0.42 km/s/Mpc

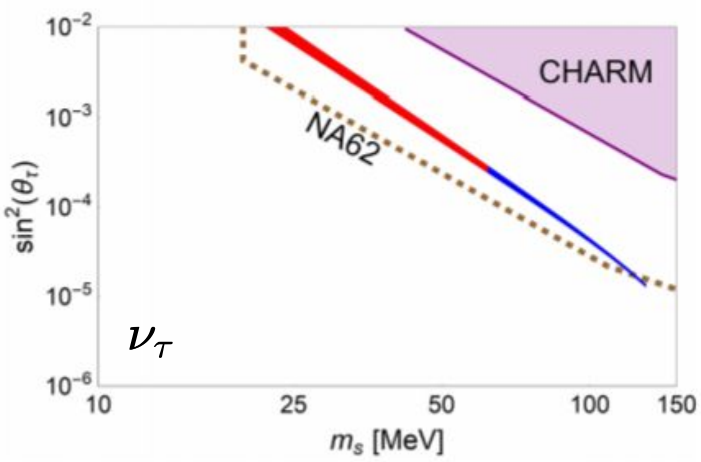
- Systematics don't appear helpful, many BSM proposals

Sterile neutrinos rescue Hubble

- H depends on energy densities and N_{eff} (effective # of relativistic neutrinos)
- Extra radiation at CMB resolves H0 discrepancy (change SM N_{eff} ~ 3 by +0.4)

→ naturally achieved by heavy steriles decaying to SM particles before BBN





→ can test in Lab !

[Gelmini, Kusenko, VT, 2019]

Sterile neutrinos rescue Hubble

- New Super-K sterile search (decay $\nu_h \rightarrow e^+e^-\nu$ inside SK, first proposal [Kusenko+, 2004])
  → different from standard sterile oscillation analysis of atmospheric data

- **Super-K can shed light on important issues of cosmology**

**** Decaying steriles can lead to rich phenomenology with BBN*
→ exploring further with help of BBN experts (Kawasaki)

Let's build Hyper-K !

Conclusions

- Advances in DM searches and neutrino physics call for large underground experiments

- Very general instruments, with promising physics programs beyond main target
  - DM detectors as “neutrino telescopes”
  - Neutrino detectors as “BSM laboratories”

important to continue exploring their capabilities to fully exploit potential