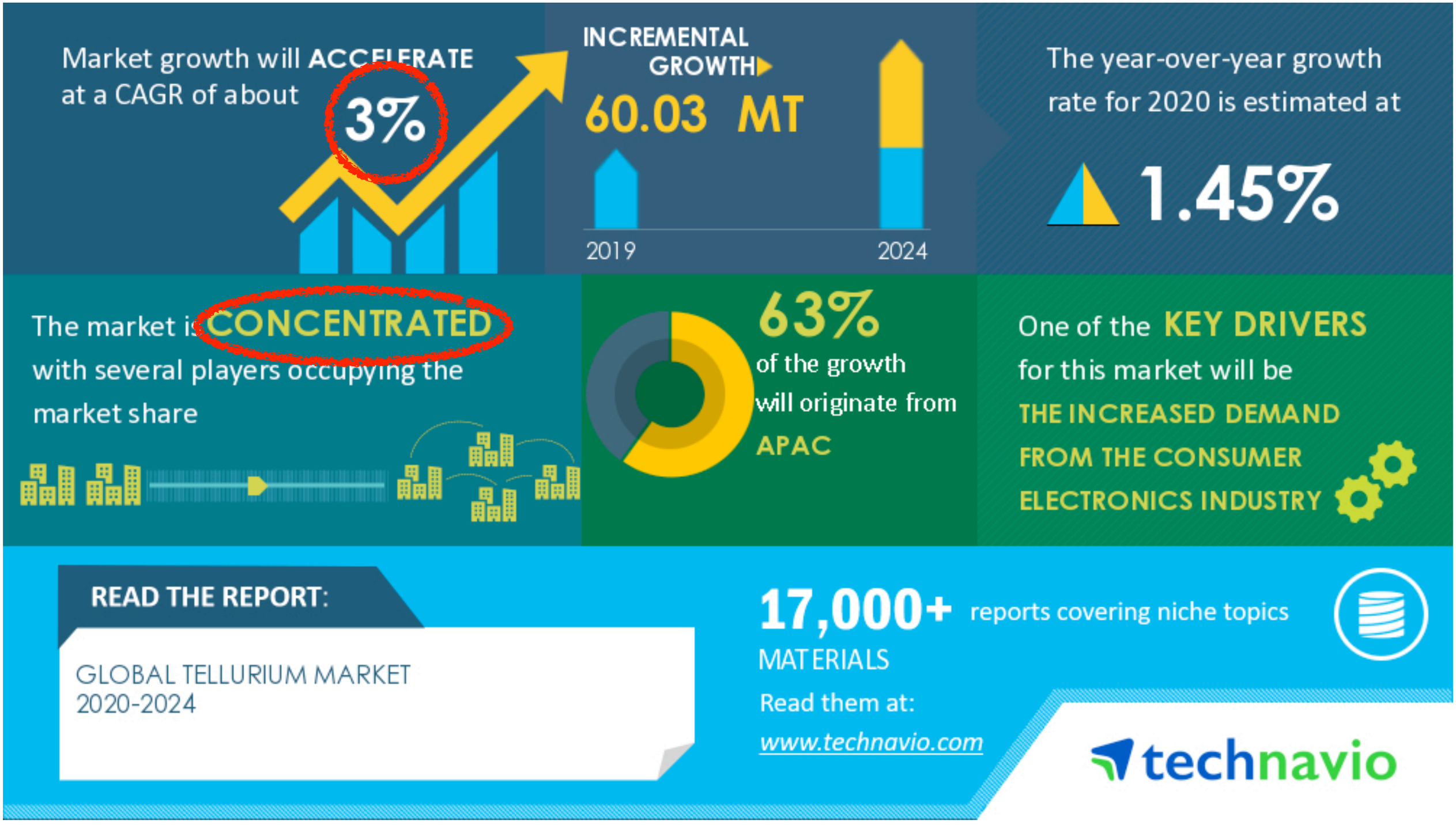
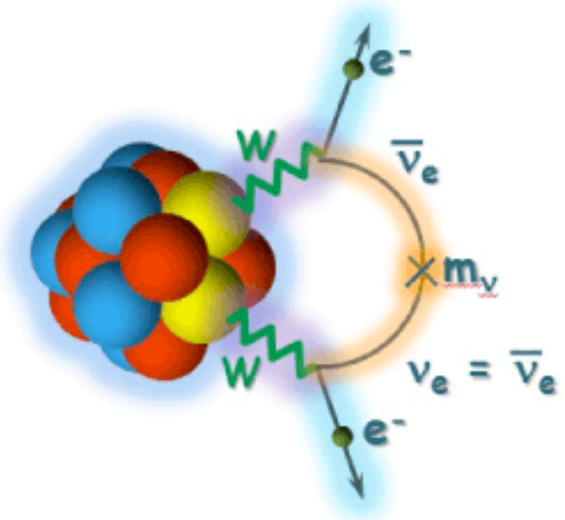
# TELLURIUM FUTURES




## Steve Biller, Oxford University

*("I don't just sell tellurium, I'm an investor!")*

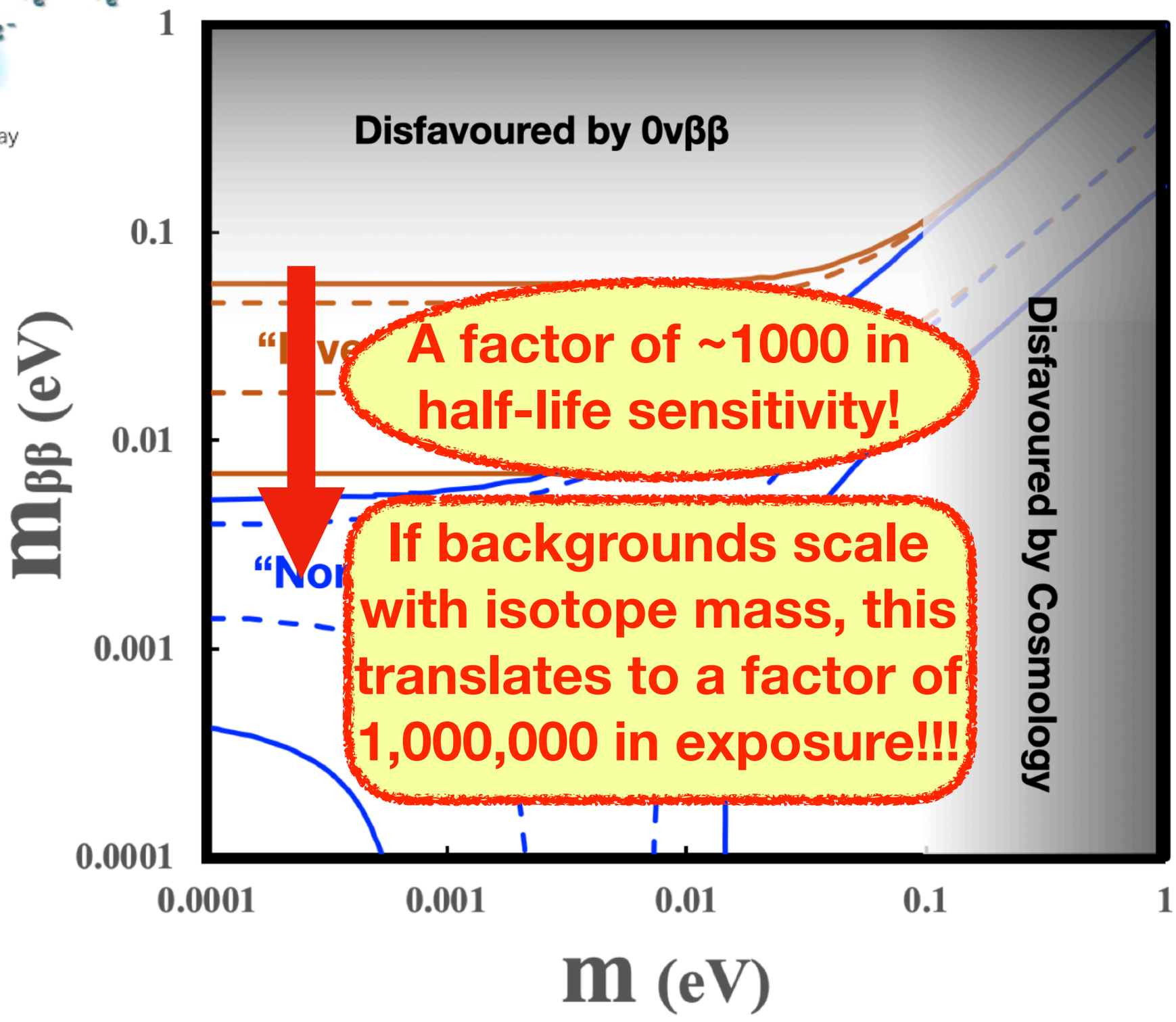



Neutrinoless
double beta decay

# The origin of neutrino mass:

clear evidence for BSM physics, one of the highest priorities in PP, and a significant experimental challenge

- Majorana nature of neutrinos
- Absolute neutrino mass scale
- Lepton number violation
- Potential bridge for GUT
- Crucial for most models of leptogenesis




**There is currently no known practical way to do this**

**One of the greatest challenges in experimental particle physics**

## Two Scenarios (we're all in this together!):

# I. Everybody Wins!

Neutrinos are Majorana
and in the IH mass region

?

Once seen, focus will turn to anyone with the potential to achieve detection sensitivity, especially with different isotopes; not only for verification, but also to try to untangle details of mechanism. (It's a party! Champagne all around!)

# II. Everybody Loses

Neutrinos are not Majorana
or are in the NH mass region

No one will see anything, even with upgrades (dog food all around!)

Focus will turn to techniques with some potential for a practical NH experiment
(>3σ at <5meV assuming average NME values)
(lose many techniques on practical grounds of isotope affordability/availability)

**The point of tellurium**

Cost of Te ~ $40/kg, $^{130}$Te fraction = 34.5%
=> raw isotope cost ~ $116k/tonne

current loading tech is ~$1-2M/tonne

**a significant figure of merit!**

$^{76}$Ge: ~80M/tonne
$^{136}$Xe: ~20M/tonne

Liquid scintillator: very clean, inexpensive, highly scalable

Looks like one of the very few possible contenders, and one with a potentially broad physics programme (may be required for "fundability" of a ~$1b experiment still with no guarantee of discovering 0νββ)

The basic target numbers for Te-loading to start looking like a serious NH experiment are: ~10% $^{nat}$Te loading in ~10kT fid volume with ~1000 hits/MeV

Not here yet, but significant progress on several development fronts…

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Note: ALL potential approaches require significant R&D and we don't know which, if any, will actually result in a practical & fundable experiment

Smart strategy: hedge your bets by developing all potential approaches!!

SNO+

*Goal: Development of an economical and highly scalable technology to sensitively test the inverted neutrino mass hierarchy region… and beyond!*

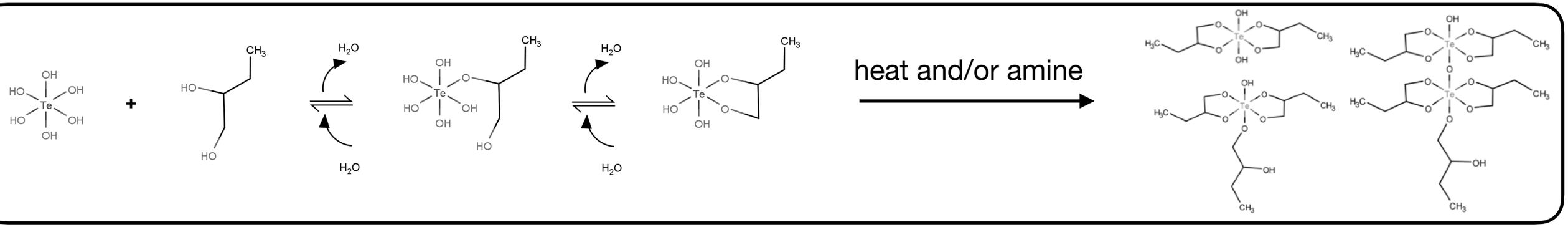
$0\nu\beta\beta$

- **Reactor neutrinos**
- **Geo anti-neutrinos**
- **Low energy solar neutrinos**
- **Supernova neutrinos**
- **Inv. modes of nucleon decay**

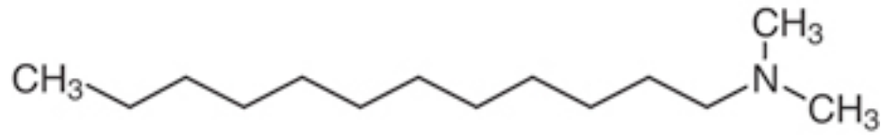
**Now a fully operational liquid scintillation detector!**

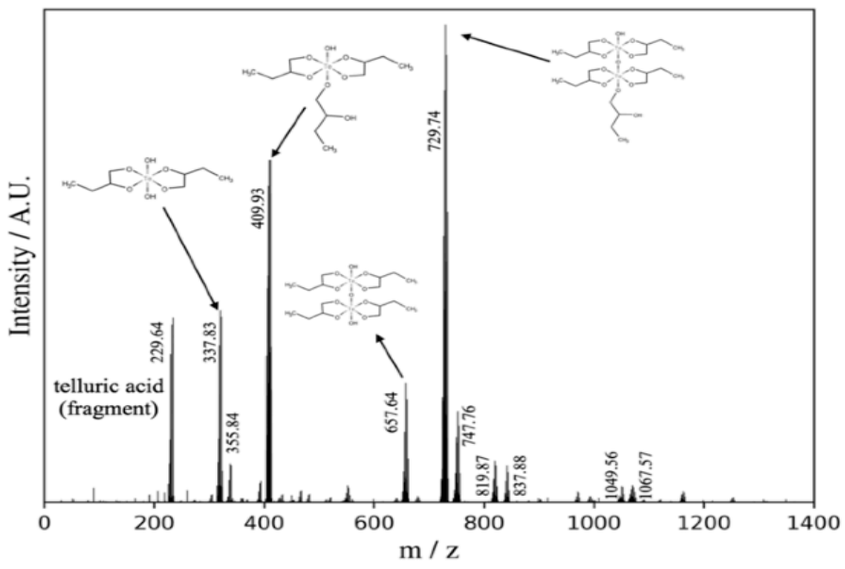
**$^{130}$Te Loading scheduled for next year**

# Te Loading in Liquid Scintillator

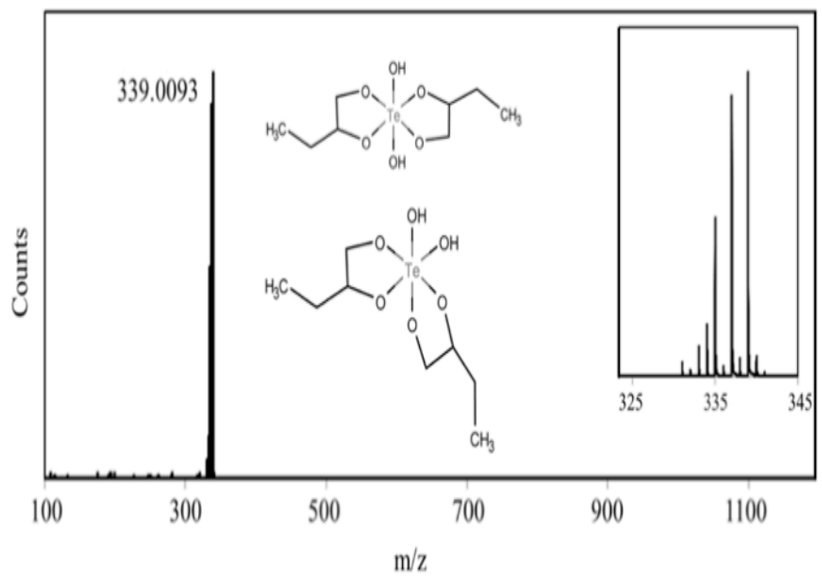



Dimethyldodecylamine (DDA) used as a solubilising/stabilisation agent






pure heated solubilisation

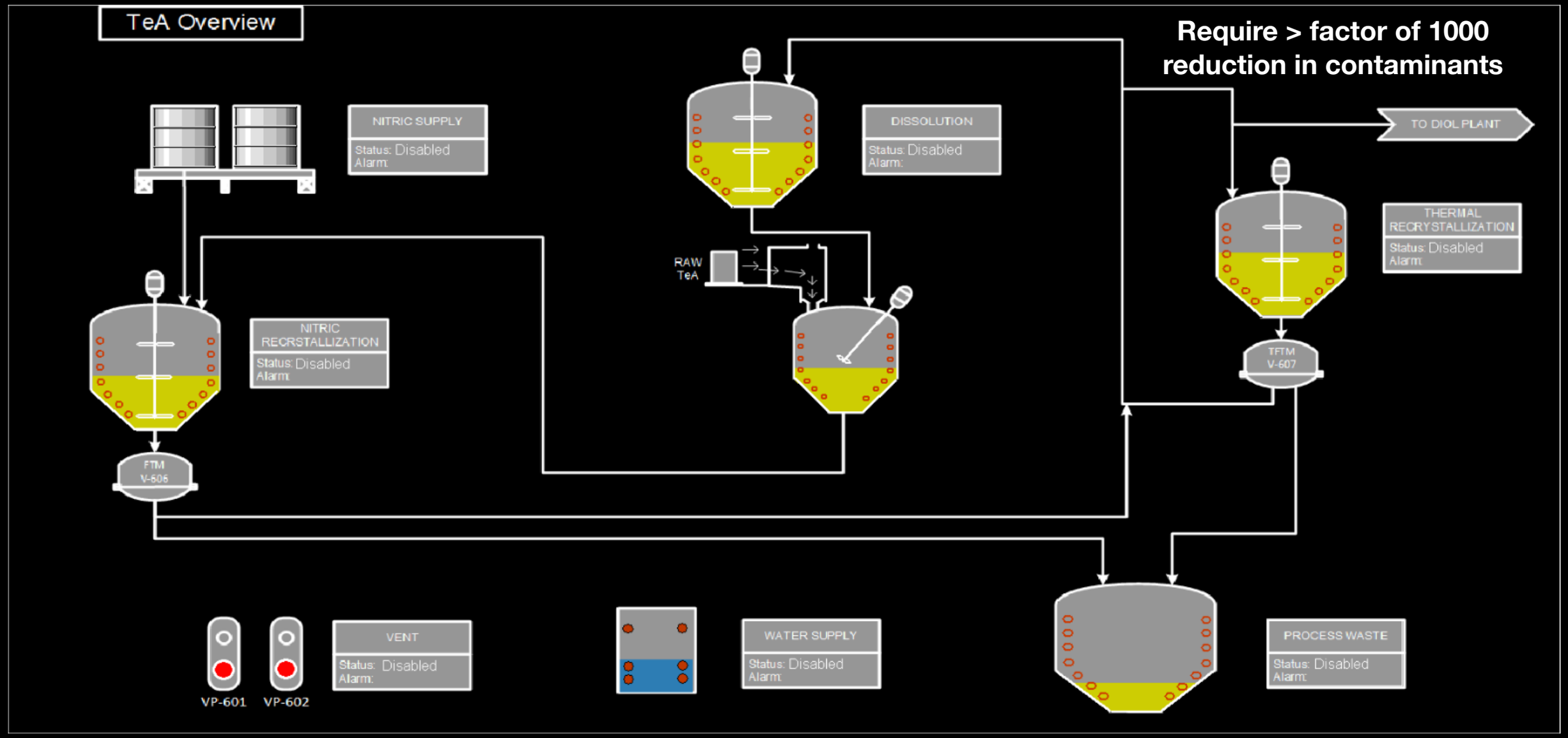


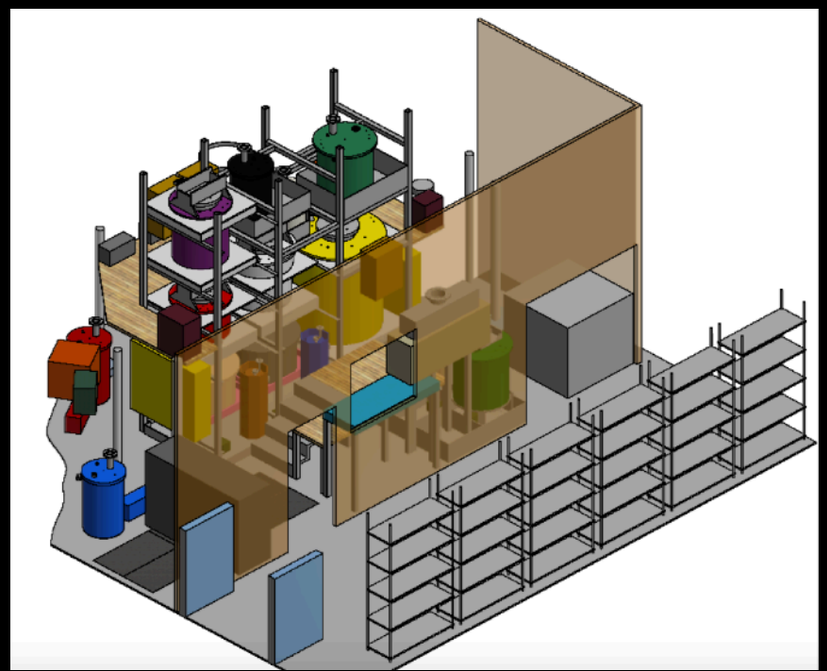

pure DDA solubilisation

miscible with LAB

Can tweak mix of forms depending on when DDA is introduced

# Telluric Acid Purification



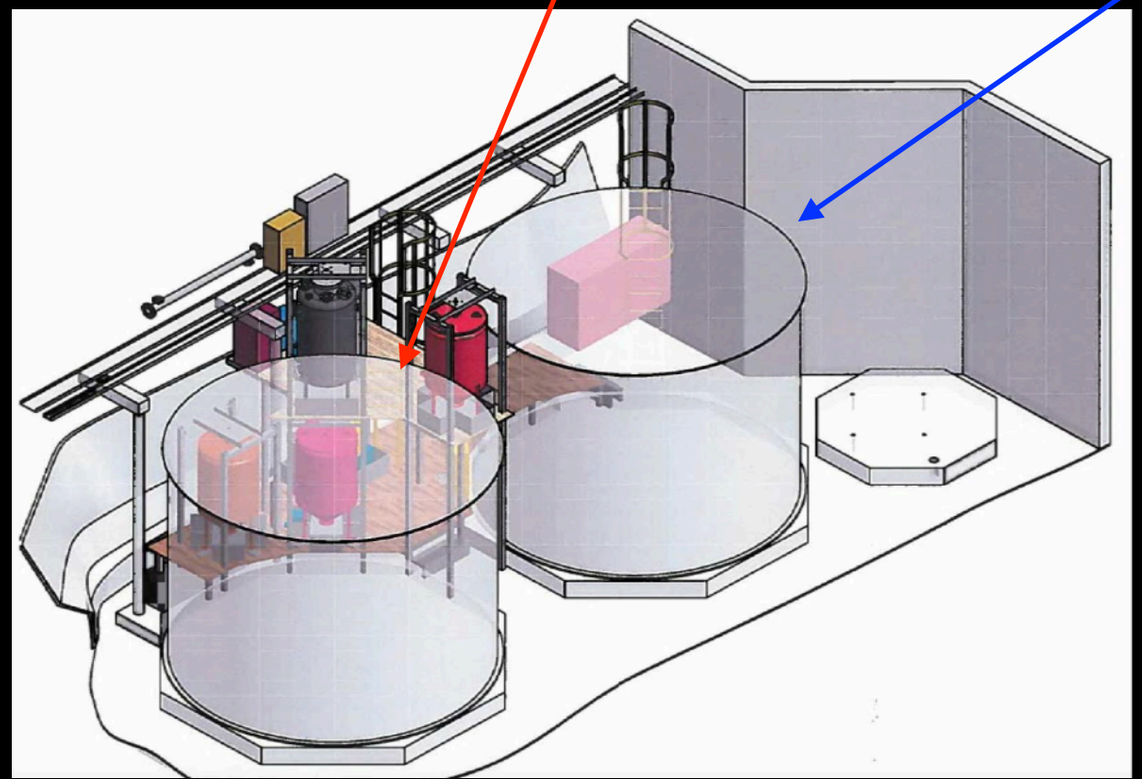
- TeA dissolved in UPW
- 2 nitric acid-induced recrystallisations (pur factor ~100 per pass)
- Thermal recrystallisation to remove nitric
- Redissolve in UPW

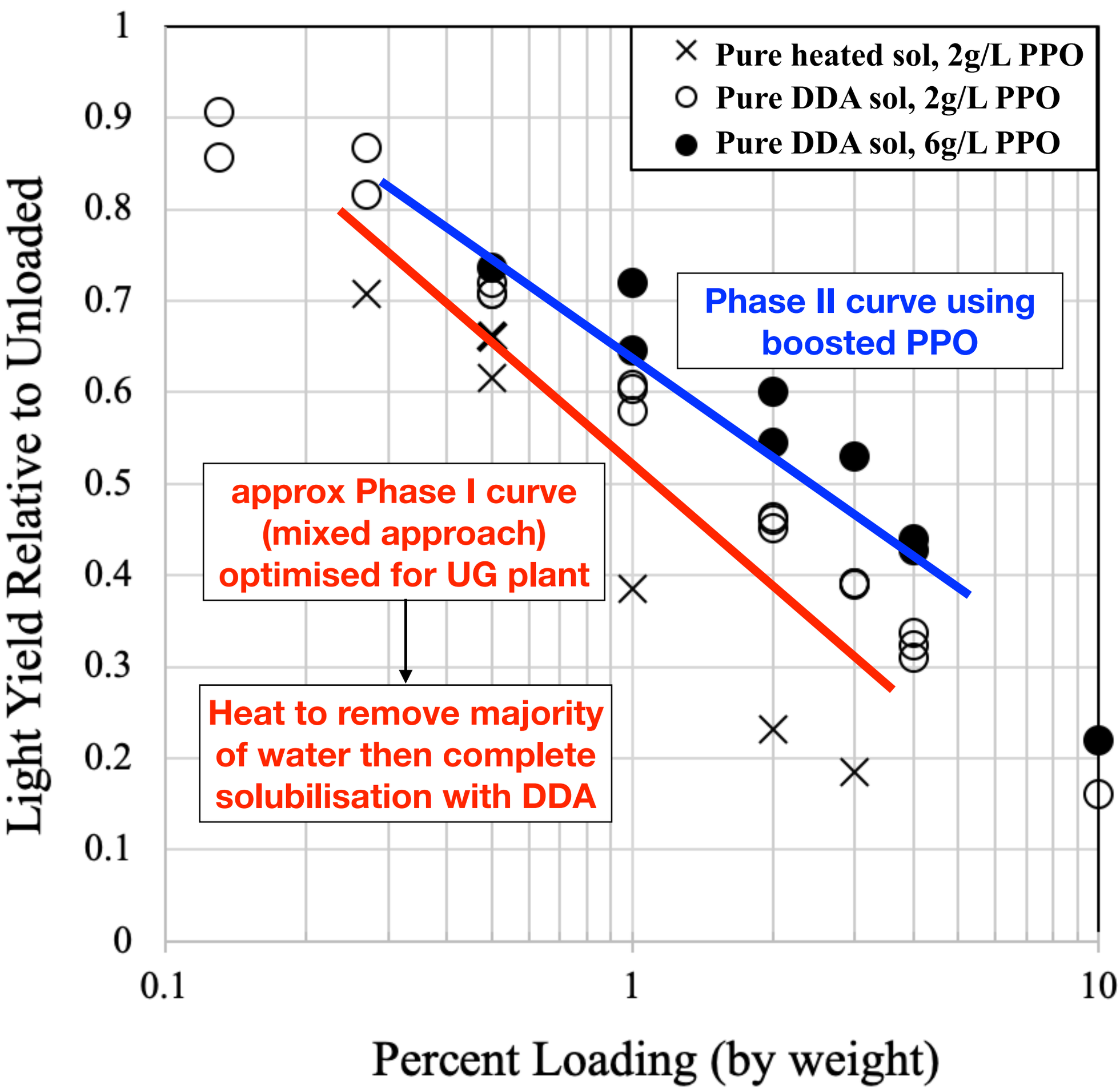
Ultimately limited by nitric and UPW wash

# TeBD Synthesis Plant

Mixture of TeA in water and distilled butanediol is heated while water is flash-evaporated in the synthesis tank

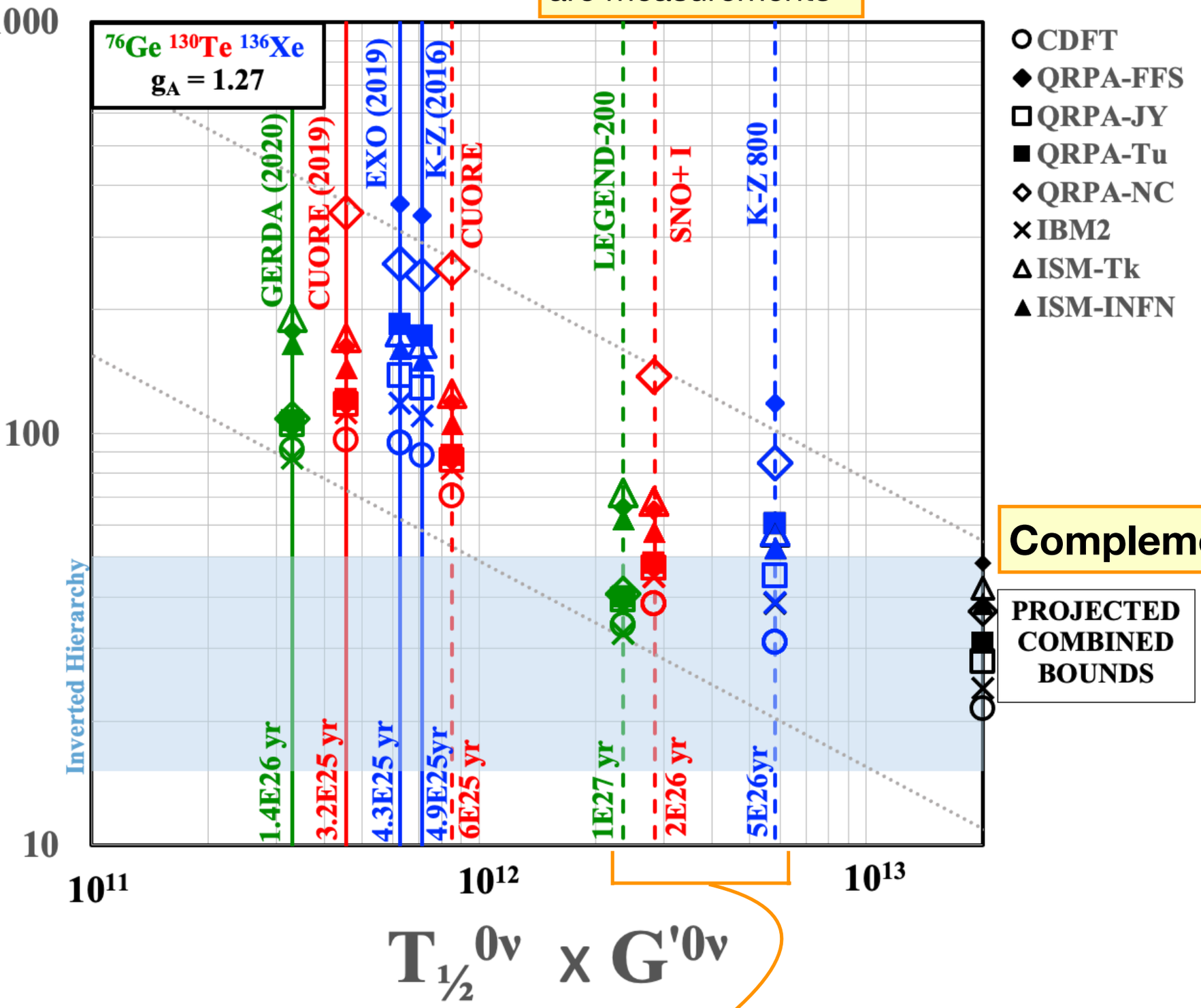
Transferred to mixing tank near solubility point to combine with LAB and 0.5mol DDA to complete solubilisation





Pure heated sol, 2g/L PPO
Pure DDA sol, 2g/L PPO
Pure DDA sol, 6g/L PPO
Phase II curve using boosted PPO
approx Phase I curve (mixed approach) optimised for UG plant
Heat to remove majority of water then complete solubilisation with DDA
Light Yield Relative to Unloaded
Percent Loading (by weight)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10

arXiv: 2103_06036

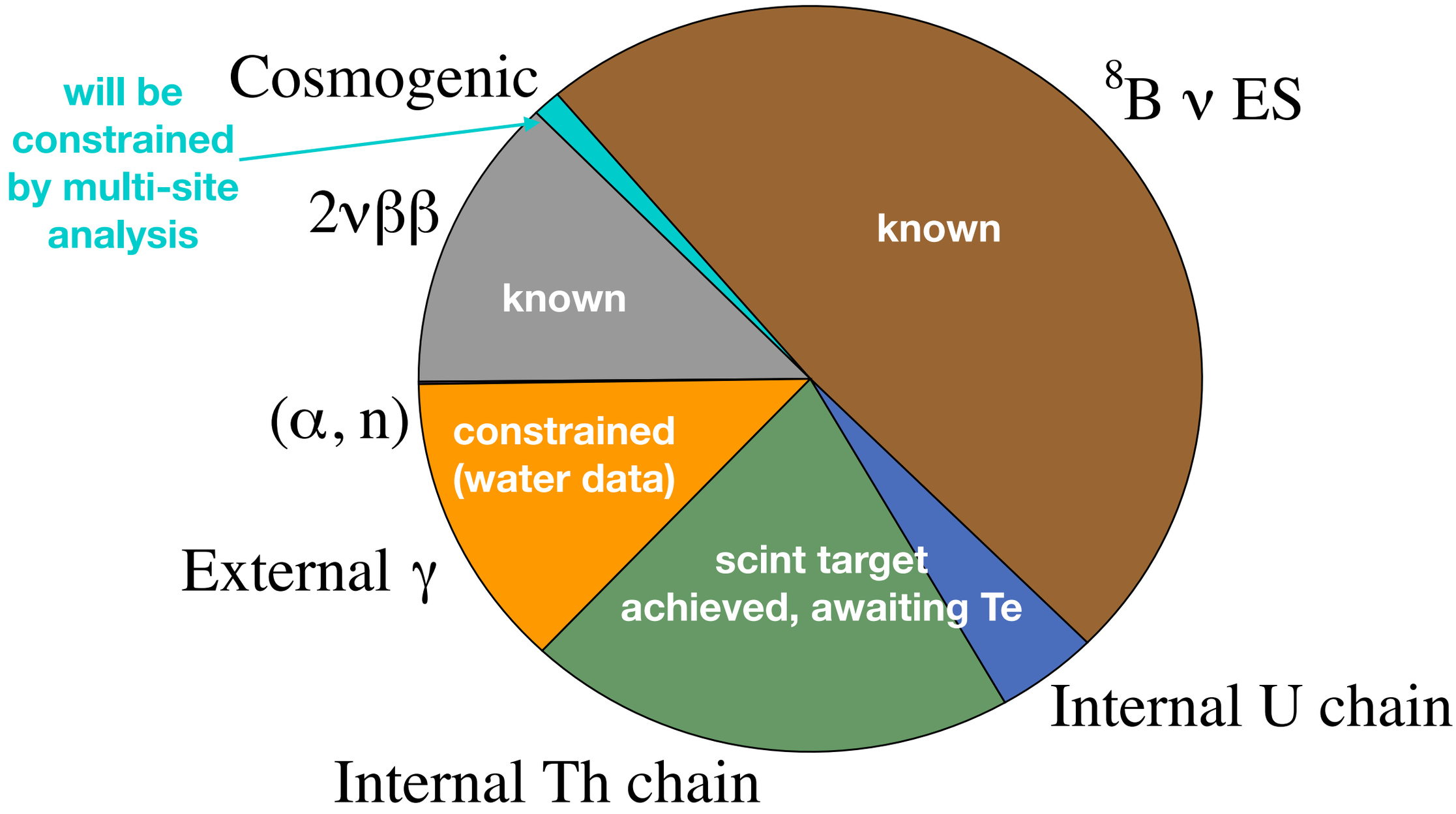
Note: none of these are measurements




Complementarity!

For each of these cases, there are mainstream NMEs that would make it the most sensitive to Majorana mass (and, almost certainly, none of these models are correct!)

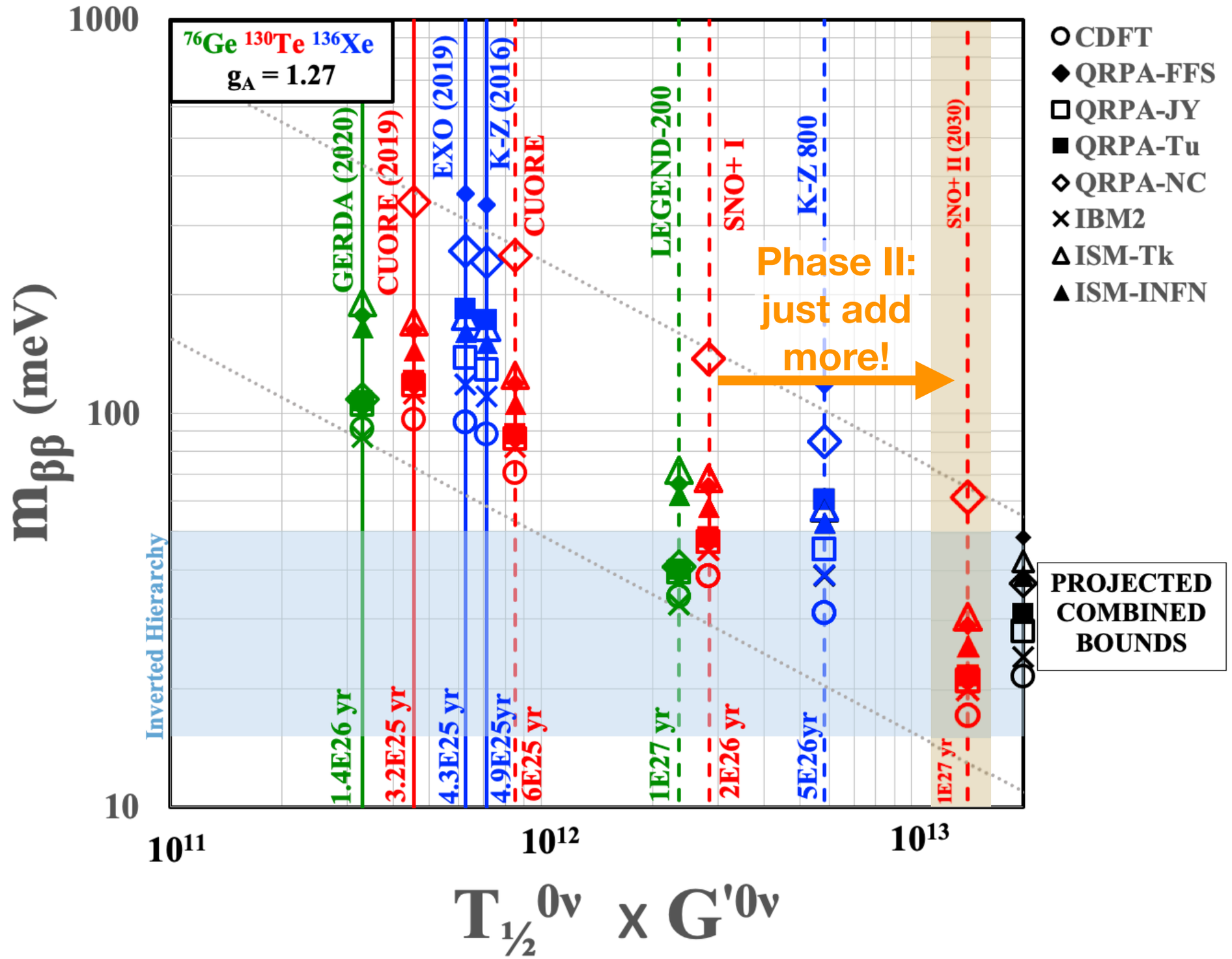
# Phase I RoI Targets (9.5 cts/yr)




**Te backgrounds do not dominate**

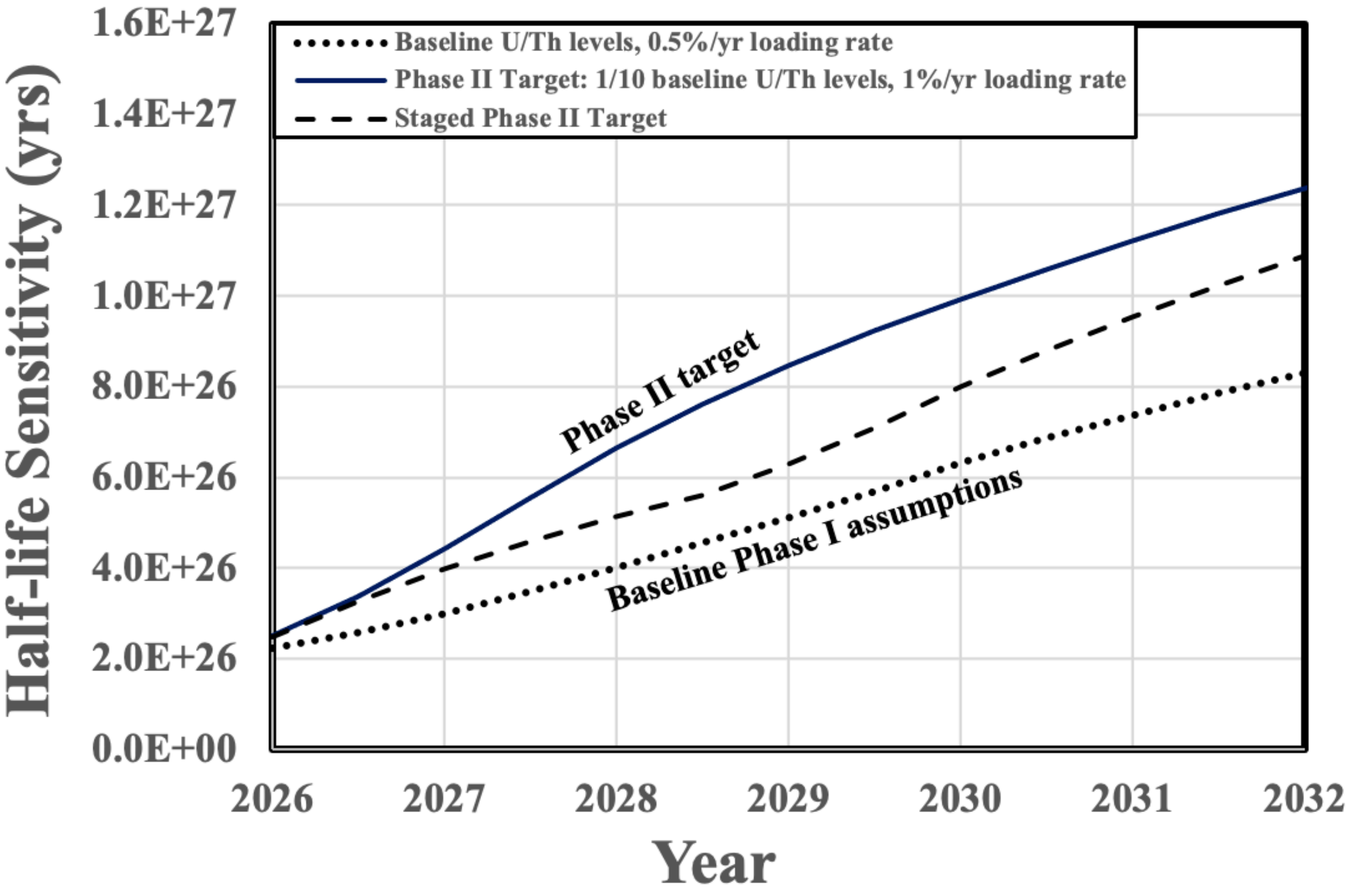
**Can increase loading with only modest change in background levels**

**(sensitivity improvement is nearly linear)**


1000
100
10
$m_{\beta\beta}$ (meV)
$^{76}$Ge $^{130}$Te $^{136}$Xe
$g_A = 1.27$
GERDA (2020)
CUORE (2019)
EXO (2019)
K-Z (2016)
CUORE
LEGEND-200
SNO+ I
K-Z 800
SNO+ II (2030)
Phase II:
just add
more!
Inverted Hierarchy
1.4E26 yr
3.2E25 yr
4.3E25 yr
4.9E25yr
6E25 yr
1E27 yr
2E26 yr
5E26yr
1E27 yr
CDFT
QRPA-FFS
QRPA-JY
QRPA-Tu
QRPA-NC
IBM2
ISM-Tk
ISM-INFN
PROJECTED
COMBINED
BOUNDS
$10^{11}$
$10^{12}$
$10^{13}$
$T_{1/2}^{0\nu} \times G'^{0\nu}$

# SNO+ Phase II

- No changes to UG systems
- No changes to loading method
- Increase PPO to ~6g/L
- Adiabatically increase Te loading towards ~3%
  (most of the gain comes from the first 1.5% addition)
- Improvement rate depends on Te U/Th levels
  (project $10^{-15}$-$10^{-16}$ g/g)
- Loading rate depends on staging and system throughput (project 0.5% per 6-9 months)
- Estimated total cost for 3% loading is ~$17M CAD, but can be easily staged over several years




3% loading would correspond to 24 tonnes of Te, or 8 tonnes of isotope, and we then “throw away” ~70% of this with fiducial cuts in our detector because it is actually still cost effective! -> Rehearsal for NH experiment

**This is all part of a larger development programme:**

**SNO+ Phase I** → **SNO+ Phase II** → **Future NH Experiment**

# Some Parallel Technical Developments Being Pioneered

# Multi-site event discrimination in large liquid scintillation detectors

(Dunger and Biller, NIM, **943**, 162420, 1 November 2019, arXiv:1904.00440)


Compton length for 1 MeV γ in LAB ~20cm, vs vertex resolution of ~10cm

→ **use time residuals from vertex fit to form PDFs for a likelihood discriminant**

## ***In situ*** **calibration of technique**

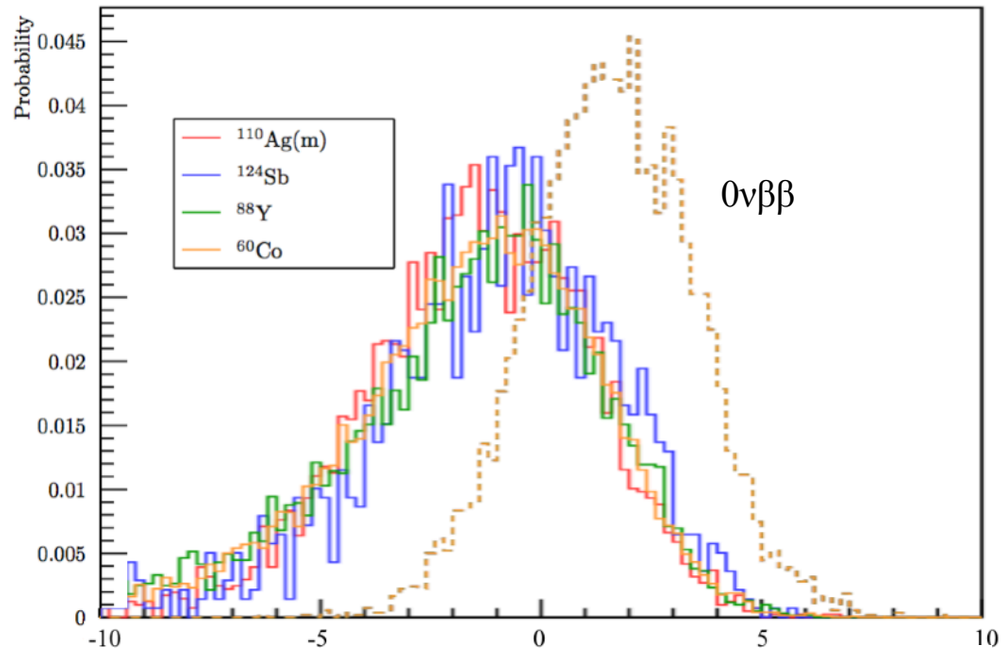
multi-site events:

- α-tagged $^{214}$Bi & $^{208}$Tl decays
- external γ's (dominant at higher radius)

single-site events:

- 2νββ events (dominant at lower energy)
- $^{8}$B solar ν (dominant at higher energies)

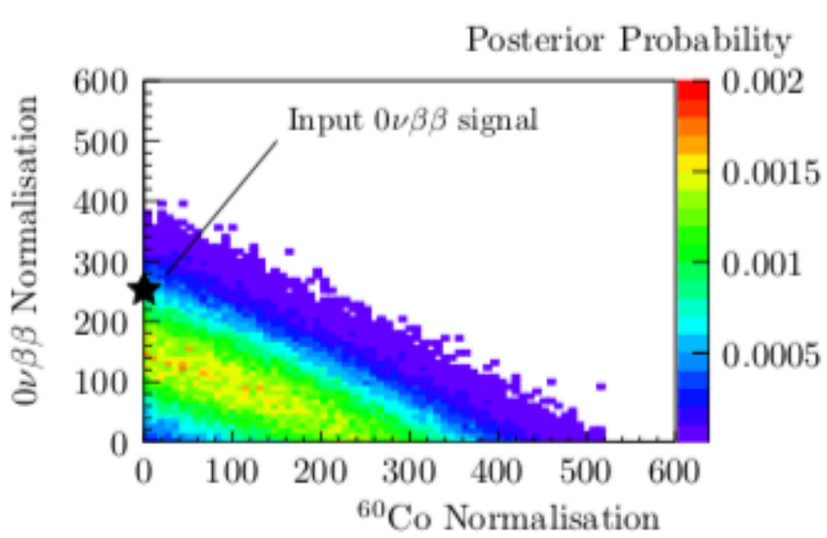
can also use deployed sources

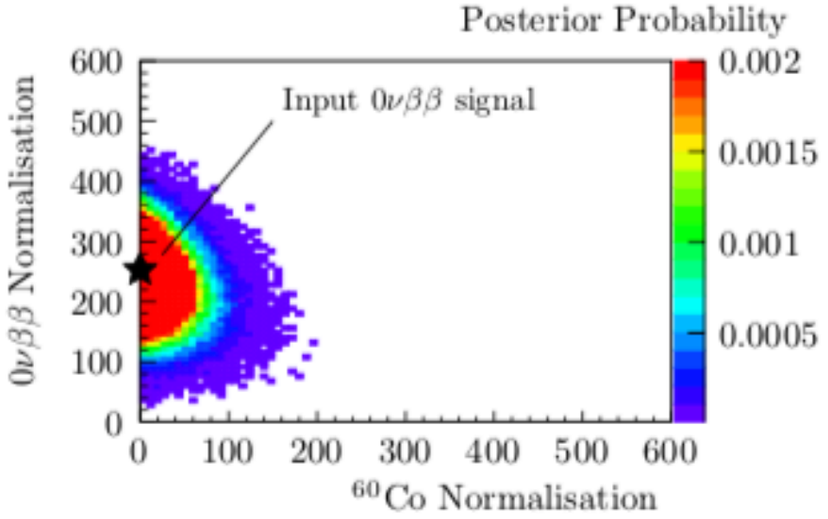


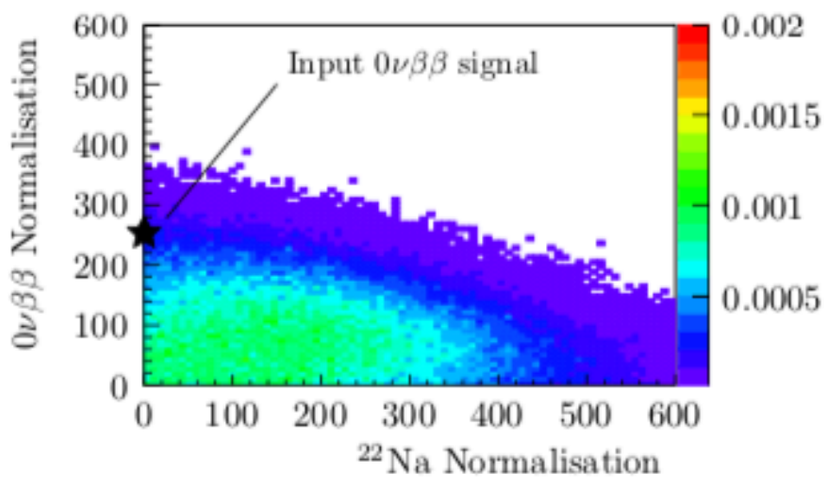

**Can identify signal as distinct from cosmogenic background -> discovery experiment!**

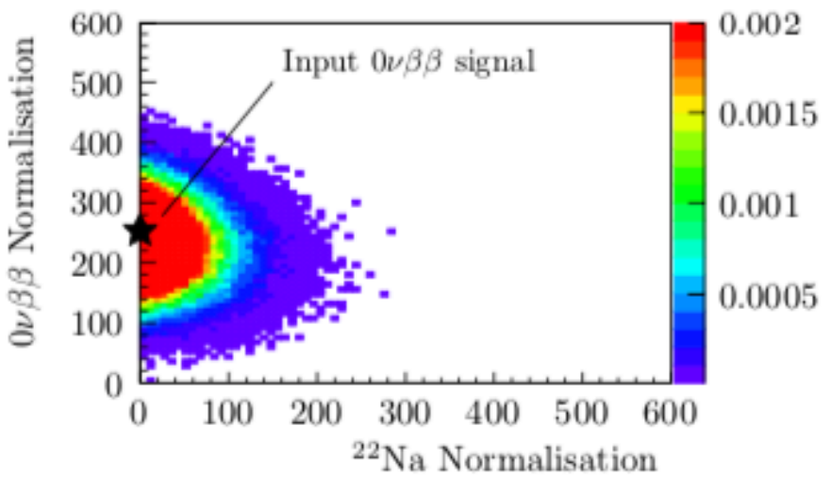
without multi-site parameter

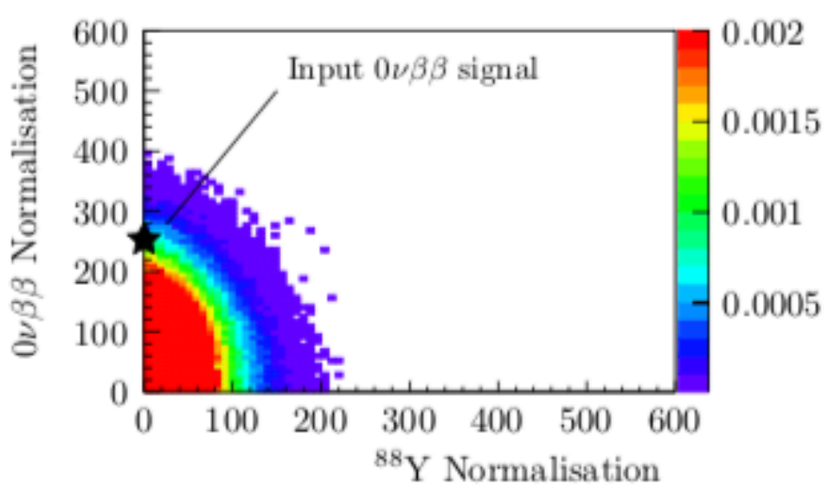
with multi-site parameter

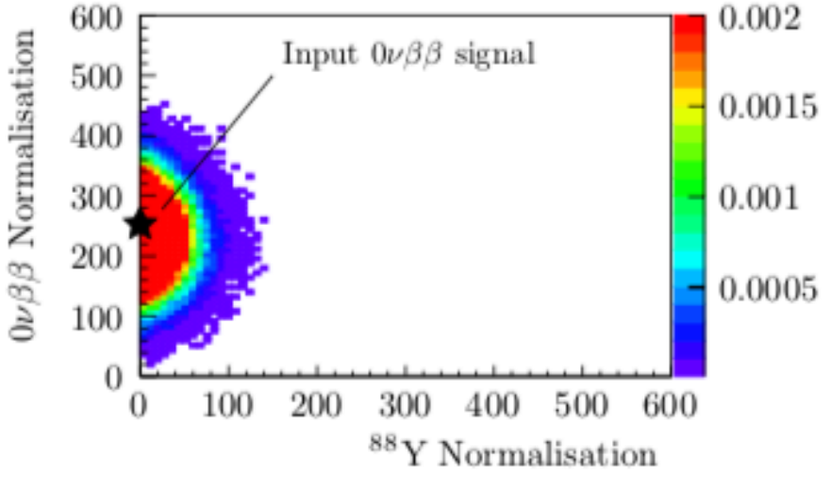


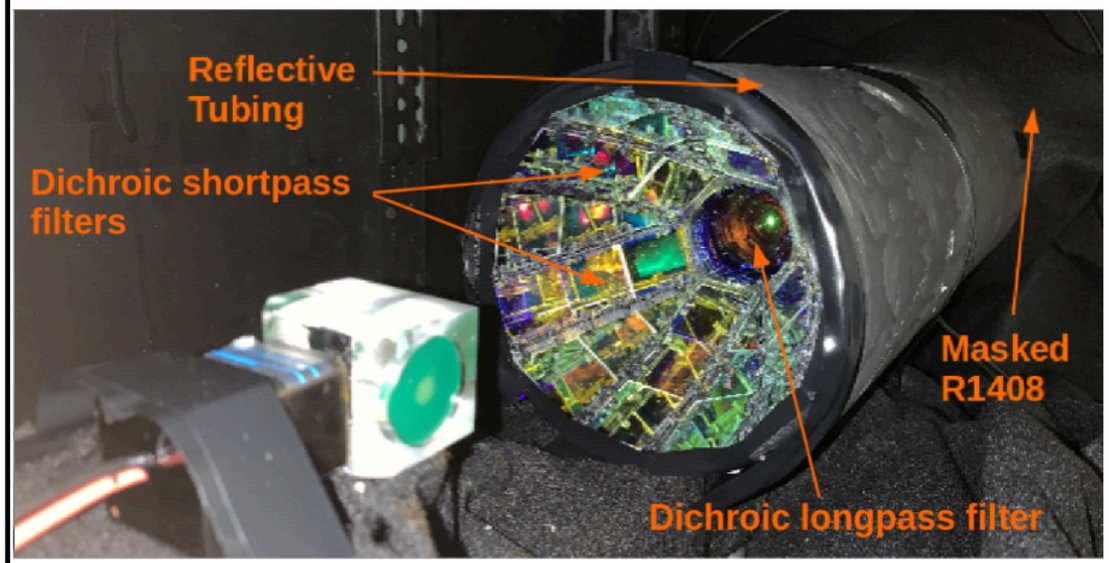



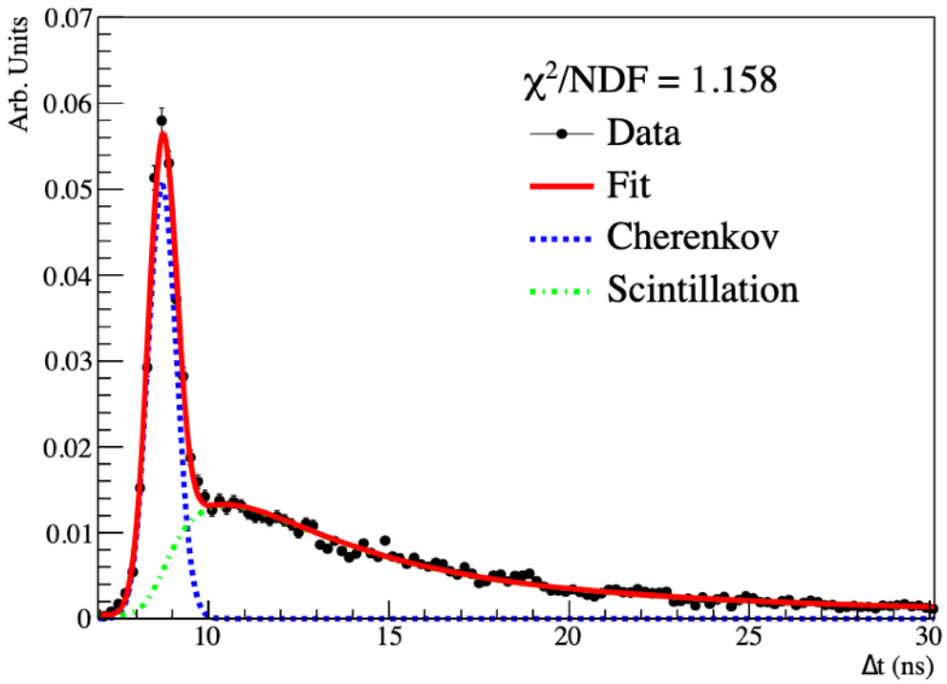
# Cherenkov Separation

**Could allow suppression of $^{8}B$ background and potentially provide topological information to test 0νββ mechanism**

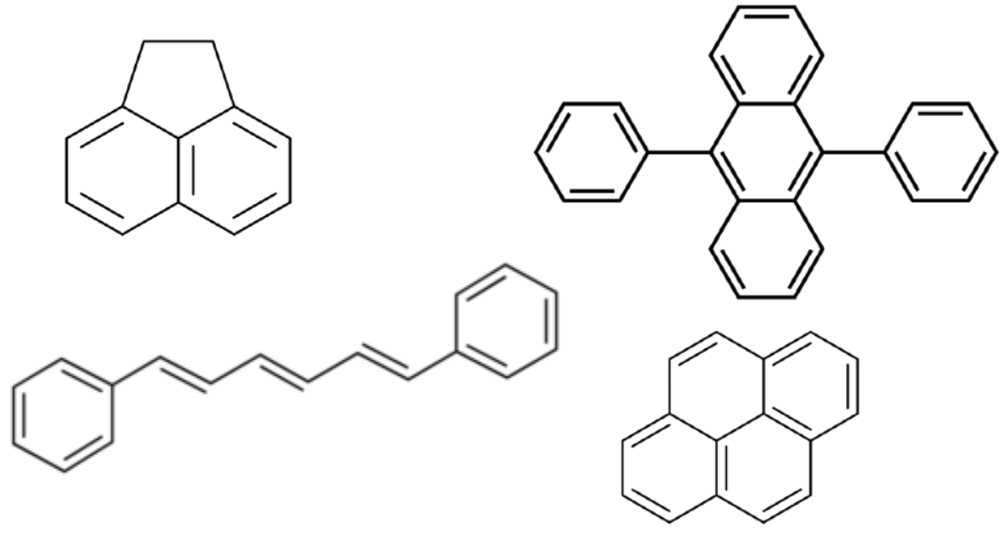
## Dichroic Concentrators



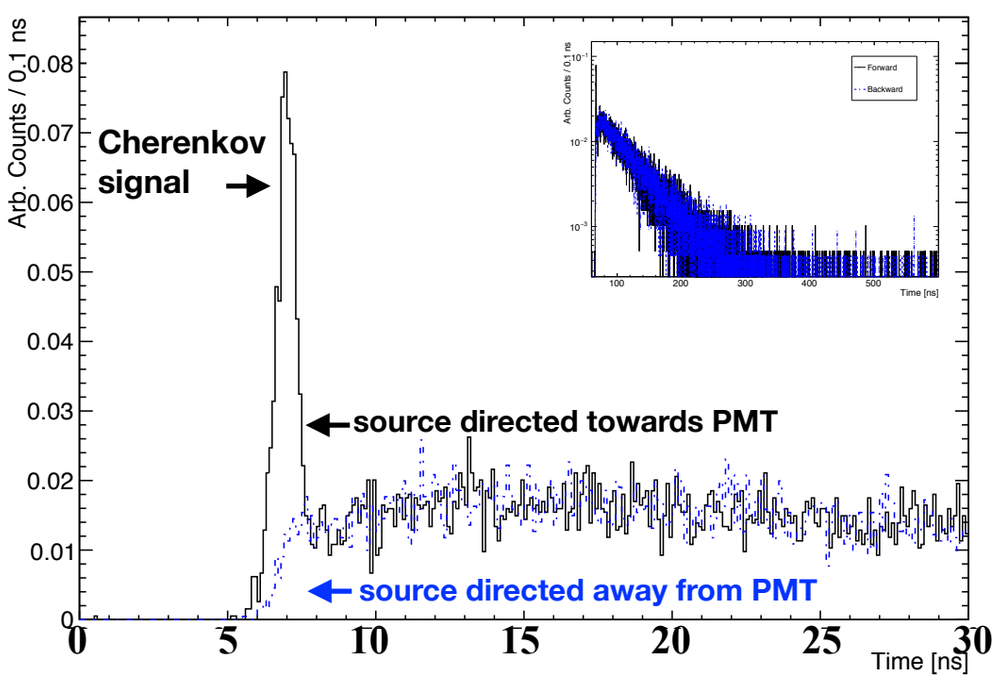

Kaptanoglu, Luo, Land, Bacon & Klein - arXiv:1912.10333




## Slow Fluors



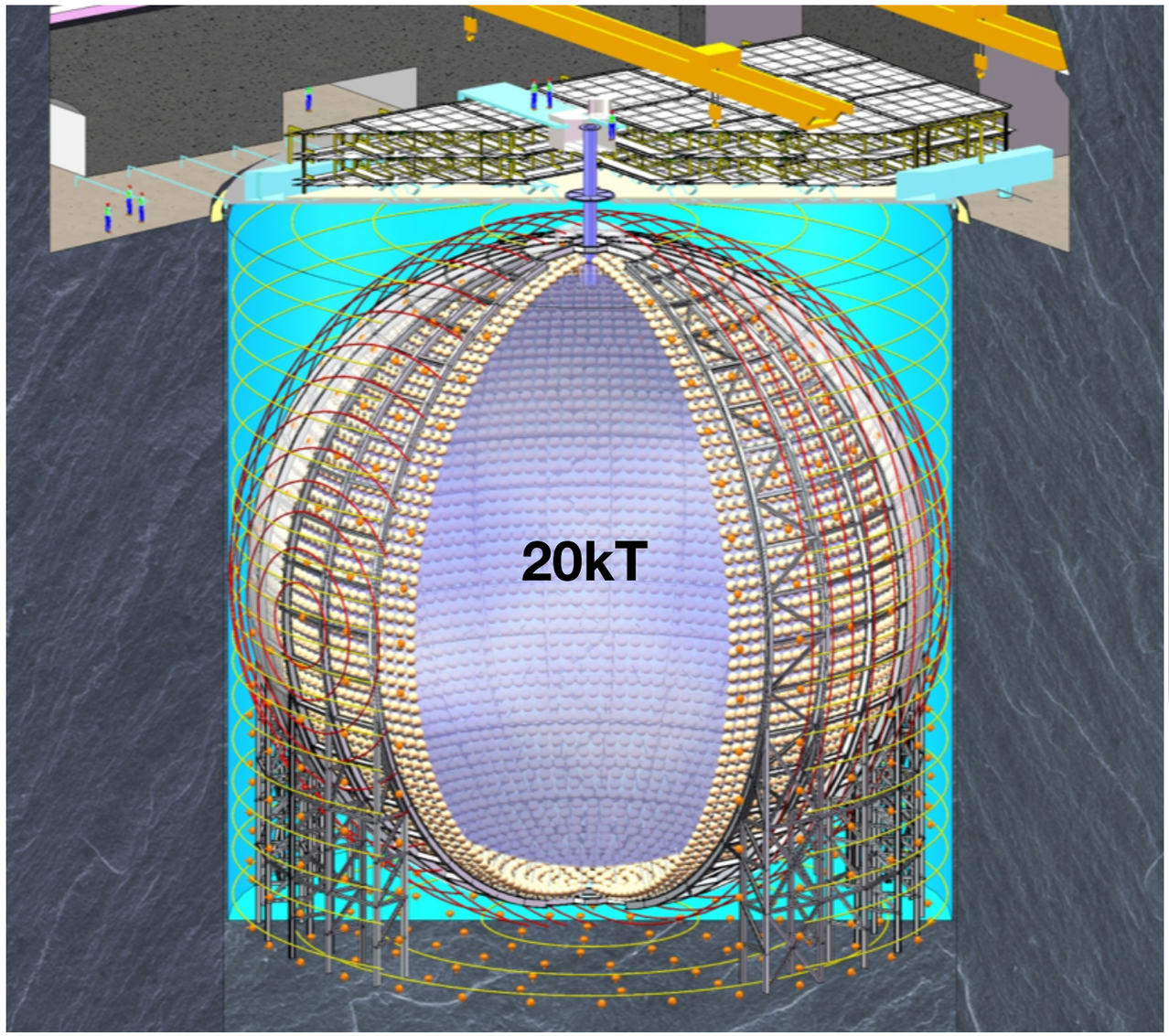
Biller, Leming & Paton - arXiv:2001.10825



# Exploration of improvements to Te loading and scintillator composition

The basic target numbers for Te-loading to start looking like a serious NH experiment are: ~10% $^{nat}$Te loading in ~10kT fid volume with ~1000 hits/MeV

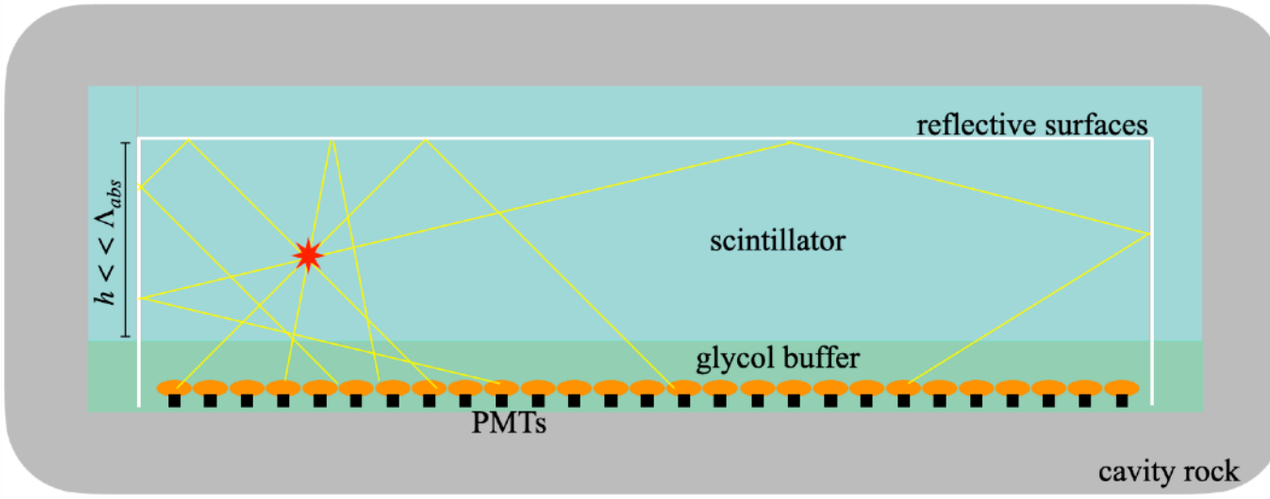
# Possible Future of Te-Loaded Scintillator:




Possible future deployment of Te in JUNO

(or perhaps THEIA, or perhaps some other similar scale of instrument)

SLIPS concept (paper in progress)




Exploring new design geometries for more economical and efficient large scale detectors