The Physics of Massive Neutrinos

Joachim Kopp (CERN & JGU Mainz)

Windows on the Universe • Quy Nhon • Vietnam • August 2023

CERN

Neutrino PLATFORM

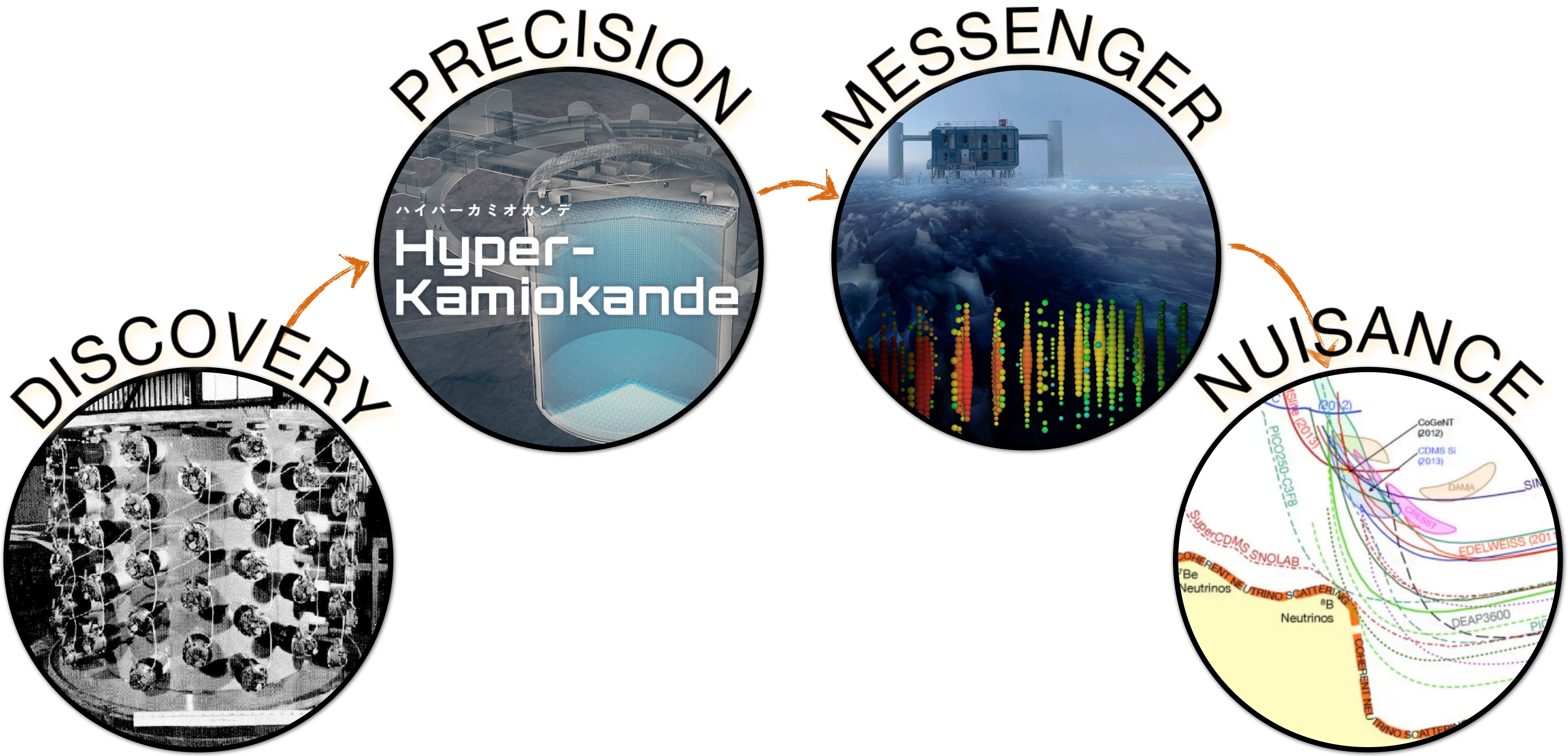
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

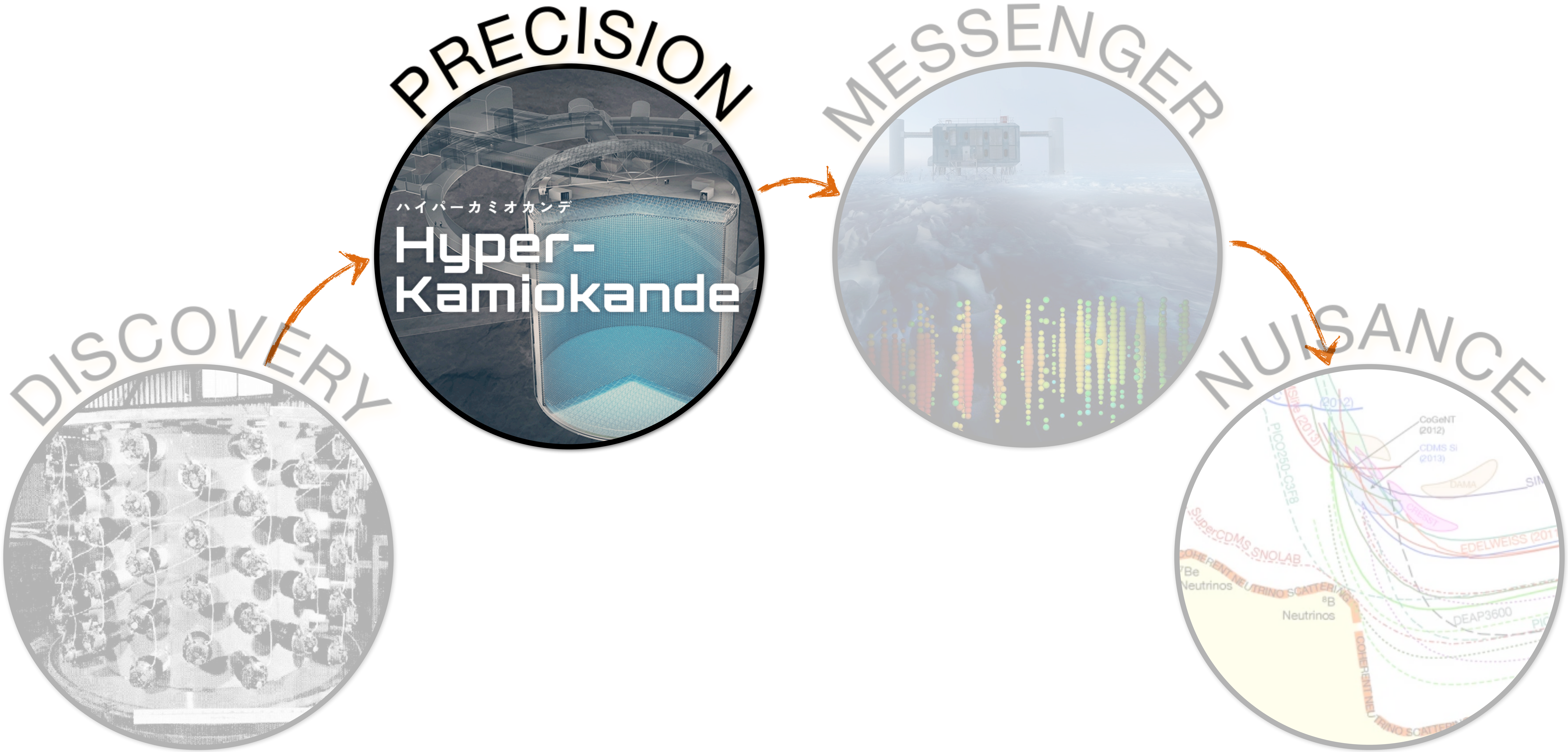

DISCOVERY


PRECISION
DISCOVERY


DISCOVERY
PRECISION
MESSENGER

DISCOVERY
PRECISION
MESSENGER
NUISANCE


DISCOVERY
PRECISION
ハイパーカミオカンデ
Hyper-Kamiokande
MESSENGER
NUISANCE
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
EDELWEISS
PICO250-C3F8
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
7Be Neutrinos
8B Neutrinos
DEAP3600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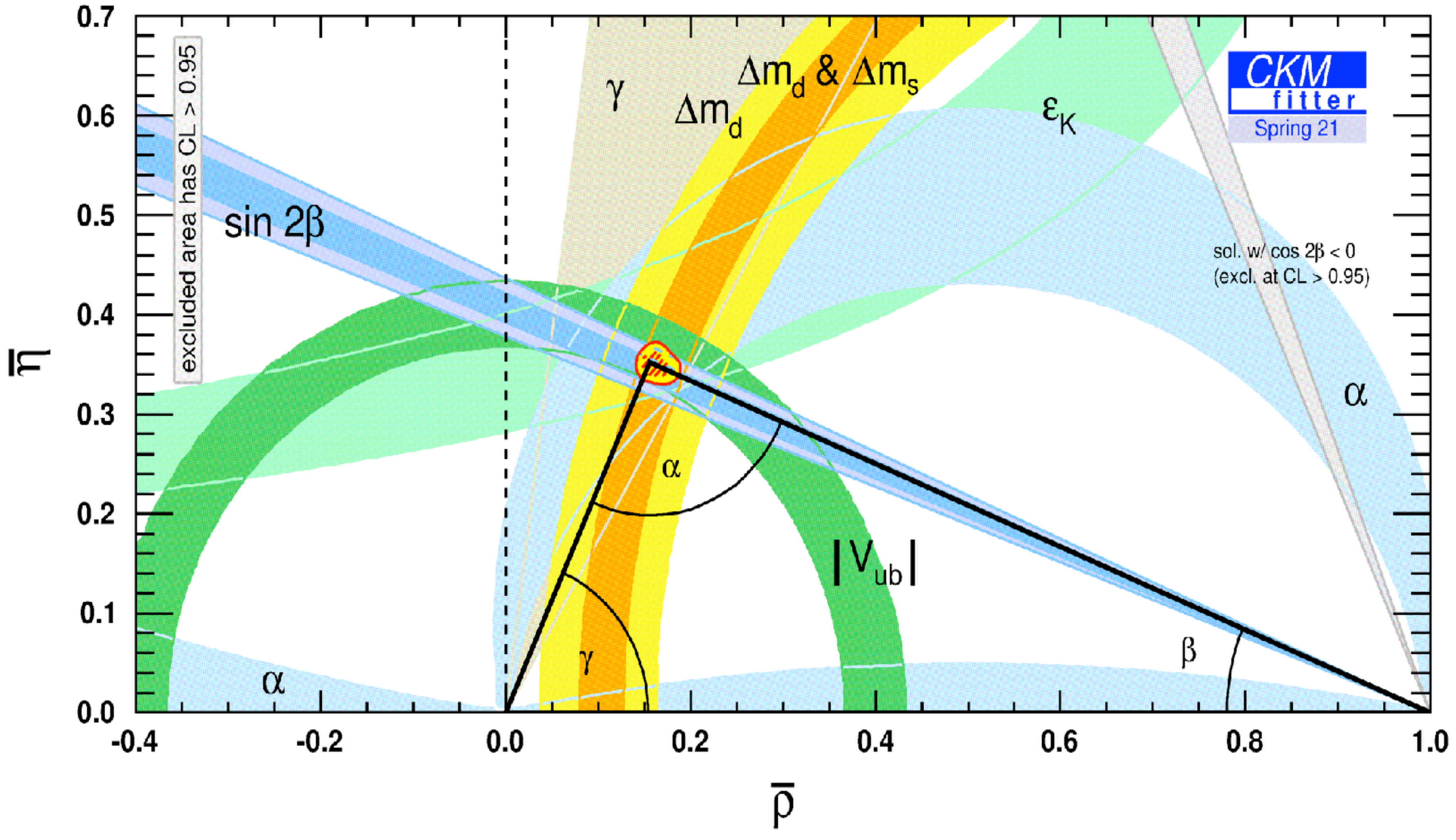
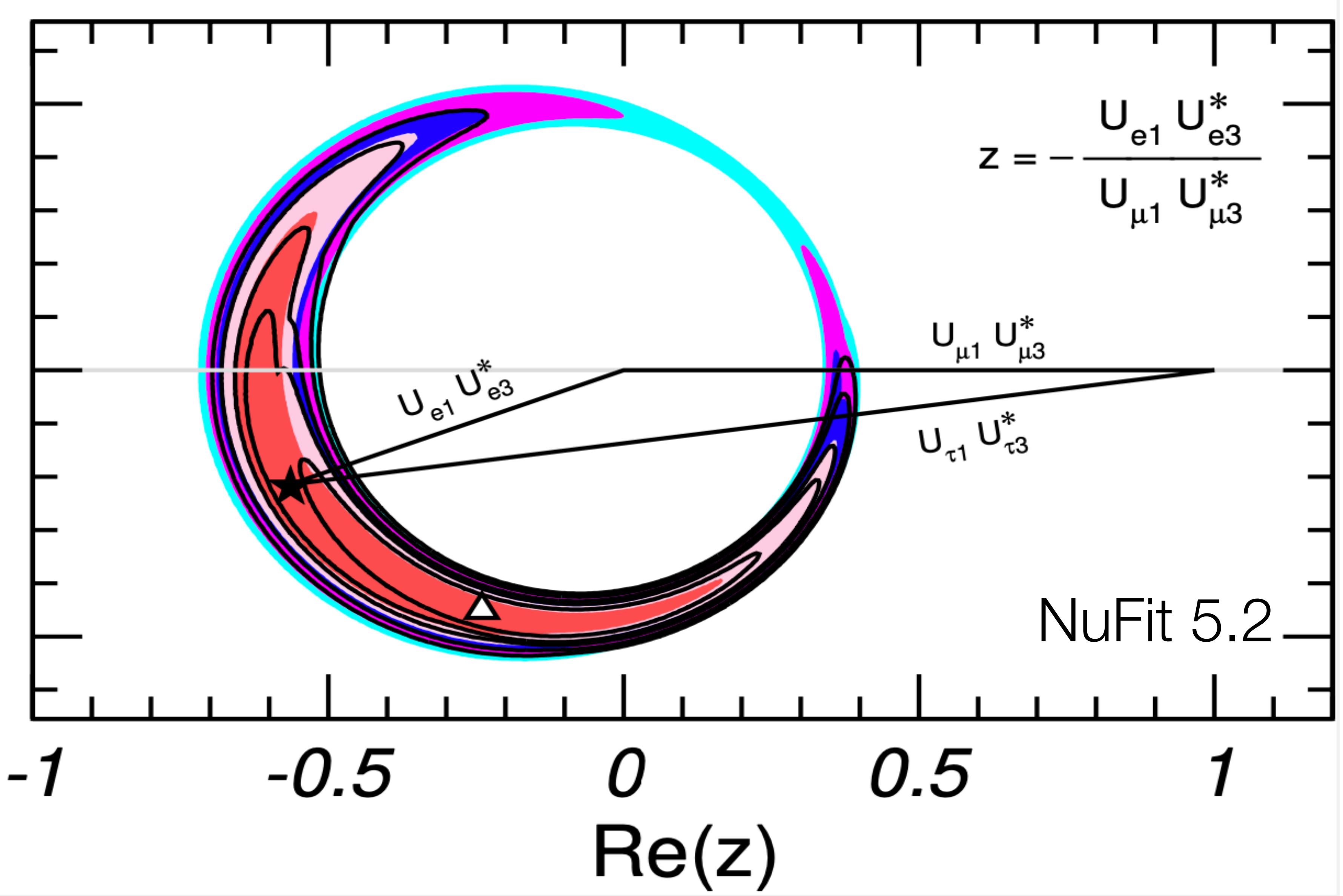
Precision Neutrino Physics

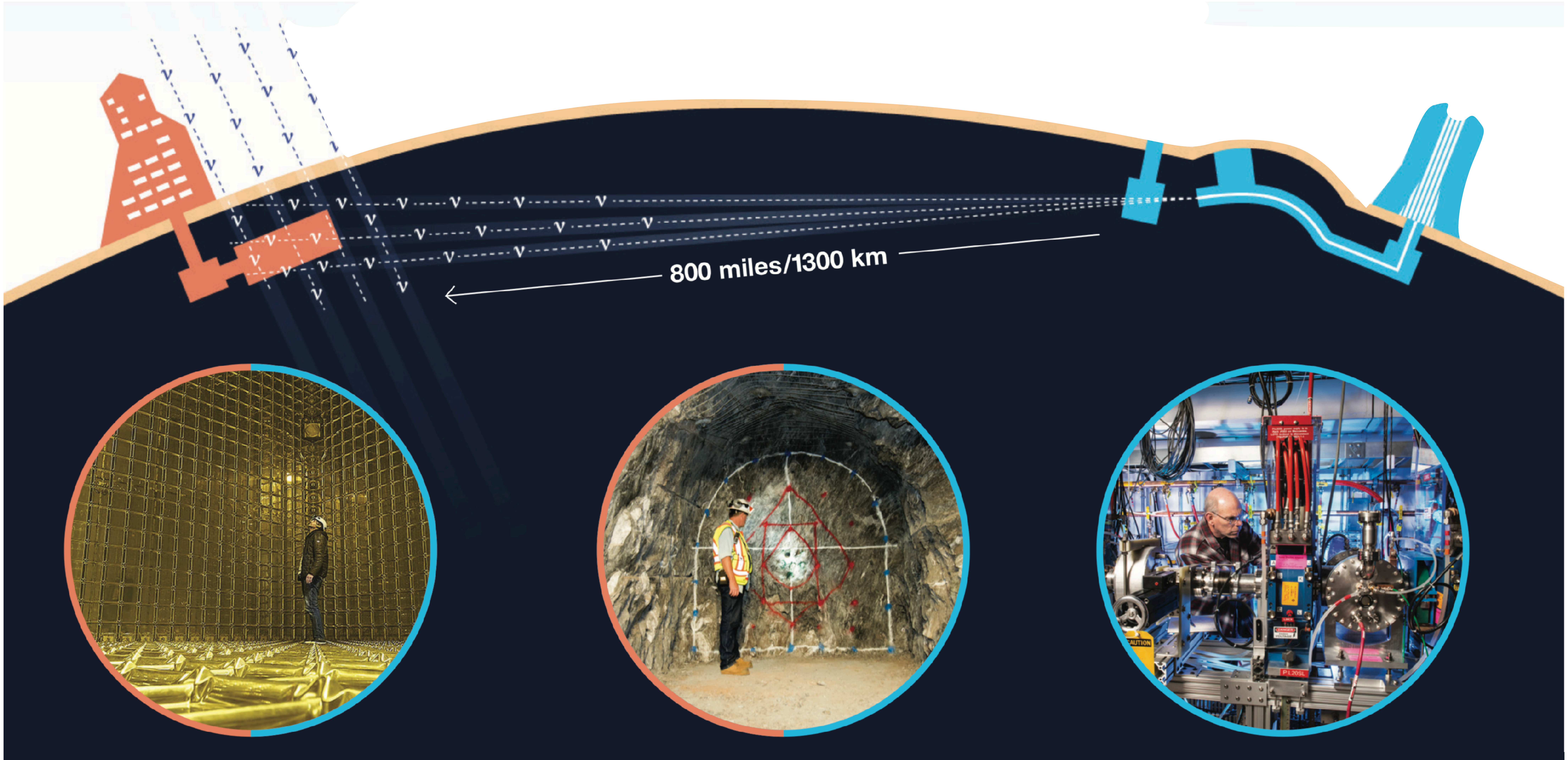
Quarks



Leptons



Next-Generation Long-Baseline Experiments



Far Detectors
(measure oscillations)

Near Detectors
(measure unoscillated flux)

Neutrino source

Yes, But Why?

- ☐ Connection between leptonic CP violation and baryogenesis
- ☐ Portal to new physics
- ☐ Precise knowledge of particle physics is indispensable for using neutrinos as astrophysical messengers
- ☐ Hints for the origin of flavour
- ☐ Multi-purpose detectors with lots of secondary opportunities (supernova neutrinos, light dark sectors, proton decay, …)
- ☐ …

➠ talk by Son Cao on Thursday

Understanding Neutrino Interactions

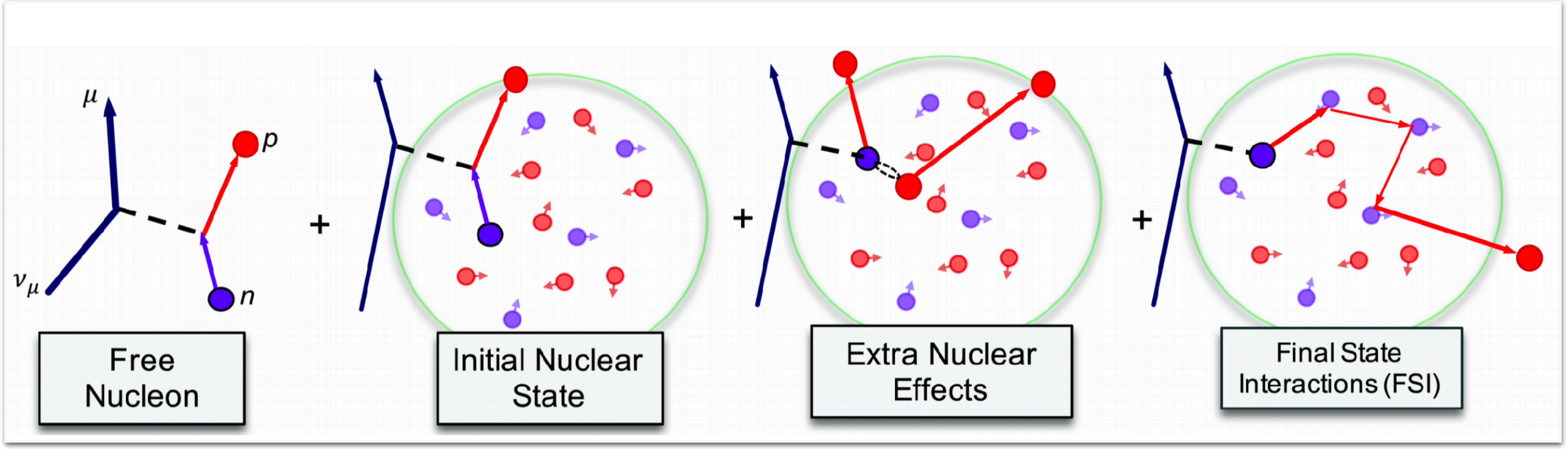
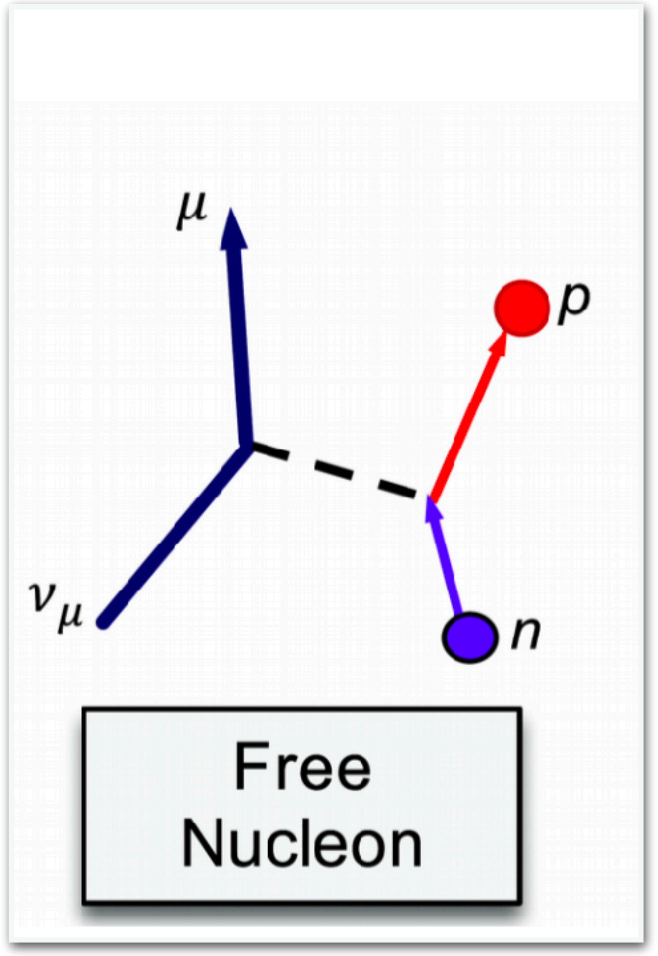


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions



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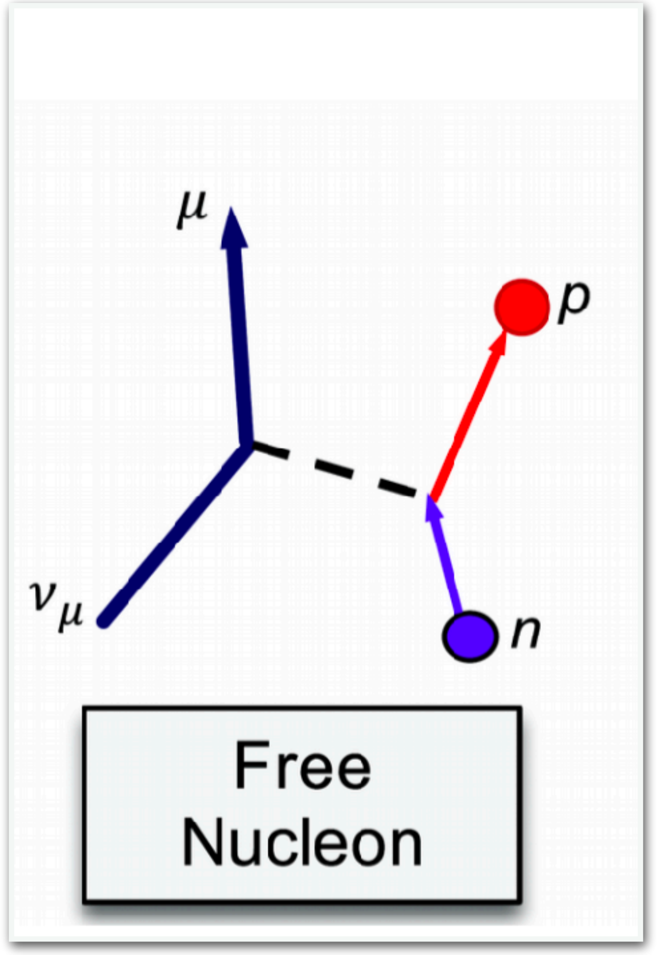

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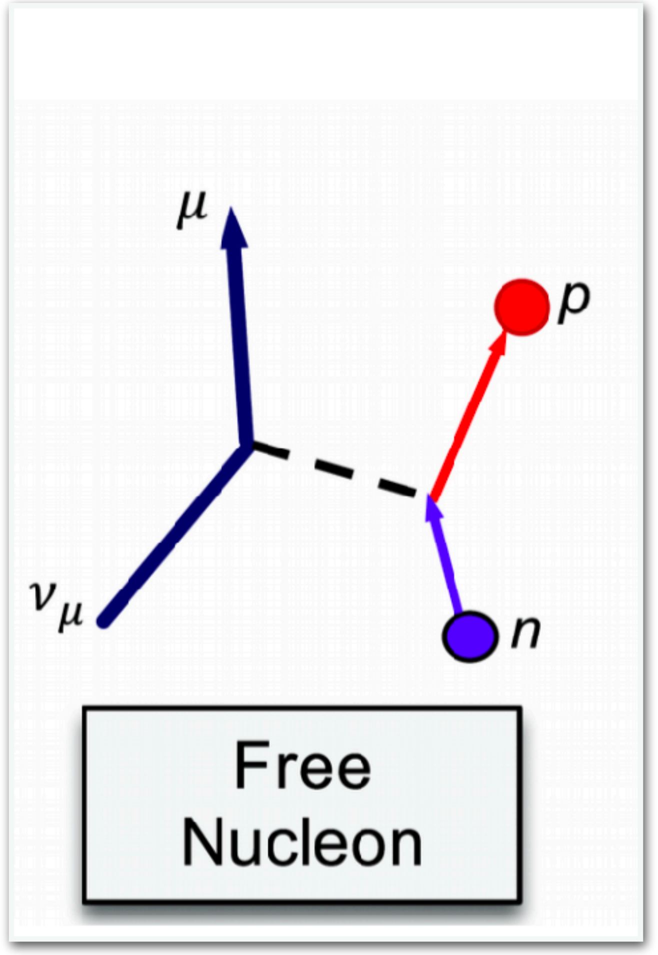

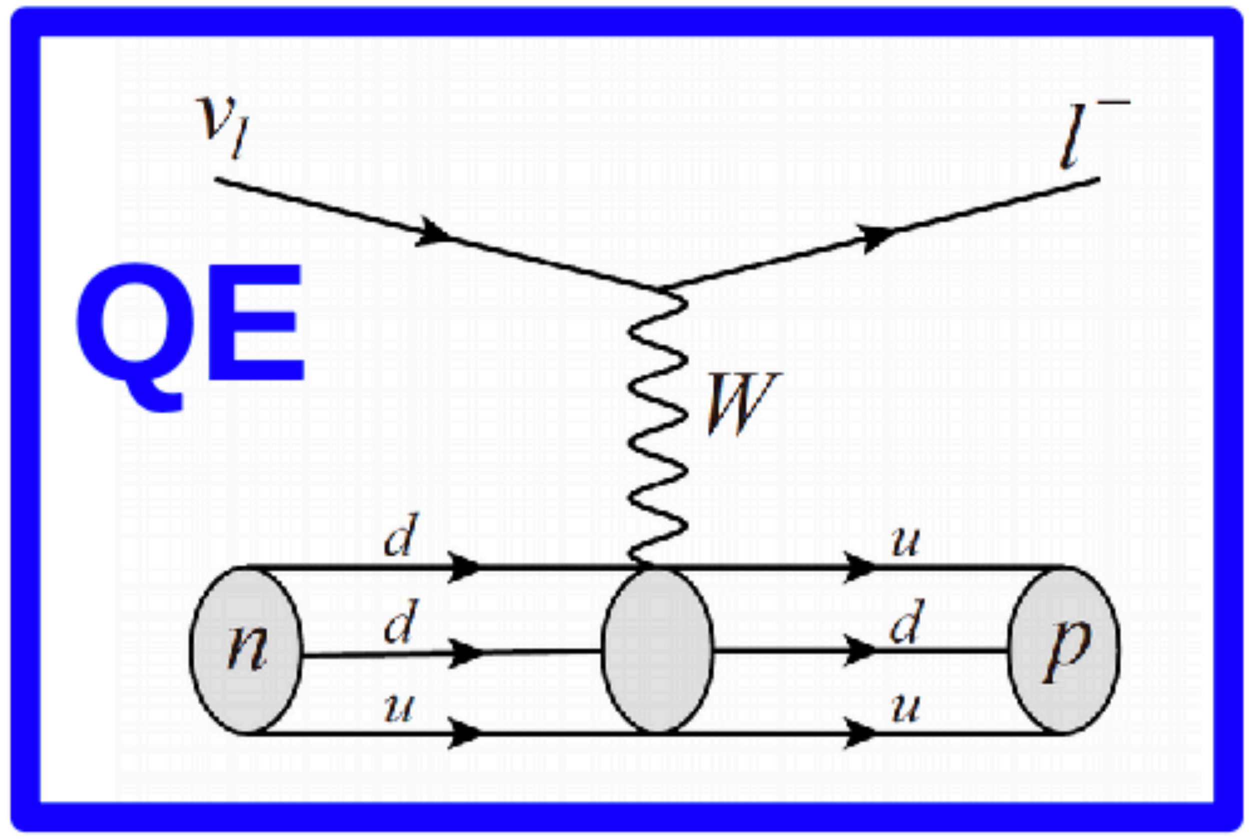

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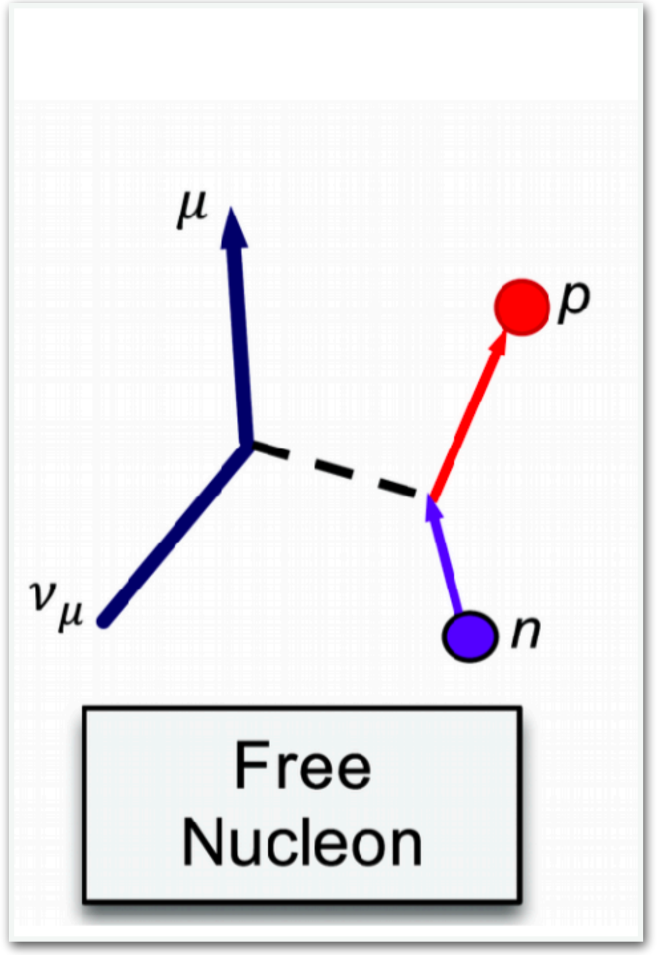

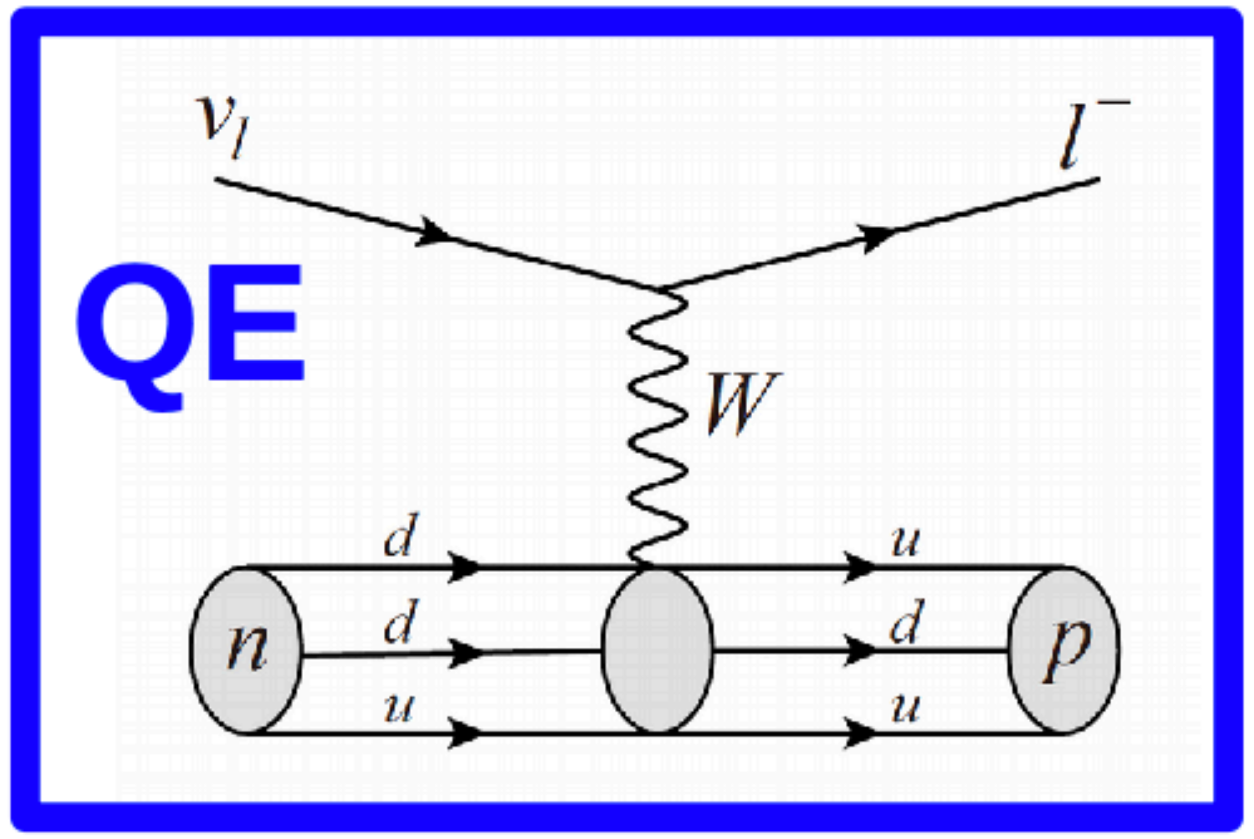

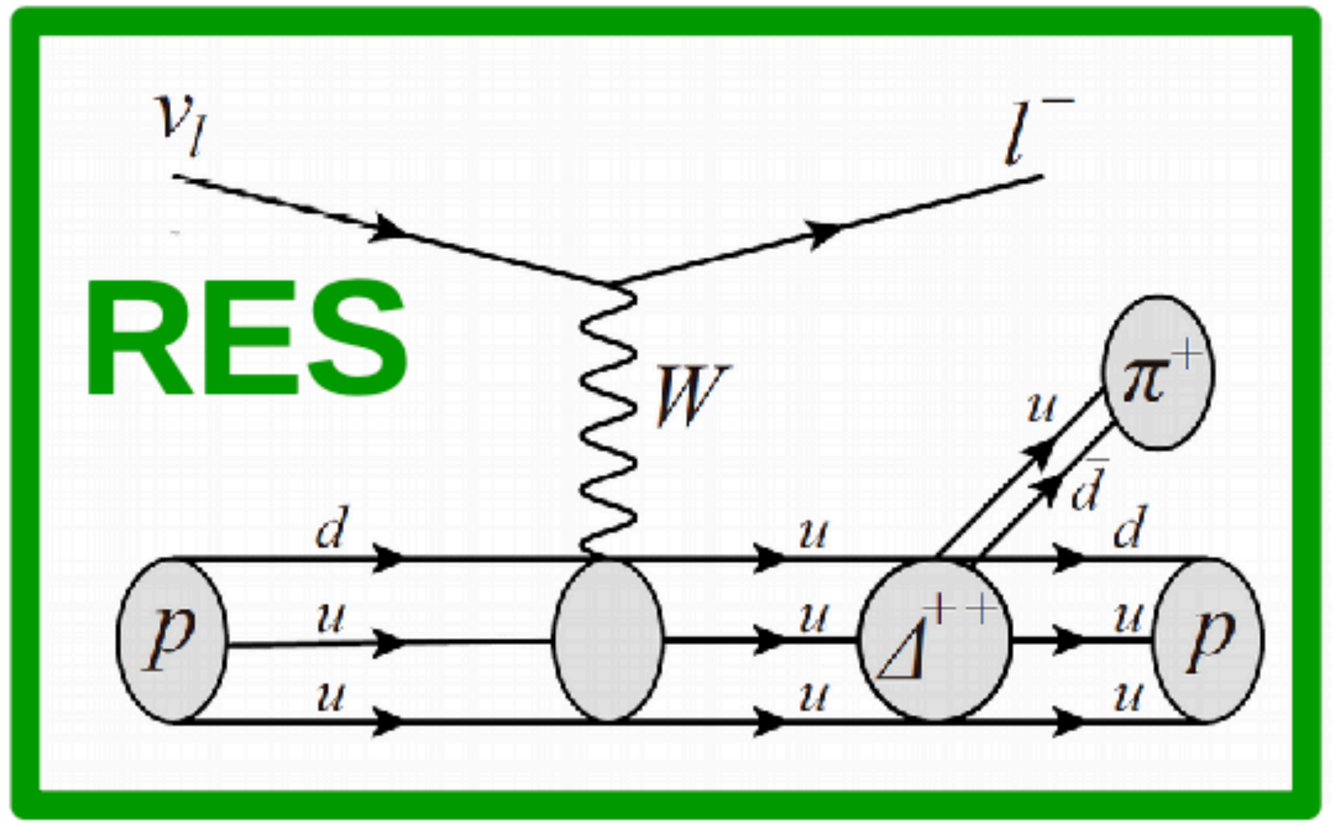

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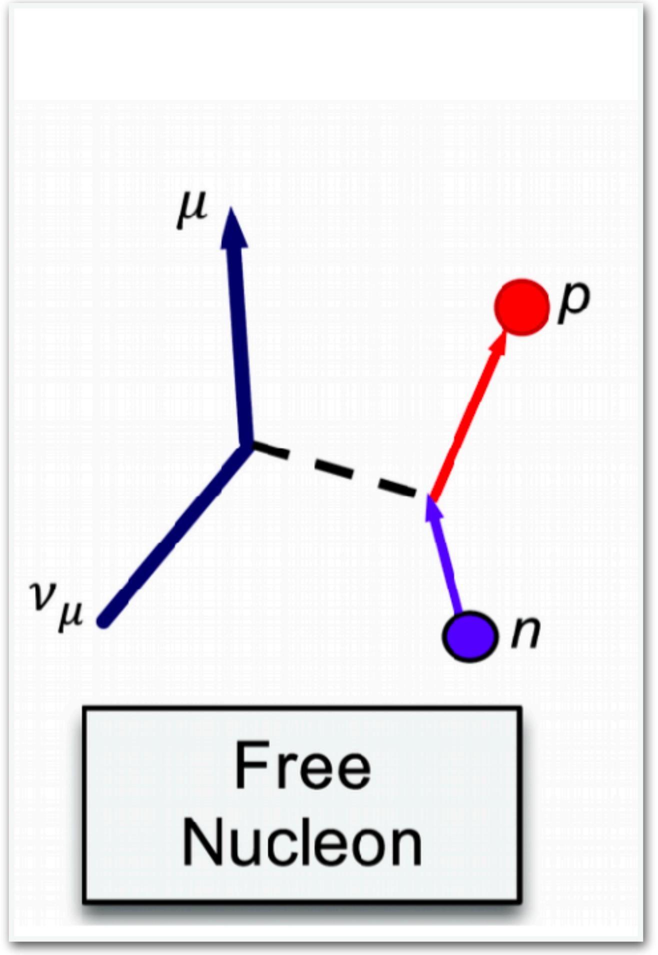

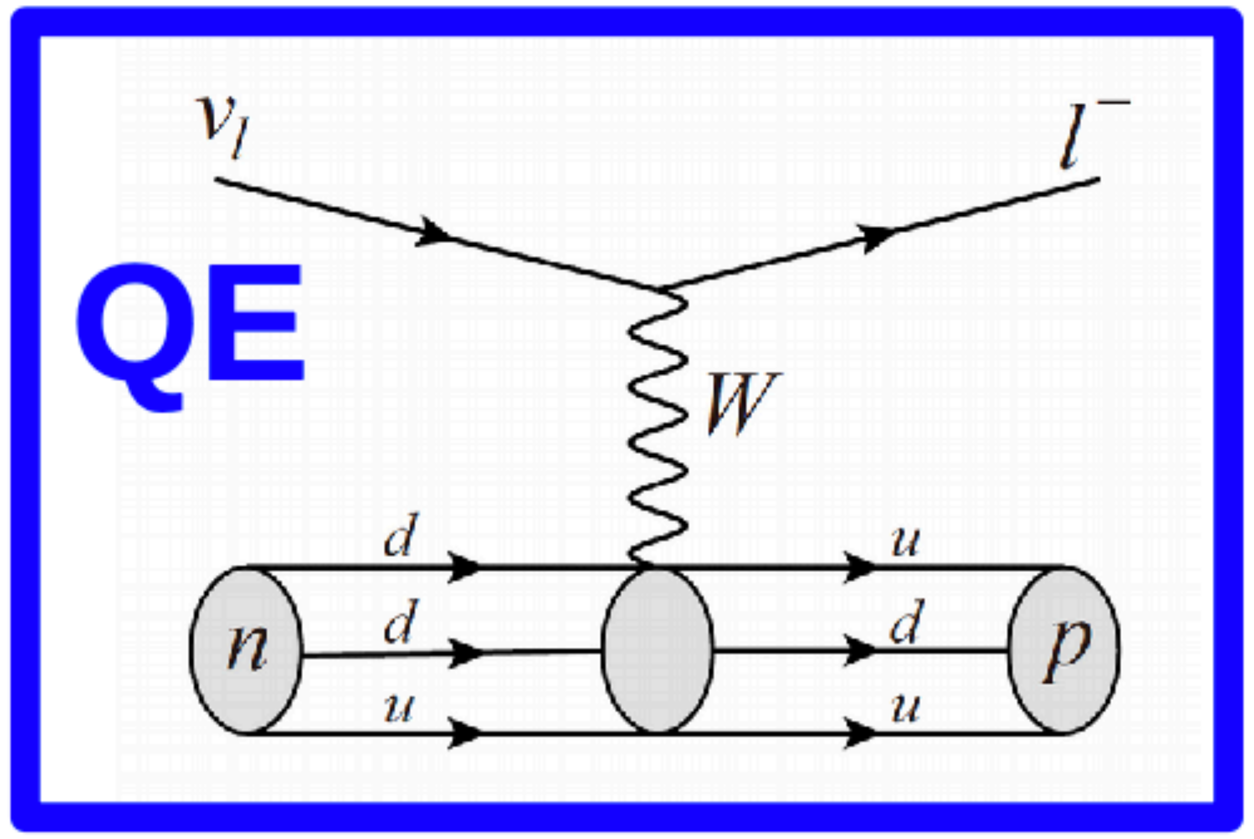

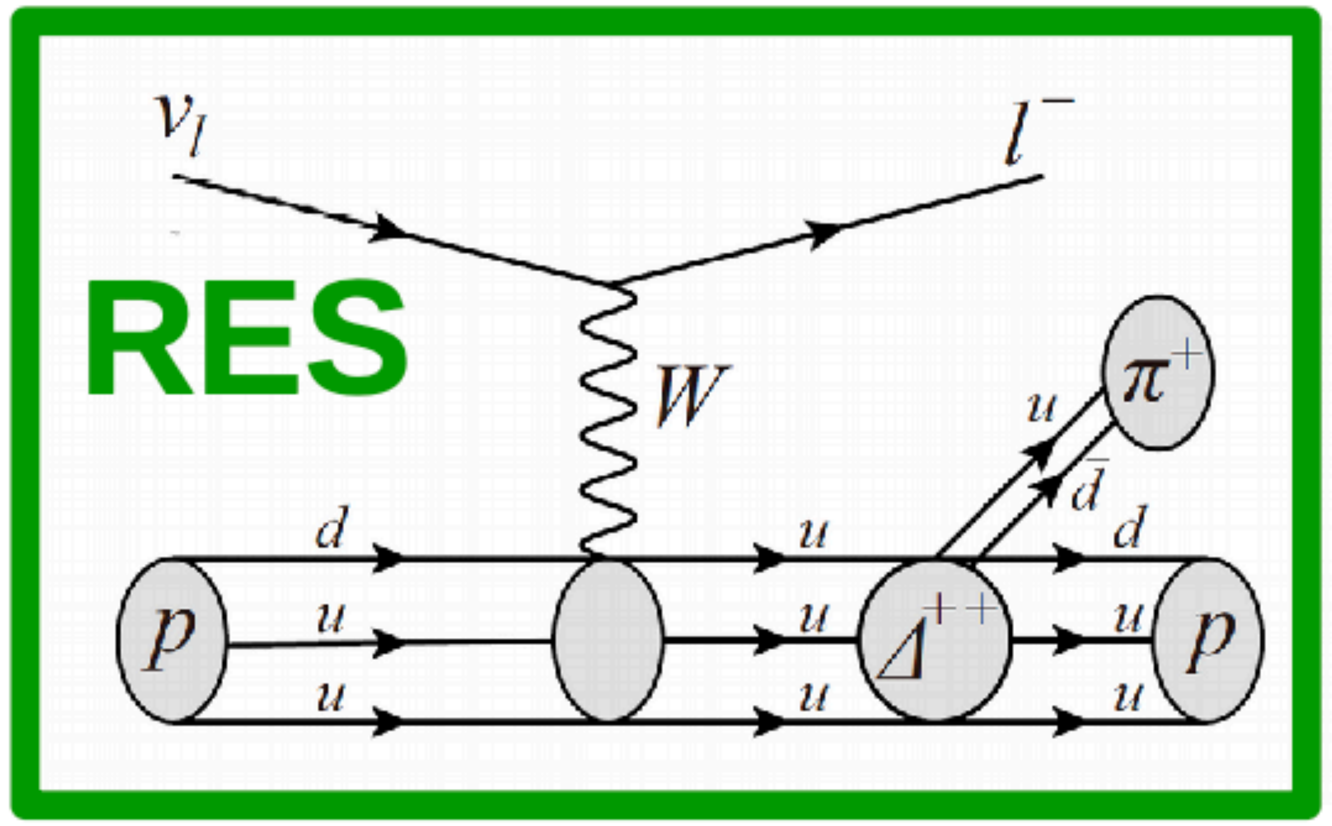

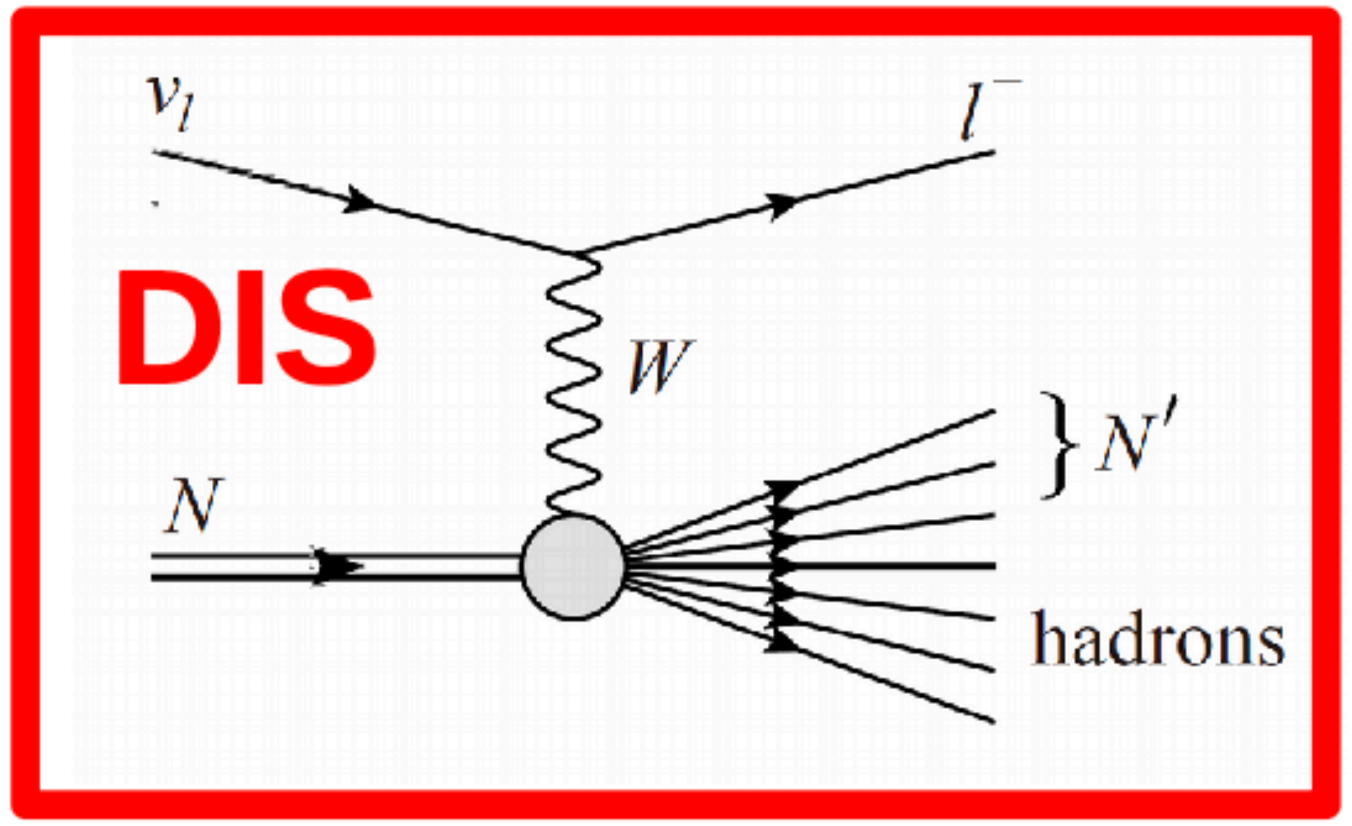

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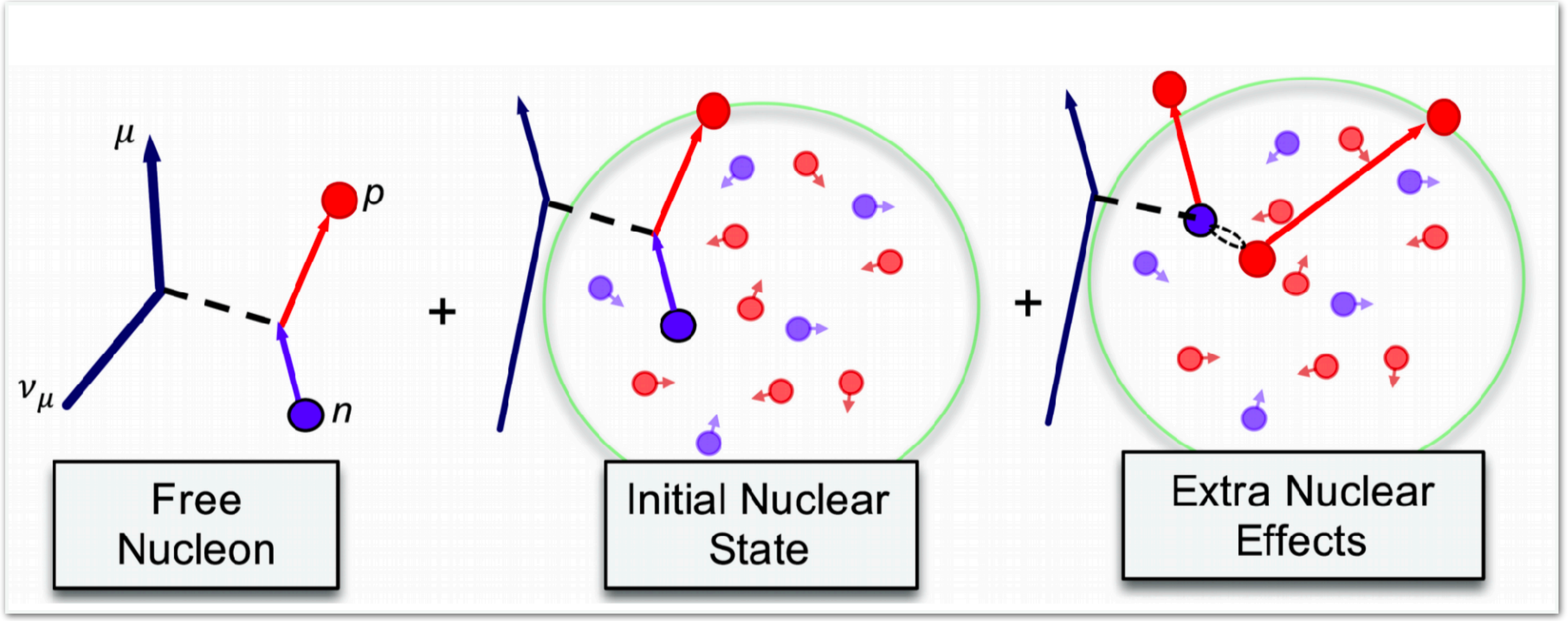
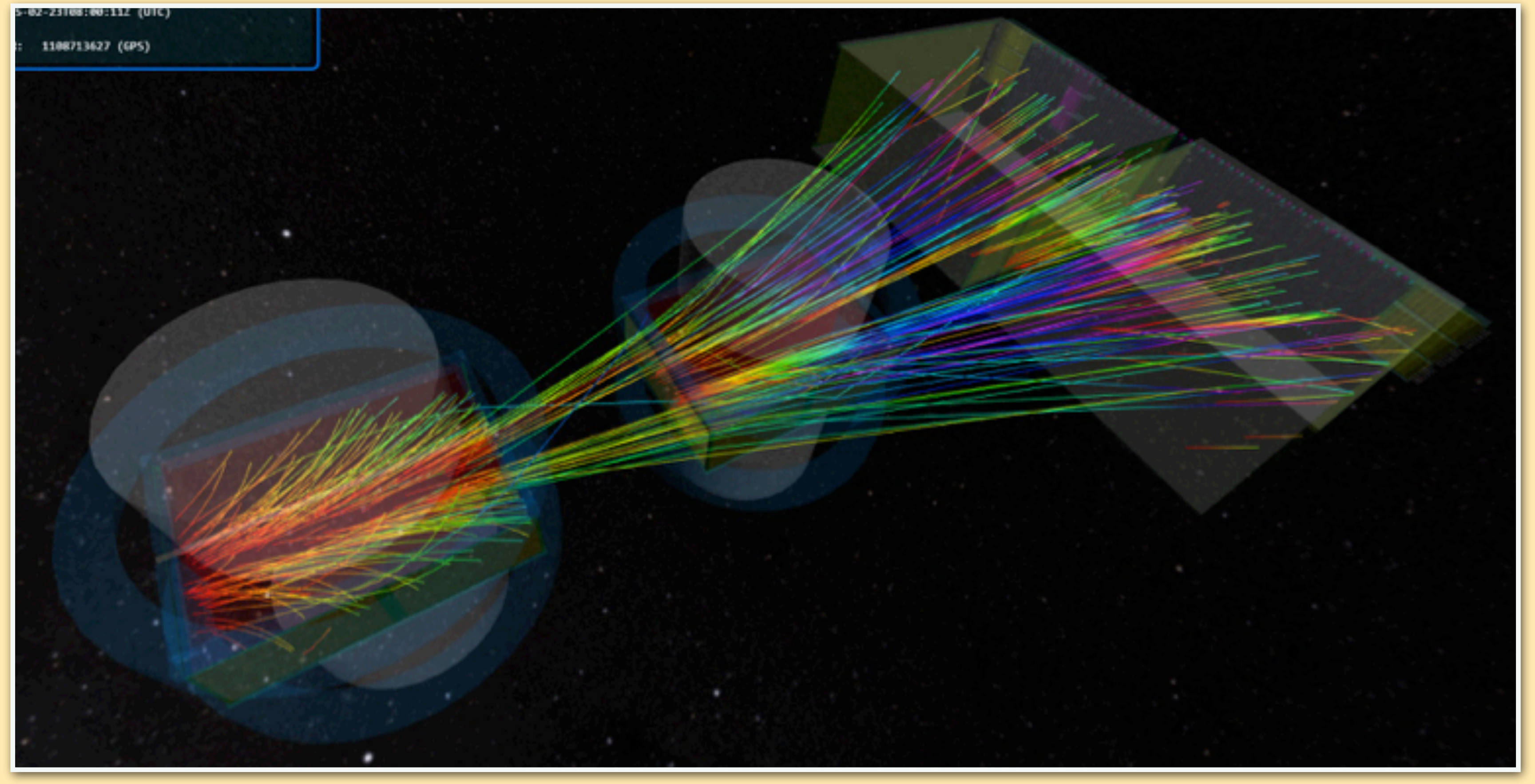


Image Credit: Callum Wilkinson

Mitigation of Systematic Uncertainties

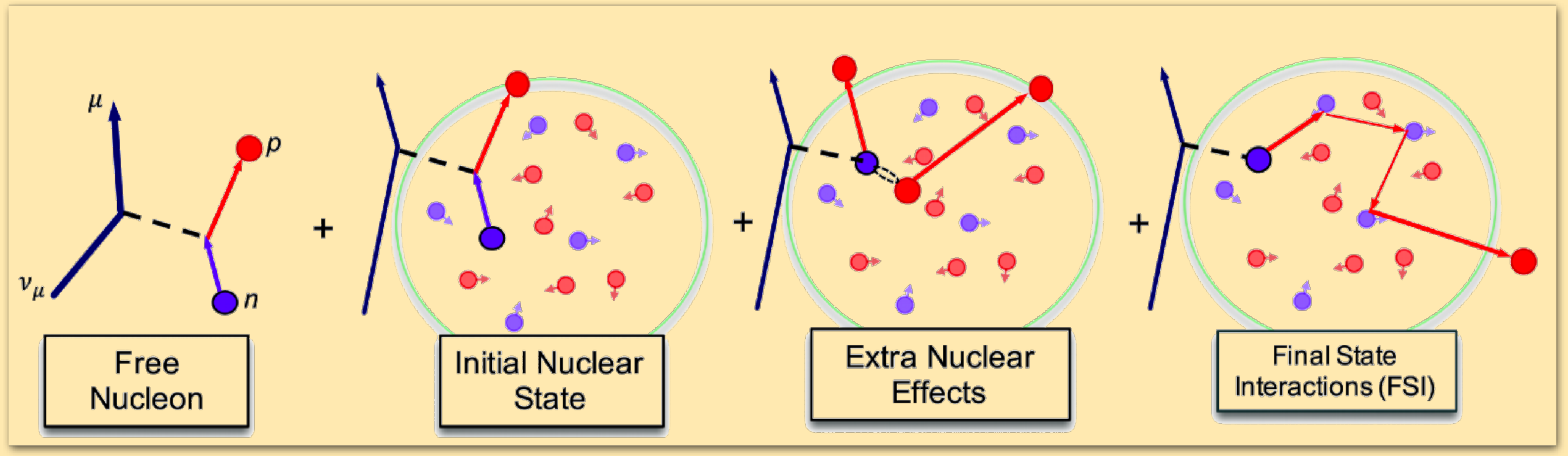
Experimental Mitigation

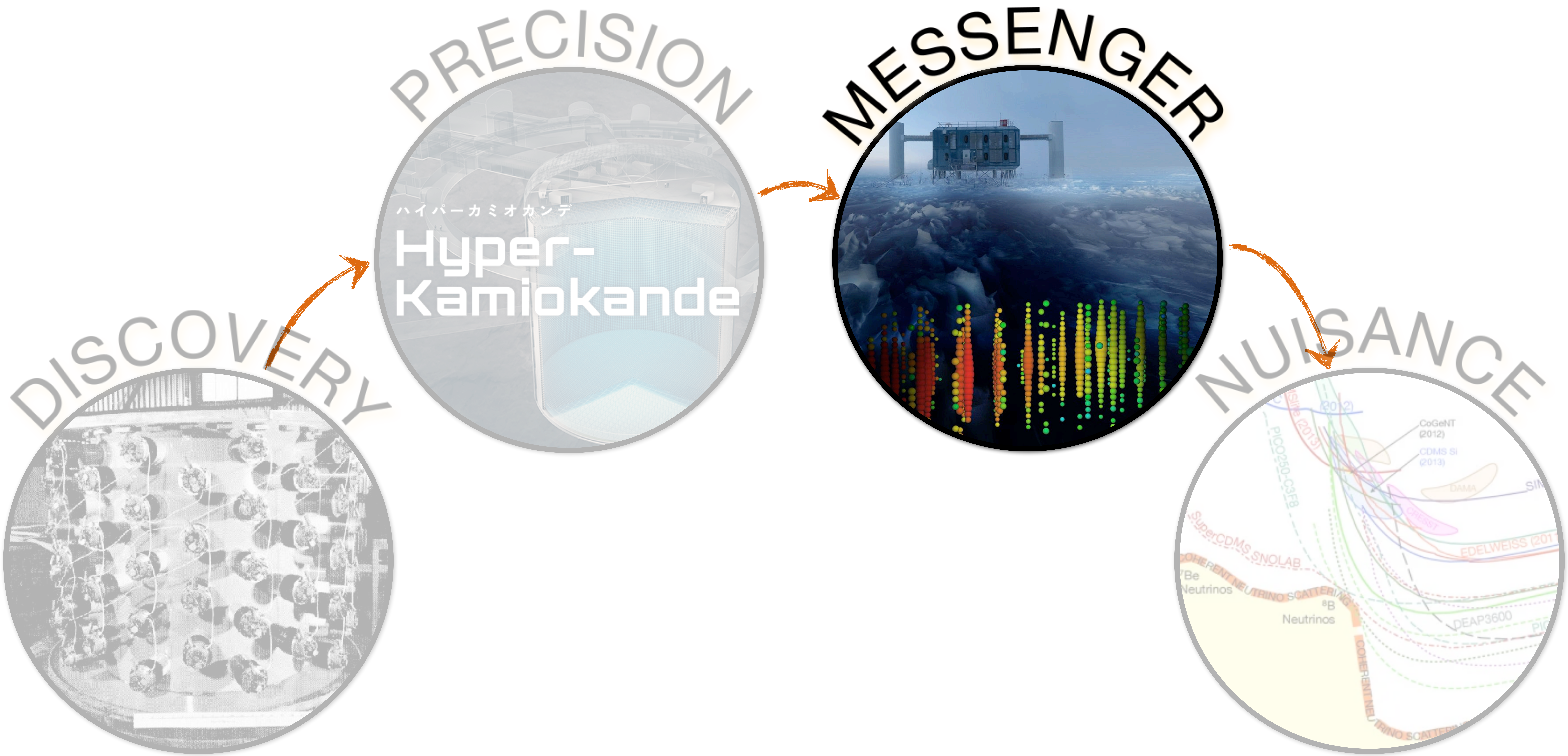
- near detectors
  (on-axis and off-axis)
- hadroproduction experiments
  (NA61/SHINE, ENUBET)



Theory Needs

- better modelling of neutrino interactions
- new strategies for optimally exploiting near detector data
  (e.g. DUNE-PRISM)

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Neutrinos as Astrophysical Messengers

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solar neutrinos

- ★ stellar evolution

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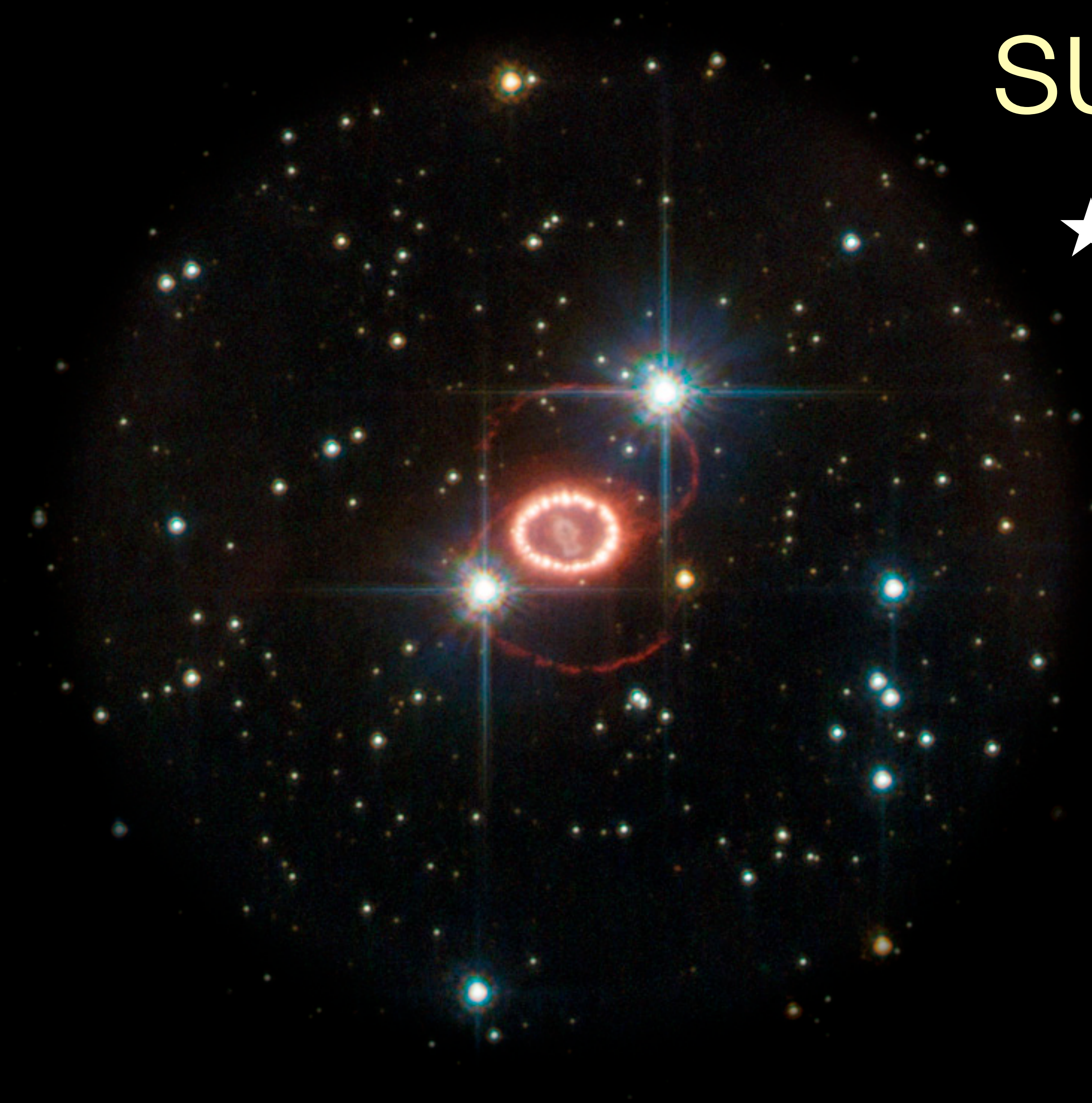


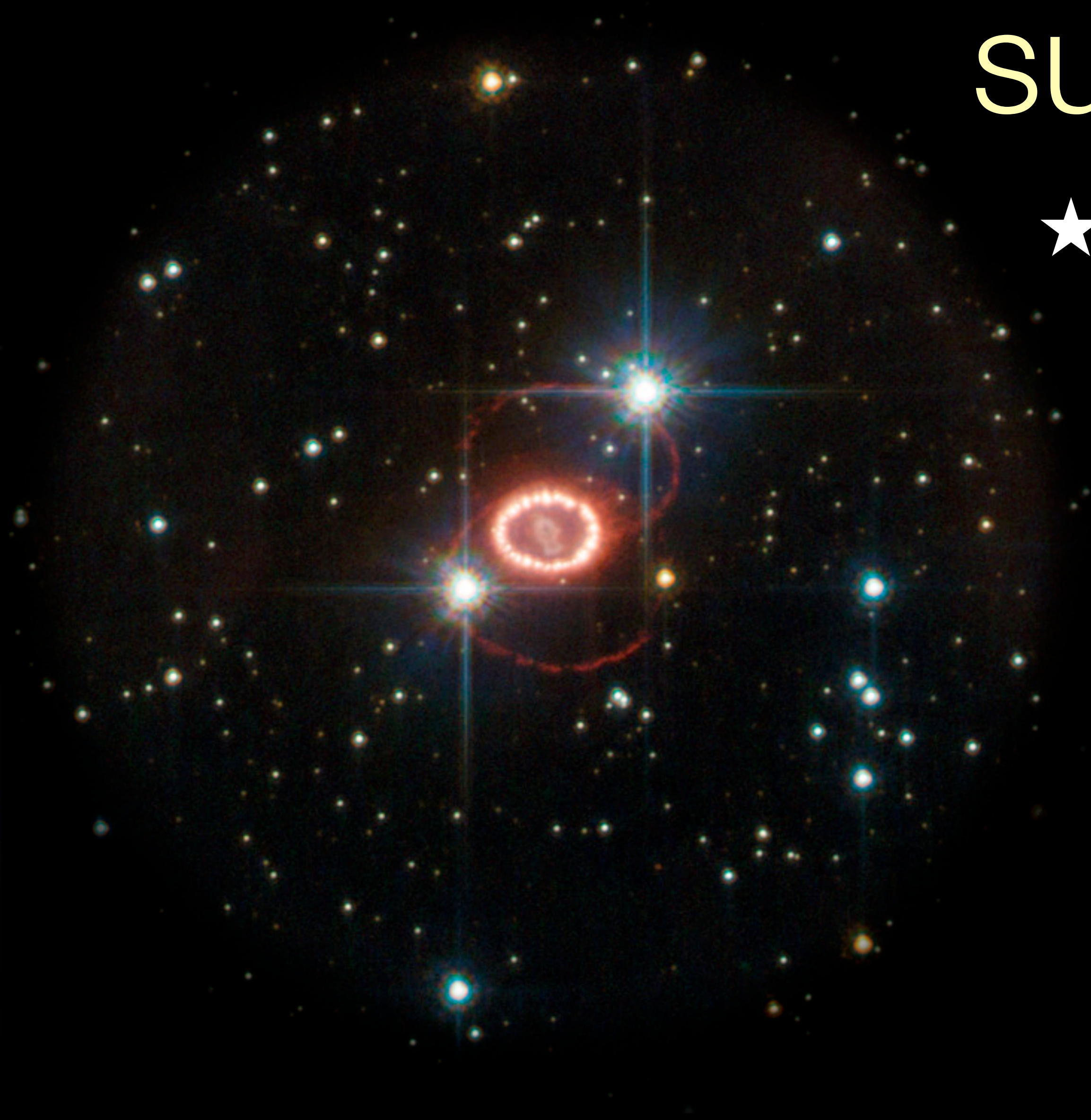
supernova neutrinos

- ⋆ death throes of massive stars
- ⋆ nucleosynthesis
- ⋆ matter under extreme conditions

Neutrinos as Astrophysical Messengers

solar neutrinos

- ★ stellar evolution



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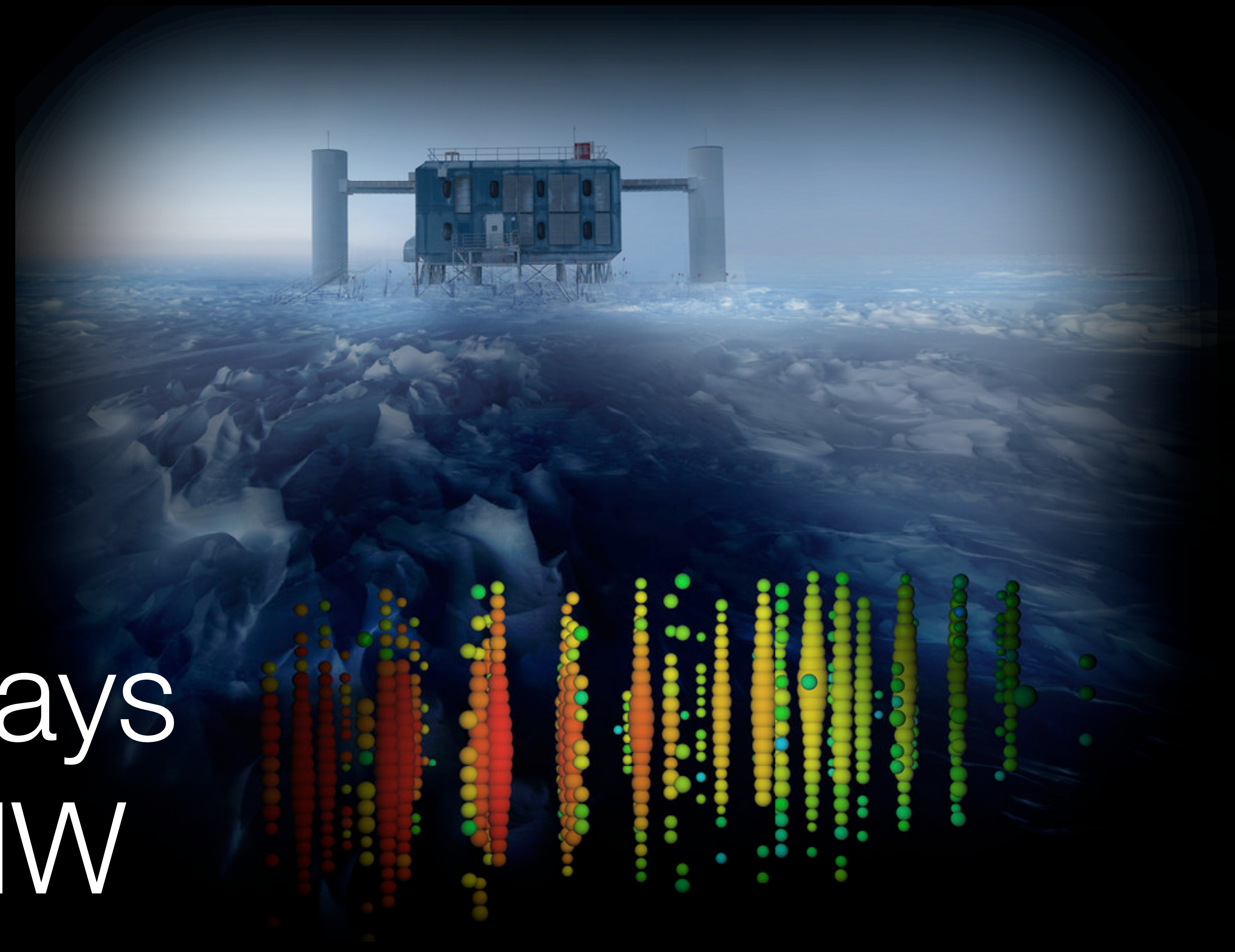
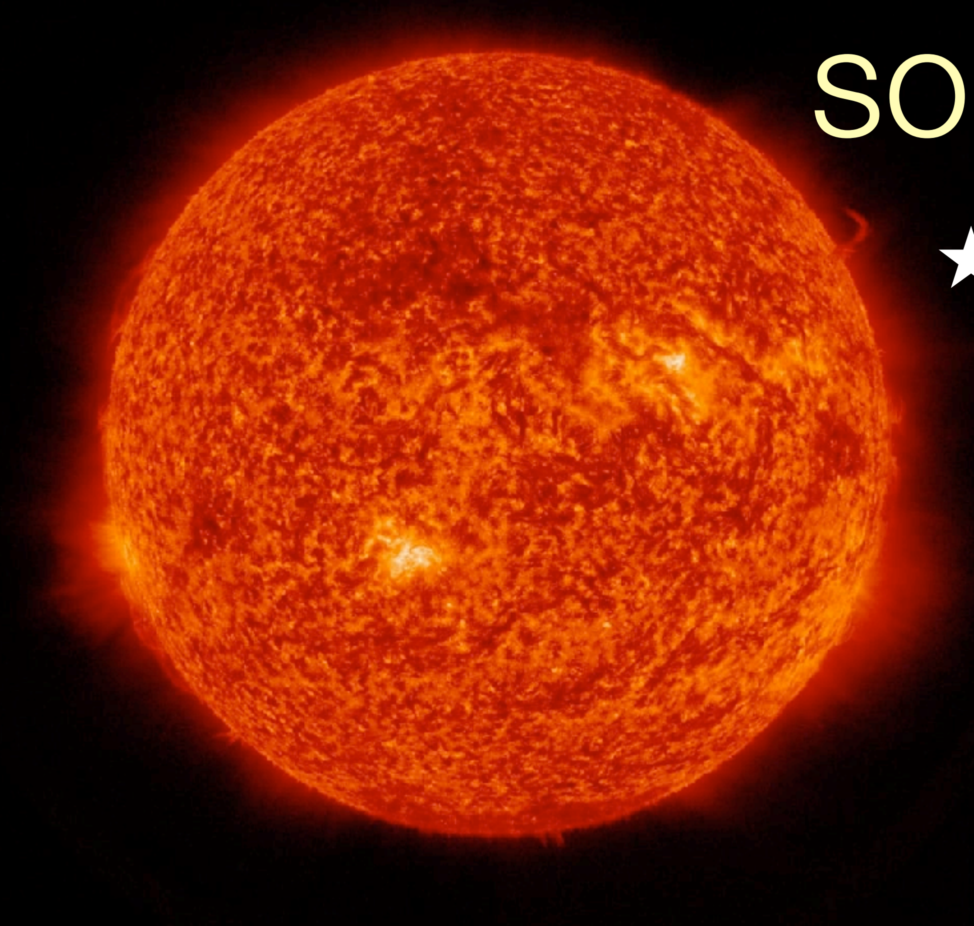


high-*E* neutrinos

- ★ origin of cosmic rays
- ★ AGNs, blazars, MW

Neutrinos as Astrophysical Messengers



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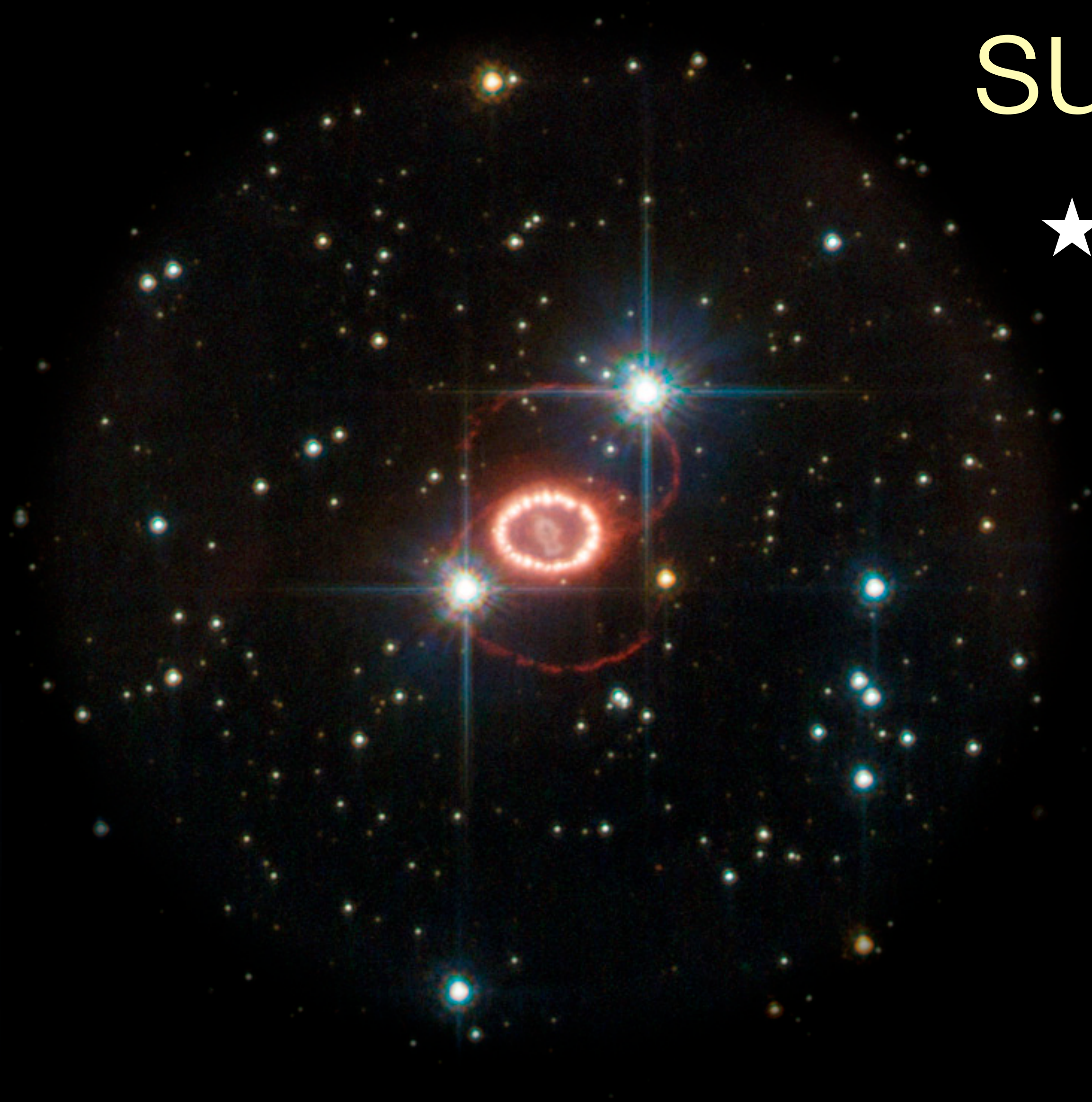
- ★ stellar evolution



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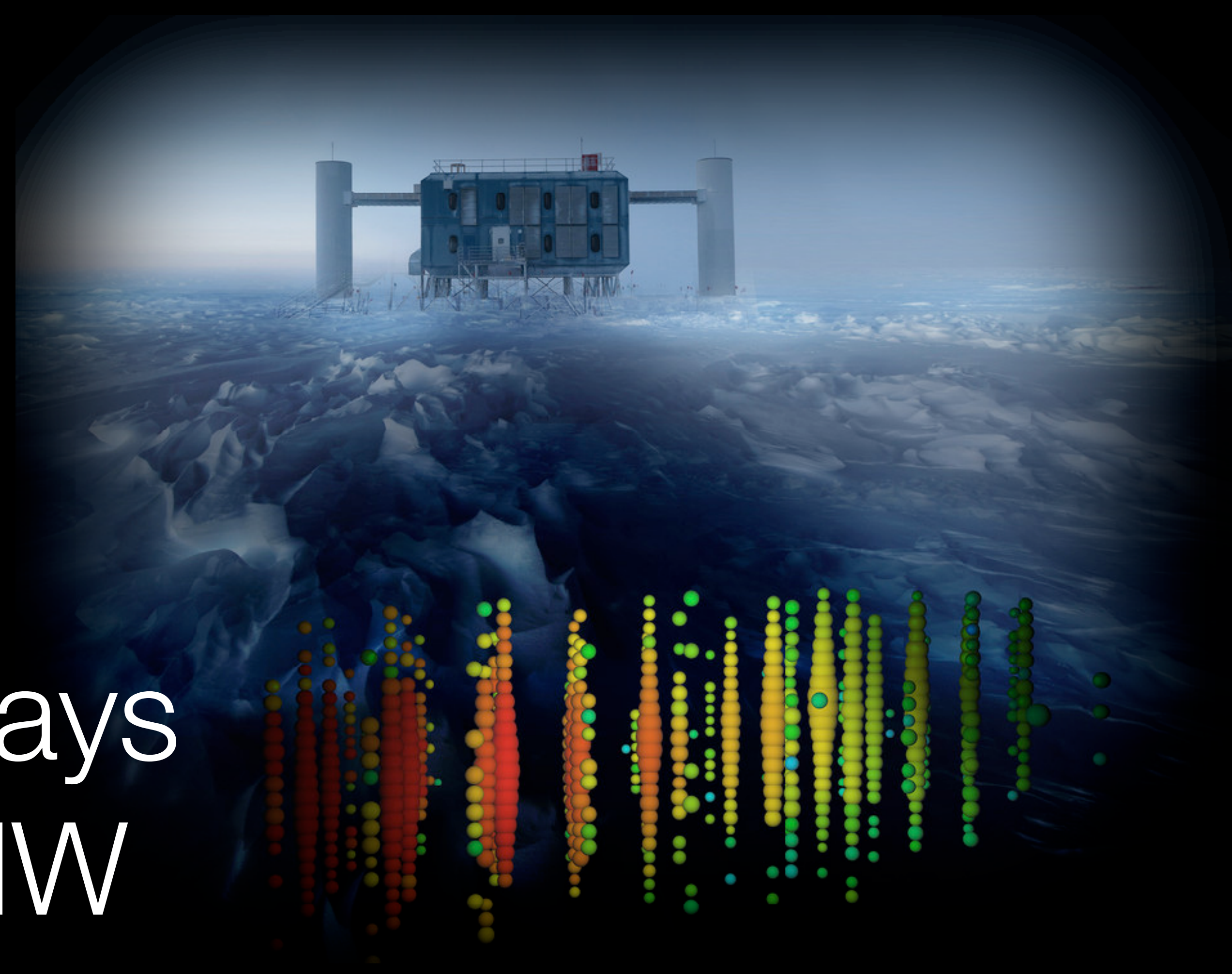

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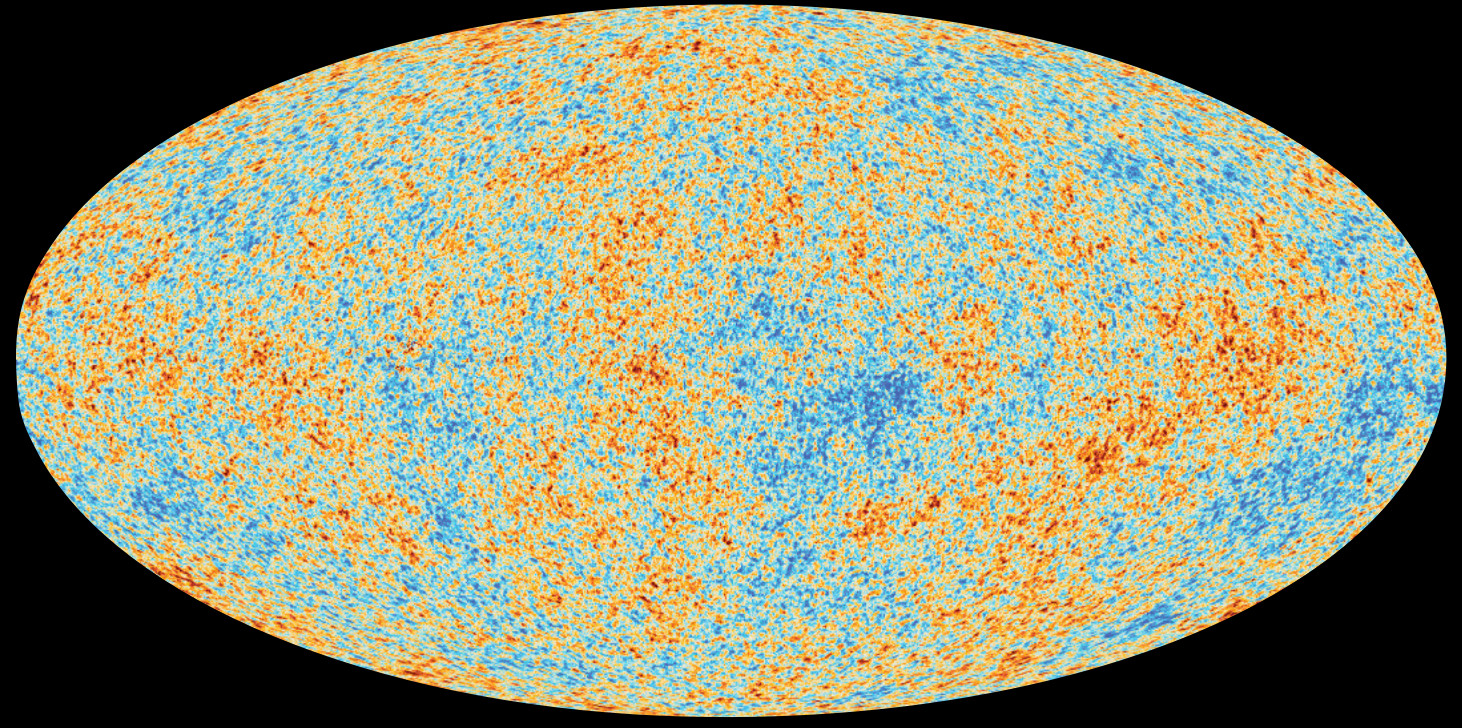
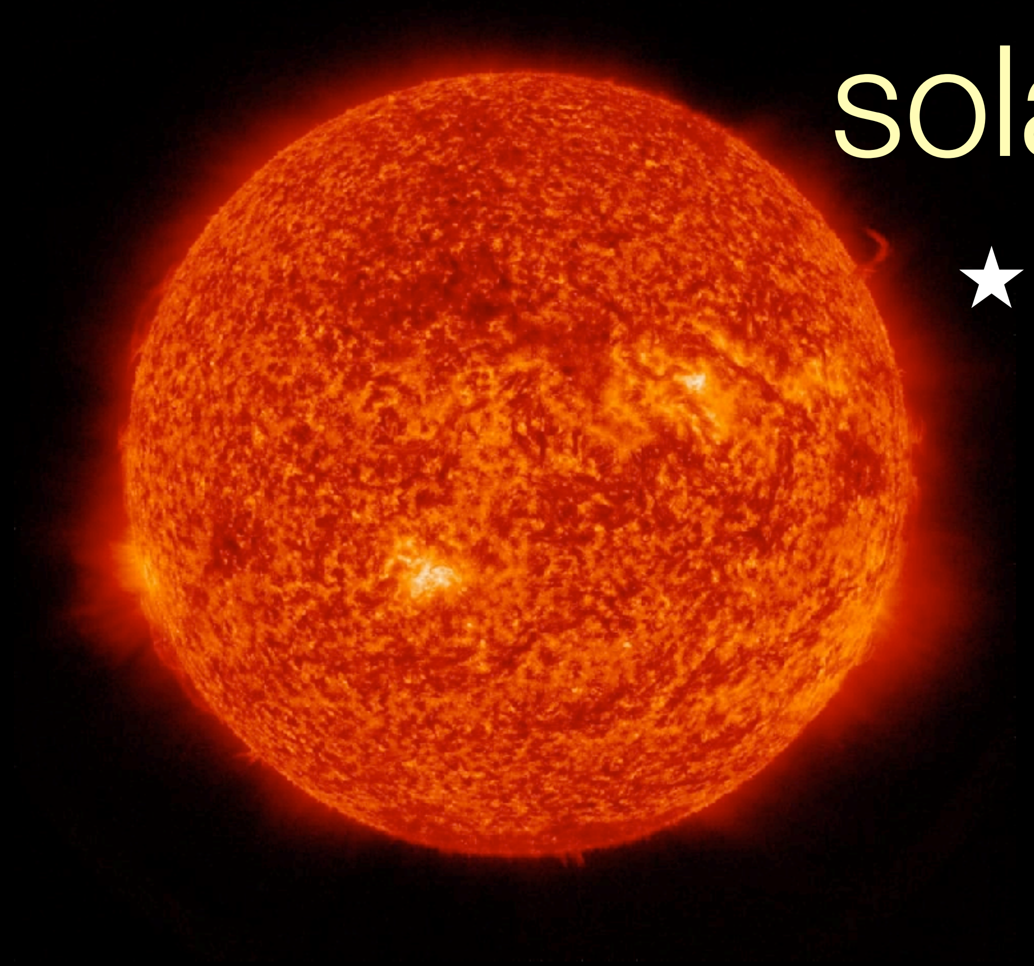


cosmology

- ★ early Universe

Neutrinos as Astrophysical Messengers



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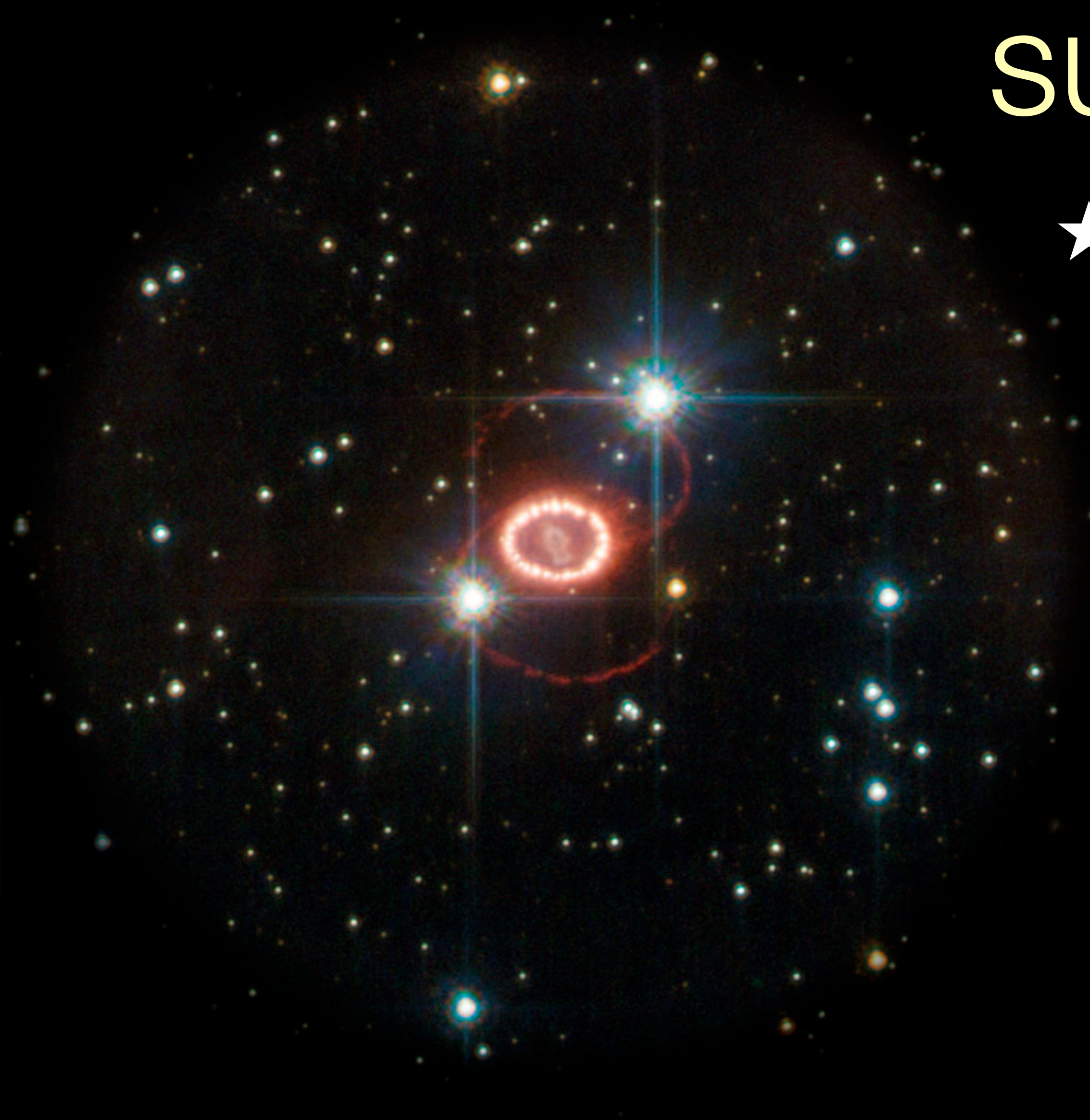

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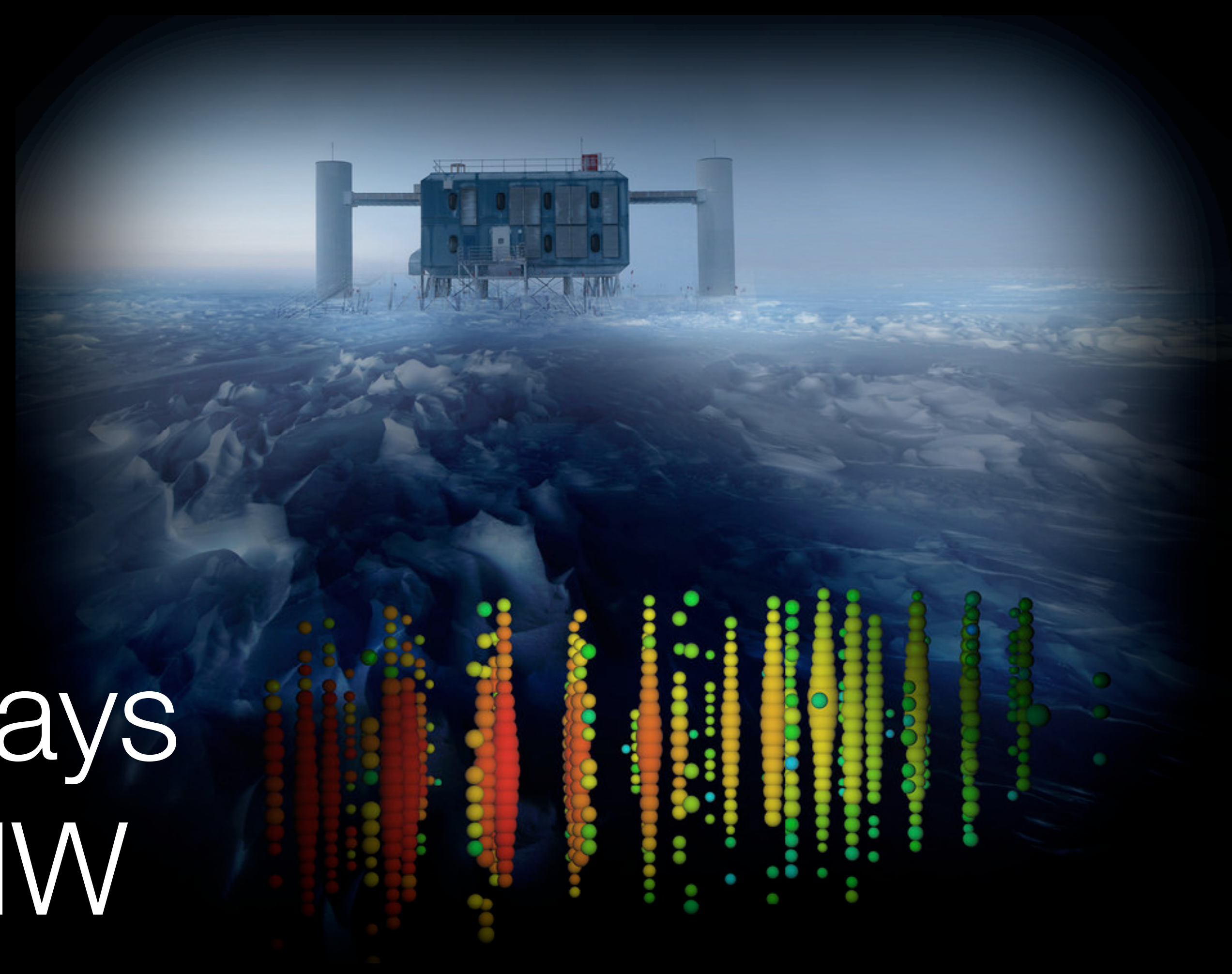

high-*E* neutrinos

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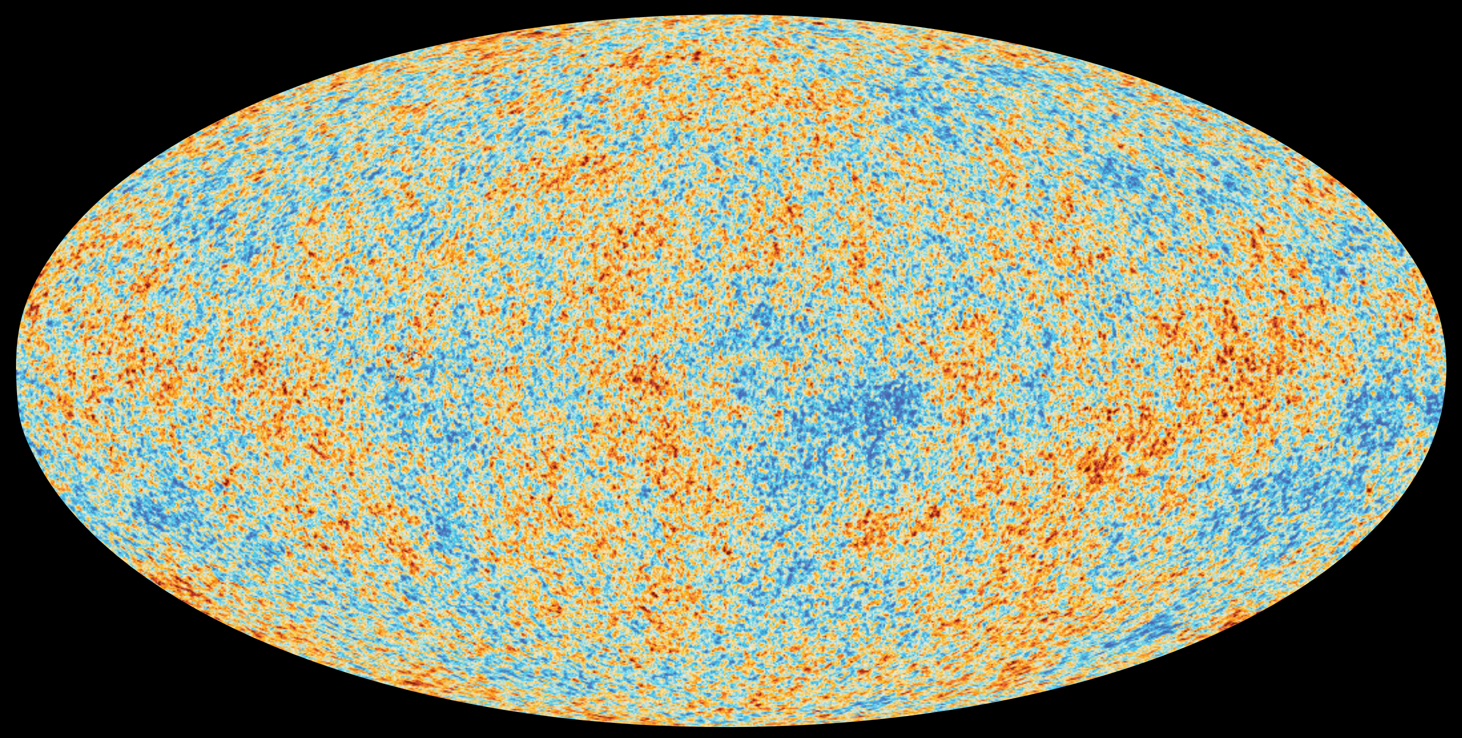
➠ talks by **Aya Ishihara** and **Yvonne Wong**



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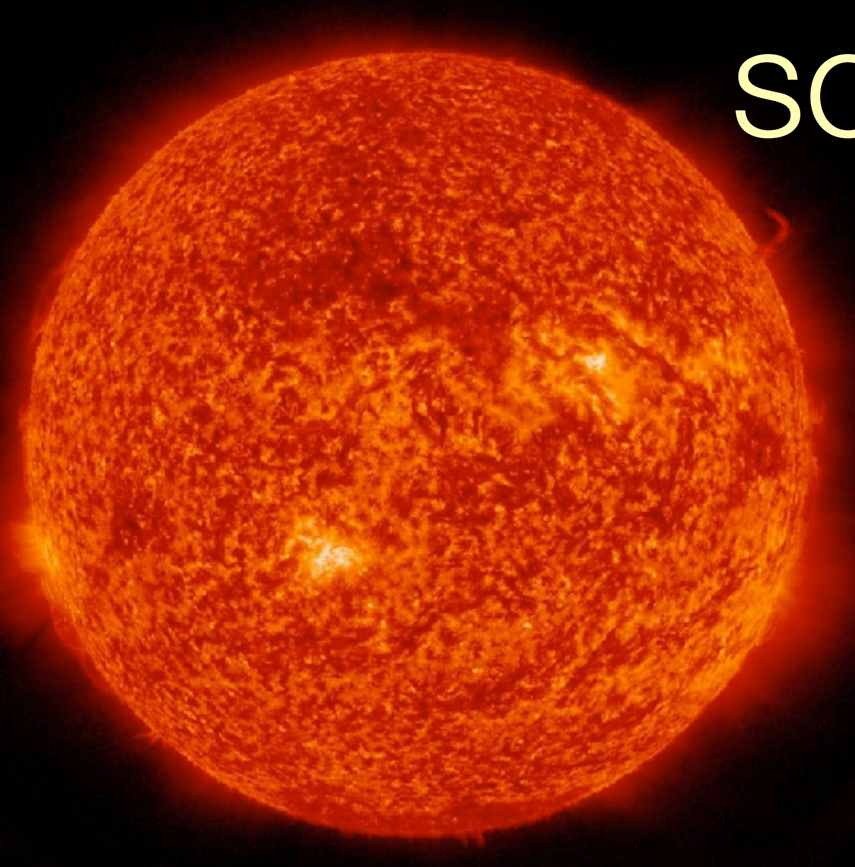
Neutrinos as Astrophysical Messengers



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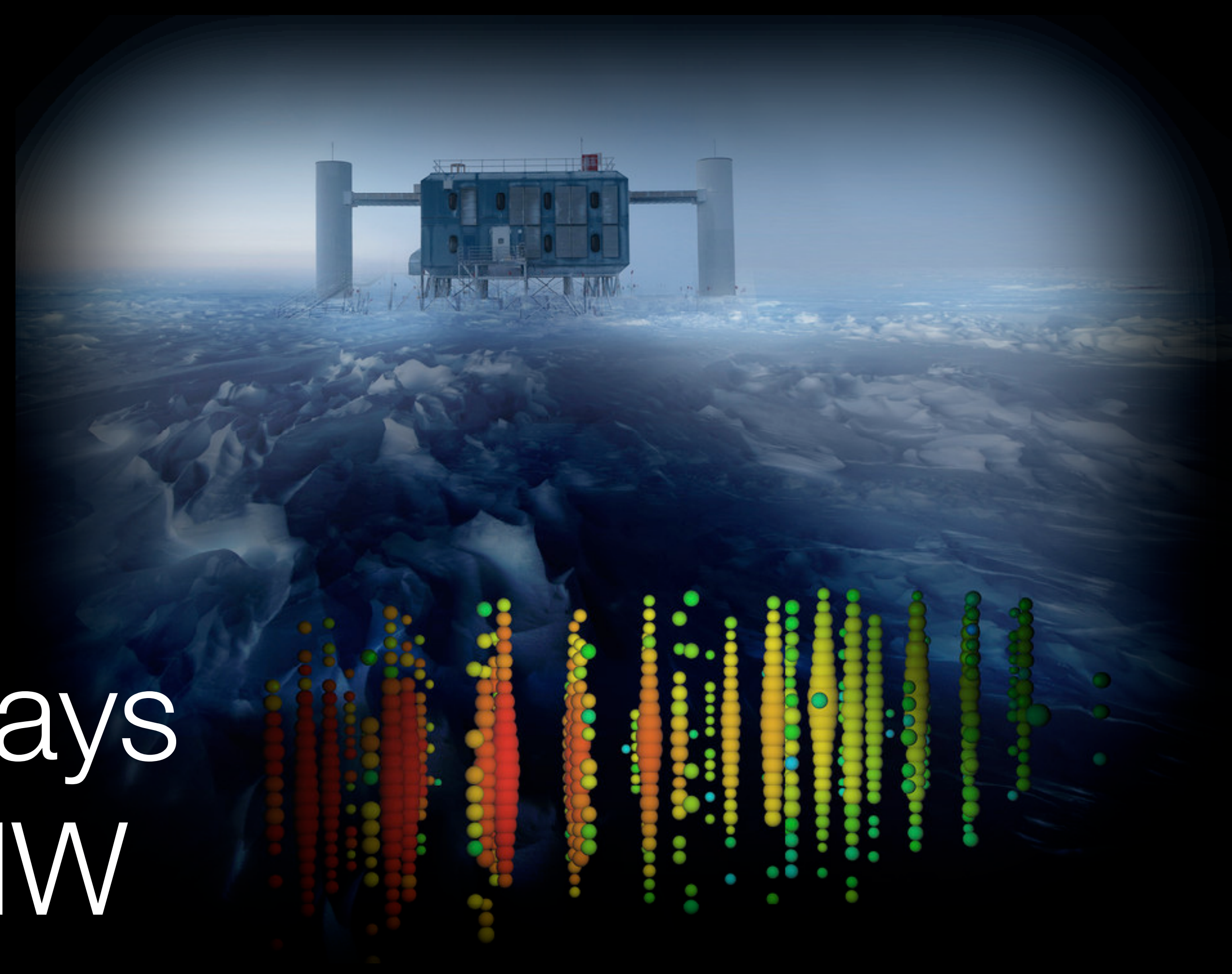
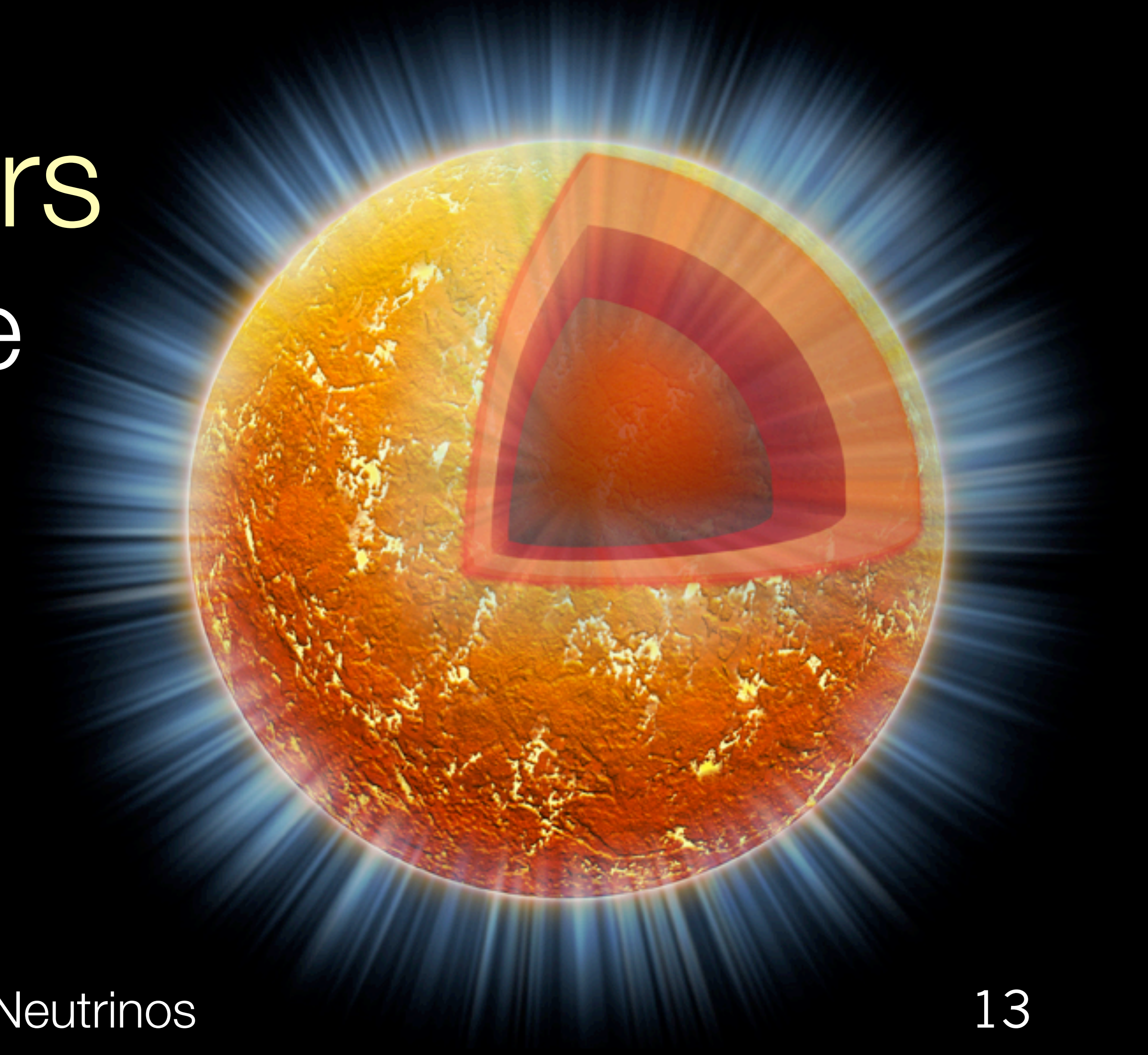
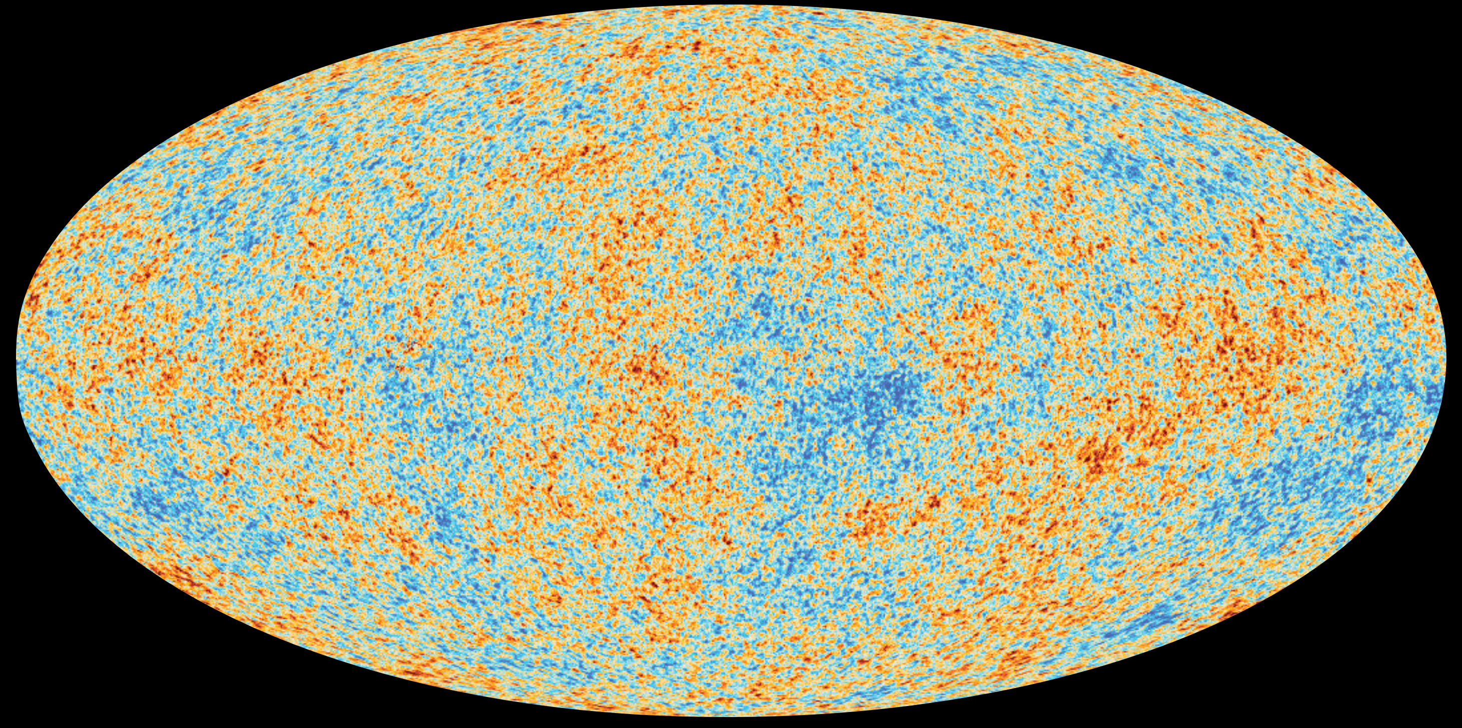


high-*E* neutrinos
- ★ origin of cosmic rays
- ★ AGNs, blazars, MW

neutron stars
- ★ common-envelope systems
- ★ muon decays (➠ bonus slides)





cosmology
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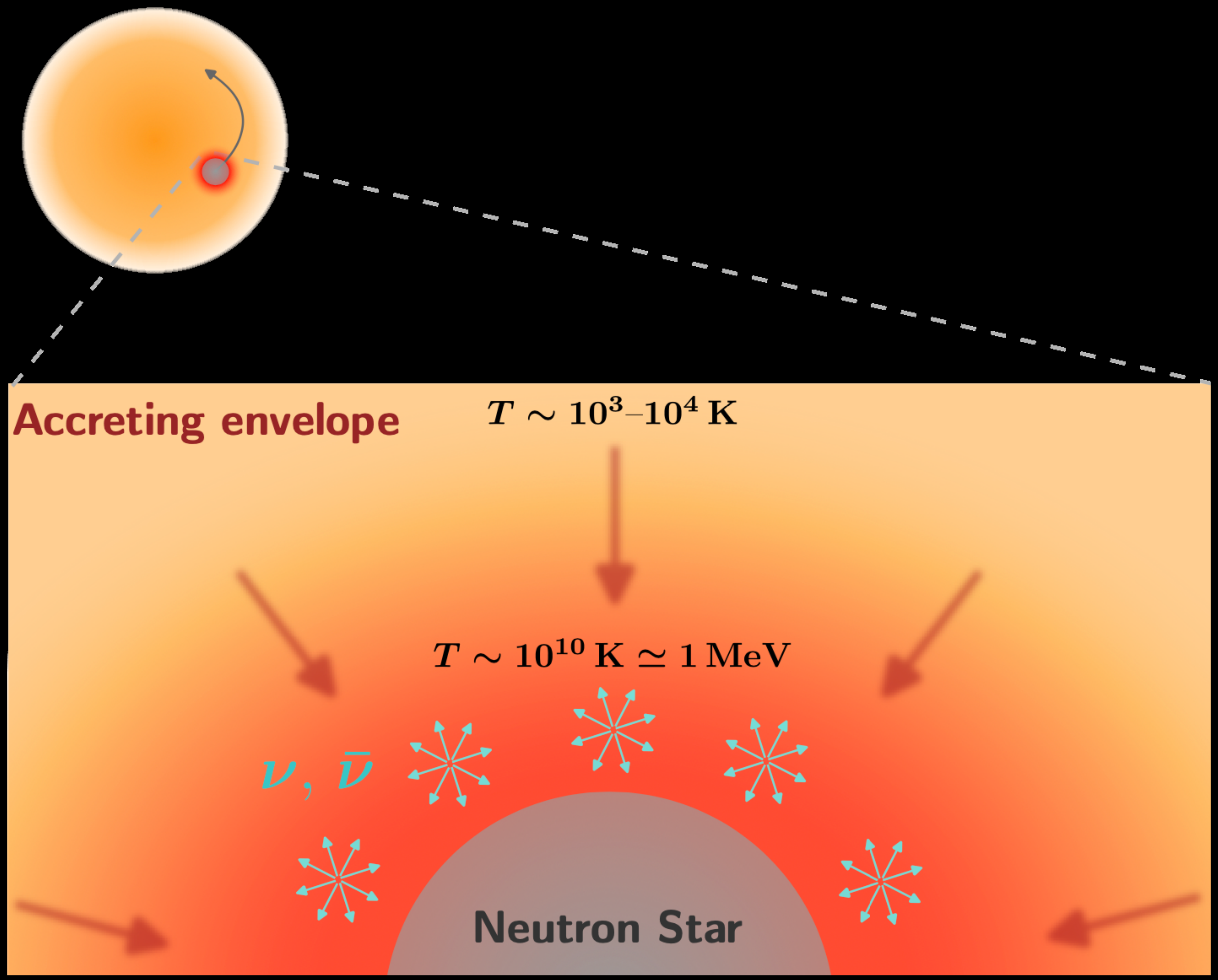
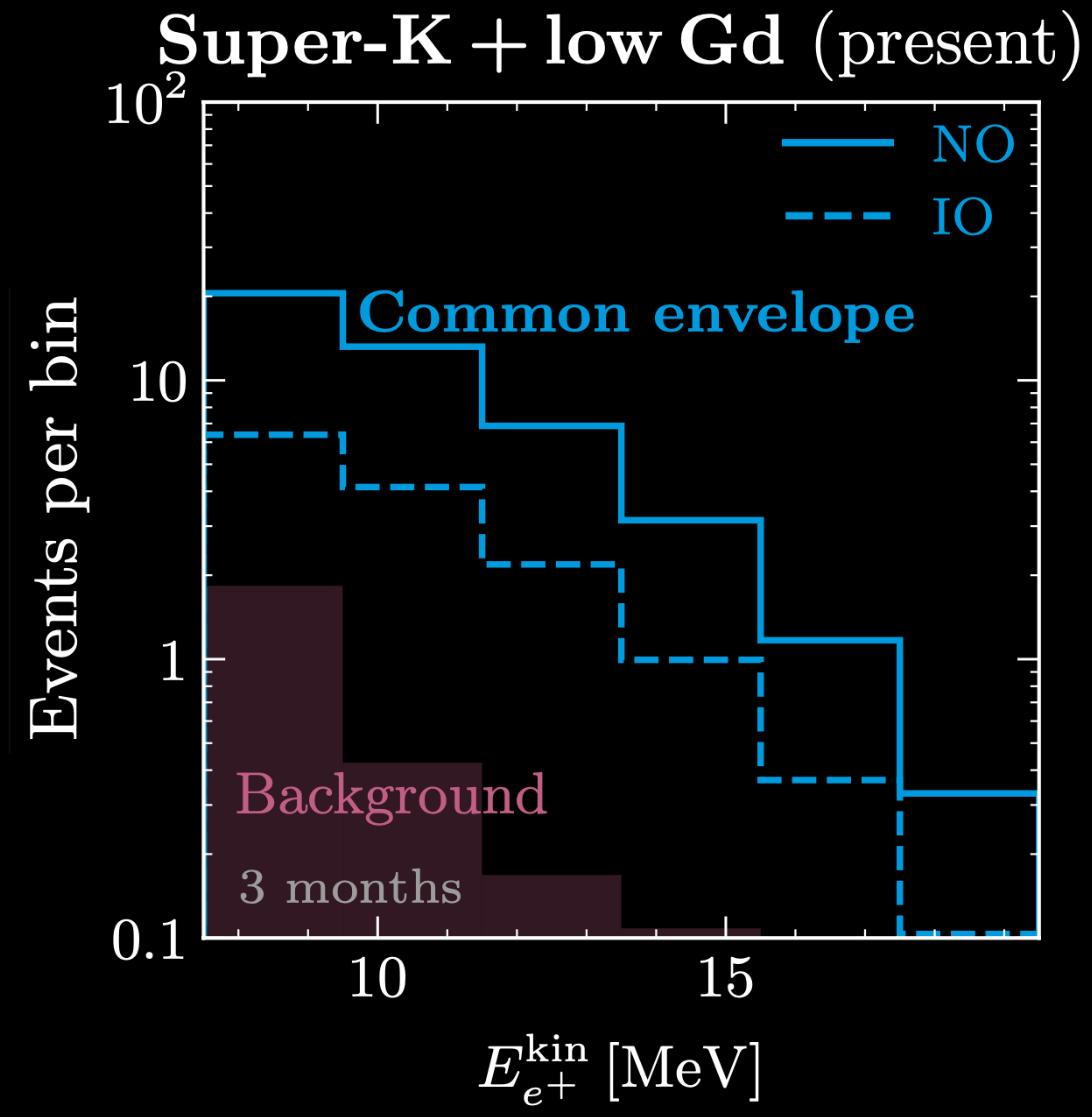
Common-Envelope Evolution



- neutron star enters companion star
- gigantic accretion rates
  (up to 0.1 $M_\odot$/yr for several months)
- only cooling channel is via neutrinos
  ➠ new type of neutrino source
- in addition: de-protonization
- rate < core collapse SN rate

Beacom Esteban JK *in preparation*

Common-Envelope Evolution



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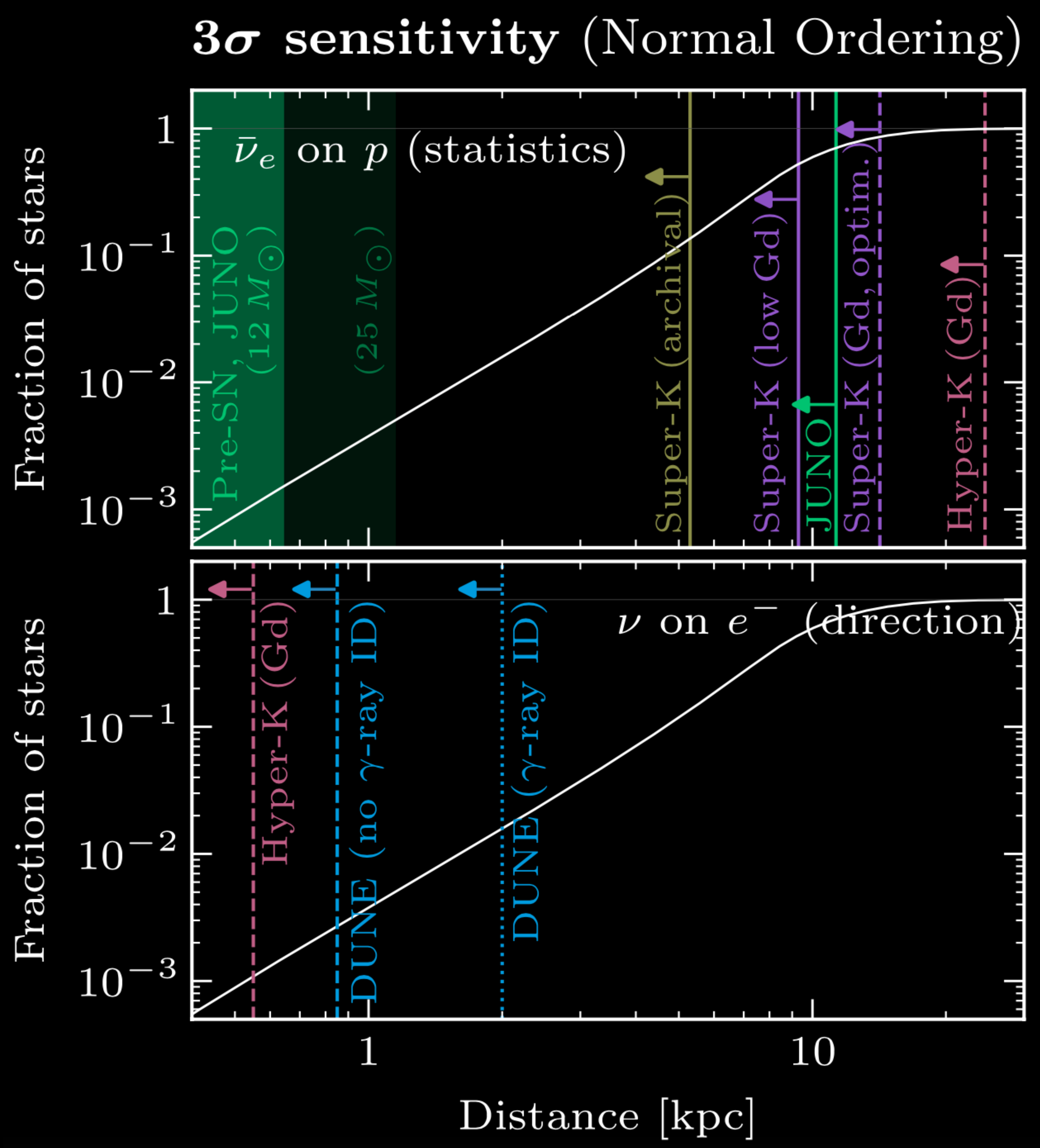

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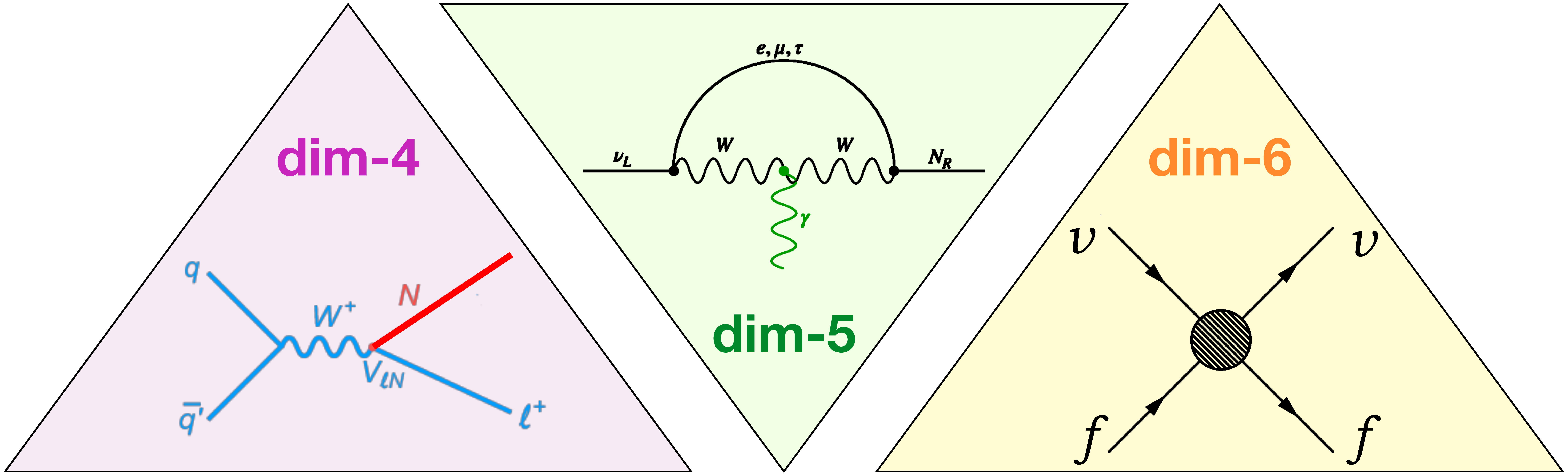
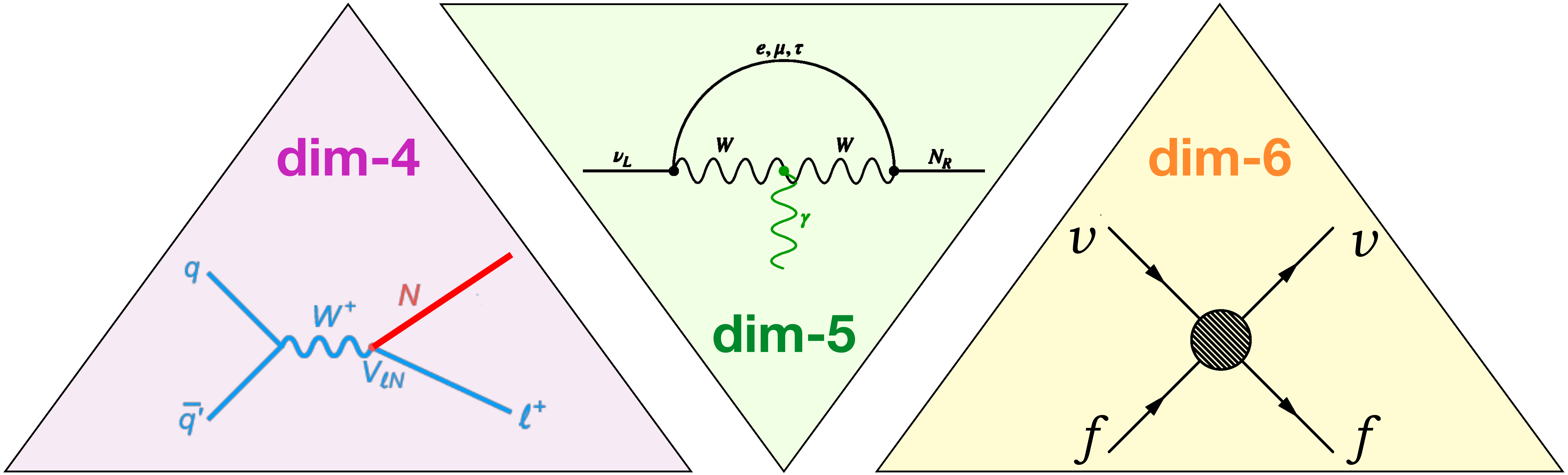
Neutrino Physics Beyond the Standard Model



Neutrino Physics Beyond the Standard Model

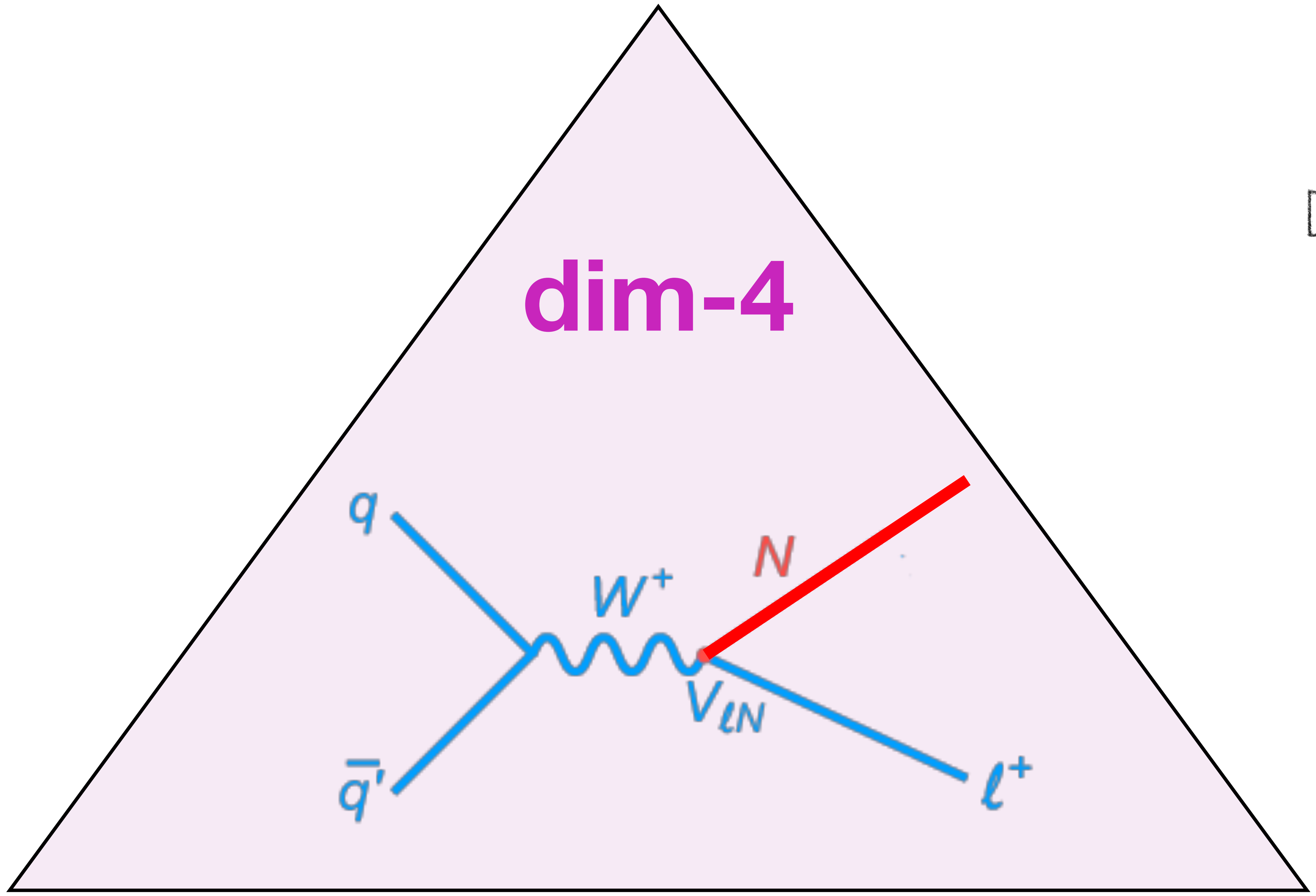
e.g. neutrino magnetic moments



e.g. sterile neutrinos

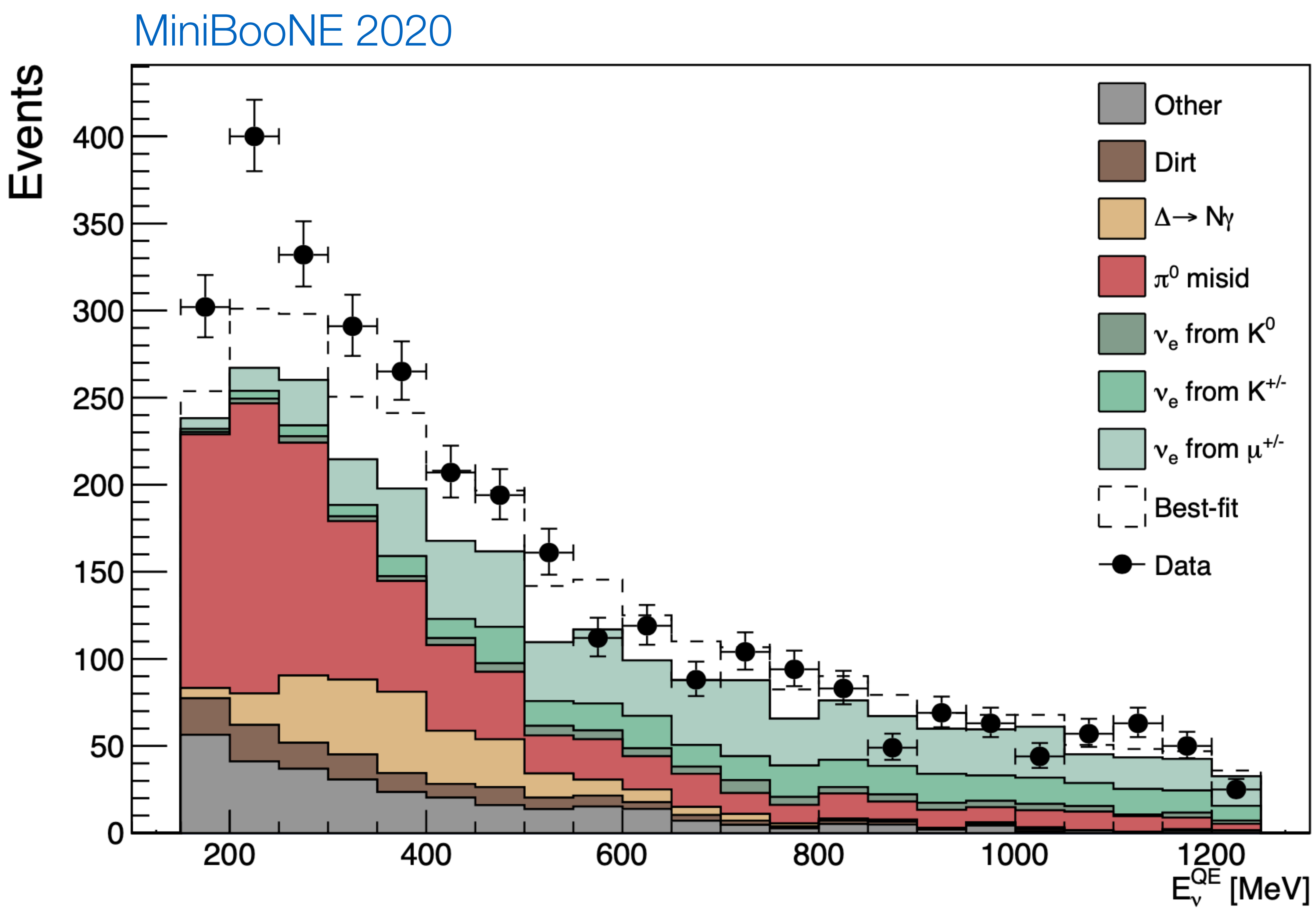
e.g. non-standard interactions

Sterile Neutrinos



- Very generic extension of SM
  - leftovers of extended gauge multiplets?
- Useful phenomenological tool
  - ν masses
    (seesaw mechanism, m ~ TeV…M_{Pl})
  - cosmic baryon asymmetry
    (thermal leptogenesis at m»100 GeV,
    ARS leptogenesis at m<100 GeV)
  - dark matter (m ~ keV)
  - mediator to a dark sector (any mass)

MiniBooNE



MiniBooNE 2020
Events
400
350
300
250
200
150
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0
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400
600
800
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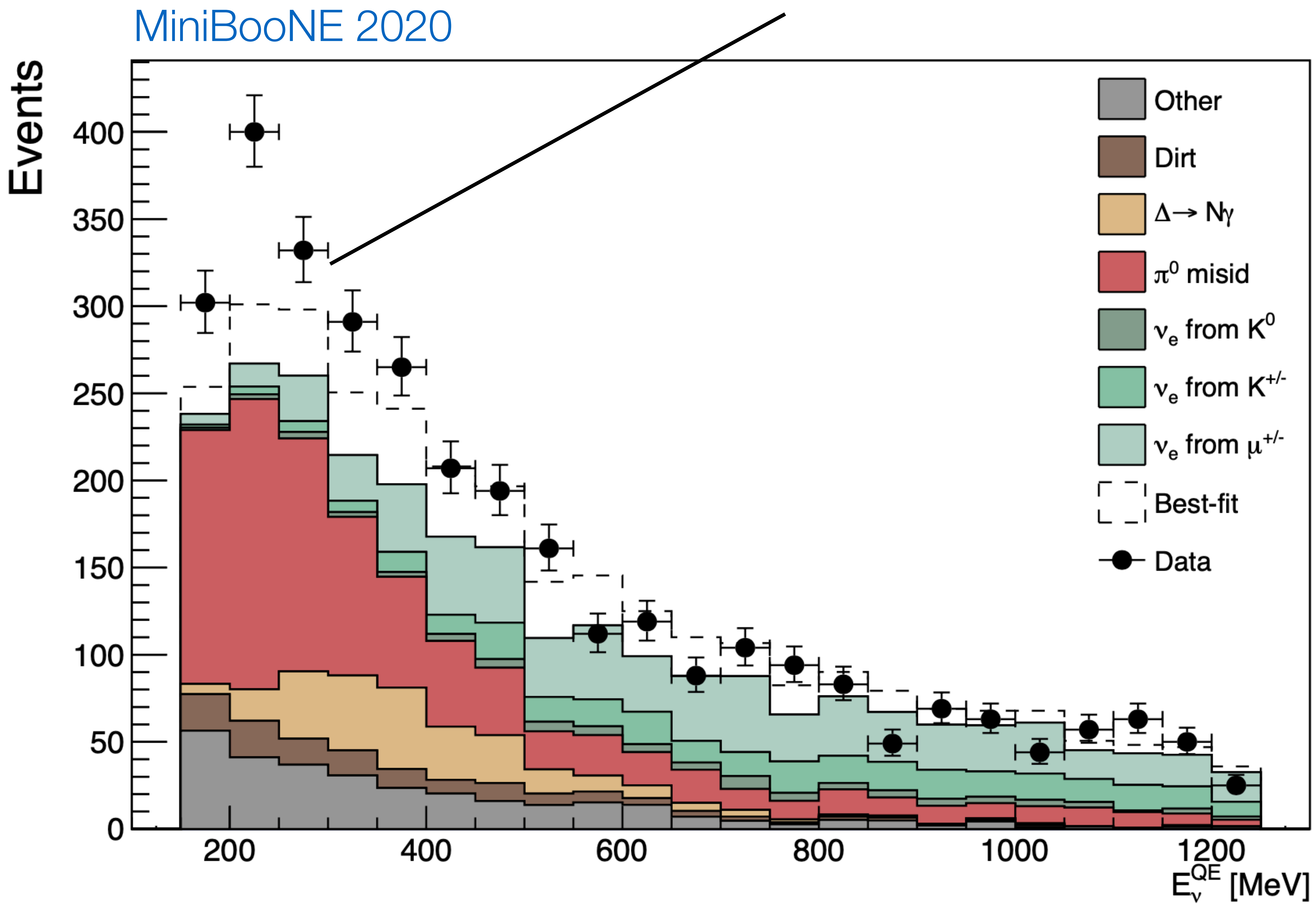
1200
E_ν^{QE} [MeV]
Other
Dirt
$\Delta \to N\gamma$
π^0 misid
ν_e from K^0
ν_e from $K^{+/-}$
ν_e from $\mu^{+/-}$
Best-fit
Data

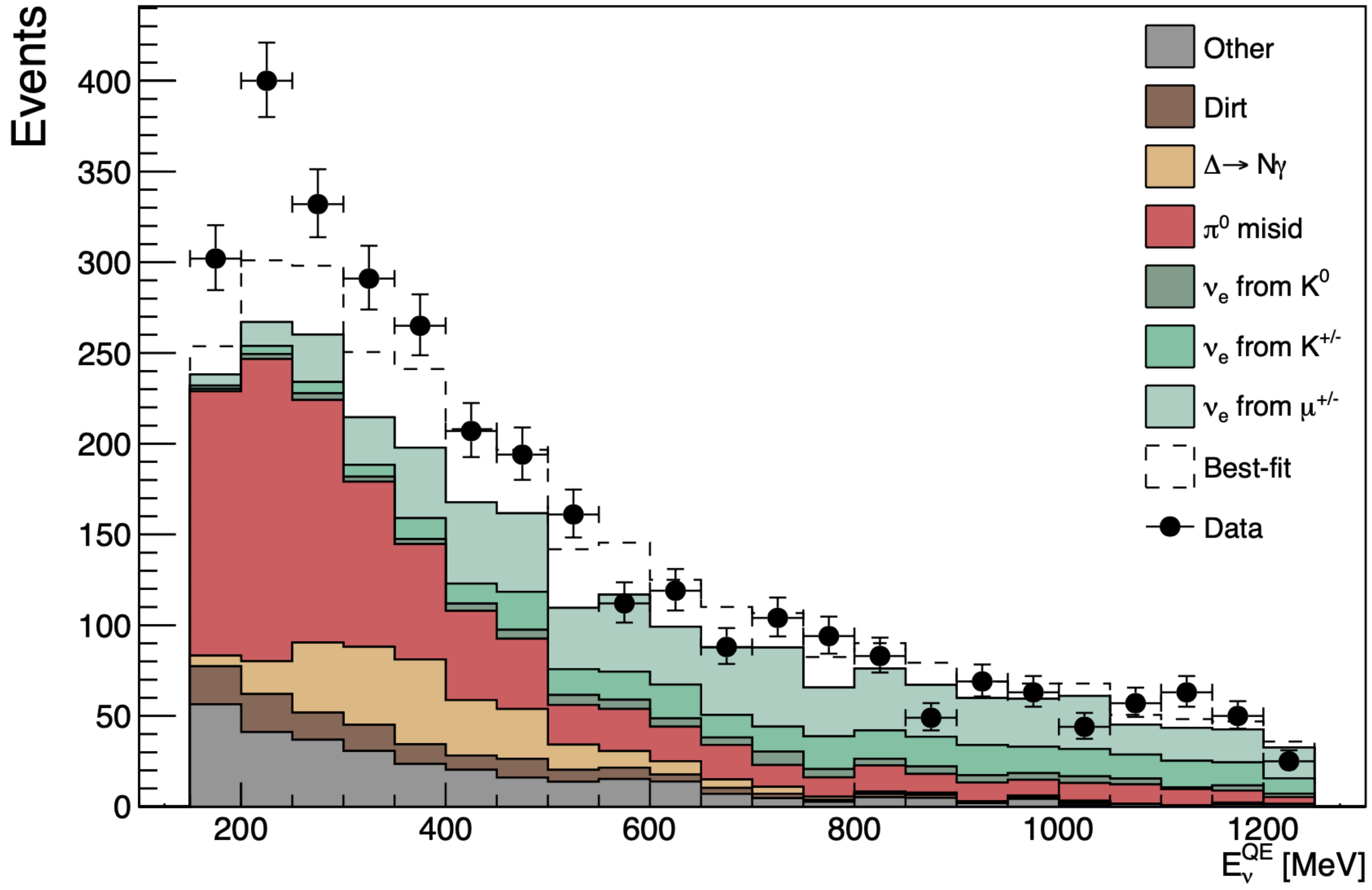
MiniBooNE

4.8 σ excess of ν_e in a ν_μ beam



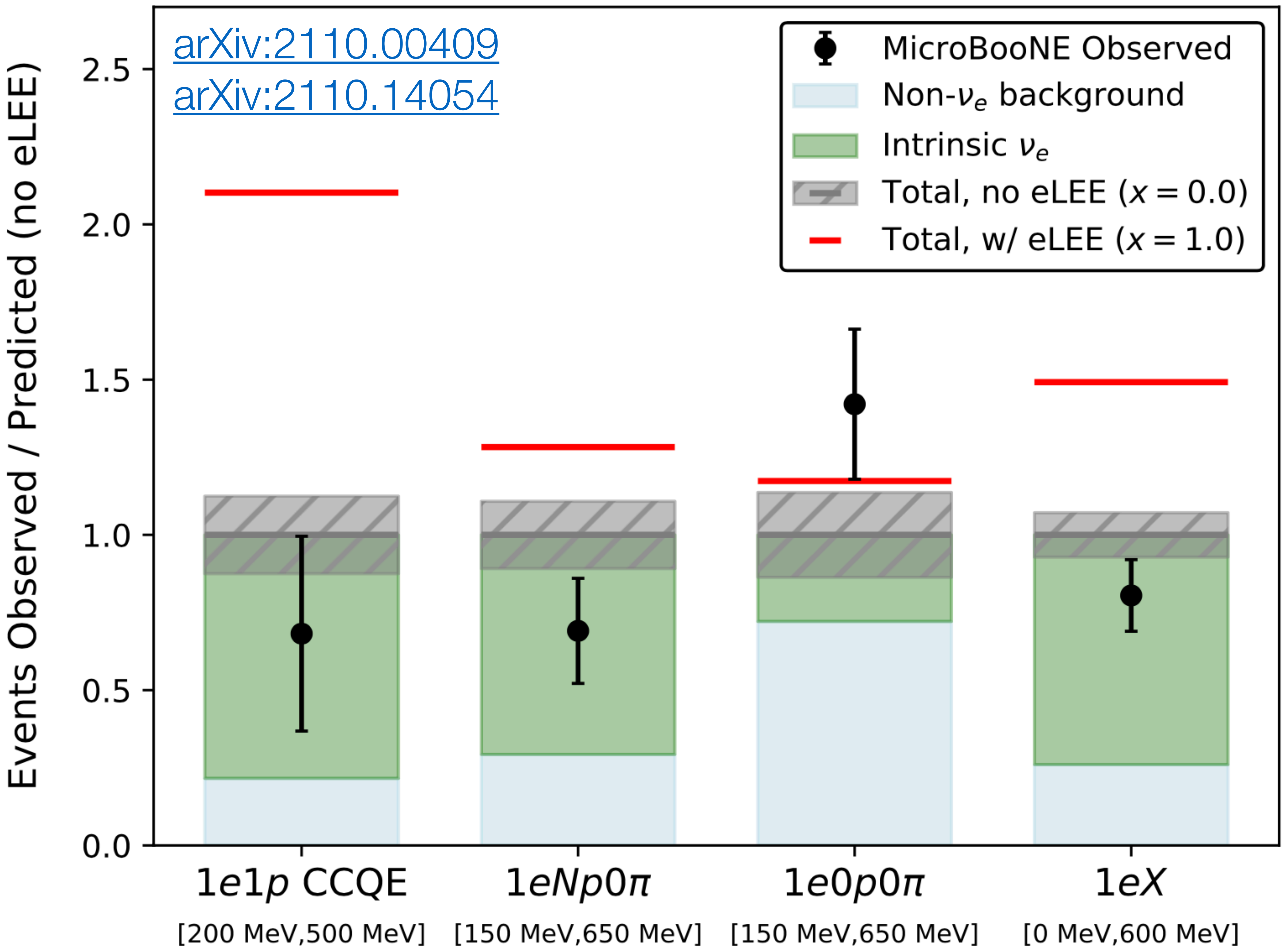
MiniBooNE

MiniBooNE 2020



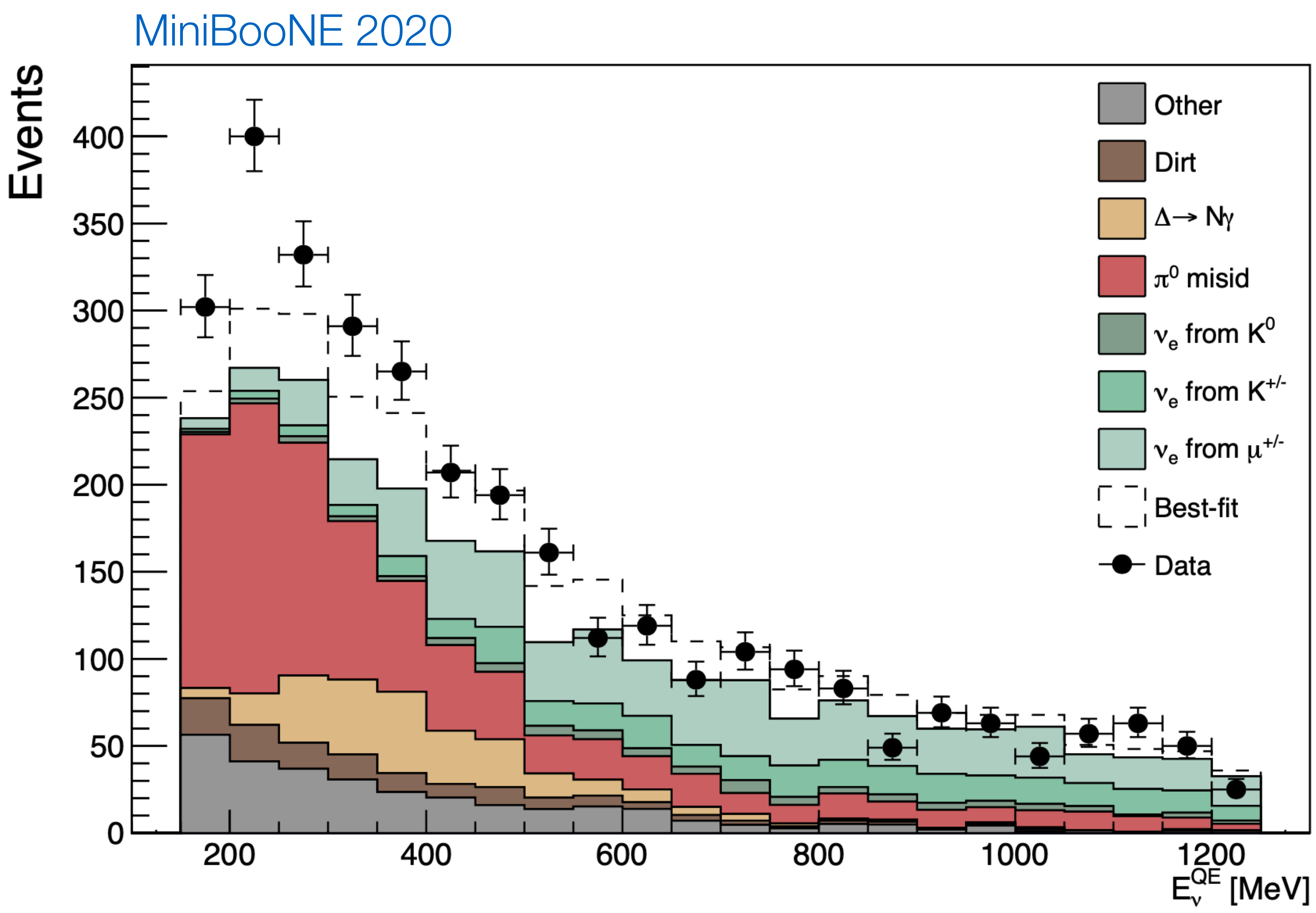
- baseline too short for std. oscillations
- but could be explained by eV-scale sterile neutrino
- ~ consistent with other anomalies
  ➠ talk by Mikhail Danilov
- but inconsistent with null searches

MicroBooNE



- LAr TPC ➠ superior event reconstruction
- no excess seen so far
  (but still consistent with MiniBooNE)

MiniBooNE



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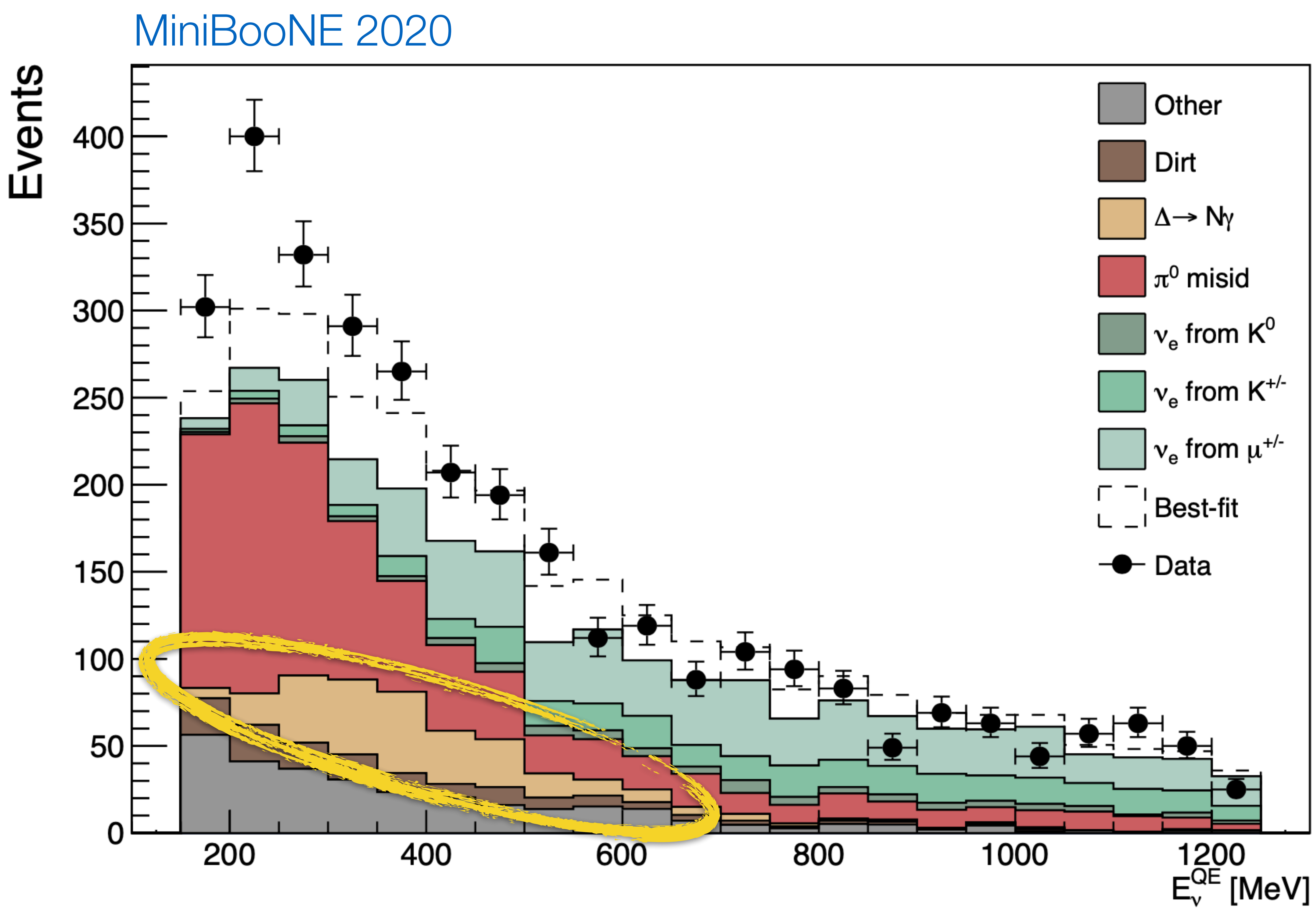

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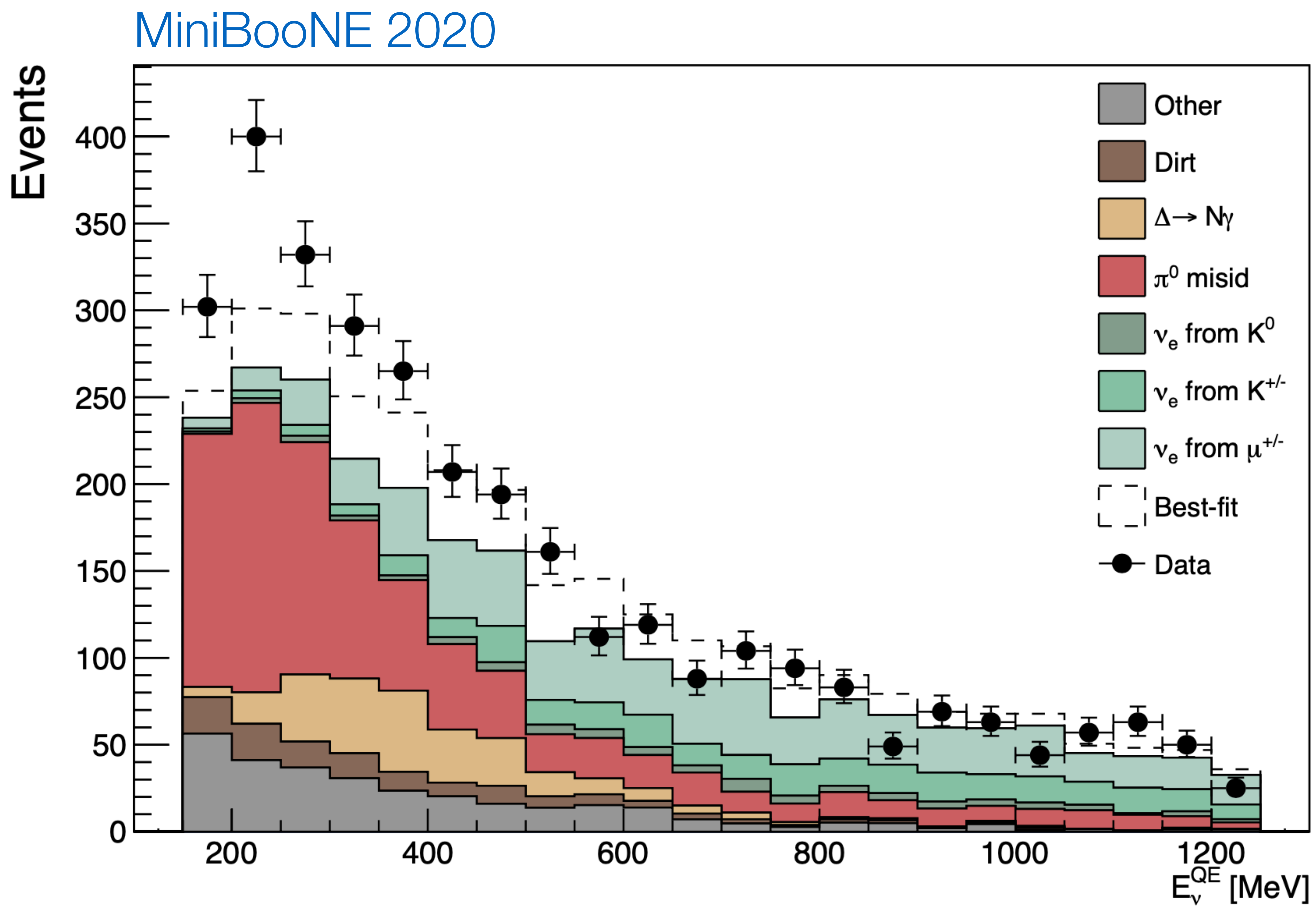
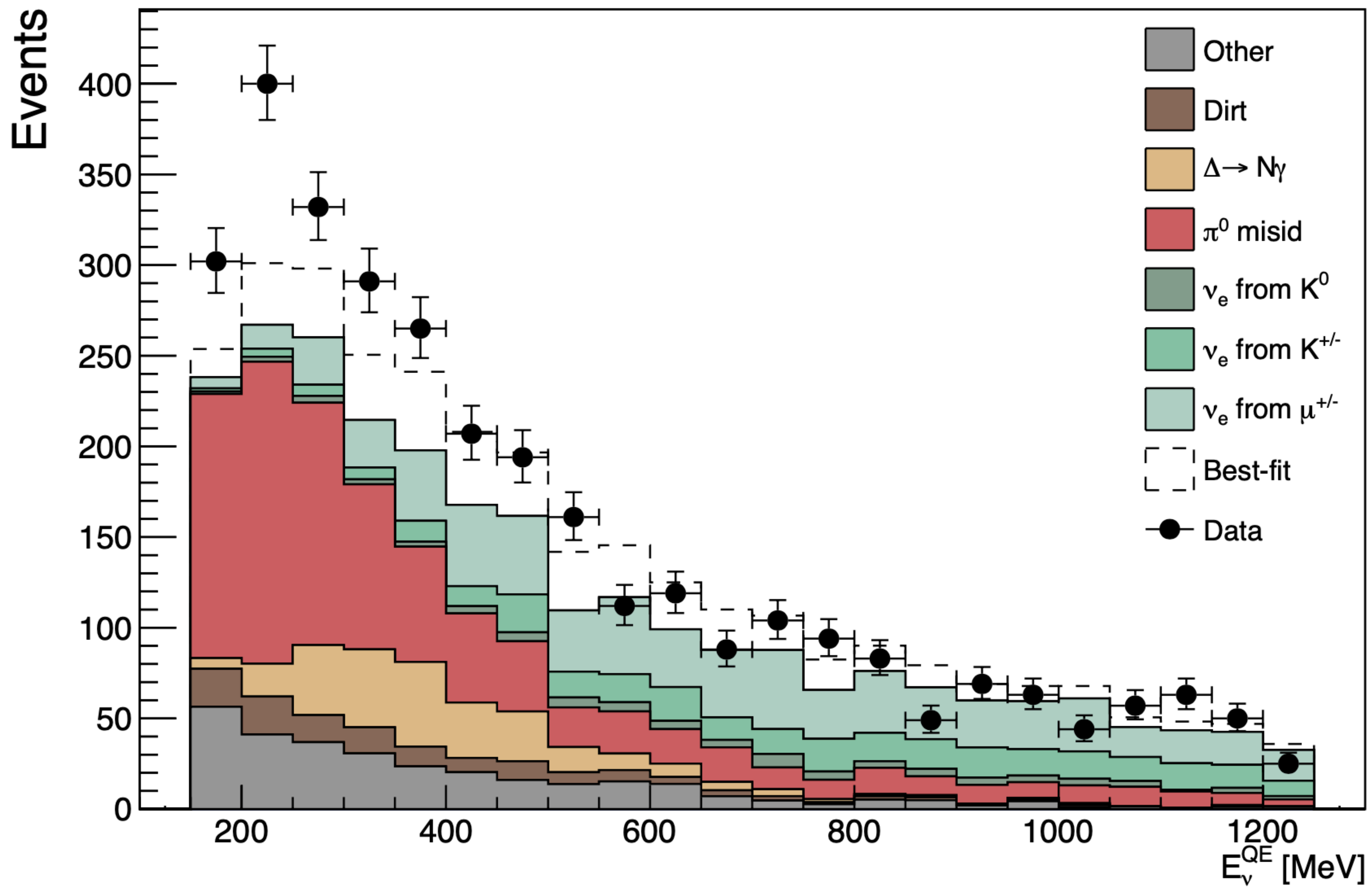
$\Delta \rightarrow N\gamma$ Background



- NC interaction:
  $\nu + N \rightarrow \nu + \Delta(1232)$
- Most $\Delta(1232)$ decay to $\pi + N$
- But rare decay exists to $\gamma + N$
- MiniBooNE cannot distinguish single-γ background from CC ν_e signal

$\Delta \to N\gamma$ Background

MiniBooNE 2020

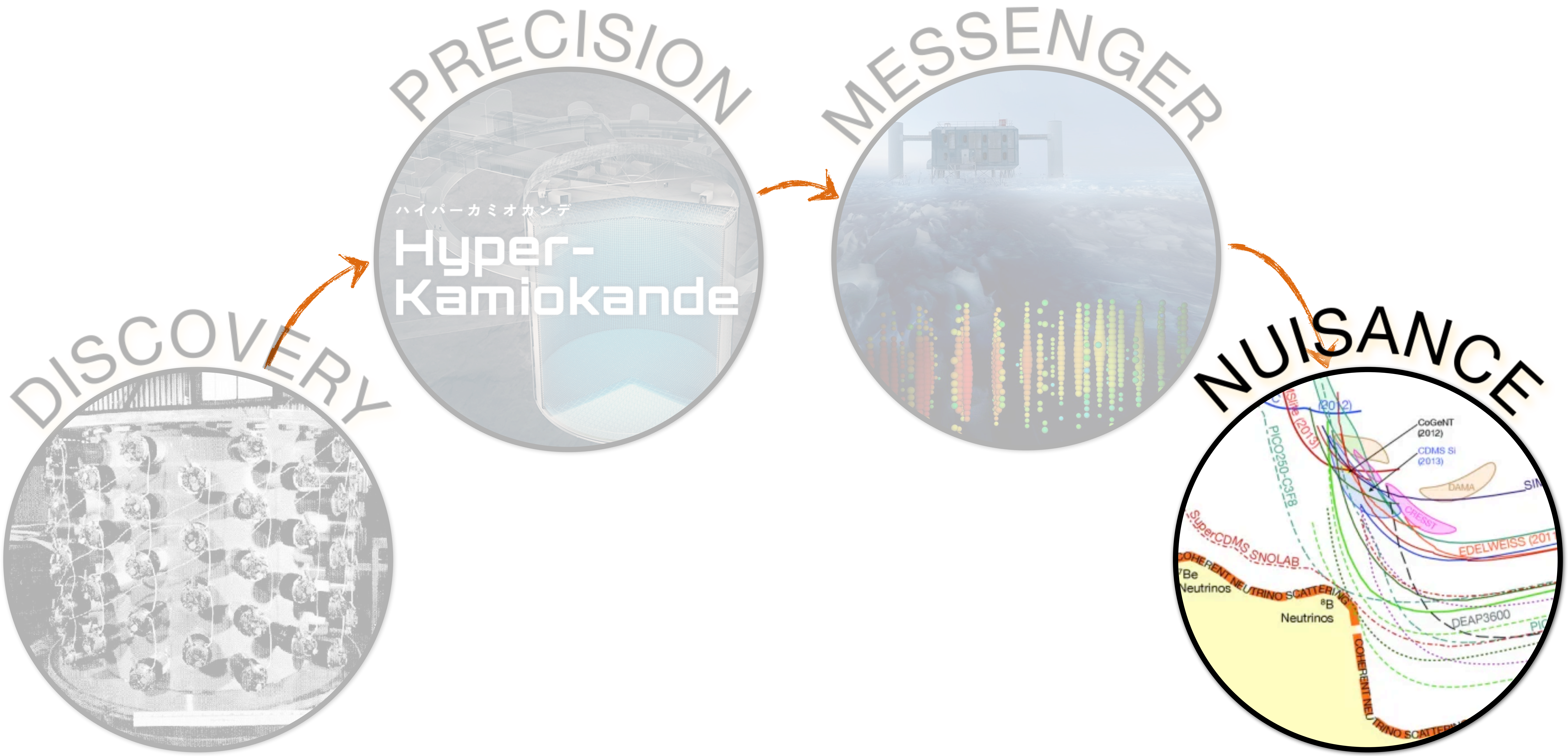


- Δ production rate can be estimated from $\Delta \to \pi N$
- Pions may be absorbed on their way out of the nucleus
  - may excite another $\Delta(1232)$ ➠ $\Delta \to \gamma N$ enhanced
  - or may be absorbed ➠ control region suppressed

Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

(These effects have been taken into account by MiniBooNE)

MiniBooNe, arXiv:2006.16883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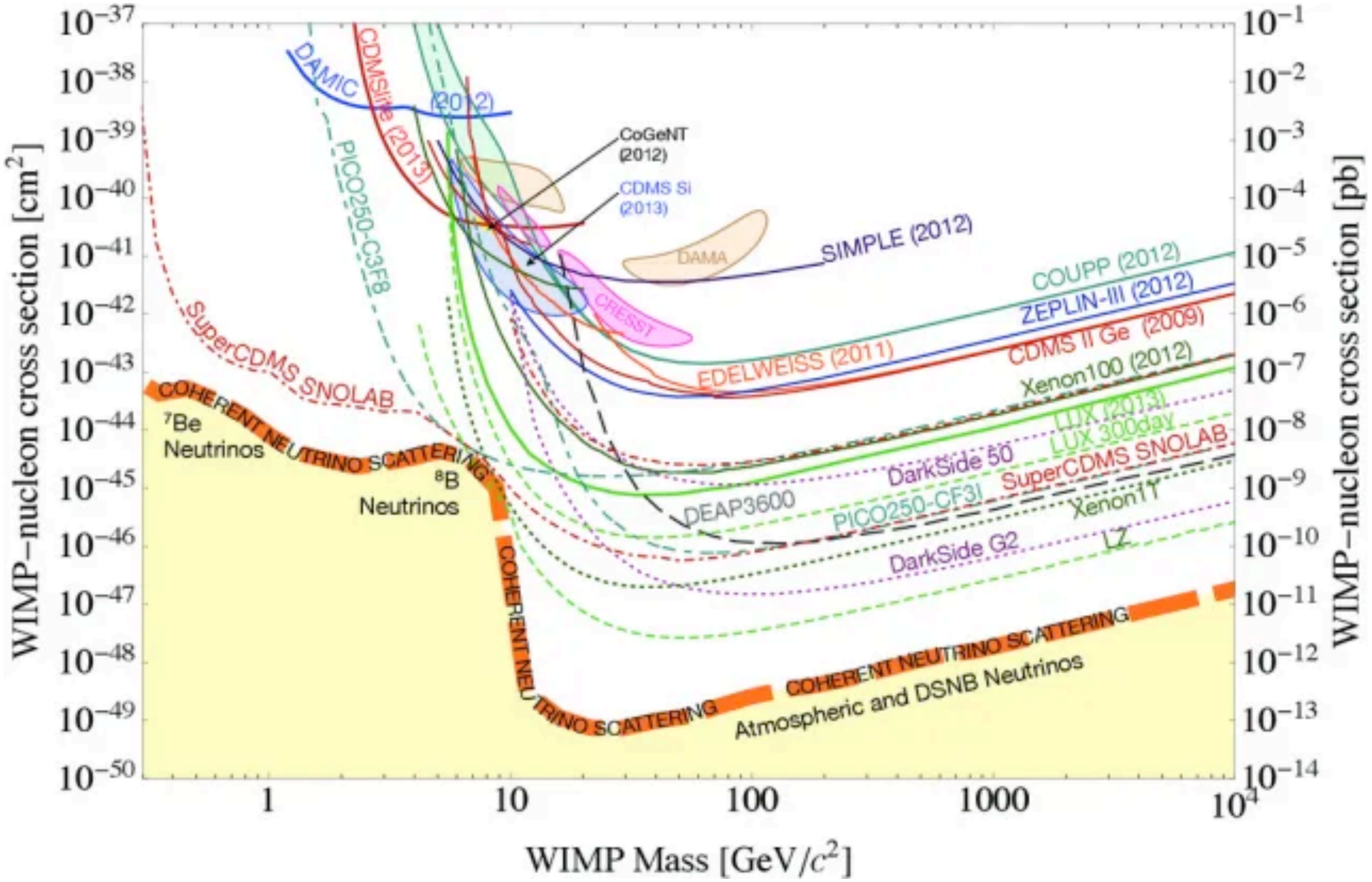
Neutrinos as a Nuisance



Neutrinos have become a major background to

- Direct Dark Matter searches
- Collider searches for dark matter
- new physics searches in beam dump experiments
- …

Turning Lemons into Lemonade

Neutrino Physics with Dark Matter Detectors

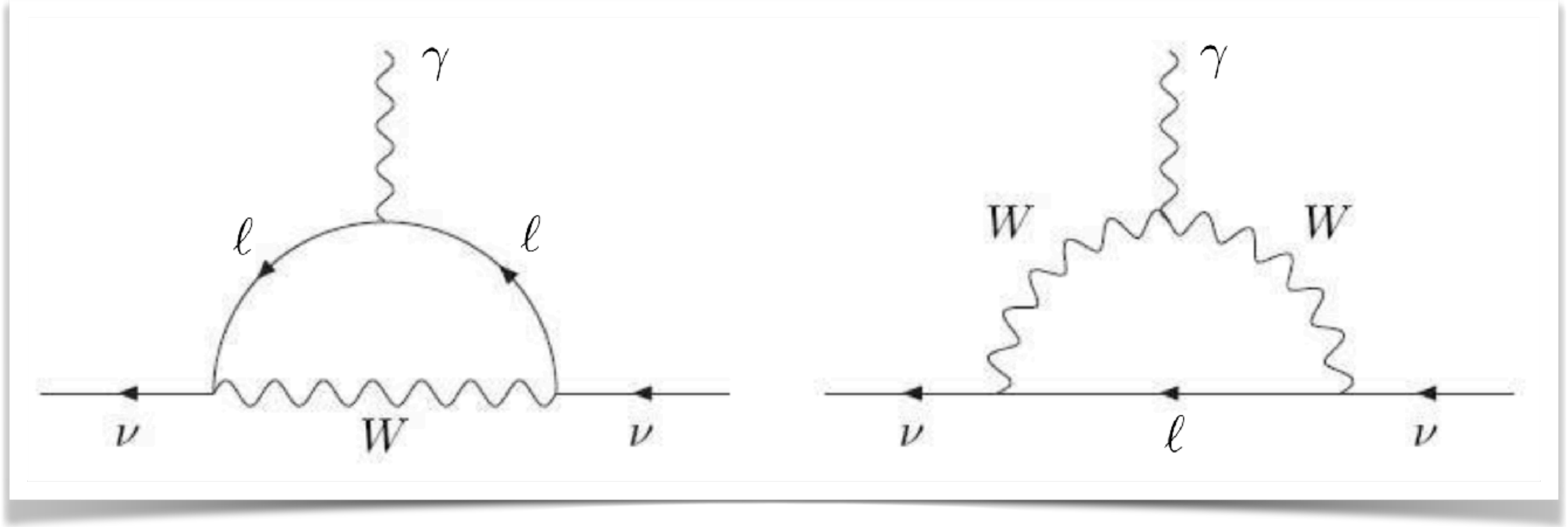
Example: Neutrino Magnetic Moments

$$\mathcal{L} \supset \frac{1}{2} \mu_\nu^{\alpha\beta} \bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

Couples LH and RH neutrinos

electromagnetic field strength tensor

In the SM: generated at 1-loop



tiny in the SM ($< 10^{-19}\ \mu_B$), but possibly much larger in BSM

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1/E enhancement due to massless *t*-channel mediator

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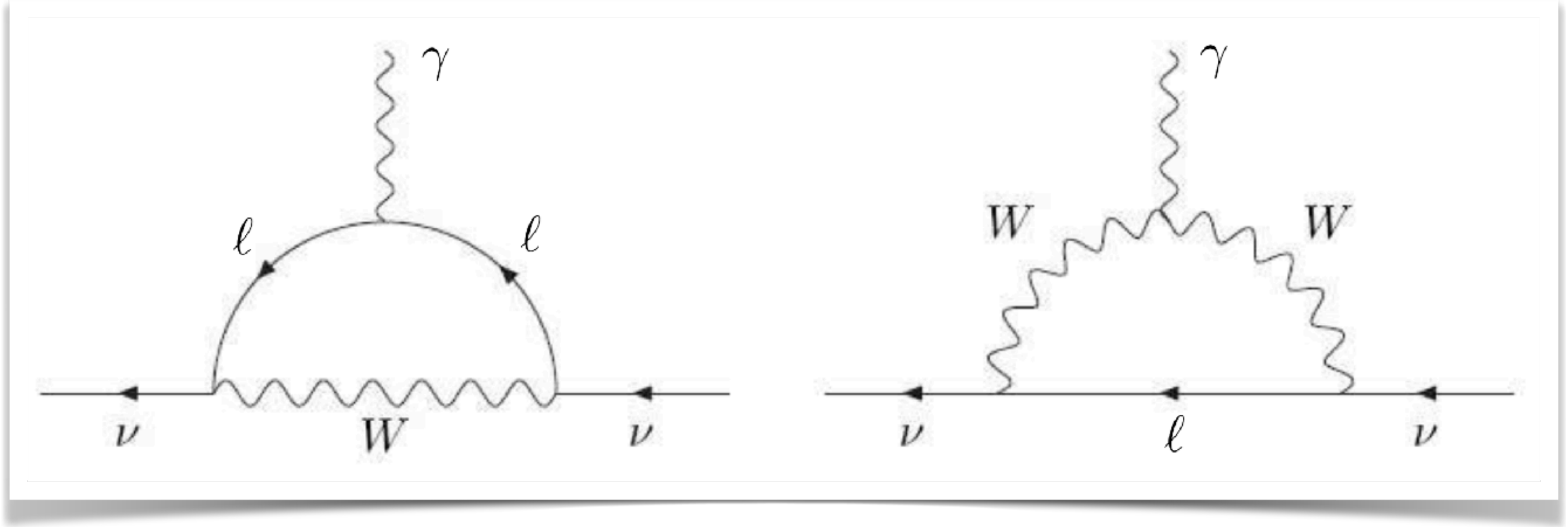

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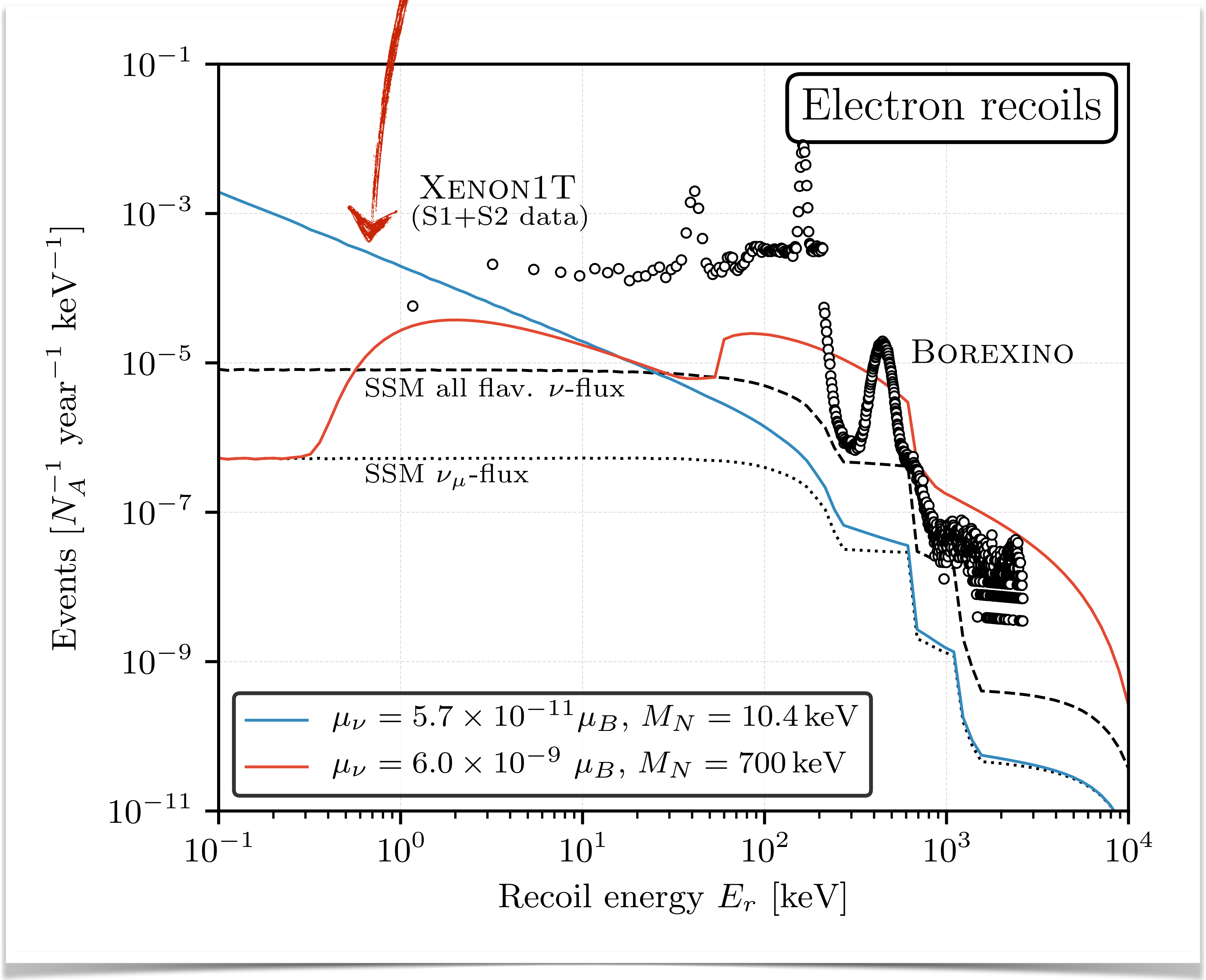

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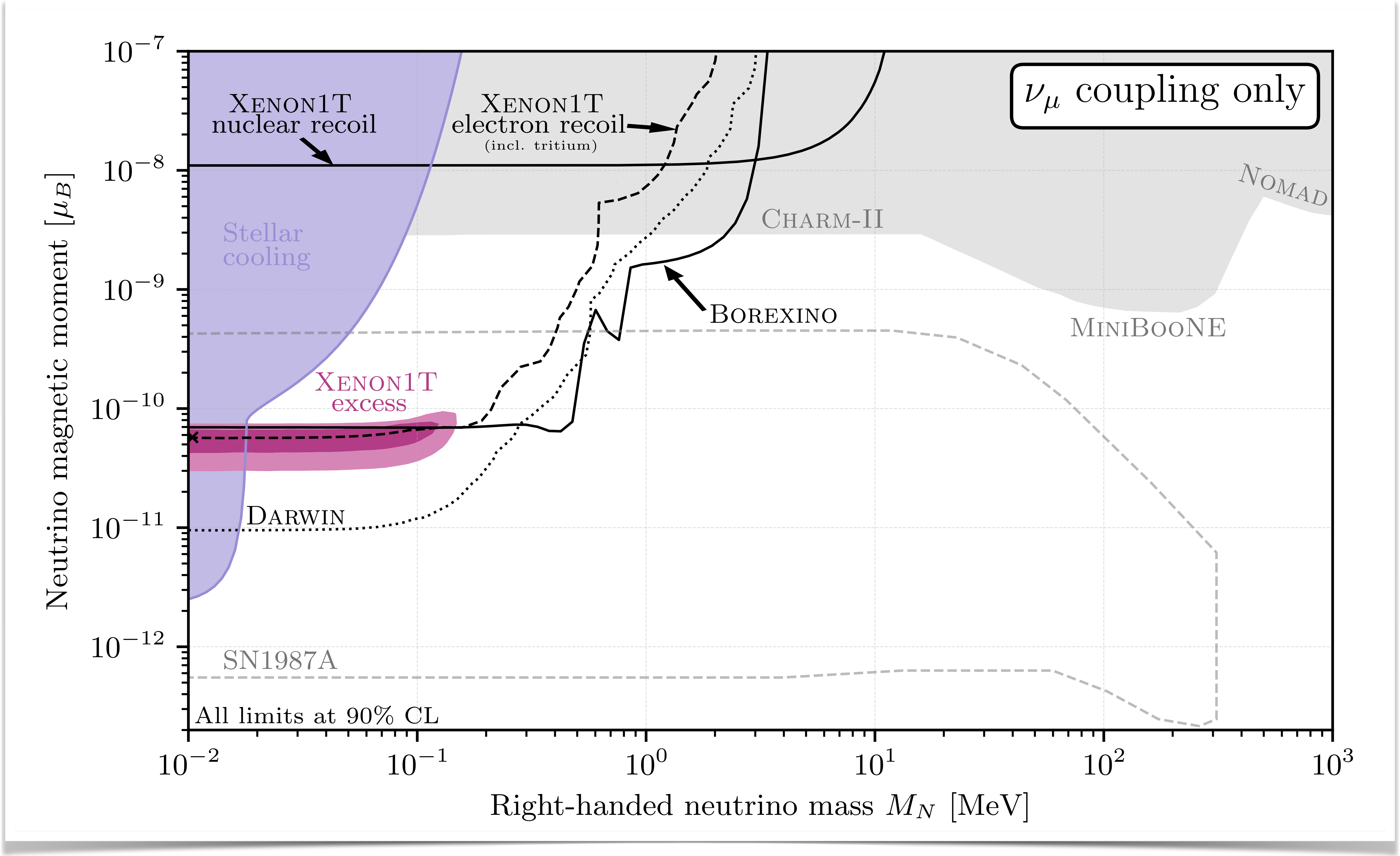

Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

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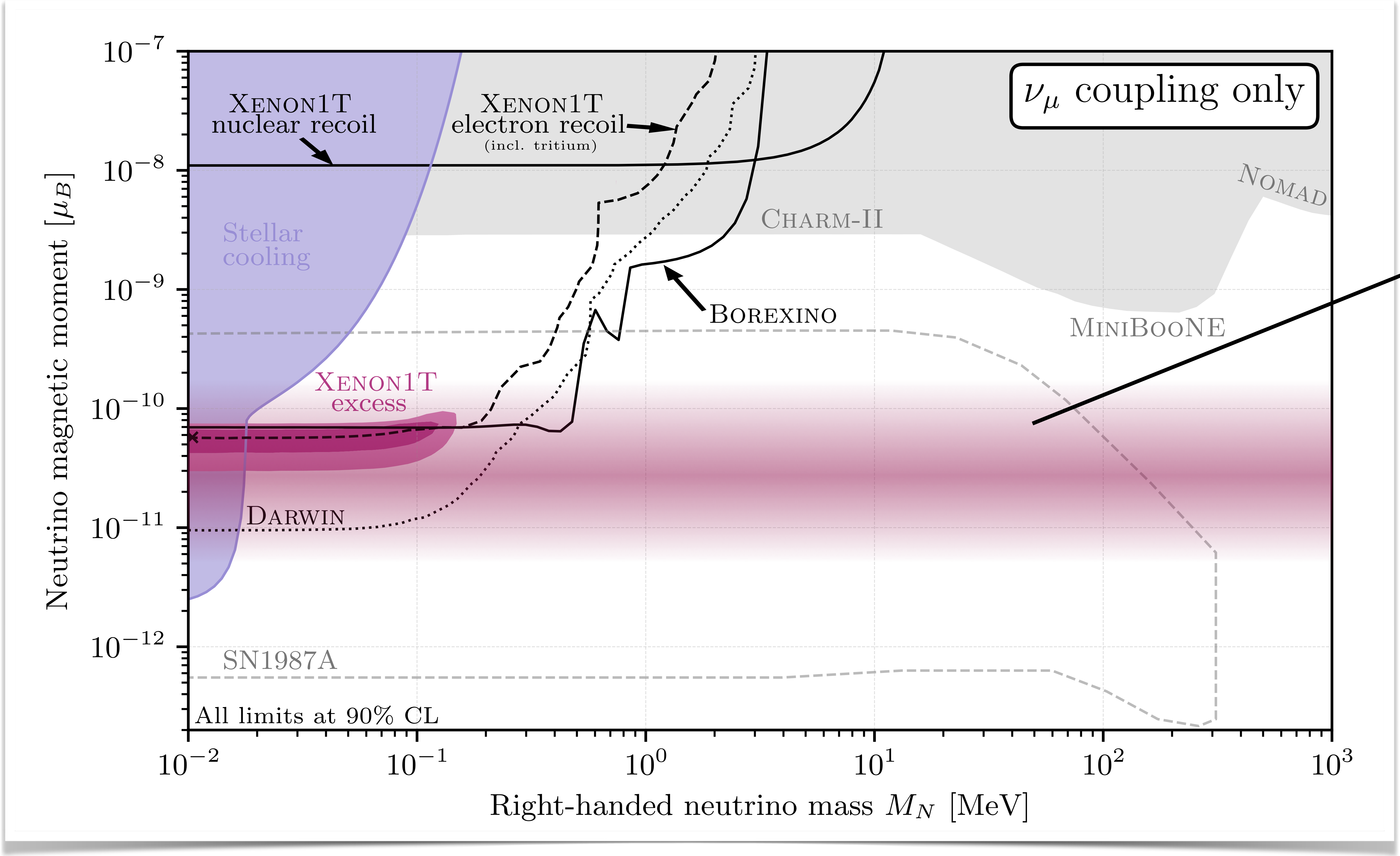

TeV scale new physics

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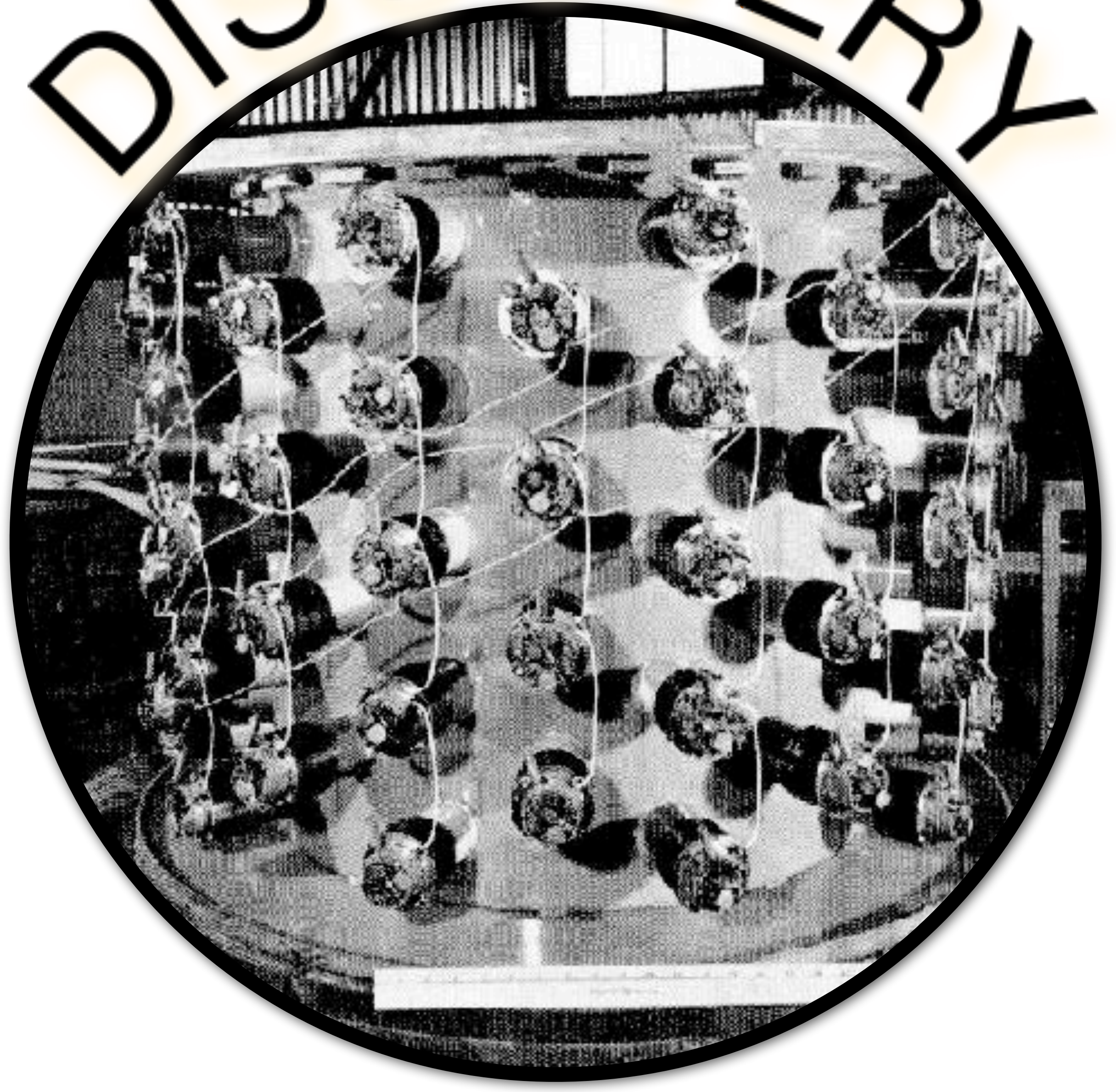
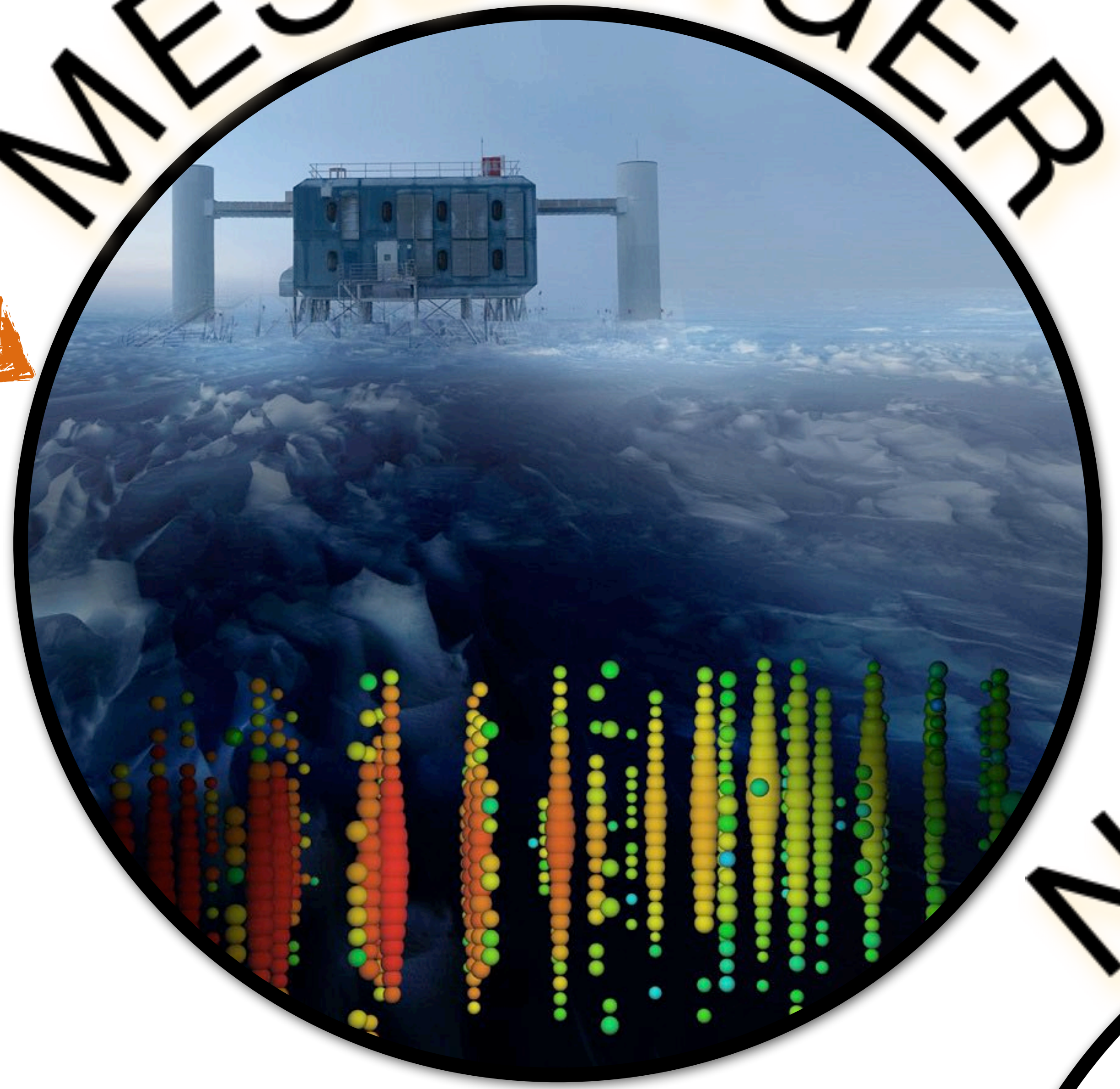
DISCOVERY

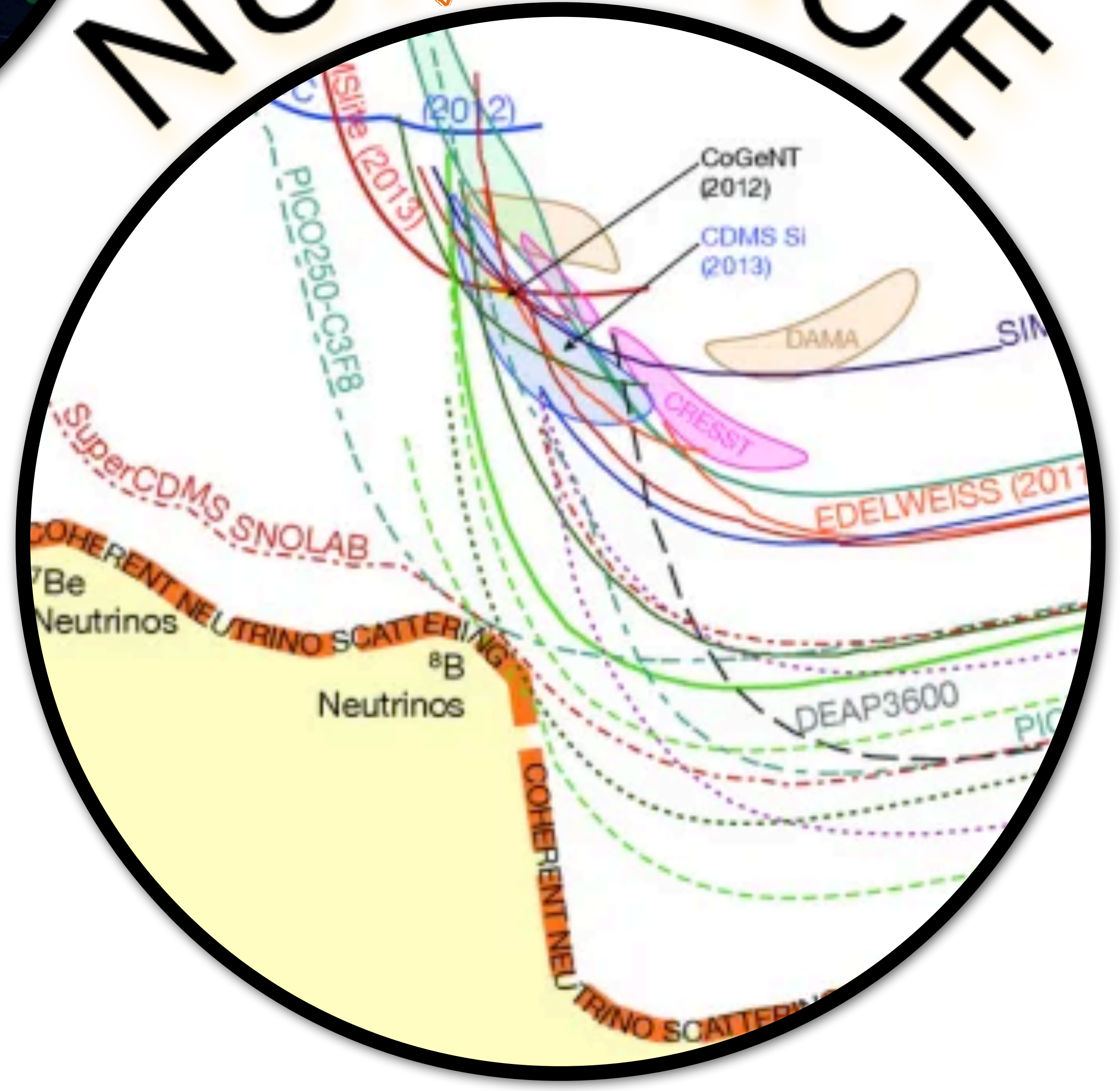


PRECISION

MESSENGER



NUISANCE



Thank You!

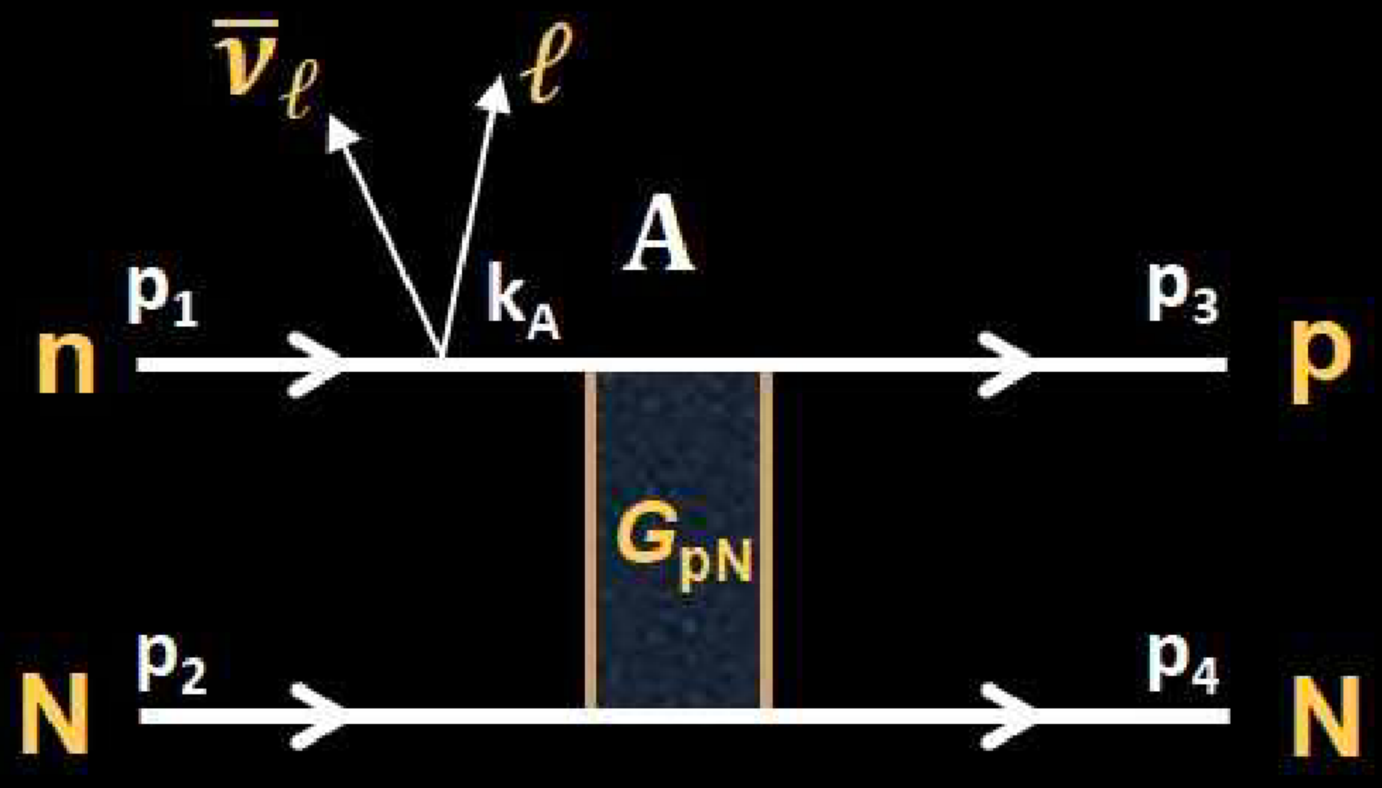
CERN

Neutrino PLATFORM

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Bonus Slides

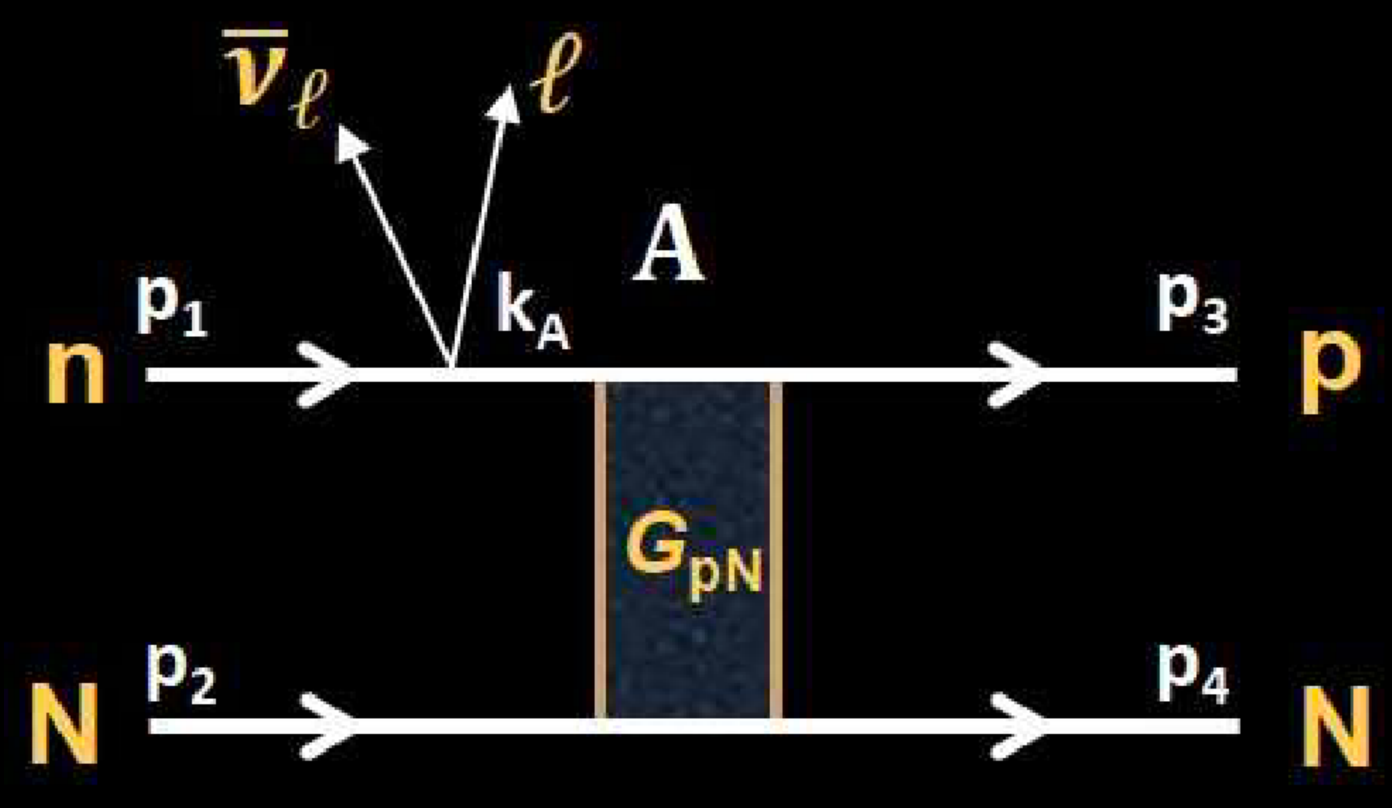
Neutrinos from Neutron Stars



thermal flux

- from "Urca" processes
- low energy
- undetectable after ~10 sec

Neutrinos from Neutron Stars



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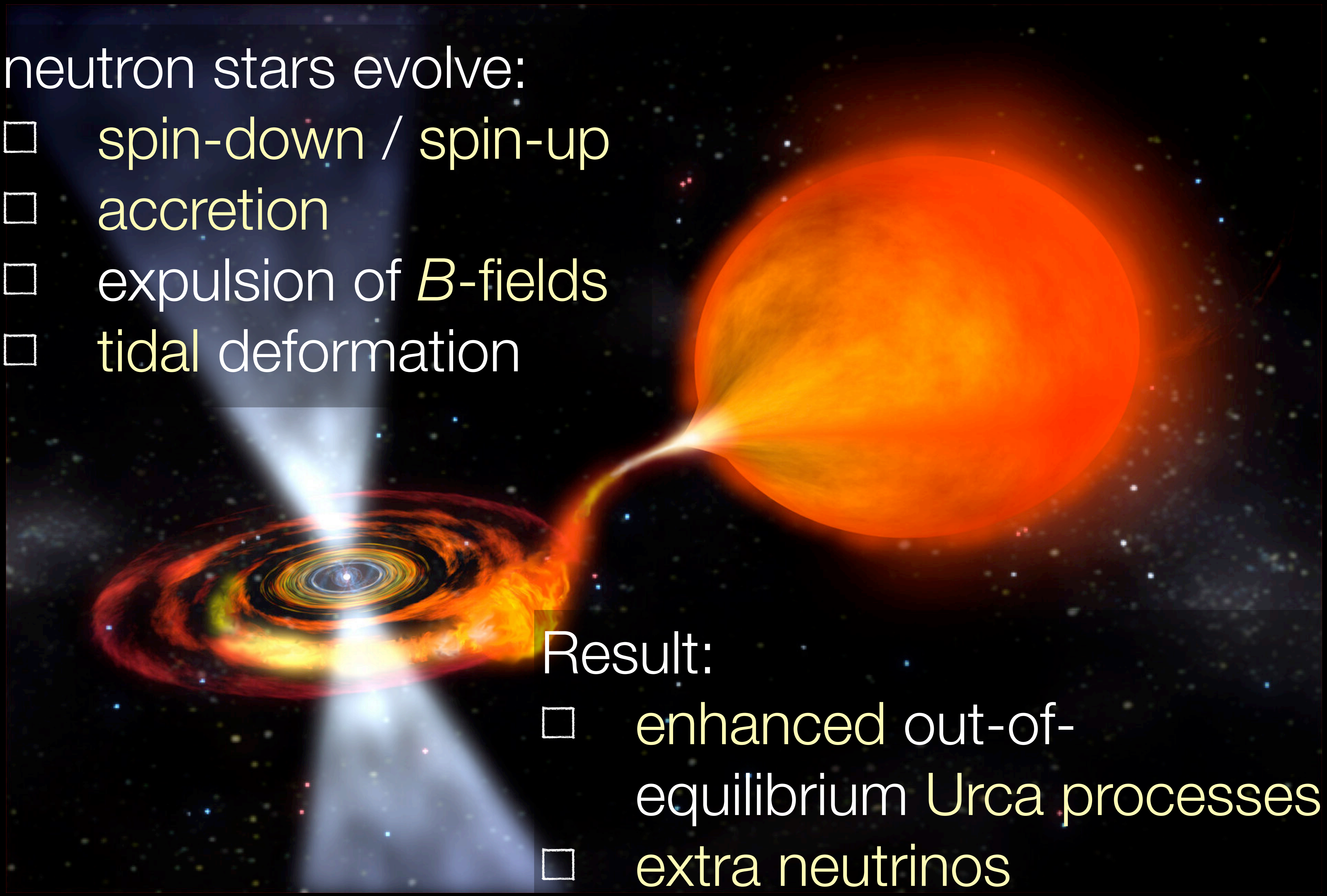


neutron stars evolve:

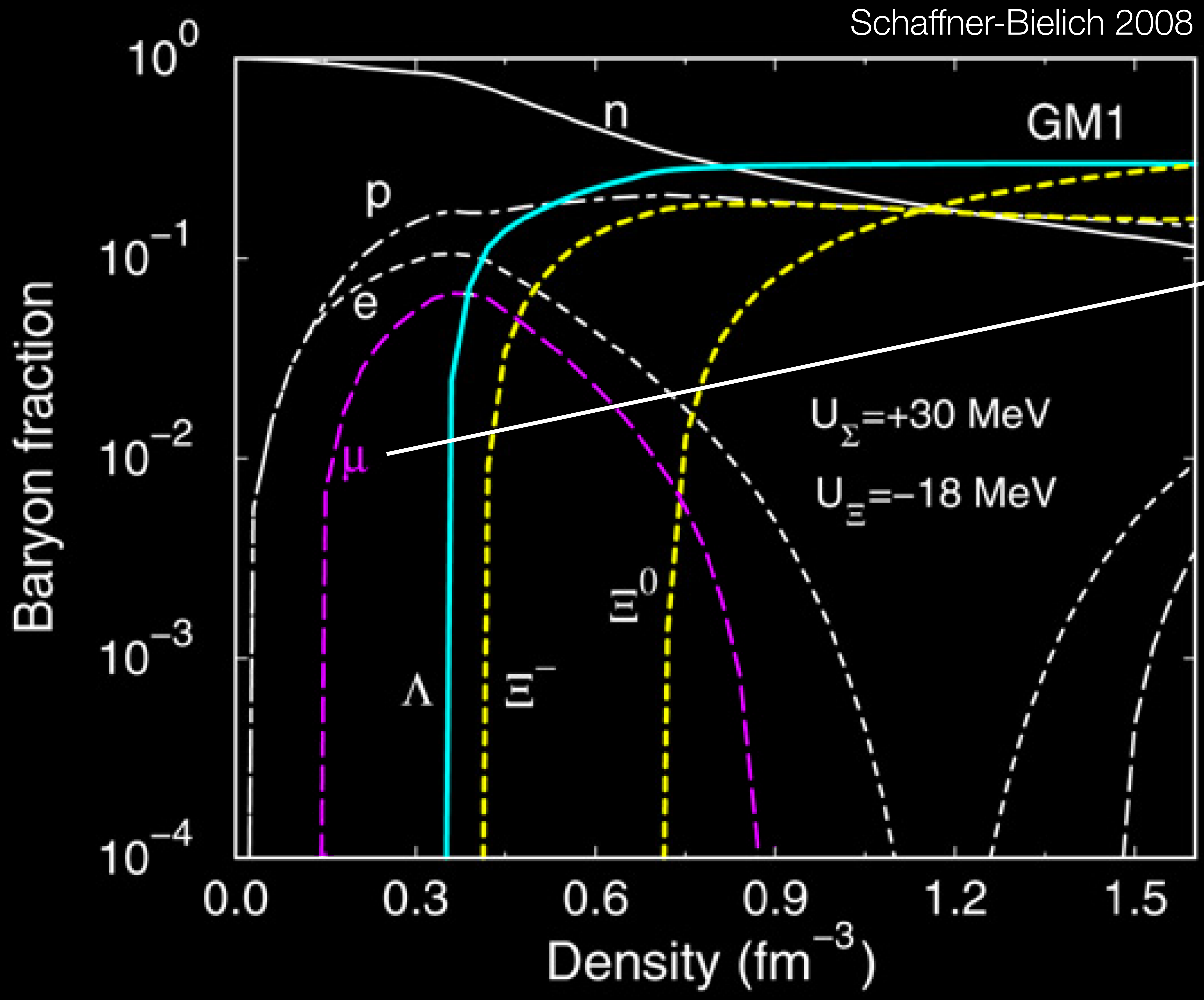
- spin-down / spin-up
- accretion
- expulsion of *B*-fields
- tidal deformation

Result:

- enhanced out-of-equilibrium Urca processes
- extra neutrinos

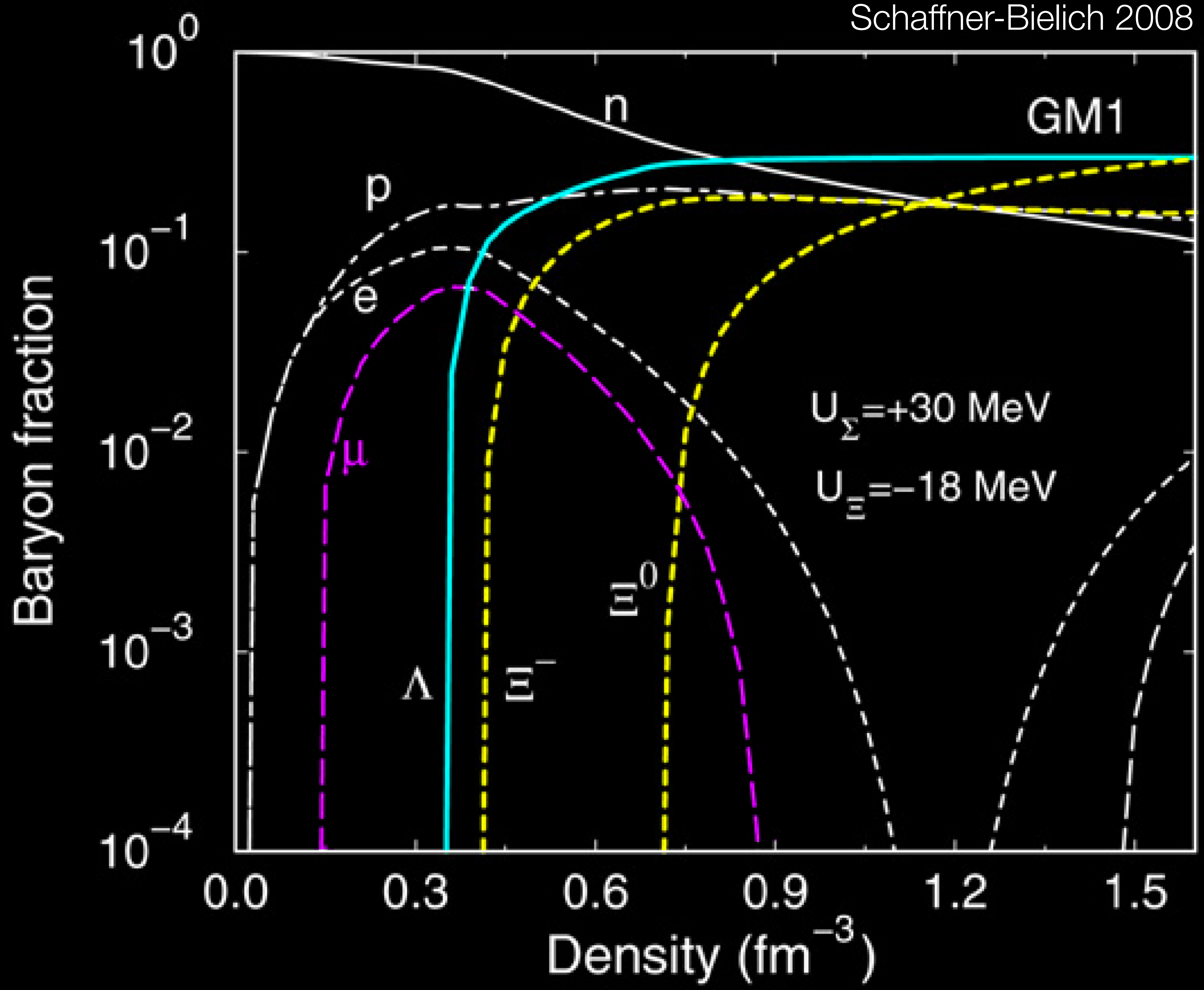
JK Opferkuch *in preparation*

Muons in Neutron Stars



neutron stars harbor abundant quantities of muons

Muons in Neutron Stars



- in the core: μ decay Pauli-blocked
- drop in core density may reduce equilibrium μ abundance
- at $t \gtrsim 10^4$ yrs, Urca interactions too slow to maintain equilibrium
- muons diffuse outward and decay ➠ neutrinos!
- observable signal requires $\mathcal{O}(0.001)$ change in μ abundance

major caveat

- equilibrium μ abundance typically *increases* over time