Revealing the strength of three-nucleon interactions with the Einstein Telescope

Rose et al., Phys. Rev. C 108 (2023) 2, 025811

Peter T. H. Pang

Nikhef

Utrecht University

Universität Potsdam

Common goal for NS study

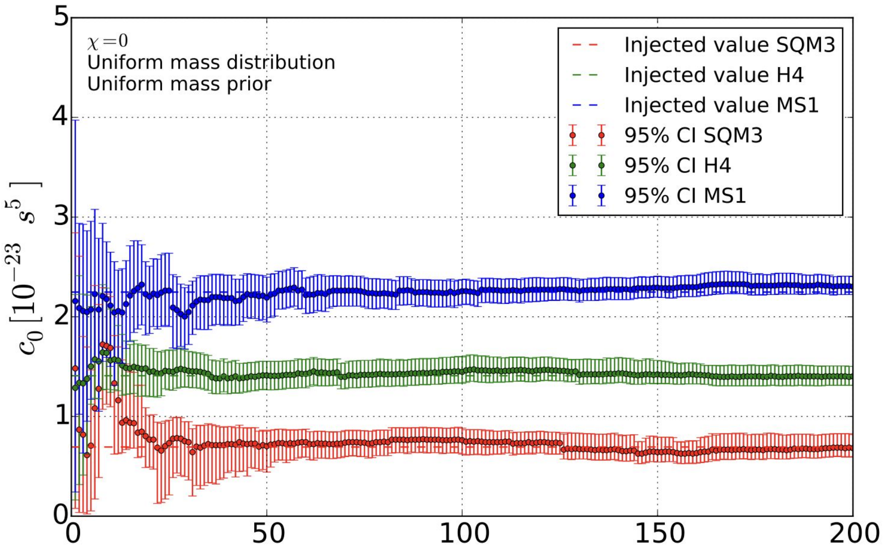
- Extract the equation-of-state

Common goal for NS study

- Extract the equation-of-state
  - Macroscopic
    - Mass, radius, …

Common goal for NS study

- Extract the equation-of-state
  - Macroscopic
    - Mass, radius, ...

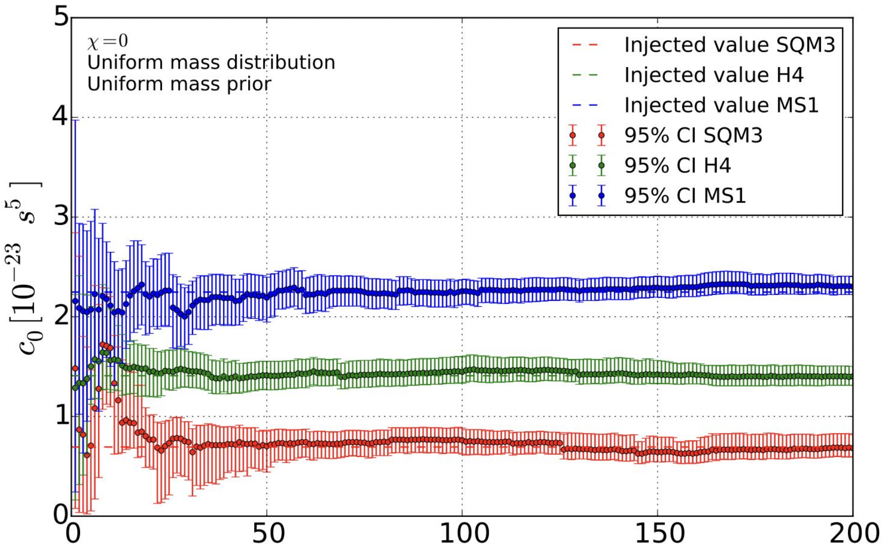


$$\lambda(m) \simeq c_0 + c_1\left(\frac{m-m_0}{M_\odot}\right) + \frac{1}{2}c_2\left(\frac{m-m_0}{M_\odot}\right)^2$$

Agathos et al., Phys.Rev.D 92 (2015) 2, 023012

Common goal for NS study

- Extract the equation-of-state
  - Macroscopic
    - Mass, radius, ...
  - Microscopic
    - Pressure, density, ...

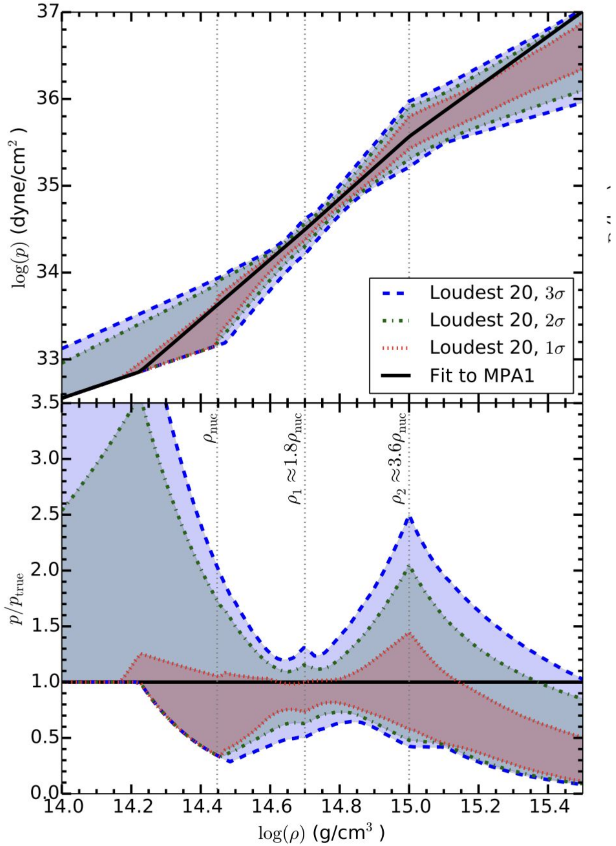


$$\lambda(m) \simeq c_0 + c_1\left(\frac{m-m_0}{M_\odot}\right) + \frac{1}{2}c_2\left(\frac{m-m_0}{M_\odot}\right)^2$$

Agathos et al., Phys.Rev.D 92 (2015) 2, 023012

Common goal for NS study

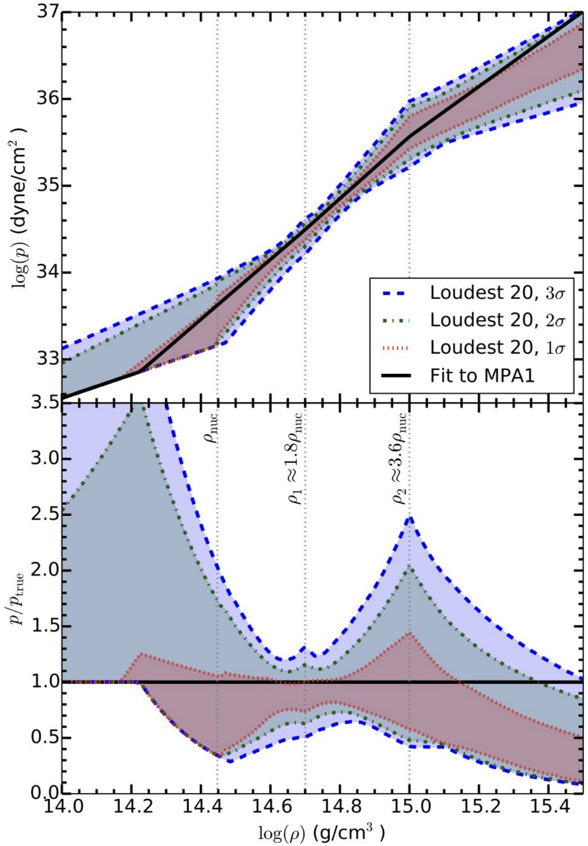
- Extract the equation-of-state
  - Macroscopic
    - Mass, radius, ...
  - Microscopic
    - Pressure, density, ...



Lackey et al., Phys. Rev. D 91, 043002 (2015)

Common goal for NS study

- Extract the equation-of-state
  - Macroscopic
    - Mass, radius, ...
  - Microscopic
    - Pressure, density, ...
  - Microphysics?
    - **Nucleon interaction**



Lackey et al., Phys. Rev. D 91, 043002 (2015)

Effective hamiltonian

Effective hamiltonian

$$\mathcal{H} = T + V_{\mathrm{NN}} + V_{\mathrm{3N}} + V_{\mathrm{4N}} + \cdots$$

Effective hamiltonian

$$\mathcal{H} = T + V_{\mathrm{NN}} + V_{3\mathrm{N}} + V_{4\mathrm{N}} + \cdots$$

Two-nucleon interaction

Three-nucleon interaction

Four-nucleon interaction

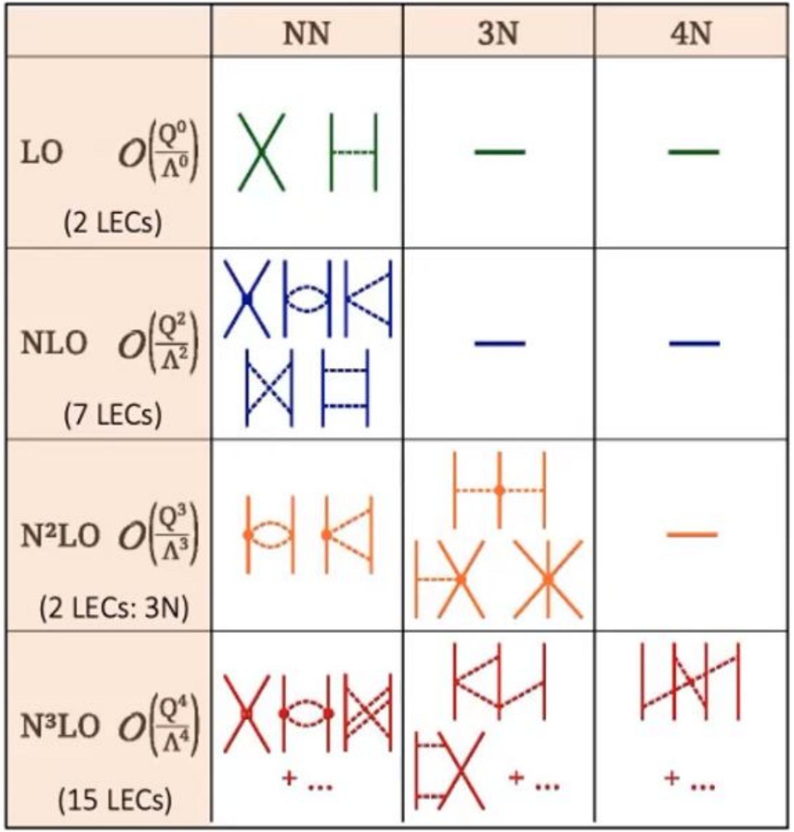
Effective hamiltonian

$$\mathcal{H} = T + V_{\mathrm{NN}} + V_{3\mathrm{N}} + V_{4\mathrm{N}} + \cdots$$

Two-nucleon interaction

Three-nucleon interaction

Four-nucleon interaction



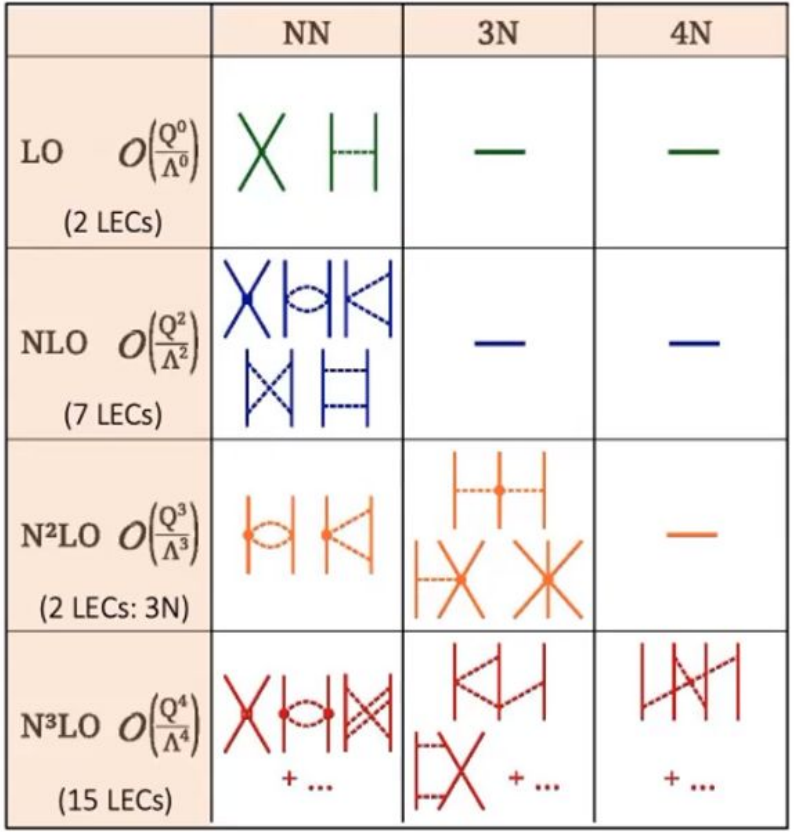
Effective hamiltonian

$$\mathcal{H} = T + V_{\mathrm{NN}} + V_{3\mathrm{N}} + V_{4\mathrm{N}} + \cdots$$

Two-nucleon interaction

Three-nucleon interaction

Four-nucleon interaction



What is a 3N interaction?

What is a 3N interaction?

- Three-body force
  - Cannot be described as a sum of pairwise interactions

What is a 3N interaction?

- Three-body force
  - Cannot be described as a sum of pairwise interactions
- Fundamental interaction
  - Quarks and gluons

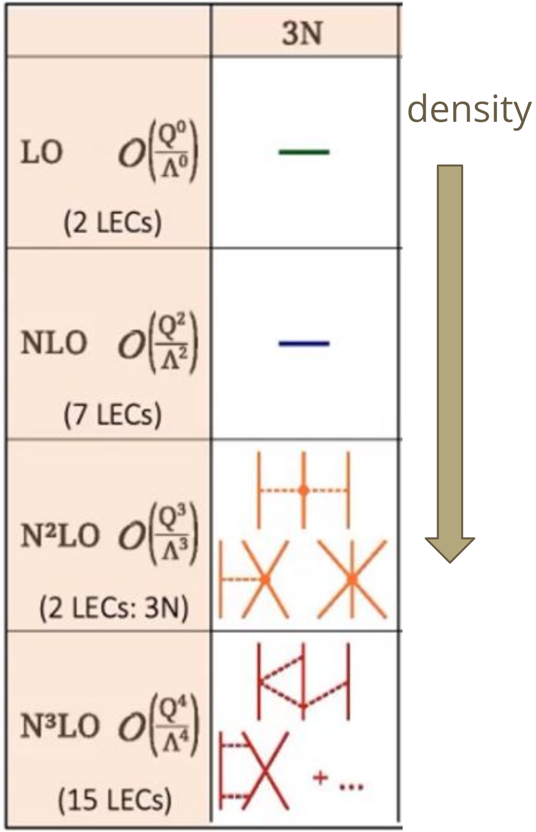
What is a 3N interaction?

- Three-body force
  - Cannot be described as a sum of pairwise interactions
- Fundamental interaction
  - Quarks and gluons
- Effective interaction
  - Pairwise interaction manifests as three-body force

What is a 3N interaction?

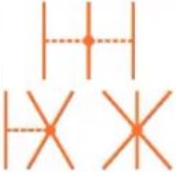
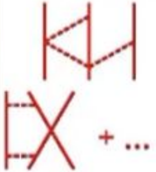
- Three-body force
  - Cannot be described as a sum of pairwise interactions
- Fundamental interaction
  - Quarks and gluons
- Effective interaction
  - Pairwise interaction manifests as three-body force
  - Tidal interaction between Sun, Earth and Moon

How to model 3N interaction



How to model 3N interaction

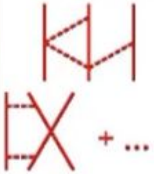
- Conventional approach

	3N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)	—
N²LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)	
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	

density ↓

How to model 3N interaction

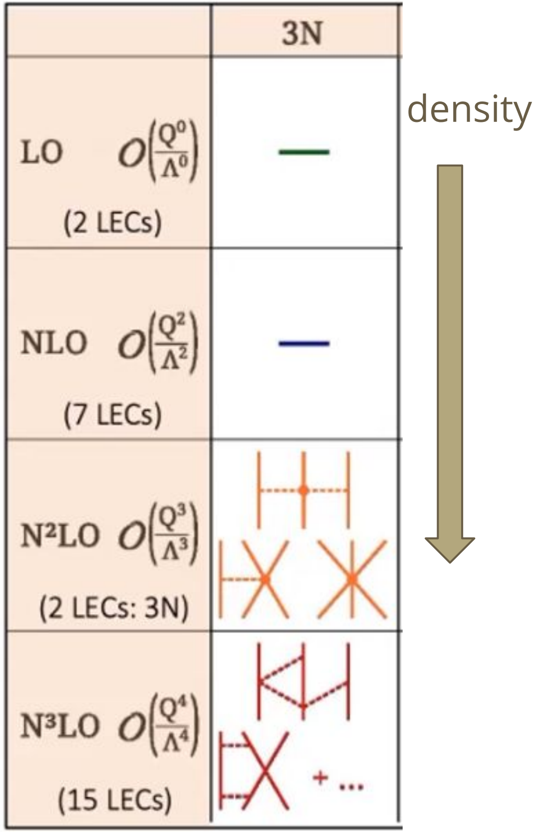
- Conventional approach
  - Properties of light nuclei

	3N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)	—
N²LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)	
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	

density

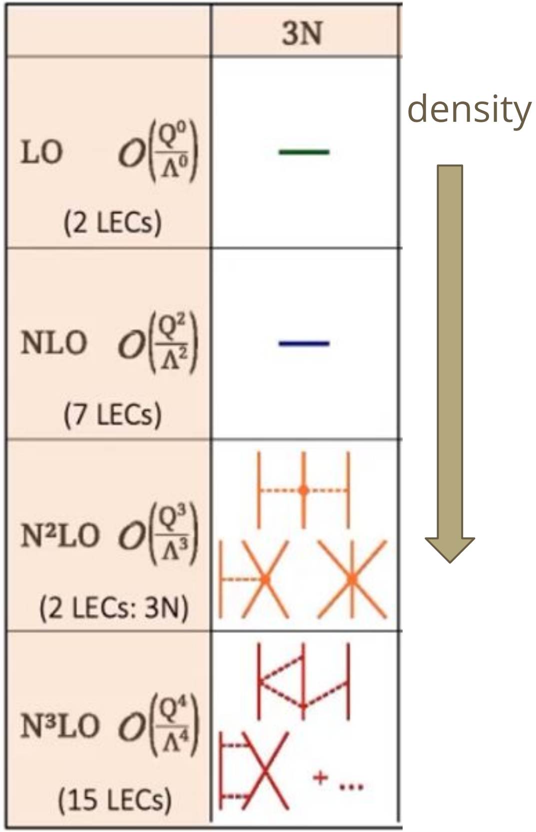
How to model 3N interaction

- Conventional approach
  - Properties of light nuclei
  - Extrapolate



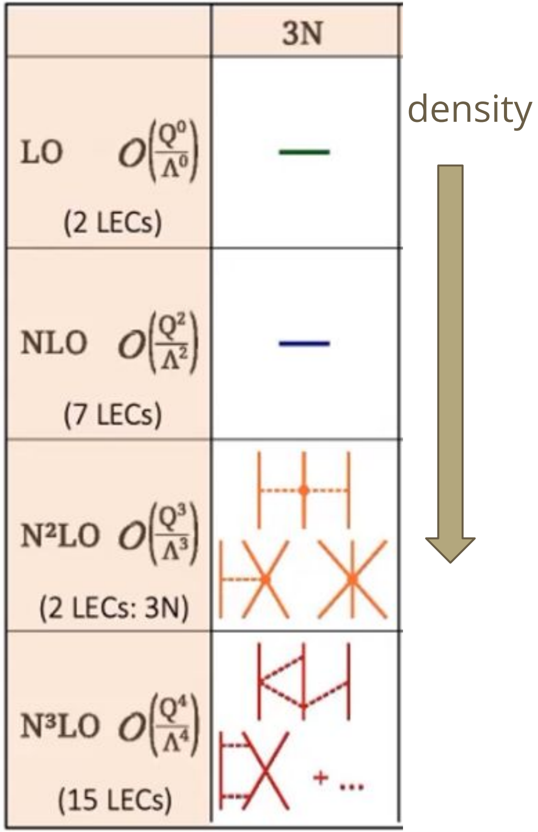
How to model 3N interaction

- Conventional approach
  - Properties of light nuclei
  - Extrapolate
    - Heavier nuclei
    - Neutron star



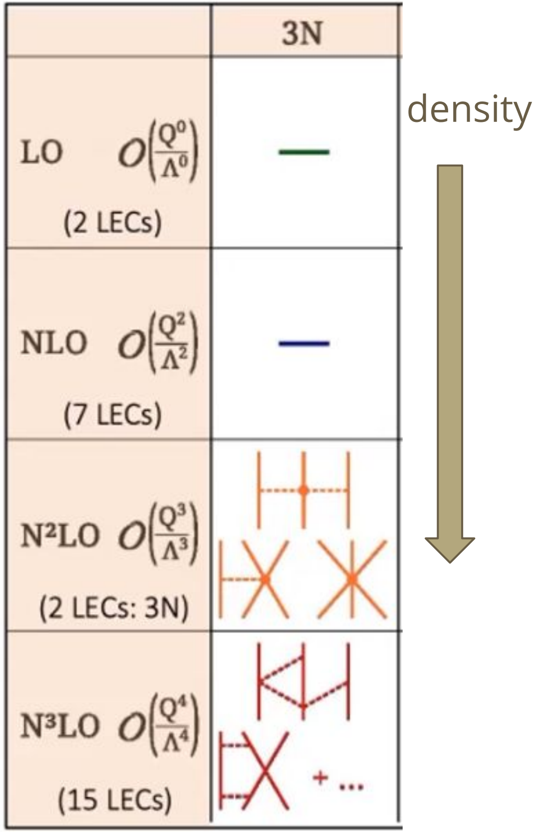
How to model 3N interaction

- Conventional approach
  - Properties of light nuclei
  - Extrapolate
    - Heavier nuclei
    - Neutron star
  - Less sensitive to 3N interaction



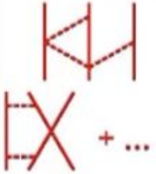
How to model 3N interaction

- Conventional approach
  - Properties of light nuclei
  - Extrapolate
    - Heavier nuclei
    - Neutron star
  - Less sensitive to 3N interaction
  - Systematic uncertainty



How to model 3N interaction

- Conventional approach
  - Properties of light nuclei
  - Extrapolate
    - Heavier nuclei
    - Neutron star
  - Less sensitive to 3N interaction
  - Systematic uncertainty

	3N
LO $O\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)	—
NLO $O\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)	—
N²LO $O\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)	
N³LO $O\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	

density ↓

What if we can study it directly with neutron star?

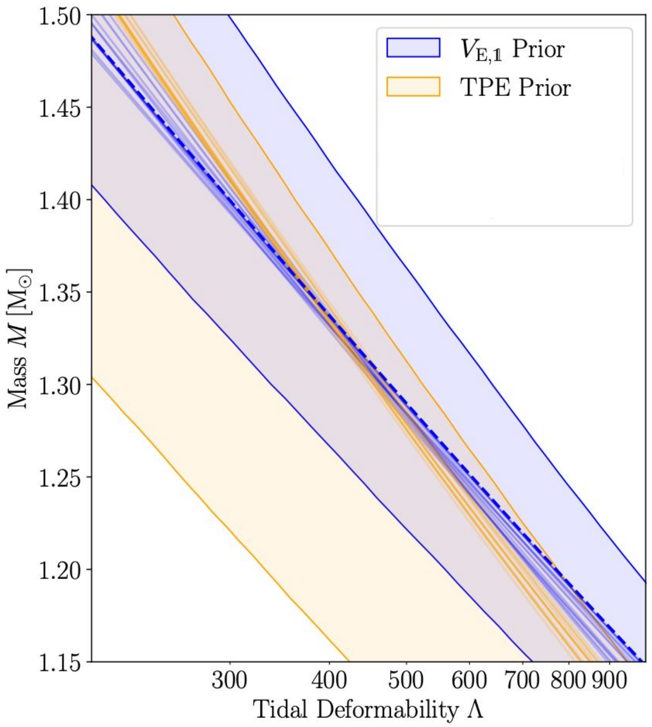
Effect of 3N interaction

Effect of 3N interaction

- TPE
  - Two-pion-exchange
- $V_{E,\,1}$
  - TPE + repulsive 3N

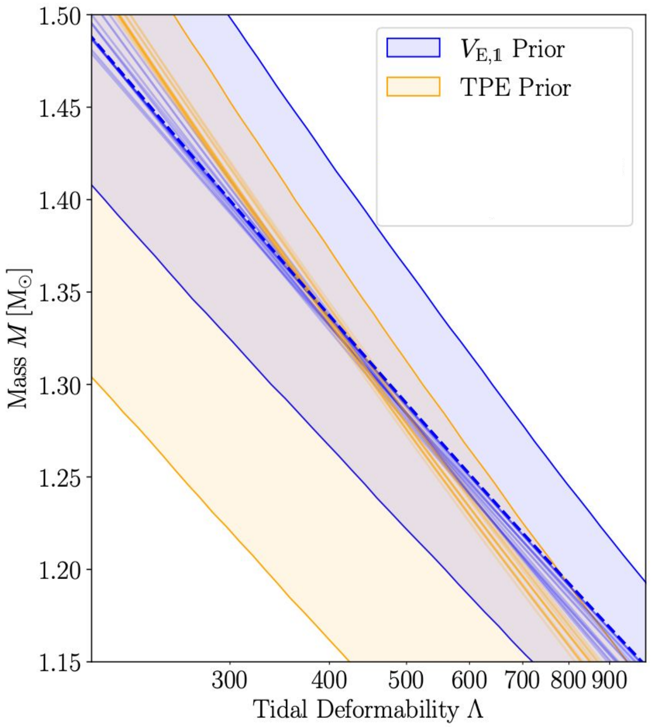
Effect of 3N interaction

- TPE
  - Two-pion-exchange
- $V_{E,1}$
  - TPE + repulsive 3N



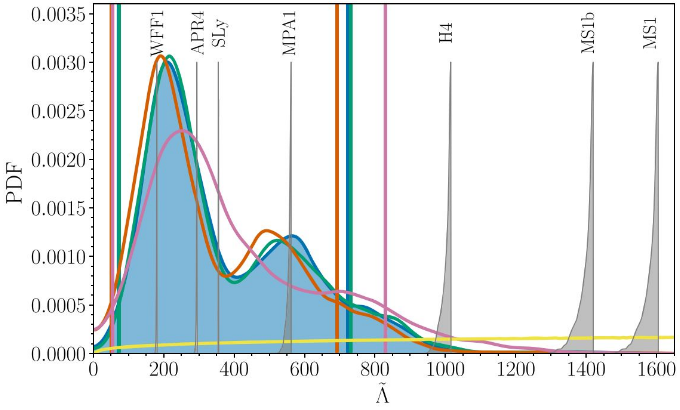
Effect of 3N interaction

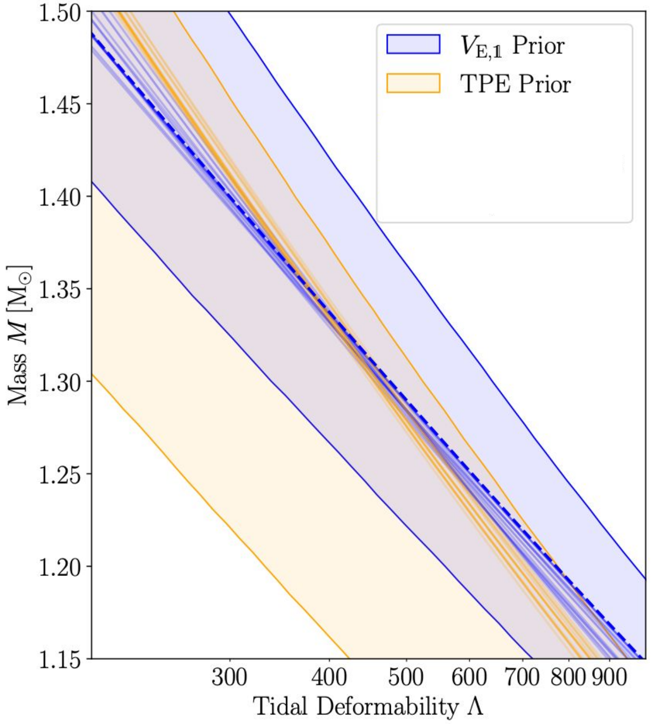
- TPE
  - Two-pion-exchange
- $V_{E,1}$
  - TPE + repulsive 3N
- Not resolvable with current detectors



Effect of 3N interaction

- TPE
  - Two-pion-exchange
- $V_{E, 1}$
  - TPE + repulsive 3N
- Not resolvable with current detectors





Could ET save the day?

Could ET save the day?

- Injection campaign
  - 3N interaction models considered
    - Two-Pion-Exchange (TPE)
    - TPE + repulsive 3N ($V_{E, 1}$)

Could ET save the day?

- Injection campaign
  - 3N interaction models considered
    - Two-Pion-Exchange (TPE)
    - TPE + repulsive 3N ($V_{E,1}$)
  - Injected BNS signals into designed triangular ET

Could ET save the day?

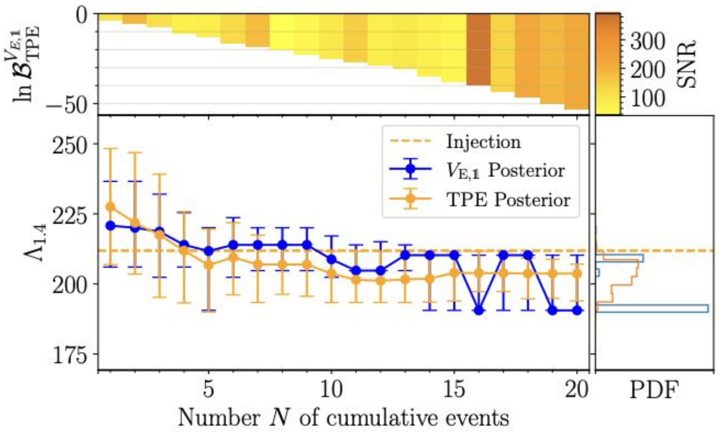
- Injection campaign
  - 3N interaction models considered
    - Two-Pion-Exchange (TPE)
    - TPE + repulsive 3N ($V_{E, 1}$)
  - Injected BNS signals into designed triangular ET
  - Parameter estimation with the two model as prior

Could ET save the day?

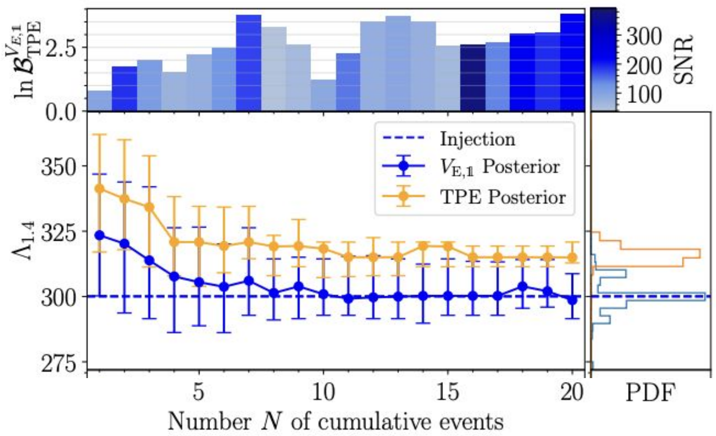
- Injection campaign
  - 3N interaction models considered
    - Two-Pion-Exchange (TPE)
    - TPE + repulsive 3N ($V_{E,1}$)
  - Injected BNS signals into designed triangular ET
  - Parameter estimation with the two model as prior
  - Calculate the Bayes factor between the two models

Results

TPE injection



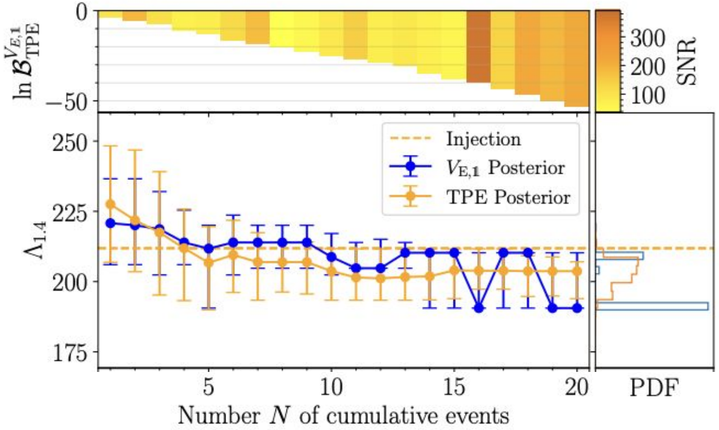
$V_{E,\,1}$ injection

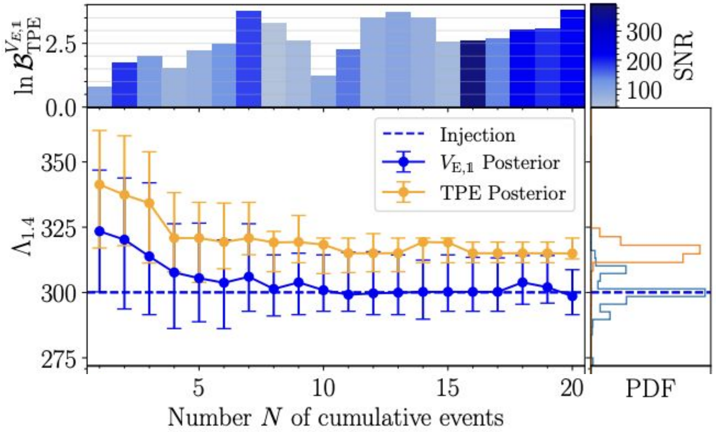


Results

TPE injection

$V_{E,1}$ injection

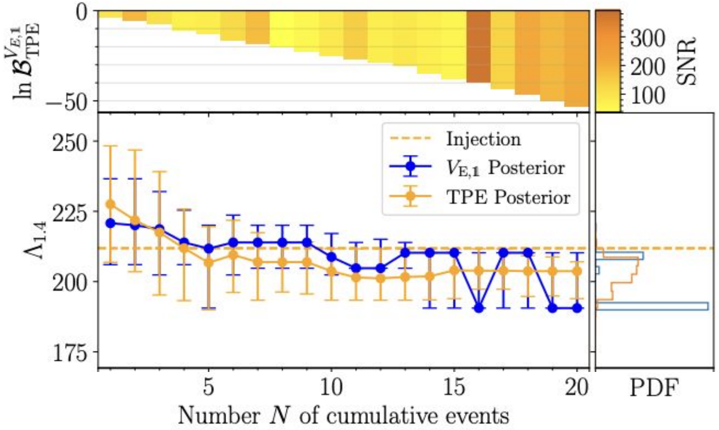




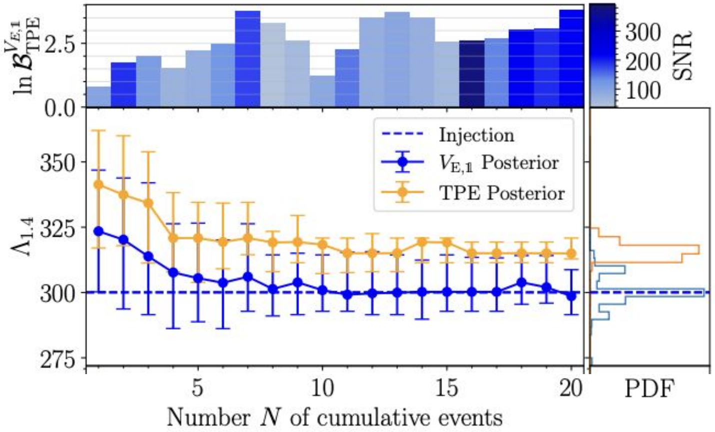
ET is sensitive to microphysics

Results

TPE injection



$V_{E,\,1}$ injection



ET is sensitive to microphysics

ET is sensitive to microphysics systematics

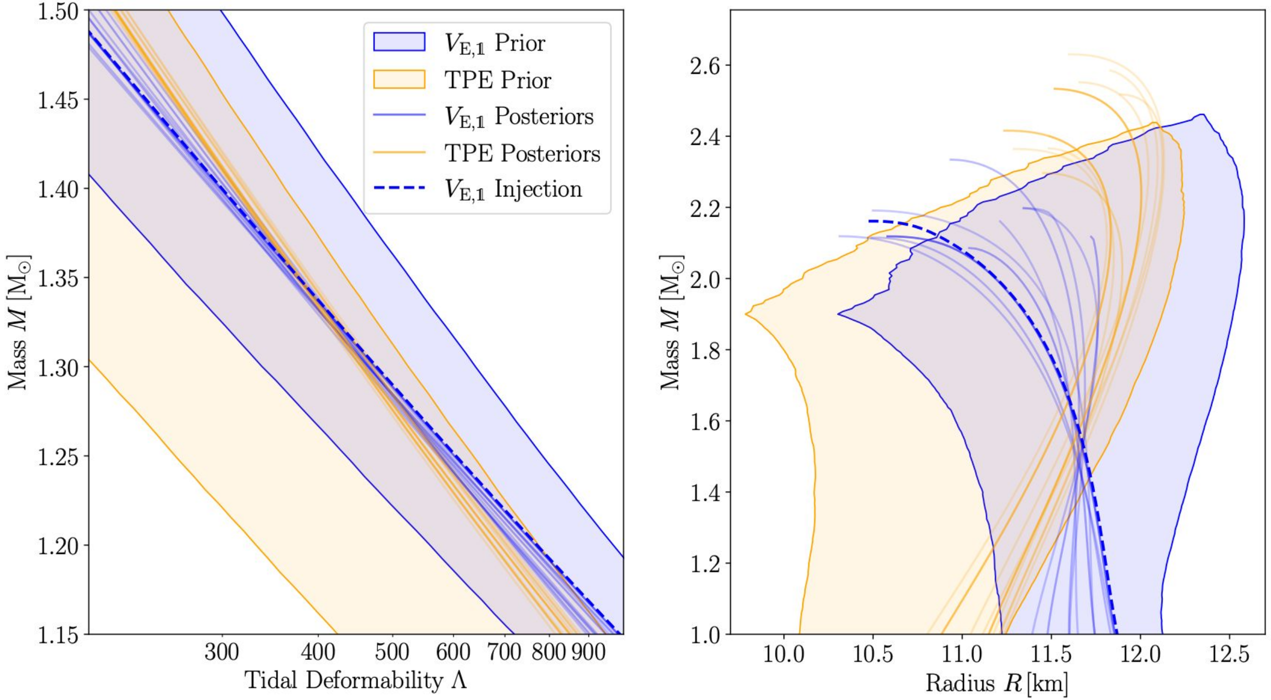
Conclusion

- ET is sensitive to microphysics
- 3N nucleon interaction
  - Distinguishable with ~20 events
- ET also suffer from microphysics systematics
  - Significant bias
  - Crucial for extracting nuclear physics

Injection setup

- Masses following galactic binary neutron star
  - Gaussian with mean = 1.33, std = 0.09
- Uniform in co-moving volume
  - Within 200 Mpc
  - A SNR 30 cutoff
- 50-th percentile EOS in TOV mass
- 30Hz - 2048Hz

Results



$V_{E,1}$ Prior
TPE Prior
$V_{E,1}$ Posteriors
TPE Posteriors
$V_{E,1}$ Injection
Mass M [$M_\odot$]
1.50
1.45
1.40
1.35
1.30
1.25
1.20
1.15
300
400
500
600
700
800
900
Tidal Deformability Λ
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
10.0
10.5
11.0
11.5
12.0
12.5
Radius R [km]

Prior

	parameter	symbol	prior bounds
observational	luminosity distance [Mpc]	d_L	5 – 500
	inclination	$\cos\,\theta_{JN}$	-1 – 1
	phase [rad]	ϕ	0 – 2π
	polarisation [rad]	ψ	0 – π
	right ascension [rad]	α	0 – 2π
	declination [rad]	δ	$-\pi$ – π
orbital	chirp mass [$M_\odot$]	$\mathcal{M}$	*1.20 – 1.30**
	source chirp mass [$M_\odot$]	$\mathcal{M}_s$	1.15 – 1.30*
	mass ratio	q	0.125 – 1
	source comp. mass [$M_\odot$]	$M_{i,s}$	*>0.5*
	aligned component spin	χ_i	-0.15 – 0.15
hyper	Equation of State	EOS	1 – 3000