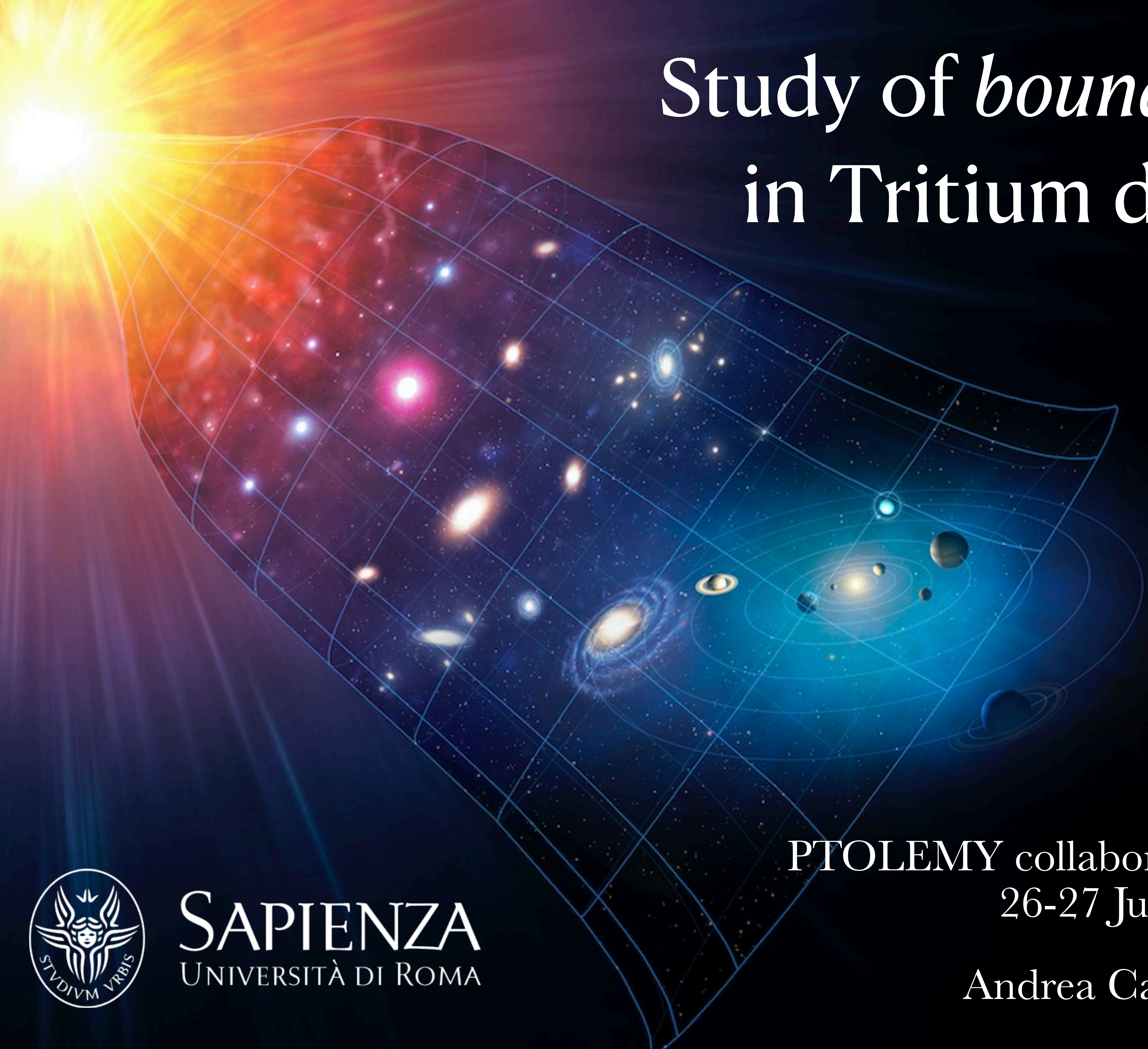


# Study of *bound states* in Tritium decay

SAPIENZA
UNIVERSITÀ DI ROMA

PTOLEMY collaboration meeting
26-27 June

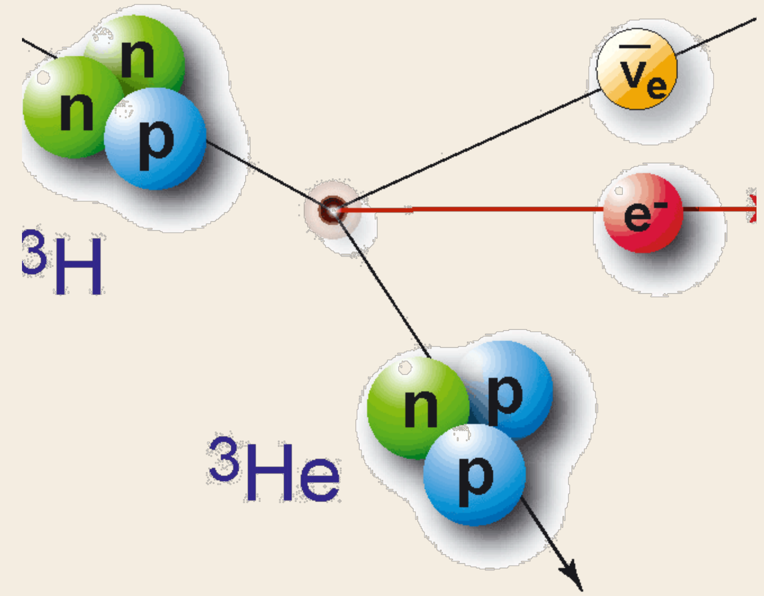
Andrea Casale

# Overview

- Qualitative confirmation of TRIMS experimental data

- Deeper study of $\beta$ and $^3He$ spectrum in PTOLEMY

- Excited $^3He$ bound states

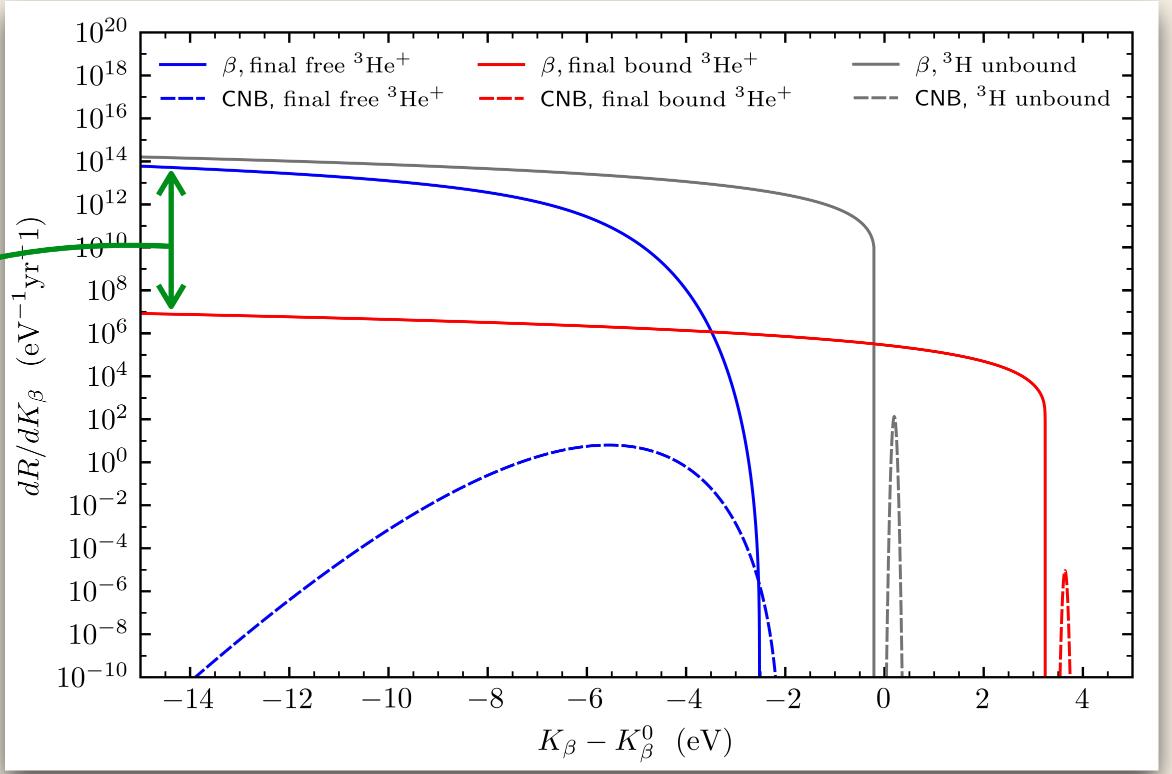


# A counting problem

[PTOLEMY – PRD 2022, 2203.11228]

- Endpoint rates in Ptolemy

Define $\Omega = \dfrac{BR(\text{ bound } {}^3He\ )}{BR(\text{ free } {}^3He\ )}$




Here we have

$\Omega \simeq 10^{-7}$

- However Trims data say otherwise:

56.51% of BR for bound *HeH*

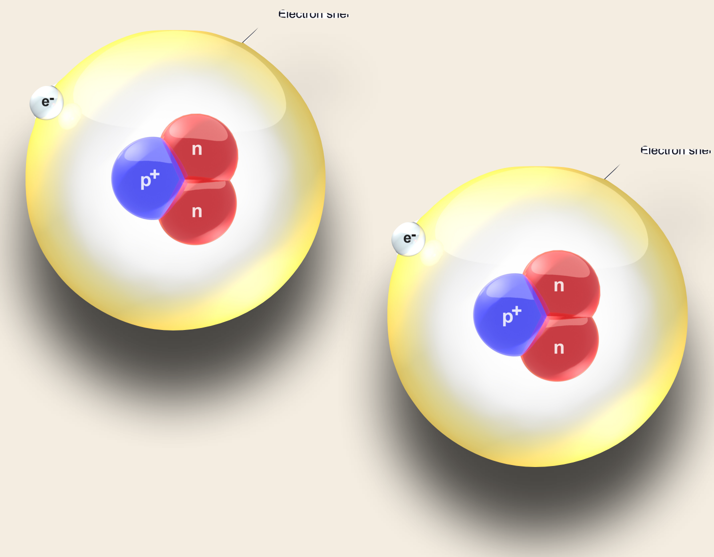
24.98 % of BR for free $He^+$

$\Omega \simeq 2.3$

| $i$ Channel | Uncertainties (absolute %) Stat. | RCF | PSF | FV | DT | Total | Branch (%) |
|---|---|---|---|---|---|---|---|
| One electron | | | | | | | |
| 2. $HeH^+$ | 0.1 | 0.39 | 0.14 | 0.35 | 0.08 | 0.55 | 56.51(55) |
| 3. $He^+ + H$ | 0.1 | 0.27 | 0.05 | 0.28 | 0.05 | 0.41 | 24.98(41) |
| 4. $He + H^+$ | 0.09 | 0.4 | 0.17 | 0.09 | 0.01 | 0.45 | 5.64(45) |
| 5. $He^{++} + H^-$ | | | | | | | $< 0.021$ |
| Two electrons | | | | | | | |
| 6. $He^+ + H^+$ | | | | | | | |
| from $He^+$ | 0.19 | 0.41 | 0.09 | 0.15 | 0.02 | 0.49 | 11.01(49) |
| from $H^+$ | 0.17 | 0.37 | 0.09 | 0.13 | 0.02 | 0.44 | 10.43(44) |
| 7. $He^{++} + H$ | 0.12 | 0.07 | 0.16 | 0.05 | 0 | 0.21 | 2.16(21) |
| Three electrons | | | | | | | |
| 8. $He^{++} + H^+$ | | | | | | | $< 0.045$ |

[Lin et al. – PRL 2020, 2001.11671]

# How to solve?

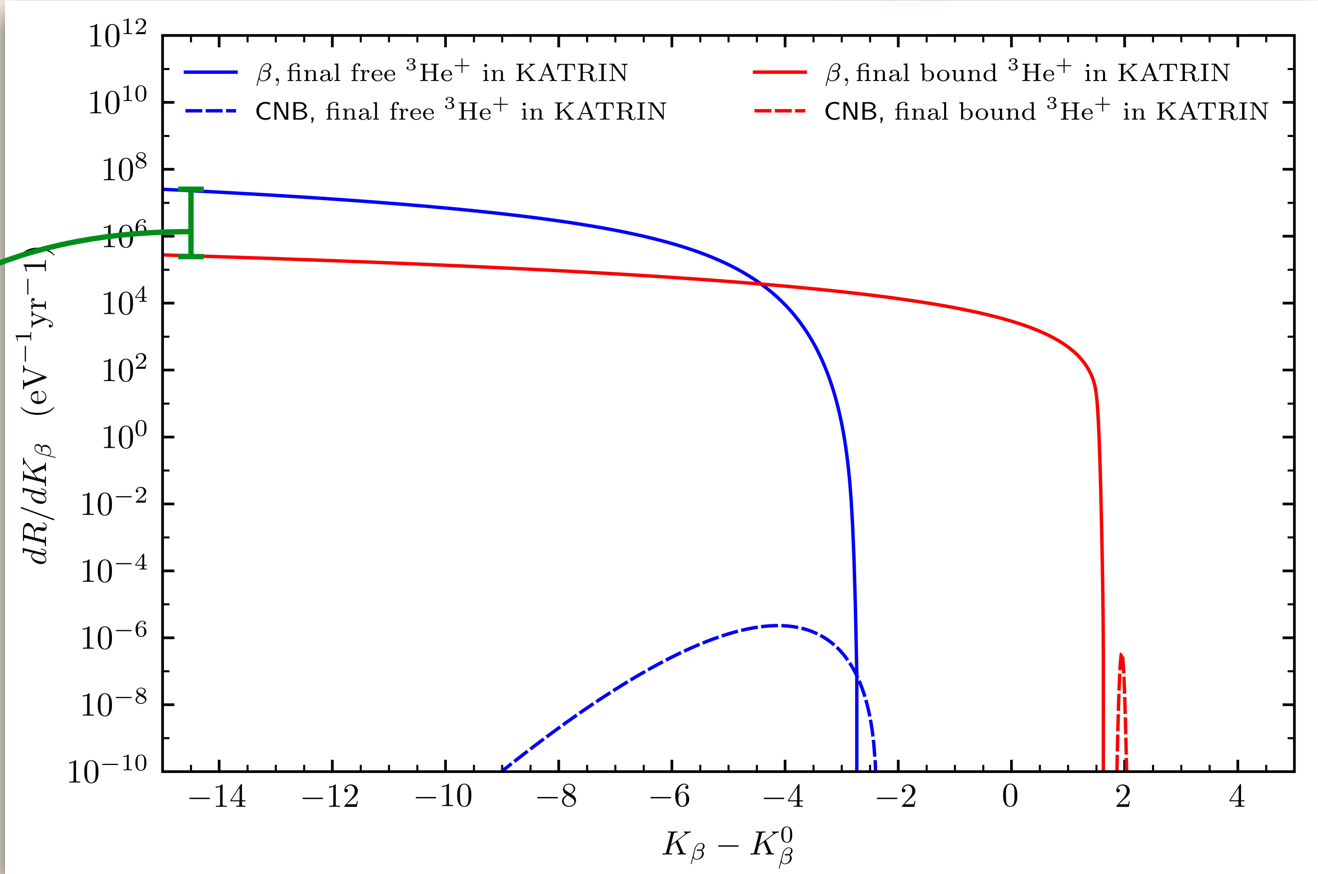


- First ingredient:
  change the physics!

- Trims deals with molecular **T2**,
  not graphene (same as Katrin)

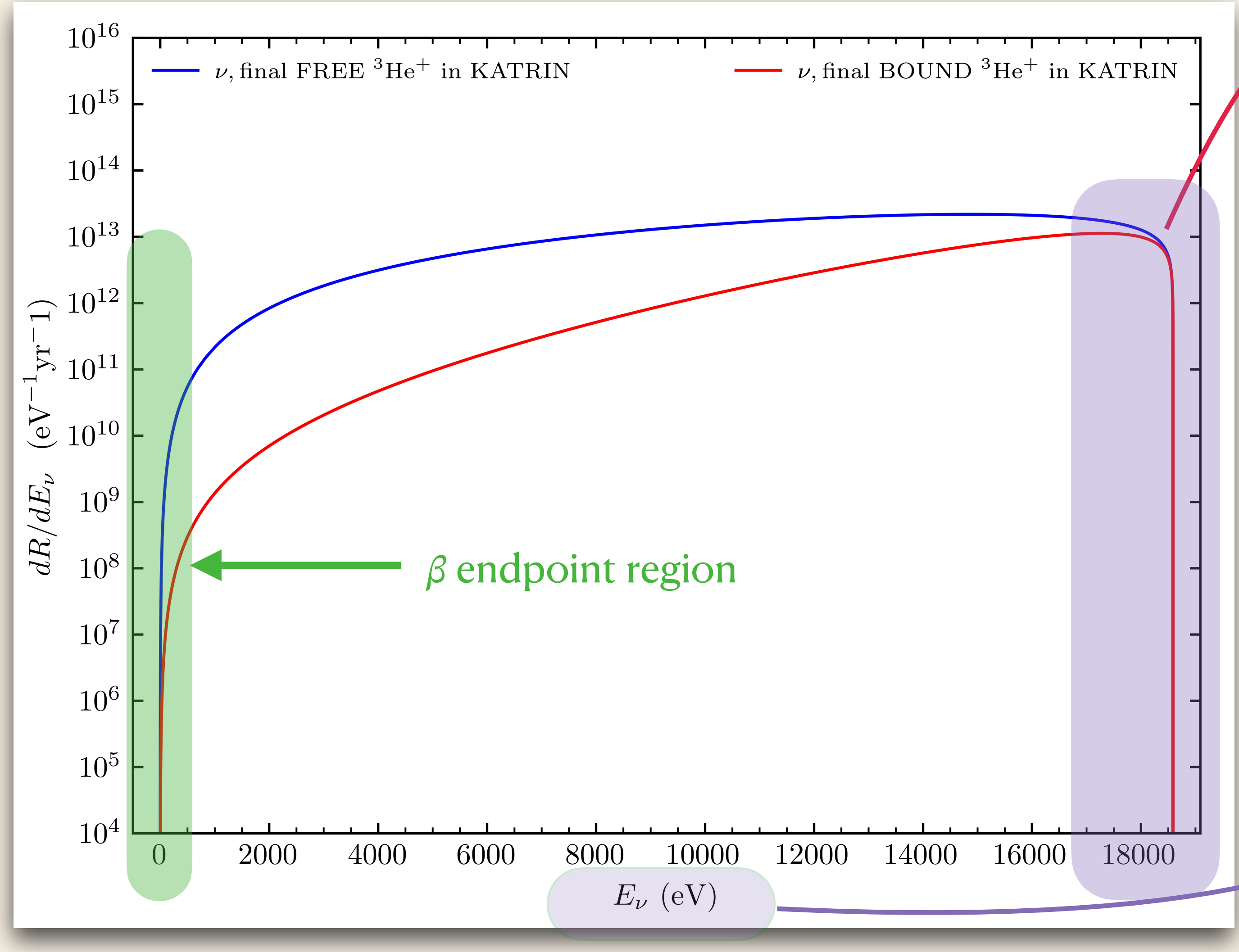
Binding potential changes

Here we have
$\Omega \simeq 10^{-2}$,
much better!



# How to solve?

- Second ingredient: look at all energies
- Trims collected data coming from the whole $\beta$ spectrum, not just the endpoint!




Bound $^3He^+$ events become more likely to happen as we depart from $\beta$ endpoint region and go towards $\nu$ endpoint region

Plotting as a function of $\nu$ energy

# Does it make sense?

- Yes! Ok but… why?

1) Differential rates are suppressed when particles have momentum such that $\lambda p \gg 1$

2) Number of configurations for bound events increases as we depart from endpoint regions

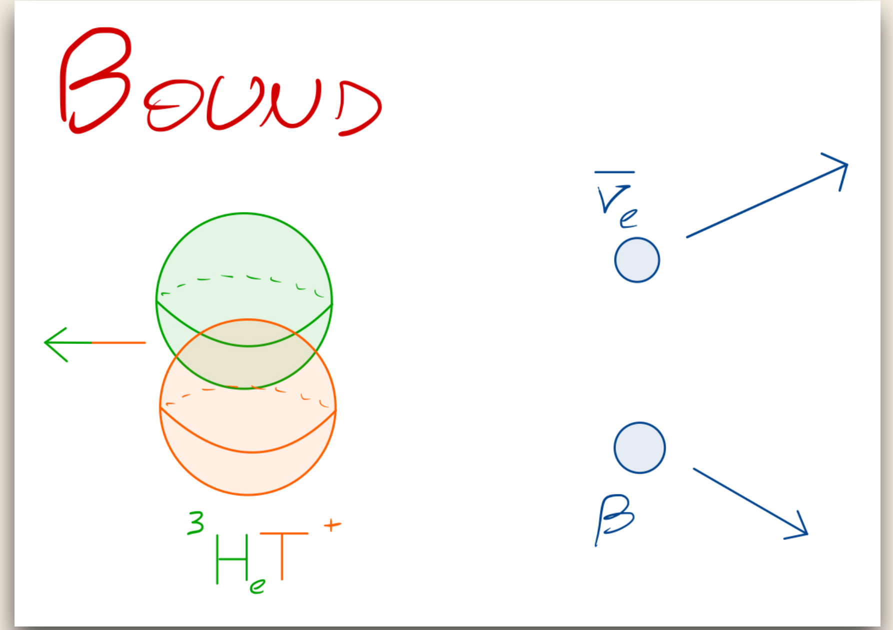
Let's see…

# Does it make sense?

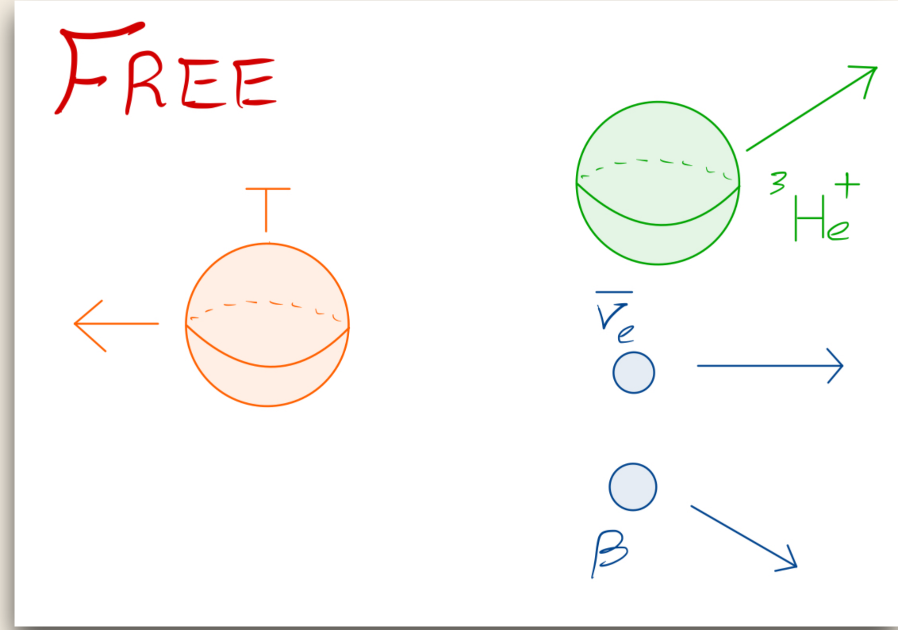
1) Differential rates are suppressed when particles have momentum such that $\lambda p \gg 1$.

It's the $\lambda$ appearing in

$$\Psi(x) \propto e^{-\frac{x^2}{2\lambda^2}}$$




$$d\Gamma \propto e^{-\frac{\lambda^2}{2}|\vec{p_\beta} + \vec{p_\nu}|^2}$$




$$d\Gamma \propto e^{-\lambda^2|\vec{p_\beta} + \vec{p_\nu} + \vec{p_{He}}|^2}$$

# Does it make sense?

- But if rates are suppressed when momenta increase, why don't we get the same suppression in $\nu$ endpoint region?

- Fixed the kinetic energy $K_p$ : greater M $\Longrightarrow$ higher $|\vec{p}|$

( $|\vec{p}| = \sqrt{2MK_p}$ in non relativistic case )

- Need to look at how big $\lambda p$ really is:

$$K_\beta^{end} \sim 18.6 \text{ keV} \Longrightarrow p_\beta \simeq 139 \text{ keV} \Longrightarrow \lambda p_\beta \simeq 5.9$$

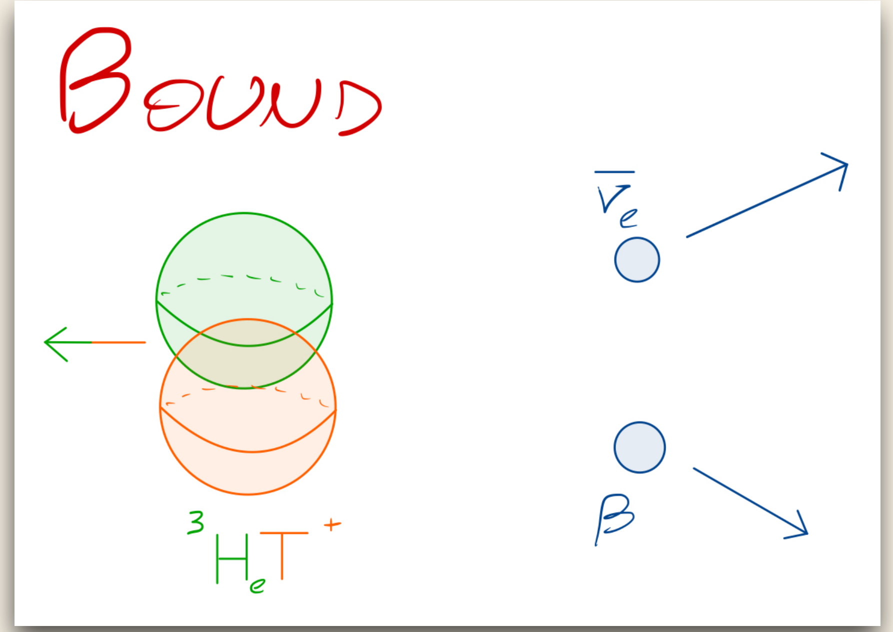
$$K_\nu^{end} \sim 18.6 \text{ keV} \Longrightarrow p_\nu \simeq 18.6 \text{ keV} \Longrightarrow \lambda p_\nu \simeq 0.8$$

$\Longrightarrow$ Bound events are more likely when $K_\beta$ is smaller and energy is given to $E_\nu \sim p_\nu$

# Does it make sense?

2) Number of configurations for bound events increases as we depart from endpoint regions

→ Now $Q \simeq 18.6\ keV$ can be distributed over both $\beta$ and $\nu$



# Counting problem solved!

- Final results:

Looking at Ptolemy endpoint region we had:
$\Omega \simeq 10^{-7}$

↓

Improving calculations we get:
$\Omega \simeq 0.3$

⟷

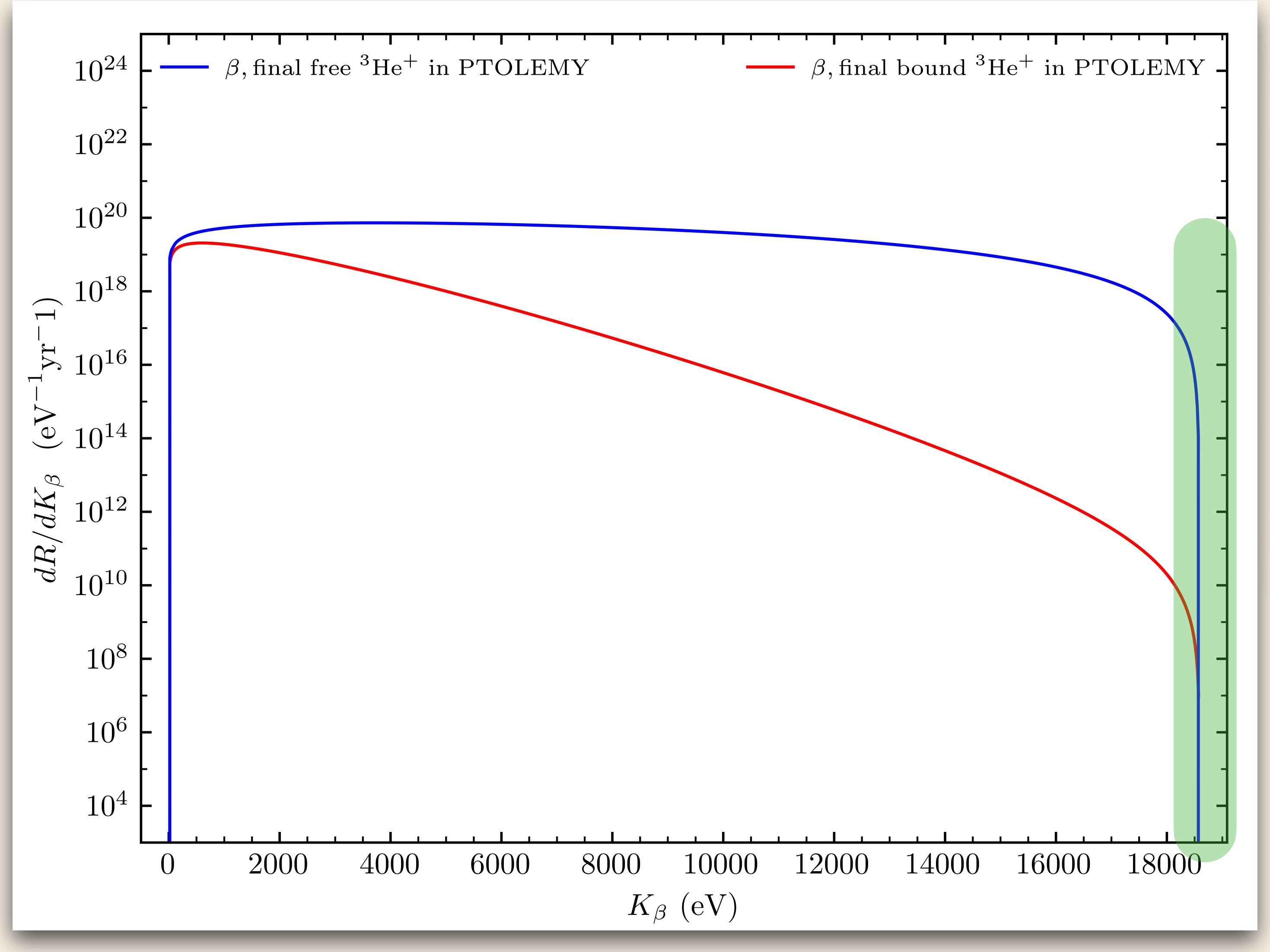
Trims data:
$\Omega \simeq 2.3$

We did NOT expect them to be the same, because we considered rates only for specific transitions.
But they are ~ same order

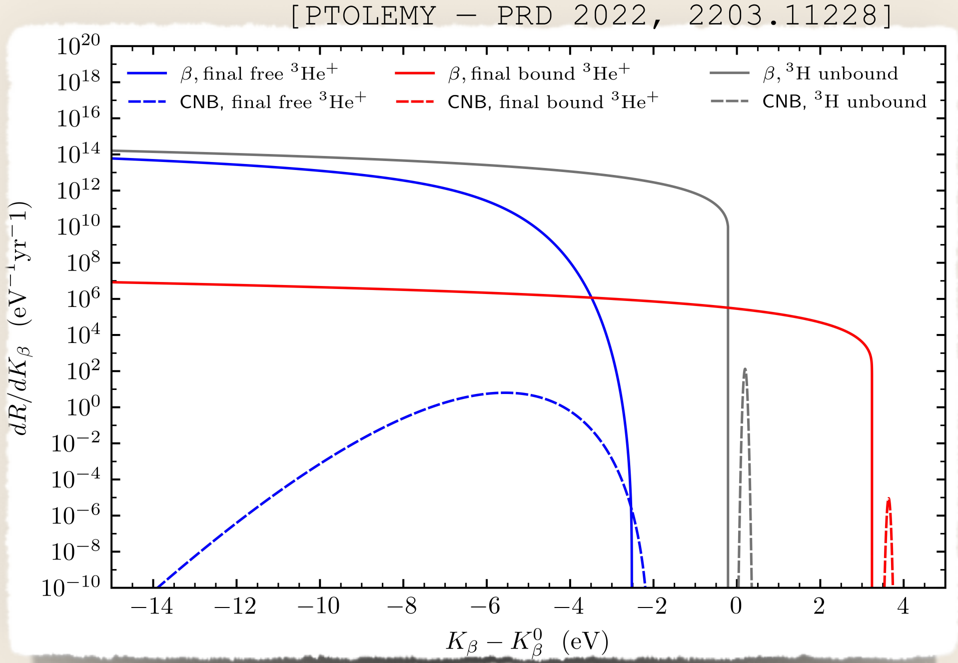
→ We can qualitatively reproduce data, awesome!

# Back to Ptolemy physics

- The same behaviour of the differential rates is found considering the Ptolemy case:



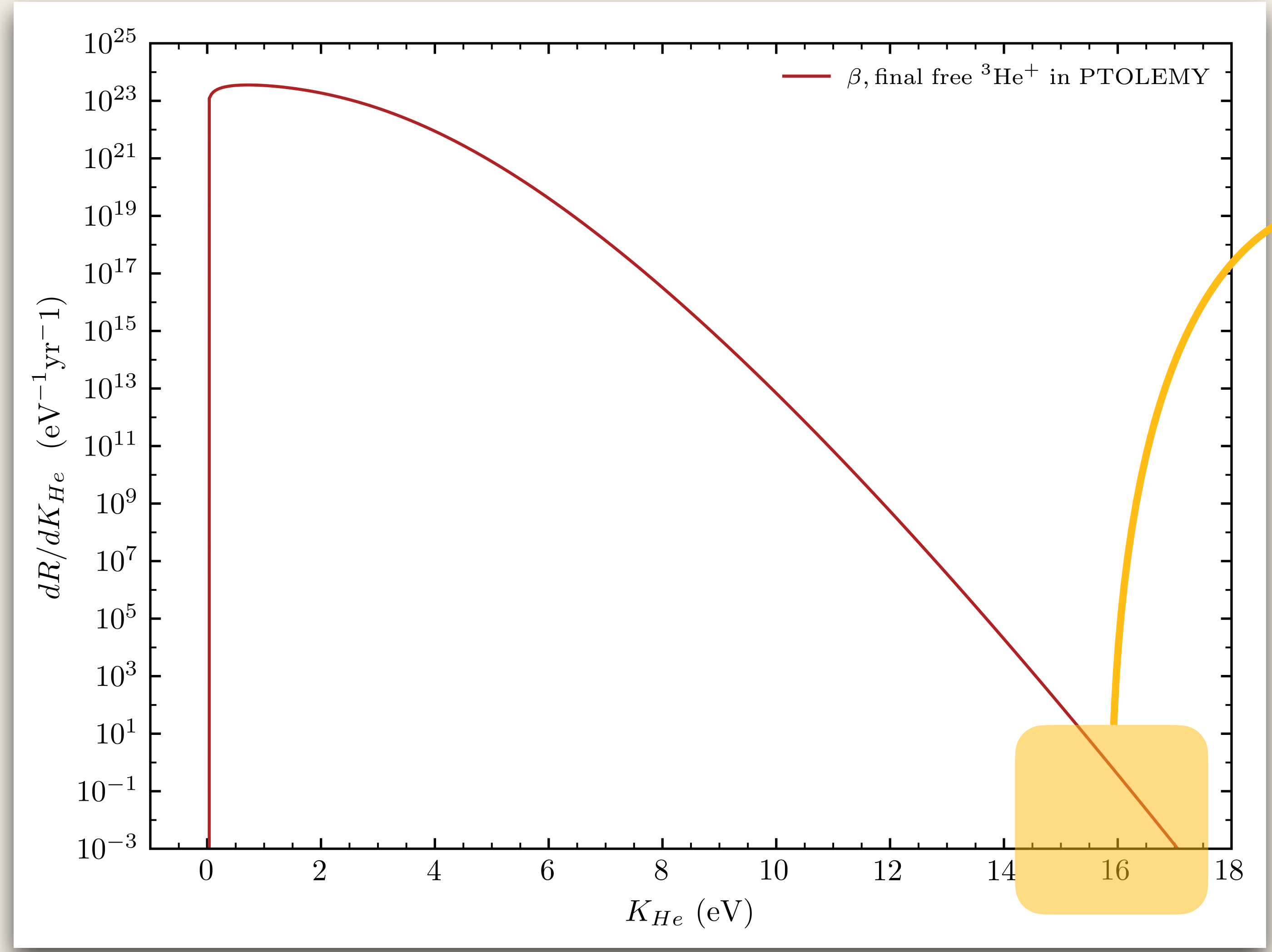

[PTOLEMY — PRD 2022, 2203.11228]




$\beta$ endpoint region

# Helium spectrum

- Same process, but from Helium point of view!




Very unlikely events as

$$K_{He} \longrightarrow 15 \text{ eV}$$

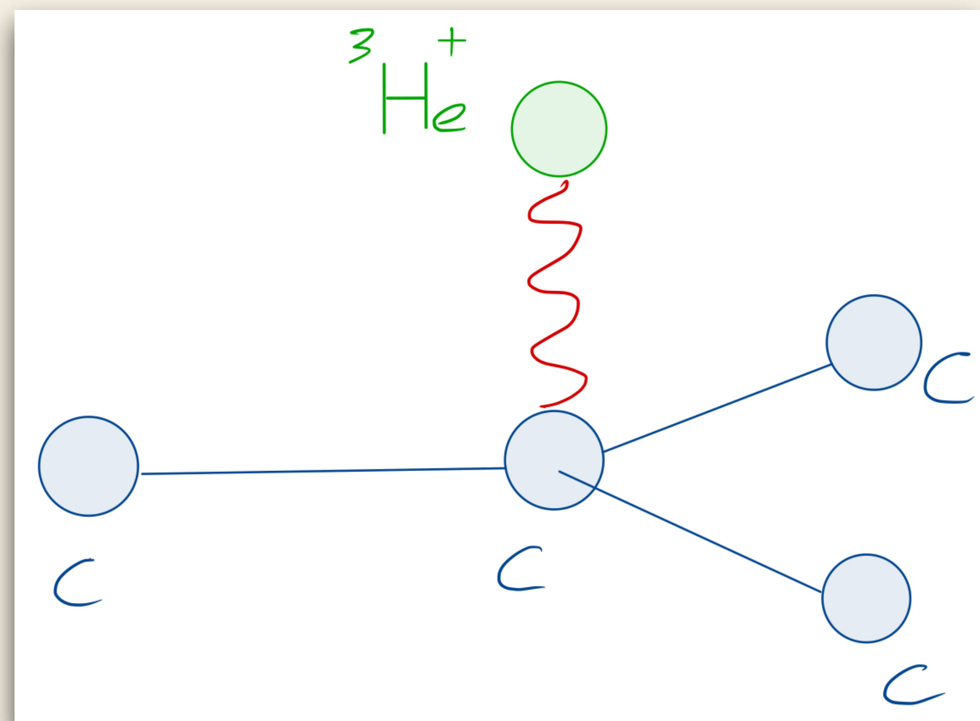
$$\lambda p_{He} \longrightarrow 12.3$$

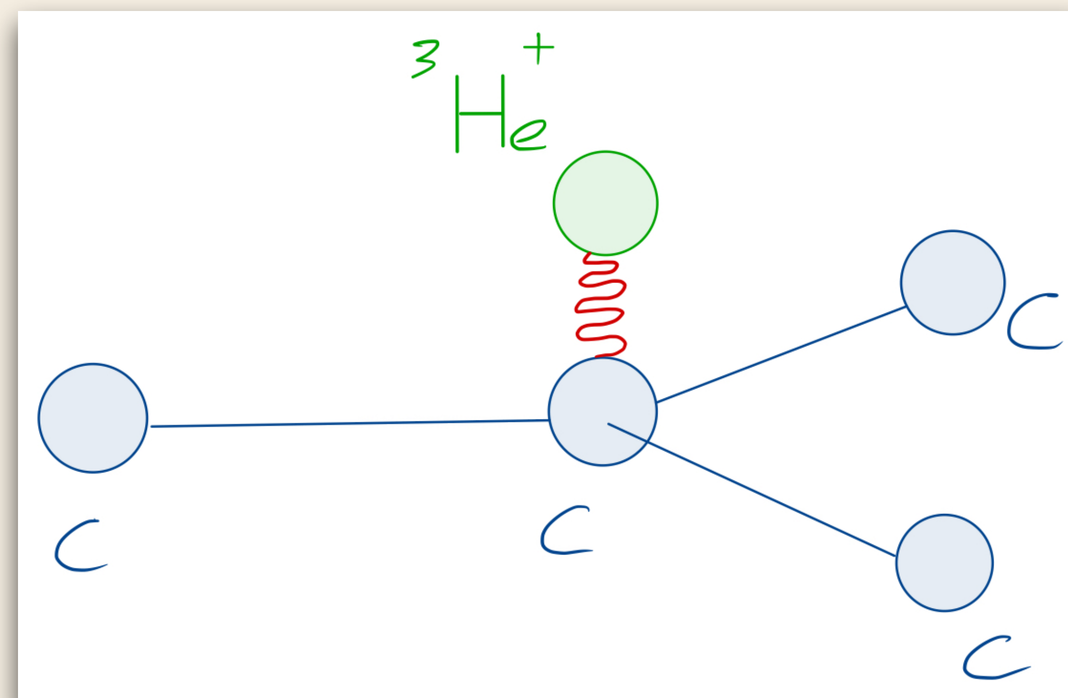
Recall indeed that:

$$d\Gamma \propto e^{-\lambda^2 |\overrightarrow{p_\beta} + \overrightarrow{p_\nu} + \overrightarrow{p_{He}}|^2}$$

# Excited bound states

- How to study bound $^3He$ vibrational modes?



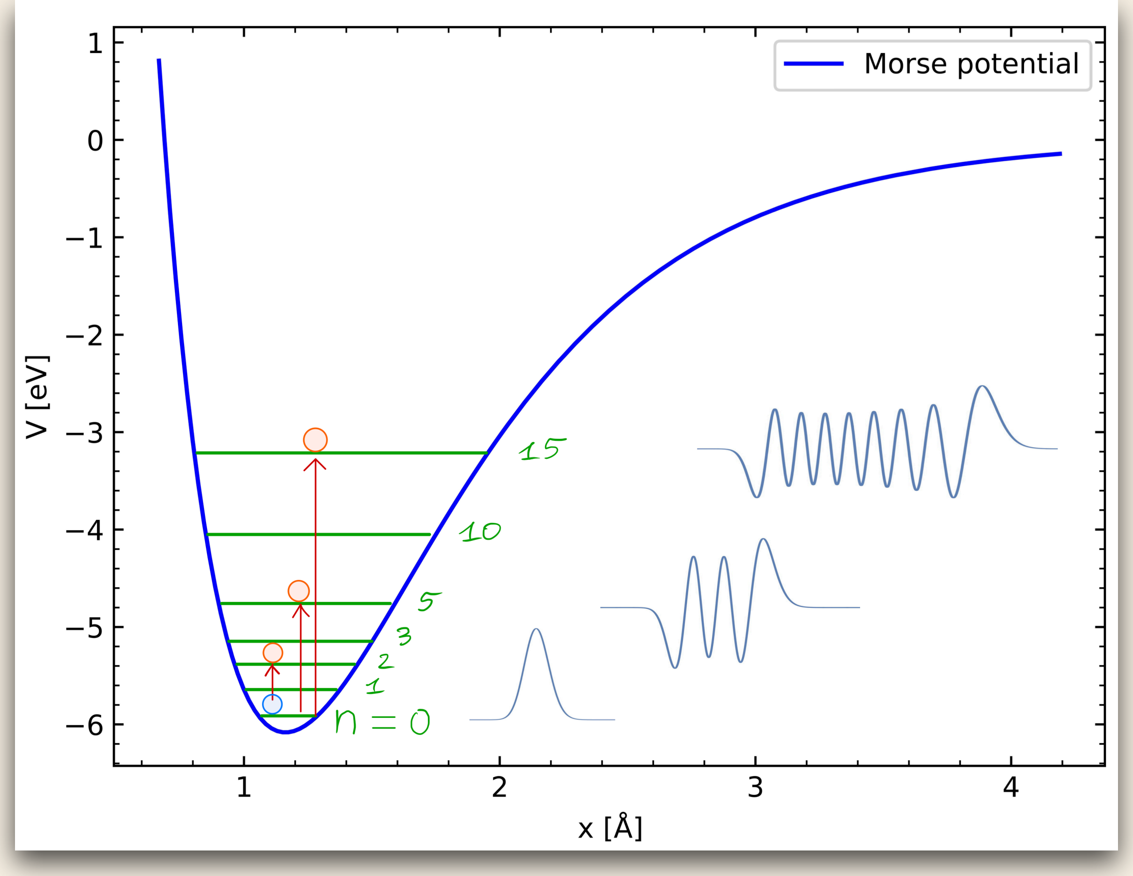
# Excited bound states

- In the past, we considered the bound $^3He$ to be in the ground state of the binding potential

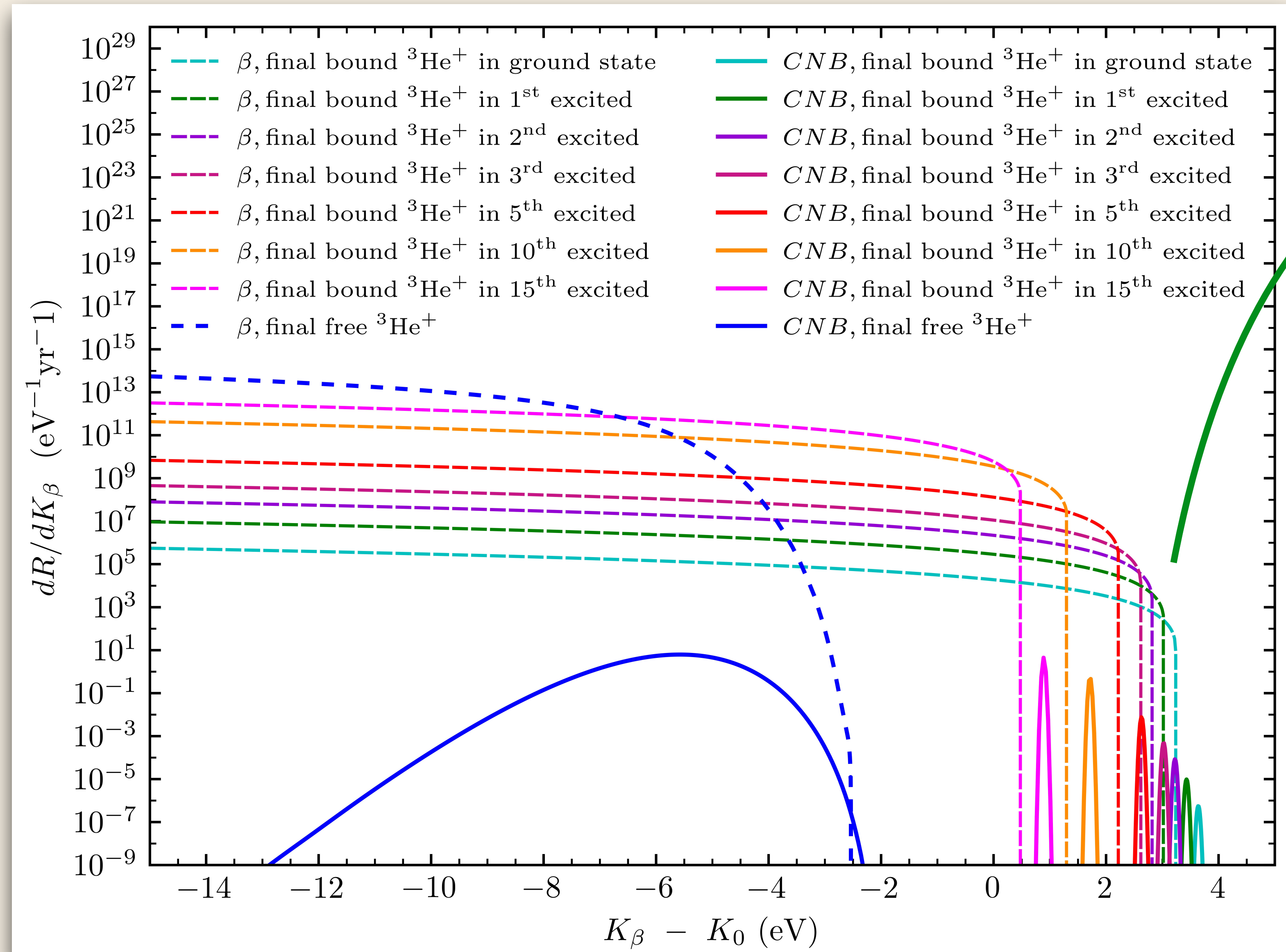
[PTOLEMY – PRD 2022, 2203.11228]

…what about excited states?

- After the decay, $^3He$ could be still bound, but with enough energy to jump over higher levels!



# Excited bound states

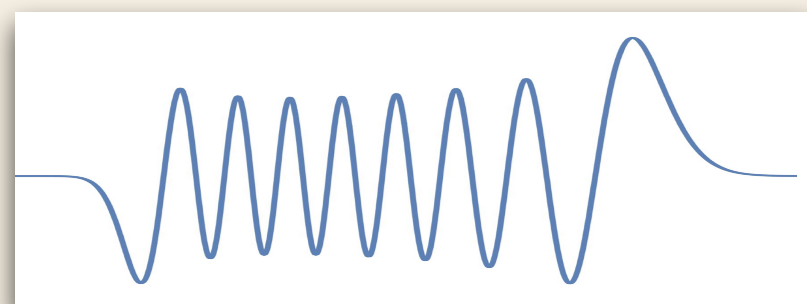



$\beta$ endpoint shifts to the left as $^3He$ is excited over higher levels

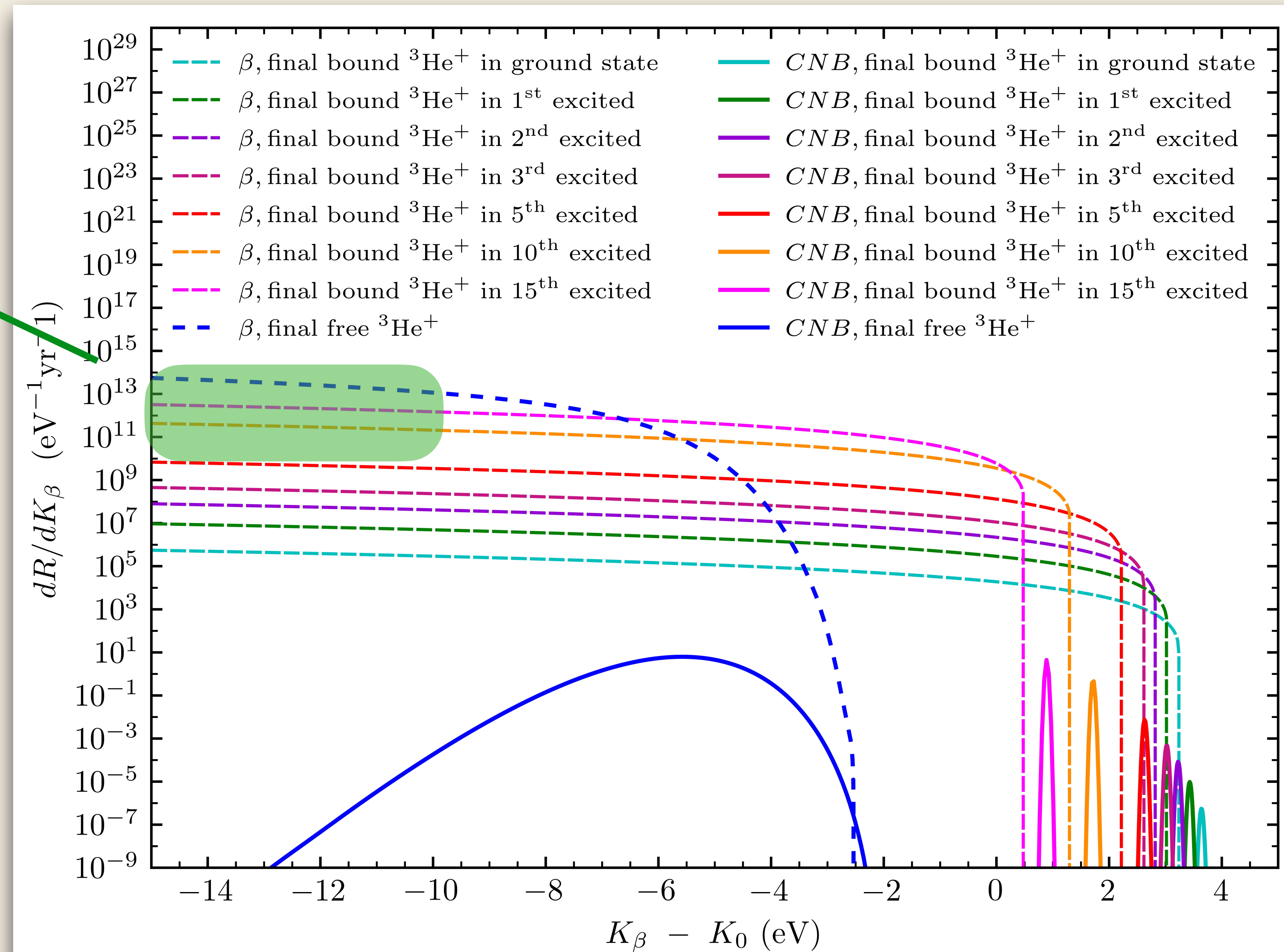
# Excited bound states

Rate for excited bound $^3He$ gradually reaches rate for free $^3He$.

Wavefunction for n=15



More and more similar to a plane wave as $n$ increases

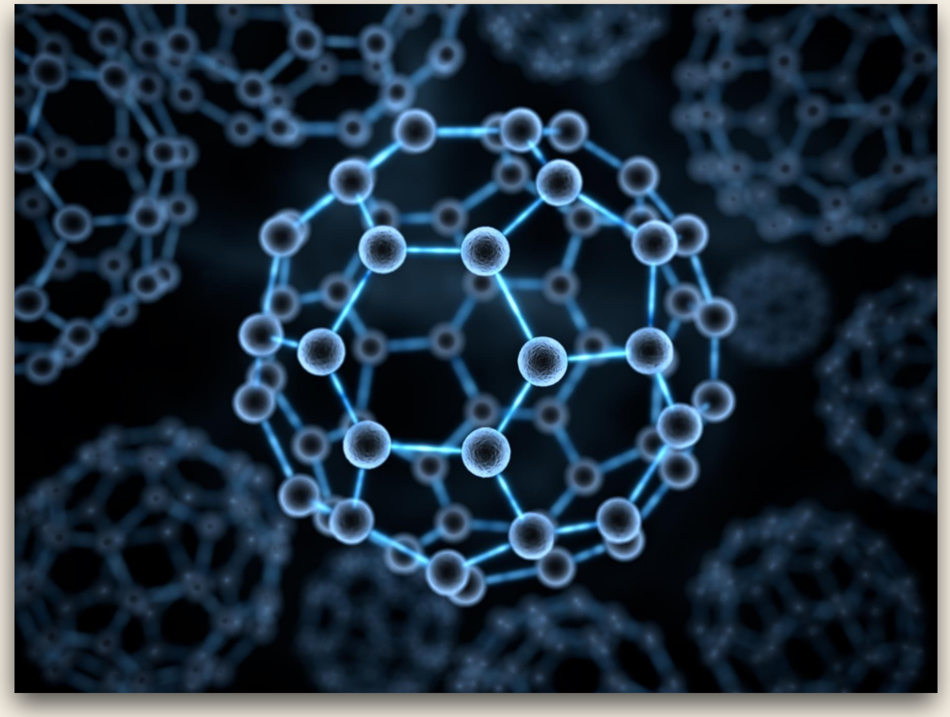


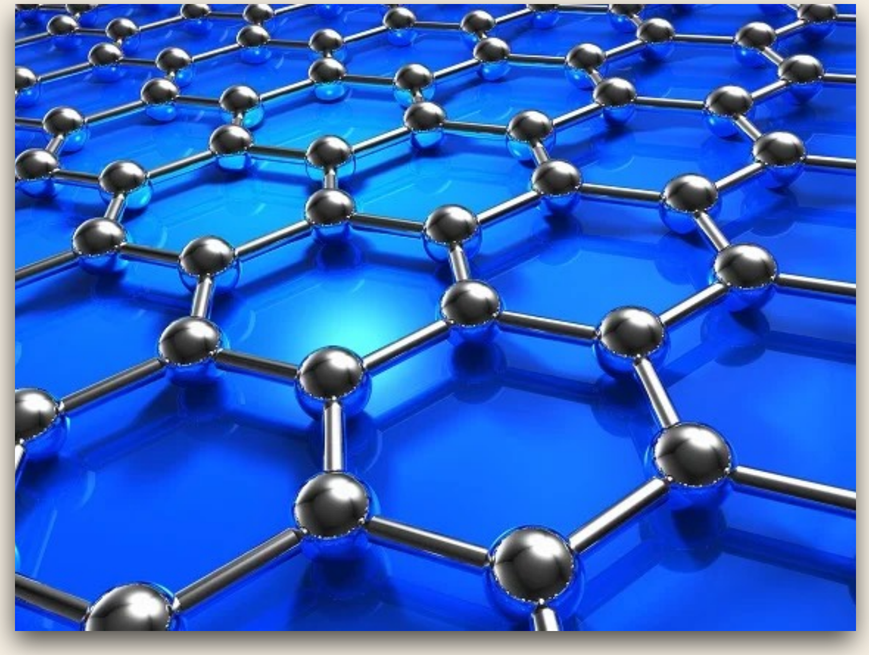
# What's next?

1) Study of potential along graphene layer → To better characterize bound $^3He$ wavefunction

2) Phonons vibrational modes

3) Fullerenes





Thank you for your attention!