Analyzing right-handed neutrino dark matter with electron recoil events

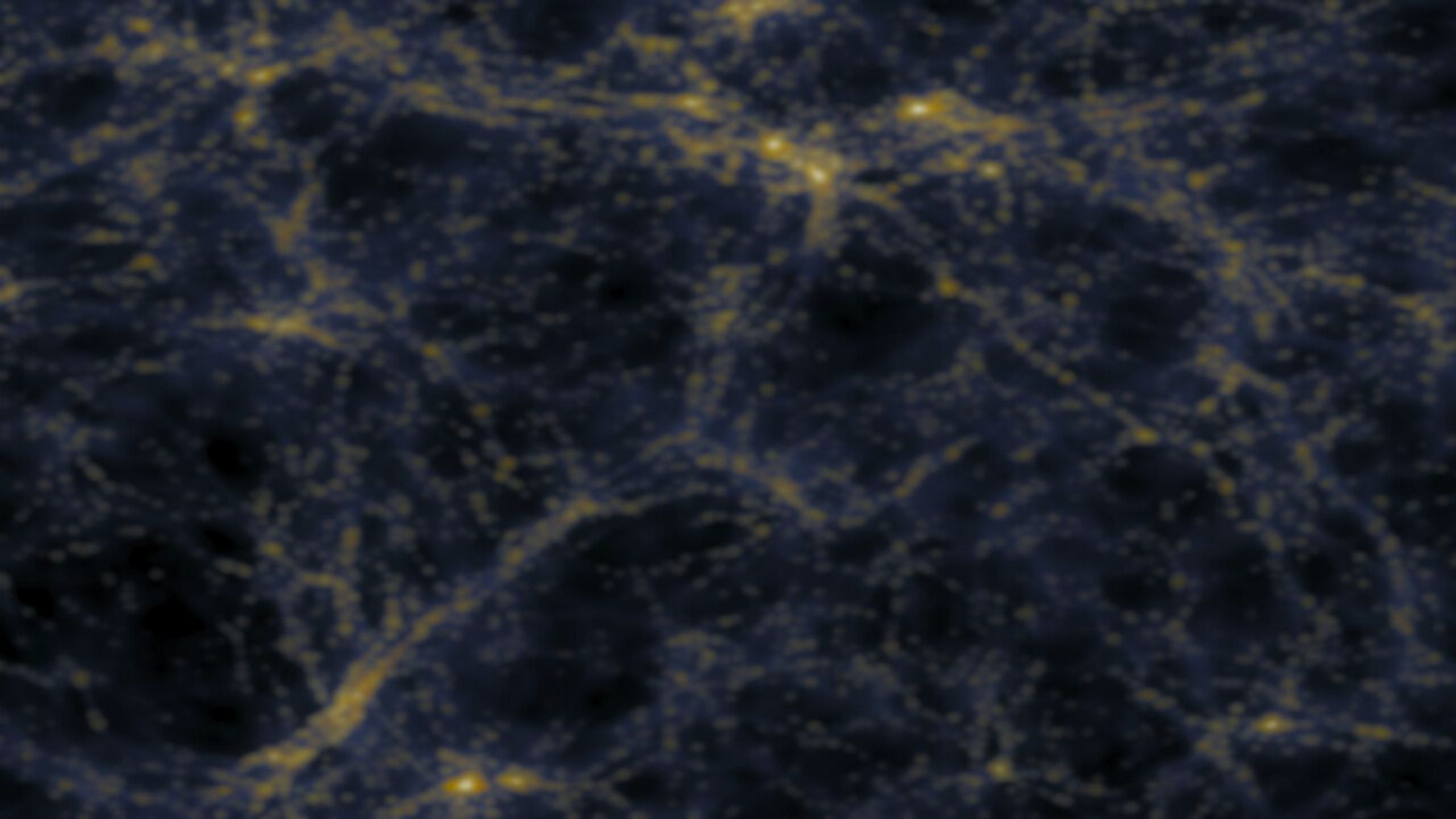
Seventeenth
Marcel Grossmann
Meeting
2024

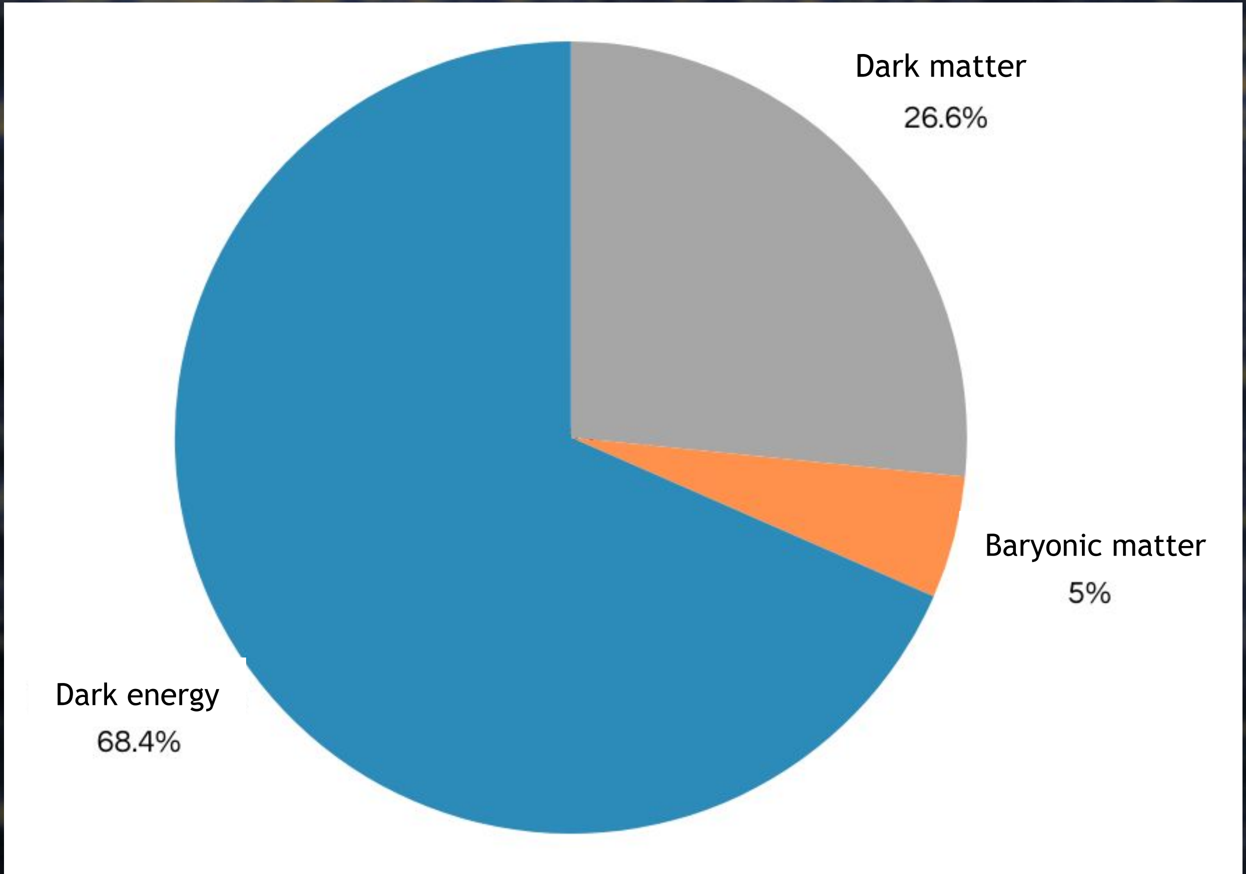
Santiago Collazo[1 2]

[1] **Instituto de Astrofísica de La Plata, CONICET**

[2] **Facultad de Ciencias Astronómicas y Geofísicas de La Plata, UNLP**

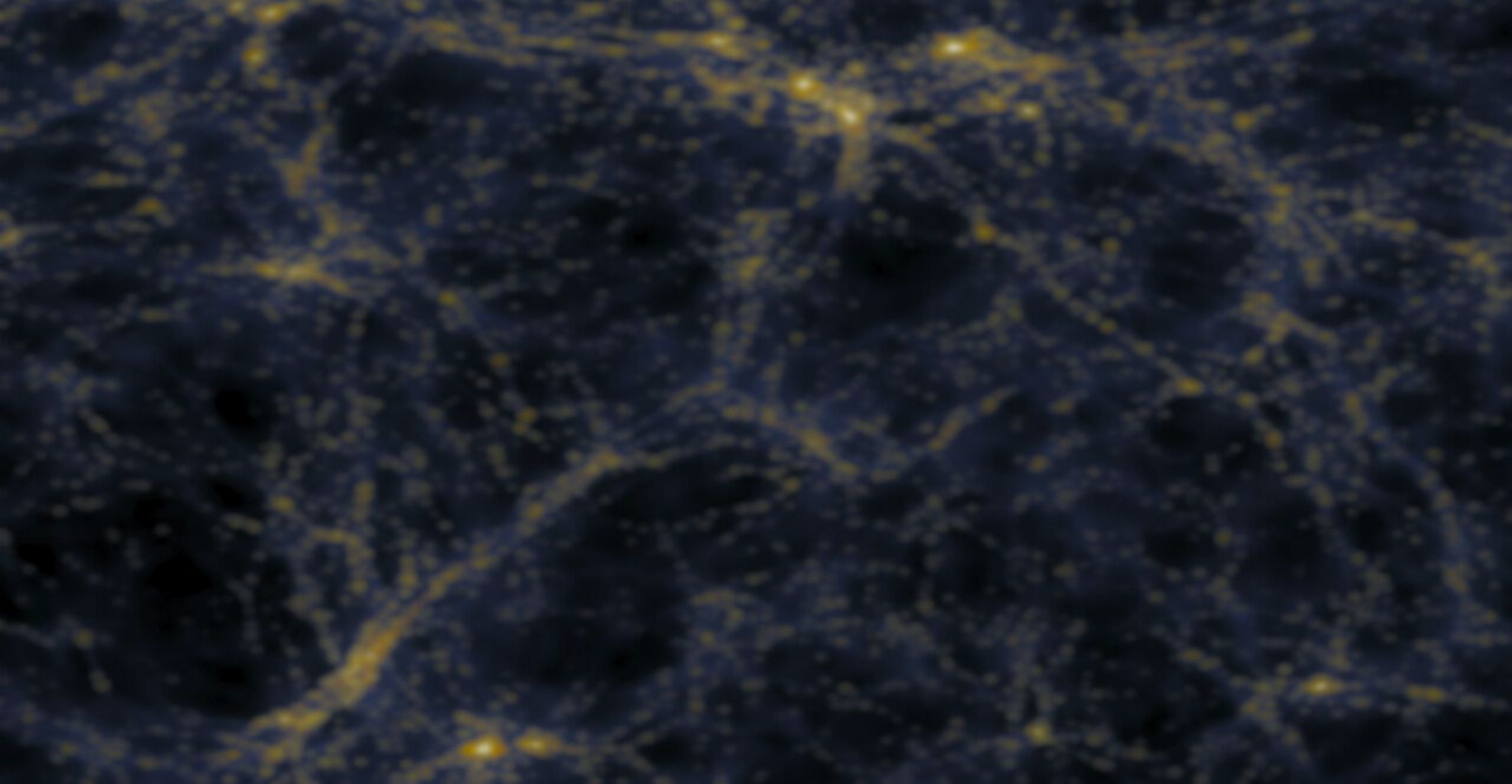
Collaborators: Carlos Argüelles,
Soroush Shakeri





Planck Collaboration 2018

What other evidence is found in nature?



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- Circular velocity curves
- Dispersion velocity curves
- Gravitational lensing
- Galaxy clusters
- *Bullet cluster*
- Lyman α forest
- Structure formation

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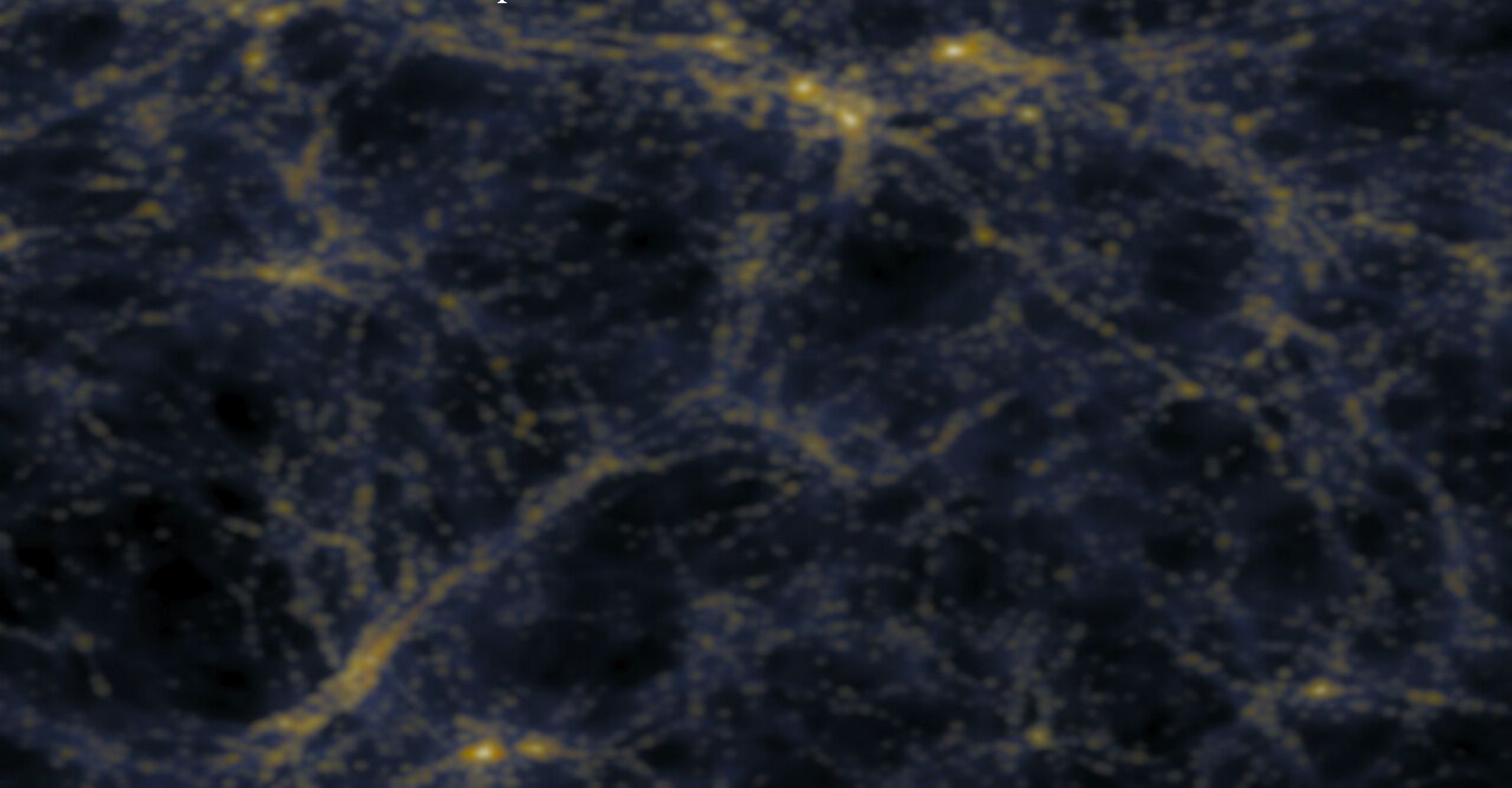
Astronomy can help us understand more about dark matter!

What about the microscopic nature of dark matter?



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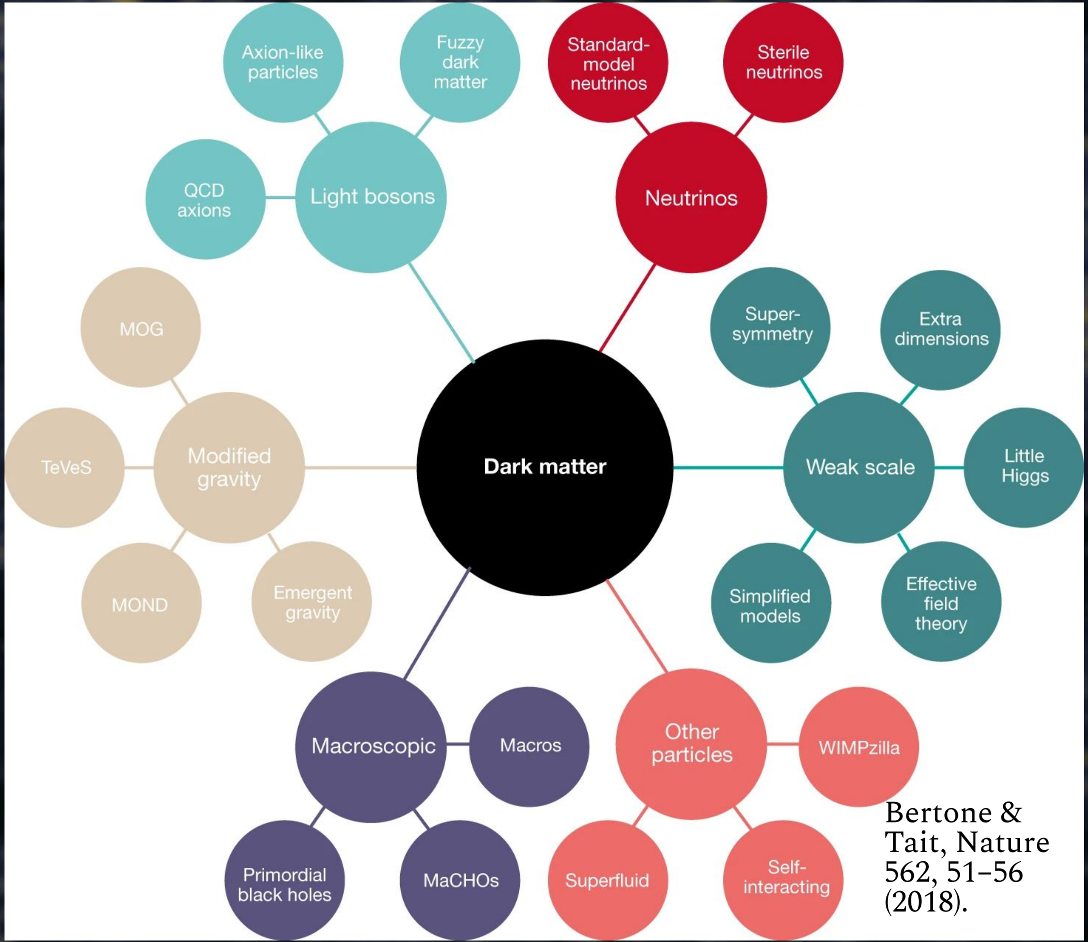
We have a plethora of different dark matter models to try



Bertone & Tait, Nature 562, 51–56 (2018).

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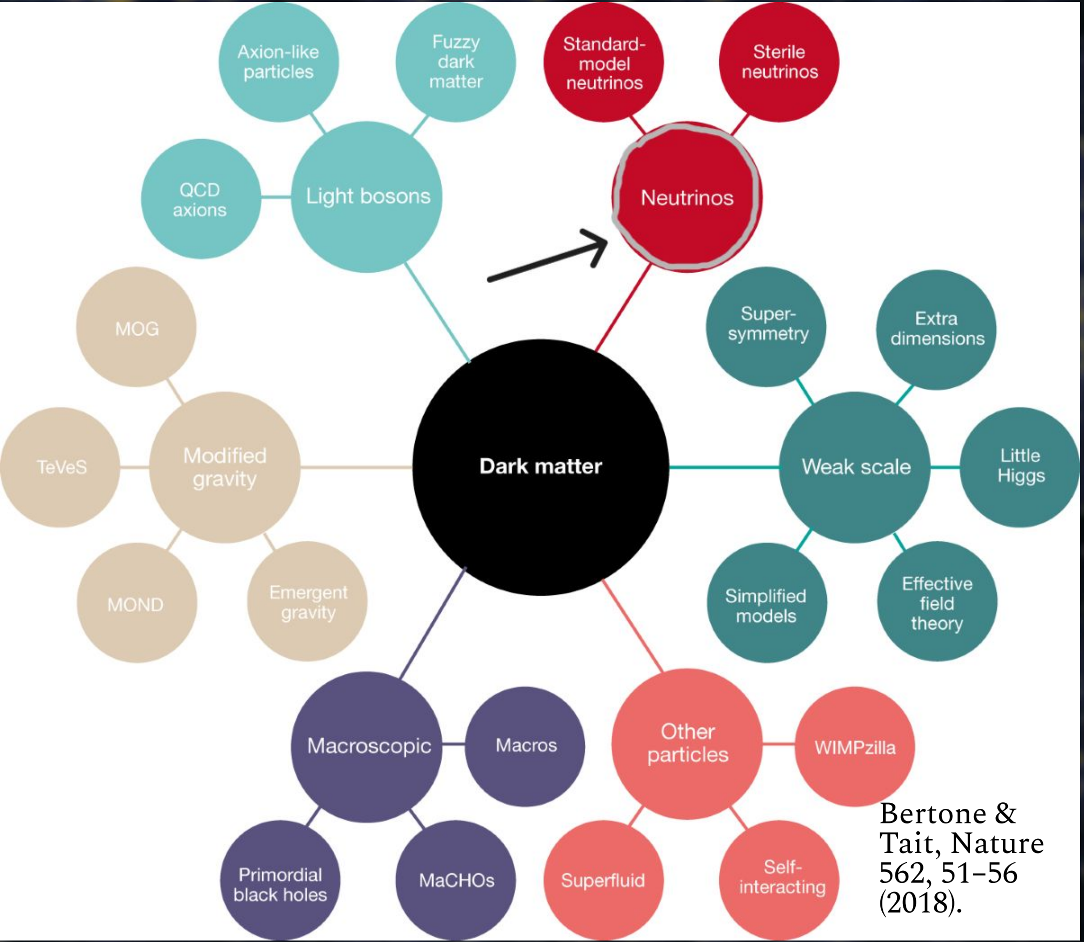
We will adopt as DM candidate a ***right-handed neutrino*** of mass of order keV



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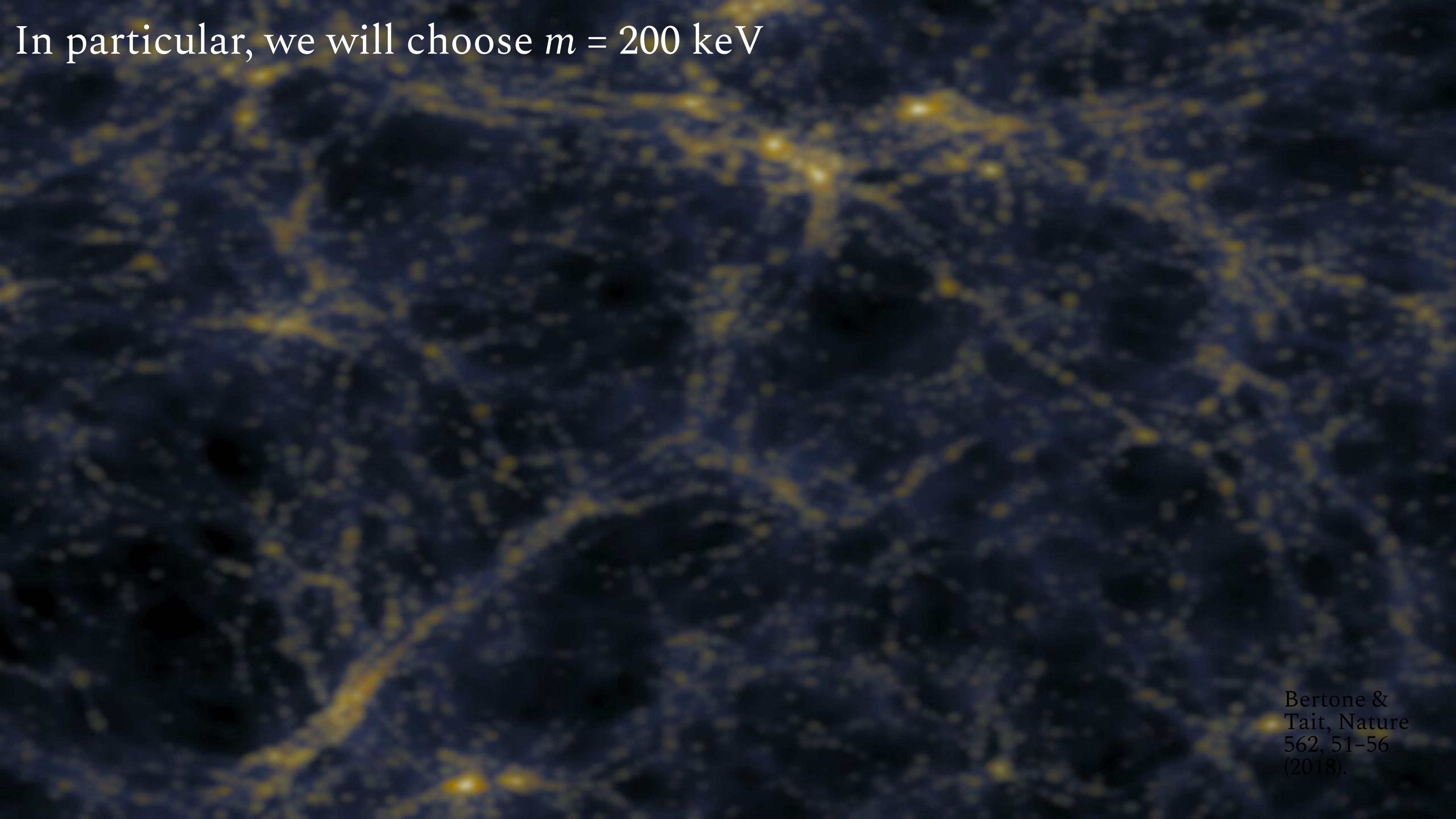
In particular, we will choose m = 200 keV



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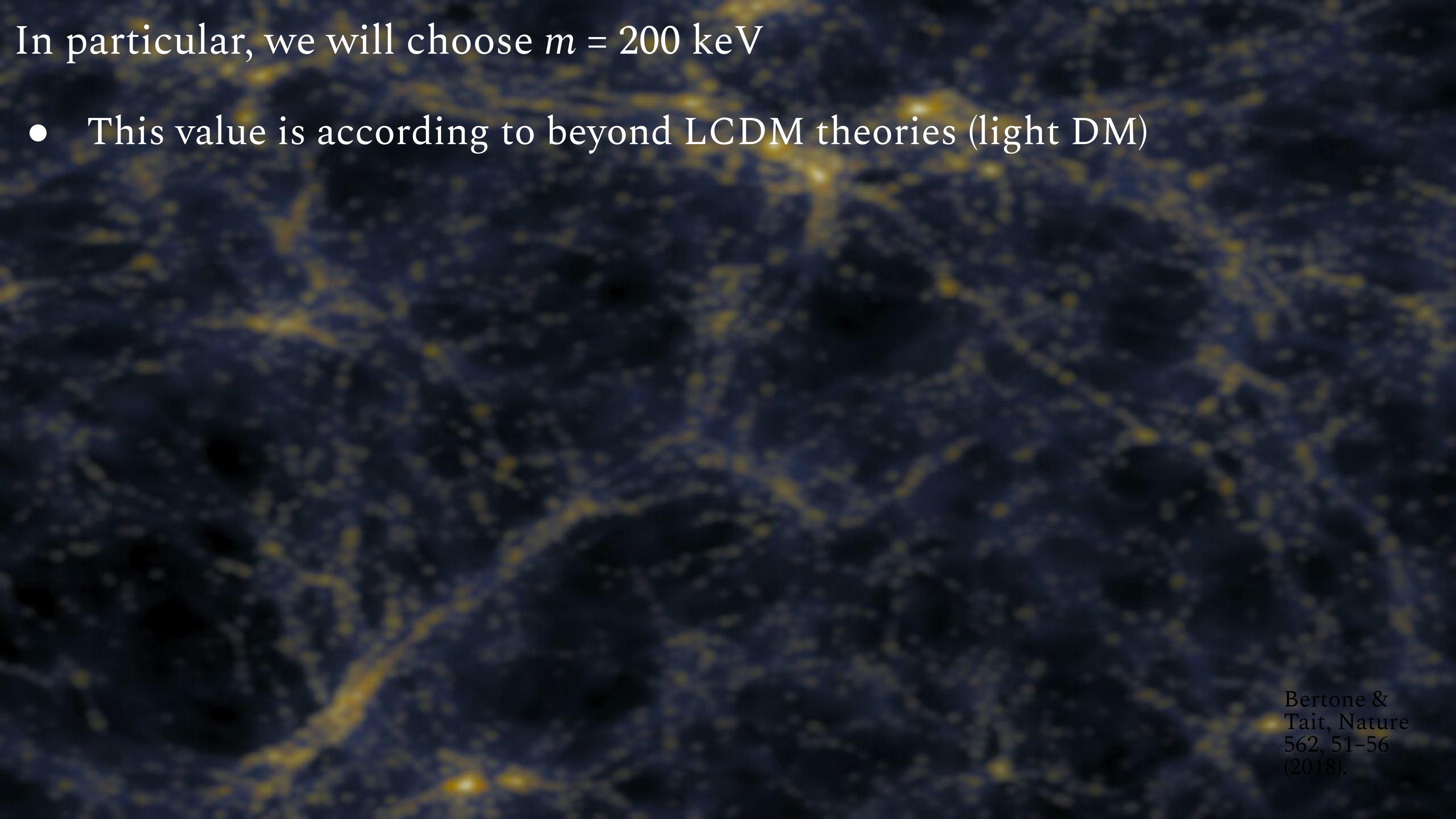

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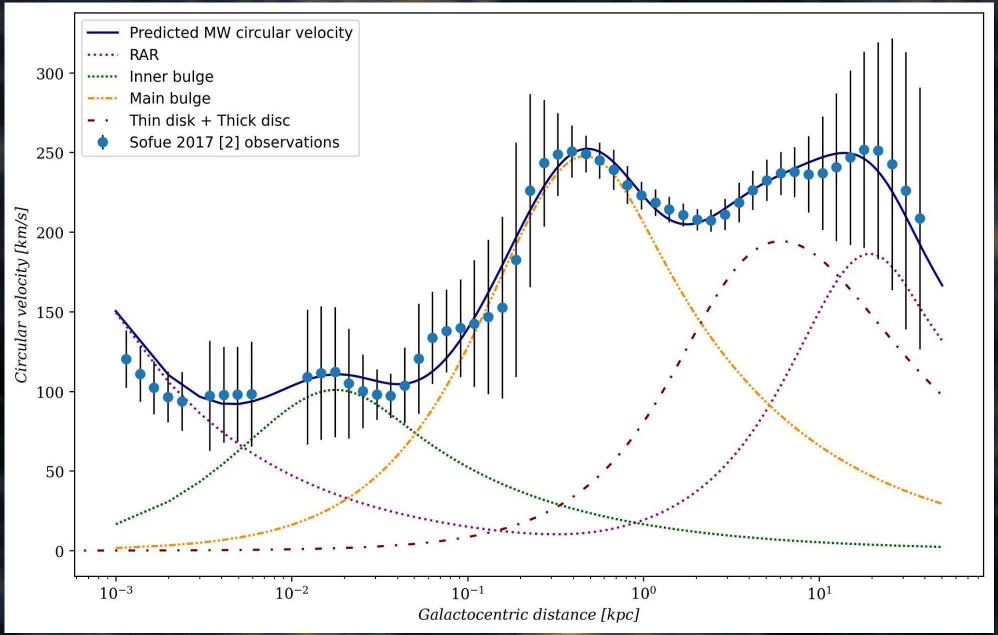

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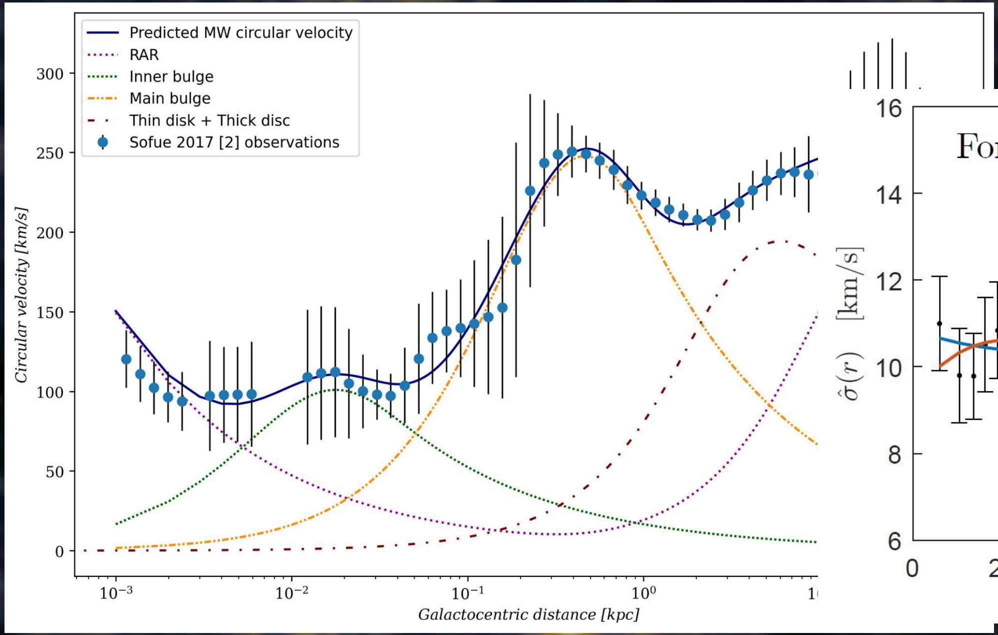

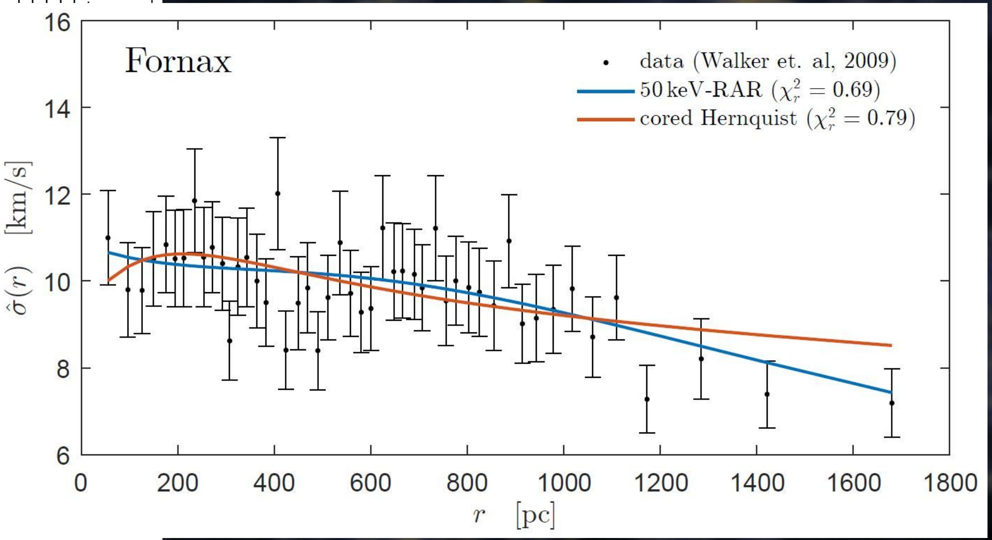

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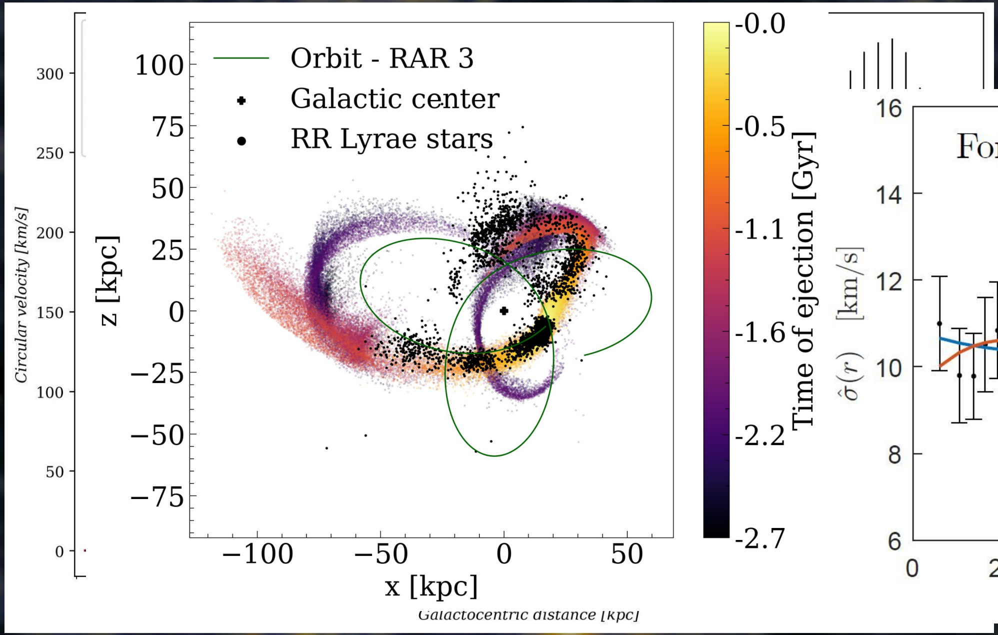

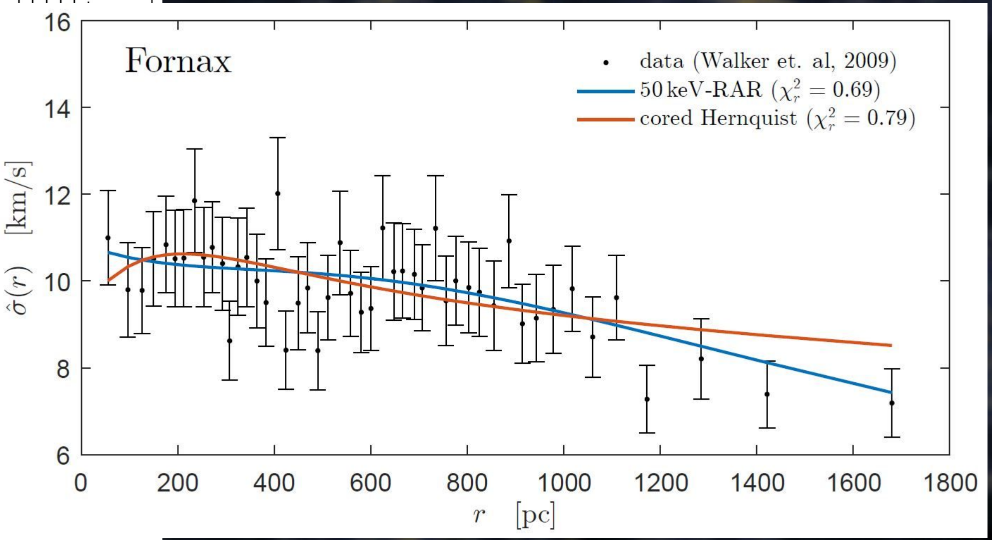

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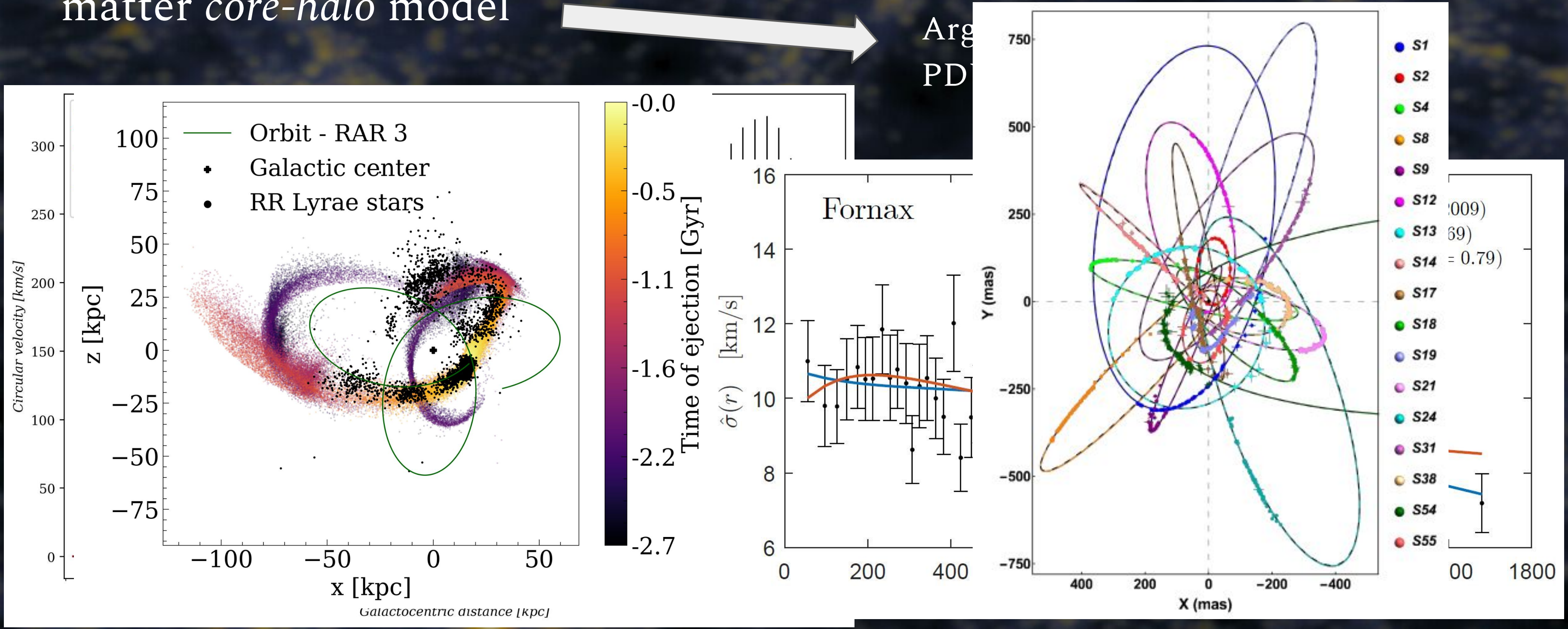

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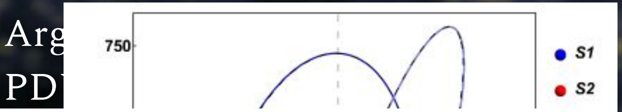

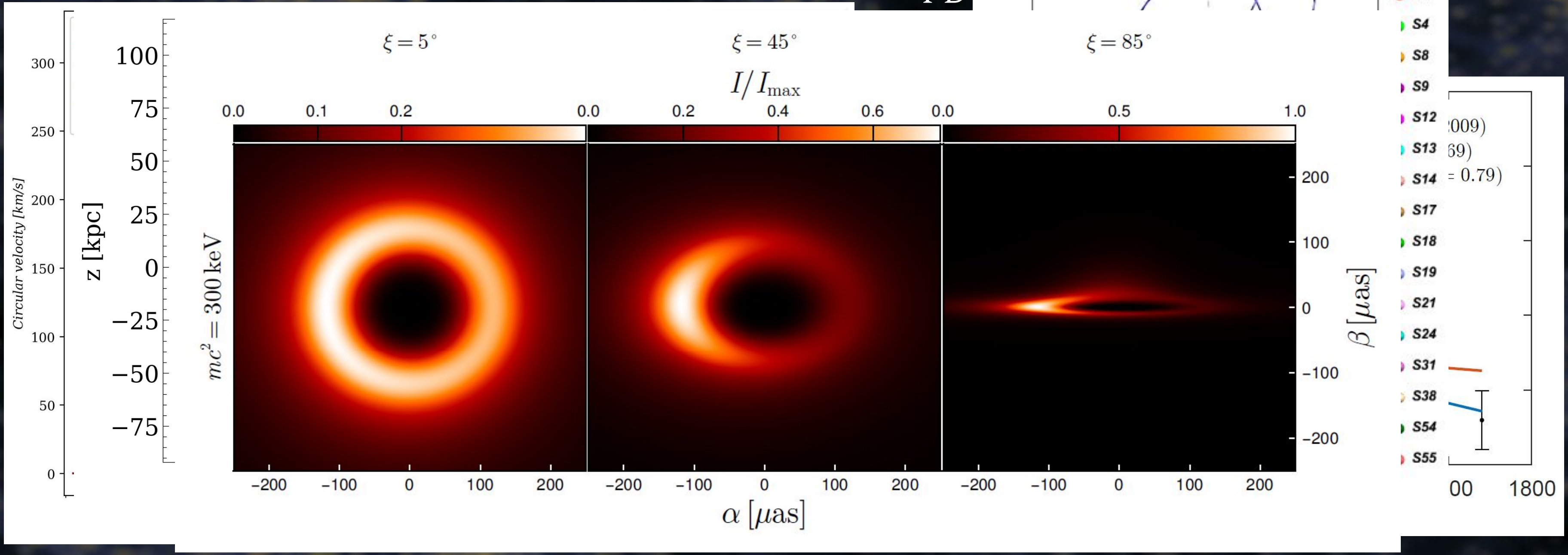

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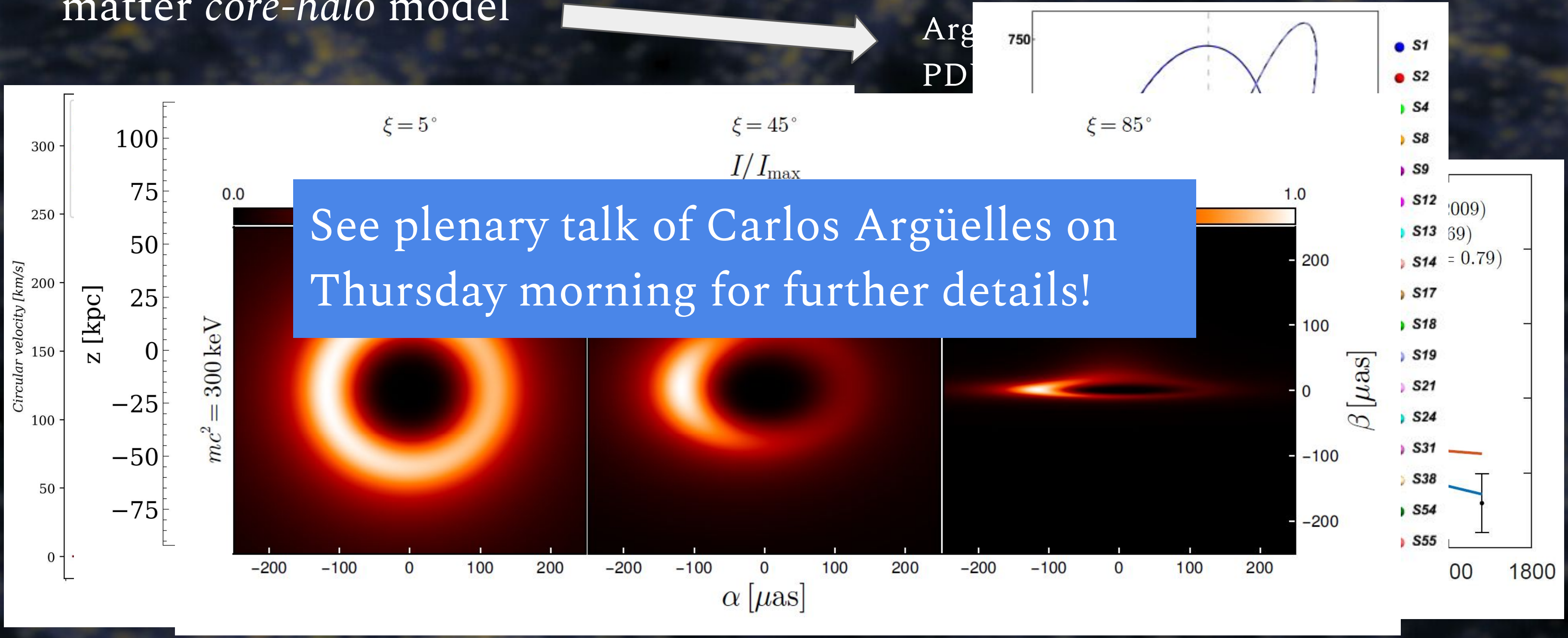

See plenary talk of Carlos Argüelles on Thursday morning for further details!

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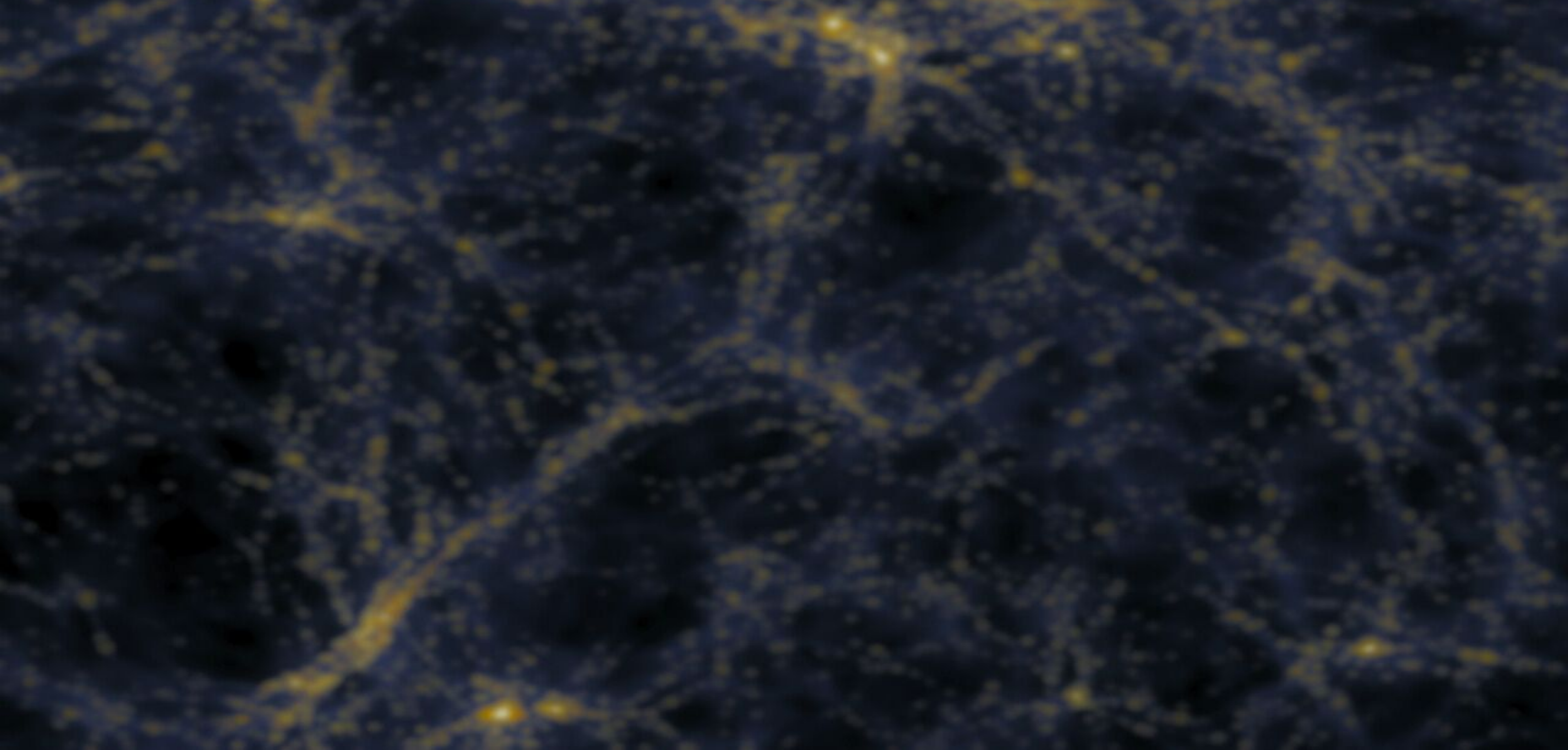

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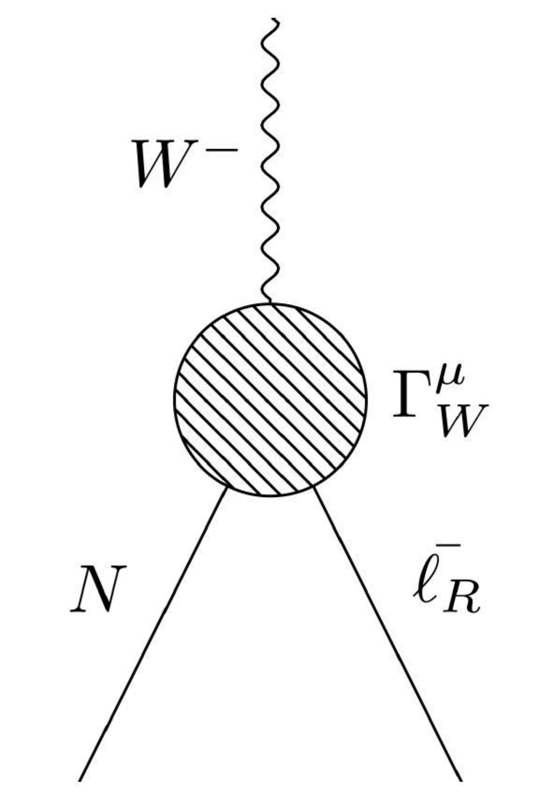

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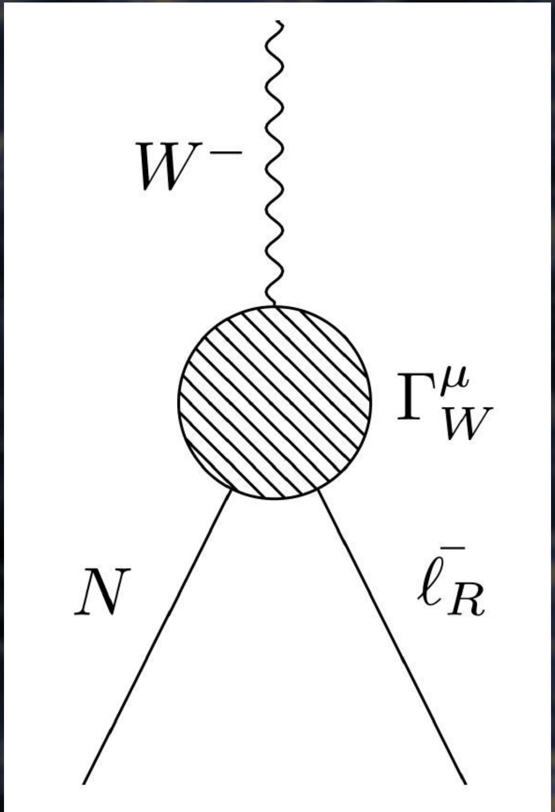

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Which corresponds to

$$\mathcal{L} \supset \mathcal{G}_R \left(g_w/\sqrt{2}\right) \left[\left(U^l_R\right)^\dagger U^\nu_R\right]^{ll'} \bar{l}_R \gamma^\mu N^{l'}_R W^-_\mu + \text{h.c.}$$

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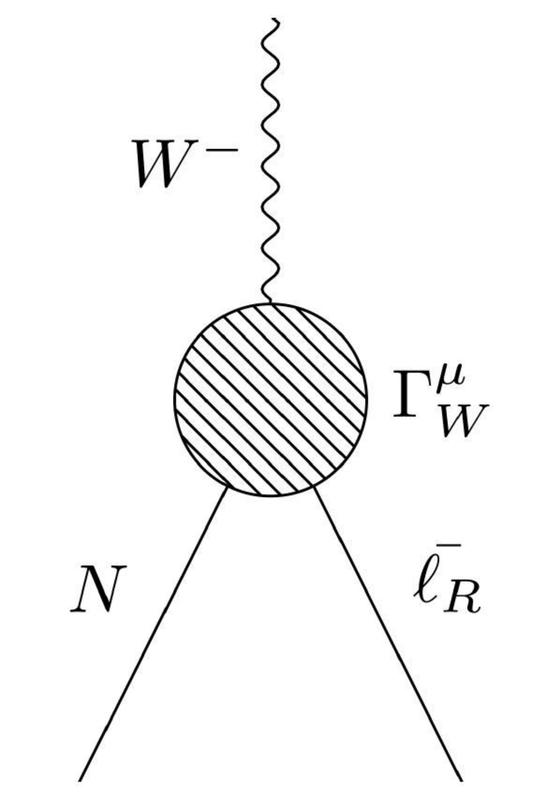

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But at tree level, right-handed neutrino electron interaction using this coupling is not dominant

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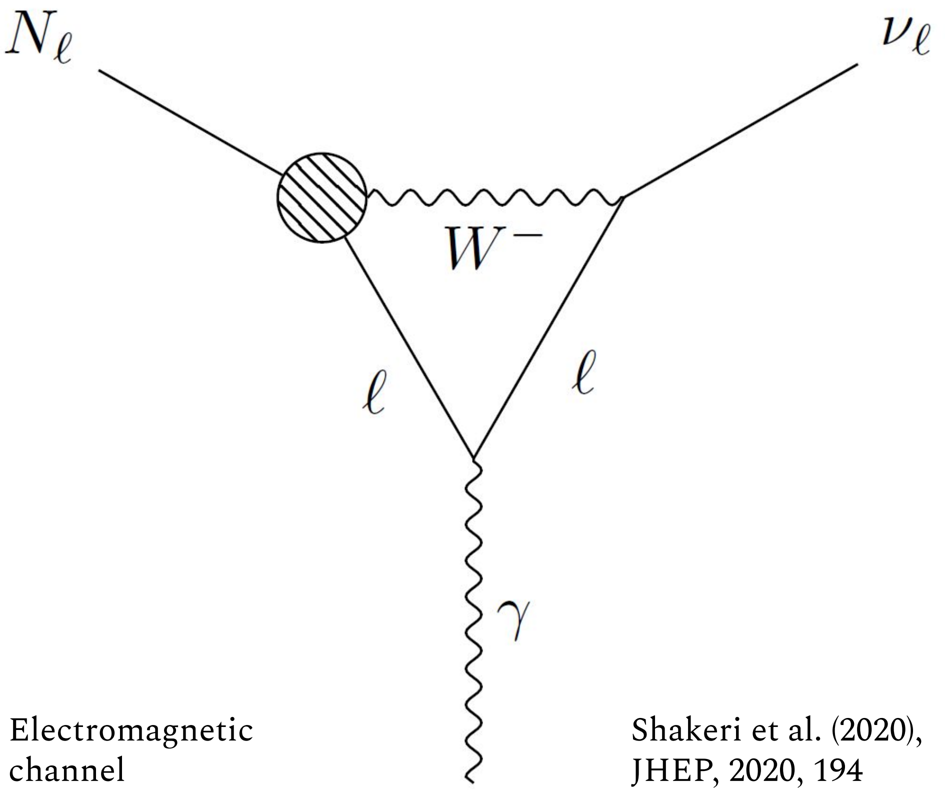
The right-handed neutrinos N can radiatively decay into a left-handed SM neutrino ν and a photon γ.



Electromagnetic channel

Shakeri et al. (2020), JHEP, 2020, 194

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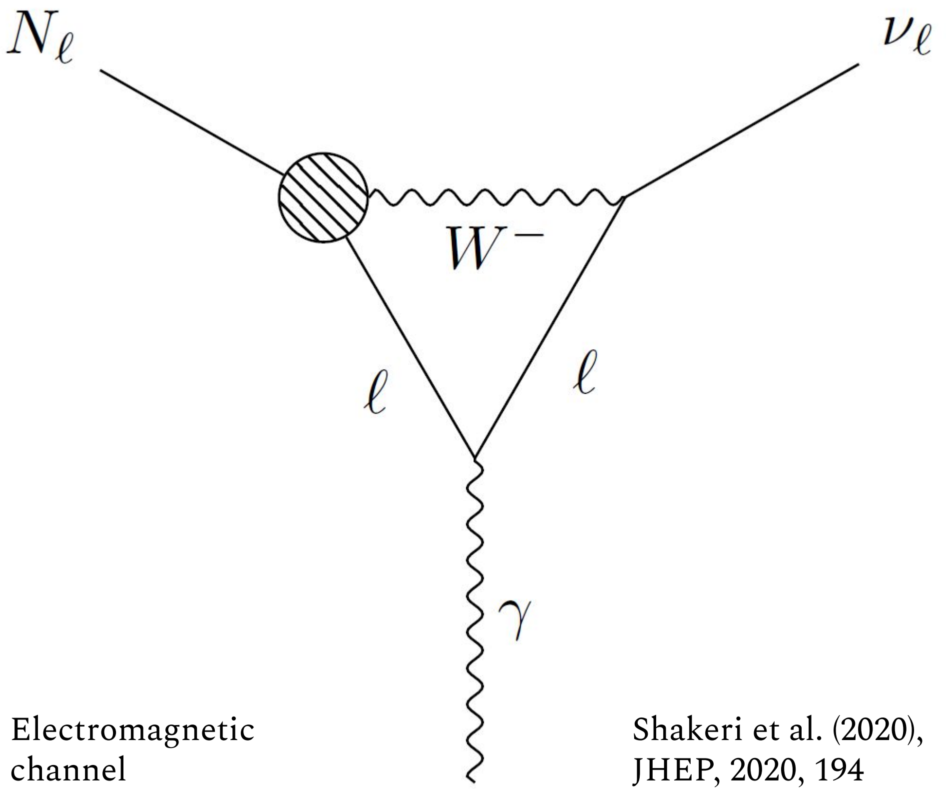
This vertex is represented as an effective operator

$$\hat{\mathcal{O}} = \left(U_L^{\nu} U_L^{\ell}\right)^{ll'} \bar{\nu}_L^{l} \Lambda_{l'}^{\mu} N_R^{l'} A_{\mu} + \text{h.c.}$$



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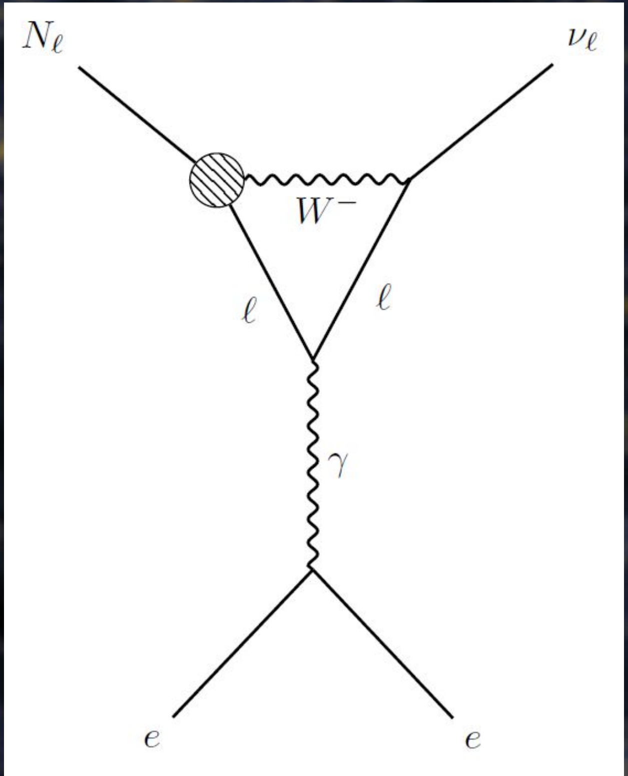
Hence, the interaction between a right-handed neutrino and a bounded electron on an atom of the detector will be described by



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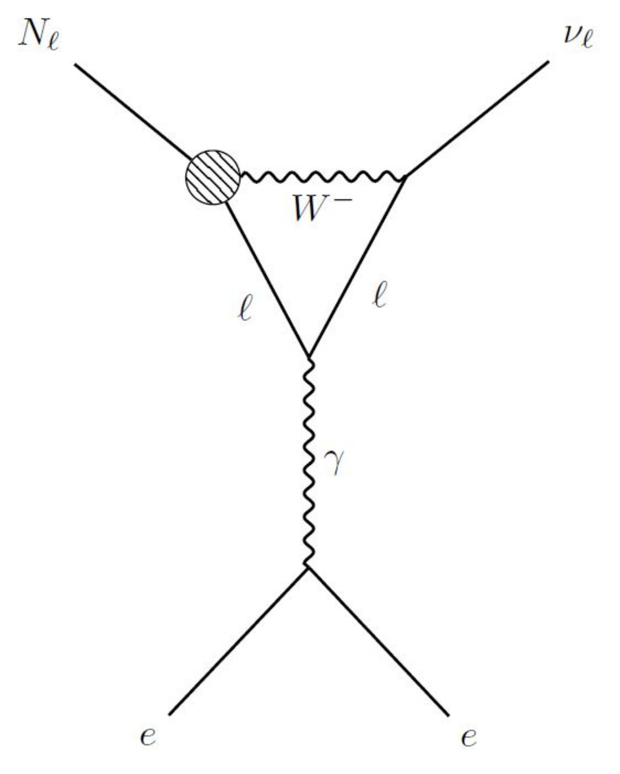

Interaction Lagrangian

$$\mathscr{L}_{\text{eff}} = -2\sqrt{2}G_F\left(\left[\bar{N}_e\gamma^\mu\mathscr{G}_R P_R u_e\right]\left[\bar{u}_e\gamma_\mu P_L \nu_e\right]\right)$$

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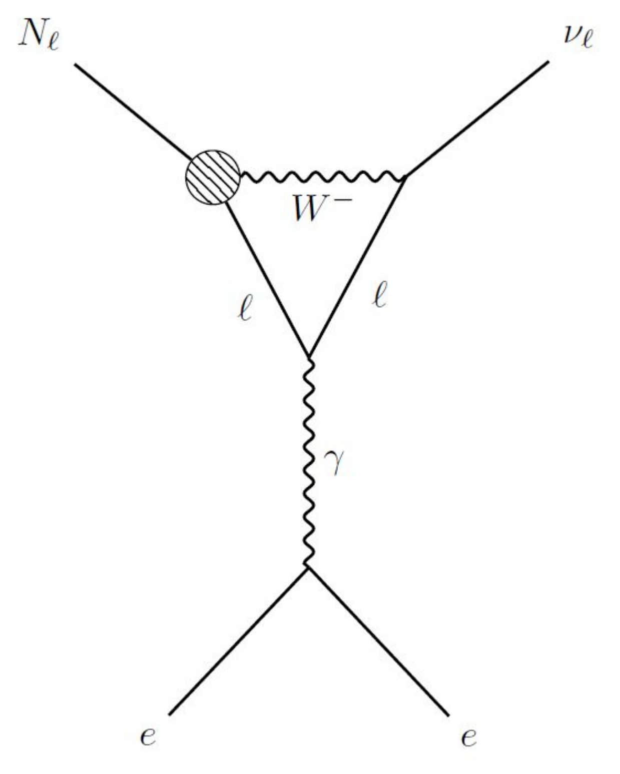

The squared matrix element is given by

$$
\begin{aligned}
|M|^2(E_R, q^2, v) = & \left(\frac{4m_l^2}{q^4}\right)\left(\frac{\alpha^2 g_w^4 \mathcal{G}_R^2}{16\pi^2}\right)\left(2m_\chi m_\nu + 2m_e E_R + m_\chi^2\right) \\
& \Big\{ (2C_1 + C_0)^2 \left[m_e \left(2m_e E_\chi + m_\chi^2\right)(E_\chi - E_R)\right] + \\
& + (2C_2 + C_0)^2 \left[m_e \left(2m_\chi E_R + m_\chi^2\right)(E_\chi - E_R)\right] + \\
& + (2C_1 + C_0)(2C_2 + C_0)\left[2m_e^2 \left(E_\chi^2 + E_R^2 - 2E_\chi E_R\right) + m_e m_\chi^2 (E_\chi - E_R)\right] \Big\}
\end{aligned}
$$

$$q^2 = q_\mu q^\mu$$

Using experimental and cosmological constraints it is possible to put an upper bound on the coupling constant

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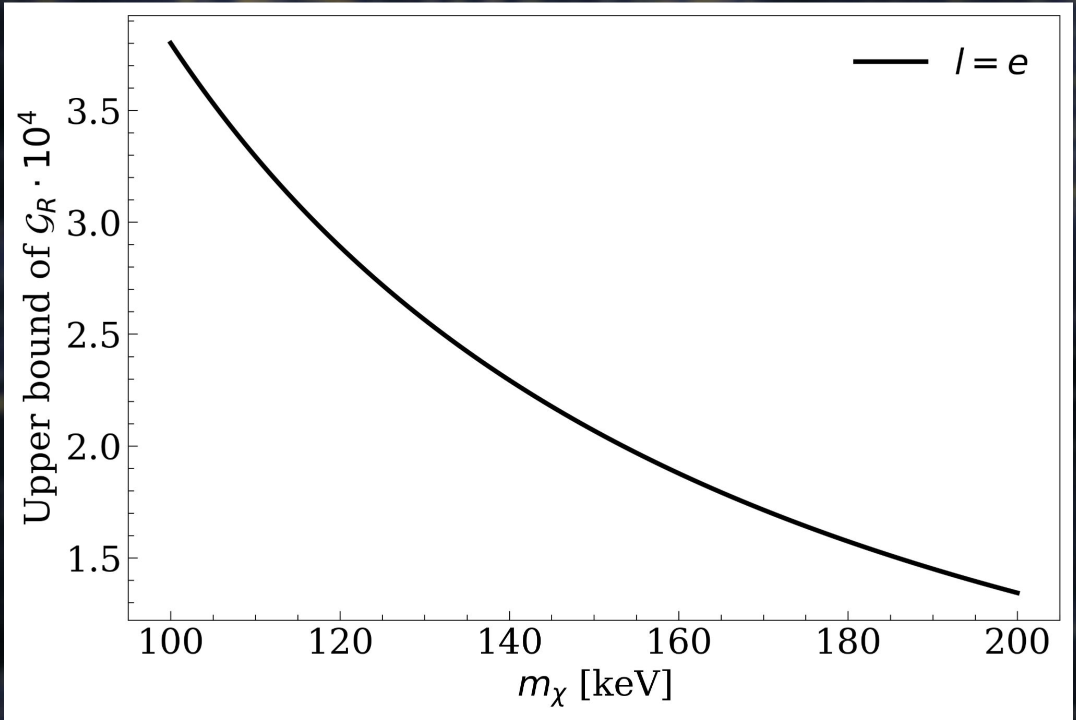
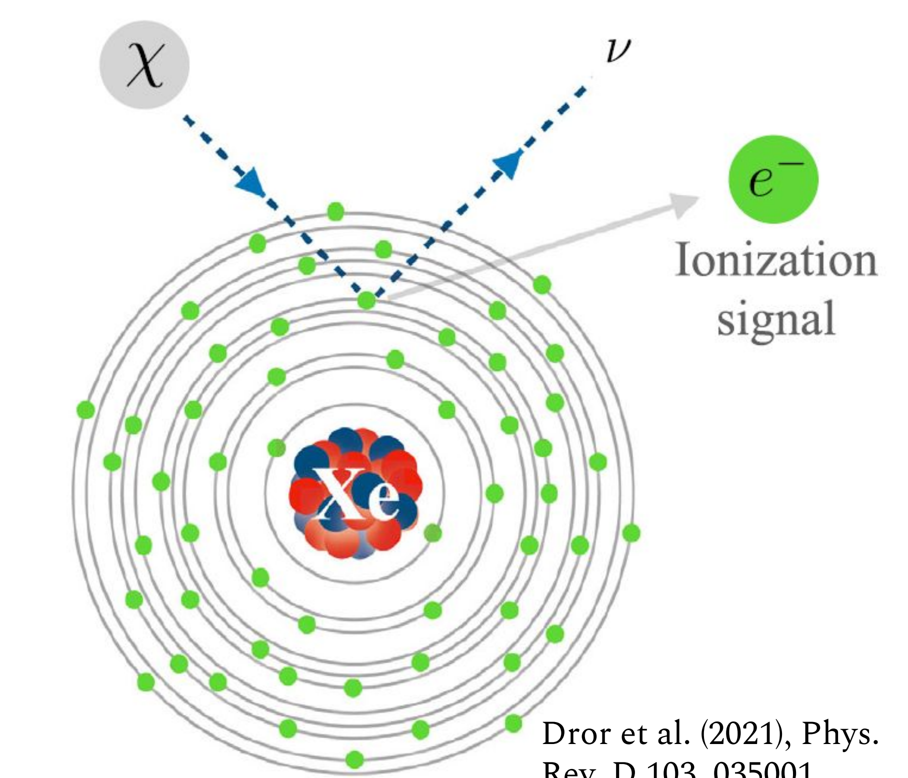
$$\mathcal{G}_R \lesssim 3.8 \cdot 10^{-4} \left(\frac{511 \text{ keV}}{m_e}\right) \left(\frac{100 \text{ keV}}{m_\chi^e}\right)^{3/2}$$



We want to study the ionization of atoms due to right-handed neutrino electron interactions



Dror et al. (2021), Phys. Rev. D 103, 035001

We can apply the Lagrangian described before to model the interaction

$\mathrm{N} + e \rightarrow \nu + e$

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N + *e* → *v* + *e*

The direct interaction ionizes the atom.
This constitutes an event and will allow the *events rate* to be defined.

$$\frac{dR_{\text{ion}}^{nl}}{dE_R} = \frac{\rho_\chi}{128\pi m_\chi^3 m_e^2} \int dq \; \frac{q}{E_R} \eta(v_{\min}(q, E_R)) |M(q^2)|^2 |f_{\text{ion}}^{nl}(E_R, q)|^2$$

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Under the assumption *mv* << *q*

$$\frac{dR^{nl}_{\rm ion}}{dE_R} = \frac{\rho_\chi}{64\pi m_\chi^2 m_e^2}\frac{q}{E_R}|f^{nl}_{\rm ion}(k',q)|^2|M(q^2)|^2.$$

Where *q* yields

$$q = m_\chi + E_B^{nl} - E_R$$

Ionization form factor:

$$|f_{\text{ion}}^{nl}(k',q)|^2 = \frac{4k'^3}{(2\pi)^3}\sum_{l'=0}^{\infty}\sum_{L=|l-l'|}^{l+l'}(2l+1)(2l'+1)(2L+1)\begin{bmatrix} l & l' & L \\ 0 & 0 & 0 \end{bmatrix}\left|\int dr r^2 R_{k'l'}(r)R_{nl}(r)j_L(qr)\right|^2$$

It is related with the quantum mechanics of the atom

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Outgoing electron radial wavefunction

Bounded electron radial wavefunction

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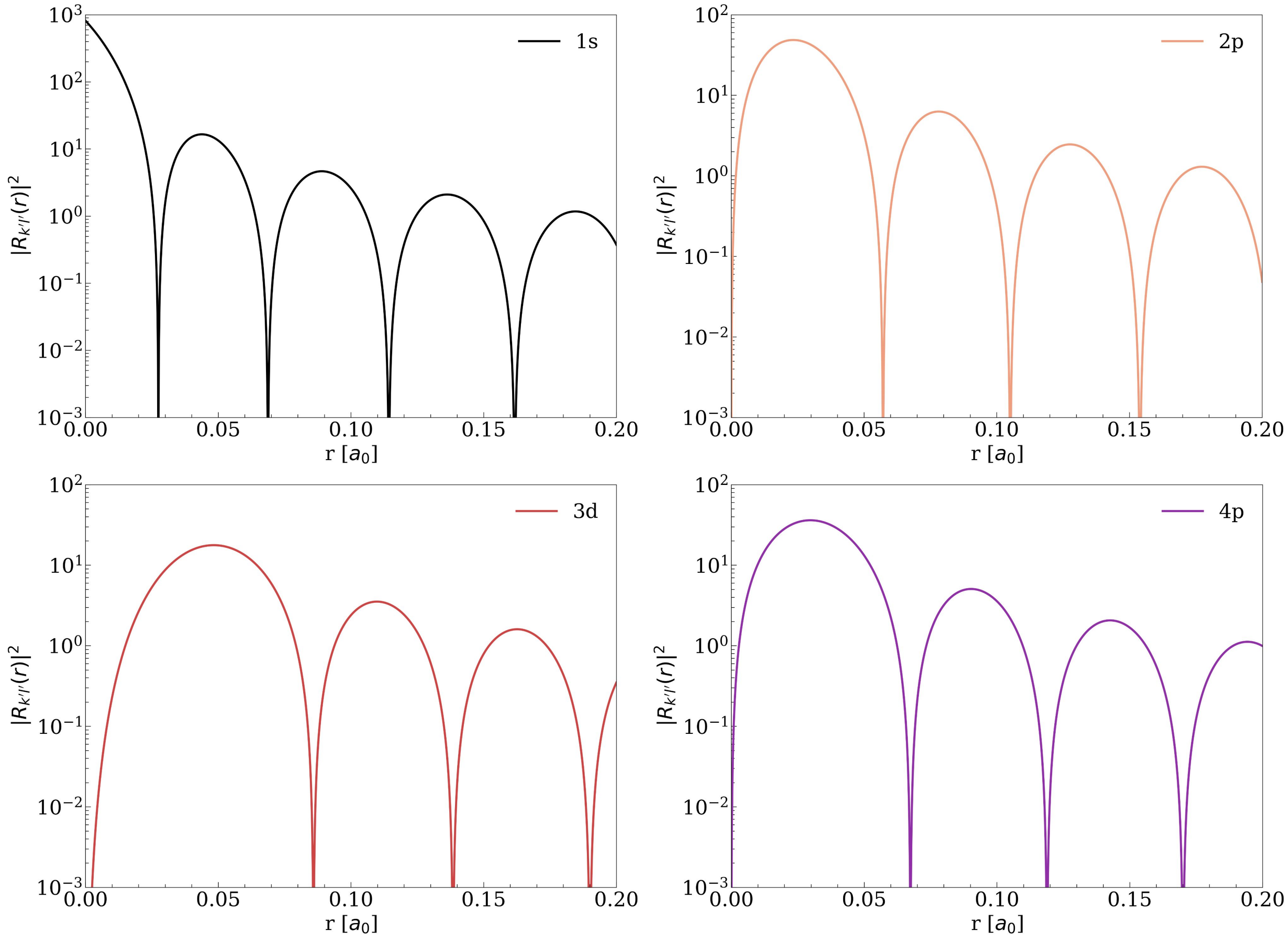
It is related with the quantum mechanics of the atom

It does not depend on the nature of the scattering process

Outgoing electron radial wavefunction

Bounded electron radial wavefunction

Outgoing radial wavefunctions

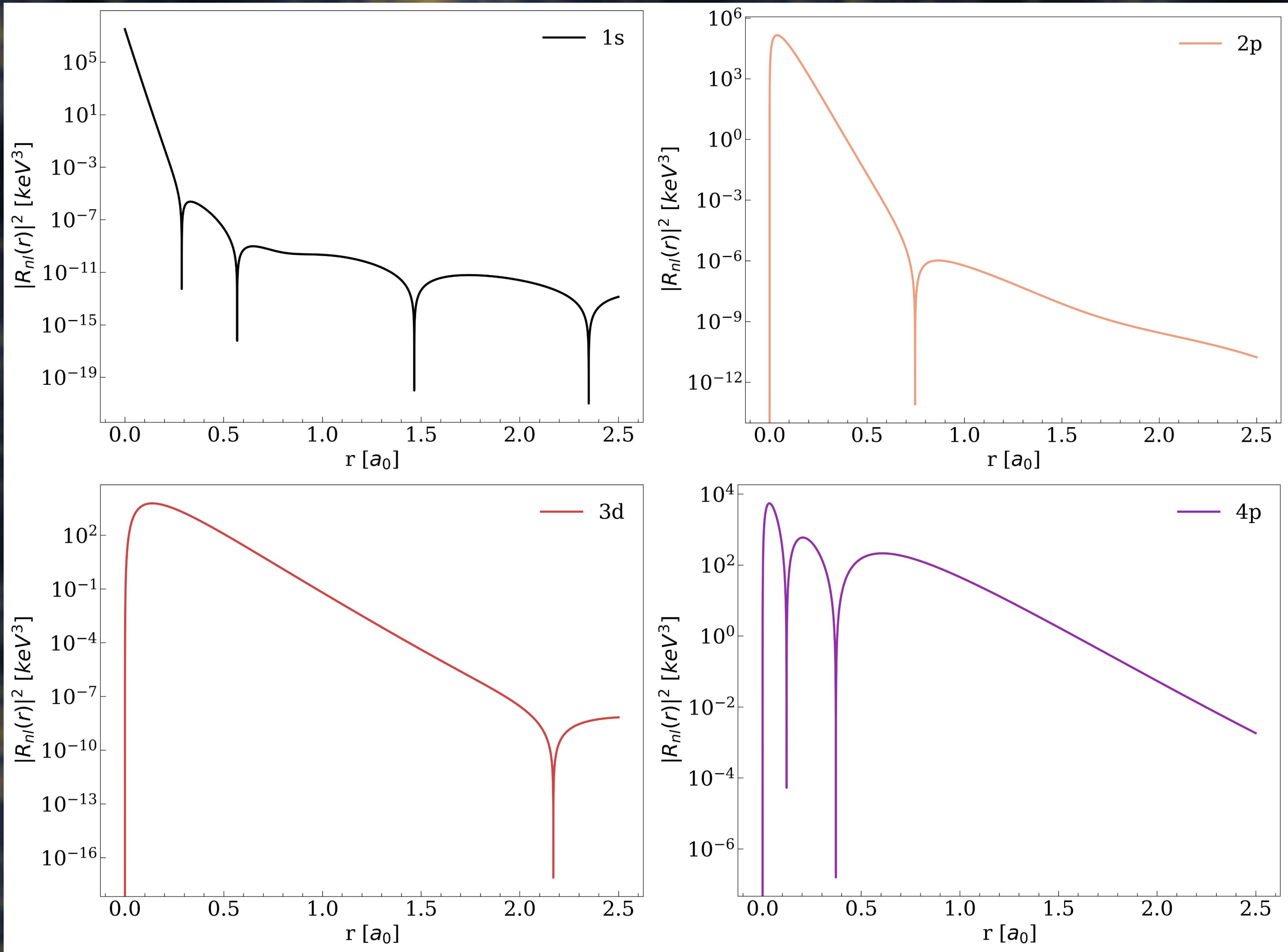


k' = 50 keV

$l' = l$

m = 200 keV

Bounded radial wavefunctions



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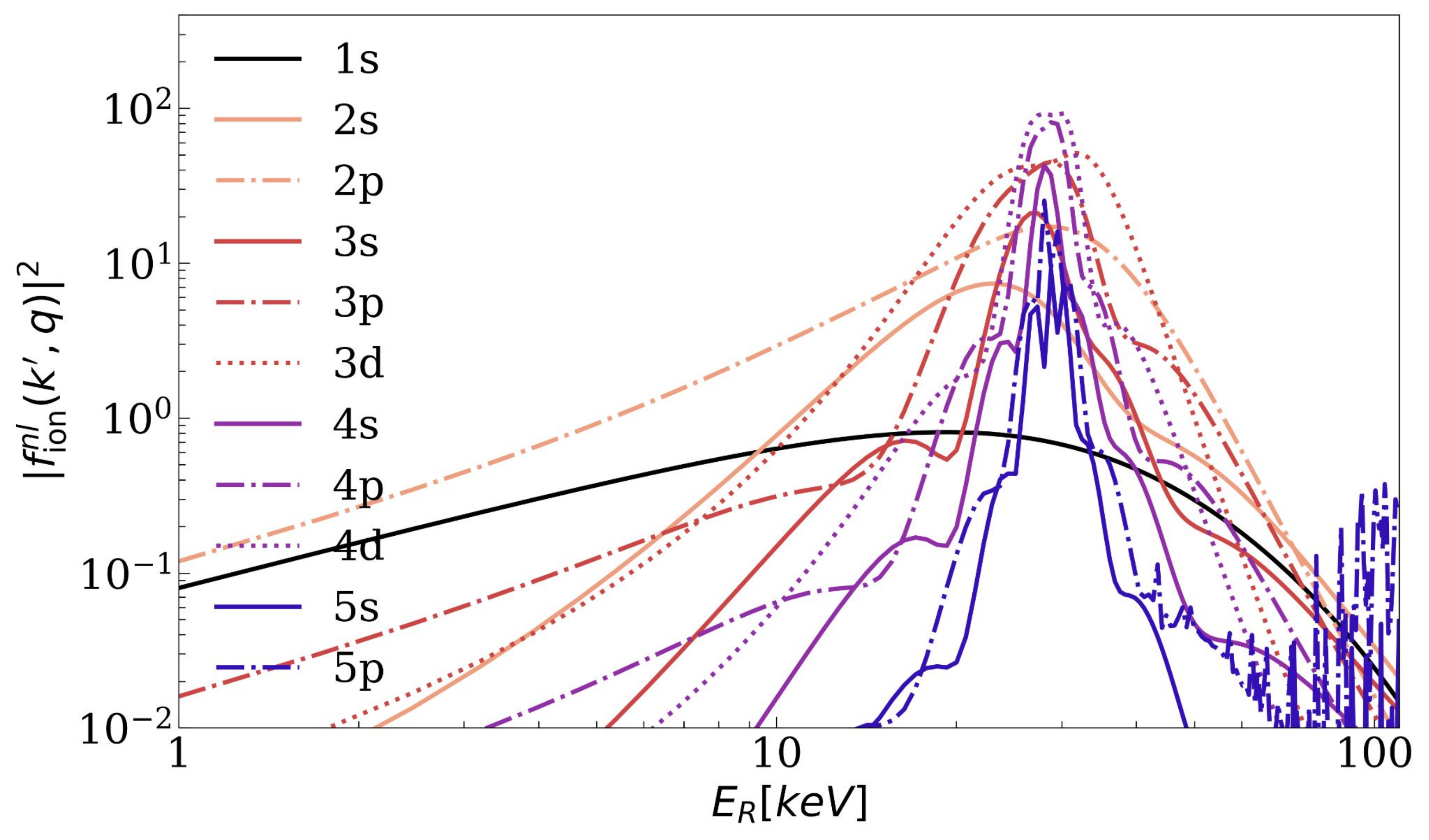
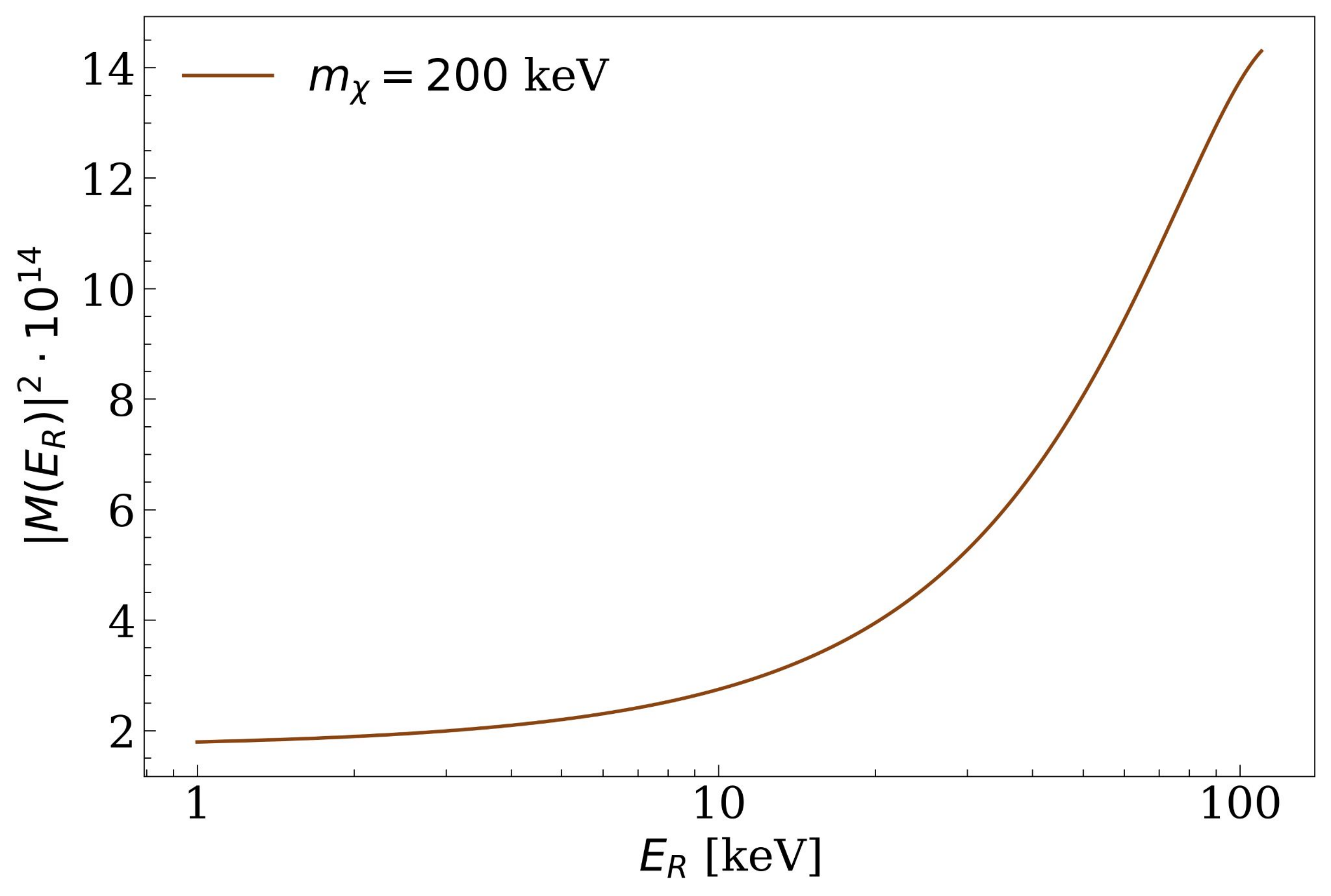


Squared matrix element



When the events rate for each shell is computed, it is possible to calculate the *total events rate*

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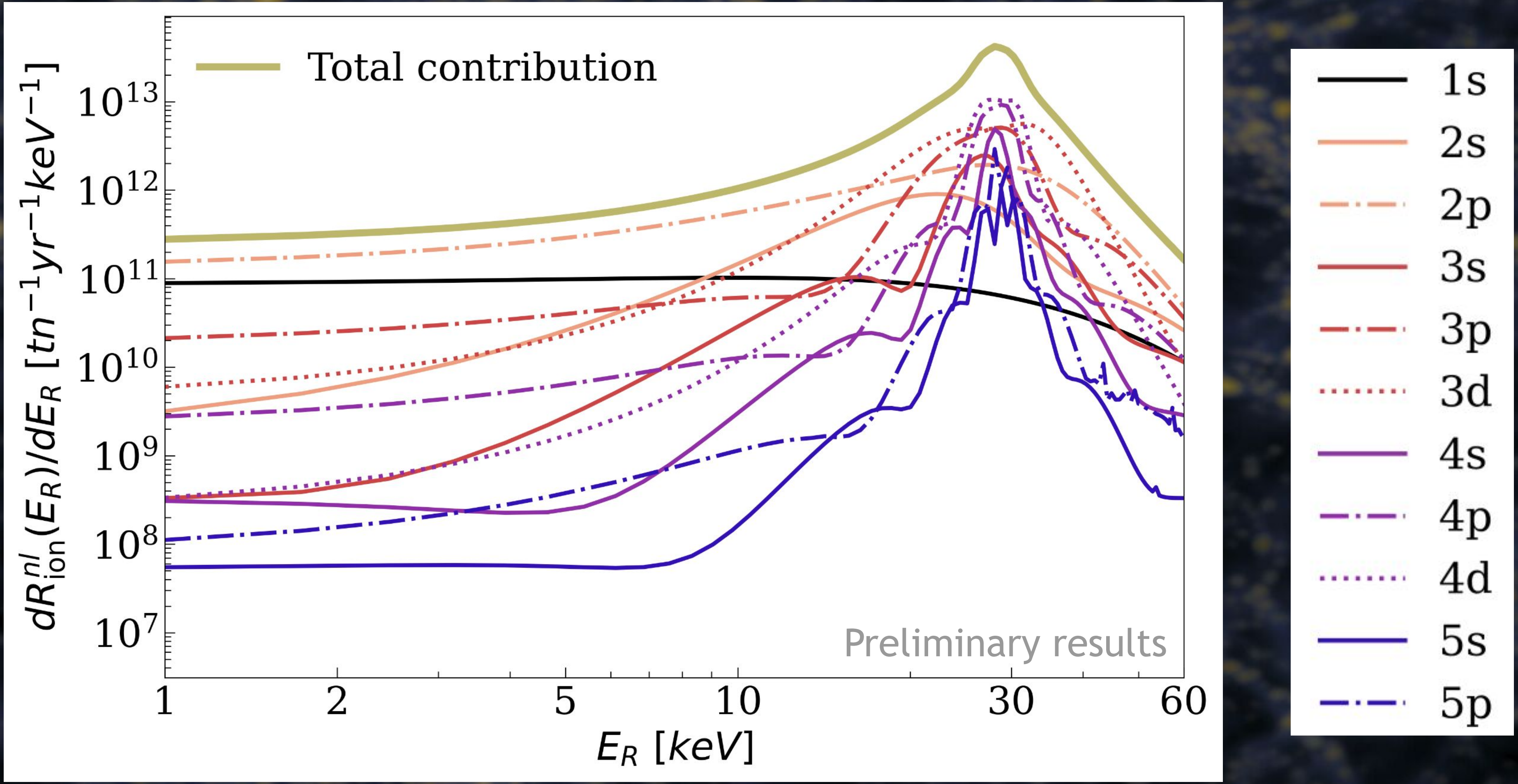
$$\frac{dR_{\text{ion}}}{dE_R} = C N_T \sum_{nl} \frac{dR_{\text{ion}}^{nl}}{dE_R}$$

Due to the separate nature of the quantum mechanics and scattering process, each events rate will reflect the behaviour of the ionization form factor

Individual and total differential events rate



Conclusions:

- We used the radiative 1 loop decay of a right-handed neutrino as an effective vertex to study DM-*e* inelastic scattering processes.
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- We developed numerical methods to compute theoretical events rate.

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Future work:

- To use the efficiencies of different DM detectors to compute the predicted events rate.
- To compute experimental limits on $\mathcal{G}_{\mathrm{r}}$ vs. m plot.