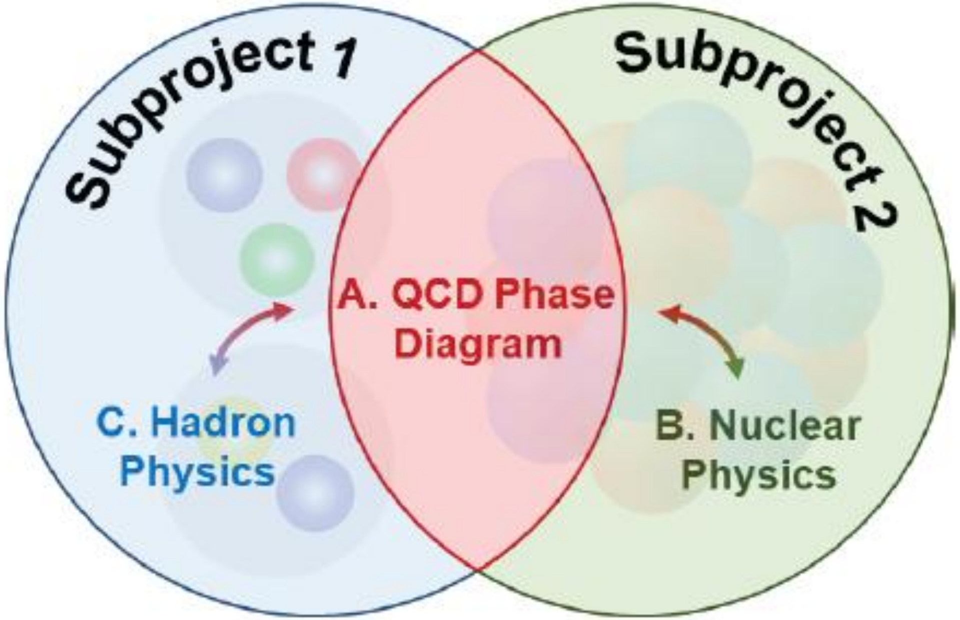
Exploring the quantum chromodynamics phase diagram: from hadrons and nuclei to matter under extreme conditions



Subproject 1:
New challenges in hadron physics: interactions, exotic hadrons and dark matter candidates

Subproject 2:
Modelling dense matter, nuclear structure and reactions with classical and quantum computers

Work Package C: Hadron Physics

WP C.1 Exotic Hadrons (Leading PI: Ramos)

- **C.1.a Pentaquarks with charm:** Study the formation and properties of pentaquark-like states with heavy quarks from a QCD-inspired interaction between meson and baryons, after unitarization of the scattering amplitudes.
- **C.1.b Effective-field theory analysis of the lattice QCD Λ(1405):** Analyse recent Lattice QCD results of the two-pole structure of the Λ(1405) with our newly developed hadronic interaction which includes higher partial waves.

Vincent Mathieu

WP C.2 Hadron Interactions & New Physics Searches (Leading PI: Torres-Rincon)

- **C.2.a Rare meson decays ↔ New Physics:** Calculate the contribution of the a2(1320) tensor meson to the rare $\eta/\eta' \to \pi 0 \gamma\gamma$ decays and constrain the leptophobic B boson parameters mass m_B and coupling α_B from experimental data.
- **C.2.b Relevant processes for hadron interactions:** Study of different meson-baryon interactions relevant for ALICE physics, like π-Σ baryon and K-d interaction for its application to baryon-rich matter. Study of baryon masses in a dense medium using the Polyakov-Nambu-Jona-Lasinio model.

Jordy de Vries

Sergi Gonzalez-Solis

WP C.3 Lattice QCD description of baryon-baryon interactions (Leading PI: Ramos)

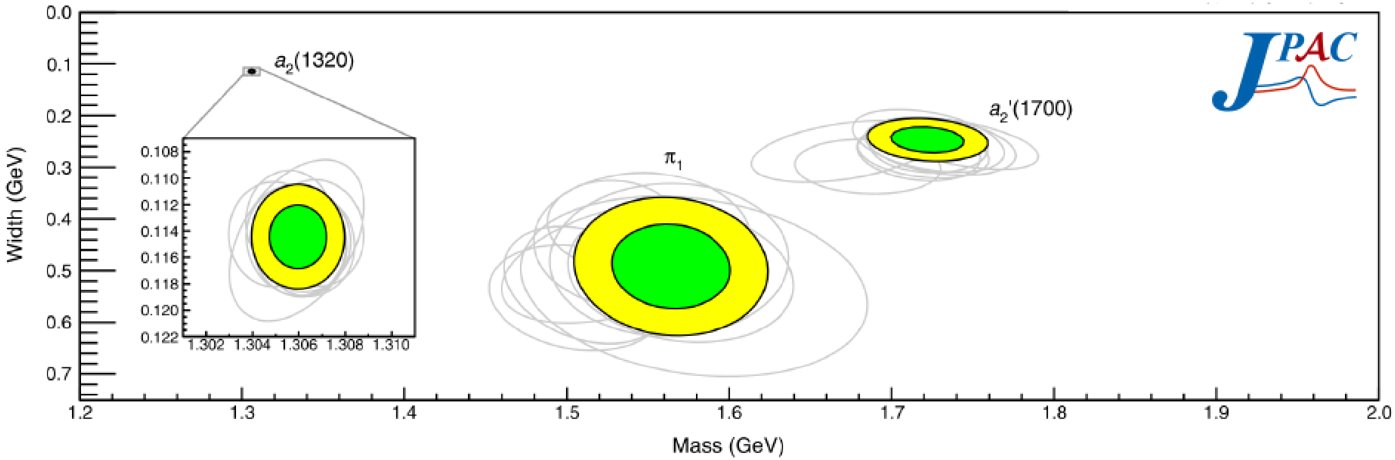
- **C.3.a Variational LQCD study of the NN and YY systems:** Application of the variational method to LQCD calculations with almost physical quark masses (m_π ~ 170 MeV) to the study of NN and YY interactions (addressing the H dibaryon state).
- **C.3.b Study of the coupled ΛN-ΣN system:** Calculation of the strangeness -1 hyperon-nucleon coupled channels in LQCD, studying its implications in hypertriton, femtoscopy and neutron star composition (role of Σ baryon).

Assumpta Parreño

Martí Rovira i Pons

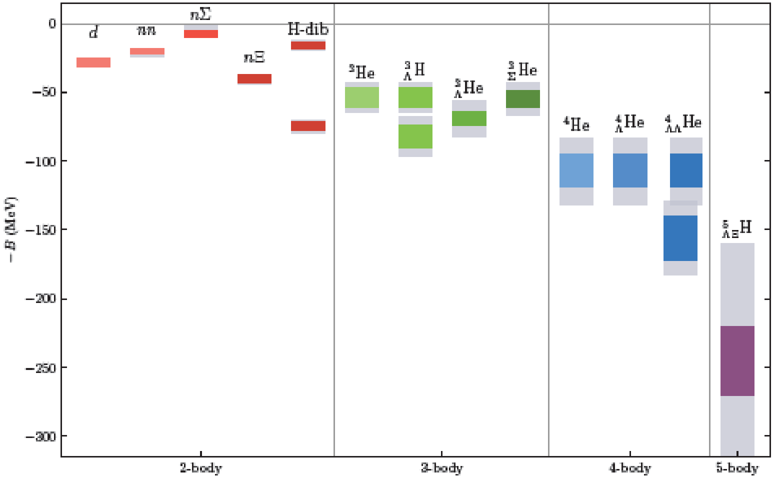
C.1 Exotic Hadrons

Vincent Mathieu

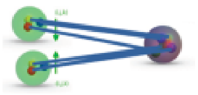


C.3 Lattice QCD description of baryon-baryon interactions

Assumpta Parreño



NPLQCD, Phys.Rev. D87 (2013) no.3, 034506; Phys.Rev. D96 (2017) no.11, 114510



$SU(3)_f$

m_π ~ 800 MeV

$b[fm] = 0.1453(16)$

L = 3.4, 4.5, 6.7 fm

T = 6.7, 6.7, 9.0 fm

O(10^5) measurements:
Different quark smearings

no e.m. interactions

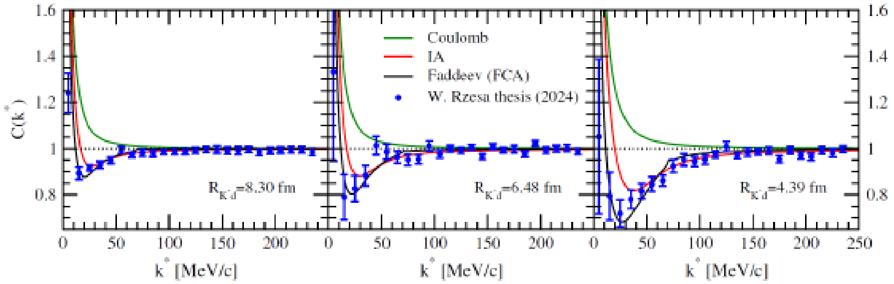
C.2.b Relevant processes for hadron interactions

A.2.b Hadron femtoscopy studies:

Kaon-Deuteron system

À. Ramos, JMTR, A. De Fagoaga, E. Cabré, 2507.22593 [hep-ph]

Centrality: 0-10% 10-30% 30-50%



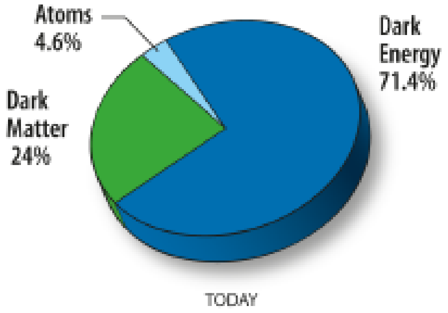
A.1 Nuclear Astrophysics of Neutron Stars

The physics of neutron stars and their mergers explored in WP A.1 is connected to the hadron properties and their interactions in dense and hot environments.

C.2.a Rare meson decays ↔ New Physics

Beyond the Standard Model

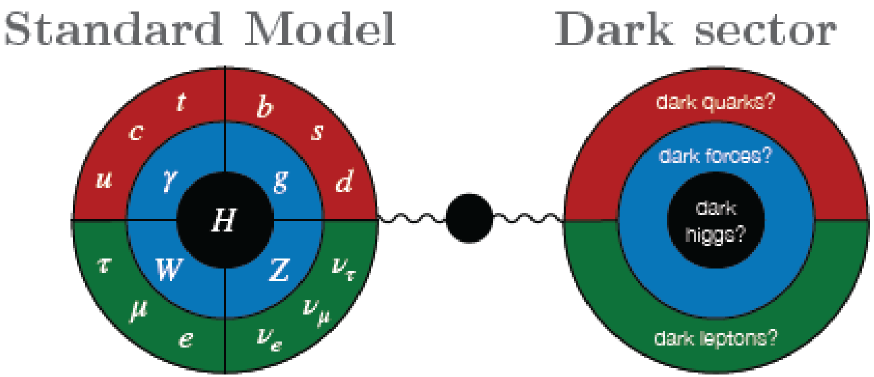
- The SM **fails** to explain:
  - **Dark matter**: what is the most prevalent kind of matter in our Universe?
  - **Dark Energy**: what drives the accelerated expansion of the Universe?



  - **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?
  - **Baryon asymmetry** of the Universe: what mechanism created the tiny matter-antimatter imbalance in the early Universe?
  - Several **anomalies in data:** $(g-2)_\mu$, B-physics anomalies, KOTO anomaly ($K_L \to \pi^0 \nu \bar{\nu}$), ^{8}Be excited decay, ...

Dark sector portals to the Standard Model

⇒ **Portal** interactions with the SM, only a few are allowed by the SM symmetries

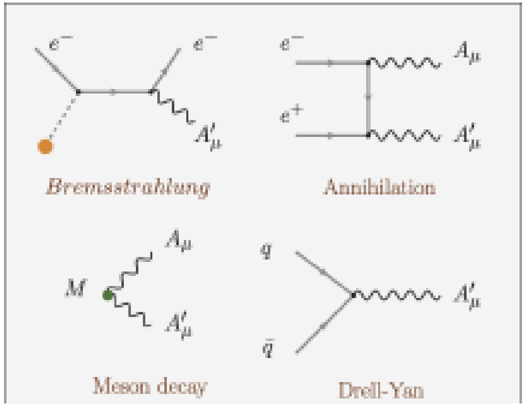


Portal	**Mediators**	**Portal interactions**
Vector	Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Scalar	Dark scalar	$\kappa \lvert H\rvert^2 \lvert S\rvert^2$
Neutrino	Sterile Neutrino	$y H L N$
Axion	Axion	$\frac{a}{f_a} \tilde{G}_{\mu\nu} G^{\mu\nu}$

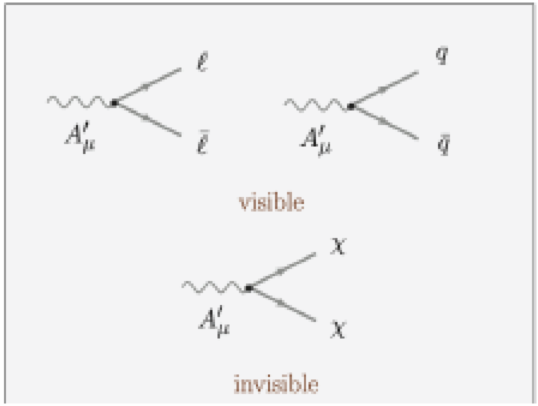
C.2.a Rare meson decays ↔ New Physics

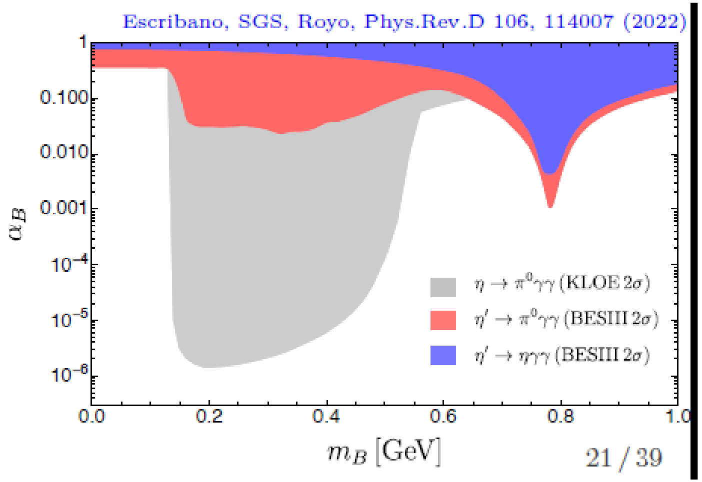
- Plenty of dark particles can be produced from **meson decays!!**

Production modes



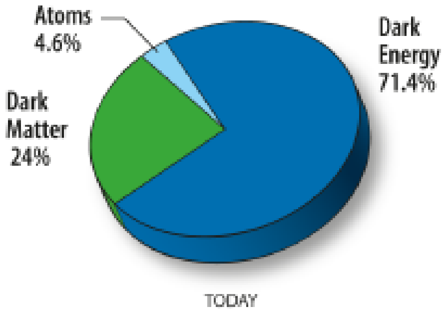
Decay modes





Beyond the Standard Model

- The SM **fails** to explain:



  - **Dark matter**: what is the most prevalent kind of matter in our Universe?
  - **Dark Energy**: what drives the accelerated expansion of the Universe?
  - **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?
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Dark photon, dark scalar, sterile neutrino, axion –
are these really allow us to solve above problems?

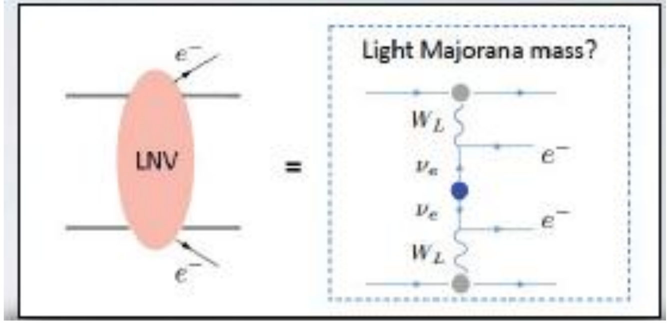
Neutrinoless double beta decay

Anatomy of a decay

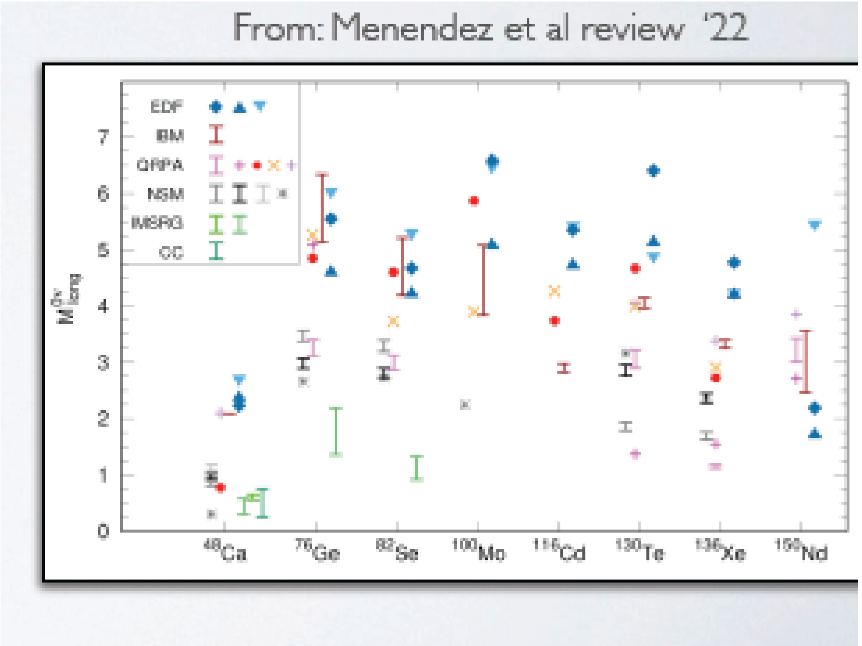
$$\Gamma^{0\nu} \sim m_{\beta\beta}^2 \cdot g_A^4 \cdot |M_{0\nu}|^2 \cdot G$$

Energy

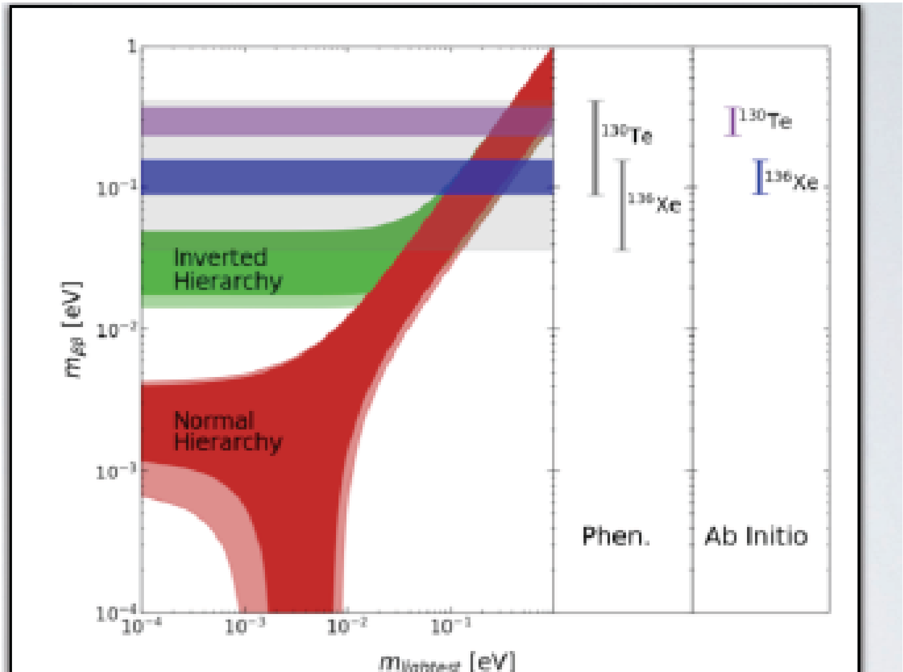
?	$m_{\beta\beta}^2$	Lepton-number-violating source (*not necessarily neutrino mass*) ***(Particle Physics)***
GeV	g_A^4	From quarks to hadrons ***(Hadronic Physics)***
100 MeV	$\|M_{0\nu}\|^2 = \|\langle 0^+ \| V_\nu \| 0^+ \rangle\|^2$	Nuclear transition matrix element ***(Nuclear Physics)***
MeV	G	Phase space factor ***(Atomic Physics)***



Neutrinoless double beta decay



How well we control nuclear matrix elements?

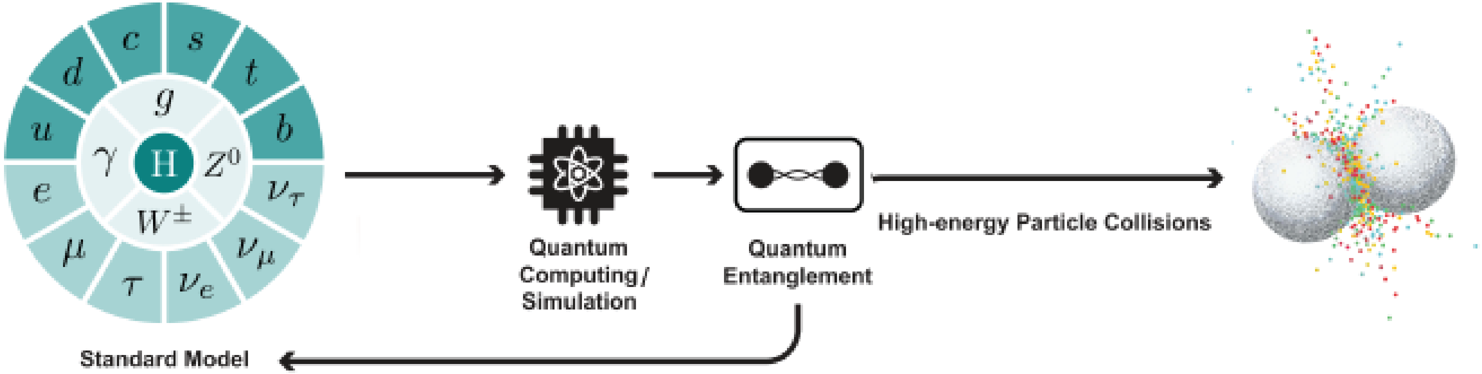


Are we quantifying uncertainties comprehensively?

Toward quantum simulation of scattering in gauge theories and other strongly correlated systems

ZOHREH DAVOUDI
University of Maryland, College Park

FIRST-PRINCIPLES PREDICTIONS FOR SCATTERING PROCESSES:
QUANTUM SIMULATIONS? **YES! GAME IS ON BUT LONG WAY TO GO!**



Bauer, ZD, Klco, and Savage, *Nature Rev. Phys.* 5 (2023) 7, 420-432.

Machine Learning approaches to Amplitude Analysis

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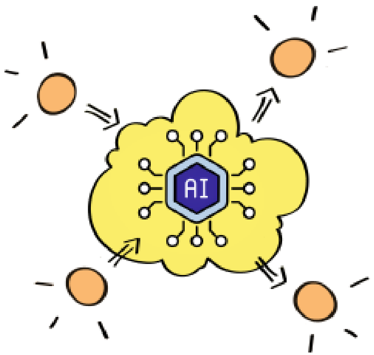

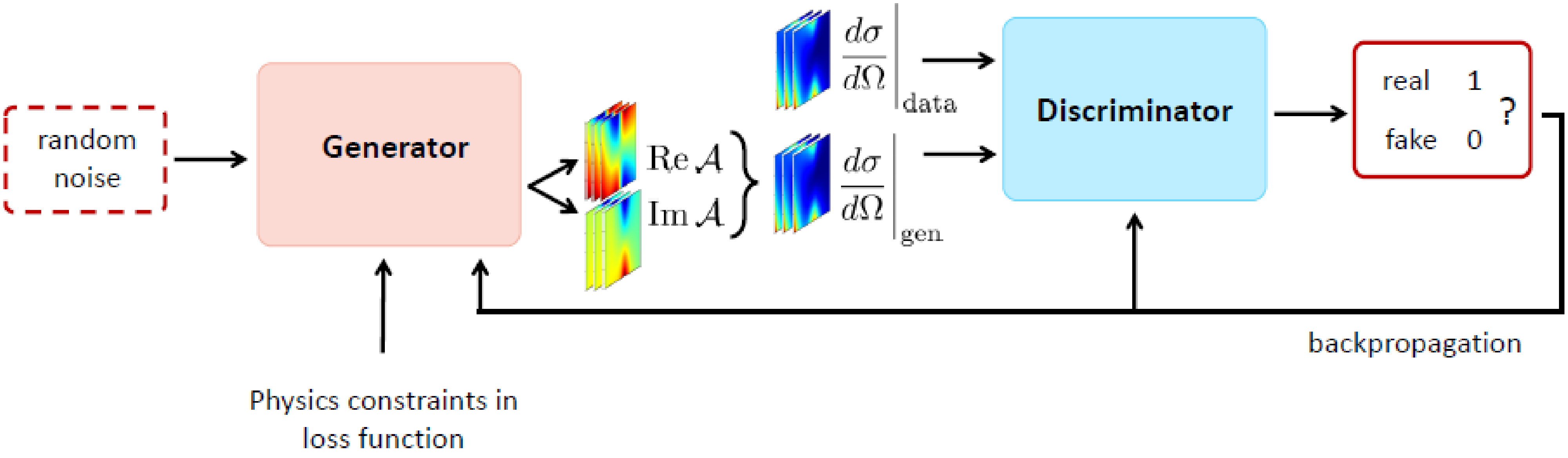

$$\mathcal{L} = \mathcal{L}_{\text{GAN}} + \lambda_{\text{u}}\mathcal{L}_{\text{u}} + \lambda_{\delta}\mathcal{L}_{\delta}$$

Big Language Models, machine learning techniques, neural networks are here!

Quantum computers are coming soon!

How should we proceed?

Should we change/adopt our codes?

Should we change our methods to study nature?