The Complexity of the Cosmos: A possible path to understand the Universe in a simple fashion

Only 105k seats…2k short of Michigan's

Raul Jimenez (ICREA & Instituto de Ciencias del Cosmos, University of Barcelona)
https://sites.google.com/site/rauljimenez/

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GOBIERNO DE ESPAÑA · MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

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The complexity of the cosmos: an interdisciplinary symposium in cosmology, astrophysics and statistical mechanics

‹ back

Print

Date	5-7 October, 2022
Room	GSSI
Speaker	many speakers
Area	Physics

Abstract

This meeting has a strong multidisciplinary character, with the idea to discuss and explore a variety of topics with partial overlap in cosmology, astrophysics and statistical mechanics, which could foster new ideas and research collaborations. Plenty of time will be devoted to discussions and round tables.

Here is a list of topics that will be tackled during the workshop:

- Non-linear problems in gravitational physics, collapse & structure formation: role of the Non-Linear Schrodinger Equatio
- Astrophysical probes of primordial quantum correlations
- Non-Markovian (non-equilibrium) effects in cosmological problems
- Black hole thermodynamics & information problem

Invited Speakers are:

Erik Aurell (Stockholm University)

Nicola Bartolo (University of Padova)

Angelo Bassi (University of Trieste)

Massimo Bianchi (Tor Vergata, University of Rome))

Lapo Casetti (University of Florence)

Kyriakos Destounis (University of Tubingen)

GIacomo Gradenigo (GSSI)

Raul Jimenez (University of Barcelona)

Cora Uhlemann (Newcastle University)

Sandro Wimberger (University Parma)

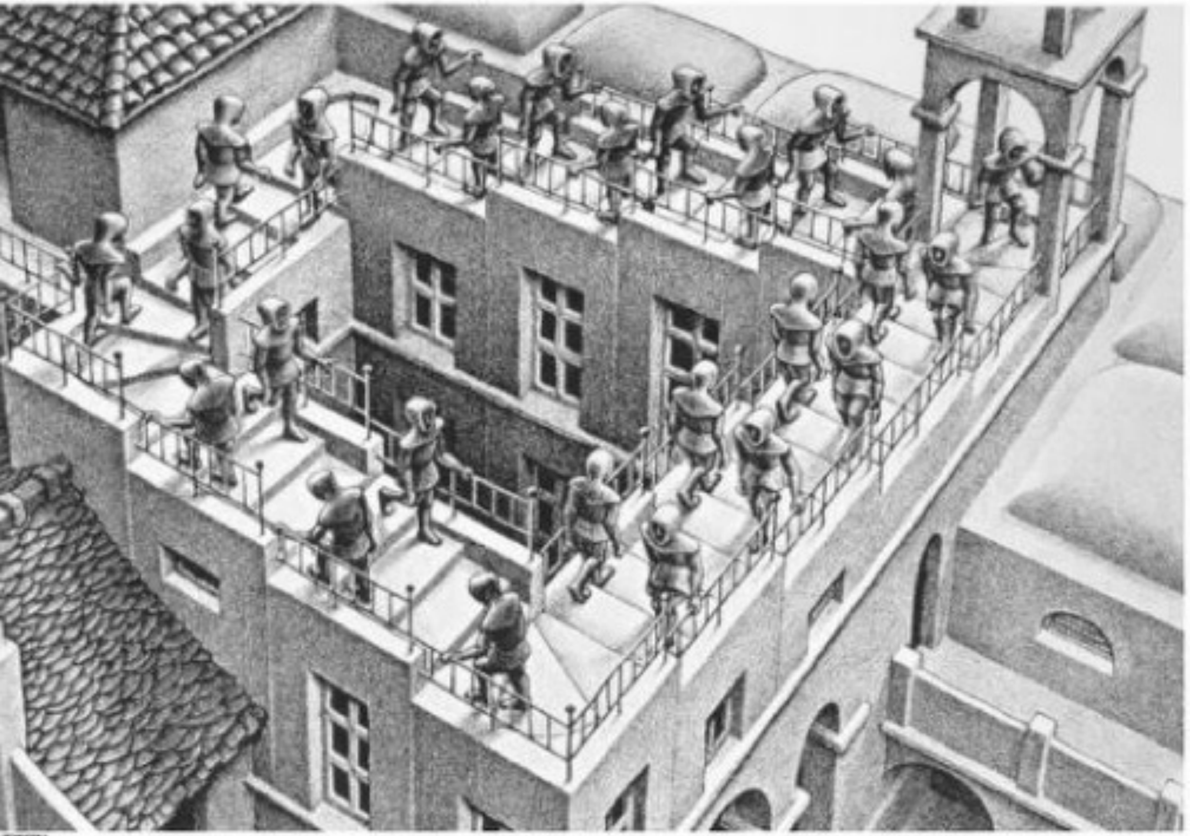
Phonons in a relativistic perfect fluid.

Show affiliations

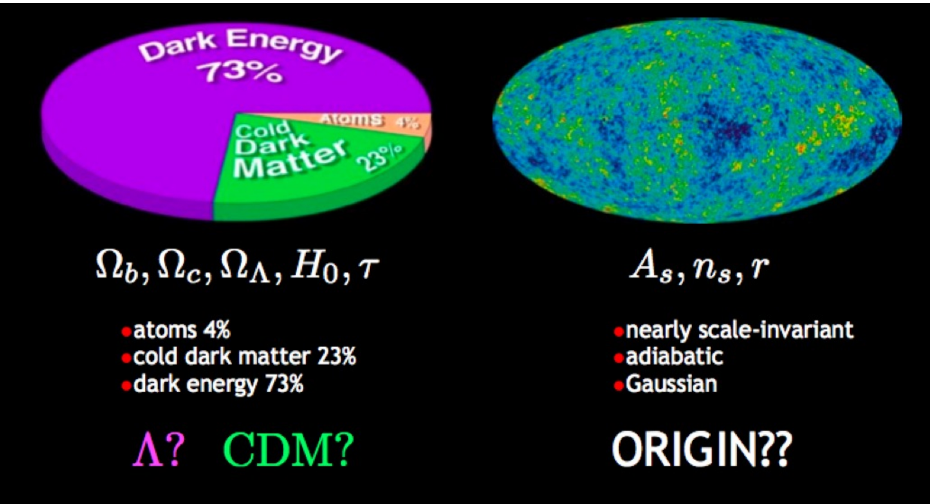
Matarrese, S.

Some aspects of general-relativistic hydrodynamics of an irrotational and isentropic perfect fluid are discussed. A variational approach to the longitudinal fluctuations of such a fluid is reviewed. The Lagrangian describing classical linear perturbations (sound waves) can be interpreted to decribe a non-interacting phonon system; a path-integral approach to the quantization of this system is proposed.

Publication:	Proceedings of the Fourth Marcel Grossmann Meeting on General Relativity, Part B, p. 1591 - 1595
Pub Date:	1986
Bibcode:	1986mgm..conf.1591M
Keywords:	Fluid Dynamics:General Relativity; General Relativity:Fluid Dynamics

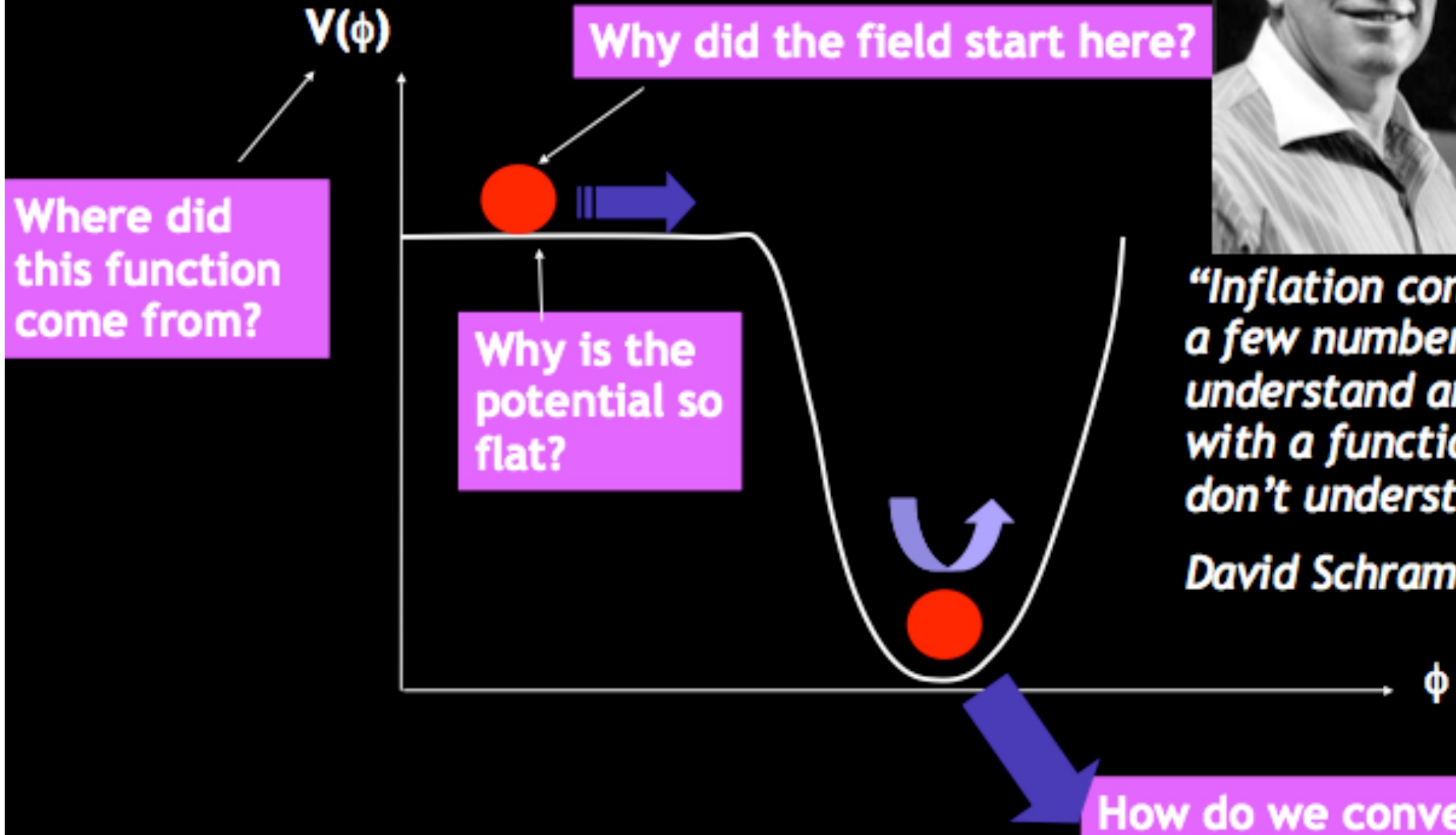


LCDM



CURIOSITY

Inflation: Theoretical Front



"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

David Schramm 1945 -1997

From Peiris

Coincidences

A World without Models

Two approaches:

You actually know how nature works

Quantum Mechanics

General Relativity

Symmetries/ Renormalization group

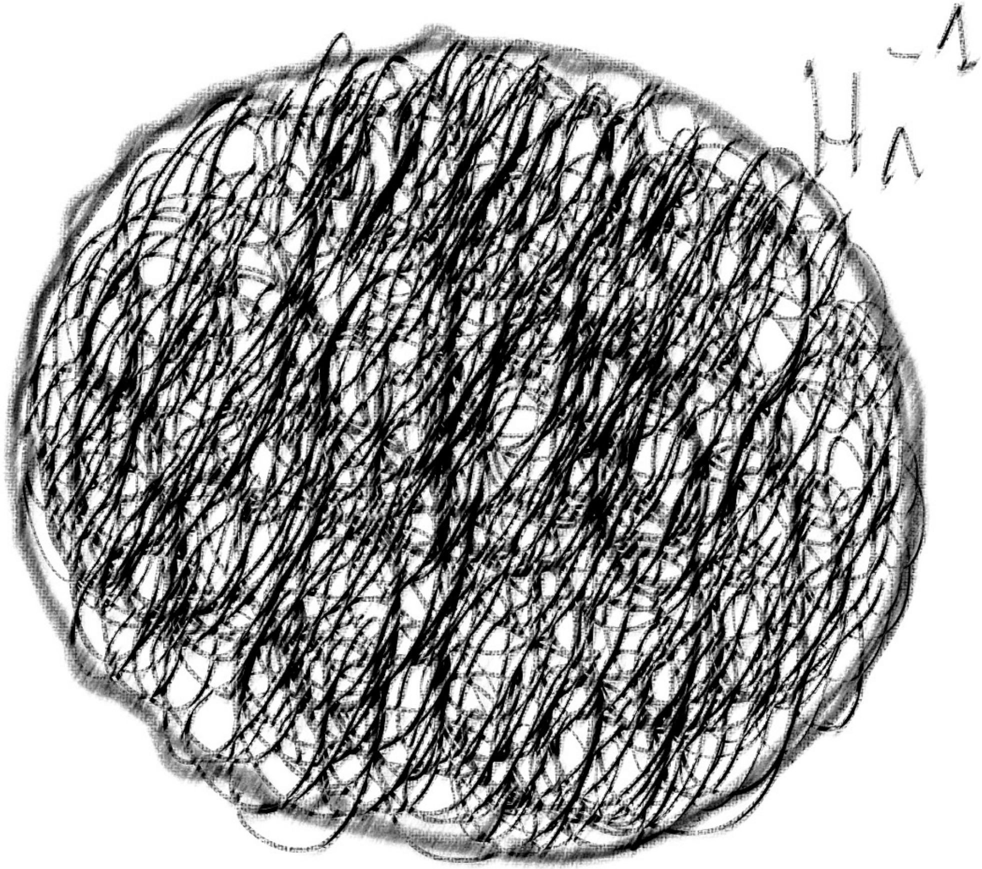
You use Machine Learning Methods (give up!)

Inflation without an Inflaton

ArXiv: 2412.14265 in Physical Review

Project by:

Daniele Bertacca, Raúl Jiménez, Sabino Matarrese and Angelo Ricciardone


H_n^{-1}

and... an inflation without the inflaton?

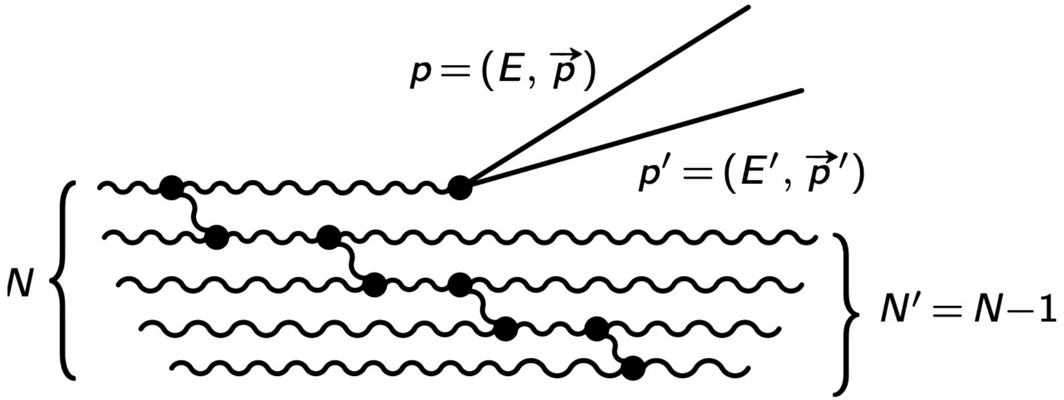
- In DB, Jimenez, Matarrese & Ricciardone, 2412.14265, we focus on how scalar perturbations are generated in a model-independent fashion, within a purely quantum physics framework.
- We propose a novel scenario in which scalar perturbations, that seed the large-scale structure of the Universe, are generated without relying on a scalar field (the inflaton).
- In this framework, inflation is driven by a de Sitter space-time (dS), where tensor metric fluctuations (i.e., gravitational waves) naturally arise from quantum vacuum oscillations, and scalar fluctuations are generated via second-order tensor effects
- We show that scalar perturbations arise as a second-order effect from tensor perturbations and can become significantly enhanced, allowing them to dominate over the linear tensor modes, which are inherently present in dS.

Generation of second-order scalar modes from tensor perturbations

- The generation of these tensor perturbations was first studied in Tomita (1971, 1972) and Matarrese, S. Mollerach and M. Bruni (1998).
- Recently, a quantitative analysis of such tensor-induced scalar perturbations was done in Bari+(2022, 2023) for post-inflationary epochs. **Our scenario relies on a similar mechanism to generate the scalar perturbations.**
- In addition, the instability of dS space [see, e.g., Mottola (1985), Antoniadis+ (2007), Polyakov (1982, 2007, 2012), Dvali+ (2007, 2014, 2017), Alicki+ (2023a, b)] provides both a natural way for a graceful exit from inflation and also the means to end into a radiation dominated epoch.

If dS metric as process of scattering and decay of the gravitons: Dvali et al. point of view

- If one describes dS as a quantum coherent state composite of gravitons, then the self-coupling of gravitons— as well as their coupling to other relativistic particle species, such as those in the Standard Model (SM), which must always be present—leads to quantum scattering and decay of the constituent gravitons of dS.
- In this case, the final quantum state cannot be described as a coherent state, and there will no longer be the dispersion relations of the free quanta propagating on a classical dS background.



Higher order process of particle production, in which the produced particles recoil against all remaining gravitons. In particular, this allows for produced particles of low energies E, $E' \ll m/2$.

Instability of dS? [Mottola point of view]

- As Antoniadis+ (2007) points out, based on particle creation Mottola (1985) and the fluctuation-dissipation theorem Mottola (1986a) or, equivalently, on thermodynamic considerations Mottola (1986b), dS spacetime is unstable and the time scale of this instability can be exponentially large given any initial perturbation.

This occurs because the geometry of the gravitational field is coupled to the energy-momentum stress tensor and this quantity, in turn, governs the dynamics of the gravitational field.
Consequently, the quantum fluctuations of the vacuum or, equivalently, the effects of particle creation are linked to a background gravitational field.

Instability of dS - thermodynamic considerations: Alicki point of view

In Alicki+ (2023a, b)] using an approach related to quantum thermodynamics:

- they provide a natural mechanism for the irreversible relaxation of the cosmological constant,
- and dS decay, in order to escape the inflationary epoch, without the need for subsequent reheating, and
- suggest an alternative way to generate the primordial perturbations which could arise from the thermal fluctuations described by the power spectrum.

About perturbations?

- In DB, Jimenez, Matarrese & Ricciardone, 2412.14265 we introduce a novel mechanism where we derive the exact expressions for the second-order scalar potentials and the scalar power spectrum resulting from second-order tensor perturbations.
- We demonstrate that the latter agrees with the expected nearly scale-invariance from observations, opening the way for numerous potential follow-up studies and extensions.

Note that here the considered fluid unavoidably arises from the vacuum expectation value of the second-order contribution to the Einstein's tensor from gravitational waves (GW), which on sub-horizon scales leads to non-vanishing energy, pressure and anisotropic stress (**this point is raised also in Dvali + 2013!!**).

SCALAR PERTURBATIONS FROM TENSOR MODES

- We consider pure dS metric, which is in Cartesian coordinates, $ds^2 = -dt^2 + e^{2t/\alpha}(dx^2 + dy^2 + dz^2)$,

where $\alpha \equiv (3/\Lambda)^{1/2}$ and $\Lambda/8\pi G$ is the vacuum energy.

- We assume Einstein gravity and the following perturbed second order metric

$$g_{00} = -a^2(1+\psi_2),$$
$$g_{0i} = \frac{a^2}{2}\omega_{2i},$$
$$g_{ij} = a^2\left[(1-\phi_2)\delta_{ij} + \chi_{1ij} + \frac{1}{2}\chi_{2ij}\right],$$

where $a(\eta) = -1/H_\Lambda \eta$.

Now a first question that we can make...

- Unless the "background" vacuum energy (by Mottola et al.) or coherent states (by Dvali et al.) $\Lambda/8\pi G$ and if we exclude any (perturbative) contributions on the right-hand side of Einstein's equations, is it possible to obtain solutions for, e.g., ψ_2 and ϕ_2, which depend only on χ_{1ij}?

No, we can't...

Indeed, if we try to solve the Einstein Equations for ψ_2 and ϕ_2 we get as inconsistence on the solution for ϕ_2 (and, at the same time ψ_2=0).

SCALAR PERTURBATIONS FROM TENSOR MODES

For generality, on the RHS of Einstein's equations, we allow for the presence of a stress-energy tensor which accounts for the sum of the cosmological constant driving our dS expansion plus a generic fluid, with energy density ρ, isotropic pressure p, four-velocity u^μ and anisotropic stress tensor π^μ_ν, namely

$$T^\mu_\nu = -\frac{\Lambda}{8\pi G}\delta^\mu_\nu + (\rho + p)u^\mu u_\nu + p\delta^\mu_\nu + \pi^\mu_\nu \, .$$

NOTE: by using the idea by Dvali et al 2013 and 2017 this seemingly-classical system quantum mechanically as the mixture of the two "Bose-gases":

1) the quantum coherent state that describes Λ;
2) a cosmological fluid that plays the role of a cosmic clock! Precisely, this compositeness acts as a quantum clock (that becomes classical at scales larger than horizon) that imprints measurable effects into cosmological observables.

These effects are cumulative and gather the information throughout the entire duration of inflation.

When $\psi_2 = 0$ and $\phi_2 = \mathcal{F}_\chi/4$

Let me focus only on the first terms in

$$\mathcal{F}_\chi = 4\nabla^{-2}\left(\frac{3}{4}\chi_1^{lk,m}\chi_{1kl,m} + \frac{1}{2}\chi_1^{kl}\nabla^2\chi_{1lk} - \frac{1}{2}\chi_{1,l}^{km}\chi_{1m,k}^{l}\right) - 6\nabla^{-4}\partial_i\partial^j\mathcal{A}_j^i\,,$$

then we have

$$\Delta_\phi(k) = \frac{k^3}{2\pi^2}\frac{1}{64(2\pi)^3}\frac{1}{k^4}\int \mathrm{d}^3k_1\mathrm{d}^3k_2\,\delta^{(3)}[\mathbf{k}-(\mathbf{k}_1+\mathbf{k}_2)]\,\mathcal{K}_h(\mathbf{k}_1,\mathbf{k}_2)\,\left[\frac{2\pi^2}{k_1^3}\frac{16}{\pi}\left(\frac{H_{\rm inf}}{m_{\rm pl}}\right)^2\right]\left[\frac{2\pi^2}{k_2^3}\frac{16}{\pi}\left(\frac{H_{\rm inf}}{m_{\rm pl}}\right)^2\right]$$

where

$$\mathcal{K}_h(\mathbf{k}_1,\mathbf{k}_2,k^2) = \left\{\left(k_1^2+k_2^2+3\mathbf{k}_1\cdot\mathbf{k}_2\right)^2\left[\left(1-\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2\right)^4+\left(1+\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2\right)^4\right]\right.$$
$$\left. +8\left(\mathbf{k}_1\cdot\mathbf{k}_2\right)\left(k_1^2+k_2^2+3\mathbf{k}_1\cdot\mathbf{k}_2\right)\left(\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2\right)^2\left[3+\left(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2\right)^2\right]+8k_1^2k_2^2\left(\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2\right)^4\left[1+\left(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2\right)^2\right]\right\}$$

For ϕ_2 is const., is it possible to have $\psi_2 \neq 0$?

At super-horizon scales, still assuming ϕ_2 is const. , where we left w and c_s generic

$$\bar{\rho}(\eta) = \bar{\rho}_{\rm in} \left(\frac{\eta}{\eta_{\rm in}}\right)^{3(1+w)} = \bar{\rho}_{\rm in} \left(c_s k|\eta|\right)^{3(1+w)}$$

for ζ_2 we find

$$\tilde{\zeta}_2 - \tilde{\phi}_2 = -\frac{H_\Lambda^2}{4\pi G(1+w)\bar{\rho}}\tilde{\psi}_2 = -\frac{H_\Lambda^2}{4\pi G(1+w)\bar{\rho}_{\rm in}}\left[-\frac{8\pi G}{H_\Lambda^2}c_s^2 k^2 \tilde{\Pi}_{2{\rm in}} + \left(\tilde{\phi}_2 - \frac{1}{4}\tilde{\mathcal{F}}_\chi\right)\right]\left(c_s k|\eta|\right)^{3\left(c_s^2 - w\right)}$$

Now we need to know the value of c_s and $\bar{\rho}_{\rm in}$ at a given mode k.
It is transparent that

$$w - c_s^2 > 0$$

for the scalar fluctuations to be larger than the tensor ones. This can be achieved by the same gravitons produced during de Sitter phase. For this particle (fluid) radiation, the scalar perturbations will no longer grow [Dvali + 2013, 2017].

This provides a natural route to end inflation!

Work in progress...

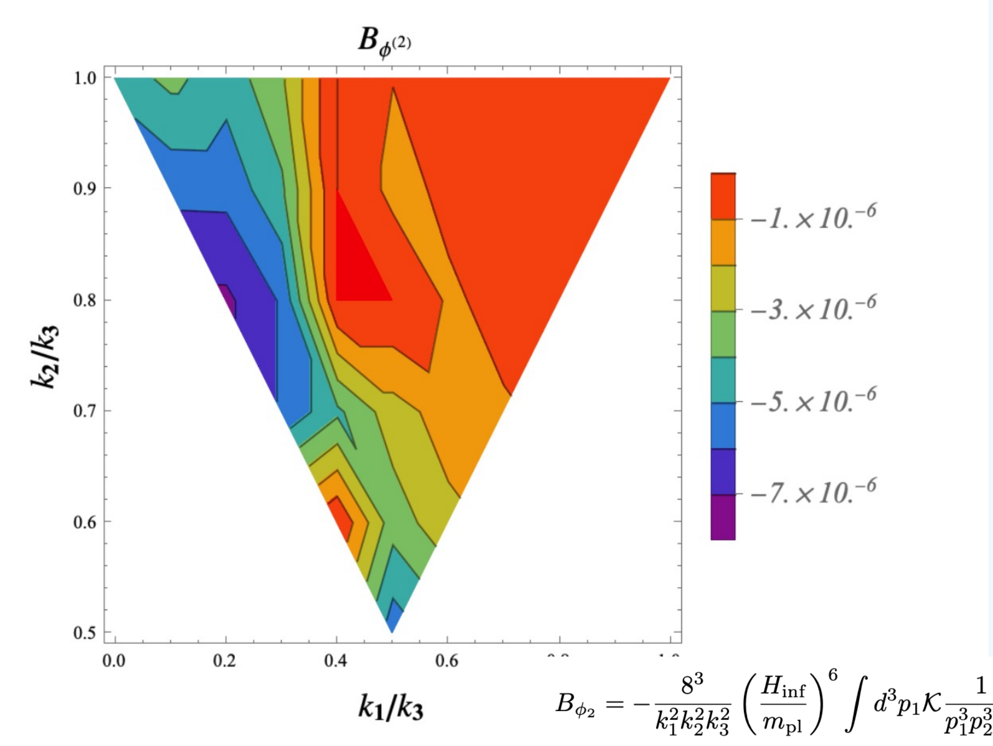
Marisol Traforetti
PhD student at ICC Barcelona

She is completing the account with the full kernel and is calculating the power spectrum on larger scales equal to the horizon until the end of inflation.

$$\mathcal{P}_\phi(k) = \frac{1}{(2\pi)^3}\frac{9}{64}\frac{1}{k^8}\int d^3k_1 d^3k_2\, \delta^{(3)}(\mathbf{k}-(\mathbf{k}_1+\mathbf{k}_2))\mathcal{P}_h(k_1)\mathcal{P}_h(k_2)$$
$$\left\{\left[3(k_1^2+k_2^2)\mathbf{k}_1\cdot\mathbf{k}_2 + k_1^2k_2^2\left(1+3(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)^2\right)+k_1^4+k_2^4\right]^2\left[\left(1-\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2\right)^4+\left(1+\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2\right)^4\right]-\right.$$
$$-8\left[3(k_1^2+k_2^2)\mathbf{k}_1\cdot\mathbf{k}_2 + k_1^2k_2^2\left(1+3(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)^2\right)+k_1^4+k_2^4\right](k_1^2+k_2^2+\mathbf{k}_1\cdot\mathbf{k}_2)$$
$$(\mathbf{k}_1\cdot\mathbf{k}_2)(\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2)^2\left[1+3(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)^2\right]+$$
$$\left.+8(k_1^2+k_2^2+\mathbf{k}_1\cdot\mathbf{k}_2)^2k_1^2k_2^2(\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2)^4\left[1+(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)^2\right]\right\}$$

Mariam Abdelaziz
PhD student in SSM Naples

She is also calculating bispectrum with a view to a more in-depth study of Non-Gaussianity for this type of model.



$$B_{\phi_2} = -\frac{8^3}{k_1^2k_2^2k_3^2}\left(\frac{H_{\rm inf}}{m_{\rm pl}}\right)^6\int d^3p_1\mathcal{K}\frac{1}{p_1^3p_2^3p_3^3}$$

E.g., Quantum Fisher Cosmology (QFC)

- Along this line of reasoning, an attempt is done in Gomez and R. Jimenez (2020, 2021a, 2021b), in a framework termed QFC. It has been shown that the tilt of the primordial scalar power spectrum can be predicted to be $n_s = 0.9672$ just by considering the Heisenberg uncertainty principle in measuring time in dS

A model Independent Prediction for the Spectral Index of Scalar Fluctuations

Step 1: Focus on quasi de Sitter modification of the effective frequency of spectator modes.
Start with the Schroedinger eq.

$z = a\sqrt{\epsilon}$

$$\Phi_k'' + \left(k^2 - \frac{z''}{z}\right)\Phi_k = 0$$

and

$$\frac{z''}{z} = \frac{\beta(\beta+1)}{\eta^2}$$

In simplest slow-roll approximation

$$\beta = -2 - \delta$$

(by definition, for convenience)

the pure **quasi** de Sitter contribution to the oscillator energy is given by

$$\delta_{qdS}E^2 = \frac{3\delta + \delta^2}{a_{qdS}^2 \eta^2}$$

$$a_{qdS} = \frac{-1}{H_0 \eta}\frac{1}{(k_0\eta)^\delta}\sqrt{\epsilon_0}$$

Choosing a pivot k_0 and H_0 then $\delta_{qdS}E^2 = (3\delta + \delta^2)H_0^2(k_0\eta)^{2\delta}$

Step 2: use the quantum variance defined by the quantum Fisher information to identify the corresponding quantum contribution to the oscillator energy. This is done by defining at first order (same order in $\hbar$ as the quasi de Sitter contribution; recall that the Fisher piece is statistical in origin) **this contribution in pure dS** as

$$\Delta_F E^2(|k_0|\eta) \equiv \frac{|k_0|\delta_F \mathcal{E}(|k_0|\eta)}{a_{dS}^2} = \frac{1}{2}|k_0|\eta H^2(|k_0|\eta)^{\alpha_F(|k_0|\eta)}$$

$$\delta_F E^2 = \frac{k\delta_F(k)}{2a_{dS}^2}$$

With $\delta_F(k)$ defined by the Quantum Fisher F $\delta_F(k) = F^{1/2}$

$$F = \frac{1}{\eta^2}(k\eta)^{\alpha_F(k\eta)}$$

Using the same pivot scale k_0 and H_0 we get

$$\delta_F E^2 = H_0^2(k_0\eta)^{\frac{1}{2}\alpha_F(k_0\eta)}(\frac{k_0\eta}{2})$$

Step 3: The final step requires to identify, locally, both contributions: namely the quasi de Sitter and the quantum Fisher. Since our task is to predict the value of the quasi de Sitter parameter δ we look for the value of δ such that $\delta_F E^2 = \delta_{qdS} E^2$. This equation identifies the value of the slow roll parameter that agrees with the quantum Fisher estimation. This leads to the equation

$$\delta_F E^2 = H_0^2 (k_0\eta)^{\frac{1}{2}\alpha_F(k_0\eta)} \left(\frac{k_0\eta}{2}\right) \quad = \delta_{qdS}\, E^2 = (3\delta + \delta^2) H_0^2 (k_0\eta)^{2\delta}$$

$$2(3\delta + \delta^2) = |k_0|\eta$$
$$\alpha_F(|k_0|\eta) = 2\delta$$

$\longrightarrow$

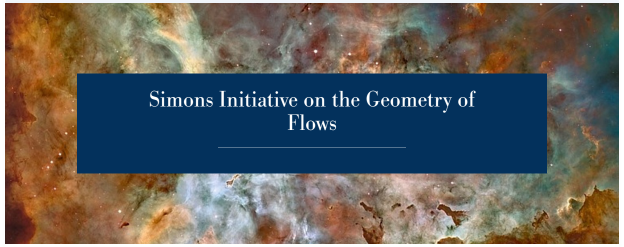
$$4\delta = \alpha_F(6\delta + 2\delta^2)$$

$$\boxed{\alpha_F \text{ (quasi de Sitter energy difference)} = \text{spectral index}}$$

There is a **unique** solution that fixes the region of slow roll at large scales, the fixed point region

$$(1 - n_s) = 2\delta = 0.0328$$

AT $k_0\eta$=0.1



Simons Initiative on the Geometry of Flows

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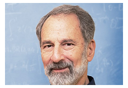

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https://github.com/AstroPilot-AI/Denario

The **Denario** Project: Modular Automation of Scientific Research with Multi-Agent Systems

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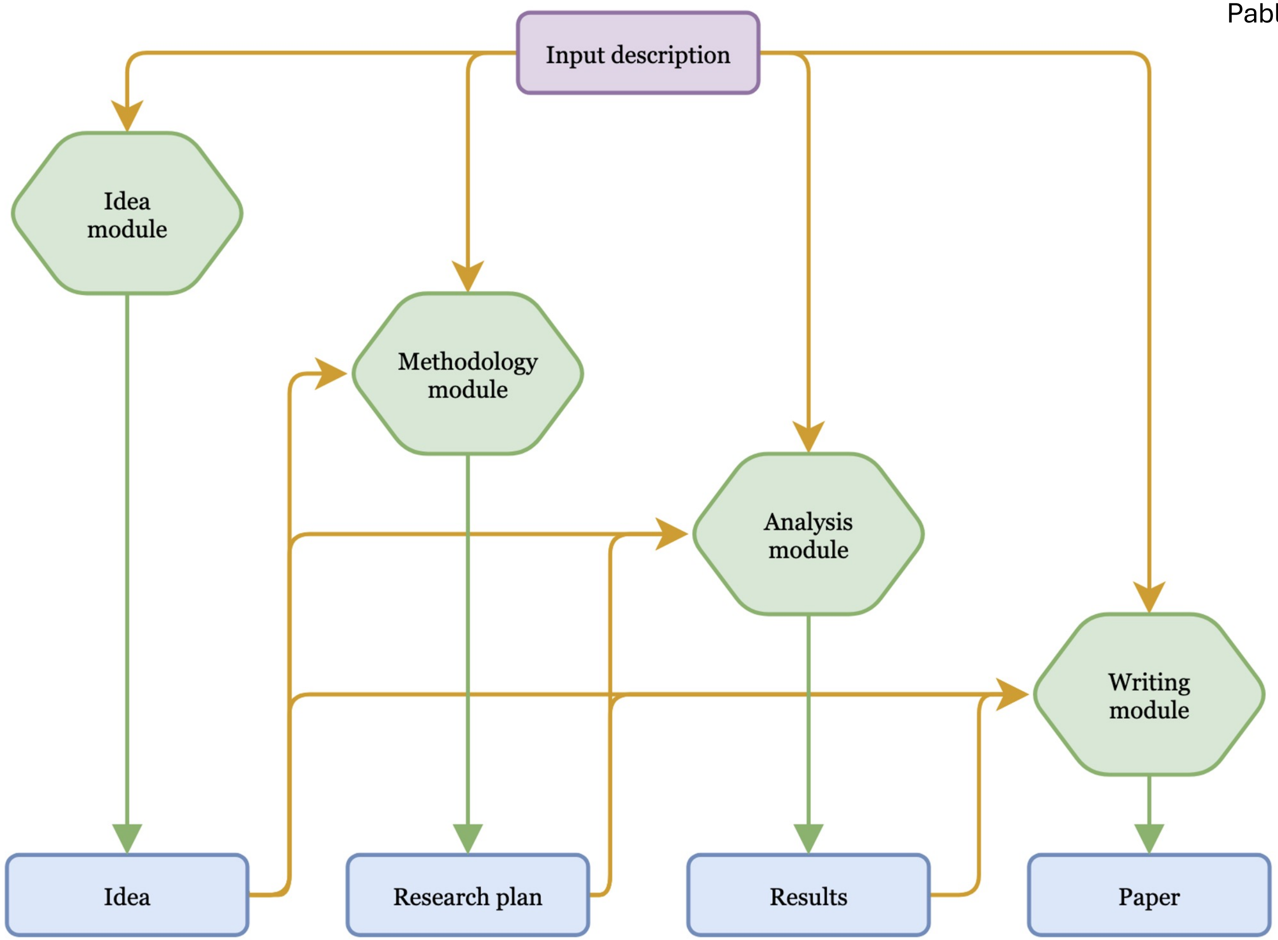
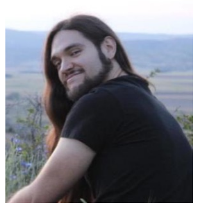
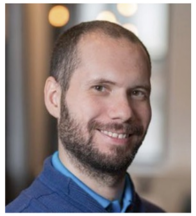
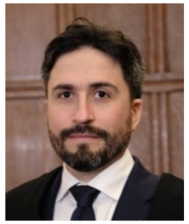
Denario: Modular Automation of Research



https://github.com/AstroPilot-AI/Denario







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Francisco Villaescusa-Navarro (Flatiron Institute)

Boris Bolliet (Cambridge)

Multi-agent orchestration with

AG2

https://ag2.ai/

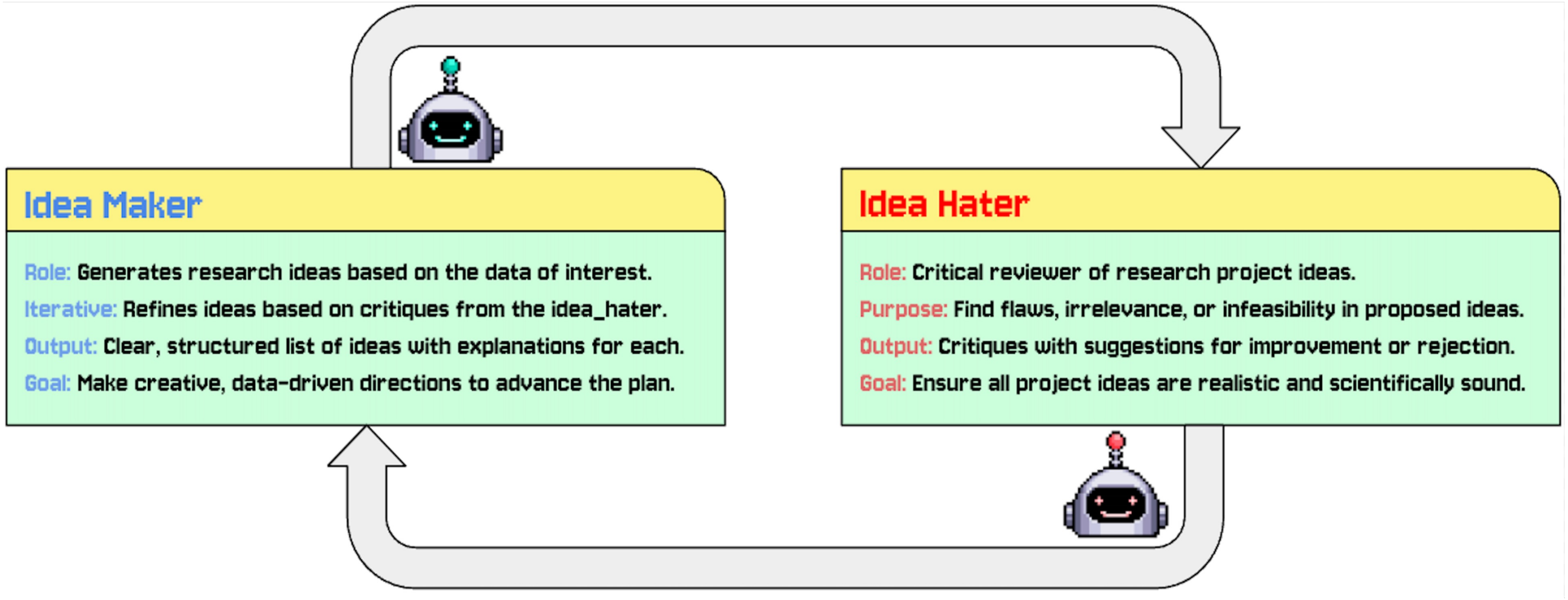
LangGraph

Deep Research with

CMBAGENT

https://github.com/CMBAgents/cmbagent

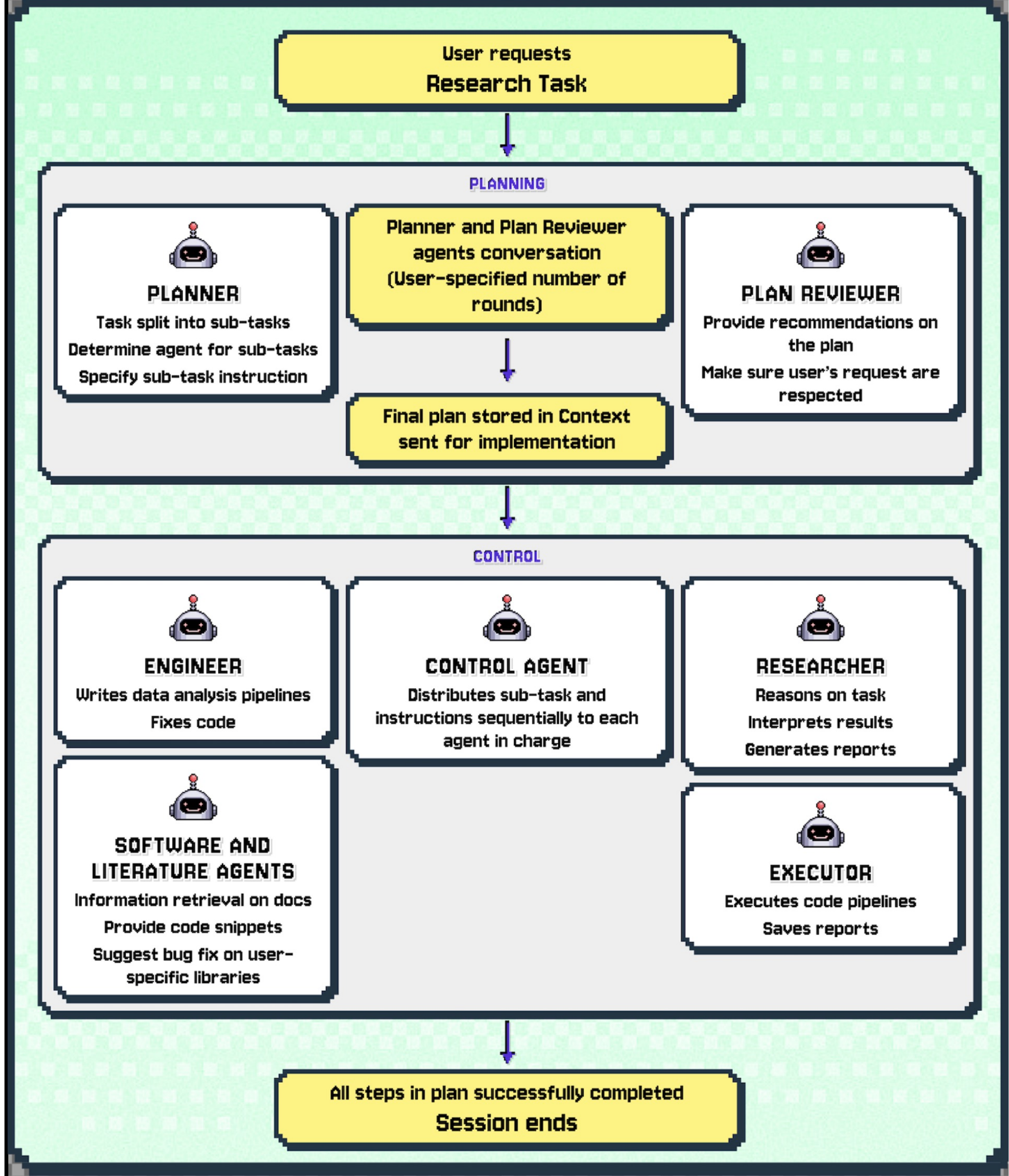
Generate Ideas



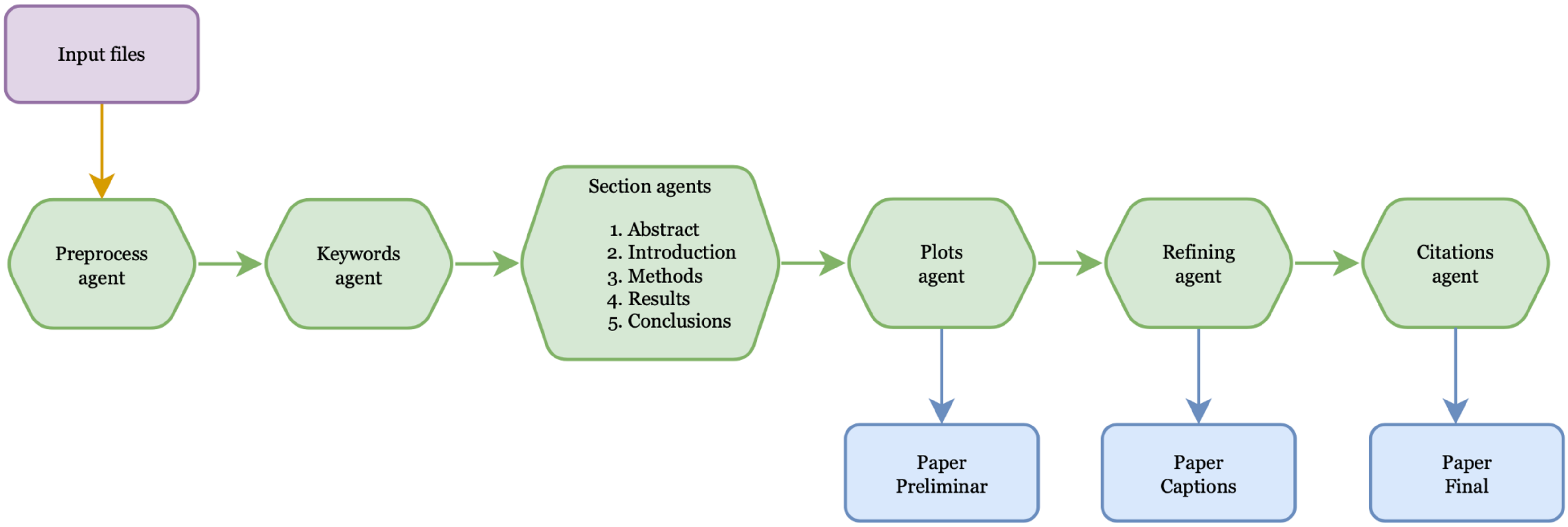
Follow plan; write and execute code.

CMBAgent

Boris Bolliet et al.



Write papers



Denario

	Module			
	Idea	**Methodology**	**Analysis**	**Paper**
Task	Generate project idea	Develop project plan	Implement plan; write and execute code; make plots	Write paper

Input	`input.md`	`input.md`
		`idea.md`
			`input.md`
			`idea.md`
			`methods.md`
				`input.md`
				`idea.md`
				`methods.md`
				`results.md`
				Plots

Output	`idea.md`	`methods.md`	`results.md` Plots	`Paper.pdf`

- input.md —-> Description of the problem, data...etc
- idea.md —-> Description of the idea
- methods.md —-> Description of the research plan
- results.md —-> Description of the results