RayGal relativistic ray-tracing (Michel-Andrès Breton)

+

e-MANTIS emulator (Iñigo Sáez-Casares PhD)

=>

Yann RASERA

LUTH/Univ. Paris Cité /Obs. de Paris /PSL/CNRS/IUF

April 23rd, 2024

The ProGraceRay Project: PRObing GRAvity at Cosmological scalEs with relativistic RAY-tracing

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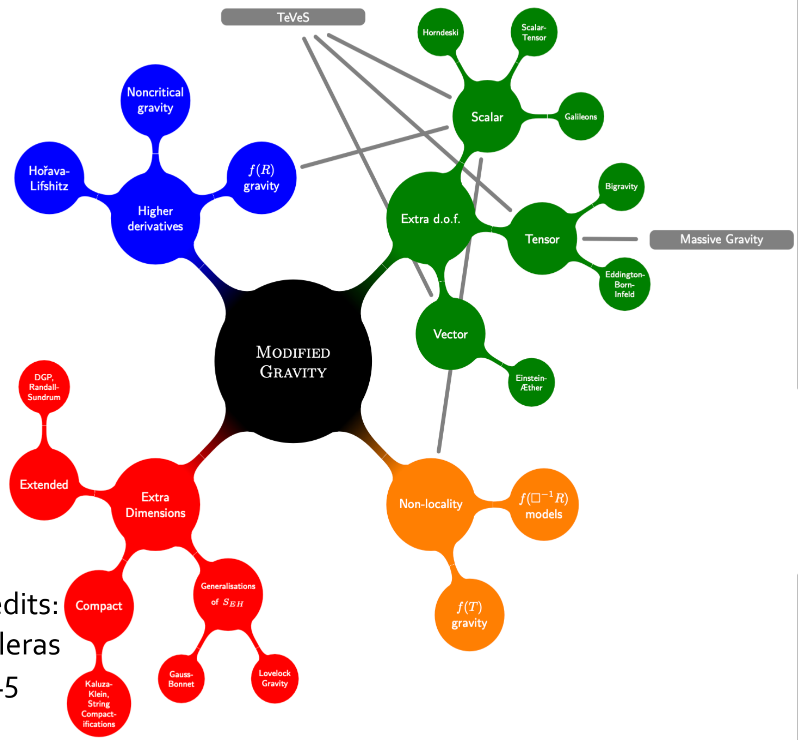
The ProGraceRay Team

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (p.month)
LUTH Paris Observatory Meudon	***RASERA***	***Yann***	*Associate professor*	***Coordinator**, Tasks 1.1, 1.2, 3.1, 3.2, 4.1-4.4, 5.1, 5.3, 5.4*	*44p.month*
	CORASANITI	*Pier-Stefano*	*CNRS Researcher*	*Tasks 1.1,1.2,3.1, 3.2, 4.4, 5.4*	*12p.month*
	ROY	*Fabrice*	*Research Engineer*	*Tasks 1.1,1.2, 3.1,3.2*	*18p.month*
	LE BRUN	*Amandine*	*CNRS Researcher*	*Tasks 1.1, 1.2, 2.1-2.3, 3.1, 3.2, 5.4*	*12p.month*
	REVERDY	*Vincent*	*CNRS Researcher*	*Tasks 3.1,3.2*	*12p.month*
	SAEZ-CASARES	*Iñigo*	*PhD student*	*Tasks 1.1,1.2, 5.1, 5.2*	*10p.month*
	Postdoc 1: To be recruited		*Postdoctoral Researcher*	*Tasks 1.1,1.2, 3.1*	*24p.month*
IAP CNRS Paris	***DUBOIS***	***Yohan***	*CNRS Researcher*	***Partner's leader** Tasks 2.1-2.3, 5.3, 5.4*	*10p.month*
	LAVAUX	*Guilhem*	*CNRS Researcher*	*Tasks 2.1-2.3*	*10p.month*
	COLOMBI	*Stéphane*	*CNRS Researcher*	*Tasks 1.1, 1.2, 2.1-2.3*	*6p.month*
	CUSIN	*Giulia*	*CNRS Researcher*	*Tasks 1.1, 3.1, 5.3*	*6p.month*
	PEIRANI	*Sébastien*	*CNRS Researcher*	*Tasks 2.1-2.3*	*8p.month*
	SAGA	*Shohei*	*Postdoctoral Researcher*	*Tasks 5.2*	*5p.month*
	Postdoc 2: To be recruited		*Postdoctoral Researcher*	*Tasks 2.1-2.3*	*24p.month*
AIM CEA Saclay Gif sur Yvette	***PIRES***	***Sandrine***	*Engineer-Researcher*	***Partner's leader** Tasks 4.1, 4.3, 4.4, 5.4*	*14p.month*
	CODIS	*Sandrine*	*CNRS Researcher*	*Tasks 4.3, 4.4, 5.2, 5.3*	*6p.month*
	Postdoc 3: To be recruited		*Postdoctoral Researcher*	*Tasks 4.1- 4.4*	*12p.month*
LAM Aix-Marseille University Marseille	***DE LA TORRE***	***Sylvain***	*Assistant Astronomer*	***Partner's leader** Tasks 4.2, 4.3, 4.4, 5.2, 5.3, 5.4*	*12p.month*
	JULLO	*Eric*	*Assistant Astronomer*	*Tasks 4.3, 4.4, 5.2, 5.3, 5.4*	*10p.month*
	Postdoc 3: To be recruited		*Postdoctoral Researcher*	*Tasks 4.3-4.4, 5.2-5.4*	*12p.month*
EXTERNAL					
ICE-CSIC-IEEC (Spain)	*BRETON*	*Michel-Andrès*	*Postdoctoral Researcher*	*External member Tasks 3.1-3.2, 4.2*	*5p.month*
YITP/Kyoto University (Japan)	*TARUYA*	*Atsushi*	*Associate professor*	*External member Tasks 4.2, 4.3, 4.4, 5.2, 5.3, 5.4*	*6p.month*

BACKGROUND

WHAT IS THE NATURE OF GRAVITY AT COSMOLOGICAL SCALES?



Credits: Trilleras 2015

Modified gravity theories

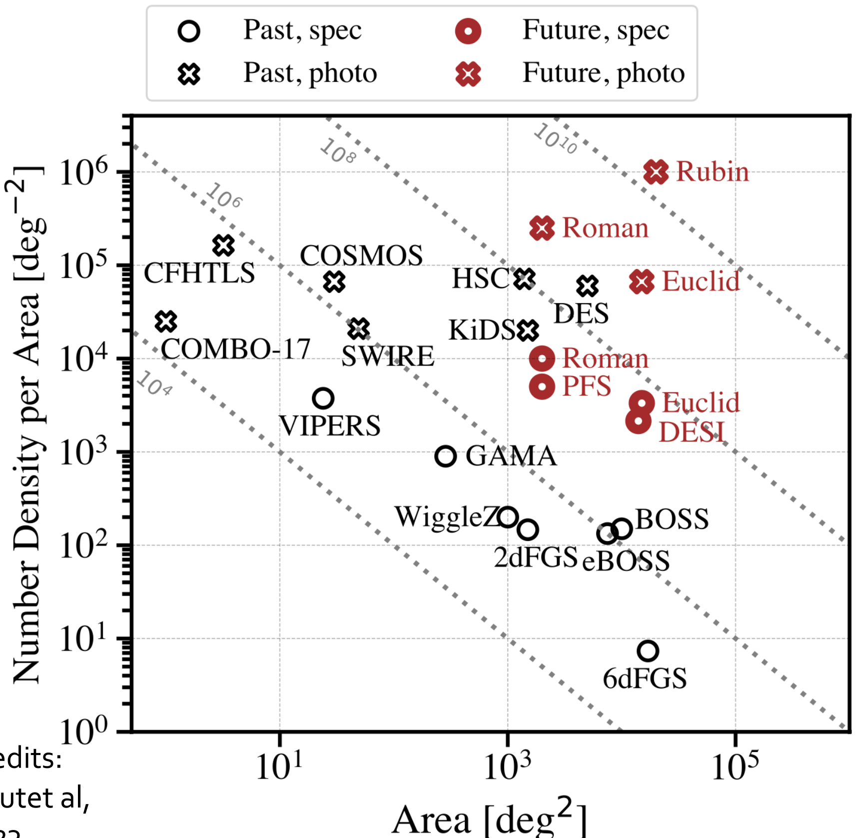
Lovelock theorem of General Relativity:

From a **local gravitational action** which contains only **second derivatives** of the **four-dimensional space-time metric**, then the only possible equations are Einstein-field equations

Modified gravity according to Lovelock theorem

1. **Non-locality** (or emergence) : no local action
2. **Higher-derivatives**: more than 2nd derivatives
3. **Extra-dimensions** : more than 4D
4. **Extra degrees of freedom**: scalar, vector and/or tensor

WHAT IS THE NATURE OF GRAVITY AT COSMOLOGICAL SCALES?

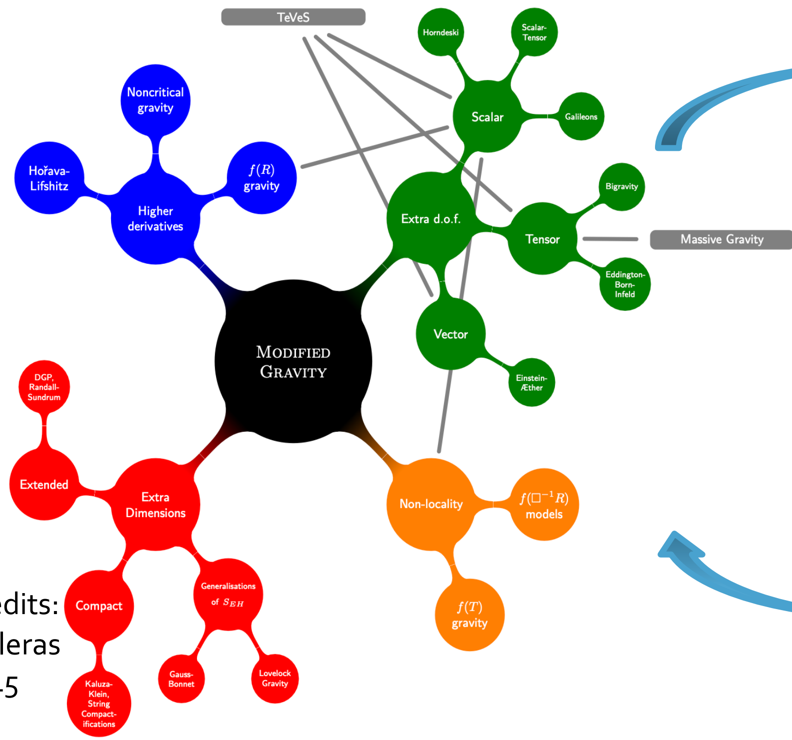


Credits: Houtet al, 2023

<u>*Past and future of photometric/spectroscopic galaxy surveys*</u>

Large-Scale Structure surveys

WHAT IS THE NATURE OF GRAVITY AT COSMOLOGICAL SCALES?



Credits: Trilleras 2015

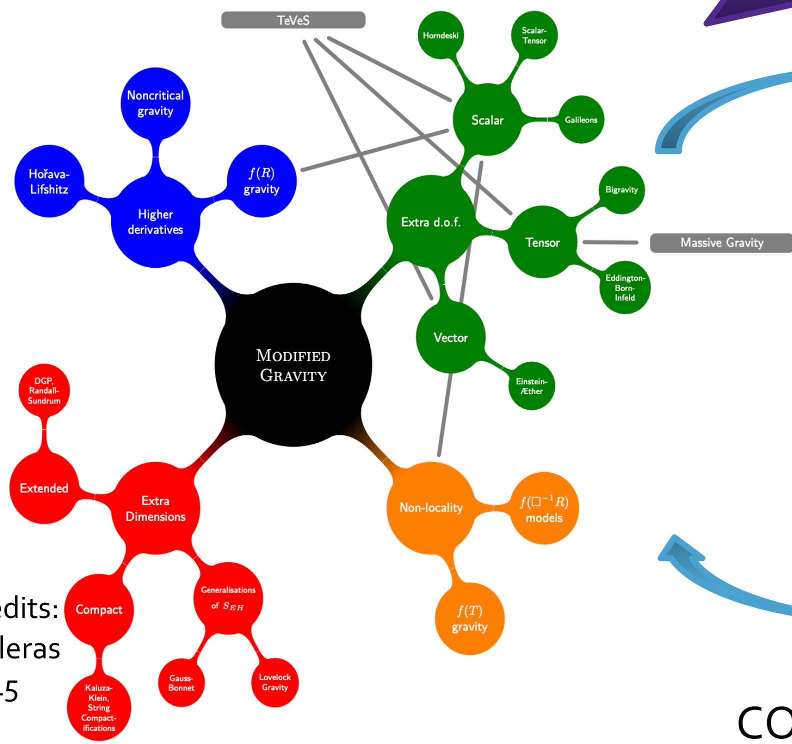
Modified gravity theories

Large-Scale Structure surveys

WHAT IS THE NATURE OF GRAVITY AT COSMOLOGICAL SCALES?

ACCURATE PREDICTIONS

We are here!



Credits: Trilleras 2015

ROBUST CONSTRAINTS

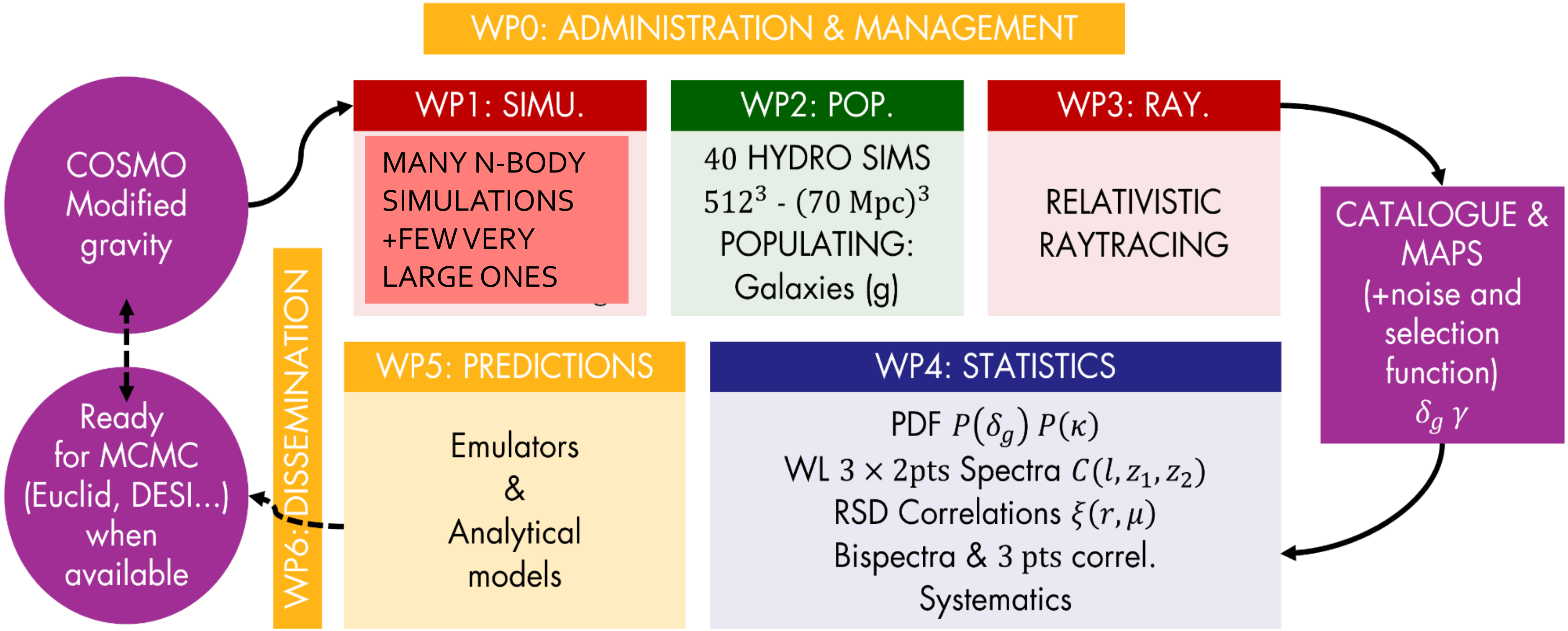
Modified gravity theories

Large-Scale Structure surveys

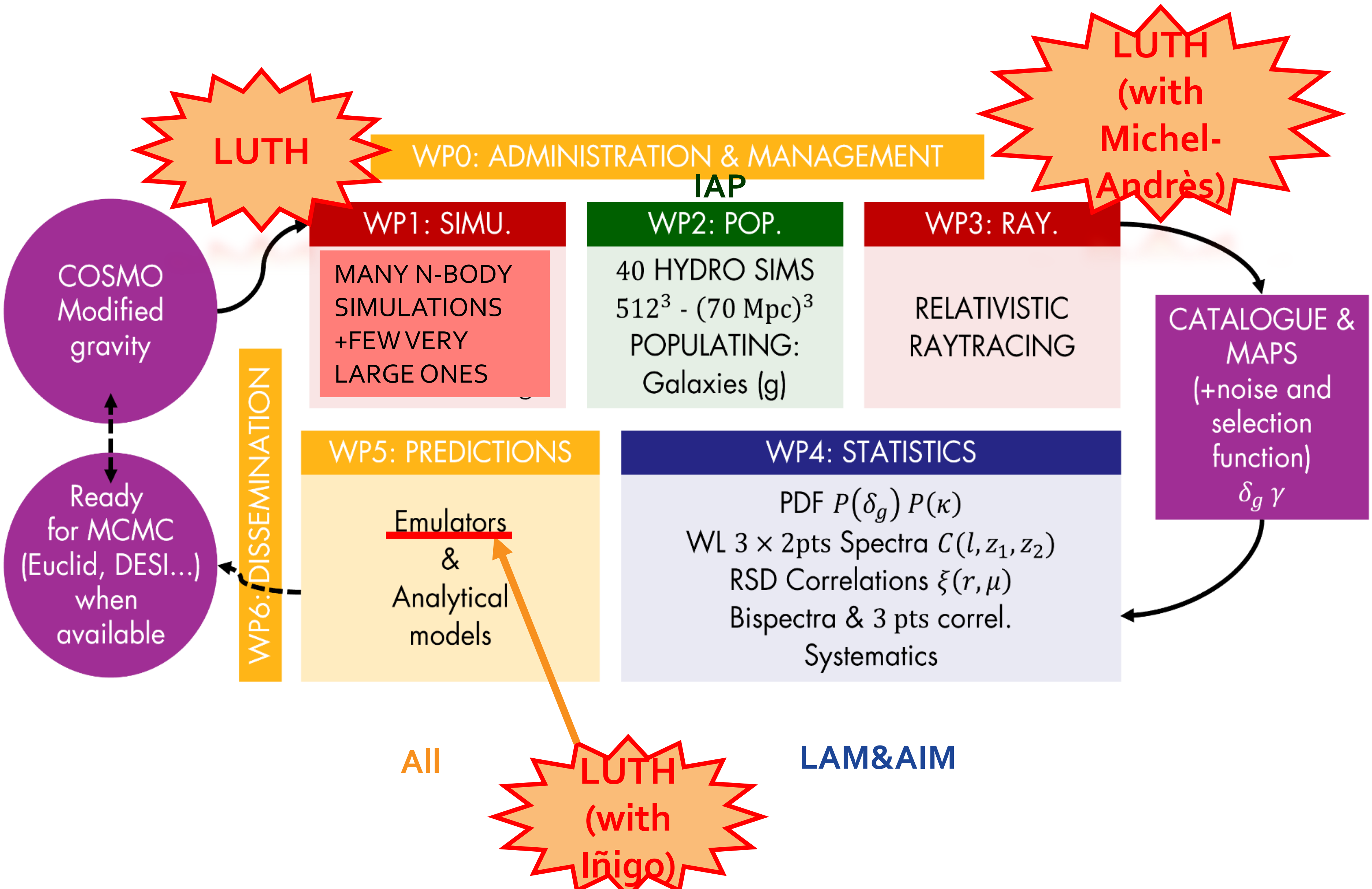
ProGraceRay: PRObing GRAvity at Cosmological scalEs with relativistic RAY-tracing

METHODS

ORGANISATION OF THE WORK



ORGANISATION OF THE WORK



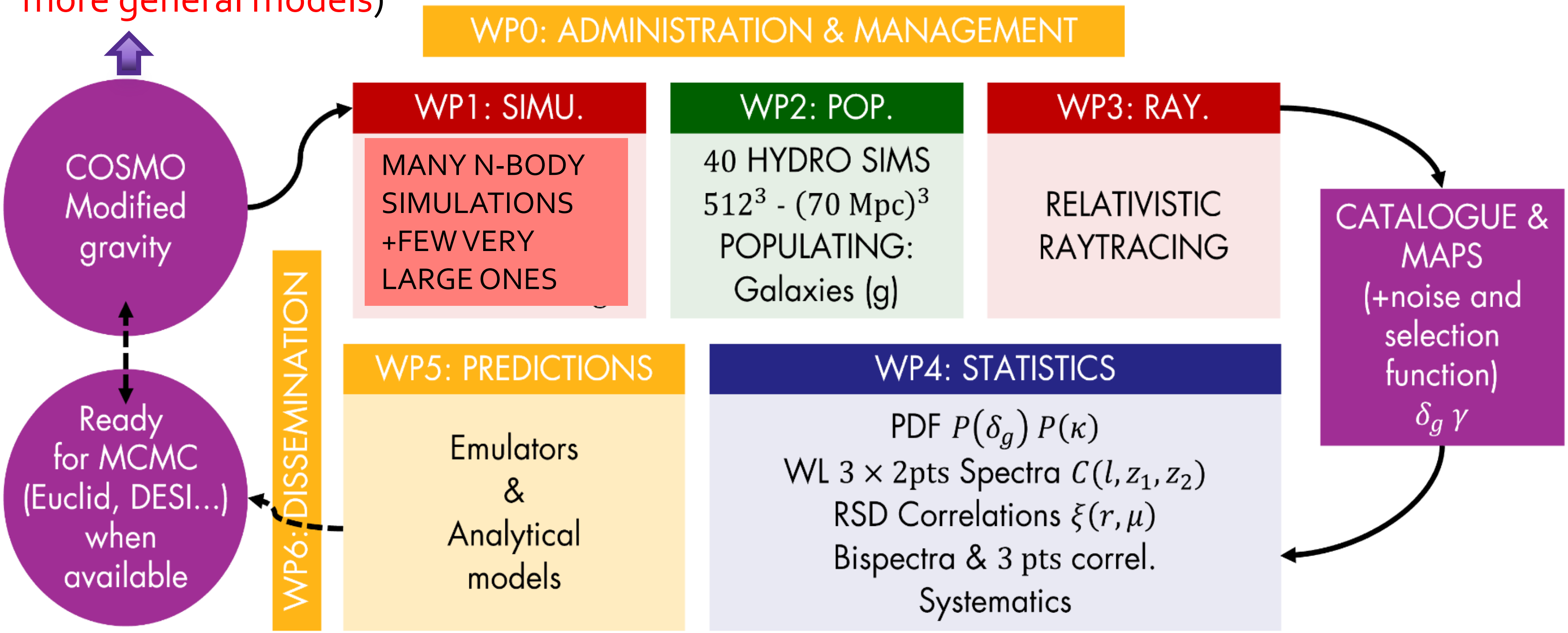
CHOOSING THE DARK ENERGY TYPE

(e.g. Λ-CDM, → Cold Dark Matter+ cosmological constant (STANDARD MODEL w=-1)

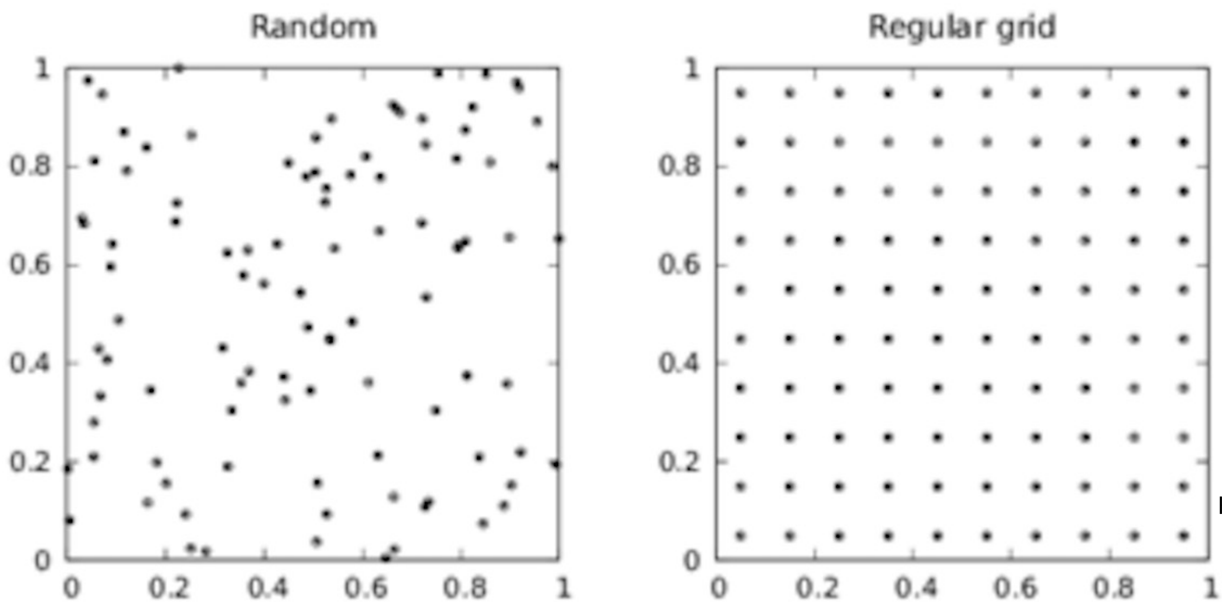
w-CDM, → CDM+ fluid of dark energy with equation of state w≠-1 (Iñigo&MAB)

f(R)-CDM, → CDM+ f(R) Hu&Sawicki modified gravity (Iñigo)

more general models) → Cold Dark Matter+ more generic modified gravity (ProGraceRay)



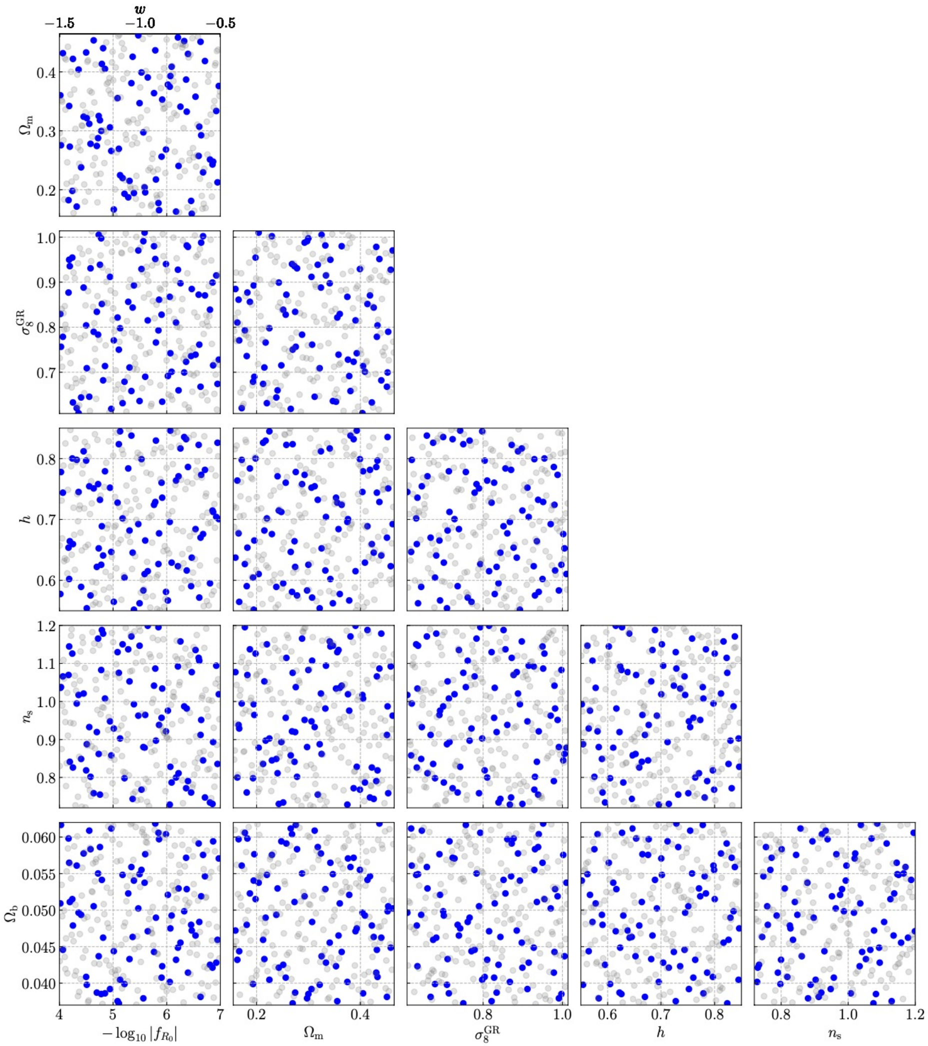
RANDOM OR GRID SAMPLING OF THE PARAMETER SPACE



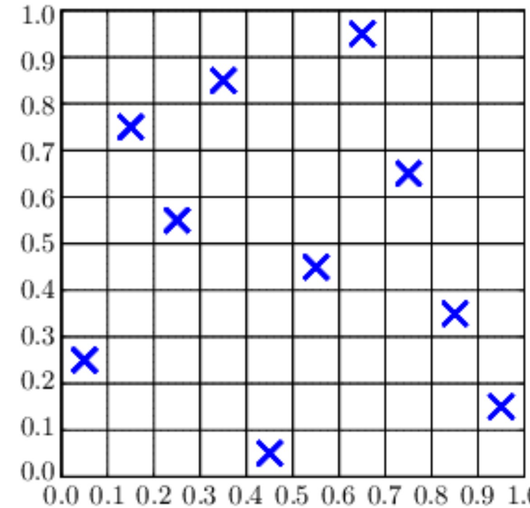
Kamath 2023

- Cosmological inference in 5D (at least) => needs ~10^5 accurate predictions
- 1 cosmological N-body simulation=> ~ 10^4 h (for 512^3 part. in modified gravity)
- Total time=> 10^9 h => TOO MUCH CPU TIME!!!!

LATIN HYPERCUBE SAMPLING OF THE PARAMETER SPACE



Sáez-Casares et al., submitted to A&A, 2024



Bramerdofer et al.2018

« Sudoku-like sampling »

Since the statistics are smooth :

- Needs ~20*NDIM points ~100 models to capture all the (cross-)derivatives
- Needs 10^6 h => THIS IS POSSIBLE!

ACCURATE MODEL OF LARGE-SCALE STRUCTURE FORMATION IN GR

METHODS

GR INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS

Gaussian

(+ GR a(t) Background)

Weak-field GR

DYNAMICS OF GRAVITATIONAL INTERACTION

Non relativistic GR geodesics

DYNAMICS OF DARK MATTER

DYNAMICS OF DARK ENERGY

Vlasov-Poisson: Cold Dark MAtter

Λ

Metric

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\delta_{ab}dx^a dx^b$$

with $\phi=\psi$

NON-LINEARITIES

ANALYTICAL PERTURBATIVE)

(I.E.

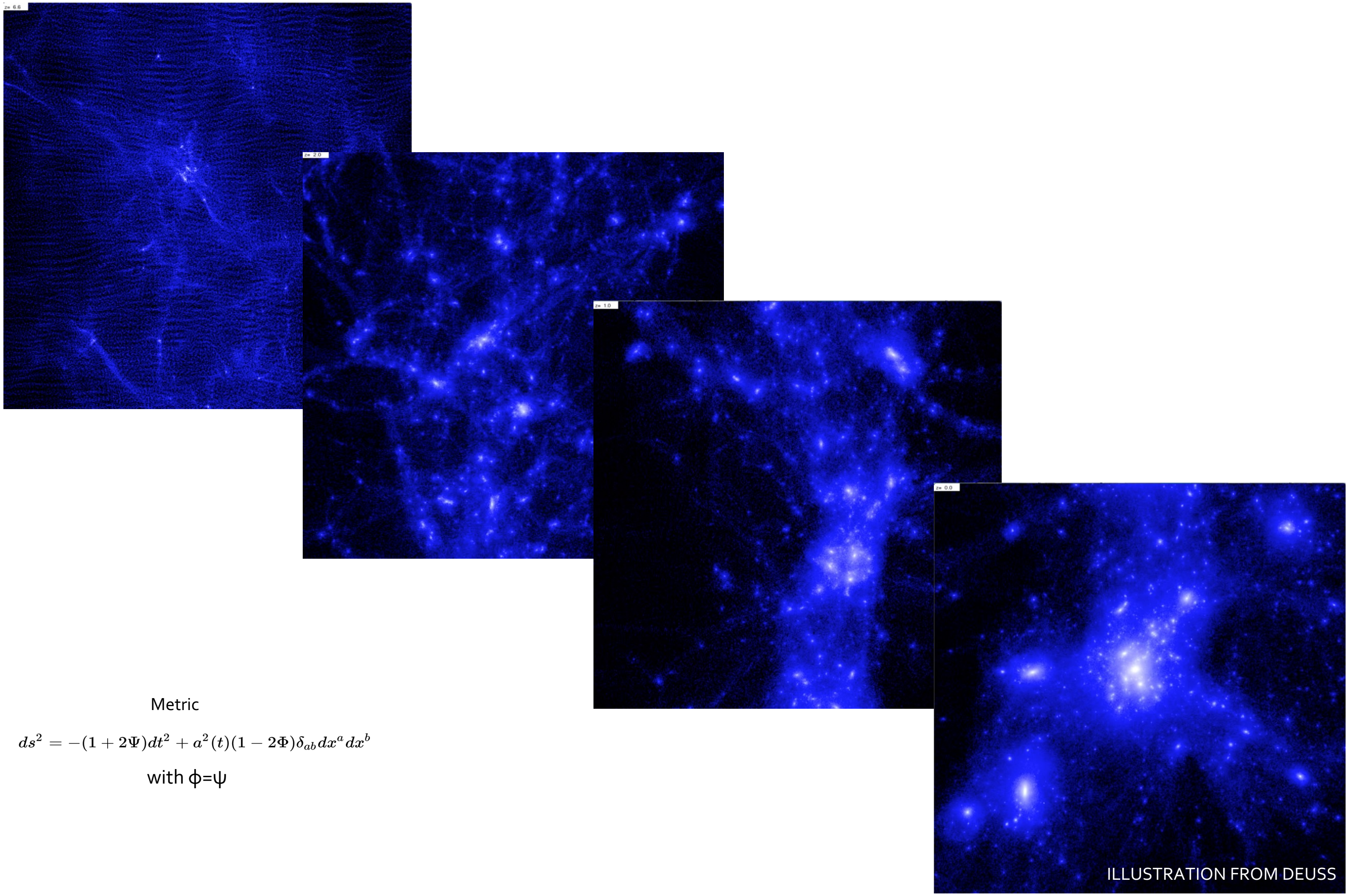
SEMI-ANALYTICAL

NUMERICS (SIMULATIONS)

ACCURATE MODEL OF LARGE-SCALE STRUCTURE FORMATION IN GR

METHODS

GR INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS



ANALYTICAL PERTURBATIVE)

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NON-LINEARITIES

Metric

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\delta_{ab}dx^a dx^b$$

with $\phi=\psi$

GR INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS

EXAMPLE

Name	Model(s)	L_{box} $[h^{-1}\text{Mpc}]$	N_{part}	m_{part} $[(\Omega_{\text{m}}/0.3071)\,h^{-1}M_{\odot}]$	N_{real}	N_{cosmo}
L328_M10_wcdm	wCDM	328.125	512^3	$2.25 \cdot 10^{10}$	64	80
L656_M11_wcdm	wCDM	656.25	512^3	$1.79 \cdot 10^{11}$	64	80
L328_M10_frcdm	$f(R)$CDM	328.125	512^3	$2.25 \cdot 10^{10}$	8	80
L656_M11_frcdm	$f(R)$CDM	656.25	512^3	$1.79 \cdot 10^{11}$	8	80
L328_M9_wcdm	wCDM	328.125	1024^3	$2.81 \cdot 10^{9}$	1	16
L656_M10_wcdm	wCDM	656.25	1024^3	$2.25 \cdot 10^{10}$	1	16
L328_M10_P18	P18	328.125	512^3	$2.25 \cdot 10^{10}$	384	1
L328_M10_w12	w12	328.125	512^3	$2.25 \cdot 10^{10}$	64	1
L328_M10_F5	F5	328.125	512^3	$2.25 \cdot 10^{10}$	64	1
L164_M10	P18, F5, F6	164.0625	256^3	$2.25 \cdot 10^{10}$	1	3
L164_M9	P18, F5, F6	164.0625	512^3	$2.81 \cdot 10^{9}$	1	3
L164_M8	P18	164.0625	1024^3	$3.51 \cdot 10^{8}$	1	1

The wCDM and f(R)CDM
e-MANTIS simulation suite
Sáez-Casares et al., 2023
Sáez-Casares et al., submitted to A&A, 2024

We combine:
- several universe realizations
- several mass resolutions
- several simulation volumes

=> to increase the effective dynamical range

Rem: to be expanded in ProGraceRay (to enable Raytracing)

ACCURATE MODEL OF LARGE-SCALE STRUCTURE FORMATION IN GR

METHODS

GR INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS

Gaussian

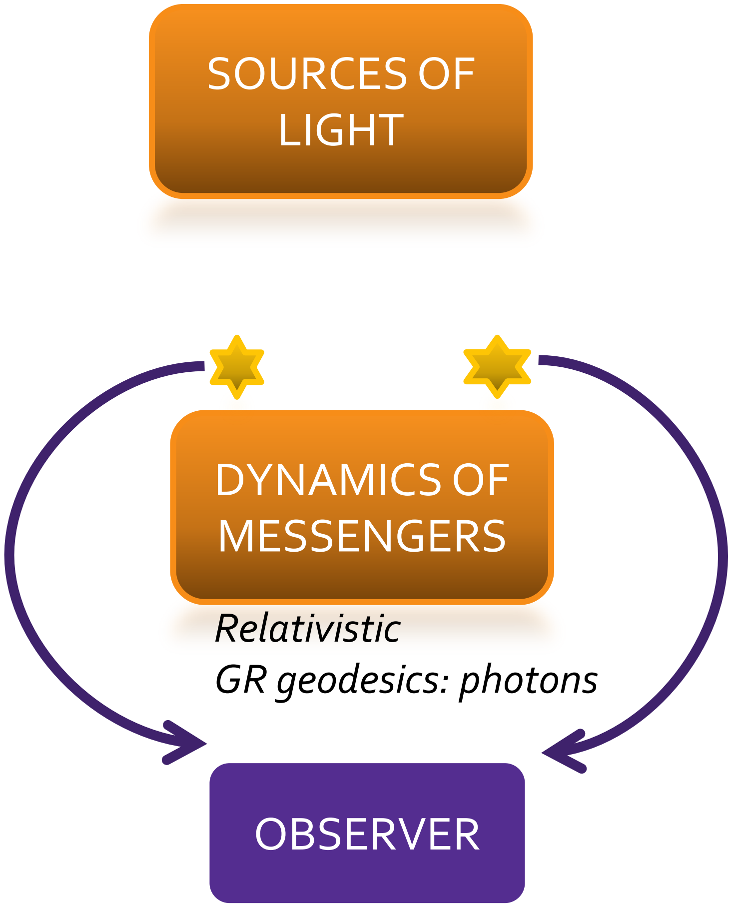
(+ GR a(t) Background)

Weak-field GR

Metric

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\delta_{ab}dx^a dx^b$$

with $\phi=\psi$



Relativistic

GR geodesics: photons

ANALYTICAL

(I.E. PERTURBATIVE)

SEMI-ANALYTICAL

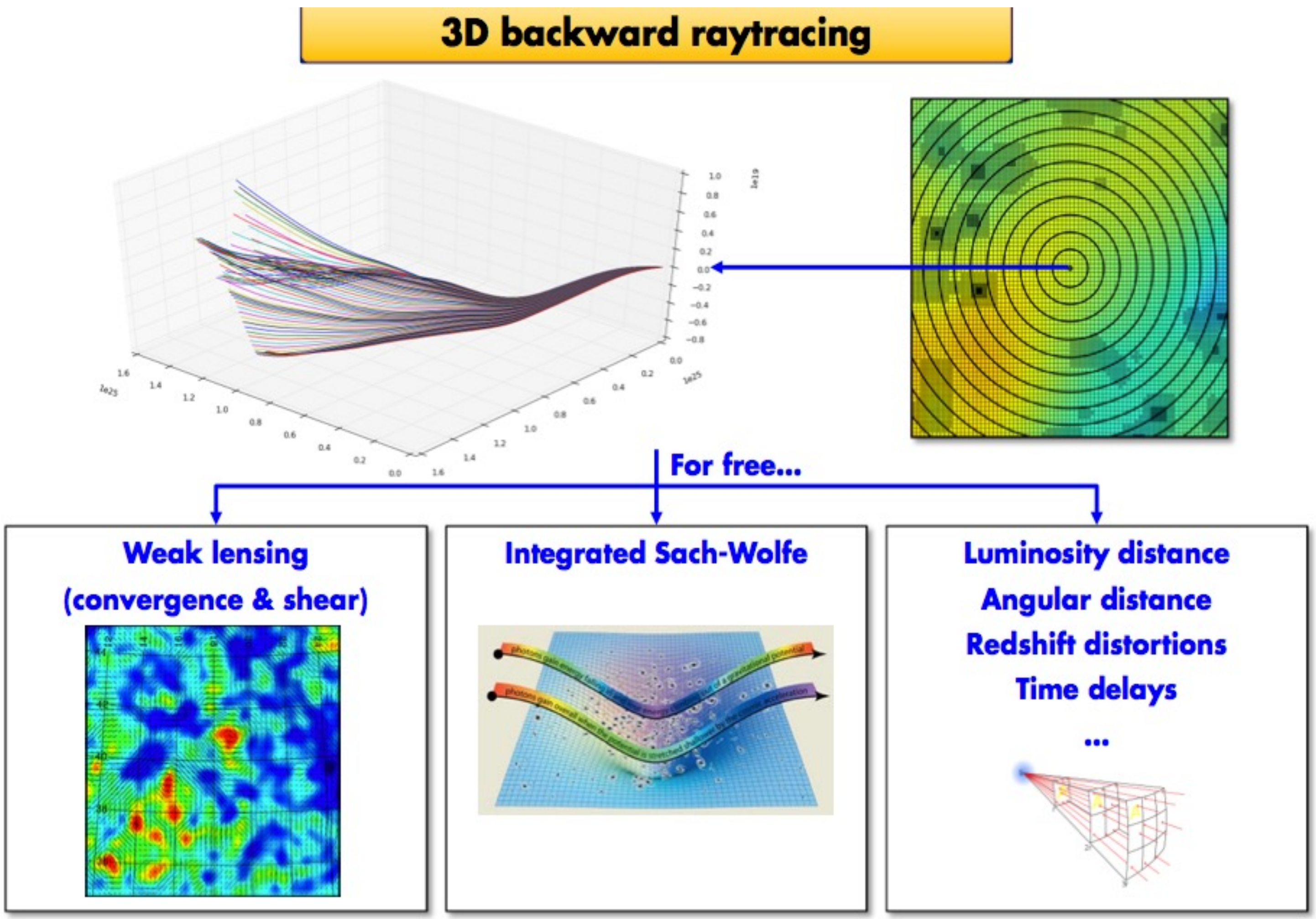
NUMERICS (SIMULATIONS)

NON-LINEARITIES

ACCURATE MODEL OF LARGE-SCALE STRUCTURE FORMATION IN GR

METHODS

GR INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS



ds^2

V.Reverdy PhD thesis
(supervisors: J-M Alimi and Y.Rasera)

ANALYTICAL (I.E. PERTURBATIVE)

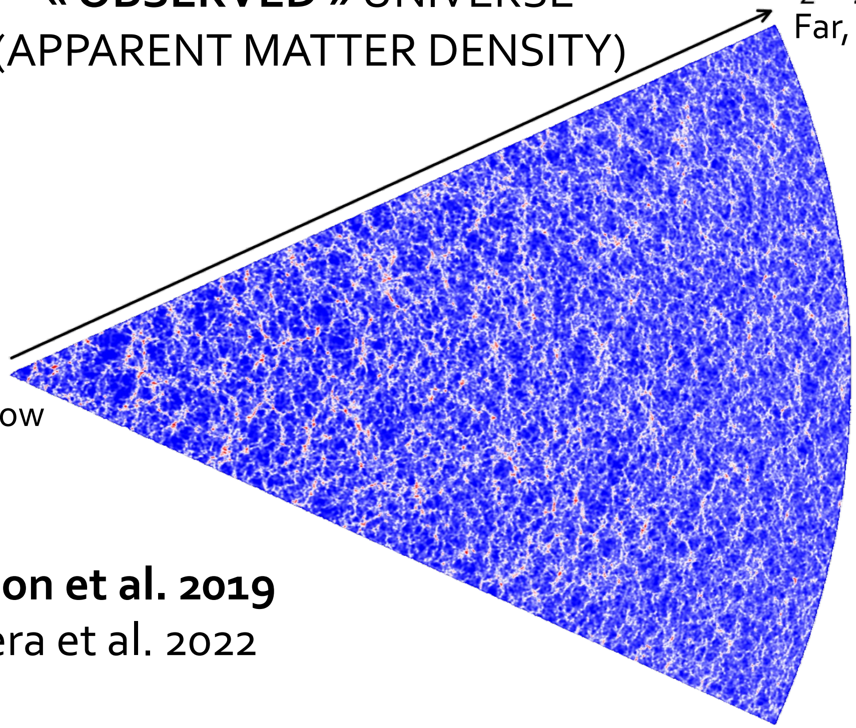
SEMI-ANALYTICAL

NUMERICS (SIMULATIONS)

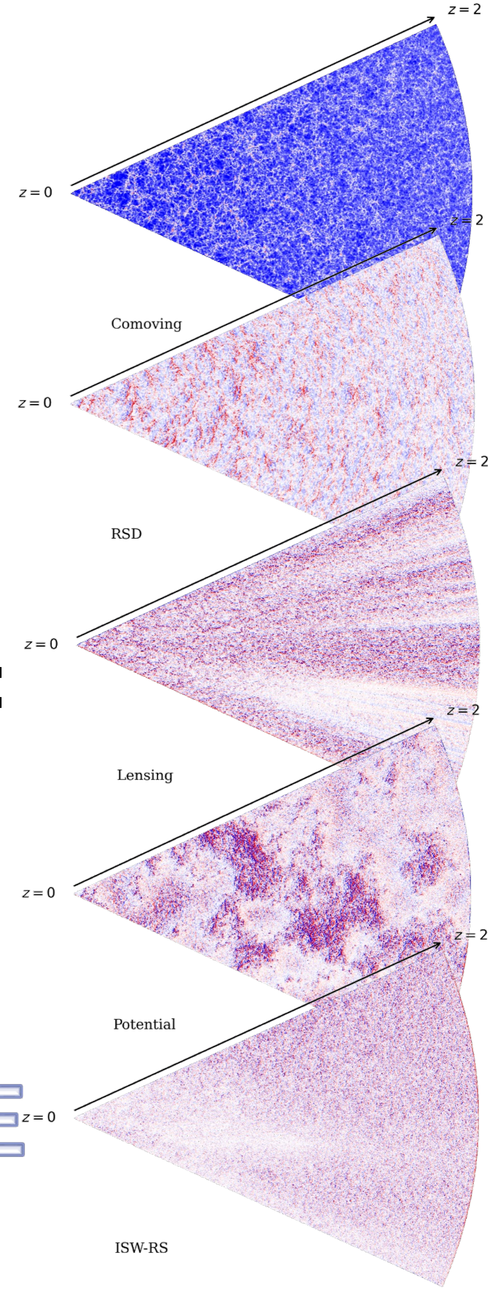
NON-LINEARITIES

EXAMPLE

SIMULATION
OF A SLICE OF THE
« **OBSERVED** » UNIVERSE
(APPARENT MATTER DENSITY)



=



« TRUE »
UNIVERSE

+

DOPPLER
EFFECT

+

WEAK
LENSING

+

GRAVITATIONAL
REDSHIFT

+

INTEGRATED
SACHS WOLFE
EFFECT

Breton et al. 2019
Rasera et al. 2022

THE RAYGAL UNIVERSE

70 billion particles ⇨ cosmic structure formation
1 billion photons ⇨ general relativistic effects

(type « **RayGal data** » on any search engine)

Rem: #of sims to be increased in ProGraceRay->emulator

LUTH l'Observatoire de Paris | PSL Université de Paris cnrs INSU LAM CINES TGCC

ACCURATE MODEL OF LARGE-SCALE STRUCTURE FORMATION IN GR

METHODS

GR INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS

Gaussian

(+ GR a(t) Background)

Weak-field GR

DYNAMICS OF GRAVITATIONAL INTERACTION

Non relativistic GR geodesics

DYNAMICS OF DARK MATTER

SOURCES OF LIGHT

DYNAMICS OF DARK ENERGY

Vlasov-Poisson: Cold Dark MAtter

Λ

Metric

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\delta_{ab}dx^a dx^b$$

with ϕ=ψ

DYNAMICS OF MESSENGERS

Relativistic GR geodesics: photons

OBSERVER

ANALYTICAL (I.E. PERTURBATIVE)

SEMI-ANALYTICAL

NUMERICS (SIMULATIONS)

NON-LINEARITIES

ACCURATE MODEL OF LARGE-SCALE STRUCTURE FORMATION IN MG

METHODS

MG INITIAL CONDITIONS: COMPOSITION AND DISTRIBUTION OF COMPONENTS

Gaussian

(+ **MG a(t)** Background)

Weak-field ***MODIFIED GRAVITY***

DYNAMICS OF GRAVITATIONAL INTERACTION

Non relativistic **MODIFIED GRAVITY** geodesics

DYNAMICS OF DARK MATTER

SOURCES OF LIGHT

DYNAMICS OF DARK ENERGY

Vlasov-Poisson: Cold Dark MAtter

Λ or other

Metric (Jordan Frame)

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\delta_{ab}dx^a dx^b$$

with $\phi \neq \psi$

DYNAMICS OF MESSENGERS

Relativistic ***MODIFIED GRAVITY*** *geodesics: photons*

OBSERVER

ANALYTICAL

PERTURBATIVE (I.E. SEMI-ANALYTICAL)

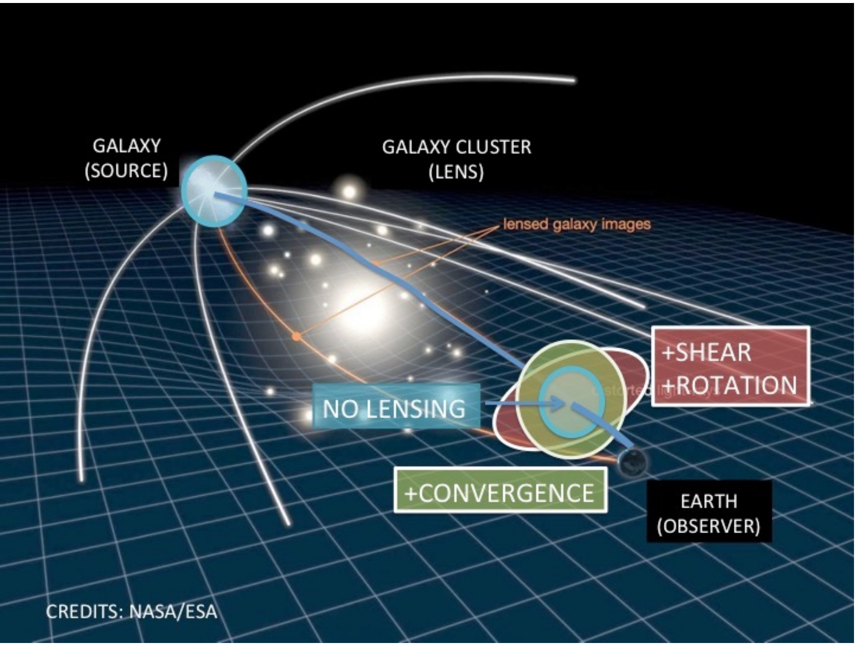
NUMERICS (SIMULATIONS)

NON-LINEARITIES

SOME RESULTS FROM RAYGAL & e-MANTIS

EXAMPLE OF RELATIVISTIC EFFECTS:WEAK-LENSING SHEAR (LEFT) AND REDHIFT SPACE DISTORTIONS (RIGHT)

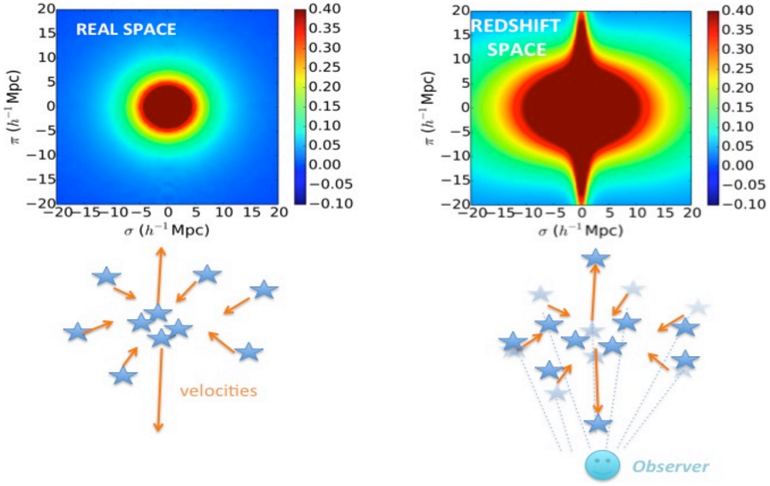
LENSING



AND

Redshift-Space Distortions (RSD)

2D CORRELATION FUNCTION $\xi(\pi,\sigma)=<\delta(x)\ \delta(x+r)>$



AND OTHERS (gravitational redshift, ISW effect, transverse Doppler, etc)

- Relativistic approach at large scales: **Yoo+ 2010; Bonvin&Durrer 2011; Yoo 2011; Lewis&Challinor 2011**

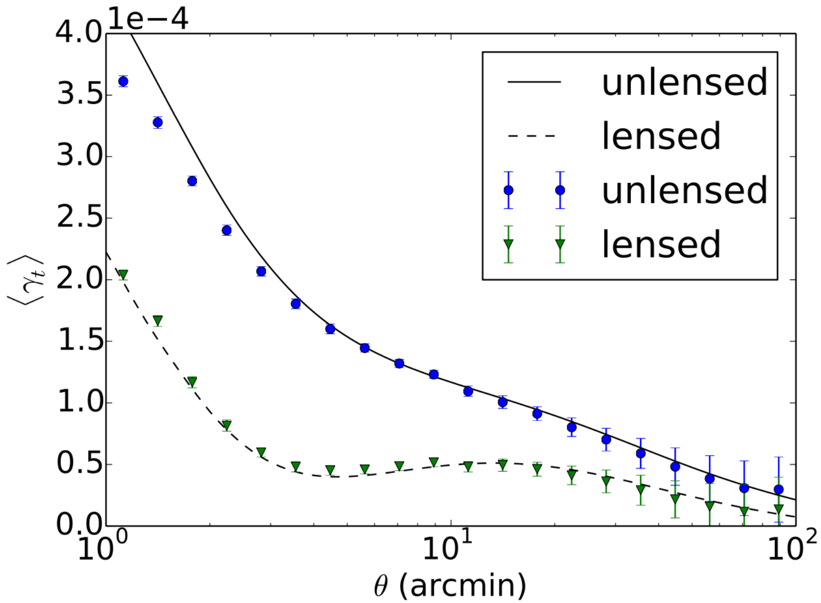
Use **similar formalism as for CMB** (i.e. weak field GR) but applied to galaxies
->LIMITATION OF ORIGINAL WORKS: **LINEAR** REGIME

- Relativistic approach at cluster scale and around: Kaiser2013, Zhao2013, Croft2013, Cai+2017

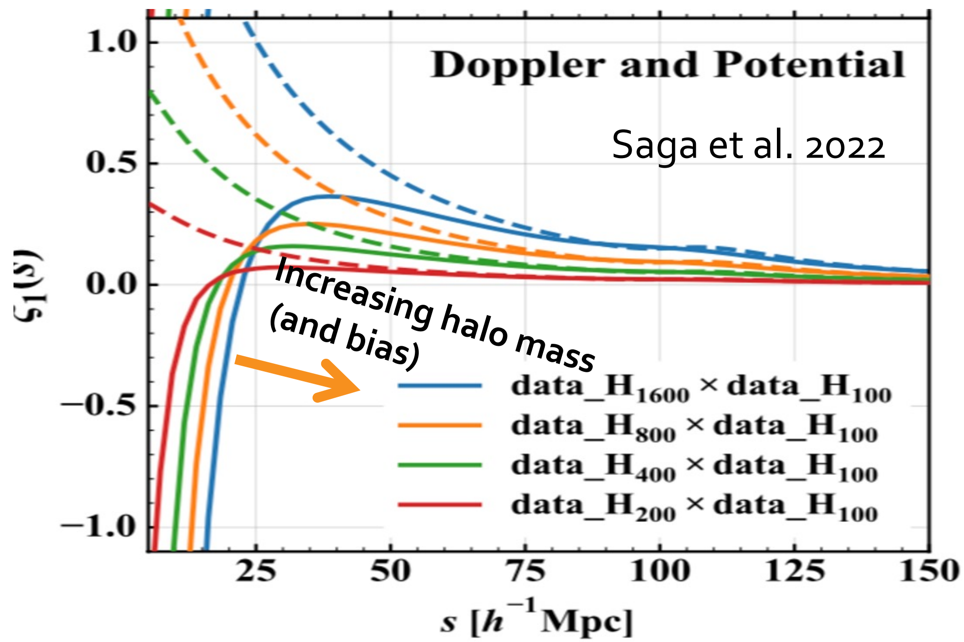
-> LIMITATION: How to connect with linear predictions ?

=> GR effects WITH SIM IS A HOT TOPIC: Killedar12, Reverdy14, Adamek16, Giblin17, Borzyszkowski17, Breton19, Adamek19 , Lepori20, Guandalin21, Lepori21, Rasera22, …

EXAMPLE OF RELATIVISTIC EFFECTS WITH RAYGAL: PROFILE OF WEAK-LENSING SHEAR (LEFT) AND HALO-HALO DIPOLE (RIGHT)



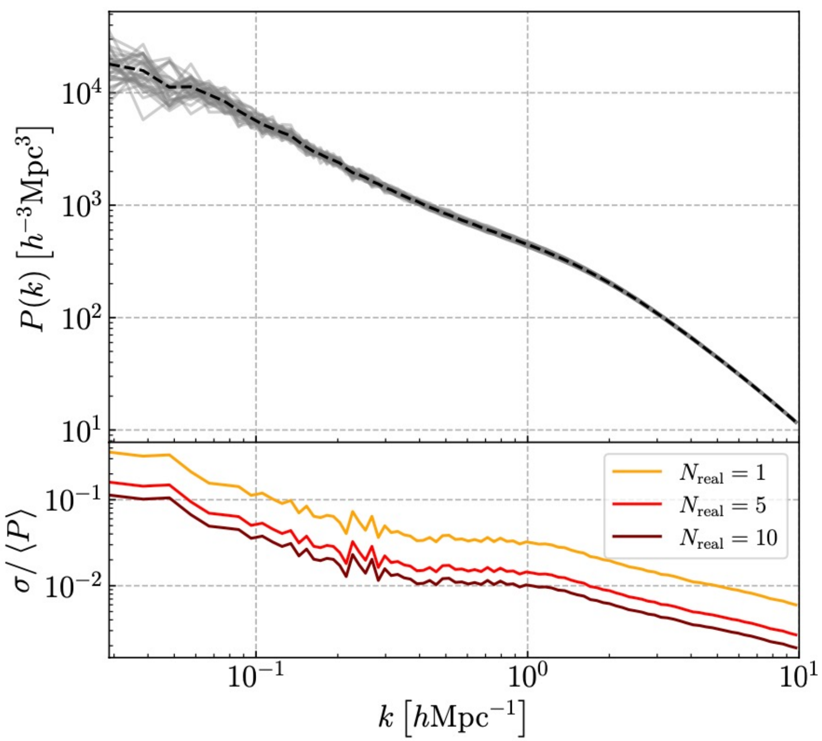
Courtesy: **Michel-Andrès Breton**

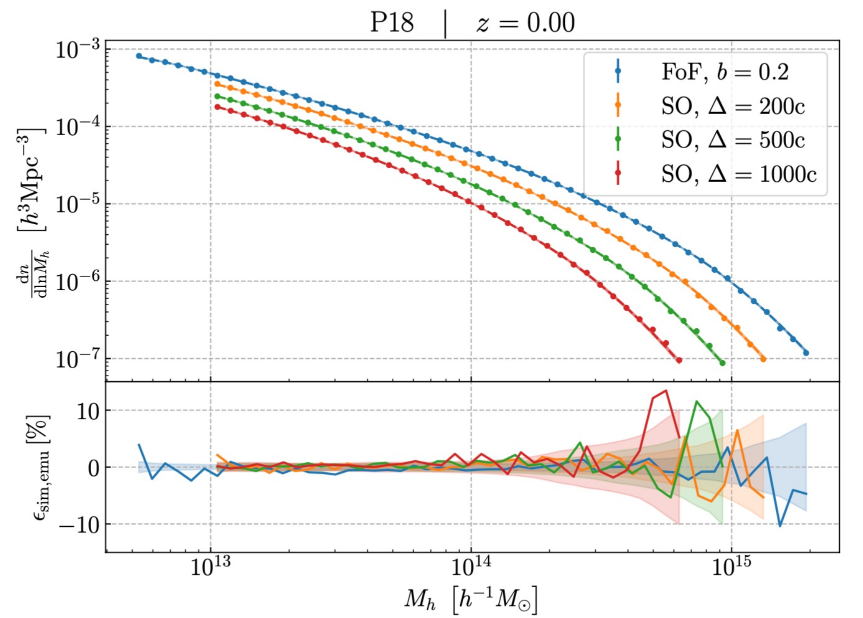


THE WEAK-LENSING SHEAR PROFILE IS SENSITIVE TO NON-TRIVIAL RELATIVISTIC EFFECTS

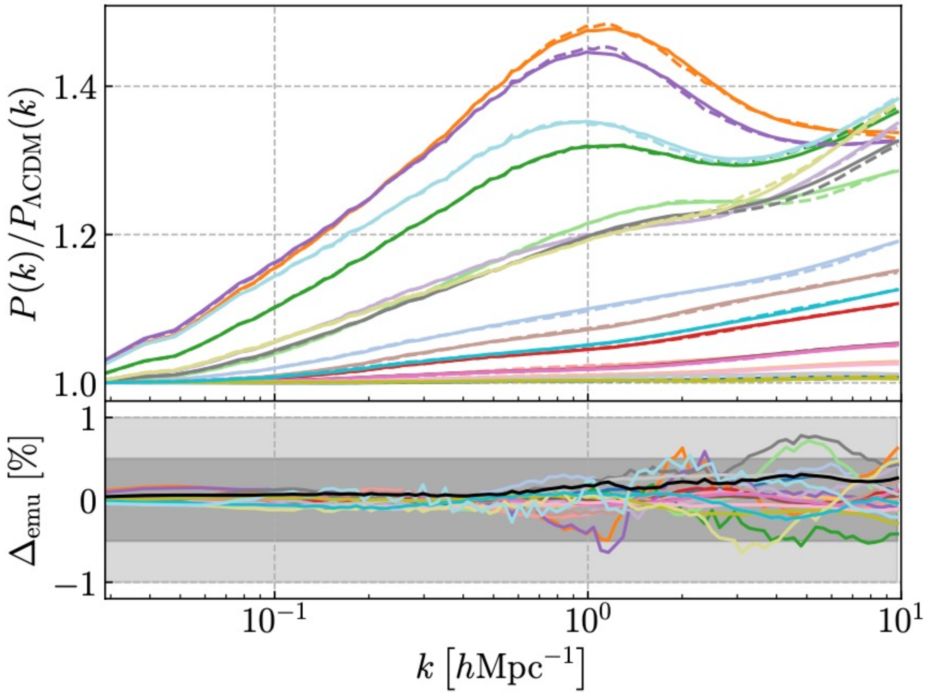
THE HALO-HALO DIPOLE IS A NEW PROBE OF THE POTENTIAL AT COSMIC SCALES

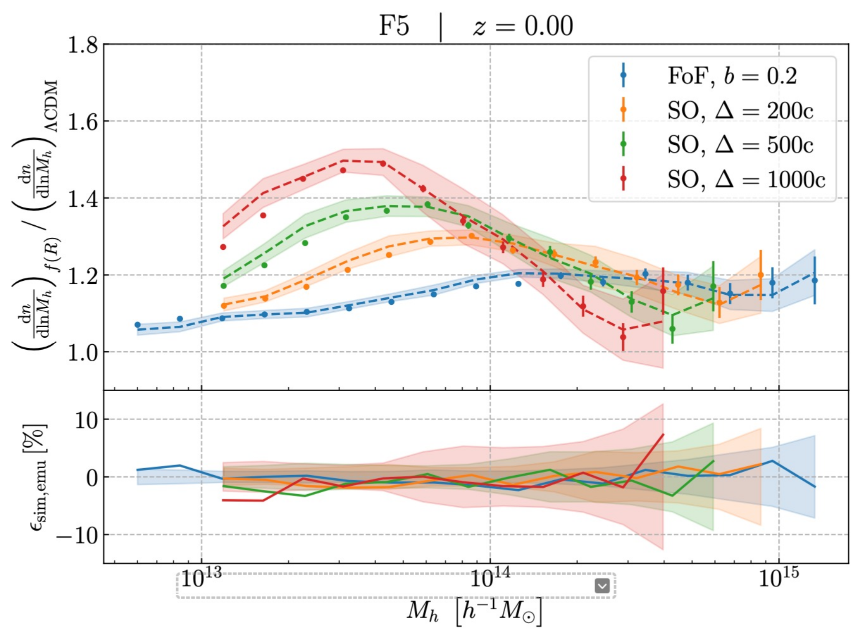
EXAMPLE OF EMULATION WITH e-MANTIS: MATTER POWER SPECTRUM (LEFT) AND HALO MASS FUNCTION (RIGHT)





EXAMPLE OF EMULATION WITH e-MANTIS: MATTER POWER SPECTRUM BOOST (LEFT) AND HALO MASS FUNCTION BOOST (RIGHT)





ACCURATE (few %) AND FAST (few ms) PREDICTIONS OF THE MATTER POWER SPECTRUM AND HALO MASS FUNCTION

SEE Iñigo'S THESIS DEFENSE EXPECTED 26 SEPTEMBER 2PM

SAVE THE DATE !

(IF EVERYTHING GOES WELL OF COURSE ;-))

CONCLUSION
PROGRACERAY PROJECT

<u>Goal</u>
Fast predictions of multiple complementary observables in a wide range of modified gravity models

<u>Methods</u>
Number of simulations as in e-MANTIS + Size of simulations as in RayGal
Relativistic ray-tracing (as in RayGal)
Emulators (as in e-Mantis)

<u>Constraints</u>
Comparison with data from DESI, Euclid and LSST will enable strong constraints on the nature of gravity at cosmic scales