INAF
leads Spoke 3
coleads Spoke 2
member of Spoke 1
member of Spoke 10

INAF

OA—Trieste
OA—Bologna
I. Radioastronomy (BO)
OA—Roma
OA—Catania

STAFF — 33 Months

2 Full
2 Associate
5 Researcher

PLAN

WP 1

Numerical simulations Nbody - fluids

1 PhD
UniTS

45% south

WP 2

Multiparameter Optimisation

1 TD (2y)
OA Napoli

WP 3

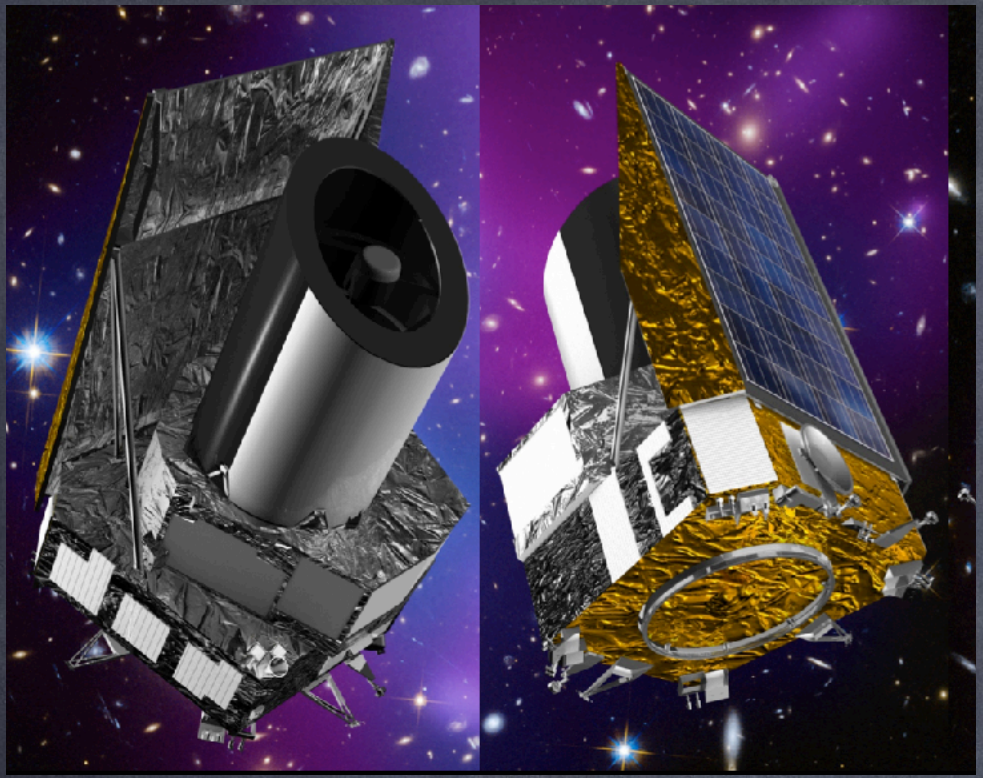
Machine Learning catalogs features

1 TD (2y)
OA Catania

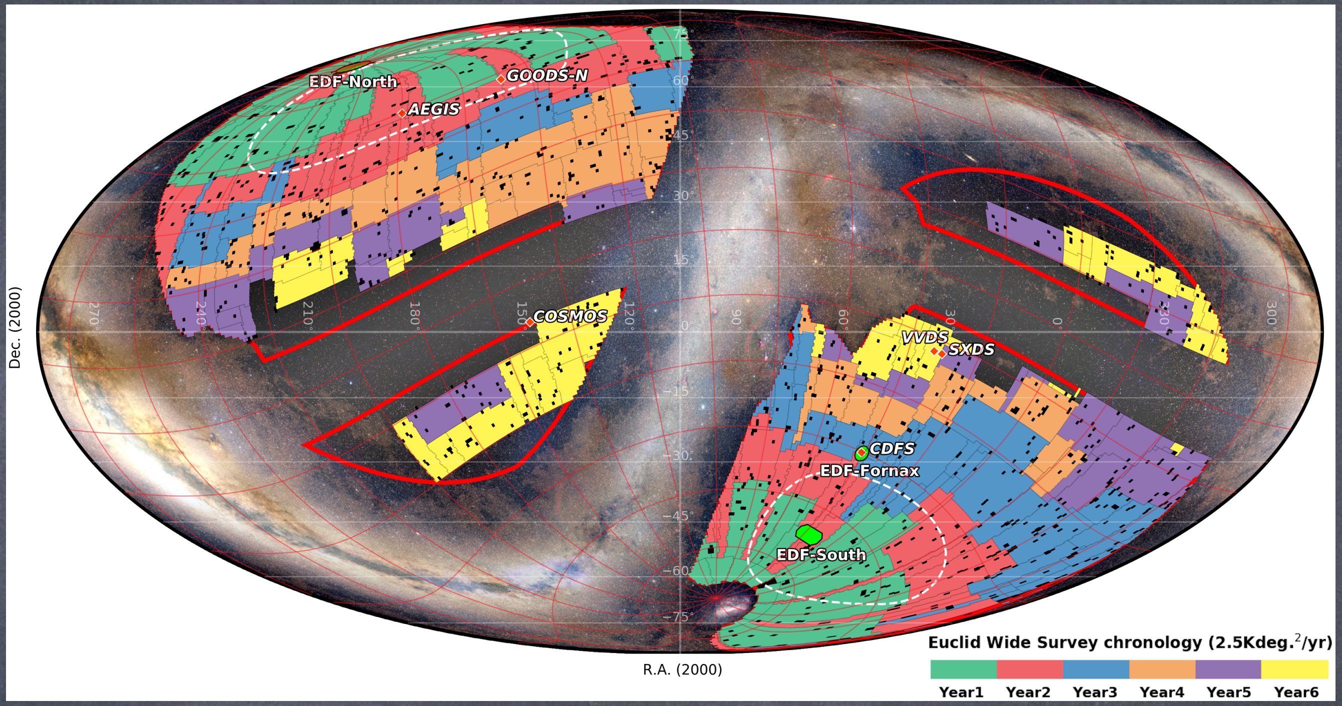
WP 4
raw data level (radio, pixel) objects, components

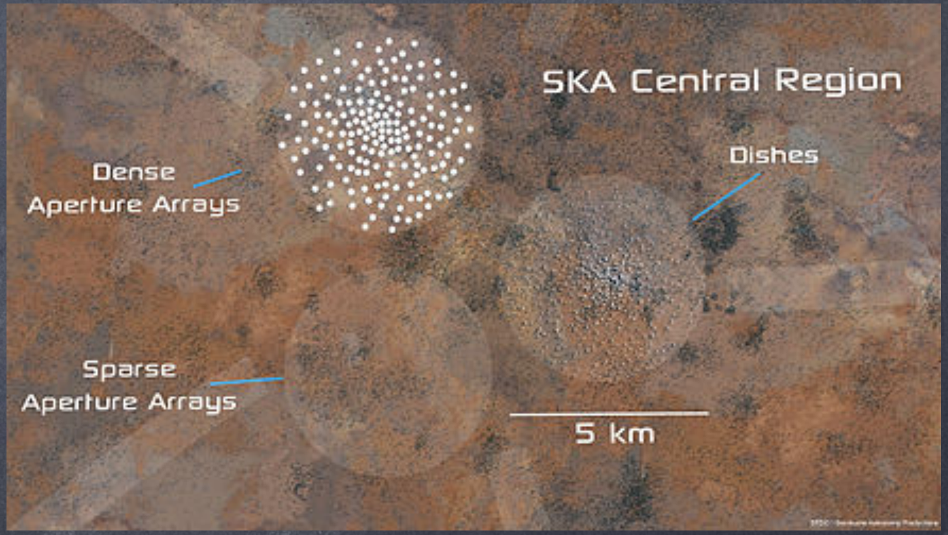
1 TD (2y)
OA Catania

Plenty of HUGE data and problems. Examples: Euclid, SKA



R. Scaramella et al.: The *Euclid* Wide Survey





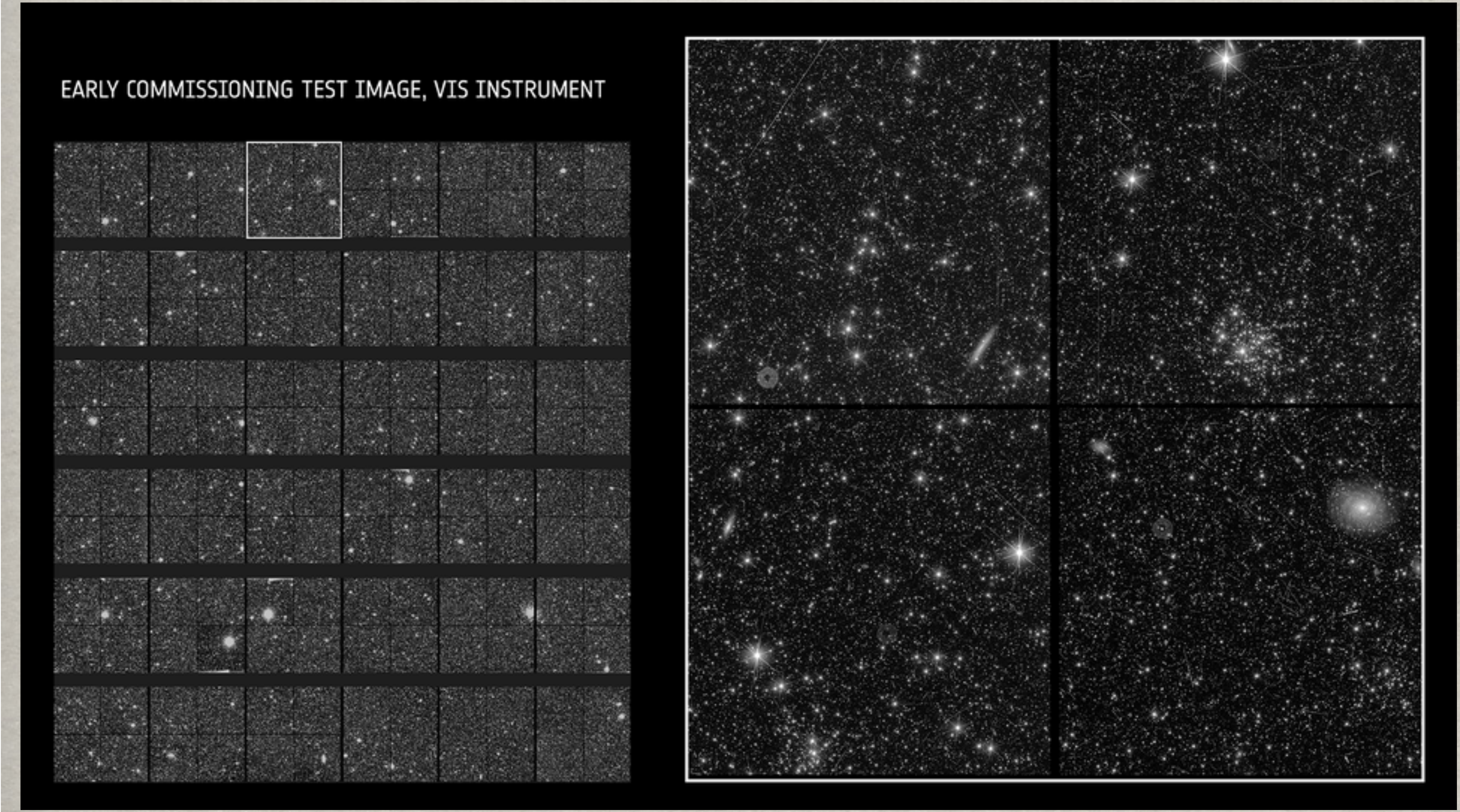
Goals:

- find if some of actual methods/problems can benefit from QC (select some toy models; examine & discard; test most promising with emulators)
- think/investigate NEW ways of approaching old problems

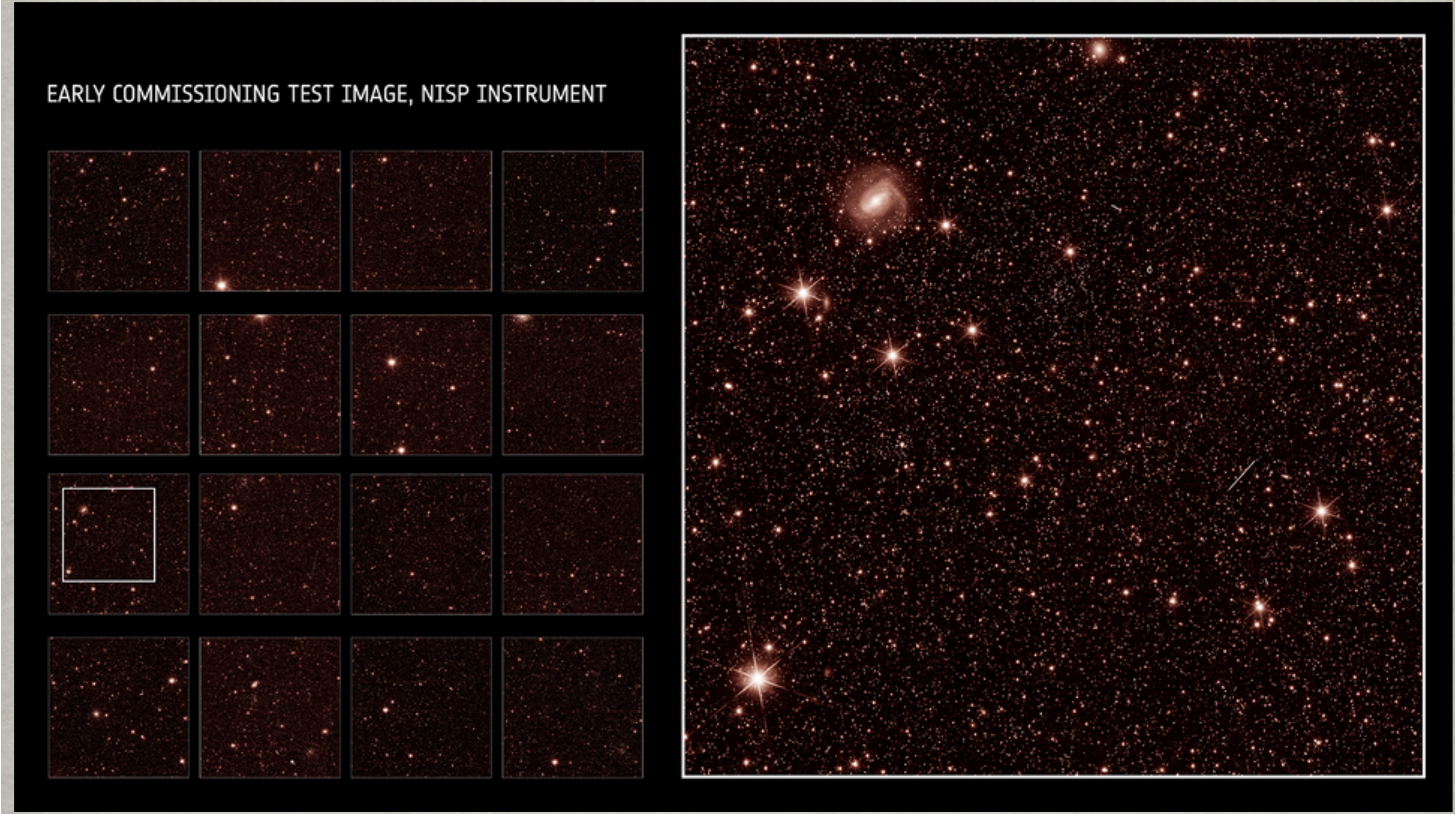
esa

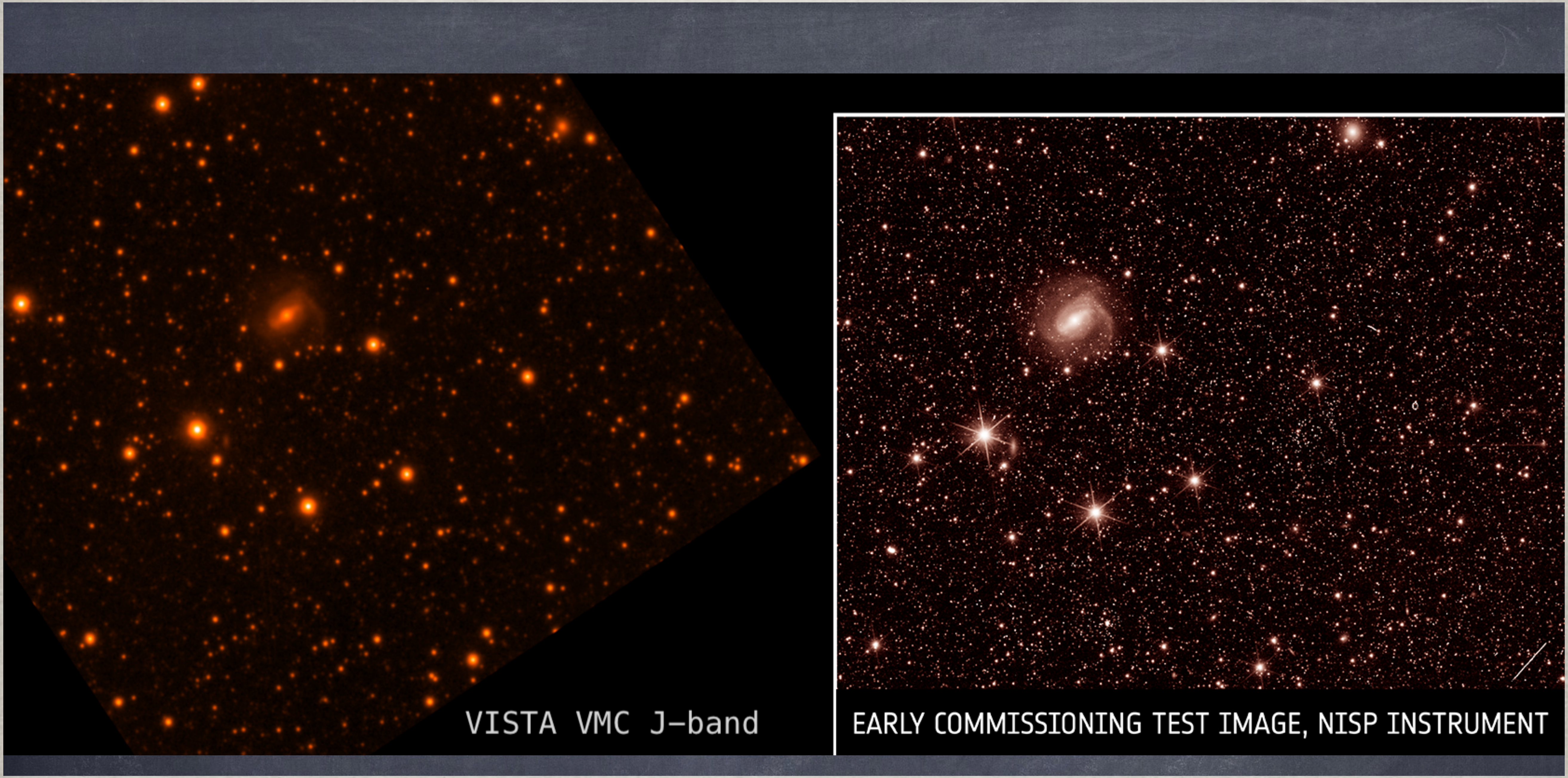
Euclid Mission (Dark Energy, Dark Matter and billions of galaxies: satellite launched July 1st 2023

Cost ∼1.5 G€, ∼150 Science Institutes, ∼1500 scientists



Euclid Mission: wide survey started in 2024, end 2030





~ 1/3 of the sky at resolution 0.1”/pix

~ 6E6 large images from two instruments

Several billions objects to study

Food for thought

Probability

Superposition

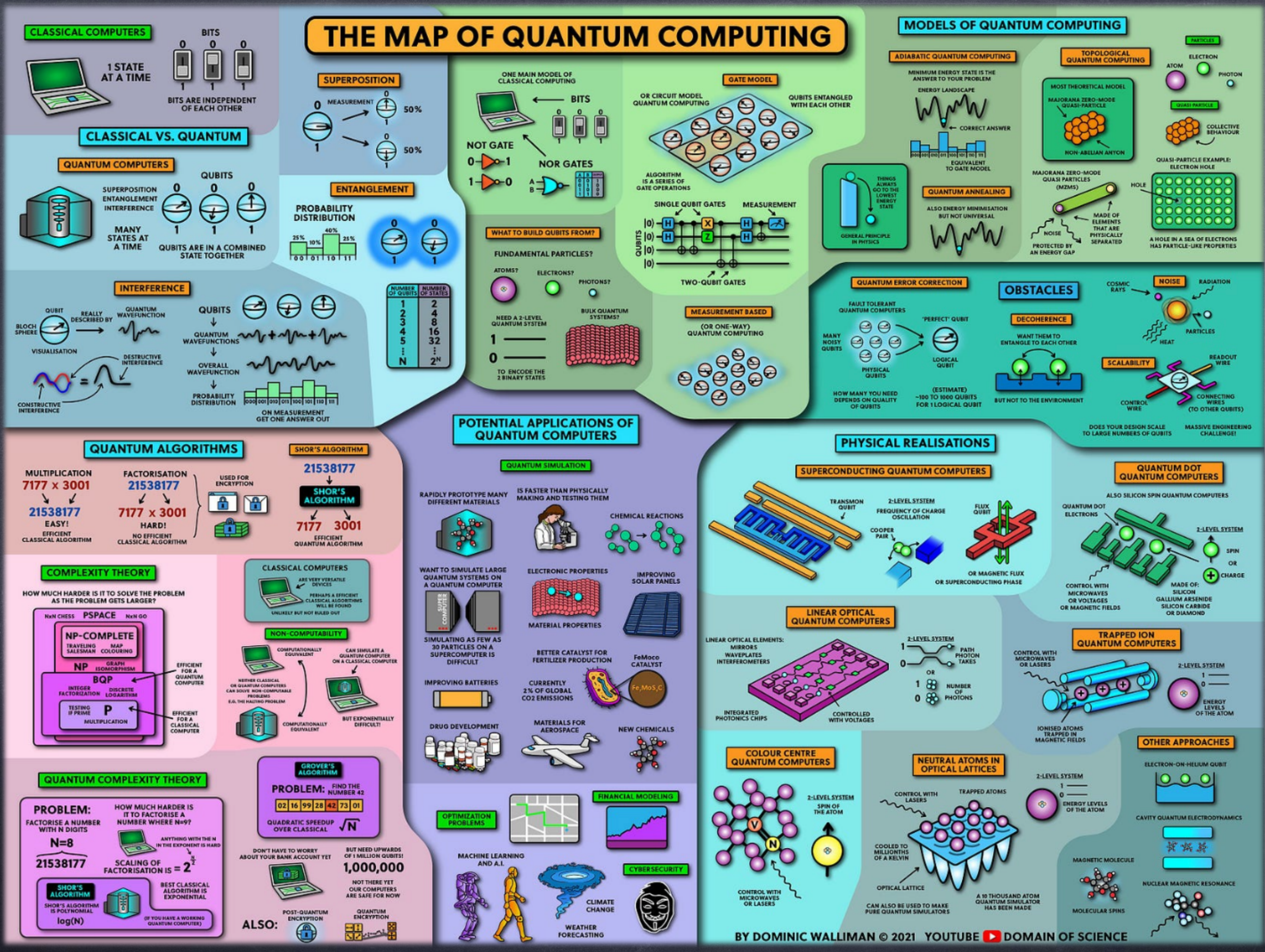
Quantum entanglement

Bell inequalities

Einstein-[Podolski]-Rosen

Non locality

Hybrid algorithms



THE MAP OF QUANTUM COMPUTING

CLASSICAL VS. QUANTUM

CLASSICAL COMPUTERS

1 STATE AT A TIME

BITS

0 0 0

1 1 1

BITS ARE INDEPENDENT OF EACH OTHER

QUANTUM COMPUTERS

SUPERPOSITION
ENTANGLEMENT
INTERFERENCE

QUBITS

0 0 0

1 1 1

MANY STATES AT A TIME

QUBITS ARE IN A COMBINED STATE TOGETHER

SUPERPOSITION

0

1

MEASUREMENT

50%

50%

ENTANGLEMENT

PROBABILITY DISTRIBUTION

25% 10% 40% 25%

00 01 10 11

NUMBER OF QUBITS	NUMBER OF STATES
1	2
2	4
3	8
4	16
5	32
⋮	⋮
N	2^N

INTERFERENCE

QUBIT

BLOCH SPHERE

VISUALISATION

REALLY DESCRIBED BY

QUANTUM WAVEFUNCTION

DESTRUCTIVE INTERFERENCE

CONSTRUCTIVE INTERFERENCE

QUBITS
↓
QUANTUM WAVEFUNCTIONS
↓
OVERALL WAVEFUNCTION
↓
PROBABILITY DISTRIBUTION

000 001 010 011 100 101 110 111

ON MEASUREMENT GET ONE ANSWER OUT

GATE MODEL

ONE MAIN MODEL OF CLASSICAL COMPUTING

BITS

NOT GATE

0 → 1

1 → 0

NOR GATES

A B

OR CIRCUIT MODEL QUANTUM COMPUTING

QUBITS ENTANGLED WITH EACH OTHER

ALGORITHM IS A SERIES OF GATE OPERATIONS

SINGLE QUBIT GATES

MEASUREMENT

QUBITS

|0⟩ |0⟩ |0⟩ |0⟩

H H X Z H H

TWO-QUBIT GATES

WHAT TO BUILD QUBITS FROM?

FUNDAMENTAL PARTICLES?

ATOMS?

ELECTRONS?

PHOTONS?

BULK QUANTUM SYSTEMS?

NEED A 2-LEVEL QUANTUM SYSTEM

1

0

TO ENCODE THE 2 BINARY STATES

MEASUREMENT BASED

(OR ONE-WAY) QUANTUM COMPUTING

MODELS OF QUANTUM COMPUTING

ADIABATIC QUANTUM COMPUTING

MINIMUM ENERGY STATE IS THE ANSWER TO YOUR PROBLEM

ENERGY LANDSCAPE

CORRECT ANSWER

000 001 010 011 100 101 110 111

EQUIVALENT TO GATE MODEL

THINGS ALWAYS GO TO THE LOWEST ENERGY STATE

GENERAL PRINCIPLE IN PHYSICS

QUANTUM ANNEALING

ALSO ENERGY MINIMISATION BUT NOT UNIVERSAL

TOPOLOGICAL QUANTUM COMPUTING

MOST THEORETICAL MODEL

MAJORANA ZERO-MODE QUASI-PARTICLE

NON-ABELIAN ANYON

MAJORANA ZERO-MODE QUASI PARTICLES (MZMS)

MADE OF ELEMENTS THAT ARE PHYSICALLY SEPARATED

NOISE

PROTECTED BY AN ENERGY GAP

PARTICLES

ATOM

ELECTRON

PHOTON

QUASI-PARTICLE

COLLECTIVE BEHAVIOUR

QUASI-PARTICLE EXAMPLE: ELECTRON HOLE

HOLE

A HOLE IN A SEA OF ELECTRONS HAS PARTICLE-LIKE PROPERTIES

OBSTACLES

QUANTUM ERROR CORRECTION

FAULT TOLERANT QUANTUM COMPUTERS

MANY NOISY QUBITS

PHYSICAL QUBITS

'PERFECT' QUBIT

LOGICAL QUBIT

HOW MANY YOU NEED DEPENDS ON QUALITY OF QUBITS

(ESTIMATE) ~100 TO 1000 QUBITS FOR 1 LOGICAL QUBIT

DECOHERENCE

WANT THEM TO ENTANGLE TO EACH OTHER

BUT NOT TO THE ENVIRONMENT

NOISE

COSMIC RAYS

RADIATION

PARTICLES

HEAT

SCALABILITY

READOUT WIRE

CONTROL WIRE

CONNECTING WIRES (TO OTHER QUBITS)

DOES YOUR DESIGN SCALE TO LARGE NUMBERS OF QUBITS

MASSIVE ENGINEERING CHALLENGE!

QUANTUM ALGORITHMS

MULTIPLICATION

7177 x 3001

21538177

EASY!

EFFICIENT CLASSICAL ALGORITHM

FACTORISATION

21538177

7177 x 3001

HARD!

NO EFFICIENT CLASSICAL ALGORITHM

USED FOR ENCRYPTION

SHOR'S ALGORITHM

21538177

SHOR'S ALGORITHM

7177 3001

EFFICIENT QUANTUM ALGORITHM

COMPLEXITY THEORY

HOW MUCH HARDER IS IT TO SOLVE THE PROBLEM AS THE PROBLEM GETS LARGER?

PSPACE

NxN CHESS

NxN GO

NP-COMPLETE

TRAVELING SALESMAN

MAP COLOURING

NP

GRAPH ISOMORPHISM

BQP

INTEGER FACTORIZATION

DISCRETE LOGARITHM

P

TESTING IF PRIME

MULTIPLICATION

EFFICIENT FOR A QUANTUM COMPUTER

EFFICIENT FOR A CLASSICAL COMPUTER

CLASSICAL COMPUTERS

ARE VERY VERSATILE DEVICES

PERHAPS A EFFICIENT CLASSICAL ALGORITHMS WILL BE FOUND

UNLIKELY BUT NOT RULED OUT

NON-COMPUTABILITY

COMPUTATIONALLY EQUIVALENT

CAN SIMULATE A QUANTUM COMPUTER ON A CLASSICAL COMPUTER

NEITHER CLASSICAL OR QUANTUM COMPUTERS CAN SOLVE NON-COMPUTABLE PROBLEMS E.G. THE HALTING PROBLEM

COMPUTATIONALLY EQUIVALENT

BUT EXPONENTIALLY DIFFICULT!

QUANTUM COMPLEXITY THEORY

PROBLEM:

FACTORISE A NUMBER WITH N DIGITS

$$\underbrace{21538177}_{}\quad N=8$$

HOW MUCH HARDER IS IT TO FACTORISE A NUMBER WHERE N=9?

ANYTHING WITH THE N IN THE EXPONENT IS HARD

SCALING OF FACTORISATION IS $= 2^{\frac{N}{2}}$

BEST CLASSICAL ALGORITHM IS EXPONENTIAL

SHOR'S ALGORITHM

SHOR'S ALGORITHM IS POLYNOMIAL

log(N)

(IF YOU HAVE A WORKING QUANTUM COMPUTER)

GROVER'S ALGORITHM

PROBLEM: FIND THE NUMBER 42

02	16	99	28	42	73	01

QUADRATIC SPEEDUP OVER CLASSICAL $\sqrt{N}$

DON'T HAVE TO WORRY ABOUT YOUR BANK ACCOUNT YET

BUT NEED UPWARDS OF 1 MILLION QUBITS!

1,000,000

NOT THERE YET OUR COMPUTERS ARE SAFE FOR NOW

ALSO:

POST-QUANTUM ENCRYPTION

QUANTUM ENCRYPTION

POTENTIAL APPLICATIONS OF QUANTUM COMPUTERS

QUANTUM SIMULATION

RAPIDLY PROTOTYPE MANY DIFFERENT MATERIALS

IS FASTER THAN PHYSICALLY MAKING AND TESTING THEM

CHEMICAL REACTIONS

WANT TO SIMULATE LARGE QUANTUM SYSTEMS ON A QUANTUM COMPUTER

SUPER COMPUTER

SIMULATING AS FEW AS 30 PARTICLES ON A SUPERCOMPUTER IS DIFFICULT

ELECTRONIC PROPERTIES

MATERIAL PROPERTIES

IMPROVING SOLAR PANELS

BETTER CATALYST FOR FERTILIZER PRODUCTION

CURRENTLY 2% OF GLOBAL CO2 EMISSIONS

FeMoco CATALYST

Fe_7MoS_9C

IMPROVING BATTERIES

DRUG DEVELOPMENT

MATERIALS FOR AEROSPACE

NEW CHEMICALS

OPTIMIZATION PROBLEMS

FINANCIAL MODELING

MACHINE LEARNING AND A.I.

CLIMATE CHANGE

WEATHER FORECASTING

CYBERSECURITY

PHYSICAL REALISATIONS

SUPERCONDUCTING QUANTUM COMPUTERS

TRANSMON QUBIT

2-LEVEL SYSTEM

FREQUENCY OF CHARGE OSCILLATION

COOPER PAIR

FLUX QUBIT

OR MAGNETIC FLUX

OR SUPERCONDUCTING PHASE

QUANTUM DOT QUANTUM COMPUTERS

ALSO SILICON SPIN QUANTUM COMPUTERS

QUANTUM DOT ELECTRONS

2-LEVEL SYSTEM

SPIN

OR

CHARGE

CONTROL WITH MICROWAVES OR VOLTAGES OR MAGNETIC FIELDS

MADE OF: SILICON GALLIUM ARSENIDE SILICON CARBIDE OR DIAMOND

LINEAR OPTICAL QUANTUM COMPUTERS

LINEAR OPTICAL ELEMENTS:
MIRRORS
WAVEPLATES
INTERFEROMETERS

INTEGRATED PHOTONICS CHIPS

CONTROLLED WITH VOLTAGES

2-LEVEL SYSTEM

1

0

PATH PHOTON TAKES

OR

1

0

NUMBER OF PHOTONS

TRAPPED ION QUANTUM COMPUTERS

CONTROL WITH MICROWAVES OR LASERS

IONISED ATOMS TRAPPED IN MAGNETIC FIELDS

2-LEVEL SYSTEM

1

0

ENERGY LEVELS OF THE ATOM

COLOUR CENTRE QUANTUM COMPUTERS

V

N

2-LEVEL SYSTEM

SPIN OF THE ATOM

CONTROL WITH MICROWAVES OR LASERS

NEUTRAL ATOMS IN OPTICAL LATTICES

CONTROL WITH LASERS

TRAPPED ATOMS

COOLED TO MILLIONTHS OF A KELVIN

OPTICAL LATTICE

CAN ALSO BE USED TO MAKE PURE QUANTUM SIMULATORS

A 10 THOUSAND ATOM QUANTUM SIMULATOR HAS BEEN MADE

2-LEVEL SYSTEM

1

0

ENERGY LEVELS OF THE ATOM

OTHER APPROACHES

ELECTRON-ON-HELIUM QUBIT

CAVITY QUANTUM ELECTRODYNAMICS

MAGNETIC MOLECULE

MOLECULAR SPINS

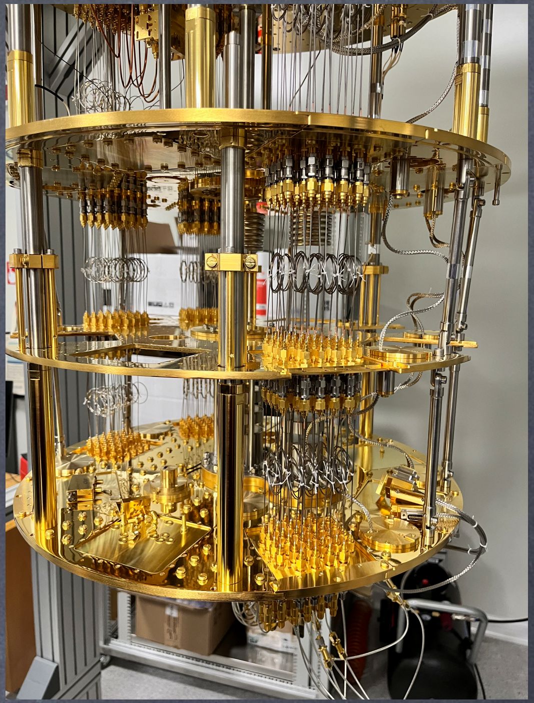
NUCLEAR MAGNETIC RESONANCE

BY DOMINIC WALLIMAN © 2021 YOUTUBE DOMAIN OF SCIENCE

Quantum computing is..

NOT a general purpose super duper computer

Undergoing **FAST** hardware evolution (but bottlenecks, errors)



In principle allows a **QUANTUM LEAP** in selected problems (optimisation, factorisation etc etc)

For the time being is **FUN!**

Cosmological numerical simulations (Schroedinger -Poisson & Vlasov-Poisson equation) with Quantum Computers

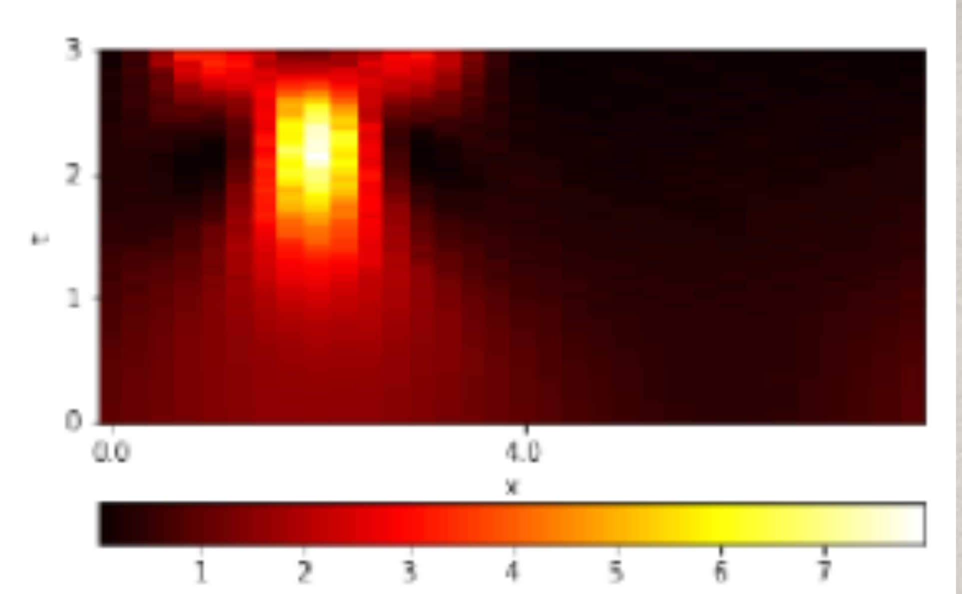
WP1

Schroedinger-Poisson:

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi,$$

$$\rho = |\psi|^2$$

$$\nabla^2 V = 4\pi G(\rho - \overline{\rho}),$$



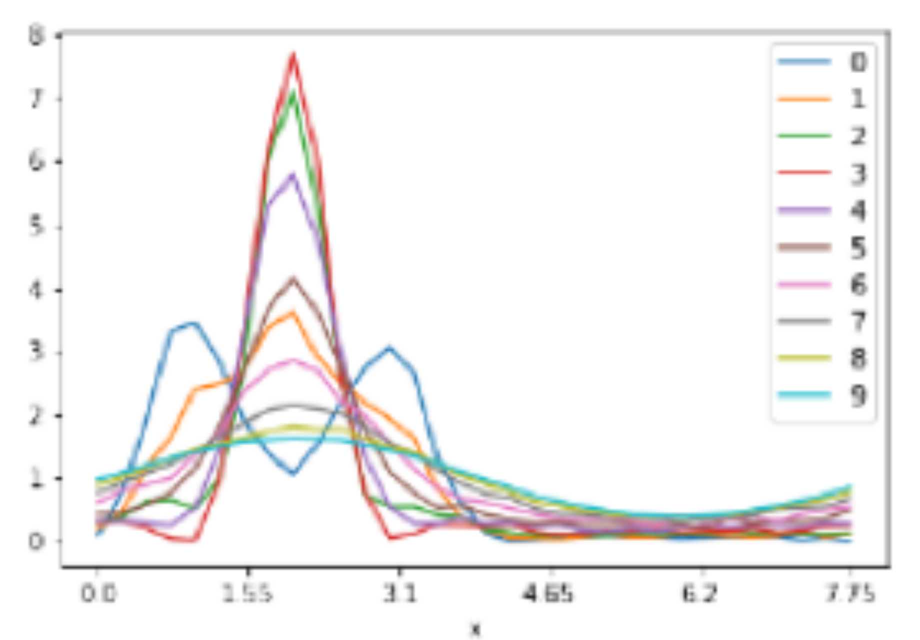


Figure 6.9: Exact potential simulation with a total number of ansatz parameters $M = 60$. $N_t = 2 \cdot 10^4$, $r_c = 10^{-7}$, No regularization.

Nonlocal quantum pressure:

$$\mathrm{p_Q} = -\left(\frac{\hbar}{2m}\right)^2 \rho\nabla\otimes\nabla\ln\rho\,.$$

Becomes Euler-Poisson when m tends to infinity

- One dimensional
- Following an idea by Mocz & Szasz, 2021, ApJ, 910, 29
- **Variational algorithm completely rewritten**

Luca Cappelli won the PhD position at Trieste University
IBM Zurich collaborates with the PhD project

Research lines for WP1

WP1

Quantum Technicality

- Study scaling properties of the QC algorithm
- Reduce circuit depth of the variational algorithm
- Implement the algorithm on a real quantum device
- Study the feasibility of 3D simulations
- Study the quantum advantage when **m** is large

Physics

- Application: fuzzy dark matter
- Comparison of Schroedinger-Poisson with Vlasov-Poisson when the field mass **m** varies
- Study the possibility to use SP as a proxy for VP, **m** acting *as the softening* in a N-body simulation
- Study if a similar variational algorithm can be applied to hydrodynamics

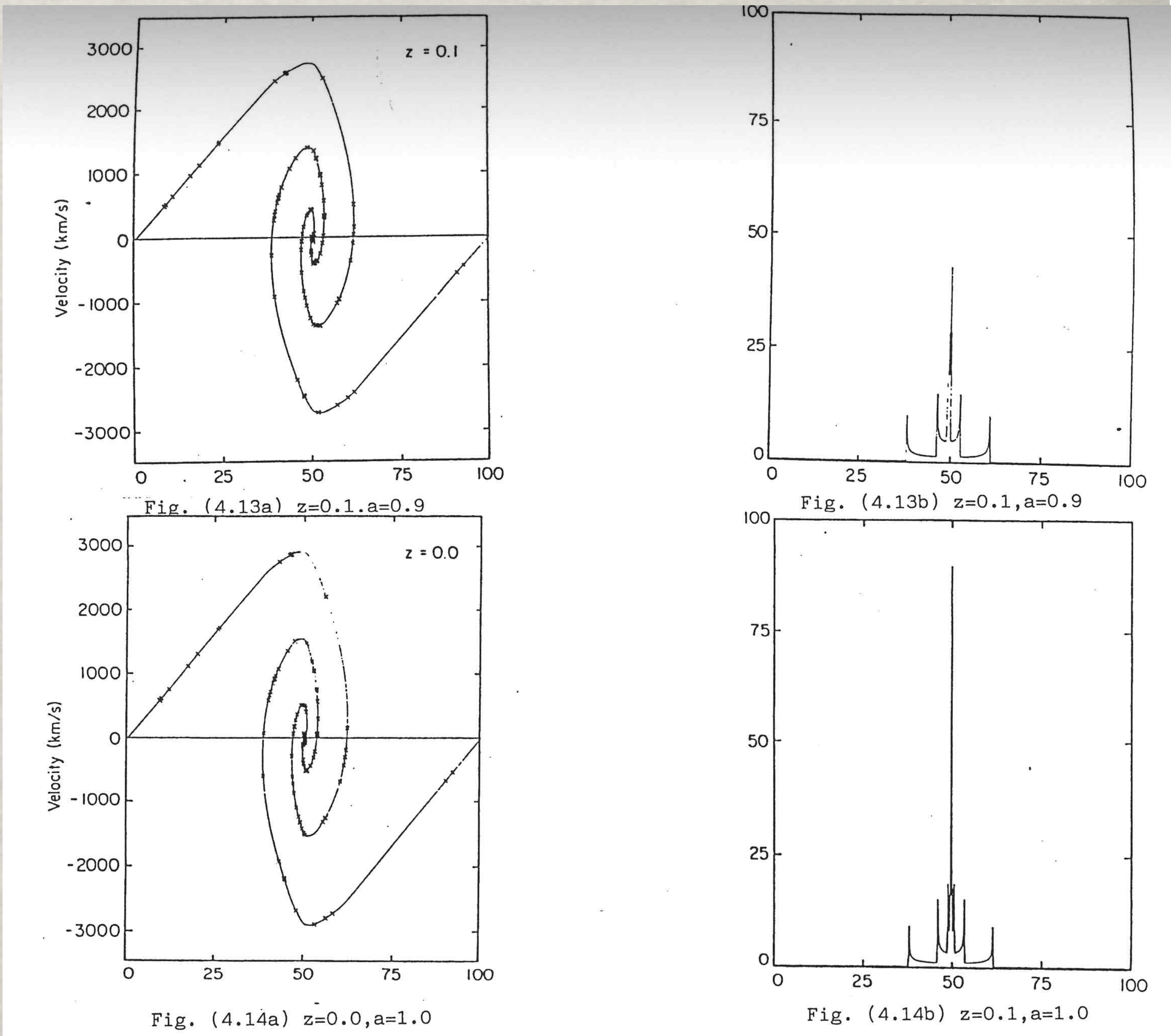


Fig. (4.13a) z=0.1.a=0.9

Fig. (4.13b) z=0.1,a=0.9

Fig. (4.14a) z=0.0,a=1.0

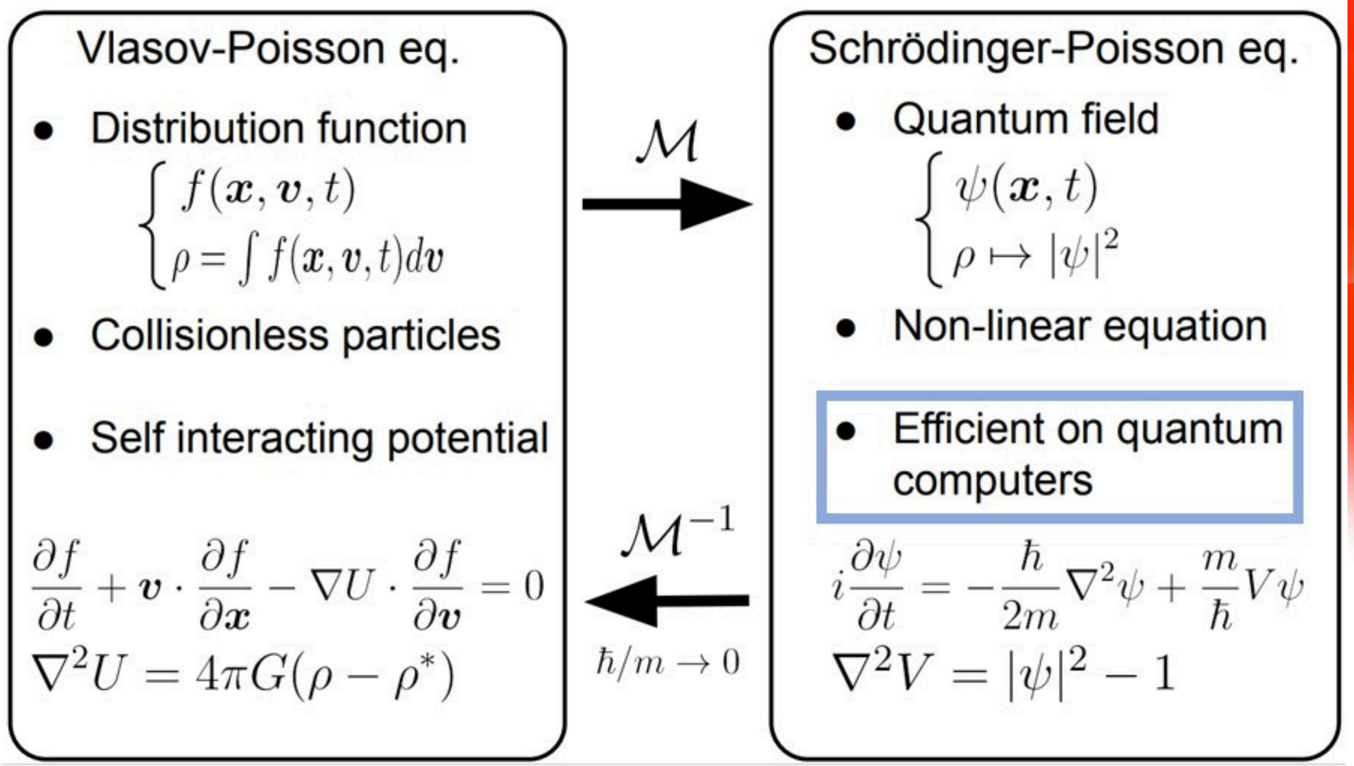
Fig. (4.14b) z=0.1,a=1.0

One-dimensional VP simulation. Left panel: phase space, v *vs* x. Right panel: density *vs* x

WP1

Schroedinger vs Vlasov - Poisson

- Collisionless dark matter
- Vlasov - Poisson equation
- hard to solve numerically
- N - body simulations
- Schroedinger equation
- goes to VP for m to infinity



Vlasov-Poisson eq.

- Distribution function

$$\begin{cases} f(\boldsymbol{x},\boldsymbol{v},t) \\ \rho = \int f(\boldsymbol{x},\boldsymbol{v},t)d\boldsymbol{v} \end{cases}$$

- Collisionless particles
- Self interacting potential

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\frac{\partial f}{\partial \boldsymbol{x}} - \nabla U \cdot \frac{\partial f}{\partial \boldsymbol{v}} = 0$$

$$\nabla^2 U = 4\pi G(\rho - \rho^*)$$

$$\xrightarrow{\mathcal{M}}$$

$$\xleftarrow[\hbar/m \to 0]{\mathcal{M}^{-1}}$$

Schrödinger-Poisson eq.

- Quantum field

$$\begin{cases} \psi(\boldsymbol{x},t) \\ \rho \mapsto |\psi|^2 \end{cases}$$

- Non-linear equation
- Efficient on quantum computers

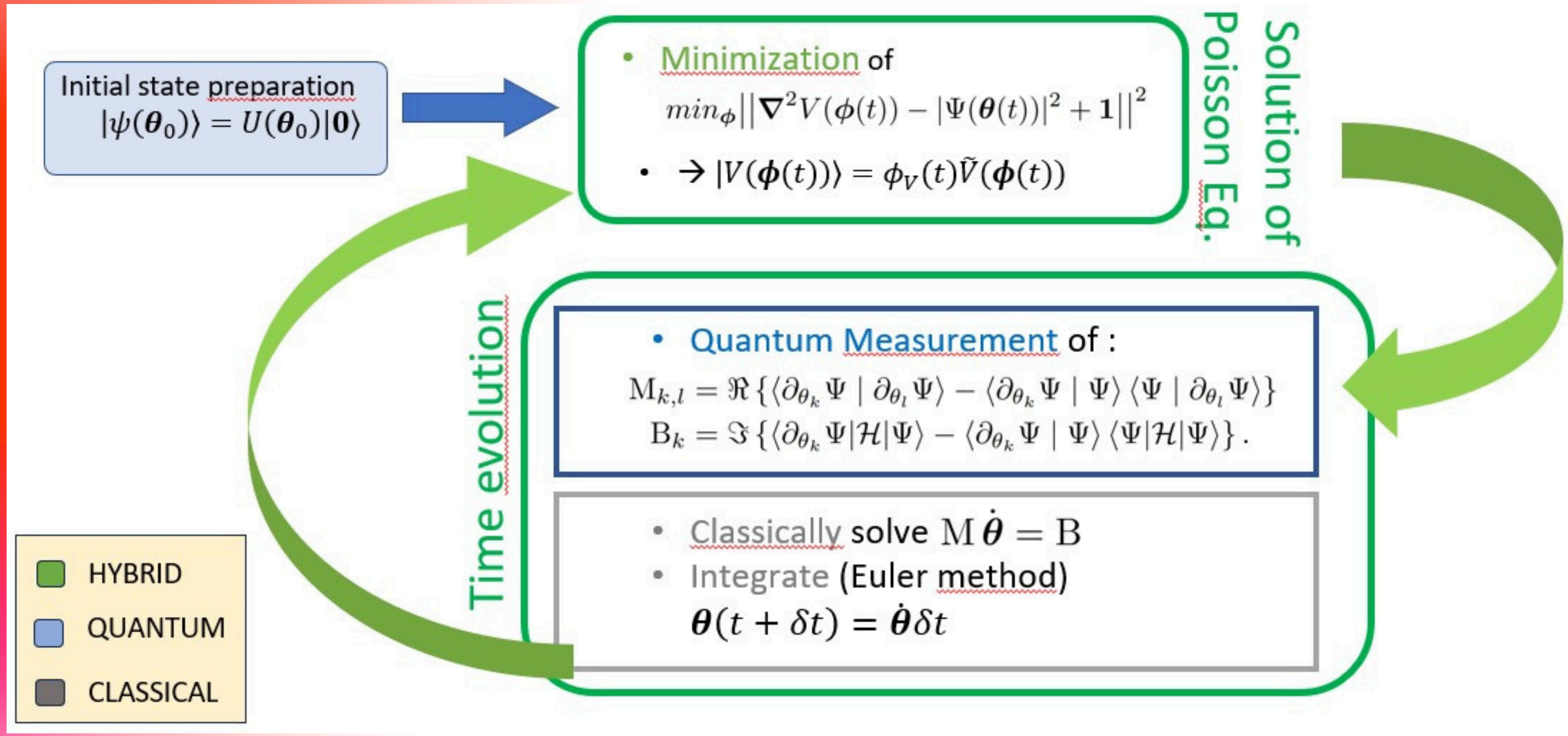
$$i\frac{\partial \psi}{\partial t} = -\frac{\hbar}{2m}\nabla^2\psi + \frac{m}{\hbar}V\psi$$

$$\nabla^2 V = |\psi|^2 - 1$$

VARIATIONAL ALGORITHM FOR SOLVING SCHROEDINGER EQUATION

CAPPELLI ET AL., 2024, PHYSICAL REVIEW RESEARCH, 6, 013282

Hybrid - Quantum Variational Algorithm



Initial state preparation
$|\psi(\boldsymbol{\theta}_0)\rangle = U(\boldsymbol{\theta}_0)|\boldsymbol{0}\rangle$

- Minimization of

$$min_{\boldsymbol{\phi}}||\boldsymbol{\nabla}^2 V(\boldsymbol{\phi}(t)) - |\Psi(\boldsymbol{\theta}(t))|^2 + \boldsymbol{1}||^2$$

- → $|V(\boldsymbol{\phi}(t))\rangle = \phi_V(t)\tilde{V}(\boldsymbol{\phi}(t))$

Solution of Poisson Eq.

Time evolution

- Quantum Measurement of :

$$\mathrm{M}_{k,l} = \Re\left\{\langle\partial_{\theta_k}\Psi \mid \partial_{\theta_l}\Psi\rangle - \langle\partial_{\theta_k}\Psi \mid \Psi\rangle\langle\Psi \mid \partial_{\theta_l}\Psi\rangle\right\}$$

$$\mathrm{B}_k = \Im\left\{\langle\partial_{\theta_k}\Psi|\mathcal{H}|\Psi\rangle - \langle\partial_{\theta_k}\Psi \mid \Psi\rangle\langle\Psi|\mathcal{H}|\Psi\rangle\right\}.$$

- Classically solve $\mathrm{M}\,\dot{\boldsymbol{\theta}} = \mathrm{B}$
- Integrate (Euler method)
  $\boldsymbol{\theta}(t+\delta t) = \dot{\boldsymbol{\theta}}\delta t$

🟩 HYBRID
🟦 QUANTUM
⬛ CLASSICAL

OPTIMISATION PROBLEMS

WP2

Combinatorial Optimisation Problems

s input models from a set S and m conditions defining a cost function to be minimised or maximised

examples:

— maximise a cosmological likelihood

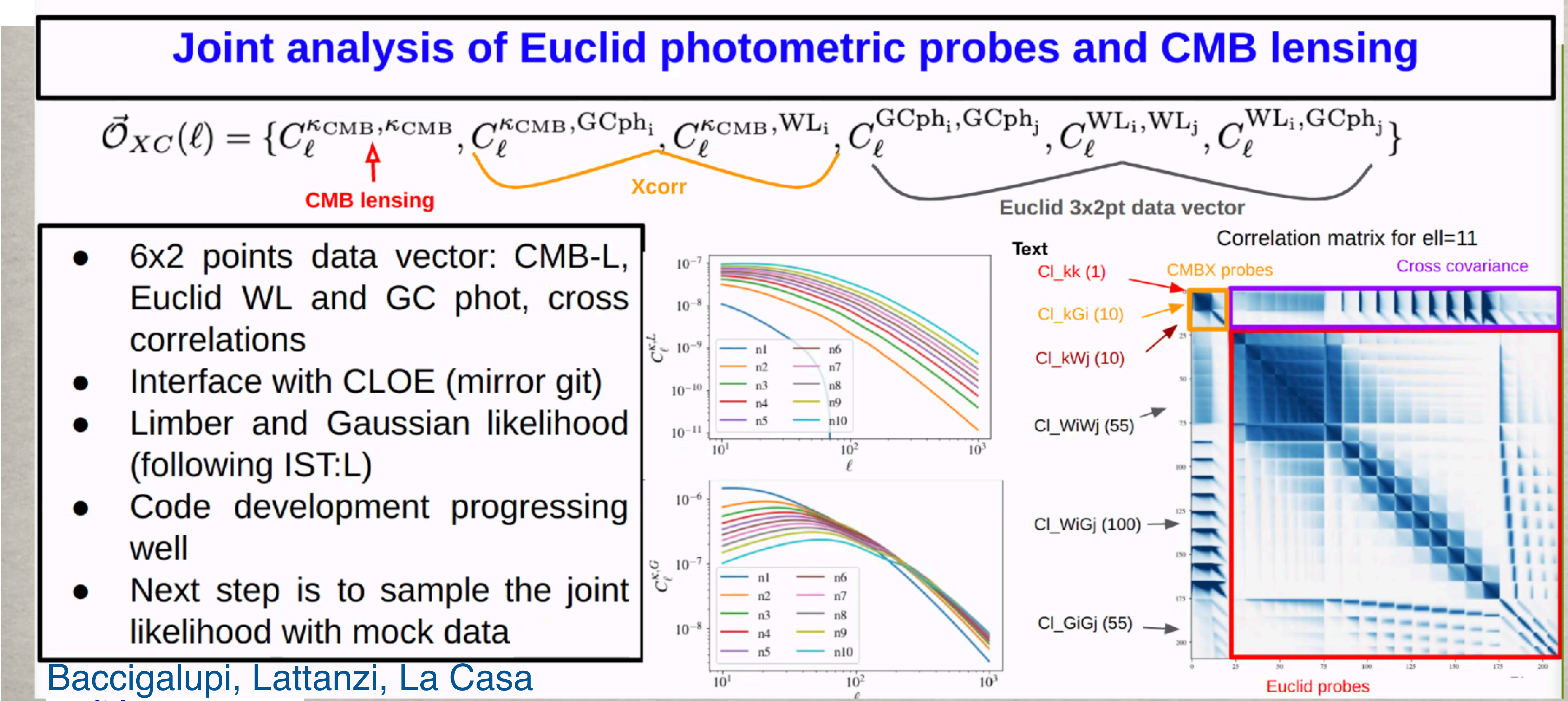
— minimise the chisq of a lens model

— choose the specifics maximizing FoM

Quantum Approximation Optimization Algorithm

Quantum Annealing

Quantum Evolutionary Algorithm



Joint analysis of Euclid photometric probes and CMB lensing

$$\vec{O}_{XC}(\ell) = \{\underset{\uparrow\ \text{CMB lensing}}{C_\ell^{\kappa_{\rm CMB},\kappa_{\rm CMB}}}, \underbrace{C_\ell^{\kappa_{\rm CMB},{\rm GCph_i}}, C_\ell^{\kappa_{\rm CMB},{\rm WL_i}}}_{\text{Xcorr}}, \underbrace{C_\ell^{\rm GCph_i,GCph_j}, C_\ell^{\rm WL_i,WL_j}, C_\ell^{\rm WL_i,GCph_j}}_{\text{Euclid 3x2pt data vector}}\}$$

- 6x2 points data vector: CMB-L, Euclid WL and GC phot, cross correlations
- Interface with CLOE (mirror git)
- Limber and Gaussian likelihood (following IST:L)
- Code development progressing well
- Next step is to sample the joint likelihood with mock data

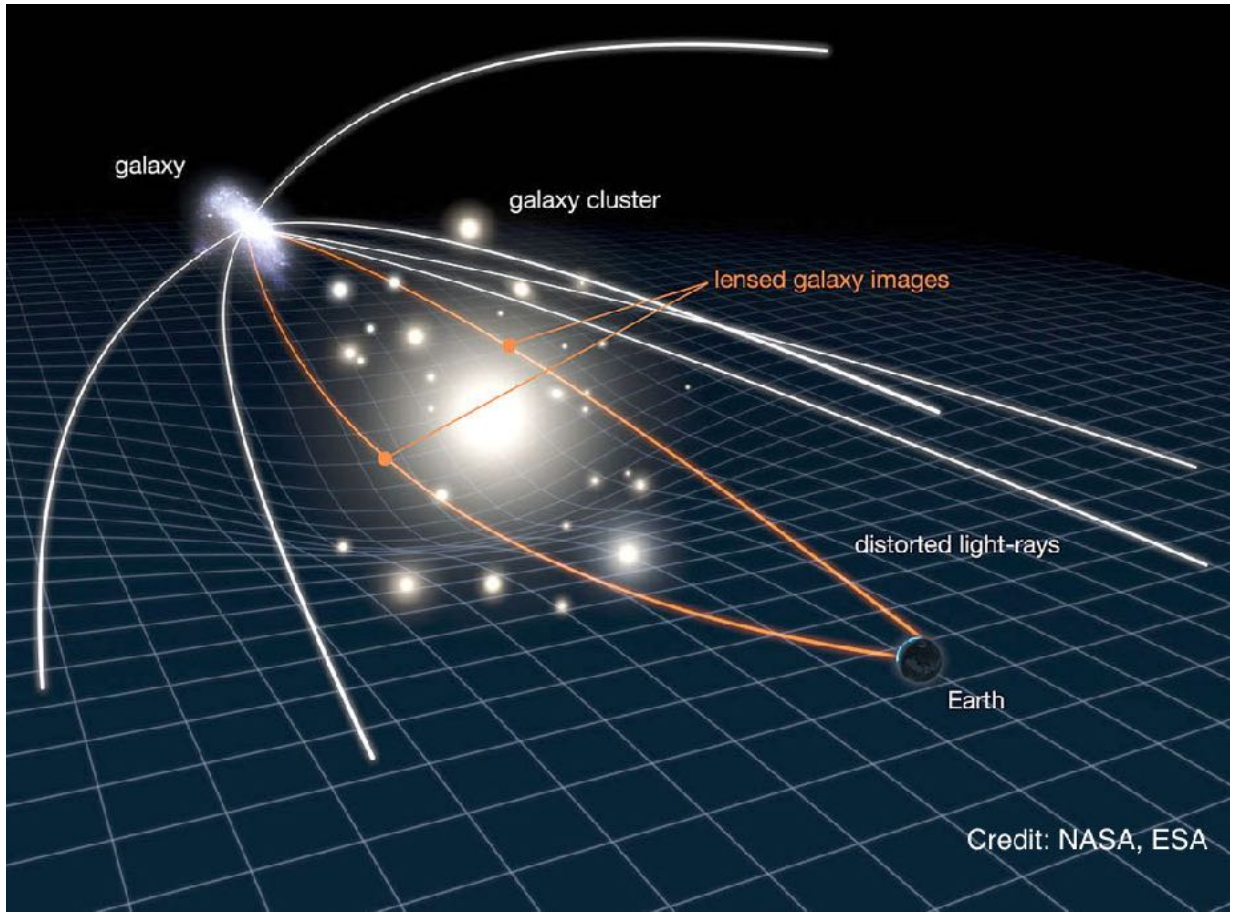
Correlation matrix for ell=11

Baccigalupi, Lattanzi, La Casa

Euclid CMBXC WP6

WP2

GRAVITATIONAL LENSING



Credit: NASA, ESA

Gravitational lensing: mass-energy curving space time.

Deflection angle

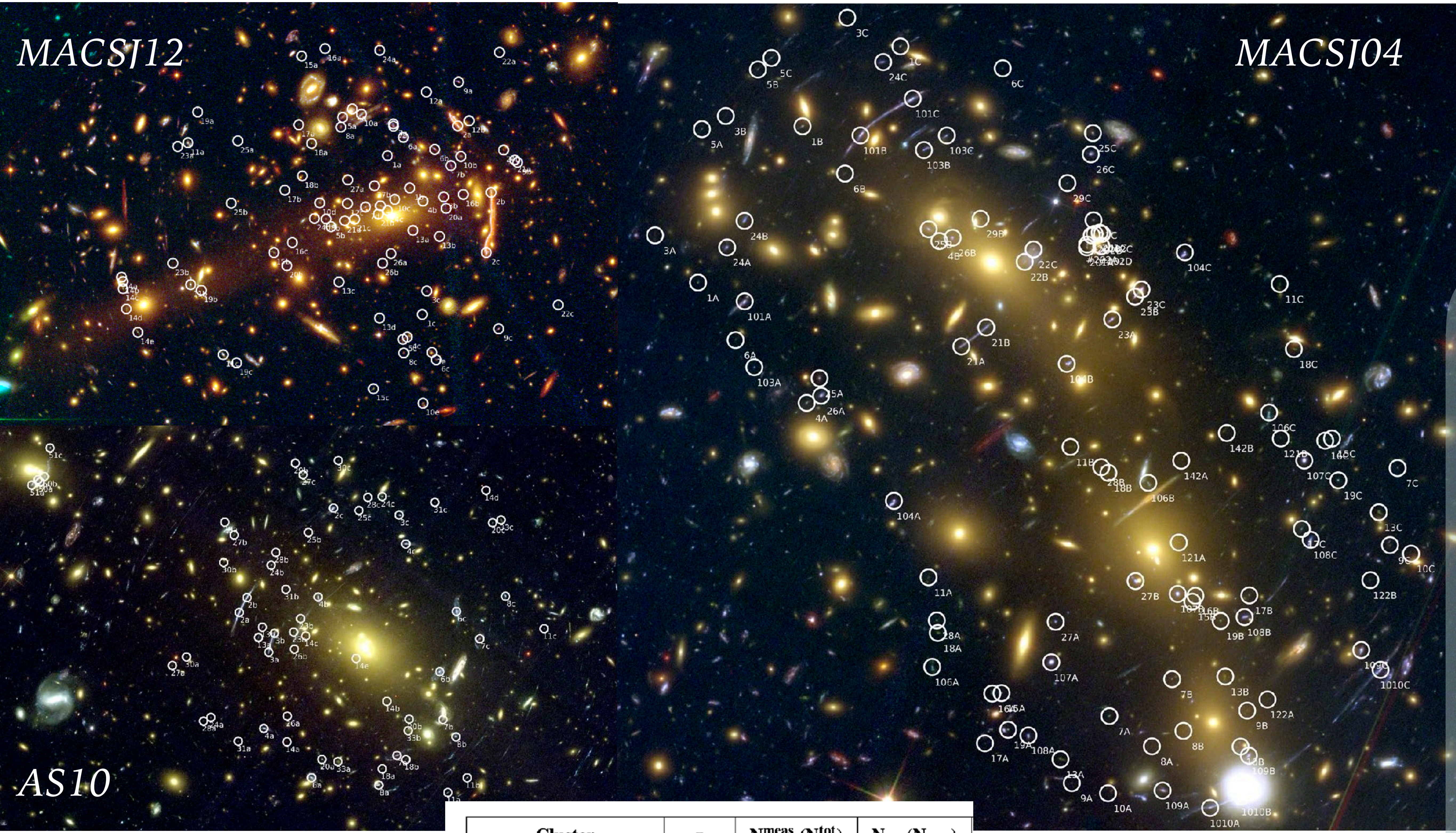
$$\vec{\alpha}(\vec{\theta}) \propto \nabla \int \Phi(\vec{\theta}, z)dz$$

Gravitational potential

Consequences:

- *Multiple images* (strong lensing — SL)
- *Distortions*: gravitational arcs (SL), induced ellipticities (WL)
- *Magnifications*

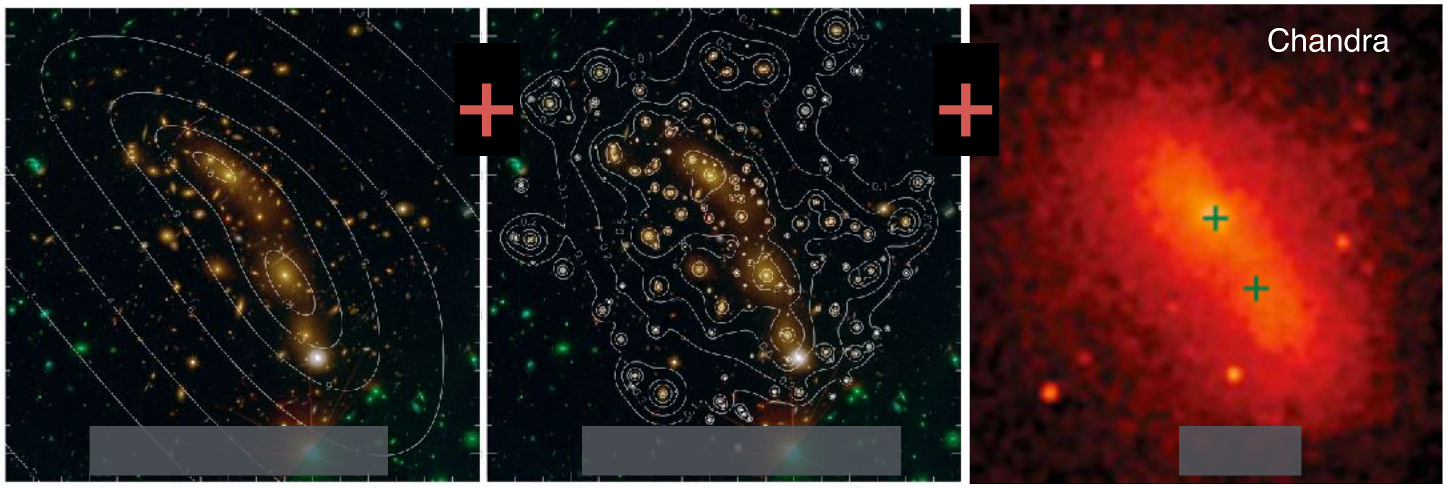
All these effects can be used to recover the mass distribution of the lens (dark matter, gas, stars)



Cluster	z	N_m^{meas} (N_m^{tot})	N_{im} (N_{fam})
MACS J1206.2−0847	0.439	58 (258)	82 (27)
MACS J0416.1−0403	0.396	49 (193)	102 (37)
Abell S1063	0.348	37 (222)	55 (20)

WP2

EXAMPLE: SL MODEL OPTIMISATION



Total gravitational potential is the sum of each component:

$$\phi_{tot}(\vec{\xi}) = \sum_{i=1}^{N_h} \phi_i^{halo}(\vec{\xi}_{halo}) + \sum_{k=1}^{N_{gal}} \phi_k^{gal}(\vec{\xi}_{gal}) + \phi_{shear}(\vec{\xi}_{shear}) + \phi_{gas}$$

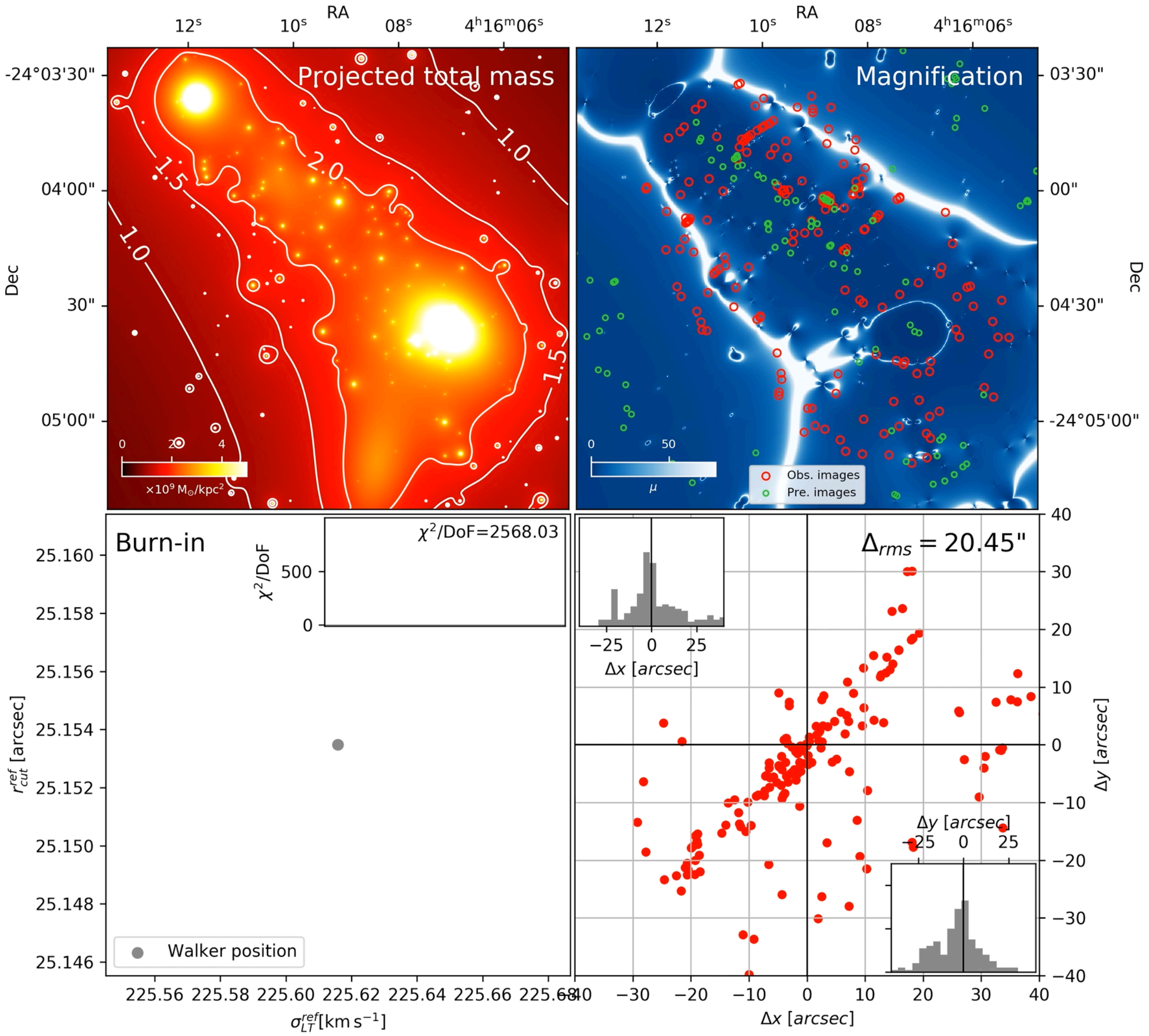
Each mass component is parametrised:

Pseudo (non-singular) Isothermal Ellipsoids:

$$\rho_{PIEMD}(r) = \frac{\sigma_0}{2\pi G(1 + r^2/r_{core}^2)}$$

Truncated-Isothermal Spheres:

$$\rho_{sub-halo}(r) = \frac{\rho_0}{(1 + r^2/r_{core}^2)(1 + r^2/r_{cut}^2)}$$

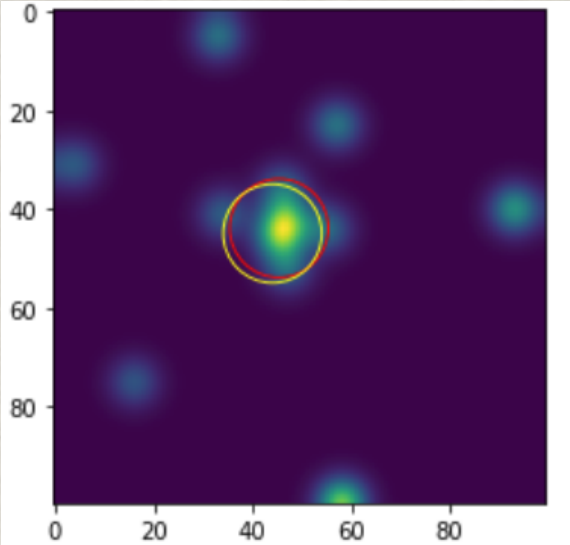


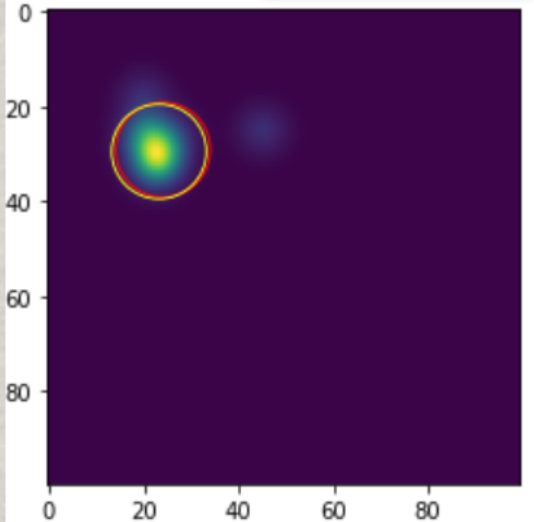
Model optimisation

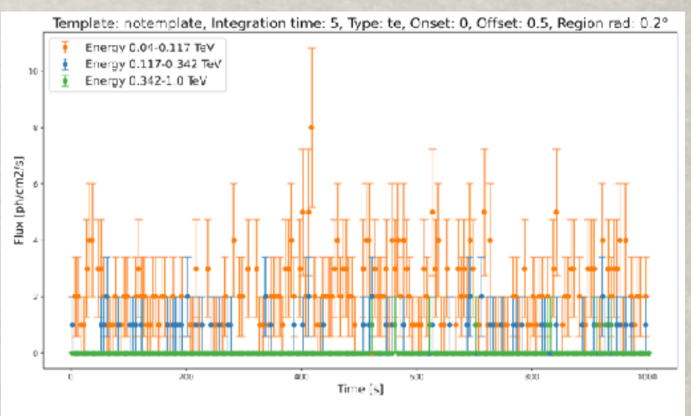
WP3

GRB detection localization in AGILE/GRID data

- We developed a new method for detecting and localizing GRB in the AGILE/GRID sky maps as a reaction to external science alerts.
- The science alerts can have error regions with different sizes depending on the instruments that detected the transient event. For this reason, we trained this method to detect GRBs in the AGILE sky maps located in a radius of 20 degrees from the map center; this radius is larger than 99.5 % of the error region present in the GRBWeb catalog.
- The method comprises two Deep Learning models implemented with two Convolutional Neural Networks. The first model detects if the sky map contains a GRB, and the second model localizes the GRB in the sky maps filtered from the first model.
- We trained and tested the models using simulated sky maps and GRBs. The detection model achieves an accuracy of 95.7 %, and the localization model has a mean error lower than 0.8 degrees.







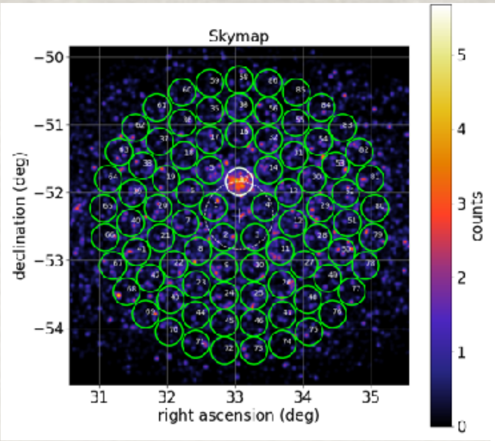
Anomaly detection for GRB search in light curves

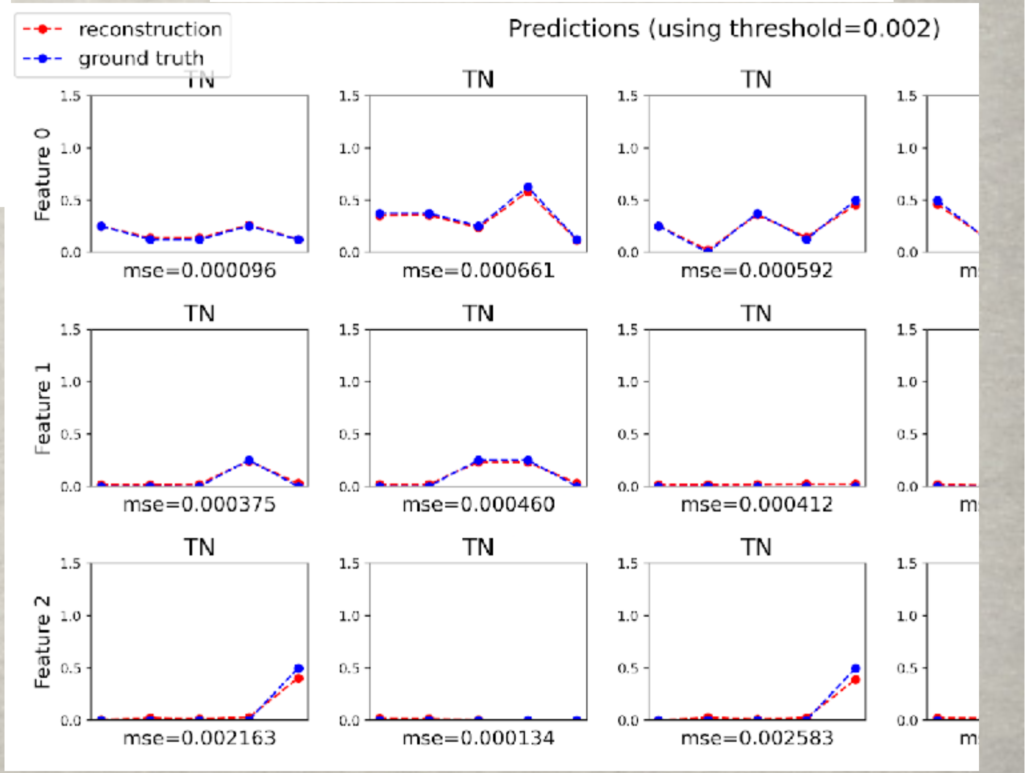
This method performs source detection with a statistical gaussian significance ≥ 5σ.

- No assumptions on the source position.
- No assumptions on the source γ-rays emission / background models.

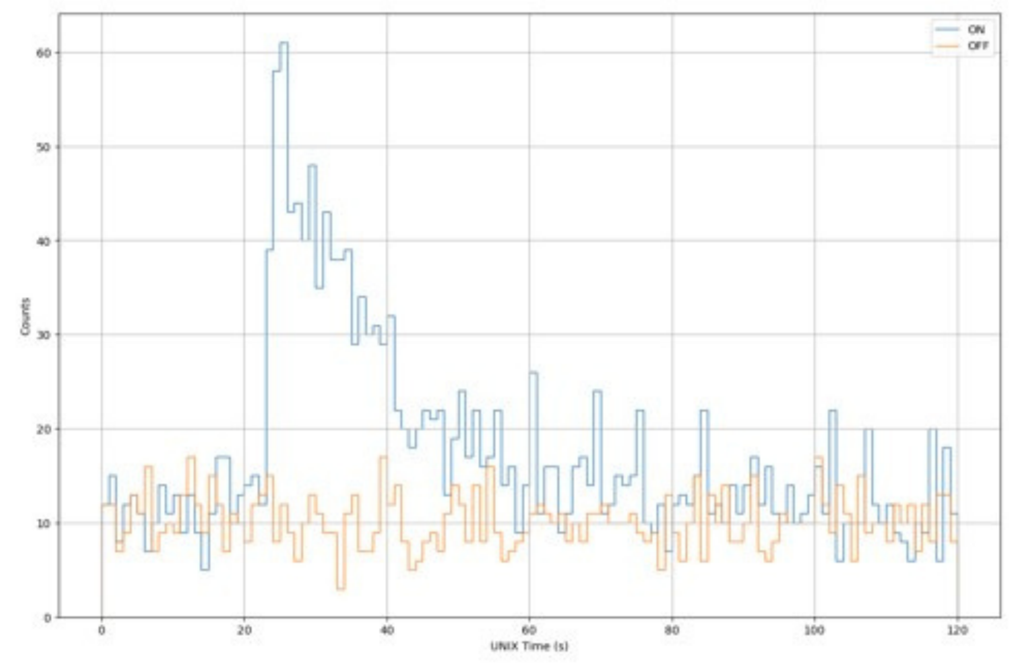
Details:

- the input data is composed by multivariate time series.
- the chosen anomaly detection techniques is based on deep learning (CNN/RNN autoencoders).
- the AE is trained offline with normal samples only (semi-supervised approach) and it learns to reconstruct the input, minimizing the reconstruction error.
- Then, the AE is fed with online data:
  - ○ the reconstruction error for anomalous time series will be higher;
  - ○ a threshold guides the classification.





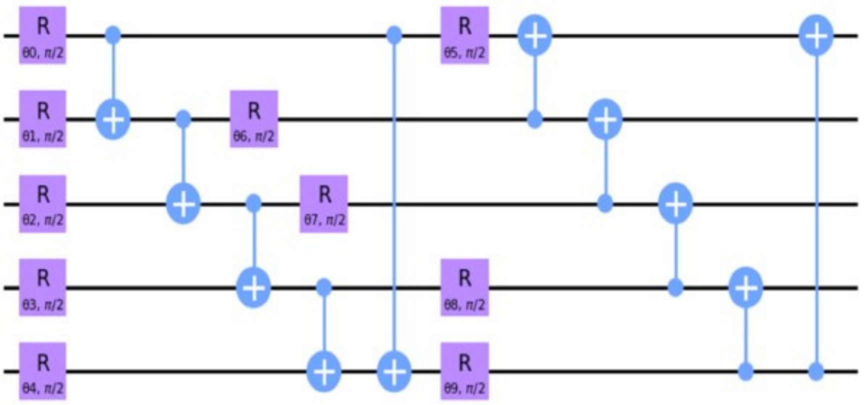
WP3
Quantum Convolutional Neural Network for GRB detection in CTA data



Classical Data

- GRB lightcurves vs noise
- 250 time series for training
- 150 time series for testing
- data mimicking CTA data
- see Farsian, F. et al. (in prep)

Quantum Convolutional Neural Network



QUANTUM CIRCUIT

parameterized in Qiskit

QUANTUM ENCODING

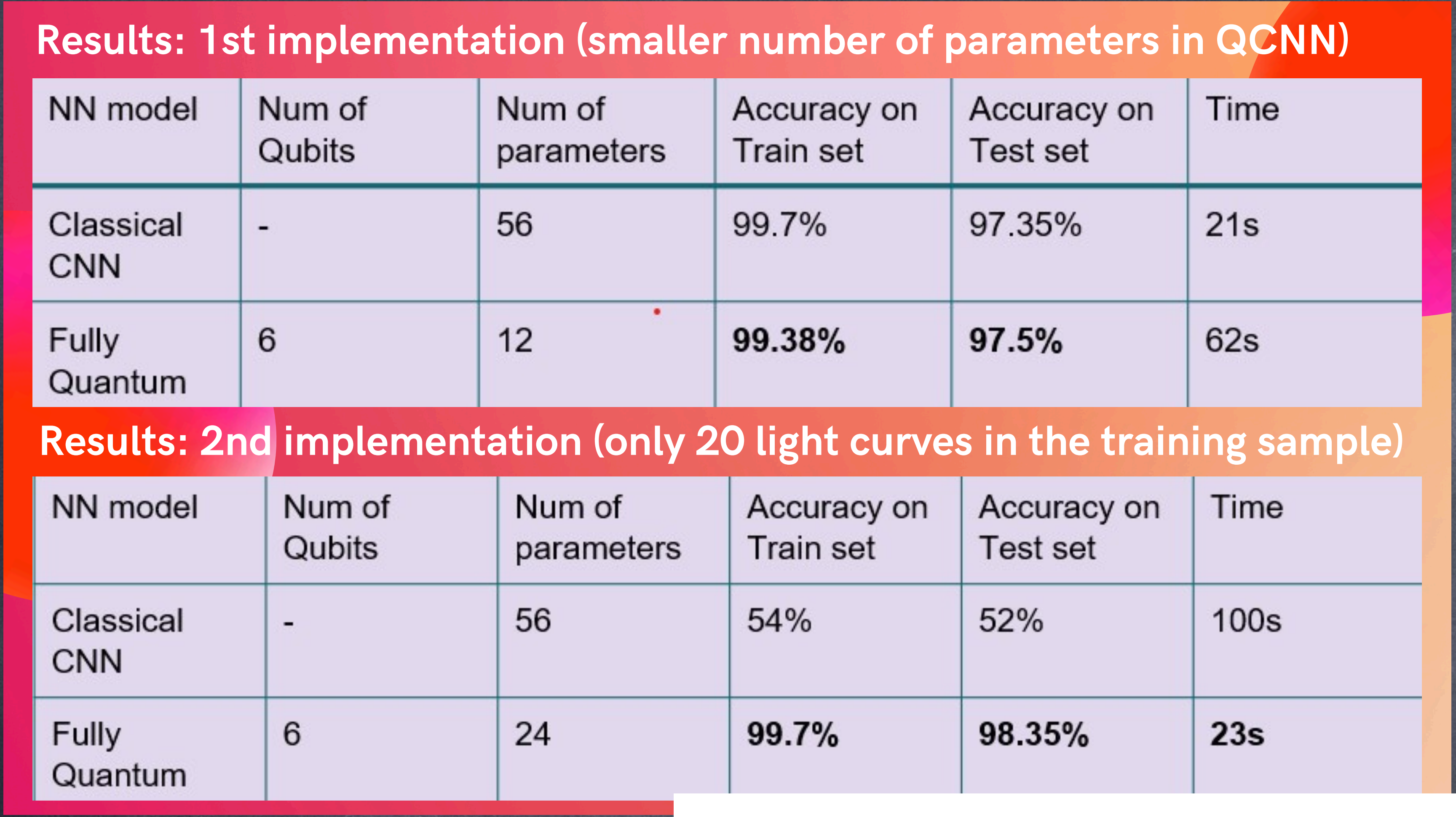
data reuploading method

OPTIMIZATION

performed using the COBYLA optimizer

LOSS FUNCTION

binary cross entropy



Results: 1st implementation (smaller number of parameters in QCNN)

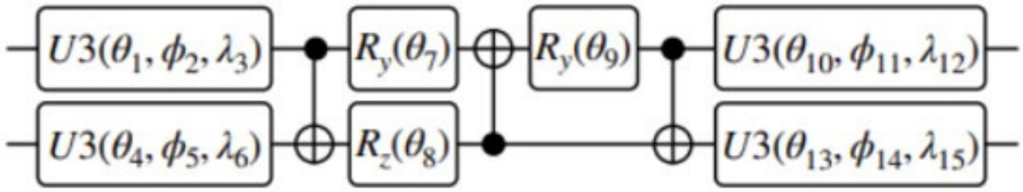
NN model	Num of Qubits	Num of parameters	Accuracy on Train set	Accuracy on Test set	Time
Classical CNN	-	56	99.7%	97.35%	21s
Fully Quantum	6	12	**99.38%**	**97.5%**	62s

Results: 2nd implementation (only 20 light curves in the training sample)

NN model	Num of Qubits	Num of parameters	Accuracy on Train set	Accuracy on Test set	Time
Classical CNN	-	56	54%	52%	100s
Fully Quantum	6	24	**99.7%**	**98.35%**	**23s**

Quantum Autoencoders for GRB detection in AGILE

Classical Algorithm



(i) Convolutional circuit 9

- classical convolutional autoencoder
- convolutional variational autoencoder
- encoders composed of 1D convolutions
- decoders composed of 1D transpose convolutions
- works on simulated data and ready to be tested on AGILE ones

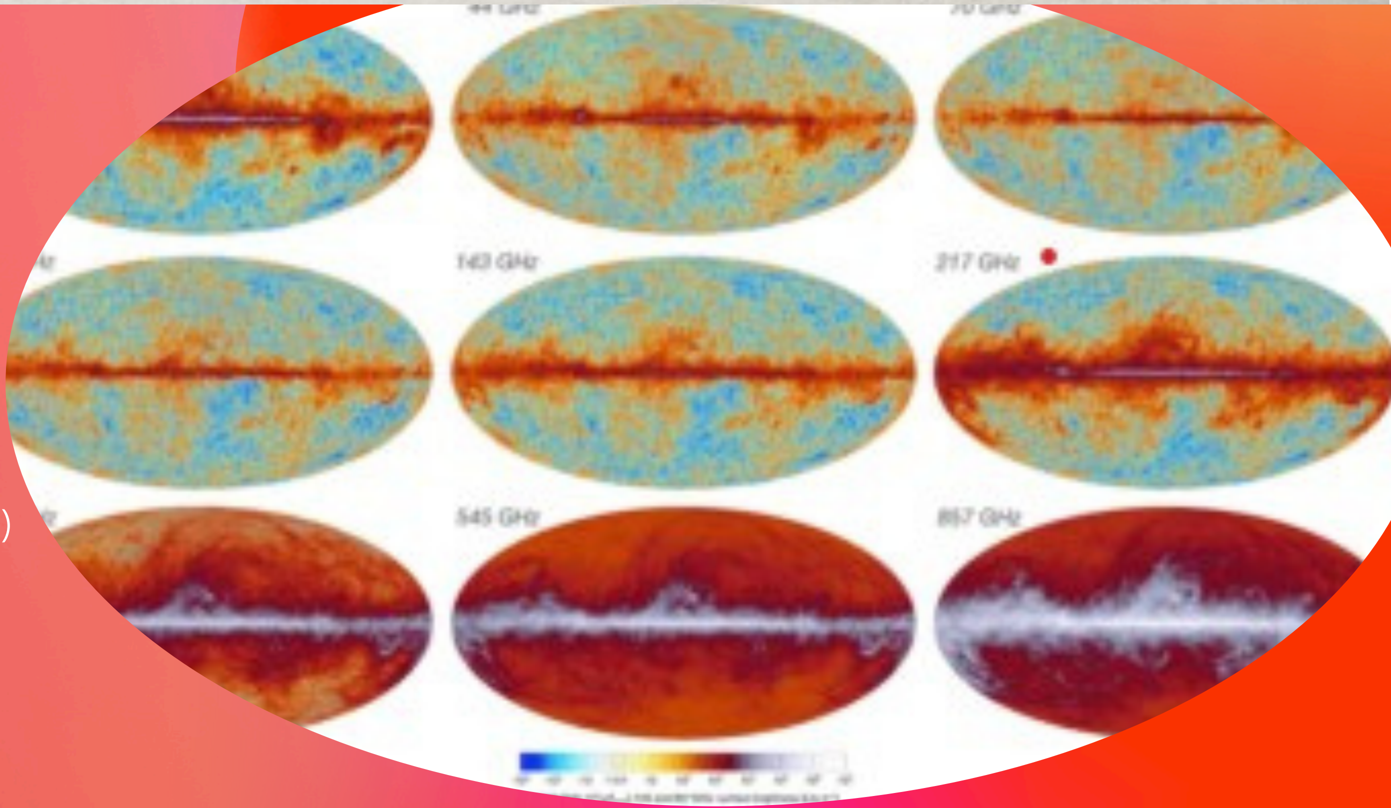
Quantum Algorithm

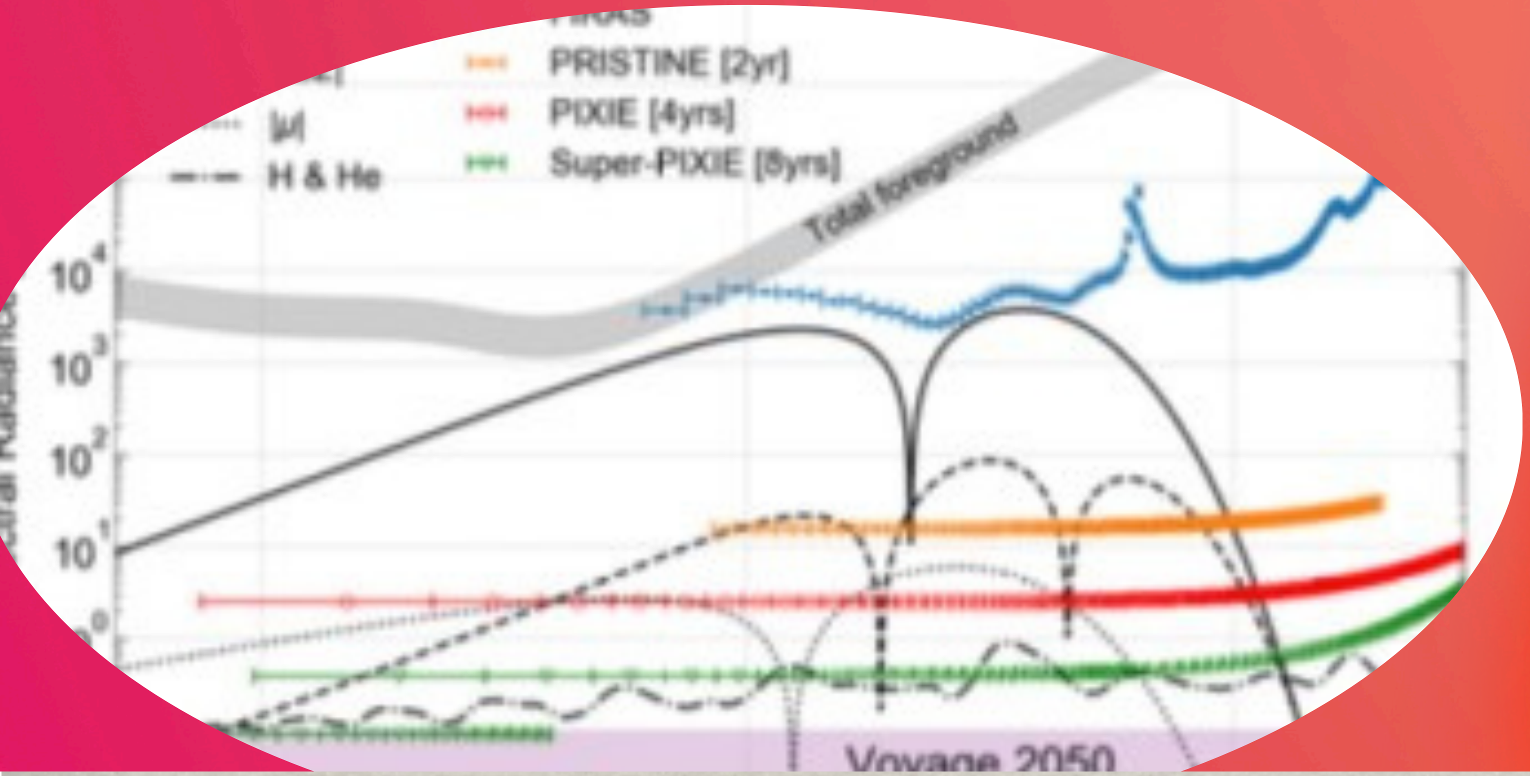
- quantum encoder + classical latent space + classical decoder
- quantum encoder + quantum latent space + classical decoder
- data reuploading and amplitude embedding as encoding techniques
- 8 qubits and 16 qubits
- interesting preliminary results but work still in progress (A. Rizzo, et al. in prep)

From 1E5 parameters —> 51 parameters!!

WP4
CMB components separation

- CMB maps as sum of different contributions
    - cosmological signal (anisotropy power spectrum)
    - galactic foregrounds (e.g., synchroton and thermal dust)
    - Cosmic Infrared Background)
    - extragalactic radio and far IR sources
- difficult to separate and time consuming





Research Plan

- different spectral features
- already available methods, e.g.
    - template fitting
    - internal linear combination
    - PCA decomposition
- develop quantum counterparts of classical methods
- use Quantum Machine Learning techniques

WP2
Multiparameter Optimisation

COSMOLOGY

Constraining a small set of cosmological parameters in a sea of nuisance ones

STRONG LENSING

Constraining halo dark matter profile marginalising over single galaxies ones

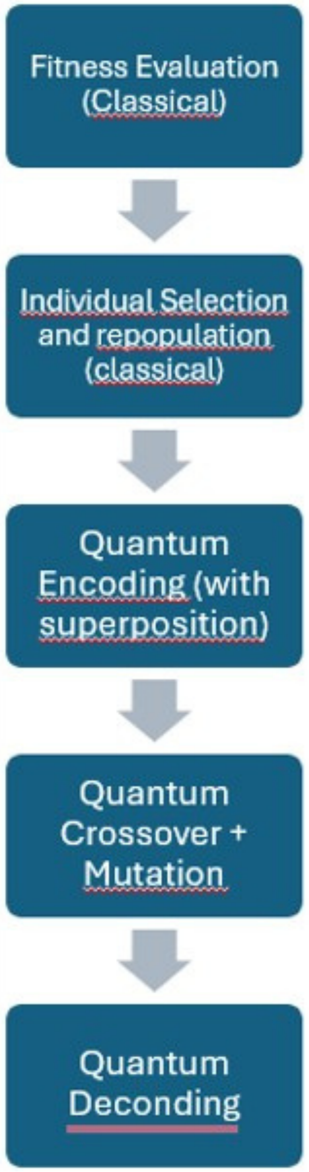
SAMPLING

Reconstructing the posterior density in many dimensional spaces

First tests

Quantum Genetic Algorithm

FINDING BEST FIT COSMOLOGICAL PARAMETERS FROM THE FIT TO SNEIA, BAO AND CMB DATA



Fitness Evaluation (Classical)

Individual Selection and repopulation (classical)

Quantum Encoding (with superposition)

Quantum Crossover + Mutation

Quantum Deconding

FITNESS EVALUATION

quantify the agreement between model and data

QUANTUM ENCODING

encode model DNA through amplitude encoding

QUANTUM CROSSOVER AND MUTATION

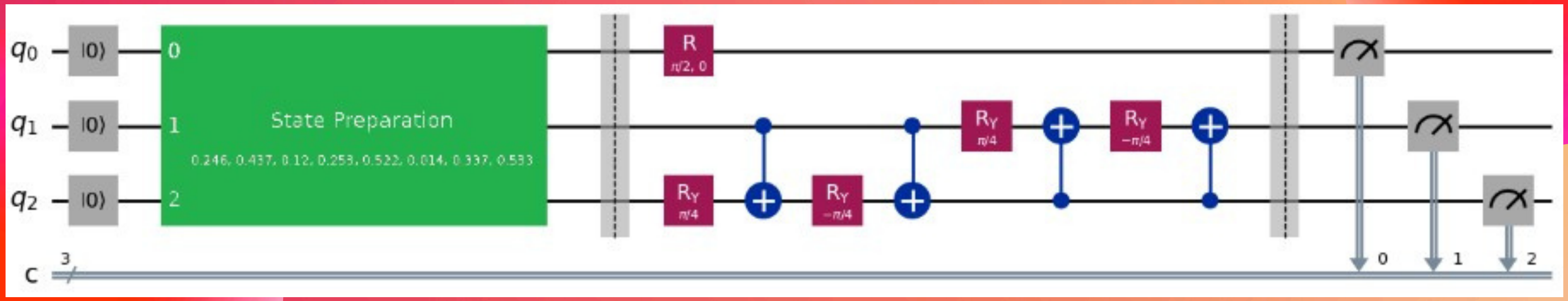
use quantum operations for genetic operations

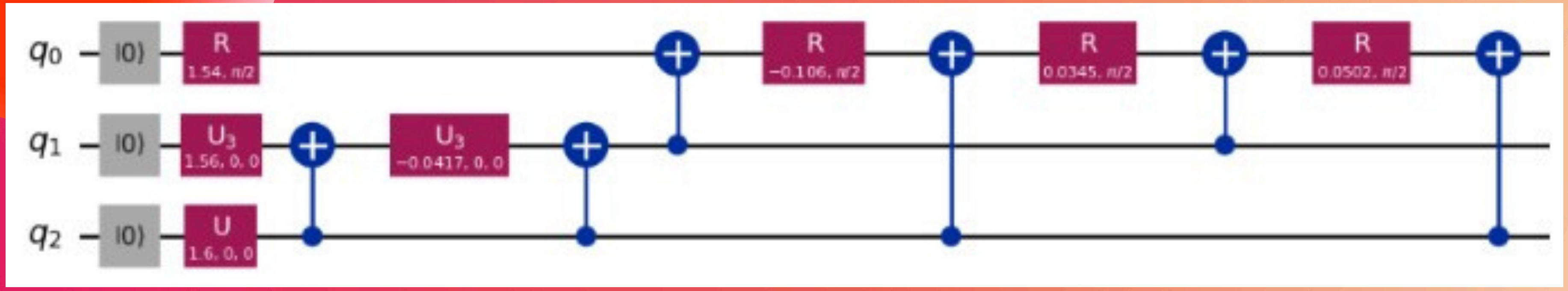
QUANTUM DECODING

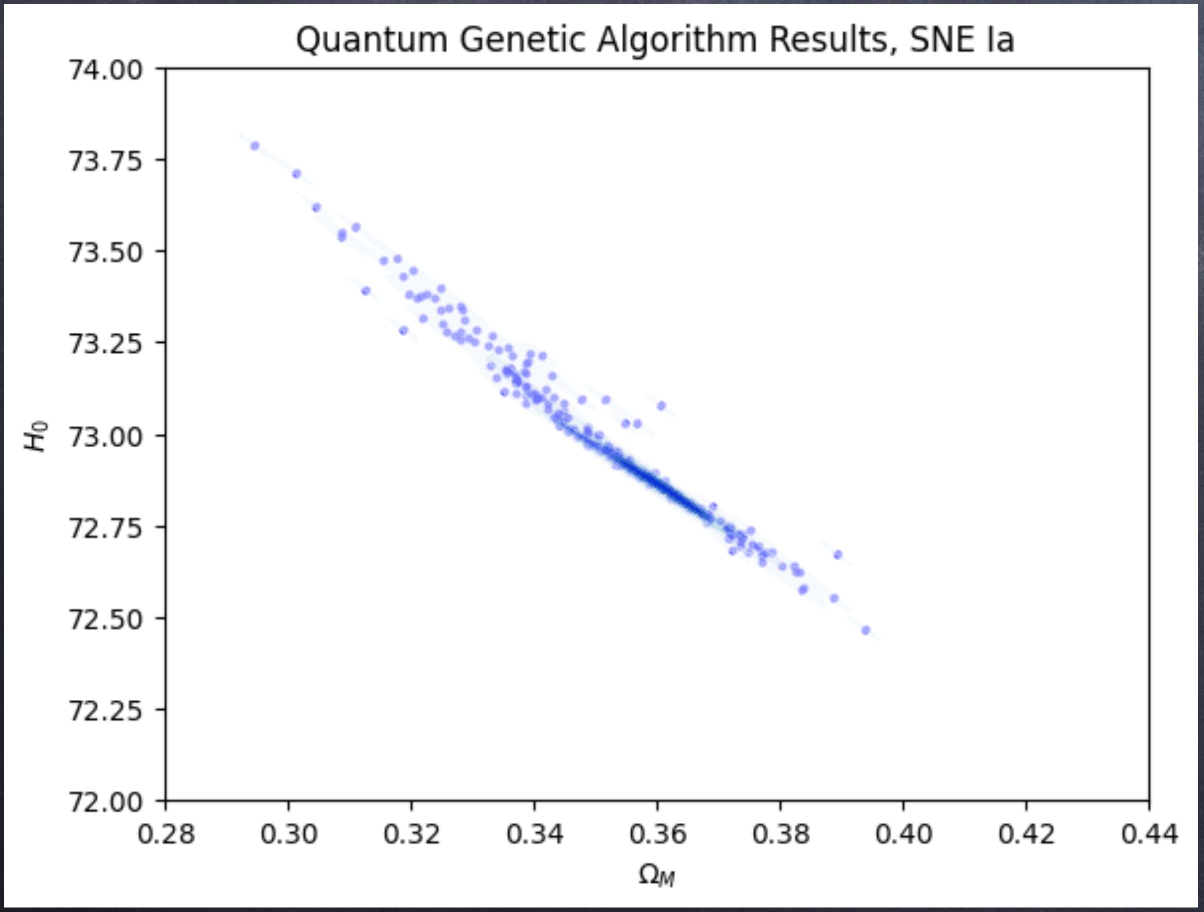
decoding back to classical algorithm and iterate

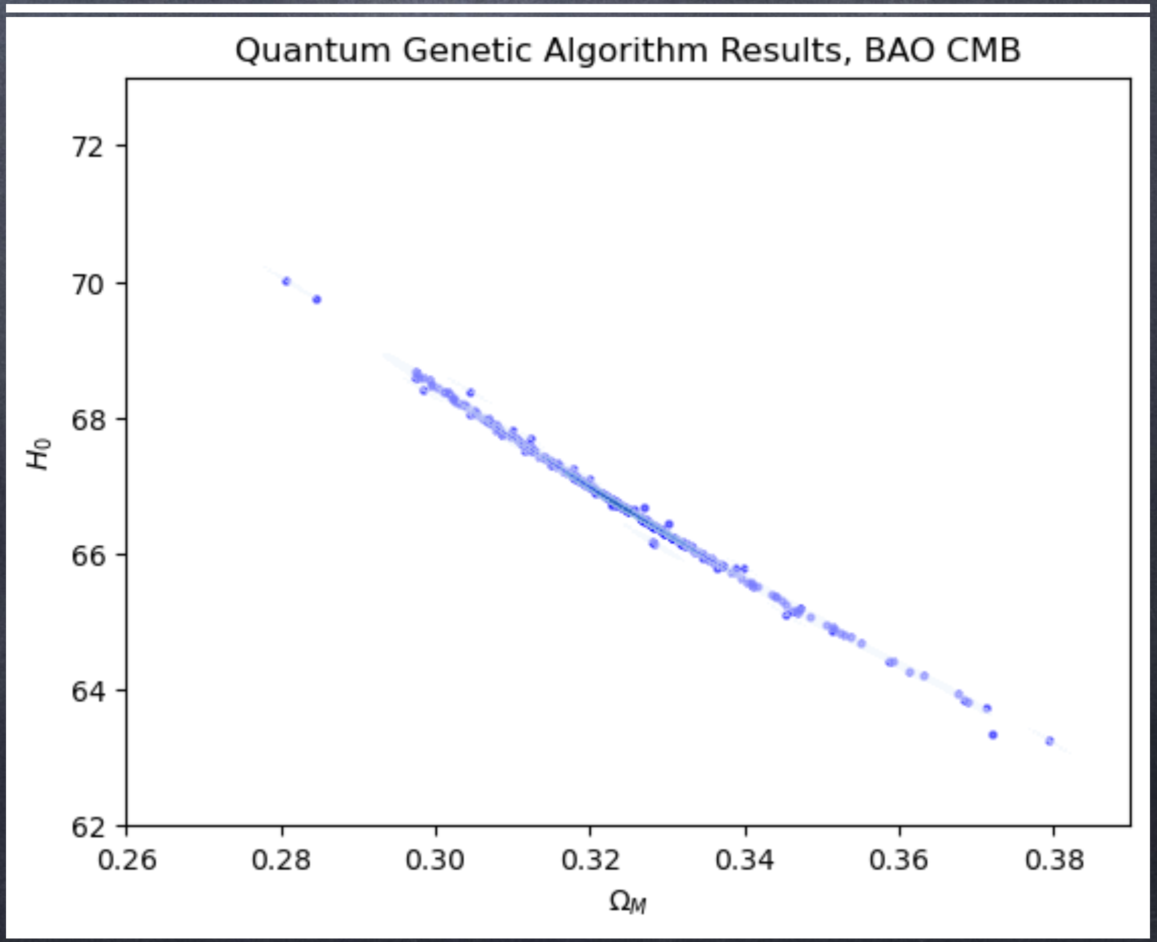
Find best Ω_0 and H_0 from SN and CMB

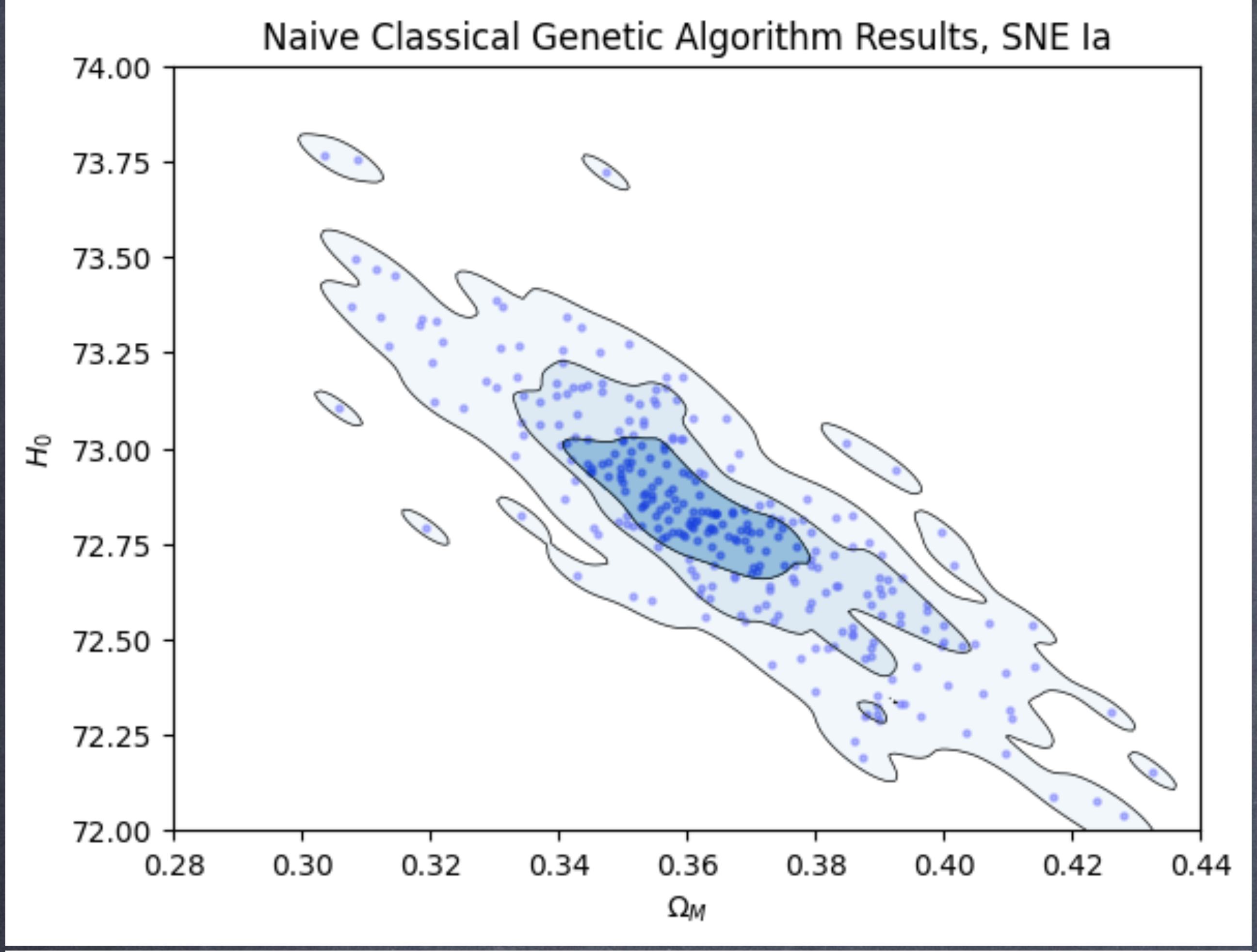
Quantum Genetic Algorithm Circuit

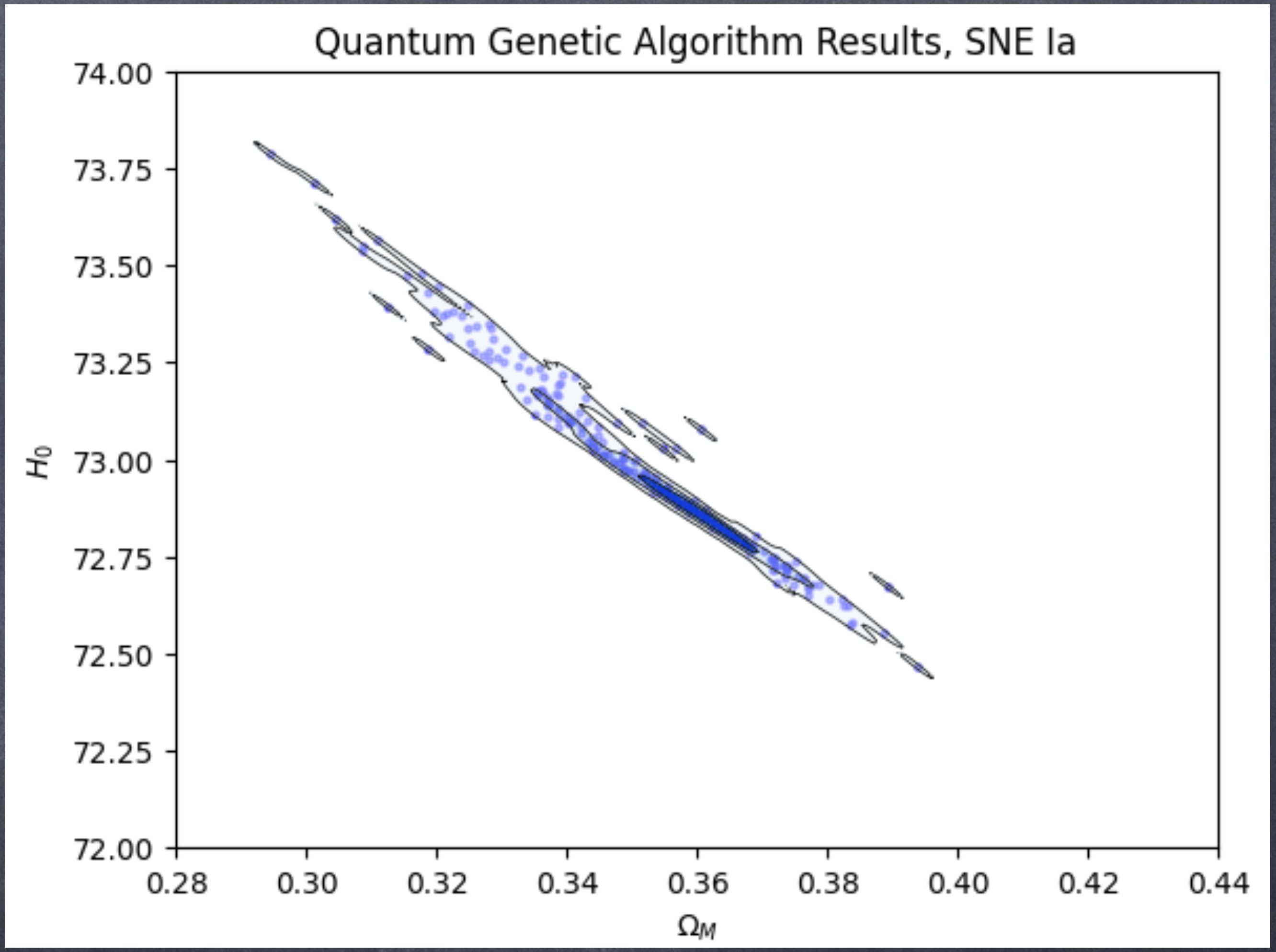












Quite encouraging!!

Stay tuned …