Galassie in un supercomputer

Come le simulazioni numeriche ci aiutano a capire l'evoluzione dell'Universo

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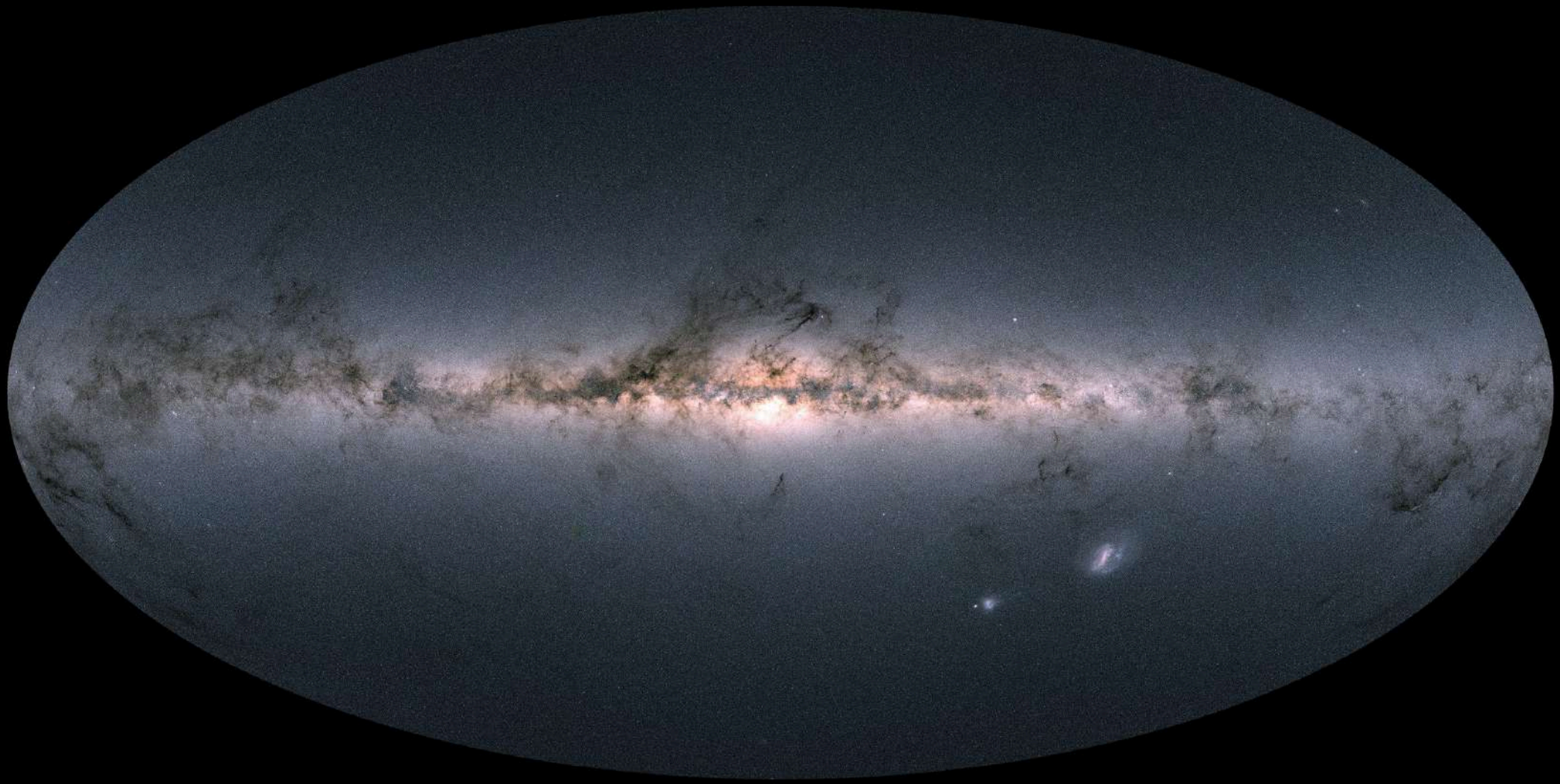
Dipartimento di Fisica e Astronomia

Conferenze alla Specola
Aula della Specola – Università di Bologna
9 Novembre 2023

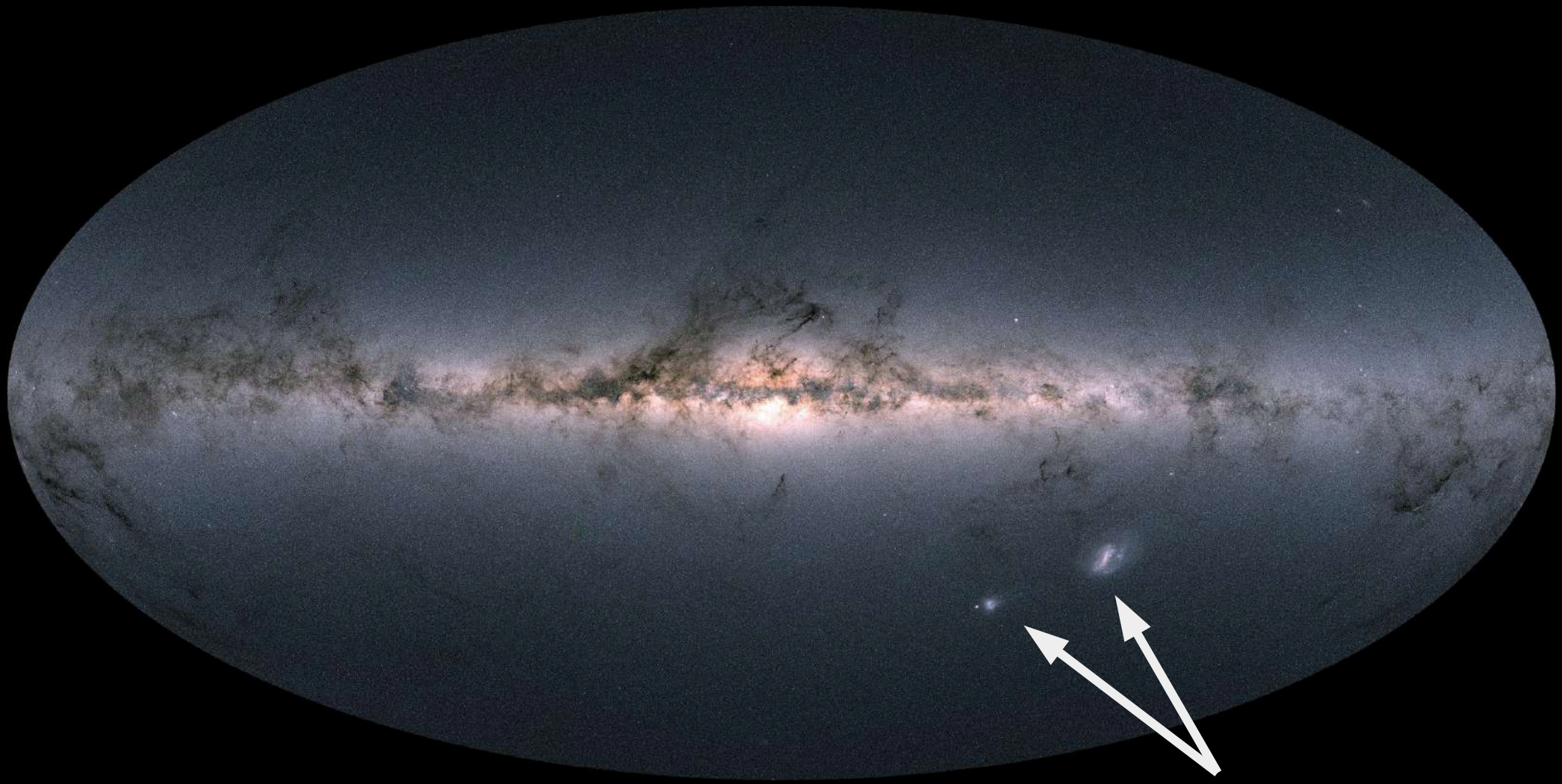
Cosa sono le galassie?


La Via Lattea

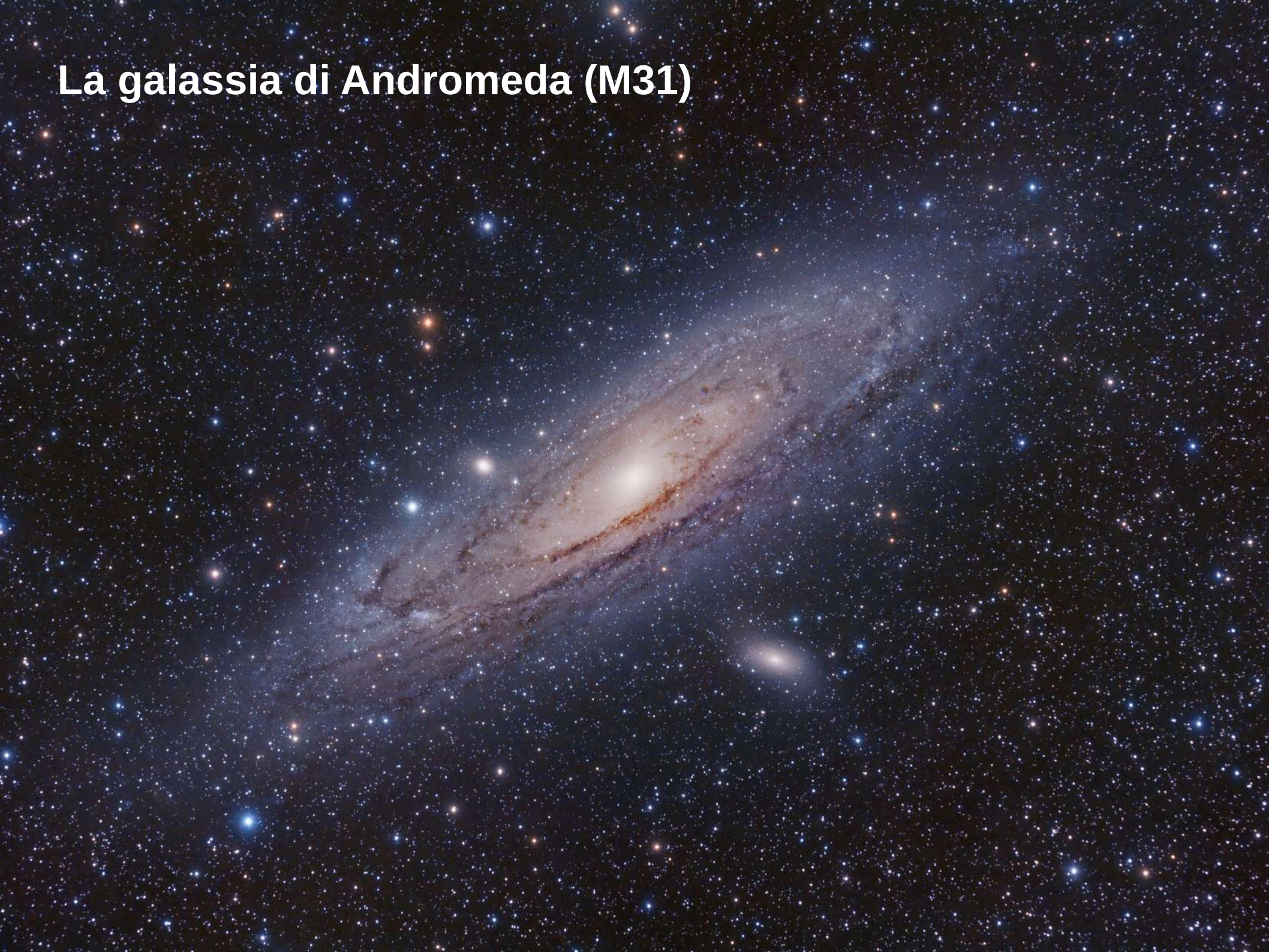
Osservazioni del satellite Gaia

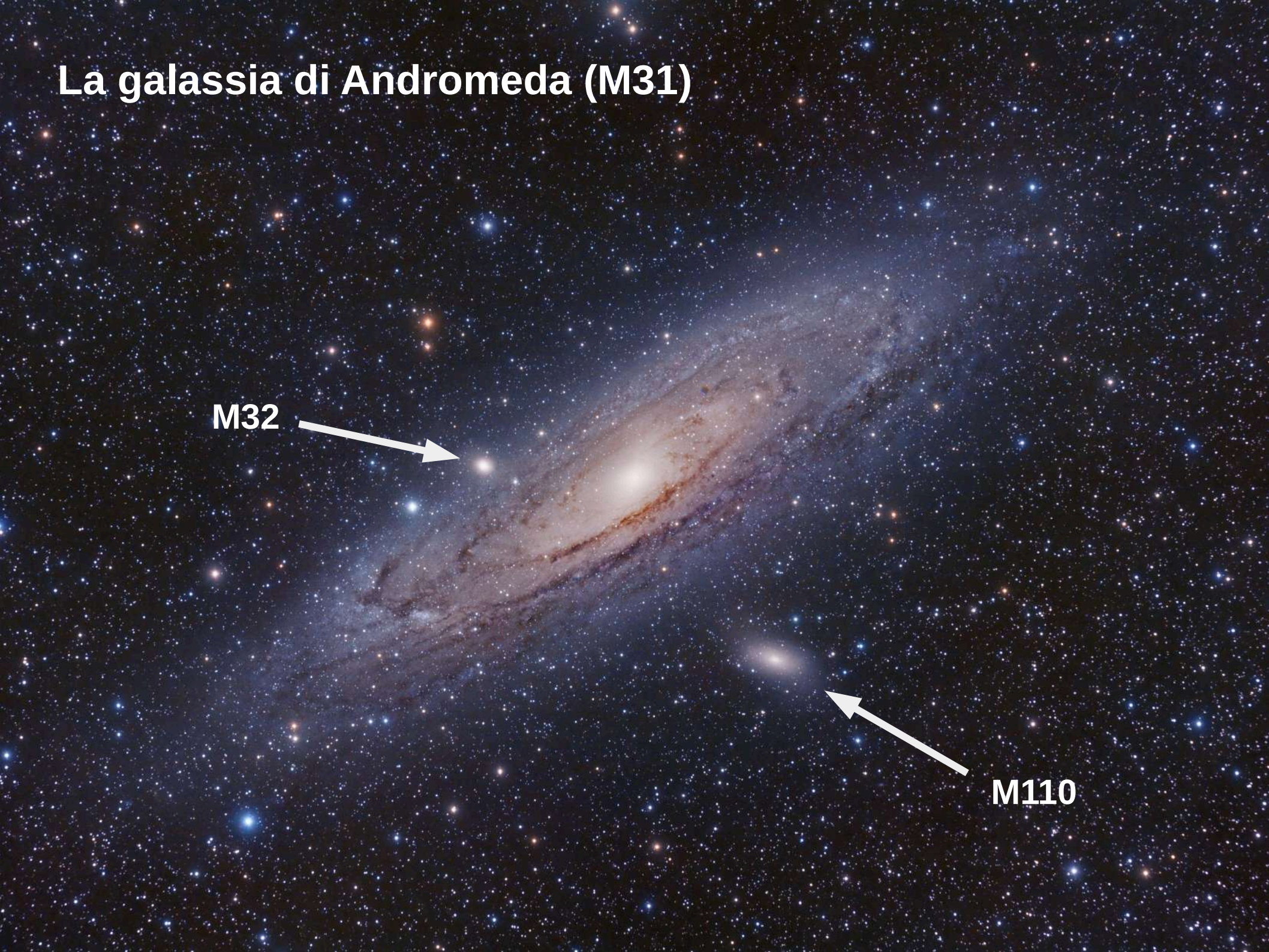


Osservazioni del satellite Gaia



La galassia di Andromeda (M31)

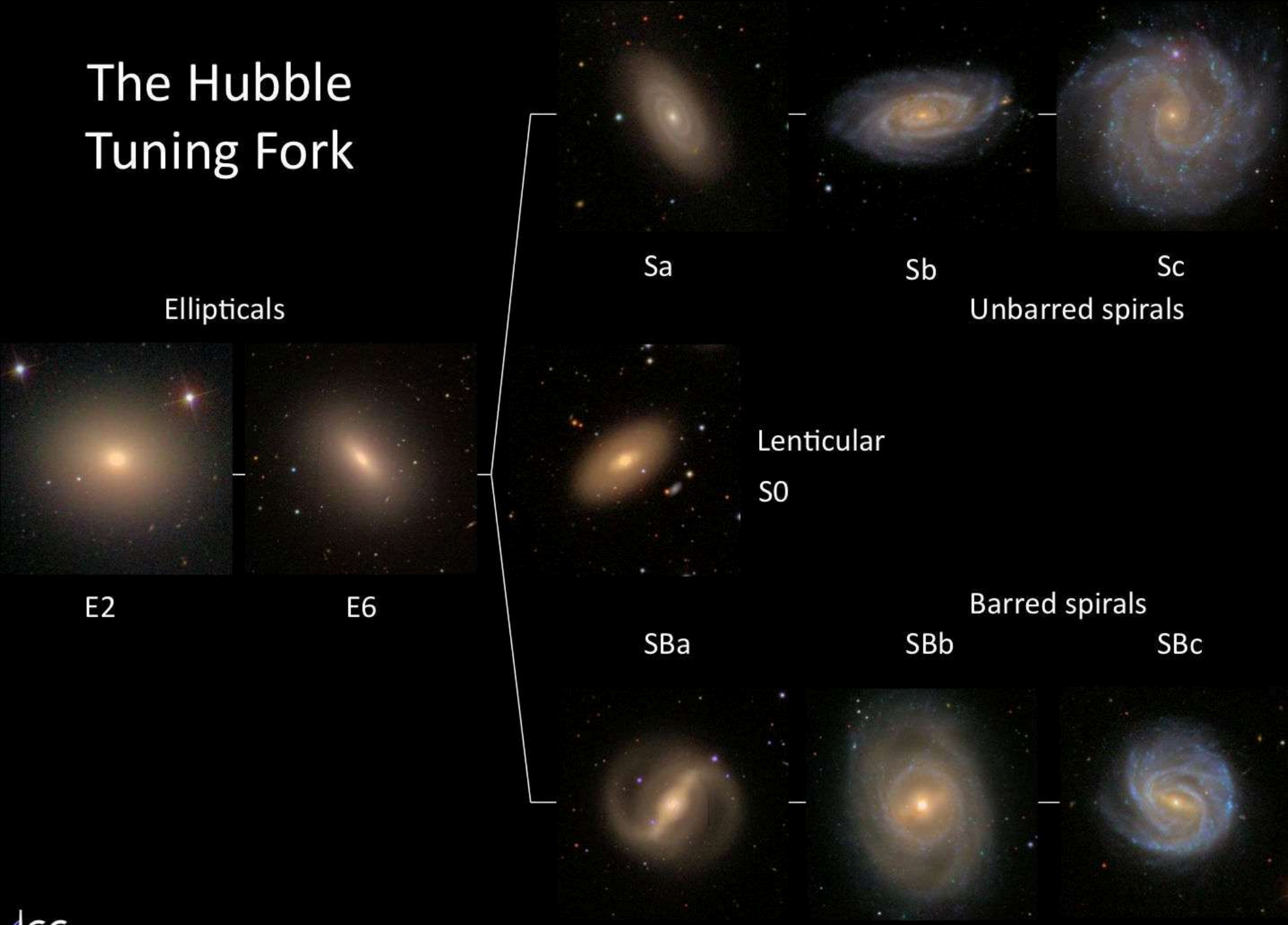



La galassia di Andromeda (M31)
M32
M110

Galassie ellittiche

IC 2006

The Hubble Tuning Fork



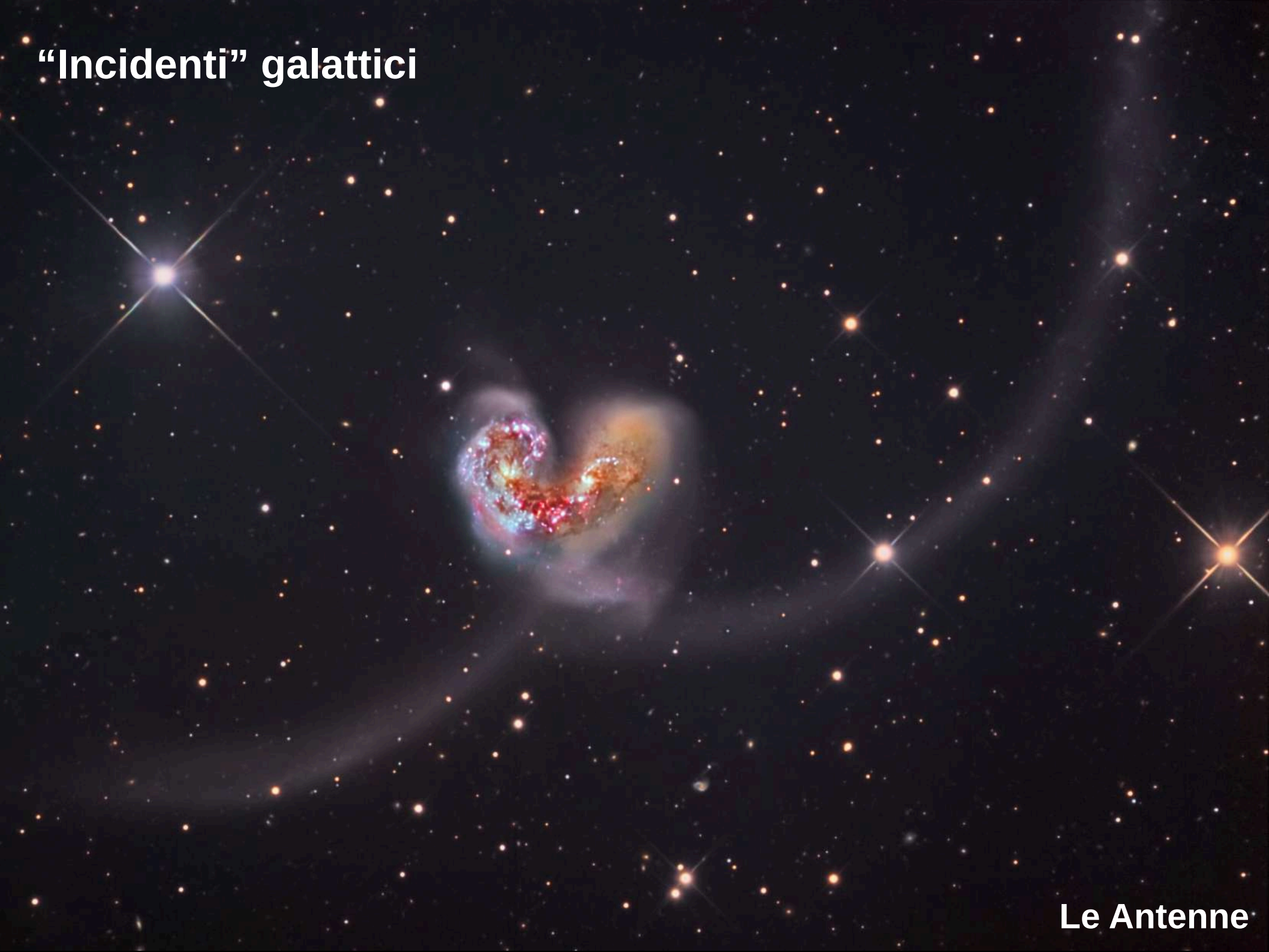
Credit: Karen L. Masters (ICG Portsmouth). Galaxies: SDSS gri colour images as used in Galaxy Zoo.

GALAXY ZOO

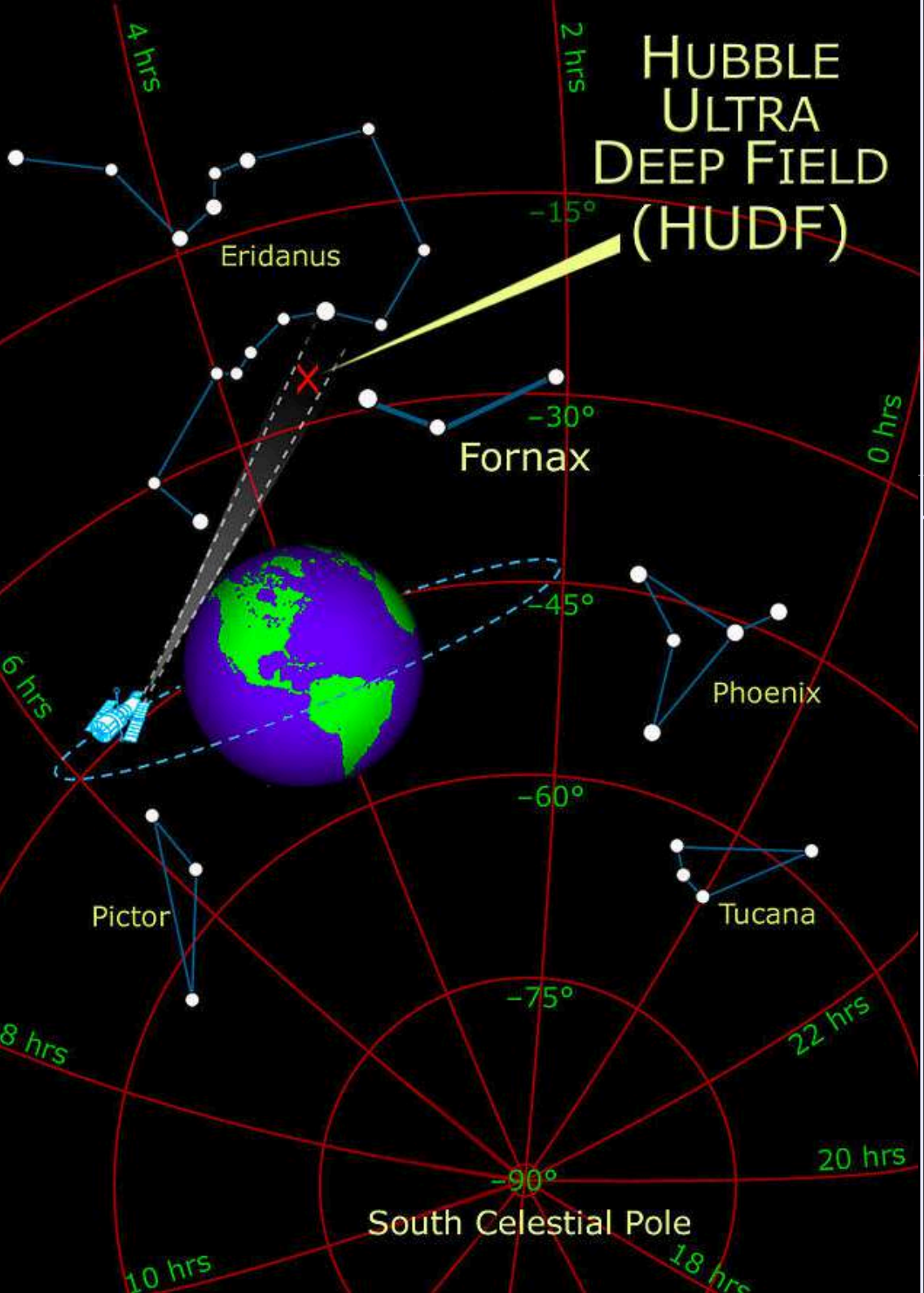
Ammassi di galassie

L'ammasso di Perseo

“Incidenti” galattici

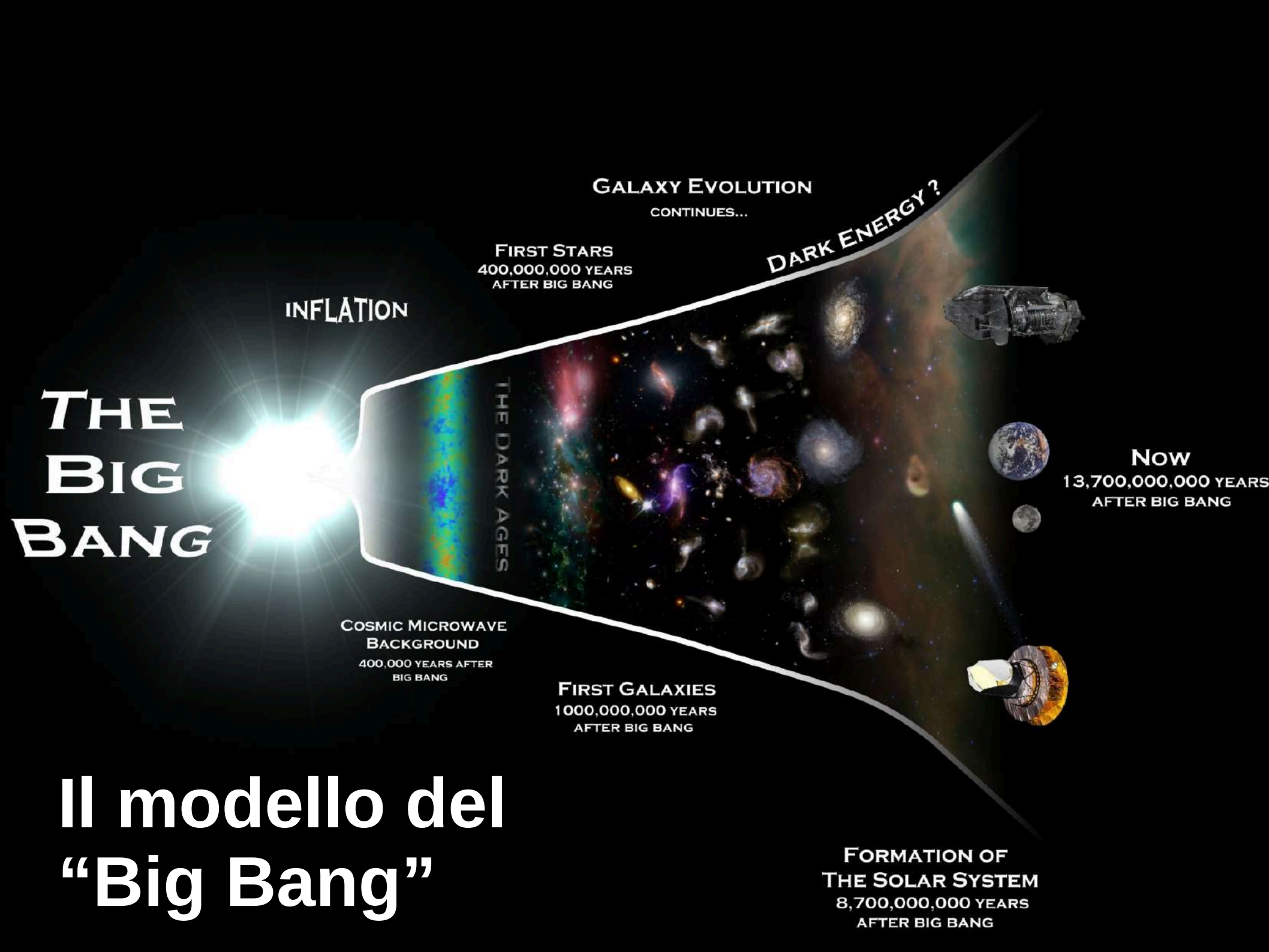


Le Antenne


Hubble Ultra Deep Field (HUDF)
4 hrs
2 hrs
0 hrs
6 hrs
8 hrs
10 hrs
18 hrs
20 hrs
22 hrs
-15°
-30°
-45°
-60°
-75°
-90°
Eridanus
Fornax
Phoenix
Pictor
Tucana
South Celestial Pole

Le galassie sono ovunque

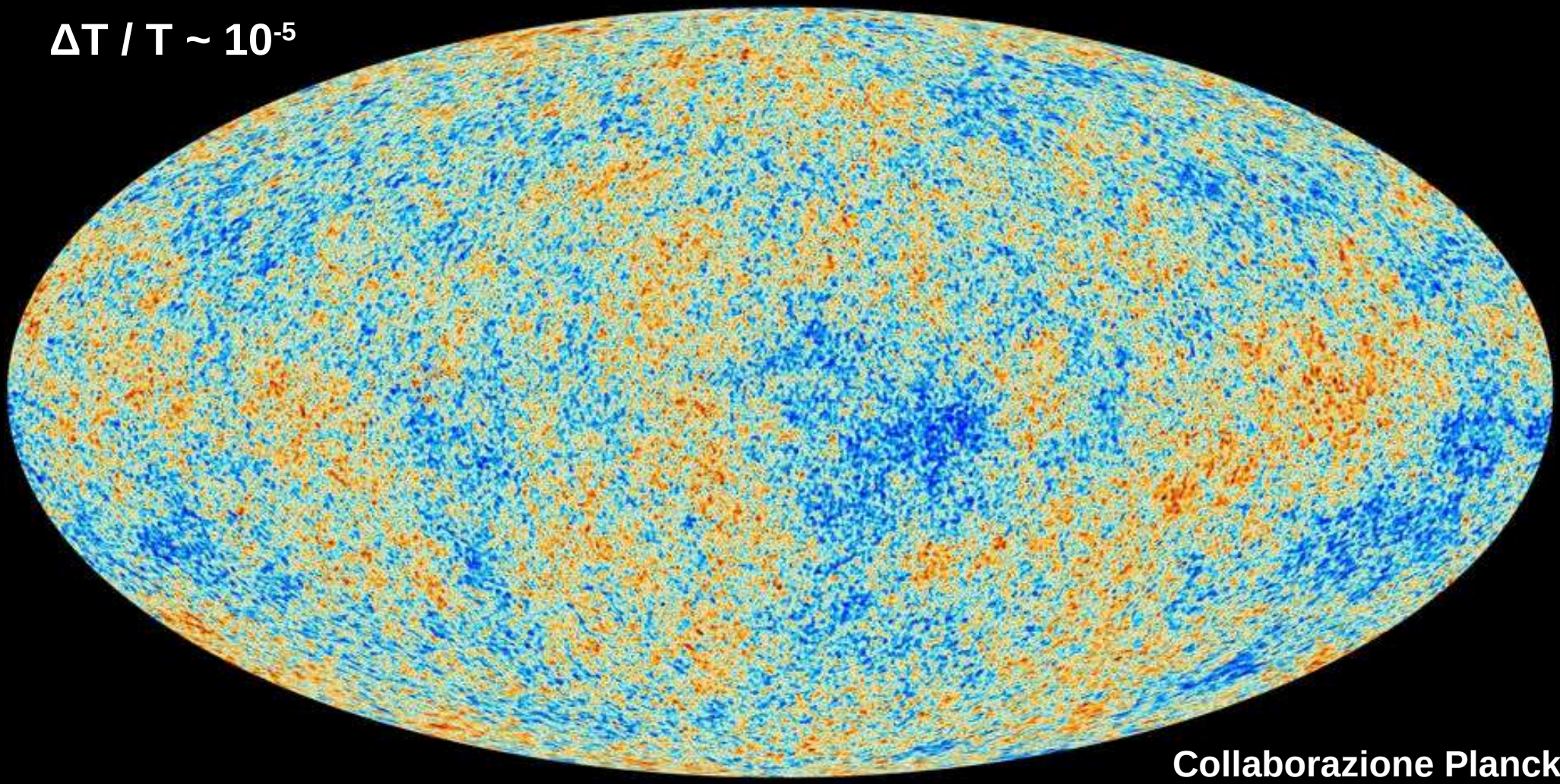
Come si sono formate?



Il modello del "Big Bang"

La radiazione cosmica di fondo

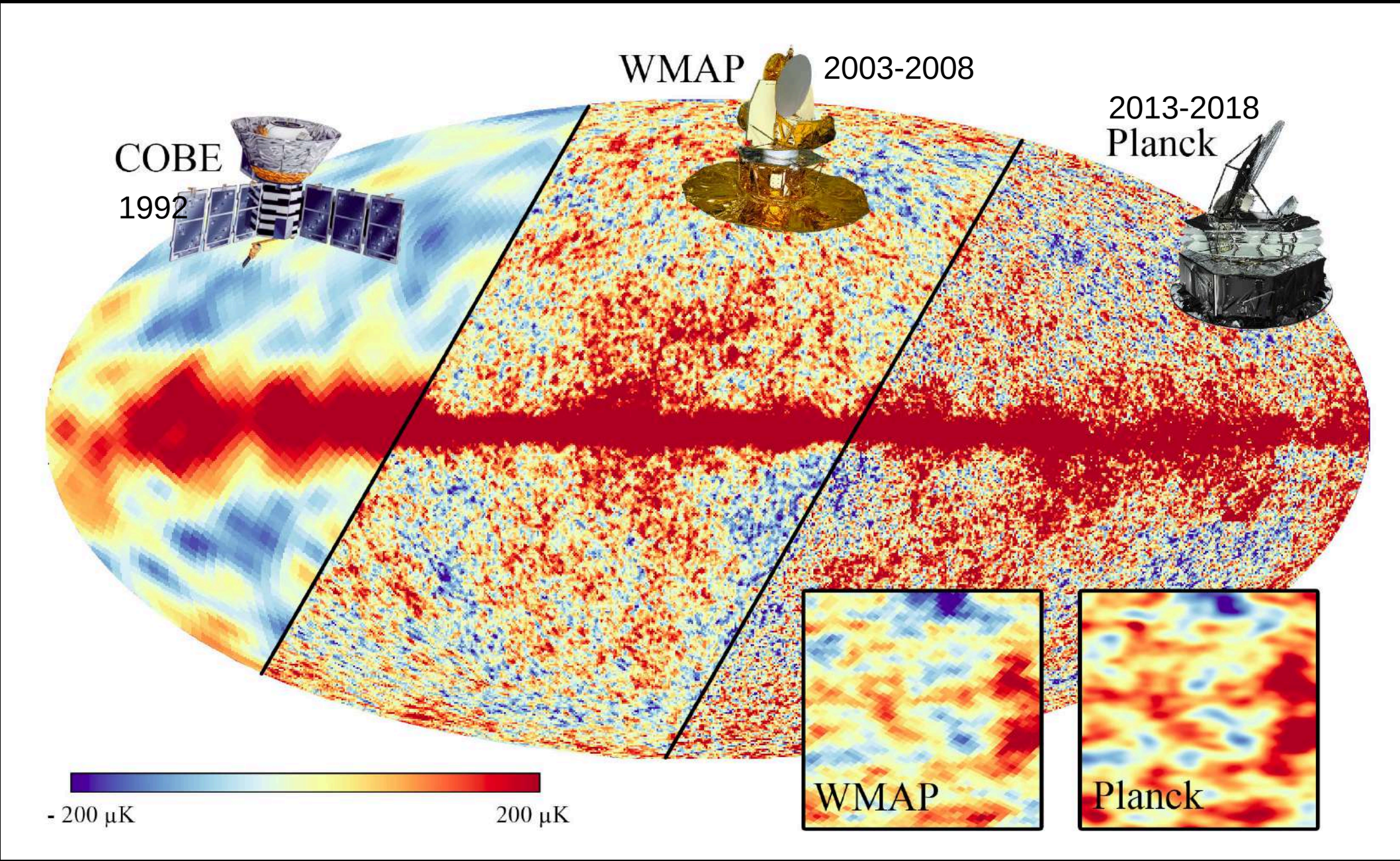
$\Delta T / T \sim 10^{-5}$



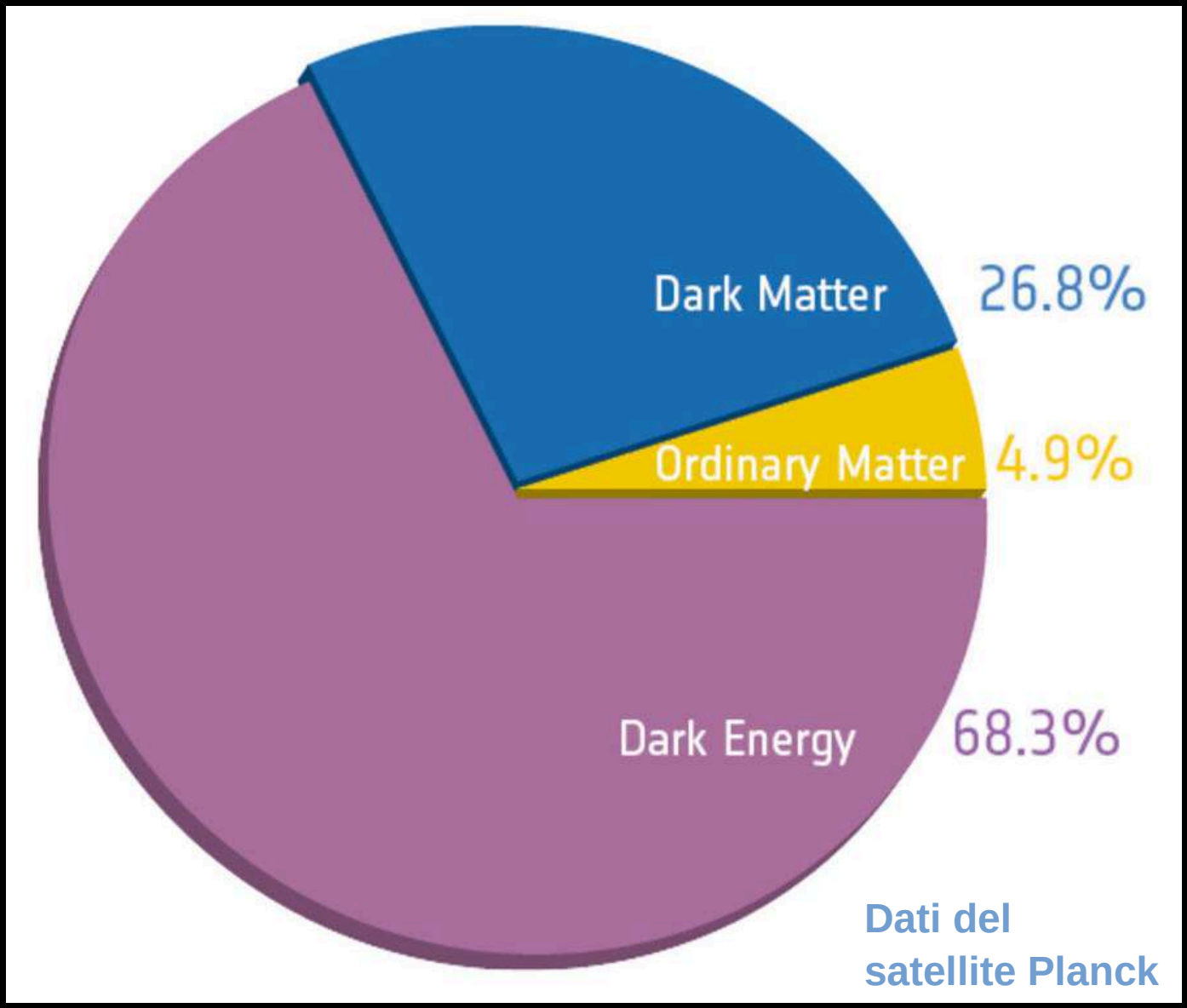
Collaborazione Planck

Da queste piccole perturbazioni nasceranno tutte le strutture che popolano oggi l'Universo

Osservazioni sempre più sofisticate misurano gli istanti iniziali dell'Universo con maggior accuratezza...



… e ci fanno capire che non conosciamo molto bene di cosa sia composto l'Universo

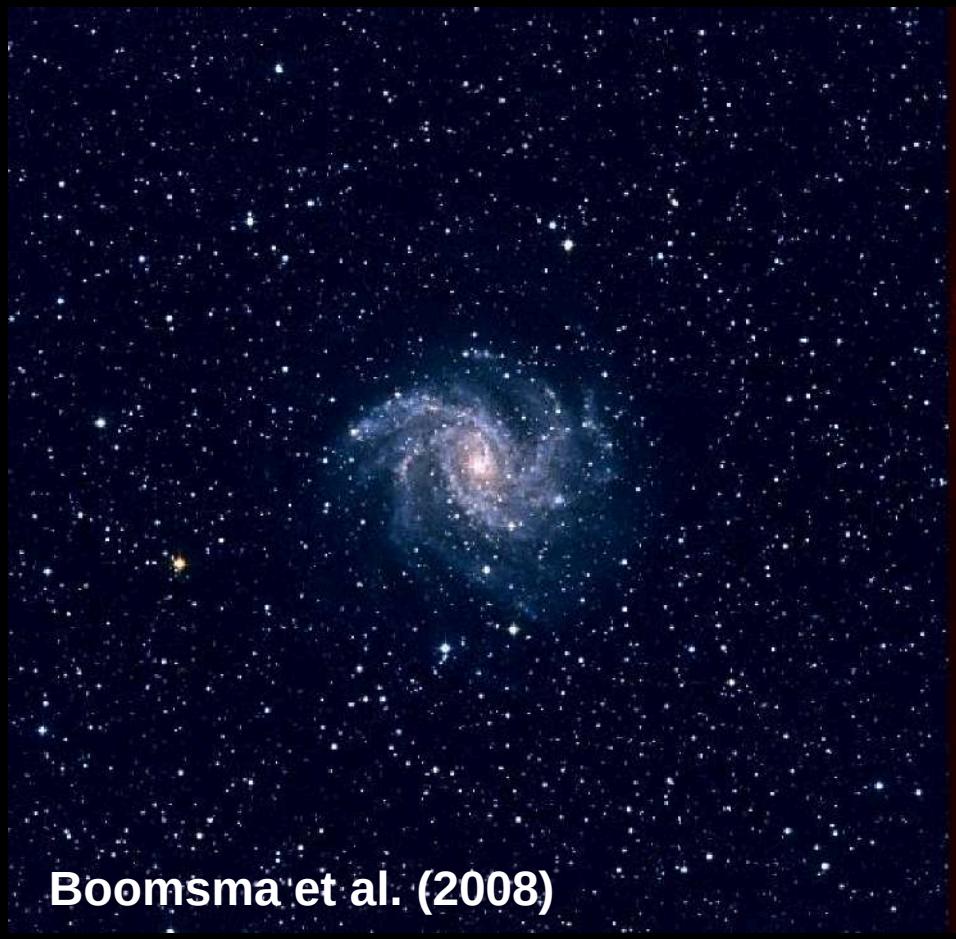


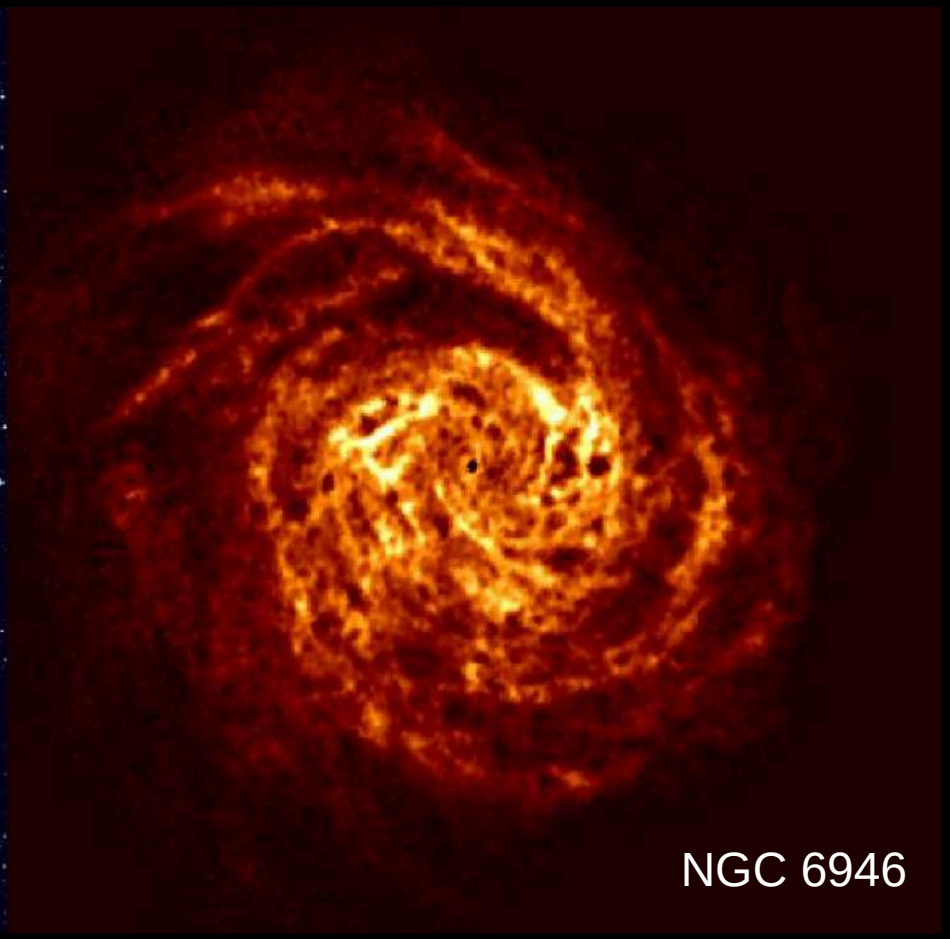
in pratica la materia di cui siamo fatti rappresenta solo Il 5% circa dell'Universo!!!

Che cos’è la materia oscura?

Stelle

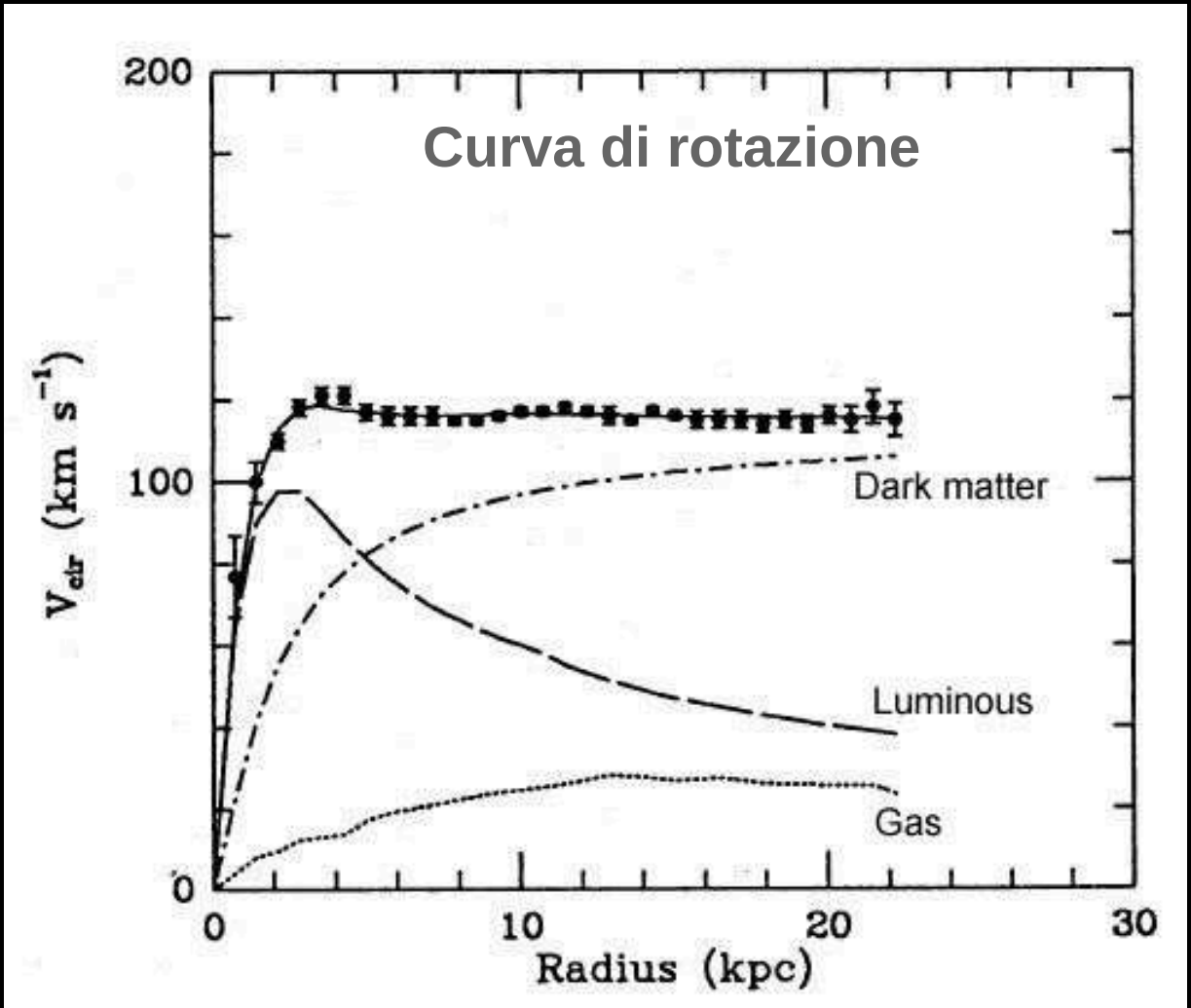
Idrogeno neutro

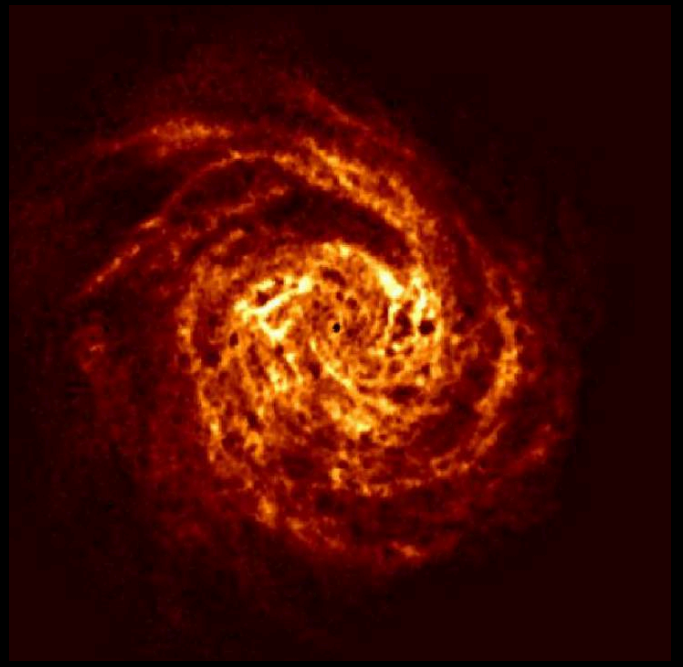




~40 kpc

Che cos’è la materia oscura?





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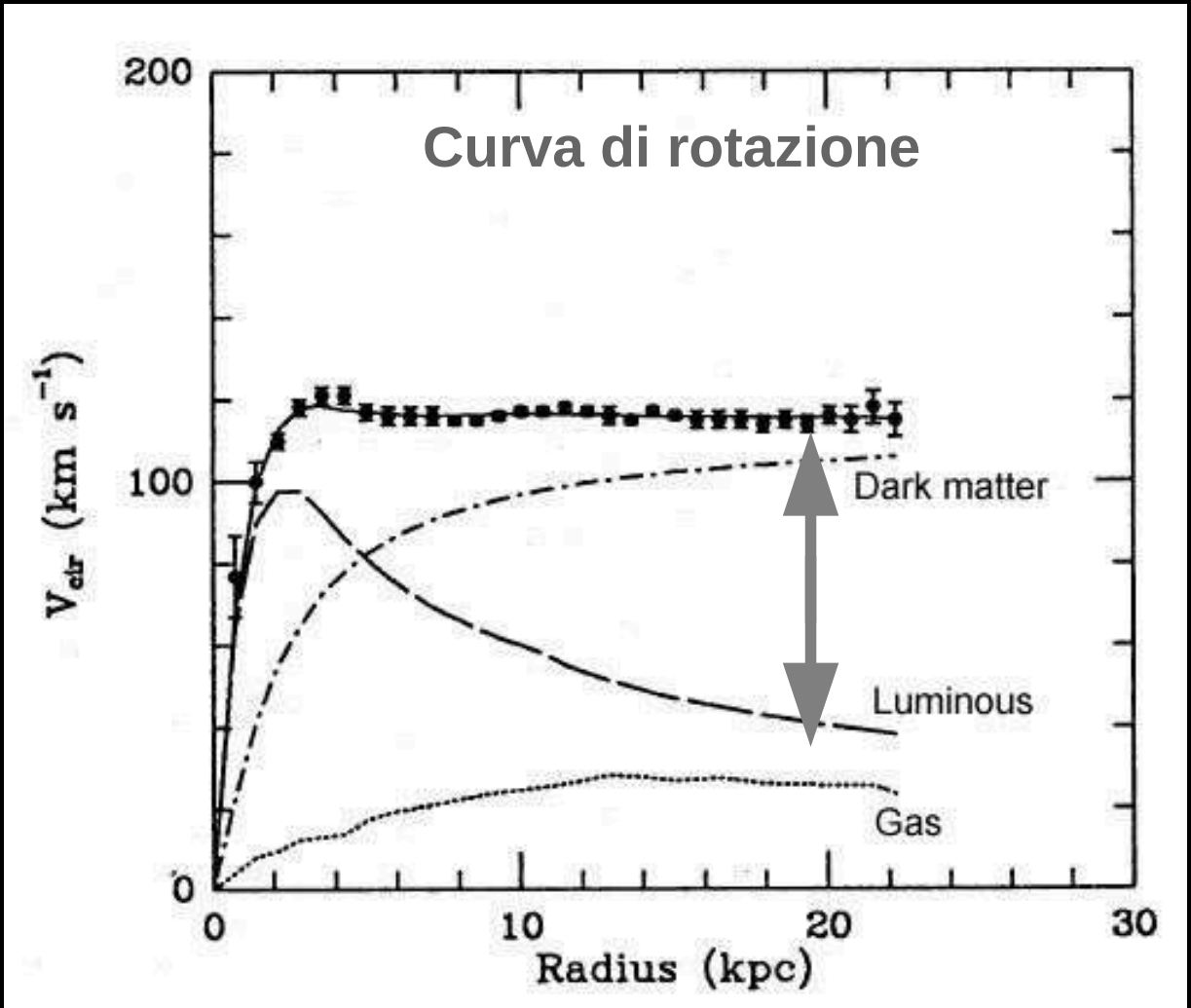
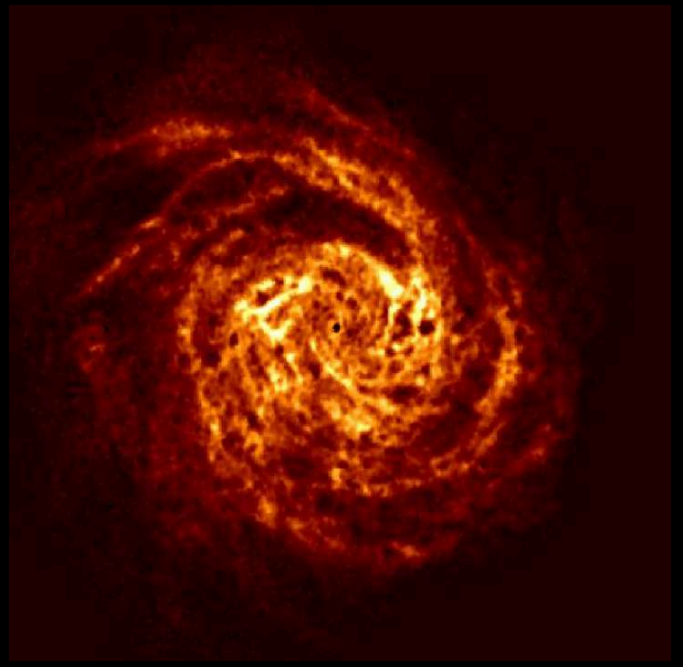
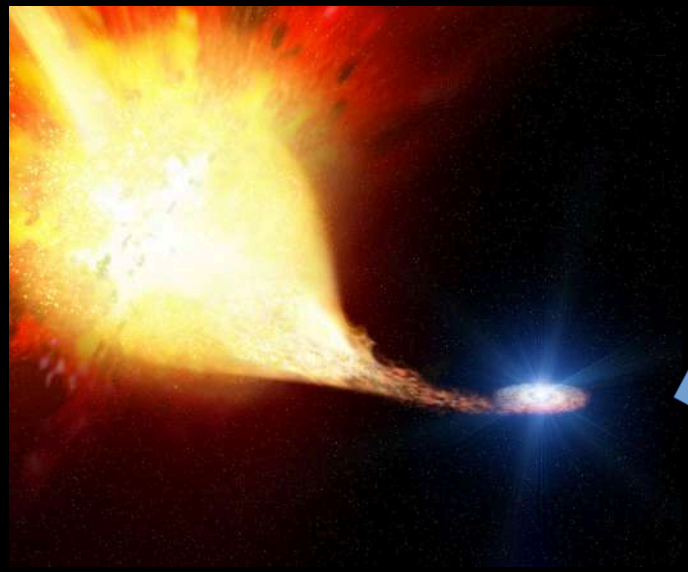
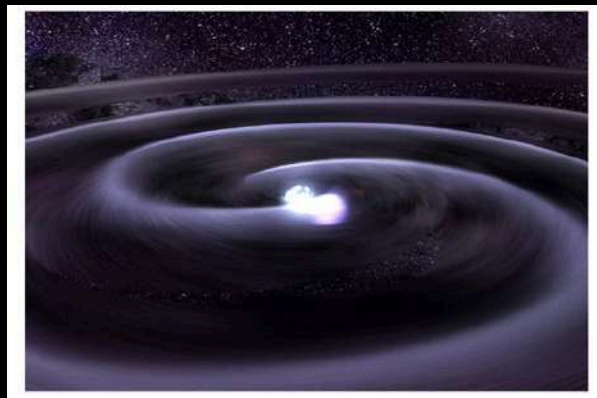
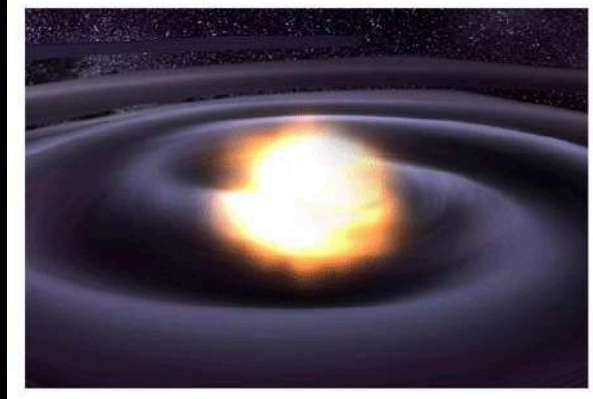




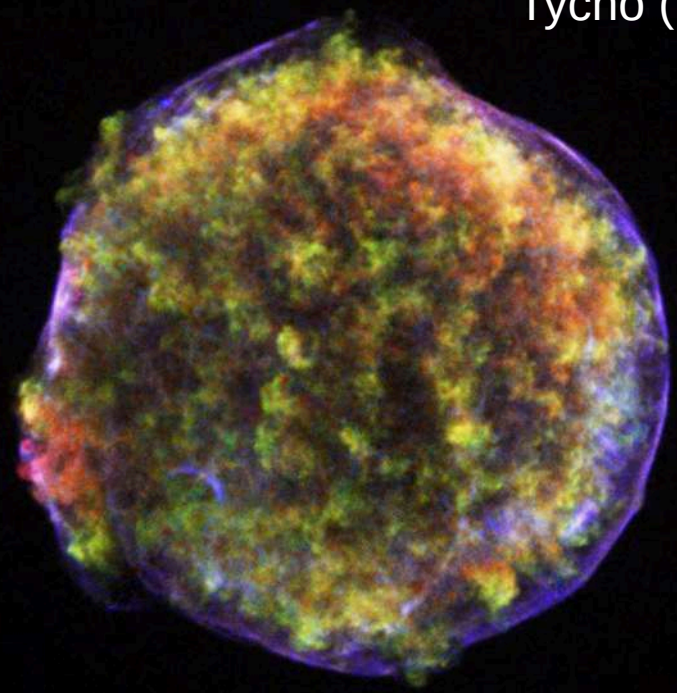
Che cos'è l'energia oscura?







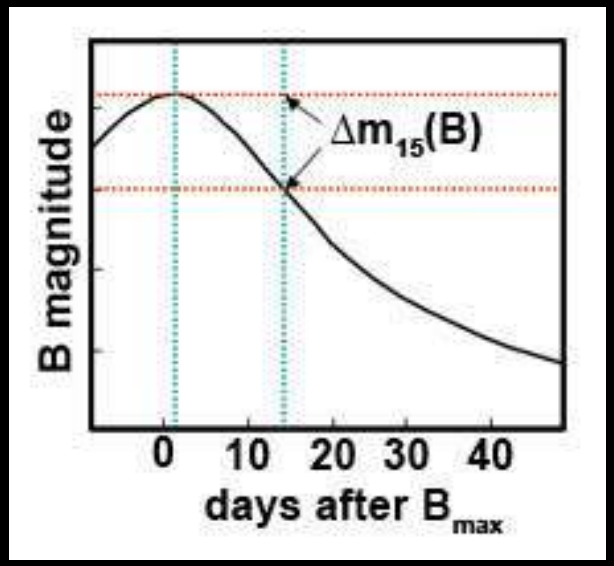
Supernova di Tycho (1572)



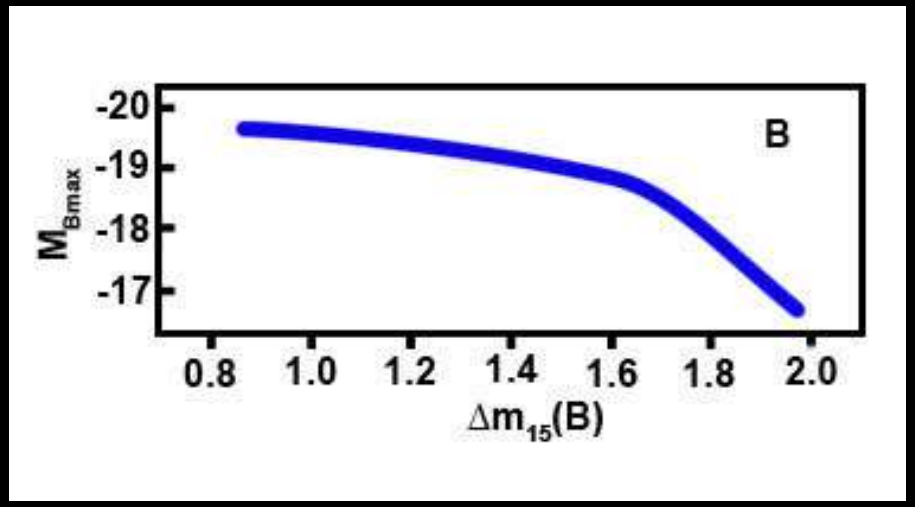
Supernove di tipo Ia: Esplosioni di nane bianche dovute a reazioni termonucleari

Molto luminose, quindi possono essere viste anche da molto lontano...

Che cos’è l’energia oscura?

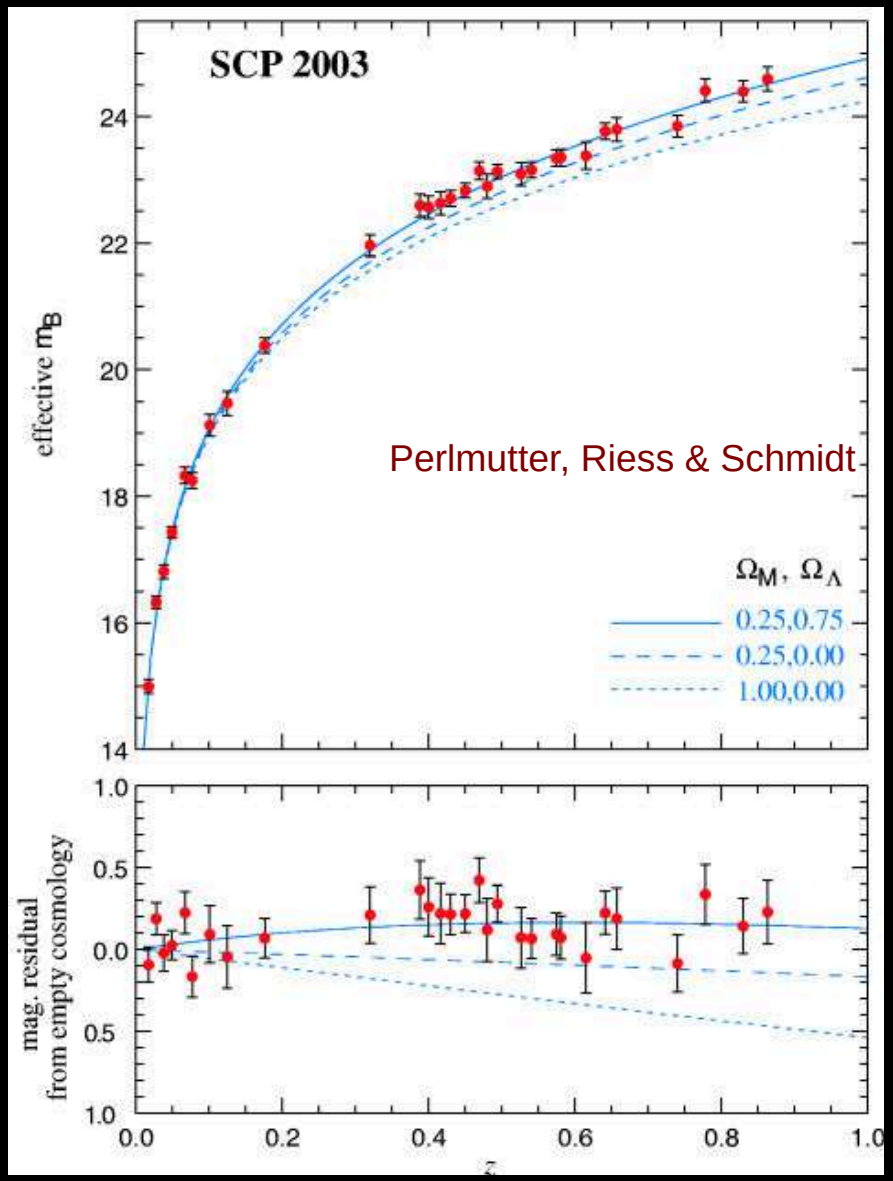


Curva di luce



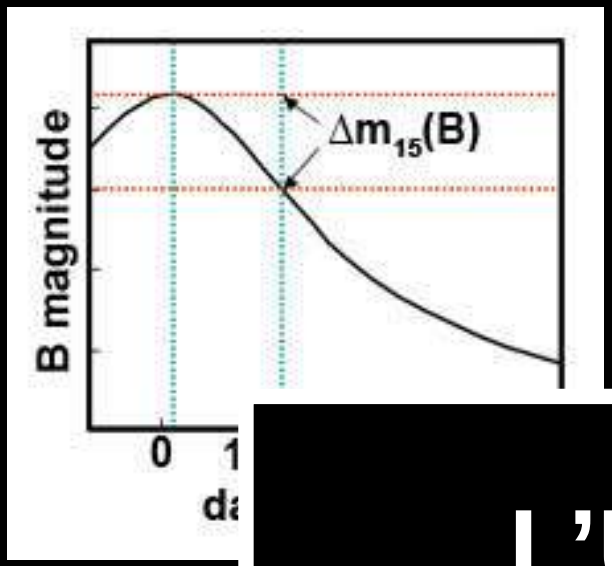
… e la loro distanza può essere determinata!!!

Luminosita'

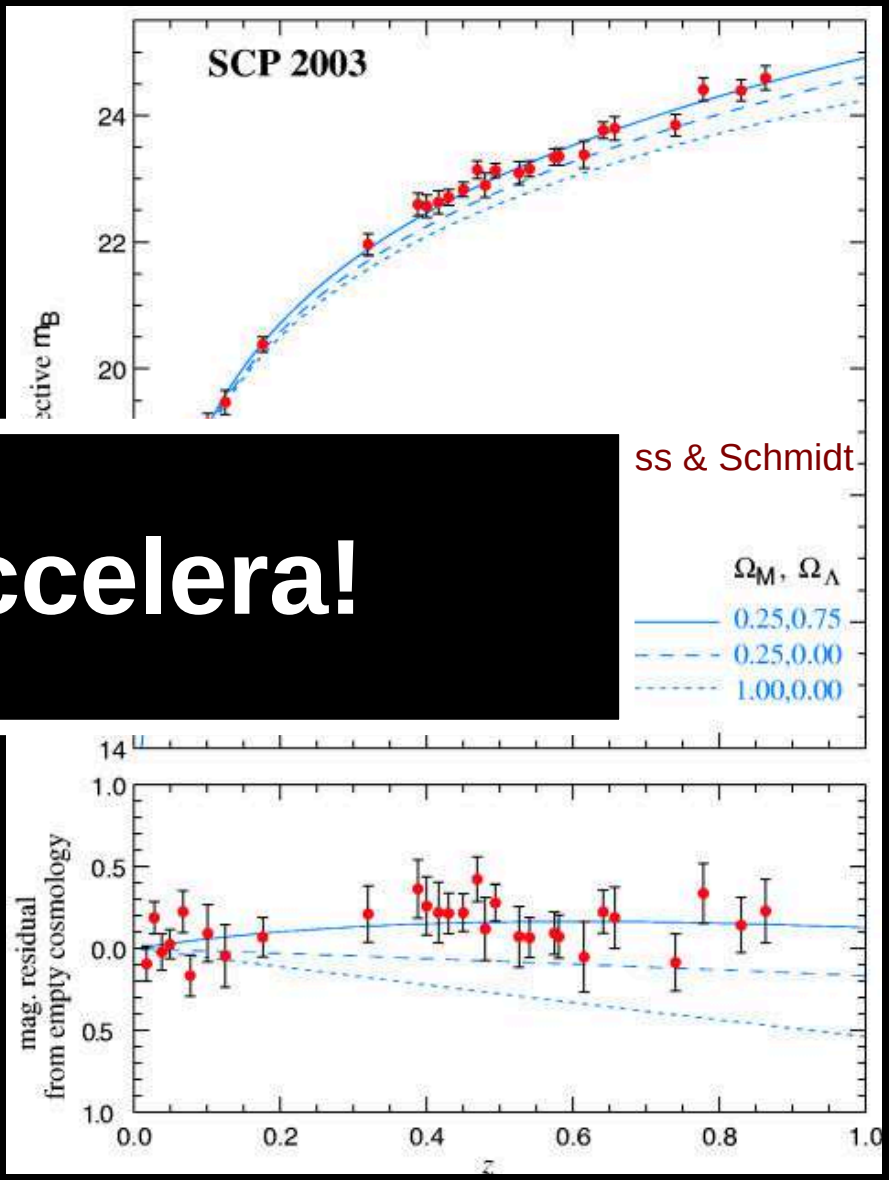


Distanza

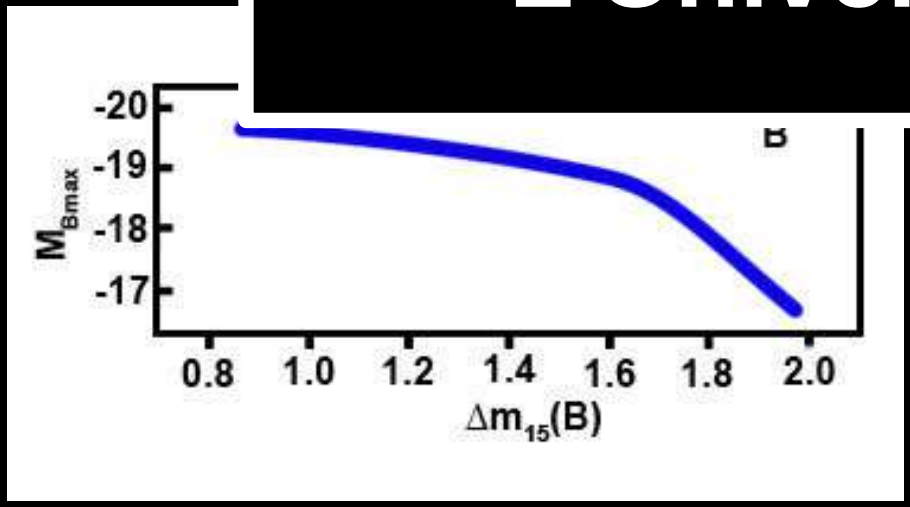
Che cos'è l'energia oscura?



Curva di luce



L'Universo accelera!



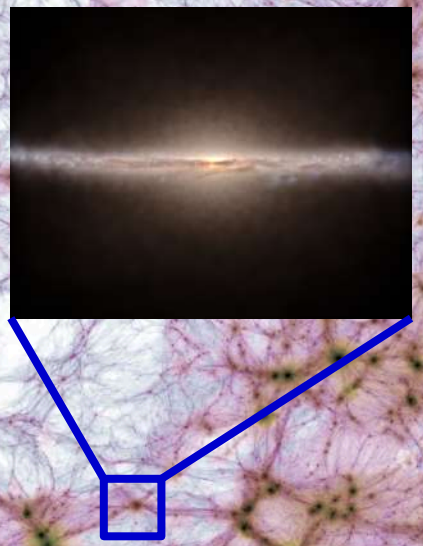
… e la loro distanza può essere determinata!!!

Distanza

Come si formano le galassie?

Progetto IllustrisTNG

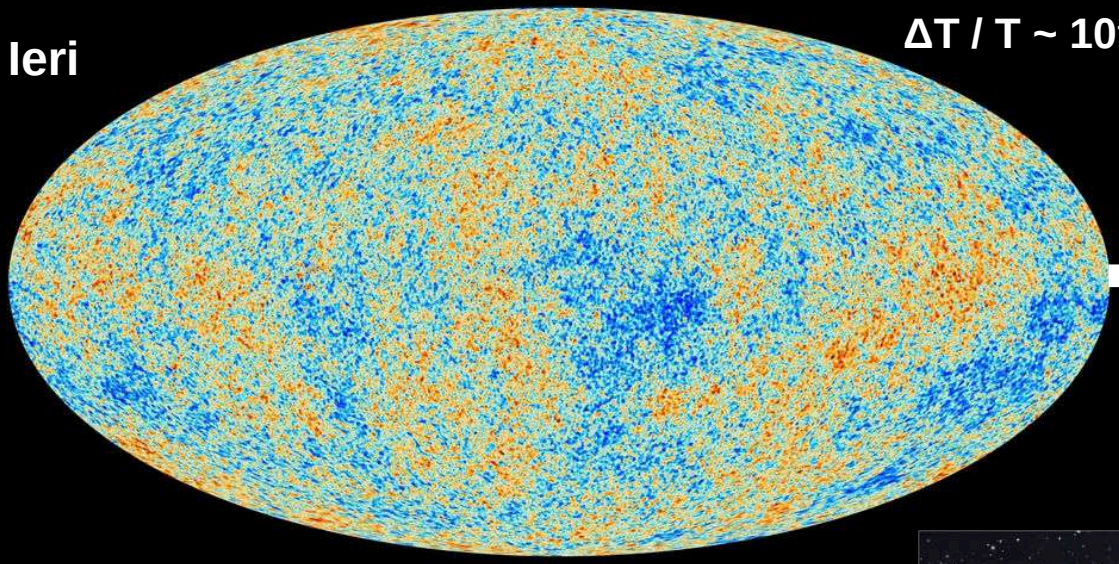
Ok, ma dove sono?



Progetto IllustrisTNG

Dal Big Bang alle galassie

Ieri



$\Delta T / T \sim 10^{-5}$

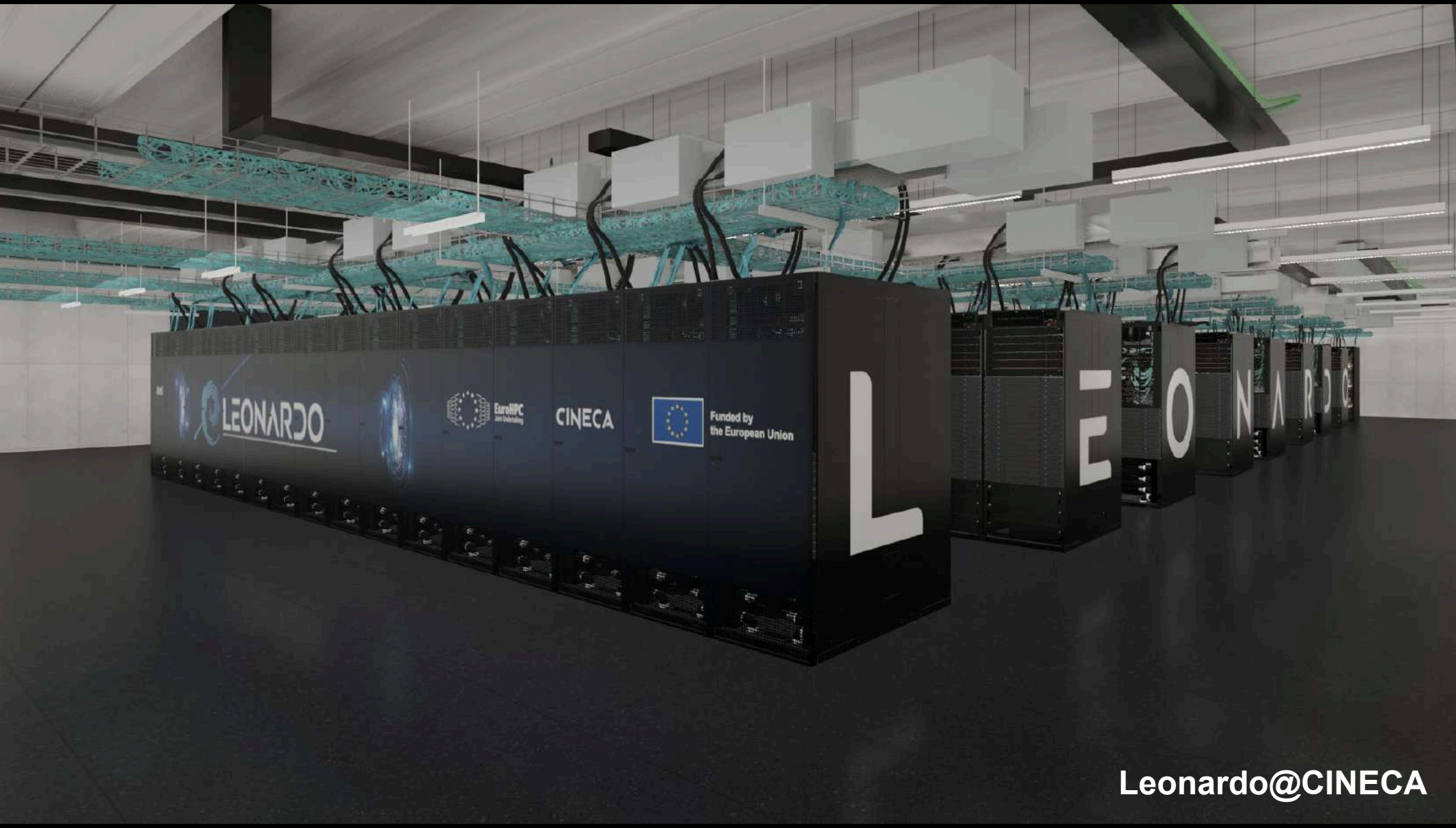
13.8 miliardi di anni
di evoluzione

Oggi

I processi che portano alla formazione delle galassie sono molto complessi

Come facciamo a capirci qualcosa?

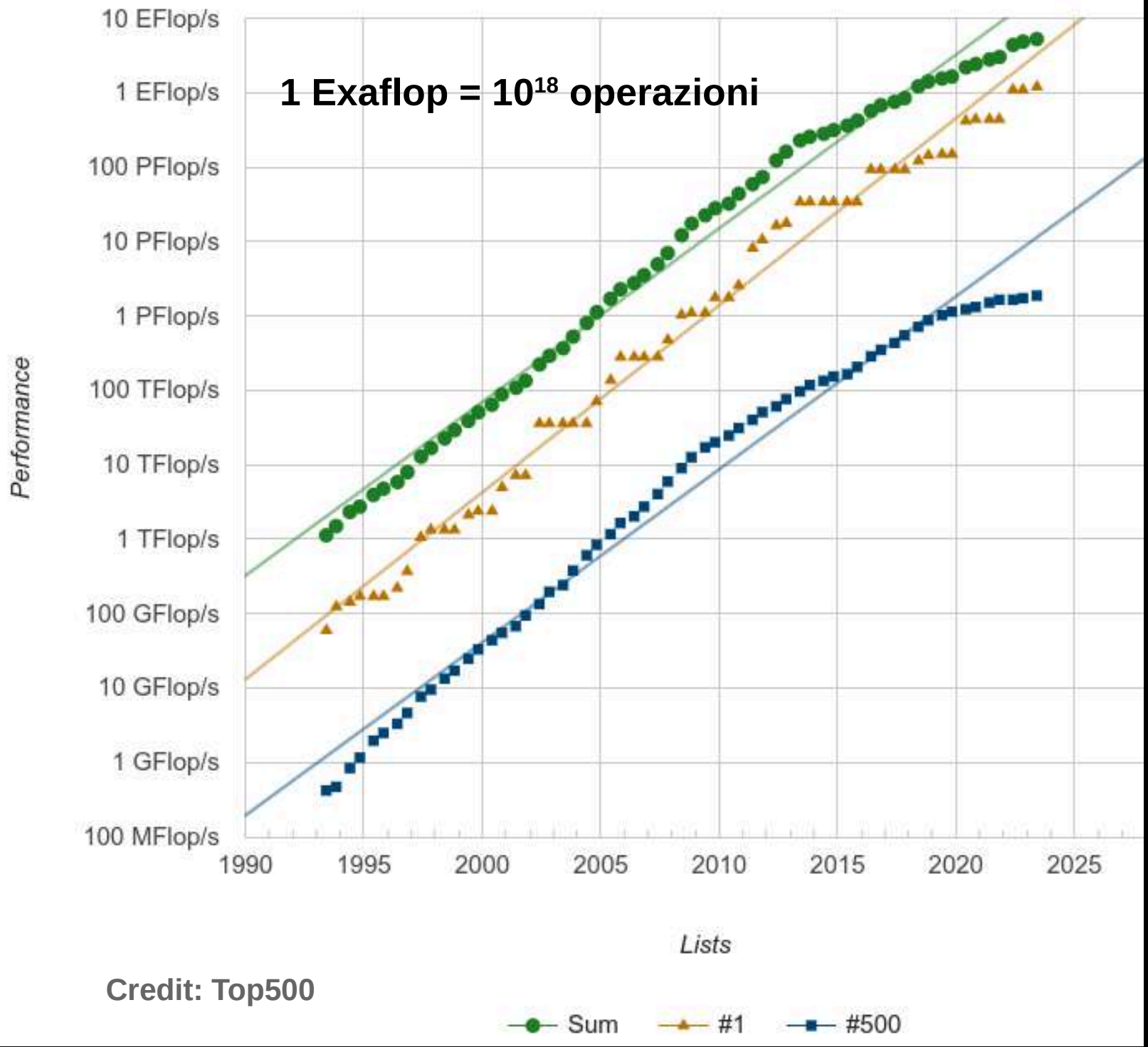
Utilizzando supercomputer



Leonardo@CINECA

Queste macchine hanno milioni di processori e consentono di effettuare i calcoli complessi necessari per lo svolgimento delle simulazioni

Sviluppo della potenza di calcolo

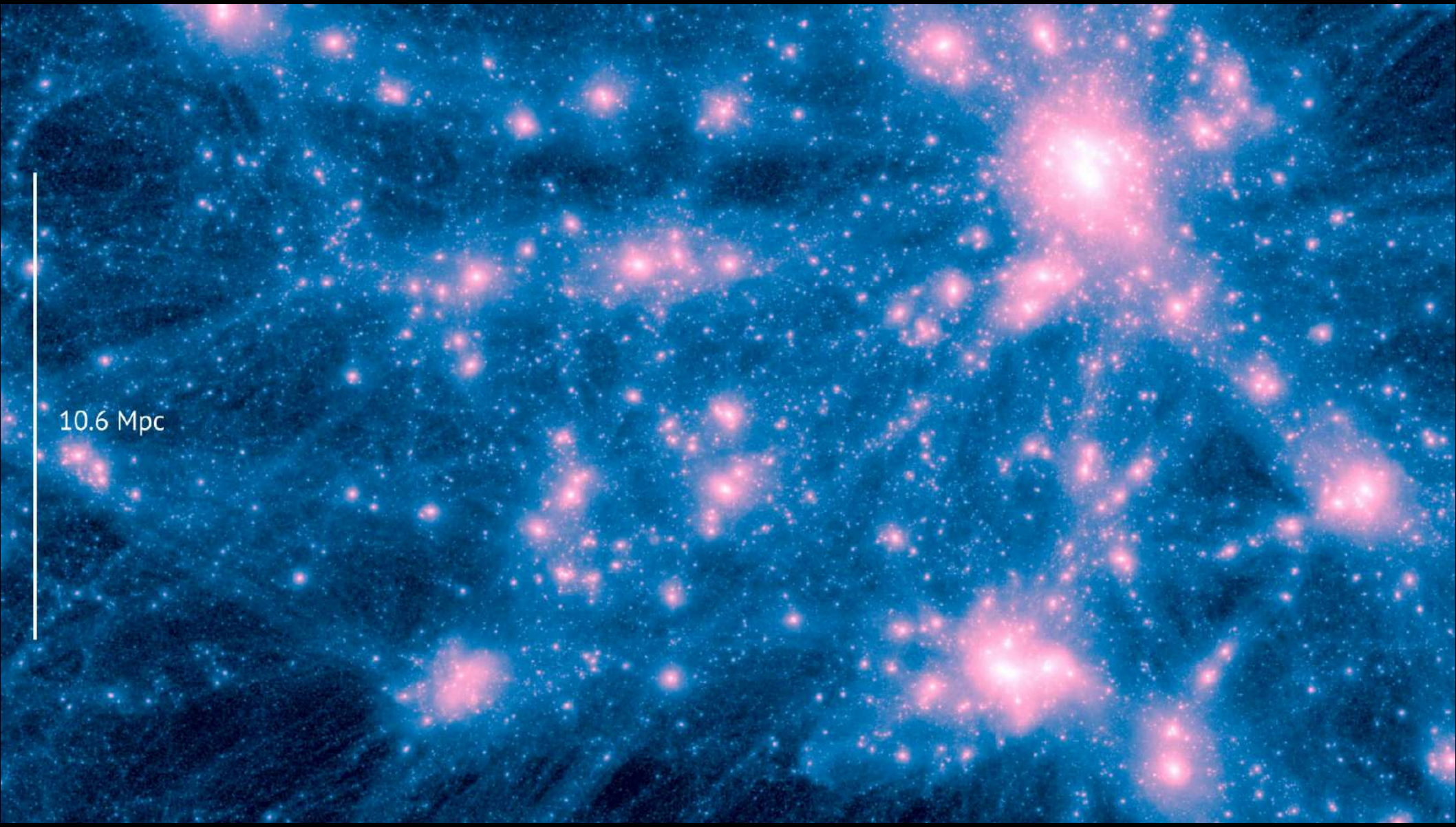


1 Exaflop = 10^{18} operazioni

Credit: Top500

Ciò che rende possibile lo sviluppo della nuove generazione di simulaizoni cosmologiche è la *crescita esponenziale* della potenza dei (super) computer

La formazione delle galassie è un problema complesso



Illustris (Vogelsberger+ 2014)

“Ingredienti” principali delle simulazioni

gas cooling	inter-stellar medium	star formation	stellar feedback	super-massive black holes	active galactic nuclei	magnetic fields	radiation fields	cosmic rays
atomic/ molecular/ metals/ tabulated/ network	effective equation of state/ multi-phase	initial stellar mass function/ probabilistic sampling/ enrichment	kinetic/ thermal/ variety of sources from stars, supernovae	numerical seeding/ growth by accretion prescription/ merging	kinetic/ thermal/ radiative/ quasar mode/ radio mode	ideal MHD/ cleaning schemes/ constrained transport	ray tracing/ Monte Carlo/ moment-based	production/ heating/ anisotropic diffusion/ streaming

most important astrophysical processes

numerical discretization of matter components

Collisionless Gravitational Dynamics

- *N*-body methods based on integral Poisson’s equation (e.g. tree, fast multipole)
- *N*-body methods based on differential Poisson’s equation (e.g. particle-mesh, multigrid)
- *N*-body hybrid methods (e.g. TreePM)
- Beyond *N*-body methods (e.g. Lagrangian tesselation)

dark matter

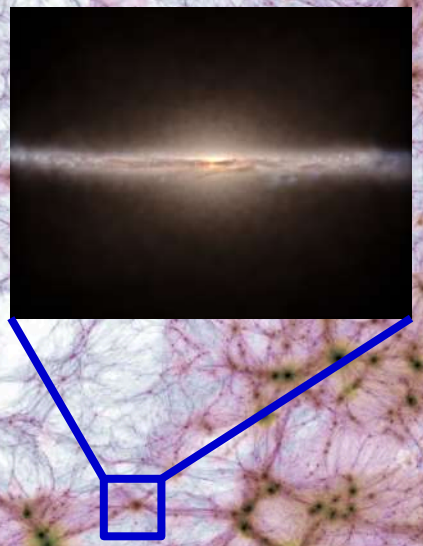
Hydrodynamics

- Lagrangian methods (e.g. smoothed particle hydrodynamics)
- Eulerian methods (e.g. adaptive-mesh-refinement)
- Arbitrary Lagrangian-Eulerian methods (e.g. moving mesh)
- Mesh-free / mesh-based

gas

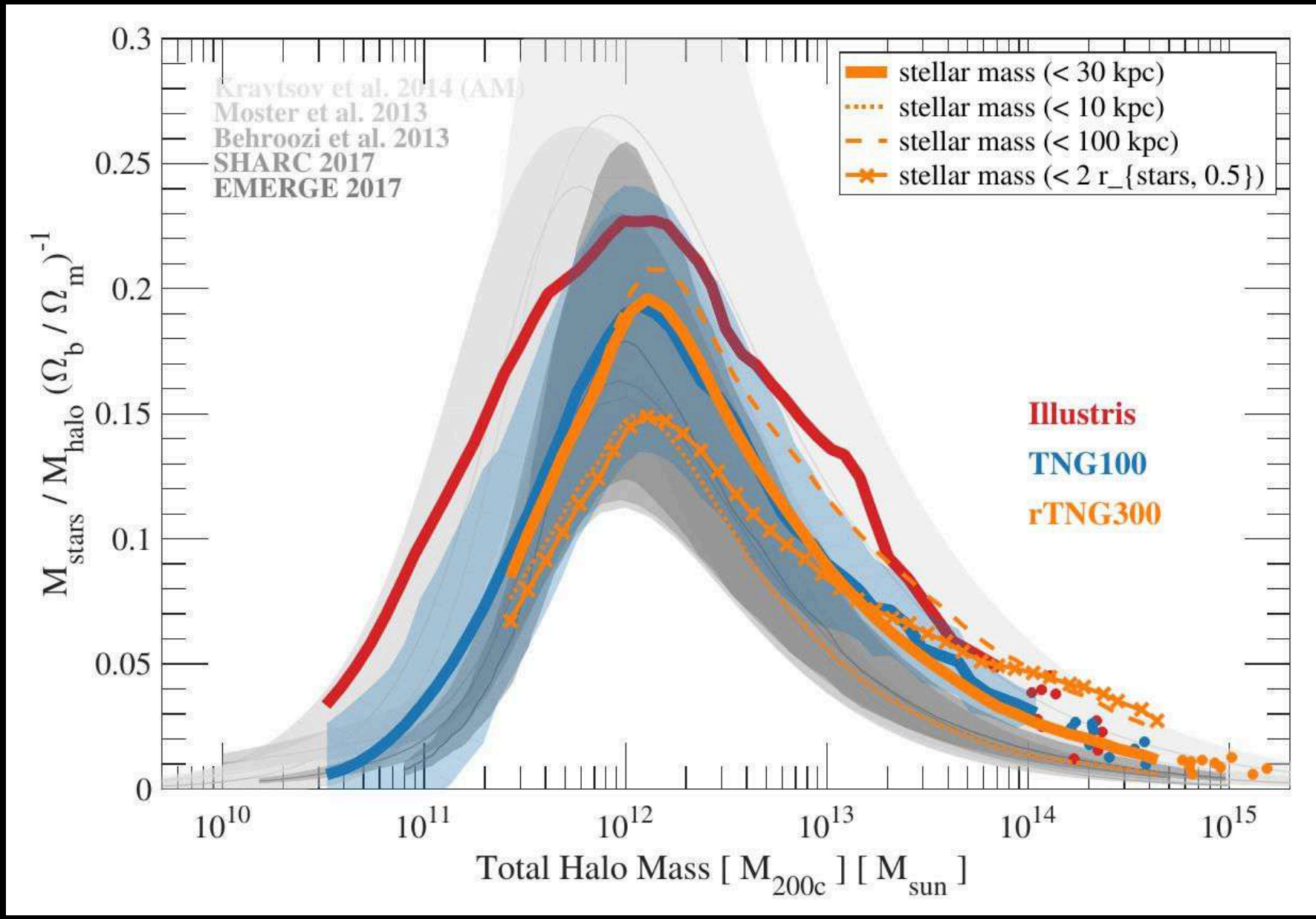
Vogelsberger, Marinacci+ (2020)

Per formare le galassie occorre “mescolare” tutti gli ingredienti insieme...



Progetto IllustrisTNG

Le galassie sono inefficienti a formare stelle

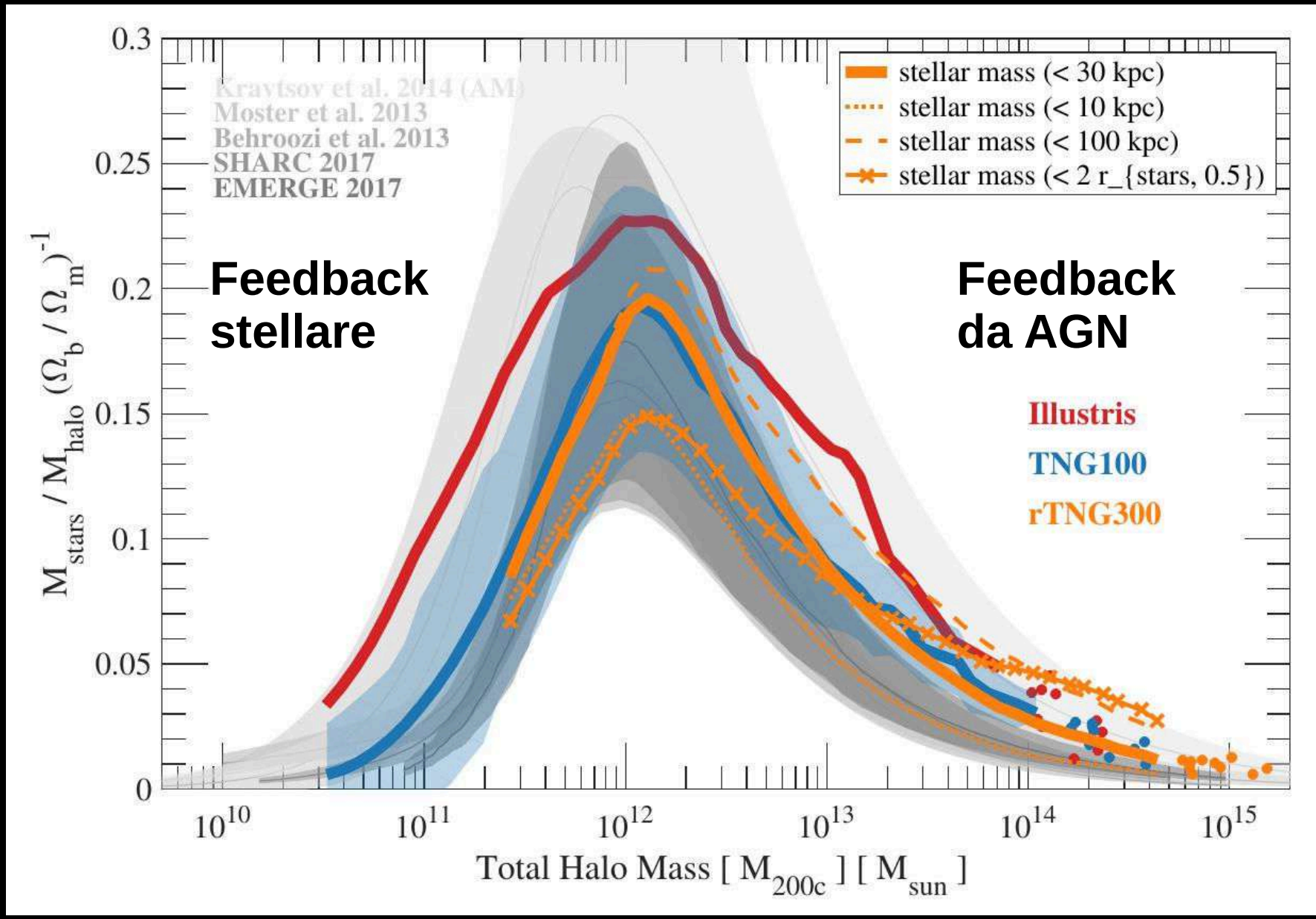


Formazione stellare più efficiente

Aloni più massicci

Pillepich, w/ FM (2017)

Le galassie sono inefficienti a formare stelle



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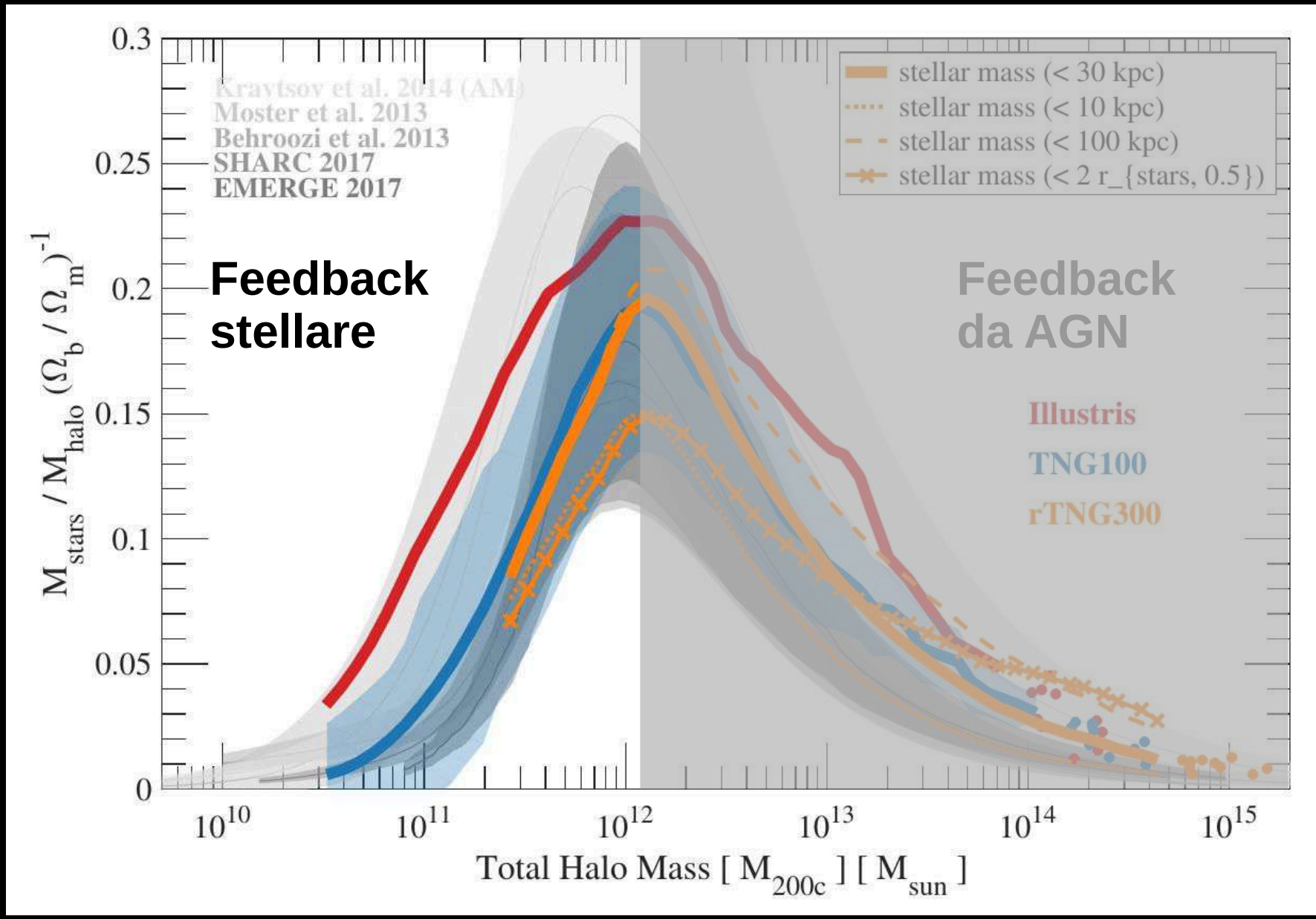
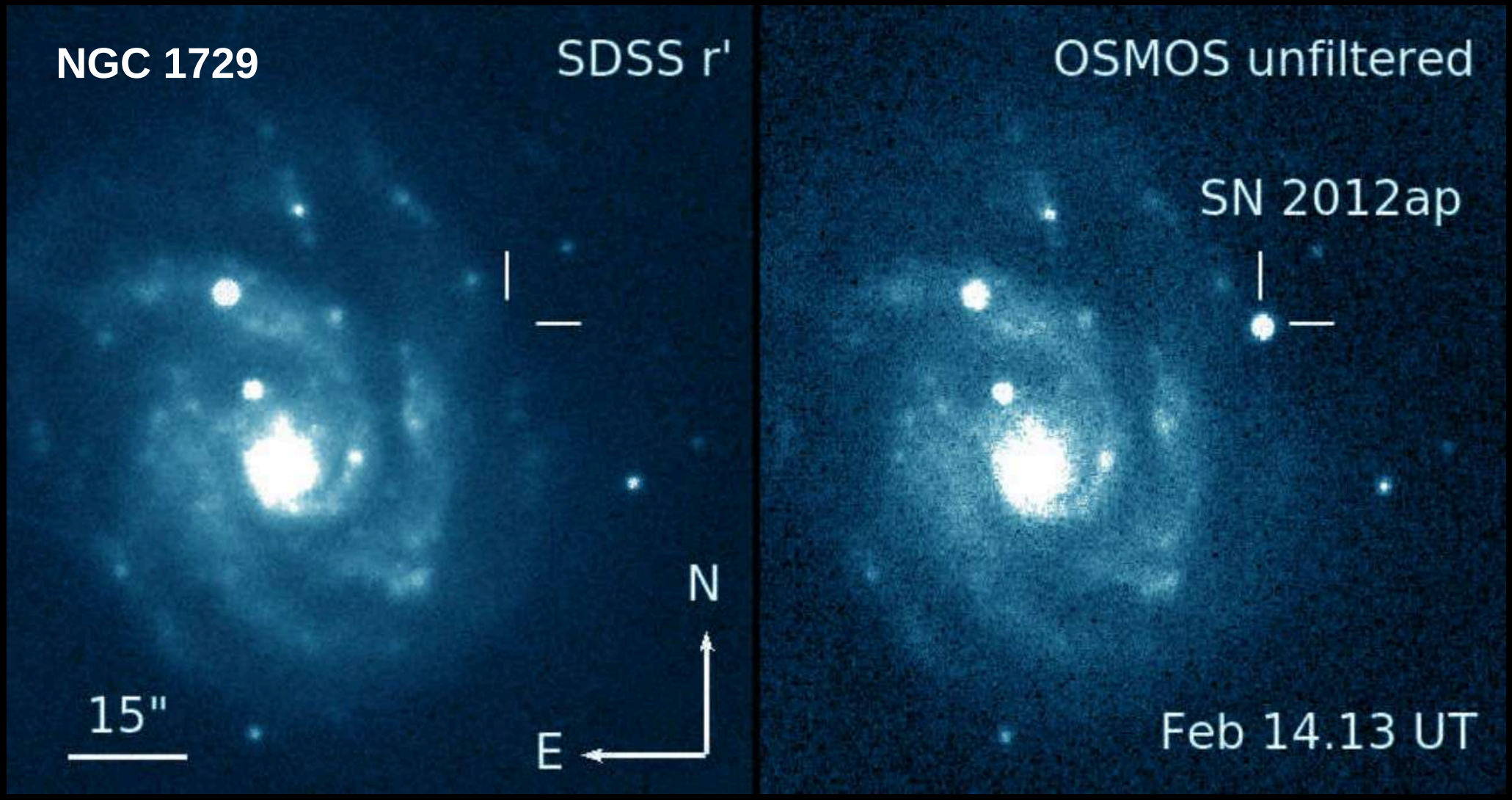


Formazione stellare più efficiente

Aloni più massicci

Pillepich, w/ FM (2017)

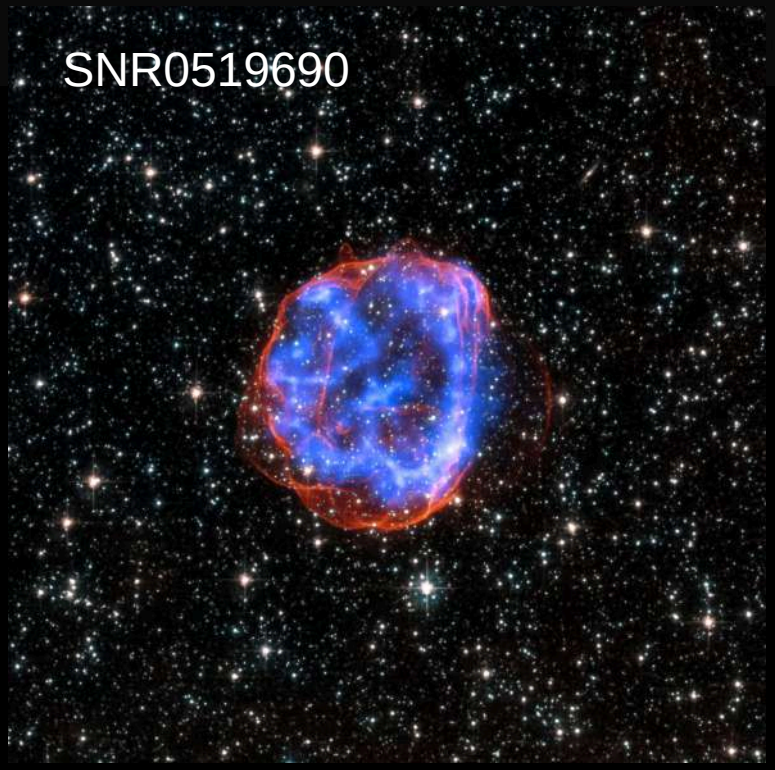
Come muore una stella

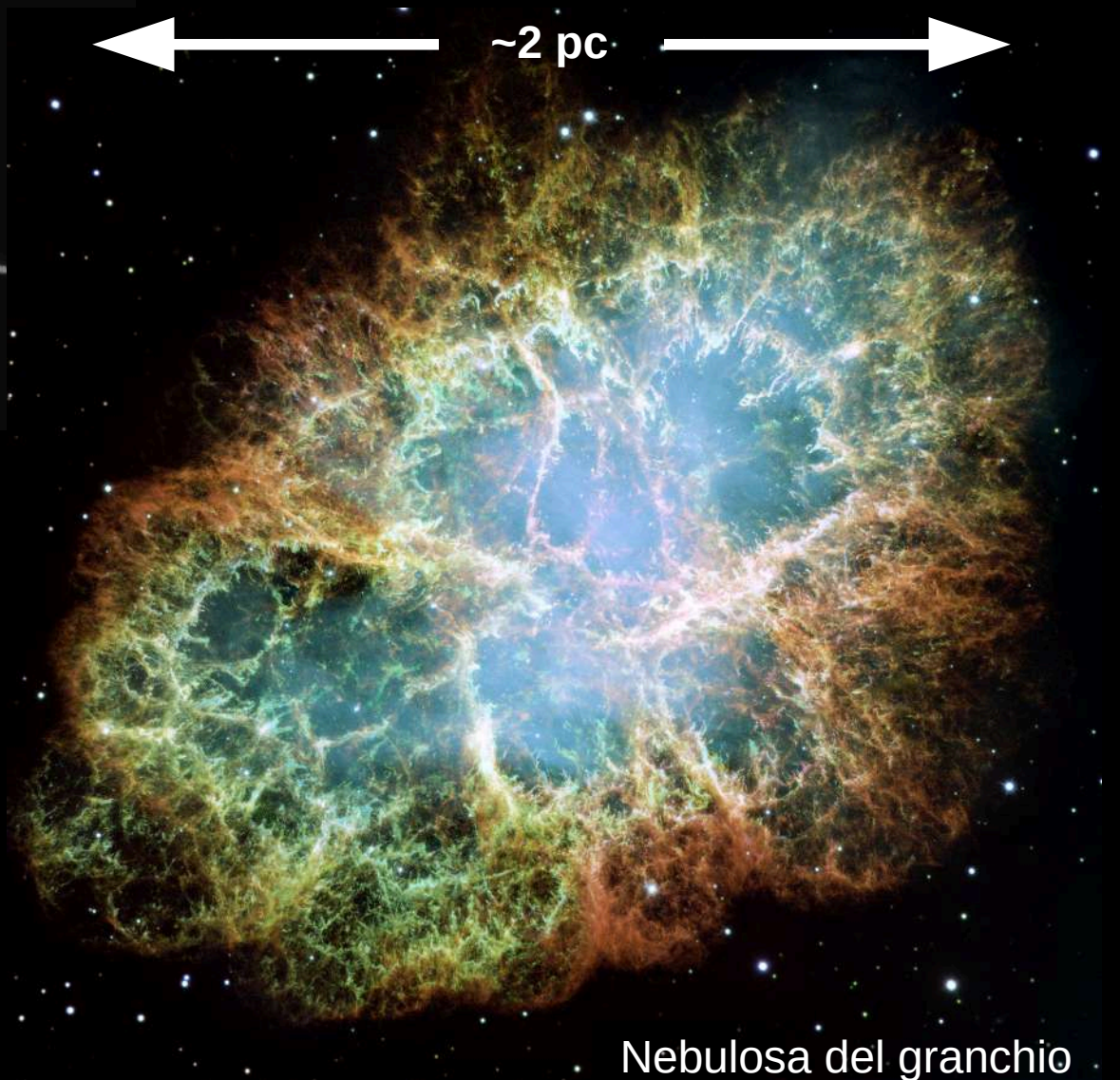


Per un breve periodo una supernova puo' diventare brillante quanto una galassia!

Bombe... stellari

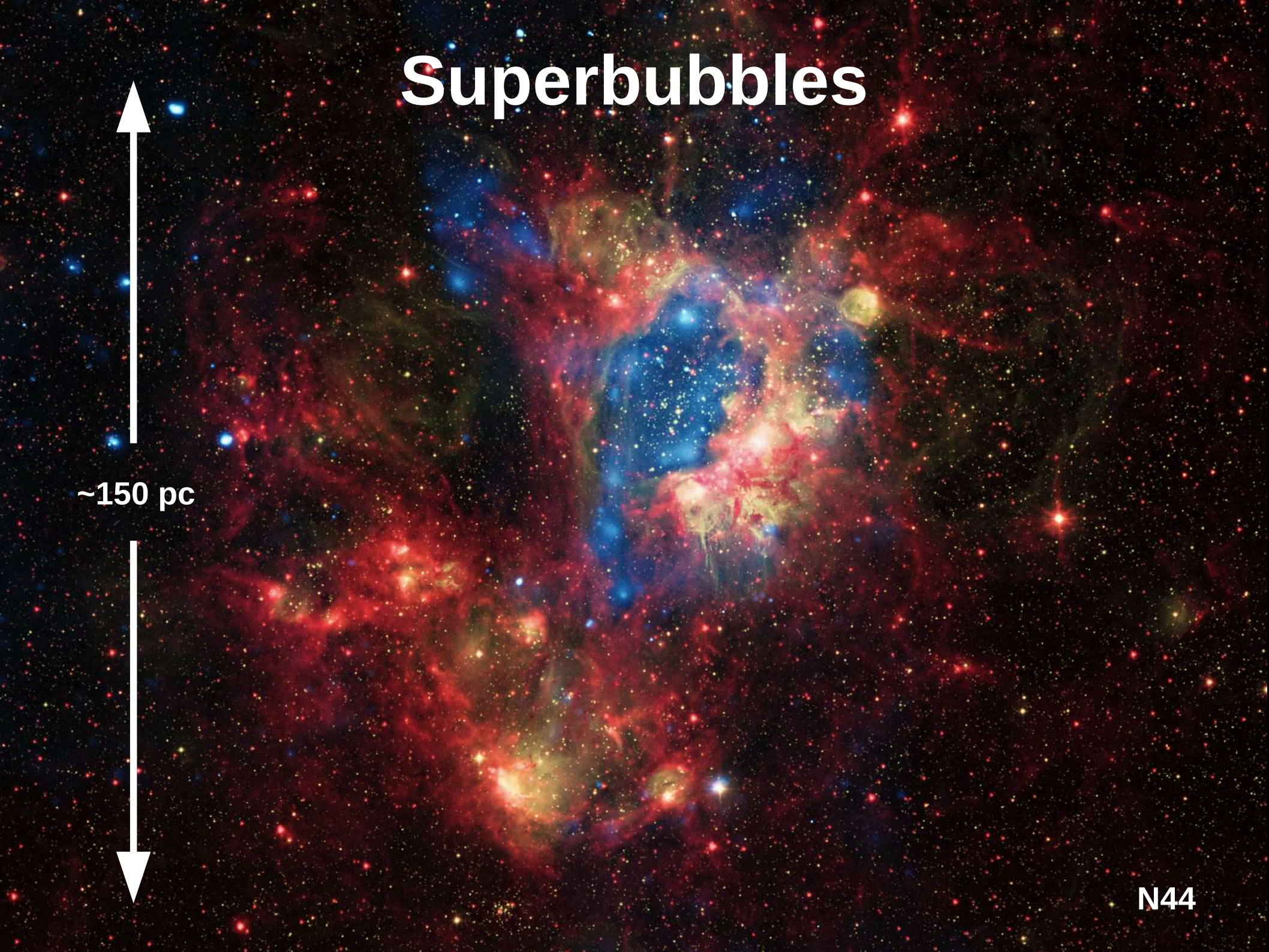
Trinity test



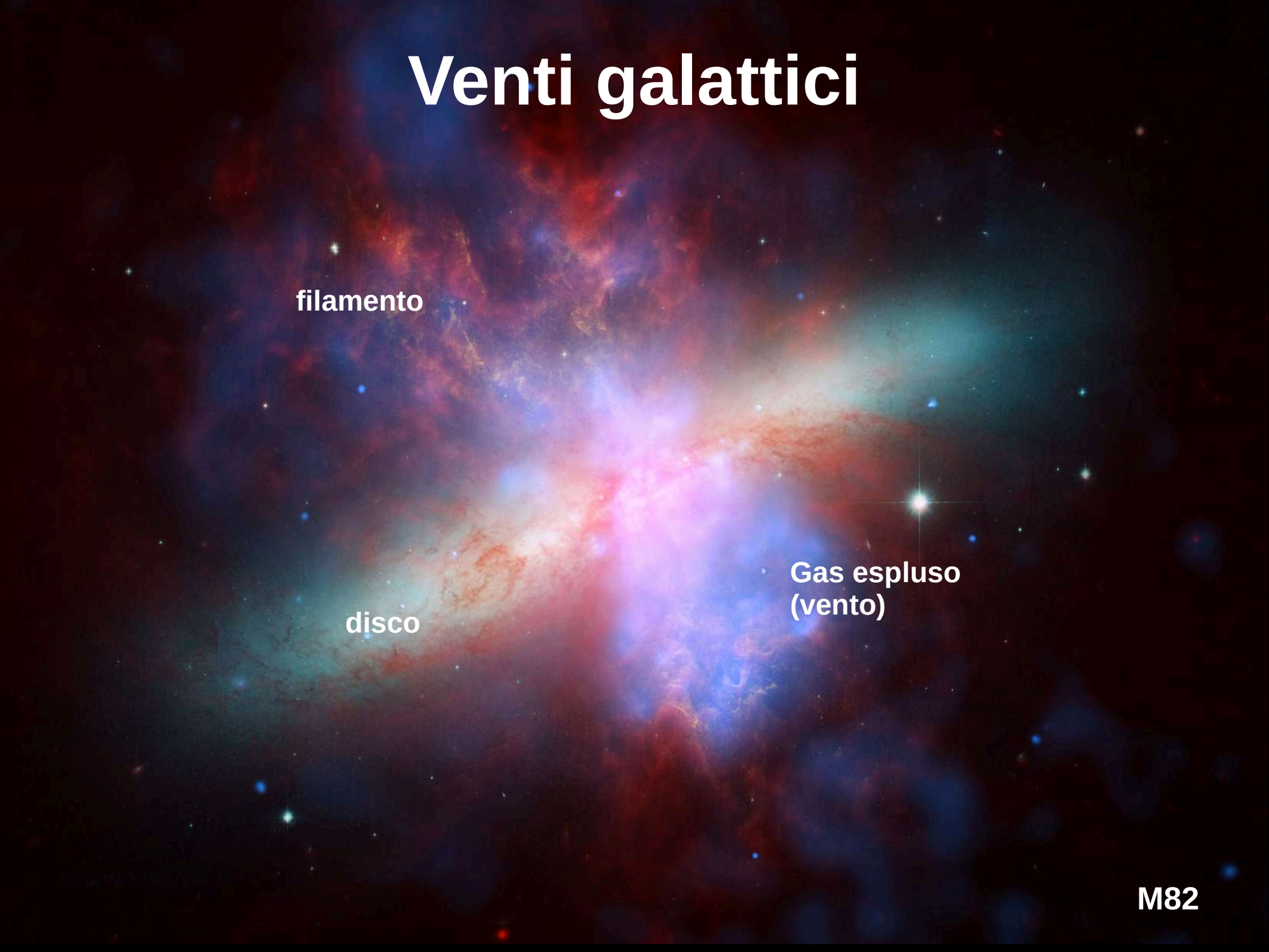


Nebulosa del granchio

Superbubbles



Venti galattici



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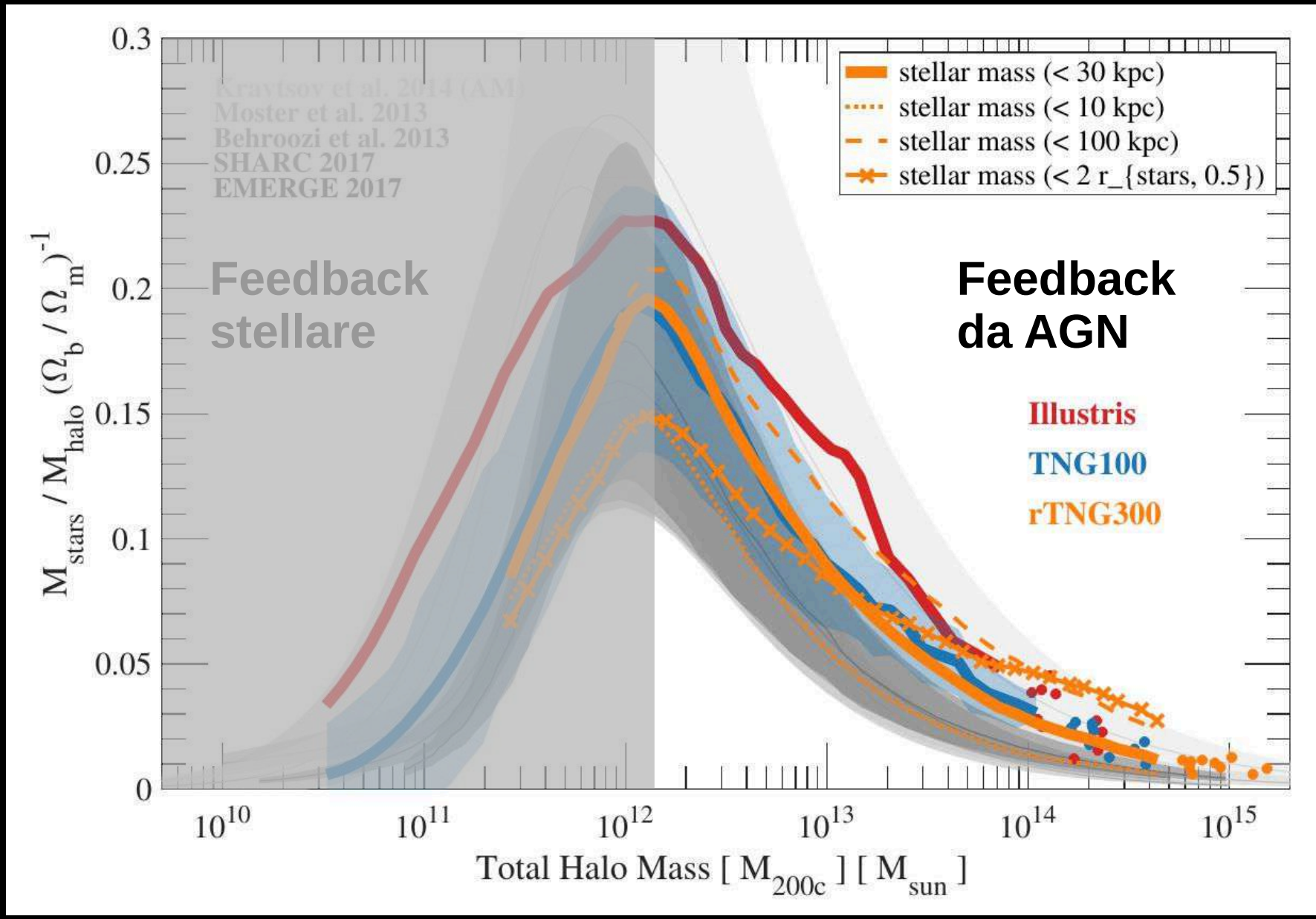
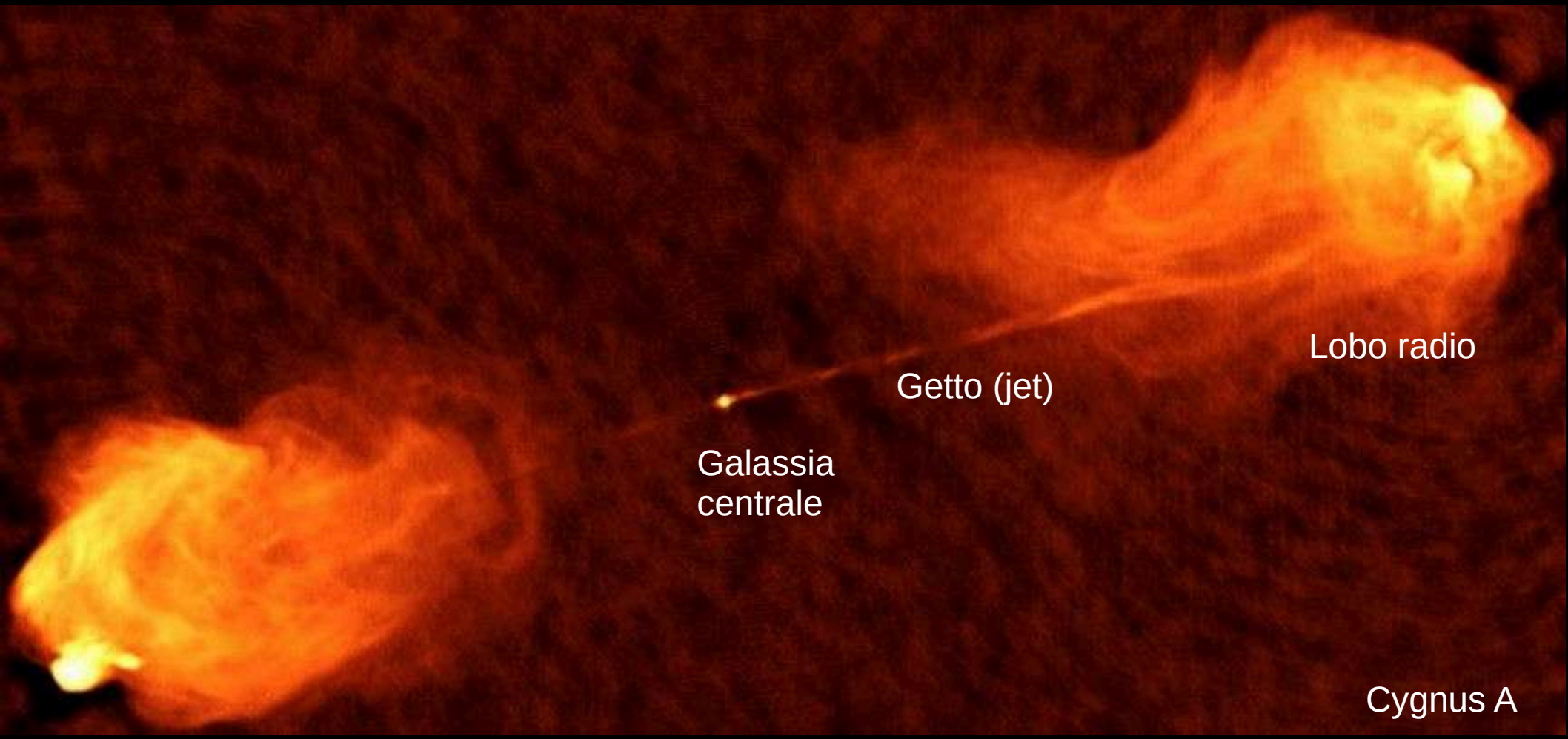


Formazione stellare più efficiente

Aloni più massicci

Pillepich, w/ FM (2017)

Il ruolo dei buchi neri/nuclei galattici attivi



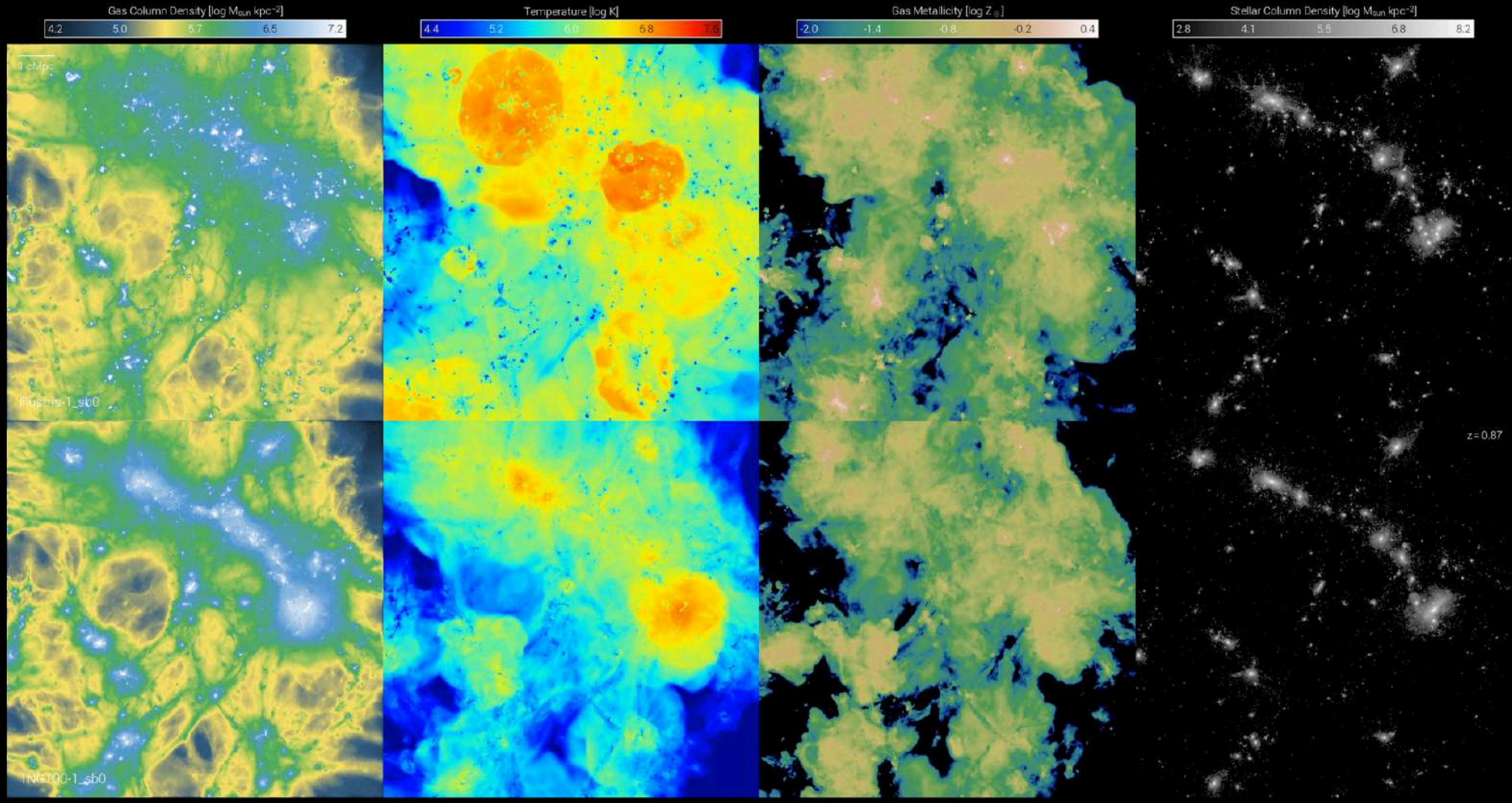
~ 100 kpc

Buchi neri in azione

L'ammasso di Perseo ai raggi X

IllustrisTNG

Simulazioni cosmologiche allo stato dell'arte

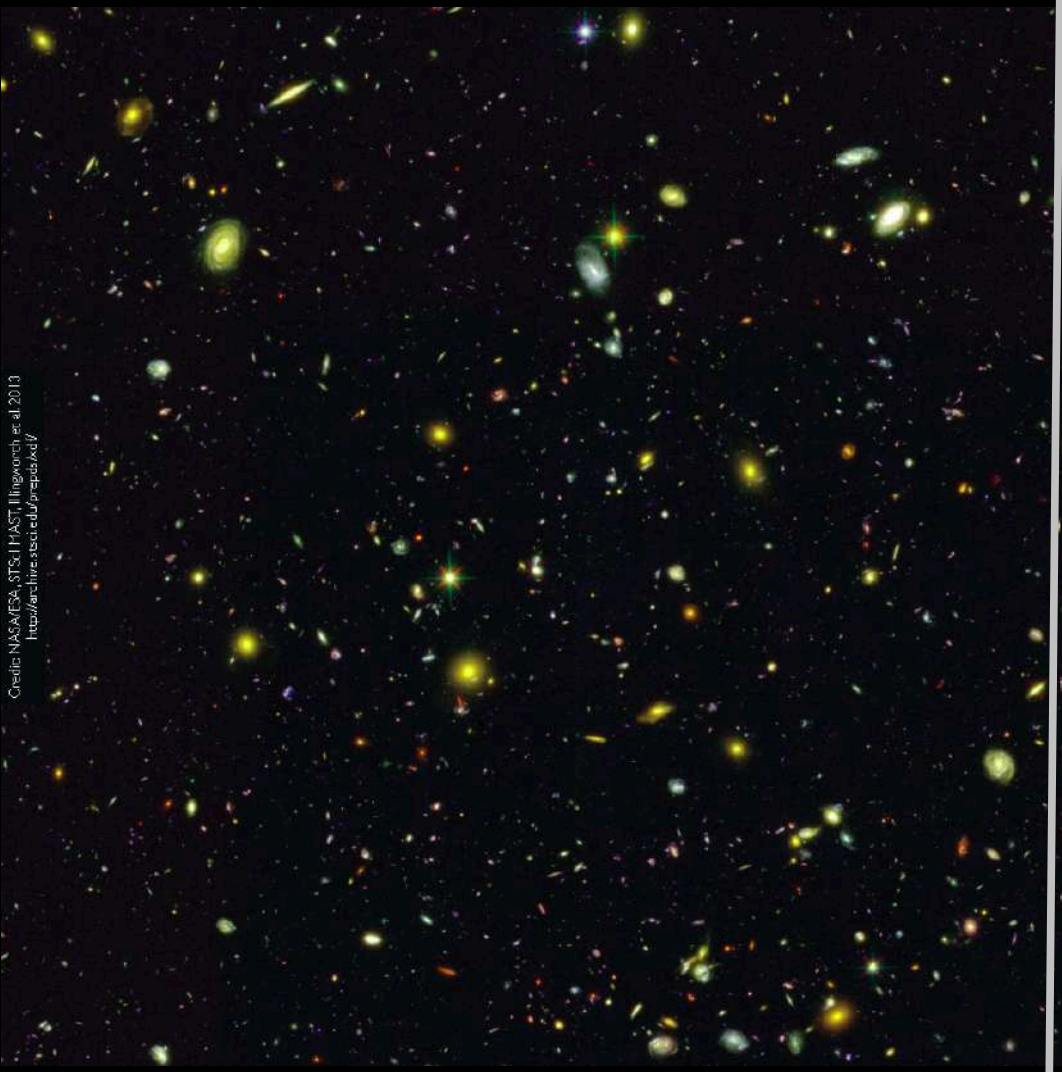


Vecchio modello

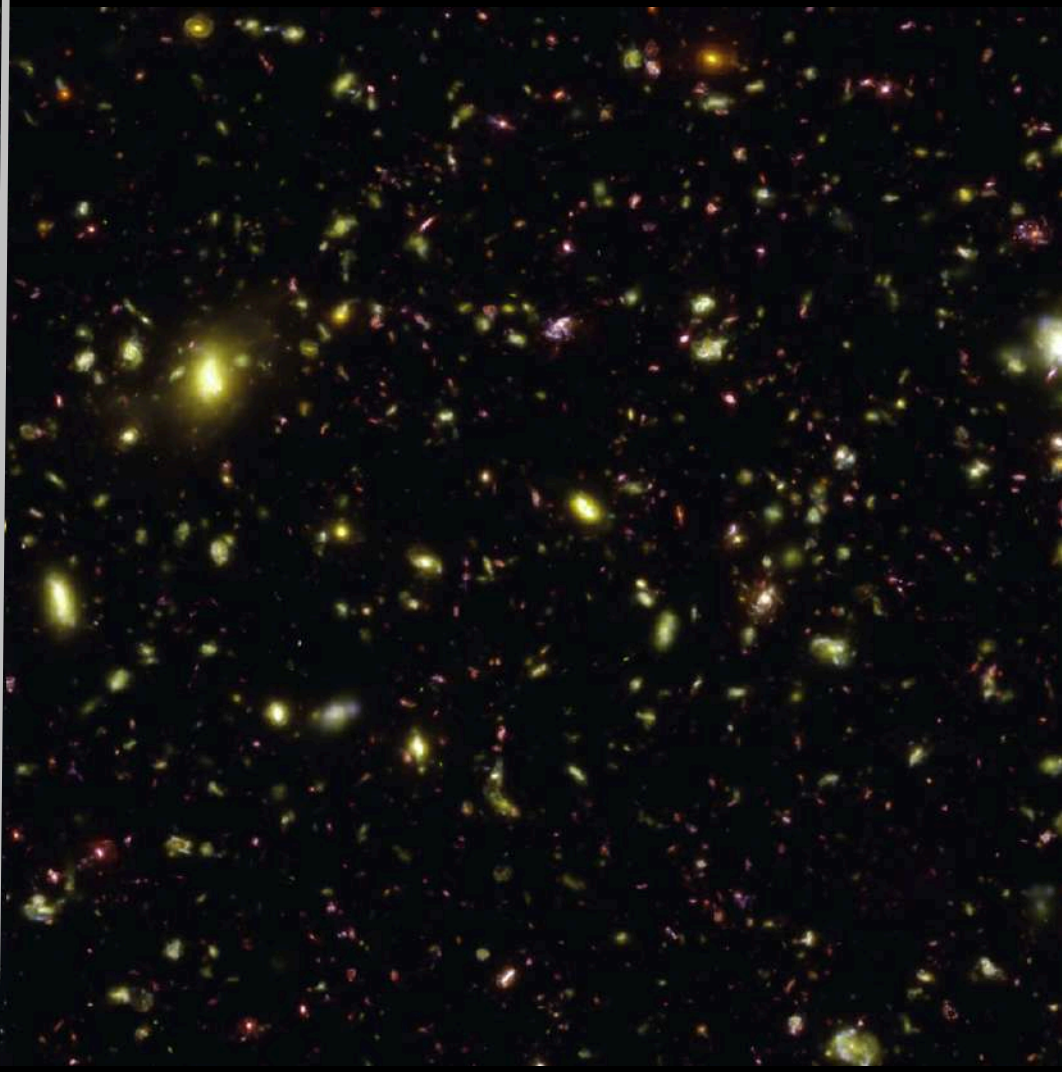
Nuovo modello

Avete la vista buona?

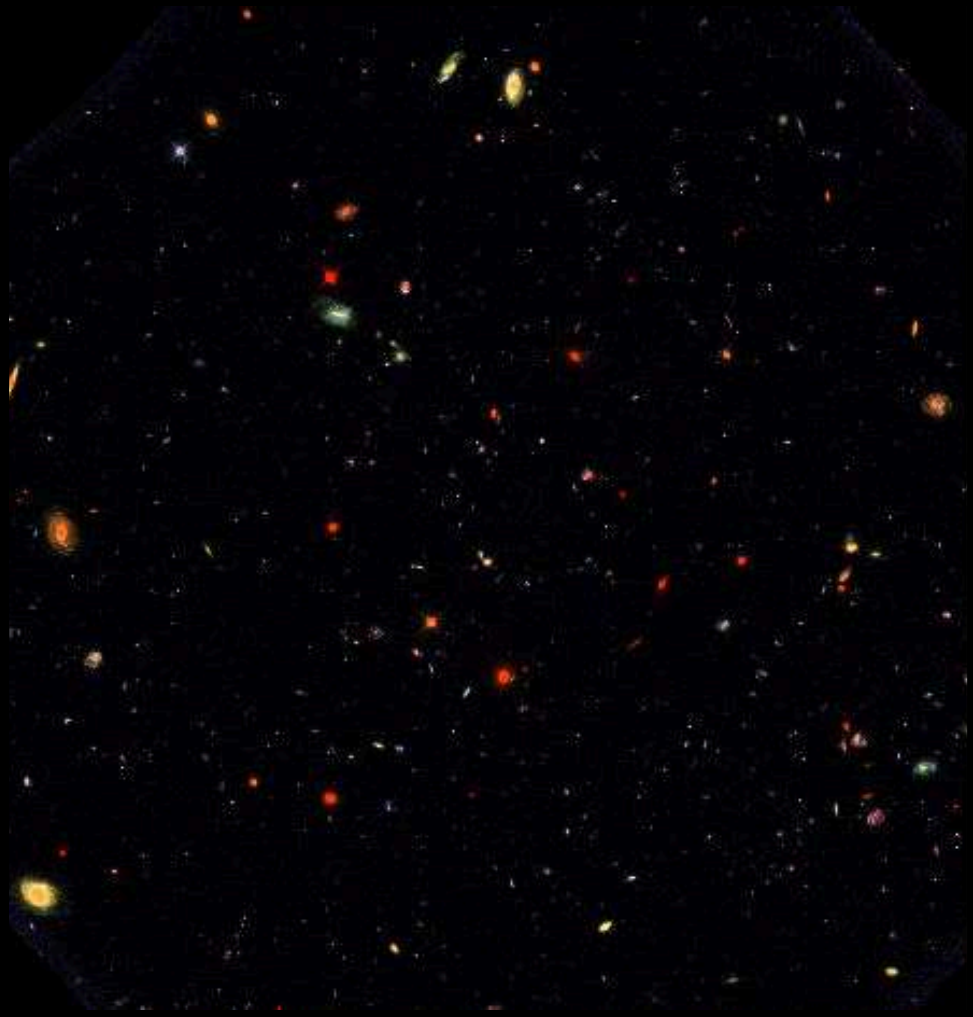
Universo reale



Universo virtuale



Esperimenti numerici

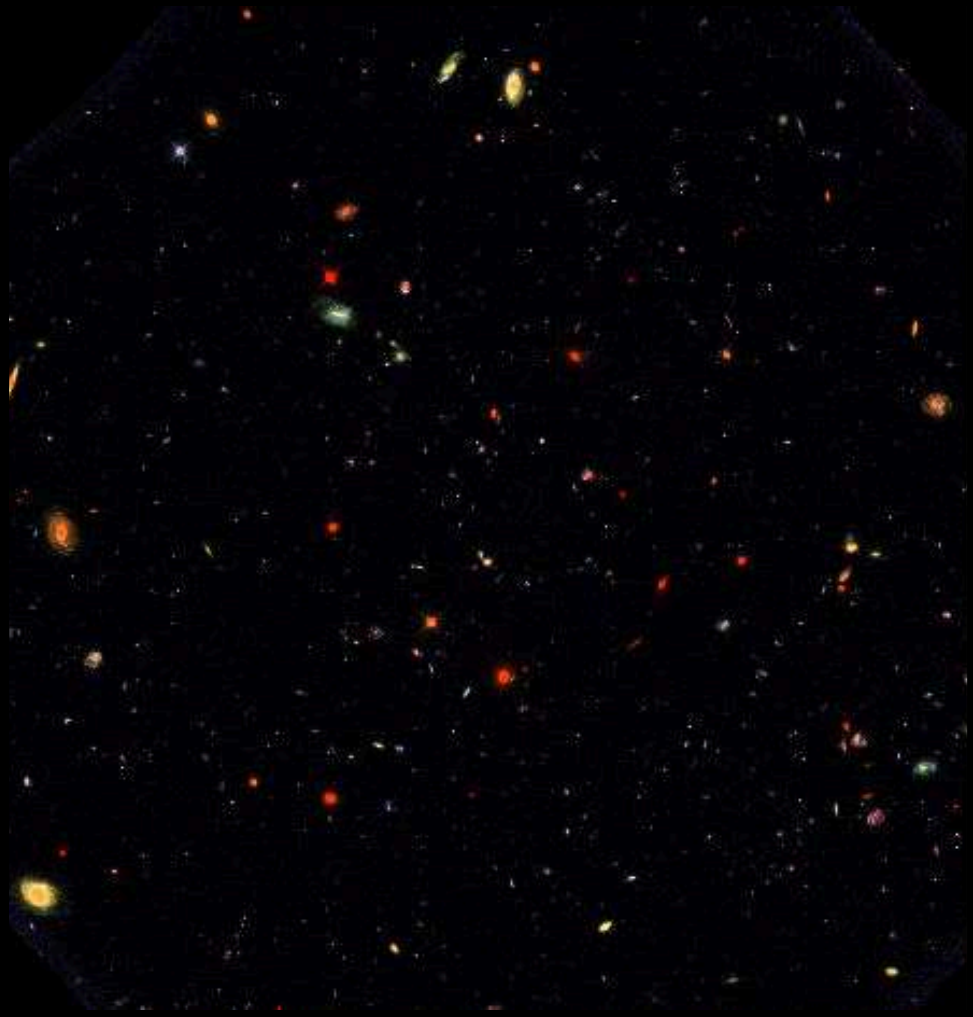


Universo osservato

Universo virtuale:

senza feedback stellare
senza feedback da AGN

Esperimenti numerici

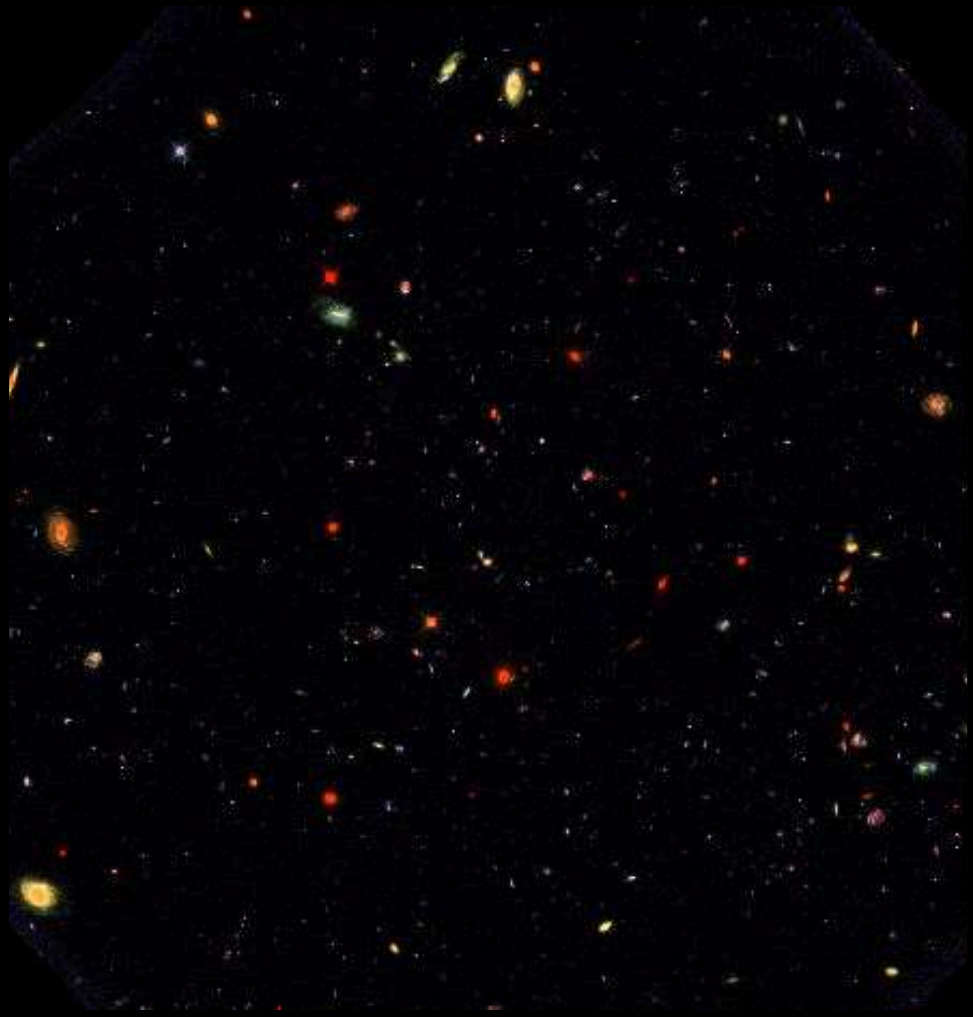


Universo osservato

Universo virtuale:

con feedback stellare
senza **f**eedback da AGN

Esperimenti numerici



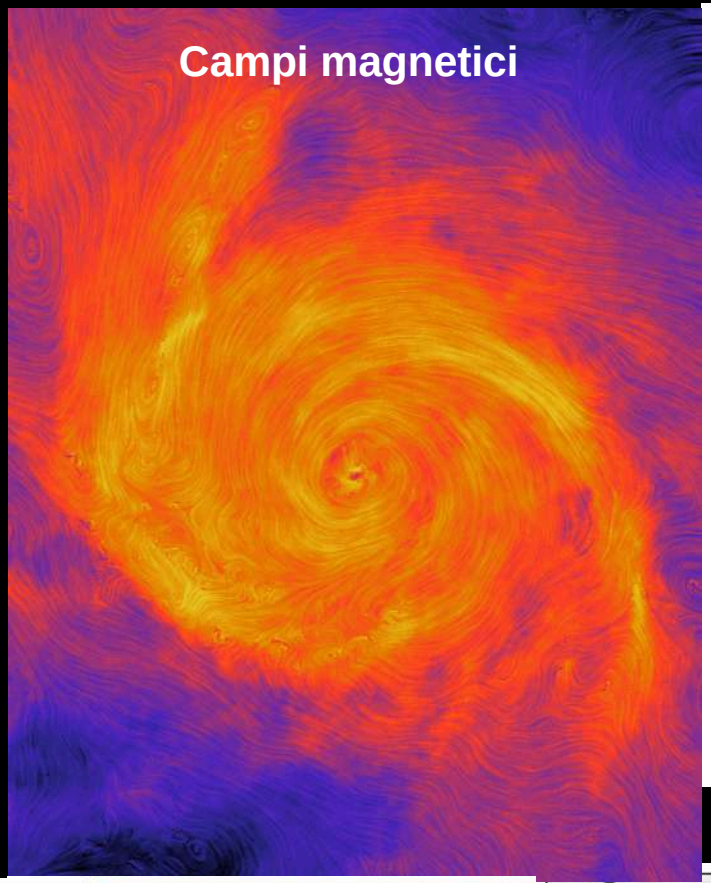
Universo osservato

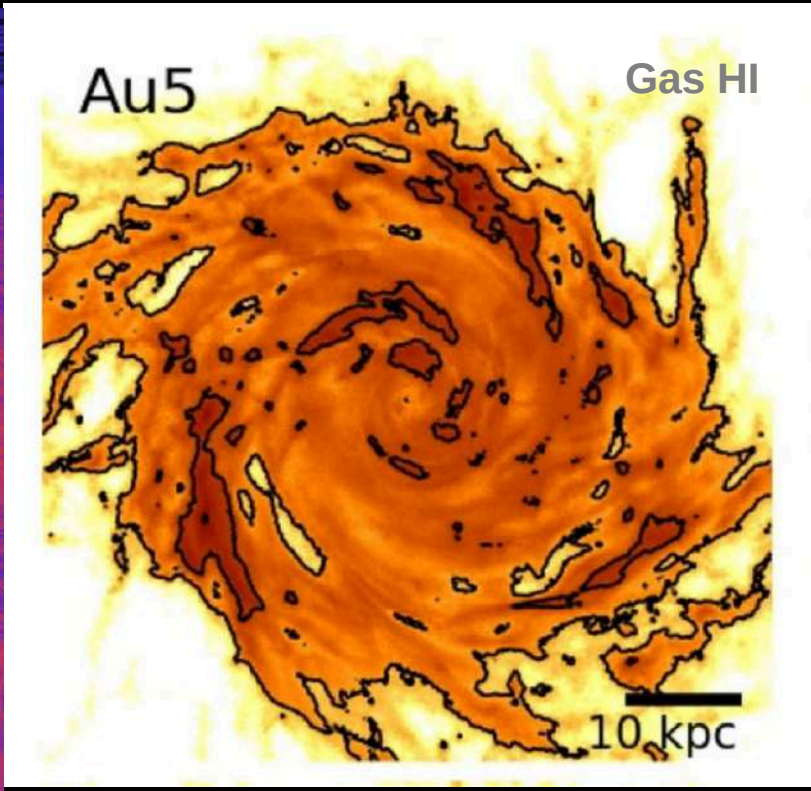
Universo virtuale:

con feedback stellare

con **f**eedback da AGN

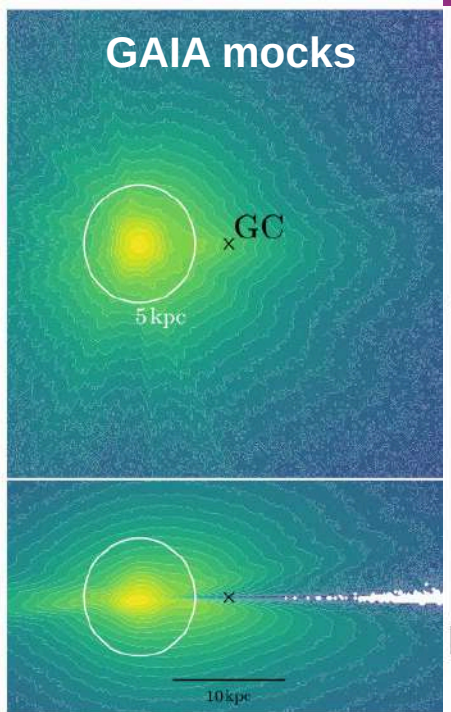

Warp

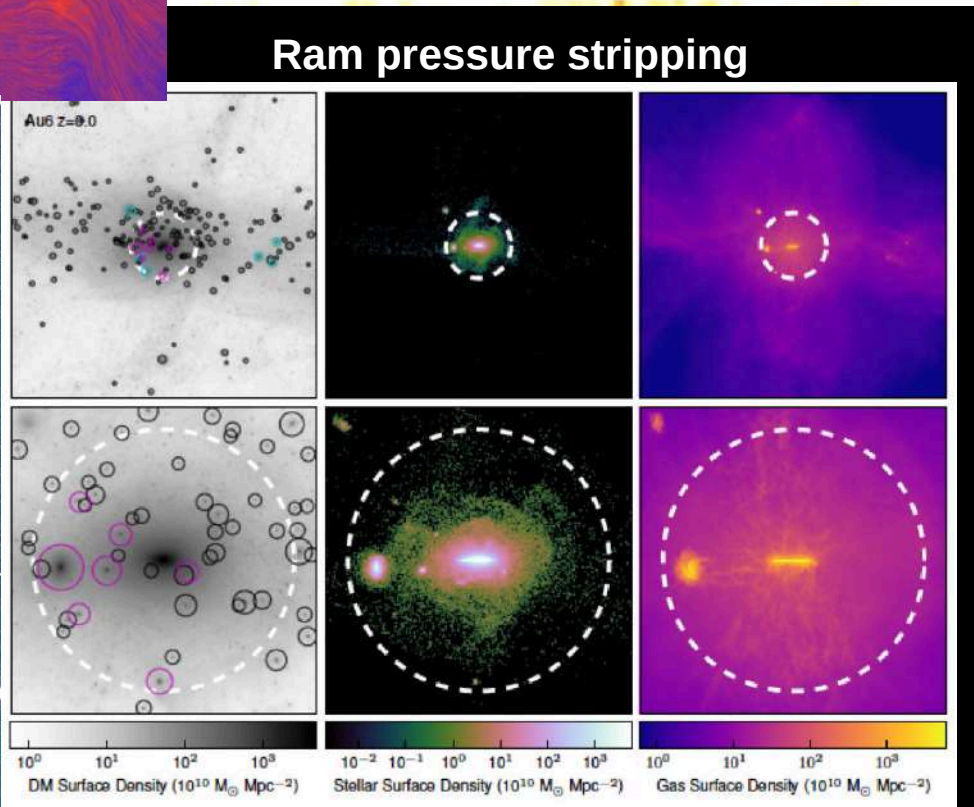

Campi magnetici


Au5
Gas HI
10 kpc


d<20 kpc


5<d<20 kpc

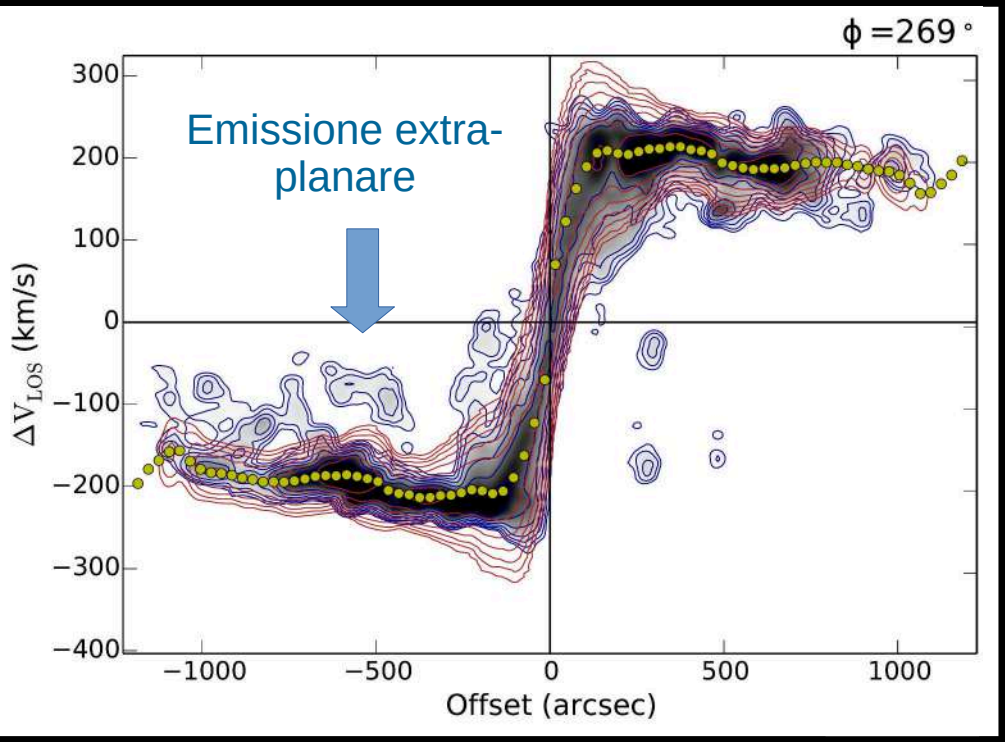

GAIA mocks
GC
5 kpc
10 kpc

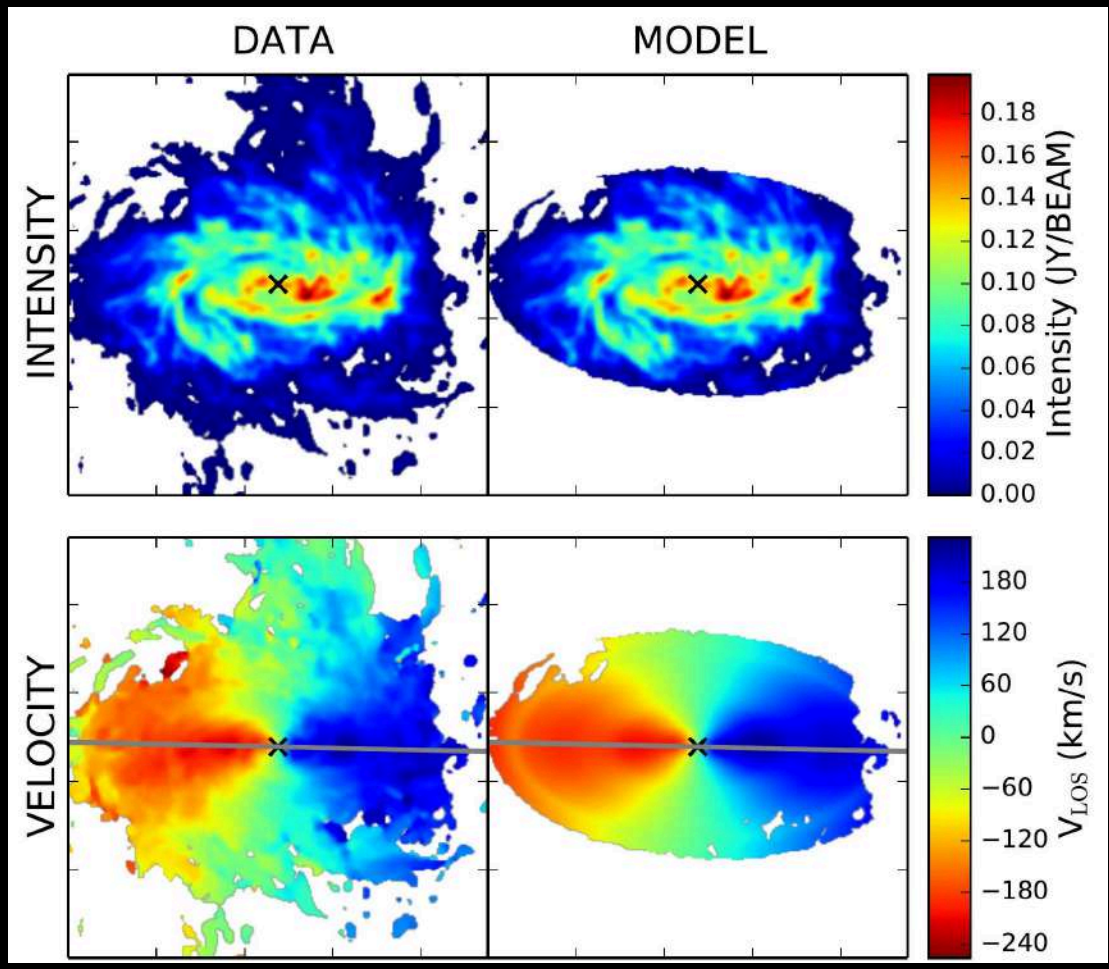

Ram pressure stripping
Au6 z=0.0
DM Surface Density (10¹⁰ M⊙ Mpc⁻²)
Stellar Surface Density (10¹⁰ M⊙ Mpc⁻²)
Gas Surface Density (10¹⁰ M⊙ Mpc⁻²)

Possiamo fare di meglio?

Miglioramento del confronto con le osservazioni

Serve come guida per lo sviluppo di simulazioni sempre più accurate



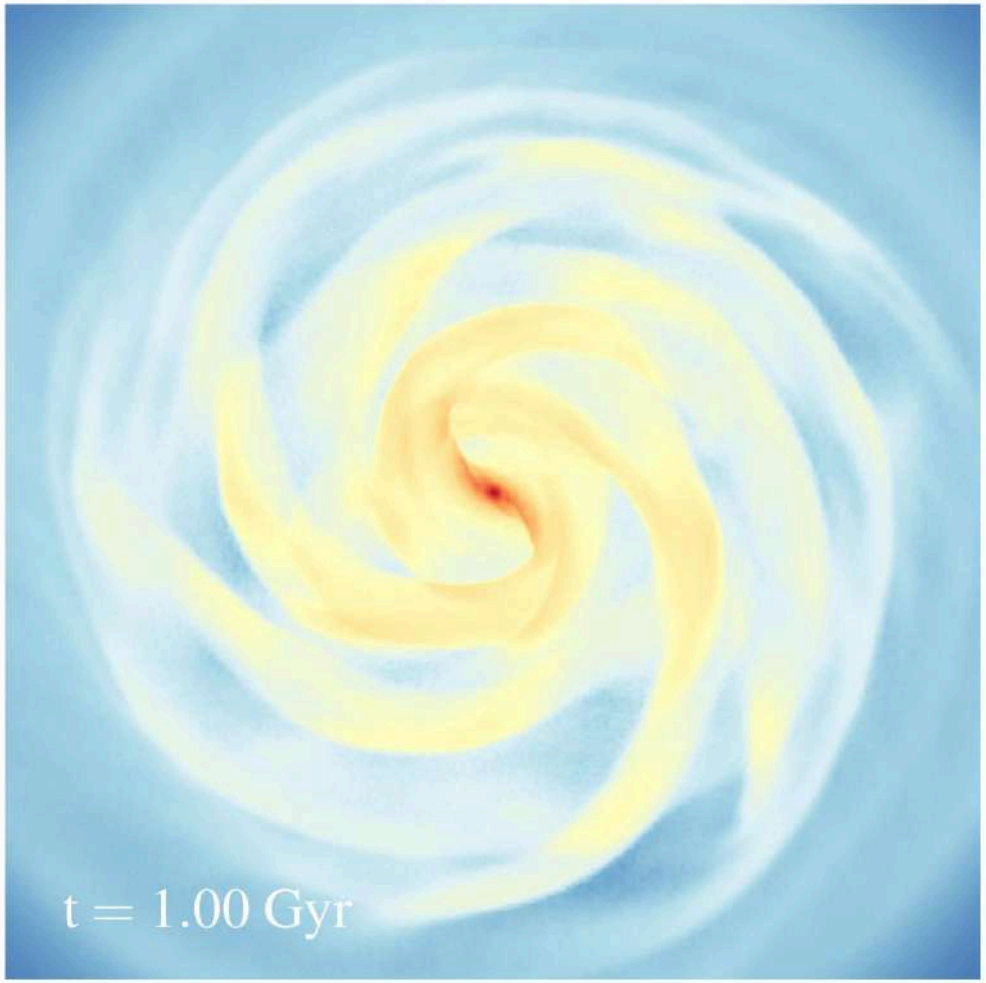


Osservazioni sintetiche (mock observations):

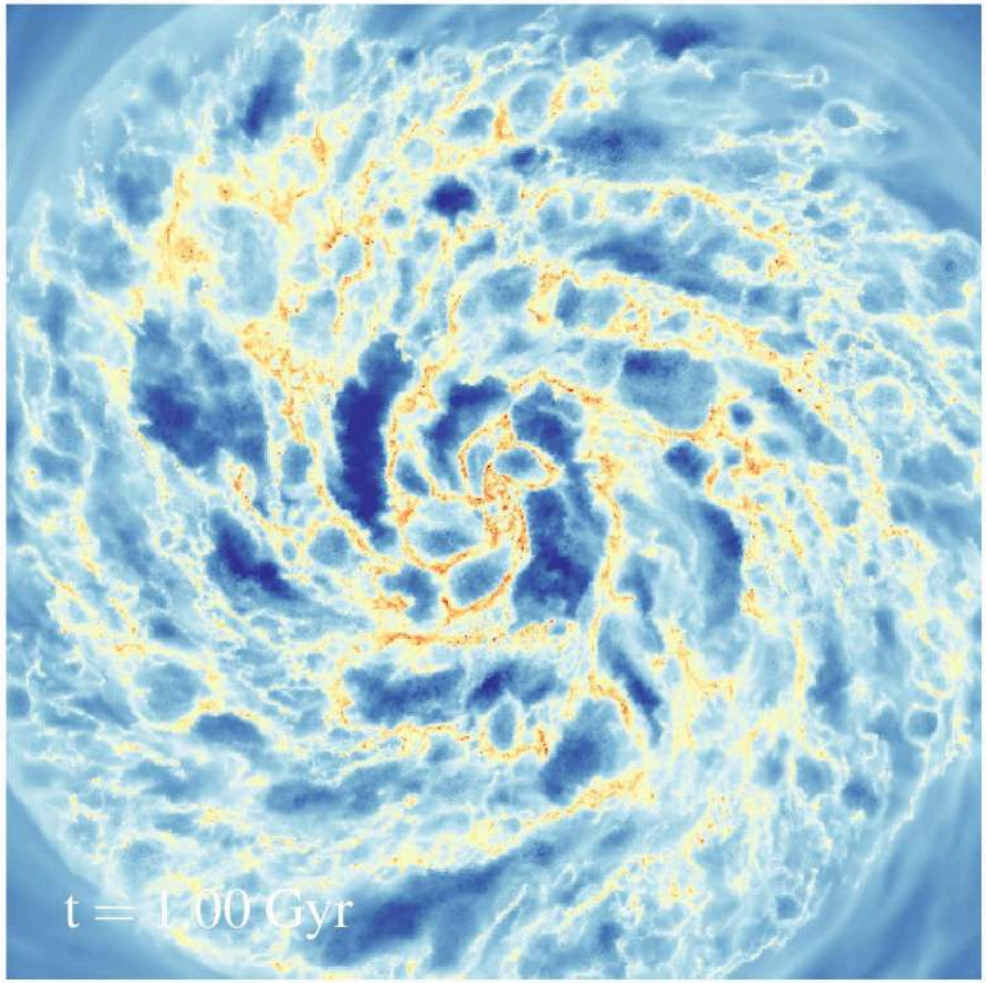
tecniche che consento di “osservare” una simulazione come se fosse un oggetto reale

Migliorare l’accuratezza delle simulazioni

Modello TNG



SMUGGLE

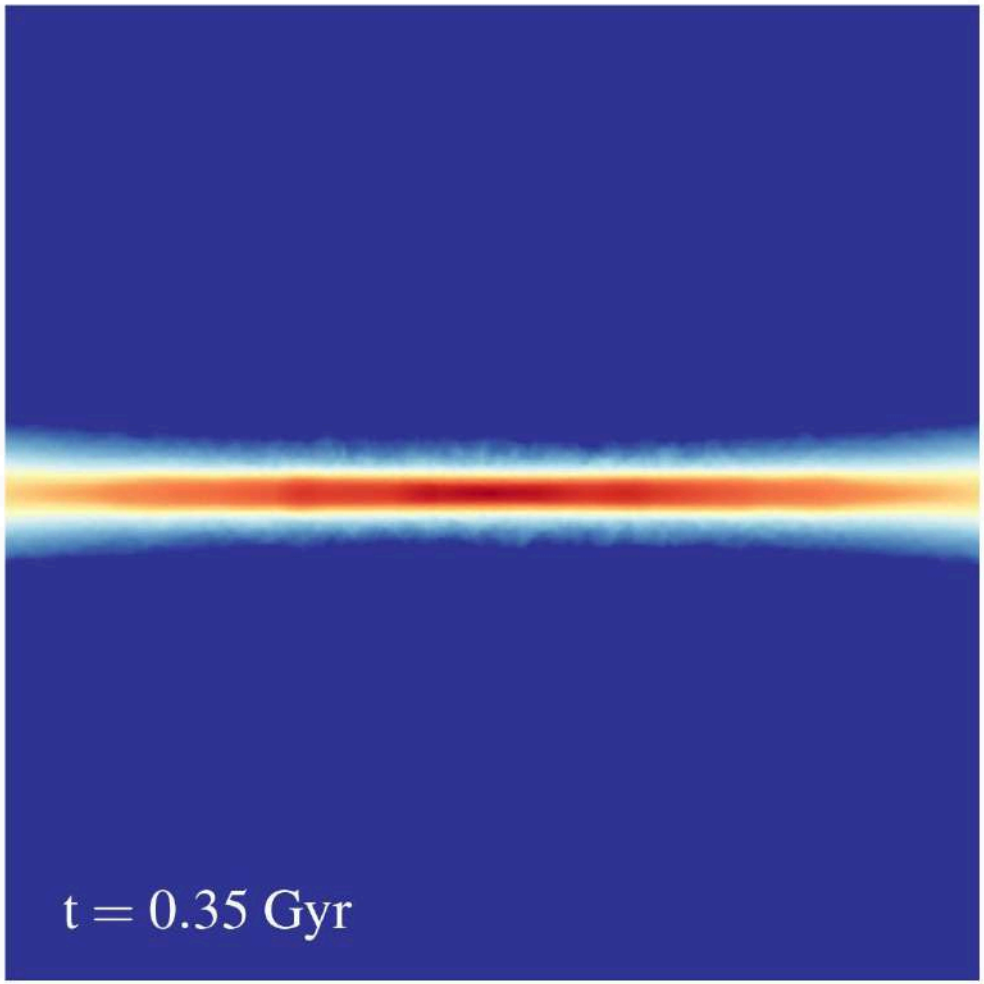


La struttura del gas nella galassia è molto differente
Gli effetti del feedback stellare sono visibili chiaramente

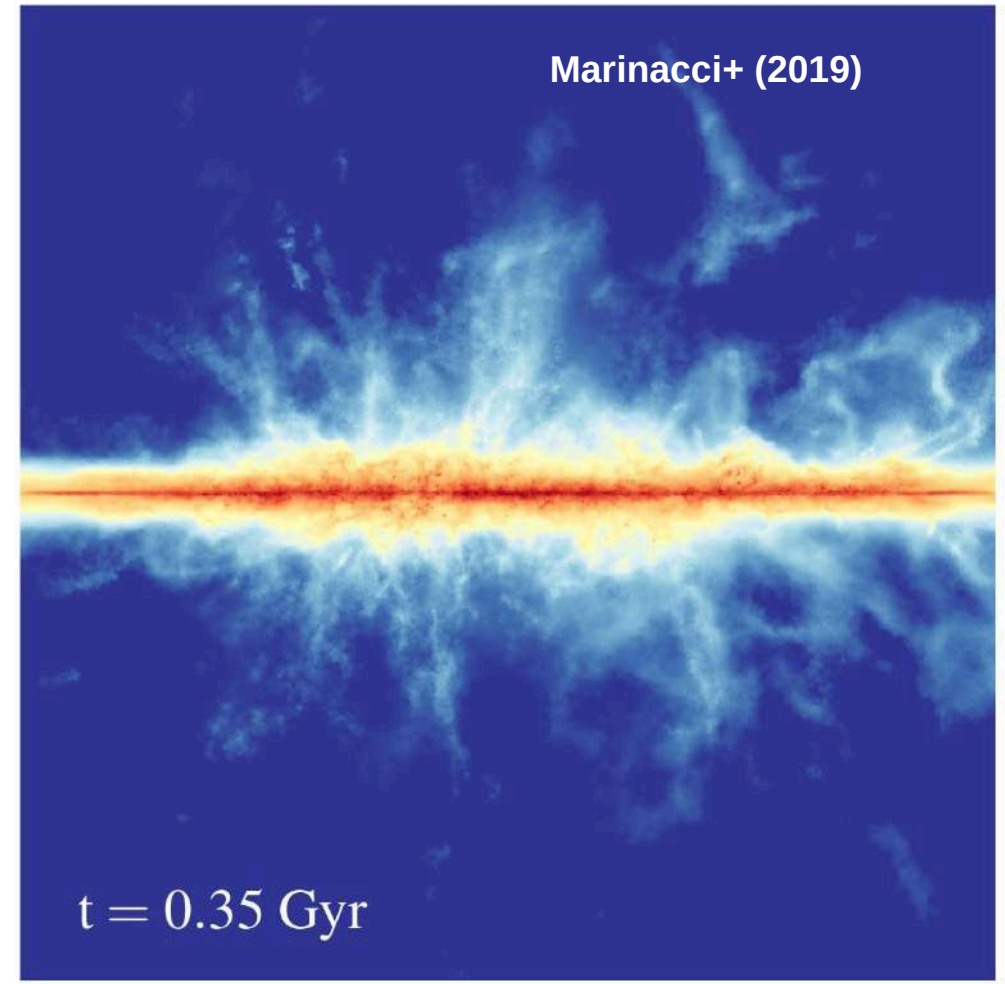
Marinacci+ (2019)

Migliorare l’accuratezza delle simulazioni

Modello TNG



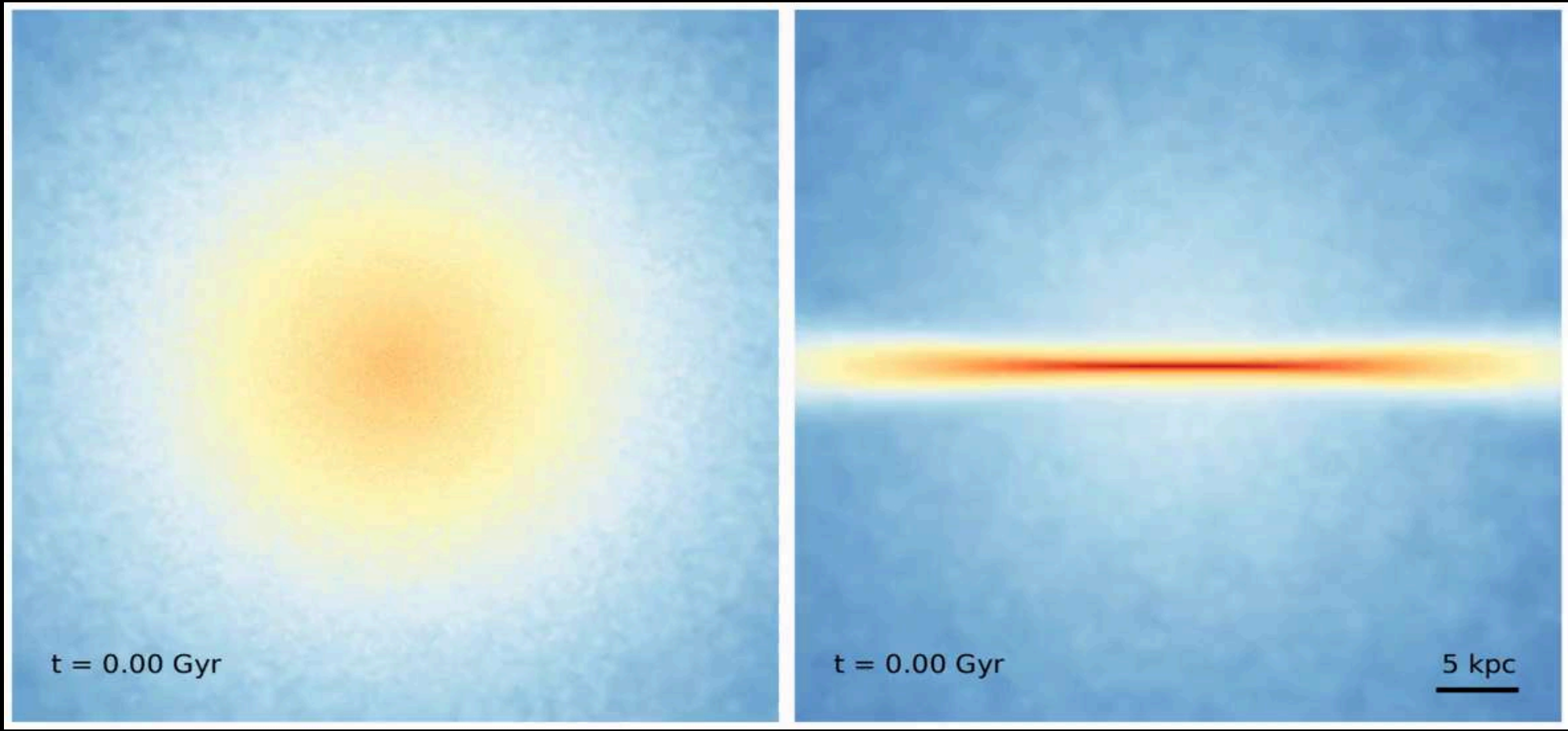
SMUGGLE



Il gas viene espulso naturamente dal modello formando un vento galattico

Migliorare l’accuratezza delle simulazioni

Filmato realizzato da F. Barbani



Vista di fronte

Vista di lato

Galassia simulata con SMUGGLE

Marinacci+ (2019)

Fusione tra Via Lattea e M31 simulata con SMUGGLE