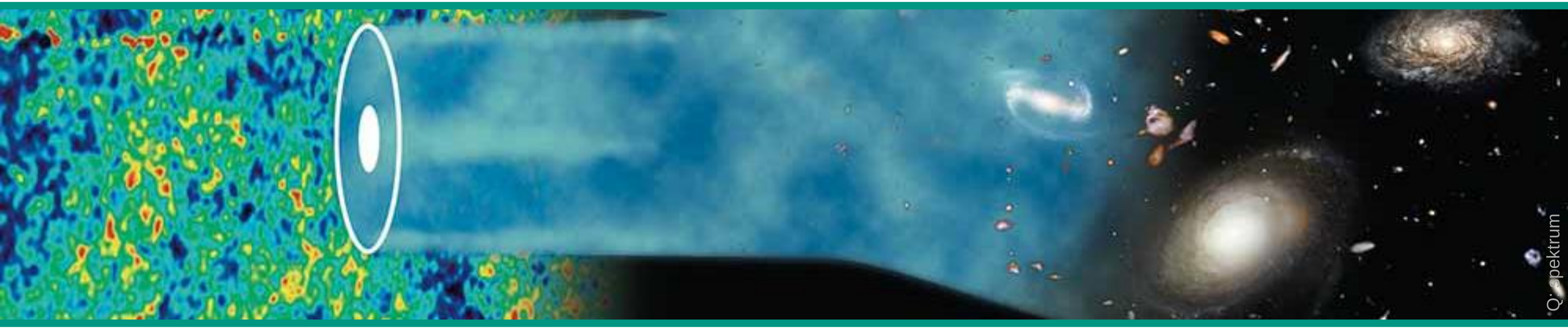
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 23/24 Lecture 15 Feb. 13, 2024



Recap of Lecture 14

- **Dark Matter: properties of CDM / WDM / HDM & evidences**

- **Lee–Weinberg:** **thermal** production of DM: relativistic / non–relativistic

  - HDM: neutrinos on eV – scale, CDM: neutralinos on GeV/TeV – scale

- ´$WIMP$ – **miracle**´ for the observed value $\Omega_{DM} \sim 0.27$ we ´only´ require annihilation cross section $\sigma \sim 1\ pb$ (interaction at weak scale!) & large mass

- **Dark Matter – early evidences**:
  Zwicky: virial theorem applied to galaxy clusters
  Rubin: constant rotation speed of stars/gas in large spiral galaxies

- **gravitational lensing**: **strong** (Einstein rings) lens to map out Dark Matter

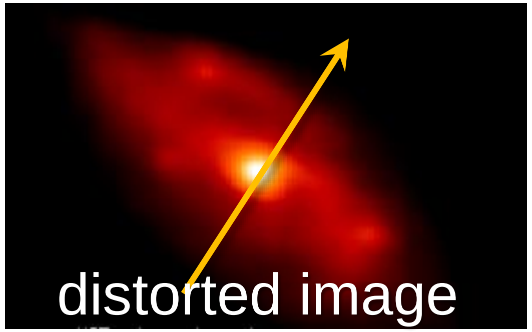
Weak gravitational lensing

- **Small (statistical) strechting of galaxy images: large−scale imaging of DM**

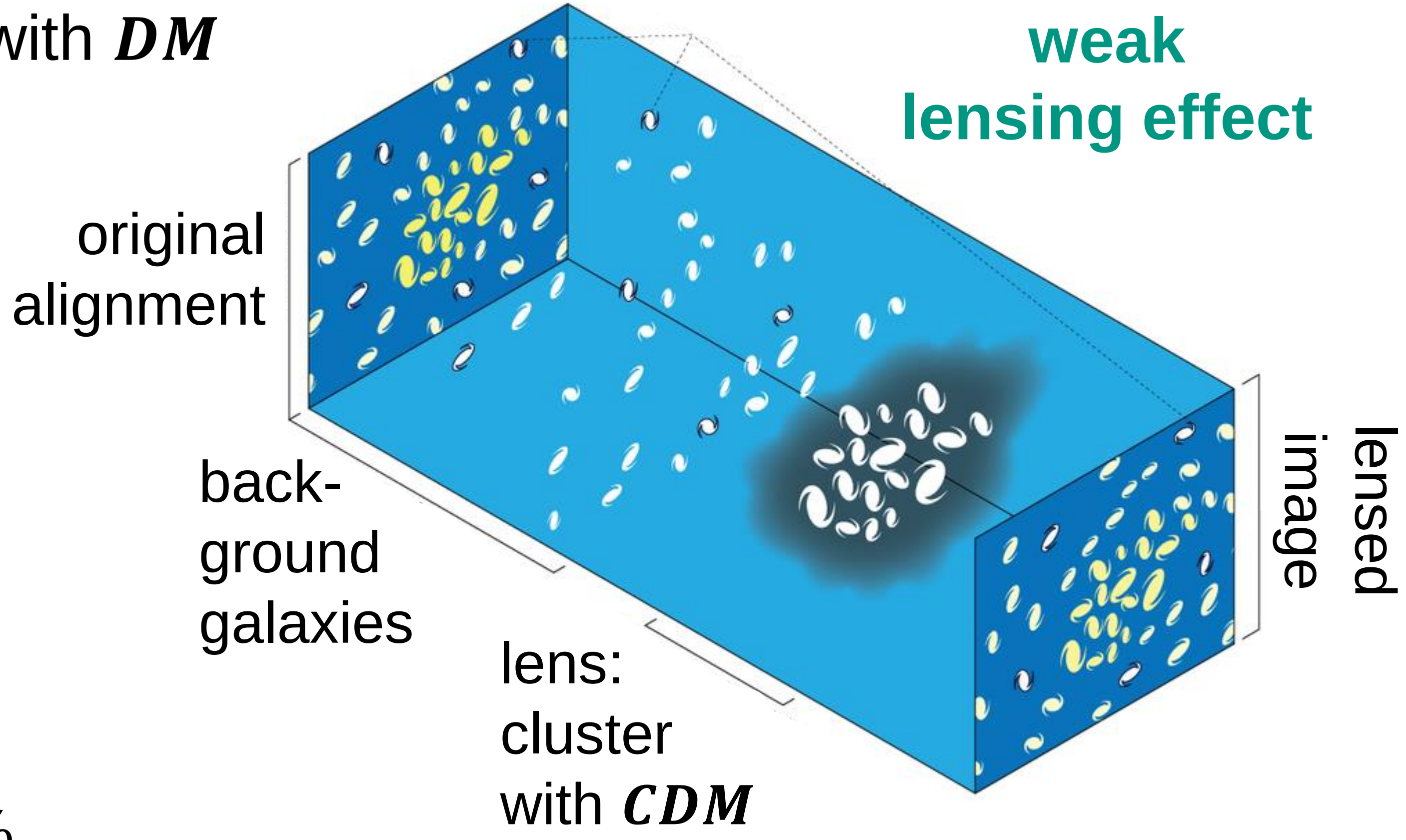
  - **weak gravitational lensing** due to extended lensing galaxy cluster with DM

    ⇨ statistical **strechting** of the images of single galaxies in the background

    ⇨ perform a statistical analysis



´**stretching**´ of a galaxy by factor $\sim 1\%$

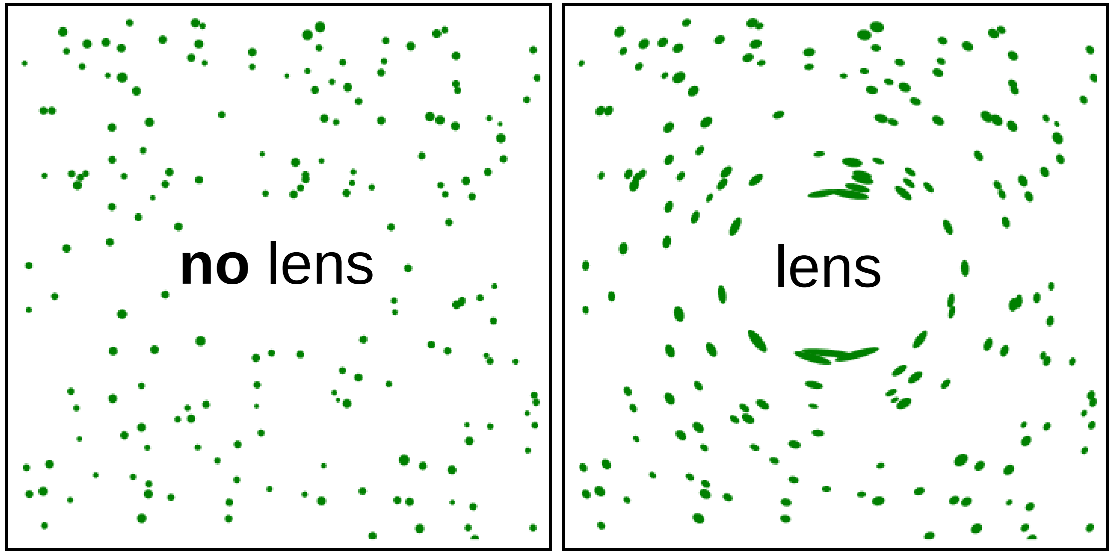


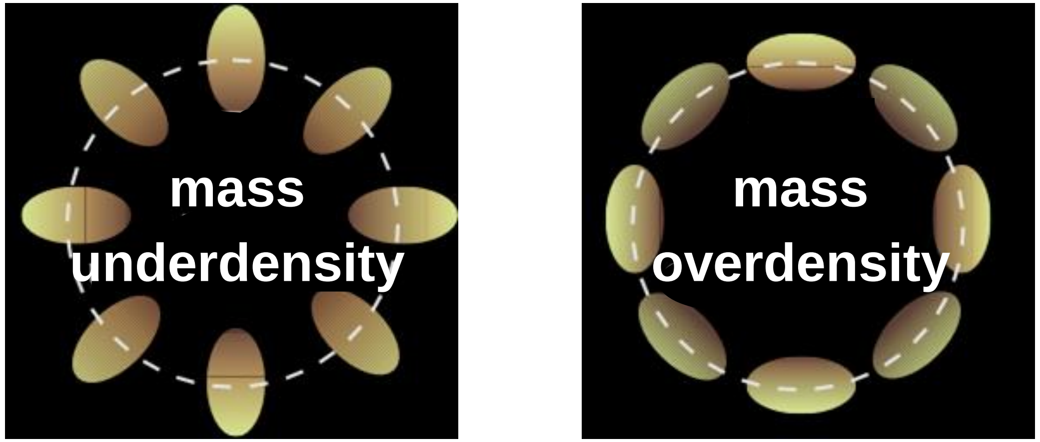
Weak gravitational lensing

- **Small (statistical) strechting of galaxy images: large–scale imaging of DM**

- primary ratios of the semi–axes (major to minor) of galaxy images are unknown:
  ⇨ **stretching of images due to a weak lens** has to be analysed **statistically**

- signature of a **void** (**under–dense** region): major axes align **radially**
- signature of a **cluster** (**over–dense** region): major axes align **ring–like**





⇒ **radially** ⇒ **ring–like**

Weak gravitational lensing

- **Small (statistical) strechting of galaxy images:** **large−scale imaging of DM**

- primary ratios of the semi−axes (major to minor) of galaxy images are unknown:
 ⇨ **stretching of images due to a weak lens** has to be analysed **statistically**

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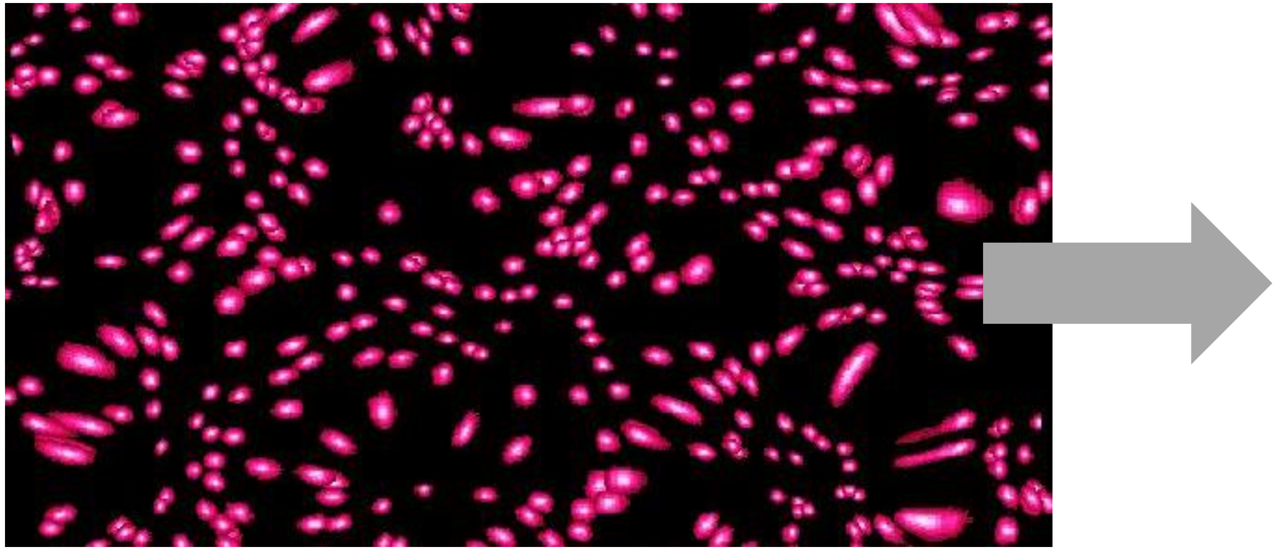
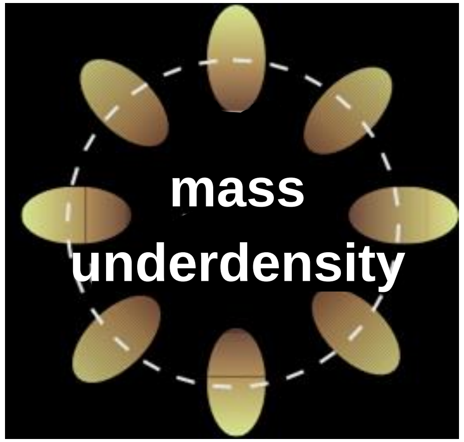
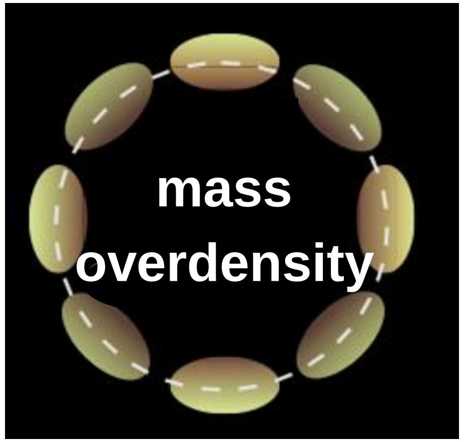




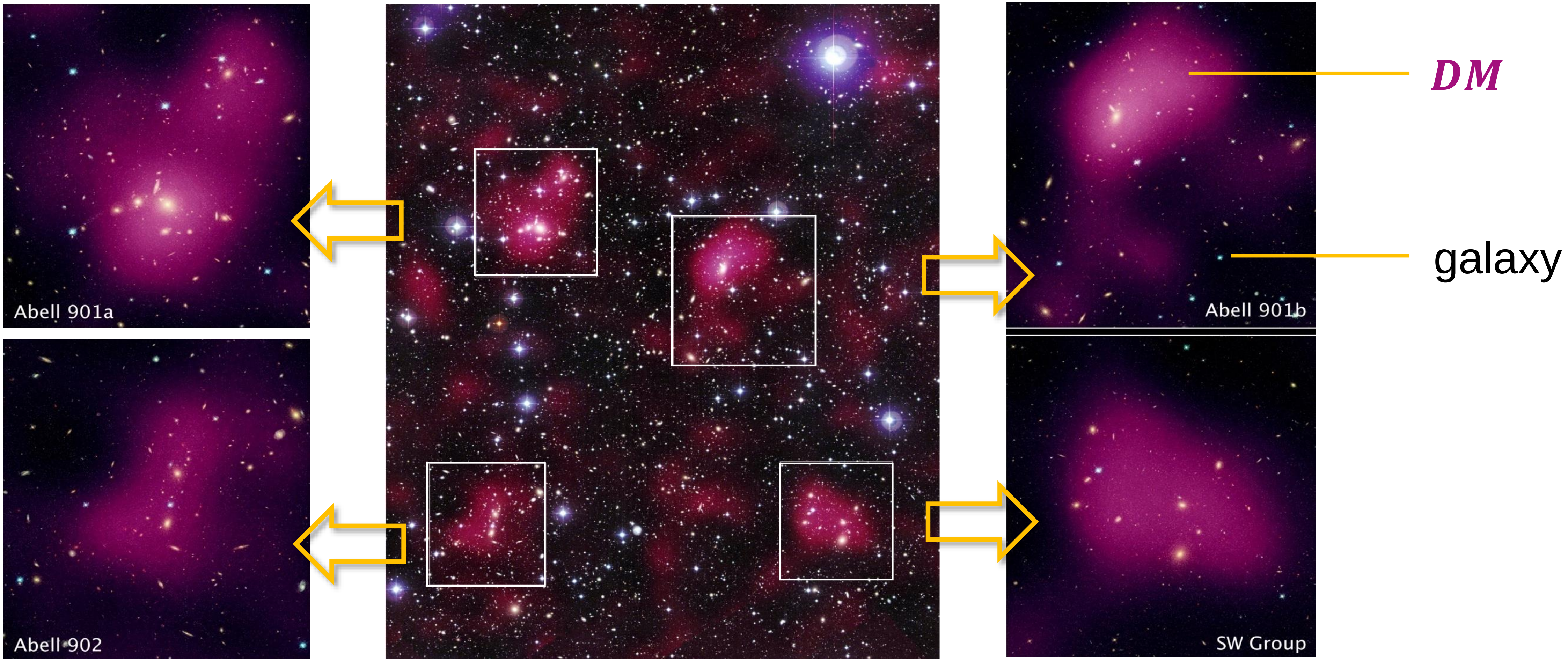
⇒ **radially**



⇒ **ring−like**

Weak lensing: distribution of DM in a cluster

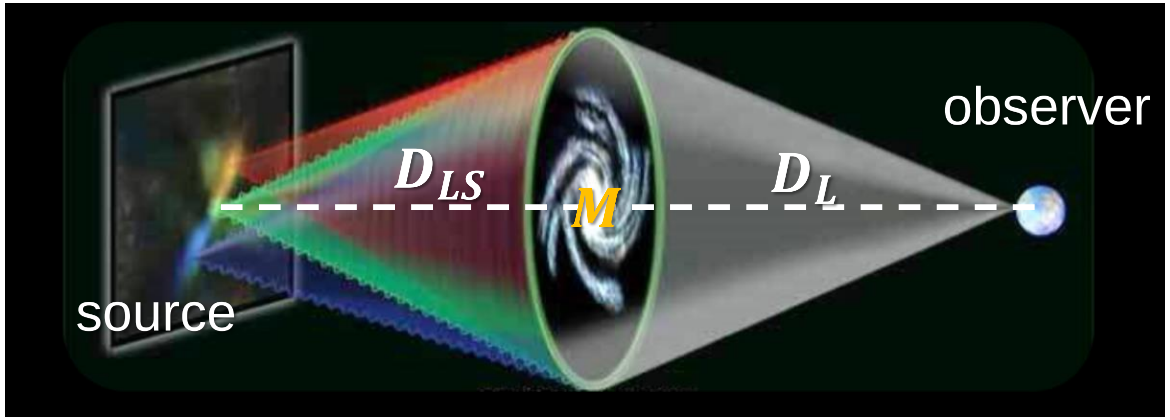
- **Example of DM – distribution in galaxy clusters $Abell\ 901/902$**



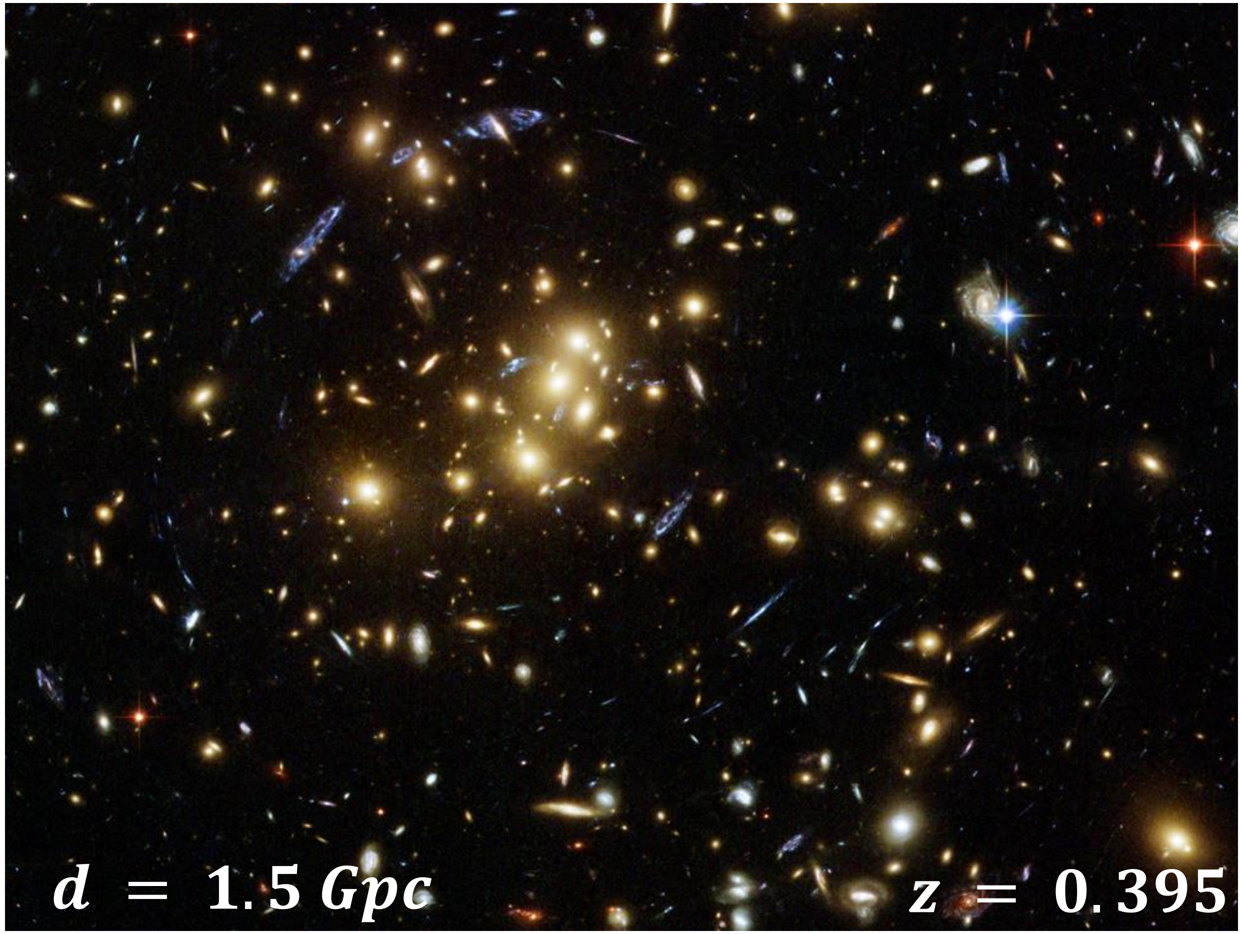
Rare: weak & strong lensing in the same picture

- **Combination of the two effects in galaxy cluster $CL0025 + 1654$**

- observation of ***strong lensing:*** several blue arcs of lensed images of far–off background galaxies



strong lensing



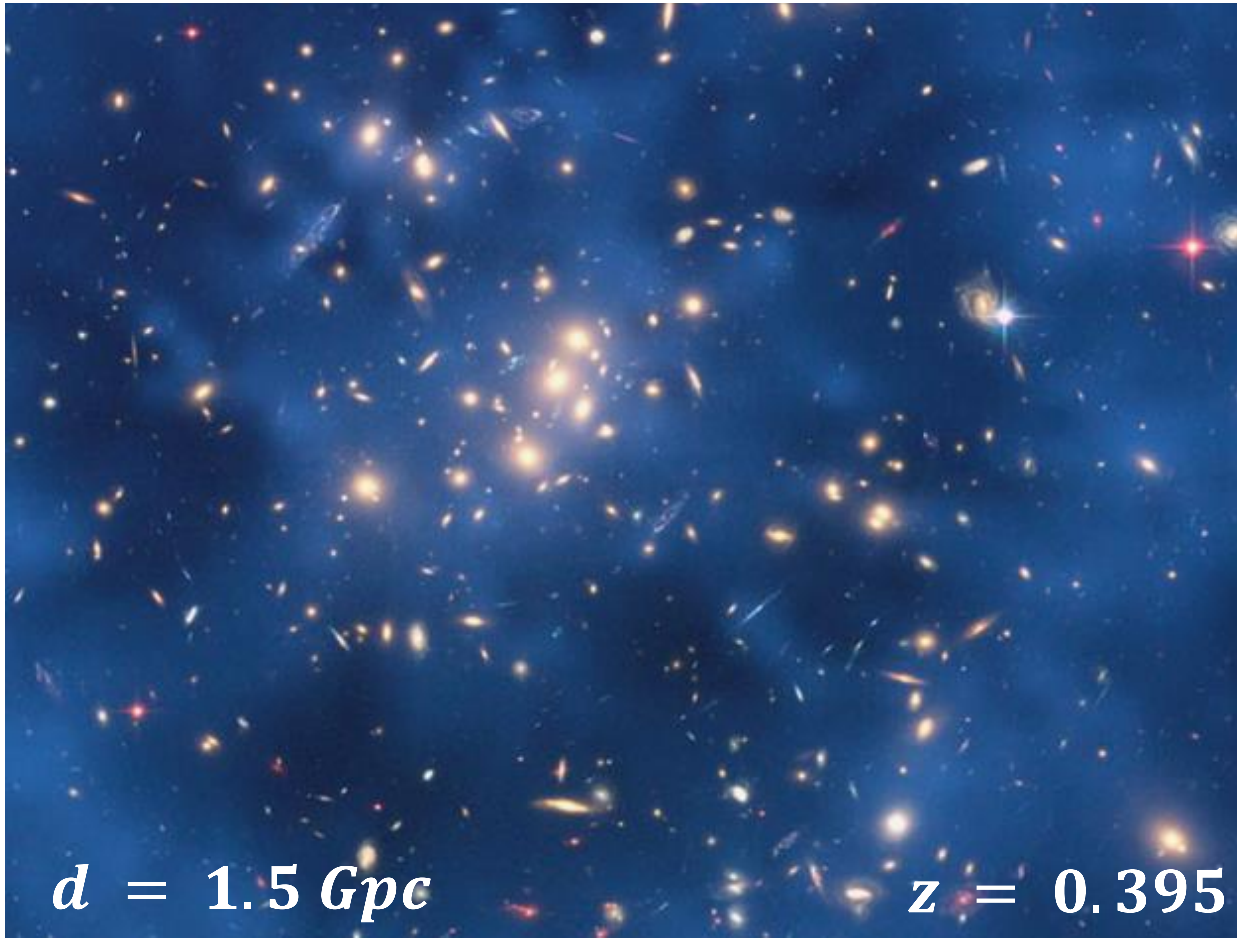
weak lensing: distribution of dark matter

- **Combination of the two effects in galaxy cluster $CL0025 + 1654$**

- observation of ***strong lensing:***
  several blue arcs of lensed images of
  far–off background galaxies

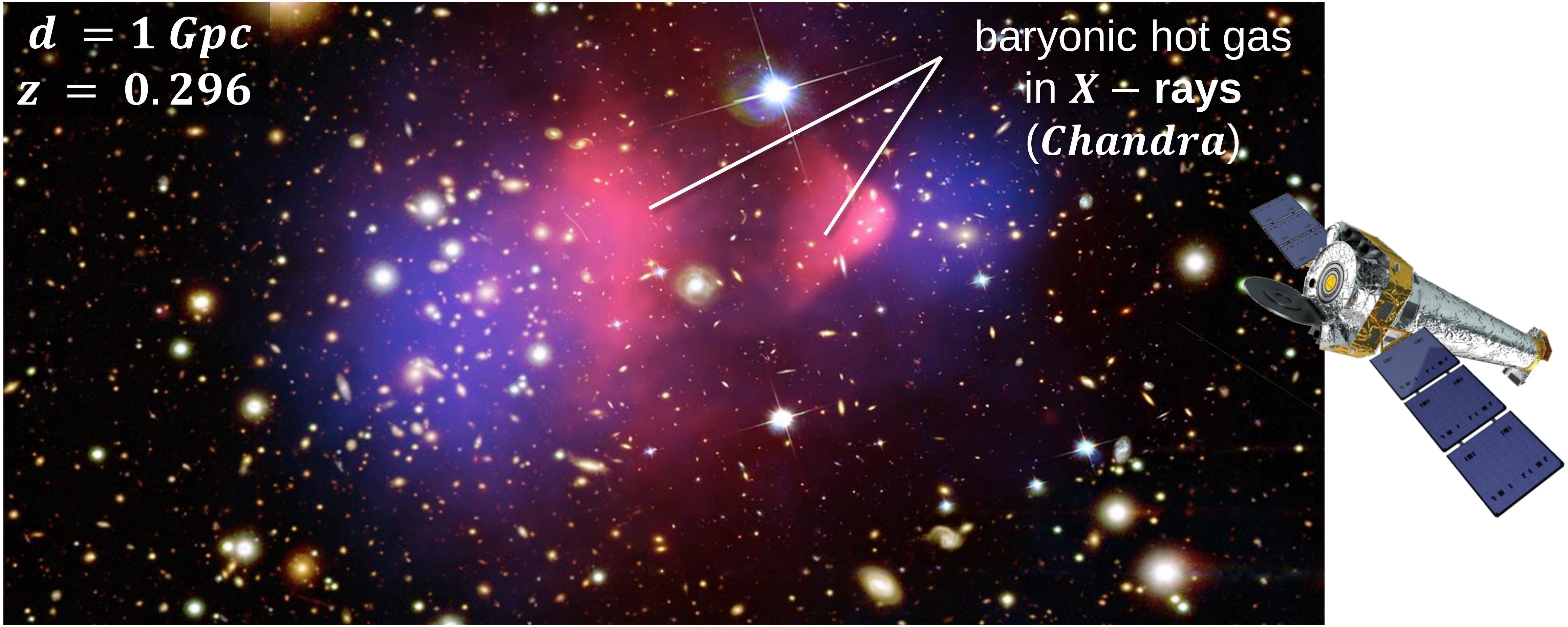
- observation of **weak lensing**:
  statistical distortion of the images of
  $\mathbf{7000}$ background galaxies

- allows to map distribution of DM of the
  in–between cluster $CL0025 + 1654$
  which acts as **weak** gravitational **lens**



Weak lensing: the famous $Bullet$ cluster

- $DM-$ distribution in cluster: it is separated from baryons after collision



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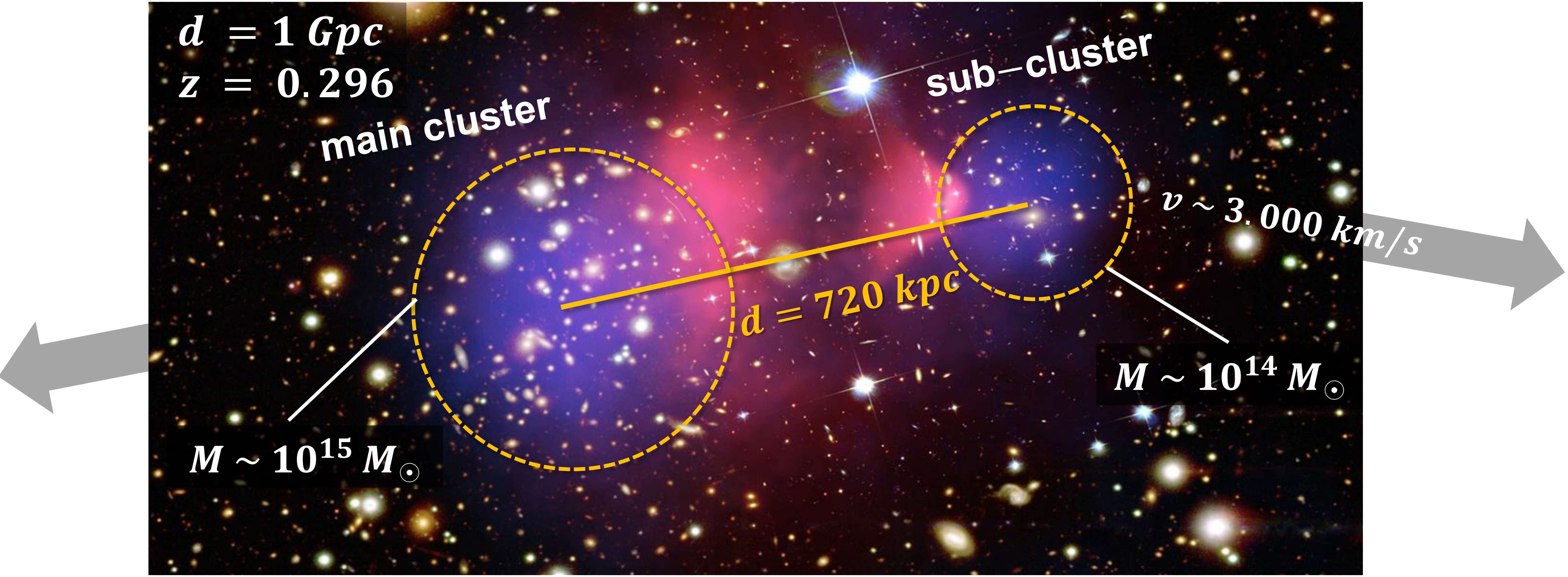


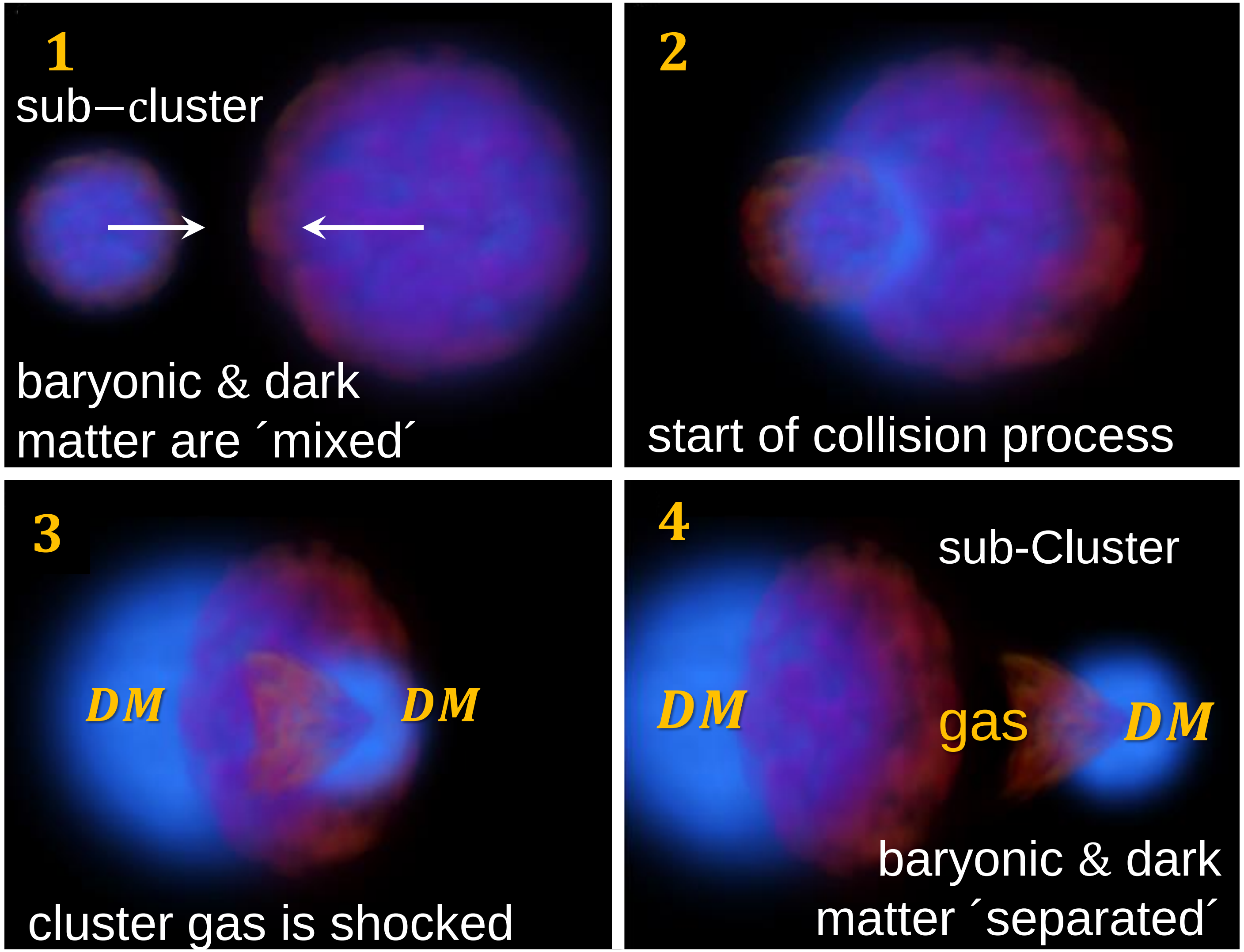
Weak lensing: the famous *Bullet* cluster

- **Phases of collision process between 2 galaxy clusters – clear evidence for *DM***

- **Dark Matter**:
  no dissipation, no interaction processes during collision

DM & **gas** separated

- **Baryonic gas**:
  during collision: gas is **shocked** & **strongly heated** due to very intense interactions (dissipation)



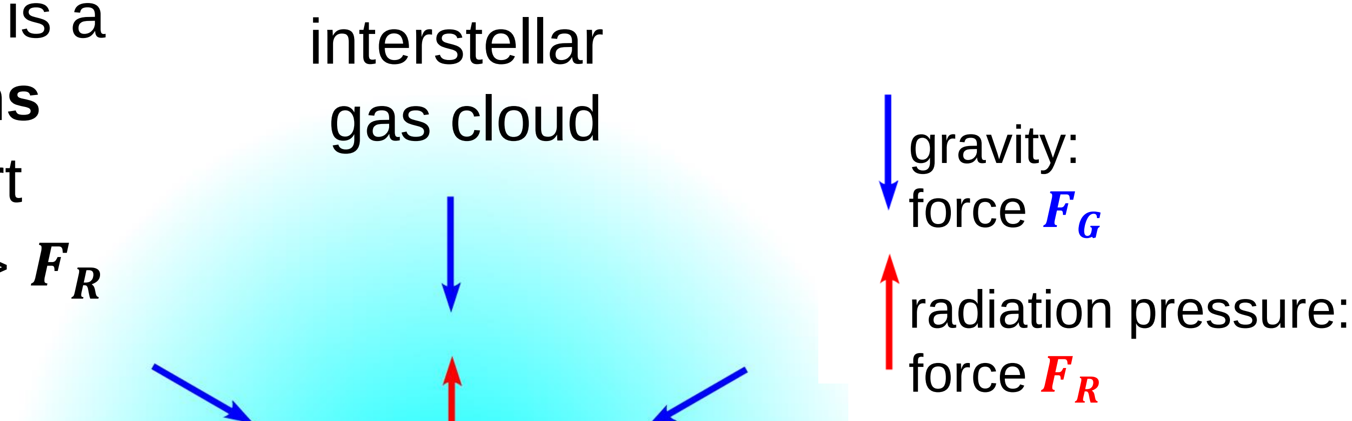
5.3 Dark Matter Halos: the NFW – profile

- **To contract or not to contract: the importance of the Jeans mass m_{Jeans}**

  - for an interstellar gas cloud, there is a minimum mass required, the **Jeans mass** m_{Jeans} : only then it can start gravitational contraction with $F_G > F_R$

$$m_{Jeans} \sim \sqrt{(k_b T)^3 / \rho}$$

  - also relevant on larger scales such as **galaxy formation,** requiring $m > m_{Jeans}$



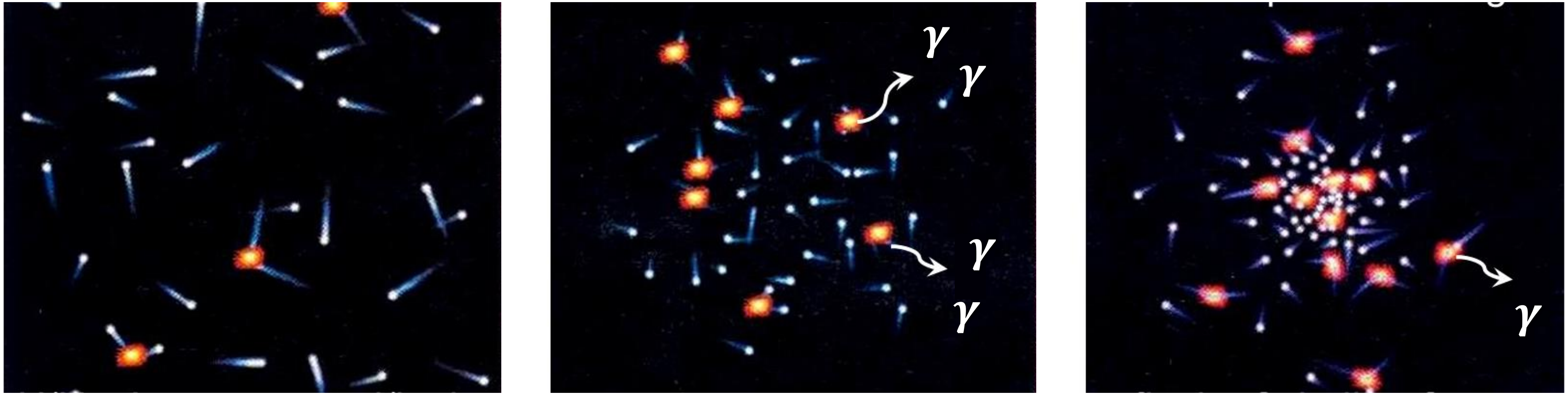
James Jeans

Gravitational contraction of baryonic matter

- **A key realisation in a baryonic collapse: EM cooling via emission of radiation**

  - ***during collapse***: baryons can **cool** via the **emission of radiation (dissipation)**

  - formation of a **flat galactic disk** with large–scale rotation due to conservation of angular momentum: formation of individual stars with angular momentum



baryons: heating, collisions | baryons: emission of γ´s | baryons: formation flat disk

Gravitational contraction of baryonic matter

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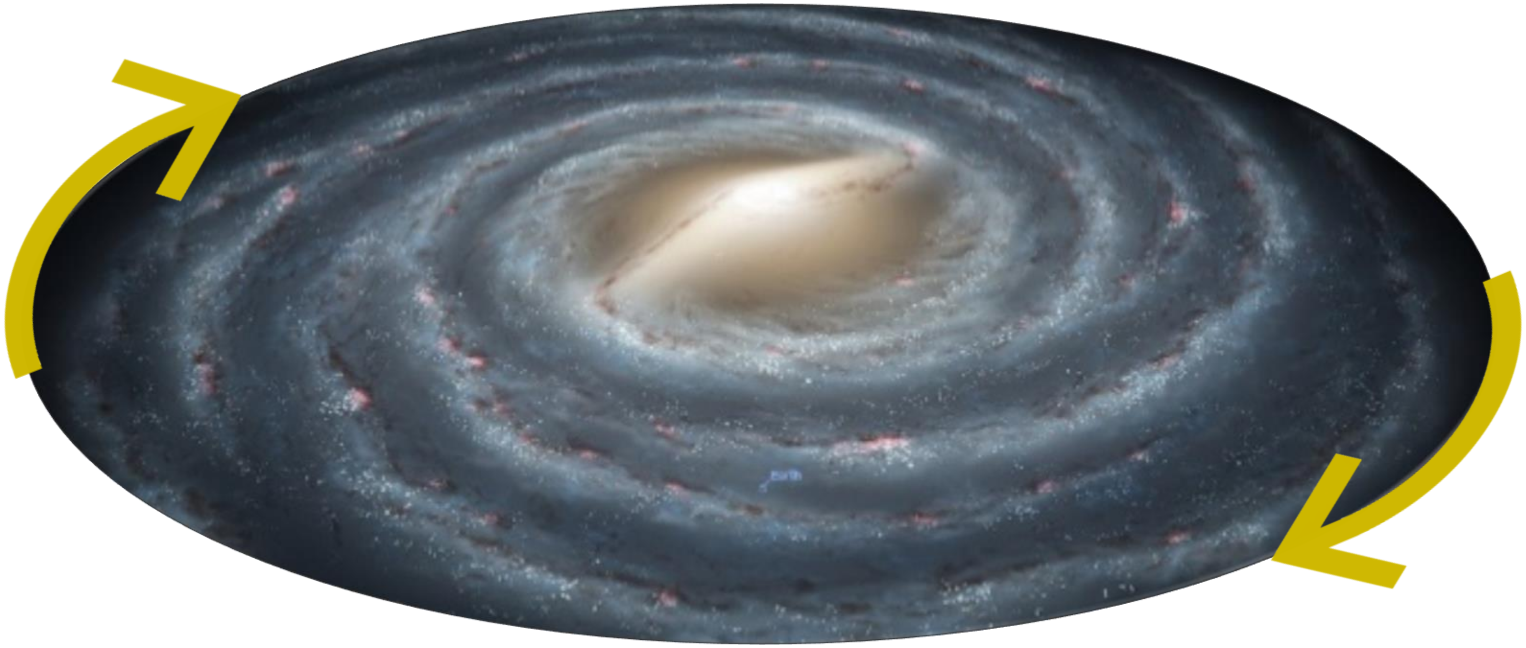
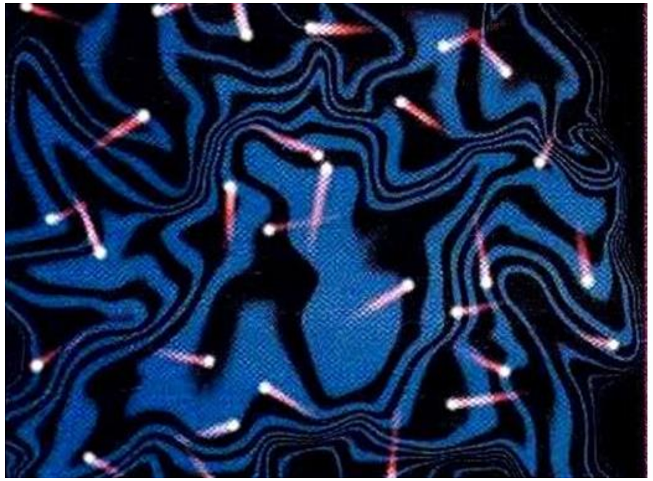


Gravitational contraction of Dark Matter

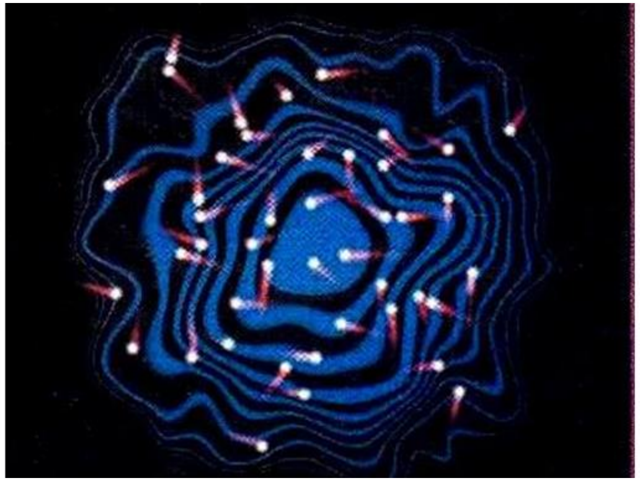
- **Dark Matter: NO $\boldsymbol{EM}$ cooling due to emission of photons is possible**

  - ***during collapse***: $\boldsymbol{WIMPs}$ cannot **cool** via **emission of radiation (no dissipation)**

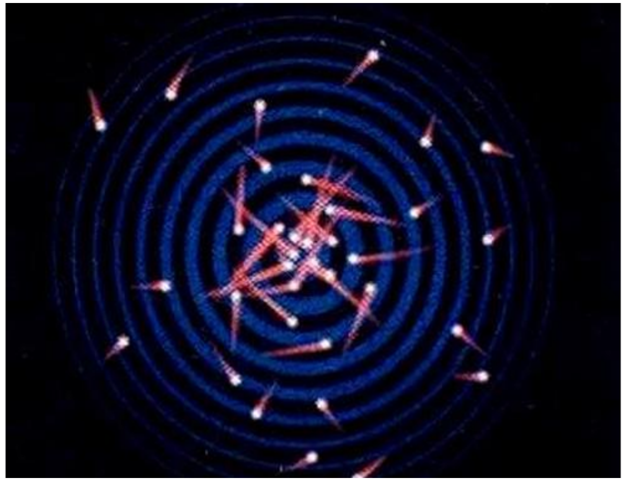
  - formation of a **spherical $\boldsymbol{DM}$ – halo (tri–axial shape)**, without large–scale (macroscopic) rotation due to conservation of angular momentum, isotropic velocity distribution of $\boldsymbol{WIMPs}$



Dark Matter: $\boldsymbol{WIMPs}$



interacts only via gravity



spherical $\boldsymbol{DM}$ – halo

Gravitational contraction of Dark Matter

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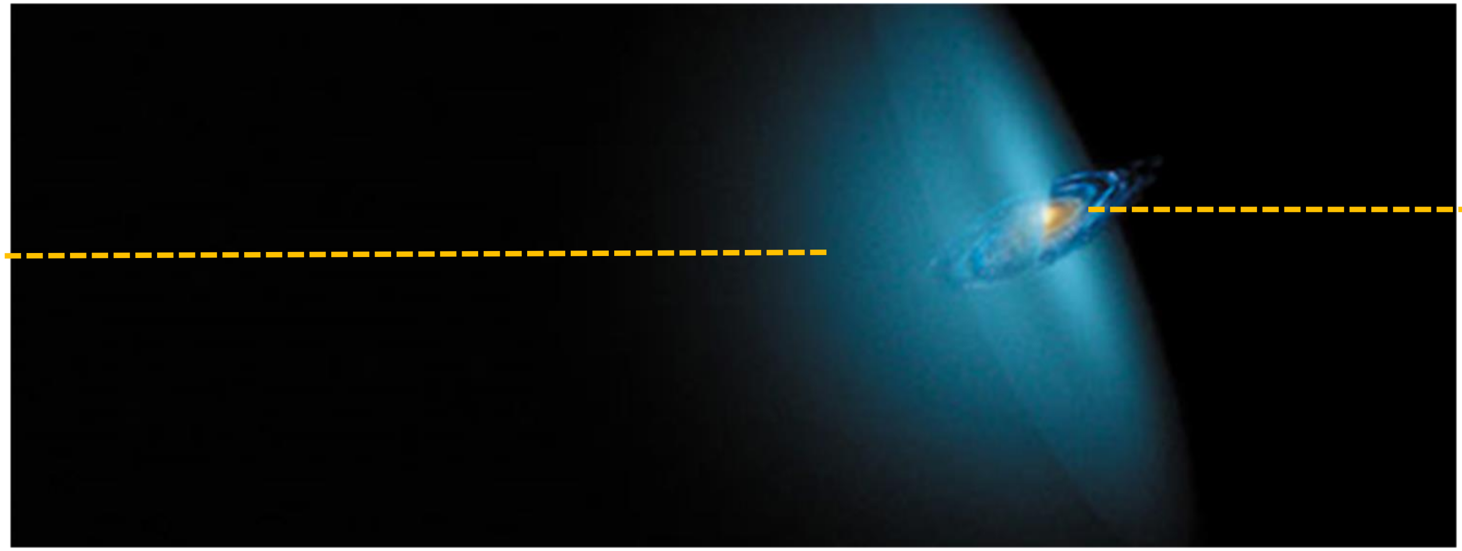


DM halo from $WIMPs$

baryonic **disk**

DM halos: the NFW – profile

- **A famous parameterization: the ´universal´ DM – halo–profile**

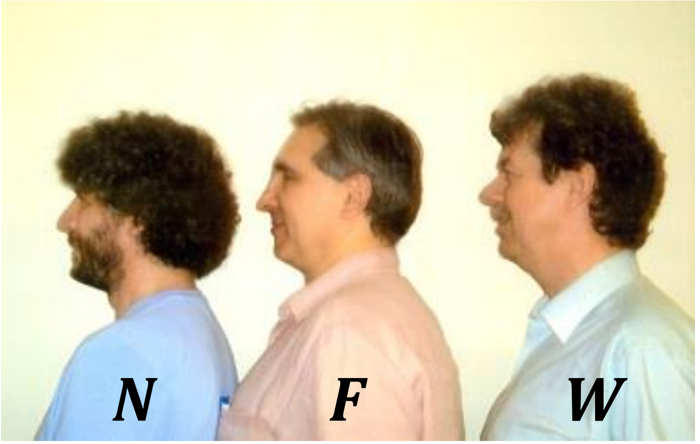
  - for a spherical halo of DM, the density typically falls off as $\rho(r) \sim r^{-2}$

  - **universal NFW – profile**

Navarro–Frenk–White–profile for **interaction–free DM** – particles

$$\rho_{DM}(r) = \frac{\rho_0}{\frac{r}{R_S} \cdot \left(1 + \frac{r}{R_S}\right)^2}$$

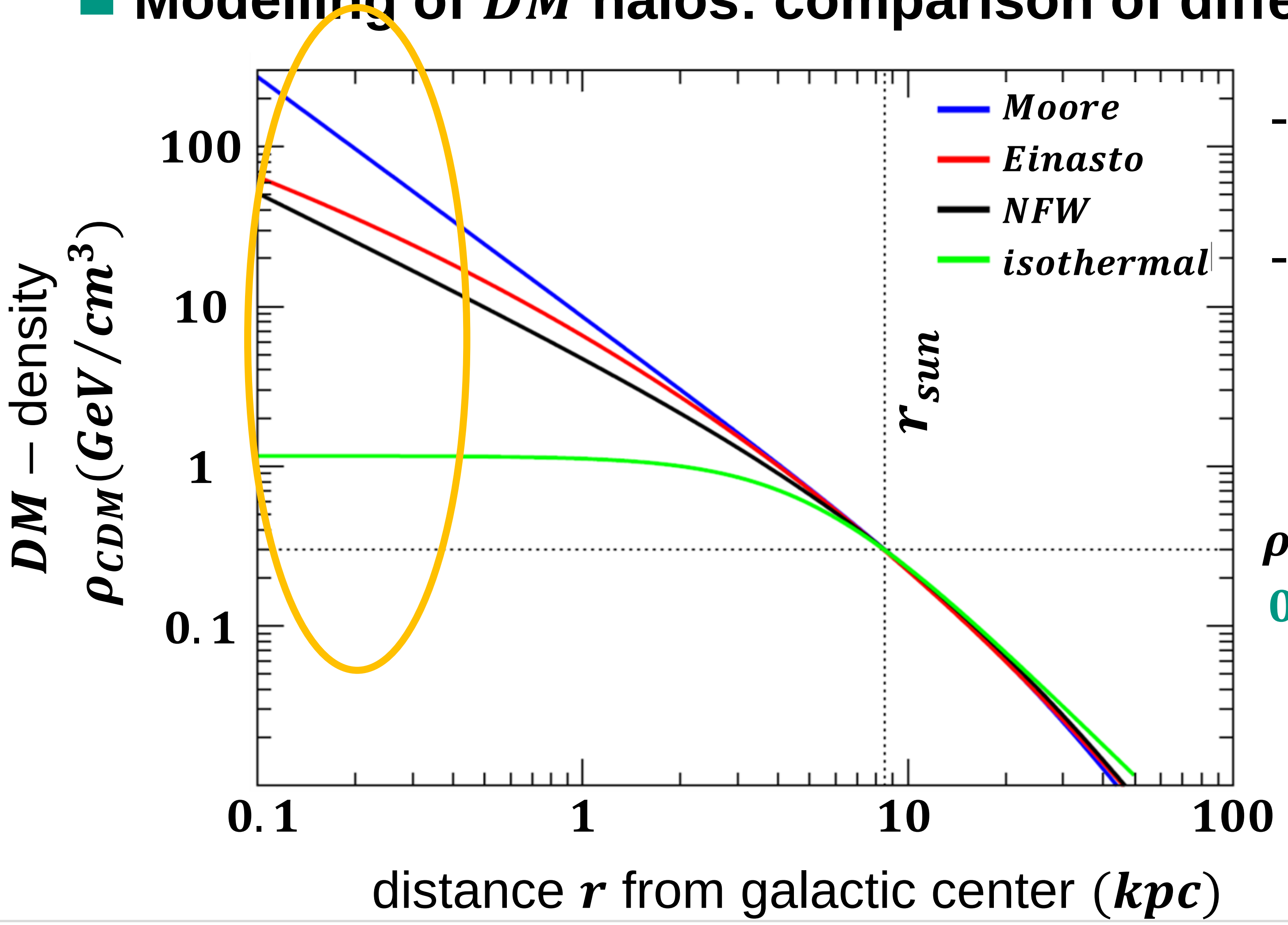
ρ_0: normalised density
R_S: scale radius of DM – halo



NFW in profile

A closer look at dark halos & inner core

- **Modelling of DM halos: comparison of different proposed halo profiles**



- halo–core: up to $300\ GeV/cm^3$

- **inner halo modelling** yields somewhat different values: compare $Moore \Leftrightarrow NFW \Leftrightarrow isothermal$

$\rho_{CDM}(r_{sun}) = 0.3\ GeV/cm^3$

DM halos: orientation of the galactic disk

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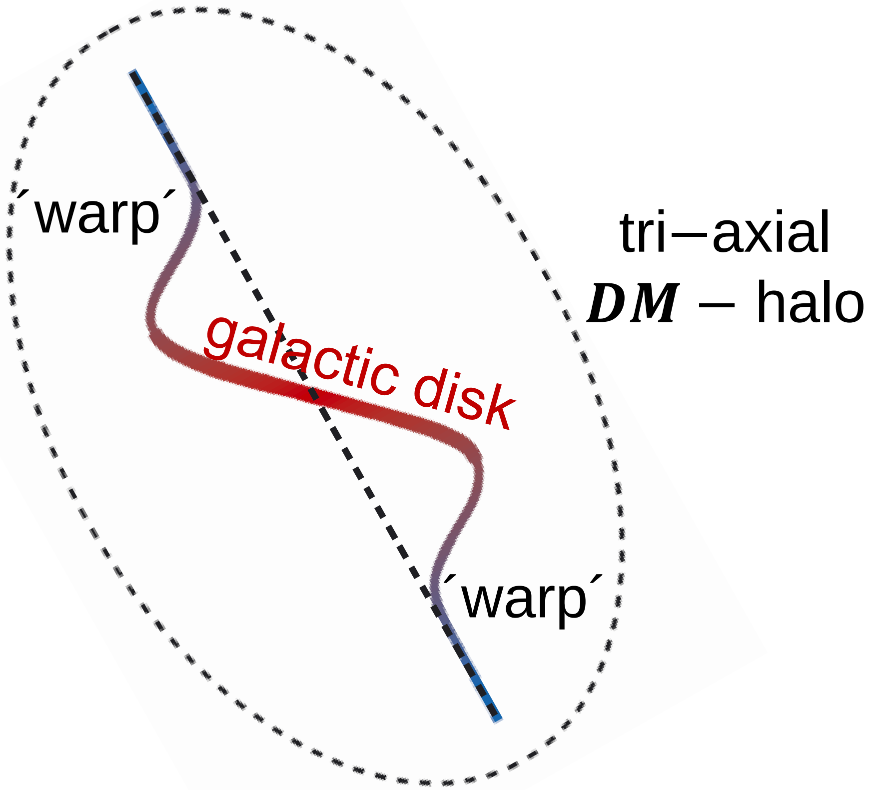
- **Dark Matter: impact of the tri−axial halo onto baryonic galactic thin disk**

- **common observation**:
  solitary (non−interacting) galaxies often display ´**warps**´ in their outer, gas−dominated regions

- explanation based on DM – halos:
  tilting of the orientation of the thin baryonic galactic disk relative to the major semi−axis of the DM – halo (e.g. as the result of a previous merger−process)



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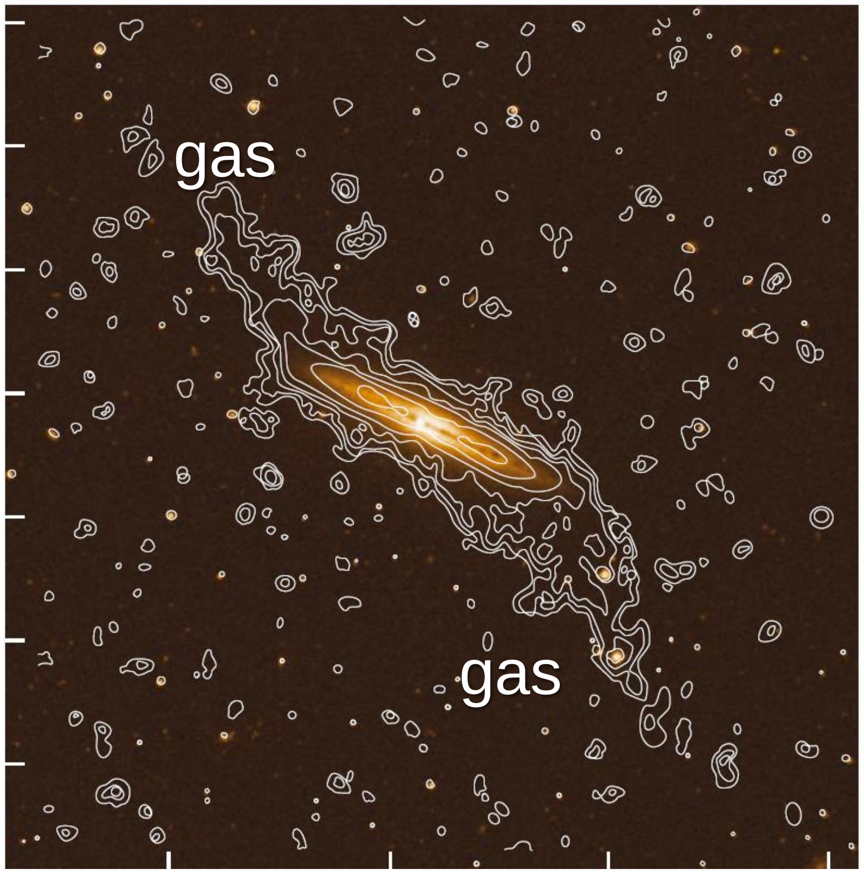
- outer gas dynamics dominated by DM – halo!



DM – halos: N – body – simulations

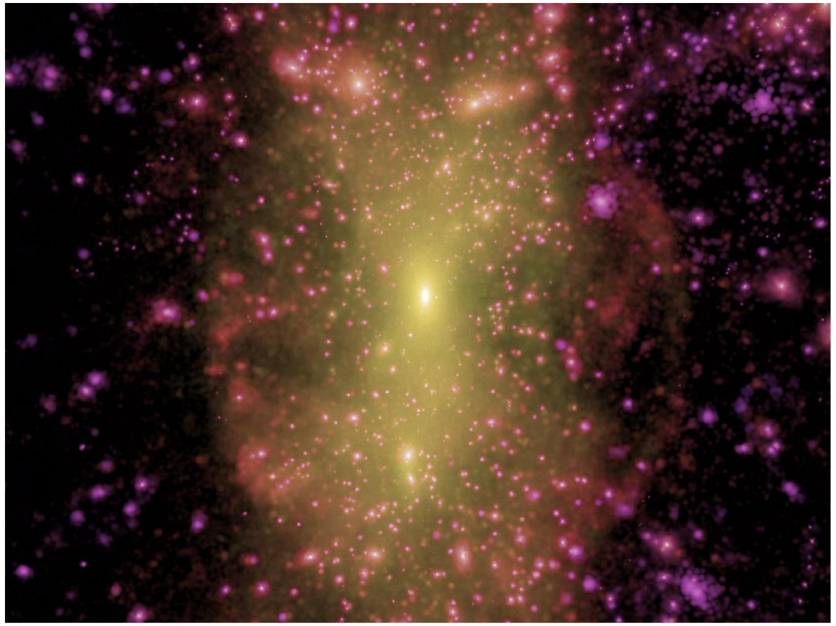
- Dark Matter halos: how much sub–structure do they contain?

DM – halos: N – body – simulations

- **Dark Matter halos: how much sub–structure do they contain?**

  - large–scale N – body – simulation studying this key topic:
    resulting sub–structures depend on the simulated **spatial resolution**

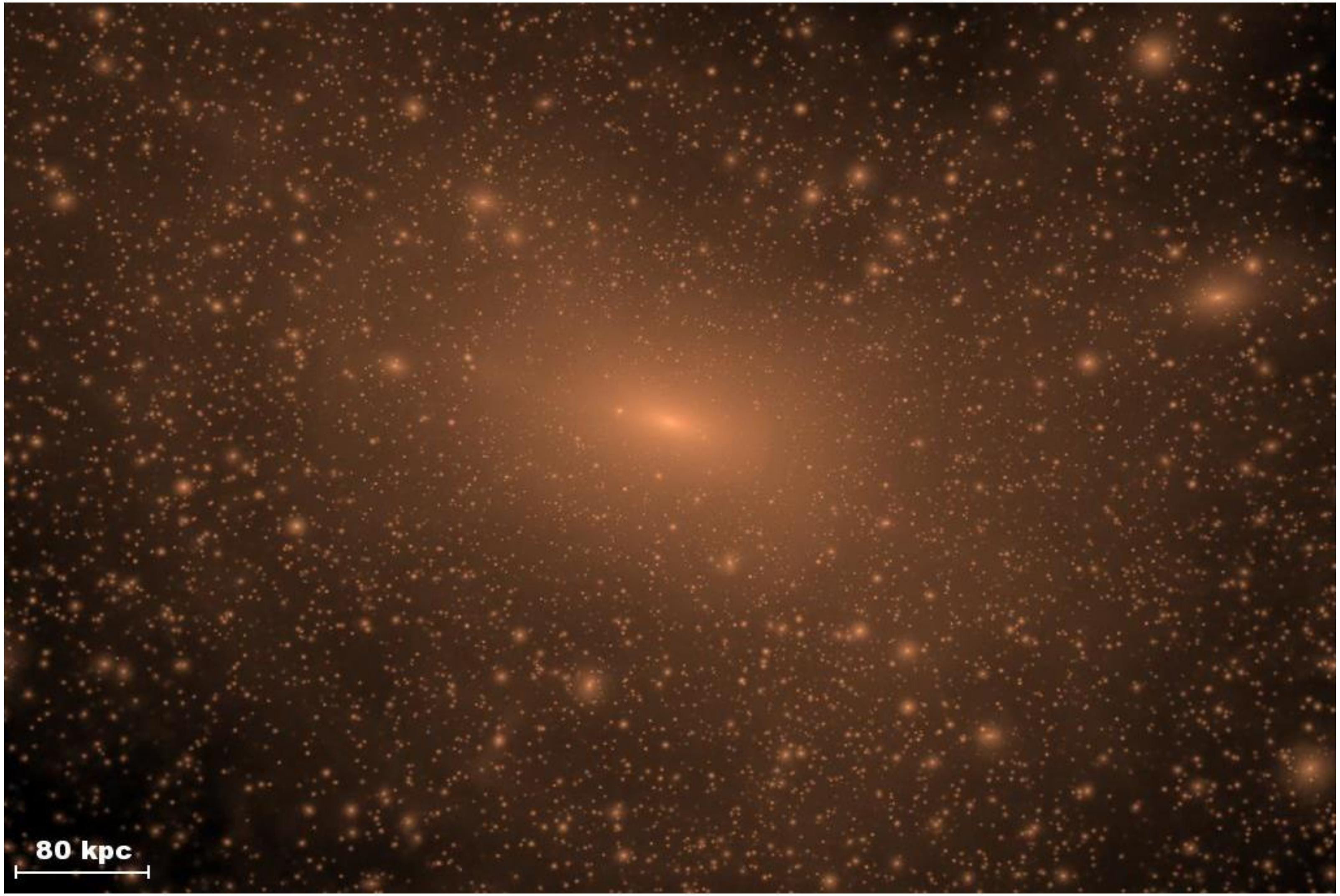
moderate mass–resolution



medium mass–resolution

excellent mass–resolution

DM – halos: N – body – simulations



$800 \times 600\ kpc$:
$234\ mio.$
DM ´particles´

$M_{tot} =$
$1.7 \times 10^{12}\ M_{\odot}$

2006 example

DM – halos: problem of missing dwarf galaxies

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■ Dark Matter halos: expected sub−halos & observed # of dwarf galaxies

- local galaxies (Milky Way & Andromeda):

  expectation: $N \sim 500$ in a standard−CDM – halo

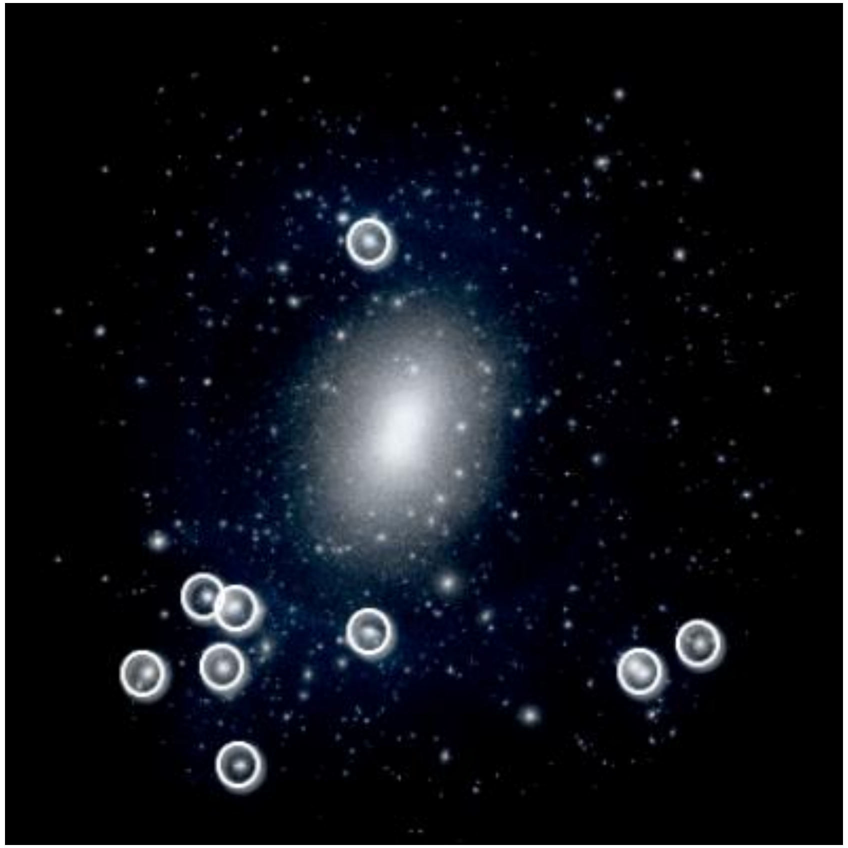
  observation: $N \sim 30$ up to $d = 420\ kpc$

  ⇨ **problem of missing dwarf galaxies**

- possible solutions :

  astrophysics: **evolution** of dwarf galaxies

  particle physics: (re−)adjust DM – **model**?



simulation of local DM – halo

DM – halos: problem of missing dwarf galaxies

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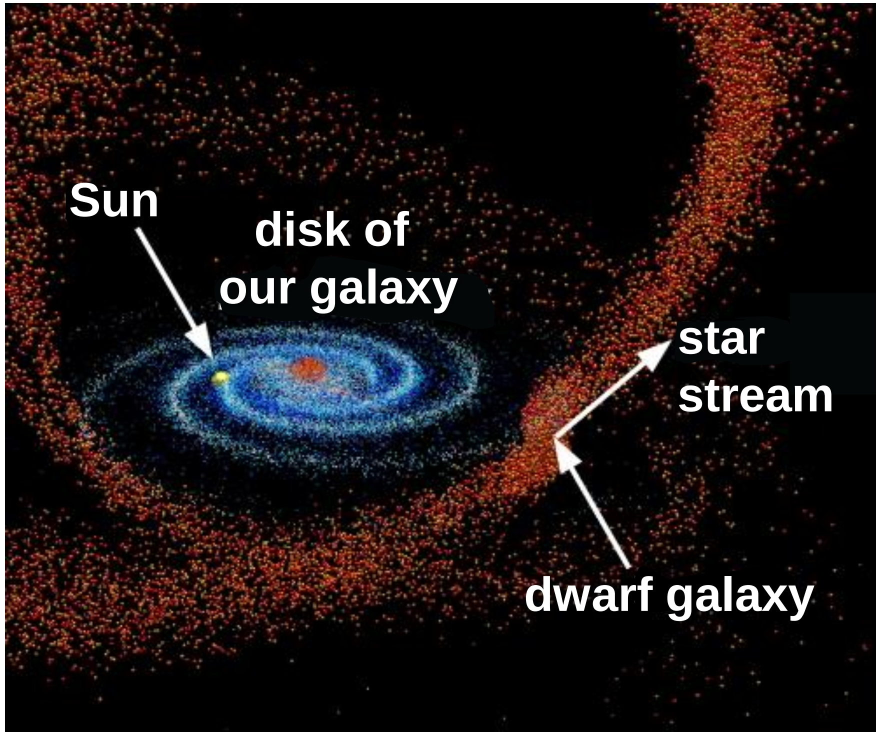
■ **Dark Matter halos I: astrophysics of dwarf galaxies (evolution)**

- **formation** & **evolution** of dwarf galaxies:

  - low–mass CDM – sub–halos simply fail to capture baryons & thus do not form dwarf galaxies

  - dwarf galaxies are disrupted by **strong tidal forces** of the central massive spiral galaxy

  - SN – explosions* drive out baryonic gas out of the dwarf galaxy (thus it has a too low brightness to be detected, as 99% DM only)



tidal interaction of dwarf galaxies

*s. ATP – II (summer term 2024)

DM – halos: problem of missing dwarf galaxies

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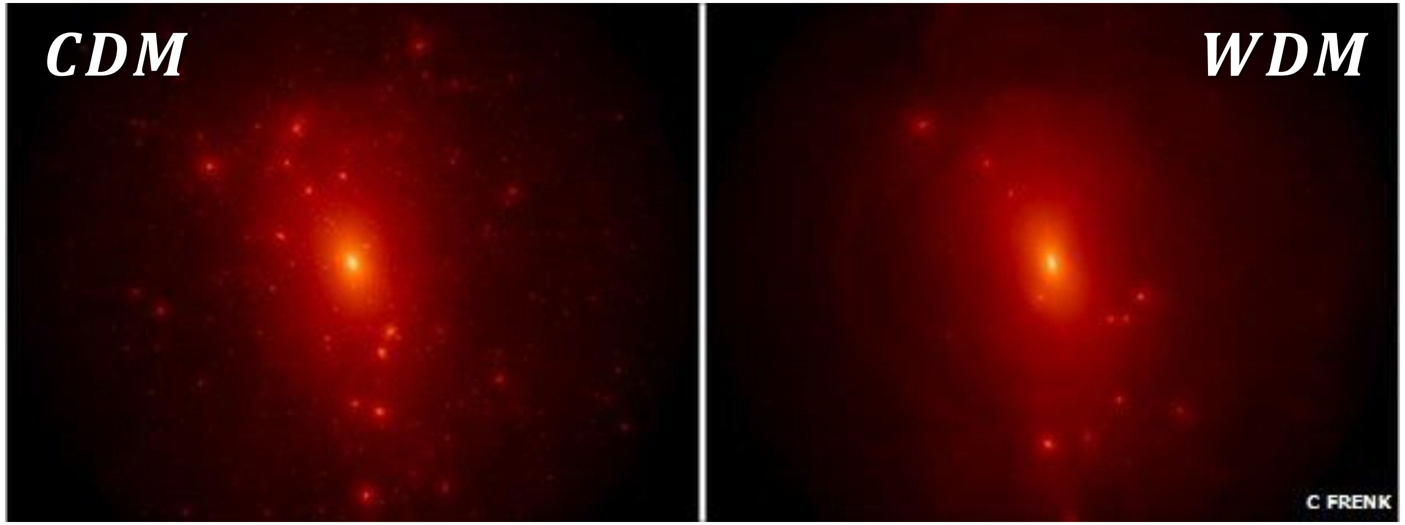
- **Dark Matter halos II: particle physics models – CDM or WDM**

  - a different (warm) DM – halo model: keV – scale **sterile $\nu{'}s$***

  - WDM – models based on sterile neutrinos predict: $N \sim 30$ ☑
    independent observation of stellar streams predict: $m(\nu_S) > 6\ keV$

impact:
wash–out of all
scales $\lambda < 1\ pc$



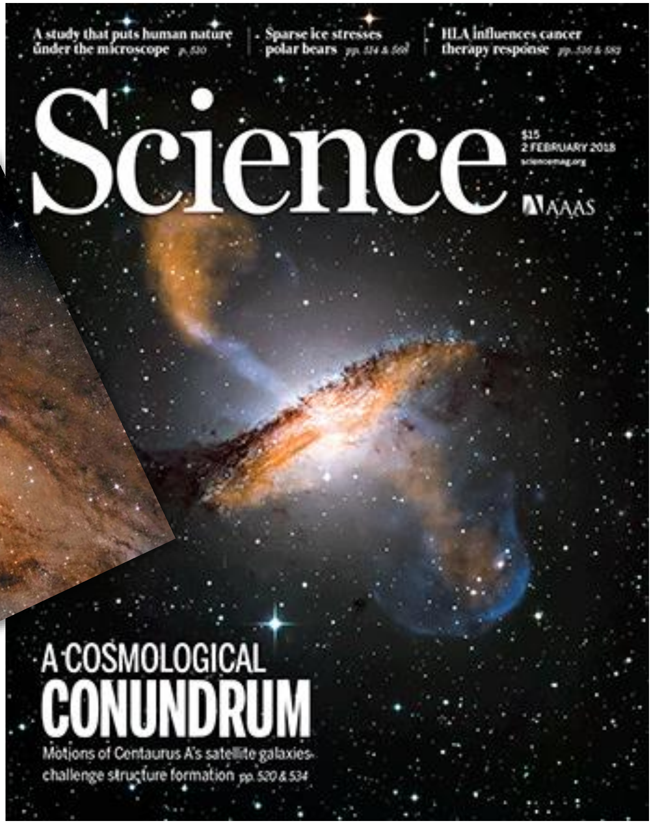
impact:
wash–out of all
scales $\lambda < 100\ kpc$

*s. $ATP - I$ (winter term $2023/24$)

DM – halos: orbits of nearby dwarf galaxies

- **Dark Matter halos: surprising alignment of orbits of dwarf galaxies**

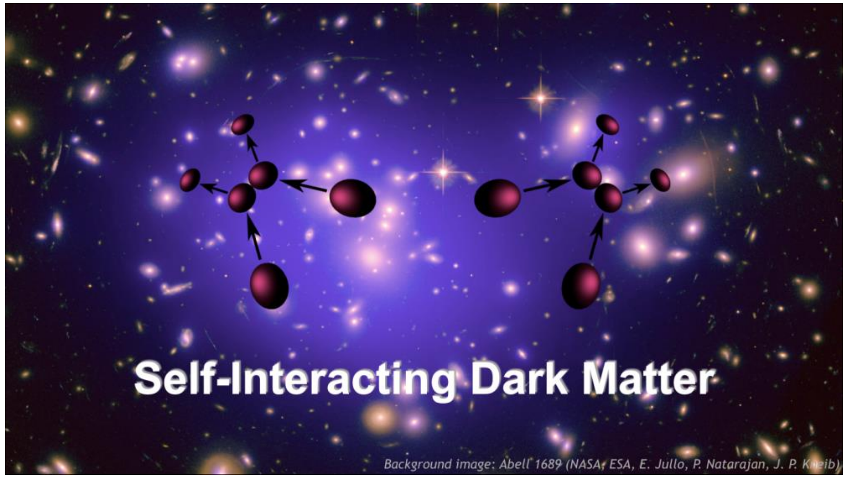
  - **2013**: discovery of a co–rotating disk of dwarf galaxies around both $M31$ & $Milky\ Way$ (probability: few percent range)



DM – halos: orbits of nearby dwarf galaxies

- **Dark Matter halos: surprising alignment of orbits of dwarf galaxies**

- is this a chance alignment (we expect a random motion around the host), or does it point to a **new form of dark matter with self interaction ($SIDM$)** ?



5. 4 Dark Energy: the future evolution

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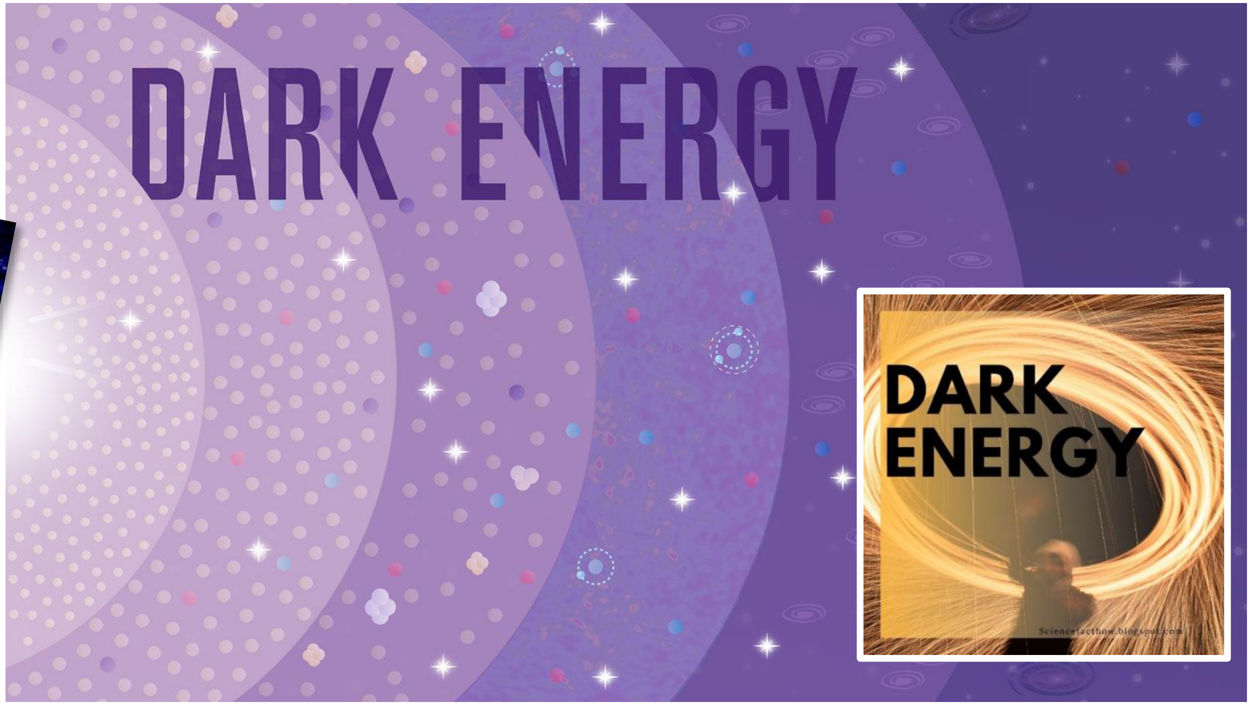
- **Evidences and future prospects**

  1 – *SNae Ia*:
  brightness & distance

  2 – *CMB* – first multipole:
  $\Omega_{tot} = 1$

  3 – *CMB* – *ISW*:
  super–clusters
  super–voids



Dark Energy & the equation–of–state $w(t)$

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Beyond the Cosmological constant of Einstein

- so far*, we have mainly focused on **Einstein´s Cosmological Constant**

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4}{3} \cdot \pi \cdot G \cdot \left(\rho_V(t) + \frac{3 \cdot P_V(t)}{c^2}\right)$$

using vacuum equation–of–state:

$$\rho_V(t) = -1 \cdot P_V(t)$$

$$\frac{\Lambda \cdot c^2}{3}$$

- **time–independent, constant** parameter $\Lambda = +\frac{8\pi \cdot G}{c^2} \cdot \rho_V$

*see Lect. #3, 4

Dark Energy & the equation–of–state $w(t)$

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- **Beyond the Cosmological constant of Einstein: dynamic Dark Energy**

  - now, we take account of other forms with different equations–of–states

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4}{3} \cdot \pi \cdot G \cdot \rho_i(t) \cdot (1 + 3 \cdot w_i(t))$$

development of density:

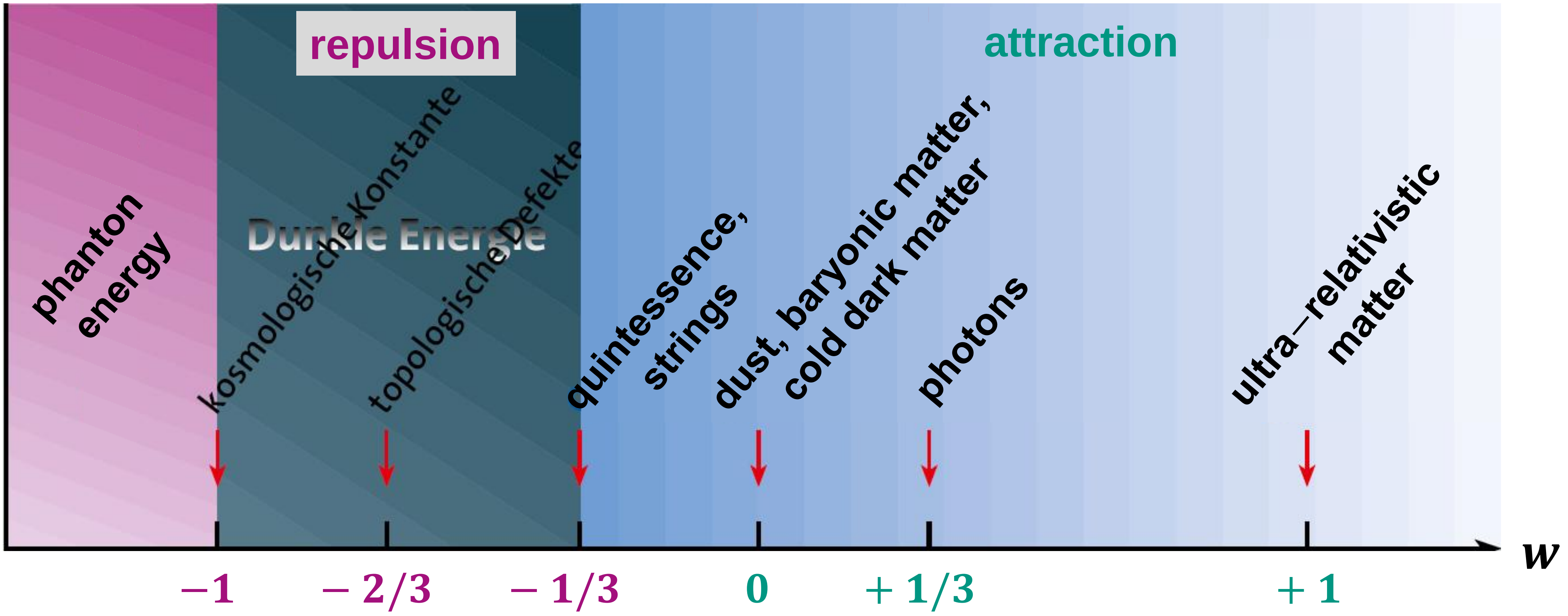
$$\rho_i(t) \sim a^{-3 \cdot [1 + w_i(t)]}$$

using ´general´ **equation–of–state** of a **component i**

$$w_i(t) = P_i(t)/\rho_i(t)$$

Dark Energy & the equation–of–state $w(t)$

- Beyond the Cosmological constant of Einstein: ordering along parameter w



Dark Energy & the equation–of–state

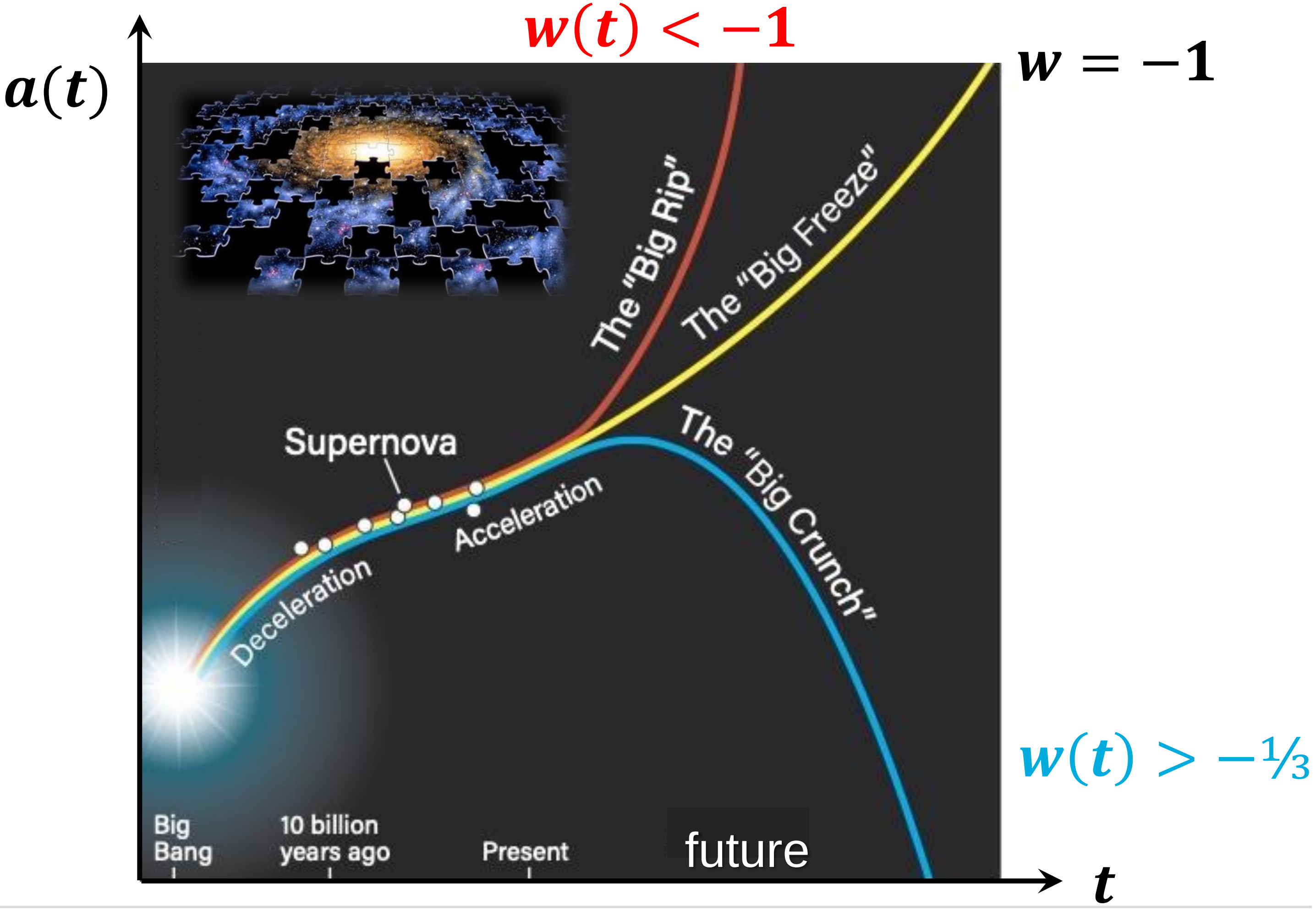
- **Beyond the Cosmological constant: from the Big Crunch to the Big Rip…**

- **the ´Big Rip´**:

scale factor	$a(t) \rightarrow \infty$
acceleration	$\ddot{a}(t) \rightarrow \infty$
eq.–of–state	$w(t) < -1$

- **the ´Big Crunch´**:

scale factor	$a(t) \rightarrow 0$
acceleration	$\ddot{a}(t) < 0$
eq.–of–state	$w(t) > -⅓$

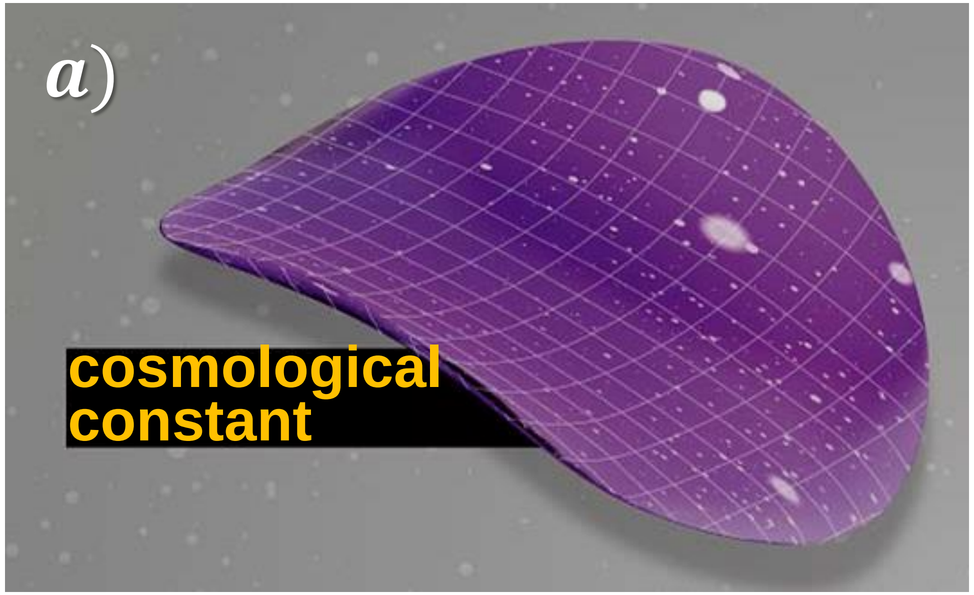


Dark Energy & other explanations

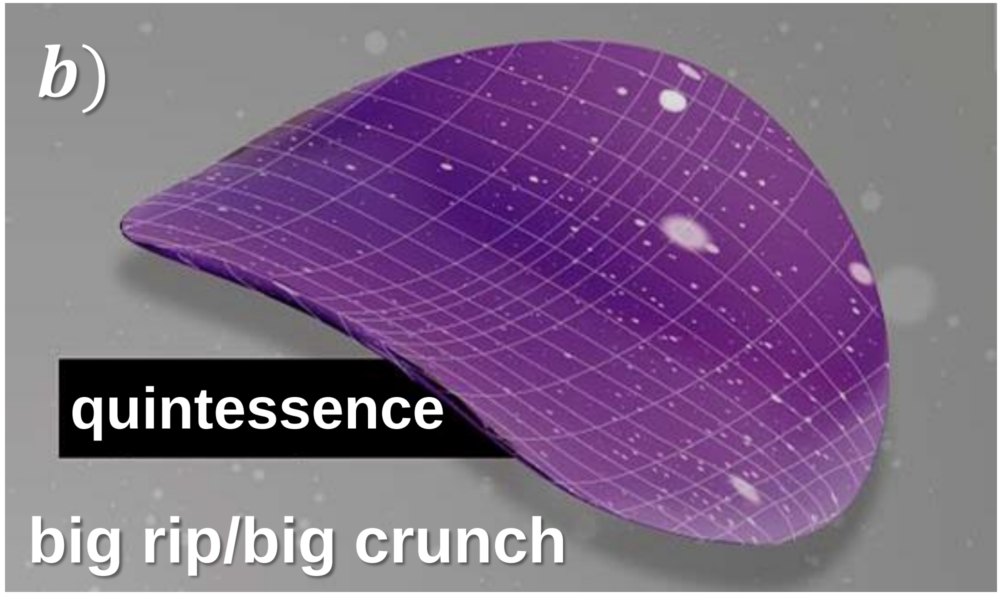
- **Beyond the Cosmological constant: from Dark Energy to modified gravity…**

$a)$ $w = -1$, **constant** parameter, generated by vacuum fluctuations

$b)$ $w \neq -1$, **dynamical** variable, value depends on time t and coordinate $\vec{r}$



$w = -1$



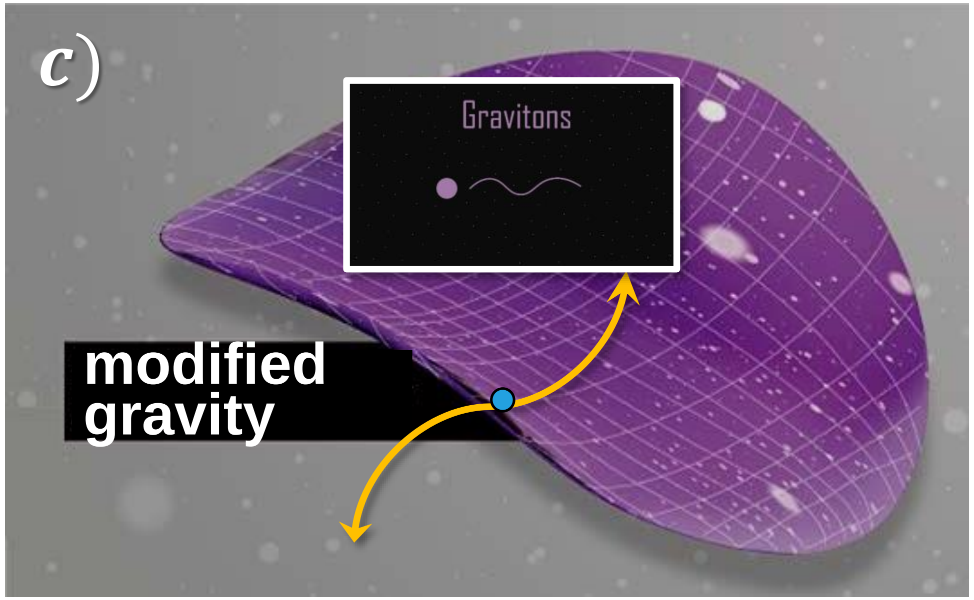
$w \neq -1$

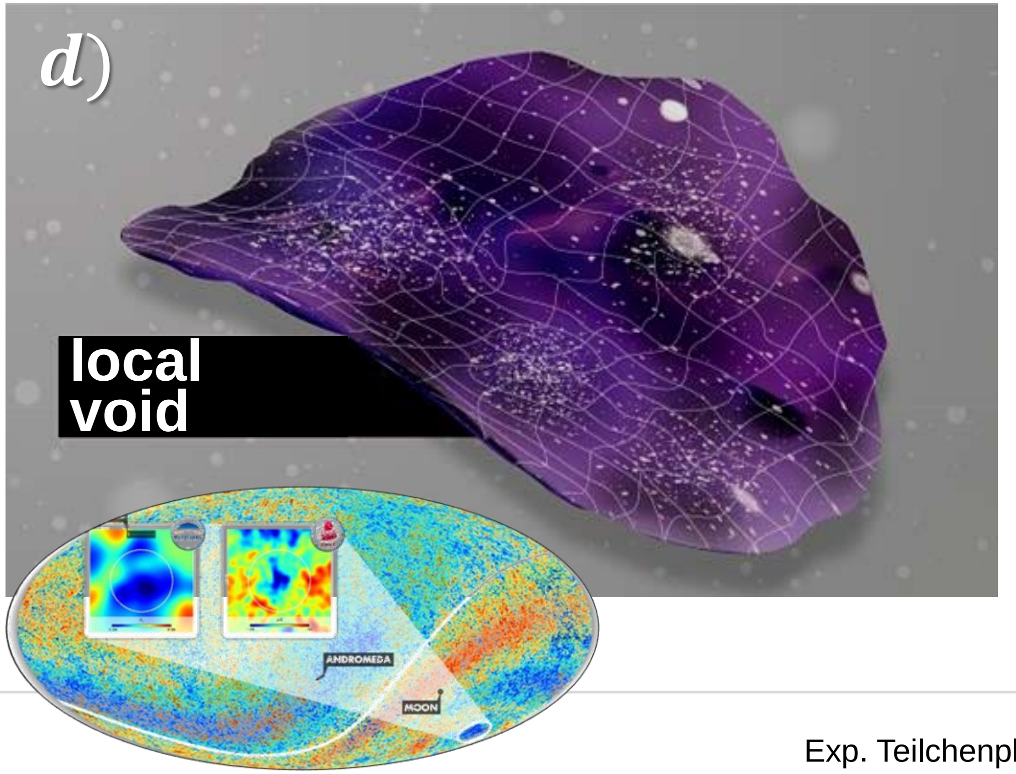
Dark Energy & other explanations

- **Beyond the Cosmological constant: from Dark Energy to modified gravity…**

$c)\ w \neq -1$, **modified gravity (space−time),** gravitons in extra−dimensions

$d)\ w \neq -1$, **local void** causes acceleration, non−homogeneous universe



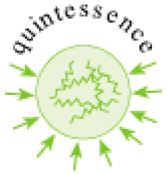


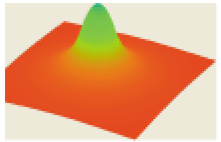
Dark Energy & dynamical quintessence

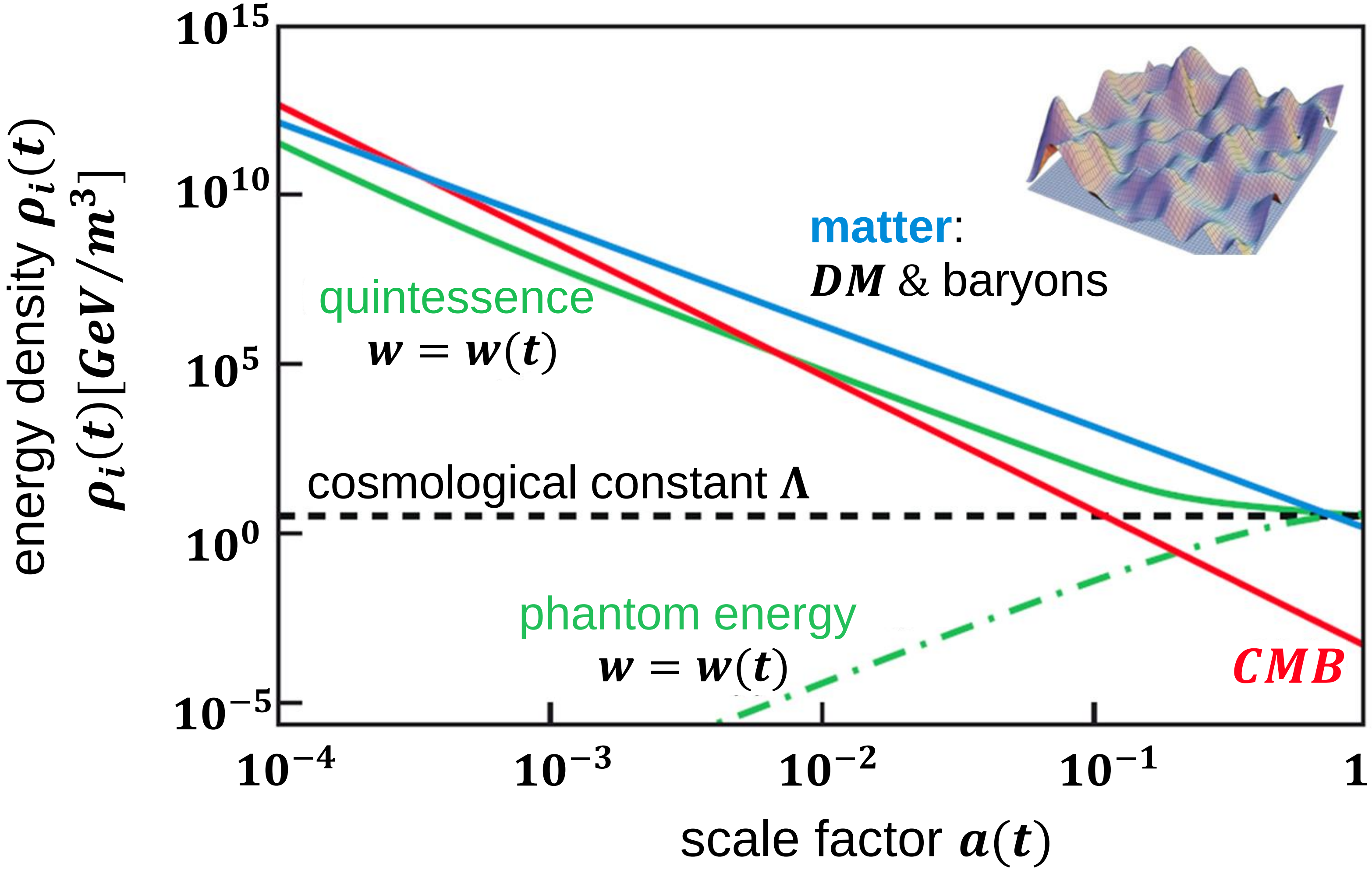
Beyond the Cosmological constant: quintessence & others…

- **quintessence** (´the fifth element´) after DM, $\nu´s$, CMB, baryons

- results from a **scalar field**: time dependence traces $\rho_{DM,baryons}(t)$







Dark Energy & origin due to (pseudo−) scalar field

Karlsruhe Institute of Technology

- Beyond the Cosmological constant: solution* via a novel wavelike particle…

NewScientist

Physics

The wonder particle: How axions could solve more than just dark matter

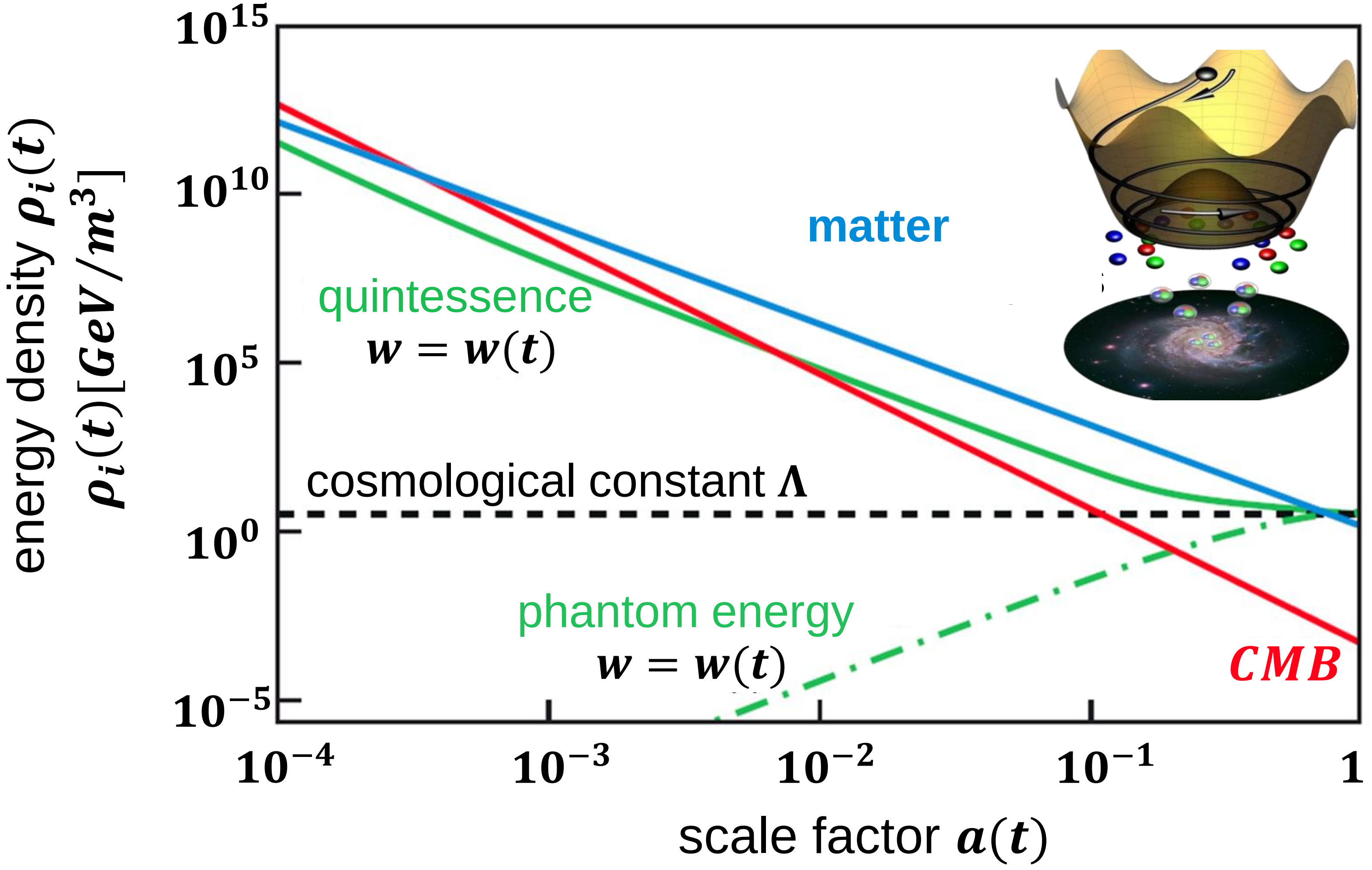
Physicists are coming to realise that hypothetical particles called axions could explain not only dark matter, but dark energy too, and more besides. Now there is fresh impetus to detect them

By Jonathan O'Callaghan

29 November 2023

Colin Reid

IN 1977, physicist Frank Wilczek took a walk that would change the course of particle physics forever. "On that walk, I had the germs of two really good ideas," he recalls. The



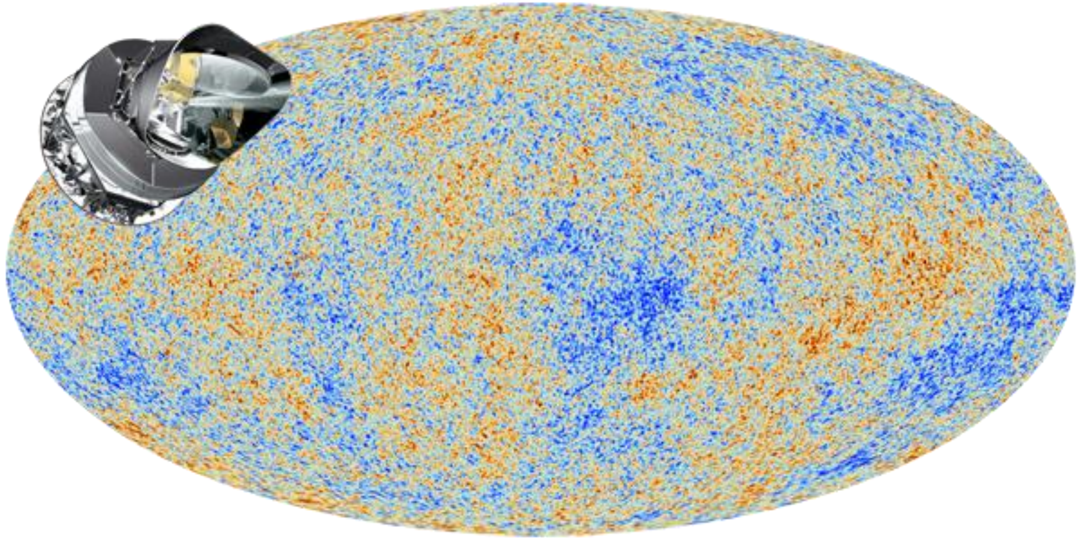
*see $ATP - I$

Dark Energy: new observations & results

- **the Cosmological constant on the ´testbed´ of CMB & LSS**

  - combining recent large–scale data–sets from the very early (CMB) & the present universe (LSS)

$Planck$: multipoles ℓ



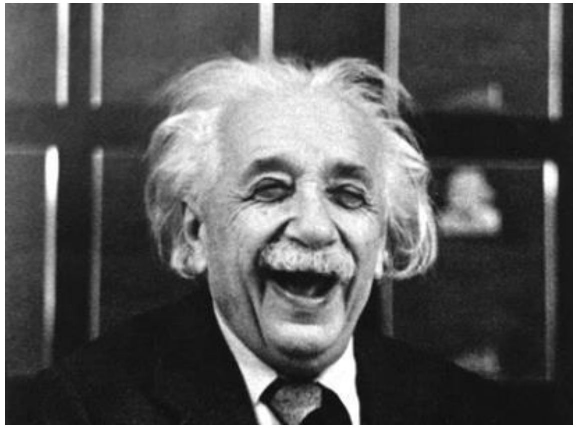
$SDSS$: matter power $C(k)$

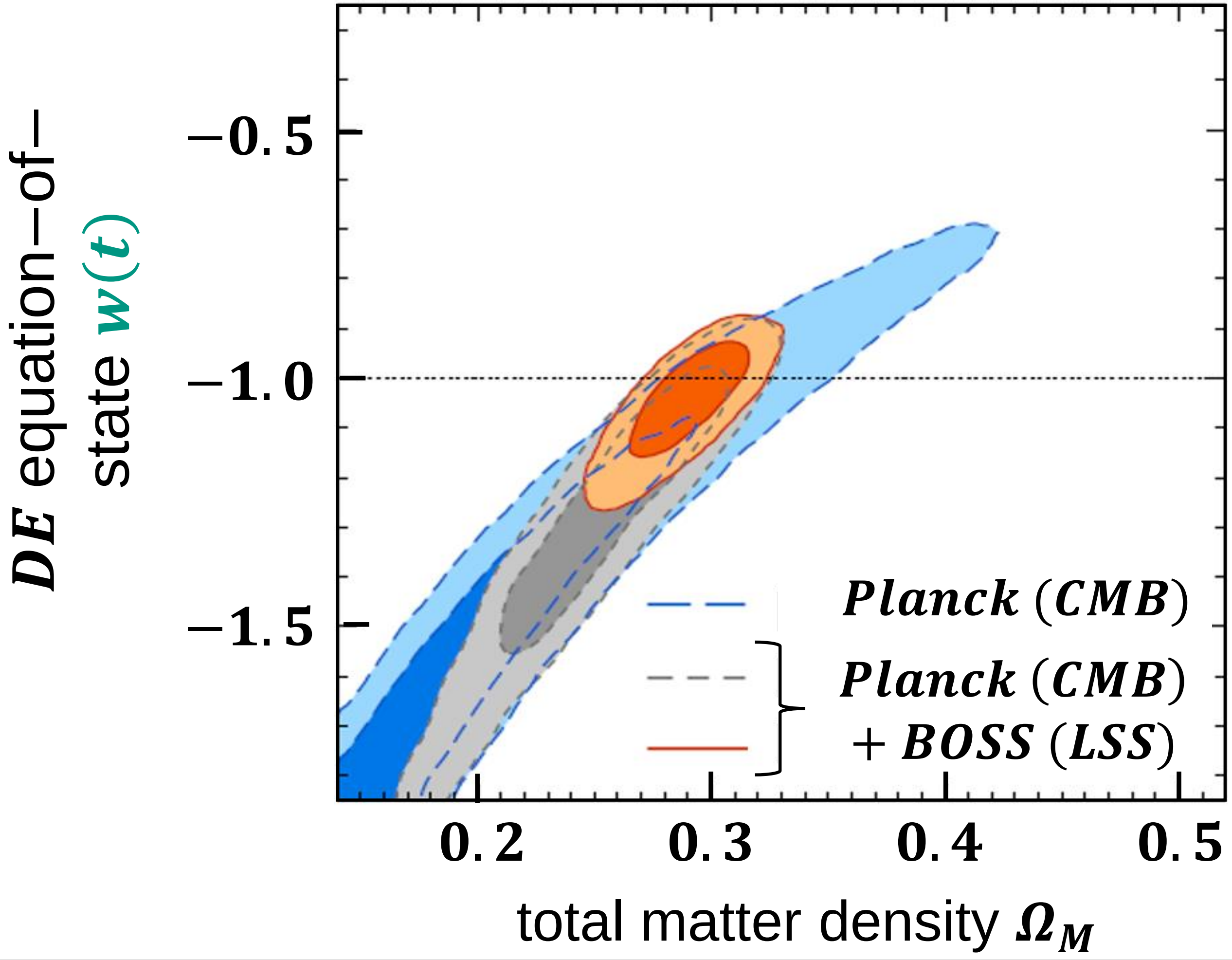
Dark Energy: new observations & results

- **the Cosmological constant on the ´testbed´ of CMB & LSS**

- best joint fit value:
  $w = -1.028 \pm 0.32$ **(2018)**

↳ clear preference for a **cosmological constant Λ**





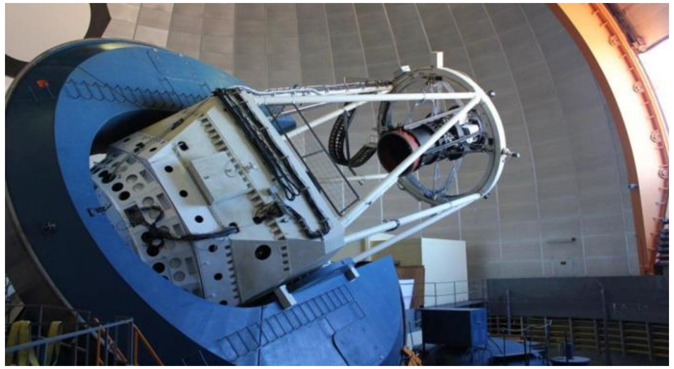
Dark Energy: new observations – DES

- **the Cosmological constant on the ´testbed´ of the Dark Energy Survey**

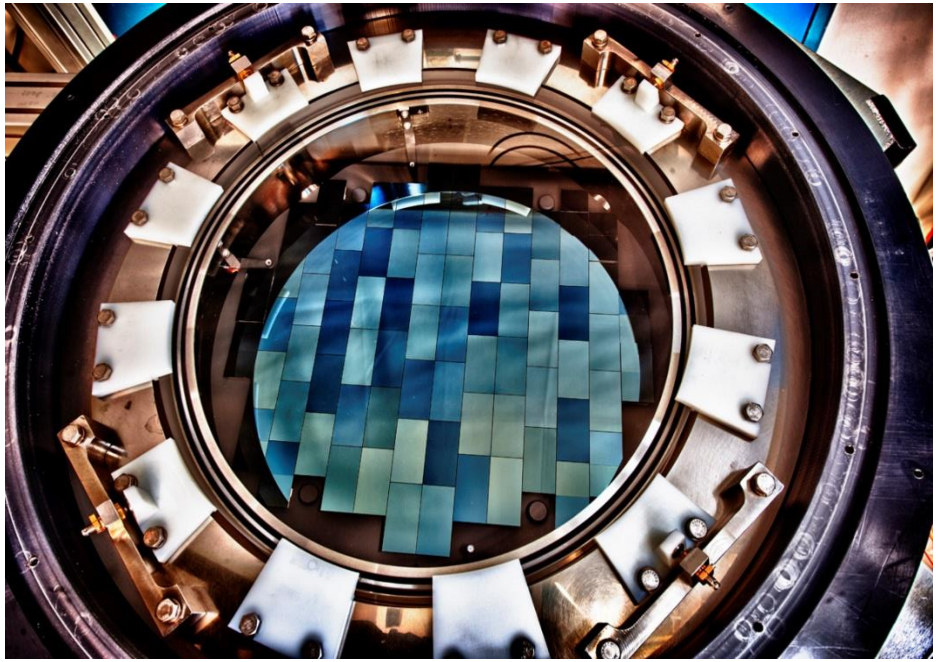
  - $4\,m$ $Blanco$ telescope at the $Cerro\ Tololo$: $Inter - American\ Observatory$ ($CTIO$) in Chile: dedicated survey to constrain the properties of Dark Energy

  - $DECam$: Dark Energy Camera
    $\mathbf{520}$ $Megapix\ CCD$
    $\mathbf{62}$ chips, each with $\mathbf{2048 \times 4096}$ pixels

  - observations from $\mathbf{2012 - 2019}$



DARK ENERGY SURVEY



$DECam$

Dark Energy: new observations – DES

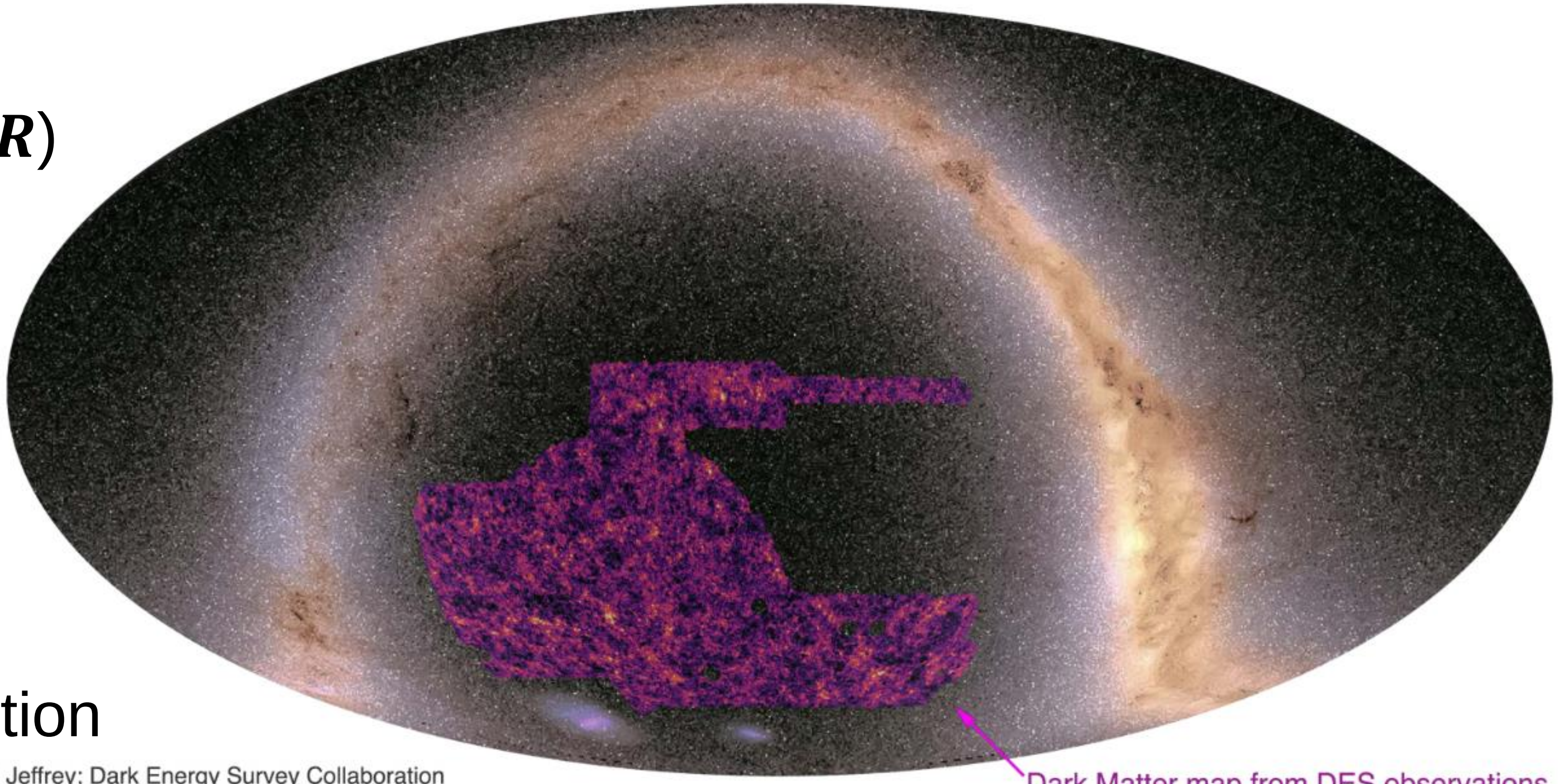
- the Cosmological constant on the ´testbed´ of the Dark Energy Survey

  - $4\,m$ $Blanco$ telescope at the $Cerro\ Tololo$: $Inter-American\ Observatory$ ($CTIO$) in Chile

  - photometric (UV, optical, IR) survey of 10^8 galaxies

  - cosmological data from year 3 of observations:
    - galaxy clustering
    - weak lensing, …

  - largest map of DM distribution



N. Jeffrey; Dark Energy Survey Collaboration

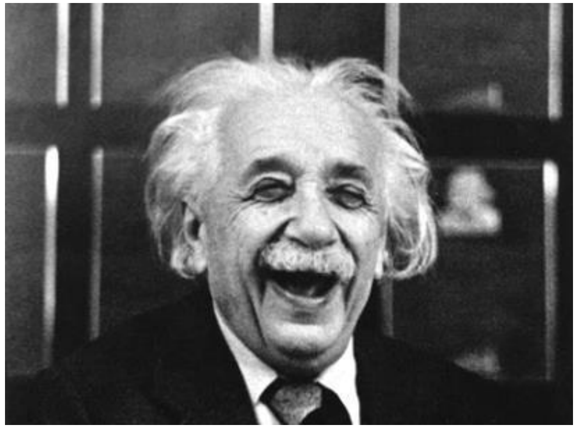
Dark Energy: new observations – DES

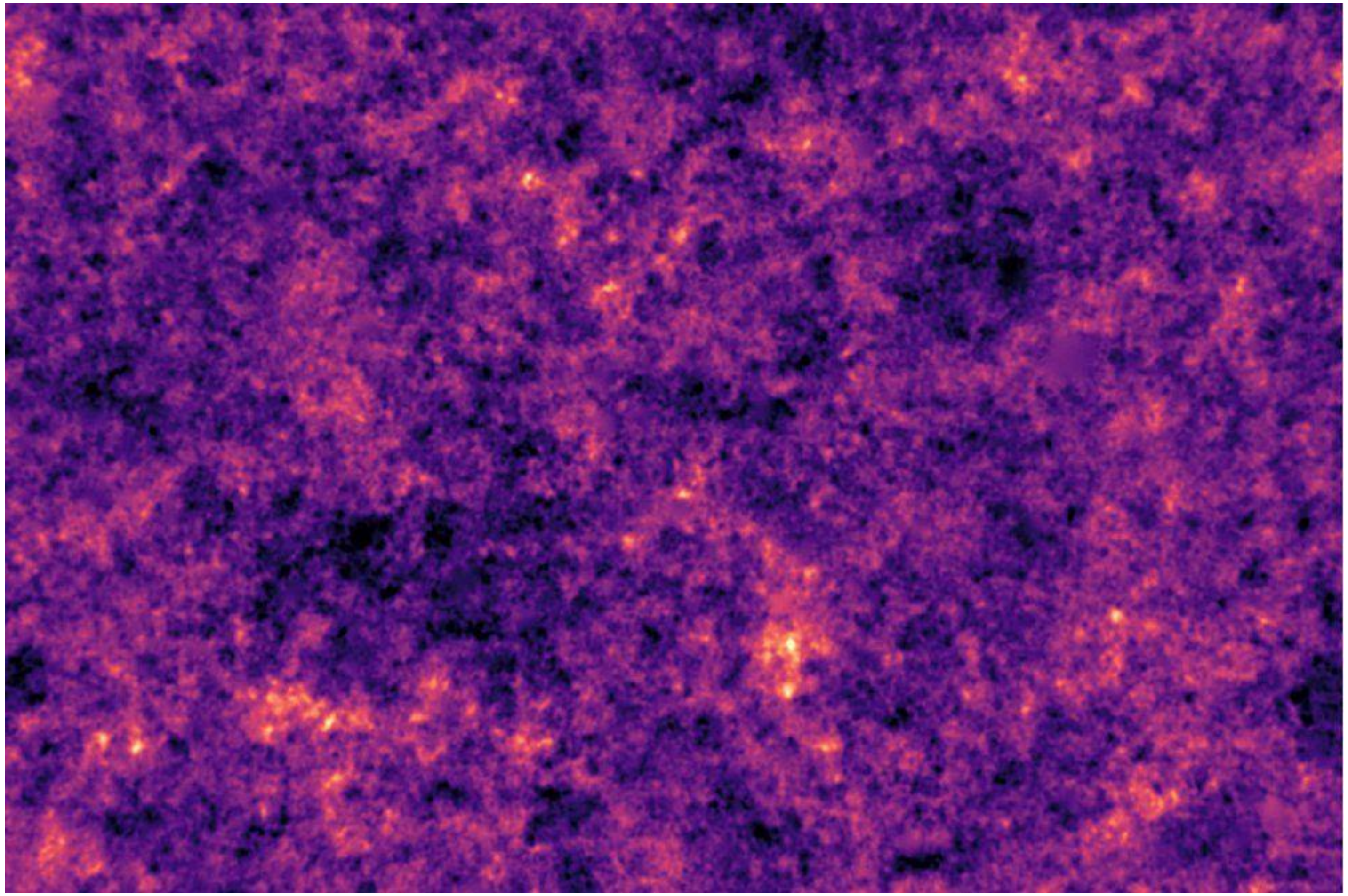
- the Cosmological constant on the ´testbed´ of the ***D**ark **E**nergy **S**urvey*

  - best joint fit value:

    $w = -0.98\,^{+0.32}_{-0.20}$ **(2021)**

  ↳ clear preference for a **cosmological constant Λ**

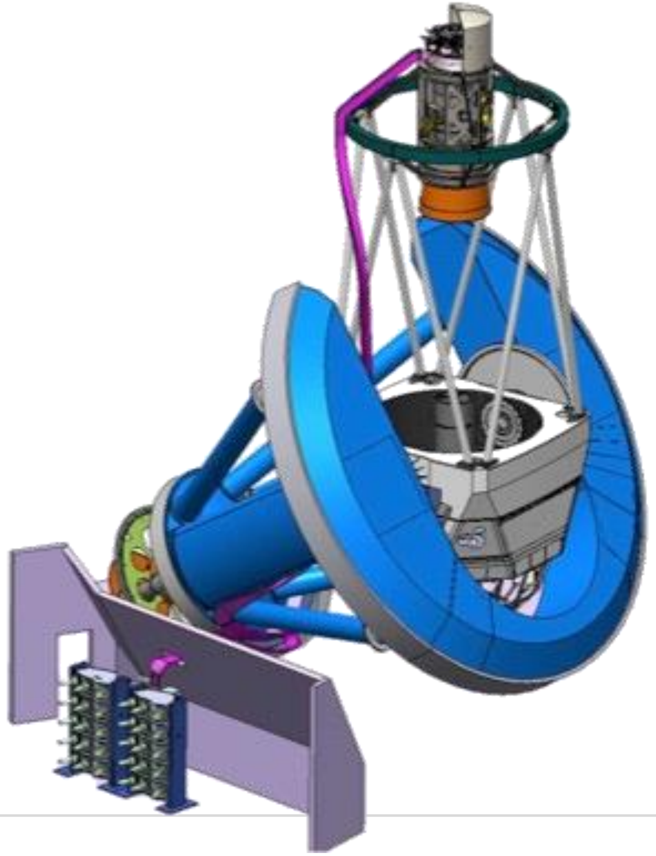


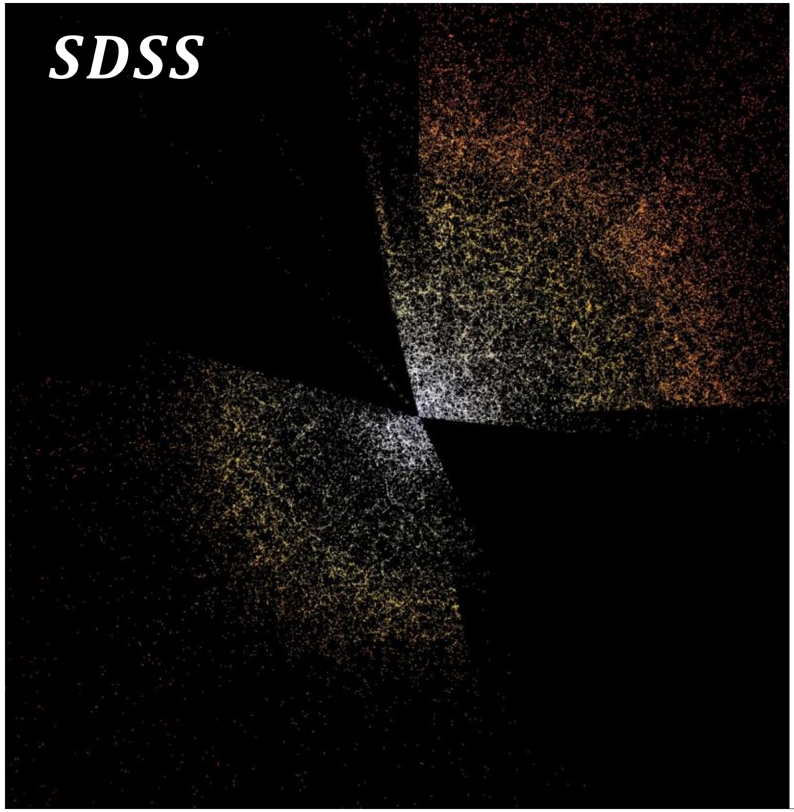


Dark Energy: new observations – $\boldsymbol{DESI}$

- **Cosmological constant: testing by $\boldsymbol{D}$ark $\boldsymbol{E}$nergy $\boldsymbol{S}$pectroscopic $\boldsymbol{I}$nstrument**

  - a large survey with a $\mathbf{4}\ \boldsymbol{m}$ telescope since mid$-\mathbf{2021}$ using $\mathbf{4000}$ optical fibres



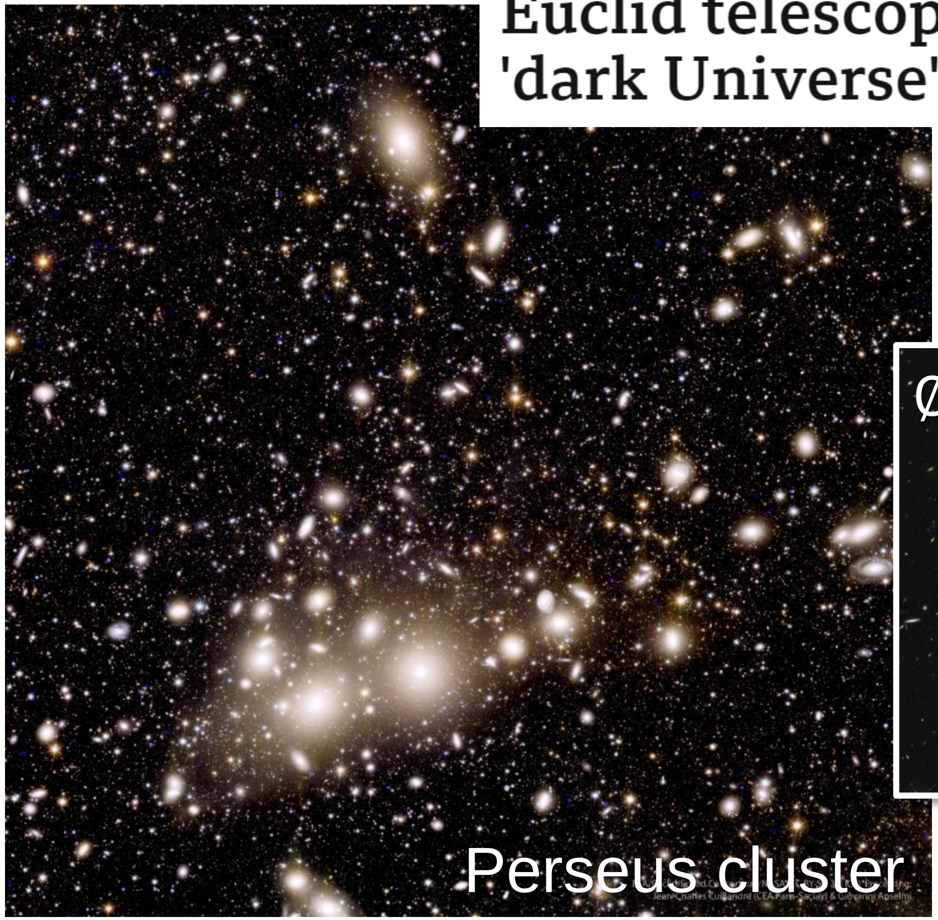


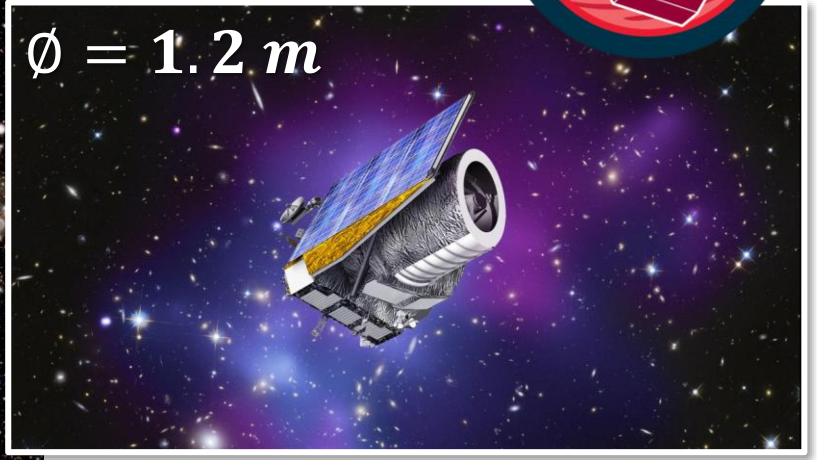
Dark Energy: new observations – *EUCLID*

Cosmological constant: testing by a dedicated space telescope (11/2023)

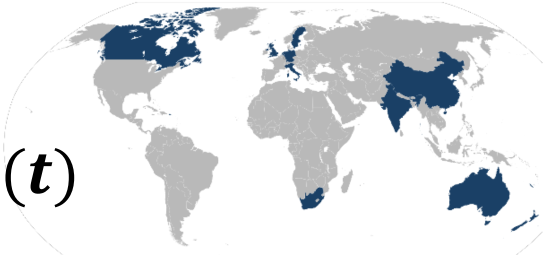
- ***ESA*** mission, operated at the ***L2*** point
- ***3D*** – map of ***DM*** weak lensing of $\sim\mathbf{10^9}$ galaxies
- targeted goal: **10**% uncertainty on $\boldsymbol{w(t)}$

Euclid telescope: First images revealed from 'dark Universe' mission



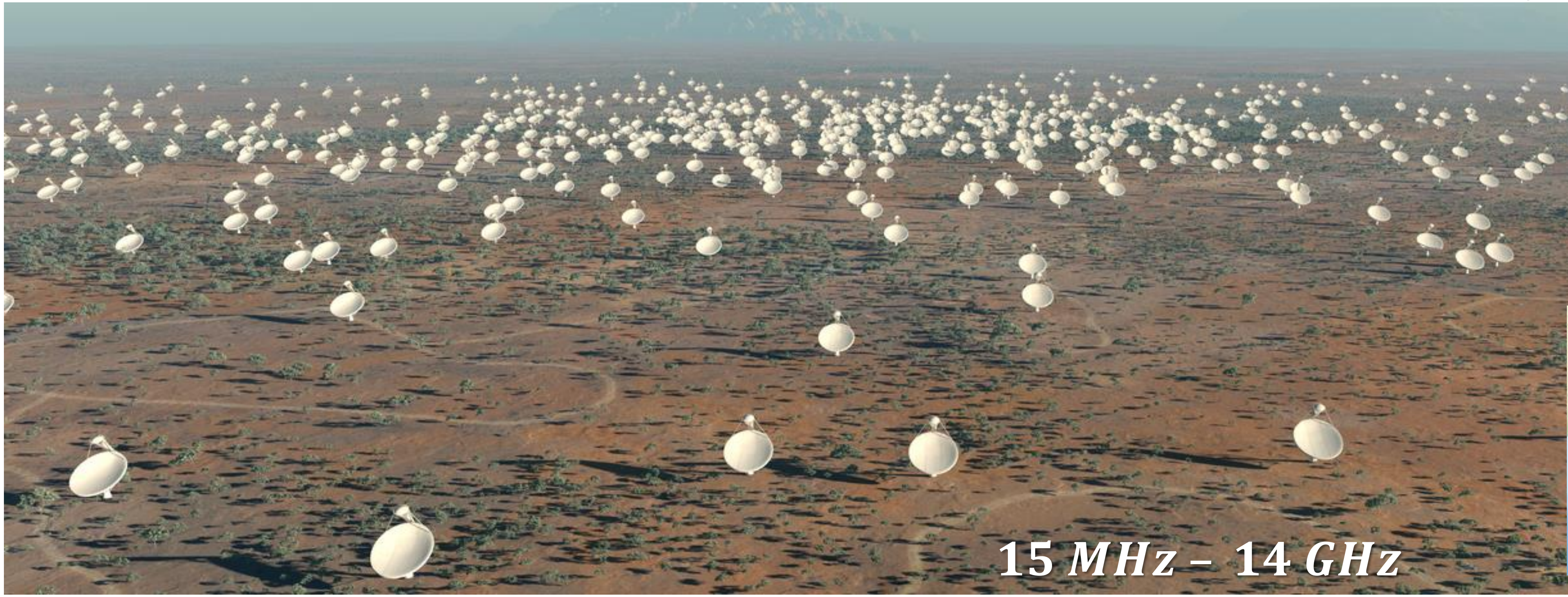


Dark Energy: future measurements with $SKAO$



- **Radio telescope with $A = 1\ km^2$ for cosmology** $(> \mathbf{2028})$

- intensity of the HI – line at $\lambda = 21\ cm$ for LSS – analyses, goal: $w(t)$

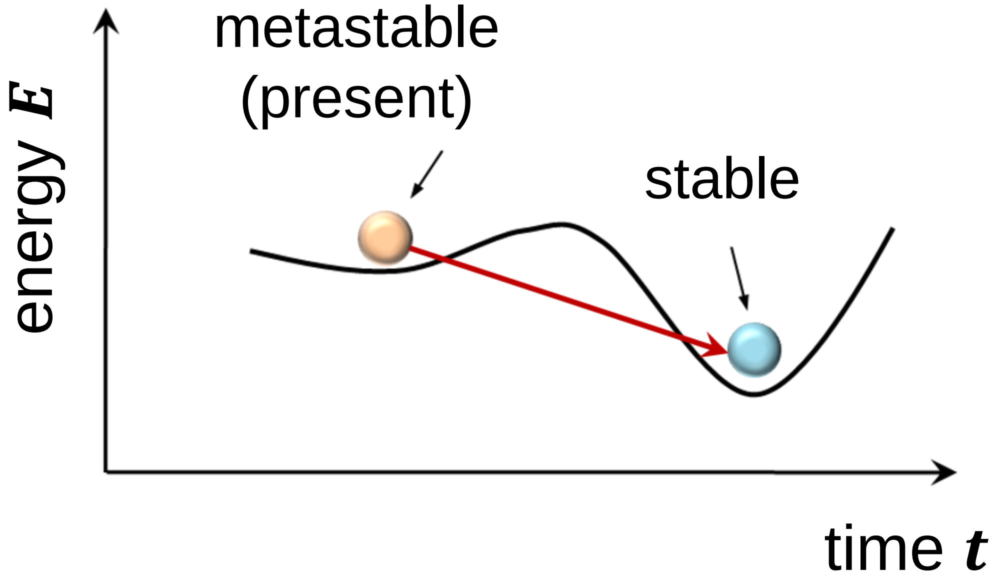


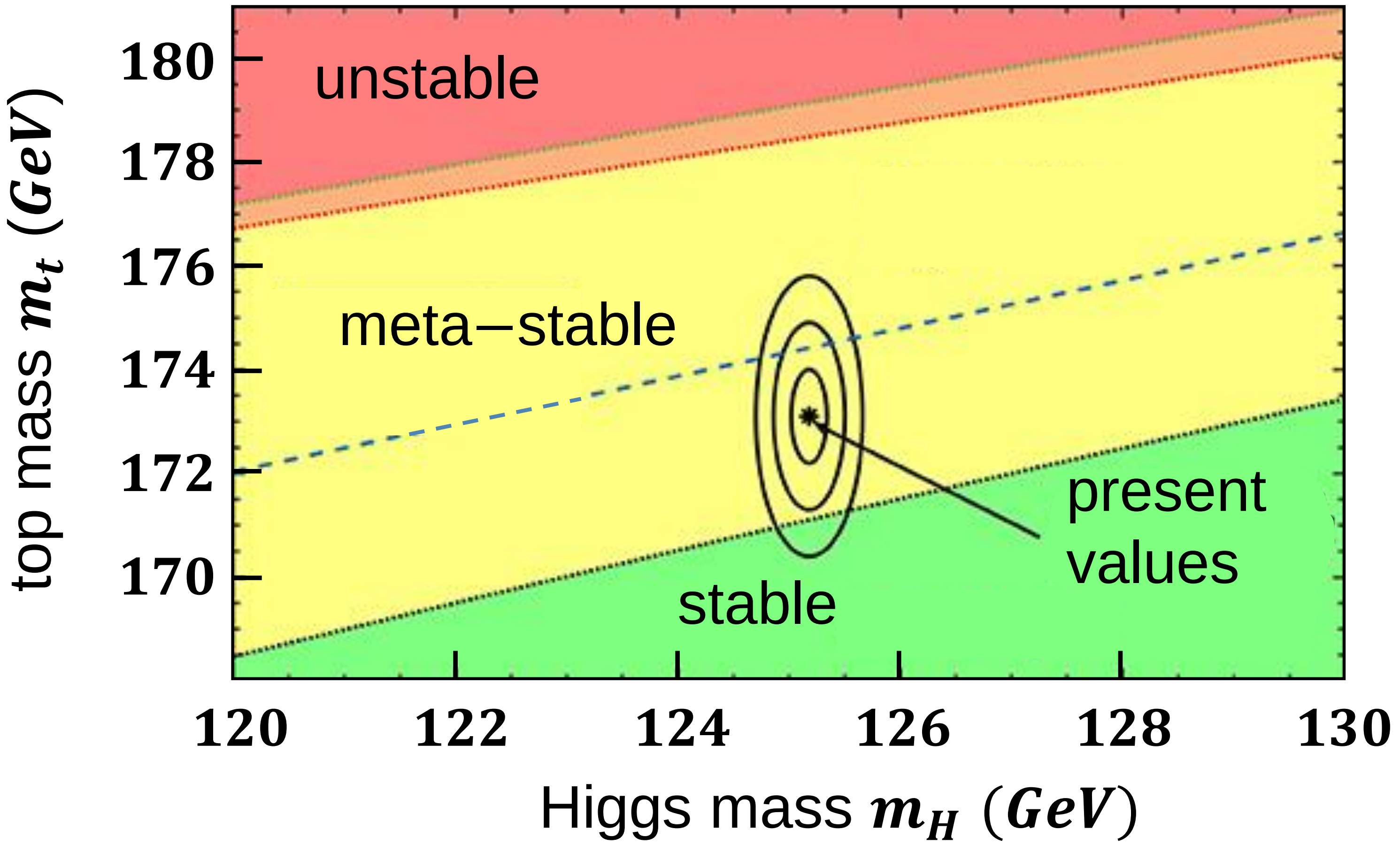
*Square Kilometre Array Observatory

Cosmology: ´final´ open questions

- **Is the vacuum (electroweak ground state) stable over very long times?**

- spontaneous decay via a **tunneling process** to the ´true´ vacuum state…





Cosmology: ´final´ open questions

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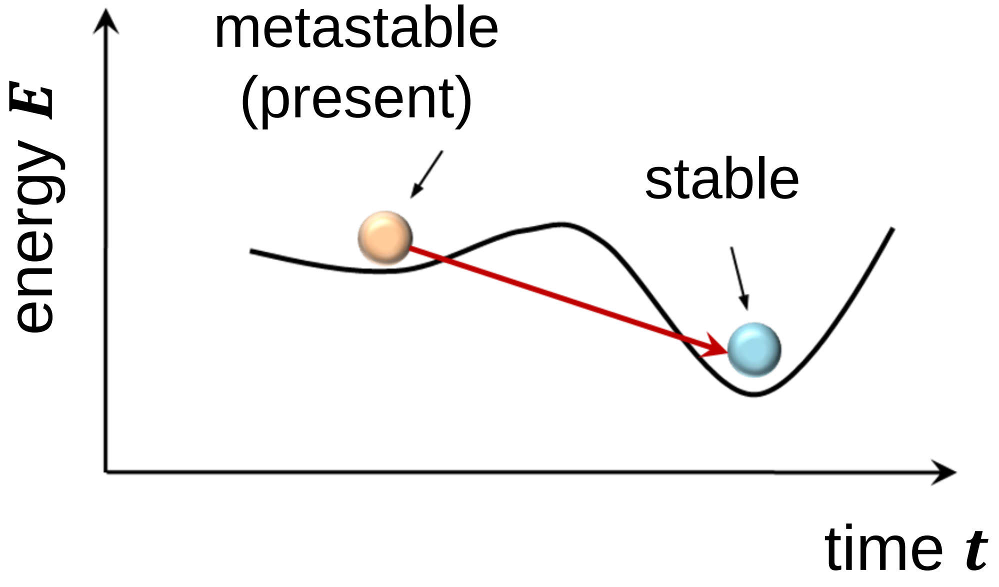
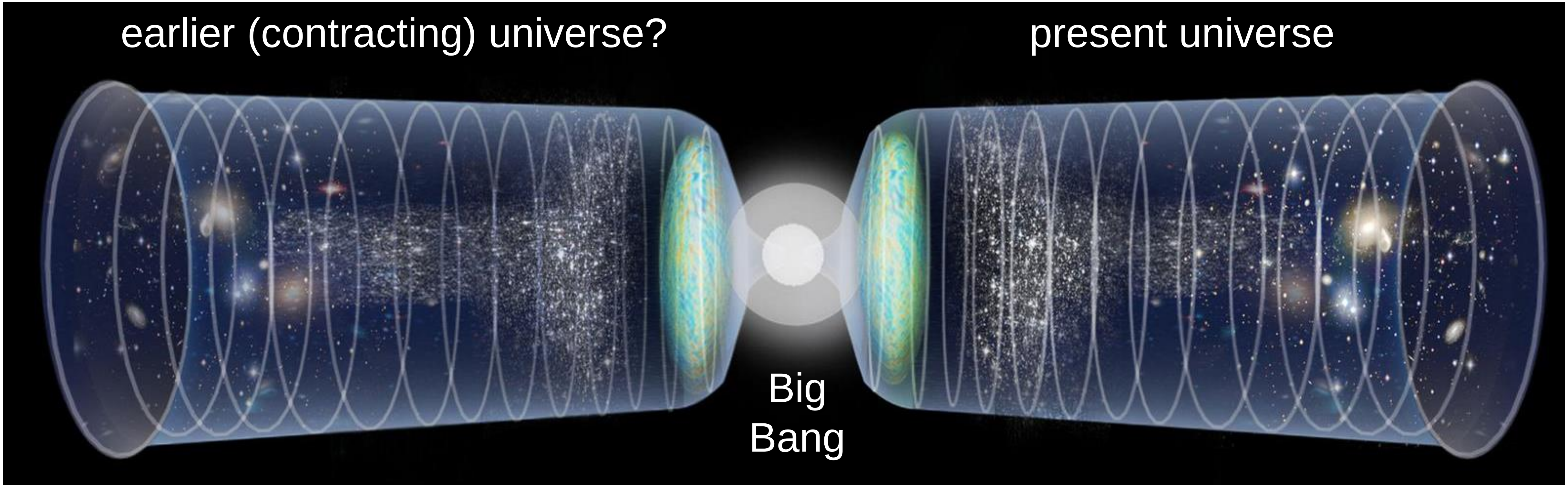


a ***new*** Standard Model….

Cosmology: ´final´ open questions

- **Where did it all come from? Did it emerge from a ´Big Bounce´?**

  - signature of a possible earlier collapsed universe: observation of **rings in the CMB**



Cosmology: ´final´ open questions

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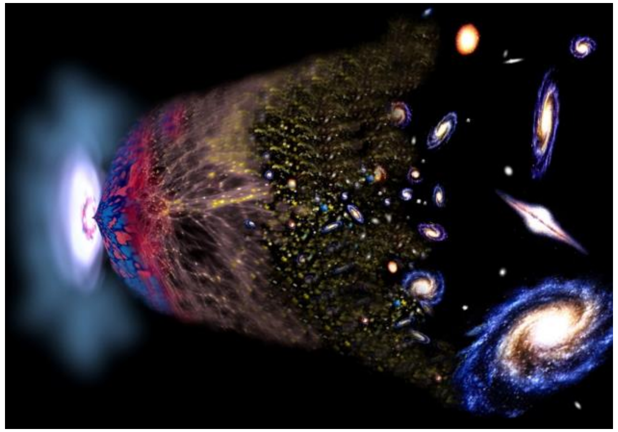

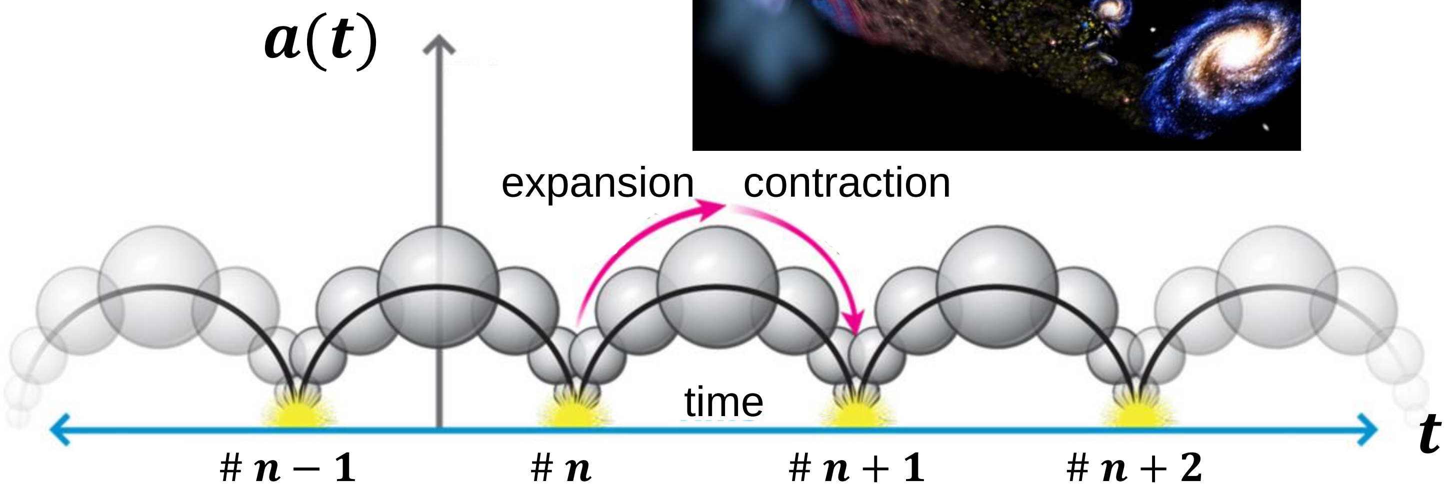

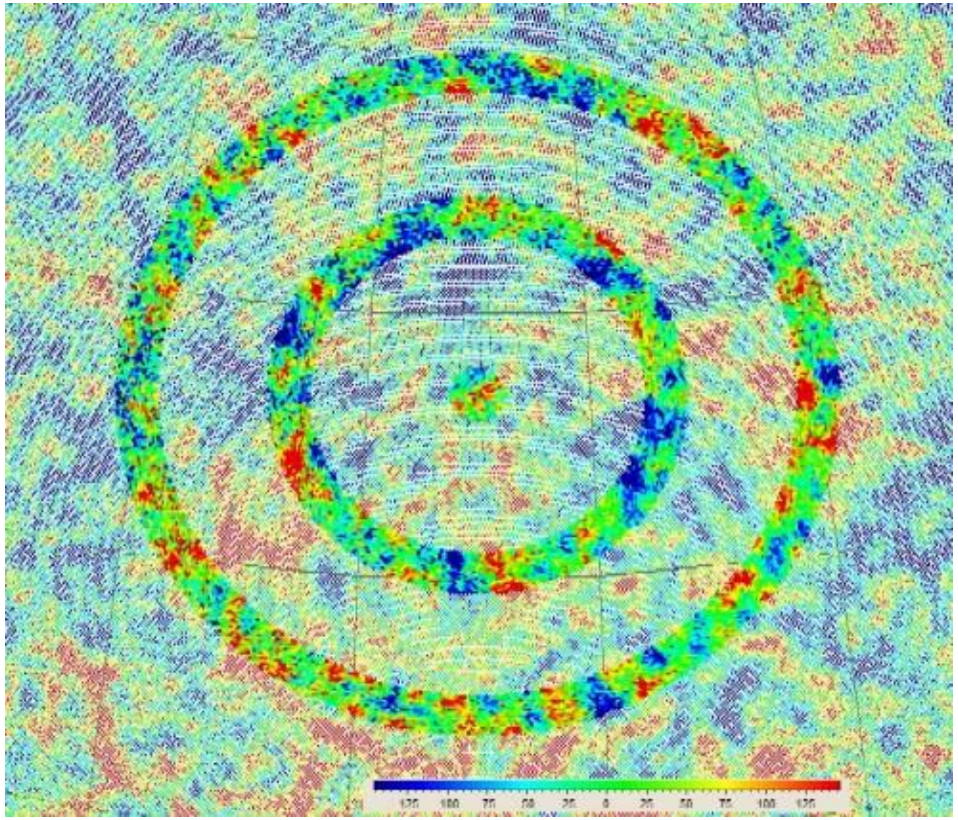

Cosmology: a ´final´ question…

- **Where did it all come from?**

THANK YOU…