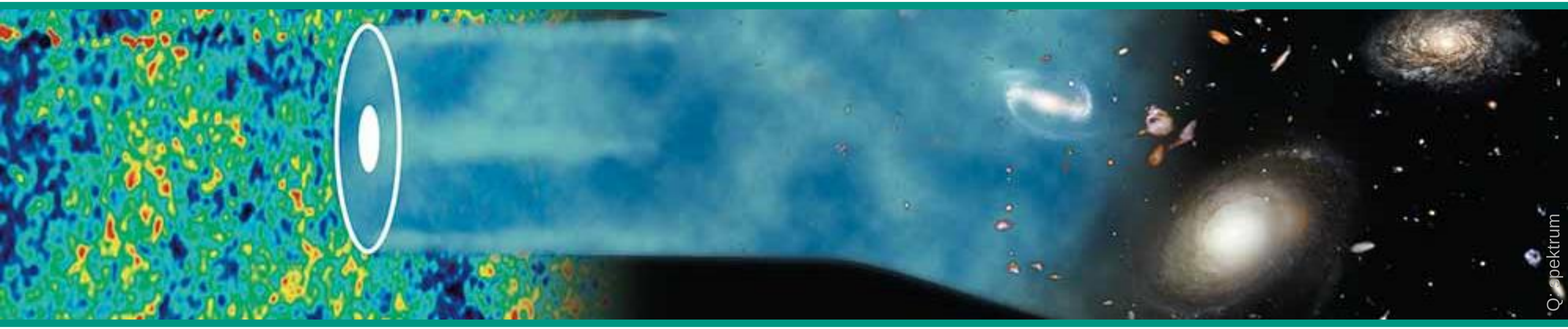
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 23/24 Lecture 14 Feb. 6, 2024



Recap of Lecture 13

- **The observed ´clumpiness´ of the universe: matter power spectrum $P(k)$**

  - analysis of **density contrast** – as function of **distance** r: **galaxy correlation function** $\xi(r)$ ⇔ as function of **wave number** k: matter power spectrum $P(k)$

  - DM – modes of specific wave number k evolve independently: important is **time of first causal contact** (in the radiation– / matter– dominated universe)

  - **small** DM – mode (large k): growth is delayed in radiation era – $P(k) \sim k^{-3}$
  - **large** DM – mode (small k): growth is not delayed in matter era – $P(k) \sim k$

  - matter power spectrum $P(k)$: allows to discriminate pure HDM vs. pure CDM

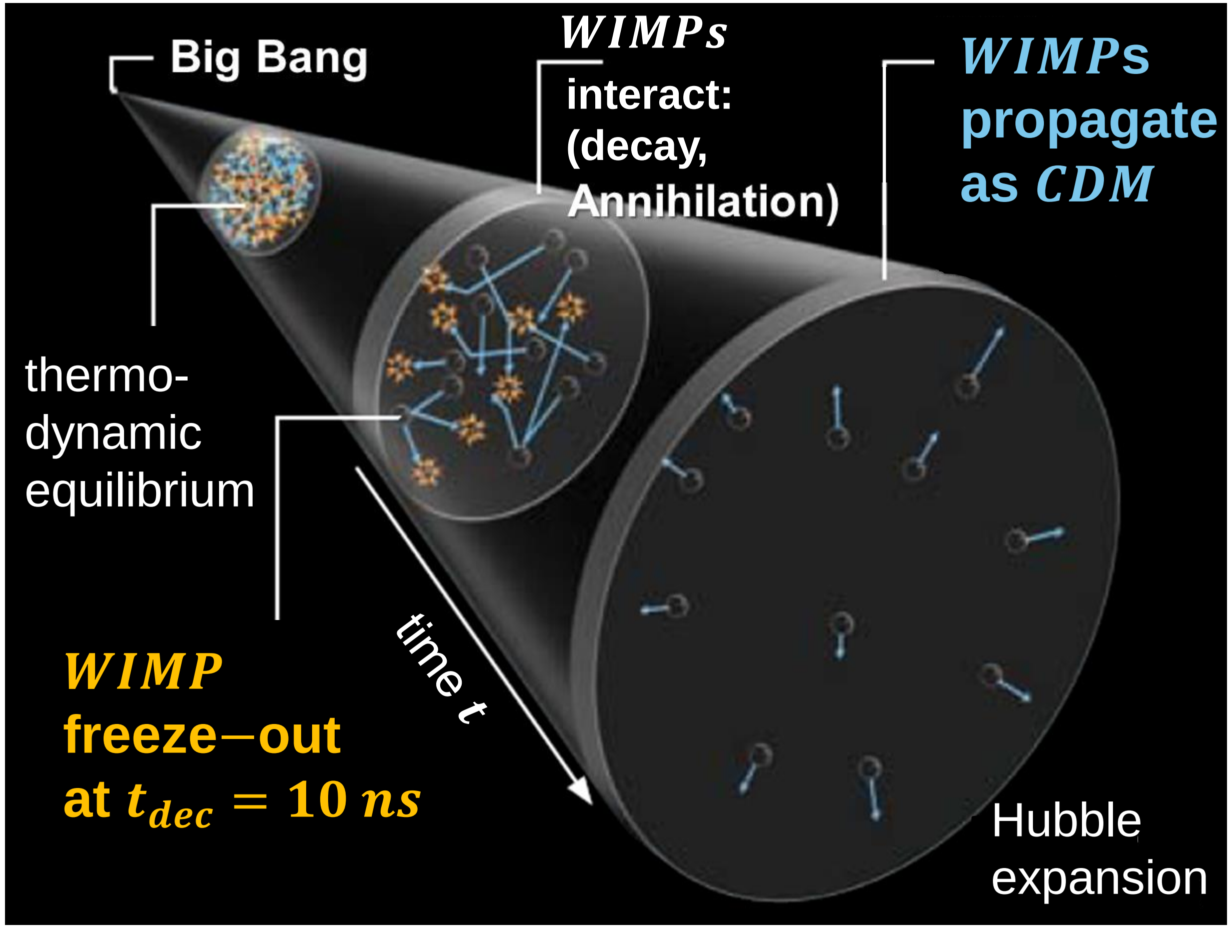
CDM: $WIMPs$ as generic thermal relics

■ Thermal production of CDM: $WIMPs$*

- $WIMPs$: massive, **non−baryonic** thermal relics left over from the Big Bang, which interact via **weak interaction** only (+ **gravity)**

- only pair production / pair annihilation of $WIMPs$ (≡ $Majorana$ particles with conserved $SUSY$ quantum number R_P)

- very **large mass** (TeV – scale):
  ⇨ huge phase space in case of decay



*Weakly Interacting Massive Particle

CDM: $WIMPs$ as generic thermal relics

Annihilation rate of $WIMPs$

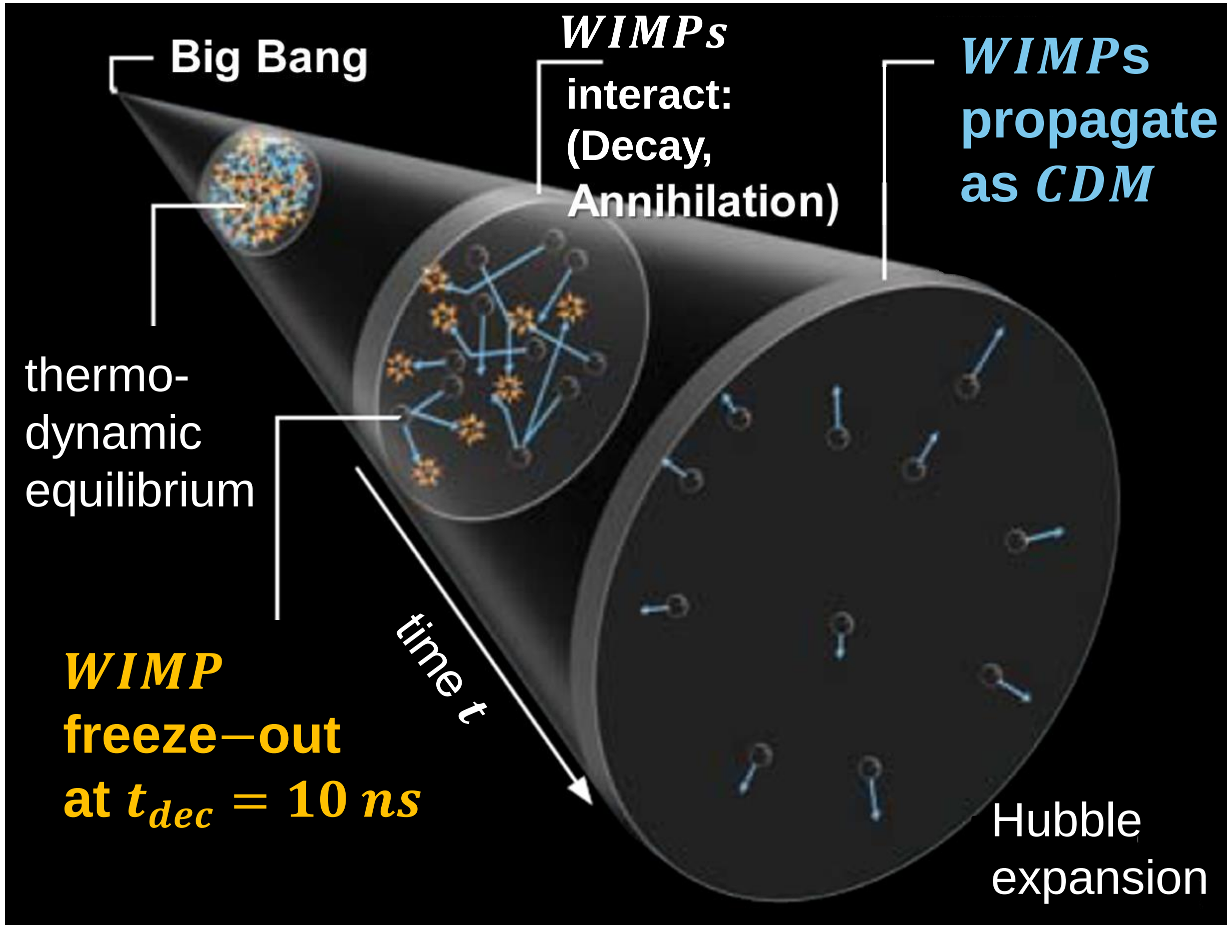
- $WIMPs$: annihilation rate given by typical **weak interaction strength**

$$\sigma_{ann} = \sigma_{weak}$$

- decoupling time t_{dec} from radiation bath is $t_{dec} \approx 10\ ns$

$$\sigma_{ann}(t_{dec}) = H(t_{dec})$$

- this will result in the so-called $WIMP$ **miracle** (to be discussed later)



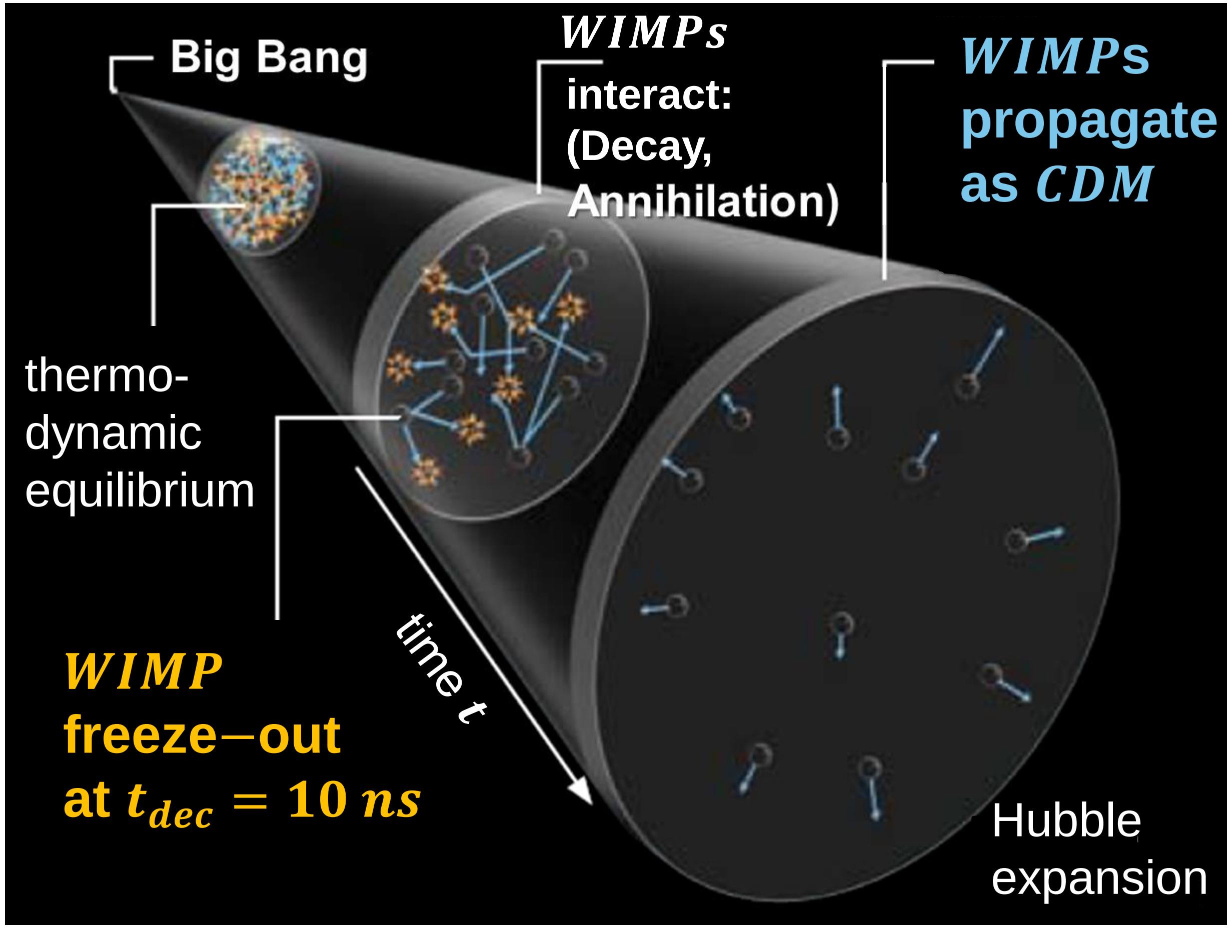
CDM: $WIMPs$ as generic thermal relics

Long–term ´slow´ propagation of $WIMPs$

- $WIMPs$: ***non–relativistic*** propagation with very **limited free–streaming range** due to kinematic relation:

$$E_{kin}(WIMP) \approx 0.05 \cdot m(WIMP)$$

- after decoupling & during propagation: χ^0 from $SUSY$ are stable over long, cosmological time scales due to intrinsic symmetry: R – parity R_P



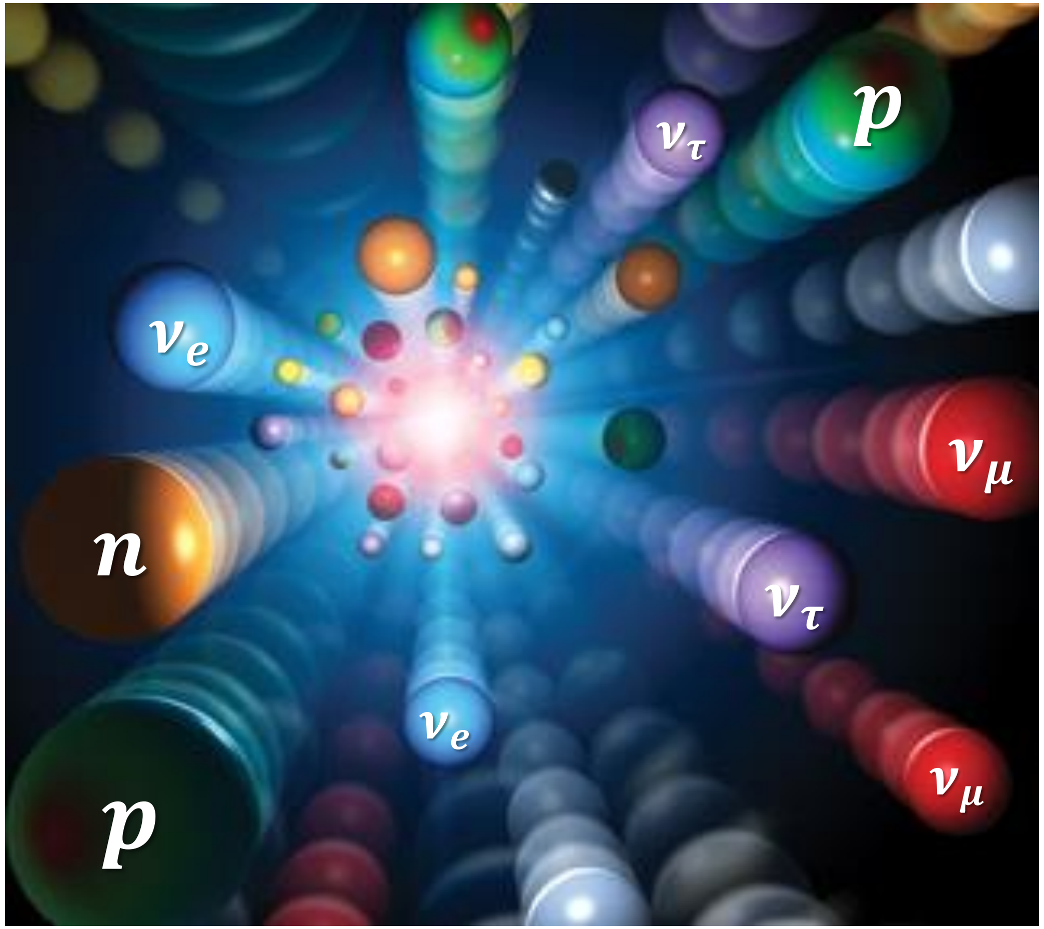
HDM: ν´s as generic light thermal relics

Hot dark matter: relativistic free−streaming

- ν´s: ***ultra−relativistic*** propagation over an exceedingly **large free−streaming range** of $> Gpc$ due to kinematic relation

$$E_{kin}(\nu) > 10^6 \cdot m(\nu)$$

- after decoupling: stable over long, cosmological time scales due to conserved **lepton number L**



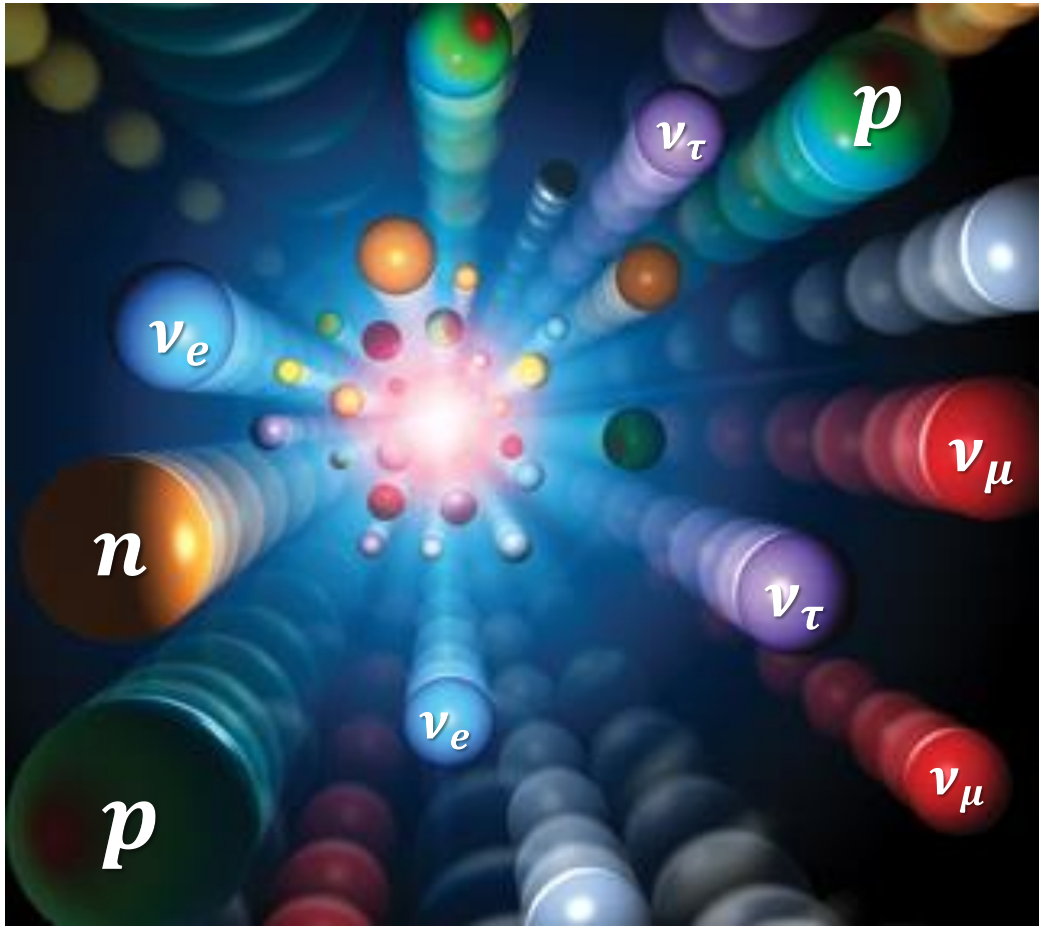
HDM: $\nu' s$ as generic light thermal relics

$\nu_{e,\mu,\tau}$

Hot dark matter: relativistic free–streaming

- $\nu' s$: ***ultra–relativistic*** propagation is strongly suppressing annihilation in the early universe (also: there exist no lighter particles carrying lepton numbers in the SM)
  ⇨ weak interaction only (with baryonic matter)

- decoupling at $t \cong 1\ s$ and $T \cong 1\ MeV$ (see also: $chap. 3.1$ on Big Bang Nucleosynthesis, lecture #5)



Dark Matter: hot, warm or cold $(HDM/WDM/CDM)$

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- Generic particle models for cosmological DM – density $\rho_{DM} \cong 1\,GeV/m^3$

Hot Dark Matter	Warm Dark Matter	Cold Dark Matter
particle candiate: ***active*** neutrinos $\nu_{e,\mu,\tau}$ $m \sim 0.05 \dots 0.8\ eV$	particle candiate: ***sterile*** neutrinos ν_s $m \sim 1 \dots 20\ keV$	particle candiate: ***SUSY*** neutralinos χ^0 $m \sim 0.1 \dots 10\ TeV$
number density: N(active): $339/cm^3$ decoupling: $T_{fr} = 2 - 3\ MeV$ $T_{fr}/m \sim 10^6 \dots 10^7$	number density: N(sterile): $< 1/cm^3$ decoupling: no thermal process, but via ν –oscillations	number density: $N(\chi^0)$: $< 10^{-9}/cm^3$ decoupling: $T_{fr} = GeV \dots TeV$ $T_{fr}/m \sim 1/20$
impact on LSS: wash-out of structure on scales $\lambda \leq 1\ Gpc$	impact on LSS: wash-out of structure on scale $\lambda < 0.1\ Mpc$	impact on LSS: wash-out of structure on scales $\lambda < 0.1\ pc$

Dark Matter: hot, warm or cold $(HDM/WDM/CDM)$

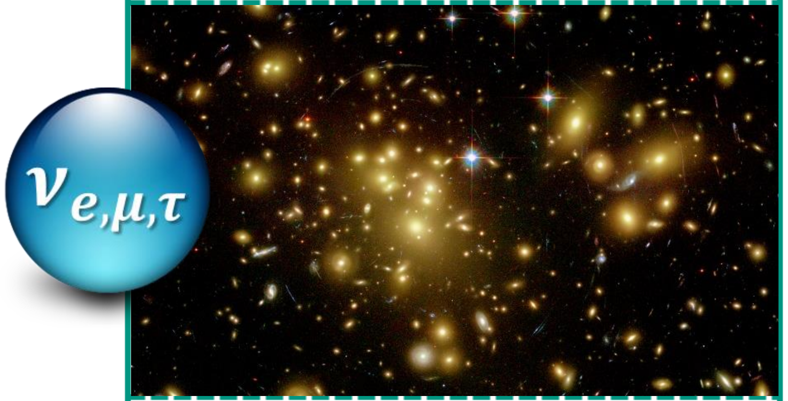
- **Generic particle models for cosmological DM – density $\rho_{DM} \cong 1\,GeV/m^3$**

Hot Dark Matter

particle candiate:

active neutrinos $\nu_{e,\mu,\tau}$

$m \sim 0.05 \ldots 0.8\,eV$



impact on LSS:

wash-out of structure

on scales $\lambda \leq 1\,Gpc$

Warm Dark Matter

particle candiate:

sterile neutrinos ν_s

$m \sim 1 \ldots 20\,keV$

impact on LSS:

wash-out of structure

on scale $\lambda < 0.1\,Mpc$

Cold Dark Matter

particle candiate:

SUSY neutralinos χ^0

$m \sim 0.1 \ldots 10\,TeV$

impact on LSS:

wash-out of structure

on scales $\lambda < 0.1\,pc$

Dark Matter: hot, warm or cold $(HDM/WDM/CDM)$

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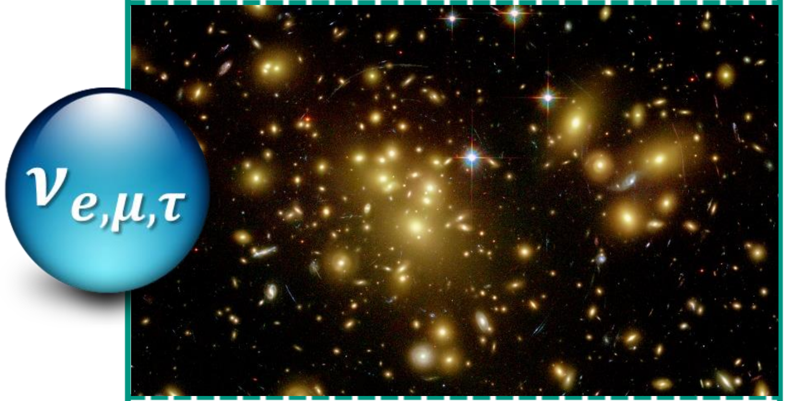
■ **Generic particle models: the important Lee–Weinberg curve**

Hot Dark Matter

particle candiate:

active neutrinos $\nu_{e,\mu,\tau}$

$m \sim 0.05 \ldots 0.8\, eV$



impact on LSS:

wash-out of structure on scales $\lambda \leq 1\, Gpc$

Lee-Weinberg curve

이휘소

Weinberg

for thermal production & subsequent reduction due to annihilation processes: only **two narrow mass regions** to explain $\Omega_{DM} \sim 0.25$

Cold Dark Matter

particle candiate:

SUSY neutralinos χ^0

$m \sim 0.1 \ldots 10\, TeV$

impact on LSS:

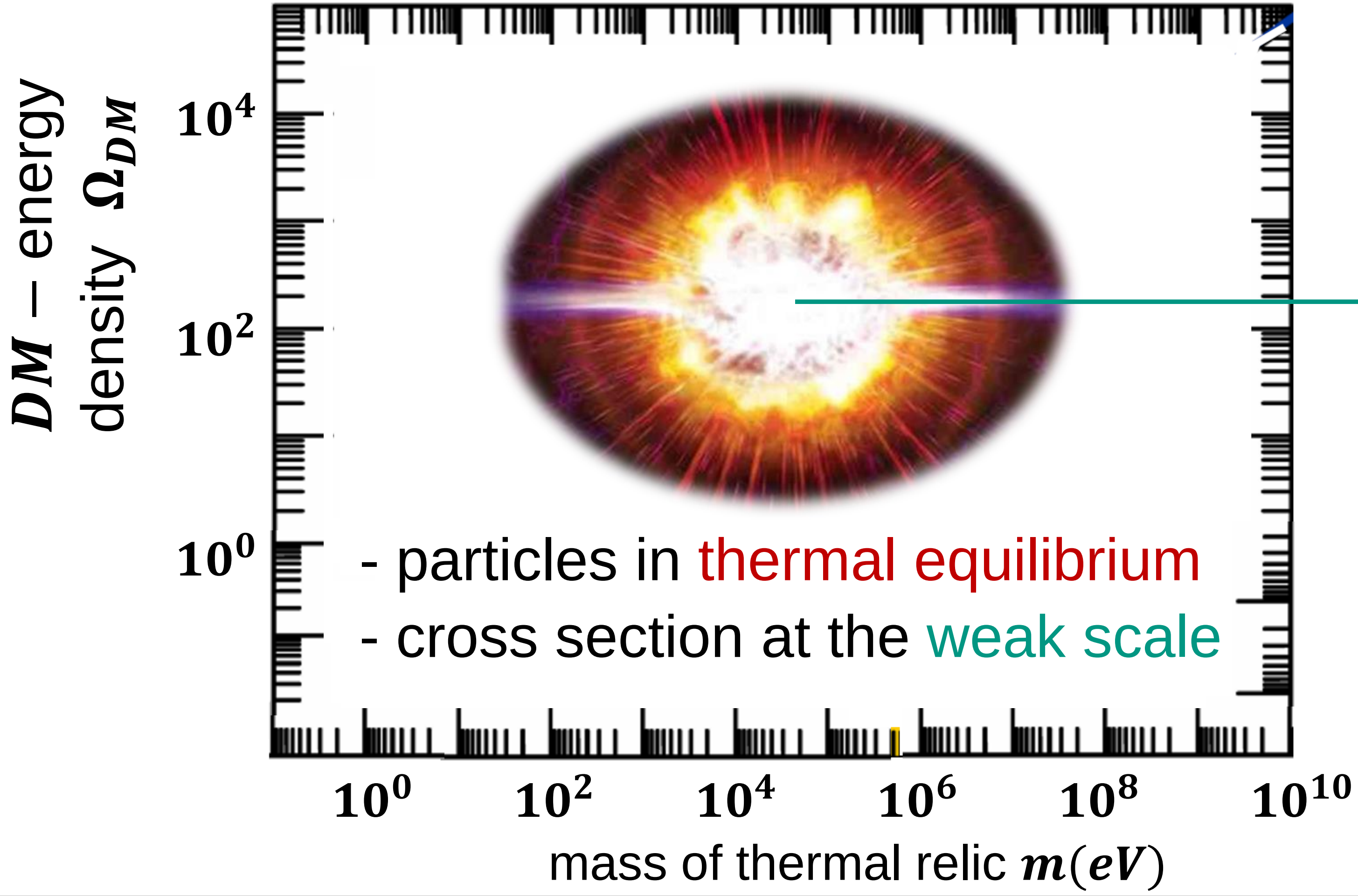
wash-out of structure on scales $\lambda < 0.1\, pc$

Lee–Weinberg curve: only HDM or CDM

- Thermal production of DM: what particle masses can be produced?

이휘소

Weinberg



particles in an evolving universe:

- it cools
- it expands

Lee–Weinberg curve: only HDM or CDM

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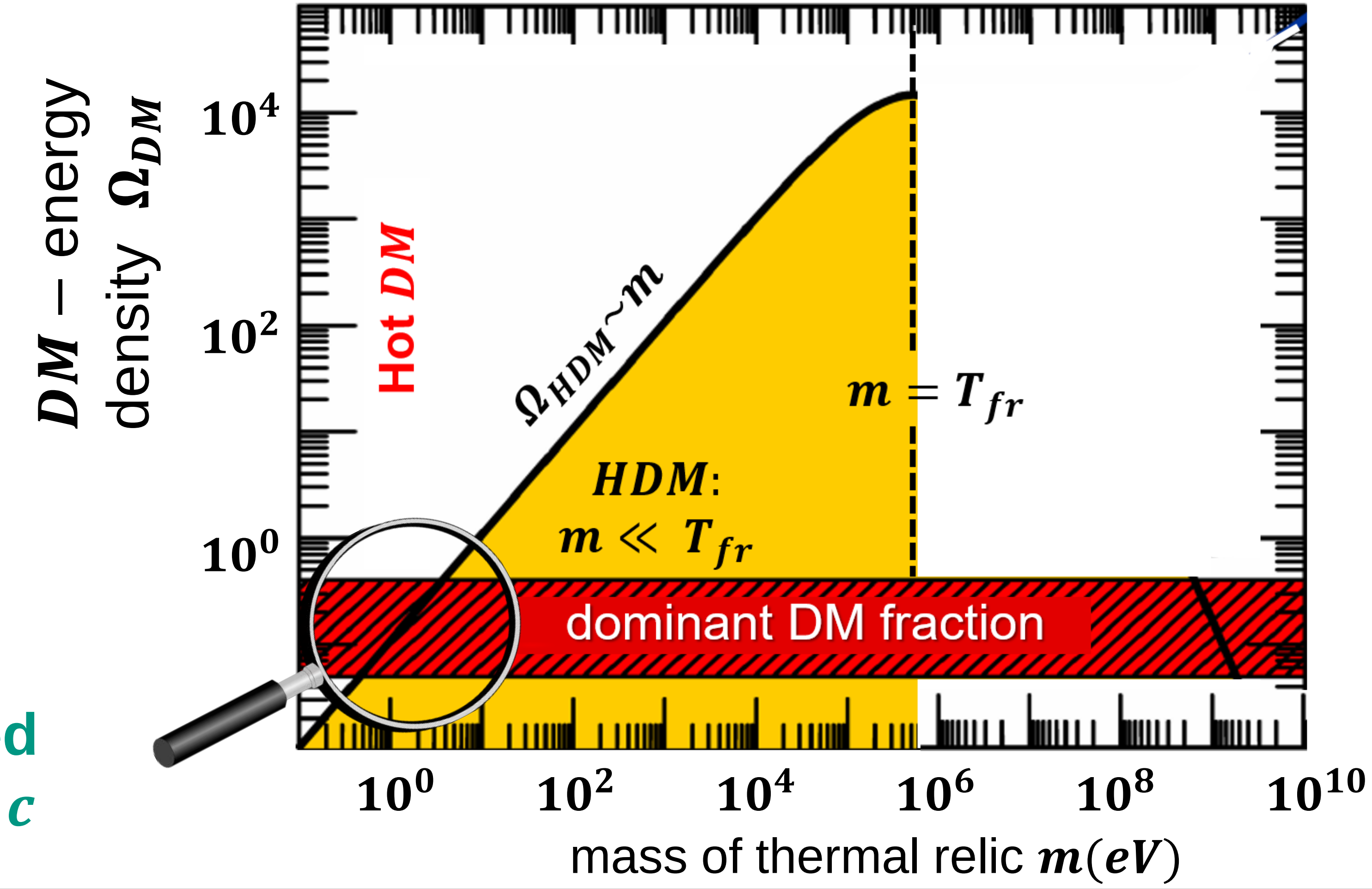
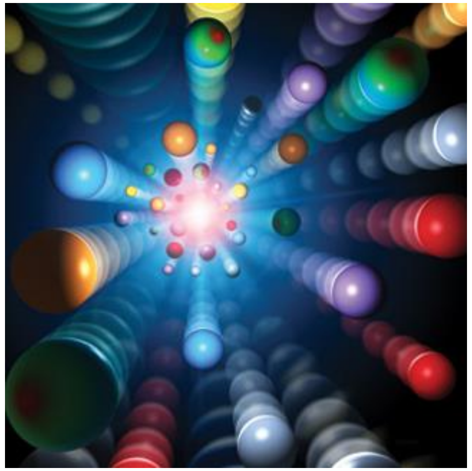
- Thermal production of DM: relativistic case of neutrinos – no annihilation

⇨ particle number density not reduced due to $v \approx c$





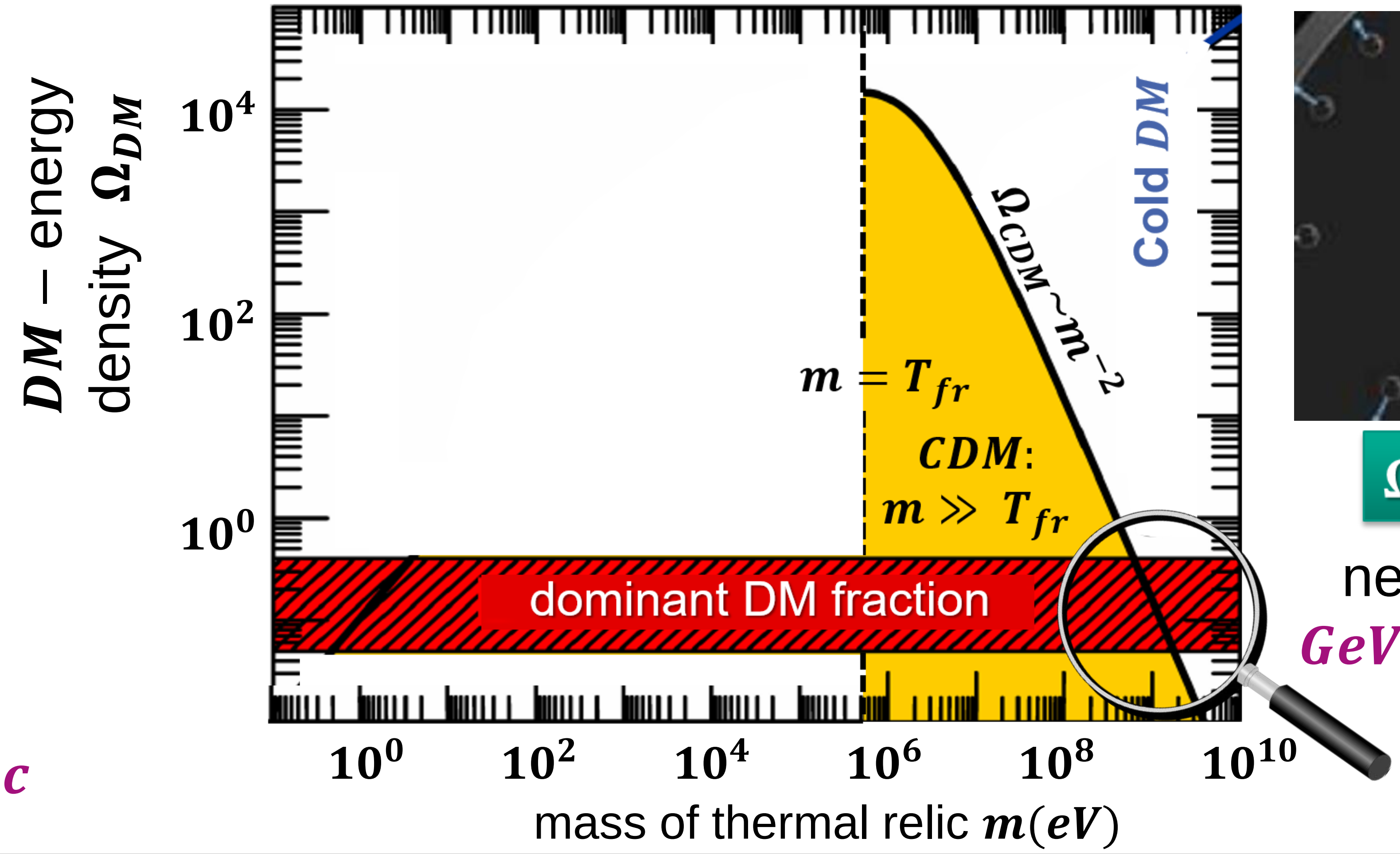
$\Omega_{HDM} \sim m$

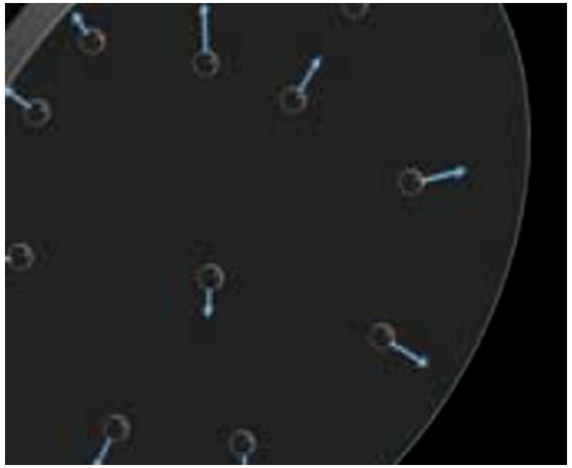
neutrinos with $sub-eV$ masses

Lee–Weinberg curve: only HDM or CDM

- Thermal production of DM: non–relativistic case of neutralinos – annihilation

⇨ particle number density **reduced** due to $v \ll c$





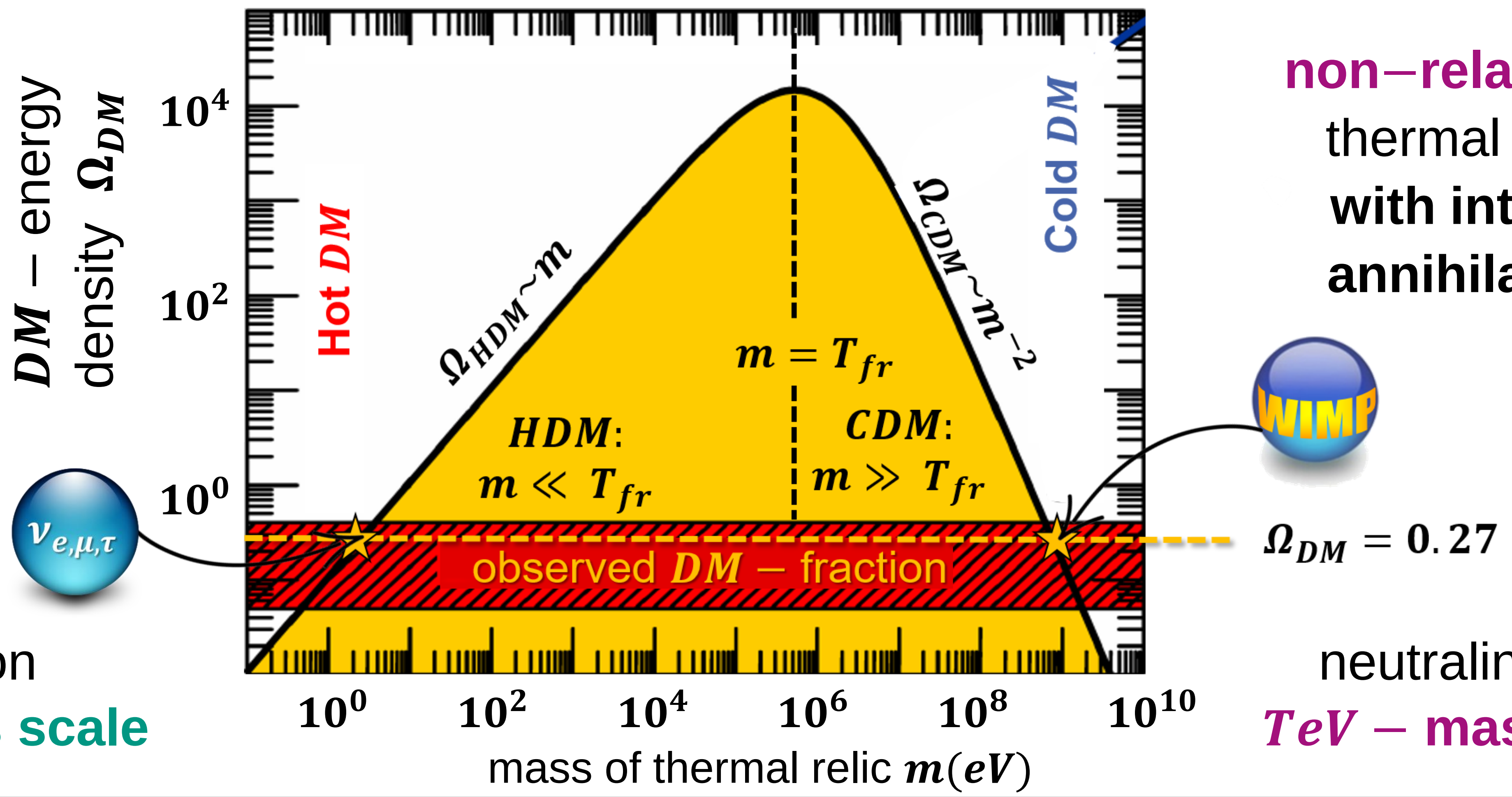
$\Omega_{CDM} \sim m^{-2}$

neutralinos with $GeV \ldots TeV$ masses

Lee–Weinberg curve: only HDM or CDM

- Thermal production of DM: only two rather narrow mass ranges – eV or TeV

relativistic thermal relics **without annihilation**:



non–relativistic thermal relics **with intense annihilation**:

neutrinos on **$sub - eV$ mass scale**

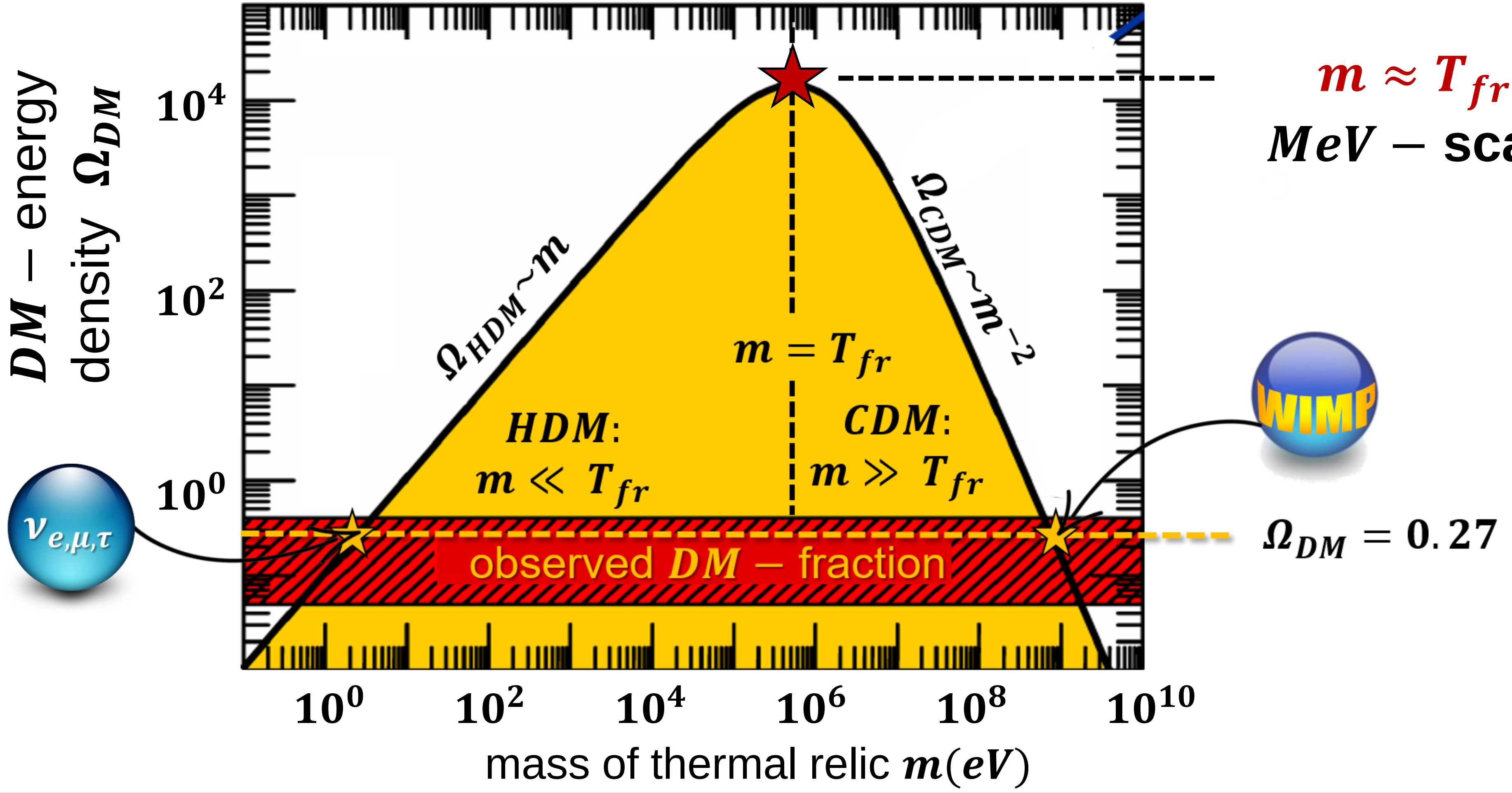
neutralinos on **TeV – mass scale**

Lee–Weinberg curve: freeze–out at $T \sim 1\ MeV$

- Thermal production of MeV – scale particles is maximum as $t_{fr} = 1\ s$

- general condition for thermal freeze–out

$$H(t_{fr}) = \Gamma(t_{fr})$$



Lee–Weinberg curve: only HDM or CDM

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- **Thermal production of DM: only two rather narrow mass ranges – eV or TeV**

  - in order to avoid overclosure of the universe due to thermally produced DM ($\Omega_{DM} \gg 1$) particles in **mass scale keV … MeV** or $\ll eV$ are **excluded**
  ⇨ assumption: **weak interaction processes** & **subsequent freeze–out**

$sub - eV$ scale

T

$\sigma_{ann} = \sigma_{weak}$

TeV scale

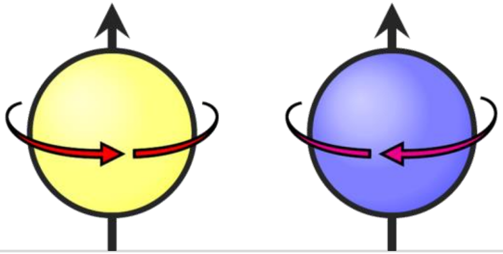
Lee–Weinberg curve: only HDM or CDM

- **Non–thermal production of DM for mass ranges: $m \sim keV \ldots MeV$**

- we need to to avoid overclosure of the universe in case of thermal production:
DM ($\Omega_{DM} \gg 1$) particles in **mass scale $keV \ldots MeV$** (or $neV \ldots \mu eV$*) are excluded!
⇨ only **non–thermal processes**: ν – **oscillations, or symmetry breaking**

oscillation from active neutrinos

keV scale



μeV scale

axion: breaking of CP – symmetry

$WISP$ =
Weakly
Interacting
Slim
Particle

*region not shown in slides $14, 15$

Thermal relics: production & annihilation

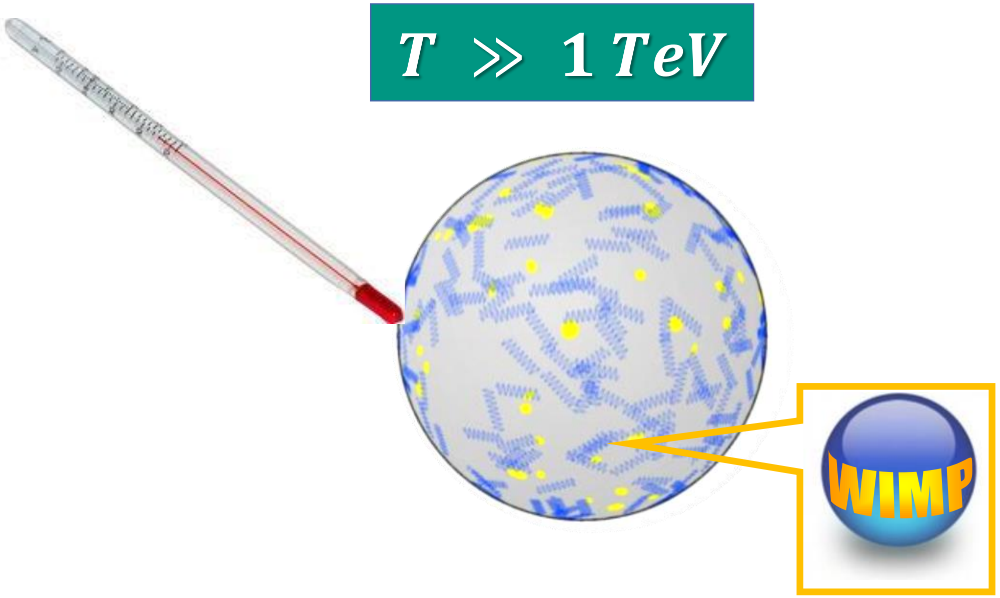
- **The $\boldsymbol{WIMP}$ miracle of $\boldsymbol{DM}$: phase 1 – thermodynamical equilibrium**

  - at $T \gg TeV$: due to their weak interaction, $\boldsymbol{WIMP}$s are in thermodynamical equilibrium

thermodynamical equilibrium

$t < 1\,ns$

$T \gg 1\,TeV$



we consider **co–moving number densities $n_\chi(t)$** where an increase of the scale factor $a(t)$ does not need to be accounted for

Thermal relics: production & annihilation

- **The $WIMP$ miracle of DM: phase 1 – thermodynamical equilibrium**

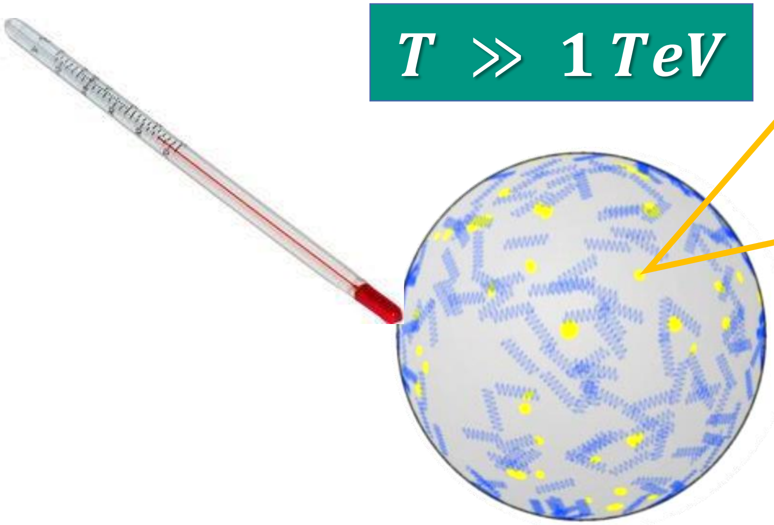
  - at $T \gg TeV$: due to their weak interaction, $WIMP$s are in **thermodynamical equilibrium**

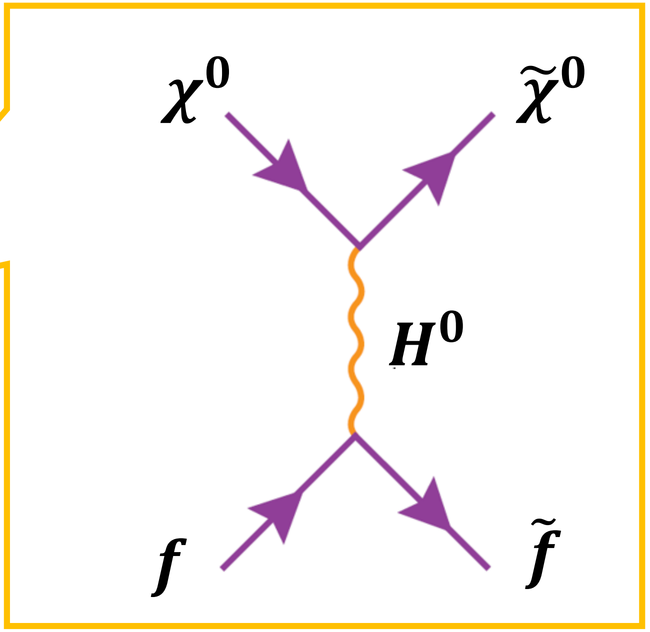
rate ($WIMP$ – **pair production**) ≡ rate ($WIMP$ – **pair annihilation**)

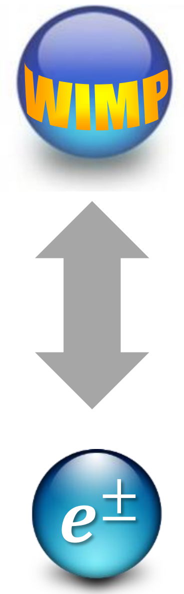
thermodynamical equilibrium

$t < 1\,ns$

$T \gg 1\,TeV$







Thermal relics: production & annihilation

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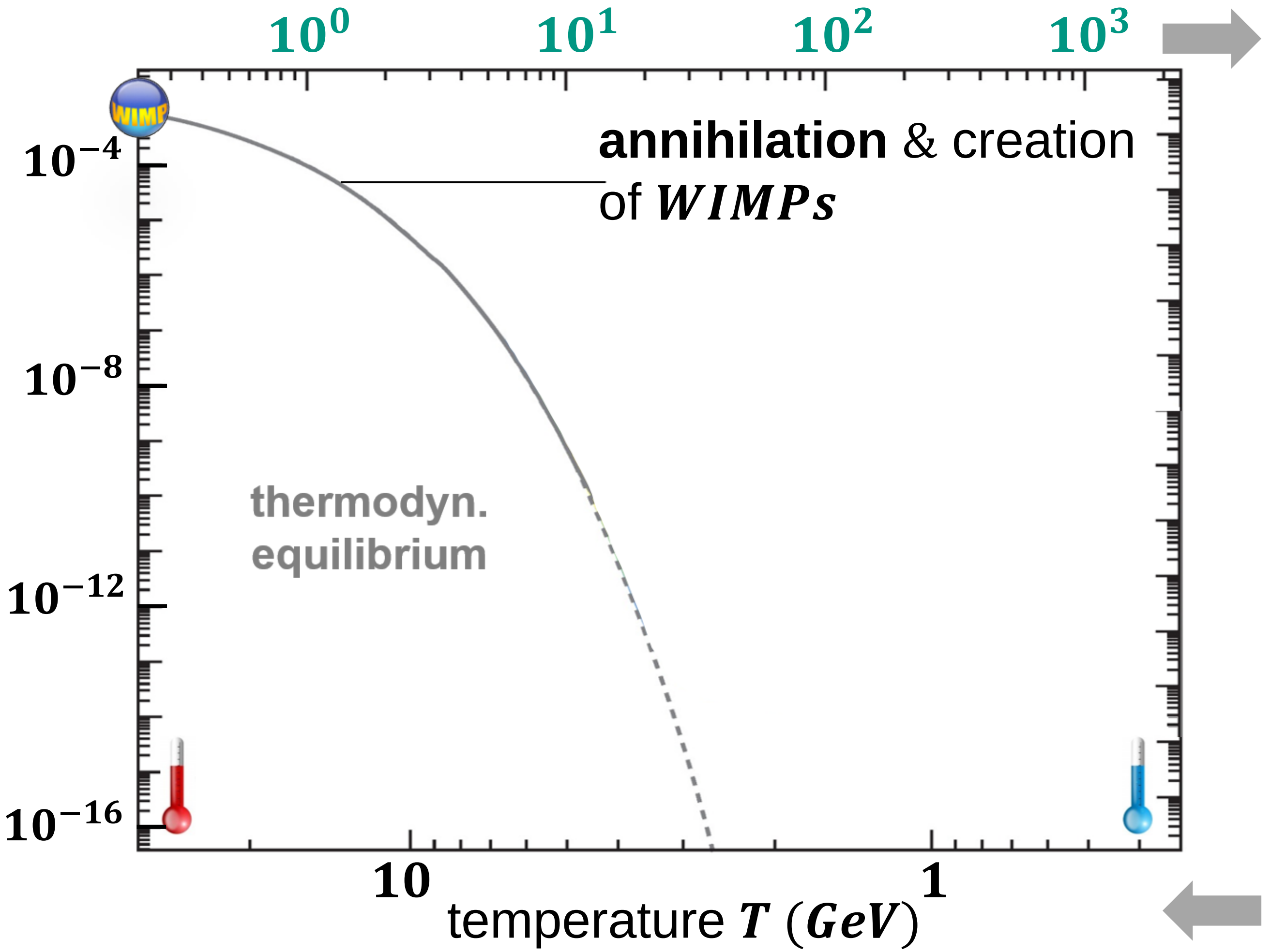
- The $WIMP$ miracle of DM: phase 2 – annihilations reduce number density

$$n_\chi(t) \sim e^{-m_{WIMP}/k_B T}$$

exponential decrease of $n_\chi(t)$

$t < 30\,ns$



$m_{WIMP} = 100\ GeV$

$T(t) \sim 1/\sqrt{t}$

Thermal relics: freeze–out & final number density

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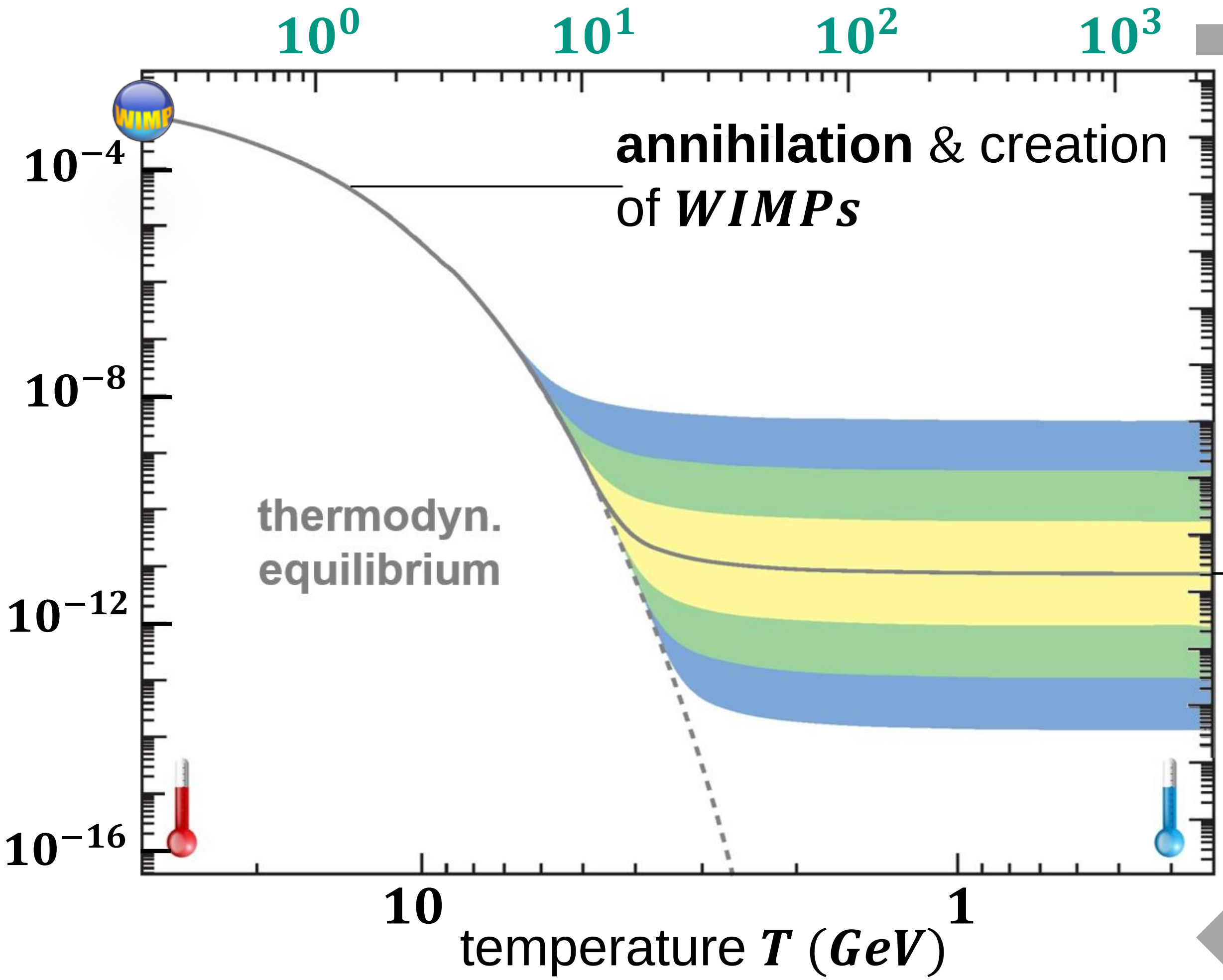
- **The $WIMP$ miracle of DM: phase 3 – freeze out & decoupling of $WIMPs$**

$$\Gamma(t) = H(t)$$

after **decoupling** of $WIMP$s: constant $n_\chi(t)$

$$t > 30\ ns$$



time $t(ns)$

$m_{WIMP} =$ 100 GeV

$\Omega_{DM} = const.$

$T(t) \sim 1/\sqrt{t}$

Thermal relics: freeze–out & final number density

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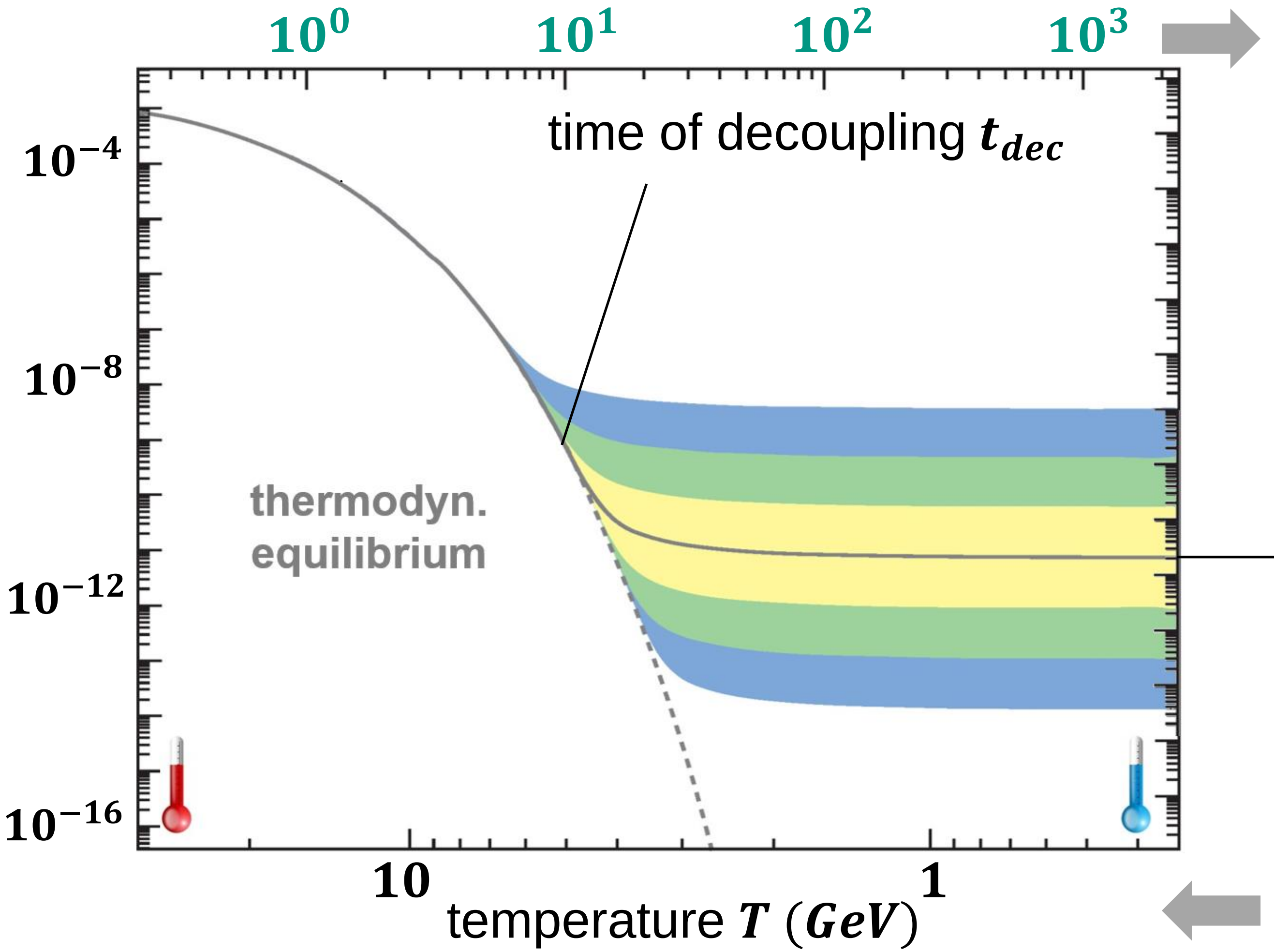
- The $WIMP$ miracle of DM: phase 3 – freeze out & decoupling of $WIMPs$

$$\Gamma(t_{dec}) = H(t_{dec})$$

after decoupling of $WIMPs$: constant $n_\chi(t)$

distance too large for annihilations



$m_{WIMP} =$ $100\ GeV$

$\Omega_{DM} = const.$

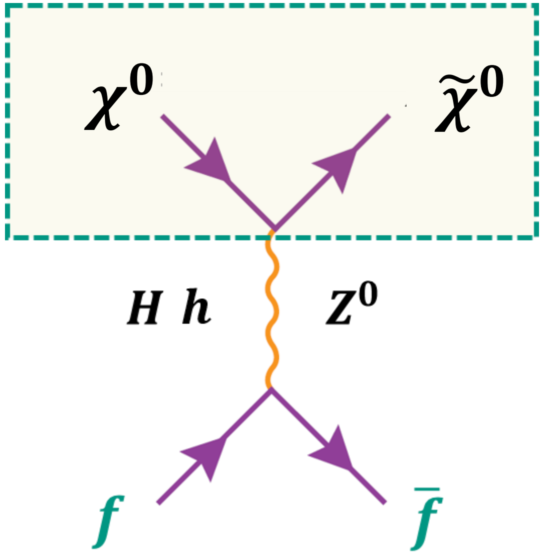
$T(t) \sim 1/\sqrt{t}$

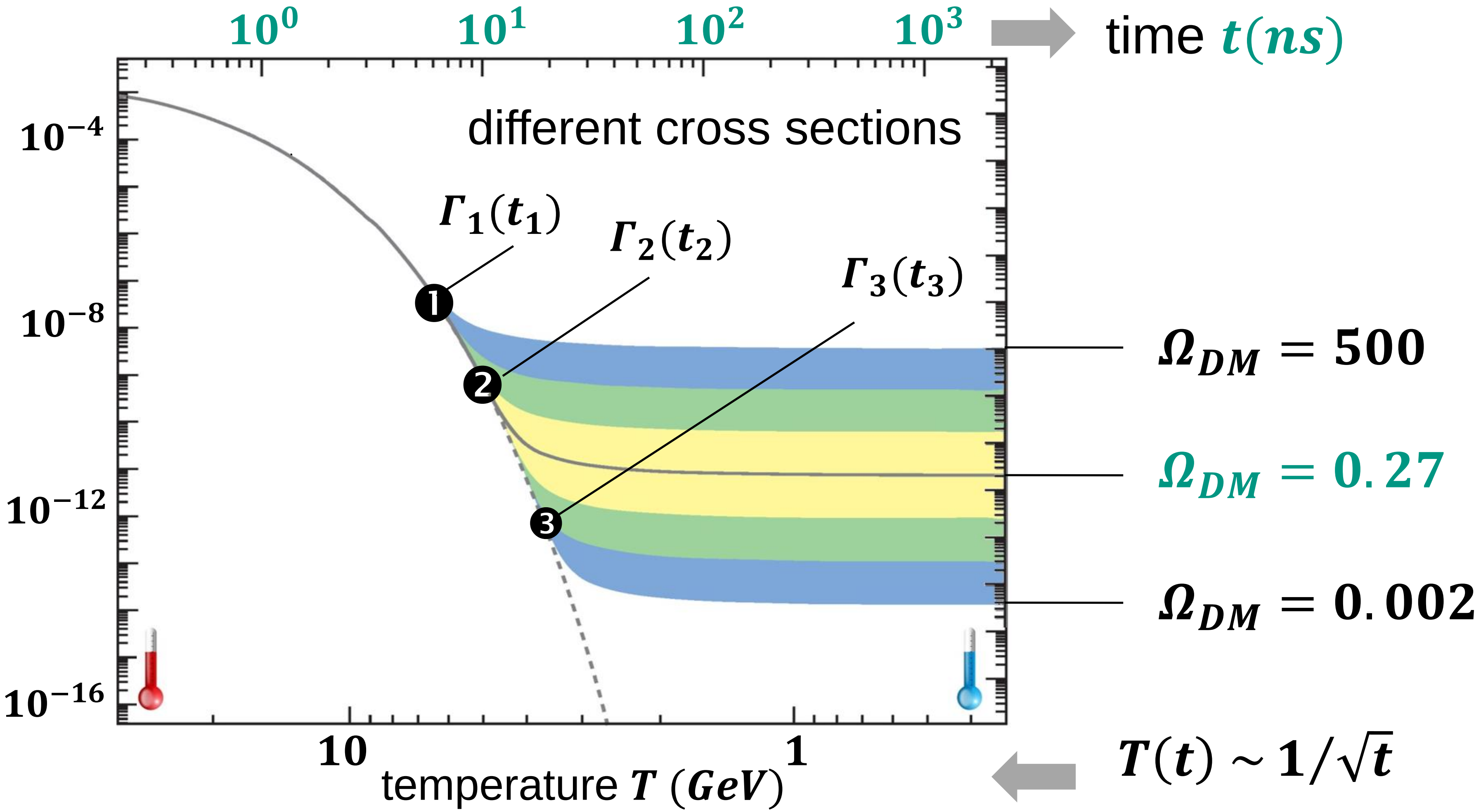
Thermal relics: freeze–out & final number density

- The $WIMP$ miracle of DM: phase 3 – freeze out & decoupling of $WIMPs$

$$\Gamma_i(t_{dec,i}) = H(t_{dec,i})$$

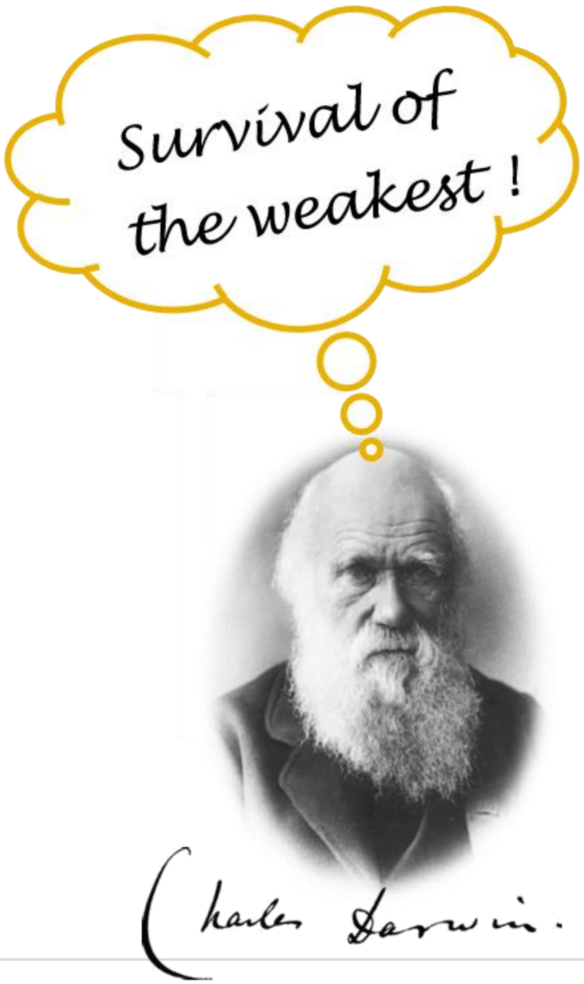
Γ_i = annihilation $xsecs$ of $SUSY-WIMPs$

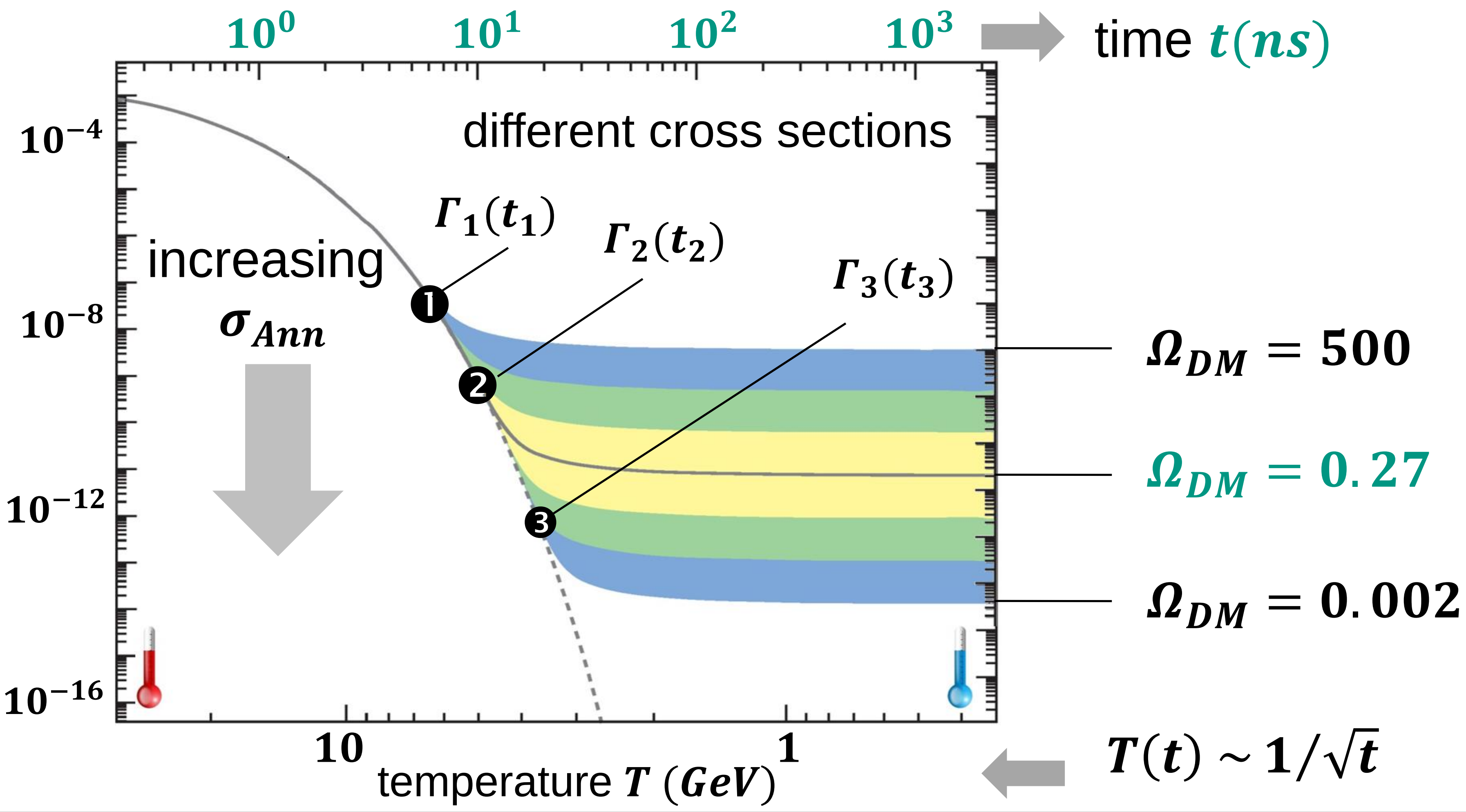




Thermal relics: freeze–out & final number density

- **The $WIMP$ miracle of DM: phase 3 – freeze out & decoupling of $WIMPs$**

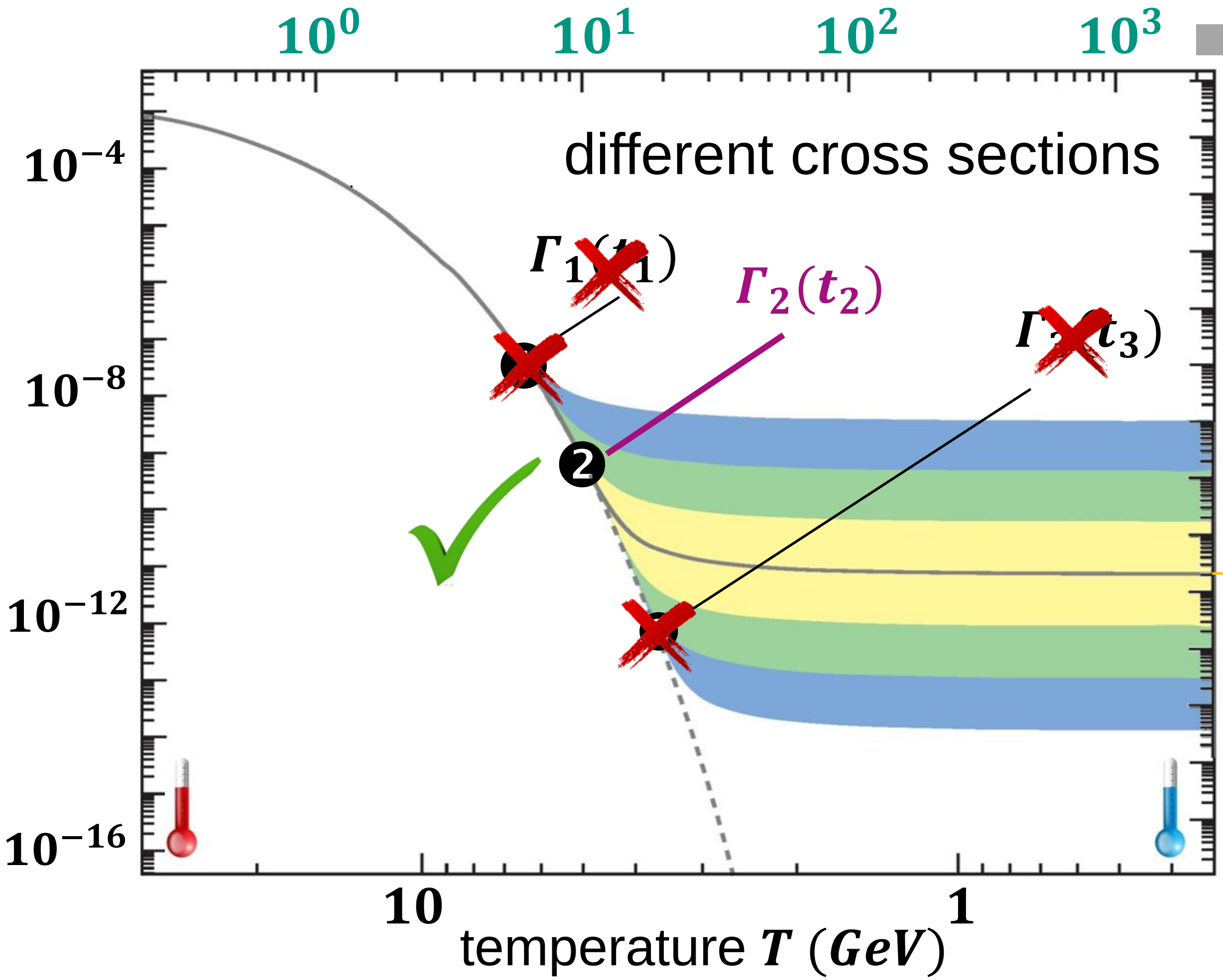


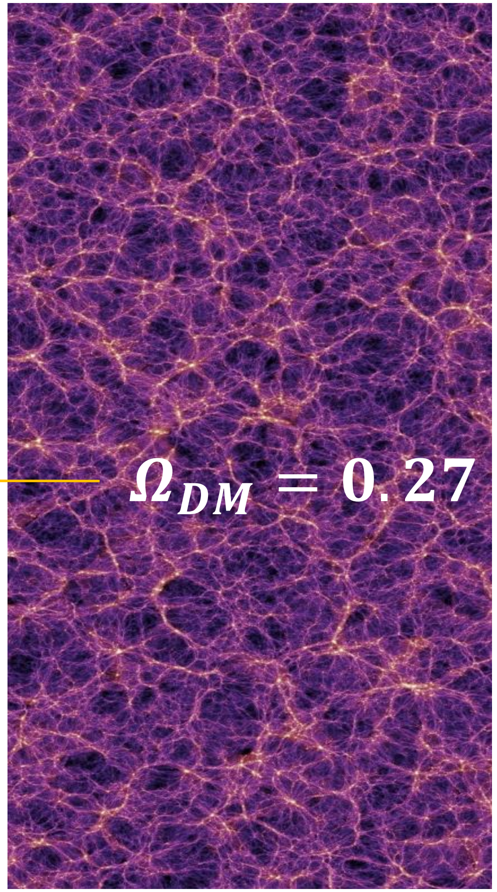


Thermal relics: freeze–out & final number density

- The $WIMP$ miracle of DM: phase 3 – freeze out & decoupling of $WIMPs$

- is the observed DM – content of the universe of $\Omega_{DM} = 0.27$ just a chance value?



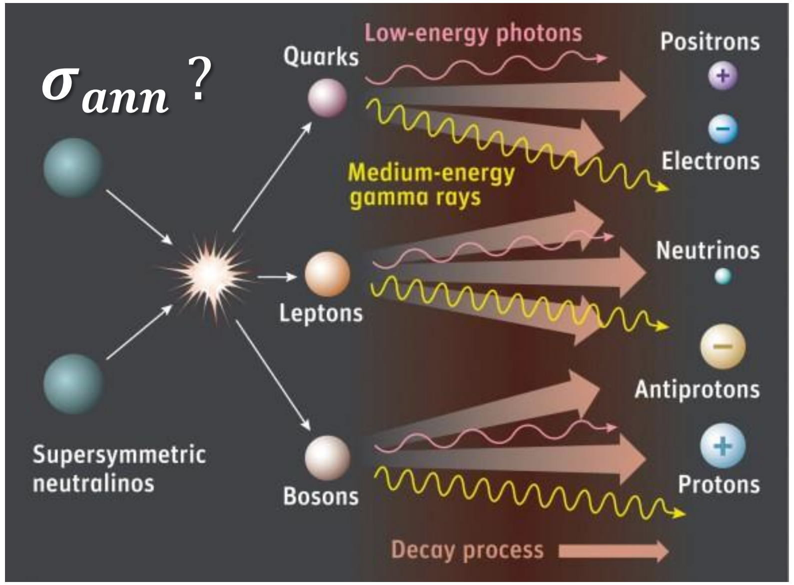


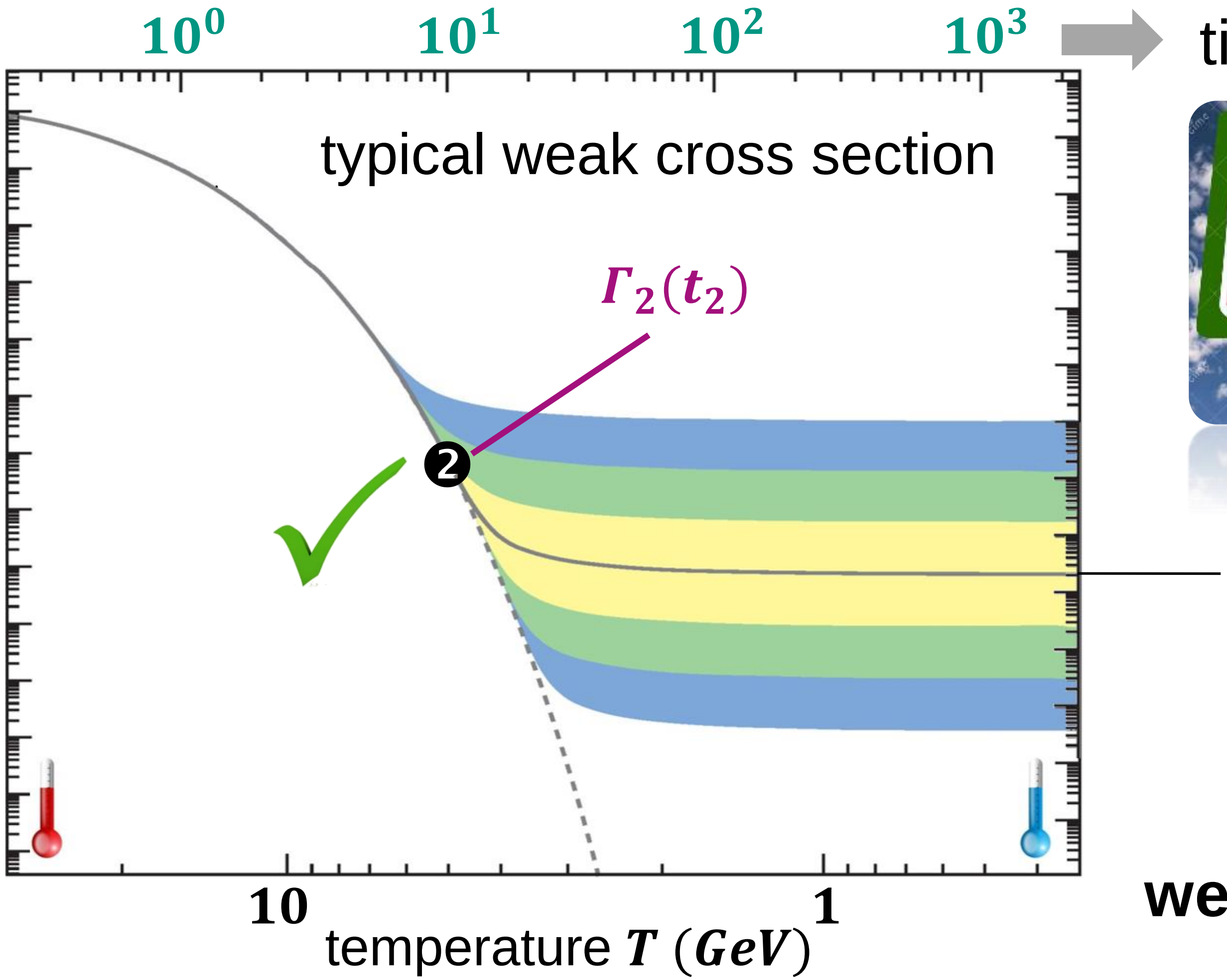
Thermal relics: freeze–out & annihilation $xsec$

- The $WIMP$ miracle of DM: we ´automatically´ obtain Ω_{DM} if $\sigma_{ann} \approx 1\,pb$

- DM – fraction today:

$$\Omega_{DM}(t = t_0) \sim \frac{1}{\langle \sigma_{ann} \cdot v \rangle}$$





$\sigma_{ann} \approx 1\,pb$

weak interaction

v: $WIMP$ velocity at decoupling

Thermal relics: freeze–out as CDM

- The $WIMP$ miracle of DM: we ´automatically´ obtain **Cold Dark Matter**

- $WIMP$ – velocity

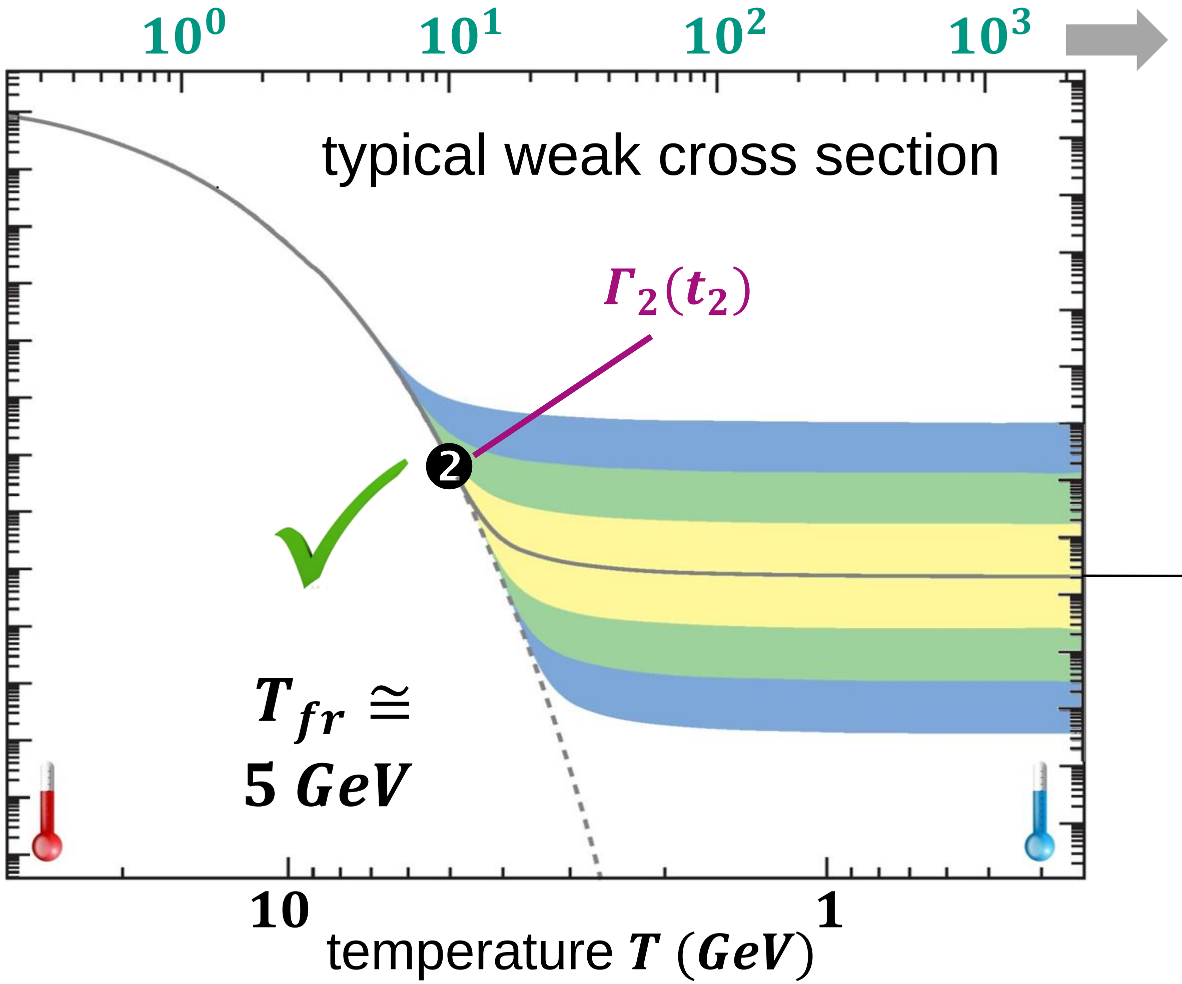
$$x_{fr} = \frac{T_{fr}}{M_{WIMP}} = \frac{1}{20}$$

is **non–relativistic**

due to relation:
$T_{fr} \ll M_{WIMP}$

↓

CDM



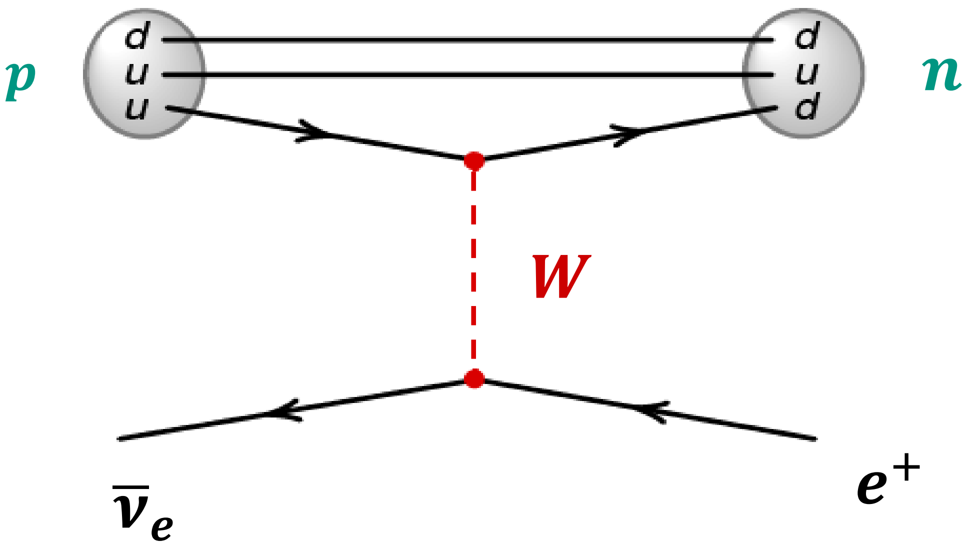
$m_{WIMP} = 100\ GeV$

Thermal Relicts: relativistic neutrinos

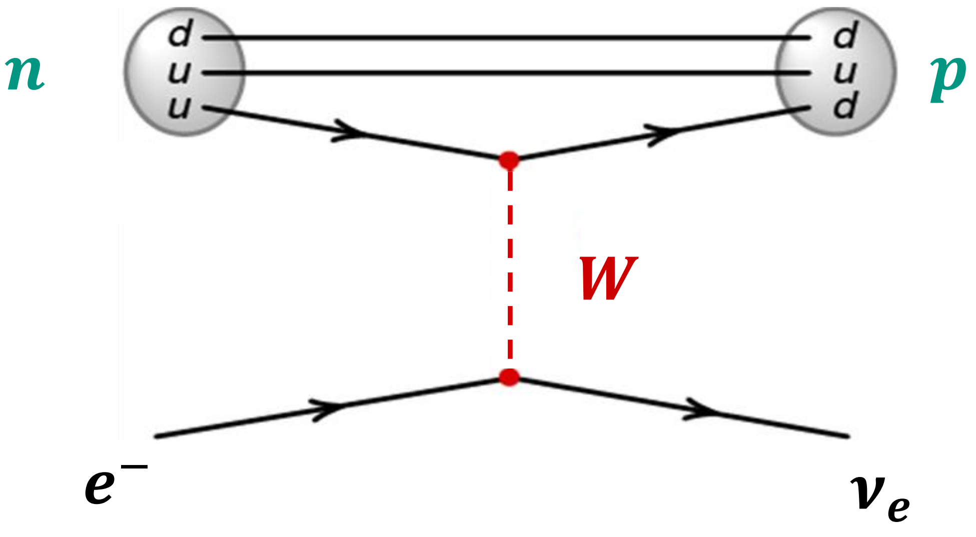
- **RECAP: neutrinos remain in thermal equilibrium until $t = 1\ s$**

  - **semi–leptonic** reactions with protons, neutrons via CC (Charged Current) and NC (Neutral Current) processes: important to fix n/p – **ratio** for BBN

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$



$$p + e^- \leftrightarrow n + \nu_e$$



*see Chap. 3.1

Thermal Relicts: relativistic neutrinos as HDM

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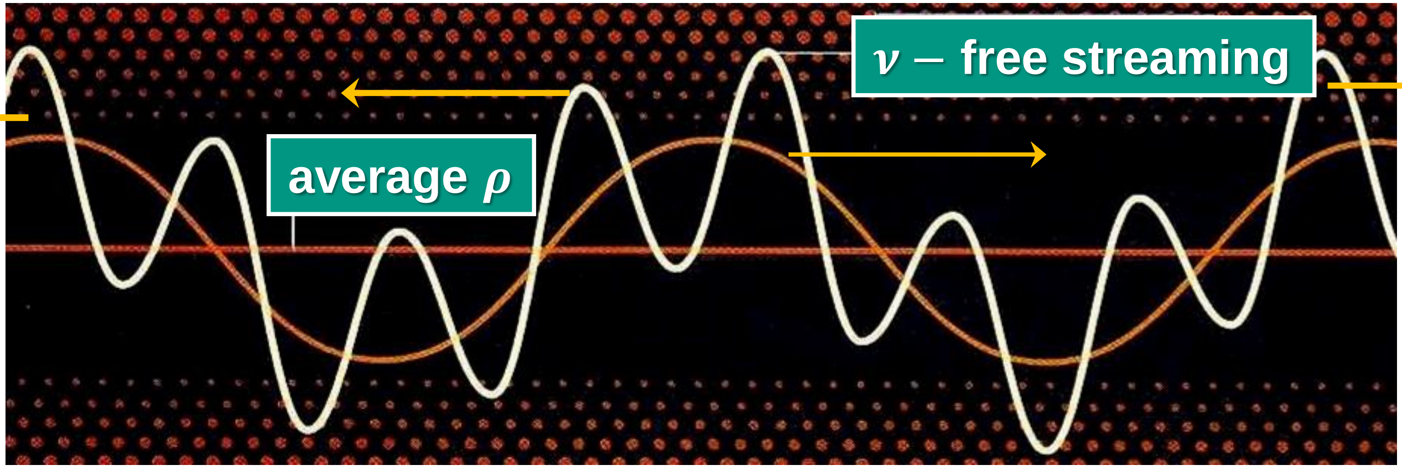
- **neutrinos free−stream in an evolving universe over distances $d \sim Gpc$**
  - neutrinos decouple after $t = 1\ s$ at freeze−out temparture $T_{fr} \sim MeV$

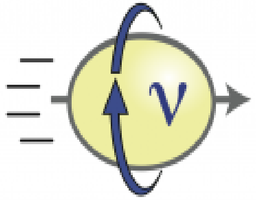
    $sub - eV$ mass ($KATRIN$ 2022: $m(\nu) < 0.8\ eV$ $(90\%\ CL)$)

    ⇨ resulting **Lorentz−$\gamma = 10^6 \dots 10^7$**

    ⇨ **free−streaming distance $d \sim Gpc$**

several Gpc





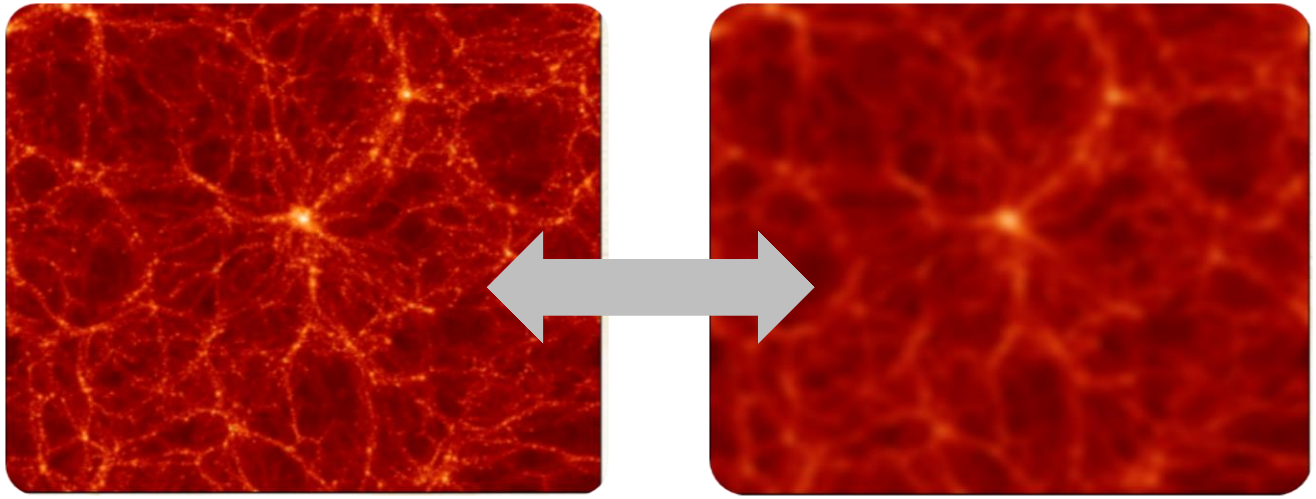
HDM

Thermal Relicts: relativistic neutrinos as HDM

- neutrinos **free–stream** in an evolving universe over distances $d \sim Gpc$

$m(\nu) = meV$

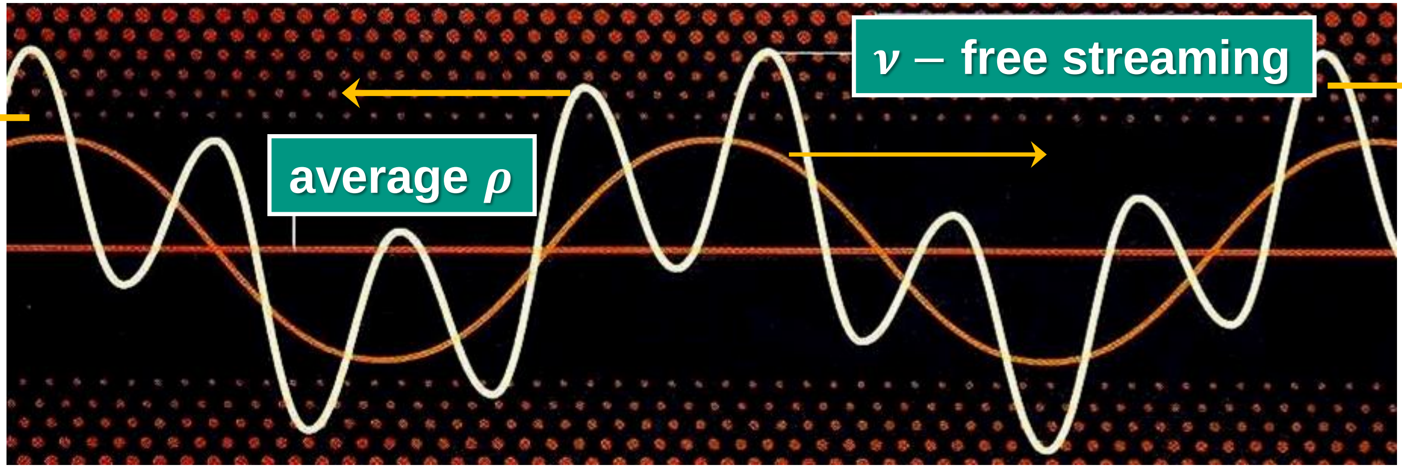
only CDM:
bottom–up
scenario

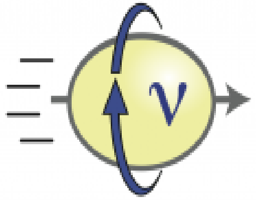


$m(\nu) = few\ eV$

mostly HDM:
top–down
scenario

several Gpc

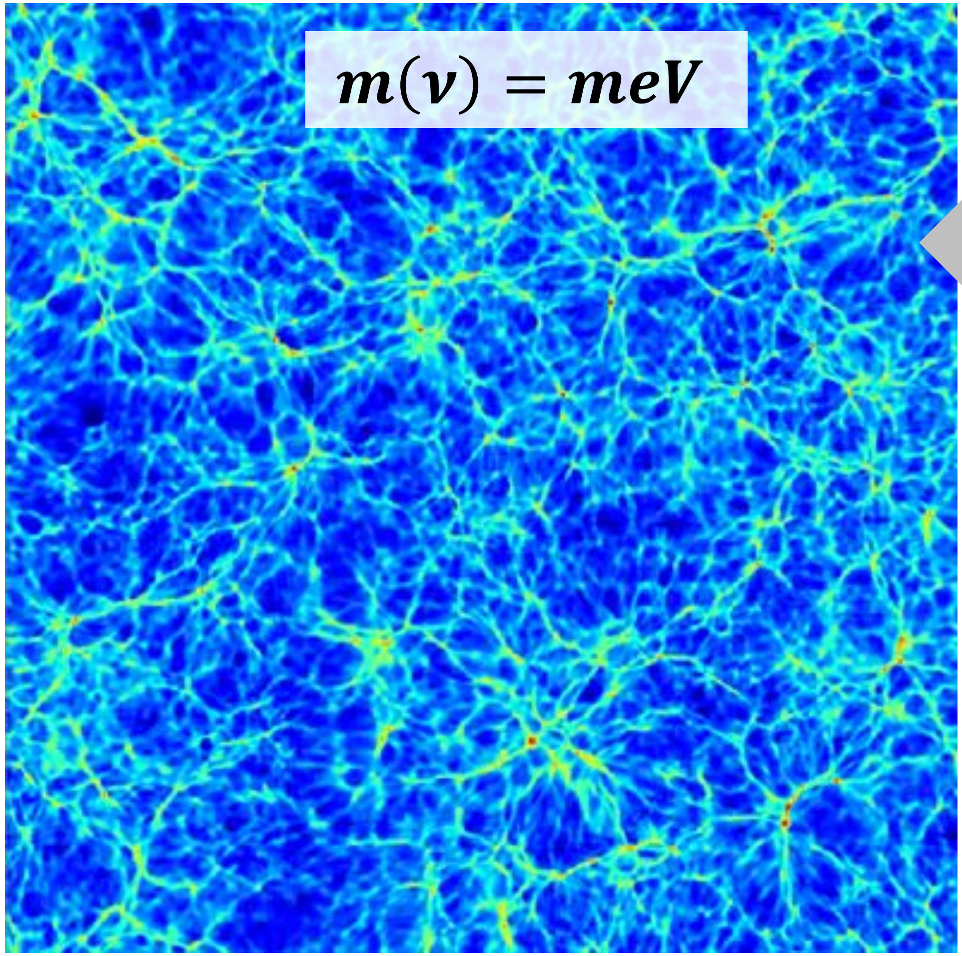


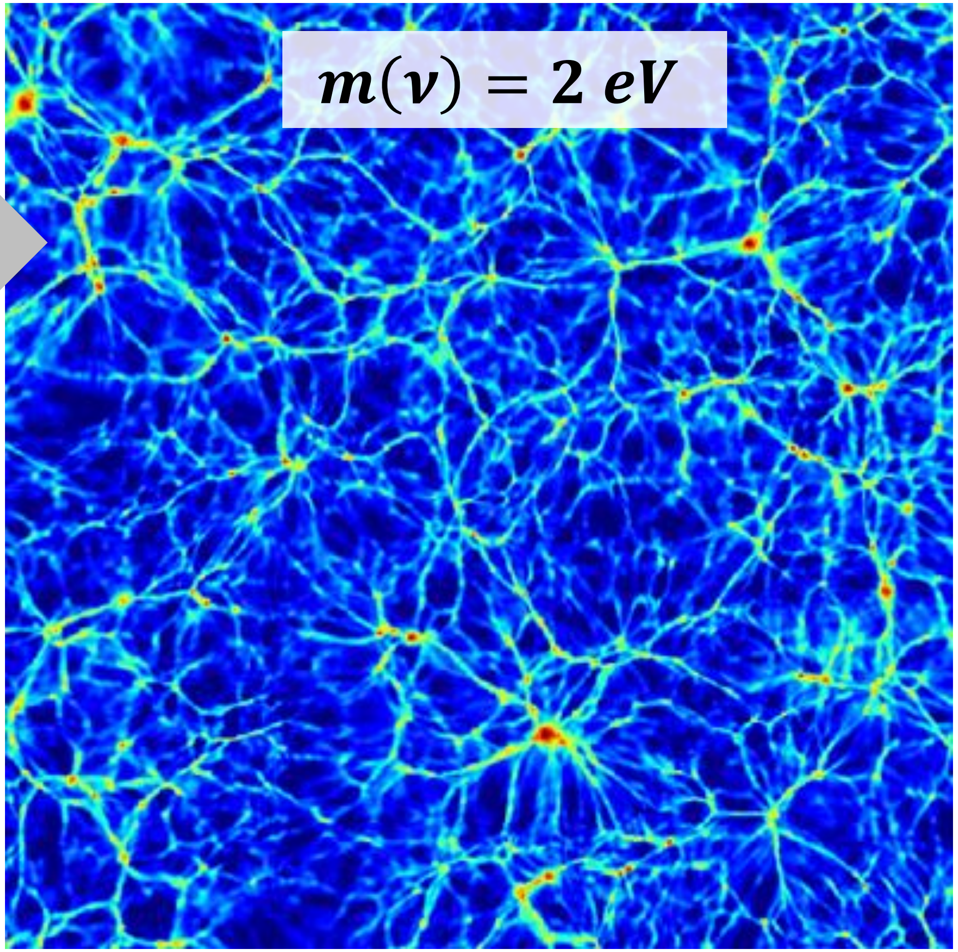


HDM

Thermal Relicts: relativistic neutrinos as HDM

- neutrinos **free–stream**: wash–out of small–scale structures in the universe





Massive ν´s (HDM) & matter power spectrum $P(k)$

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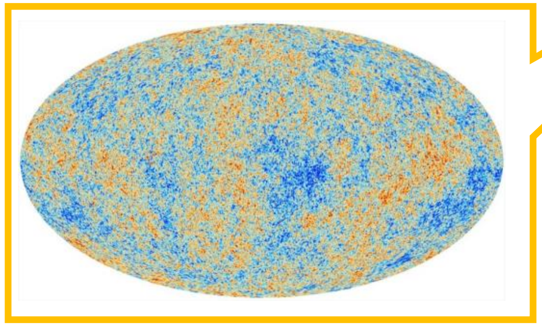
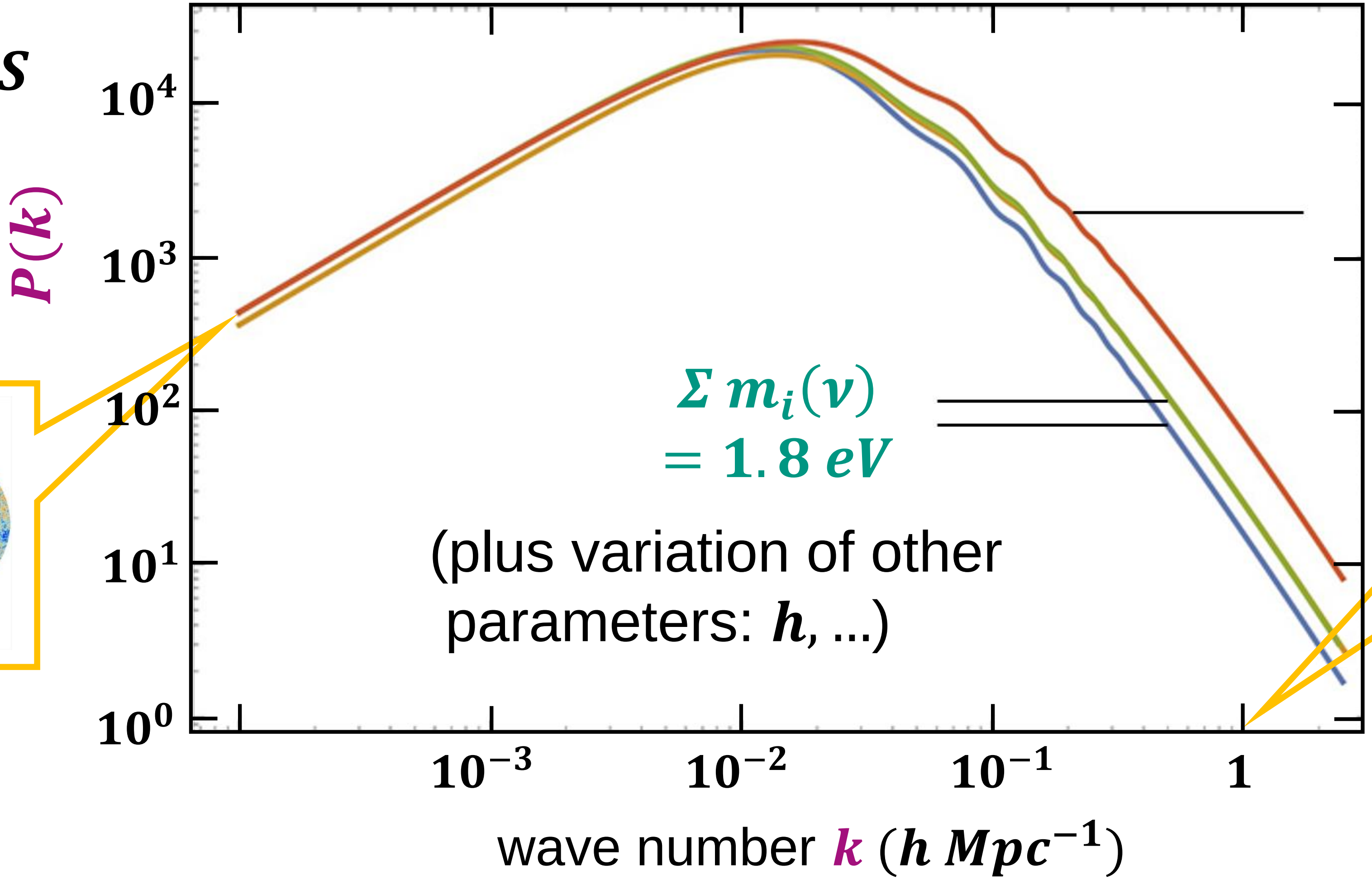
- Imprint of massive neutrinos on large wave numbers k of spectrum $P(k)$

- $CMB + LSS$





minimum value:

$\Sigma\, m_i(\nu)$
$= 0.06\ eV$

Massive ν´s (HDM) & matter power spectrum $P(k)$

Karlsruhe Institute of Technology

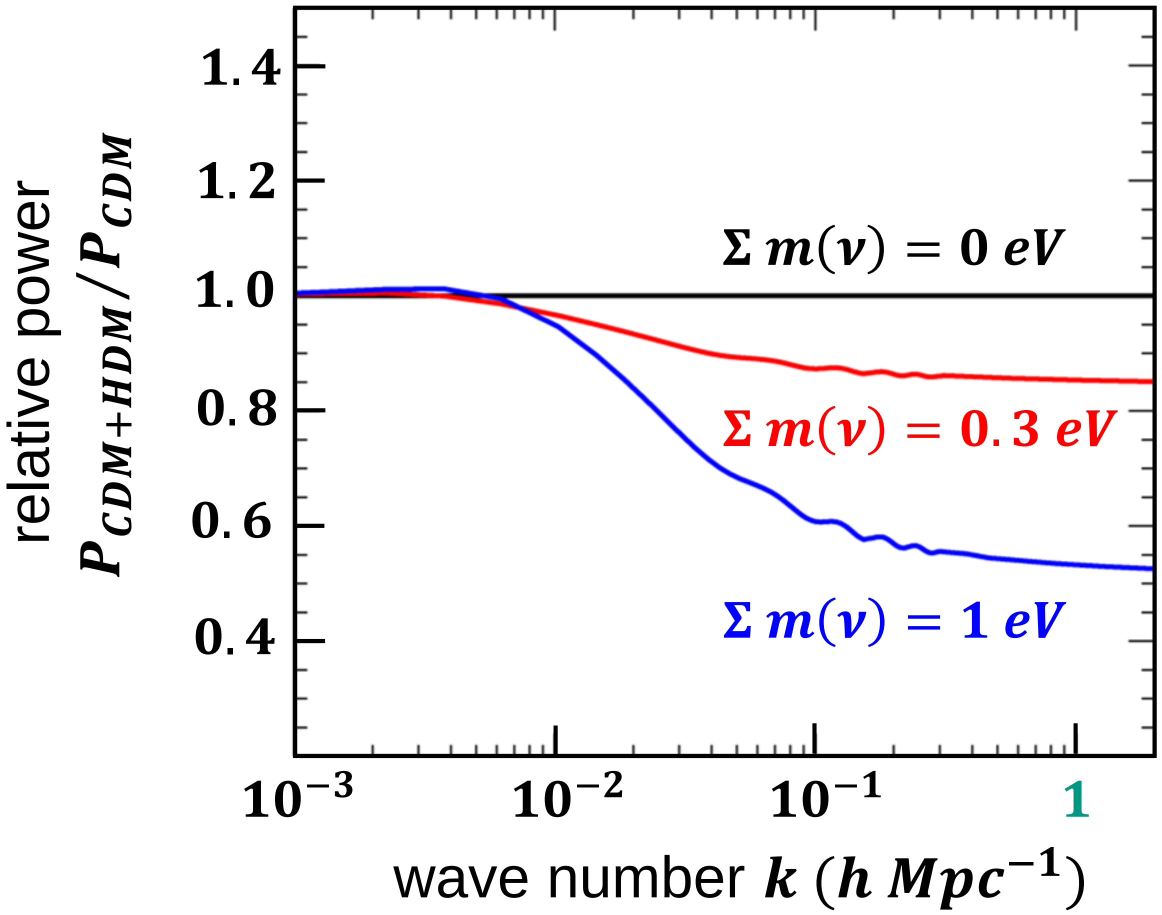
- **Imprint of massive neutrinos on large wave numbers k of spectrum $P(k)$**

- adding small amounts of HDM to evolution of LSS **reduces** $P(k)$

large factor

$$P(k) \sim P_{CDM}(k) \cdot \left(1 - \frac{8 \cdot \Omega_\nu}{\Omega_M}\right)$$

- example: $\Sigma\, m(\nu) = 0.3\ eV$
  $\sim 15\ \%$ reduction of power for ´small´ structures at
  $k = 1\ h\ Mpc^{-1}$



Massive ν´s (HDM): mass eigenstates $m_{1,2,3}$

Karlsruhe Institute of Technology

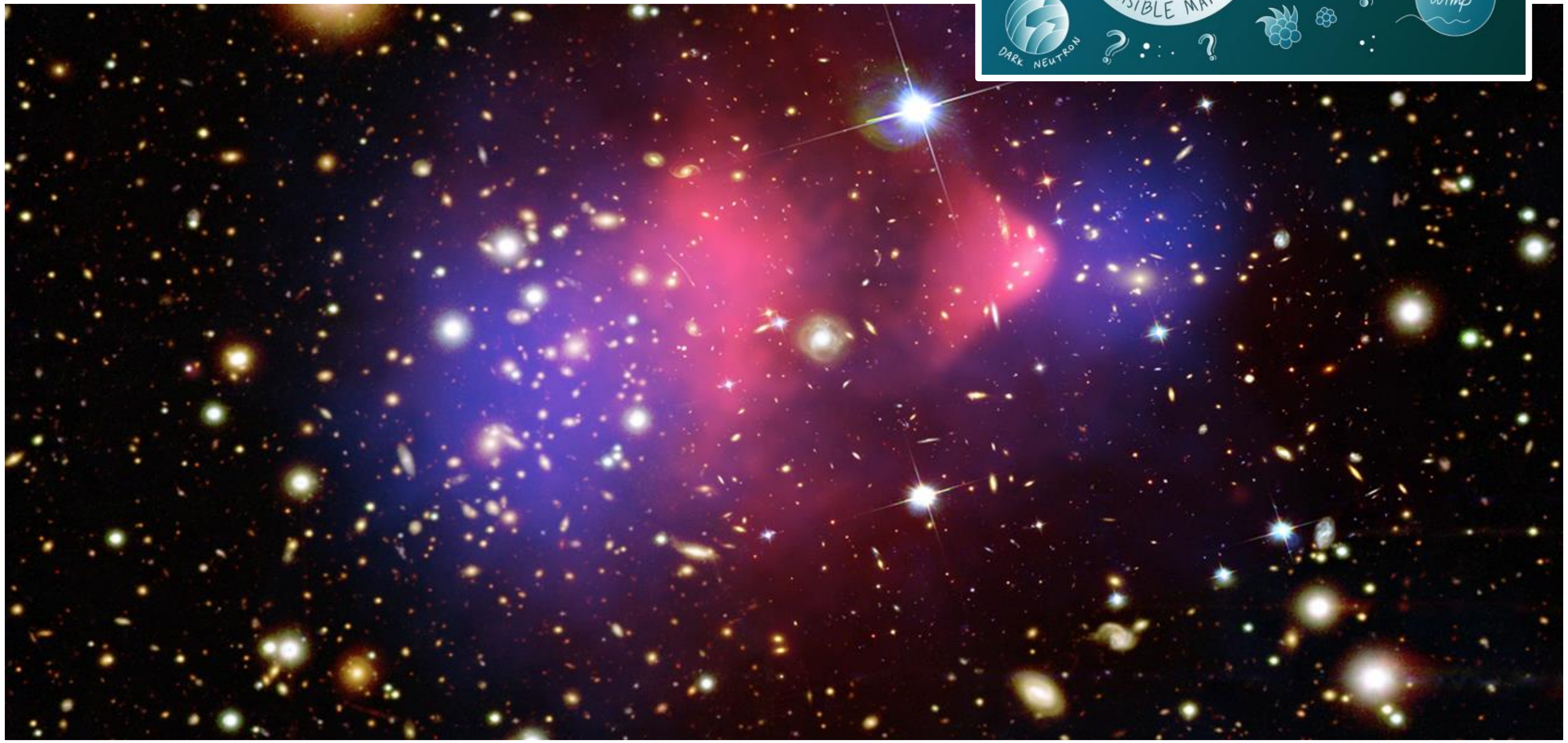
- **primordial ν´s have cooled down to $T = 1.9\ K$ in today´s universe**

  - neutrinos from $Big\ Bang$ with masses $m \approx 50\ meV$ today are **bound** gravitationally in galaxy clusters (i.e. on scales $d \approx 50\ Mpc$)

  - **flavour states $\nu_{e,\mu,\tau}$** produced up to $t = 1\ s$: today they have fully ´**decoupled**´ to **mass eigenstates $\nu_{1,2,3}$** (very long $de\ Broglie$ wavelengths)

$\nu_e =$

$incoherent$
mass eigenstates
of a former ν_e

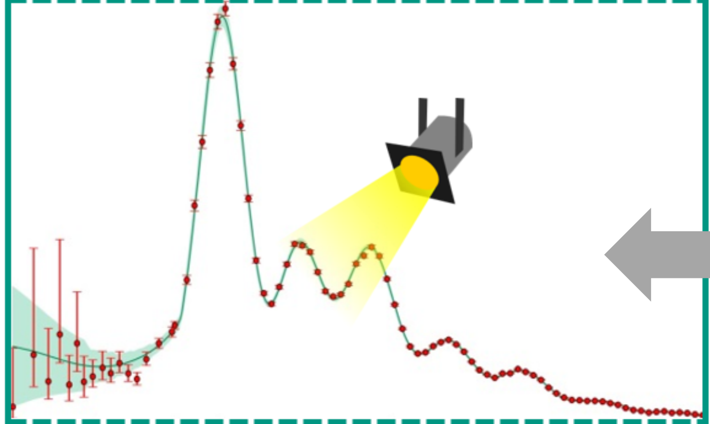


CHAPTER 5 – DARK UNIVERSE

5. 1 Evidences for Dark Matter

cosmological scale

method:
- 2./3. acoustic peak of CMB multipoles



result:
- (Cold) Dark Matter is dominant $\Omega_{DM} \sim 0.27$

Gpc ⟷ Mpc

galaxy clusters

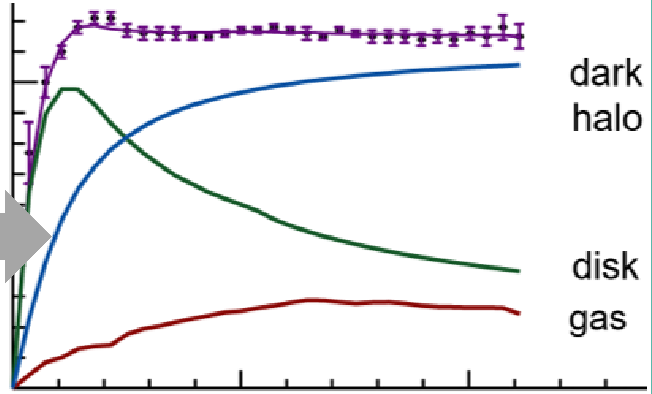
method:
- virial theorem (*Zwicky*)
- hot gas, gravit. lensing

result:
- extended DM – halos in galaxy clusters

Mpc ⟷ kpc

galaxy (local)

method:
- rotation curves of galaxies (*V. Rubin*)



result:
- dark galactic halo
- local value Ω_{DM}

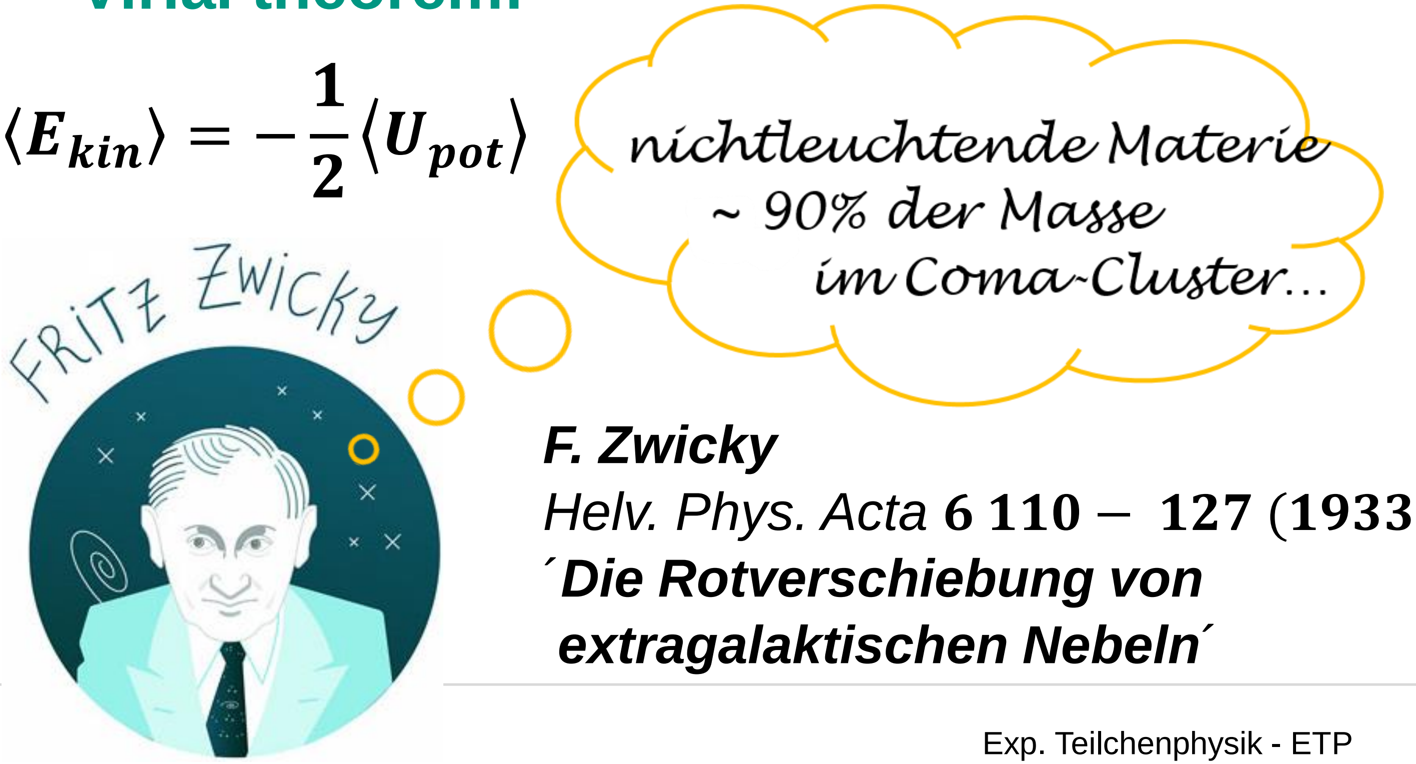
Dark Matter & galaxy clusters

- ***Fritz Zwicky*** **proposes the existence of Dark Matter (from the Coma cluster)**

  - **observation**: (too) **high peculiar velocities** of single galaxies in the very large **Coma cluster of galaxies** !

Virial theorem:

$$\langle E_{kin} \rangle = -\frac{1}{2} \langle U_{pot} \rangle$$

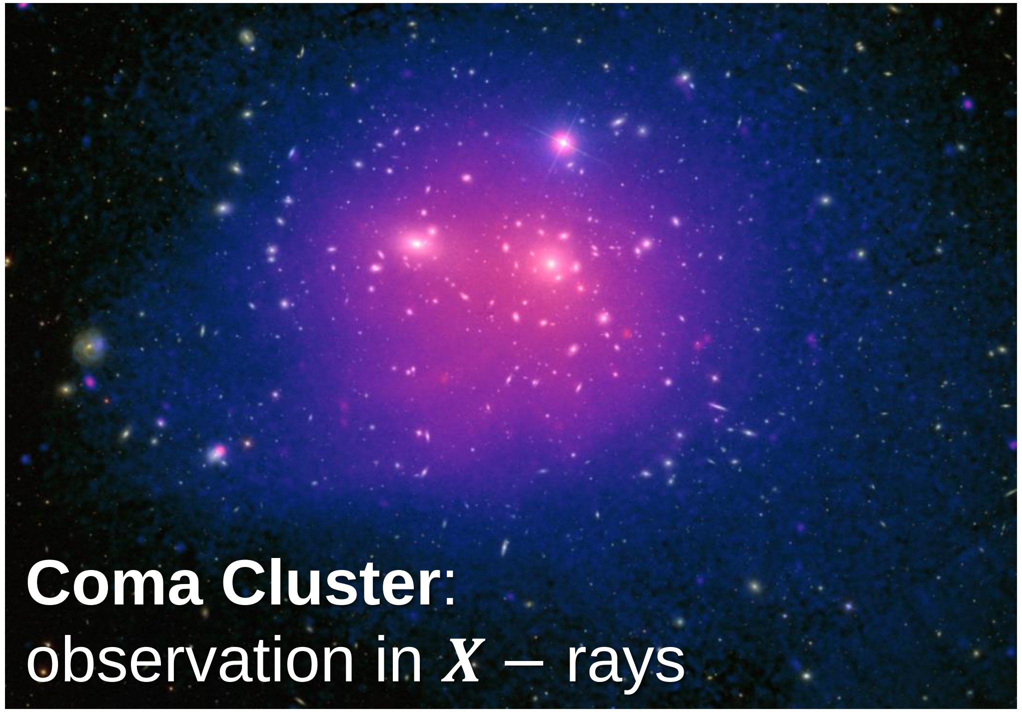


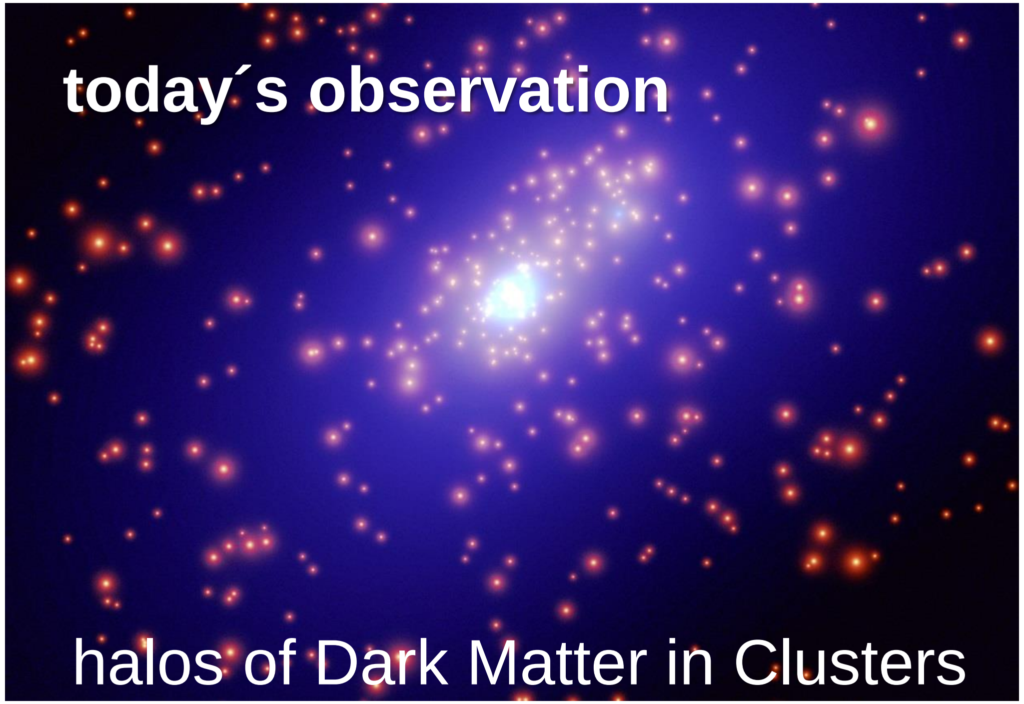
F. Zwicky
Helv. Phys. Acta $\mathbf{6}\ \mathbf{110-127}$ (1933)
´Die Rotverschiebung von extragalaktischen Nebeln´

Dark Matter & galaxy clusters

- ***Fritz Zwicky* proposes the existence of Dark Matter (from the Coma cluster)**

  - **explanation**: non–luminous form of matter (´**Dark Matter**´) which interacts only via its dominant **gravitational potentials**!

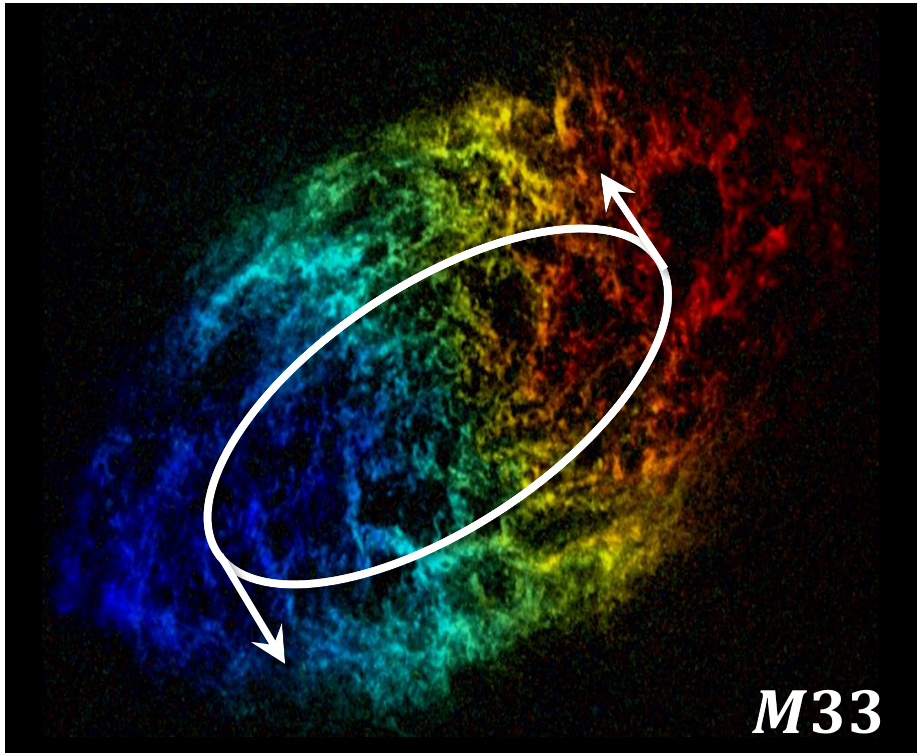


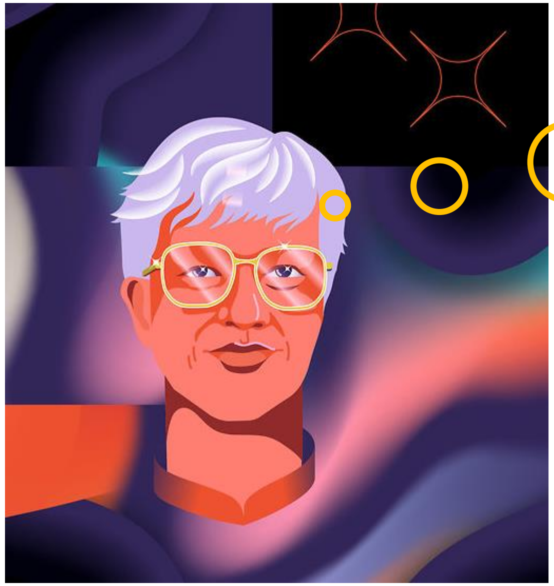


Dark Matter & rotational curves of galaxies

- ***Vera Rubin*** **observes flat rotational profiles of galaxies**

  - **observation**: (too) high velocities of **single stars** & **gas clouds** in the very large **Andromeda spiral galaxy**!



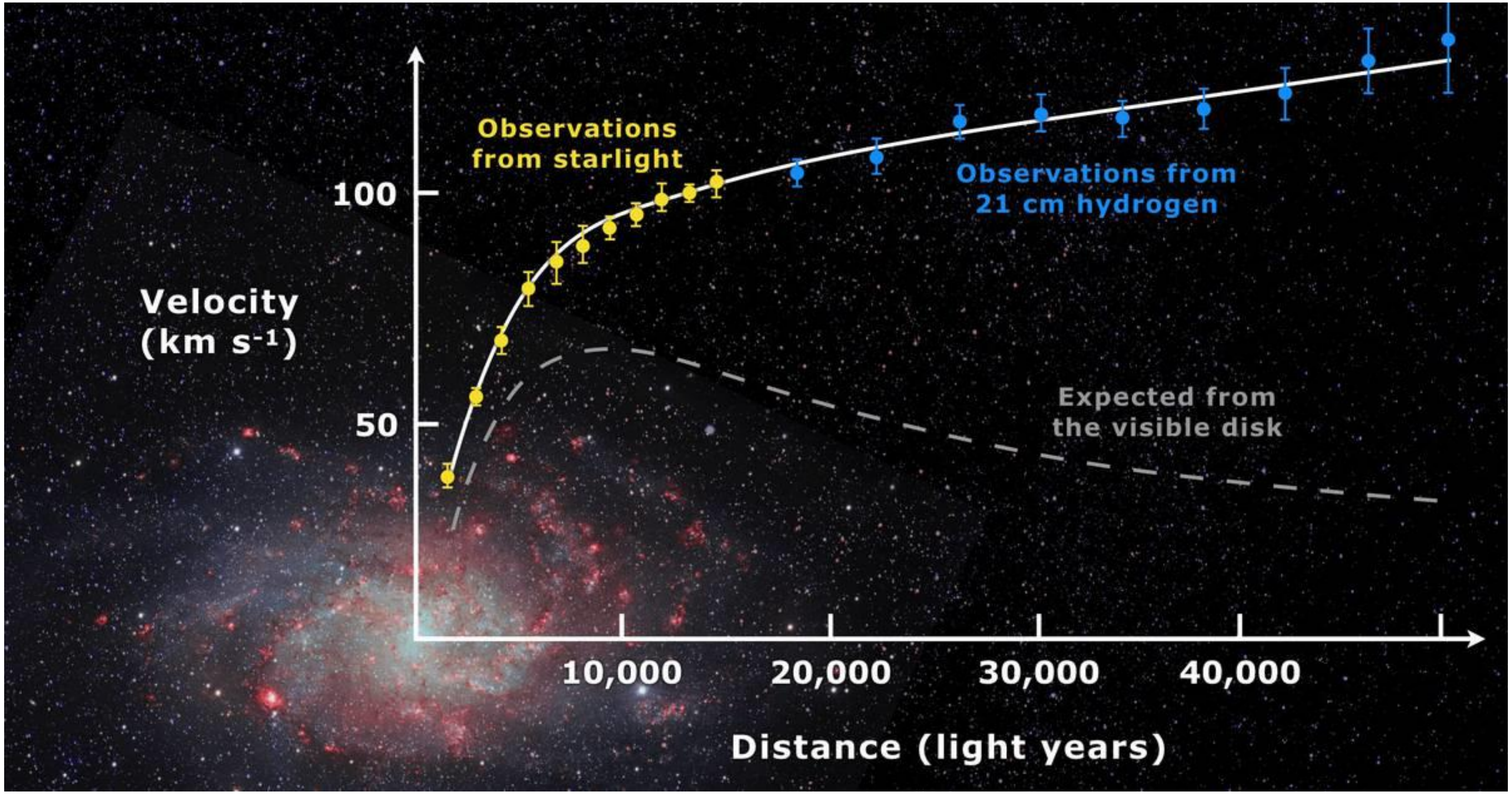


non-luminous matter ~90% of the mass in galaxies…

[Vera Rubin, giant of astronomy | symmetry magazine]

Dark Matter & rotational curves of galaxies

- *Vera Rubin* observes flat rotational profiles of galaxies

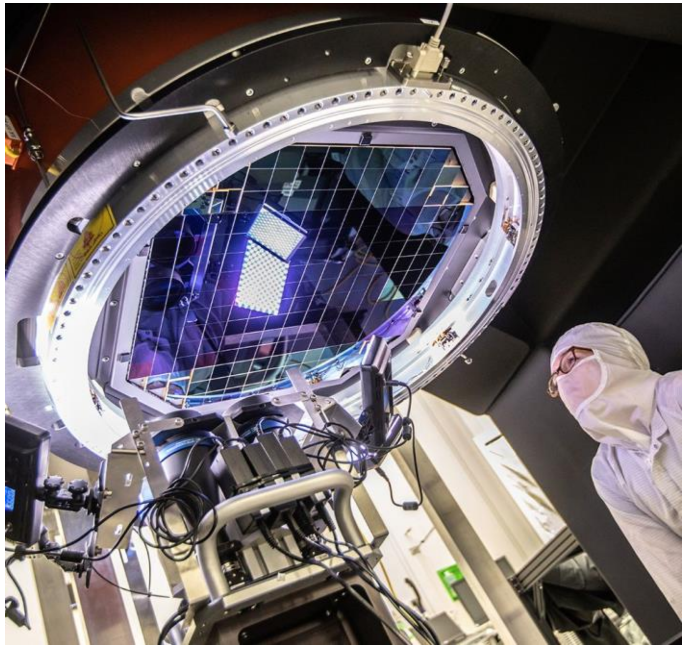


V. Rubin et al.,
***ApJ* 159 379 (1970)**
´Rotation of the
Andromeda Nebula´

Dark Matter – future surveys

- ***Vera Rubin*** **observatory: Legacy Survey of Space and Time**

- $\mathbf{8.4\ m}$ mirror telescope with $\mathbf{3.2\ giga-pix\ CCD\ (2025\ ff)}$



Dark Matter – future surveys

Karlsruhe Institute of Technology

- *Vera Rubin* observatory: Legacy Survey of Space and Time

- $8.4\ m$ mirror telescope with $3.2\ giga - pix\ CCD$ $(2025\ ff)$

VERA C. RUBIN OBSERVATORY

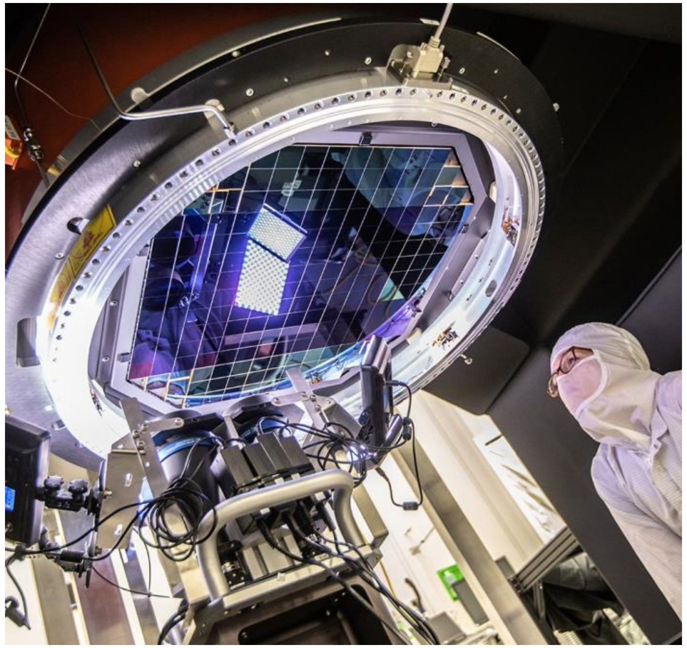
Courtesy of Margaux Lopez

symmetry
dimensions of particle physics

A day in the life of a mountaintop telescope builder

01/18/24 | By Joe Howlett

Margaux Lopez is one of a team of engineers preparing the Vera Rubin Observatory in Chile for the arrival of the largest digital camera ever built for astrophysics and cosmology.

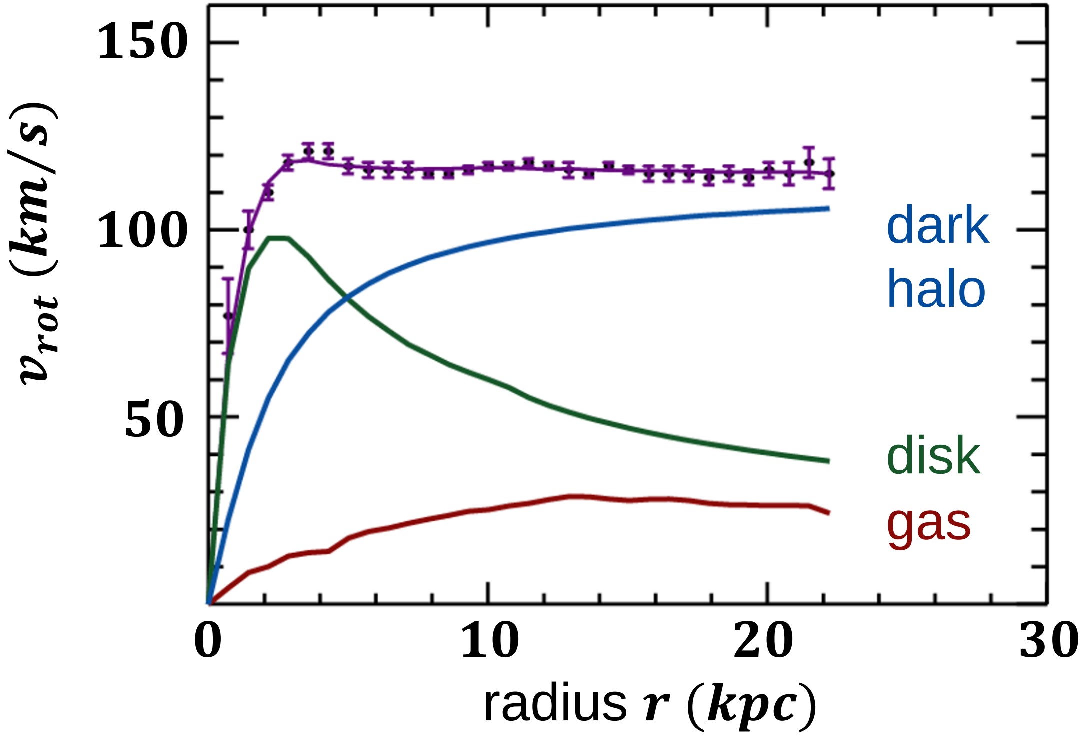


Dark Matter & flat rotational curves of galaxies

Karlsruhe Institute of Technology

- **Sir Isaac: rotational velocity profile of a galaxy should fall off**

  - **explanation**: non–luminous form of matter (´**Dark Matter**´) which interacts only via **gravitational potential**!



$$F = G \cdot \frac{M_r}{r^2} \cdot m = m \cdot a$$

galactic mass enclosed in r

´test mass´ (star, gas cloud,...)

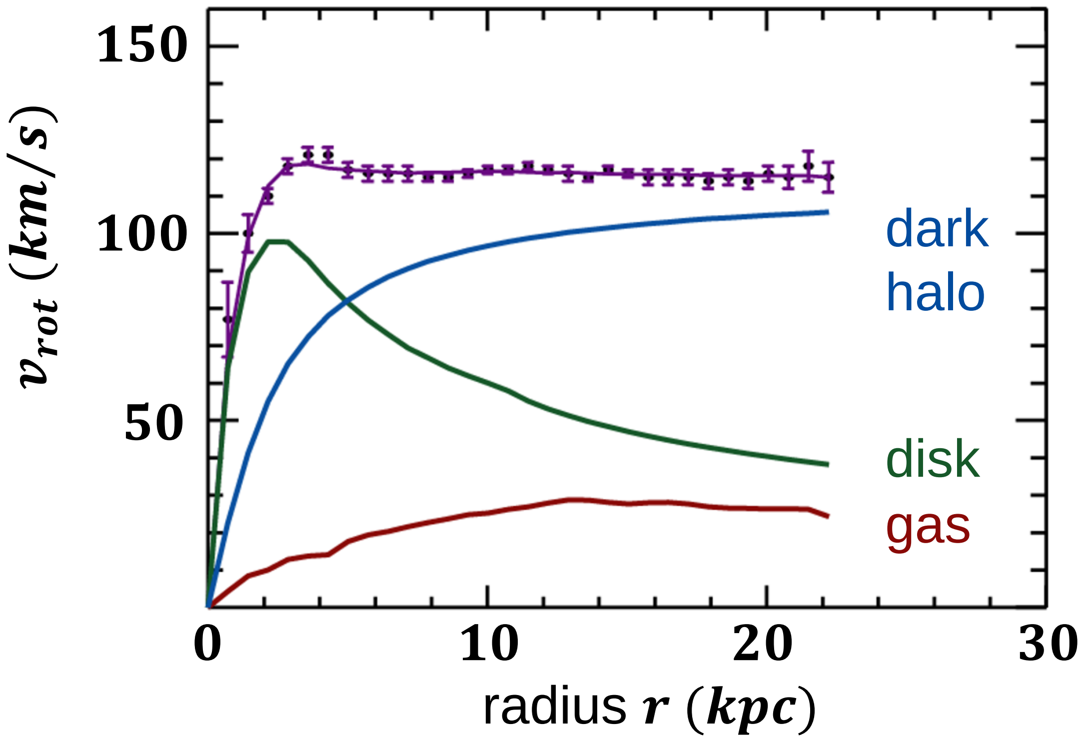
Newtonian Gravity

Dark Matter & flat rotational curves of galaxies

Karlsruhe Institute of Technology

- **Sir Isaac: rotational velocity profile of a galaxy should fall off as** $v_{rot} \sim 1/\sqrt{r}$

  - **explanation**: non–luminous form of matter (´**Dark Matter**´) which interacts only via **gravitational potential**!



- expected rotation curve for stars

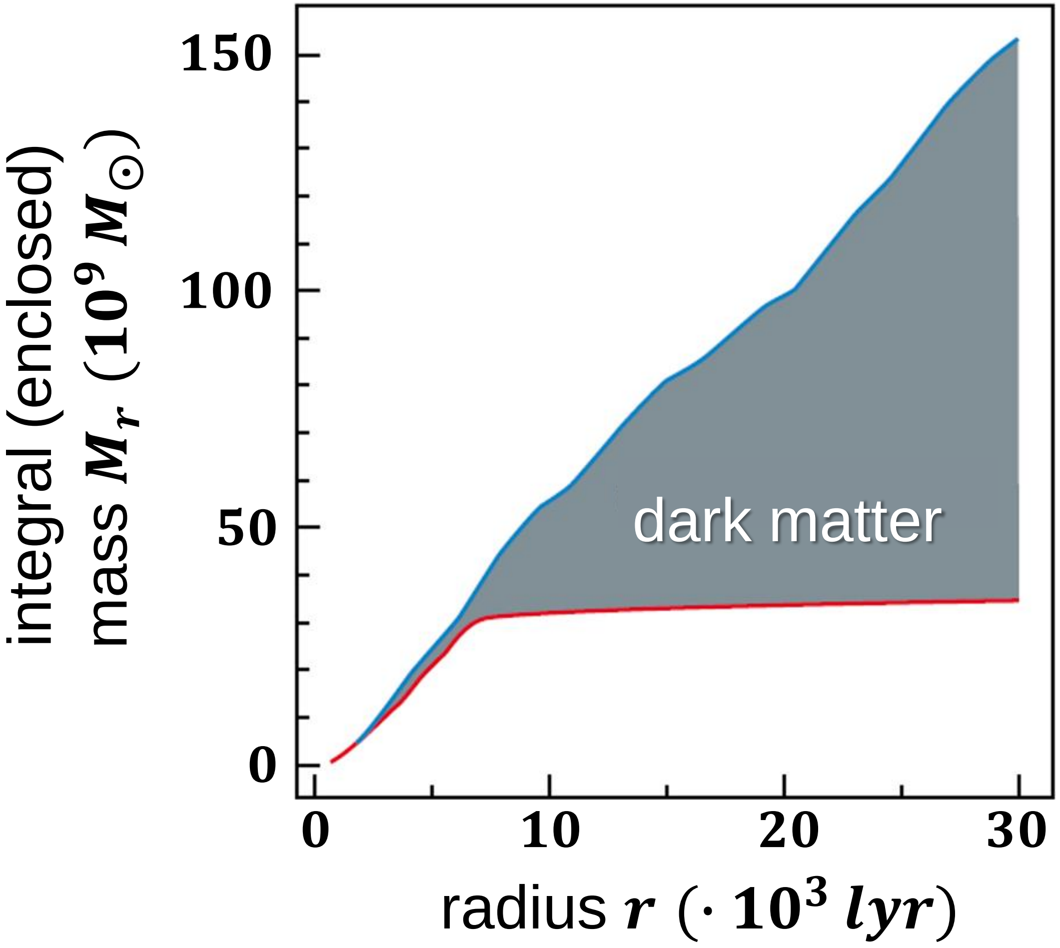
$$a = G \cdot \frac{M_r}{r^2} = \frac{v_{rot}^2}{r}$$

$$\Rightarrow v_{rot}(r) = \sqrt{\frac{G \cdot M_r}{r}}$$

- falling curve expected (if there is **no** DM)

Flat rotational curves reveal a Dark Matter halo

- **Today´s observations: linear increase of enclosed mass M_r up to $r = 50\ kpc$**



$v_{rot}(r) = const.$

$\Rightarrow M_r \sim r$ — **linear** increase of enclosed mass M_r

$\Rightarrow \rho(r) \sim \frac{1}{r^2}$ — halo profile

- **DM – halo with $(80 \ldots 90)\%$ of entire mass**

based on validity of **Newtonian Gravity**

DM halo: characteristic $1/r^2$ density profile

- Today´s observations: linear increase of enclosed mass M_r up to $r = 50\ kpc$

$$v_{rot}(r) = \ const.$$

$$\Rightarrow \ M_r \sim r$$

linear increase of enclosed mass M_r

$$\Rightarrow \boxed{\rho(r) \sim \frac{1}{r^2}}$$

halo profile

- DM – halo with $(80 \ldots 90)\%$ of entire mass

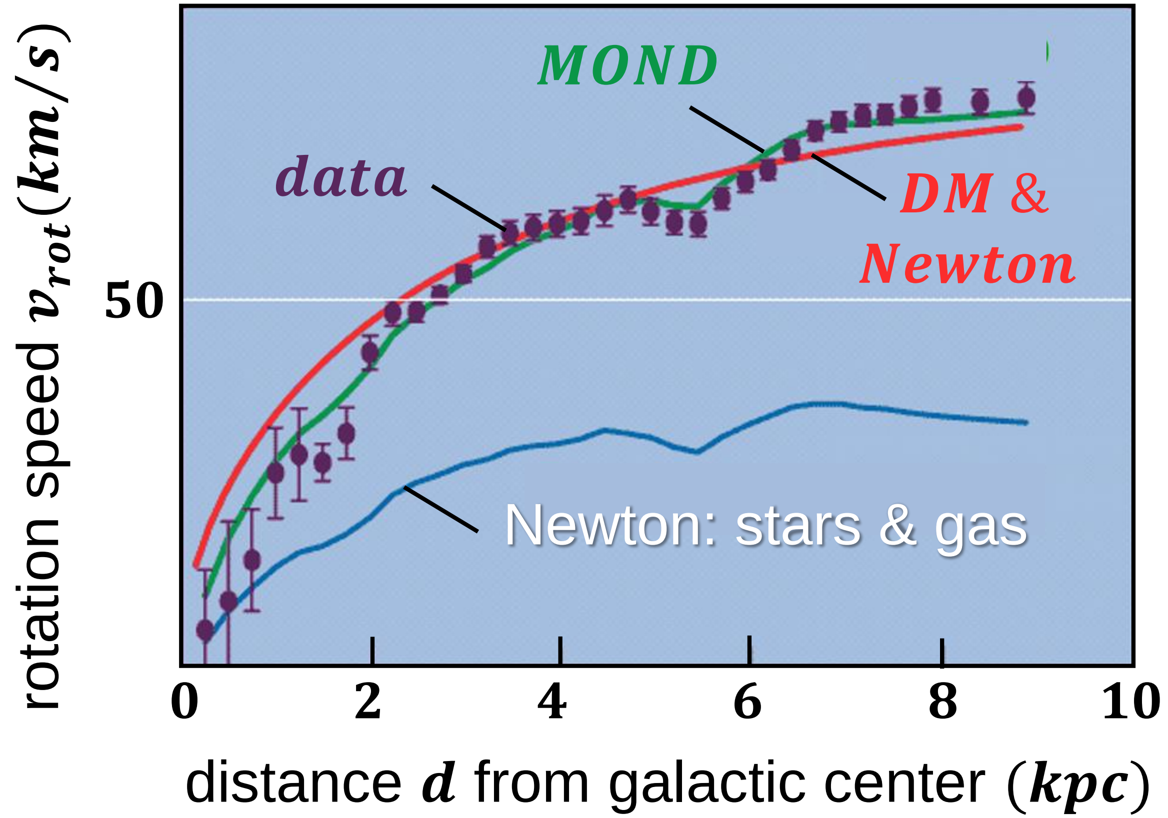
based on validity of **Newtonian Gravity**

DM ´alternative´: the ´ad hoc´ $MOND$ theory

Karlsruhe Institute of Technology

- $MOND$: MOdified Newton Dynamics - a rather unlikely DM ´competitor´

  - galactic **rotation profiles** can be ´reproduced´ by **modifying Newtonian gravity**



$$F = m \cdot \mu\left(\frac{a}{a_0}\right) \cdot a$$

- case #1: $a/a_0 \ll 1$: $\mu = \frac{a}{a_0}$
- case #2: elsewhere: $\mu = 1$
- introduction of ´fundamental acceleration´

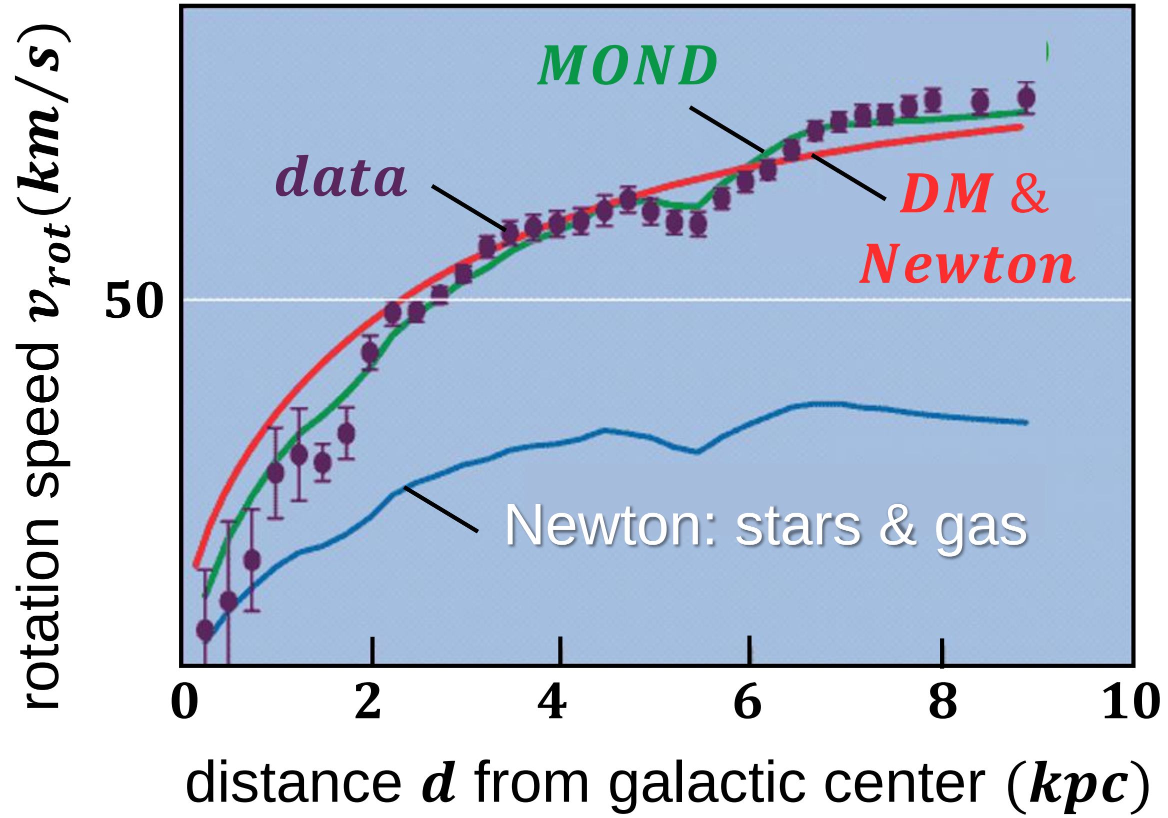
$$a_0 \approx 1.2 \cdot 10^{-10}\, m\, s^{-2}$$

$MOND$ theory: a one–trick pony ?

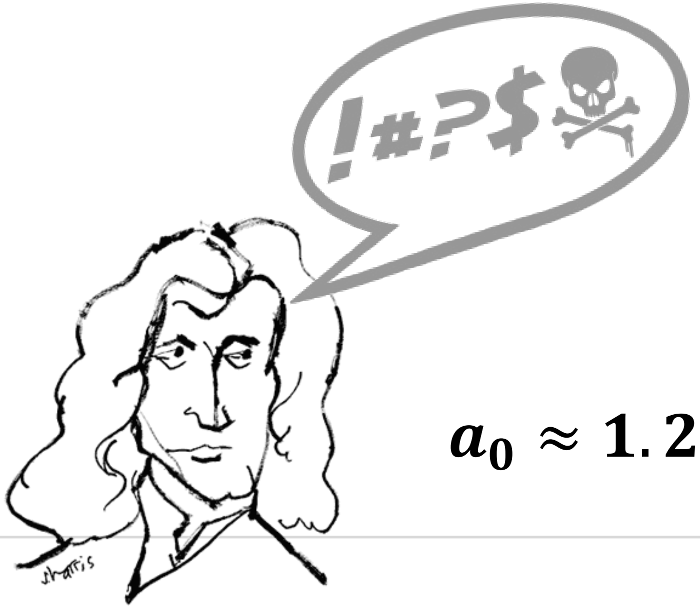
Karlsruhe Institute of Technology

- $\boldsymbol{MOND}$: $\boldsymbol{Mo}$**dified** $\boldsymbol{N}$**ewton** $\boldsymbol{D}$**ynamics as an ´alternative´ to Dark Matter**

  - galactic **rotation profiles** can be ´reproduced´ by **modifying Newtonian gravity**



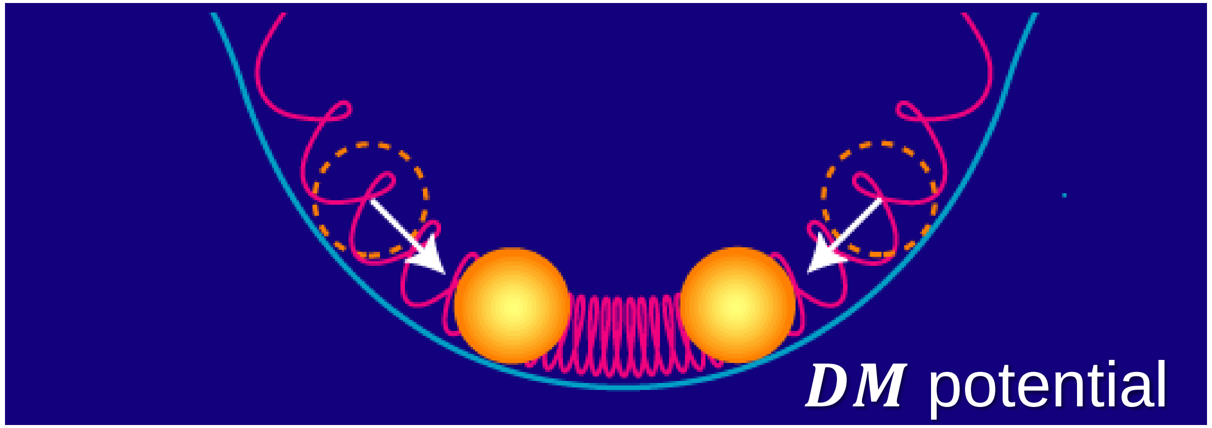
- an ´*ad hoc*´ theory only (so far)
- $\boldsymbol{MOND}$ cannot explain galaxy clusters, or $\boldsymbol{BAO}$, or…

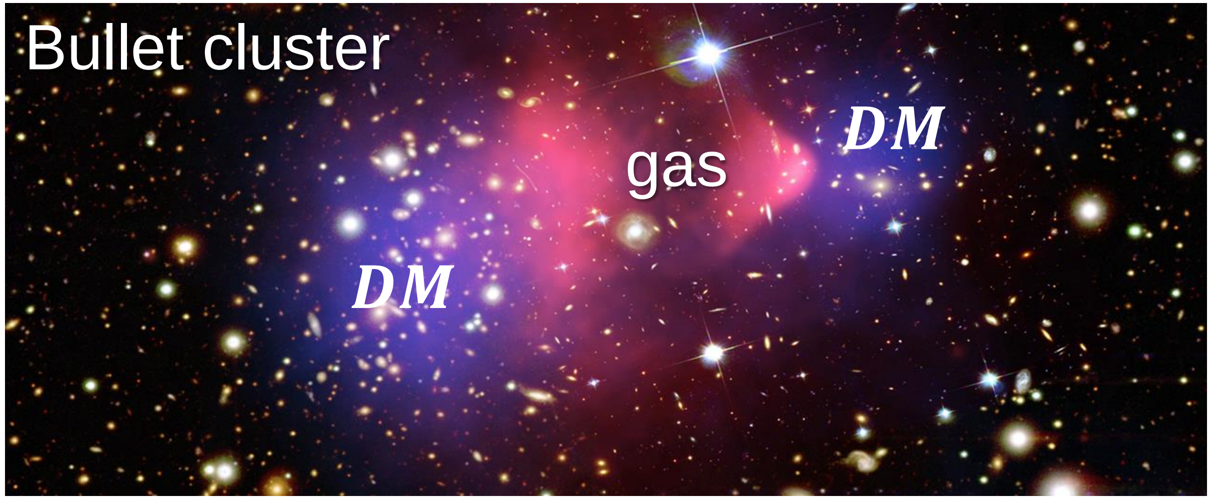


$$a_0 \approx 1.2 \cdot 10^{-10}\, m\, s^{-2}$$

Rotational Curves & BAO: irrefutable proof of DM

- $MOND$ theory: you may fit rotation curves but fail to describe BAO, clusters,...





$MOND$ theory not compatible with

a) **Baryon Acoustic Oscillations** via gravitational potential by **Dark Matter**

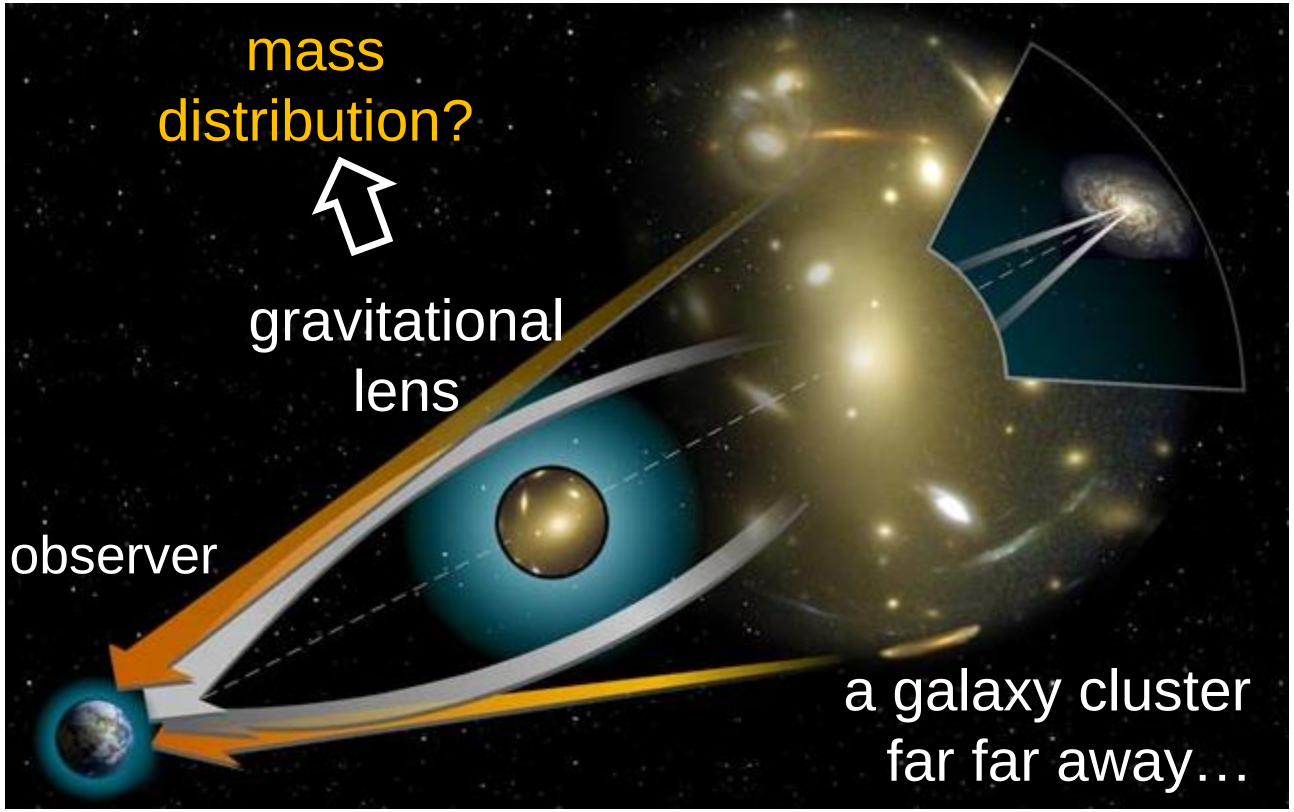
b) **Bullet cluster**
collision of **two galaxy clusters**:
separation of baryons (hot cluster gas) from **Dark Matter** (made visible by gravitational lensing)

5.2 Gravitational Lenses

- **Revealing the presence of DM via the process of gravitational lensing**

- ***A. Einstein***: light is propagating along **geodesic lines**

- **gravitational lenses**:
  distortion of the optical imaging due to gravitational potentials can be used to dervie **mass distribution of large objects** (galaxy clusters,…)



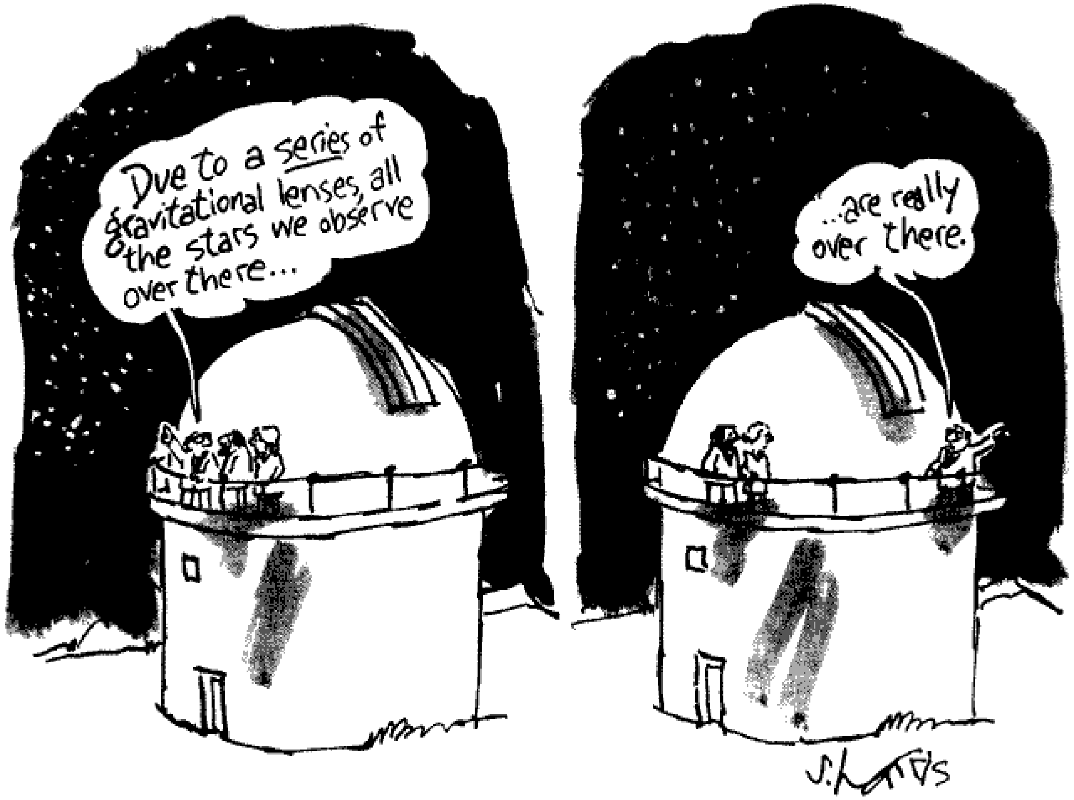
- **strong lensing**: arcs, rings, multiple images of far–off galaxies/quasars

- **weak lensing**: **statistical** distortion of images of single galaxies

Strong and weak gravitational lensing

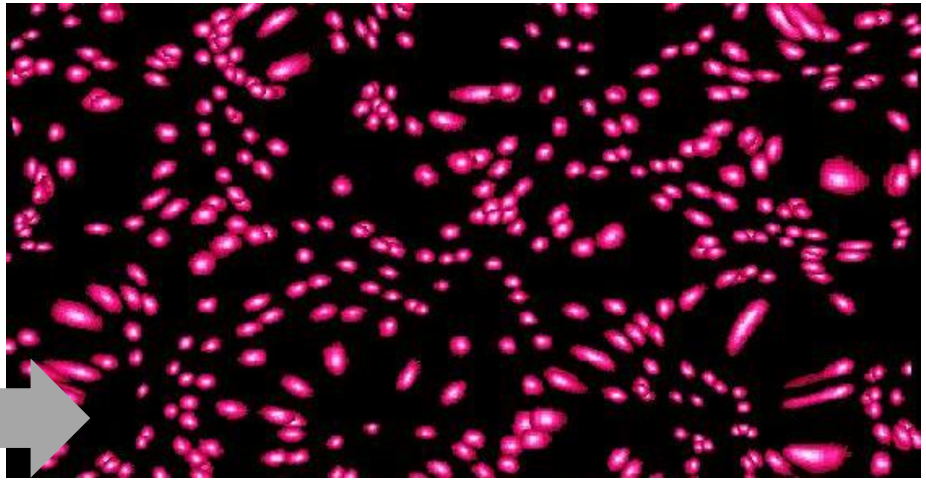
- **Important techniques to map out regions of Dark Matter: strong & weak**

- we can ´**see**´ where **Dark Matter** is



strong

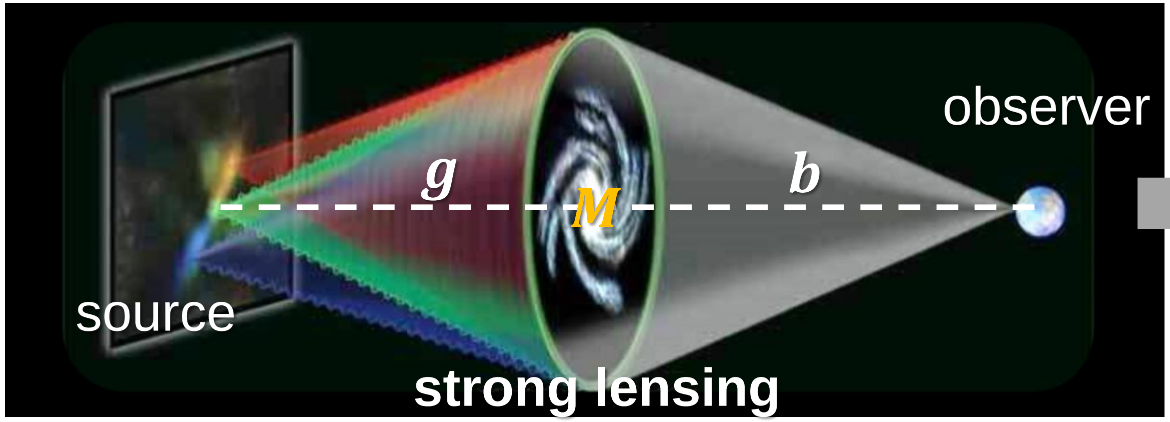
lensing

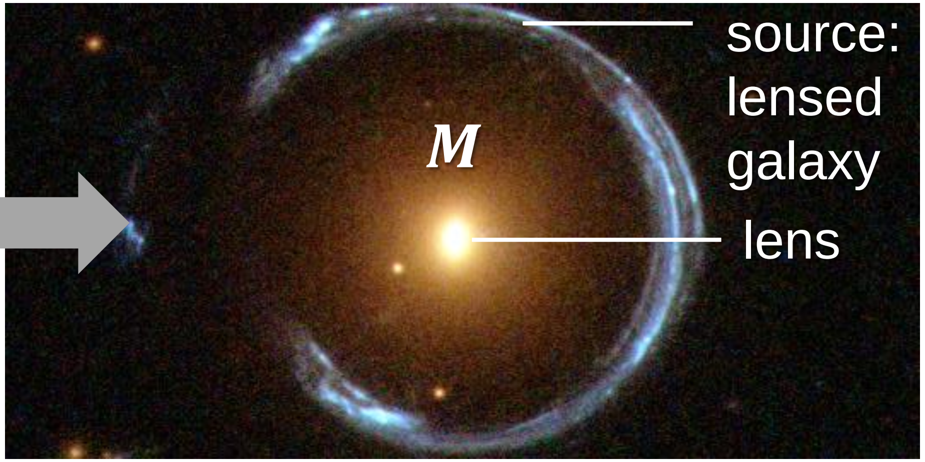


weak

Strong gravitational lensing

- An ideal method to map the spatial distribution of DM on galactic scales





thin lens formula

$$\frac{1}{g} + \frac{1}{b} = \frac{1}{f}$$

- perfect alignment of source, lens & observer:
  we see an Einstein ring with an opening angle θ_E

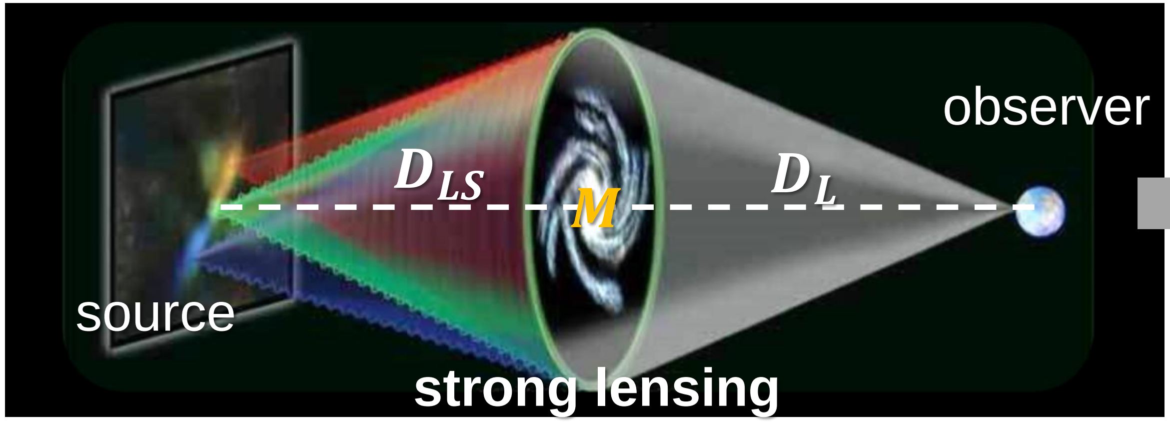
g : distance of source

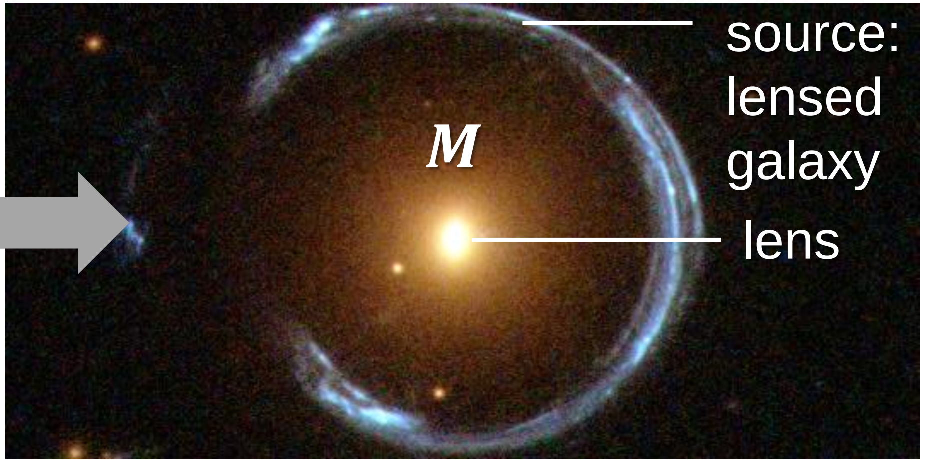
b : distance of observer

f : focal length

Strong gravitational lensing

- An ideal method to map the spatial distribution of DM on galactic scales





lensing formula

$$\theta_E = \sqrt{\frac{4\,G\cdot M}{c^2}\cdot\frac{D_{LS}}{D_S\cdot D_L}}$$

M : **Mass** of the lens (shows presence of DM)

$D_S = D_{LS} + D_L$ (source – observer)

- perfect alignment of source, lens & observer
- $\sim$ **70** Einstein rings/arcs observed: always considerable amount of DM