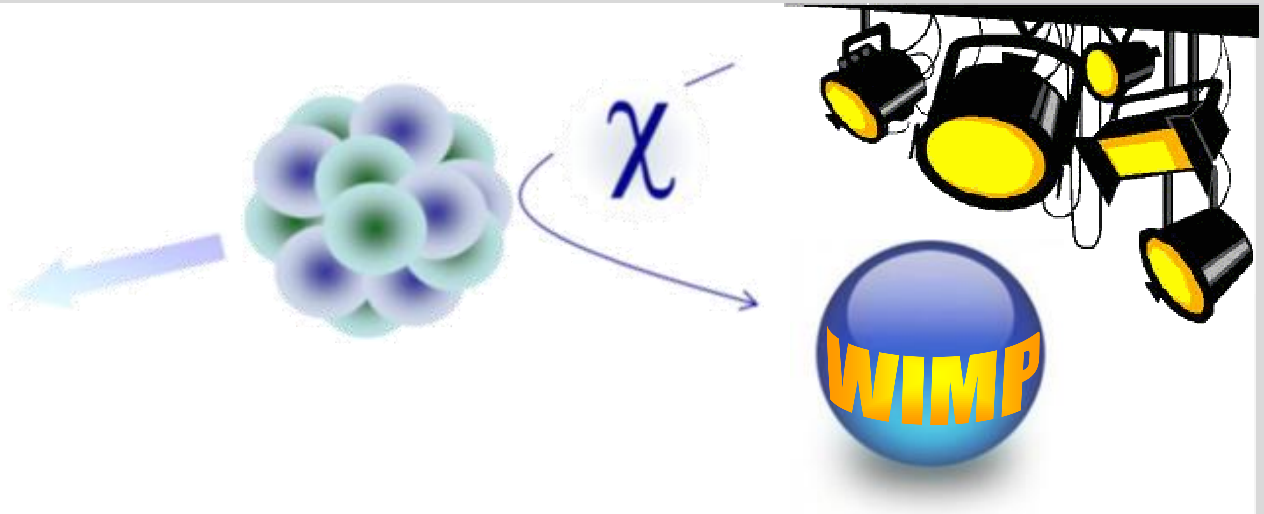
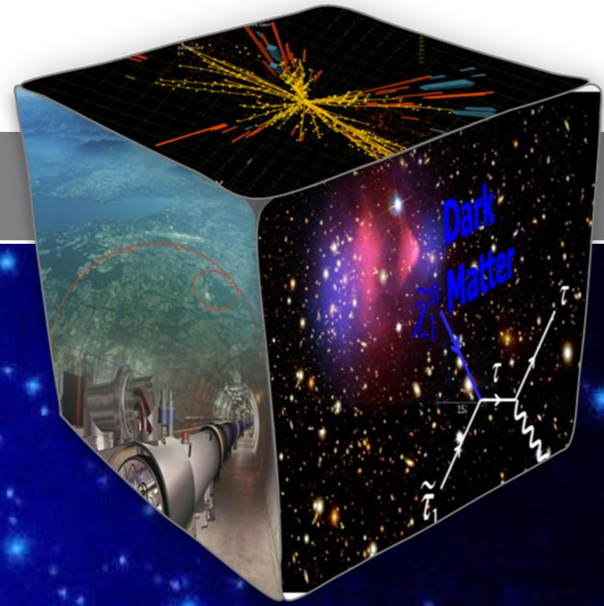


Dark Matter – I

GRK 1694: Elementarteilchenphysik bei höchster Energie und höchster Präzision

Workshop Freudenstadt 2015



Guido Drexlin, Institut für Experimentelle Kernphysik

dark matter – Why me?

KIT
Karlsruhe Institute of Technology

DARWIN-LXe: a future large dark matter and neutrino observatory at LNGS

DARWIN

R&D and design: Infrastructure and Detectors

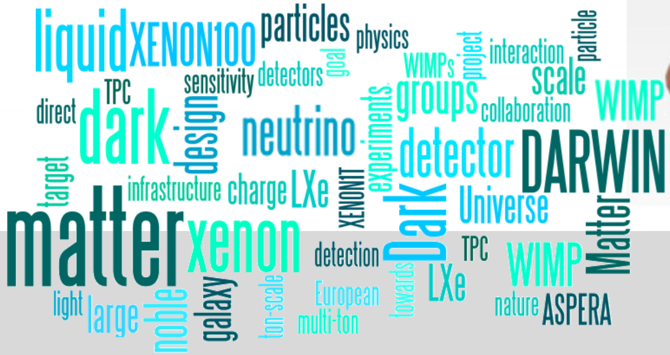
5. Electric field simulations: study and optimise E-field configurations in the drift and extraction regions, focused on 3D boundary element methods (KEMField) developed for KATRIN

30-50 t Lxe
TPC Ø > 2 m

The DARWIN Consortium

- **Subatech (France)**: group of Dominique Thers
- **University of Münster (Germany)**: group of Christian Weinheimer
- **MPIK Heidelberg (Germany)**: group of Manfred Lindner
- **University of Karlsruhe (Germany)**: group of Guido Drexlin
- **University of Mainz (Germany)**: group of Uwe Oberlack
- **TU Dresden (Germany)**: group of Kai Zuber
- **Imperial College London (Great Britain)**: group of Roberto Trotta
- **INFN (Italy), Sezione LNGS:** group of Walter Fulgione
- **INFN (Italy), Sezione di Bologna:** group of G. Sartorelli
- **Weizmann Institute of Science (Israel)**: group of Amos Breskin
- **Nikhef, Amsterdam (The Netherlands)**: group of Patrick Decowski
- **University of Coimbra (Portugal)**: group of Jose Matias Lopes
- **Stockholm University (Sweden)**: group of Jan Conrad
- **University of Zürich I (Switzerland)**: group of Laura Baudis *(DARWIN project coordinator)*
- **University of Zürich II (Switzerland)**: group of Ben Kilminster
- **University of Bern (Switzerland)**: group of Marc Schumann
- **Columbia University (USA)**: group of Elena Aprile
- **University of Calfornia at Los Angeles (UCLA, USA)**: group of Hanguo Wang
- **Arizona State University (USA)**: group of Lawrence Krauss
- **Purdue University (USA)**: group of Rafael Lang
- **Rice University (USA)**: group of Peter Shagin

plus: keV-scale ν_r @KATRIN



outline of lectures

Karlsruhe Institute of Technology

Dark Matter – 1

- introduction
- astrophysical evidences for DM
- thermal relics & freeze-out
- non-thermal relics: sterile ν´s
- WIMP candidates
- experimental searches

Dark Matter – 2

- indirect searches: principles & (selected) results

Dark Matter – 3

- direct detection: experiments & (selected) results

introduction - a brief history of dark matter

a buzz of excitement or the final round?

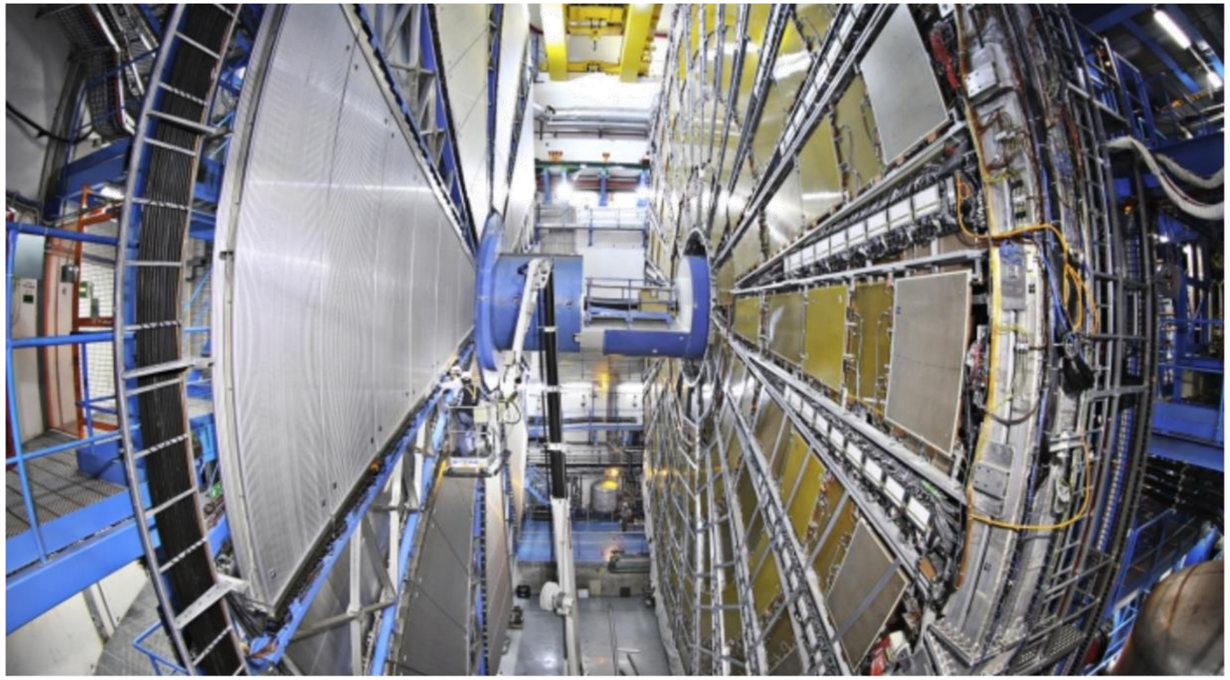


Photo by Claudia Marcelloni De Oliveira, CERN

see 2014 lectures by
I. Melzer-Pellmann, DESY Hamburg :
„SUSY Searches at the LHC“

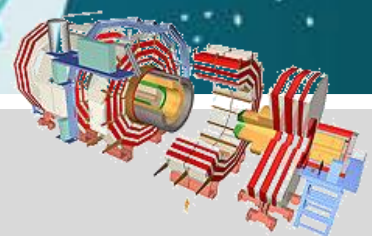
LHC searches not covered here

signal to background
April 29, 2015

Natural SUSY's last stand

Either Supersymmetry will be found in the next years of research at the Large Hadron Collider, or it isn't exactly what theorists hoped it was.

CERN

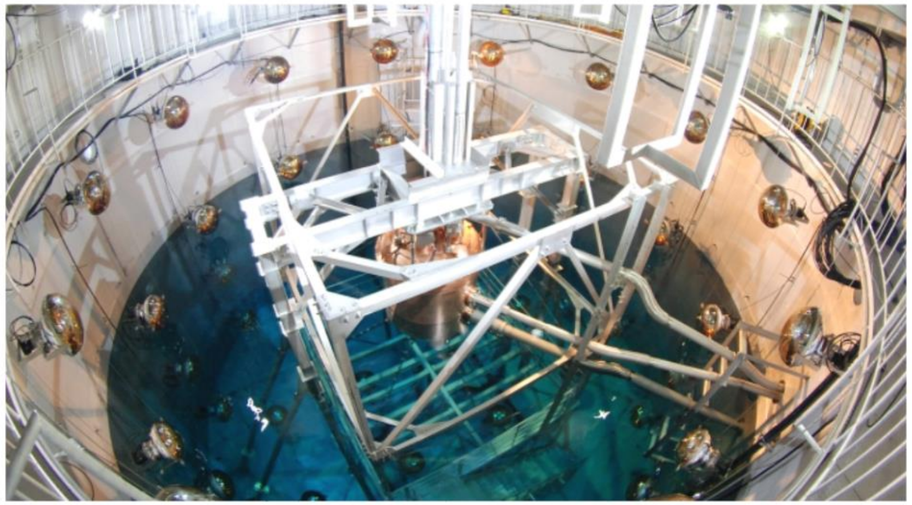


a buzz of excitement or the final round?

Karlsruhe Institute of Technology

Sept. 15, 2015: MiniCLEAN – starting up

Nov. 11, 2015: XENON1T inauguration



Sept. 10, 2015: XMASS - new results

Sanford Underground Research Facility

INFN Laboratori Nazionali del Gran Sasso

SNOLAB

a buzz of excitement or the final round?

Karlsruhe Institute of Technology

- (too?) many astrophysical evidences for dark matter keV – MeV – GeV …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News & Comment > News > 2014 > October > Article

NATURE | NEWS

Physicists see potential dark matter from the Sun

X-ray data hinting at axion particles draw interest and cautionary warnings.

Elizabeth Gibney

17 October 2014

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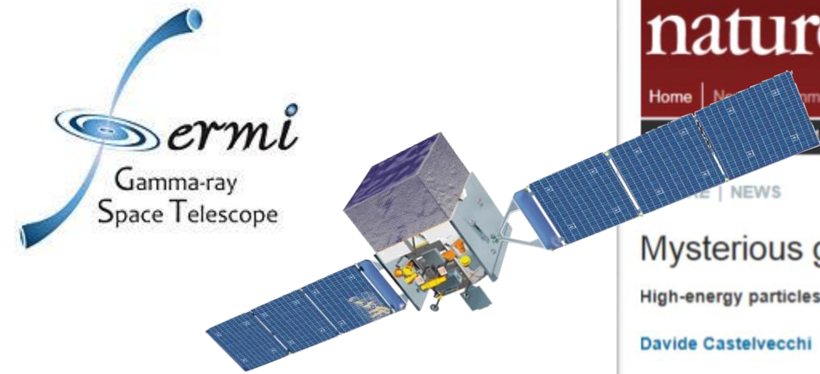


Fresh hint of dark matter seen in neutrino search

- 17:11 25 February 2014 by Lisa Grossman
- Magazine issue 2958. Subscribe and save
- For similar stories, visit the Cosmology Topic Guide

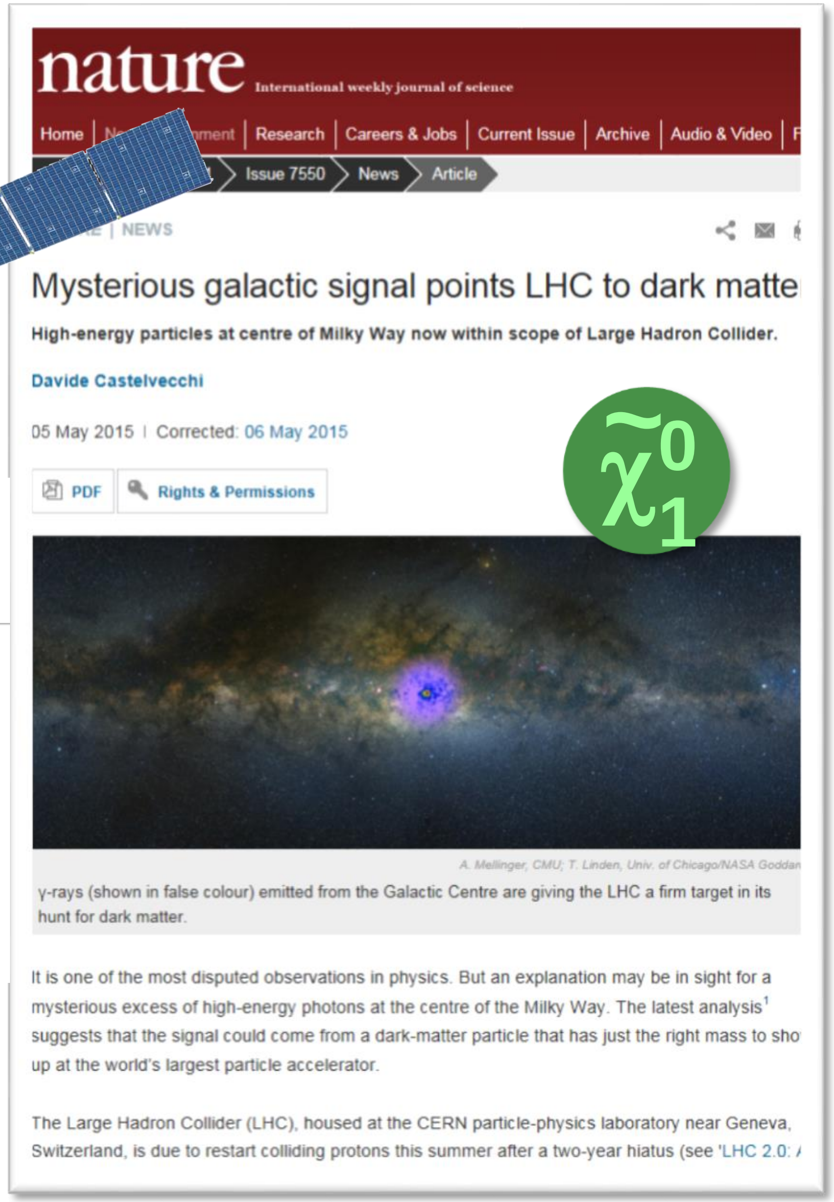
Flashes of X-rays from crowded galaxy clusters could be the long-awaited sign that we have found particles of dark matter – the elusive substance thought to make up the bulk of all matter in the universe.

If the results stand up, dark matter would consist of ghostly particles called "sterile" neutrinos. These tantalising particles would be the first kind found beyond the standard set known to science.

Dark matter interacts with ordinary matter via gravity but otherw... ...ly makes itself known. Physicists think its mass could be tied... particle. The leading theoretical candidate is a weakly inte... particle (WIMP), but our best detectors have yet to yield ...

Neutrinos also seem like good candidates, as they are long...

ν_R


nature International weekly journal of science

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Issue 7550 > News > Article

NEWS

Mysterious galactic signal points LHC to dark matte

High-energy particles at centre of Milky Way now within scope of Large Hadron Collider.

Davide Castelvecchi

05 May 2015 | Corrected: 06 May 2015

PDF | Rights & Permissions

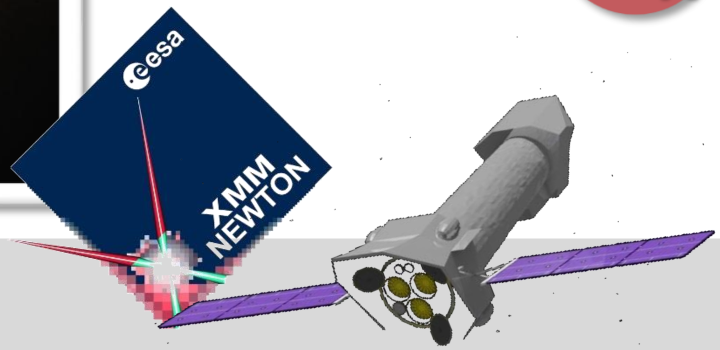
$\tilde{\chi}_1^0$

A. Mellinger, CMU; T. Linden, Univ. of Chicago/NASA Goddar

γ-rays (shown in false colour) emitted from the Galactic Centre are giving the LHC a firm target in its hunt for dark matter.

It is one of the most disputed observations in physics. But an explanation may be in sight for a mysterious excess of high-energy photons at the centre of the Milky Way. The latest analysis[1] suggests that the signal could come from a dark-matter particle that has just the right mass to sho up at the world's largest particle accelerator.

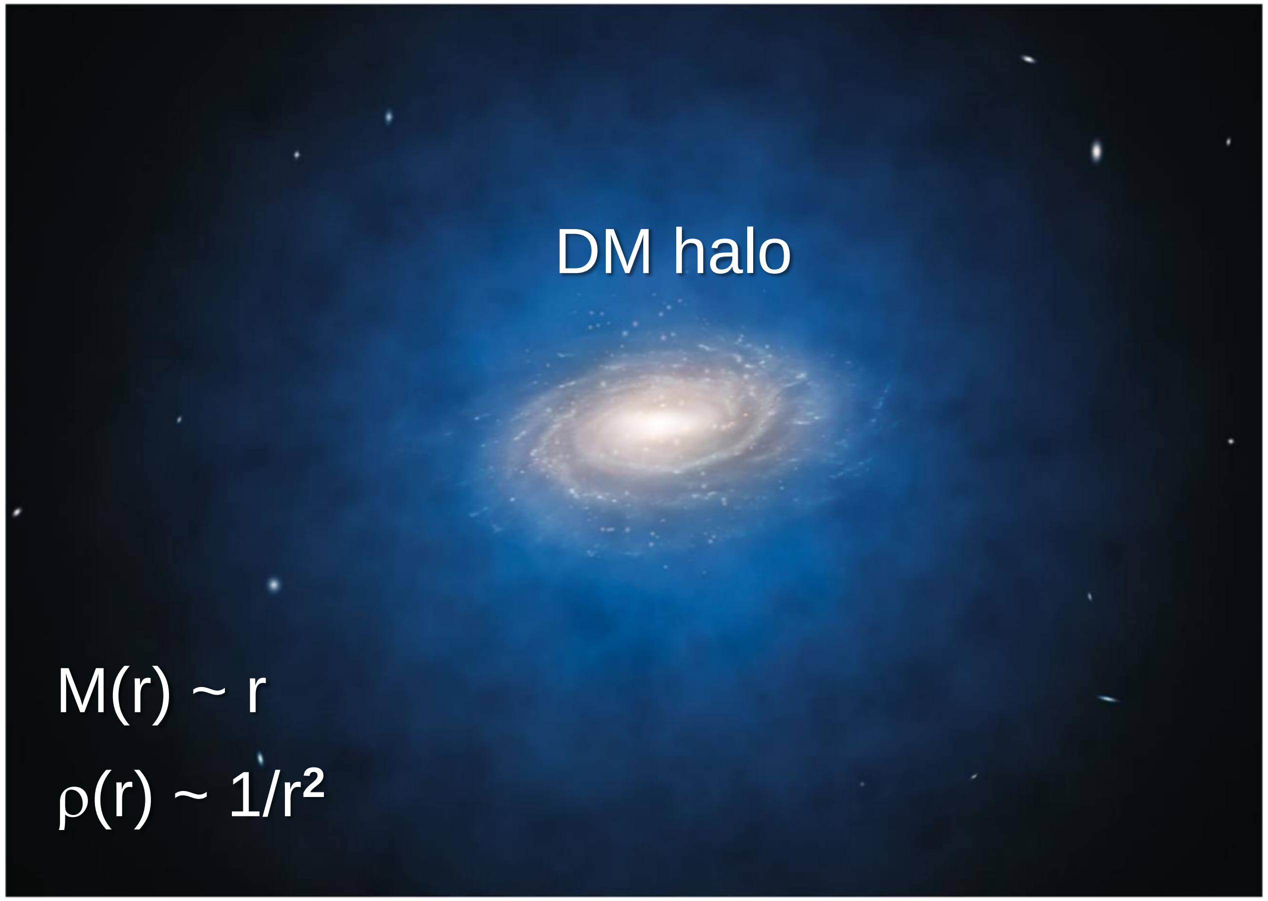
The Large Hadron Collider (LHC), housed at the CERN particle-physics laboratory near Geneva, Switzerland, is due to restart colliding protons this summer after a two-year hiatus (see 'LHC 2.0: /

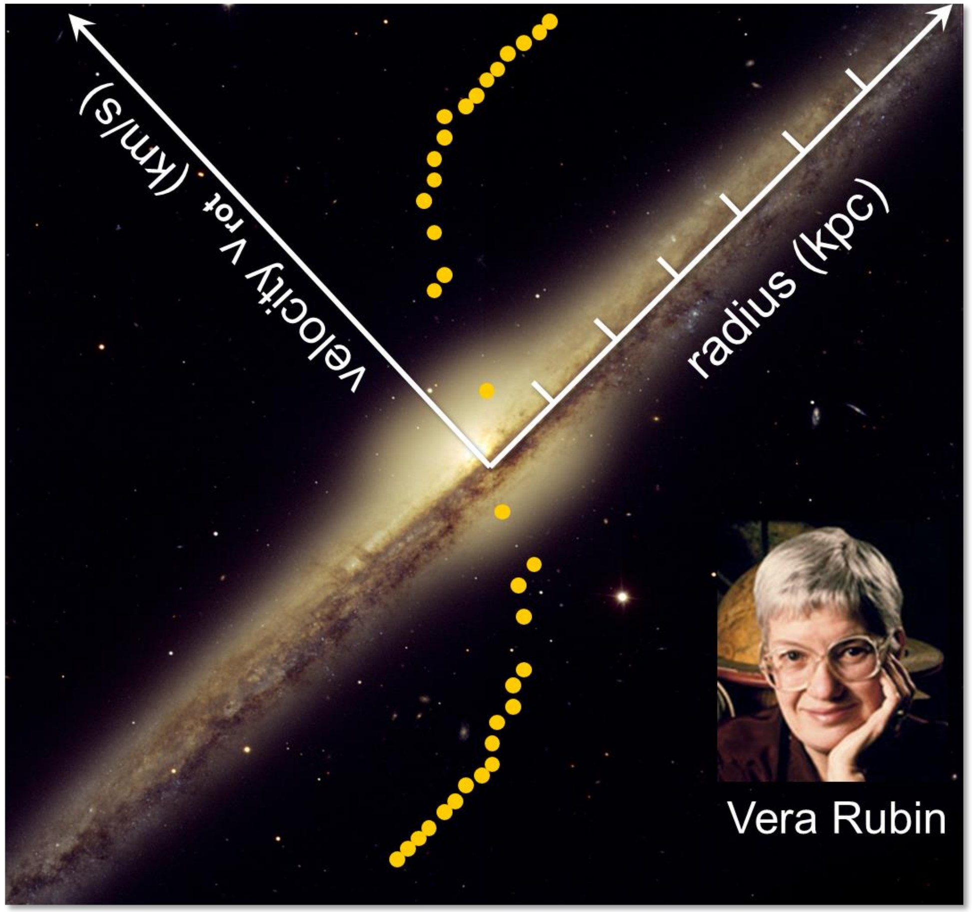


dark matter – galactic halo

- **flat rotation curves imply extended dark matter halos** (V. Rubin) :
  - DM halos contain 80-90% of entire mass of a galaxy
  - detailed modelling gives ´universal´ NFW-profile

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





dark matter – galactic halo

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dark matter – galactic halo

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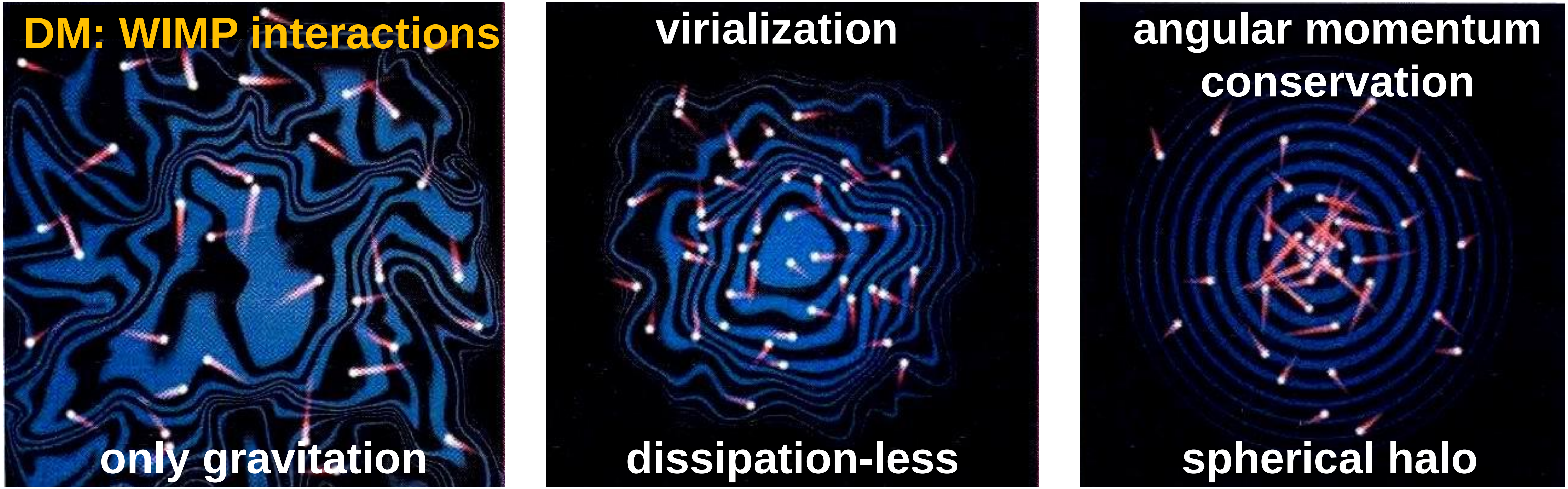
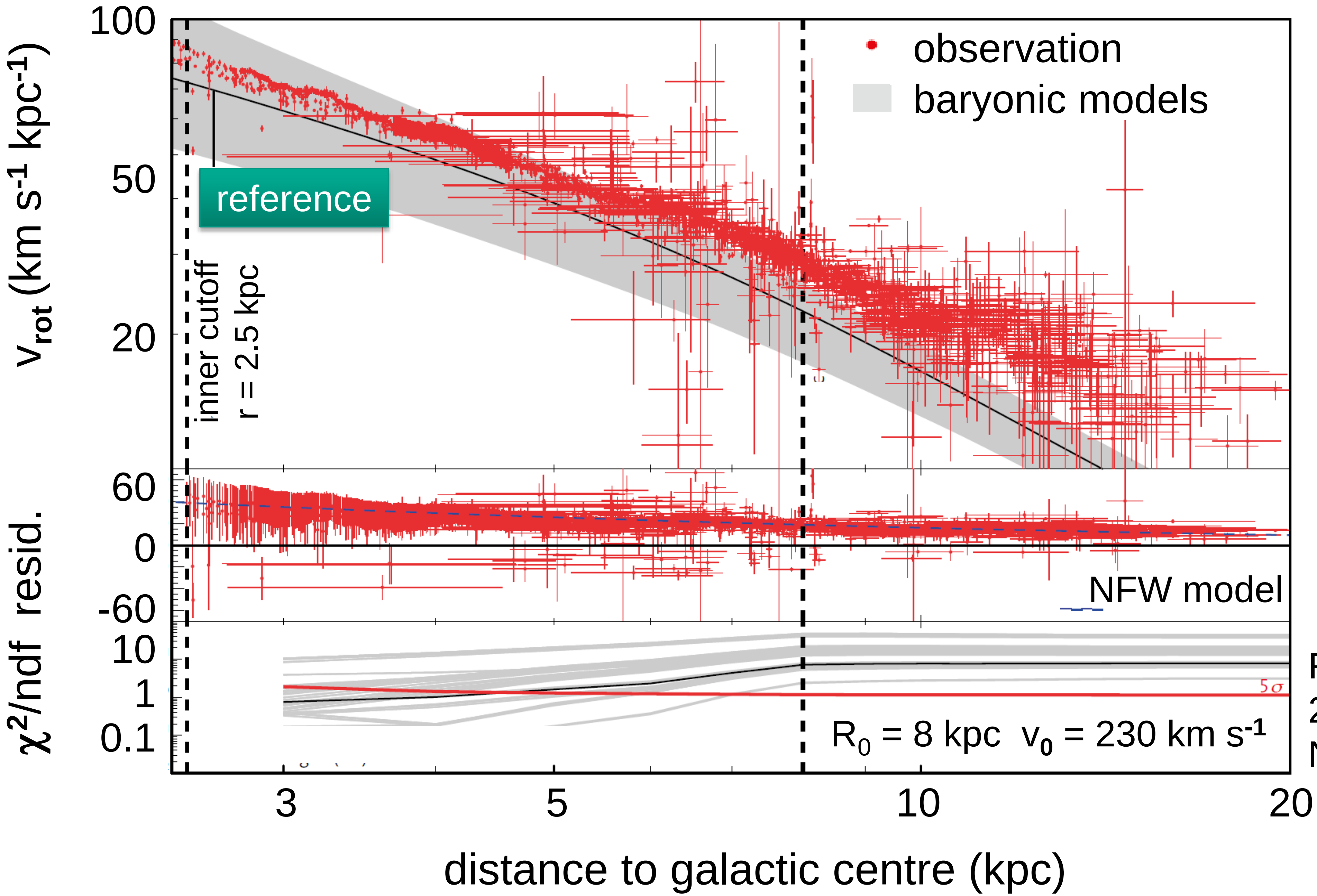
  - detailed modelling gives ´universal´ NFW-profile
  - **clumpy sub-structure** (DM simulations)
  - DM halos from **virialization of dissipation-less WIMPs** & tidal disruption of ´primoridal´ DM halos

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



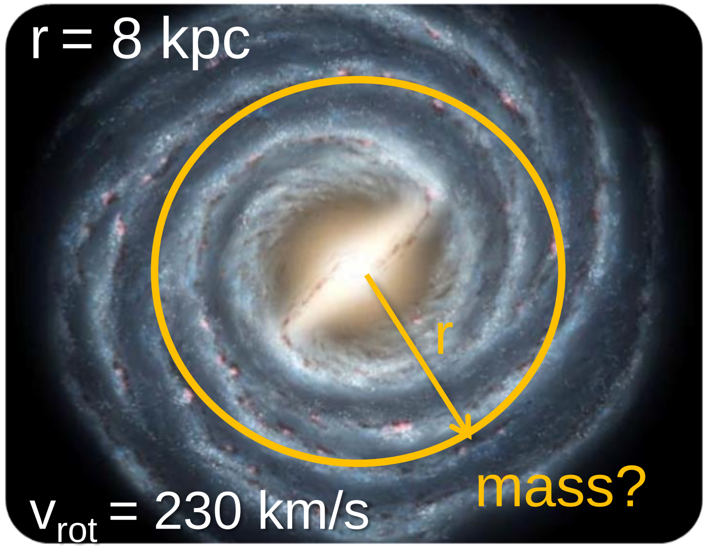
dark matter – rotation curve of Milky Way

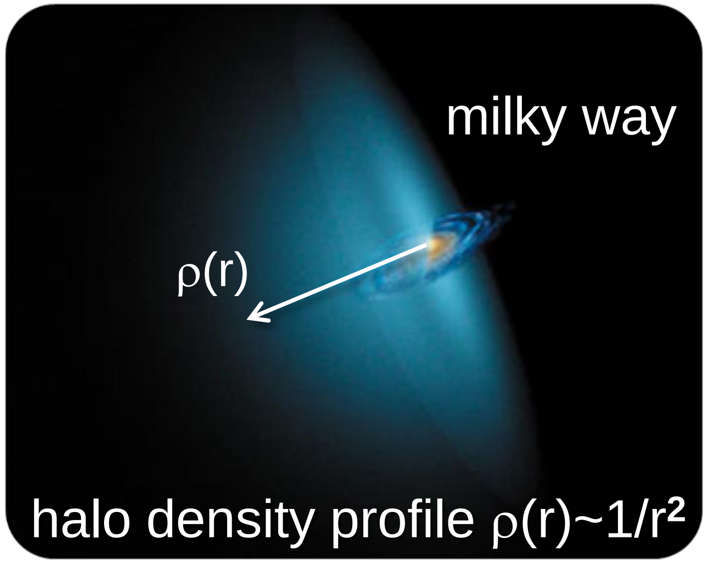


F. Iocco et al., 2015 Nature Physics

local DM density

- ***local* DM density much higher than cosmological *mean* DM density**





- estimate: from solar rotation speed v_{rot} to ρ_{local}

$$\frac{v_{rot}^2}{r} = \frac{GM_r}{r^2} \quad \text{with} \quad M_r = \frac{4}{3}\pi r^3 \cdot \rho$$

$$\rho_{local} = \frac{3\, v_{rot}^2}{4\pi\, r^2 G}$$

⇒ $\rho_{DM,local} \sim 0.3\ \mathrm{GeV/cm^3}$

$\approx \rho_{baryonic}$

$$\rho_{DM,\,lokal} \approx 10^5 \langle \rho_{DM} \rangle$$

- local DM-density ρ: important parameter for directe WIMP searches

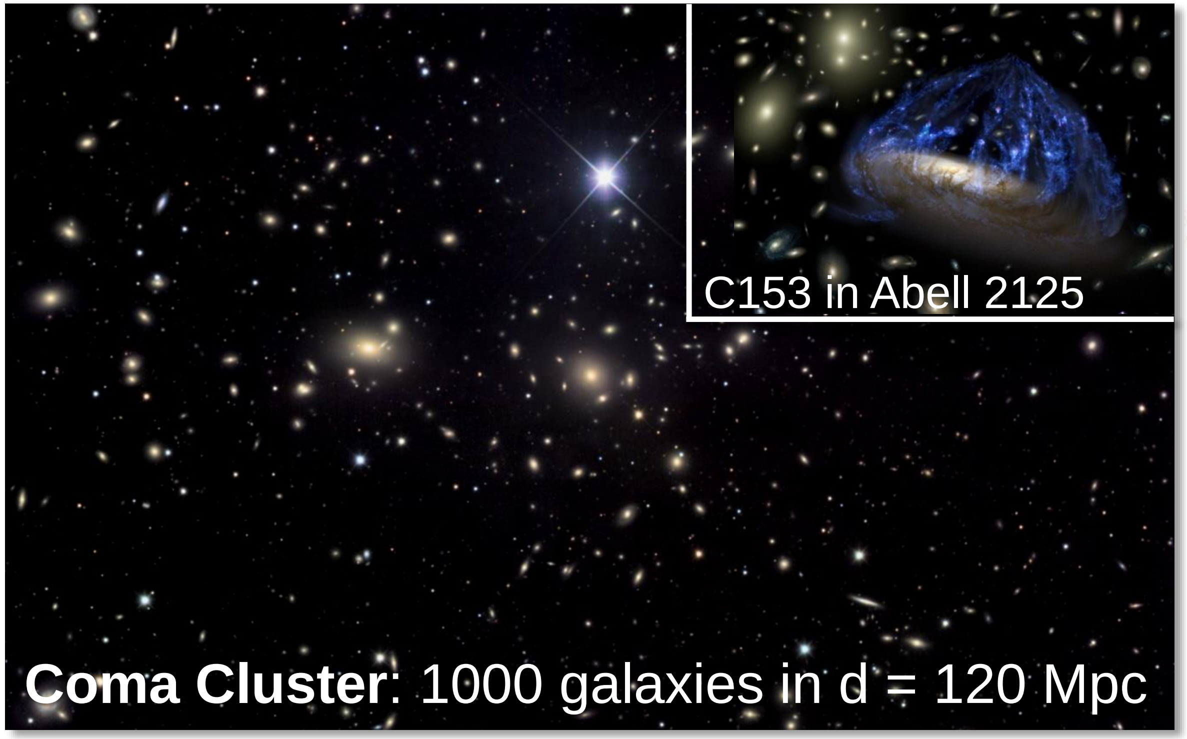
$\rho_{WIMP} = 50\ \mathrm{GeV}/150\ \mathrm{cm^3}$

dark matter – galaxy clusters

- **first postulation of dark matter** (F. Zwicky, 1933) :
  - DM: non-luminous matter, interacts only via gravitational forces
    - ↳ explains the very high peculiar velocities of single galaxies in the Coma galaxy cluster

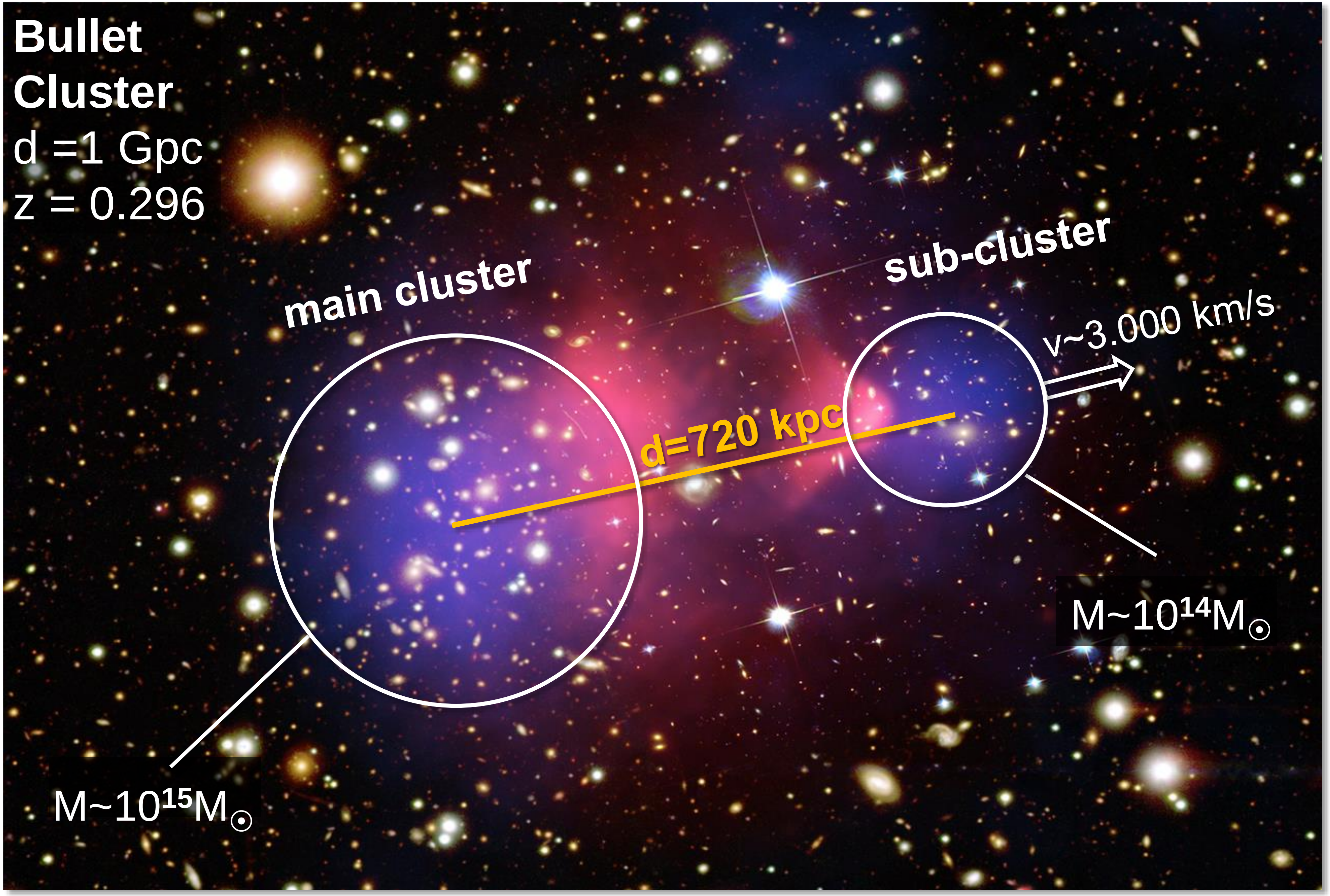
virial theorem: $\langle E_{kin} \rangle = -\frac{1}{2} \langle U_{pot} \rangle$

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



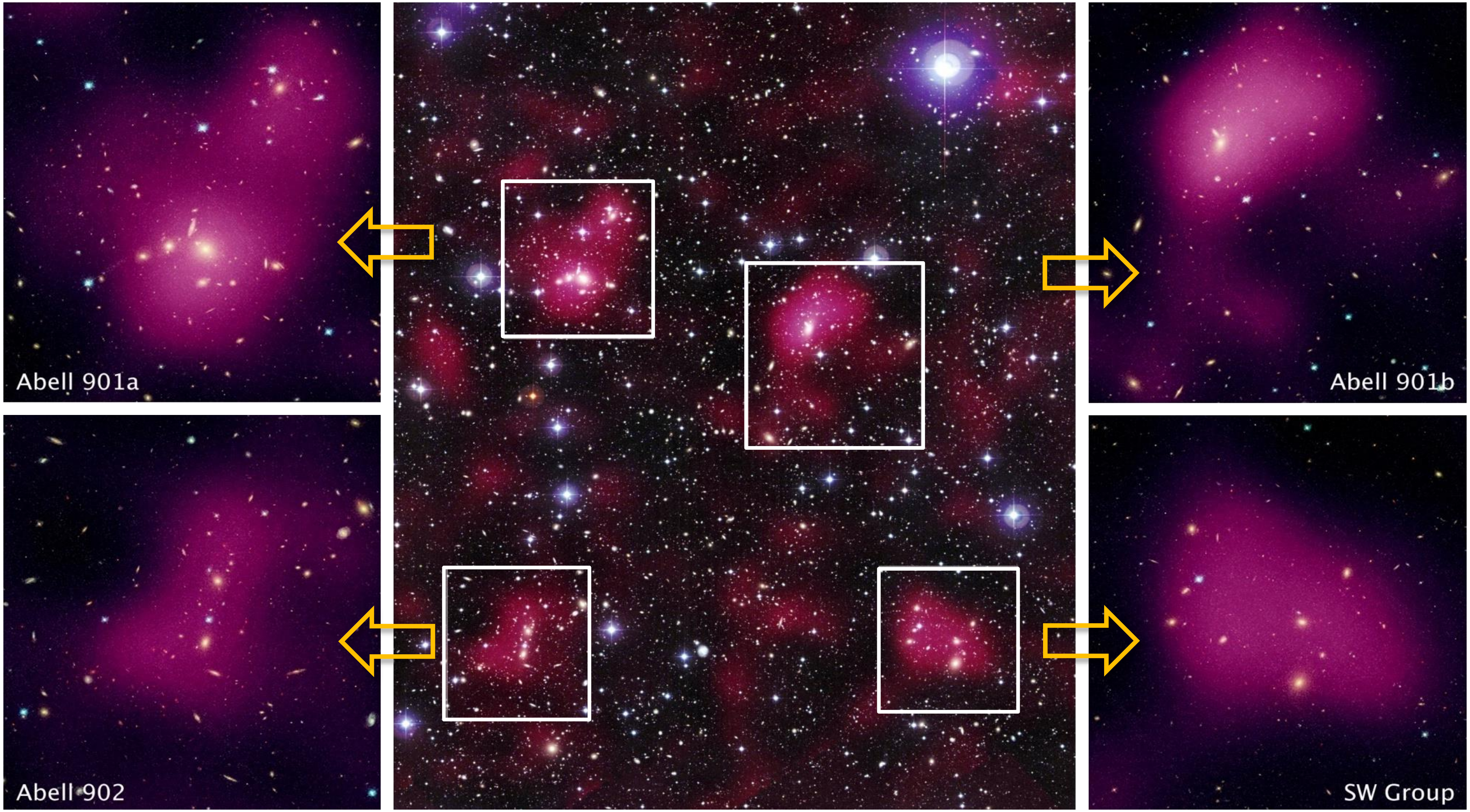
F. Zwicky
Helv. Phys. Acta **6**
110-127 (1933)
´Die Rotverschiebung von extragalaktischen Nebeln´

Dark matter – galaxy cluster 1E 0657-556



mapping of dark matter - Abell 901/902

- distribution of dark matter (*weak lensing*) & baryonic matter



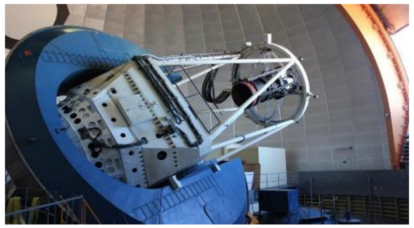
2015 update: DM map from DE survey

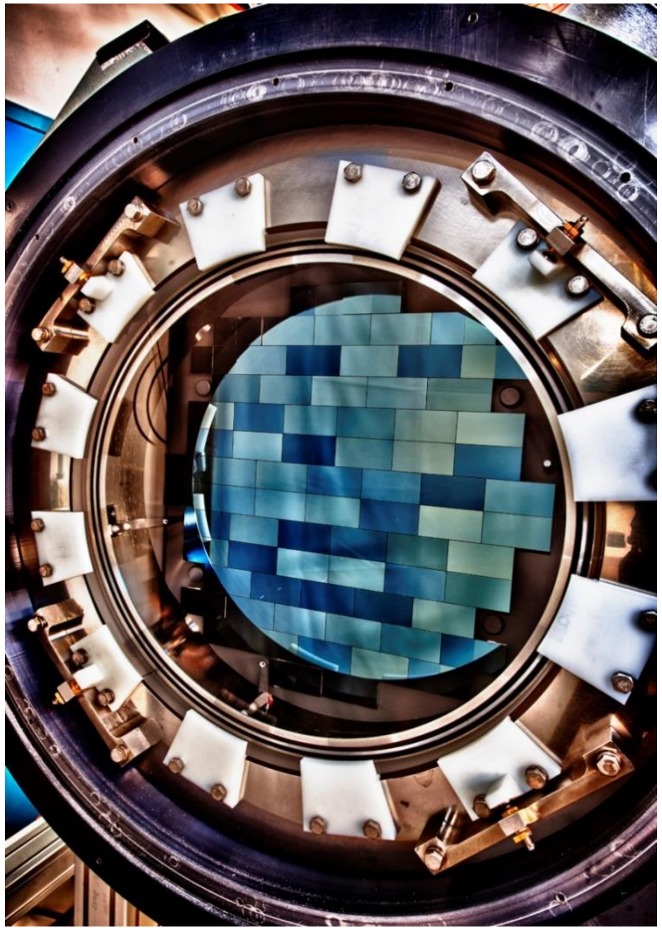
Dark Energy Survey:

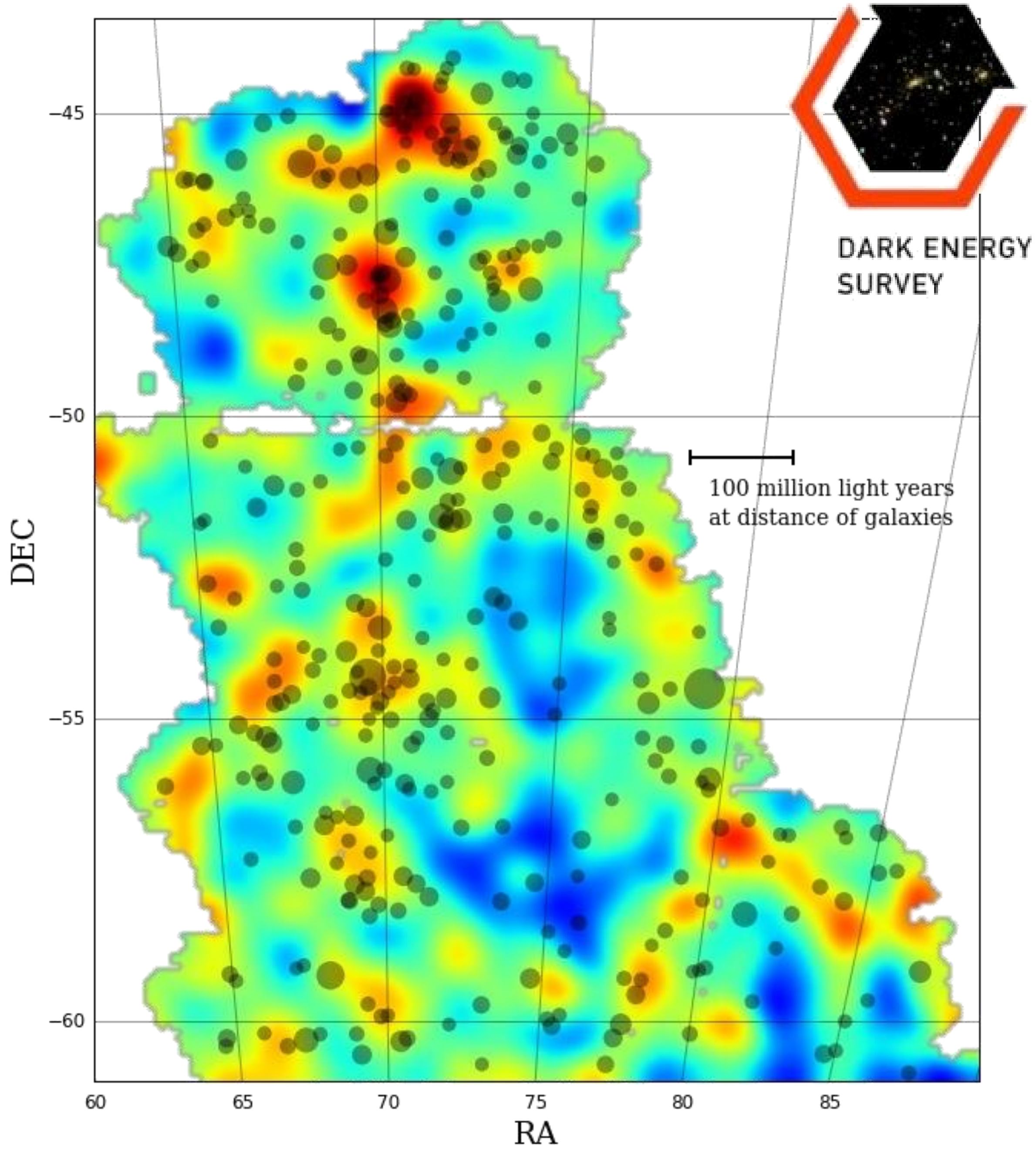
- large-scale weak lensing studies

520 Megapixel CCD

4 m Blanco telescope at Cerro Tololo

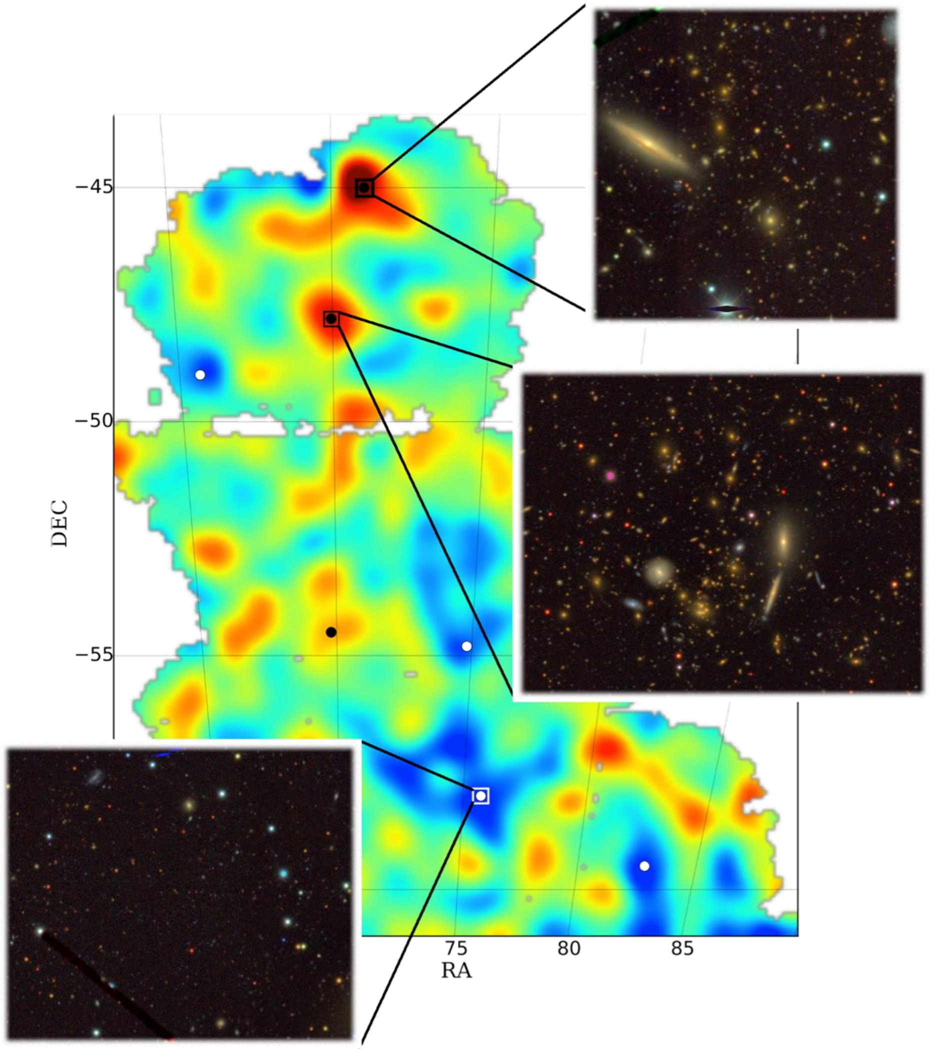


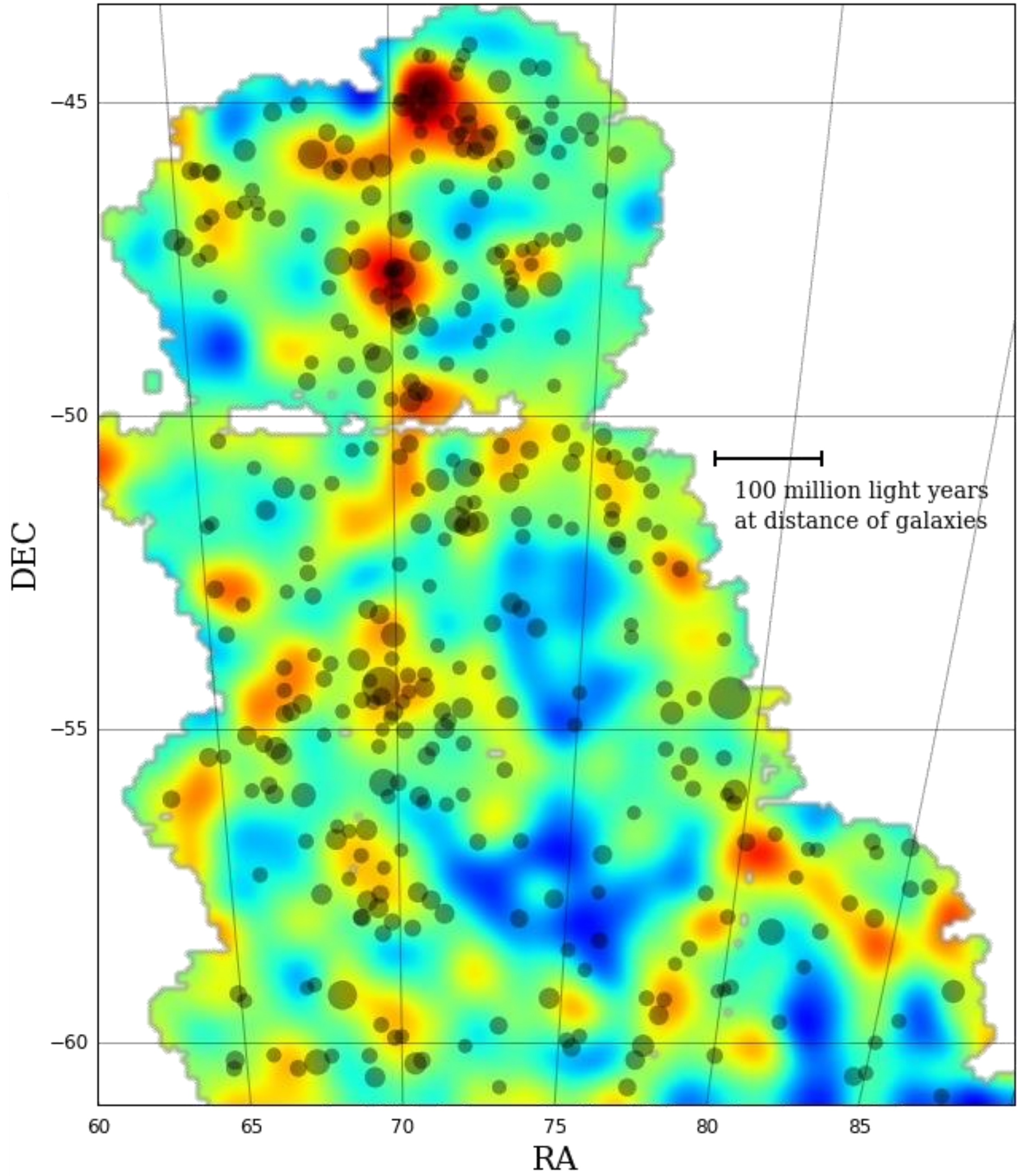




2015 update: DM map from DE survey

Dark Energy Survey:
- large-scale weak lensing studies
  DM forms large filaments

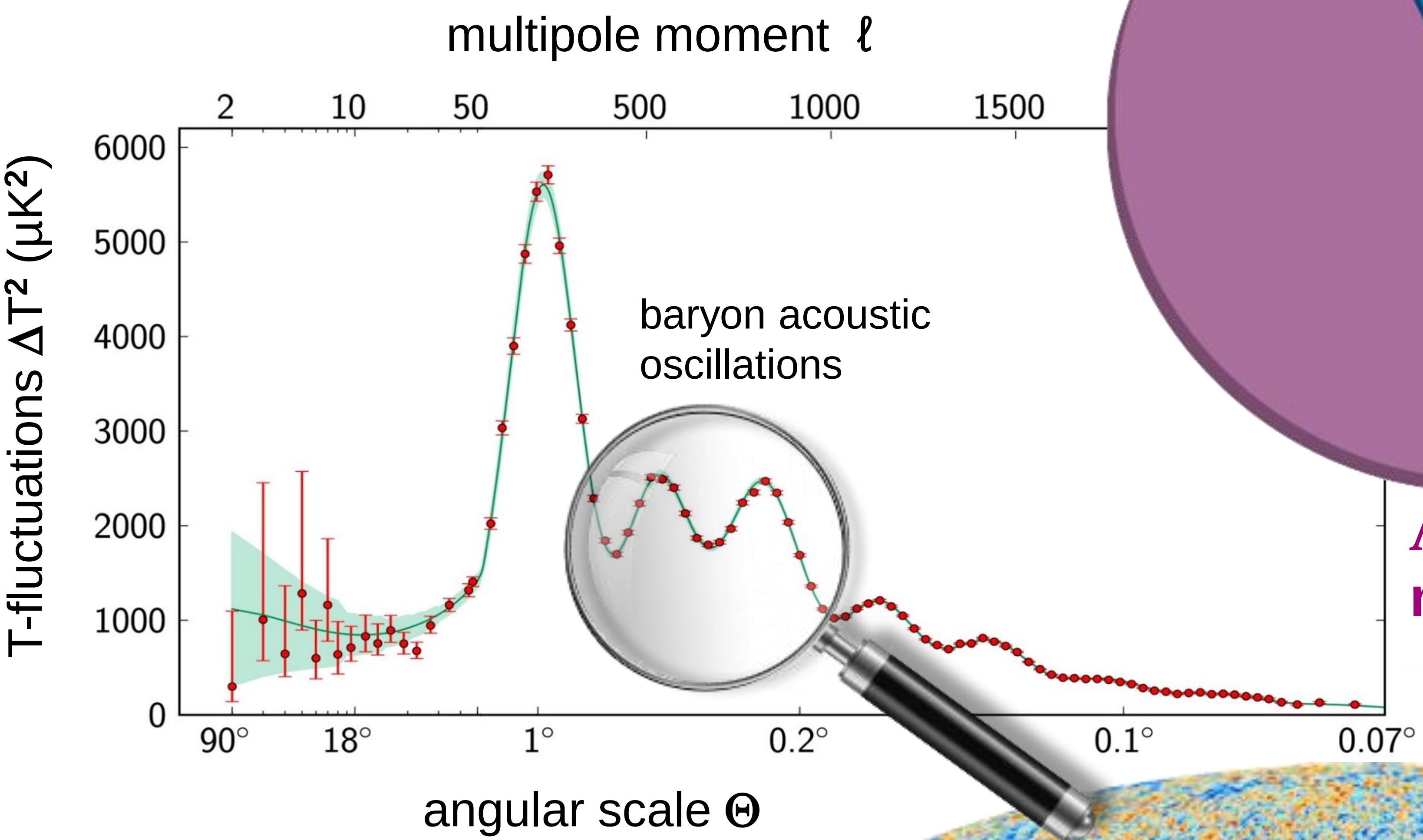


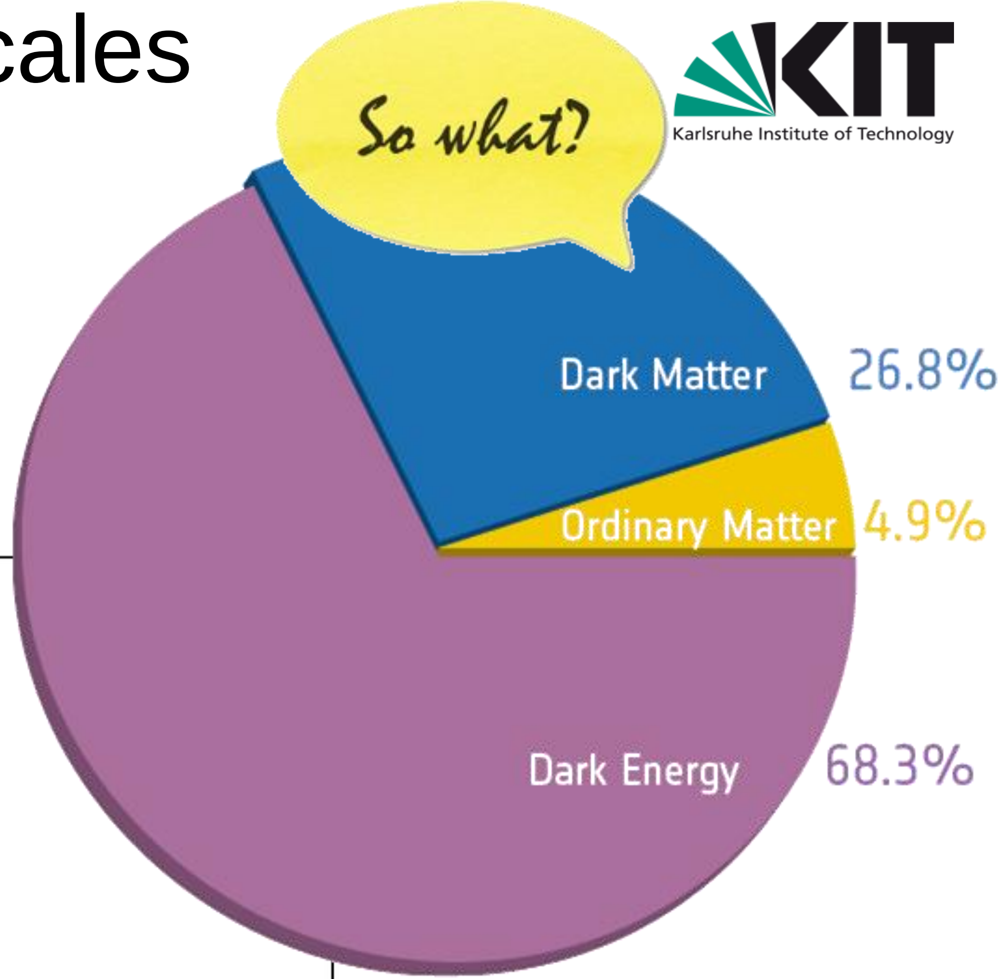


dark matter – cosmological scales

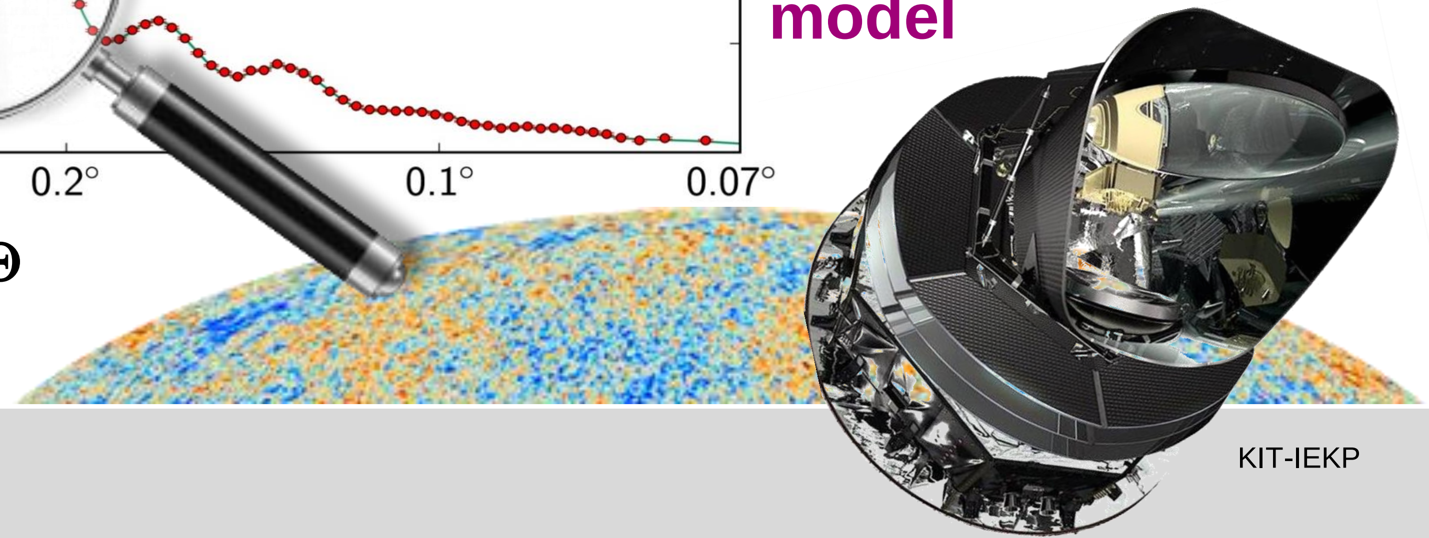
- overall fraction of dark matter

$$\Omega_{DM}\, h^2 = 0.1199 \pm 0.0027$$



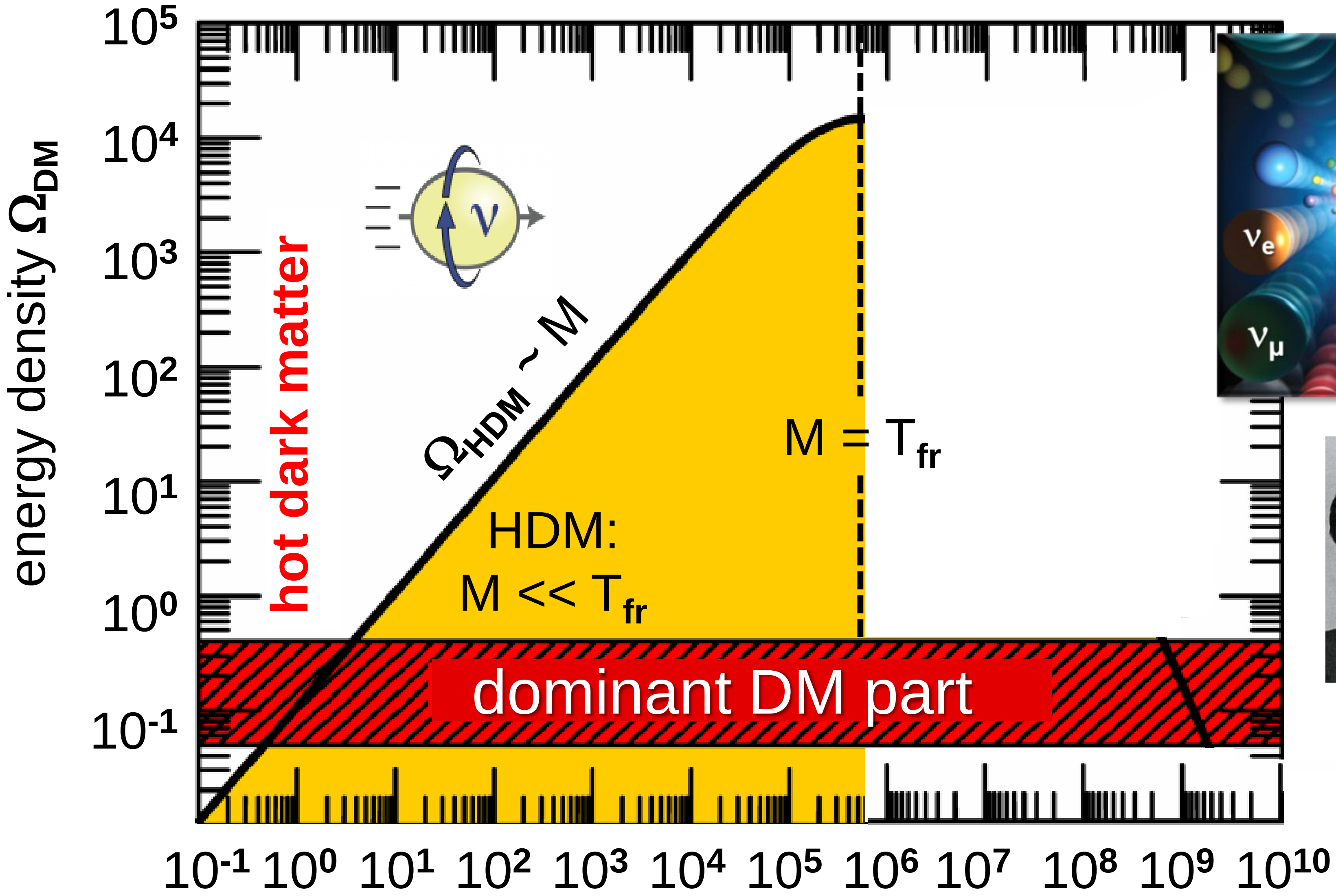


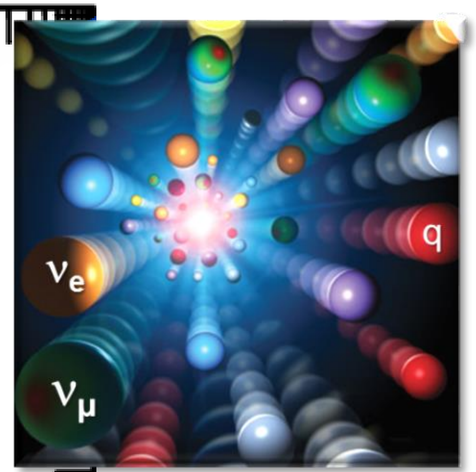
ΛCDM concordance model



Lee-Weinberg curve for HDM & CDM

- **HDM:** relativistic free-streaming after decoupling, no annihilation processes
  thus: $\Omega_{HDM} \sim M$, result: **HDM particle density not reduced**





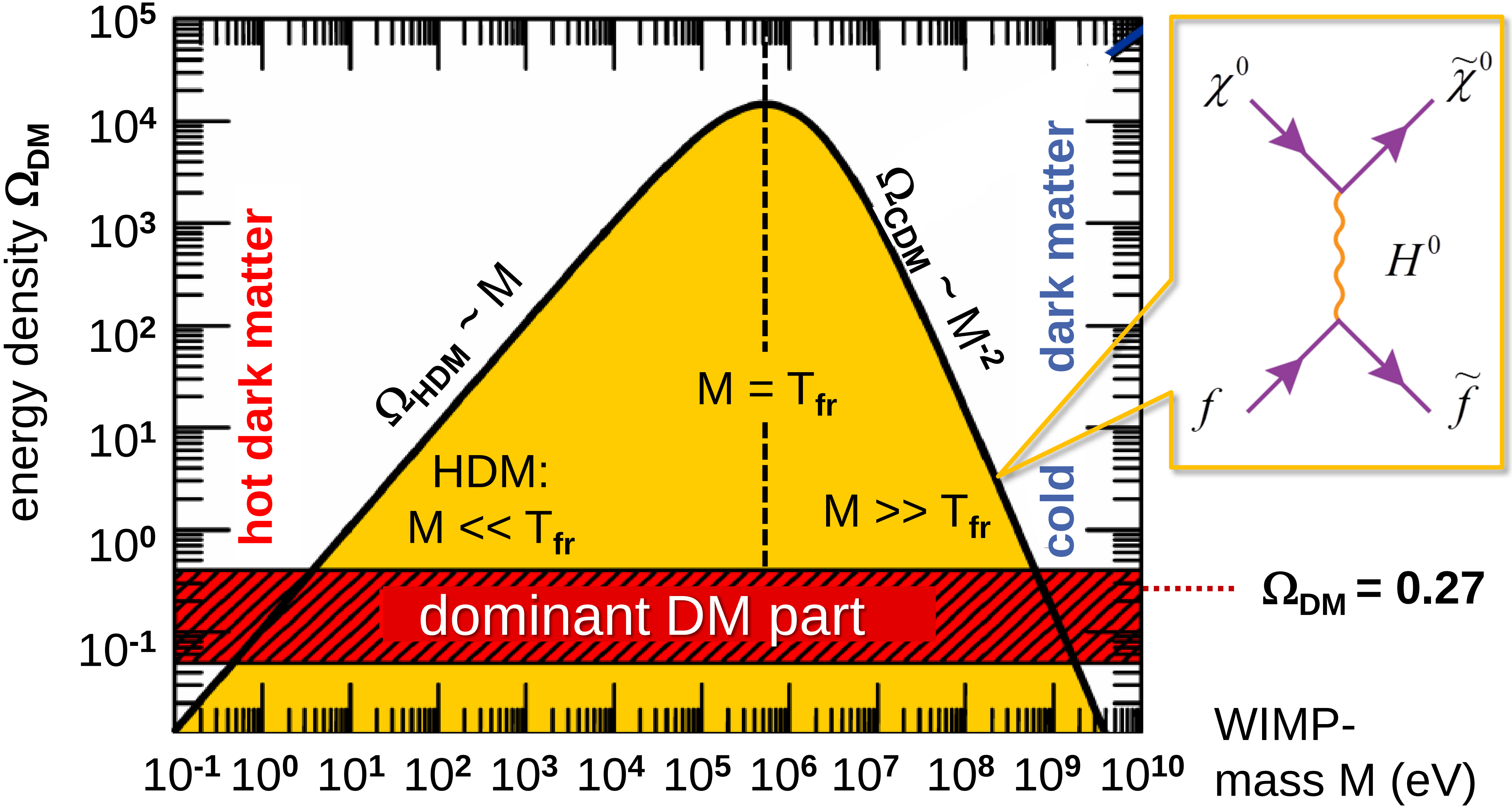
이휘소

Wein-
berg

WIMP-
mass M (eV)

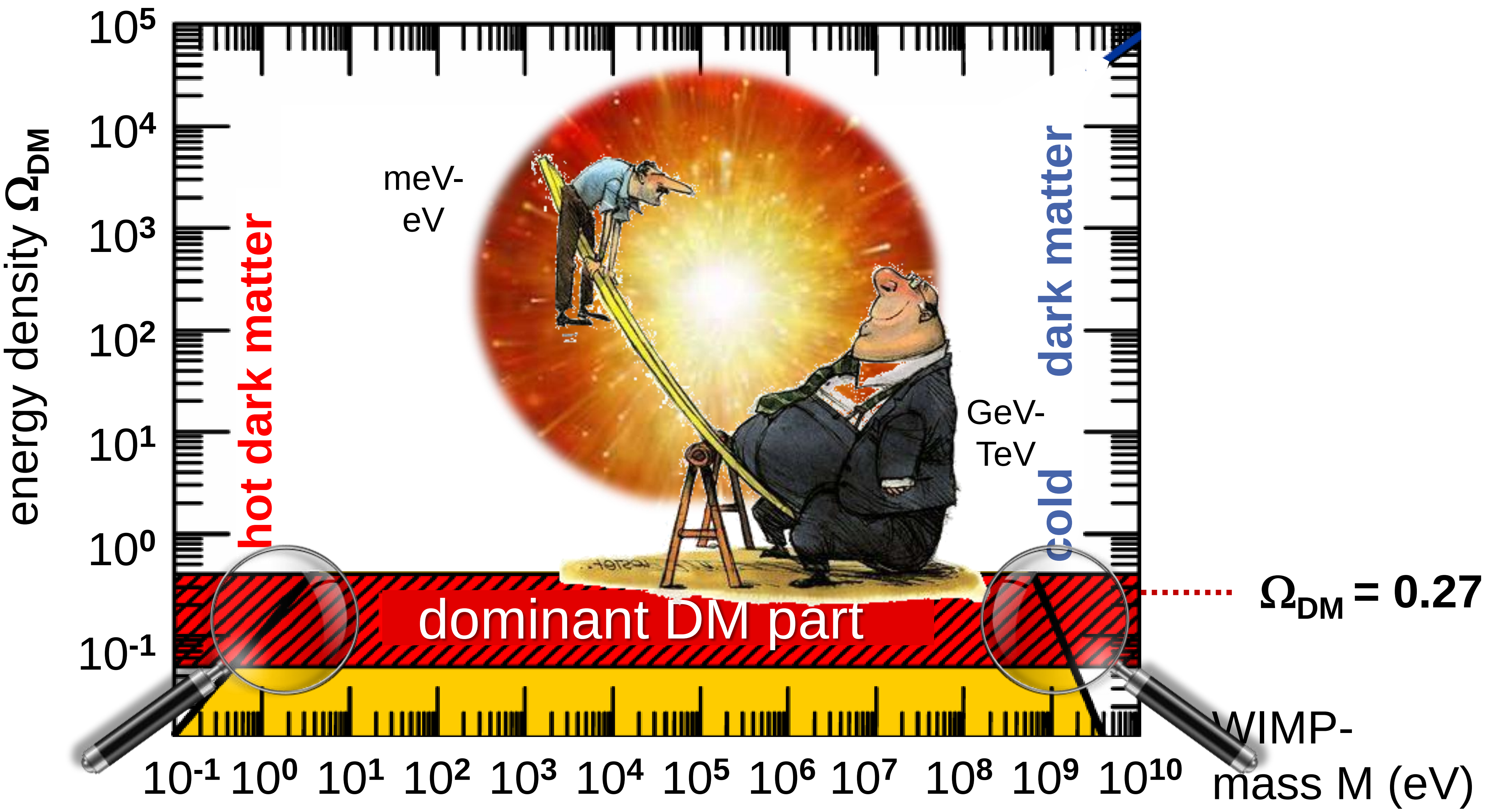
Lee-Weinberg curve for HDM & CDM

- **CDM:** non-relativistic before decoupling, strong annihilation processes with $\sigma_{Ann} \sim M^2$, result: **CDM particle density extremely reduced**

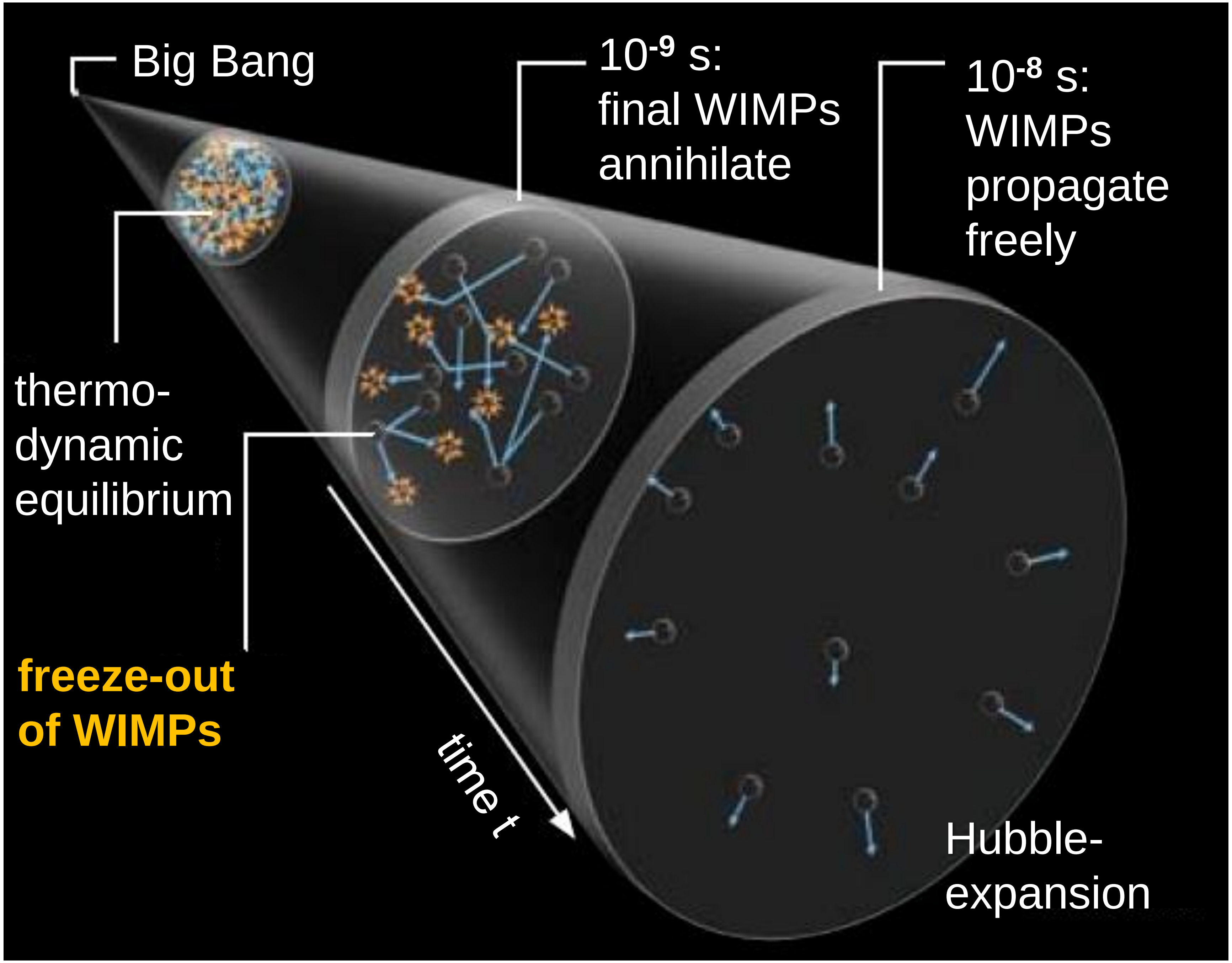


Lee-Weinberg curve for HDM & CDM

- **CDM/HDM:** only two narrow regions remain for thermal relics from Big Bang very light neutrals (meV-eV neutrinos), heavy neutralinos (TeV)

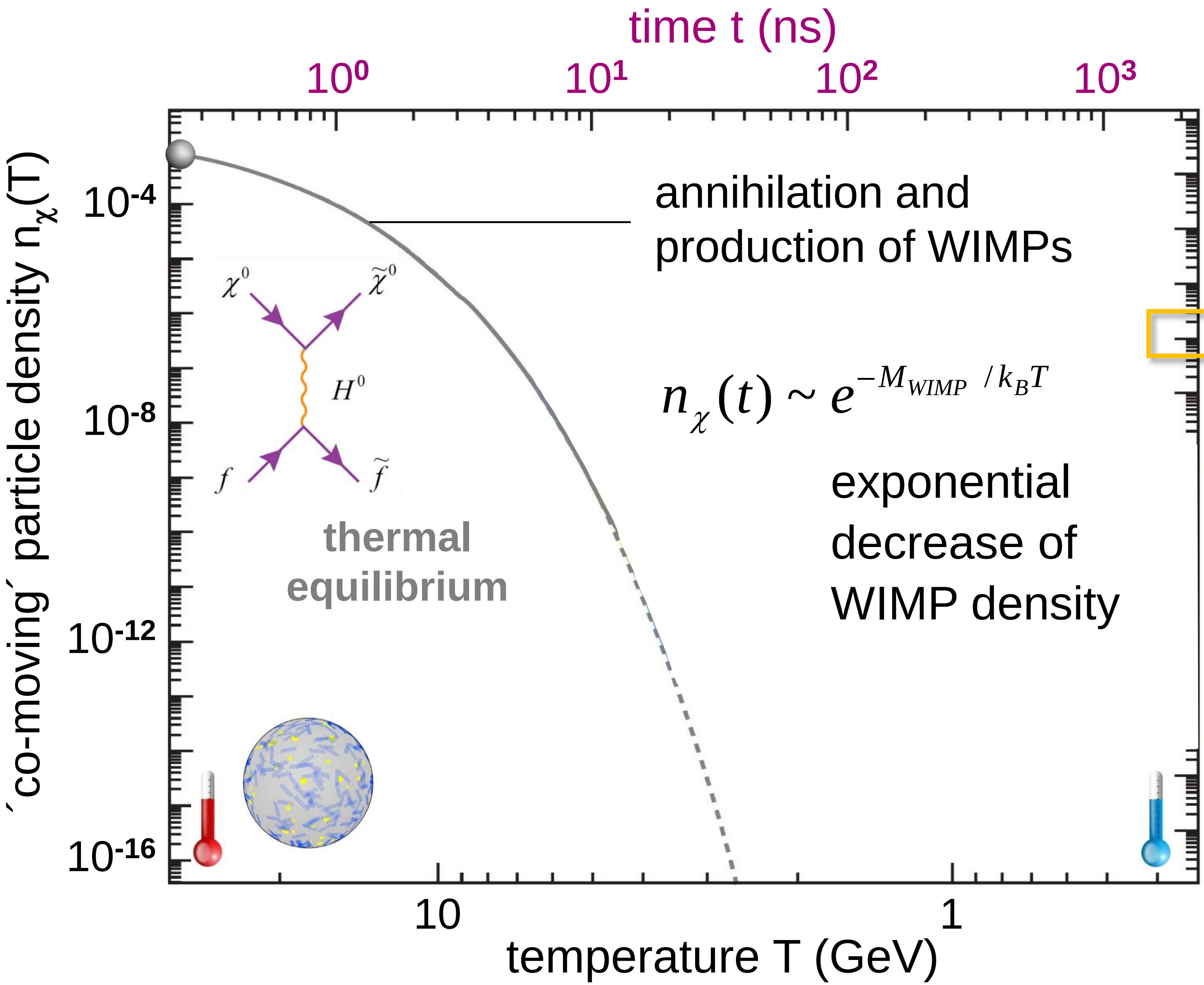


WIMPs – thermal relics of the early universe

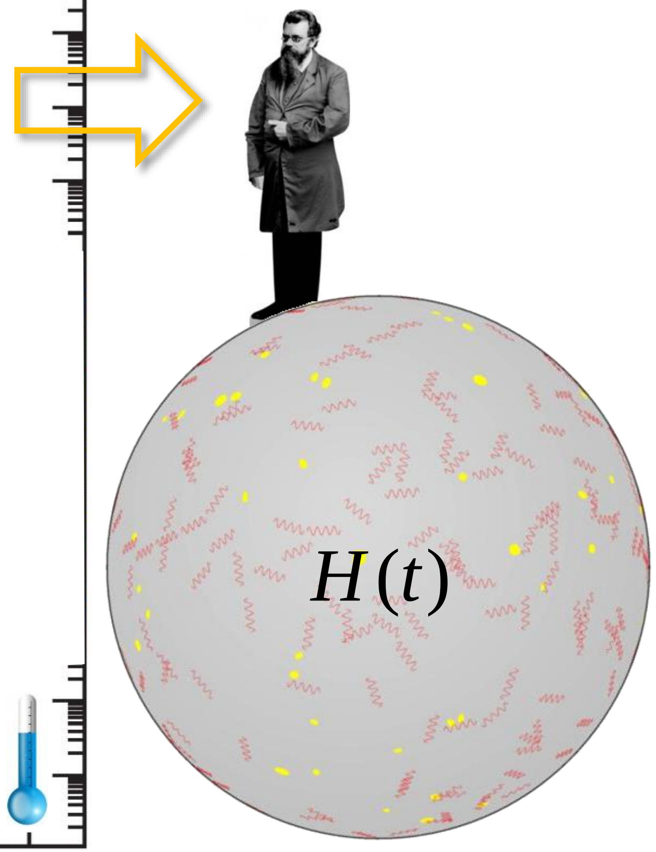


$$T(t) \sim 1 / \sqrt{t}$$

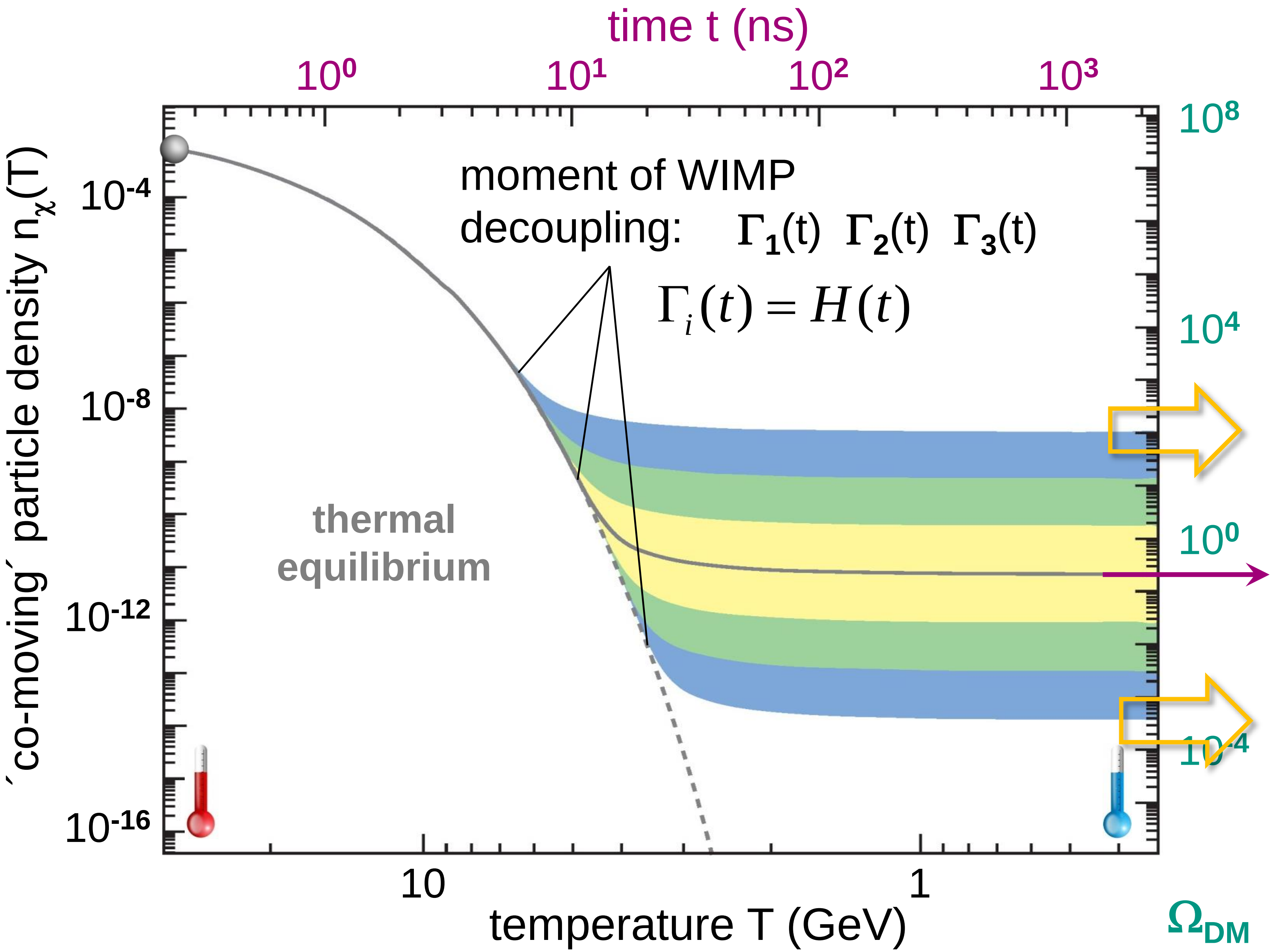
WIMPs in radiation-dominated universe



m_χ = 100 GeV



WIMP decoupling and Ω_{DM}



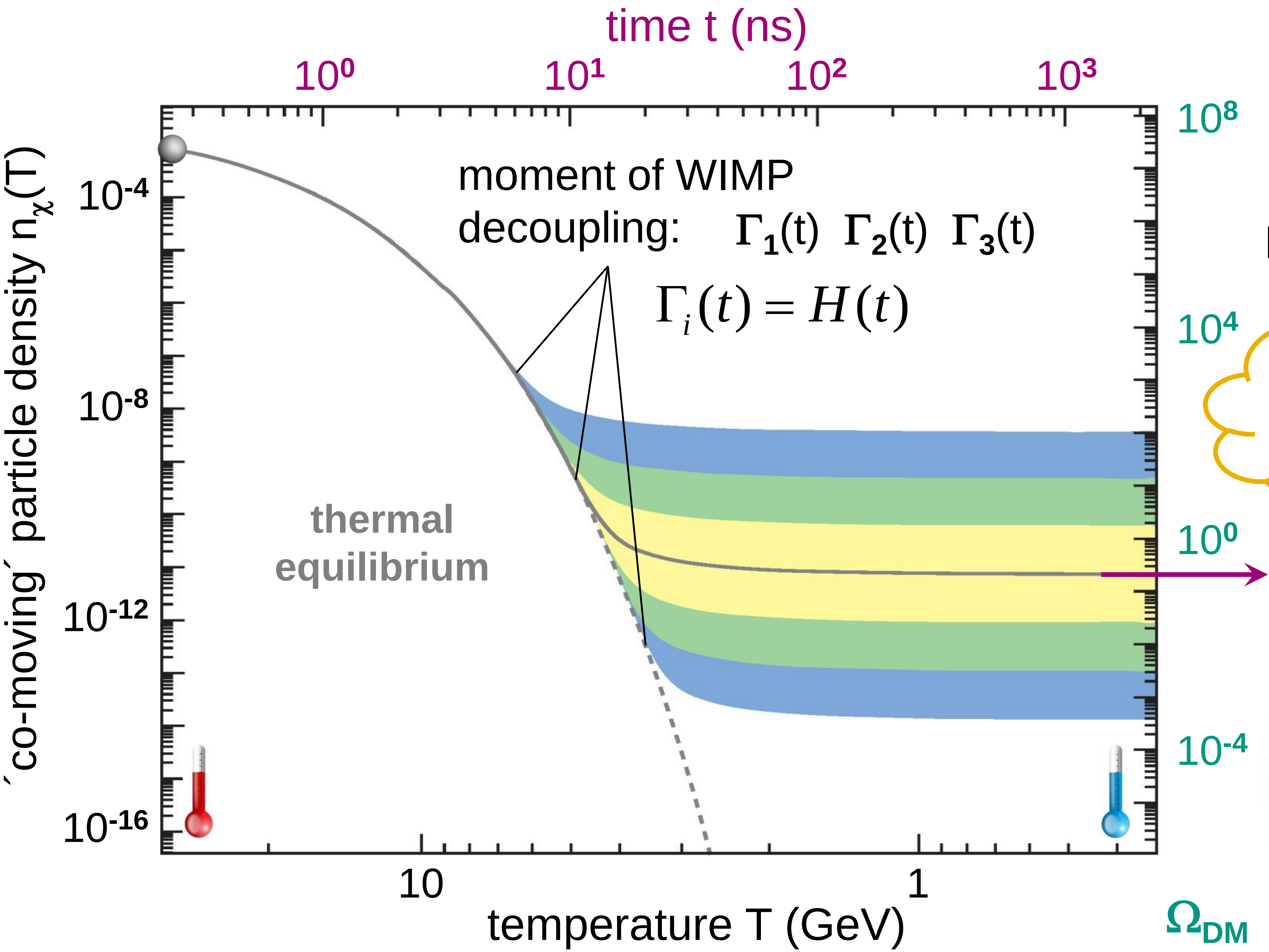
m_χ = 100 GeV

WIMP-density
Ω_{DM} = 100

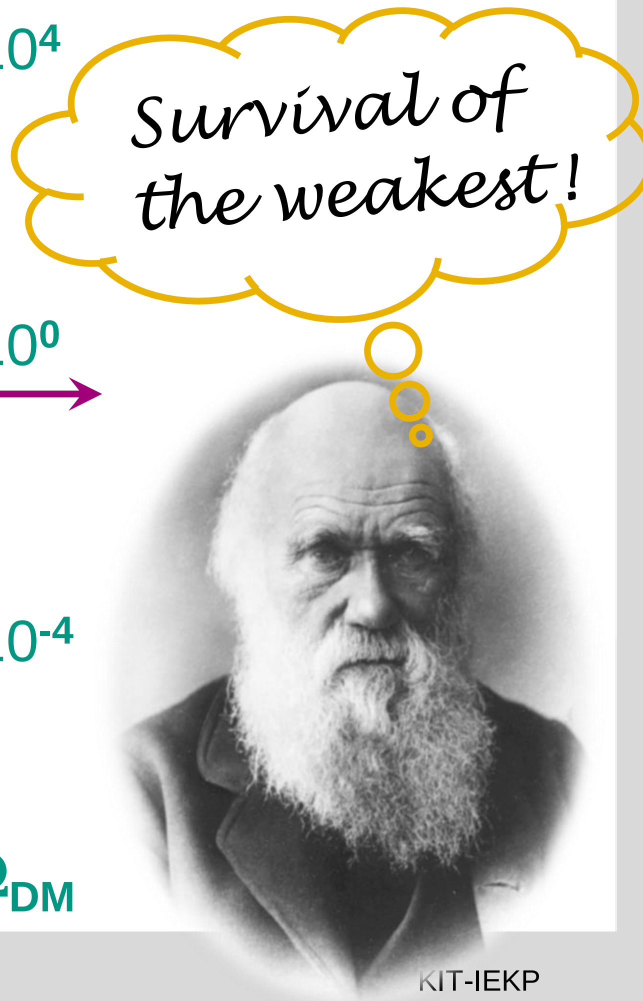
Ω_{DM} = 0.27

WIMP-density
Ω_{DM} = 0.001

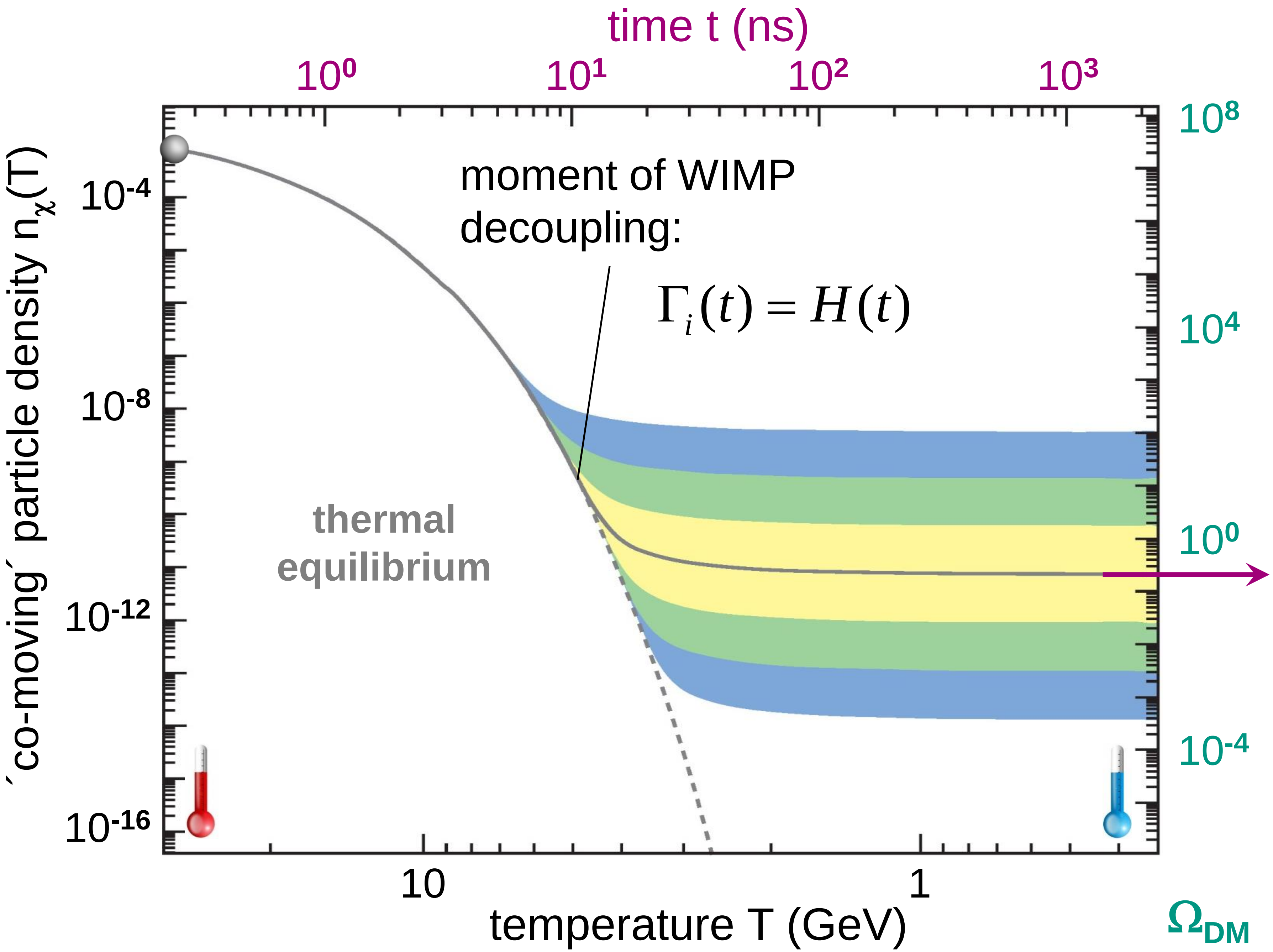
WIMP decoupling to $\Omega_{DM} = 0.27$



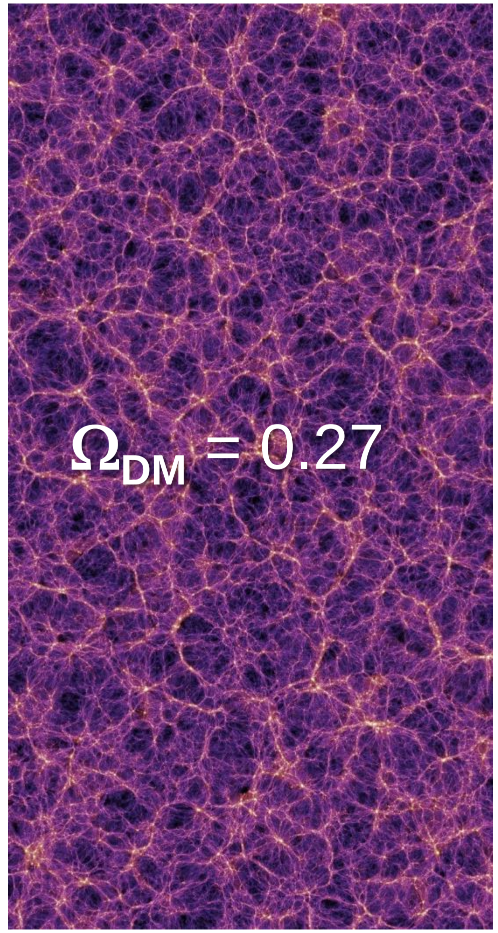
sneutrinos (LH)
Interact too strong



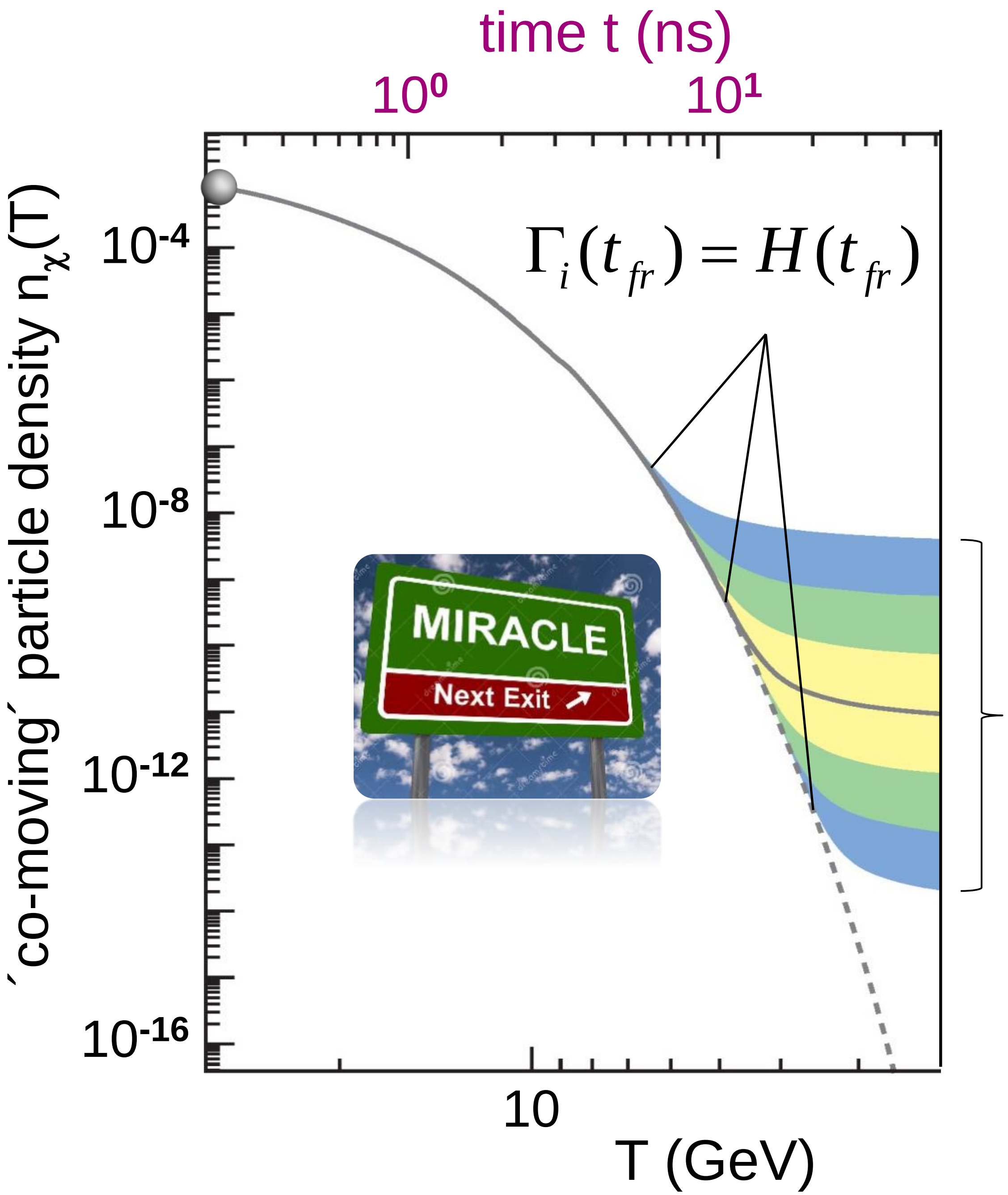
WIMP decoupling to Ω_{DM} = 0.27



m_χ = 100 GeV



WIMP ´miracle´ & annihilation rate



- **the WIMP ´miracle´**:
  WIMP density $\Omega_\chi(0)$ today & σ_{Ann}:

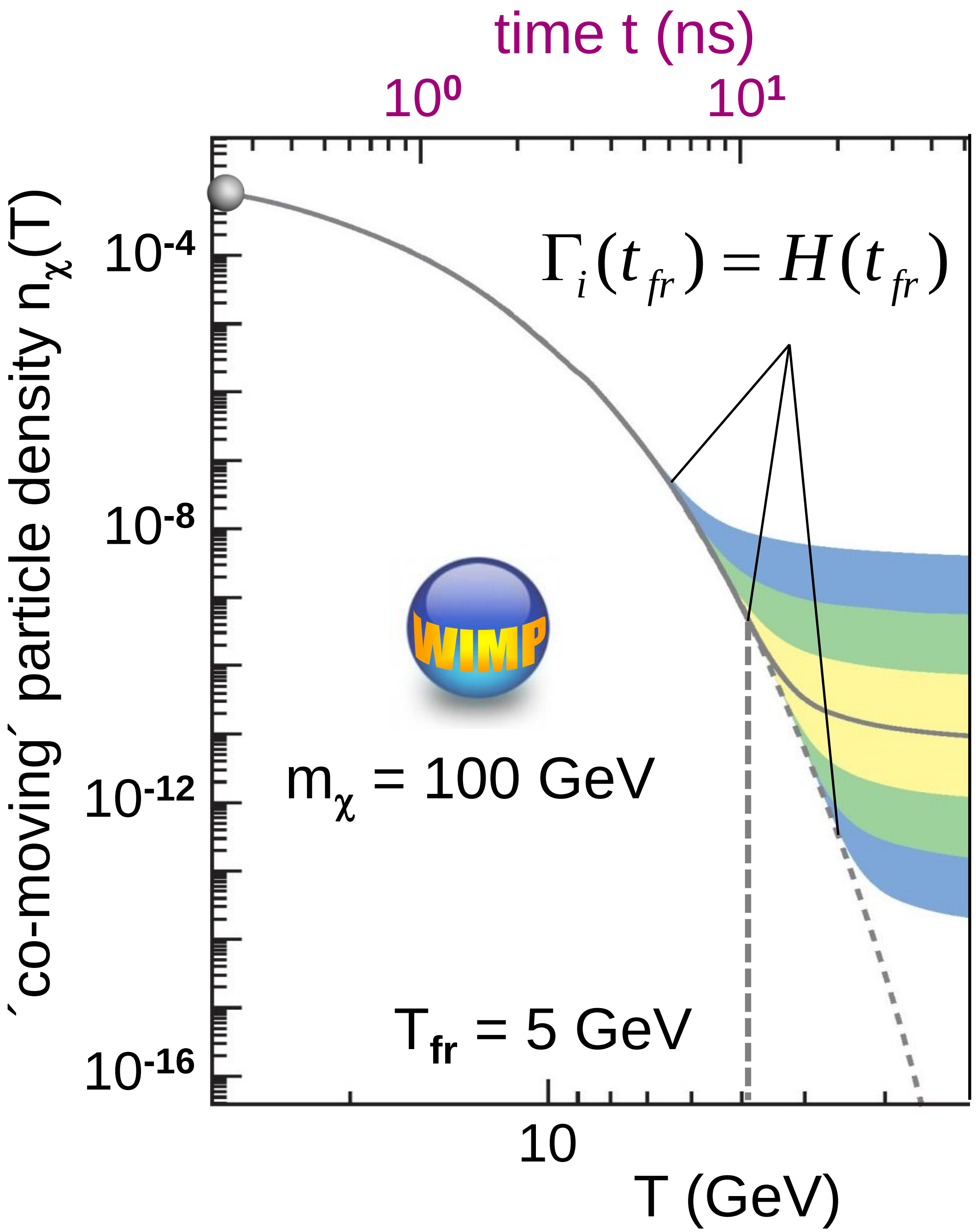
$$\Omega_\chi(0) \sim \frac{10^{-25}}{\langle \sigma_{Ann} v \rangle} cm^3 s^{-1}$$

for **v ~ 0.3 c** at WIMP decoupling
one obtains for Ω_χ ~ 0.27

$\sigma_{Ann} \sim 10^{-36}\ cm^2$

⇨ **weak interaction**

WIMP decoupling – non-relativistic



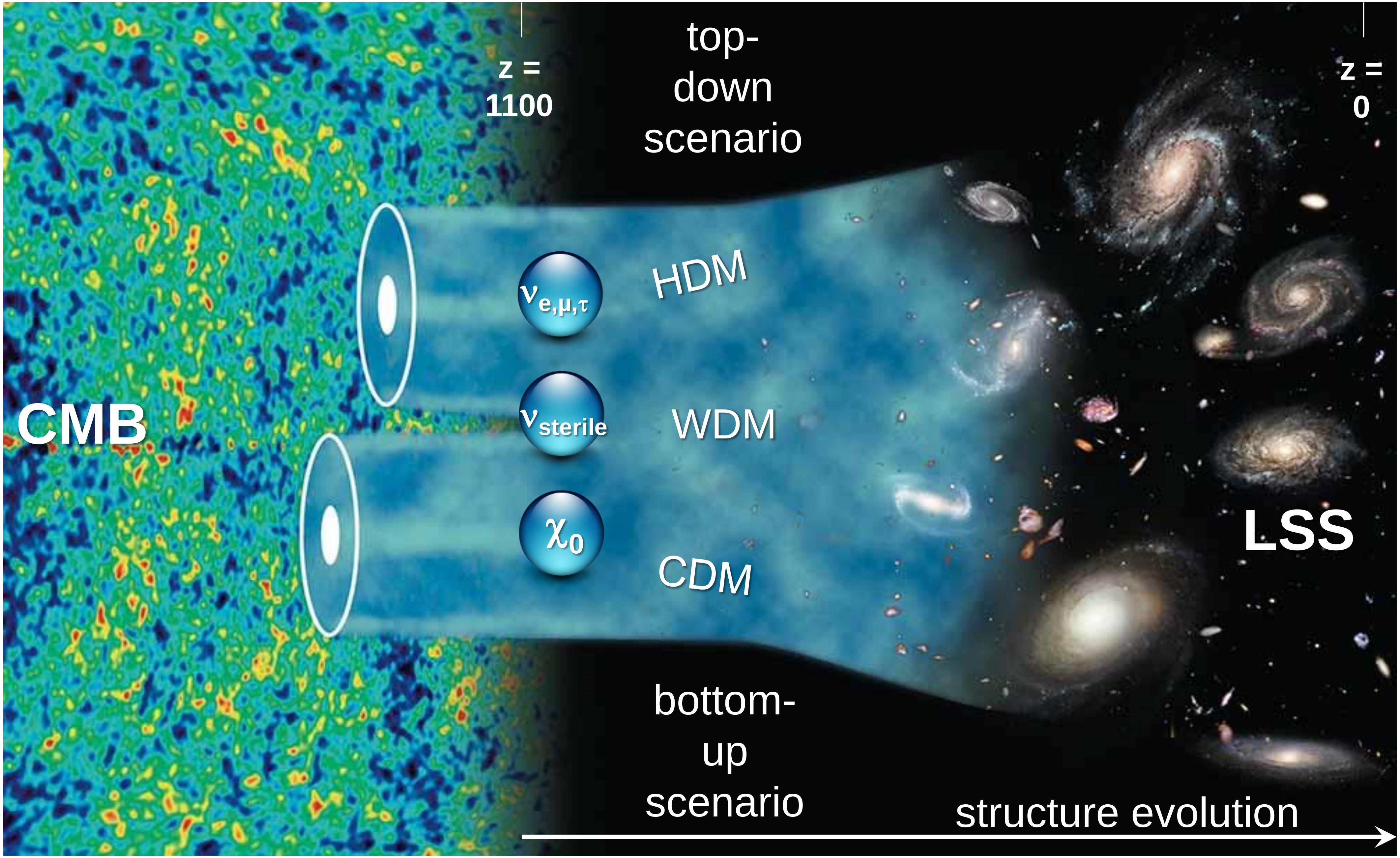
- time of WIMP-freeze-out: t ~ few ns
  non-relativisitic propagation

$$x_{fr} = \frac{M_\chi}{T_{fr}} \sim 20 \qquad T_{fr} \sim \frac{M_\chi}{20}$$

CDM: $M_\chi c^2 \gg k_B T_{\text{freeze out}}$

- WIMPs after freeze-out act as
  CDM (cold dark matter)

structure formation with CMD, WDM, HDM



dark matter: hot, warm or cold?

Karlsruhe Institute of Technology

- comparison of **DM-models** with observations ($<\rho_{DM}> \sim 1$ keV/cm³):
  wash-out on different length scales ($\lambda_{free-streaming}$)

Hot Dark Matter HDM	Warm Dark Matter WDM	Cold Dark Matter CDM
particles: ***active*** neutrinos $\nu_{e,\mu,\tau}$ m ~ 0.05 – 2 **eV**	particles: ***sterile*** neutrinos ν_s m ~ 1 – 20 **keV**	particles: SUSY neutralinos χ^0 m ~ 10 – 1000 **GeV**
number density: N(active): 339/cm³ decoupling: T = 2 – 3 MeV T/m ~ $10^6 – 10^7$	number density: N(sterile): ~0.1-1/cm³ decoupling: none, produced via ν-oscillations	Number density: N(χ^0): 10^{-7}-10^{-9}/cm³ decoupling: T = 0.5 – 50 GeV T/m ~ 1/20
LSS implication: wash-out on scales **λ < 1 Gpc**	LSS implication: wash-out on scales **λ < 100 kpc**	LSS implication: wash-out on scales **λ < 0.1 pc**

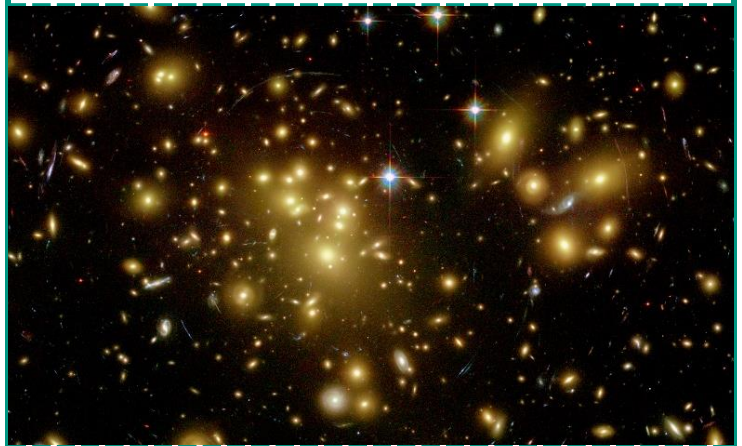
dark matter: hot, warm or cold?

- comparison of **DM-models** with observations ($<\rho_{DM}> \sim$ 1 keV/cm³):
  wash-out on different length scales ($\lambda_{\text{free-streaming}}$)

Hot Dark Matter HDM

particles:

active neutrinos $\nu_{e,\mu,\tau}$
m ~ 0.05 – 2 **eV**



LSS implication:

wash-out on scales
λ < 1 Gpc

Warm Dark Matter WDM

particles:

sterile neutrinos ν_s
m ~ 1 – 20 **keV**

LSS implication:

wash-out on scales
λ < 100 kpc

Cold Dark Matter CDM

particles:

SUSY neutralinos χ^0
m ~ 10 – 1000 **GeV**

LSS implication:

wash-out on scales
λ < 0.1 pc

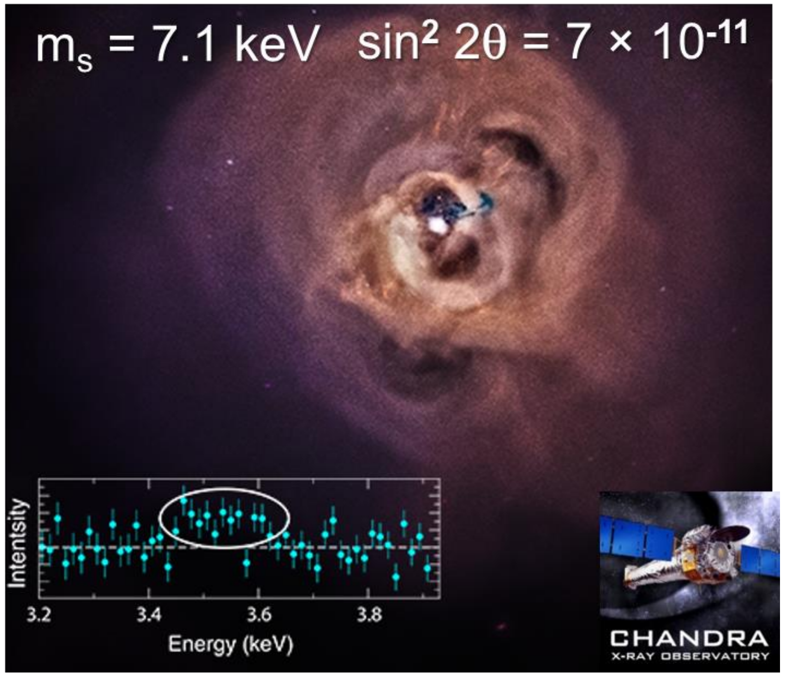
intermission: keV-scale sterile neutrinos

- **keV-scale sterile neutrinos** would be produced via non-thermal processes and act as CDM/WDM in evolustion of LSS

astrophysics

a faint X-ray line at 3.5 keV in clusters?

(Bulbul et al 2014)



Warm Dark Matter WDM

particles:

sterile neutrinos ν_s

m ~ 1 – 20 **keV**

LSS implication:

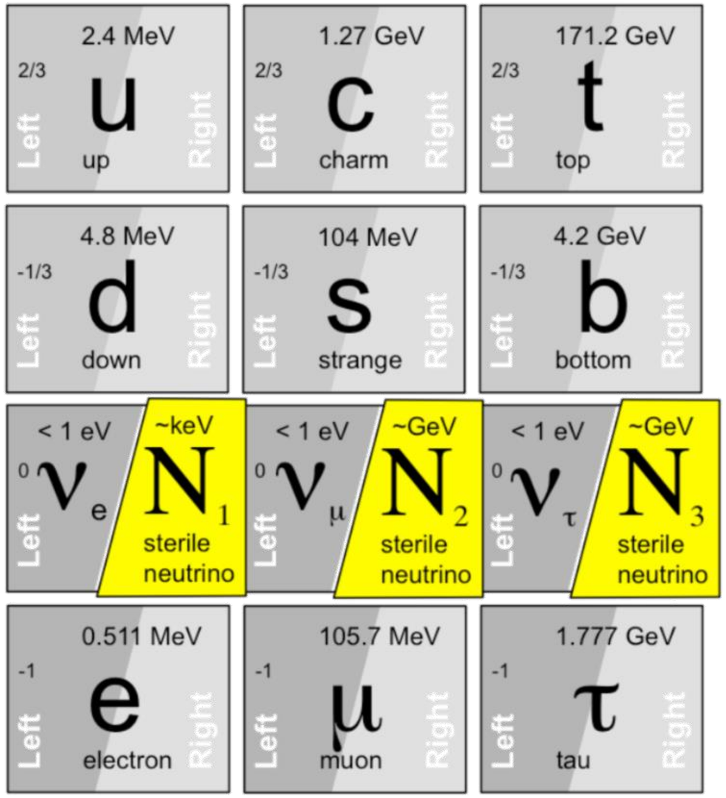
wash-out on scales

λ < 100 kpc

particle physics

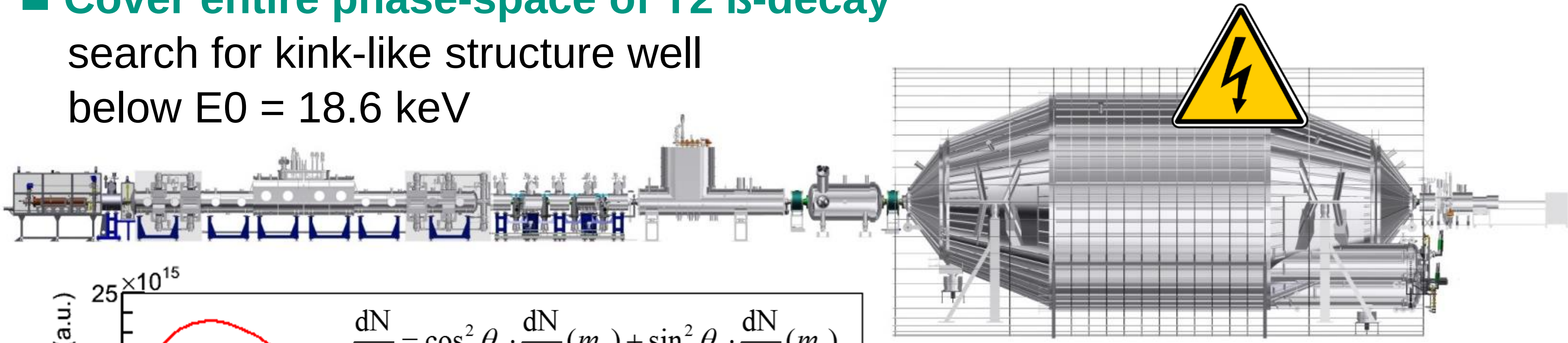
νMSM – a SM extension

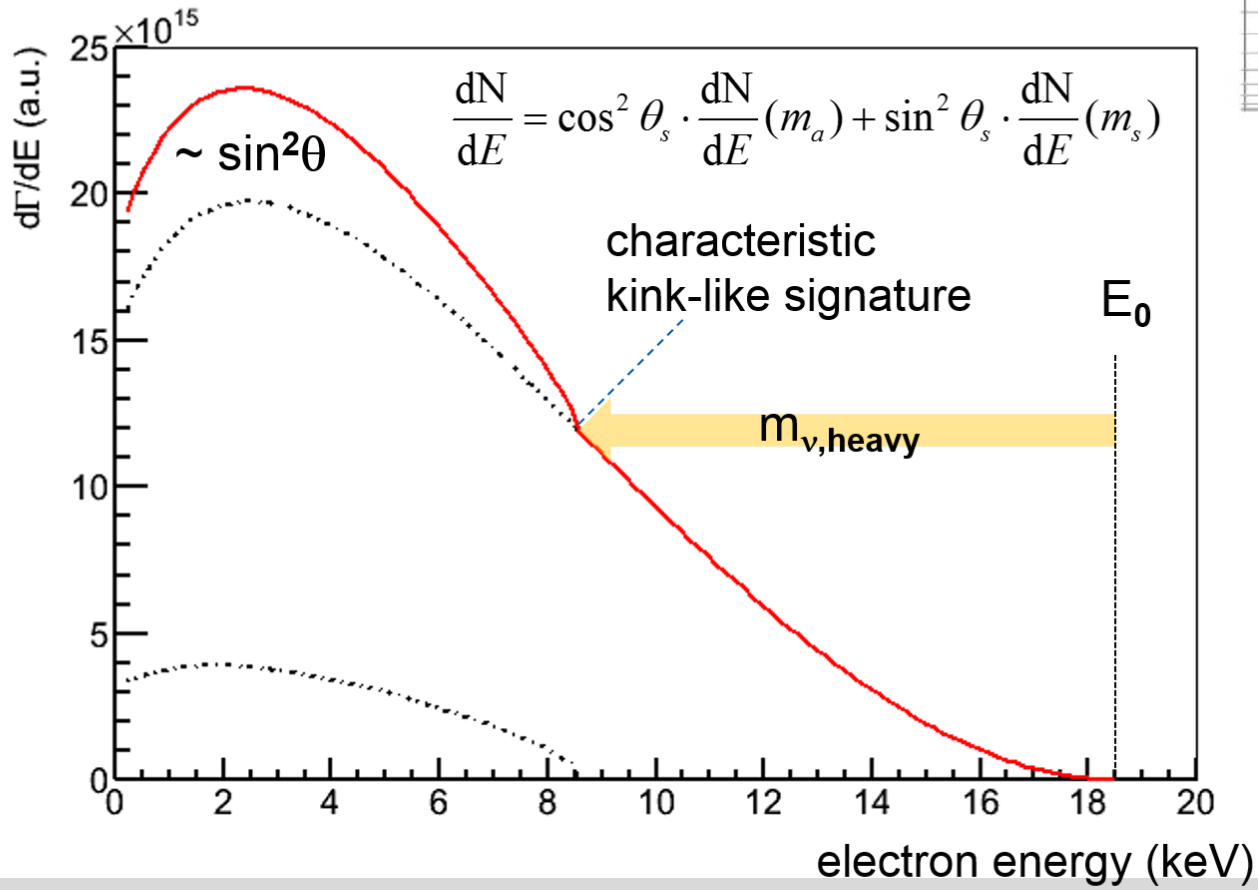
(Shaposhnikov et al 2013)



KATRIN – a novel detector system for ν_s

- **Cover entire phase-space of T2 ß-decay**
  search for kink-like structure well
  below E0 = 18.6 keV





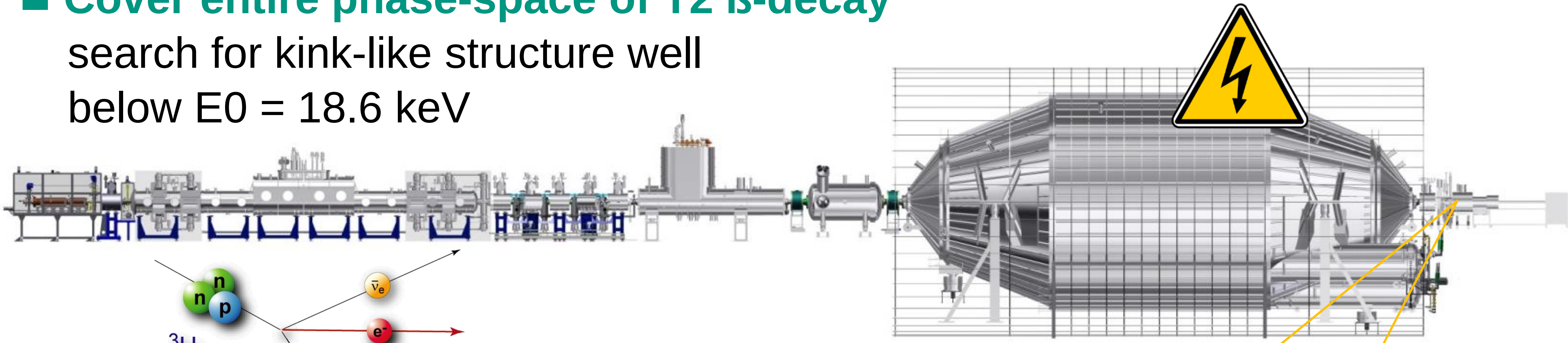
- shape modification by keV-mass sterile neutrino with mass m_s

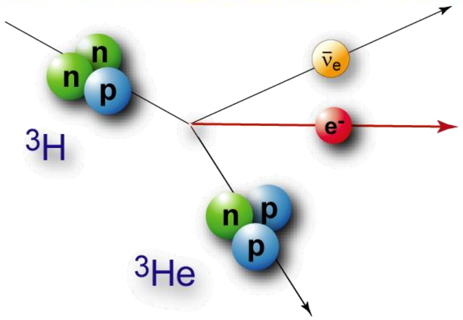
KATRIN – a novel detector system for WDM

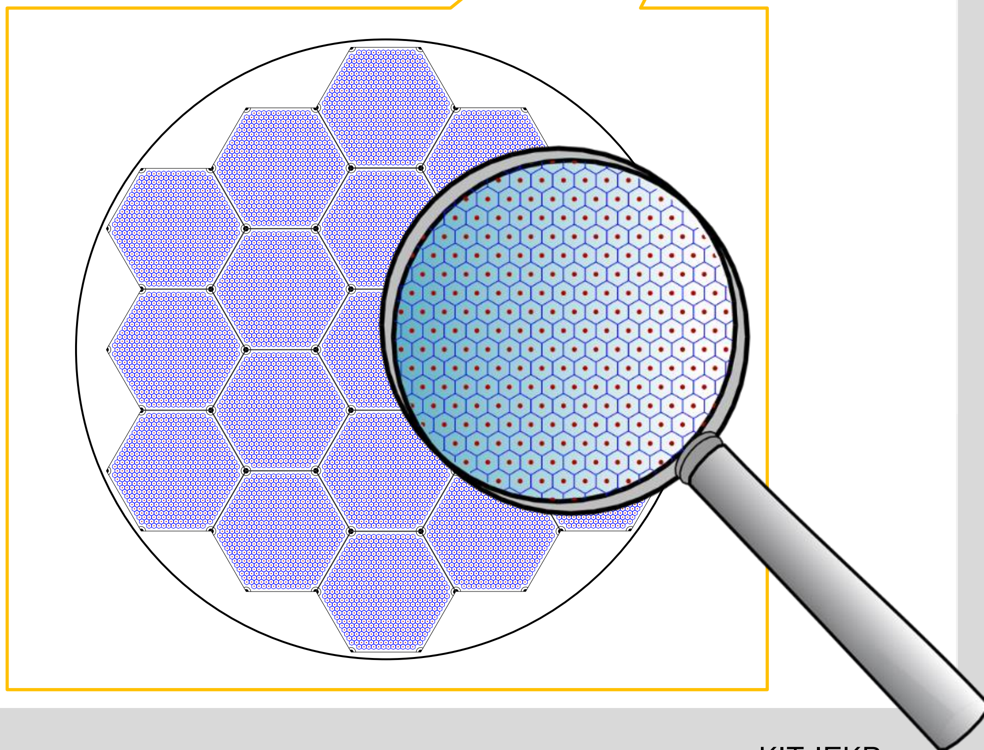
Karlsruhe Institute of Technology

- **Cover entire phase-space of T2 ß-decay**

  search for kink-like structure well below E0 = 18.6 keV





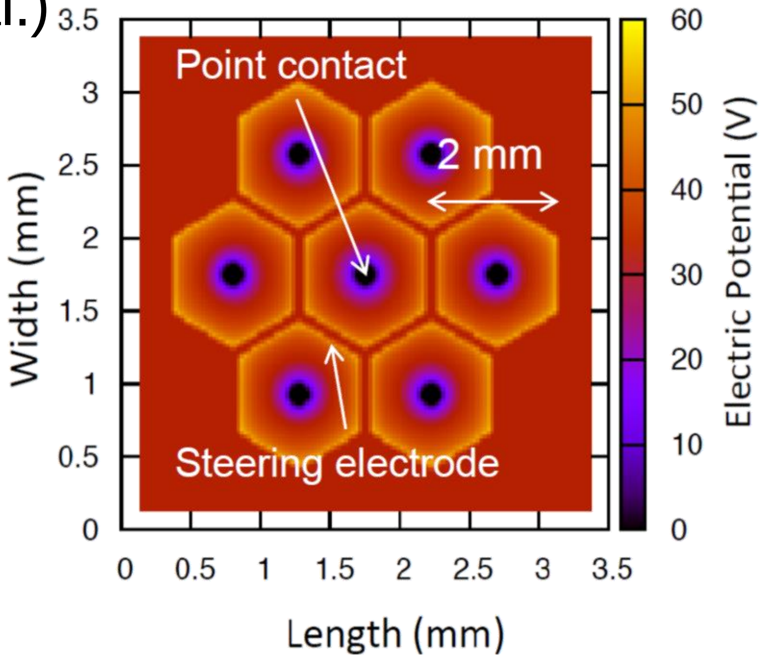


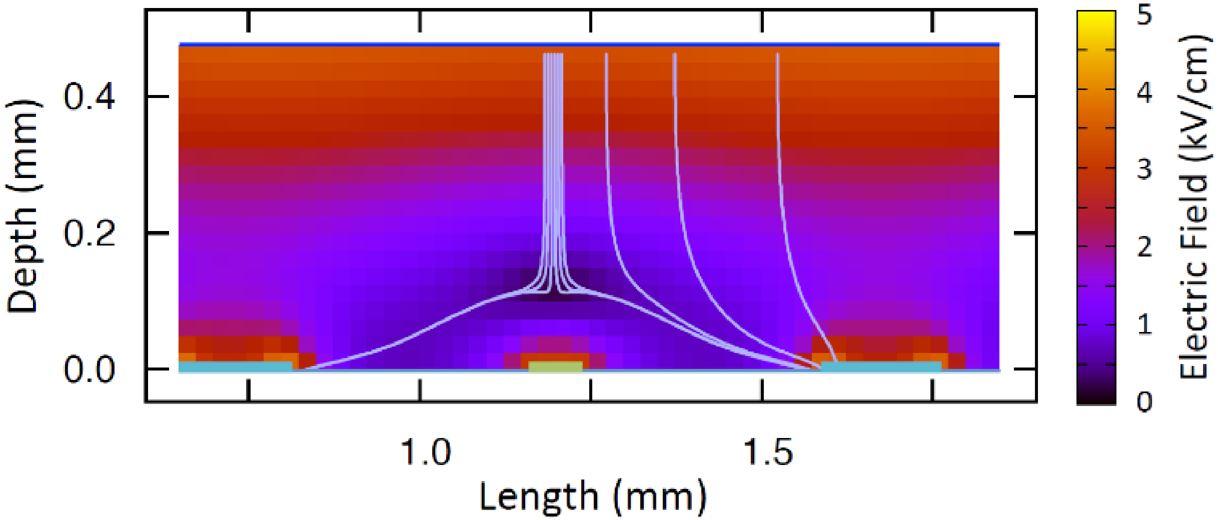
- main spectrometer operated at variable retarding potential (0-18.6 keV)
  huge signal rates $\mathcal{O}(10^{10}$ cps)

- need detectors with energy resolution of ΔE ~ 300 eV for kink identification

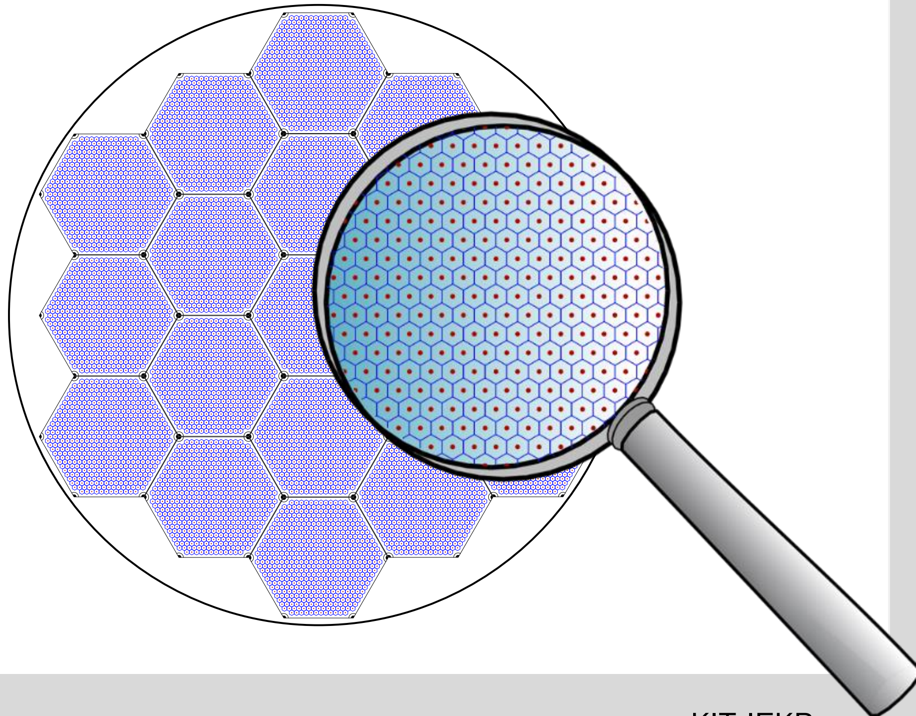
TRISTAN – R&D on detector technology

- **TRISTAN** – **TR**itium beta decay **I**nvestigation on **S**terile **T**o **A**ctive **N**eutrino mixing (S. Mertens et al.)





- promising **differential read-out** technology:
  p-type point contact detectors array with 10^4 pixels

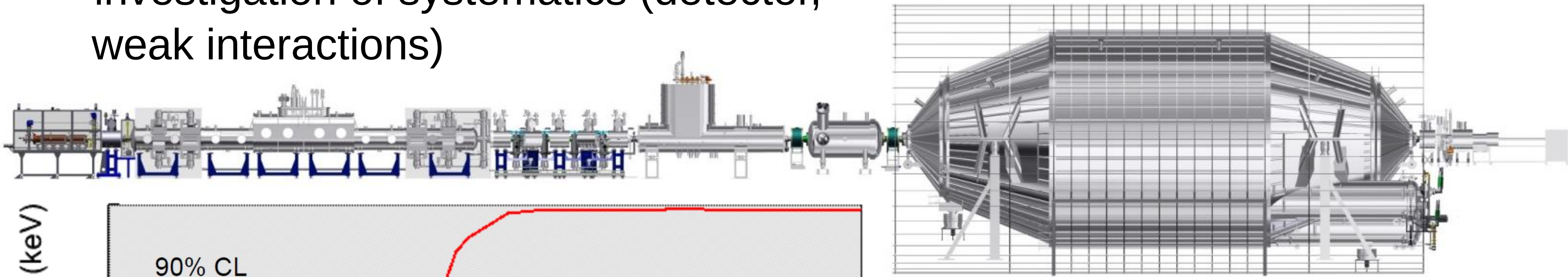


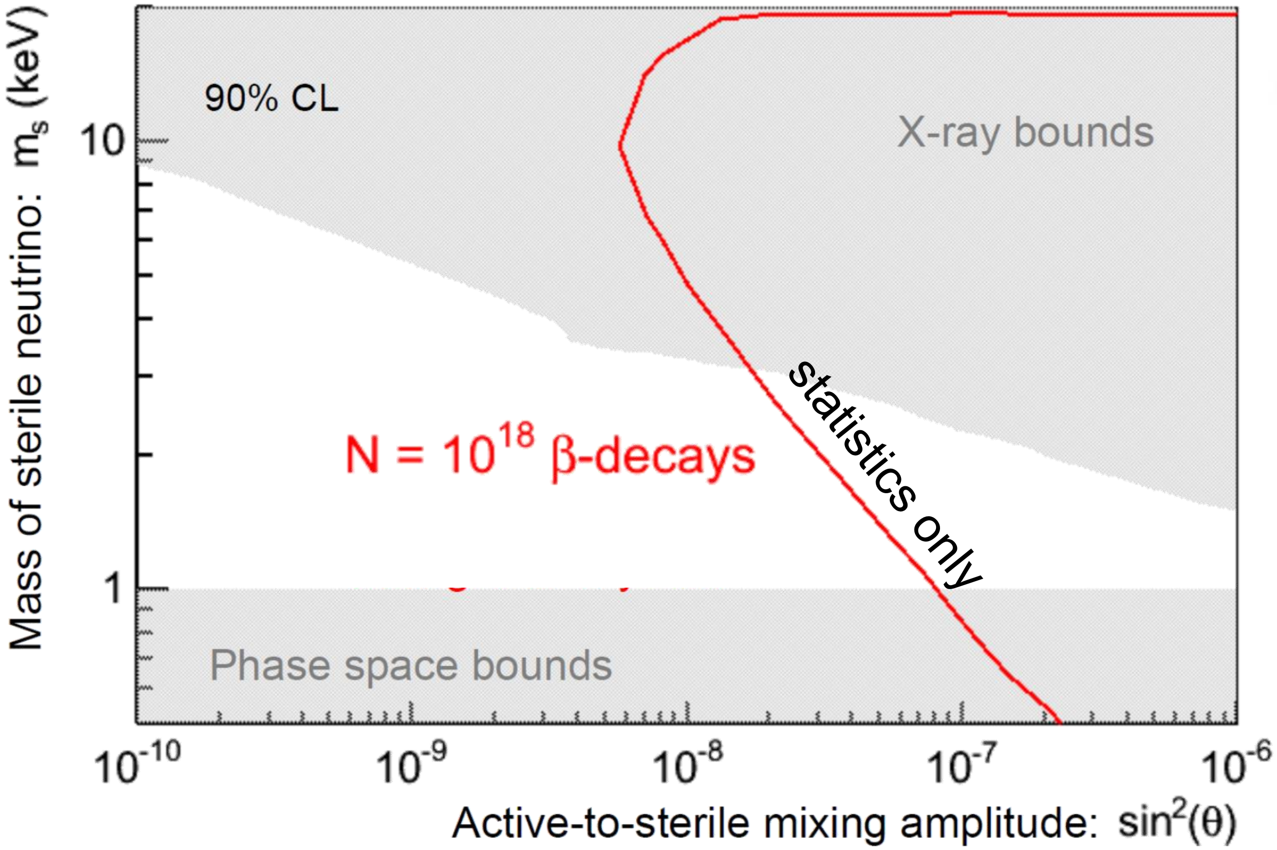
KATRIN – sensitivity to keV-scale sterile ν´s

Karlsruhe Institute of Technology

■ sensitivity estimates for 3 full KATRIN years

- investigation of systematics (detector, weak interactions)





wavelet approach