Markus Brugger asked me originally to give a "Big Picture talk"

Particle Physics Questions: Future Insights from CERNs' Fixed Target and Collider Experiments

There are very good balanced big picture talks, reflecting the European Particle Physics Strategy Update (EPPSU) recommendations:

Shaping the Future of Particle Physics:

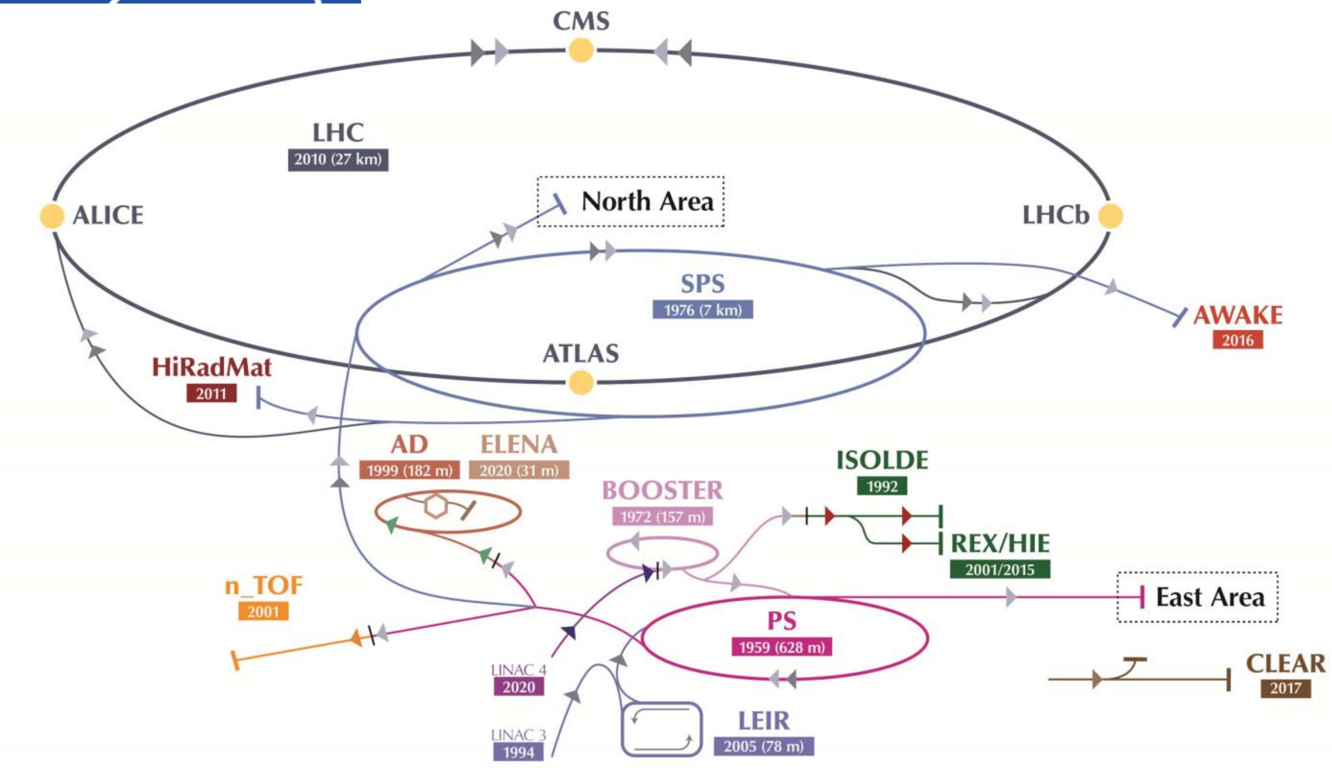
(CERN Academic Training Lecture Series)

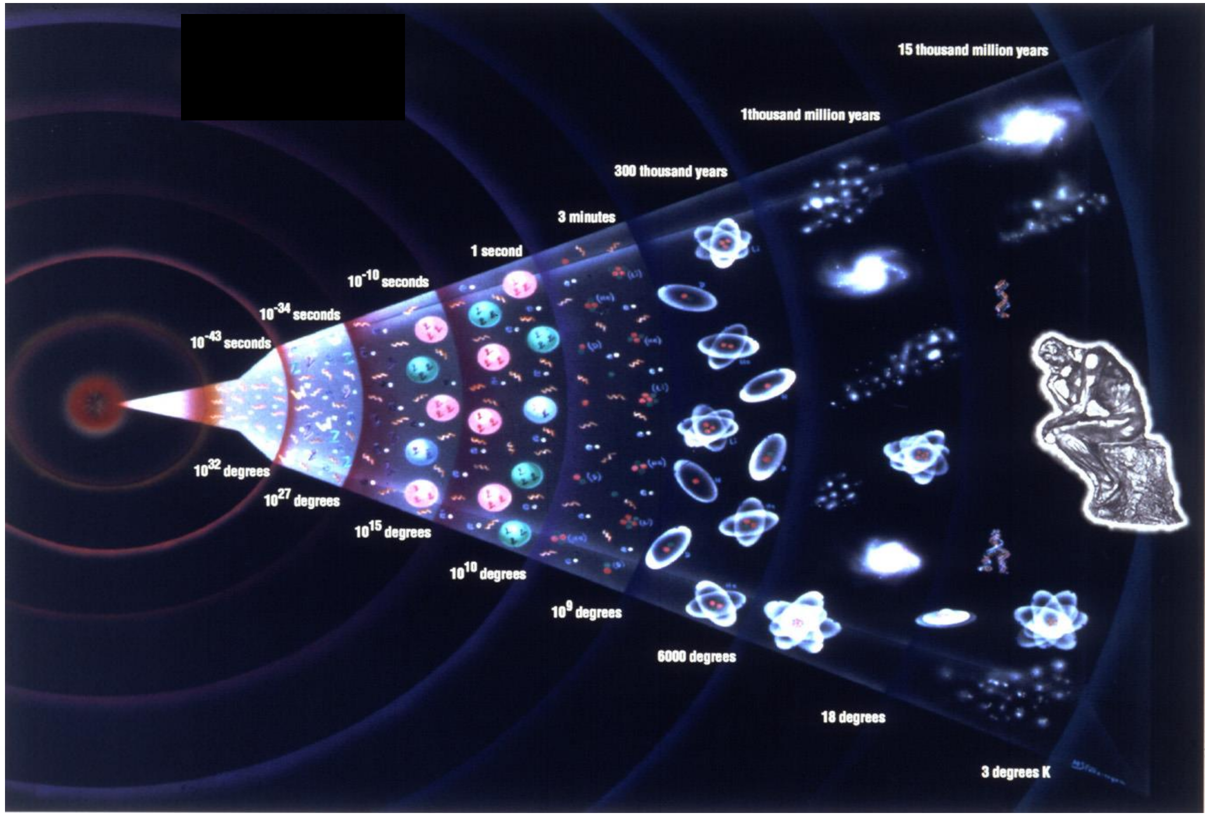
- Theory[1] Keith Ellis,
- Experiment[2] Paris Sphicas
- Accelerators[3] Frank Zimmermann

1 https://www.youtube.com/watch?v=tEt542BipsY
2 https://www.youtube.com/watch?v=cYyOHqupRDU
3 https://www.youtube.com/watch?v=qHe79o_-lzg

I focus instead on one recurrent theme

Space-based science meets accelerator-based science at CERN

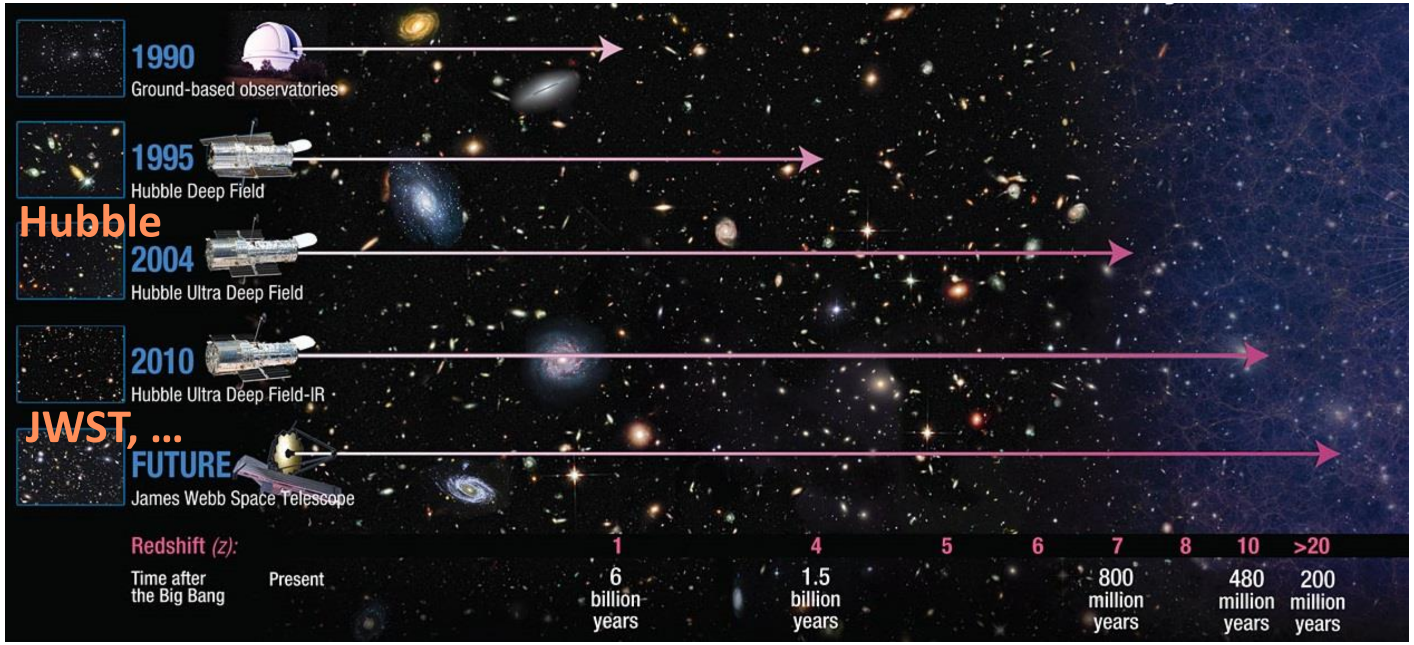


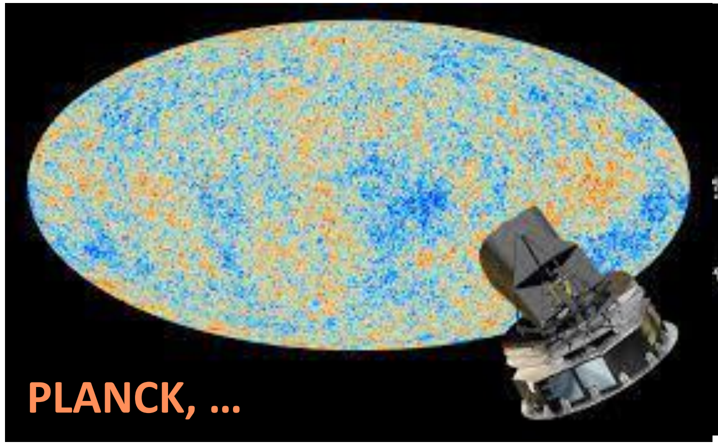


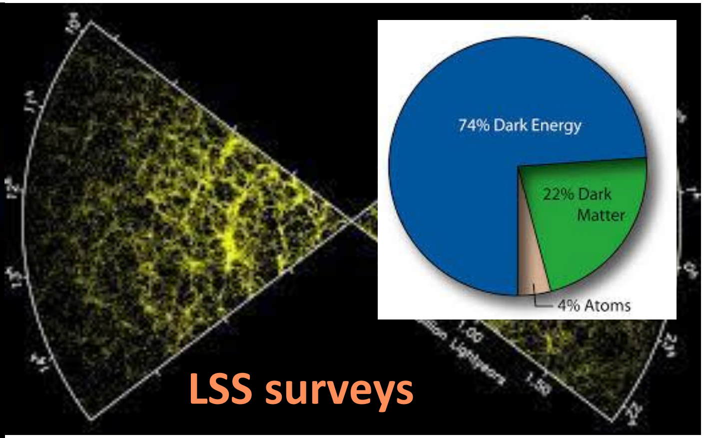
Urs Achim Wiedemann

JAPW Joint Accelerator Performance Workshop, CERN, 7 Dec 2022

Space-based observatories for astrophysics & cosmology

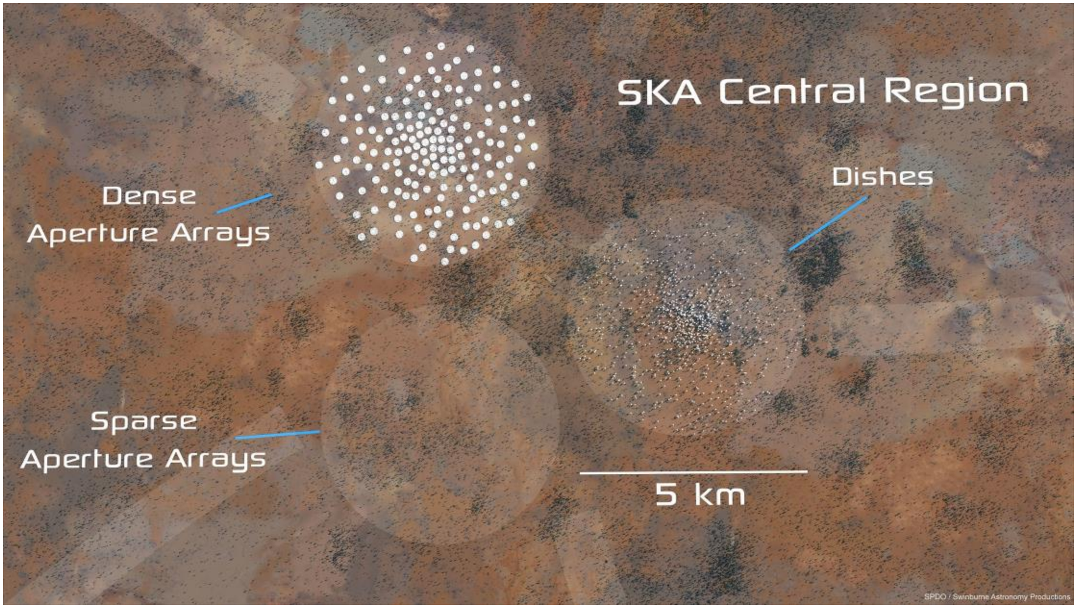




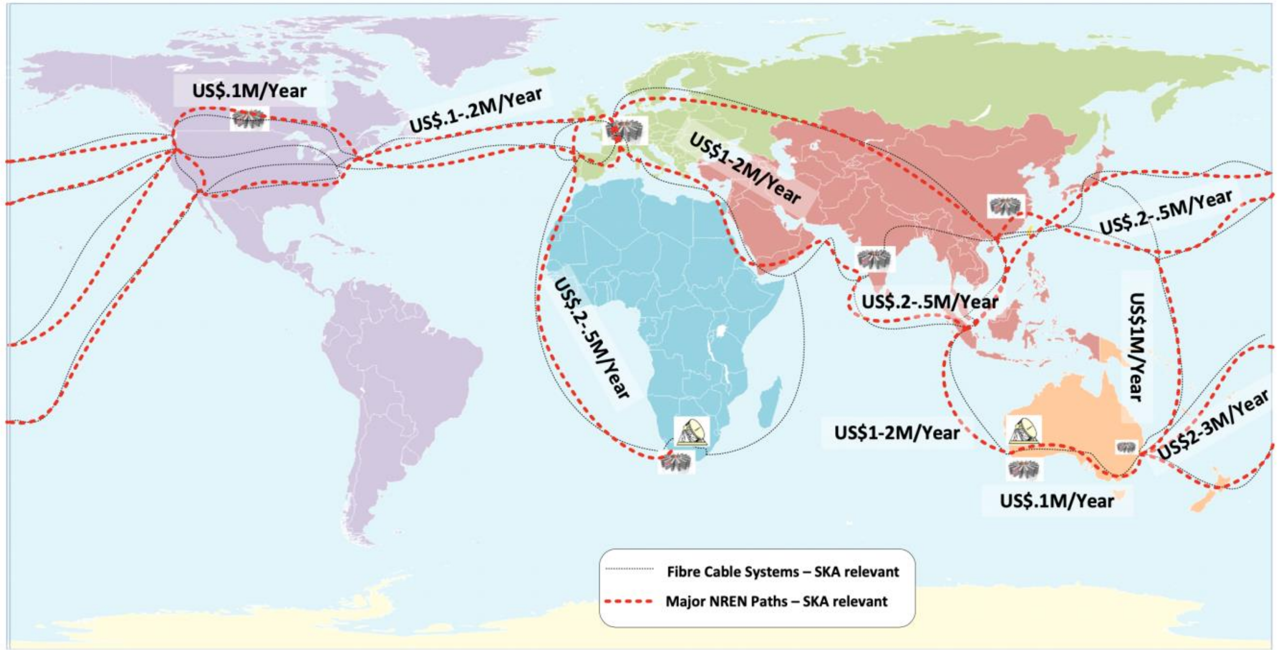


and more …

…and big earth-based observatories

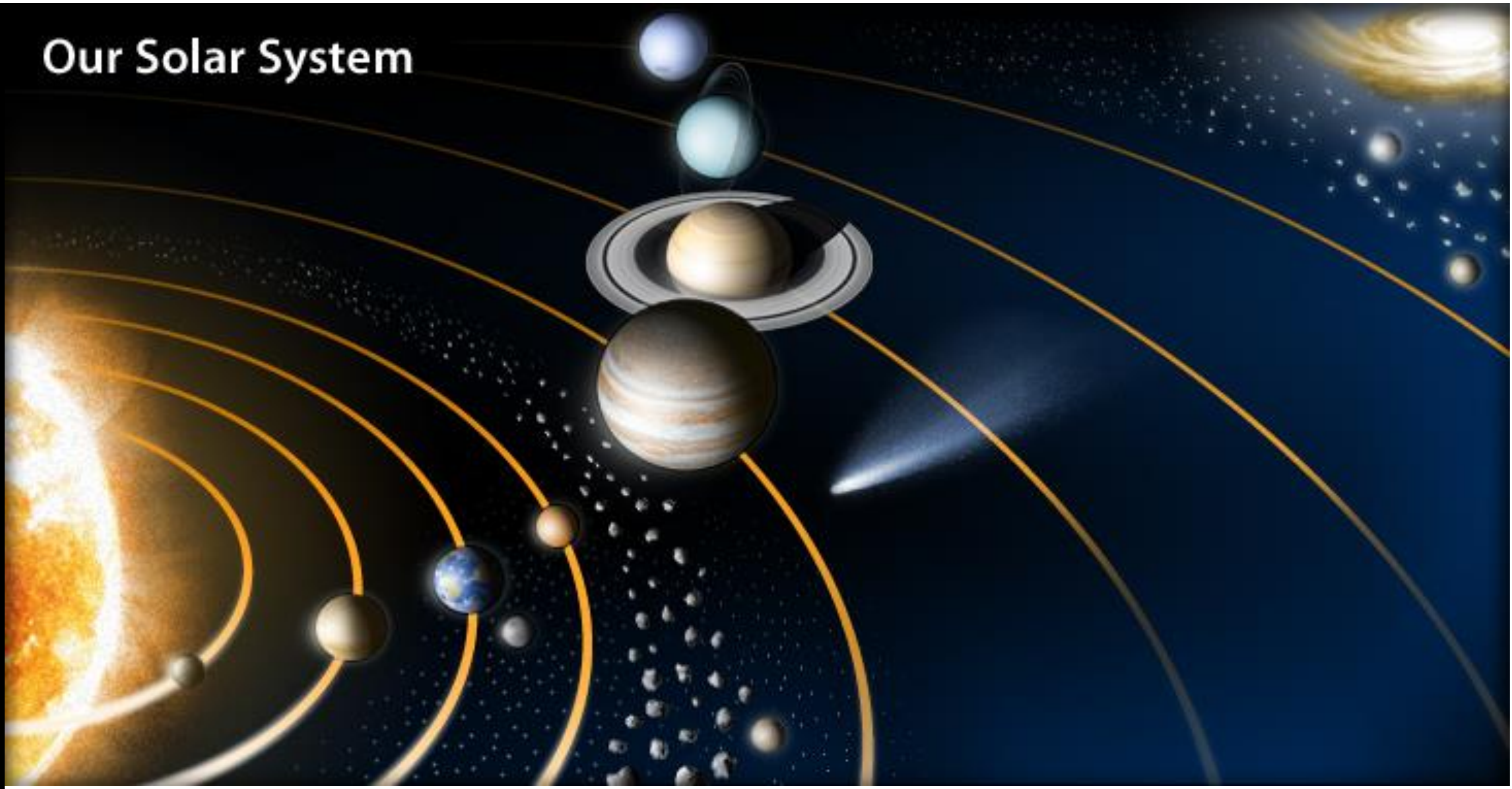


- Big Science: technological and scientific complexity comparable to CERN's flagship program.
- Competitors for resources (science funding, expert physicists)
- Colleagues in science: informing related fundamental questions in physics



Let’s start with some cosmological tourism …

Our Earth … 1.3×10^7 m Our solar system: 10^{13} m



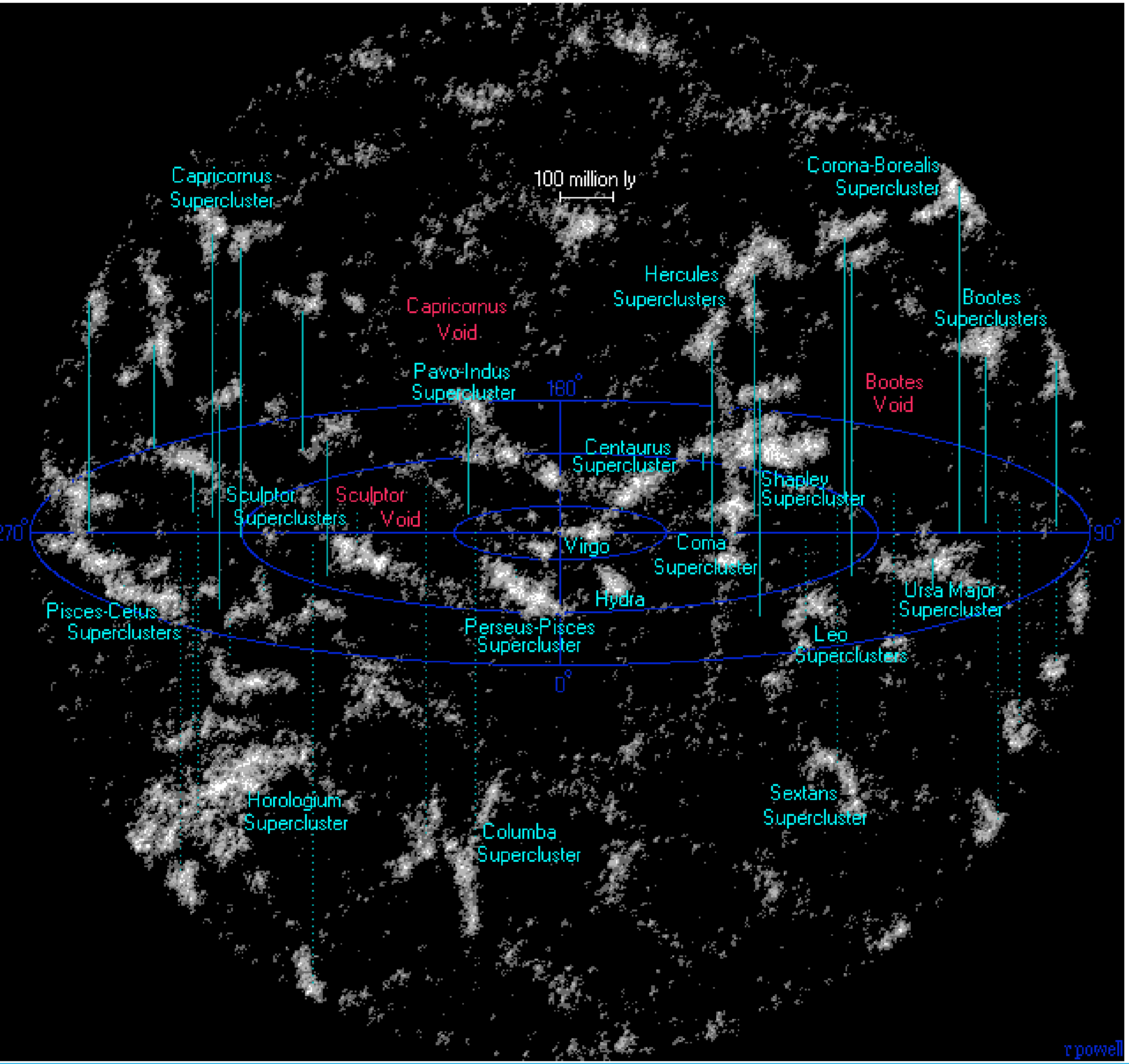
Our galaxy, the milky way: 10^{21} m = 100’000 lightyears

100 - 400 billion stars

Our neighboring galaxy, the Andromeda nebula: 2.5×10^6 lightyears distance

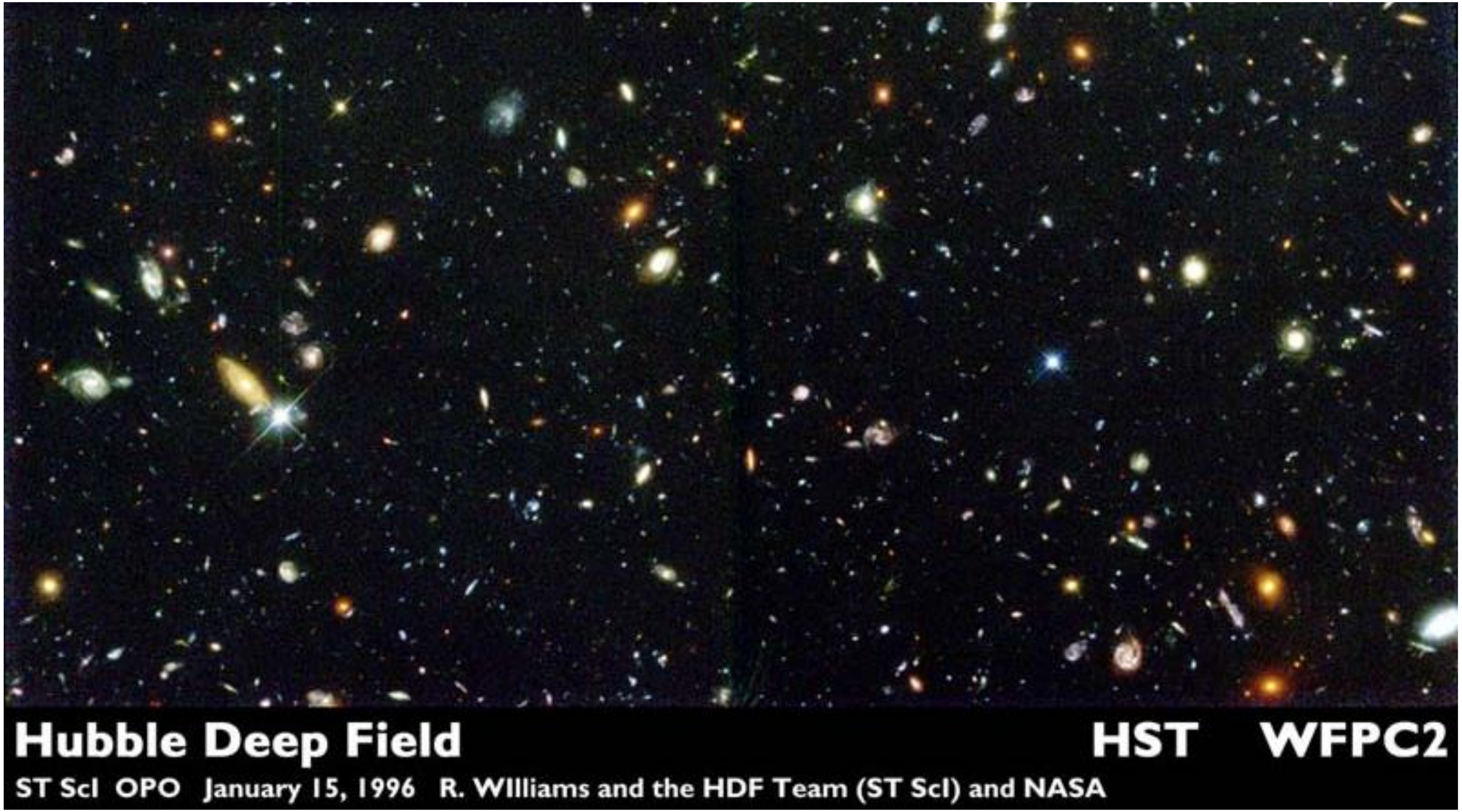
Our local neighborhood

The neighboring superclusters

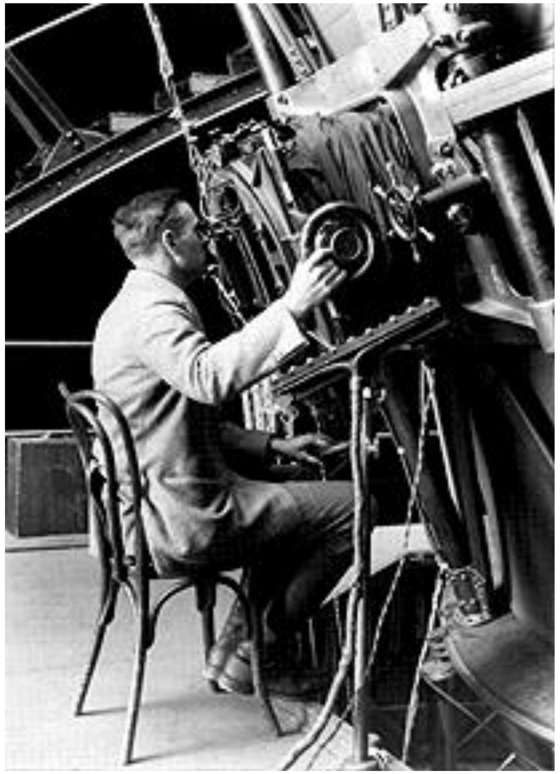


- Our local supercluster
  = local group + Virgo Cluster
- Each supercluster contains
  ~ 1000 galaxies
- Each supercluster extends over
  ~ 100 million lightyears

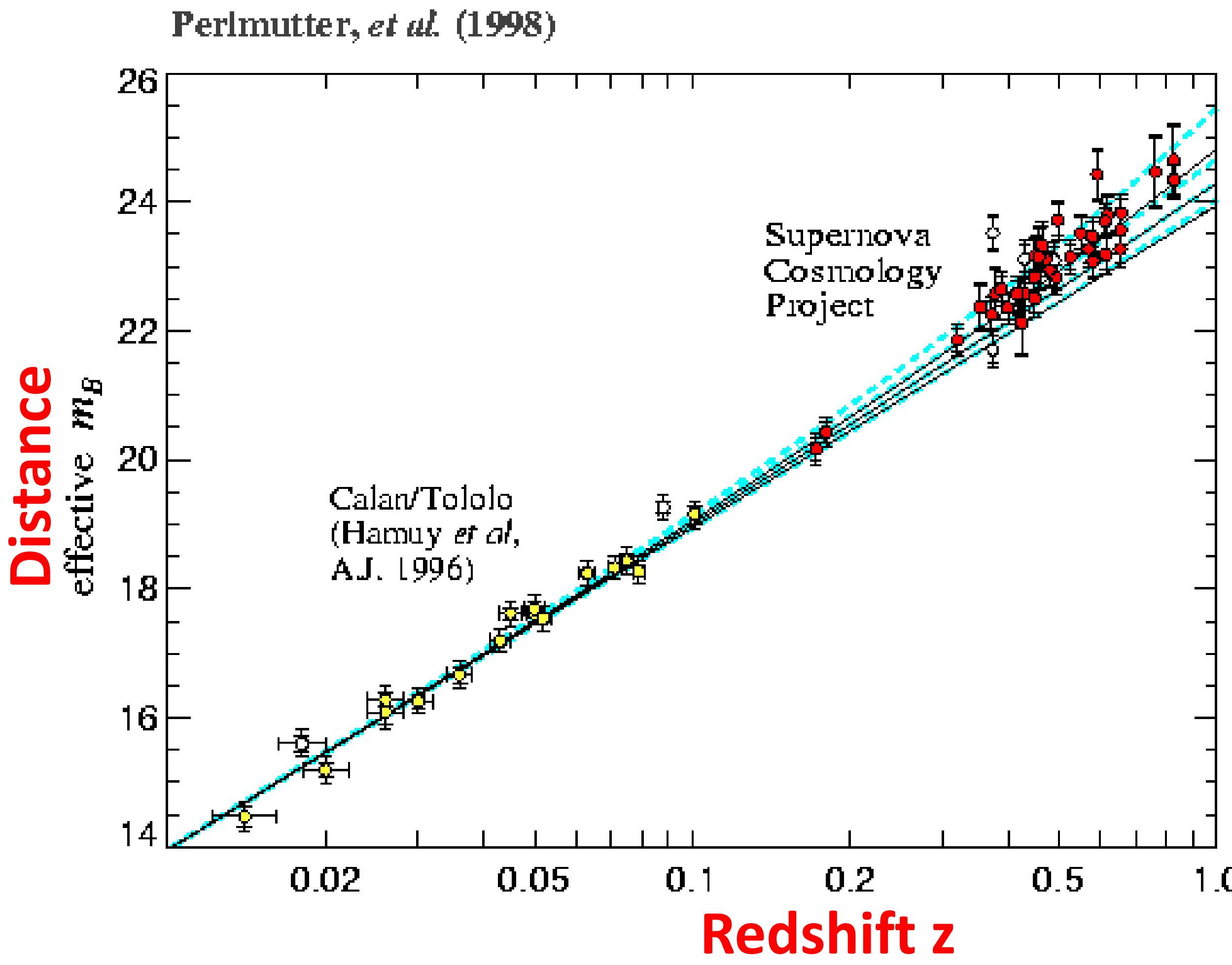
There are ~ 10 million superclusters in our visibile Universe

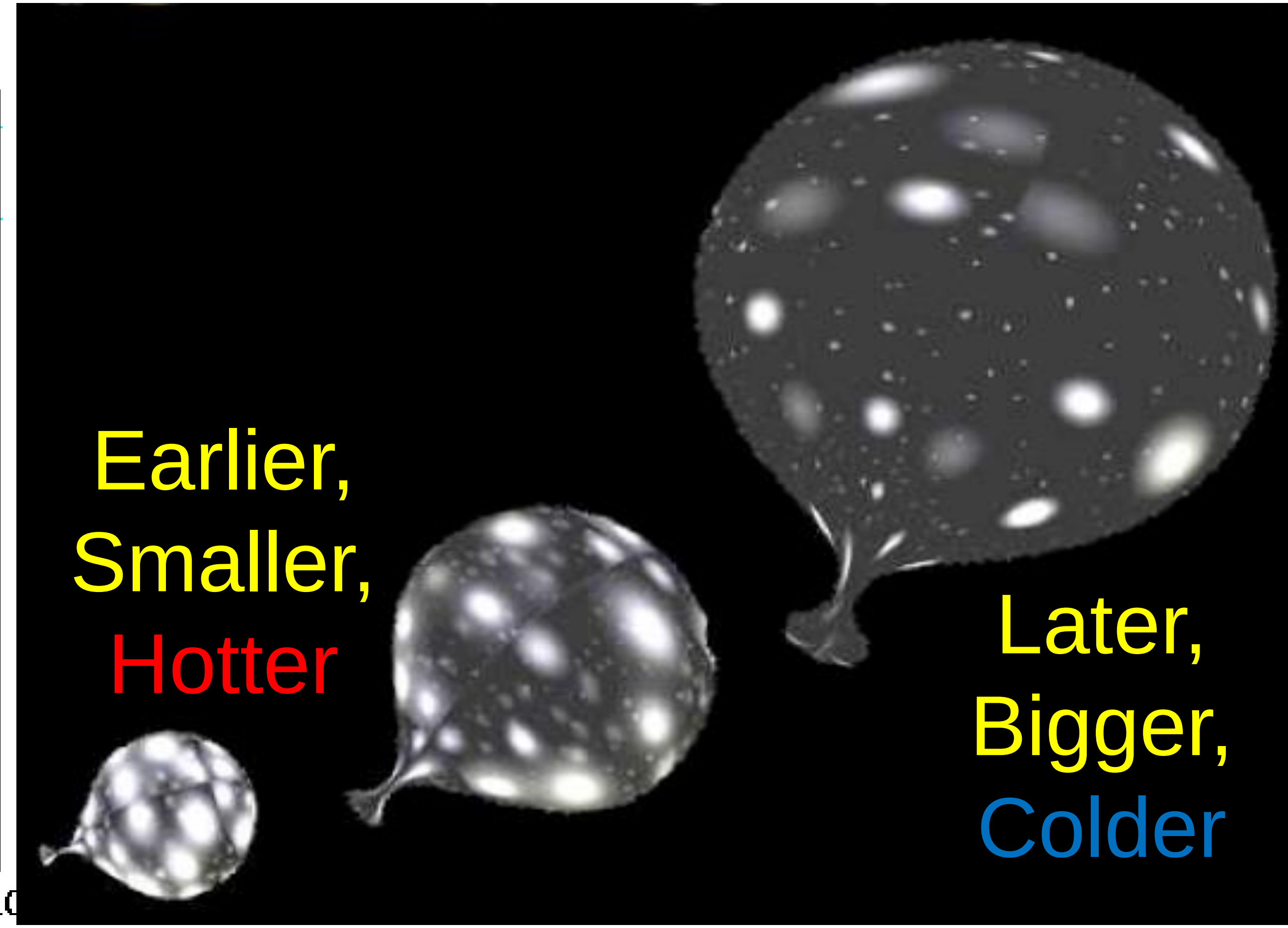


How does it all function?



The Hubble Diagram – the Universe expands



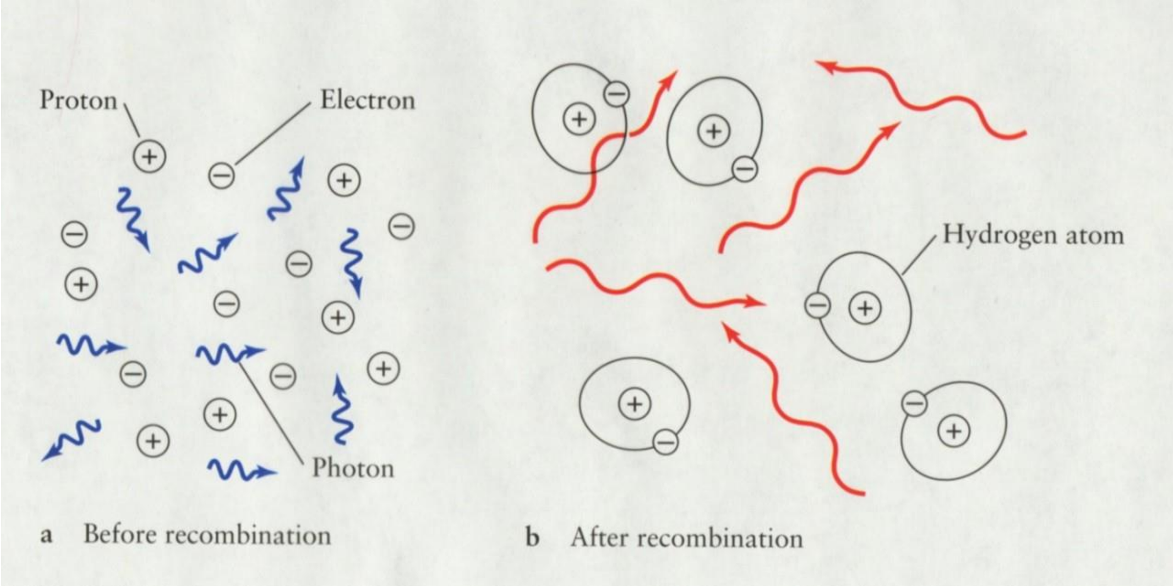


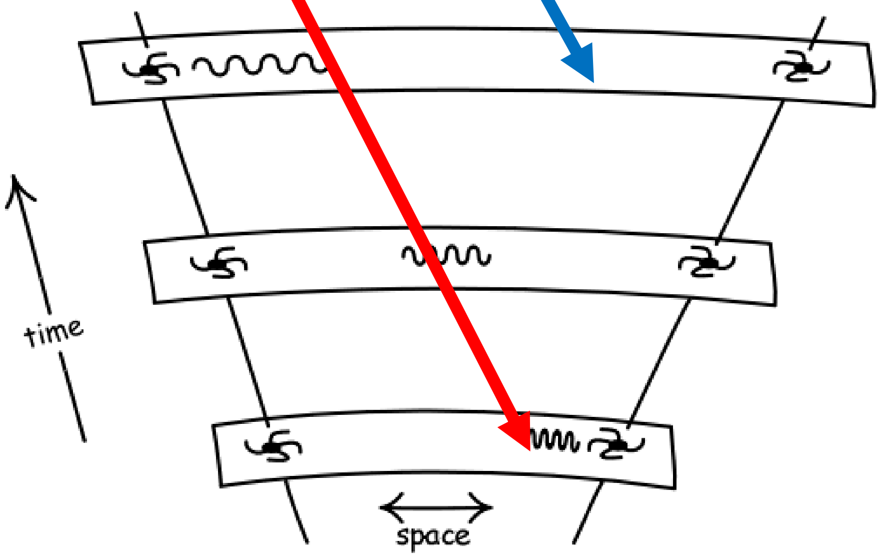
The hot early Universe

- At Temperature $T_{\rm recomb} \approx 3000\,K$

$$t = 10^{13} s \approx 380'000\,yrs$$

$$T_{\rm recomb} = \underbrace{T_{\rm CMB}}_{=2.725\,K} \cdot \underbrace{(1+z)}_{=\frac{a_{\rm now}}{a_{\rm then}}}$$



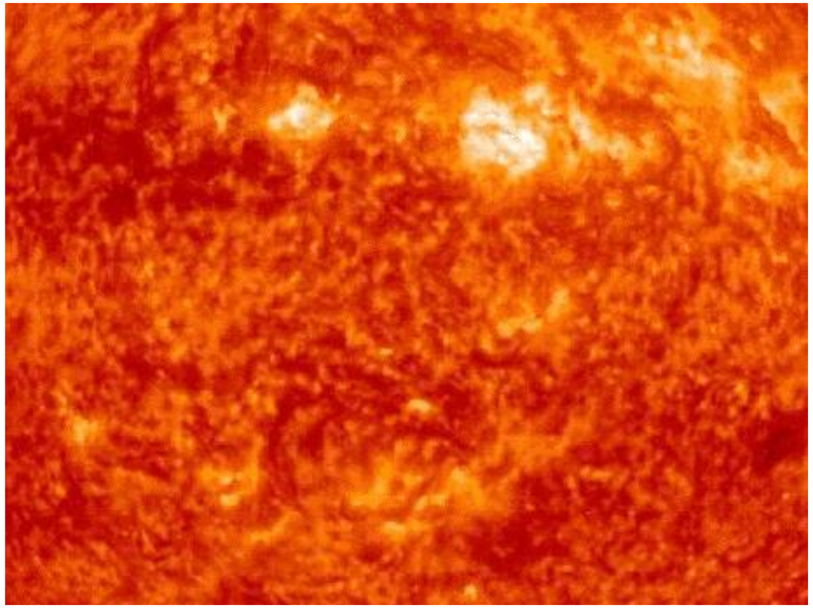


$$z \approx 1100$$

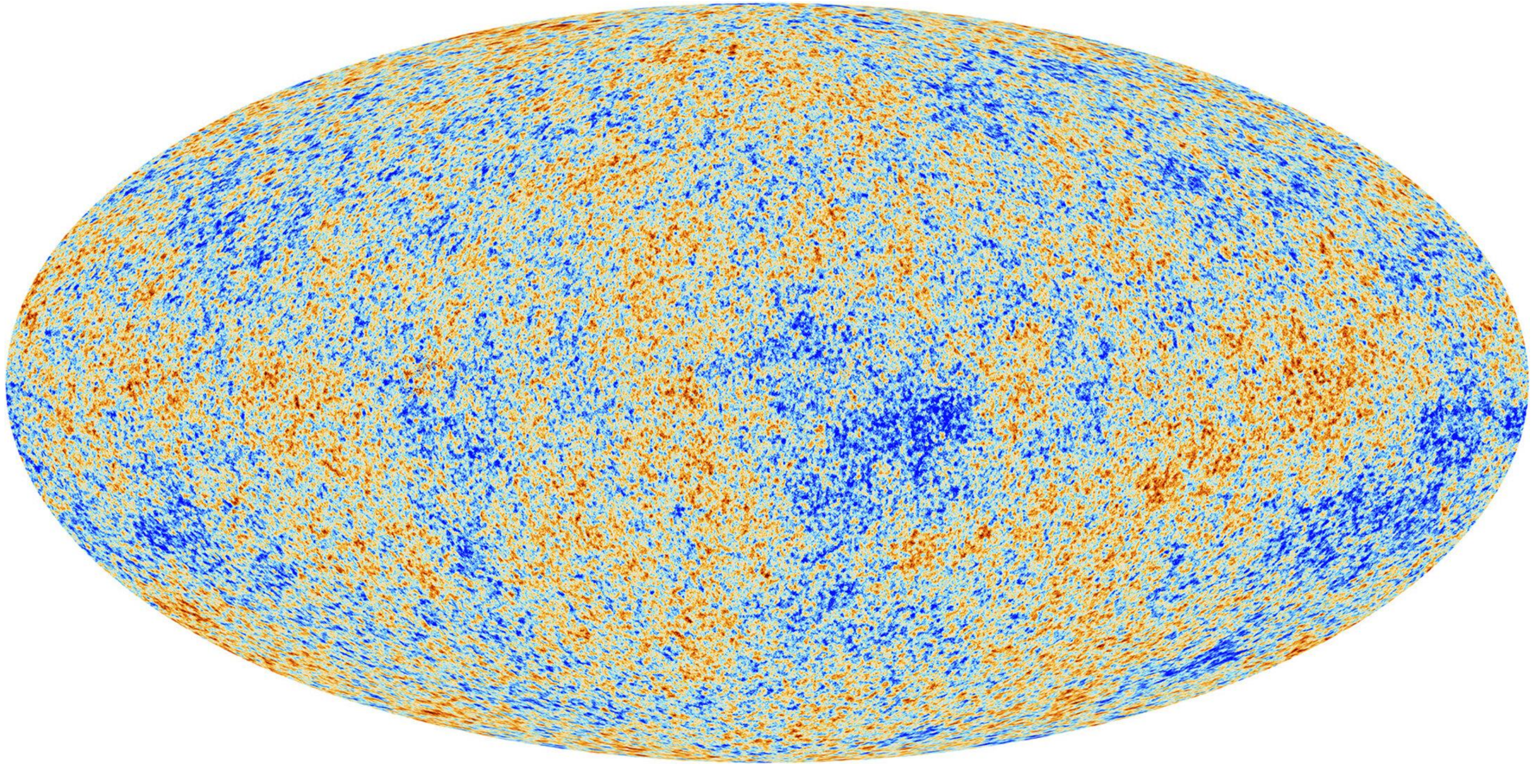
The cosmic microwave background (CMB)

At recombination

$$T_{\text{recomb}} \approx 3000\,K$$



and as seen today (z = 1100) $T_{\text{CMB}} \approx 2,725\,K$



Overdensities on scale $\delta = \dfrac{\delta\epsilon}{\epsilon} \approx 10^{-5}$ at $z = 1100$

The dynamics of cosmological expansion

The growth of overdensities of the CMB

- Cosmological perturbation theory

$$\epsilon = \bar{\epsilon} + \delta\epsilon\,, \qquad \vec{\nabla}\cdot\vec{v} = H + \Theta$$

- Homogeneous and isotropic bkg solution

(Friedmann equations) $$\bar{\epsilon} = \frac{3}{8\pi G_N} H^2$$

$$\frac{1}{a}\dot{\bar{\epsilon}} + 3H\left(\bar{\epsilon} + p\right) = 0$$

- Linear evolution of cosmic perturbations

$$\dot{\delta}_{\mathbf{k}} = -(1 + w)\theta_{\mathbf{k}} - 3\mathcal{H}\left(c_s^2 - w\right)\delta_{\mathbf{k}}$$

$$\dot{\theta}_{\mathbf{k}} = -\left(1 - 3c_{\mathrm{ad}}^2\right)\mathcal{H}\theta_{\mathbf{k}} + k^2\,\Phi_{\mathbf{k}} + \frac{c_s^2}{1+w}k^2\,\delta_{\mathbf{k}}$$

$$k^2\Phi_{\mathbf{k}} = -\frac{3}{2}\mathcal{H}^2\delta_{\mathbf{k}}$$

= vanishes in absence of pressure

- If pressure negligible in cosmol. fluid

$$\delta \propto a$$ overdensities grow

- But **baryons have pressure**

Jeans criterion: pressure resists gravitational collapse, overdensities oscillate

$$c_s^2 = \frac{\partial p}{\partial \epsilon} = \frac{k_{\mathrm{B}} T_b}{\mu_{\mathrm{mol}}}$$

$$c_s \approx 2 \cdot 10^{-5} \text{ at } z = 1100$$

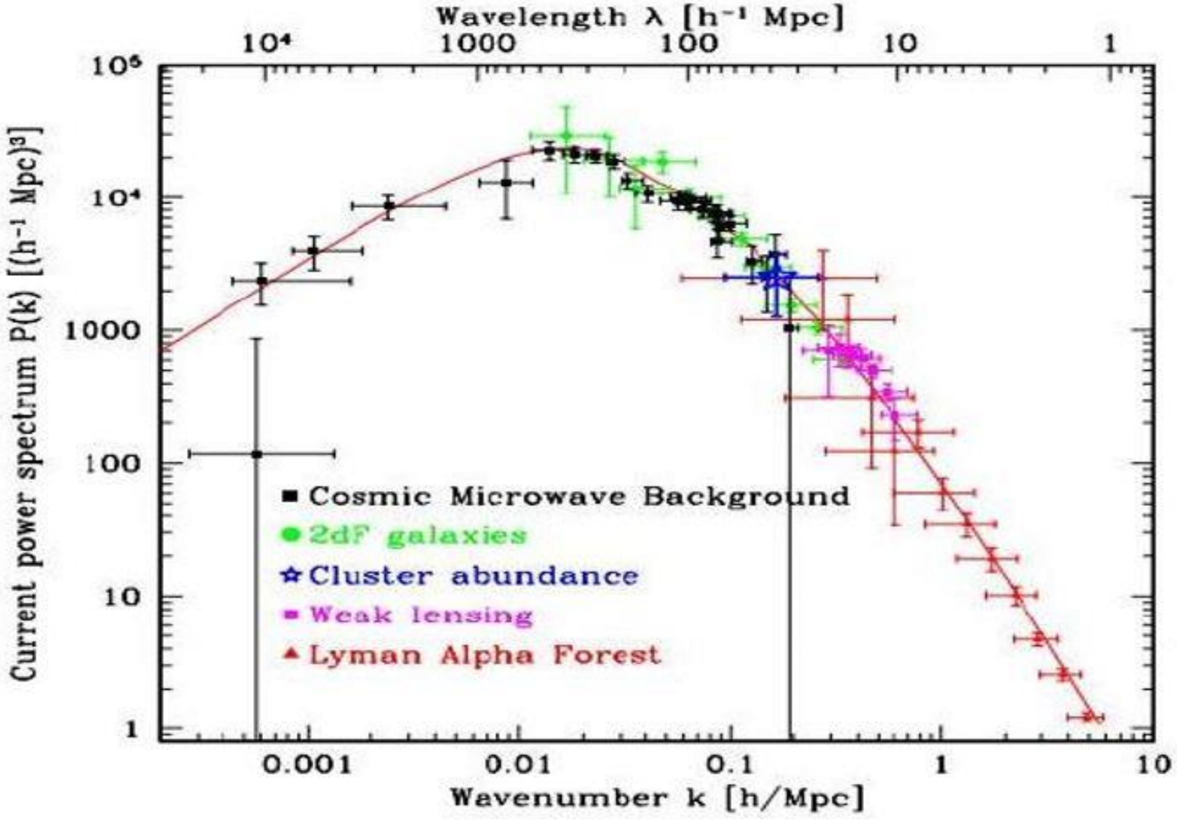
Small but non-negligible!

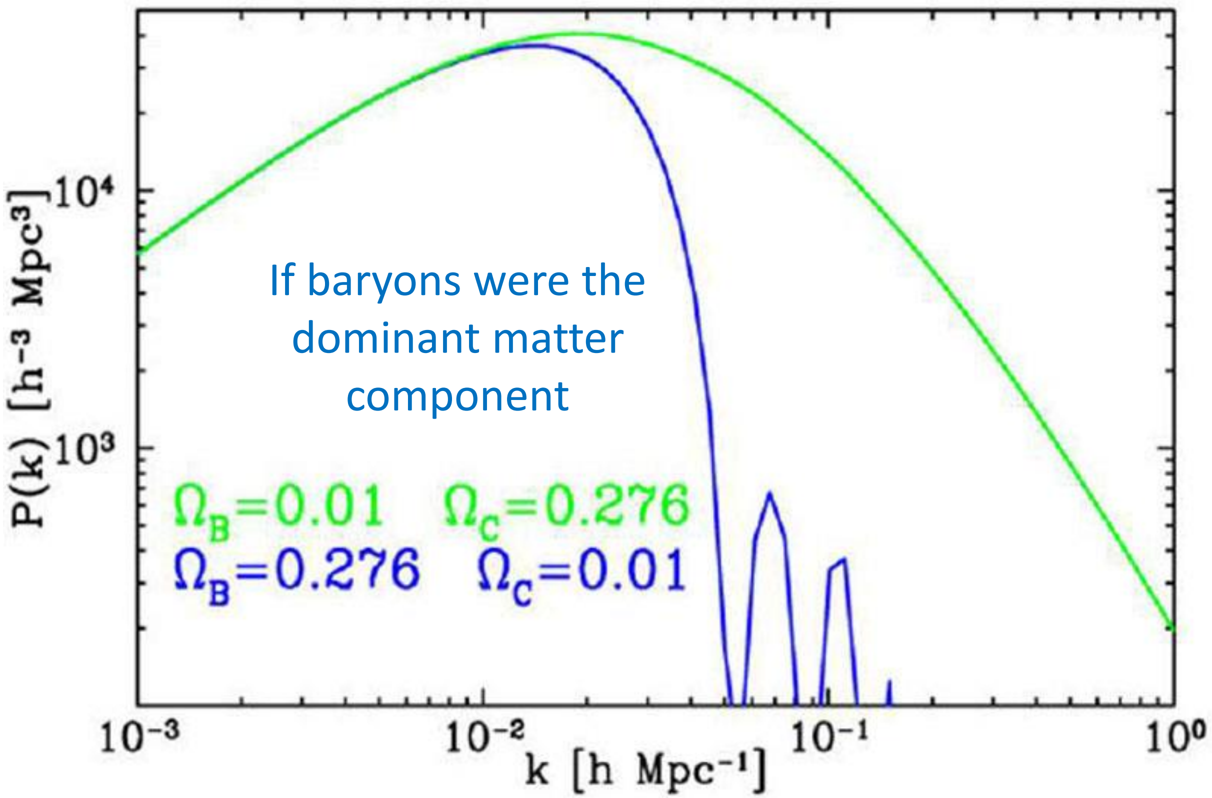
It follows from cosmological large scale structure that baryonic matter must be pulled into the gravitational wells of a cold dark matter component.[1]

1. S. Weinberg “Cosmology”, Oxford Univ. Press 2008

The growth of overdensities of the CMB

$$\langle \delta_{\mathbf{k}_1}\, \delta_{\mathbf{k}_2} \rangle = \delta^{(3)}\left(\mathbf{k}_1 + \mathbf{k}_2\right)\, P(\mathbf{k}_1)$$

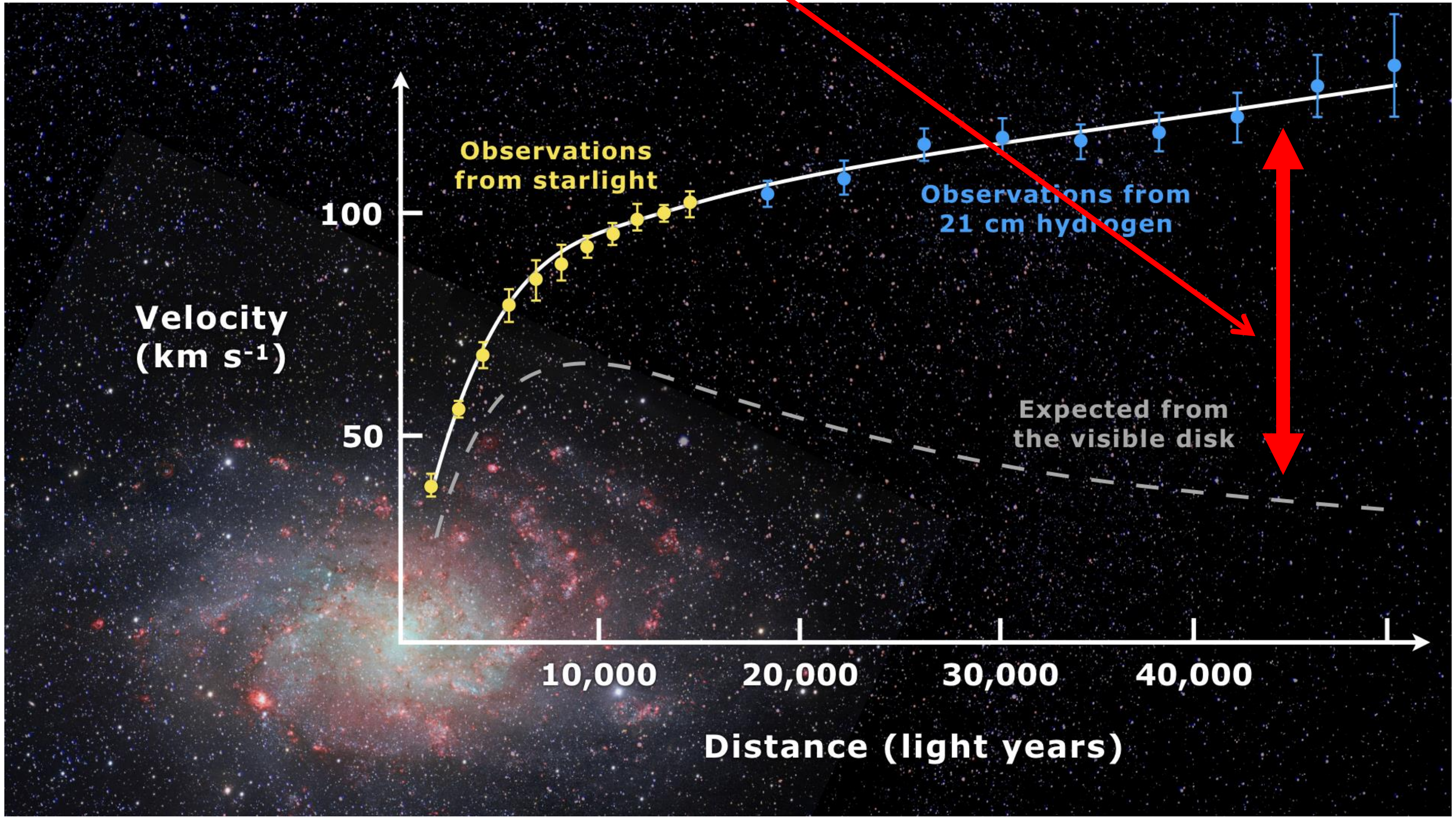




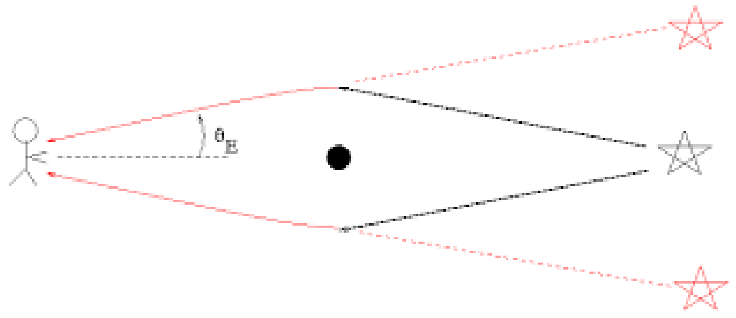
Large Scale Structure of Universe implies a Cold Dark Matter component

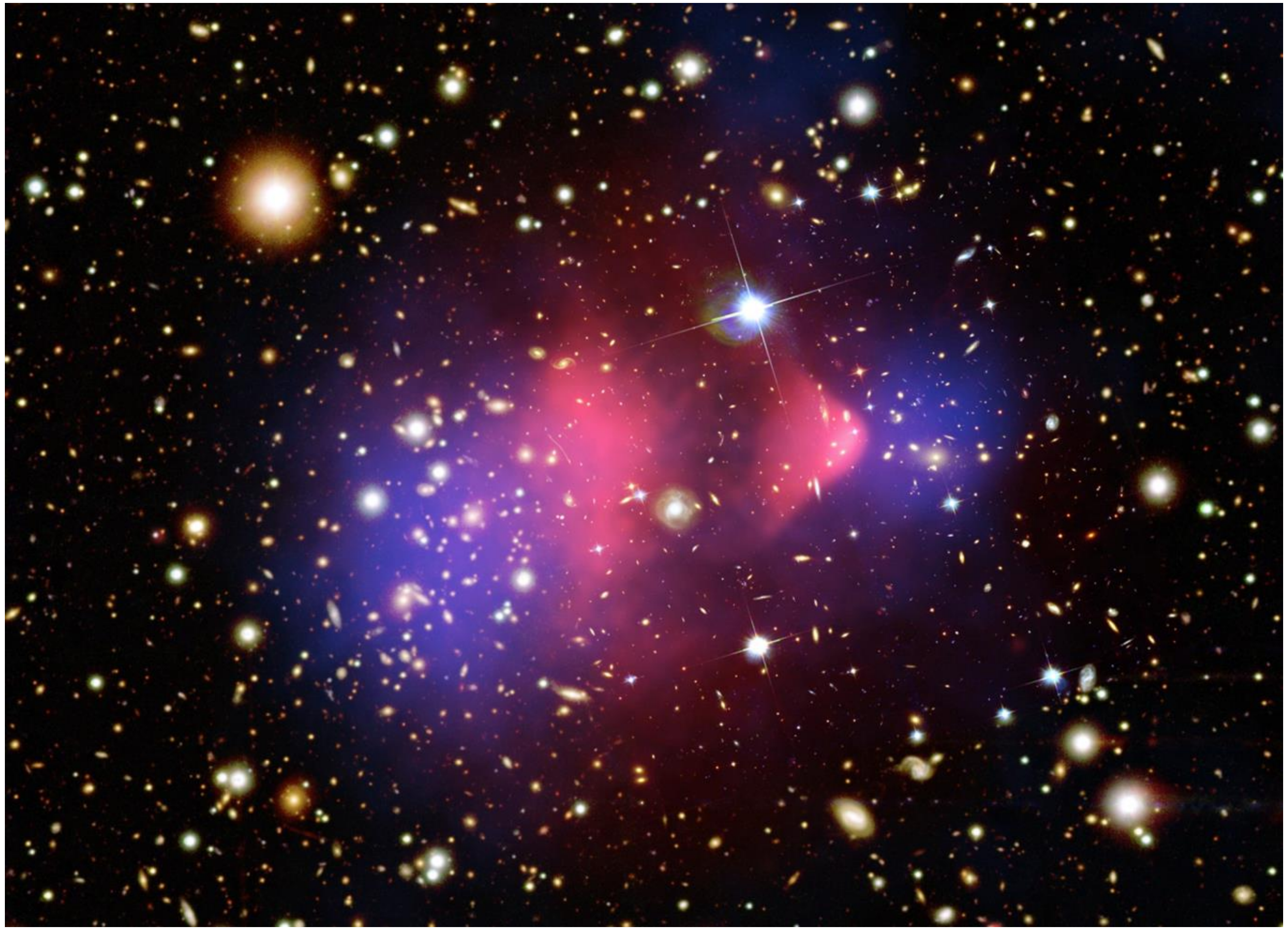
Rotation Curves: evidence for Cold Dark Matter at much smaller scale

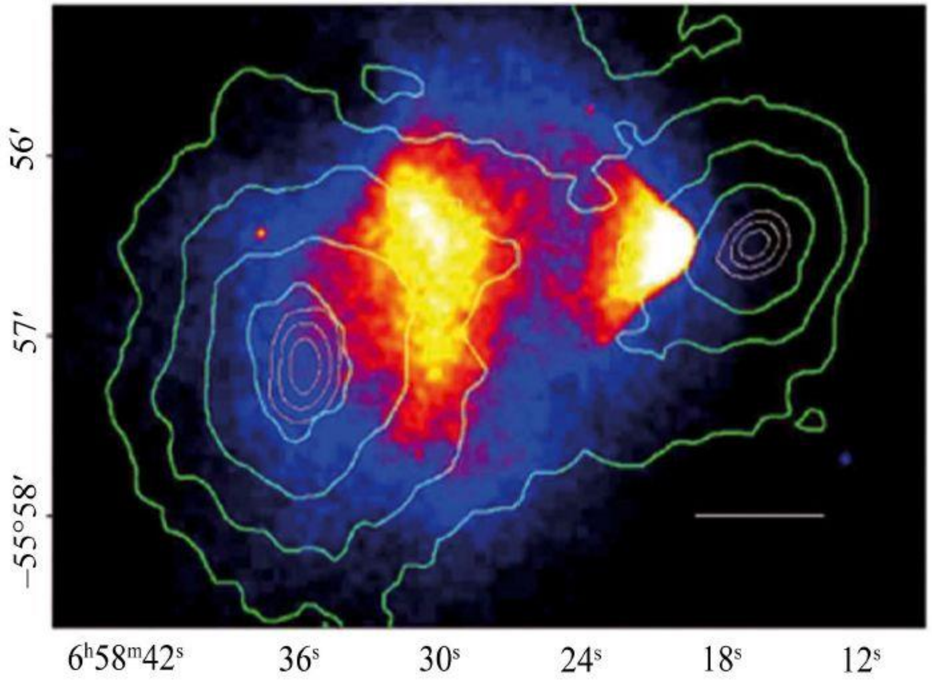
This difference cannot be explained with known physics



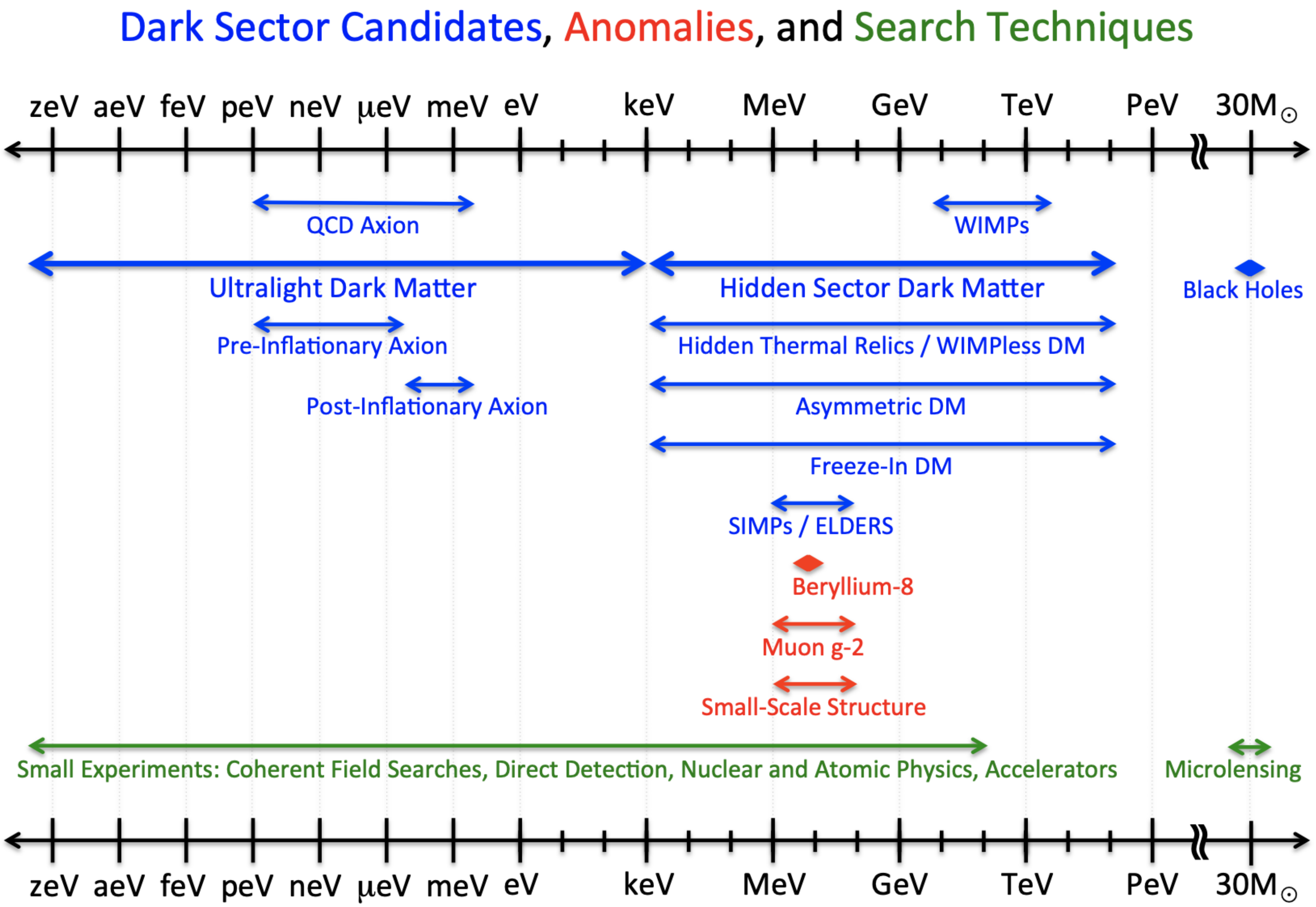
Dark Matter: evidence from gravitational lensing



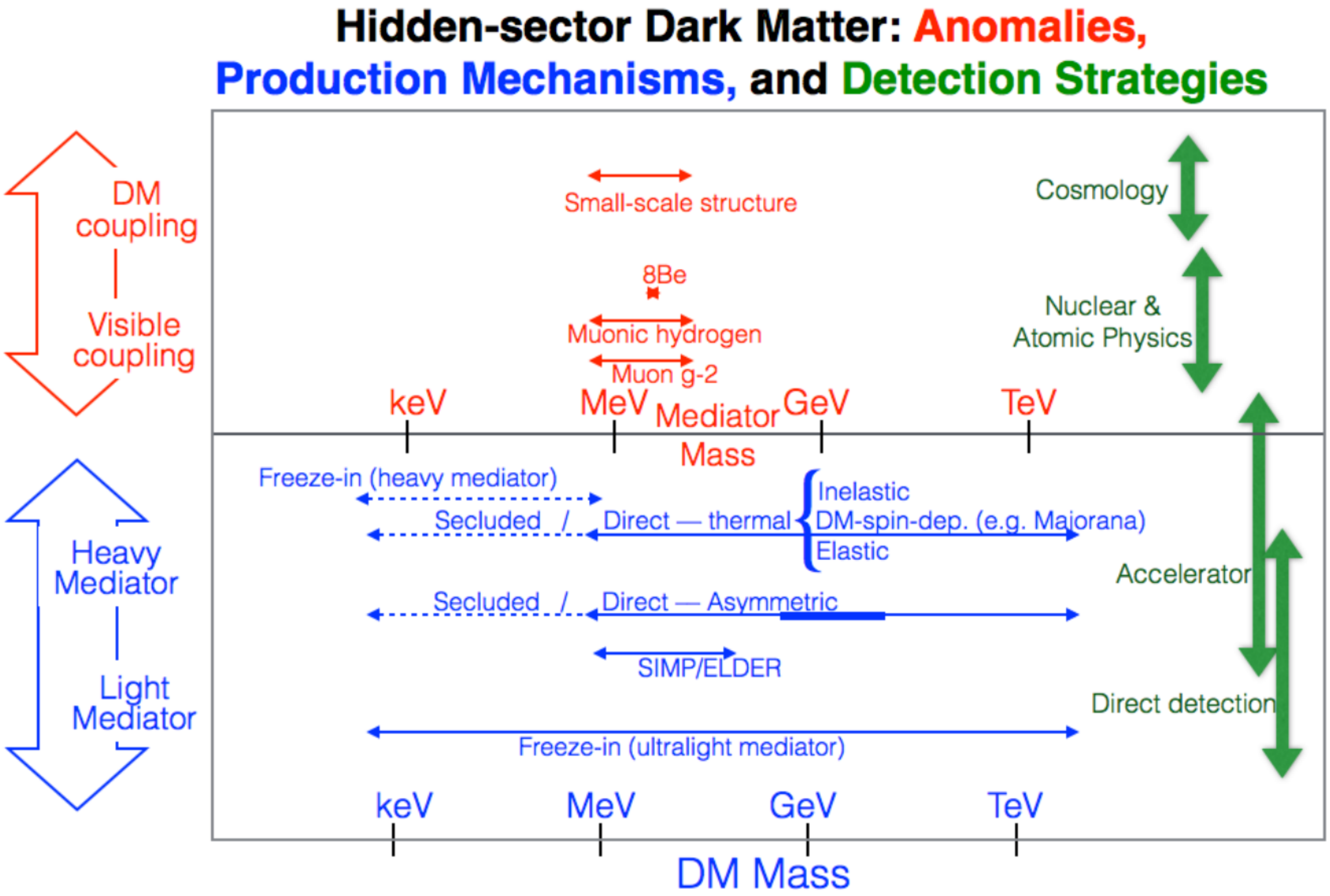




What could dark matter be?



What could dark matter be? – and how could it be searched for?



US Cosmic Visions: New Ideas in Dark Matter 2017, arXiv:1707.04591

- From observations on different astronomical scales, we have independent evidence for the existence of Dark Matter as a gravitational phenomenon.

- Observations so far provide non-trivial upper bounds on the self-interaction of Dark Matter and on its interaction with baryonic matter.

What about clues of what CDM could be from earlier time cosmology?

The Universe at a redshift of a billion

$$z = 10^9$$

$$10^{-2}s < t < 10^2 s$$

Георгій Антонович Гамов

George Gamow

* Одéса, 1904 -- Boulder Colorado 1968

Father of BBN

The Universe at a redshift of a billion

All four fundamental forces are at work:

- **Gravity**
  determines the expansion rate
- **Weak Interactions**
  determine n/p balance
- **Strong Interactions**
  fuse nuclei
- **Electromagnetic repulsion**
  shuts fusion off

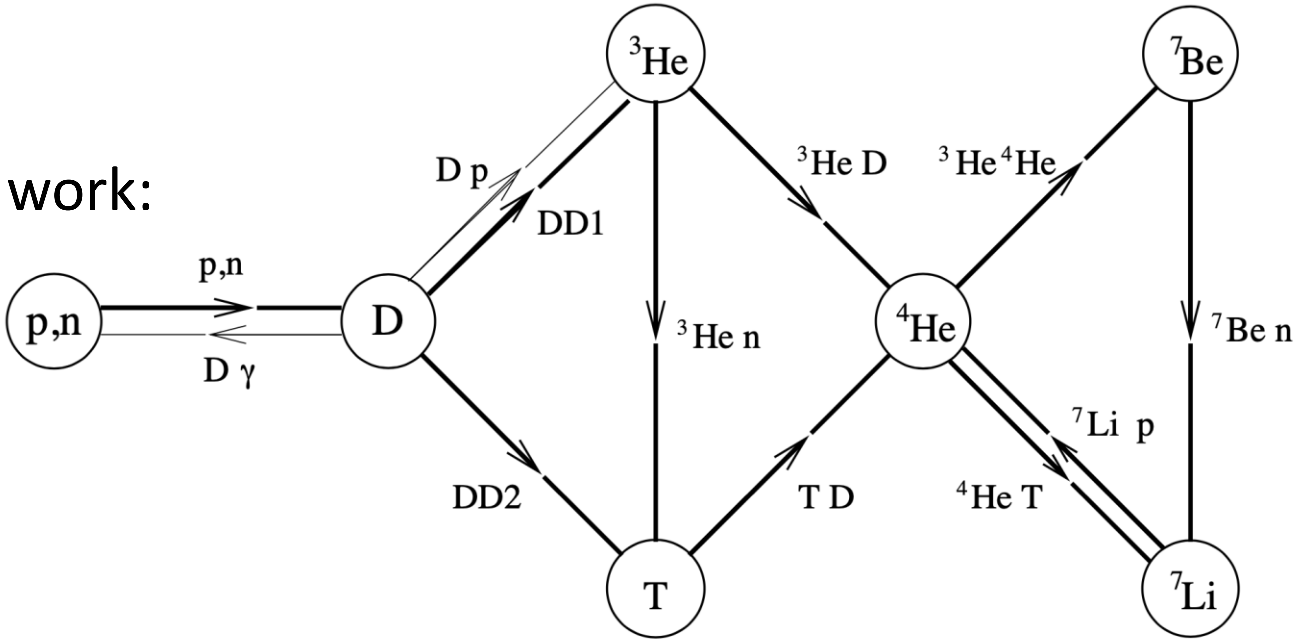


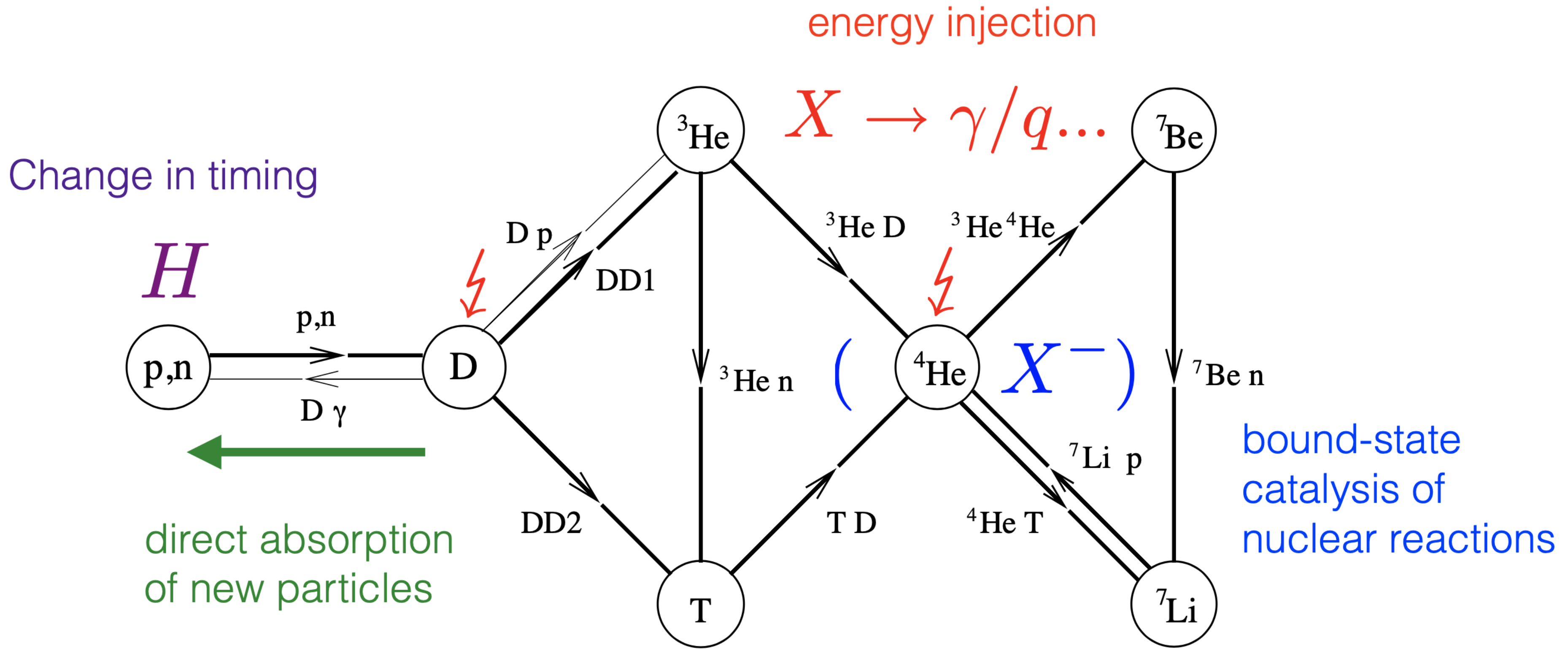
Fig. from Mukhanov "BBN without a computer"

Precision measurements of nuclear reactions + Baryon/ γ ratio from CMB

→

BBN = parameter free theory (in "Standard Model")

BBN highly sensitive to new physics (BSM)



Metalicity floor of old stars

- **Li- problem? (He-problem)?**
- **systematics - problem ?**

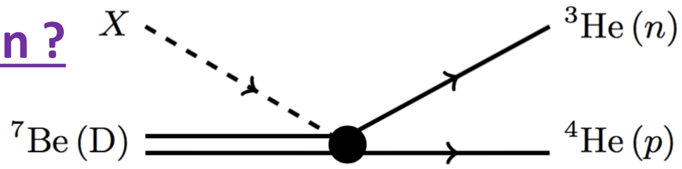
Challenge for precision nuclear physics + astrophysical modeling

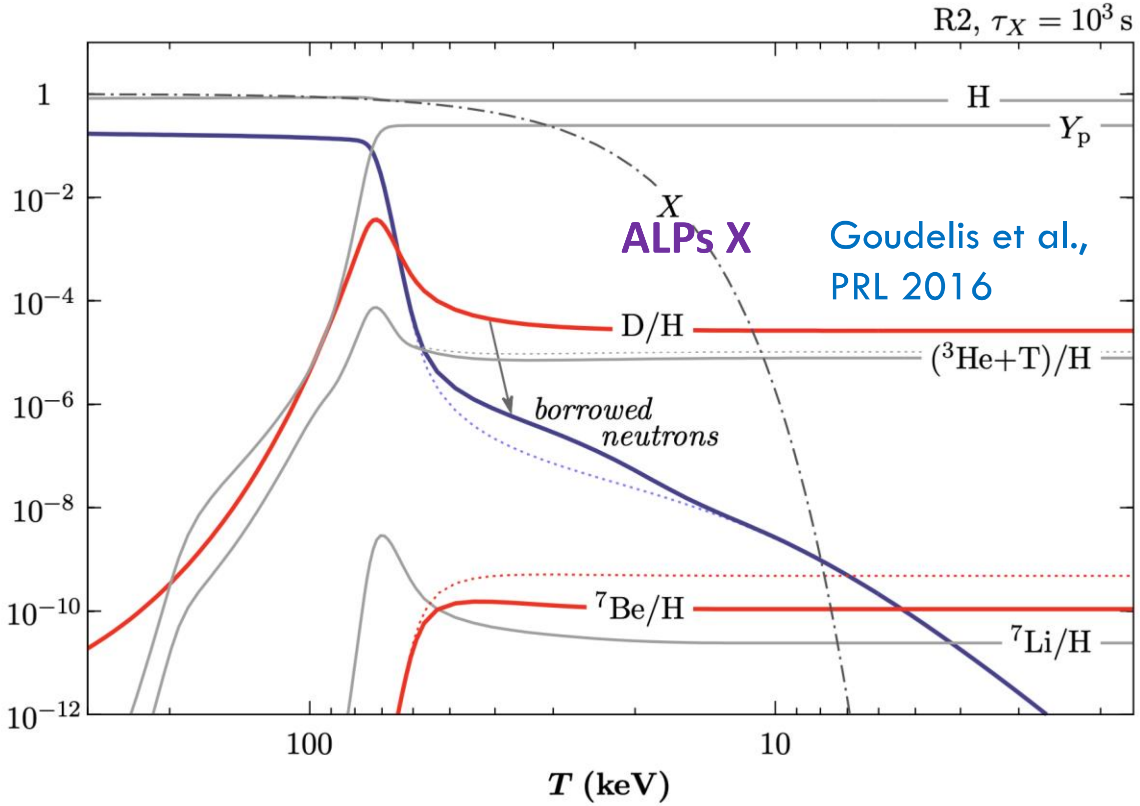
Hints for new physics ?

and if the problem is not NP (nuclear physics) but NP (new physics)...

BSM sources for additional neutrons during BBN epoch, many scenarios conceivable

- **Direct absorption ?**
- **Decay of X ?**

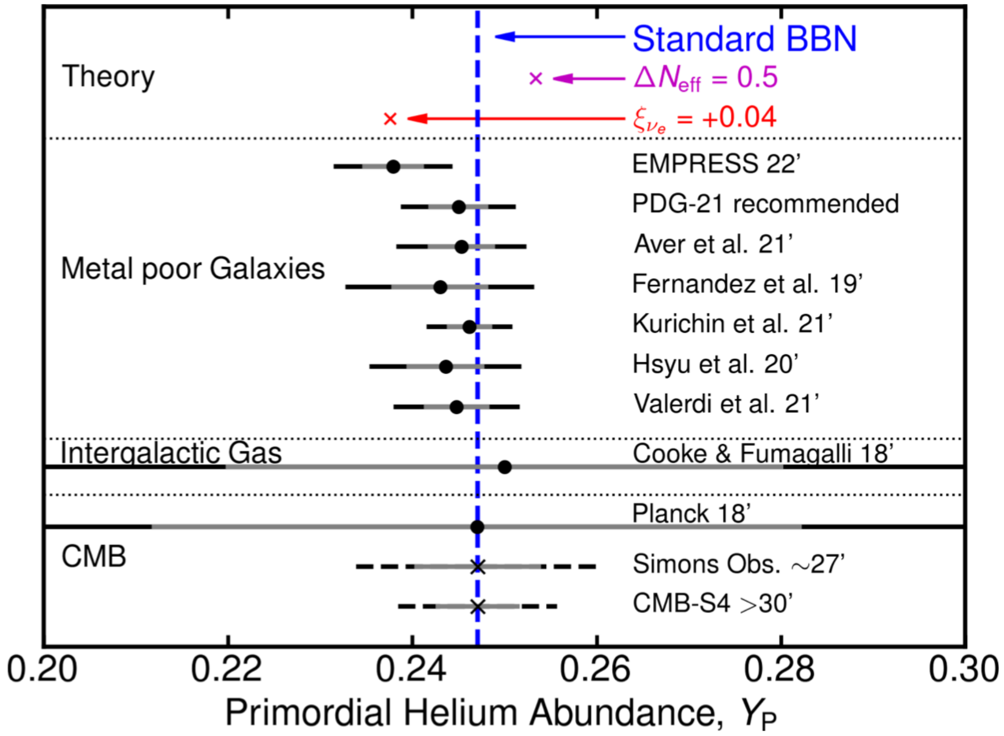




- **Leptogenesis ?**

Neutrino chemical potential

$$Y_P(\xi_{\nu_e}) \simeq Y_P|_{\mathrm{SBBN}} \times e^{-0.96\,\xi_{\nu_e}}$$

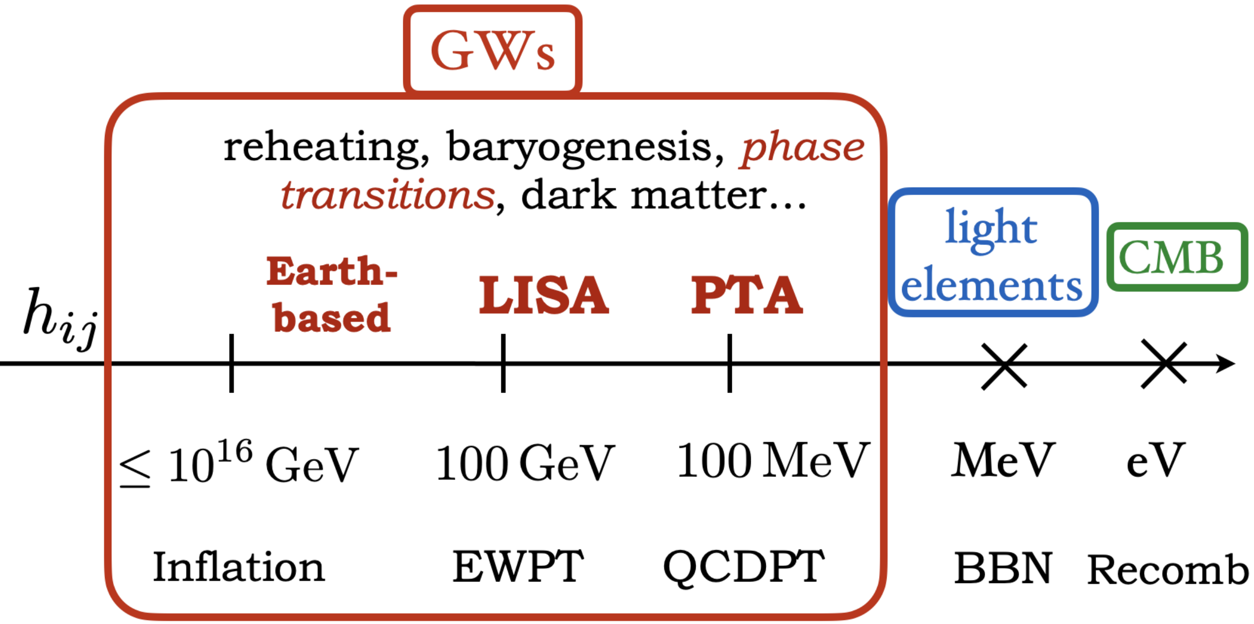


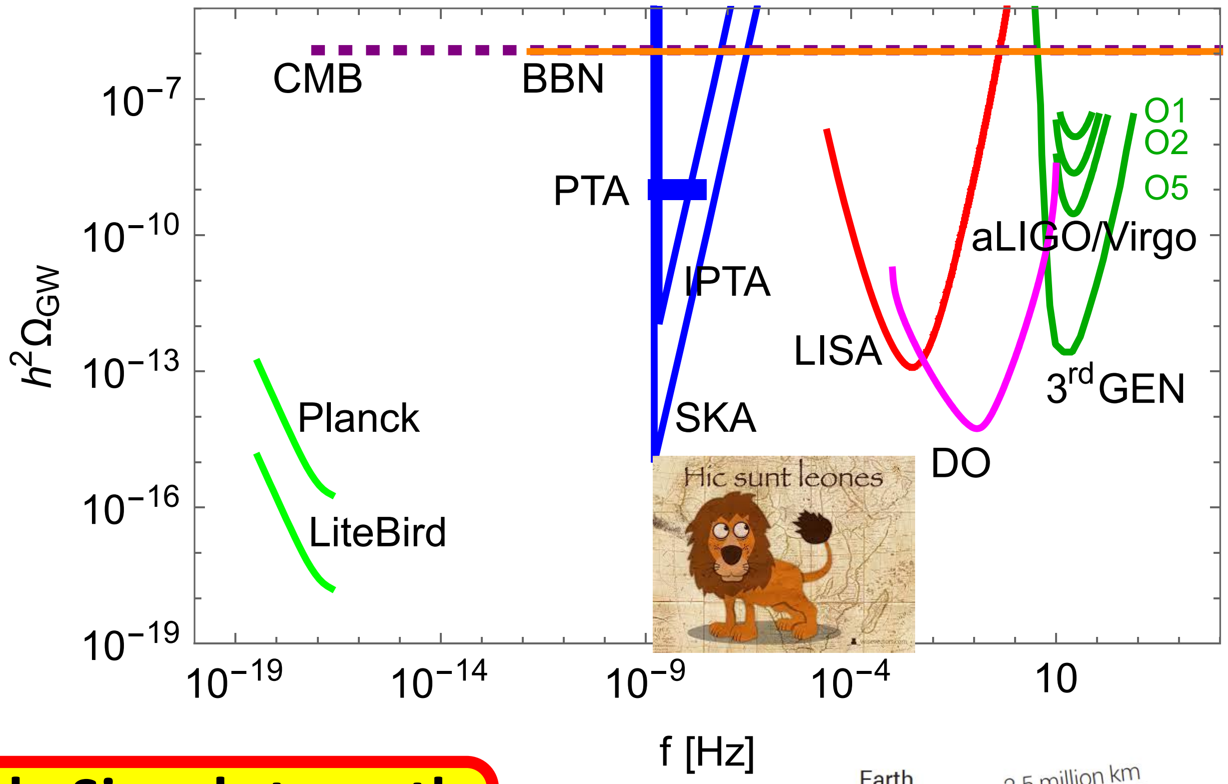
Escudero et al., 2208.03201

- Once an anomaly persists in nuclear astrophysics or cosmology, accelerator physics is likely needed to understand its microscopic origin.
- Precision particle physics and nuclear physics is a prerequisite for limits of astrophysical interpretation.

What about even earlier time cosmology?

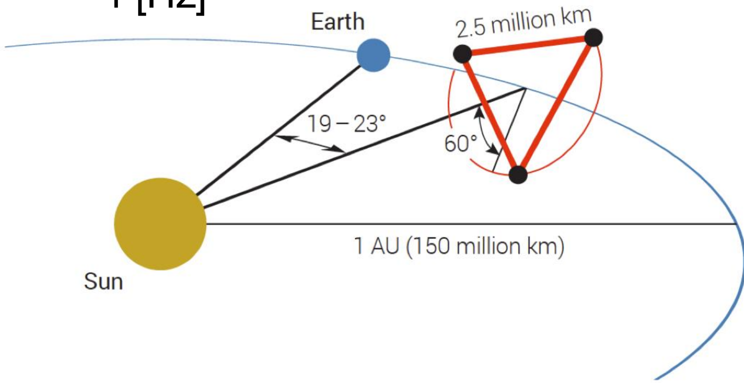
Seeing farther with gravitational waves





$0.1ns$ $10\mu s$

Measurable Signal strength iff phase transition 1st order



- GW **stochastic sources**

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$

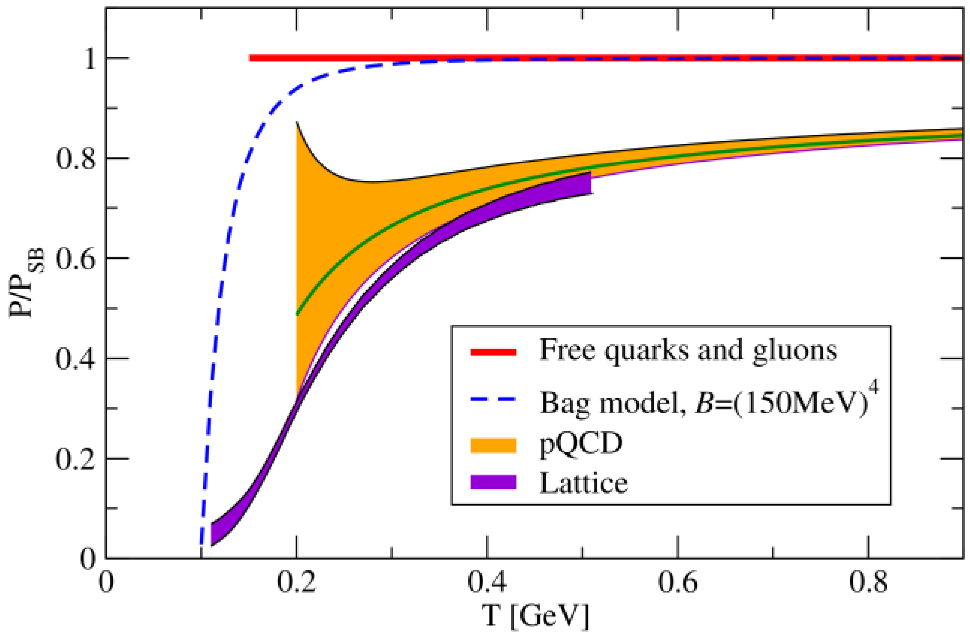
PTA laboratories (NANOGrav,Parkes,European) report noise excess: arXiv: 2009.04496, 2107.12112, 2110.13184

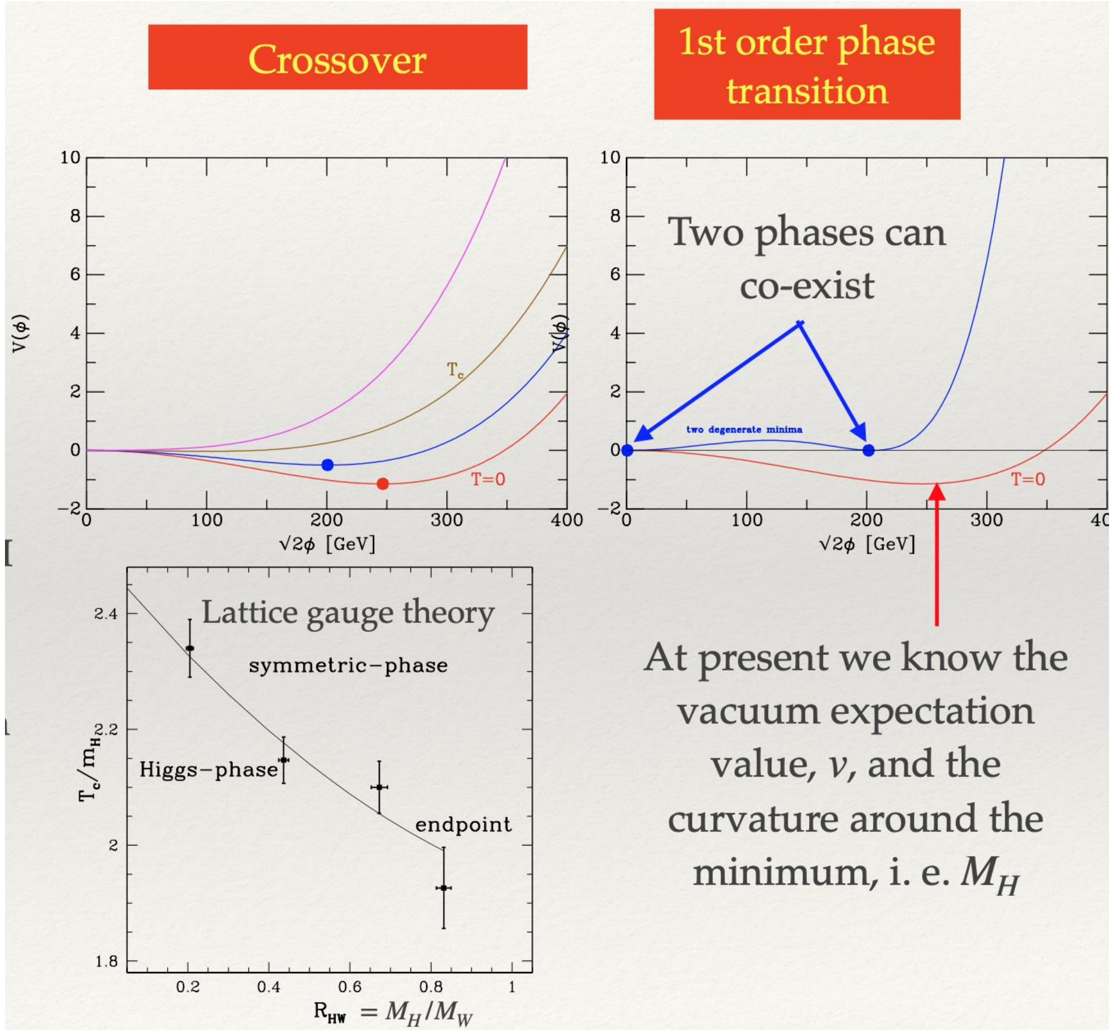
but in the Standard Model w/o BSM, PTs are not 1st order …

- QCD PT is smooth cross over*
- EWPT** is 1st order only for

$$M_H < 72\,GeV$$

(that's a feature, but also a potential problem …)





*D. Bazavov et al, Phys. Rev. D90 (2014) 094503
S. Borsanyi et al, JHEP 09 (2010) 073

*K. Kajantje, M. Laine, K. Rummukainen, Y. Schroder, PRD67 (2003)

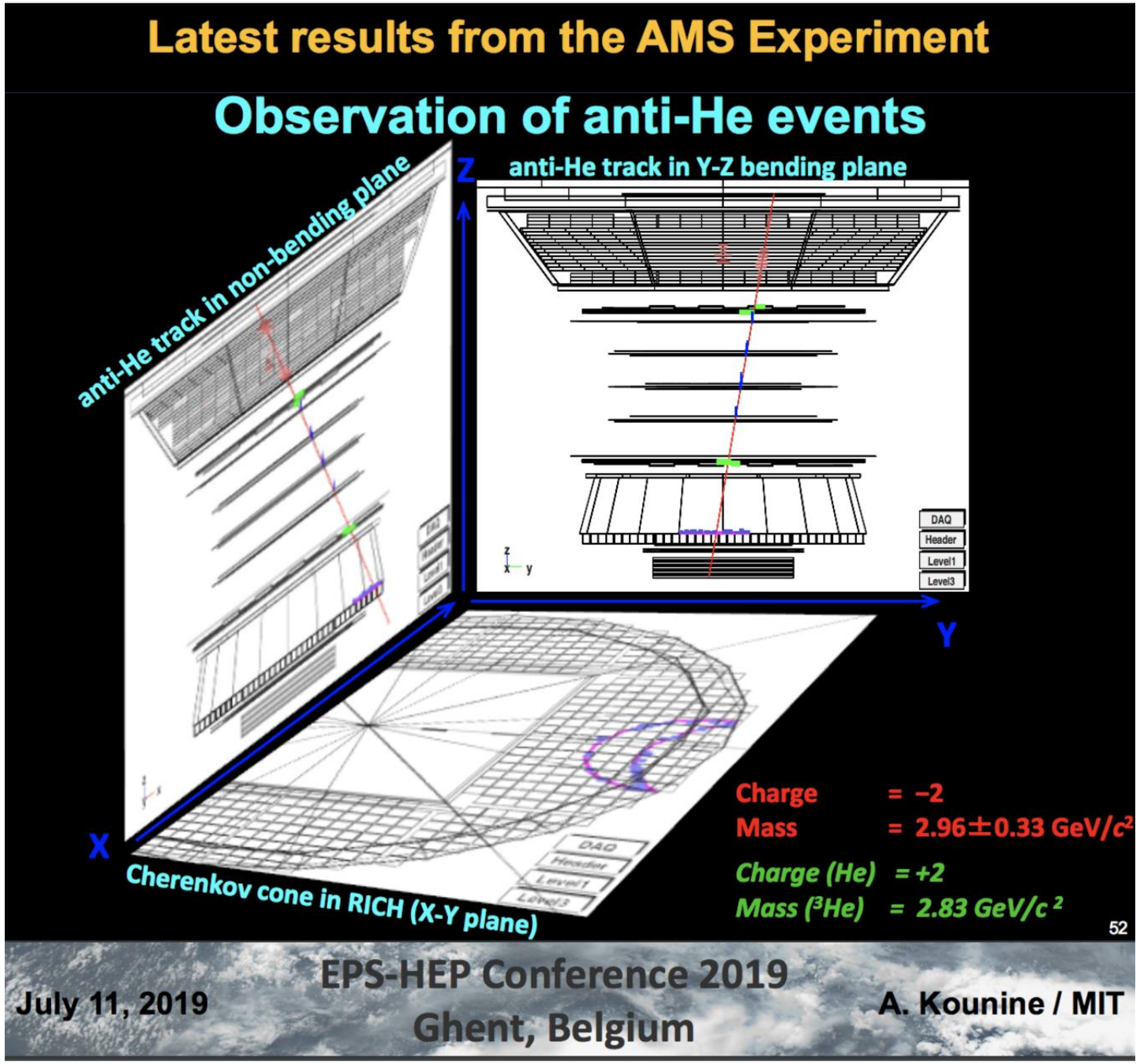
*Csikor, Fodor, Heitger, hep-ph/9809291

Don’t look only at the “big” questions.

There are many interesting “smaller” questions at the interface between accelerator-based and space-based science.

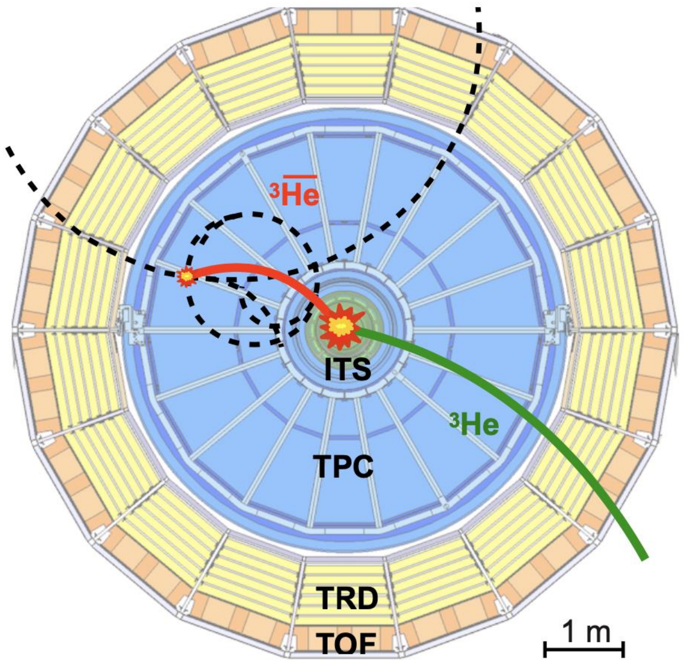
One example …

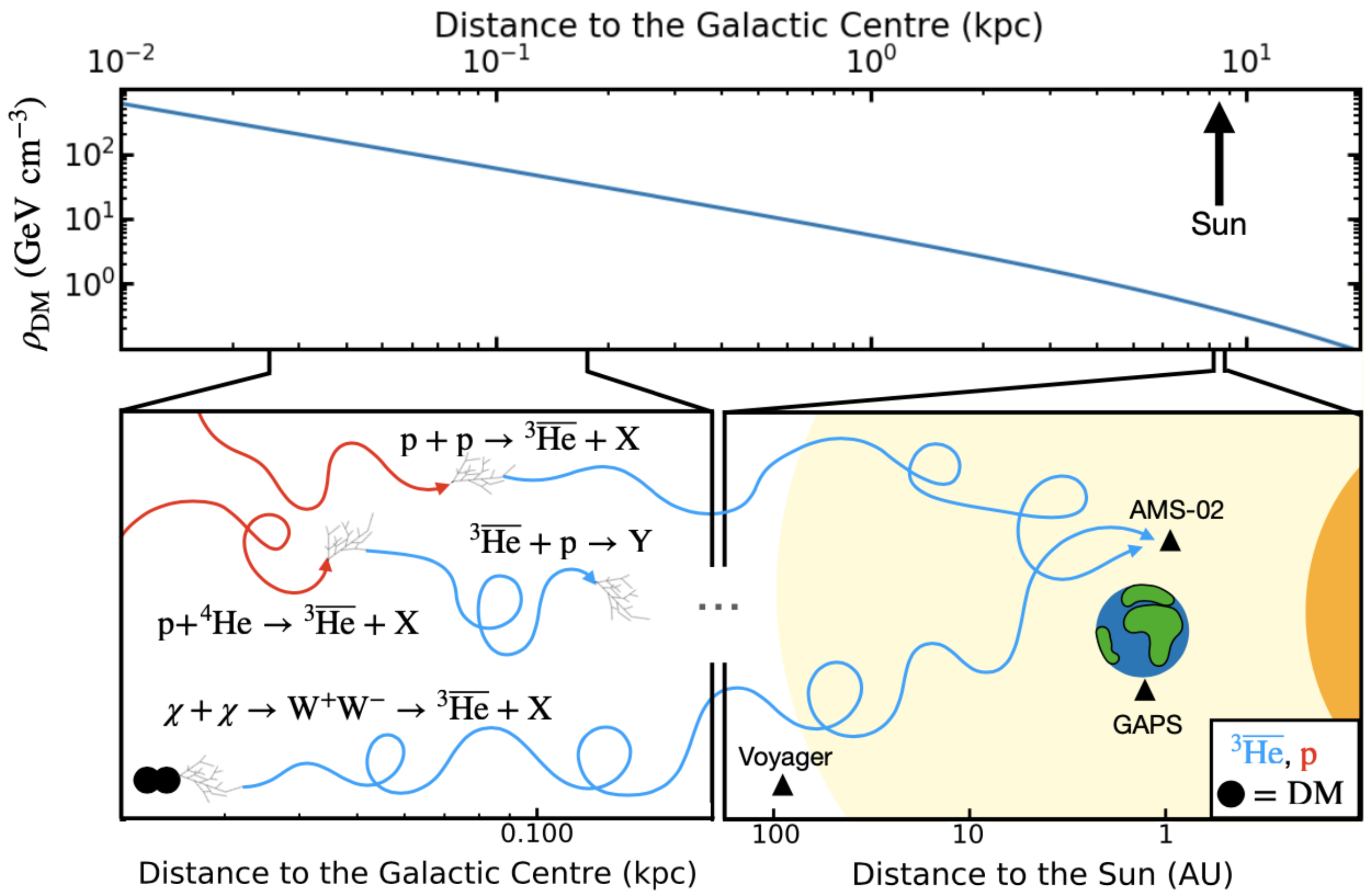
Anti-matter in Cosmic Rays



Anti-matter in Cosmic Rays

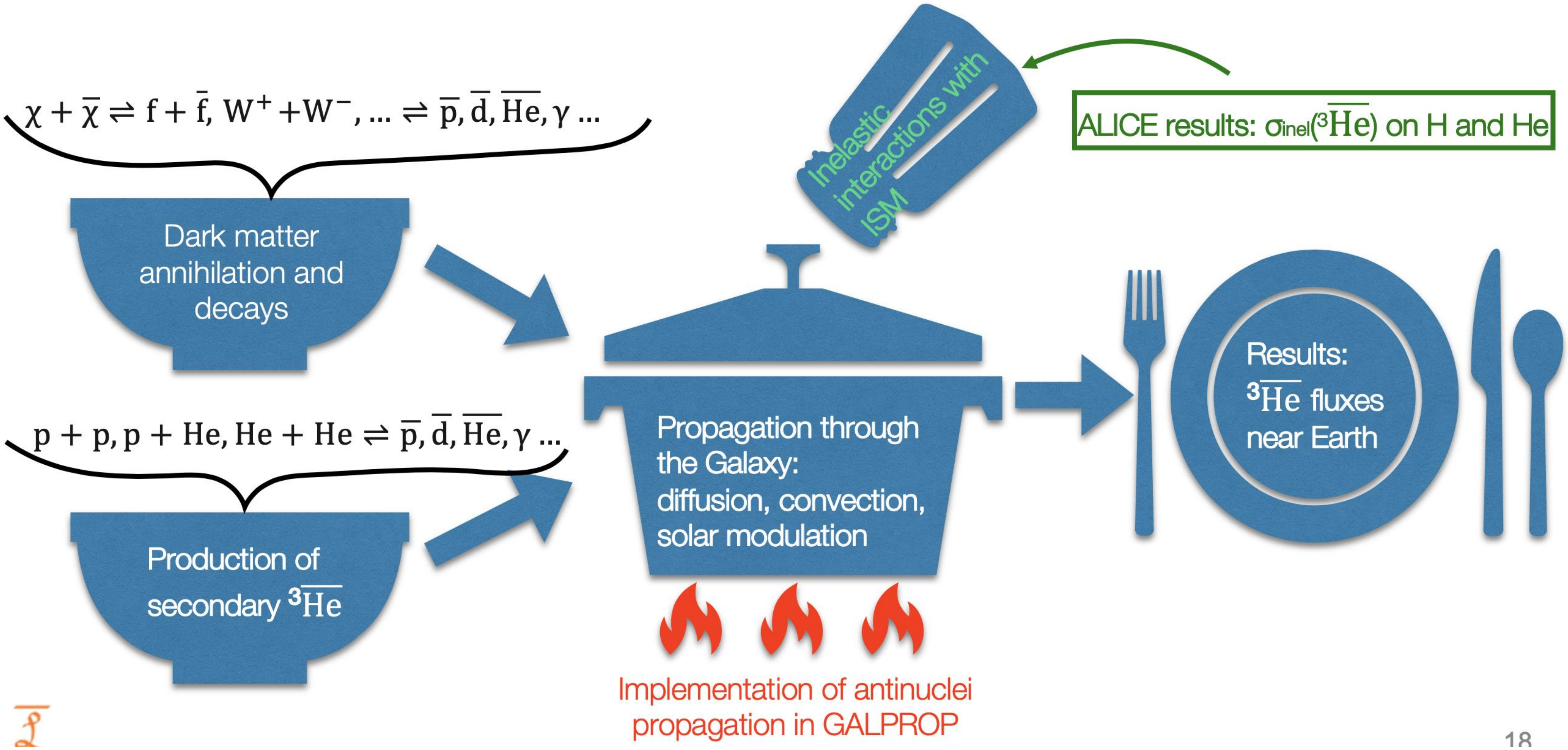
- Observation of light anti-nuclei may be signature of dark matter annihilation*
- Collider experiments produce
  $\overline{d}\,,^{3}\,\overline{\mathrm{He}}\,,^{4}\,\overline{\mathrm{He}}$
- First $^{3}\overline{\mathrm{He}}$ absorption measurement informs propagation through galaxy



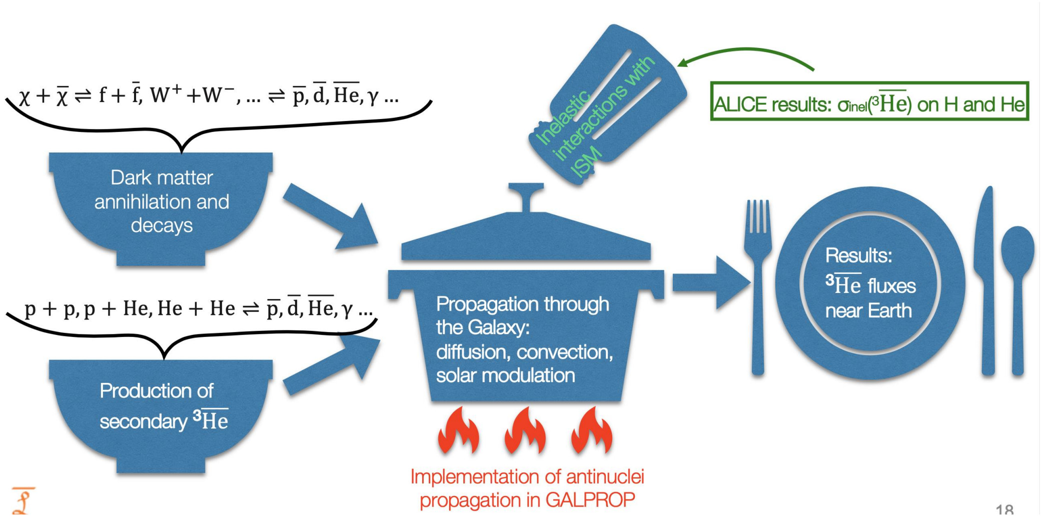


ALICE Coll., arXiv:2202.01549

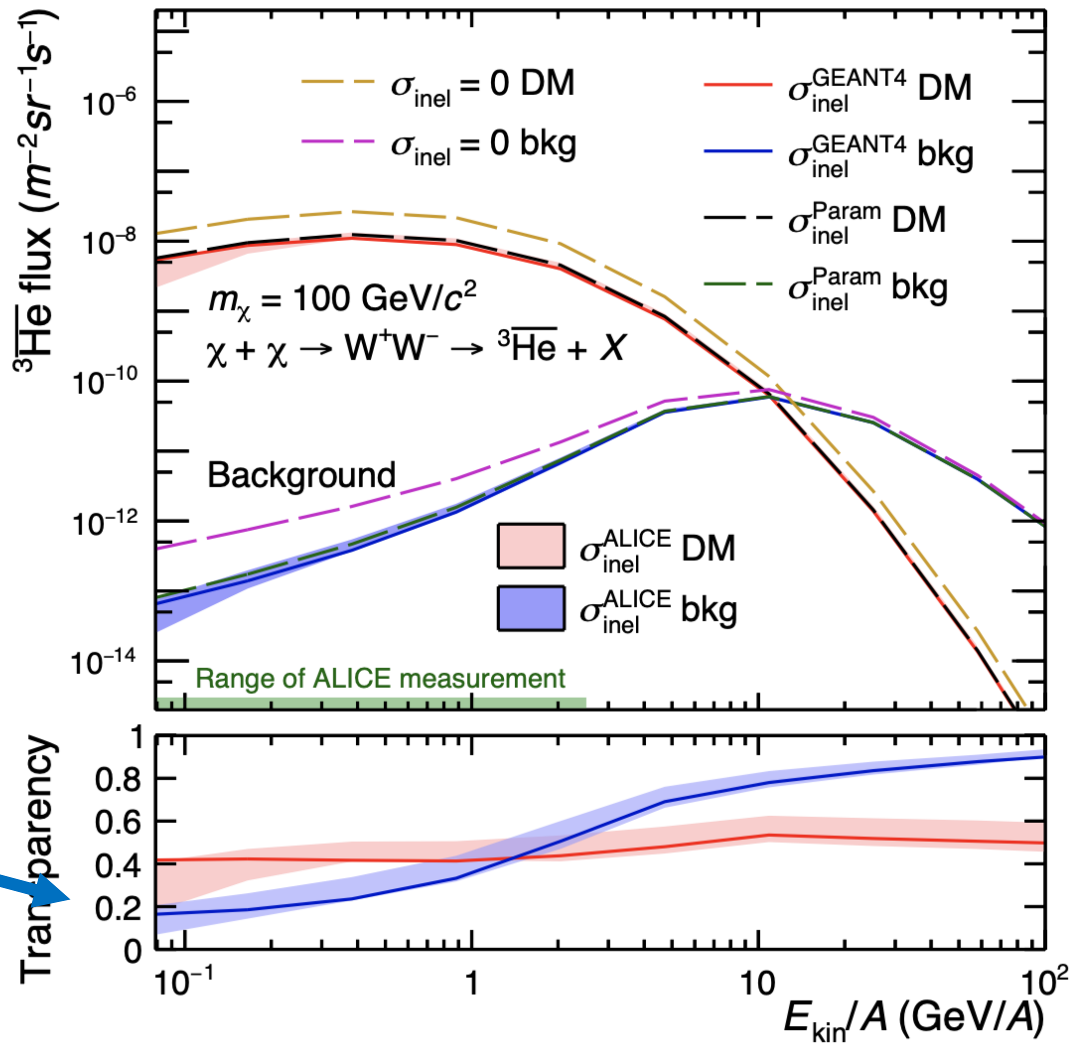
Cooking anti-nuclei fluxes



Cooking anti-nuclei fluxes

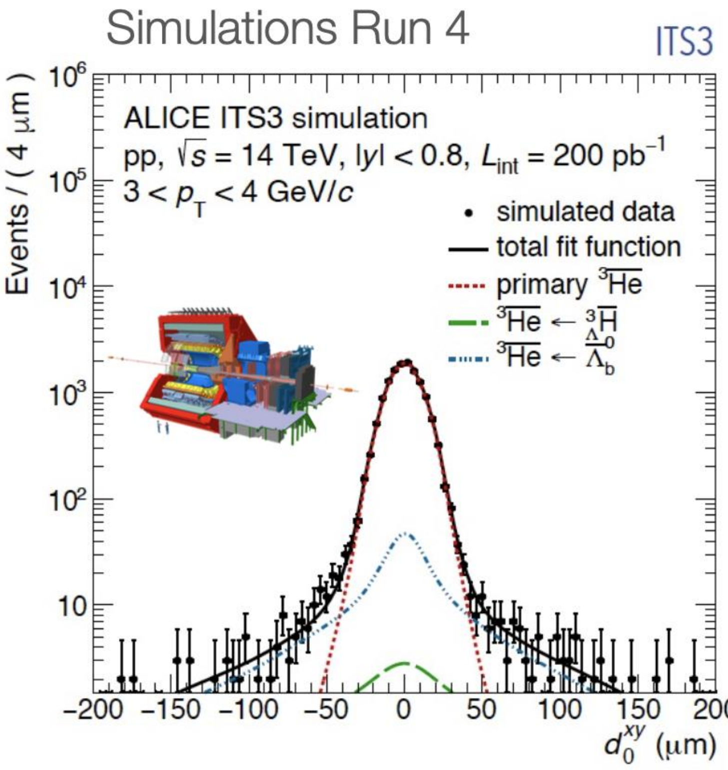


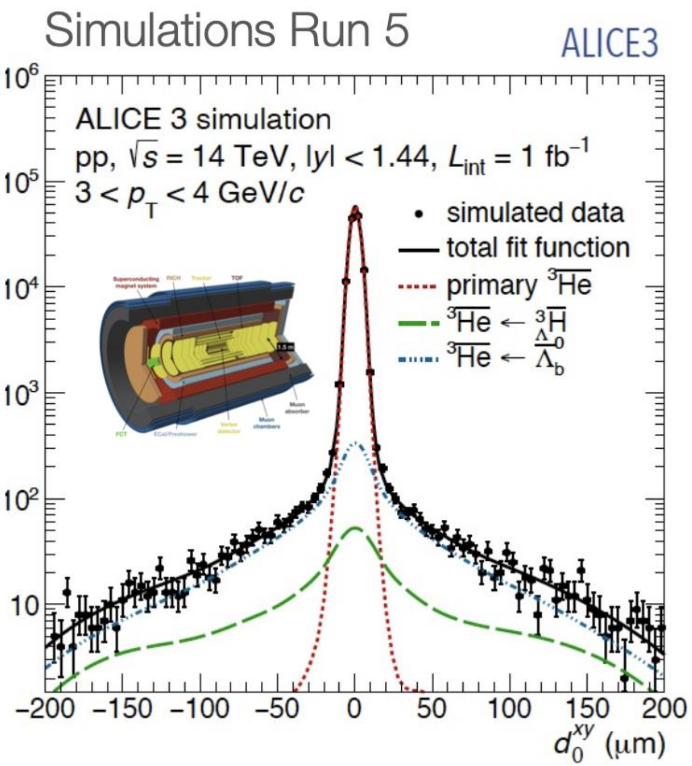
- Absorption reduces known background by factor up to 5

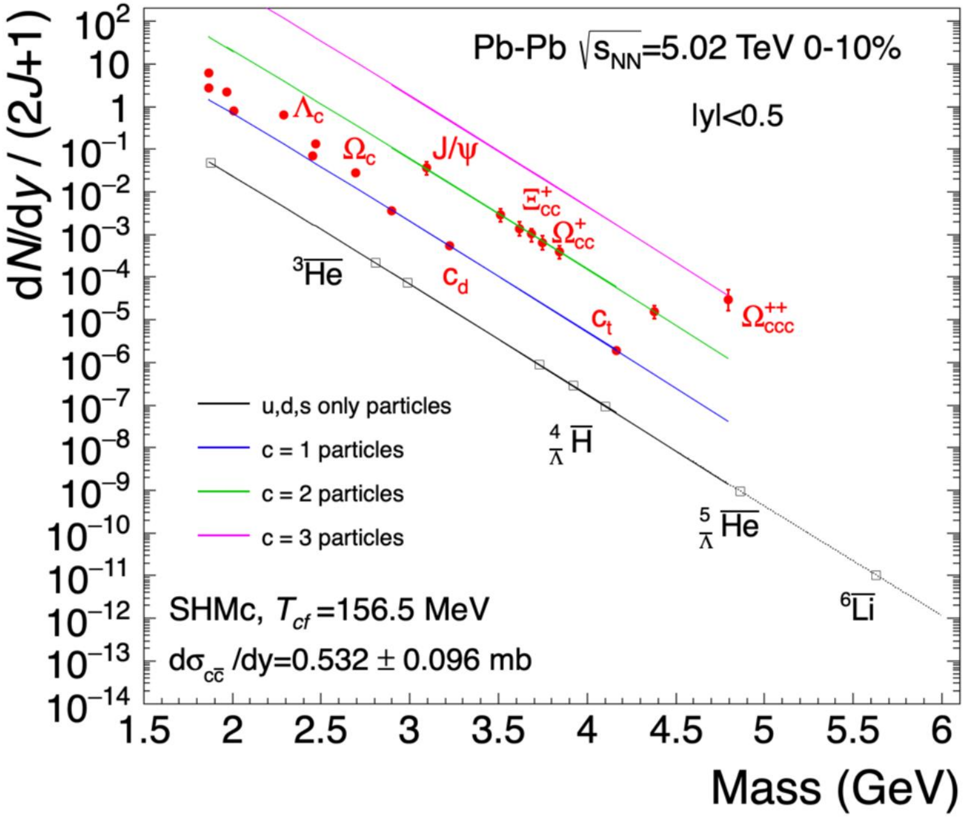


ALICE Coll., arXiv:2202.01549

Future opportunities at the LHC (ALICE + LHCb)





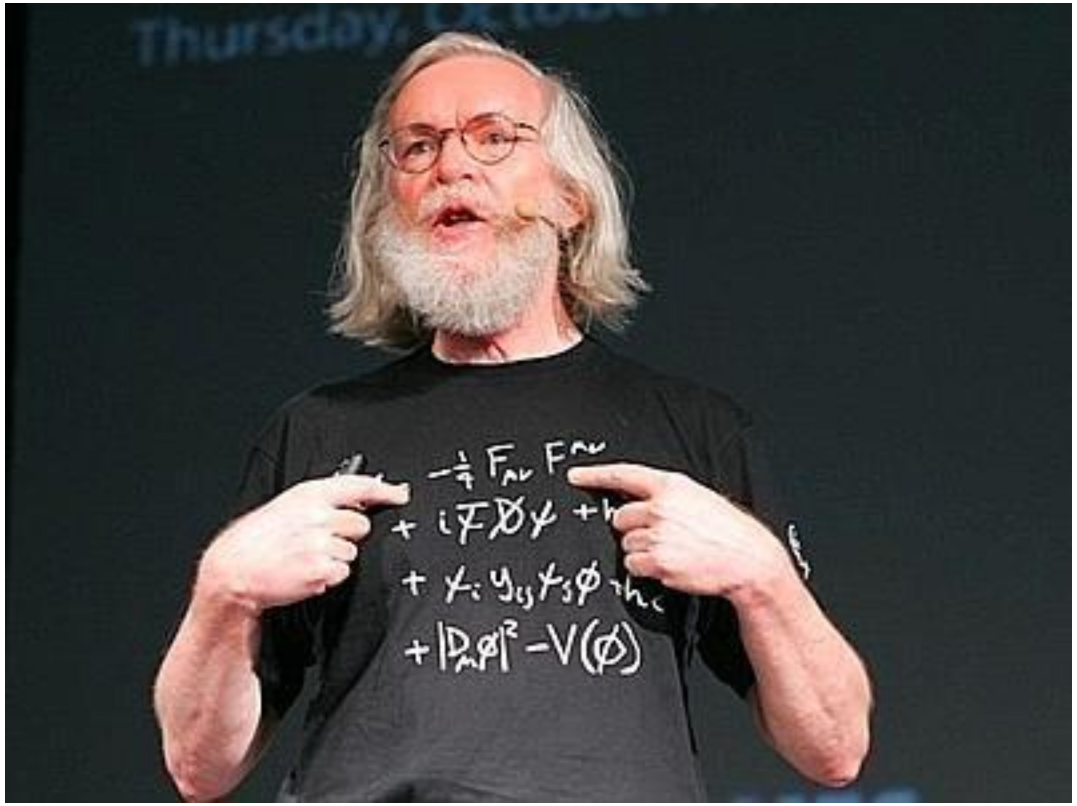


Strong PID+ high rate
+ wide acceptance
+ excellent vertexing

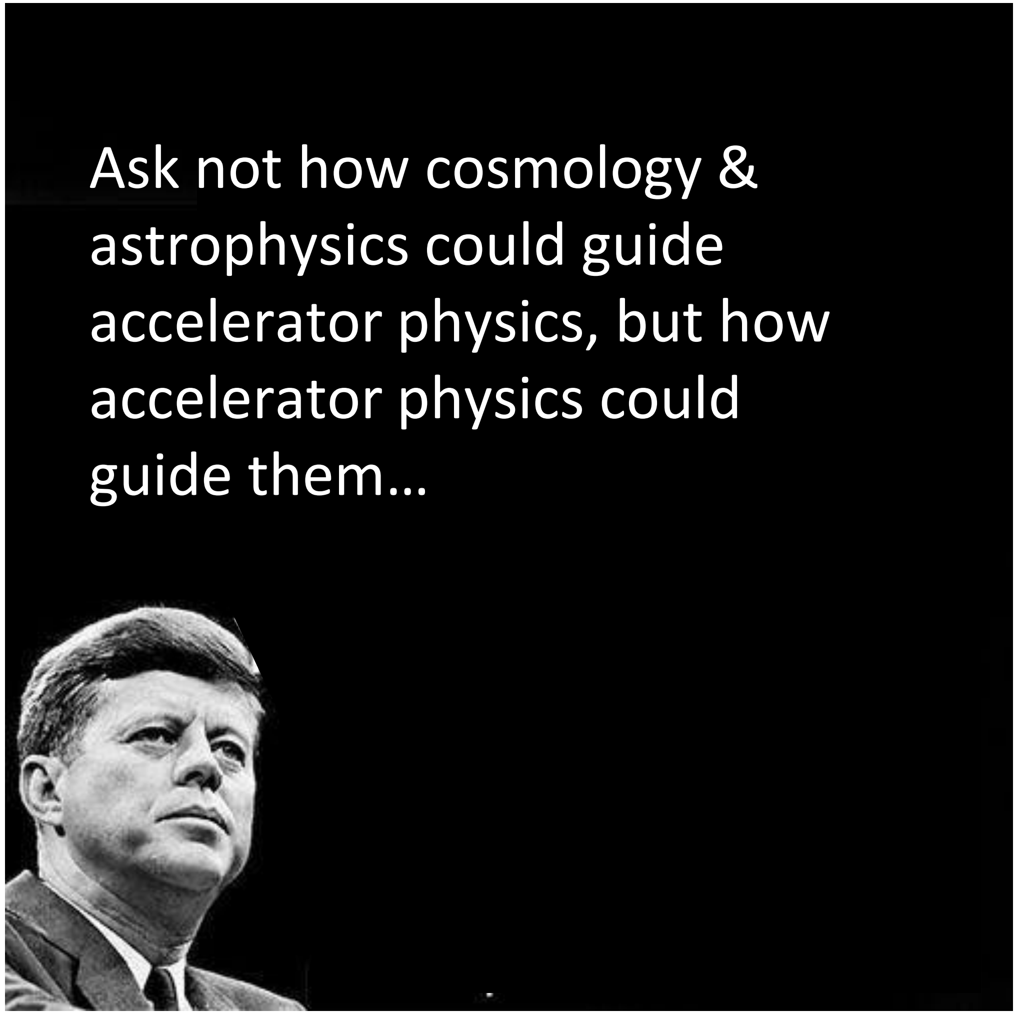
Search for exotic anti-, hyper- and super-nuclei

"Super-nuclei" in reach
- Charmed deuterium
- Charmed triton $c_t \to t + K^- + \pi^+$

Back to the big questions



i.e. open questions related to
- the last line of this T-shirt
- beyond the last line



I think we've got it[1] - what's next?[2]

1 DG P. Heuer, 4 July 2012

2 Charge to numerous theory speakers since then

The big open questions of High Energy Physics

Data-driven

- Dark matter
- Matter/anti-matter asymmetry
- Neutrino masses
- Dark energy
- ….

Theory-driven

- Hierarchy problem /naturalness prob
- Flavour problem
- Origin of inflation
- Quantum gravity
- ….

The guaranteed deliverable for HL-LHC / FCC*

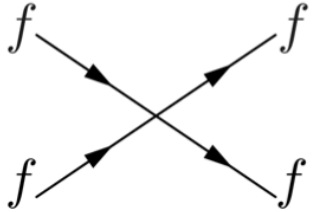
- Is that the correct Higgs-sector?
- What happens at the electroweak phase transition?

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

* See e.g. M. Mangano, https://www.youtube.com/watch?v=XPaep7Hcr_c

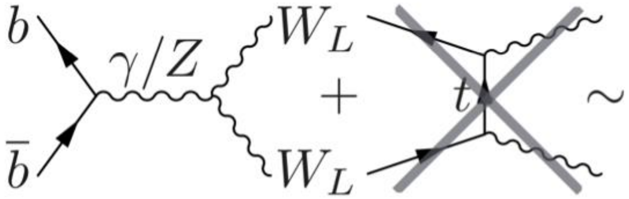
Well-known no-lose theorems of particle physics till 2012

- There must be physics beyond the Fermi scale => intermediate vector bosons



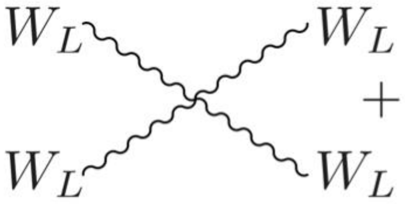
$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \Longrightarrow m_W < 4\pi v$$

- There must be physics beyond the bottom quark => top quark



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \Longrightarrow m_t < 4\pi v$$

- There must be new physics at the TeV scale => Higgs boson



$$+ \ldots \sim g_W^2 E^2/m_W^2 < 16\pi^2 \Longrightarrow m_H < 4\pi v \text{ ~ 3 TeV}$$

Since 2012, there is no no-lose theorem and thus no guaranteed discovery to organize our future efforts in the investigation of fundamental interactions.[1] In principle, the Standard Model could be valid up to the Planck scale.

1 A. Wulzer, arXiv:1901.01017

SMEFT: Agnostic parametrization of what is unknown

- If new physics couples to SM and lies above a high energy cut-off scale Λ
  , it can be parameterized as

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i,n\geq 5} \frac{c_i\, \mathcal{O}_i^{(n)}}{\Lambda^{n-4}}$$

- There are many gauge-invariant operators $\mathcal{O}_i^{(n)}$ (2499 operators for n=6 …)

- "Higgs portal" operators at n=4, 5, e.g.

$$\Delta\mathscr{L}_4^S = -\frac{1}{2}M_S^2S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}H^\dagger H S^2,$$

- In this framework, conceivable solutions to fundamental problems (such as dark matter, matter/anti-matter asymmetry and neutrino masses) can be formulated.

An example: baryon asymmetry

- Baryon asymmetry (as measured from CMB) $n_B/n_\gamma = (6.12 \pm 0.04) \times 10^{-10}$
- Sakharov's three conditions for generating baryon asymmetry in Our Universe:

i. Baryon number must be violated

ii. C and CP must be violated

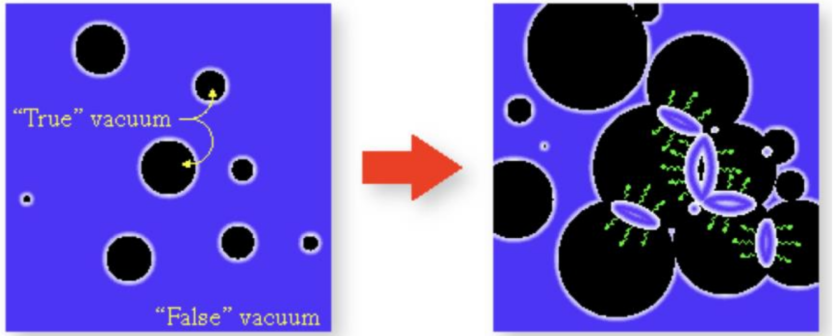
iii. Interactions must be out-of-equilibrium

In Standard Model at elwk scale:

$$\partial_\mu J^\mu_B = \frac{n_f}{32\pi^2} g^2 F^a_{\mu\nu} \tilde{F}^{a\,\mu\nu}$$

Not enough CP violation in CKM matrix, additional sources of CP-violation needed

elweak phase transition not 1st order



What's next? – the sober answer of EPPSU

"The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark- gluon plasma, should be exploited."

The scientific and technological reasoning behind this recommendation has been explained repeatedly, see e.g.

Shaping the Future of Particle Physics:

(CERN Academic Training Lecture Series)

- Theory[1] Keith Ellis,
- Experiment[2] Paris Sphicas
- Accelerators[3] Frank Zimmermann

1 https://www.youtube.com/watch?v=tEt542BipsY
2 https://www.youtube.com/watch?v=cYyOHqupRDU
3 https://www.youtube.com/watch?v=qHe79o_-lzg

Widely varying personal (!) opinions:

"… Can this capture the imagination of society and effectively compete for research funds with the likes of the breath- taking images and deeper understanding of the universe from the James Webb telescope?" *J. Kirkby, Cloud spokesperson*

"Today, there is no known alternative to colliders to clarify the origin of the Higgs boson. So, colliders must go on."
M. Mangano, CERN theorist, LPCC coordinator

"As scientists, we should welcome the important complementarities of lab-based experimental and space-based observational approaches – since the early days of observational cosmology, we have historical evidence for how fruitful their interplay can be." *UAW*

The END

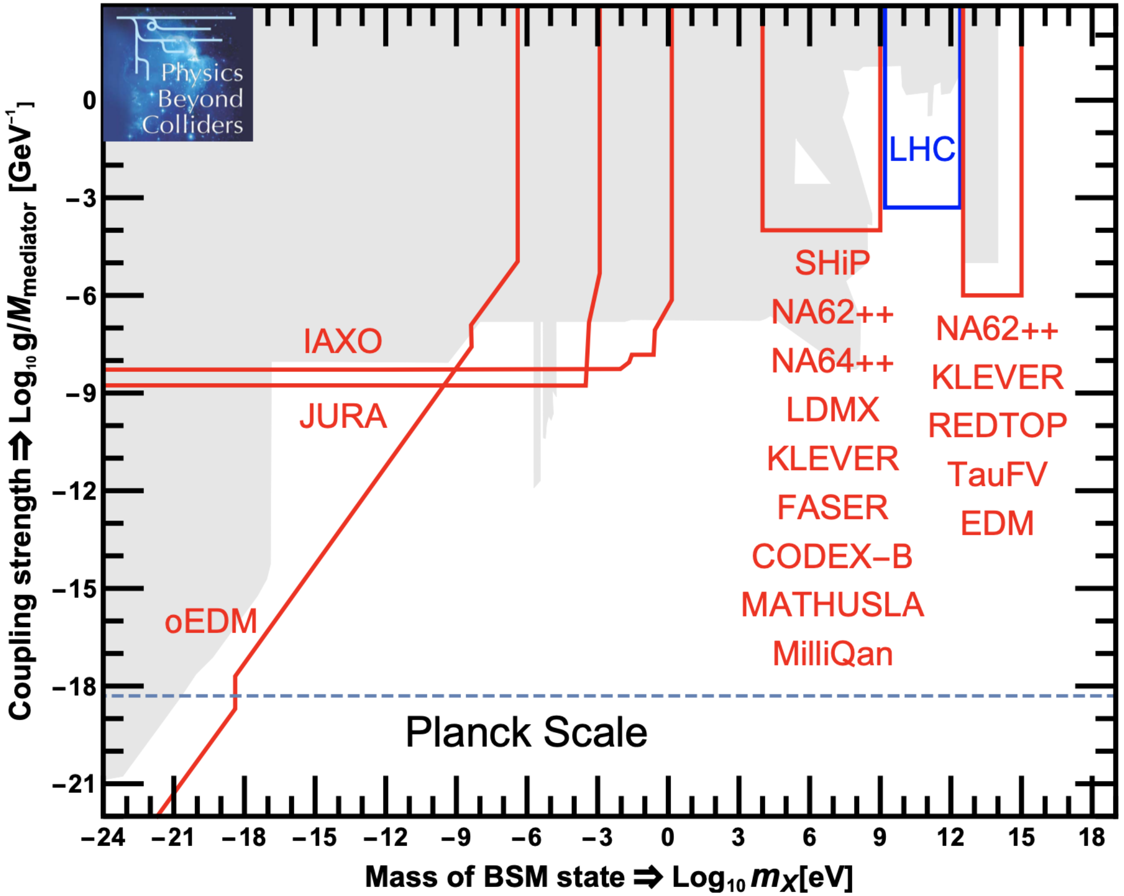
Physics beyond Colliders @ CERN

- The **portal framework** classifies BSM models for "dark sector" DS

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

- Opportunities for lab-based discoveries evaluated in community-wide studies*

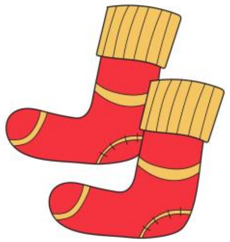


*PBC initiative, J.Phys.G 47 (2020) 1, arXiv:1901.

Searching for the Higgs is not searching for socks

Assume your kid has lost its socks

i. Either in the bathroom ("LEP")
ii. Or in its bedroom ("nearby LHC")
iii. Or on a school trip ("far away, Planck scale")



Your search in the bathroom yields **nothing.**
You **can't conclude that the socks are nearby** in the bedroom.

When **LEP didn't find the Higgs** at $m_H < 114$ GeV,

we could conclude that the Higgs is nearby.

Our search logic differs in a subtle but qualitative way.