Cosmology and Particle Physics

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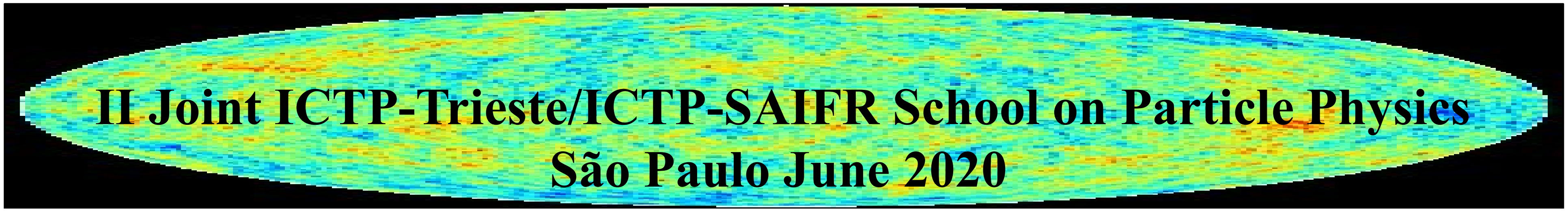
Lecture I: The average Universe
Lecture II: Origins
Lecture III: The perturbed Universe



Plan:

II.1 – Origin of light elements

II.2 – Origin of baryons

II.3 – Origin of dark matter

II.4 – Origin of atoms and the CMB

II.5 – Origin of inhomogeneities

II.1–Origin of light elements

Big Bang Nucleosynthesis (BBN): one of the pillars of the Standard Cosmological Model [review 1505.01076]

- the earliest cosmological probe (~ few minutes)

- idea goes back to George Gamow and students (late 1940's)

- details involve a complicated set of nuclear reactions which can be studied with sophisticated codes

- here will present a very simplified picture of BBN

BBN in four easy time steps

a. When T>>1 MeV (t<<1 s): Universe made out of n, p, e, n, γ
Neutrons and protons in thermal equilibrium due to the weak for

When T~ few MeV, protons and neutrons are non-relativistic wit

$$\frac{n_n}{n_p} = e^{-(m_n - m_p)/T} = e^{-Q/T}$$

Notice that the neutron-proton mass difference (Q~ 1.3 MeV) is very small compared to their masses (m_n~m_p~ 1 GeV).

b. Neutrons and protons freeze out at T=0.8 MeV; their number remain constant aftwerwards (number densities ~ a^{-3}). Neutron fraction becomes:

$$X_n^{\mathrm{f.o.}} = \frac{n_n}{n_n + n_p} = \left.\frac{e^{-Q/T}}{1+e^{-Q/T}}\right|_{T=0.8\mathrm{MeV}} \simeq \frac{1}{6}$$

c. This number is almost frozen except for the fact that free neutrons decay with a lifetime t_n~900 s. Hence, after freeze-out

$$X_n(t) = e^{-t/\tau} X_n^{\mathrm{f.o.}}$$

d. Formation of helium:

$$n + p \leftrightarrow D + \gamma$$

$$D + p \leftrightarrow^3 He + \gamma$$

$$D +^3 He \leftrightarrow^4 He + p$$

^{4}He can only form when D and ^{3}He can be present – temperature must be smaller than D binding energy – $T_D \sim 0.06$ MeV ($t_D \sim 330$ s)

$$X_n(330\text{ s}) \sim 1/8$$

At this point it is a good approximation to assume that all neutrons are used to make ^{4}He.

Exercise 1: show that the mass fraction in ^{4}He is: $Y_{He} = \frac{4n_{He}}{n_p} \sim \frac{1}{4}$

fter the first 3 minutes of the Universe ~ 25% of the mass o
oms are in the form of ^{4}He. There are also small quantites o
, ^{3}He, and ^{6}Li.

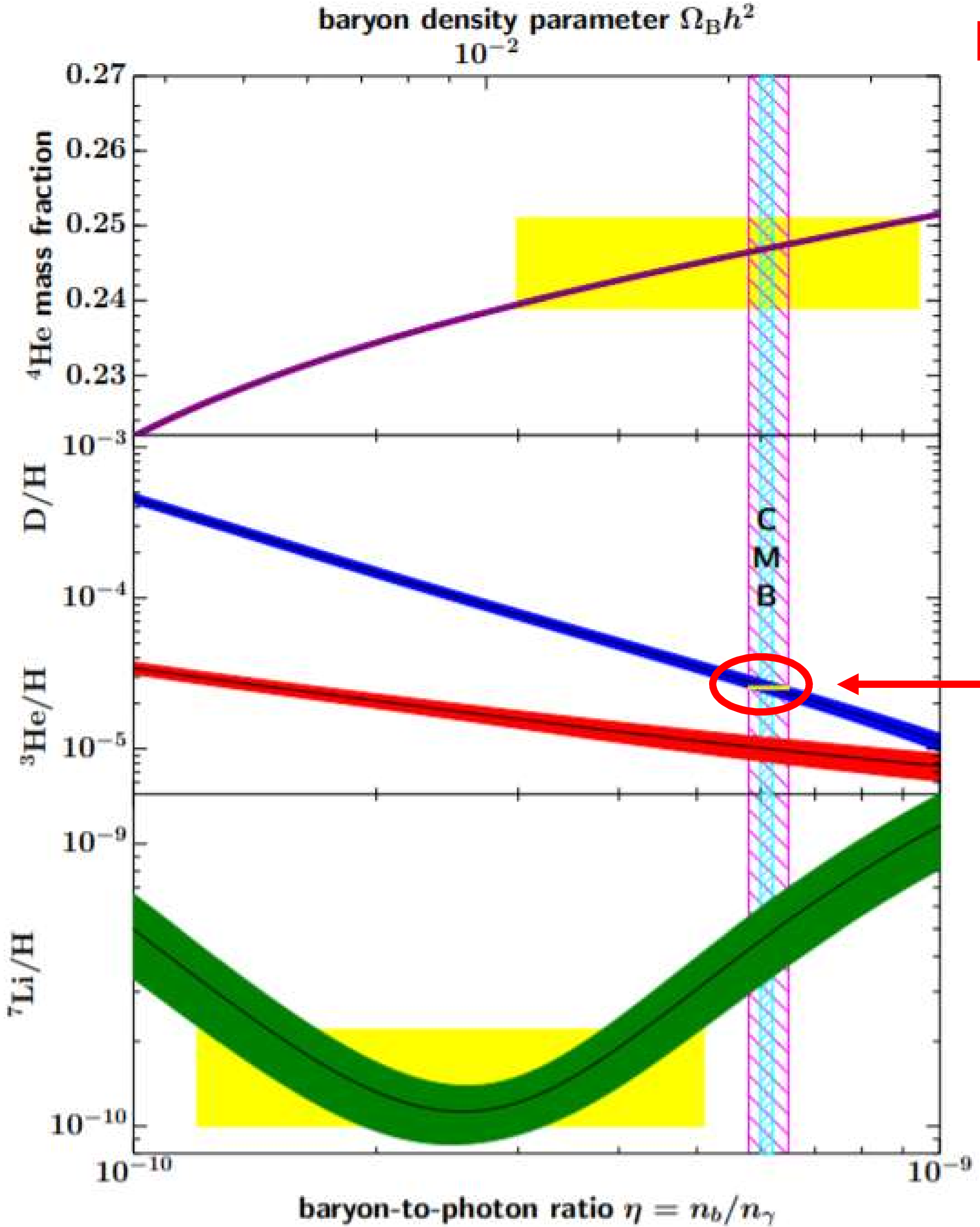
hese difficult measurements determine the number of baryo
d the number of neutrinos in the Universe.
ood agreement with other probes (such as CMB)

aryon-to-photon ratio:

$$\eta = \frac{n_b}{n_\gamma} = (6.10 \pm 0.04) \times 10^{-10}$$

(Planck)

euterium abundance is very sensitive to η.



PDG 2020

Amazing agreemen

BBN ~ 100 sec

CMB ~ 380000 ye

II.2– Origin of baryons

very disturbing calculation for baryogenesis

t's estimate the freeze-out of baryons assuming a
pical baryonic cross section: $\langle \sigma v \rangle = \dfrac{1}{m_\pi^2}; \ m_\pi \sim 100$ M

$$n(T_F)\langle \sigma v \rangle = H(T_F)$$

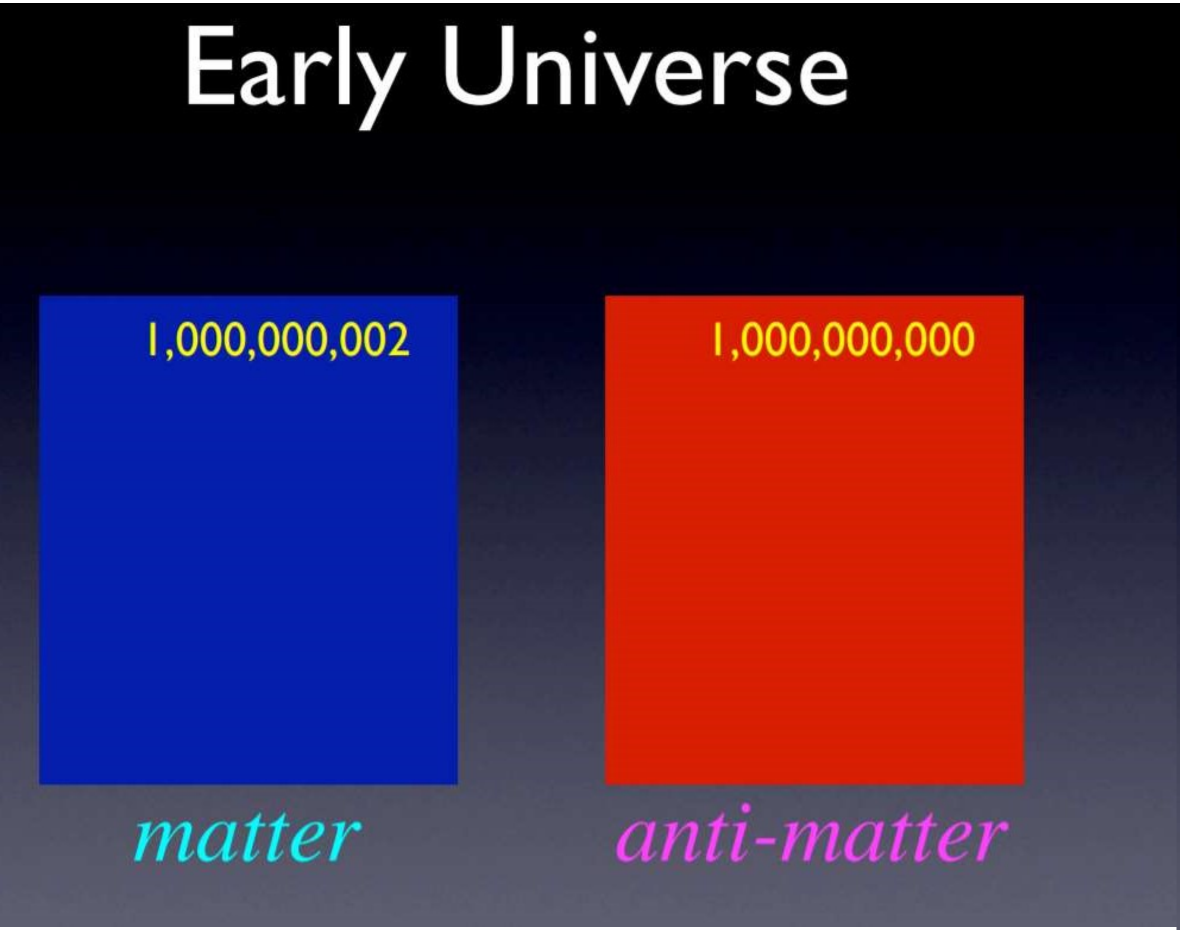
eeze-out temperature: $\dfrac{m_N}{T_F} \simeq \ln \dfrac{m_N M_{\rm Pl}}{m_\pi^2} \simeq 50$

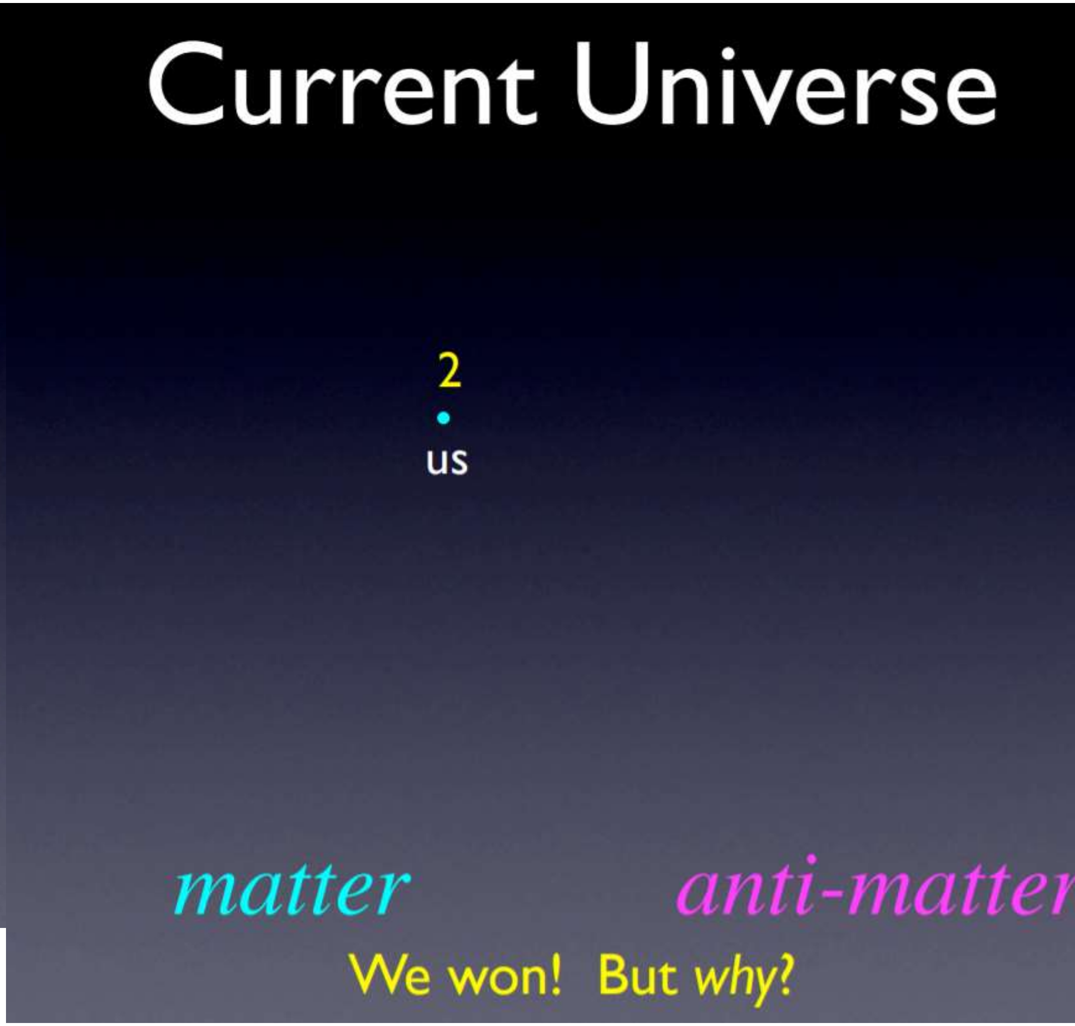
rcise 2: show that the freeze-out temperature is given by value above

Why is this disturbing? Because the resulting η is:

$$\eta = \left(\frac{m_N}{T_F}\right)^{3/2} e^{-m_N/T} \sim 10^{-19}!!$$

The Universe can not be baryon–antibaryon symmetric:
here must exist a mechanism to create a tiny asymmetr
1 in 10^9 is enough).


Early Universe
1,000,000,002
1,000,000,000
matter
anti-matter


Current Universe
2
us
matter
anti-matter
We won! But why?

Murayama

How can one generate this asymmetry?

Sakharov's conditions (1967!):

- baryon number violation
- C and CP violation
- Non-equilibrium process

There is no standard model of baryogenesis:
GUT's, leptogenesis, SM

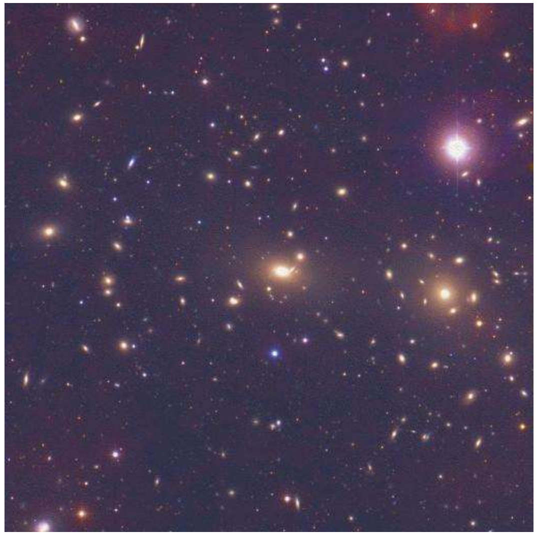
Motivates searches for new sources of CP violation (eg, LHCb, neutrino sector). Jury is still out.

II.3- Origin of dark matter

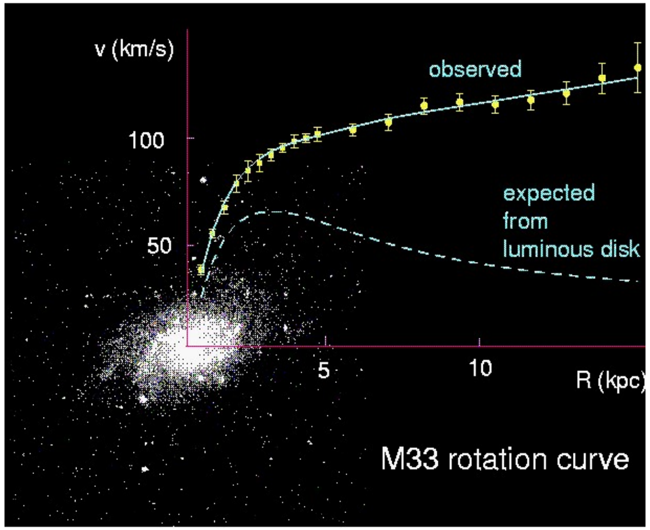
II.3.I – Observational evidences

Dark matter exists – Ω_{DM}~0.25.
Evidences from many different observations at different scales – all astronomical so far!

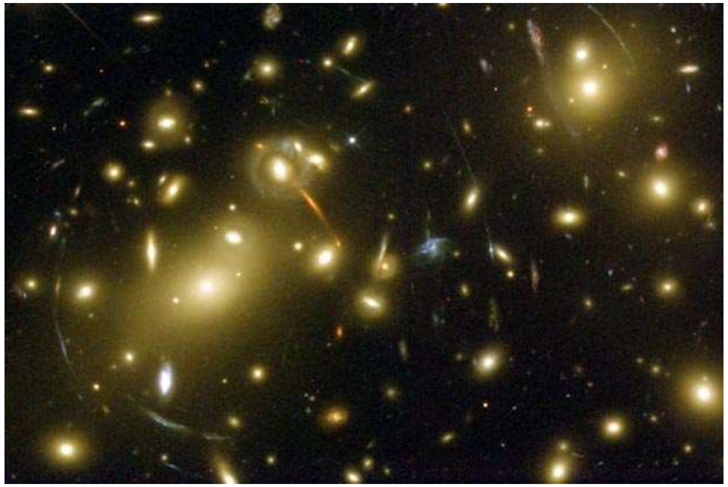
Dispersion velocity of galaxies in clusters (30's)



Galaxy rotation curves (70's)



Gravitational lensing



The DARK MATTER problem has been with us since the 1930's, name coined by Fritz Swicky in Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

On page 122

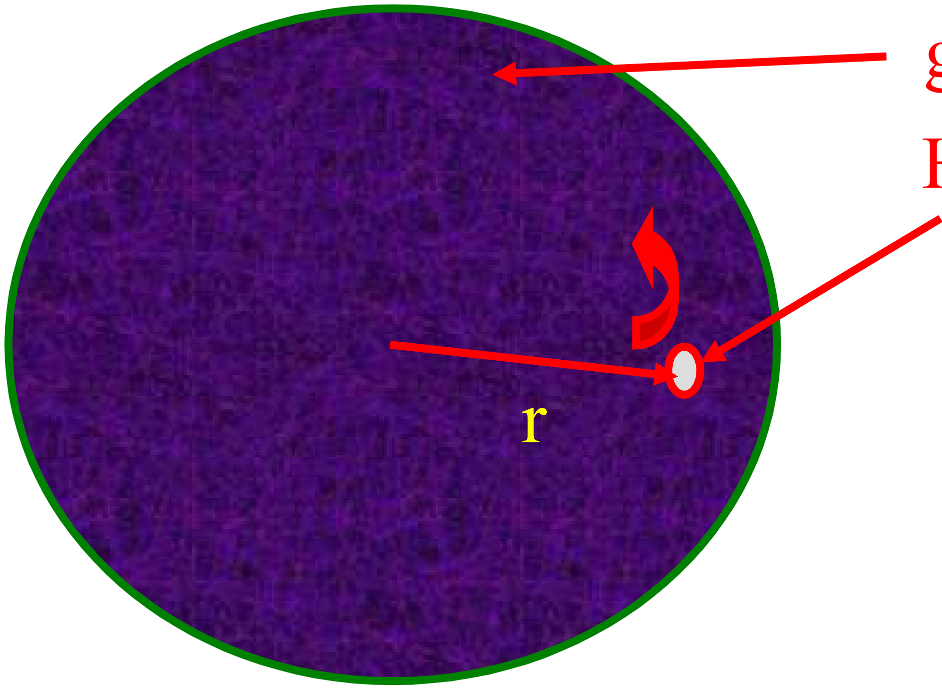
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm³ erscheint daher nicht

He used the Virial theorem in the Coma Cluster: found its galaxies move too fast to remain bounded bv the visible mass onlv

Dunkle = dark
Kalte = cold!!

Gelmini WIN 2013

Galaxy rotational curves



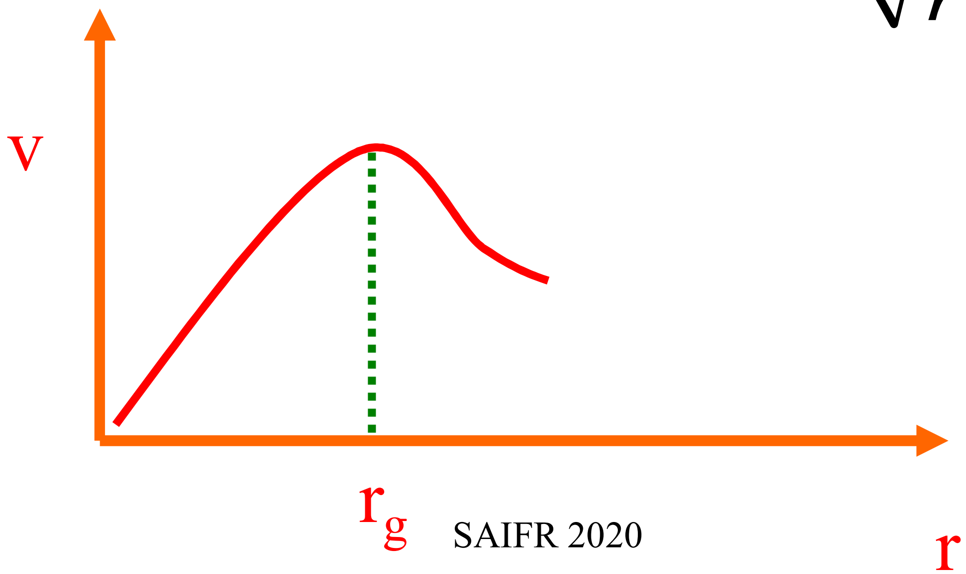
$$m\frac{v^2}{r} = \frac{GmM(r)}{r^2}$$

“Inside” the galaxy:

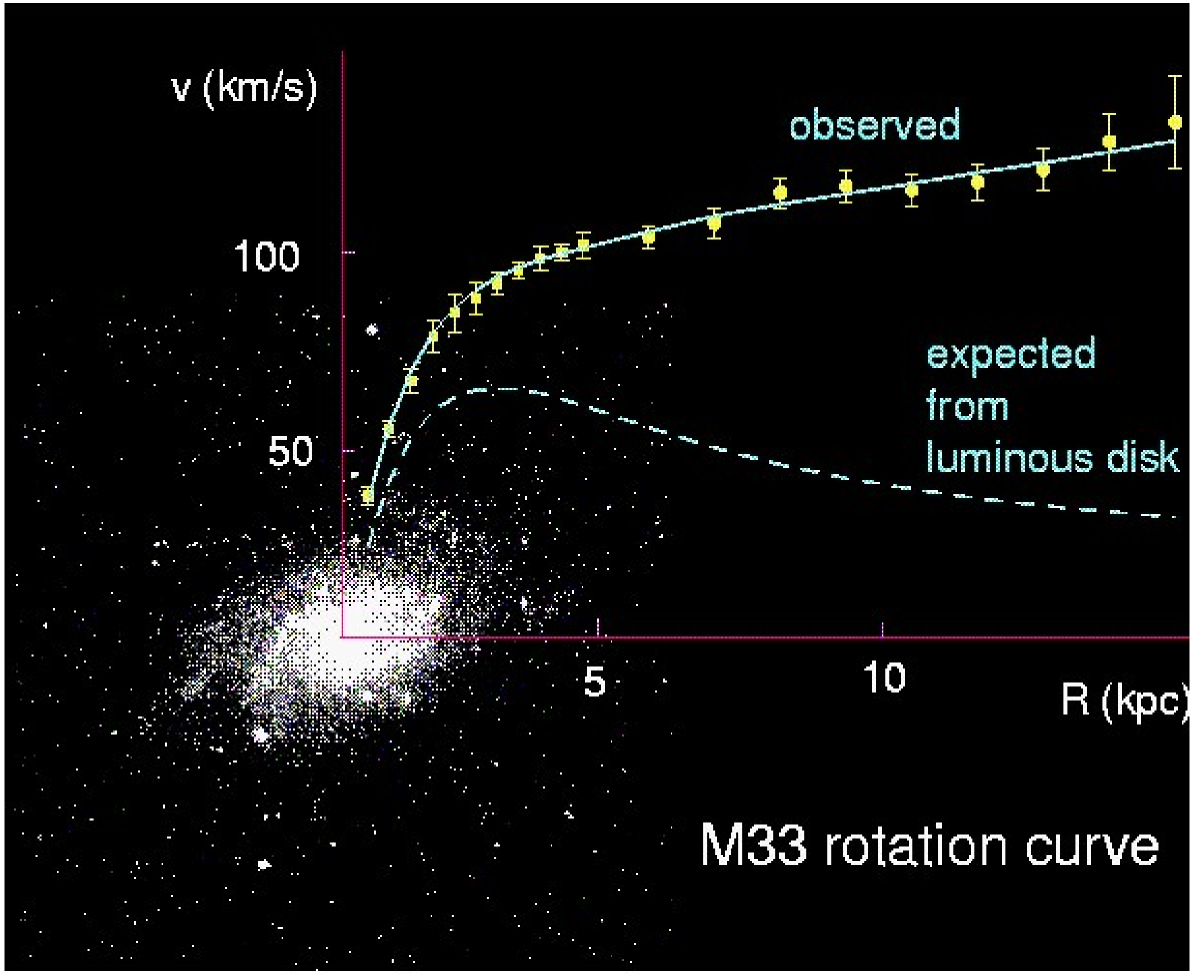
$$M(r) = \frac{4\pi}{3} r^3 \rho \Rightarrow v \propto r$$

“Outside” the galaxy:

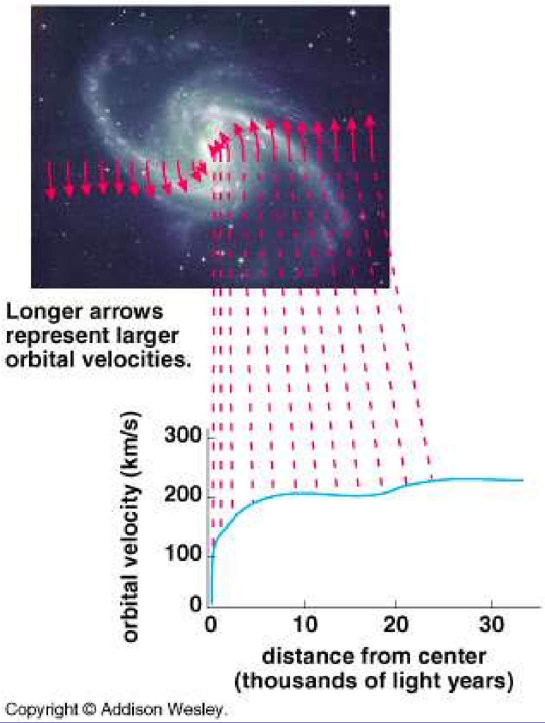
$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$

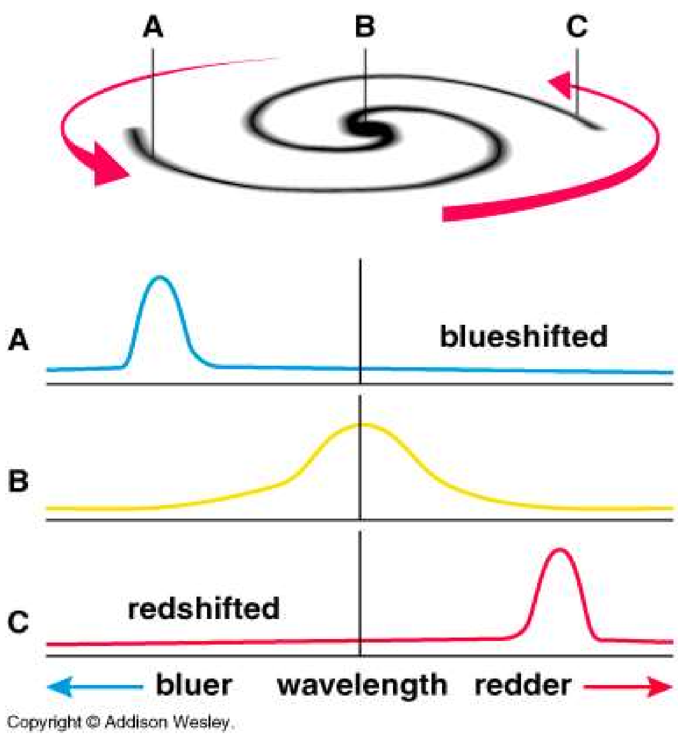


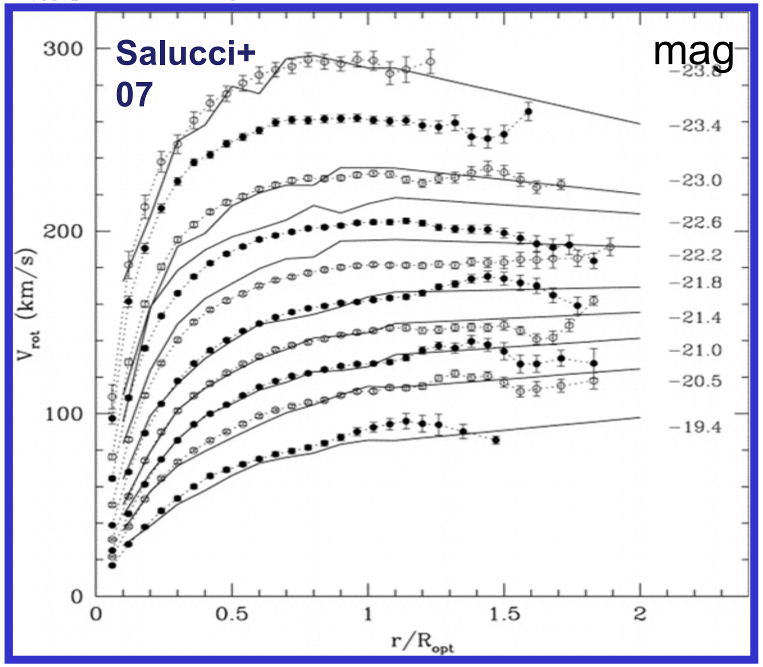
Vera Rubin
1928- 2016



1970's and 1980's





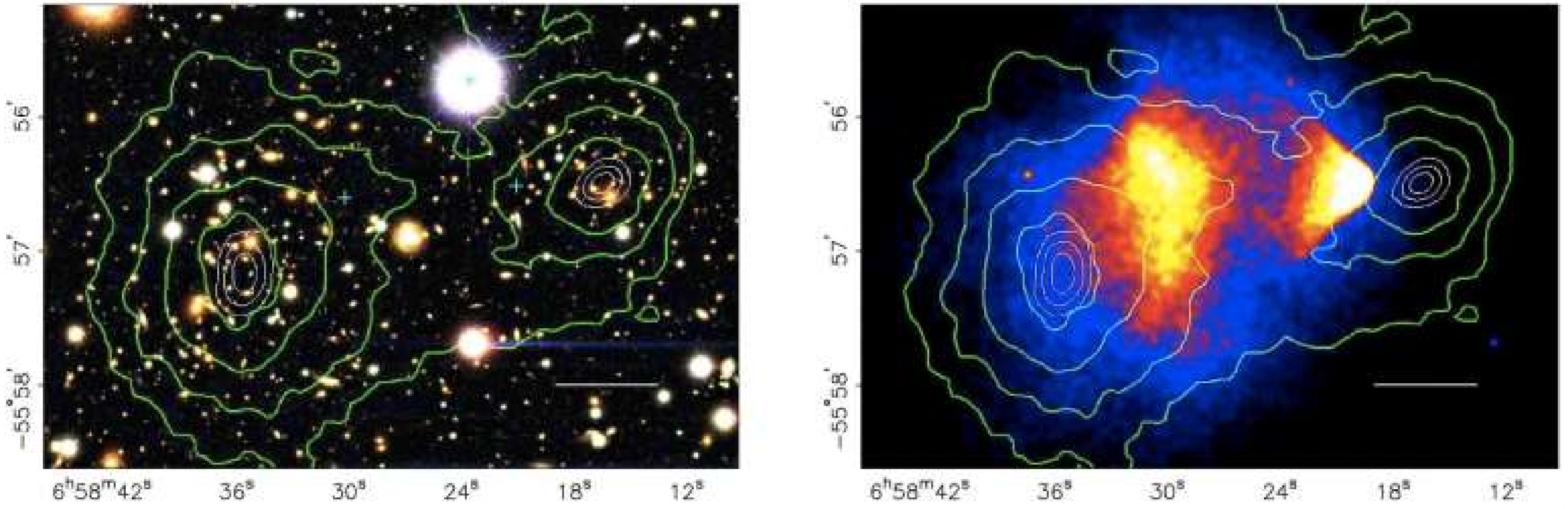


In ΛCDM scenario the density profile for virialized DM halos of all masses is empirically described at all times by the universal (NFW) profile (Navarro+96,97).

$$\rho(r)/\rho_{crit} \approx \delta\, r_s / r(1 + r/r_s)^2$$

Bullet cluster

https://youtu.be/rLx_TXhTXbs



a) Optical images from the Magellan telescope with overplotted contours of spatial distribution of mass, from gravitational lensing . b) The same contours overplotted over Chandra x-ray data that traces hot plasma in a galaxy. It can be seen that most of the matter resides in a location different from the plasma (which underwent frictional interactions during the merger and slowed down).

https://astrobites.org/2016/11/04/the-bullet-cluster-a-smoking-gun-for-dark-matter/

Dark matter in our vicinity

Important parameter for direct dark matter detection!

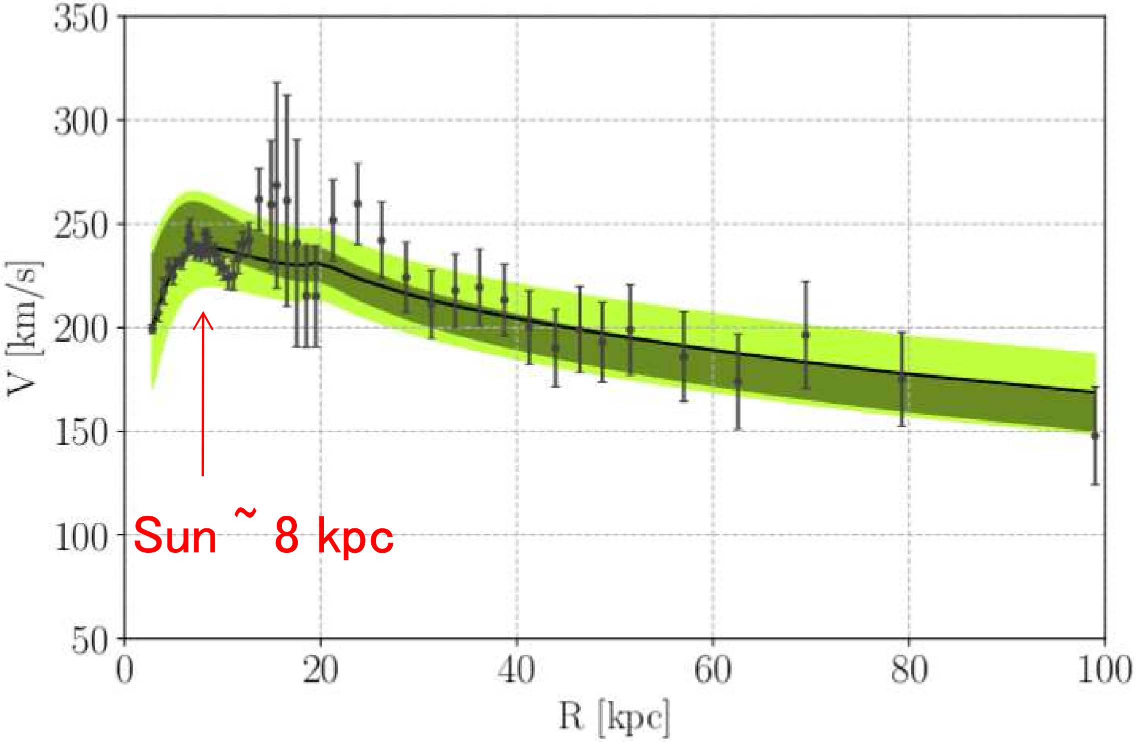


Figure 8: *Based on real data.* Black solid line indicates the RC using the maximum likelihood parameter values for our reference baryonic morphology. Dark green and light green bands show the RC corresponding to 68% and 95% credible region (HPD) in our parameter space (dark matter + baryonic nuisance parameters), using our reference baryonic morphology.

Karukes et al. 1901.02463

- Based on the kinematic data and the Galactic parameters used in this work, we infer a local dark matter density is $\rho_0 = 0.43 \pm 0.02 \pm 0.01\,\mathrm{GeV/cm^3}$, where the first errors are statistical and the second systematic (assuming different baryonic morphologies).

Observational evidences for DM

I. Dynamics of clusters of galaxies
II. Rotational curves of galaxies
III. Gravitational lensing
IV. Cosmic microwave background
V. Big bang nucleosynthesis
VI. Structure formation in the universe
VII. Baryon acoustic oscillations
VIII. Bullet cluster

What is dark matter? Most possibly a stable (or very long-lived), neutral particle.

In the SM there are neutrinos but:

- they are light and $\Omega_\nu < 0.01$
- actually dark matter particles that are relativistic at decoupling are ruled out by the observations of the structure of the Universe – small scale perturbations are suppressed.

$\boxed{\text{Dark matter implies physics beyond the SM}}$

Several candidates: weakly interacting massive particles (WIMPs), new scalars (phion, inert Higgs models), ν_R, axions, primordial black holes, lightest KK particle,...

WIMPs are predicted in SUSY extensions of the SM: The lightests supersymetric particle (LSP), usually a neutralino (combination of gauginos and higgsinos).

Candidates must pass several observational constraints:

Dark matter candidates

arXiv:0711.4996

DM candidate	I. Ωh^2	II. Cold	III. Neutral	IV. BBN	V. Stars	VI. Self	VII. Direct	VIII. γ-rays	IX. Astro	X. Probed	Result
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
Sterile Neutrinos	~	~	✓	✓	✓	✓	✓	✓	✓!	✓	~
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
B^1 **UED**	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

Table I: Test performance of selected DM candidates. The ✓symbol is used when the candidates satisfy the corresponding requirement, and it is accompanied by a ! symbol, in the case that present and upcoming experiment will soon probe a

II.3.2 – Thermal production of DM: the “miracle”

Disclaimer: we will present a very simple way to estimate the relic abundance of thermally produced DM particles.

For accurate estimates one must solve the appropriate Boltzmann equation with the correct thermally averaged cross section. There are specialized codes such as MicroOmegas, DarkSUSY, …

Dark matter particles were in thermal equilibrium

$$\chi\bar{\chi} \leftrightarrow f\bar{f}, VV, \ldots$$

$$\Gamma = n\langle\sigma\,\mathrm{v}\rangle >> \mathrm{H}$$

Interaction rate

Density of particles

velocity

Scattering cross section (thermal average)

Expansion rate

If number of dark matter particles does not change (reactions that can change it are inefficient)

$$\mathrm{DM}\ \mathrm{DM} \not\rightleftharpoons \mathrm{SM}\ \mathrm{SM}$$

Number of DM particles is frozen (out of chemical equilibrium). That happens when

$$\Gamma \approx H$$

$$\frac{dN}{dt} = \frac{d\left(a^3 n\right)}{dt} = a^3 \frac{dn}{dt} + 3a^2 \frac{da}{dt} n = 0 \Rightarrow$$

$$\frac{dn}{dt} + 3Hn = 0$$

Recall that: $$H(T) \sim \frac{T^2}{M_{\rm Pl}}$$

and at freeze-out:

$$n_F \sim \frac{T_F^2}{\langle \sigma v \rangle M_{\rm Pl}}$$

Since we are interested in cold dark matter, its number density at freeze-out is:

$$n_F = (m_\chi T_F)^{3/2}\, e^{-\frac{m_\chi}{T_F}}$$

Exercise 3: define $x = m_x / T$ and show that:

$$x^{1/2} e^{-x} = \frac{1}{m_\chi \langle \sigma v \rangle M_{\mathrm{Pl}}}$$

For $m_x = 100$ GeV, $s = G_F^2 m_x^2$, $v=0.3$ show that

$$x_F \sim 30$$

Computing the dark matter relic abundance:

$$\Omega_\chi = \frac{m_\chi n_\chi(T = T_0)}{\rho_c^{(0)}}$$

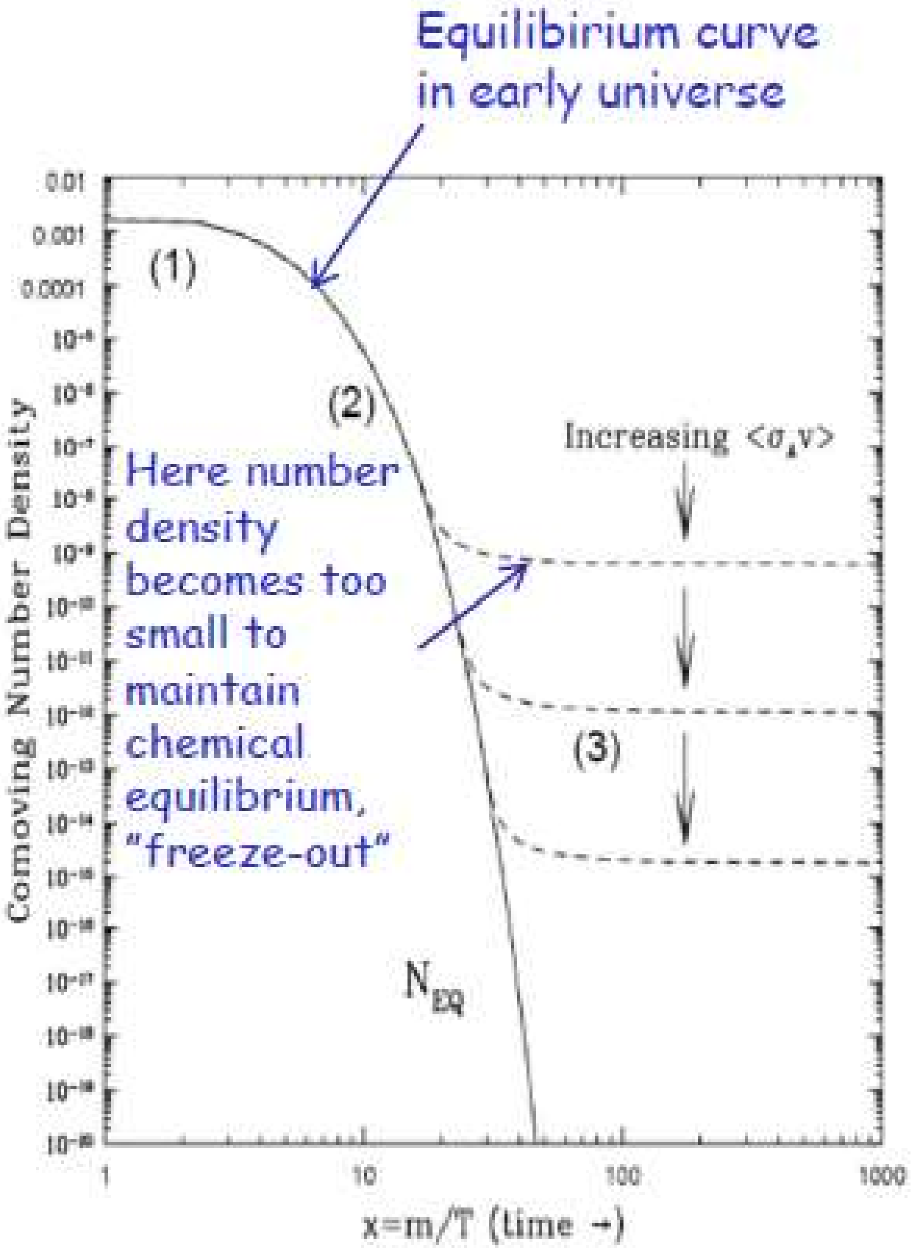
Exercise 4: using $$\frac{n_\chi(T = T_0)}{T_0^3} = \frac{n_\chi(T = T_F)}{T_F^3}$$

show that:

$$\Omega_\chi = \left(\frac{T_0^3}{\rho_c M_{\rm Pl}}\right)\frac{x_F}{\langle\sigma v\rangle} \sim \frac{x_F}{20}\frac{10^{-7}\ \mathrm{GeV}^{-2}}{\langle\sigma v\rangle}$$

This is the so-called “WIMP miracle”: the WIMP relic abundance is of the order of the observed one for a typical weak cross section.

“Survival of the weakest”: the larger the cross section, the longer the particle stays in thermal equilibrium, the smaller is its final abundance.



Solving Boltzmann equation in Python http://bit.ly/singletscalar
(Diego Restrepo and Valentina Montoya)

II.3.3 – Non-standard DM model:

Models for dark matter usually require a discrete symmetry to render the DM particle stable.
(e.g. R-symmetry in SUSY)

Simplest model of DM: SM + extra scalar field with a Z_2 symmetry – so called Higgs portals

$$\mathcal{L}_{\rm portal} = H^\dagger H \phi\phi \qquad \phi \to e^{i\pi}\phi$$

It is possible to generalize the Z_2 symmetry in scalar DM models to a Z_N symmetry :

$$\phi \to e^{i\frac{2\pi}{N}} \phi$$

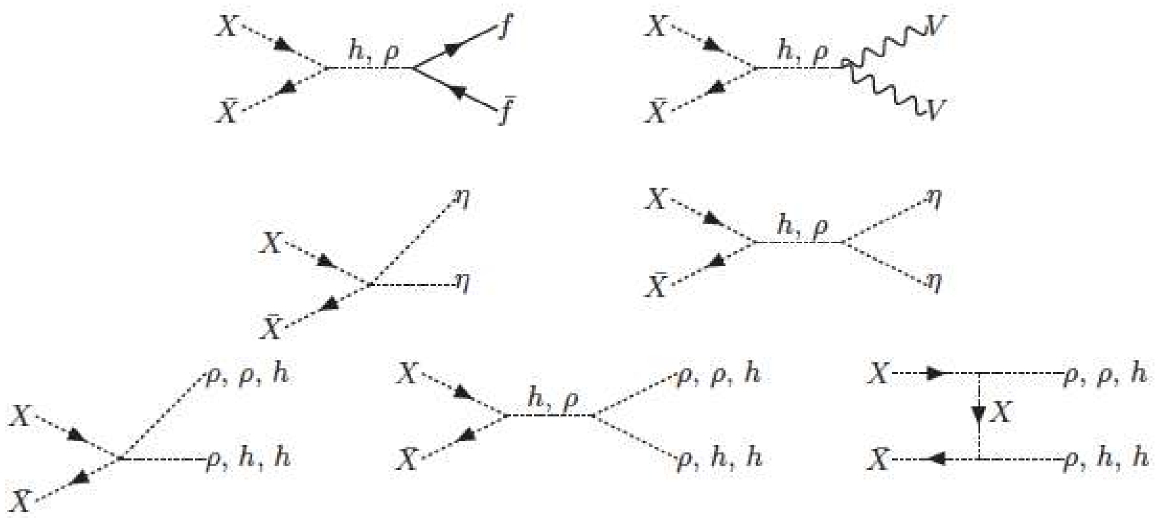
Simplest generalization: Z_3 symmetry

Bernal, Garcia-Cely and RR (2015)

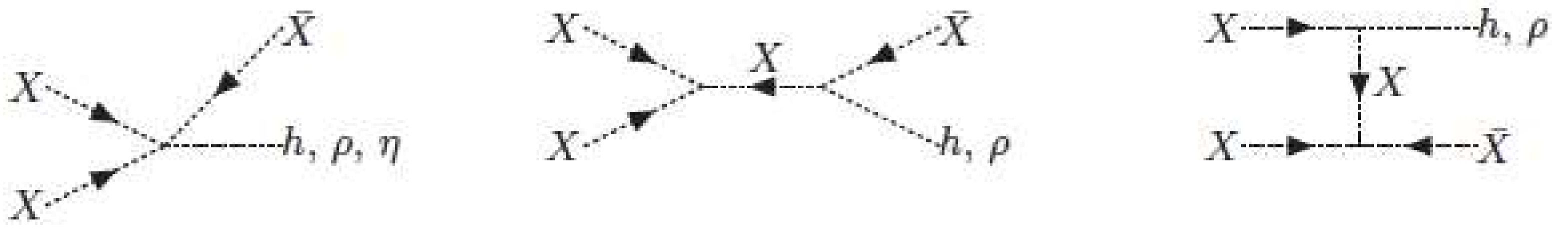
- Model implemented in FeynRules ➔ CalcHEP
- MicrOMEGAs is used for solving Boltzmann equation

Three main processes for relic abundance:

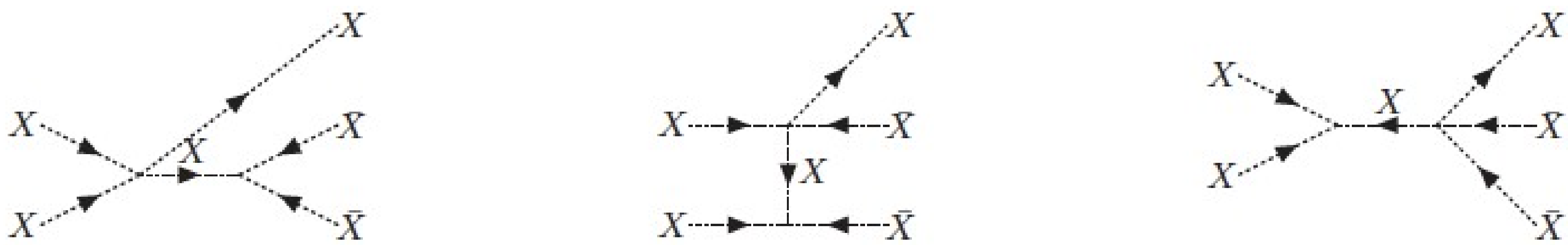
Self-annihilation:



Semi-annihilation:



3 → 2:



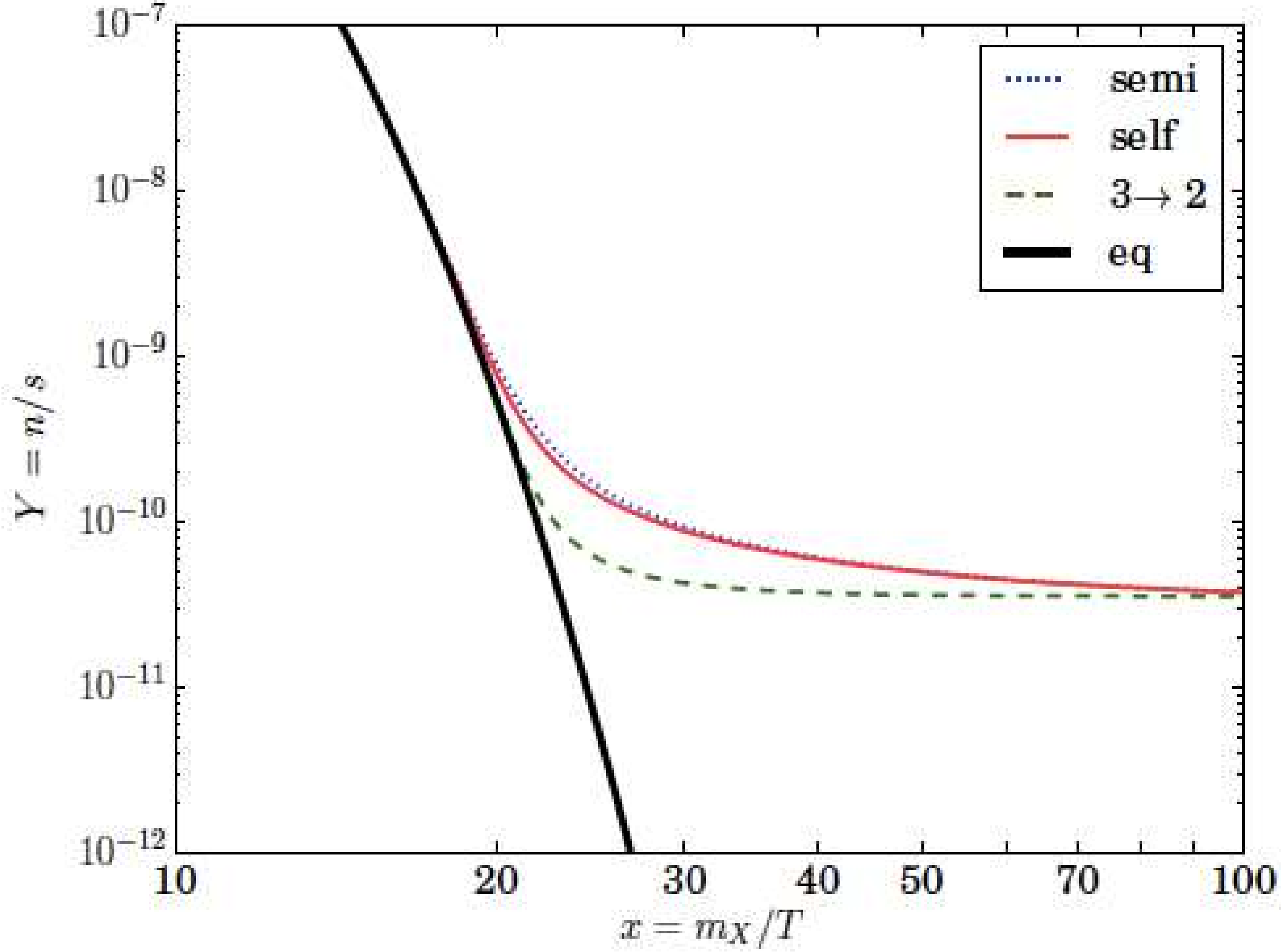
Semi-annihilation and 3 → 2 processes possible only because of Z_3 symmetry.

Boltzmann equation

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle_{\rm self}\left(n^2 - n_{\rm eq}^2\right)$$

$$\underbrace{-\,\langle\sigma v\rangle_{\rm semi}\left(n^2 - n\,n_{\rm eq}\right) - \langle\sigma v^2\rangle_{3\to 2}\left(n^3 - n^2\,n_{\rm eq}\right)}_{\text{New terms}}$$

Example



10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$Y = n/s$
10
20
30
40
50
70
100
$x = m_X/T$
semi
self
$3 \to 2$
eq

DM can be produced non-thermally – eg from the non-equilibrium decay of other particles or by coherent field oscillations (axions).

There are many searches for DM:

- direct detection in underground labs (eg LUX, CDMS, …)

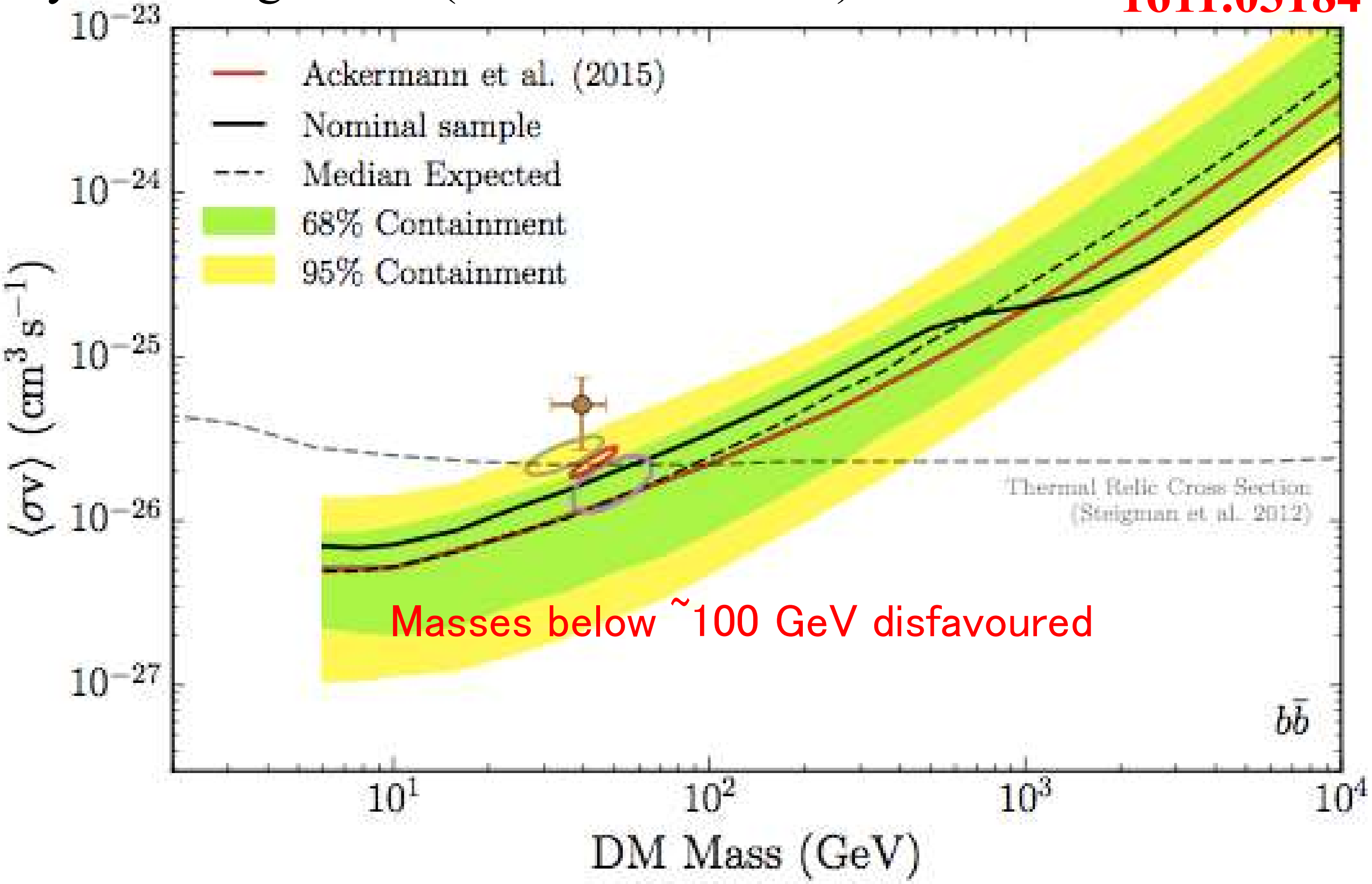
- indirect detection from DM annihilation (eg Fermi satellite)

- production at the LHC (missing energy signature)

Is the WIMP Scenario Challanged?

Indirect searches: results from Fermi-LAT & DES using 45 dwarf Milky Way satellite galaxies (rich in dark matter)

1611.03184



Direct searches (PDG 2018)

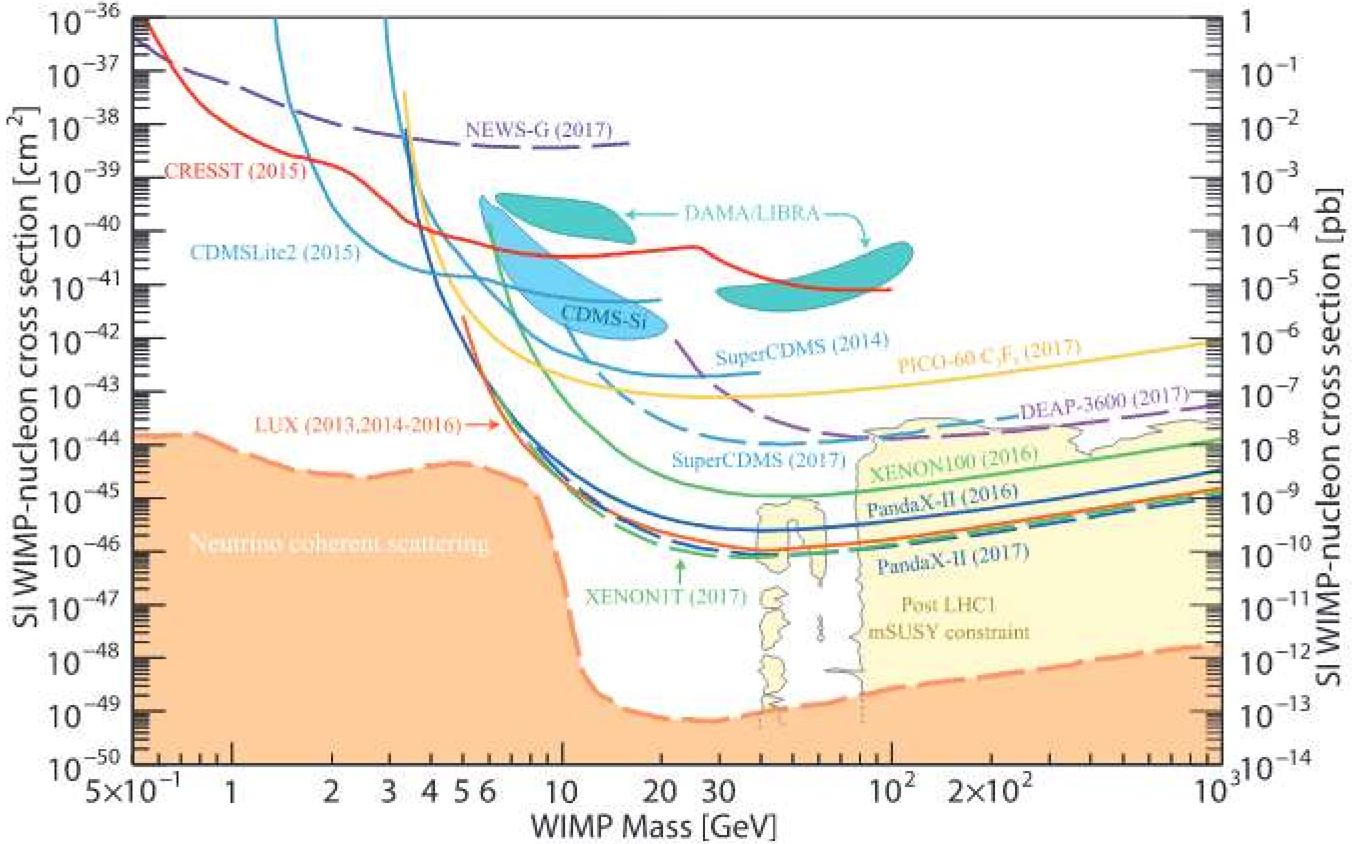
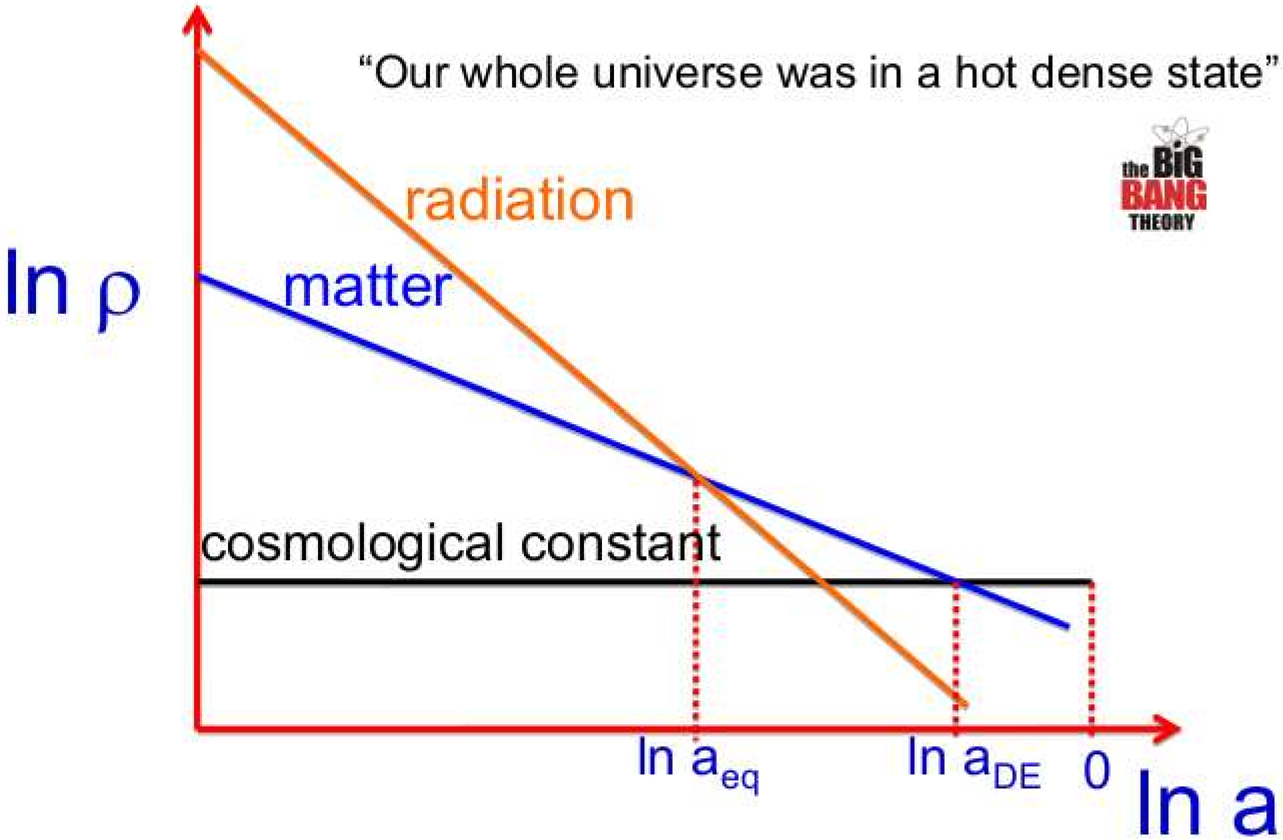


Figure 26.1: WIMP cross sections (normalized to a single nucleon) for spin-independent coupling versus mass. The DAMA/LIBRA [72], and CDMS-Si enclosed areas are regions of interest from possible signal events. References to the experimental results are given in the text. For context, the black contour shows a scan of the parameter space of 4 typical SUSY models, CMSSM, NUHM1, NUHM2, pMSSM10 [73], which integrates constraints set by ATLAS Run 1.

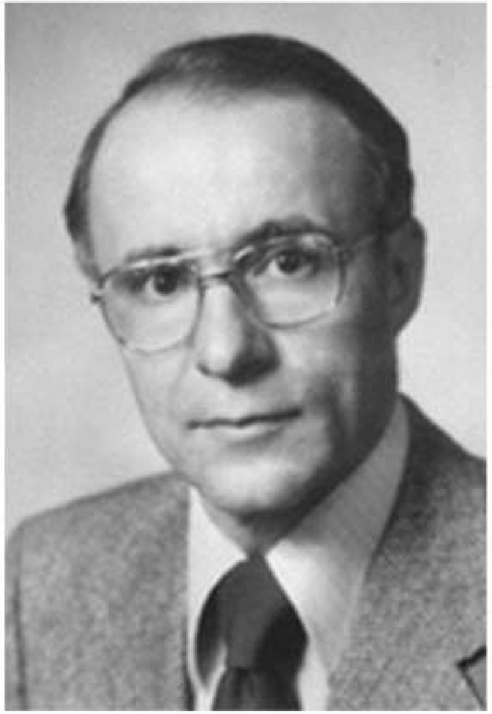
II.4- Origin of Atoms and the CMB

Universe cools down and electrons and protons/nucleus first became bound to form electrically neutral atoms. This is called **recombination** and occurred about 378,000 years after the Big Bang at a redshift of z =1100. Equality happened at z~3500.



Winners of the 1978 Nobel Prize in Physics

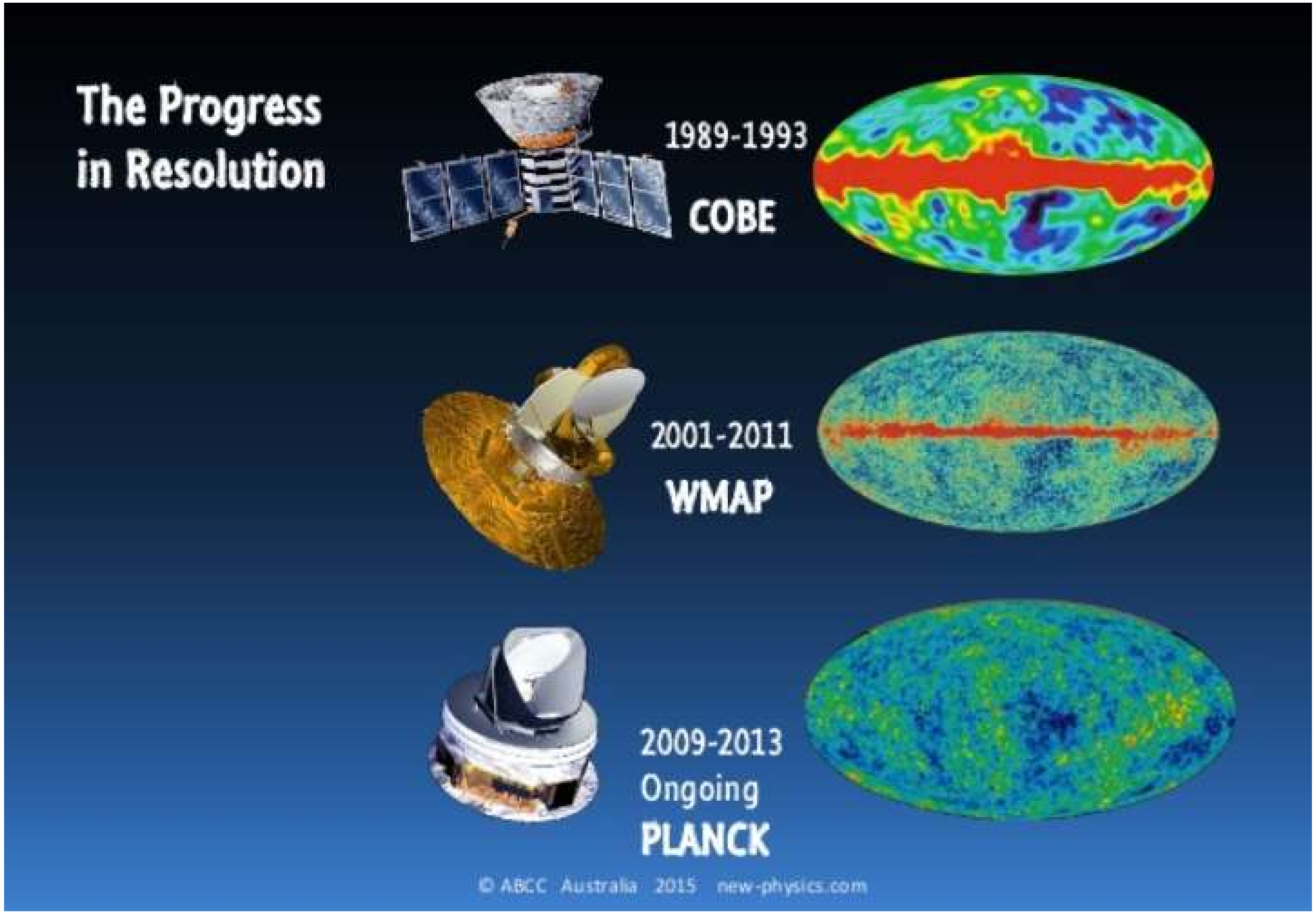
Robert Woodrow Wilson
1936, USA



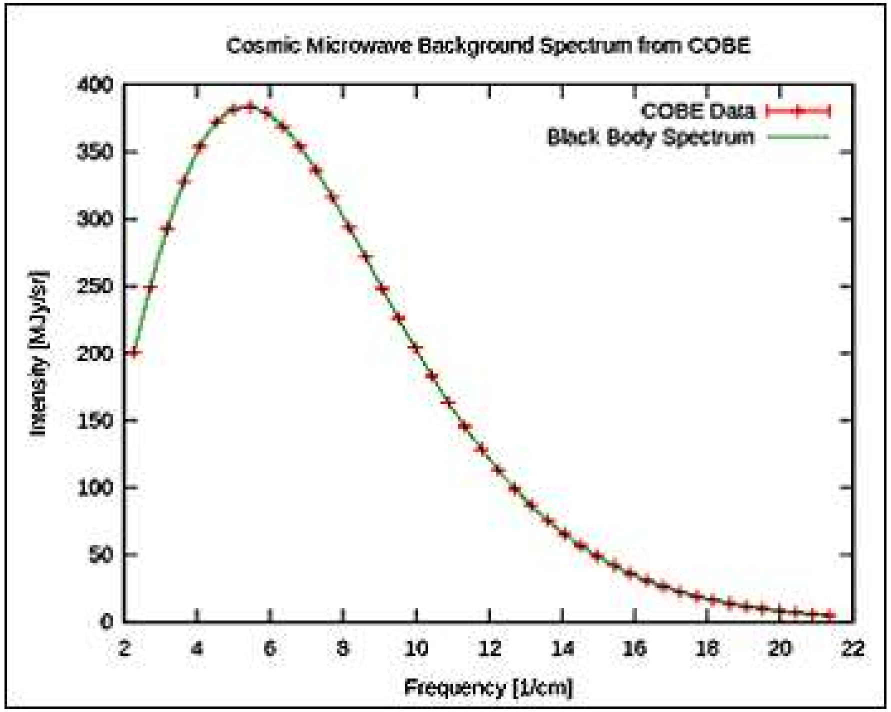
Arno Allan Penzias
1933, Germany

T=3.1K ~ -270 ^{0}C	in 1965
T=2.725K,	in 2003

* A.A.Penzias and R.Wilson, APJL 142,419 (1965)
* R. Dicke. P. Peebles, P. Roll and D. Wilkinson, APJL 142, 414 (1965)


The Progress
in Resolution
1989-1993
COBE
2001-2011
WMAP
2009-2013
Ongoing
PLANCK
© ABCC Australia 2015 new-physics.com

$T = 2.72548 \pm 0.00057$ K



II.5– Origin of inhomogeneities

II.5.1 – The causality problem

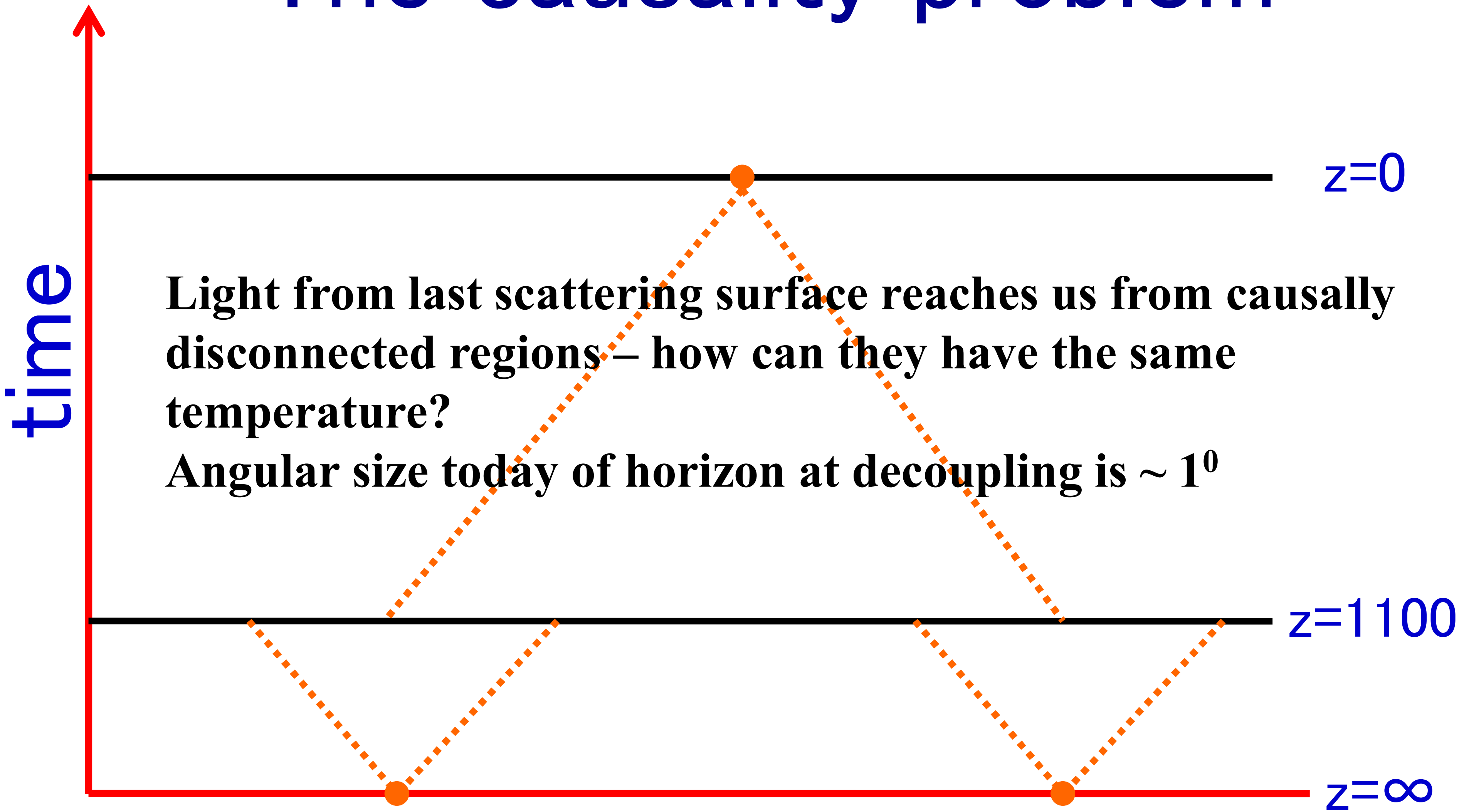
CMB is originated at the "last scattering surface" when atoms are ormed and the Universe becomes transparent to radiation. Radiation decouples from matter. This happens at z~1100 (t~380,000 years after the bang). There are regions in the last scattering surface that were never in ausal contact – no reason to have the same temperature.

Nevertheless the CMB is very uniform over the whole sky, with mall variations of 1 part in 10^5! How can this be?

The causality problem

Light from last scattering surface reaches us from causally disconnected regions – how can they have the same temperature?

Angular size today of horizon at decoupling is $\sim 1^0$



II.5.2 – Inflation

Inflation is a period of very fast (exponential) expansion of the Universe.

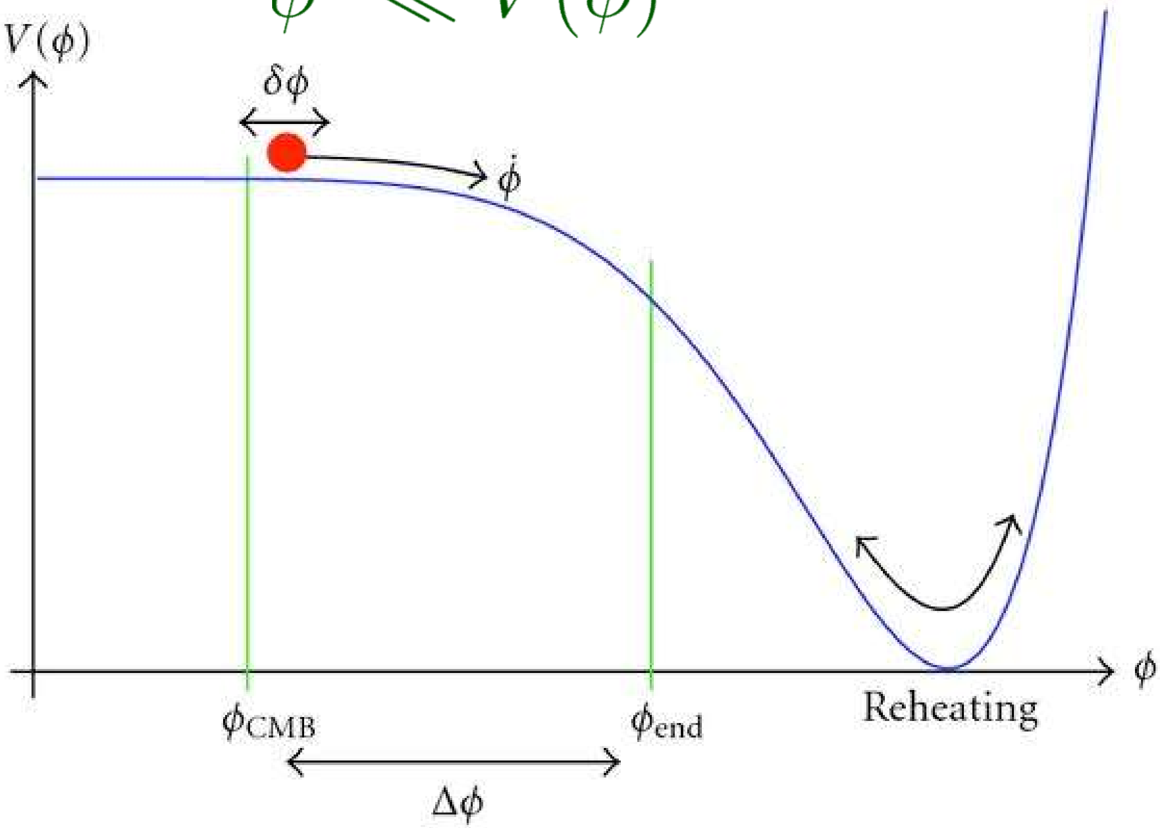
A single small patch can fill the whole horizon at decoupling.

Inflation also predicts that the Universe is spatially flat – as observed!

Inflation also provides quantum fluctuations that are the seeds for inhomogeneities in the Universe.

Basic idea: the very early Universe is dominated by the energy density of a (surprise!) scalar field – called inflaton – that is slowly rolling down in a potential.

$$\dot{\phi}^2 \ll V(\phi)$$



Encyclopædia Inflationaris

http://arxiv.org/1303.3787

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lation must end!

cillating field around the minimum of the potential produces the s
led reheating of the Universe.

cillating field is equivalent to a gas of inflaton particles ($m \sim 10^{12}$
V) that decay into radiation (model dependent).

tual reheating process is more complicated – possibility of
heating, etc.

e only bound on the reheating temperature T_R is that it must be lar
n temperatures required by BBN (~1 GeV).

II.5.3 – How much inflation?

Let's require that the observable Universe today of comoving size ($1/a_0 H_0$) was to fit in the comoving Hubble radius at the beginning of inflation ($1/a_i H_i$):

$$\frac{1}{a_i H_i} > \frac{1}{a_0 H_0}$$

After inflation ends (at a_e) the Universe is radiation dominated:

$$H \propto a^{-2}$$

and let's assume it is so until today. Hence

$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_R}$$

Therefore:

$$\frac{1}{a_i H_i} > \frac{1}{a_0 H_0} = \frac{T_R}{T_0} \frac{1}{a_e H_e}$$

Finally, using that H is approximately constant during inflation (H_i ~H_e) we obtain the amount the Universe has to expand during inflation:

$$\frac{a_e}{a_i} = \frac{T_R}{T_0}$$

The so–called number of e–folds is defined by:

$$N = \ln\left(\frac{a_e}{a_i}\right) = \ln\left(\frac{T_R}{T_0}\right) = 26 - 64$$

where the range arises from taking the reheating temperature from 1 to 10^{15} GeV. Usually one takes N=50.

II.5.3 – Perturbations in the Universe

Einstein equation:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Perturbed Einstein equation:

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

Perturbations in the metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

FLRW

Can write the line element as:

$$ds^2 = (1+A)dt^2 - a(t)B_i dt dx^i - a(t)^2 \left[(\delta_{ij} + h_{ij})dx^i dx^j\right]$$

Roughly– A: scalar perturbation, B_i: vector perturbation,
h_{ij}: tensor perturbation
[more complicated: S–V–T decomposition, gauge freedom]

Scalar perturbations: density perturbations

Vector perturbations: decay rapidly and are not important

Tensor perturbations: primordial gravitational waves

Perturbations in the energy–momentum tensor are caused by perturbation in the inflaton field:

$$\phi = \bar{\phi} + \delta\phi$$

The size of quantum fluctuations of the inflaton field during inflation is set by H:

$$\langle(\delta\phi)^2\rangle \sim \frac{H}{2\pi}$$

Inflation models are great:

- predict why the Universe is spatially flat

- solve the causality problem

- generate almost gaussian, almost scale invariant fluctuations

- generate both scalar and tensor fluctuations

- given a inflation potential one can predict the spectrum of scalar and tensor perturbations

- the scalar (density) perturbations will give rise to the large scale structure of the Universe

Spectrum of scalar and tensor perturbations

Perturbations can be decomposed in Fourier modes

$$\delta(\vec{x},t) = \int d^3k\ \delta_k(t) e^{i\vec{k}\cdot\vec{x}}$$

and the power spectrum is defined as:

$$\langle \delta_k \delta_{k'} \rangle = (2\pi)^3 \delta^3(\vec{k} - \vec{k}') P(k)$$

Inflation predicts a primordial power spectrum of scalar and tensor perturbations:

$$P_s(k) = A_s\; k^{n_s - 1}$$

$$P_t(k) = A_t\; k^{n_t}$$

A_s, A_t: scalar and tensor amplitudes
n_s, n_t: scalar and tensor spectral indices
r: ratio of tensor to scalar amplitudes

$$r = \frac{A_t}{A_s}$$

Given an inflaton model r can be computed (in terms of the so-called slow-roll parameters)

PLANCK 2015:

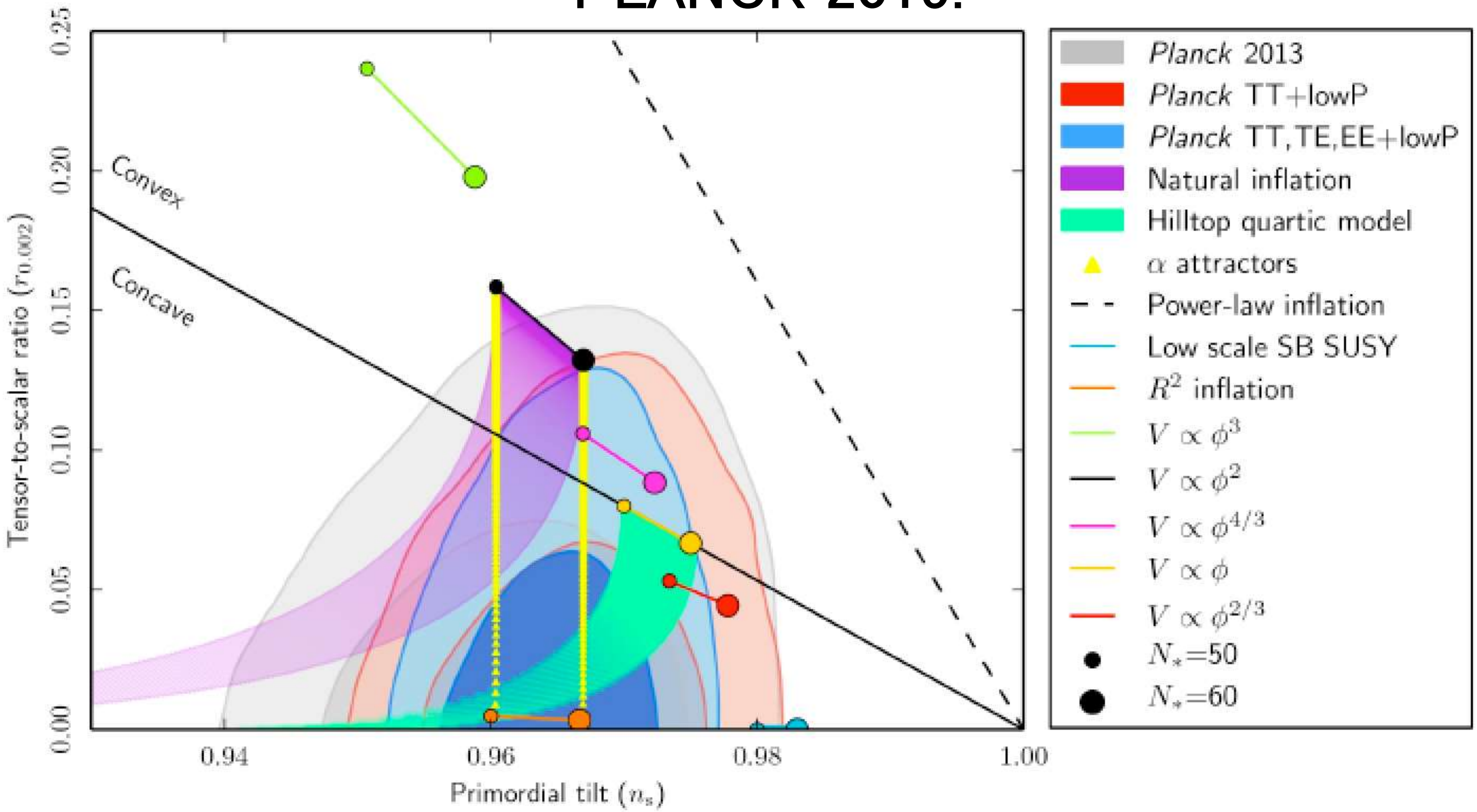
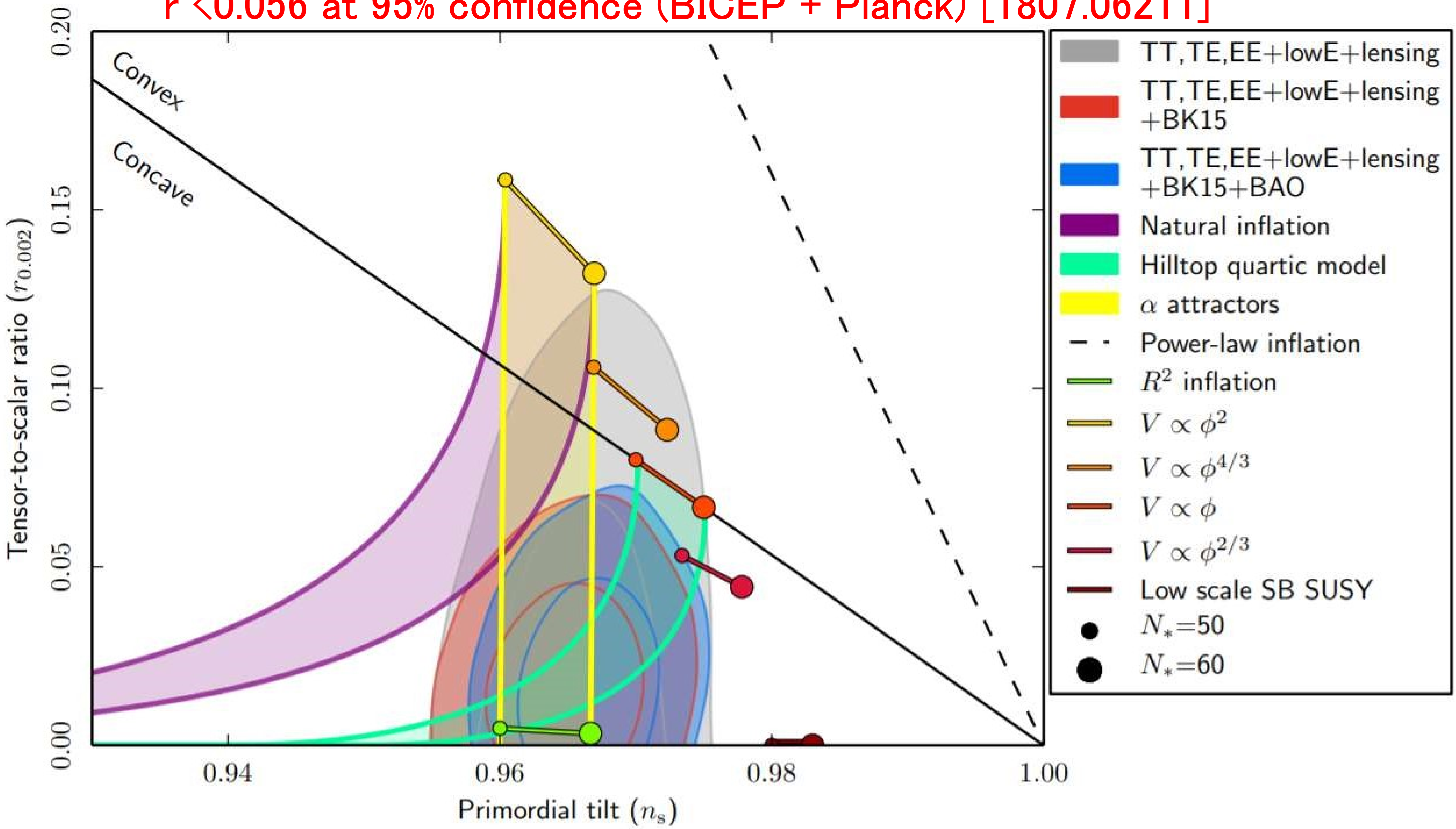


Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

PLANCK 2018:

r <0.056 at 95% confidence (BICEP + Planck) [1807.06211]



Bound on the ratio of tensor to scalar perturbations r from Planck 2018 imply bounds on the energy scale at the inflation epoch (at 95% CL):

$$V_{\mathrm{infl}} < (1.6 \times 10^{16}\ \mathrm{GeV})^4$$

$$\frac{H_{\mathrm{infl}}}{M_{Pl}} < 2.5 \times 10^{-5}$$