Dark Matter

I. Evidence and properties

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ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

LAPIS school

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Forewords to the first class:

The slides of these classes have been put together by looting the excellent ones created by some of the teachers of the “School on Dark Matter”, held at ICTP-SAIFR in São Paulo in 2016.
Reorganized and trimmed for a more compact purpose, for this class I have used mostly material from P.D. Serpico’s classes (as well as little additional material).

The complete material can be found at this address
http://www.ictp-saifr.org/school-on-dark-matter-2/

and I strongly encourage you to download and study them to have a broader view on the subject. Excellent exercises are suggested, and references available.
Of course, do not hesitate to contact me for any question you may have.

SOME REFERENCES

General references

- **The Early Universe", E. W. Kolb & M. S. Turner**

- **"Physical Foundations of Cosmology", V. Mukhanov**

...

Specific monographs

- **"Kinetic Theory in the expanding Universe", J. Bernstein**
- **"Neutrino Cosmology", J. Lesgourgues, G. Mangano, G. Miele, Pastor**
- **"Particle Dark Matter" Edited by Gianfranco Bertone**

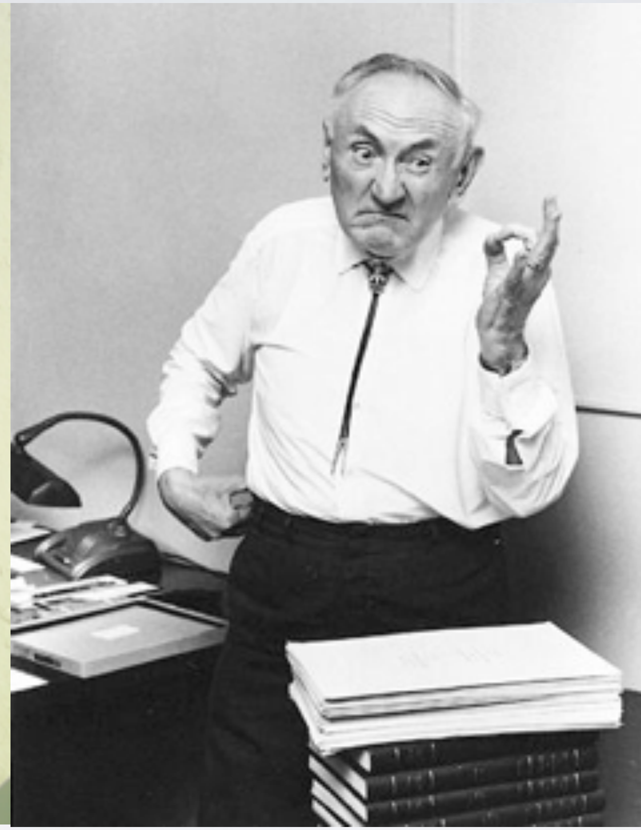
(chapters on different particle physics candidates and probes)

- **For DM history, G. Bertone and D. Hooper, "A History of Dark Matter," arXiv:1605.04909, see also http://www.ymambrini.com/My_World/Physics.html**

...

others will be introduced along the course

DM “DISCOVERY” IN COMA CLUSTER (~1933)



Remarkable application of Virial Theorem (basically pioneered in astronomy only by Poincaré, previously!) and **realized that this was a puzzle**.

Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta (1933) **6**, 110–127.*

"On the Masses of Nebulae and of Clusters of Nebulae", ApJ (1937) **86**, 217*

*Nebula=Early XXth century name for what we call now galaxy

Jan Oort had in fact found the need for “dark matter” already while studying the force ⊥ to the Galactic plane due to stars, but dismissively attributed to unaccounted gas or too dim bodies…

Bulletin of the Astronomical Institutes of the Netherlands 6, 249 (1932)

RECAP OF VIRIAL THEOREM

Given a system of N bodies/particles, define the function $$G = \sum_{k=1}^{N} \mathbf{r}_k \cdot \mathbf{p}_k$$

The average value of its time derivative must vanish if the system is bound (no particles "leave to infinity or acquire infinite velocity")

This condition is equivalent to $$2\langle T \rangle = -\sum_{k=1}^{N} \langle \mathbf{r}_k \cdot \mathbf{F}_k \rangle$$

For conservative forces coming from a potential U, $$\mathbf{F}_k = -\frac{\partial U}{\partial \mathbf{r}_k}$$

For the case $$U(r) = A\,r^n \implies -\sum_{k=1}^{N} \langle \mathbf{r}_k \cdot \mathbf{F}_k \rangle = n\langle U_{tot} \rangle$$

For Gravity, U~ r $^{-1}$ $$\boxed{2\langle T \rangle + \langle U_{tot} \rangle = 0}$$

SKETCH OF THE METHOD

$$T = N\frac{m}{2}\langle v^2\rangle$$

$$\langle U_{tot}\rangle \simeq -\frac{N^2}{2}G_N\frac{m^2}{d}$$

~$N^2/2$ pairs of Galaxies

where m is the typical Galaxy mass, d the typical distance between Galaxies

$$M_{tot} \simeq N\,m = \frac{2\langle v^2\rangle\, d}{G_N}$$

e.g. for N Galaxies in a sphere of radius R, $d = \left(\frac{N}{V}\right)^{-1/3} = \left(\frac{4\pi}{3N}\right)^{1/3} R$

Alternatively, could directly estimate the gravitational potential energy of a self-gravitating homogeneous sphere of radius R

$$\langle U_{tot}\rangle \simeq -\frac{3}{5}\frac{G_N\, M^2}{R}$$

from doppler shifts in spectra

$$\boxed{M_{tot} \simeq \mathcal{O}(1)\frac{\langle v^2\rangle R}{G_N}}$$

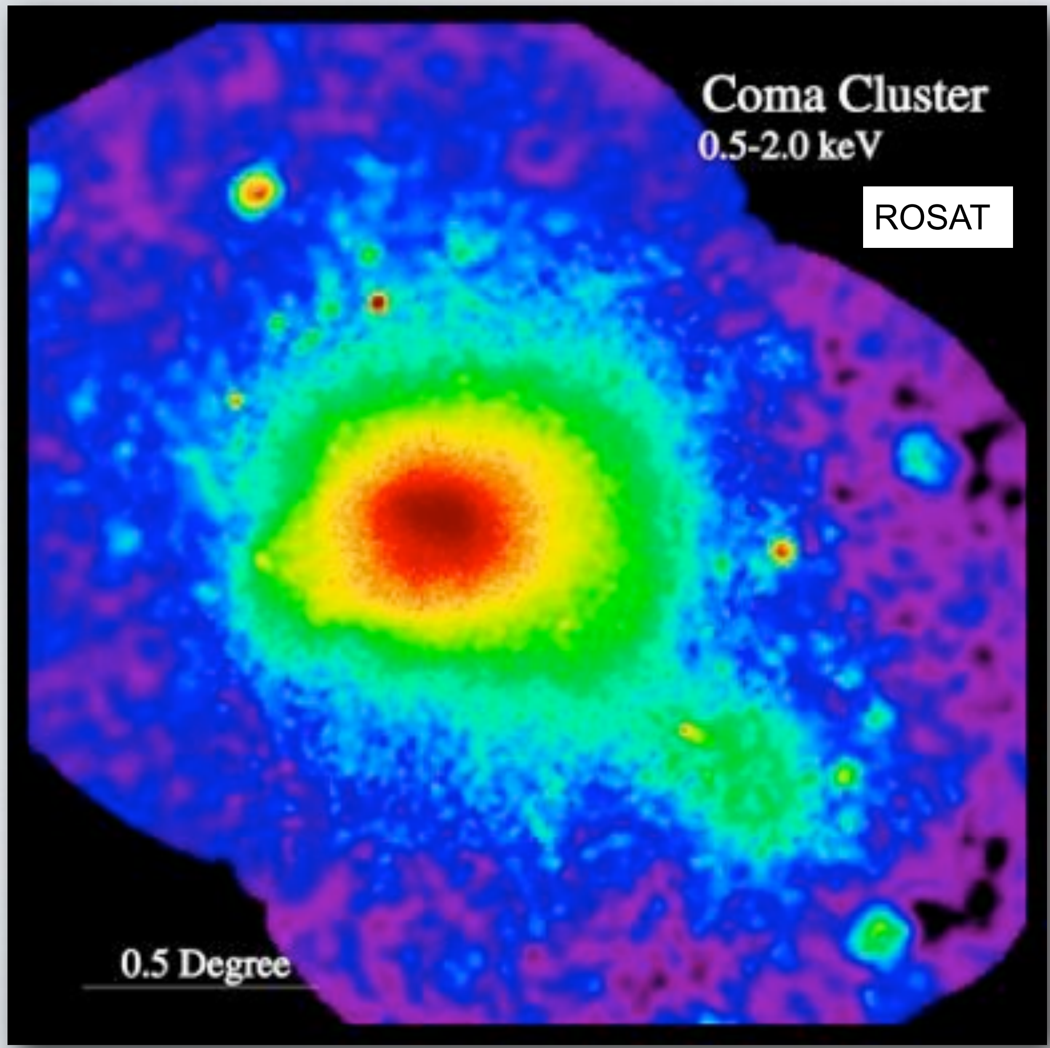
inferred from distance & angular size

weakly depends on geometry/distribution of Galaxies in the cluster

Zwicky found 2-3 orders of magnitude larger M than expected from converting luminosity into mass!

MODERN PROOFS FROM CLUSTERS: X-RAYS

We know today that most of the mass in clusters (not true for galaxies!) is in the form of hot, intergalactic gas, which can be traced via X rays: X-luminosity and spectrum provide mass profile!



Again, a factor ~7 more mass than those in gas form is inferred (also its profile can be traced...)

See for example
Lewis, Buote, and Stocke, ApJ (2003), 586, 135

SKETCH OF THE METHOD

Spherical symmetric, hydrostatic equilibrium for the gas:

Newton's law in the fluid limit (shell)

$$dF = -\frac{G_N\, M(r)\, \rho_g(r)\, S}{r^2} dr$$

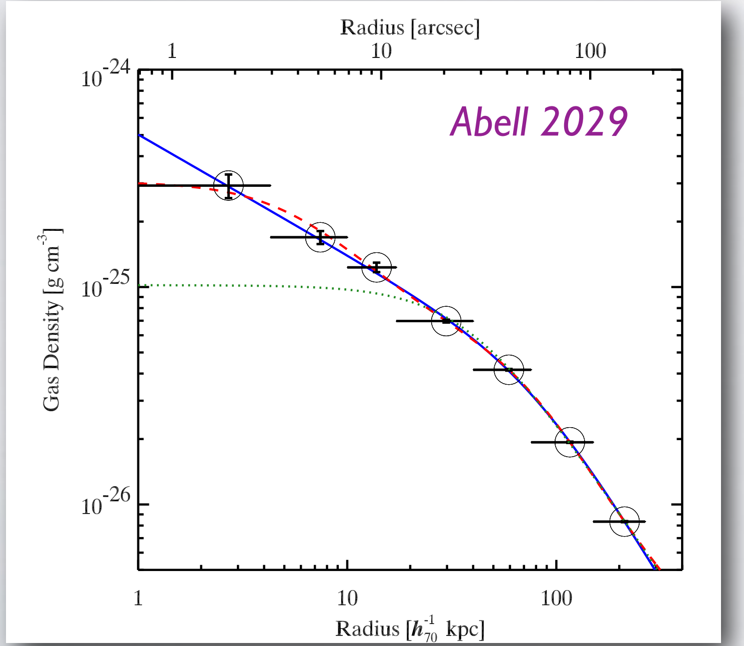
$$\frac{dP_g}{dr} = -\frac{G_N\, M(r)\, \rho_g(r)}{r^2}$$

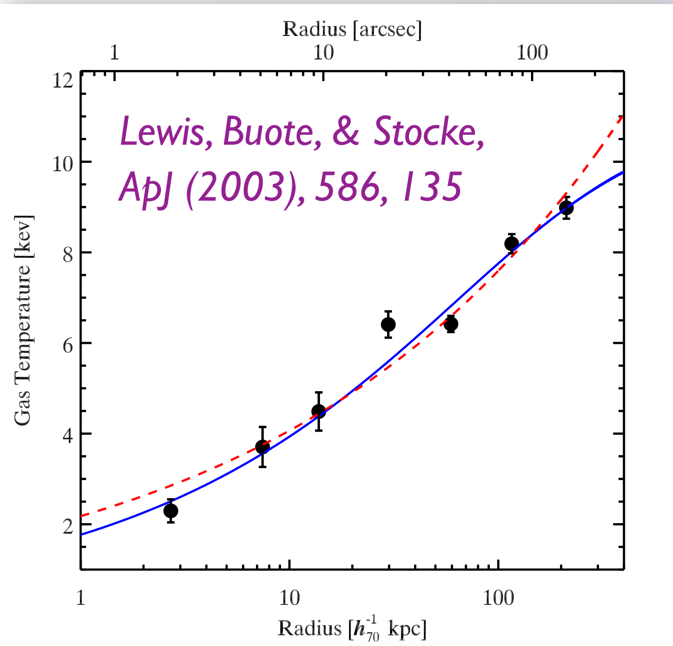
Use perfect gas EOS

$$P_g = \frac{\rho_g}{\mu\, m_p} k_B\, T_g$$

$$M(r) = -\frac{r\, k_B\, T_g}{G\, \mu\, m_p}\left[\frac{d\ln \rho_g(r)}{d\ln r} + \frac{d\ln \rho_g(r)}{d\ln r}\right]$$

The method does not depend on gas density normalization (which controls the baryonic mass)!



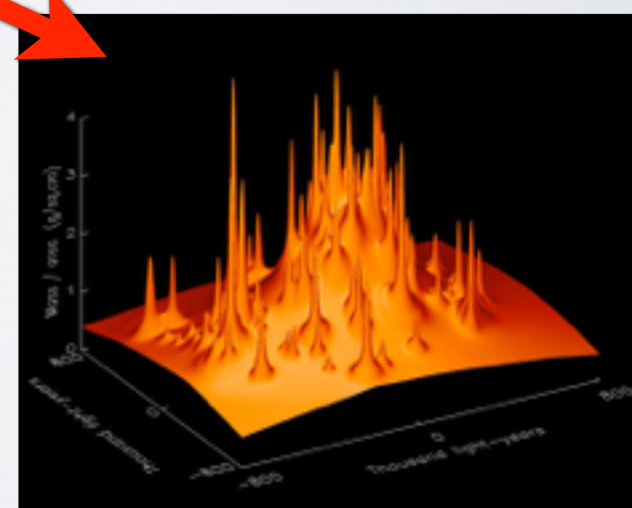


MODERN PROOFS FROM CLUSTERS: LENSING

CL0024+1654,
Hubble space telescope

(more on lensing in Cypriano's lecture)

its gravitating mass distribution inferred from lensing tomography

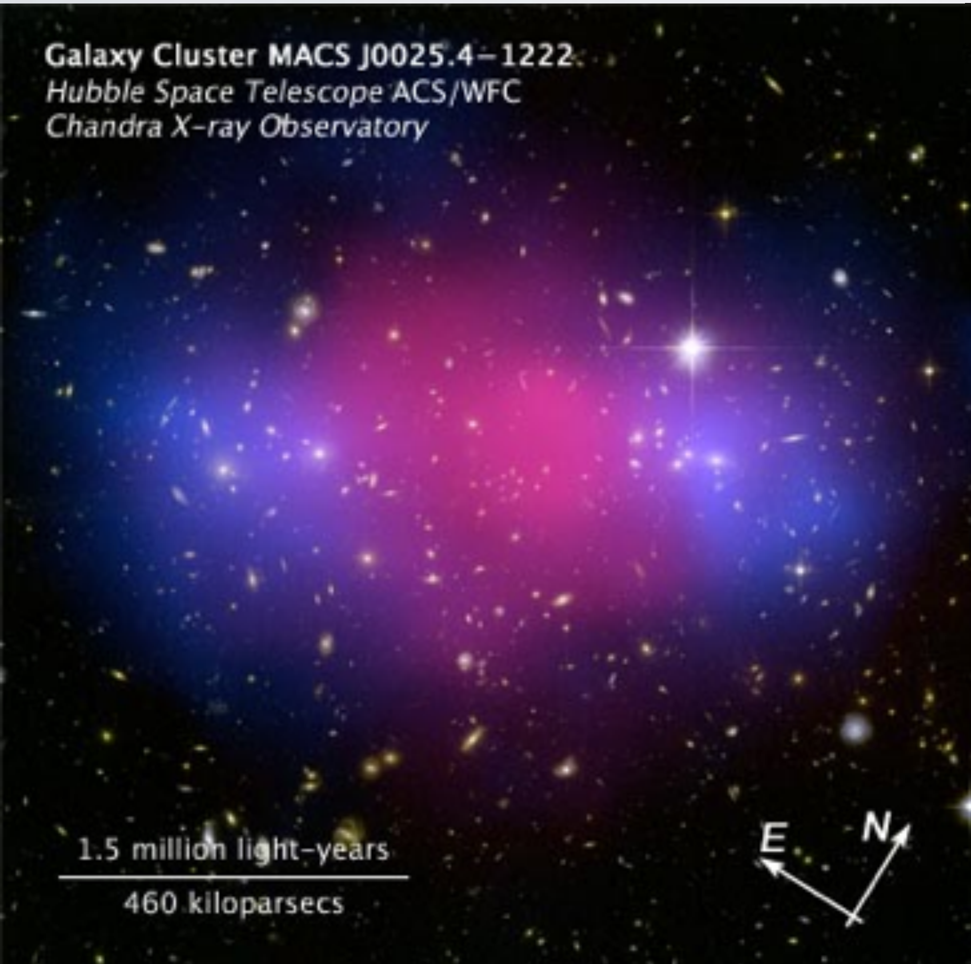


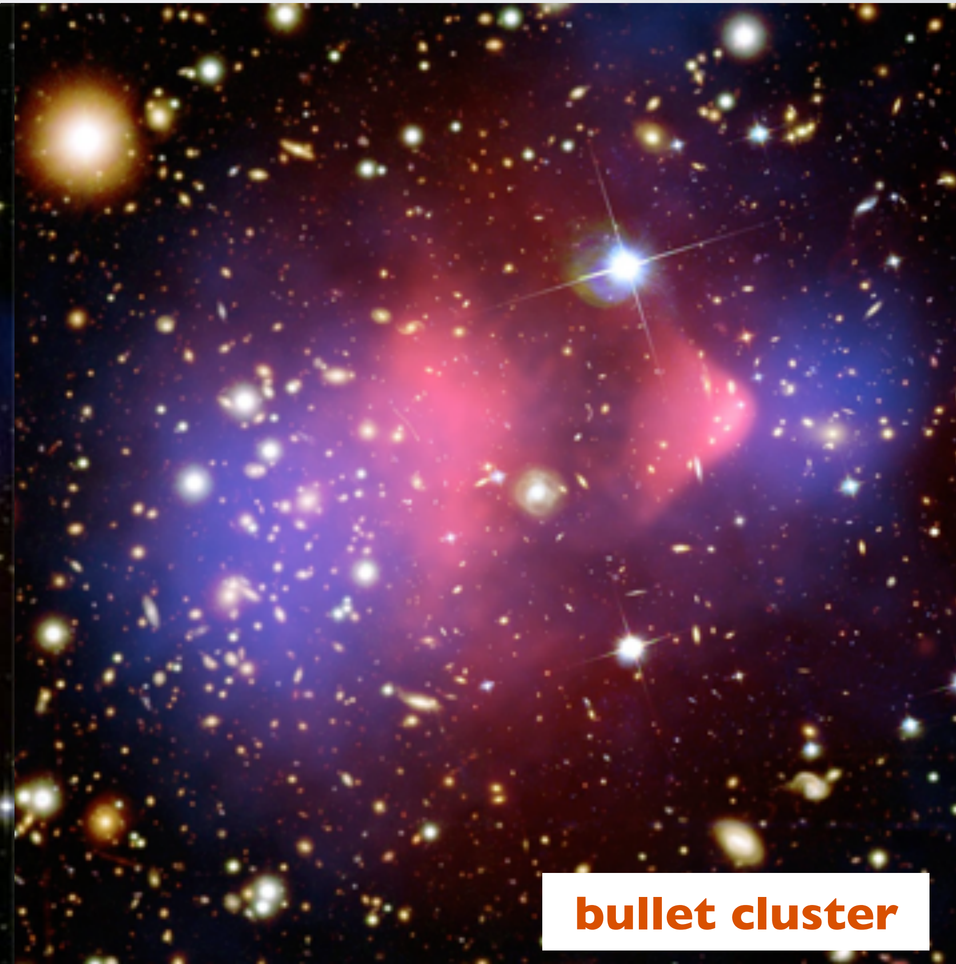
Consistent inference done from clusters of Galaxies: Presence of Dark Matter smoothly distributed in-between galaxies is required
(and actually must dominate total potential)

MORE SPECTACULAR: SEGREGATION!

Baryonic gas gets "shocked" in the collision and stays behind. The mass causing lensing (as well as the subdominant galaxies) pass trough each other (non-collisional)

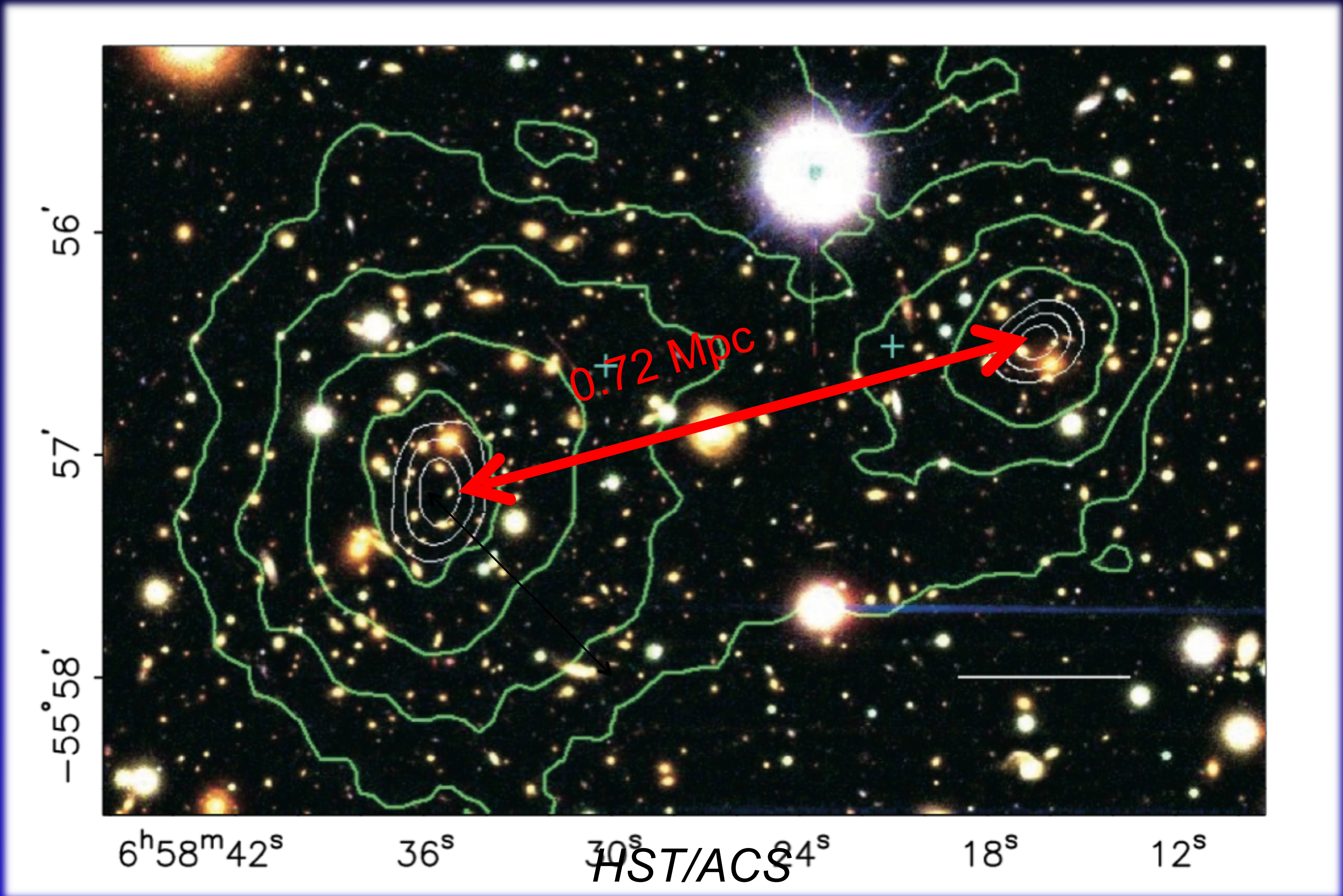
(most of the) Mass is not in the collisional gas, as would happen if law of gravity had been altered!





The "Bullet Cluster"

1E 0657-558



Z = 0.296

collision in the plane of the sky

[Markevitch et al. `06]

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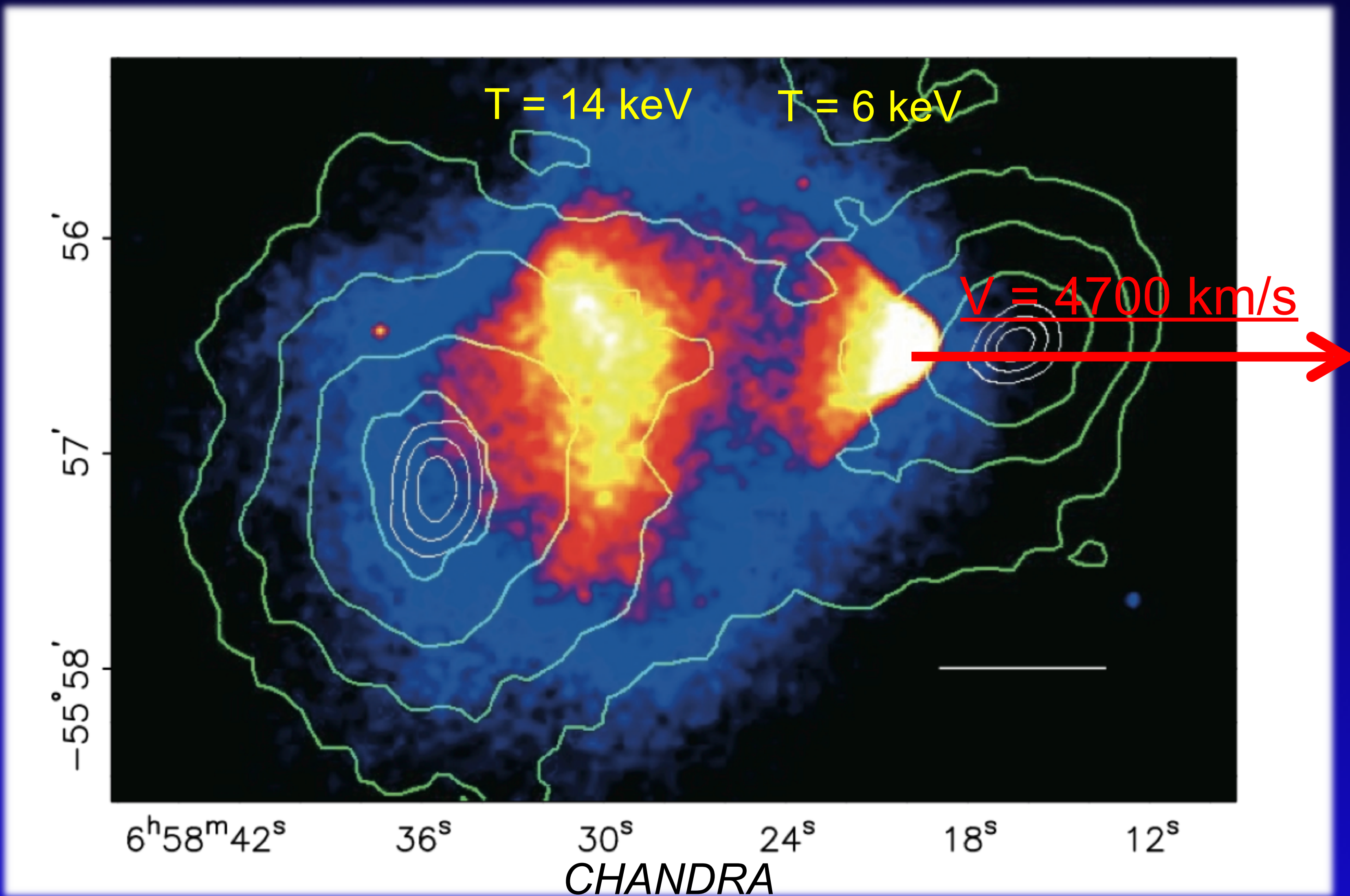
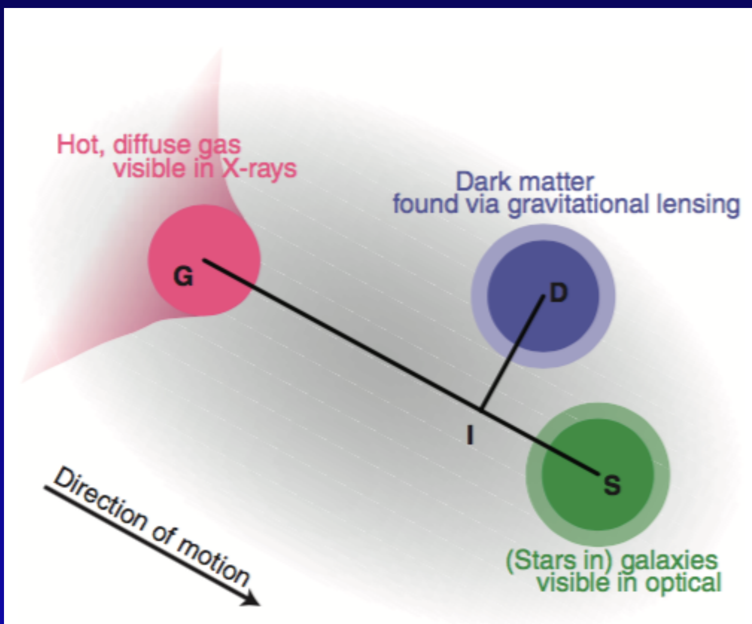
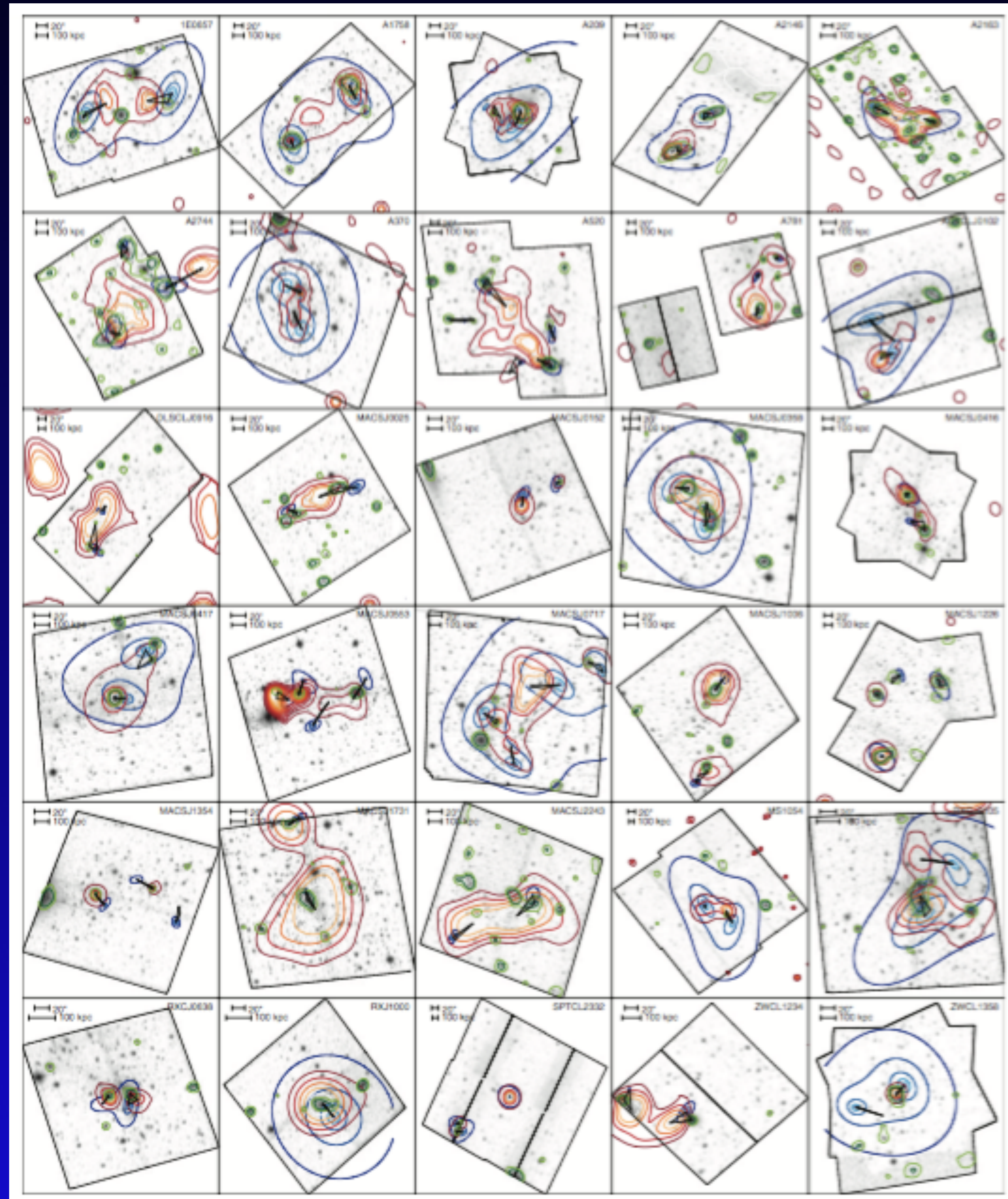


Merger 100 Myr ago

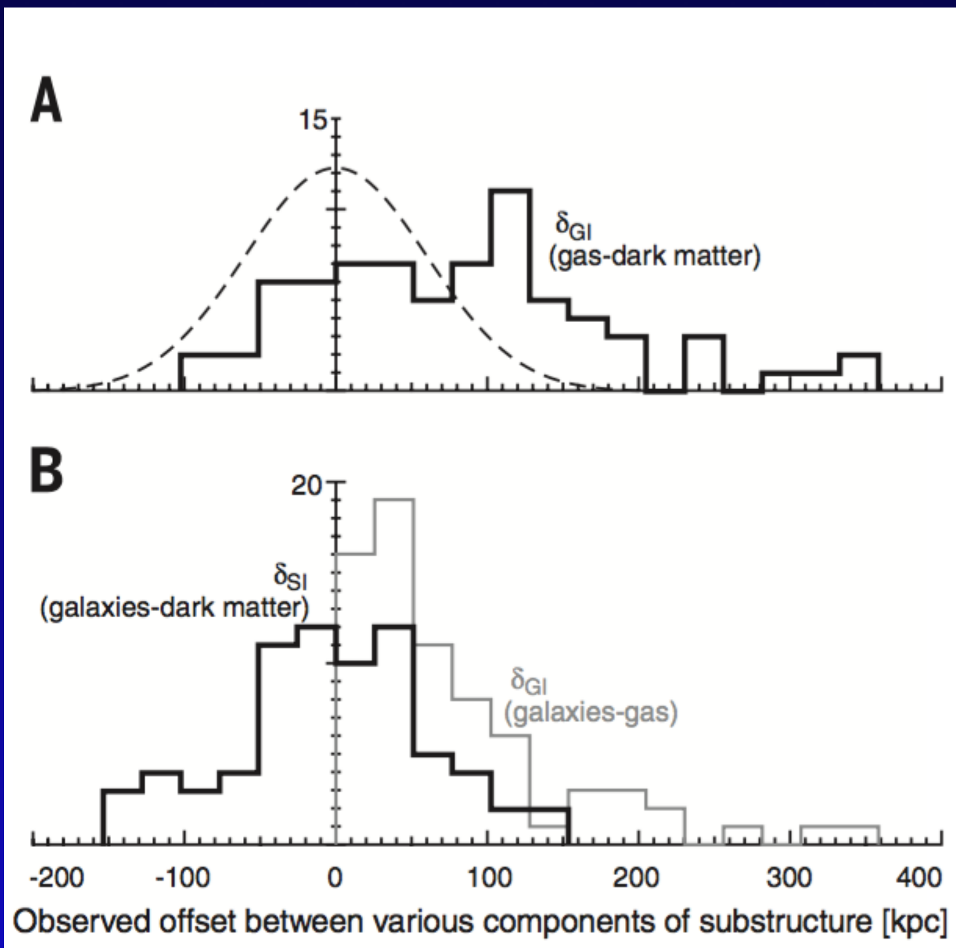
The Bullet is only the first, most famous, of a plethora of similar systems.

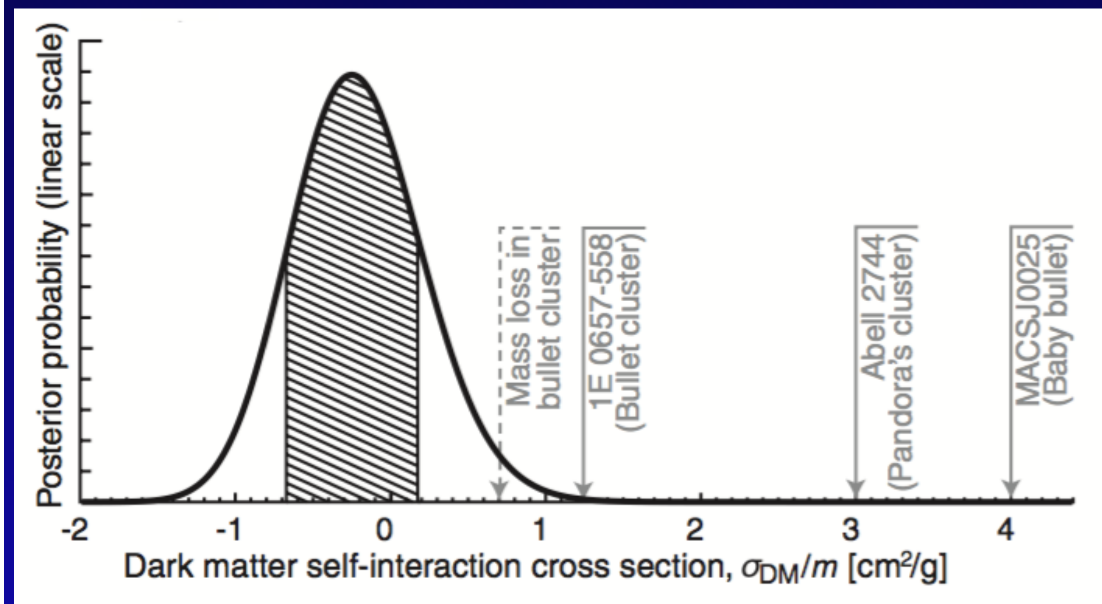




[Harvey et al. `16]

Quantitative constraints on DM-baryon separation





[Harvey et al. `16]

ANOMALOUS GALAXY ROTATION CURVES

age mass per cubic parsec is 0.98⊙. The total luminosity of M31 is found to be 2.1×10^9 times the luminosity of the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun. The difference can be attributed mainly to the very great mass calculated in the preceding section for the outer parts of the spiral on the basis of the unexpectedly large circular velocities of these parts.

H.W. Babcock (1939), PhD Thesis

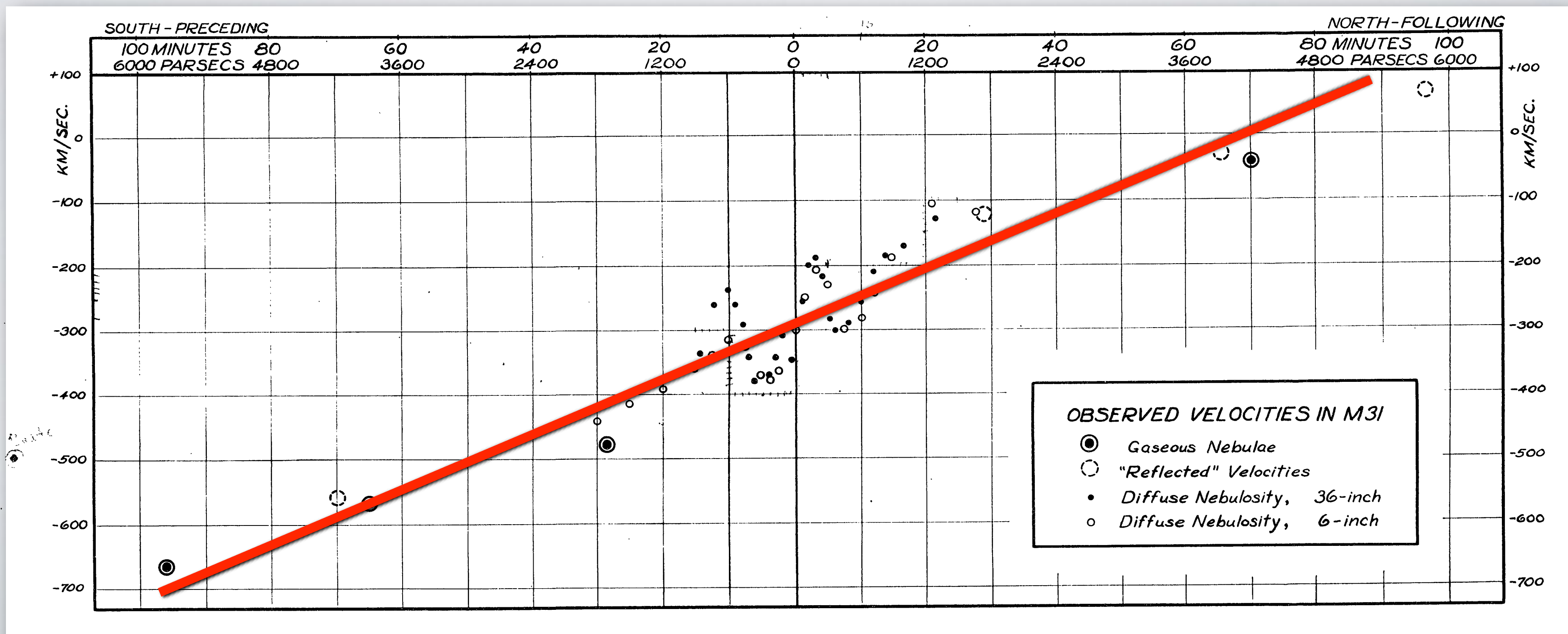
(& Lick observatory bulletin # 498 (1939) 41)

building upon works by Slipher (1914), Pease (1918)…

THE ROTATION OF THE ANDROMEDA NEBULA*

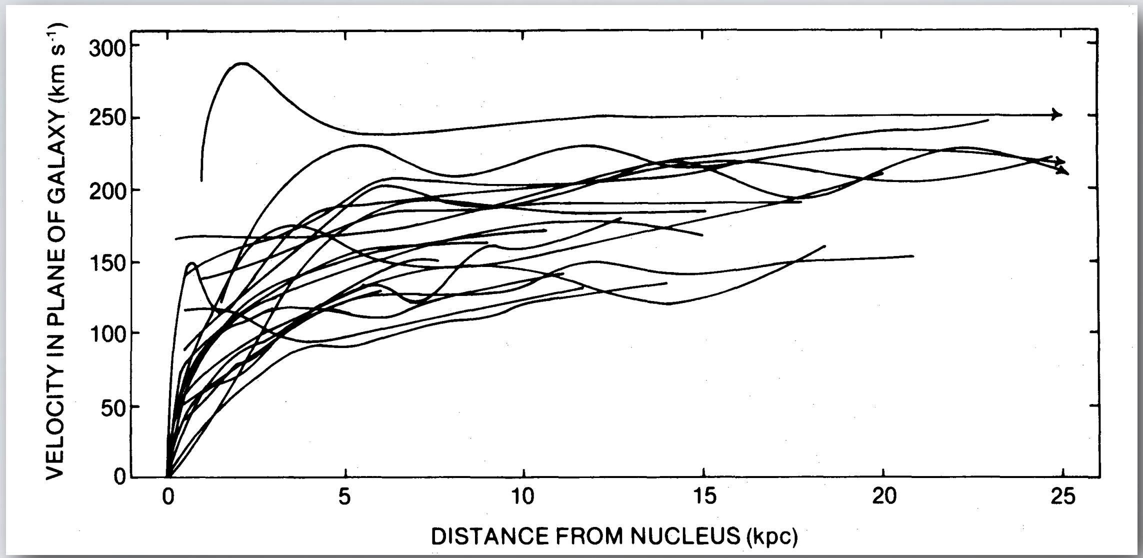
BY

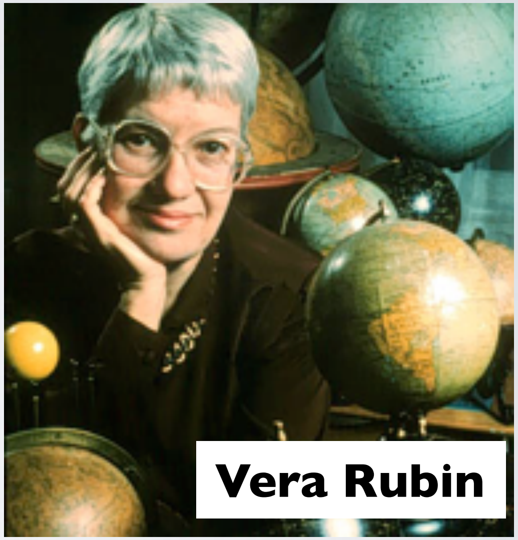
HORACE W. BABCOCK



FLAT GALAXY ROTATION CURVES

A few decades later, after a number of developments (radioastronomy, 21 cm indicators, improved spectroscopic surveys…) starting from around ~1970 astronomers like V. Rubin, W. K. Ford Jr. et al. embarked in a campaign to obtain rotational curves of Spiral Galaxies to their faint limits outer limits





V. C. Rubin and W. K. Ford, Jr., "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions," ApJ 159, 379 (1970) […] V. C. Rubin, N. Thonnard and W. K. Ford, Jr., "Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/," ApJ 238, 471 (1980).

By the '80, many people started to take the dark matter problem seriously (partly due to technical refinements, part sociology?)

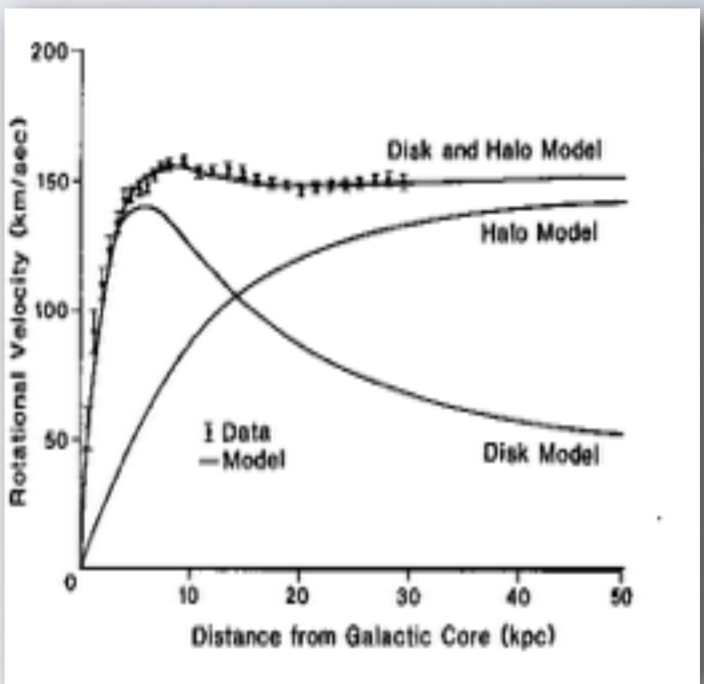
WHERE'S THE PROBLEM?

- observed (equate centripetal acc. & Newton's law)

$$v_{rot}^2 = \frac{G\,M(R)}{R} \simeq const. \qquad M(R) = \int_0^R 4\pi\, r^2\, \rho(r)\, d\, r$$

- predicted based on visible light

$$v_{rot}^2 \propto \frac{1}{R}$$



Data are well described by an additional component extending to distance >> visible mass scale, with a profile $\rho(r) \propto r^{-2}$ (clearly not valid at asymptotically large r!)

The determination of "local" (Galactic) DM properties requires a multi-parameter fit including stellar disk, gas, bulge yielding $\rho_\odot \simeq 0.4\,\mathrm{GeV/cm^3}$

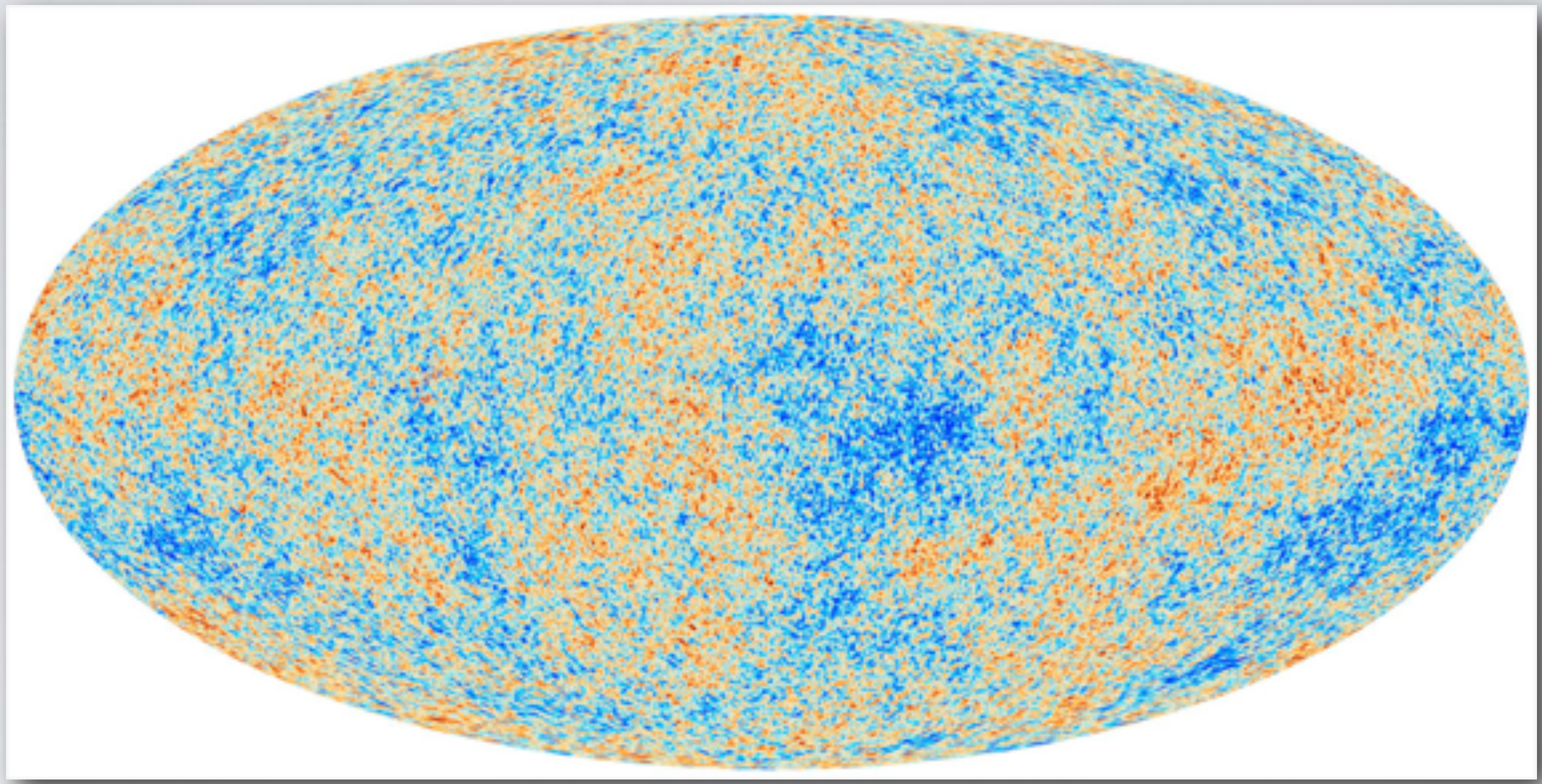
Such techniques, as well as analogous ones used to infer DM in other systems (like dwarf Galaxies) are extremely important for direct and indirect searches of DM, *but people often forget about it…*

not the most crucial or unambiguous ones to infer DM existence and properties *…yet often presented as "smoking gun"!*

Will hear much more about that about in lectures by F. Iocco, M. Pato

GROWTH OF STRUCTURES

This picture, plus some (linear) theory is a robust proof for the existence of DM!



Key argument

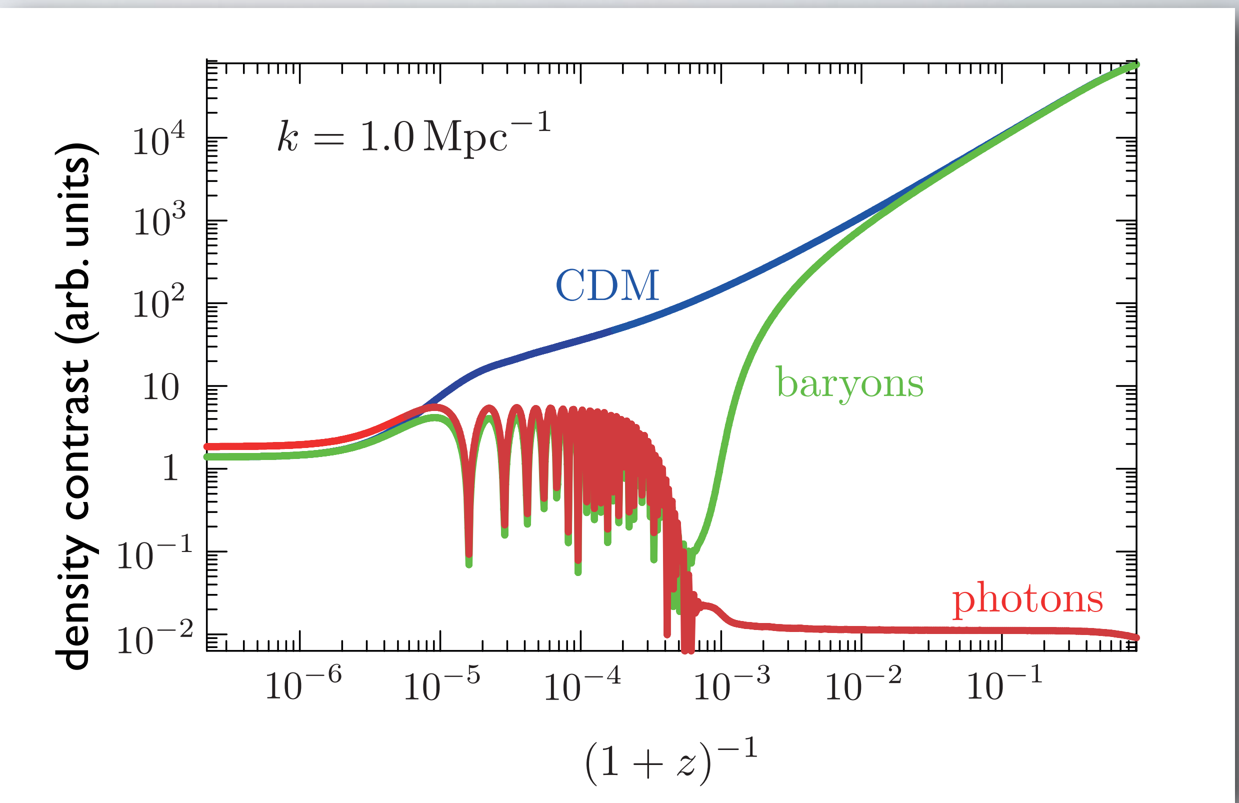
- Before recombination: baryons & photons coupled, "share perturbations"
- We measure amplitude ~10^{-5} at recombination (*picture above*)
- Evolving forward in time, insufficient to achieve collapsed structures as we see nowadays, unless lots of gravitating matter (not coupled to photons) creates deeper potential wells!

IN GRAPHIC TERMS

$$\delta = \frac{\rho}{\langle \rho \rangle} - 1$$

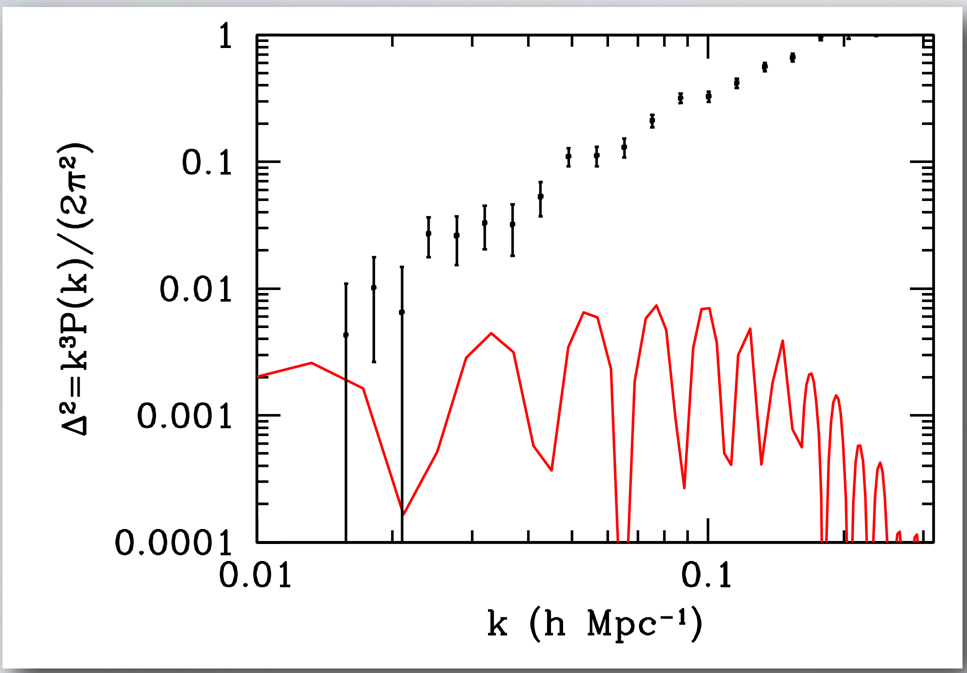
$$= \sum_{\mathbf{k}} \tilde{\delta}_{(\mathbf{k})} e^{i\mathbf{k}\cdot\mathbf{x}}$$

Density contrast for a "mode" (in Fourier space). Indep. evolution in linear theory, its "variance" is the power spectrum *P(k)*



- Ignore evolution at very early times (before entering the Hubble horizon, gauge dependent).
- Upon horizon entry, as long as the baryonic gas is ionized, it is coupled to radiation & oscillates, as pressure prevents overdensities from growing. The (uncoupled, pressureless) CDM mode instead grows, first logarithmically during radiation domination, then linearly in the matter era.
- After recombination, baryons behave as CDM, quickly fall in their "deep" potential wells... but, had not been for CDM, they would need much longer to reach the same density contrast!

WHAT IF ONLY BARYONS PRESENT?

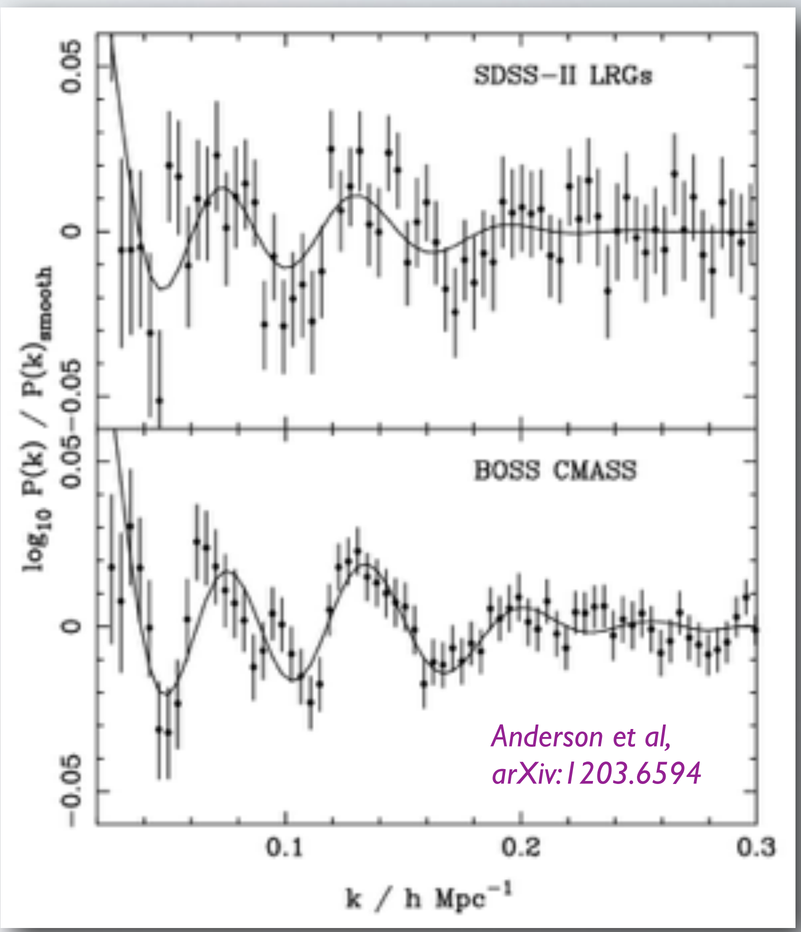


No structure non-linear by now & pattern of "clumpiness" would be very different!

Models where "baryonic gravity is enhanced" so to "boost" growth (e.g. TeVeS...) have hard time to get the right shape!

See pedagogical discussion in S. Dodelson, 1112.1320

More quantitative understanding of several of these issues will be possible after lectures by R. Sheth!

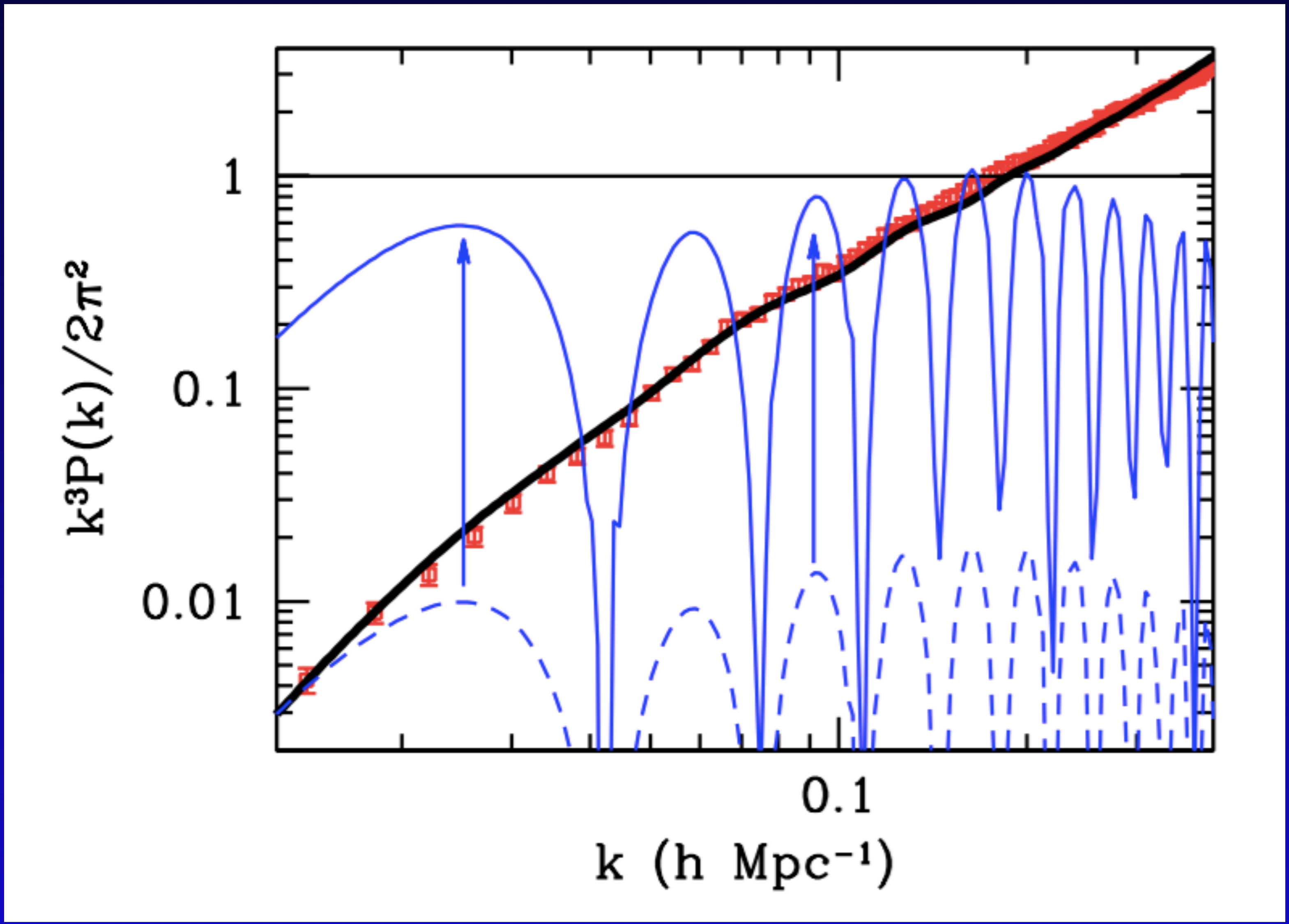


Credibility of our understanding reinforced since we see the residual "oscillations" due to coupling of subleading baryons with photons (BAO)!

The problem with modified gravity:

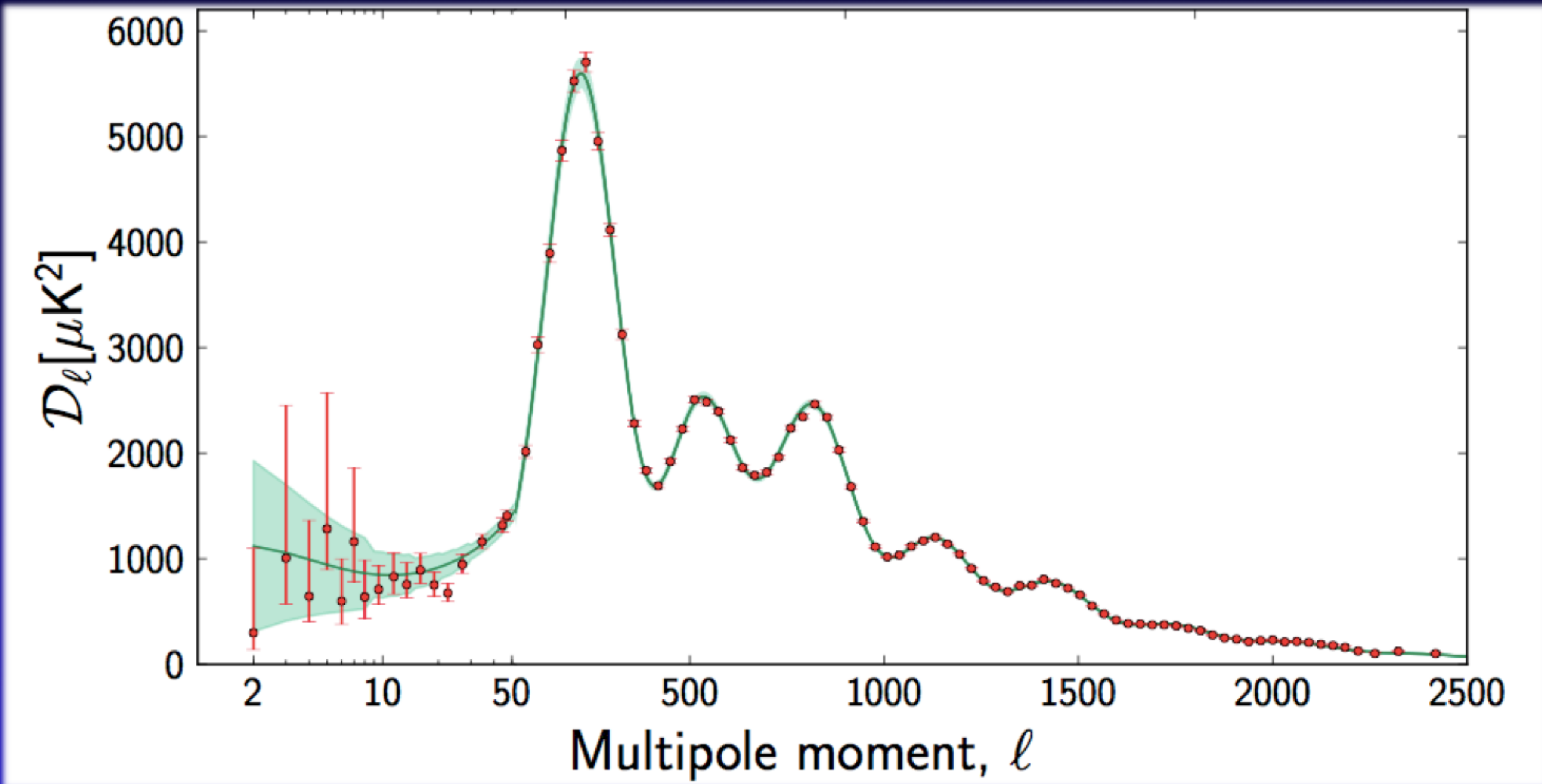
baryon only power spectrum is not right

(one can maybe obtain correct normalization, but not shape)

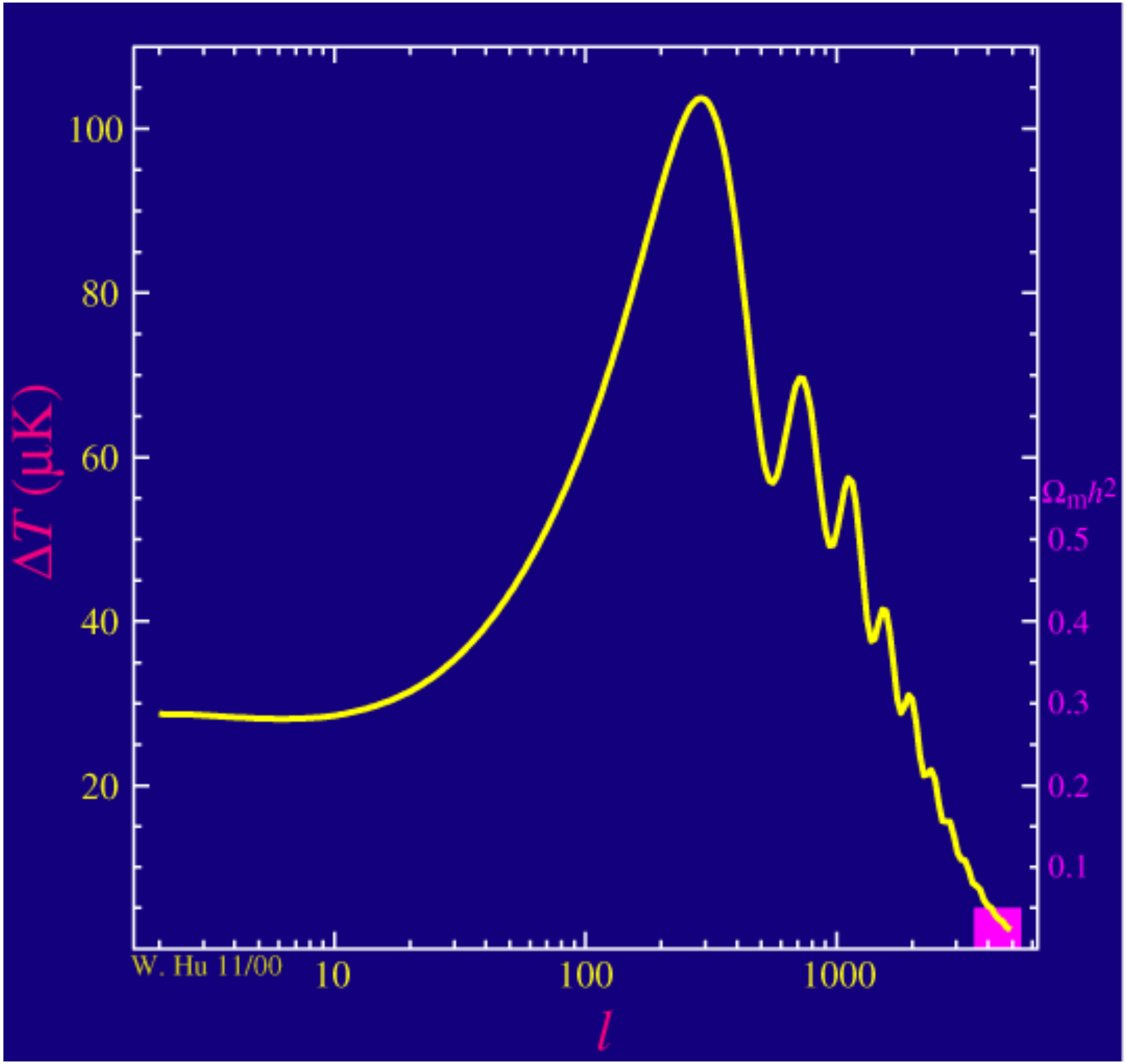


S. Dodelson arXiv:1112.1320

CMB, a dark matter probe



ω_m and ω_{bar} from CMB only



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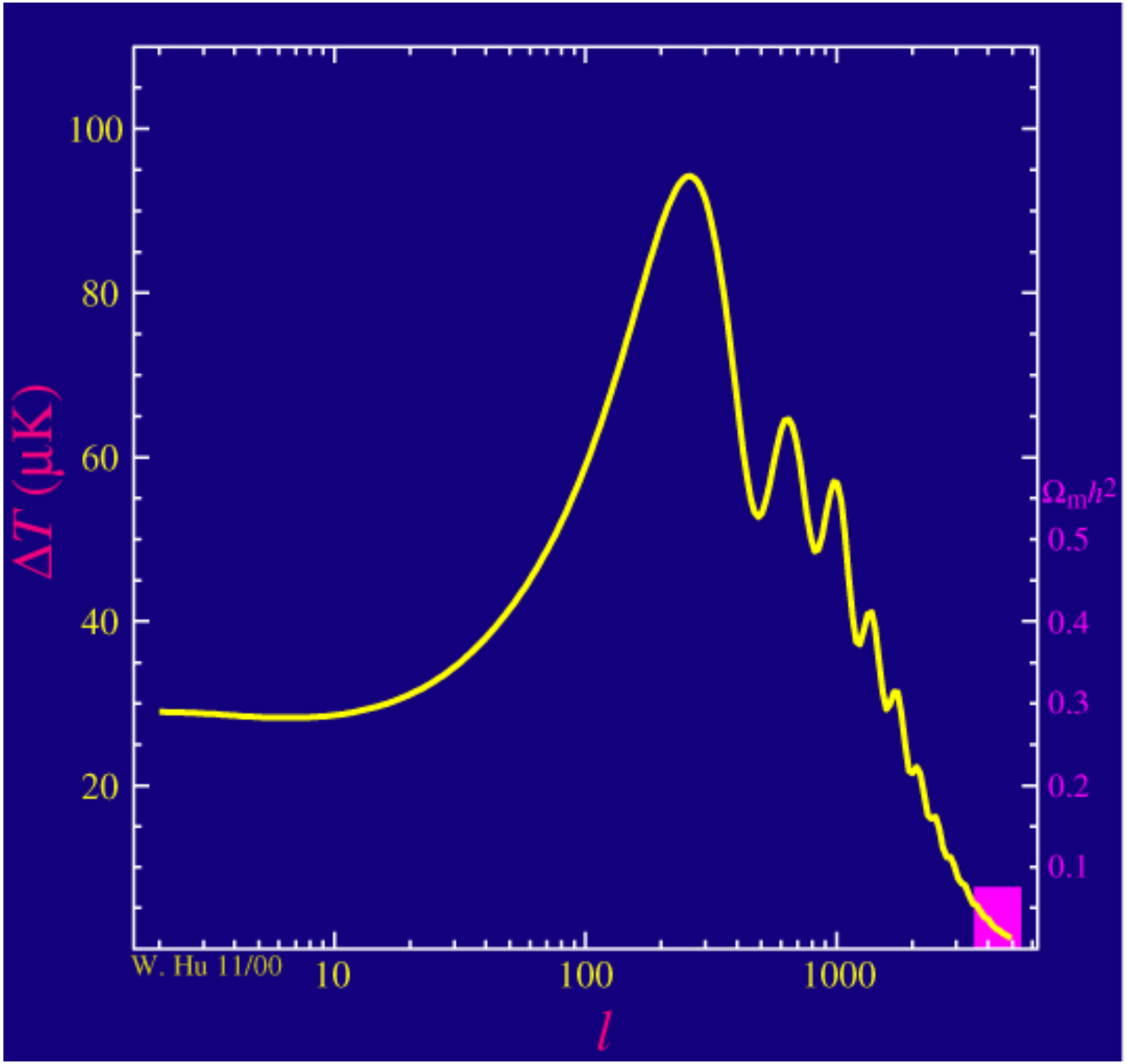
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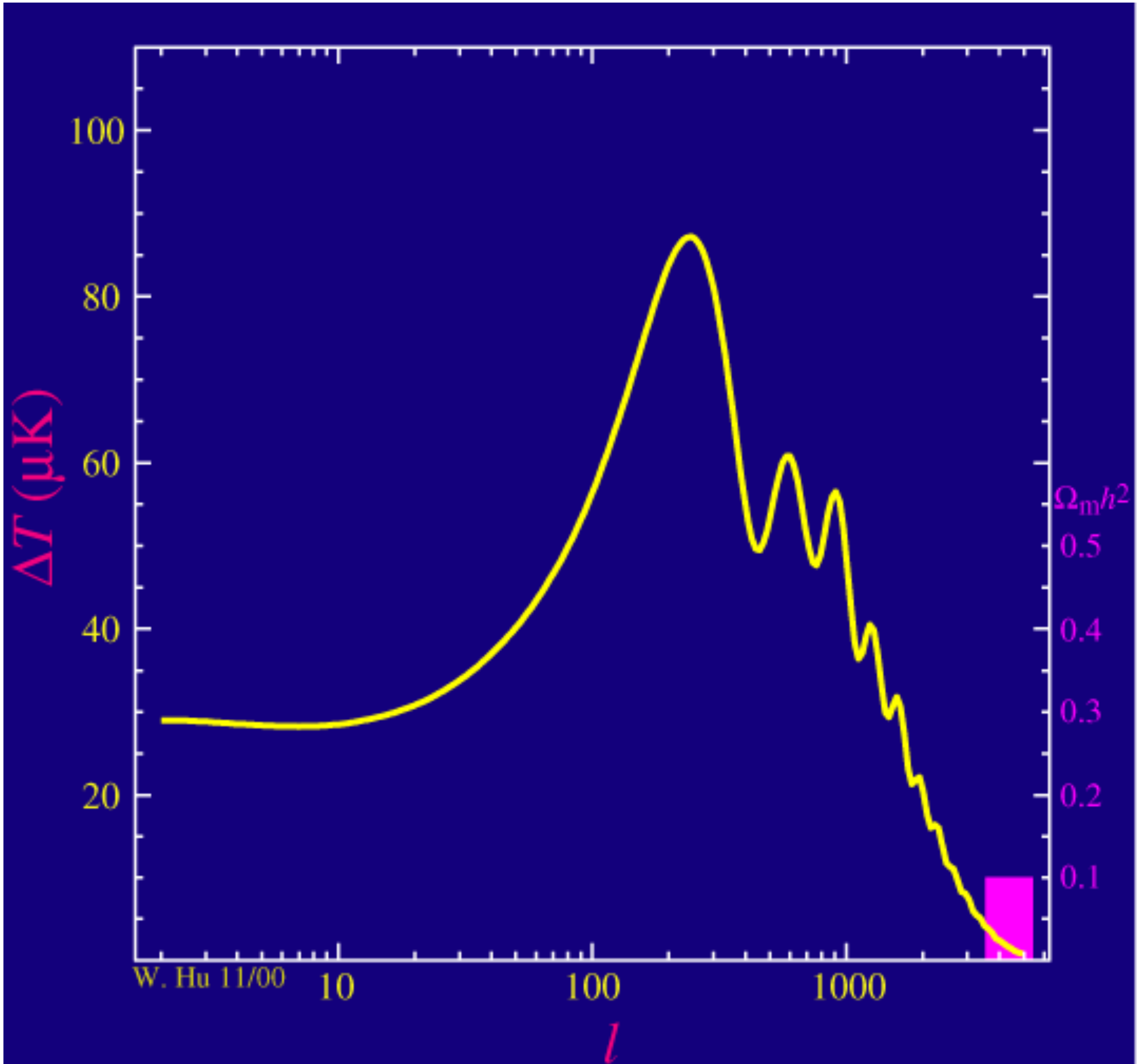

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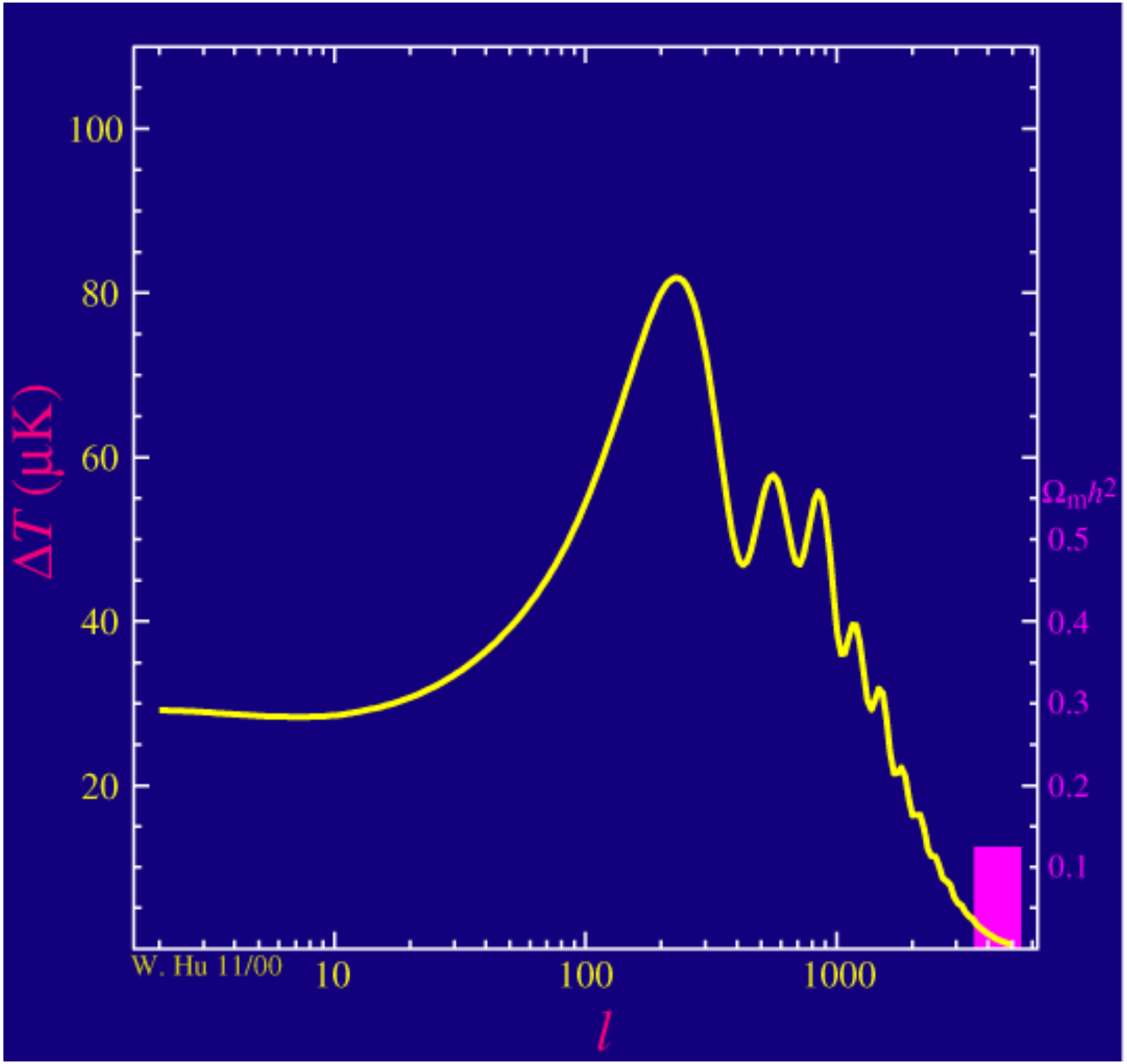

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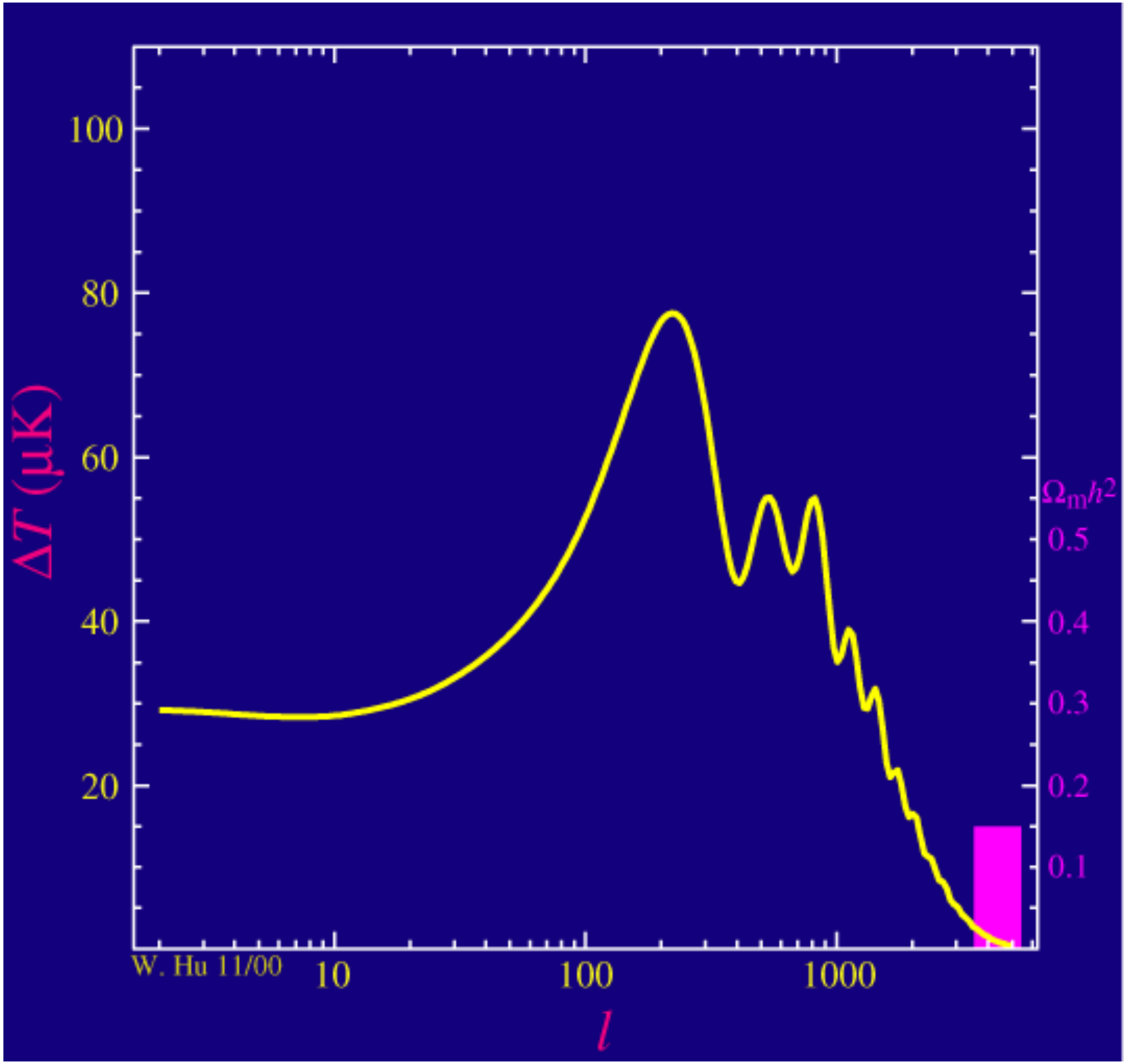

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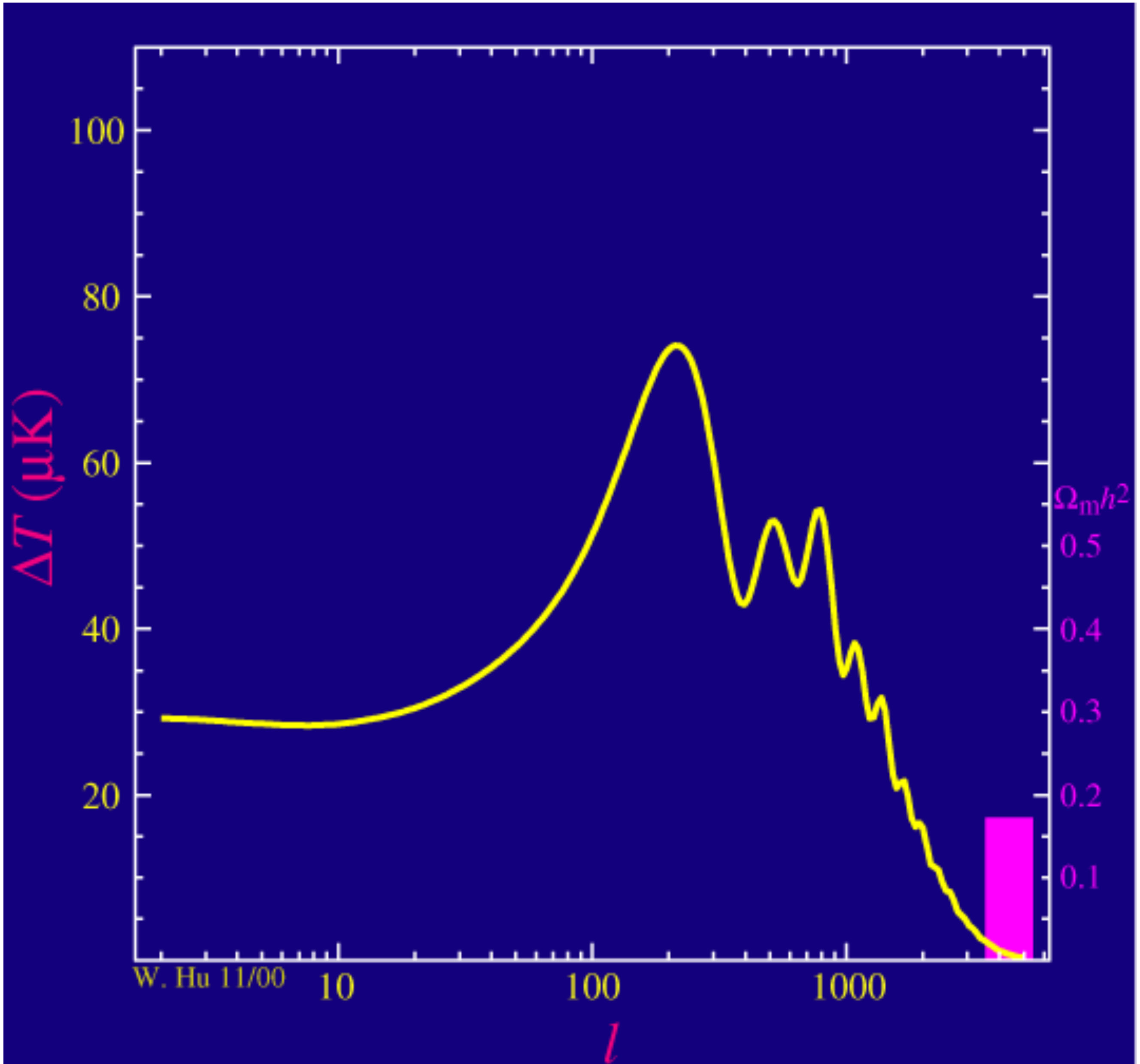

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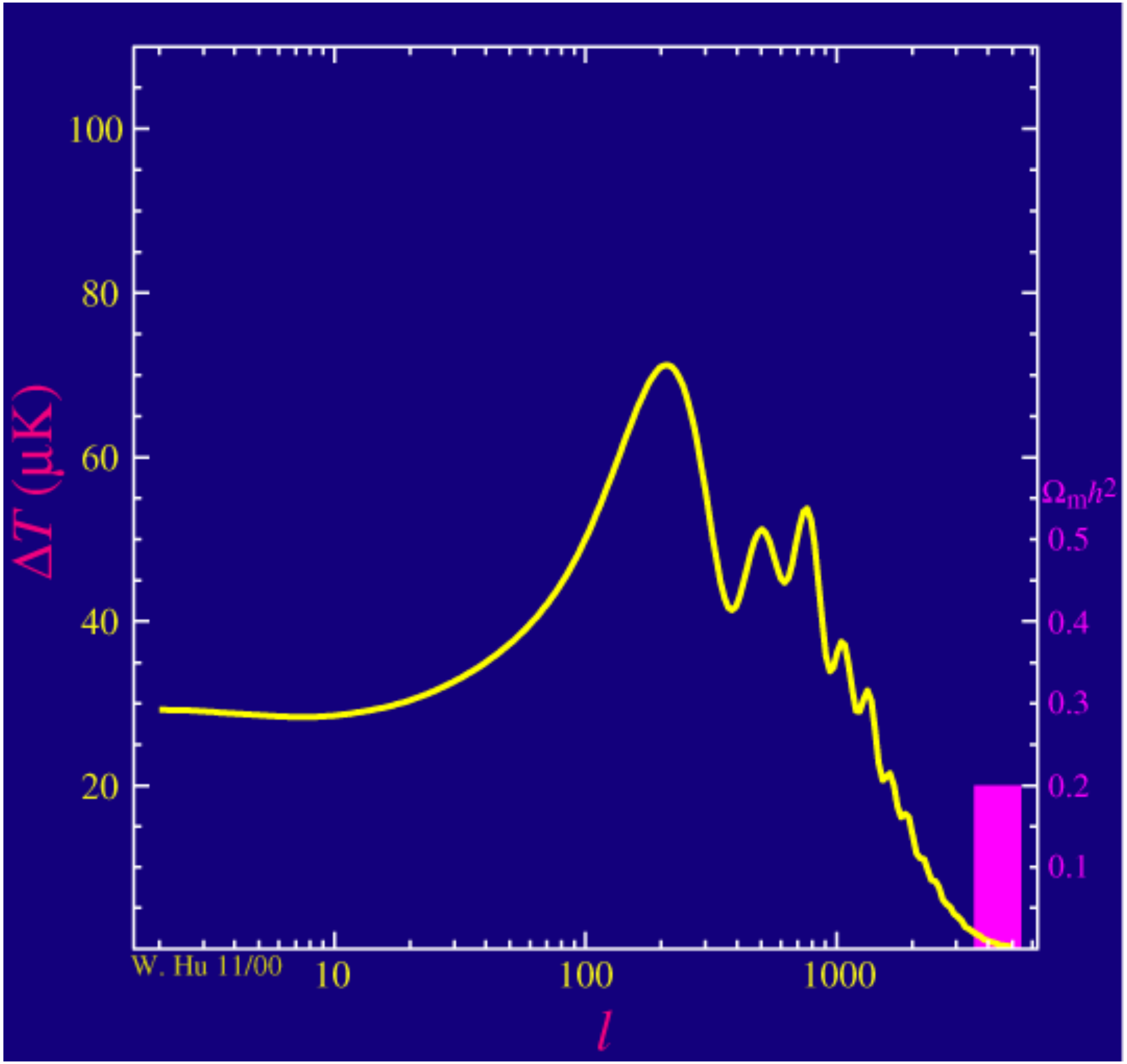

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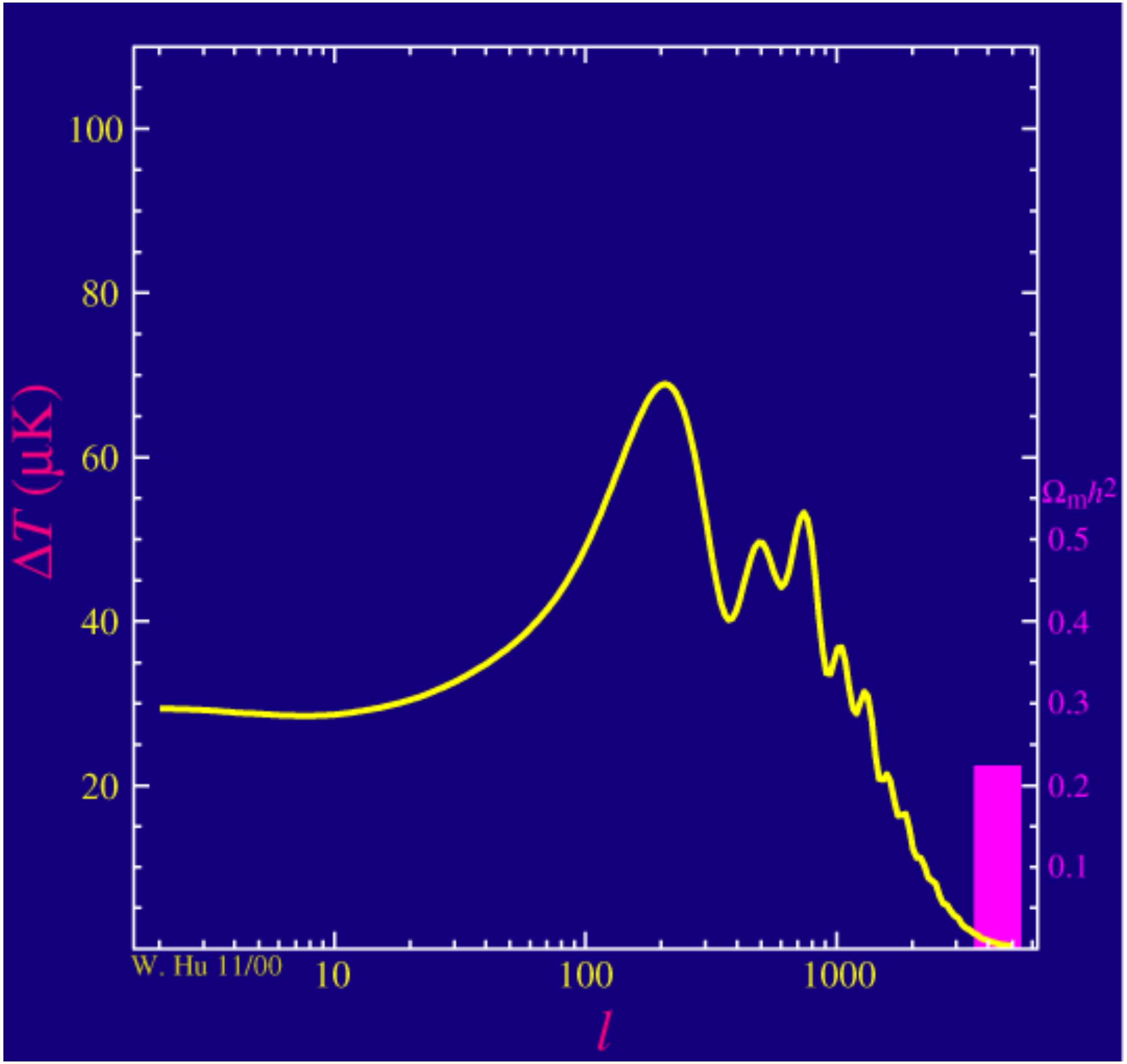

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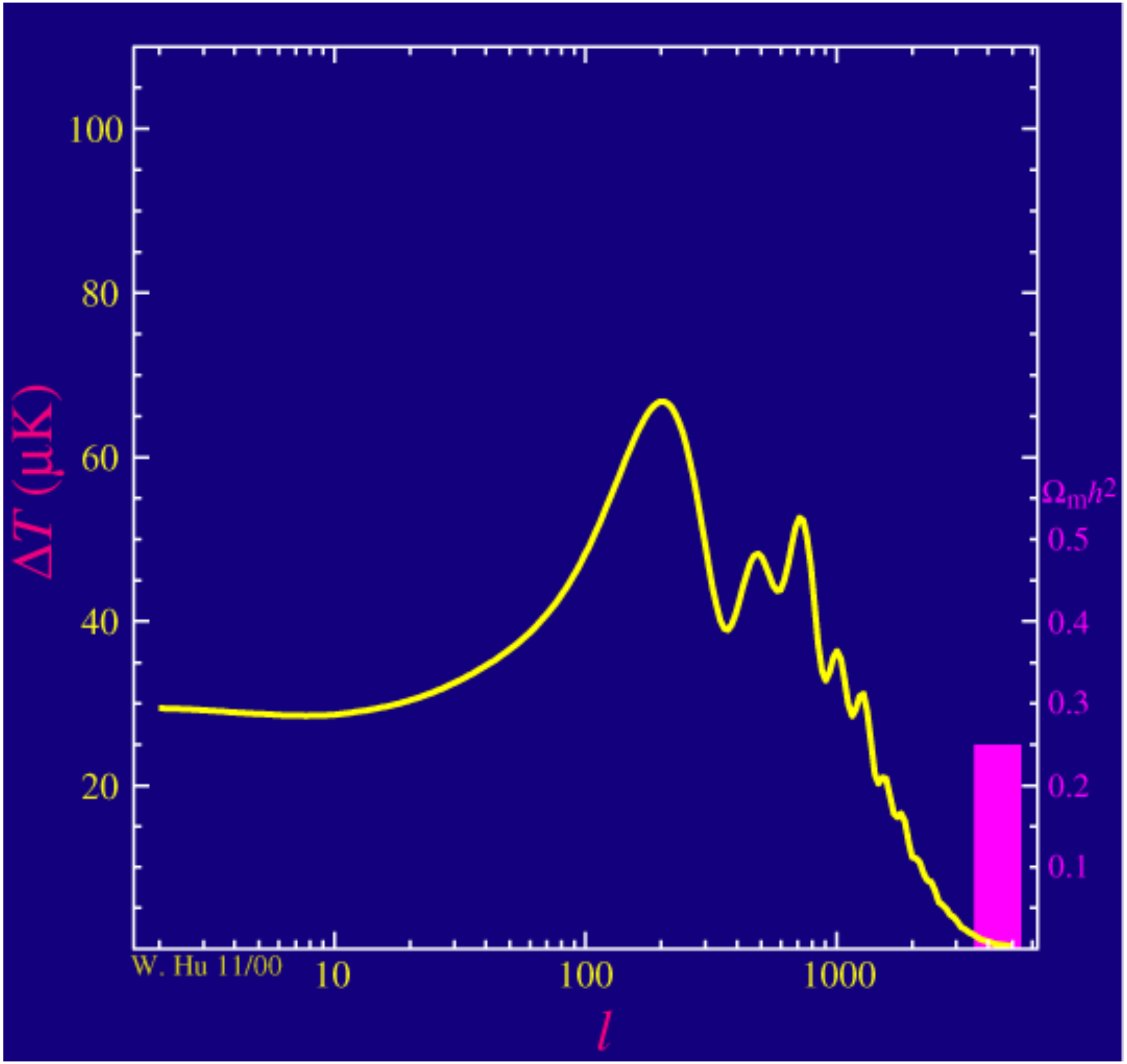

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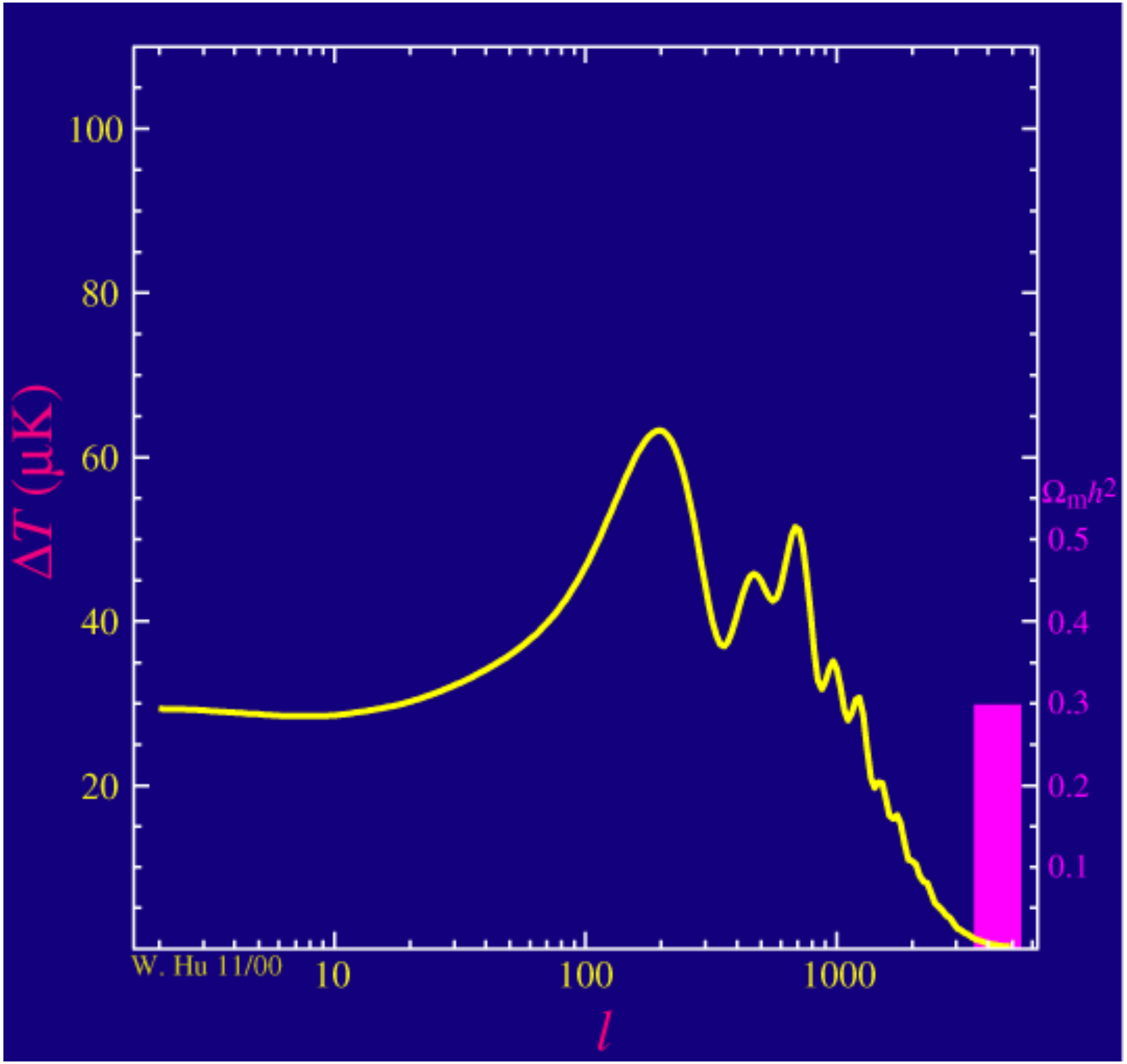

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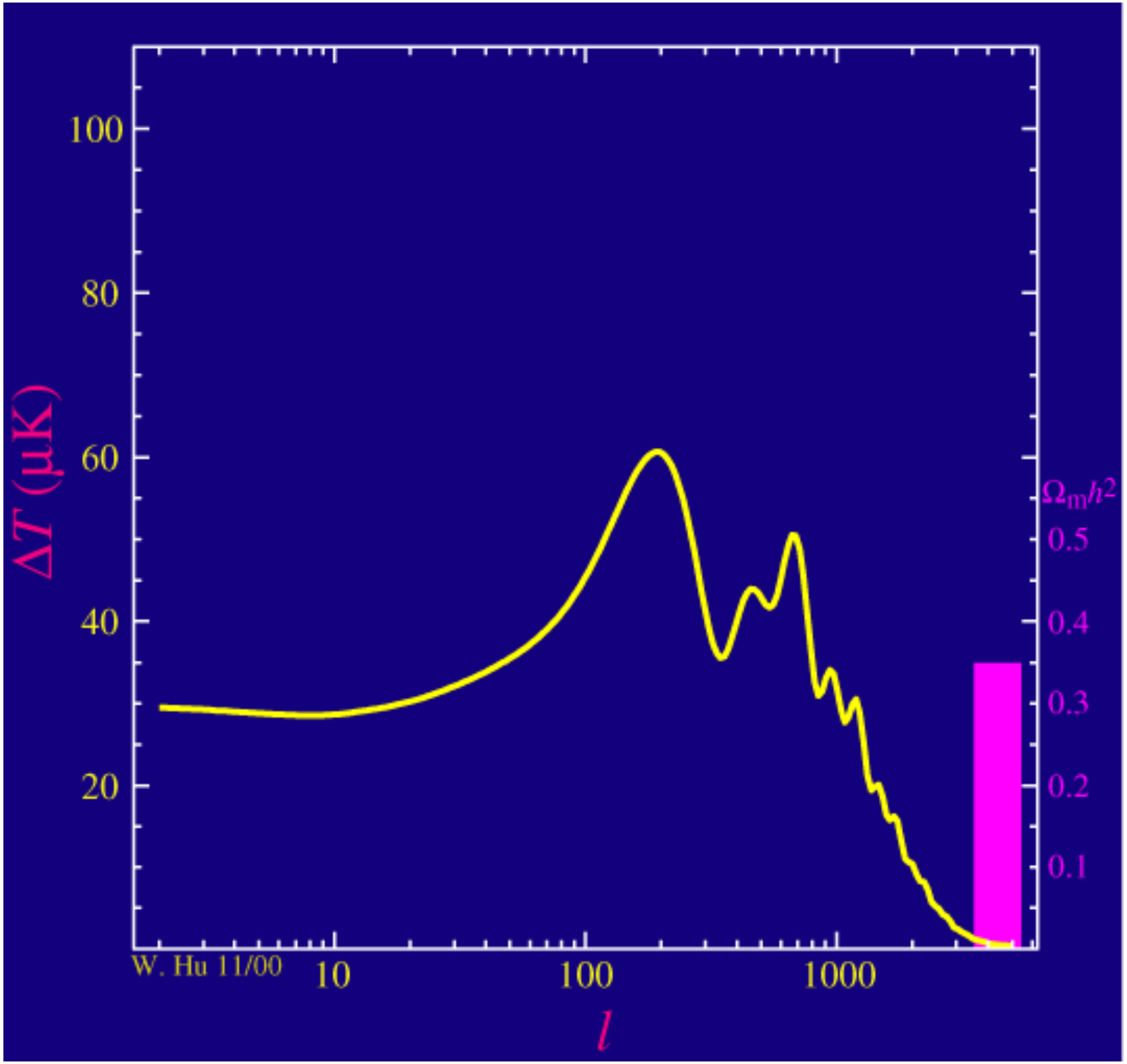

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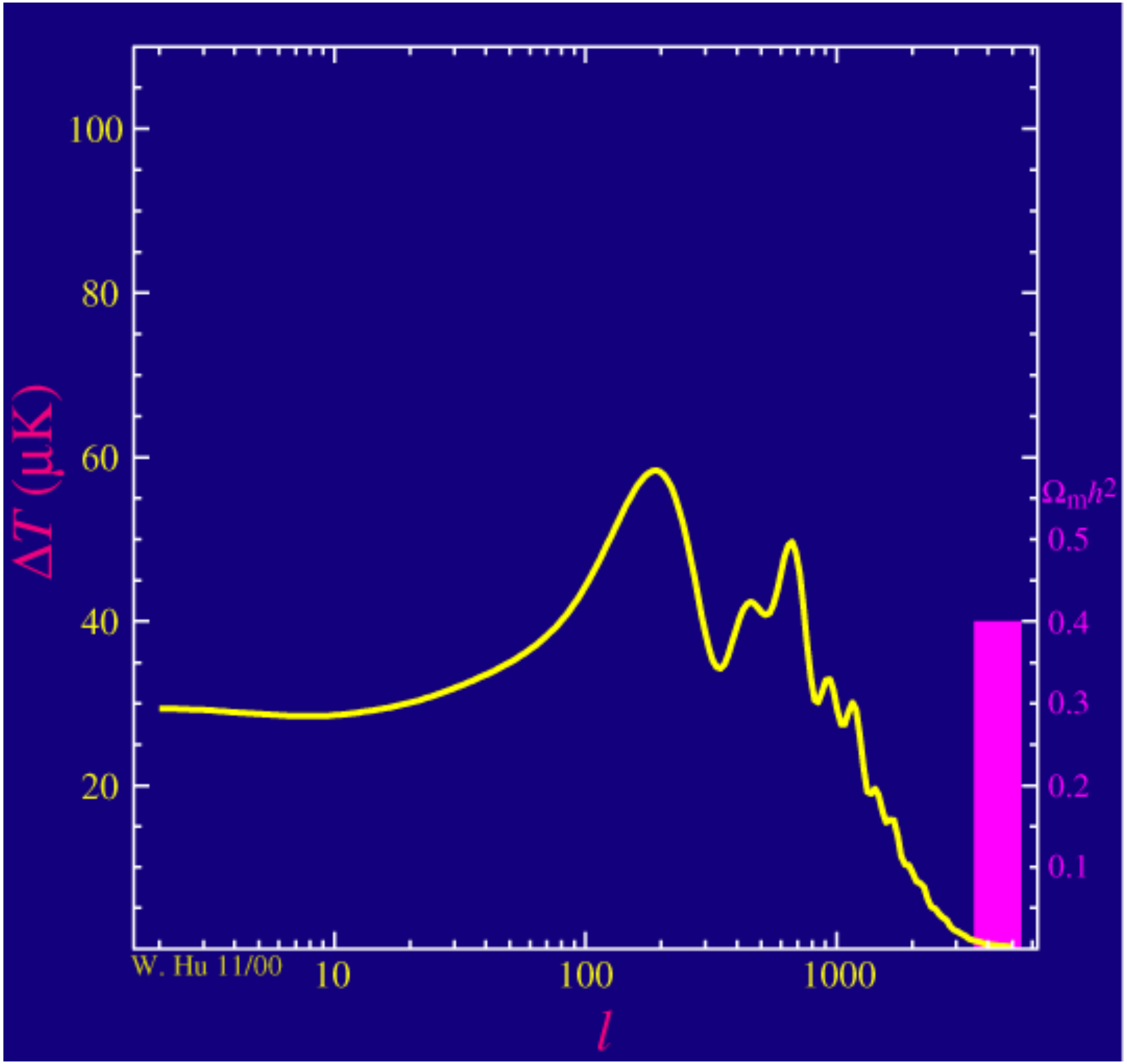

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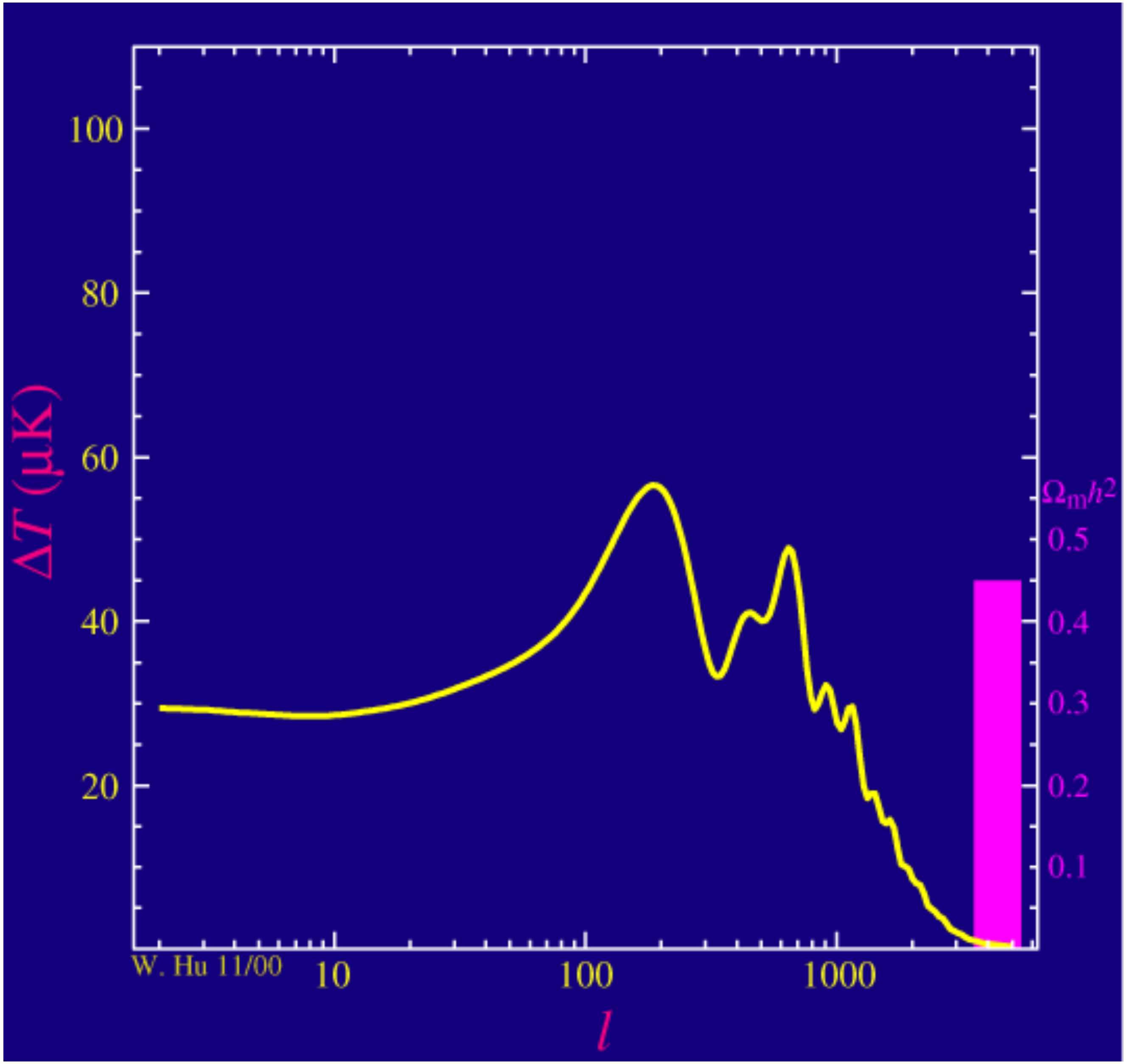

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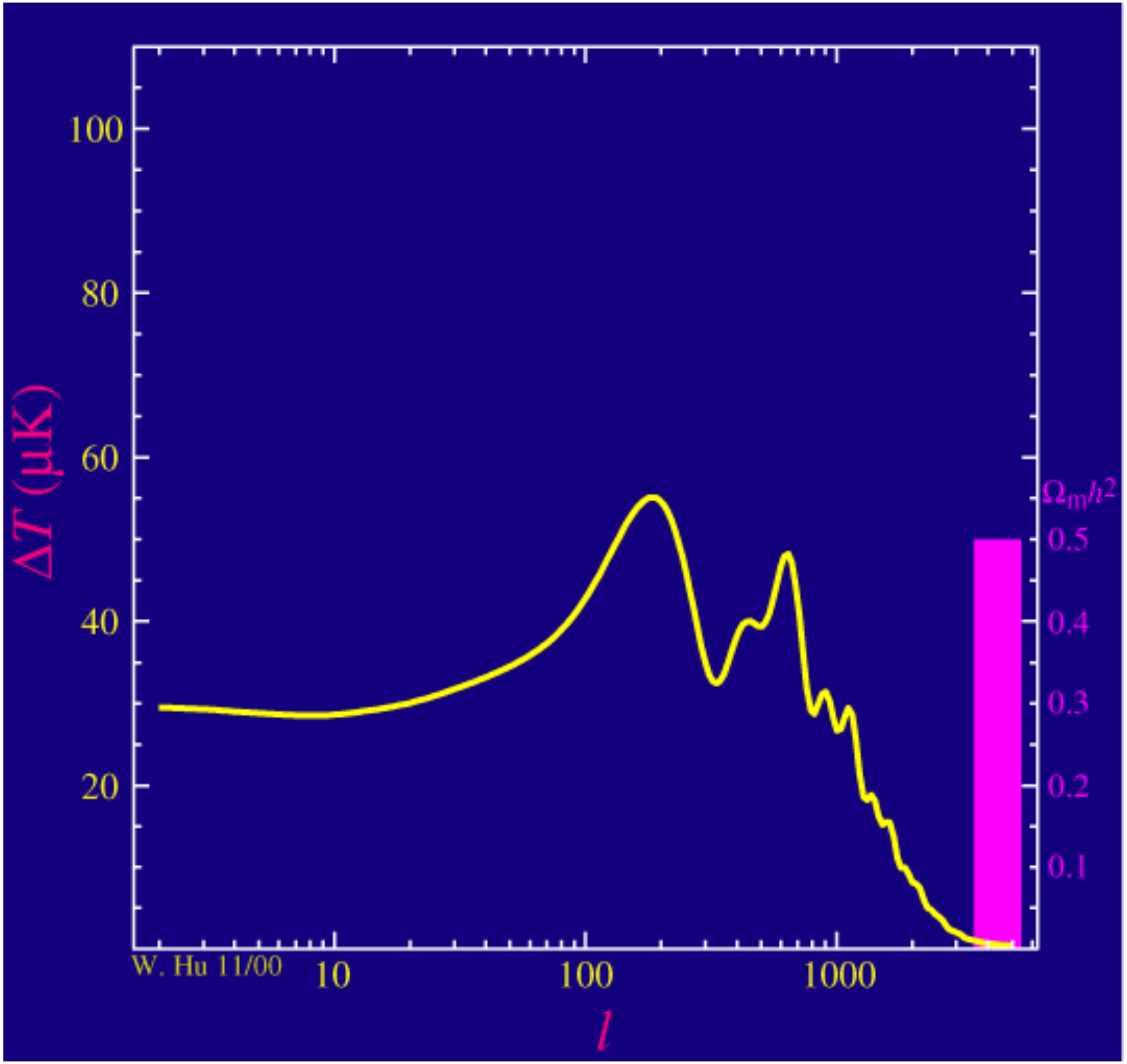

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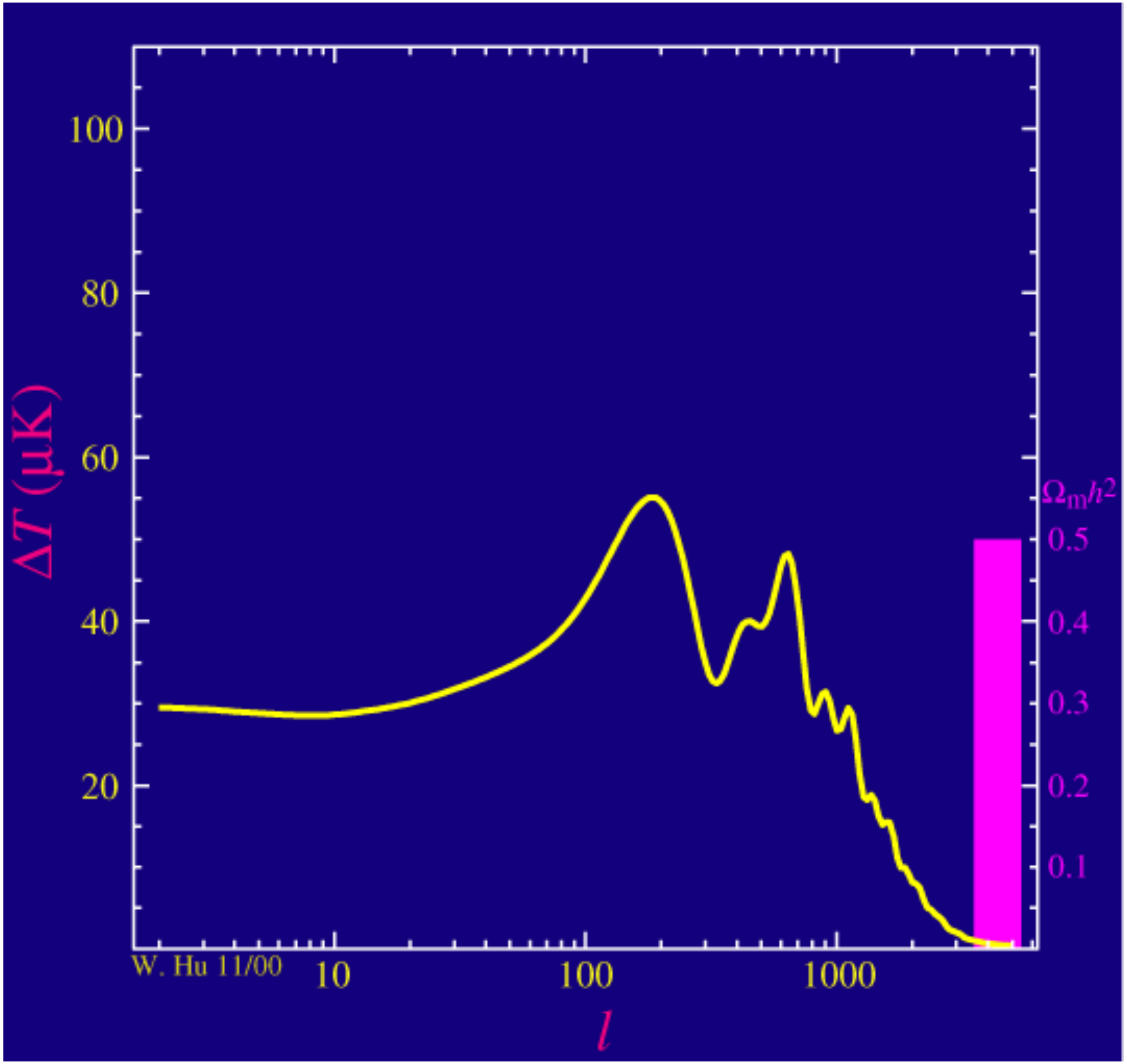

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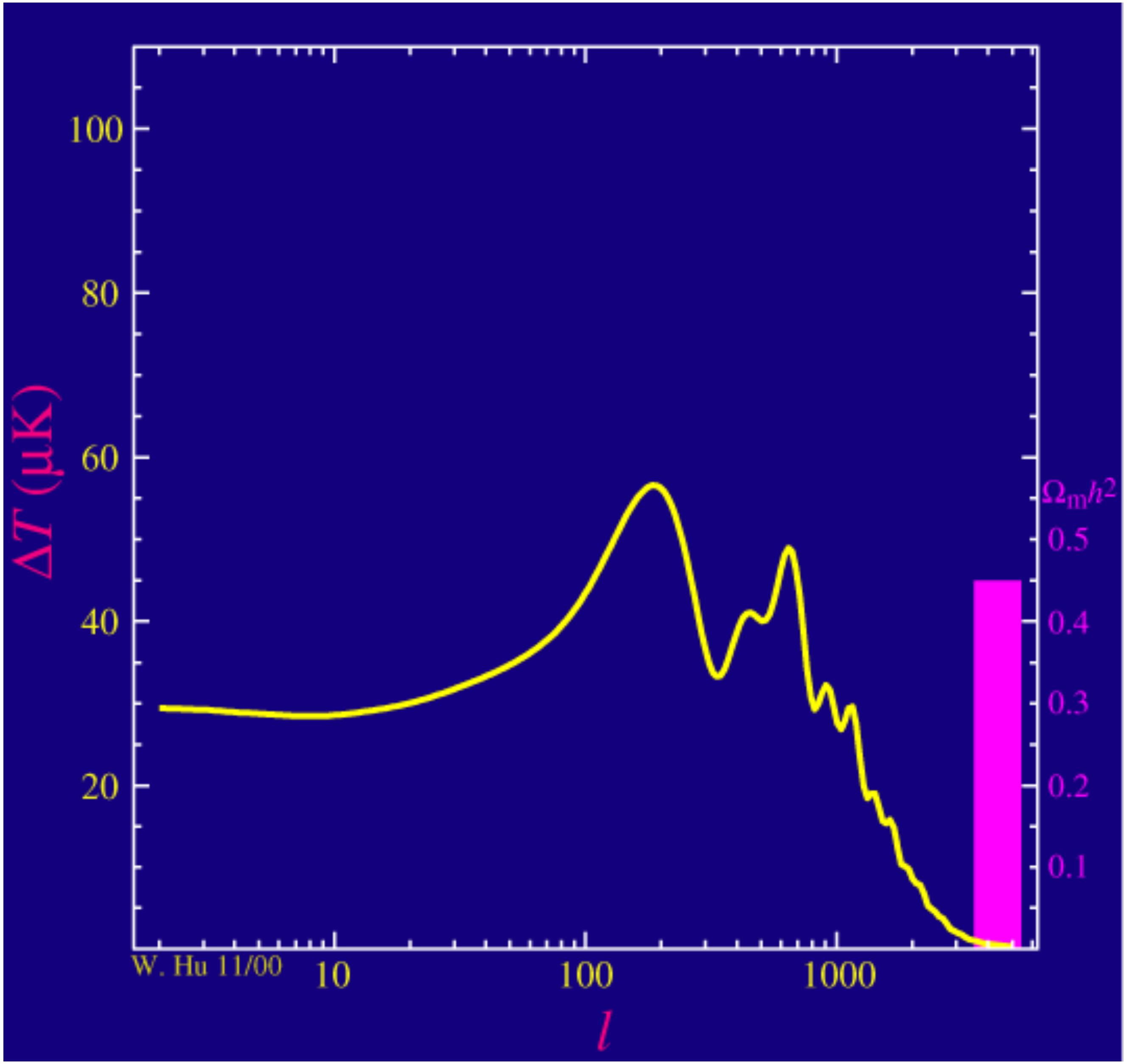
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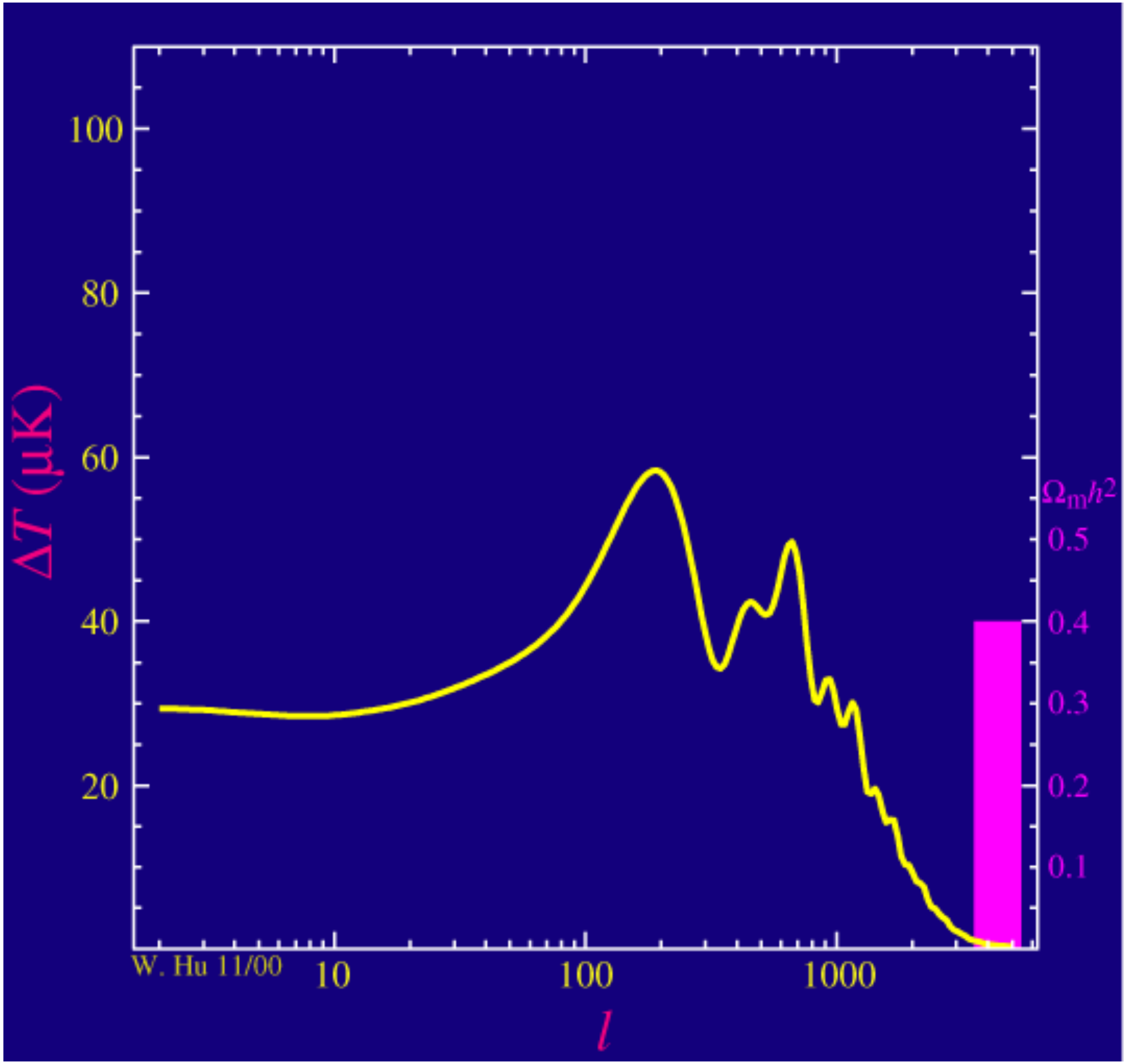

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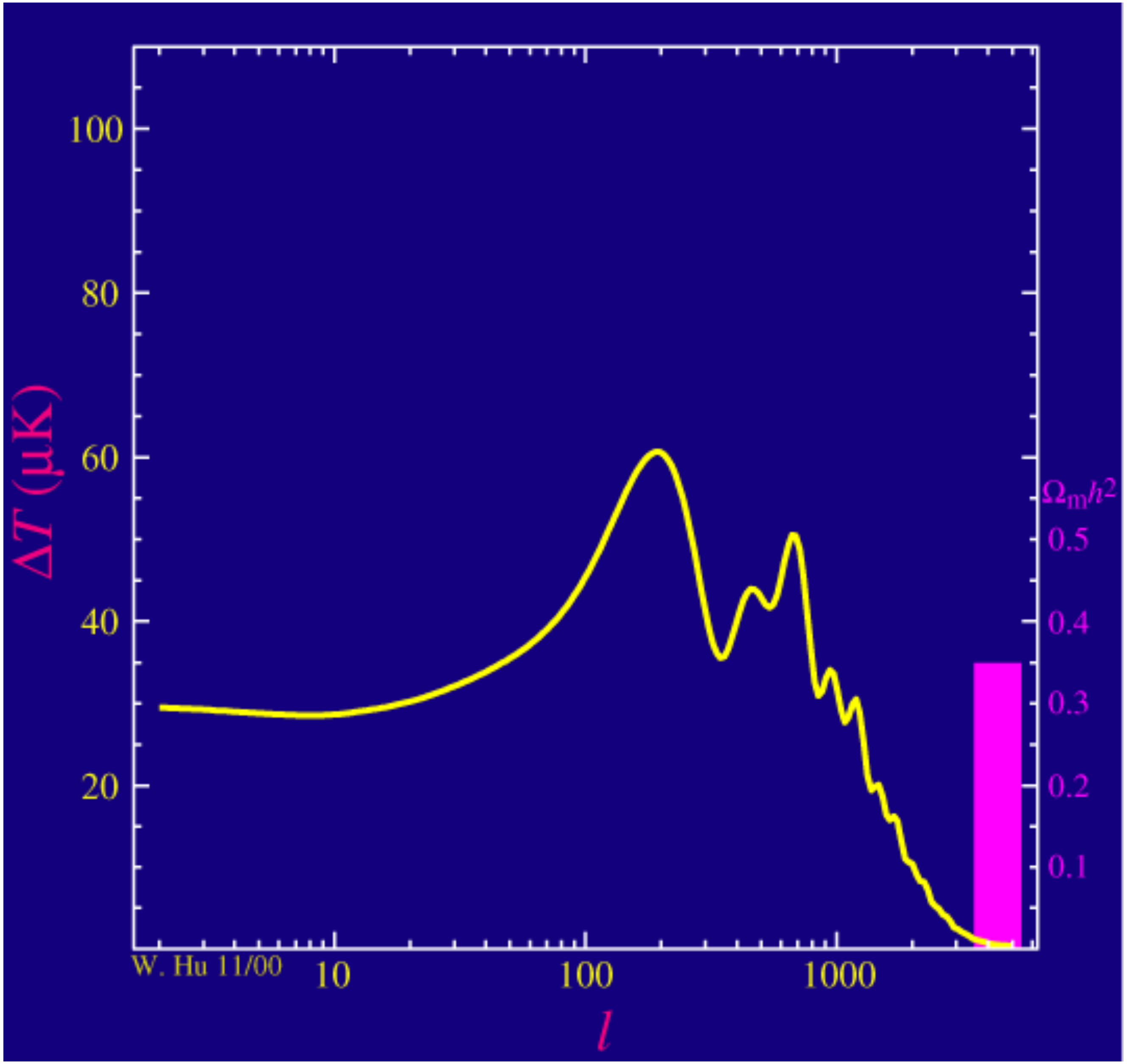

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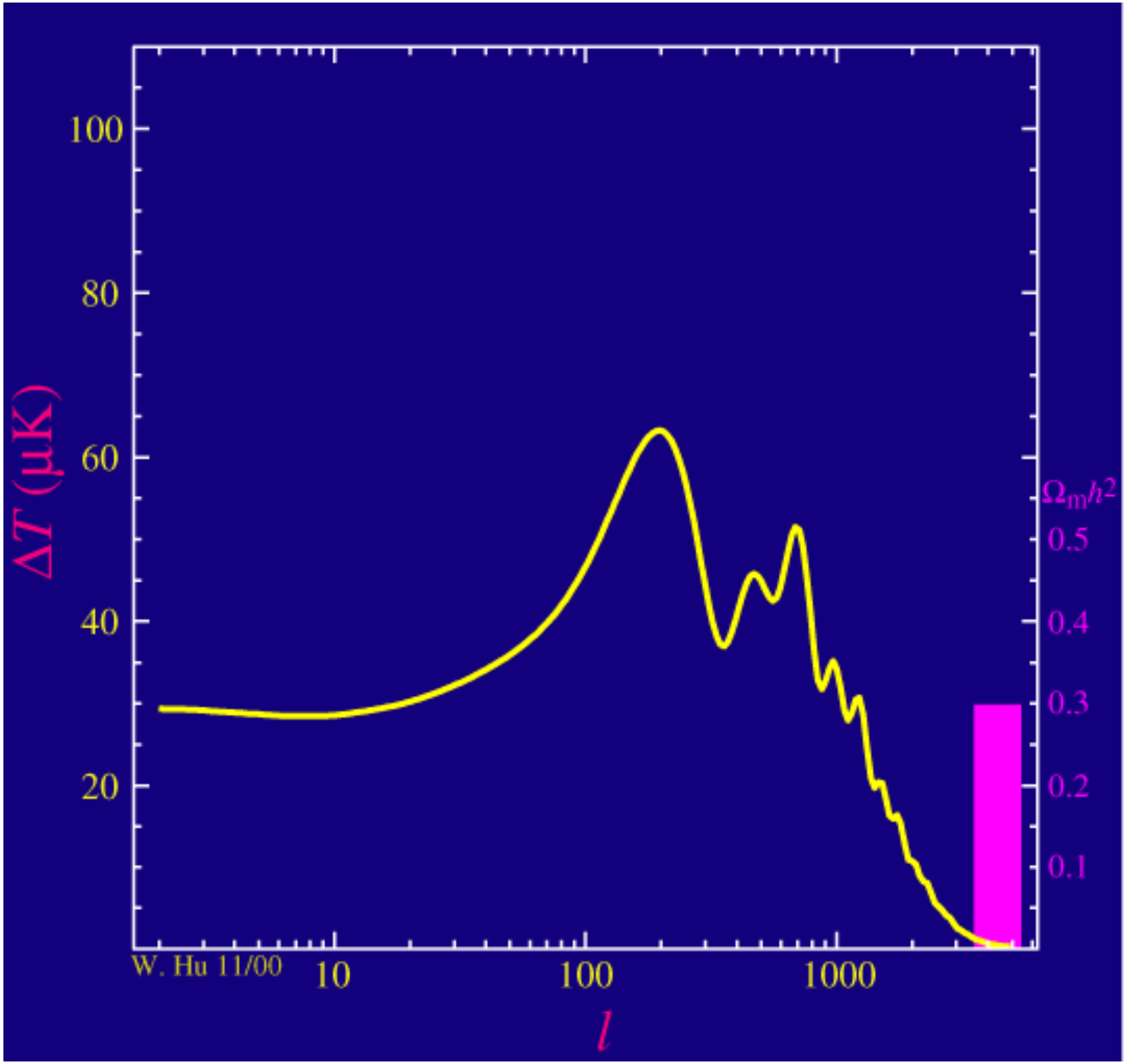

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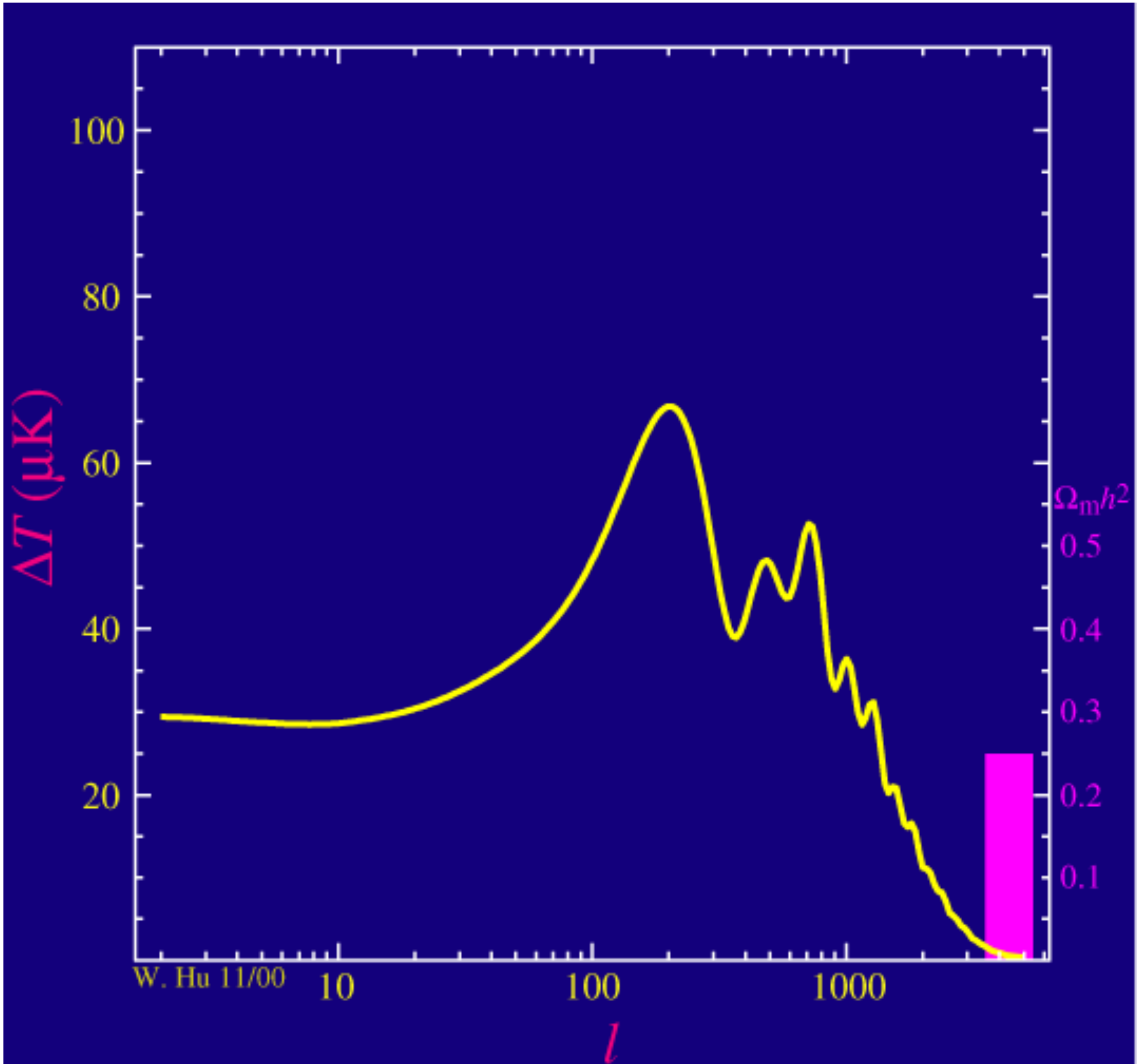

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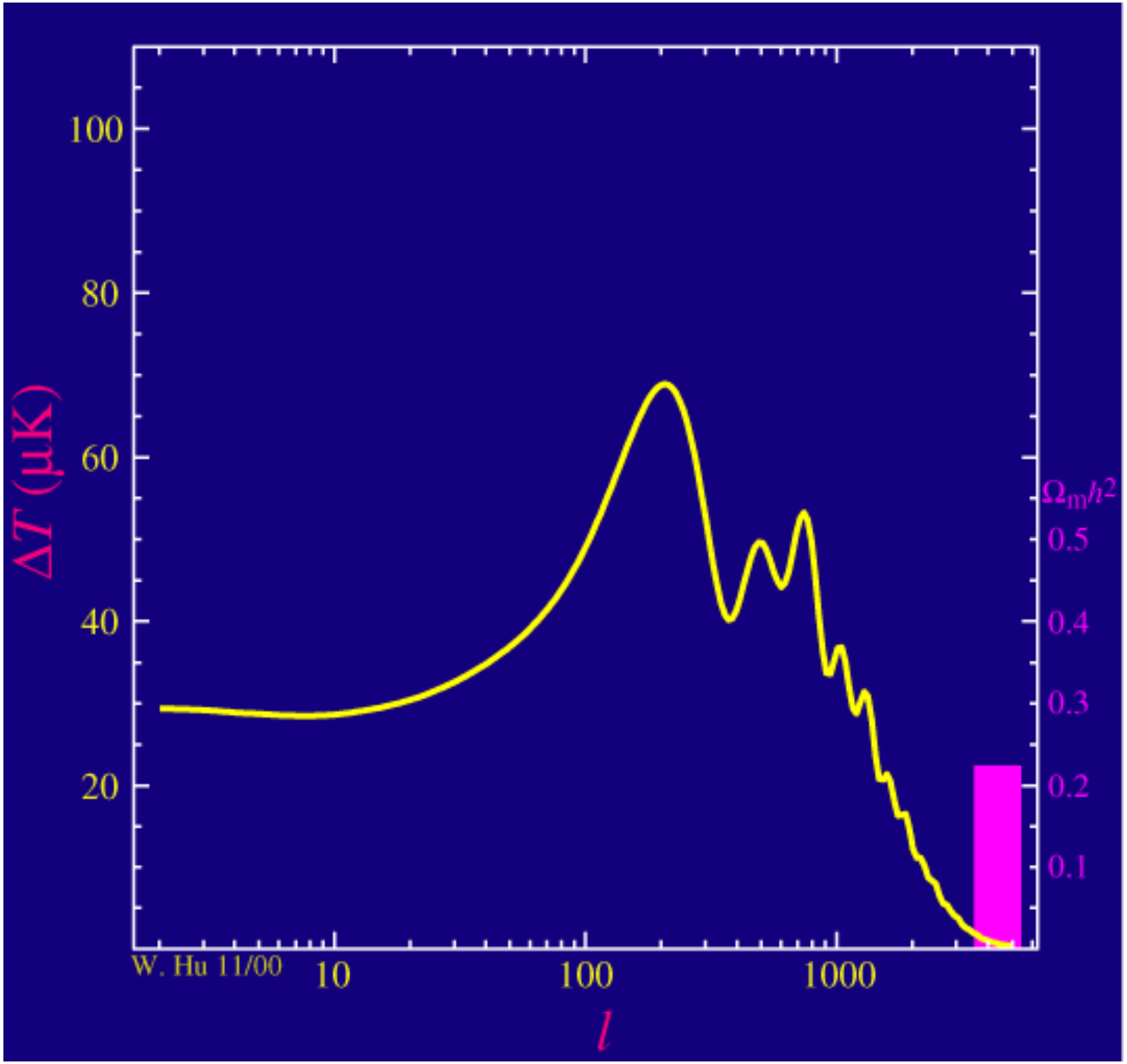

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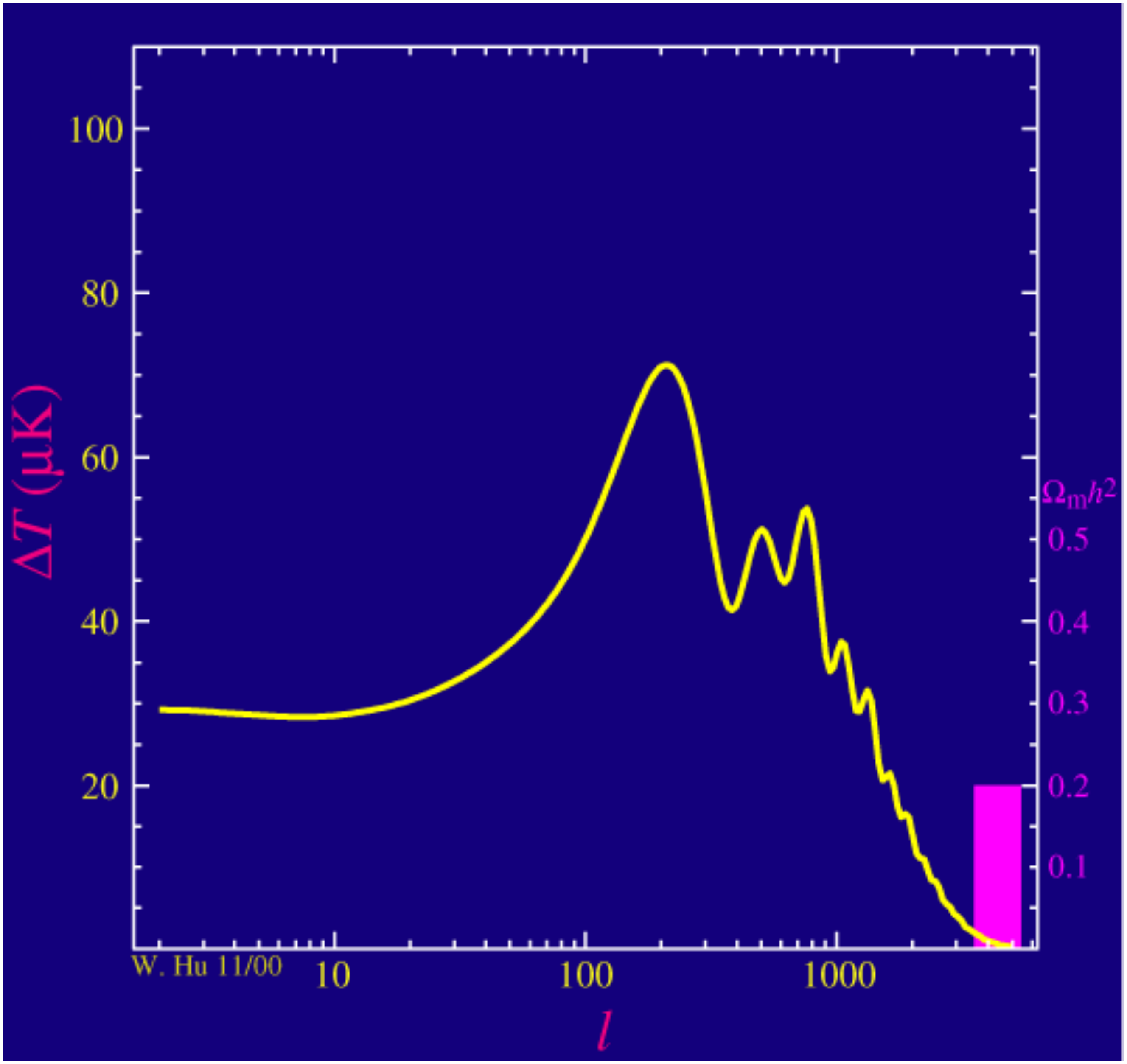

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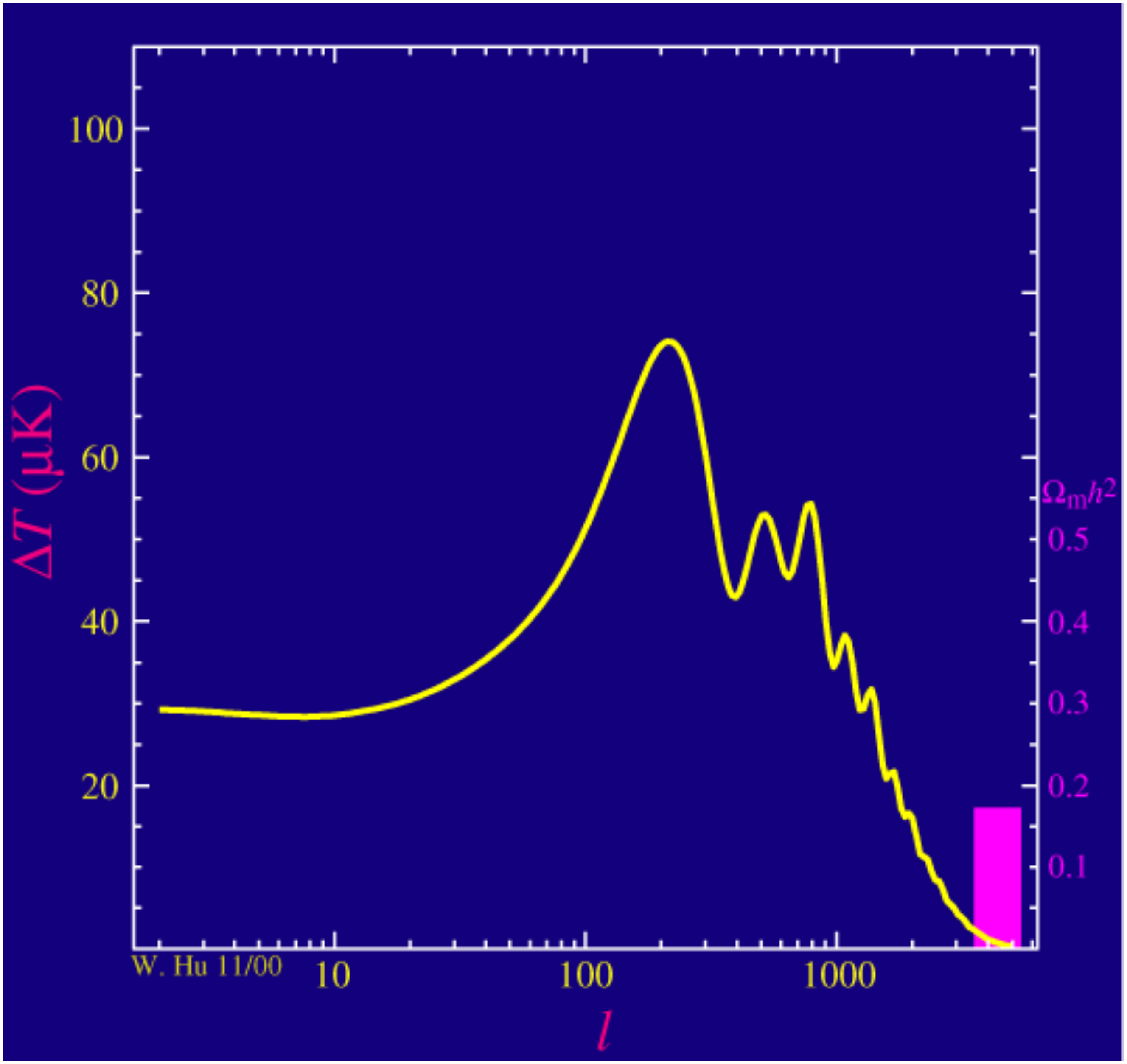

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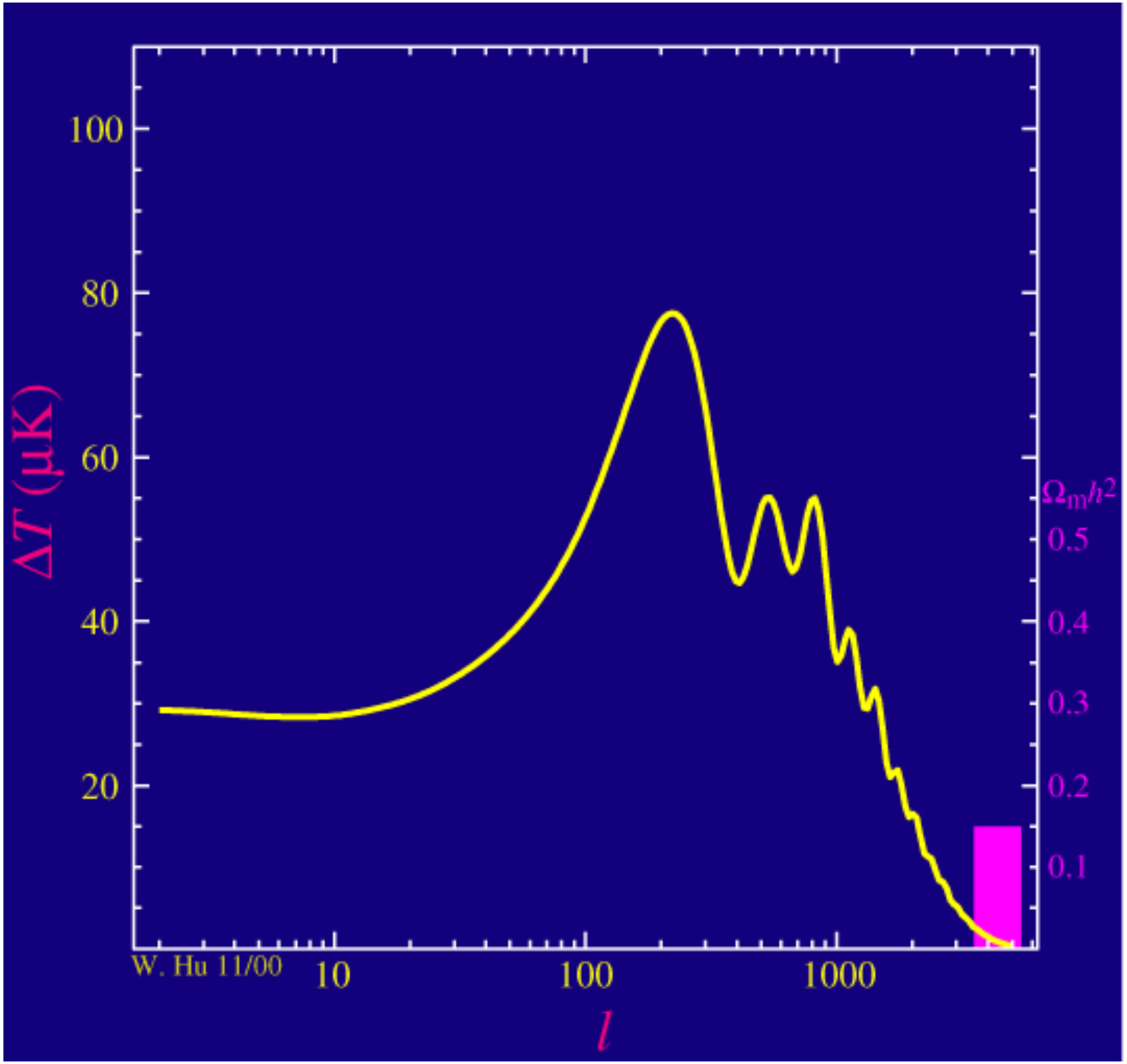

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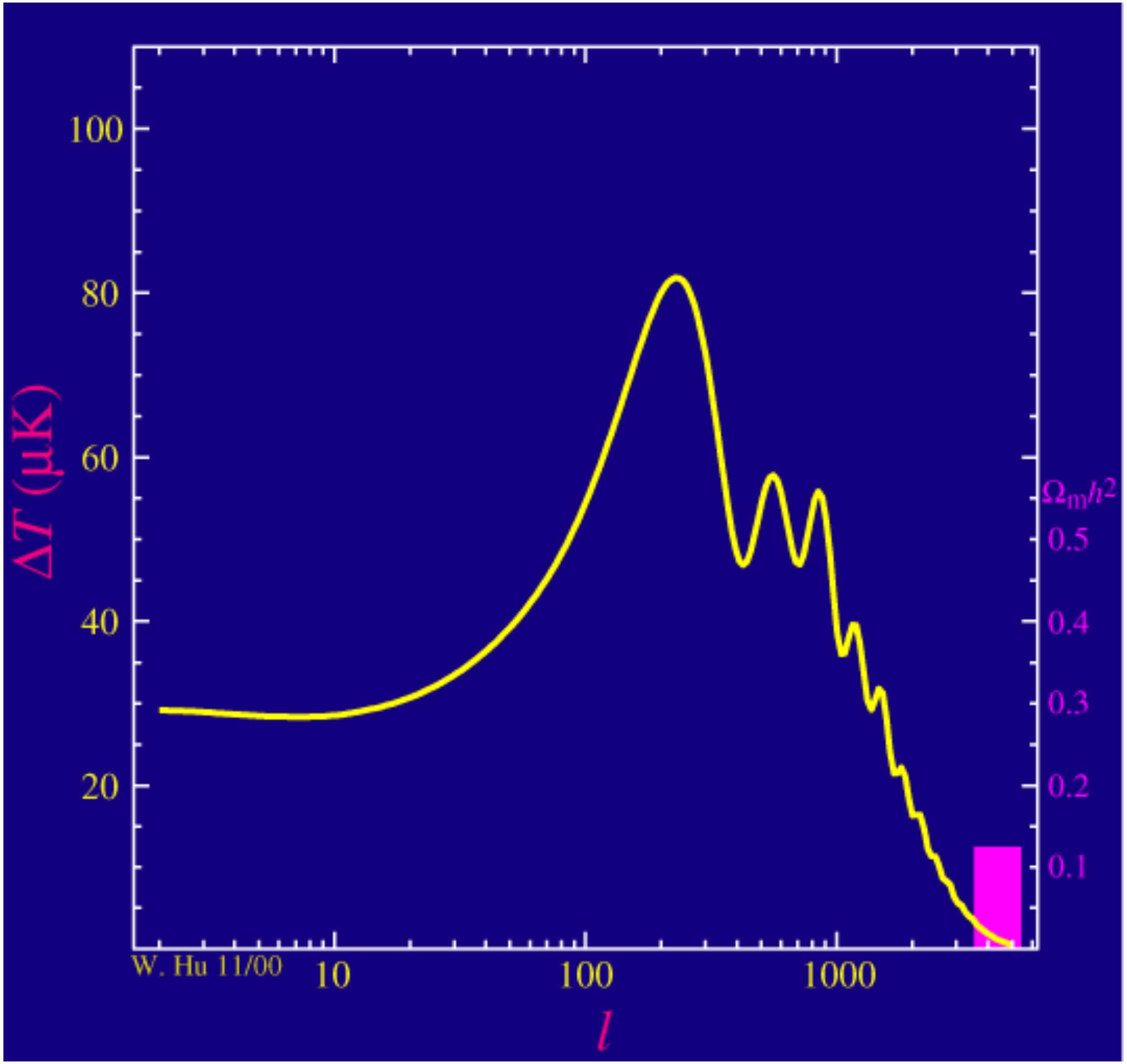

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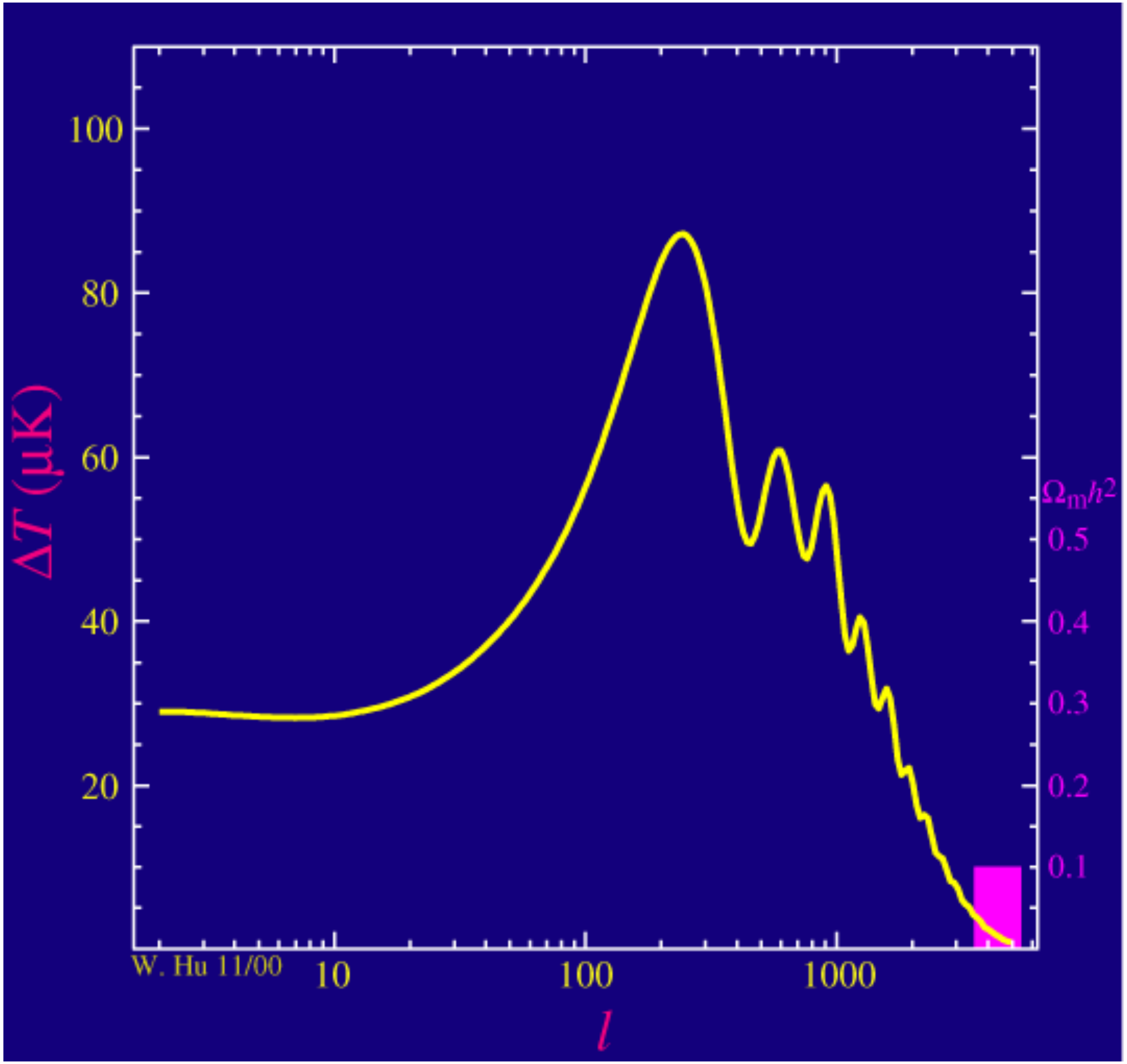

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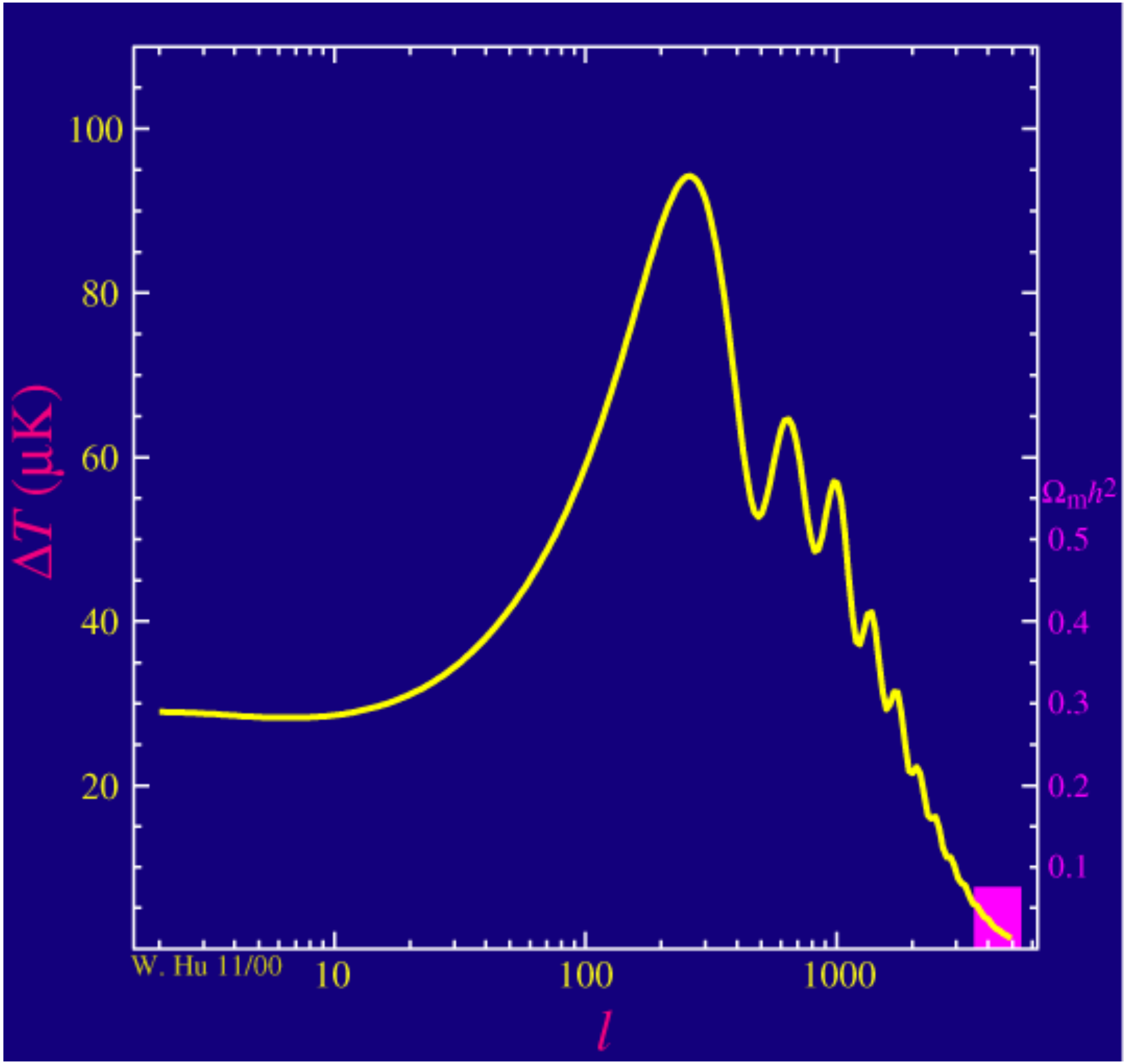

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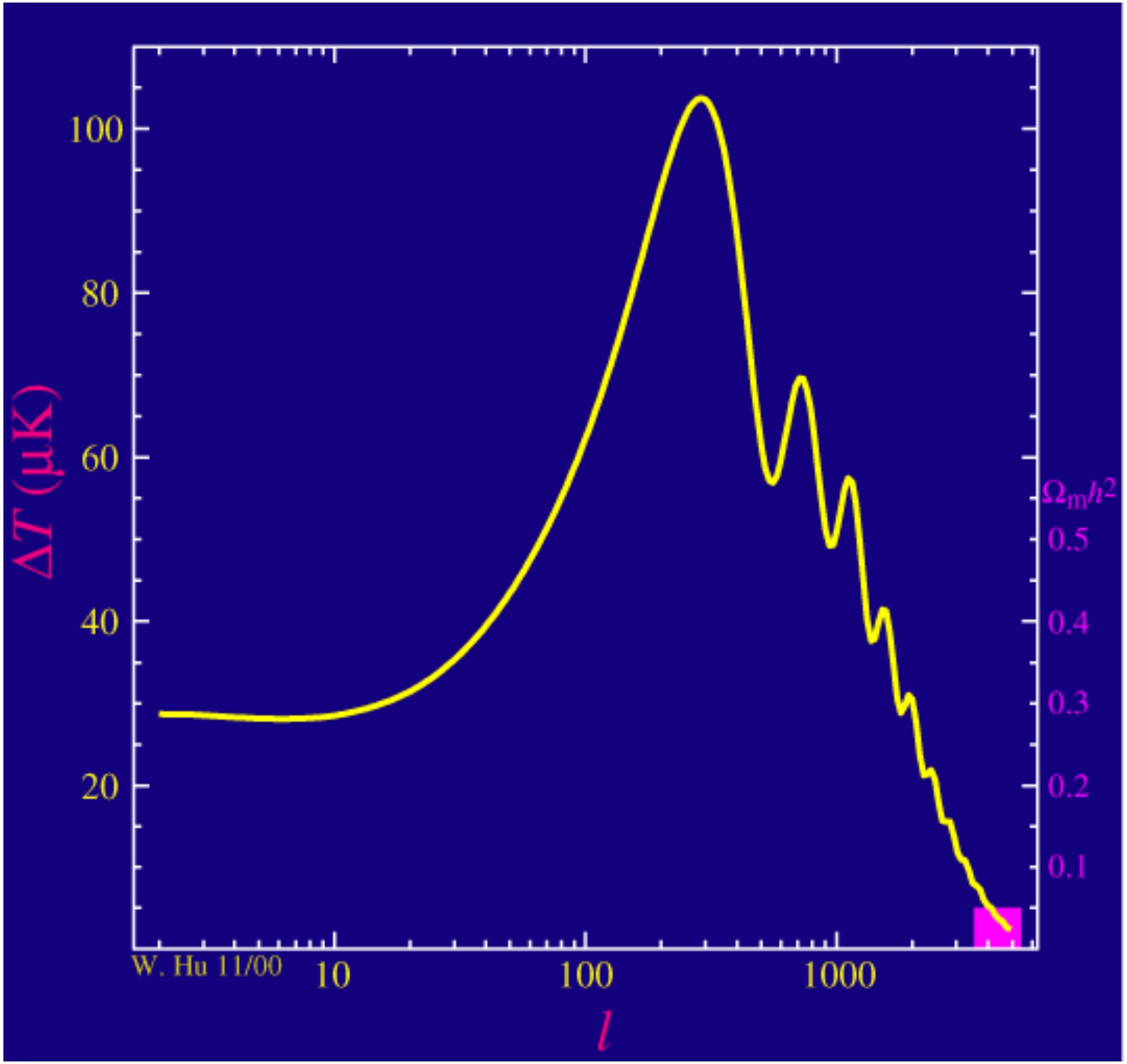

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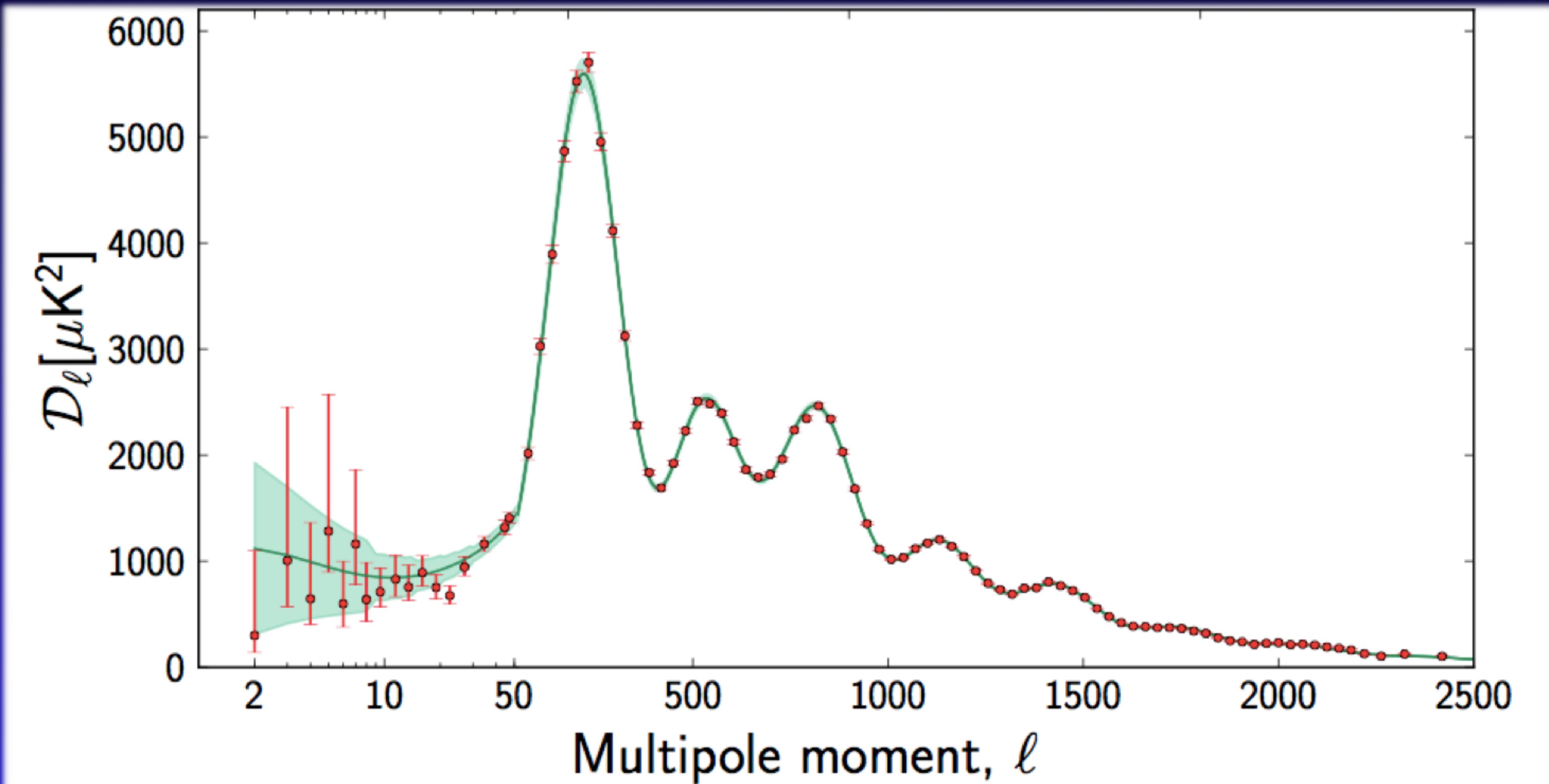
CMB, a dark matter probe



ω_m and ω_{bar} from CMB only

AN INDEPENDENT TEST: BBN

CMB data (and BAO) sensitive to baryons via e.m. coupling with photons (plus gravity)

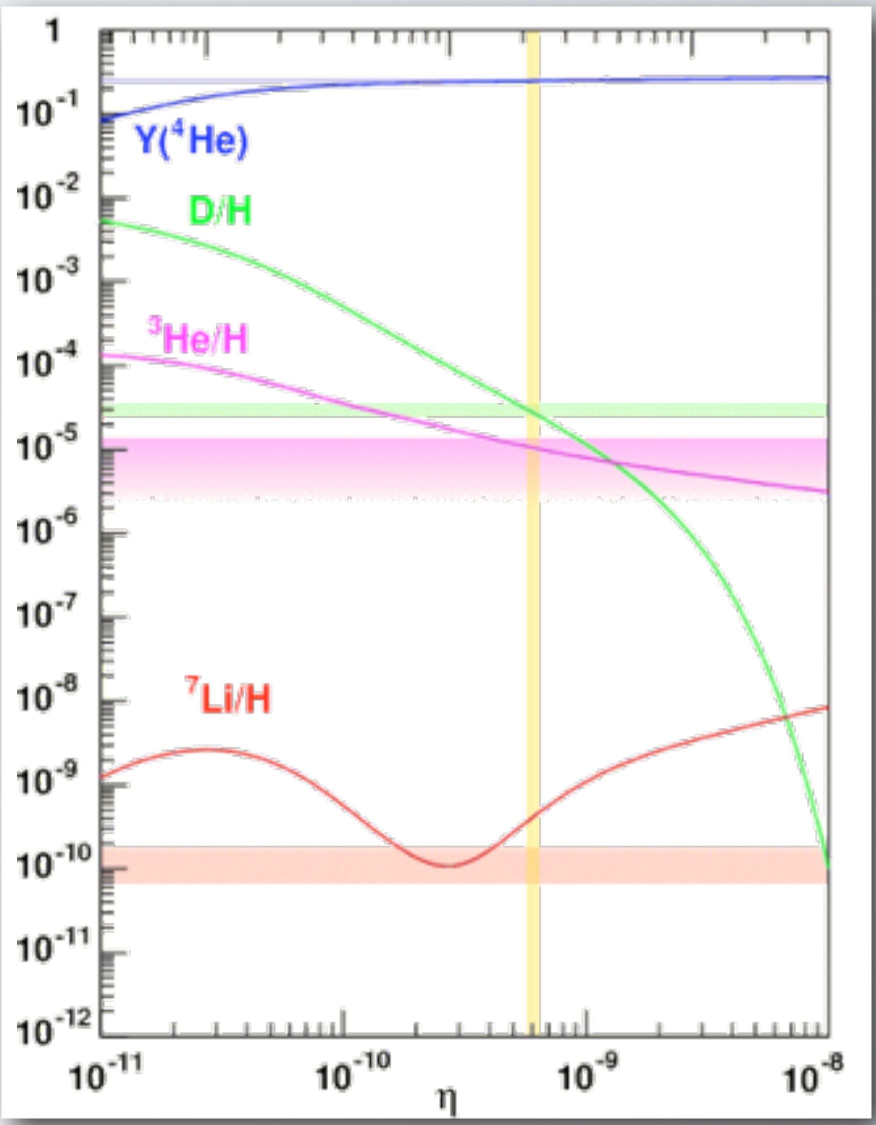
BBN is an over-constrained theory: all relevant observables **depend only** on the **baryon to photon number density ratio η.**

CMB provides an independent measurement of $\eta \sim 6 \times 10^{-10}$, hence BBN is parameter-free (a single nuclide determination suffices to test cosmology, wonderfully provided by D/H)

Exercise: prove $\eta \equiv n_b/n_\gamma = 2.74 \times 10^{-8} \Omega_b h^2$

η^{CMB} (from atomic physics, T~eV) is also in agreement with η^{BBN}, sensitive to total number of nucleons in the plasma at T~0.1 MeV (nuclear physics)
Great success of cosmology!

Can we understand the dependence on η in this plot, notably of Deuterium?



DEUTERIUM BOTTLENECK

D formation crucial for triggering further nuclear reactions, since multi-body (as opposed to 2-body) processes as $2n+2p \to {}^4He$ are inhibited by the low density: @T=0.1 MeV baryon density ~ air density

Two competing processes

- fusion: $n+p \to D+\gamma$
- photodissociation: $\gamma+D \to n+p$

One expects that when T drops below ~ B_D= 2.23 MeV, photodissociation processes become ineffective. However: too many photons!!

$$\frac{X_D}{X_p X_n} = \frac{12\,\zeta(3)}{\sqrt{\pi}} \left(\frac{T}{m_N}\right)^{3/2} \eta\, e^{\frac{B_D}{T}}$$

D formation starts only when $\eta \exp(B_D/T_*) \sim 1 \Rightarrow T_* \sim B_D/(23 - \ln \eta_{10}) \sim 0.1$ MeV

Despite availability of high-T, **BBN starts late and ends soon**, it's an incomplete/inefficient combustion, leaving fragile nuclear ashes behind!

BBN IN FOUR STEPS

- T>> 1 MeV: initial conditions dictated by NSE & input parameters.

- T~ 1 MeV: $p \leftrightarrow n$ freeze-out (weak physics… <u>^{4}He yield tracks n/p</u>)

(departure from isospin equilibrium)

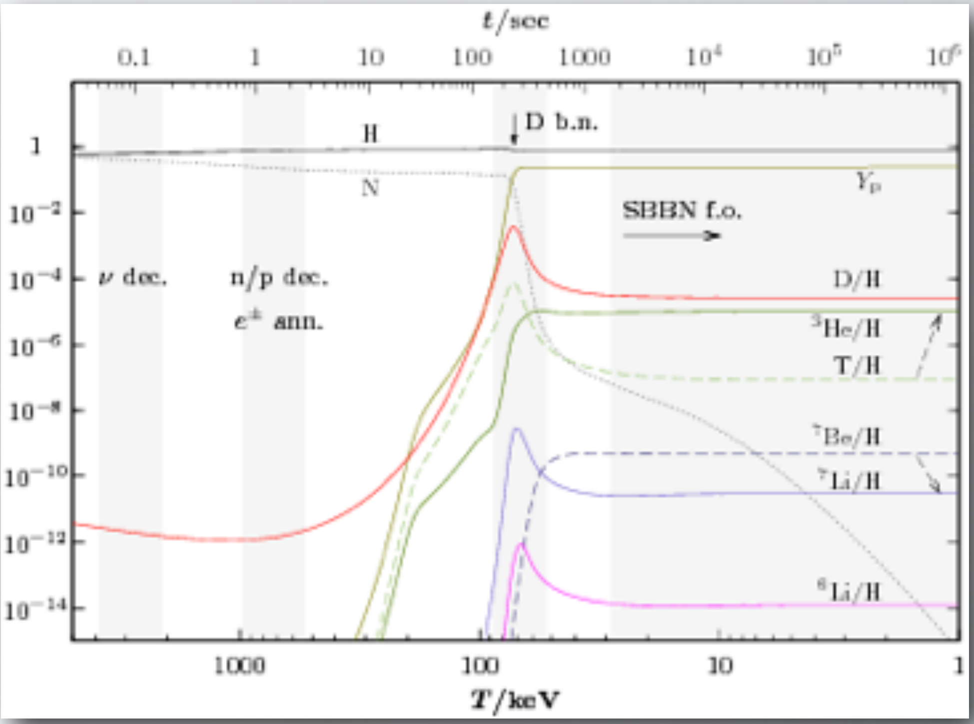
- T~ 0.1 MeV Deuterium bottleneck opens *(late, due to high entropy per baryon!)*
- 0.1~T~ 0.01 MeV nuclear reactions take place.

(departure from NSE equilibrium)

Despite availability of high-T,
BBN starts late and ends soon!
(inefficient combustion, leaving fragile nuclear ashes behind)

Remember: for quick estimates compare

Rate of process of interest $\Gamma \approx H$ Hubble expansion rate



INITIAL CONDITIONS AND NSE

- T>> 1 MeV: *p*,*n* & nuclei are in thermal (kinetic & chemical) equilibrium

✓ high entropy per baryon → negligible fractions of all but *p* & *n* (which in turn easily intercovert into each other)

$$n_A = g_A \left(\frac{m_A T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_A}{T} + \frac{\mu_A}{T}\right)$$

Boltzmann thermal distribution

$$\begin{aligned} m_A &= Z\,m_p + (A-Z)\,m_n - B_A \\ \mu_A &= Z\,\mu_p + (A-Z)\,\mu_n \end{aligned}$$

Impose mass balance and chemical equilibrium

$\Downarrow$

$$X_A \equiv \frac{n_A}{n_b} = \left(\frac{2\zeta(3)}{\sqrt{\pi}}\right)^{A-1} \frac{g_A}{2} A^{\frac{3}{2}} \left(\frac{n_p}{n_b}\right)^Z \left(\frac{n_n}{n_b}\right)^{A-Z} \left(\frac{T}{m_N}\right)^{\frac{3(A-1)}{2}} \boxed{\eta^{A-1} e^{\frac{B_A}{T}}}$$

Abundance mostly controlled by

B_A= binding energy ≅ few MeV x A

$\eta \equiv n_b/n_\gamma = 2.74 \times 10^{-8} \Omega_b h^2$

N/P FREEZE-OUT (T~1 MEV)

All nuclei abundances negligible for T>>1 MeV, while

the ratio of neutrons to protons is kept in chemical equilibrium by weak processes:

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

$$\frac{n_n}{n_p} = \exp\left(-\frac{m_n - m_p}{T}\right)$$

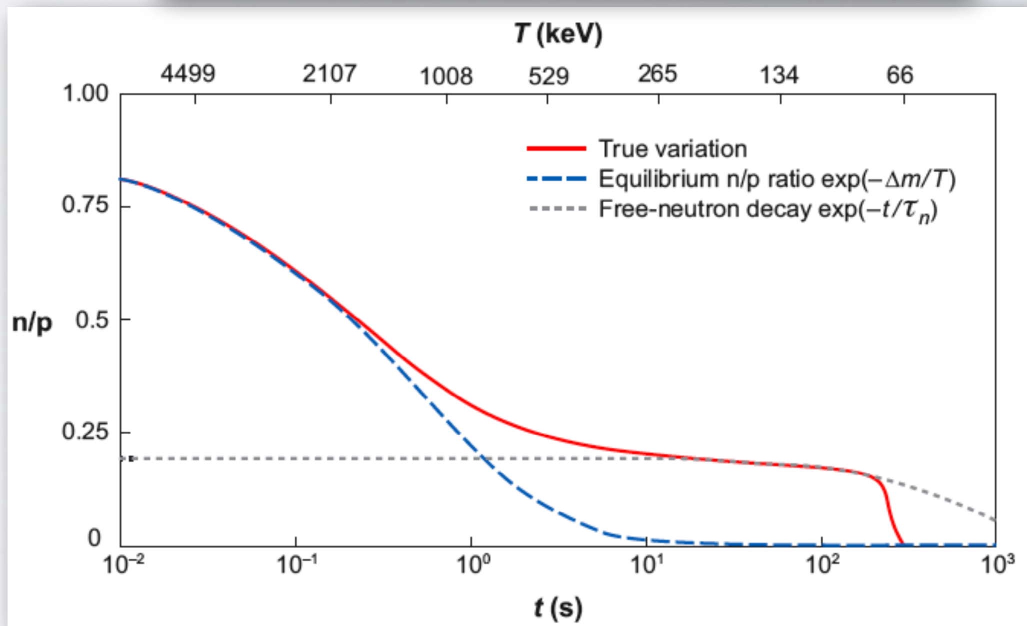
T~0.7 MeV: $p \leftrightarrow n$ freeze-out ($\Gamma_{pn} < H$) n/p only changes due to n decay

$$\frac{n_n}{n_p} = \exp\left[-\frac{m_n - m_p}{T_F}\right] \exp\left(-\frac{t(T)}{\tau_n}\right)$$

Exercise: Estimate the order of magnitude temperature of this freeze-out from the condition

$$\Gamma \approx H$$

(look for the inverse beta decay cross-section from textbooks)



^{4}He = endpoint of most nuclide fusions, insensitive to nuclear details, traces n/p

WHY NUCLEAR BURNING ENDS PRETTY SOON…

for typical non-resonant reactions:

$$\langle \sigma v \rangle (T) = \sqrt{\frac{32}{4^{1/3}} \frac{3E_G^{1/3}}{\mu_{ab}}} T^{-2/3} S_0 \exp\left[-\frac{3}{4^{1/3}} \left(\frac{E_G}{T} \right)^{1/3} \right]$$

where $E_G \equiv 2\pi^2 \mu_{ab} (Z_a Z_b \alpha)^2$

combined with the nucleon abundance

$$n_{\rm target} \simeq \eta T^3$$

leads to a reaction rate scaling as

$$\Gamma \propto T^{7/3} \exp\left[-(\kappa/T)^{1/3} \right]$$

which should be compared to

$$H \propto \sqrt{G_N} T^2$$

Although e.g. ^{12}C has binding energy > ^{4}He, 'metals' not produced in sensible amounts since:

i) No stable isotopes with A=5, 8

ii) Coulomb barrier starts to be significant

iii) Low baryon density suppress triple α

The ratio H/Γ quickly rises with lowering temperatures, at T<κ

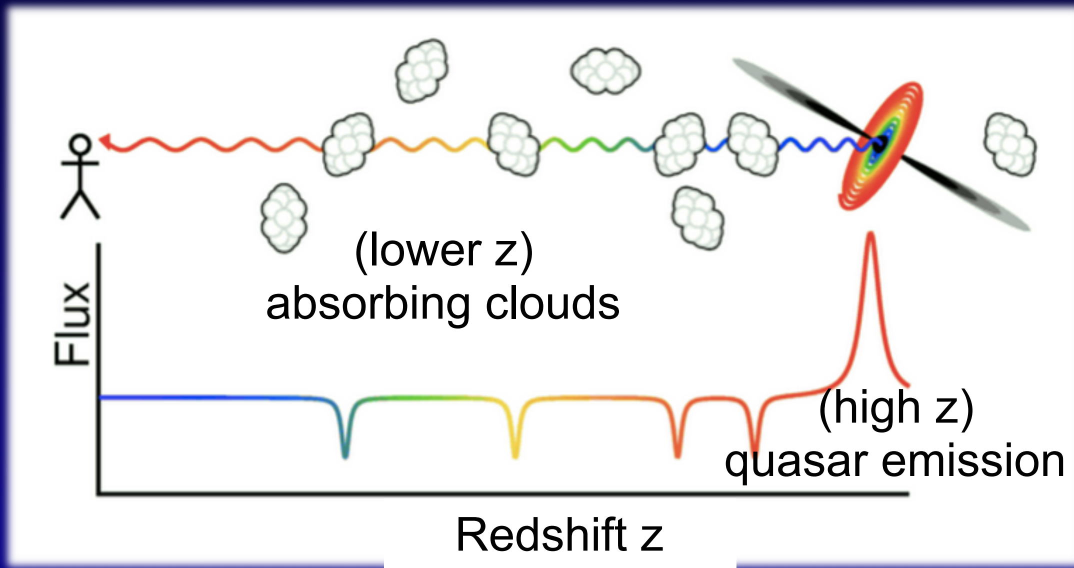
SUMMARY OF WHAT WE LEARNED

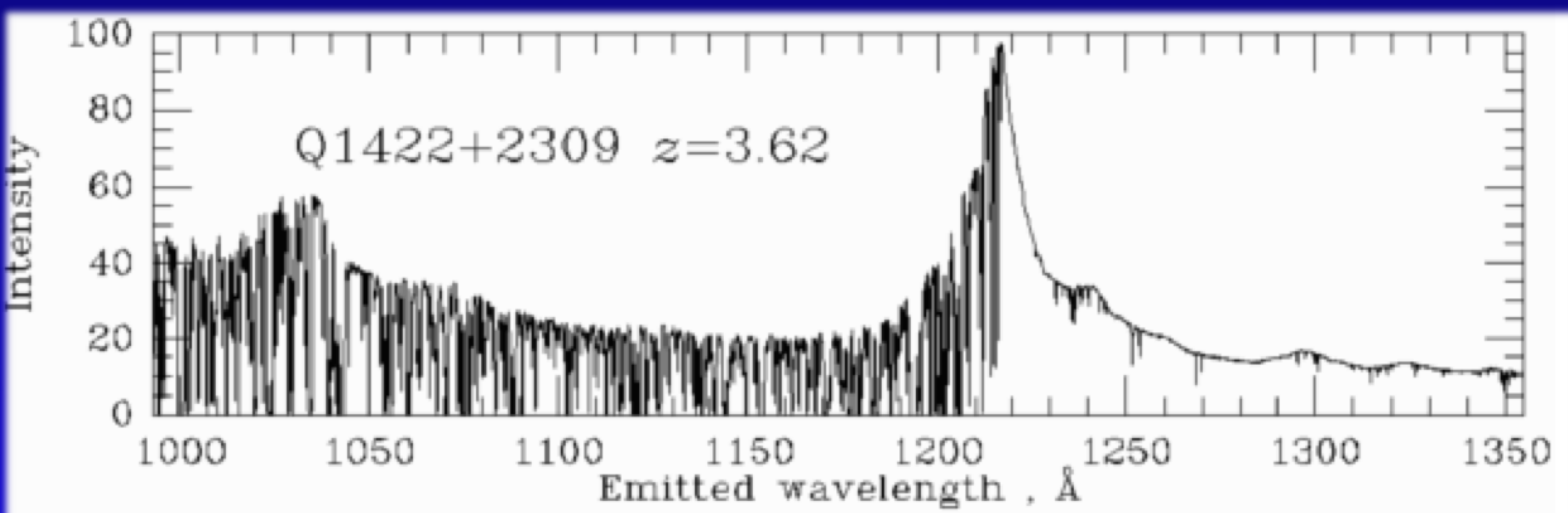
- A number of observations, collected over the past century, show the need for "some dark stuff" contributing dominantly to the dynamics of bound objects from sub-Galactic to Cluster scales, and which also seems to be needed to explain the timely formation of non-linear scales via gravitational instabilities starting from tiny fluctuations as inferred from CMB temperature perturbations.

- Whatever it is, it cannot be made by "hidden baryons" (like dim stars, gas, planets) because we can measure the amount of baryons at a time where the universe was smooth (no stars, no planets…) via electromagnetic/gravitational coupling and via purely nuclear effects: the measurements agree, and point to a too low amount of baryons

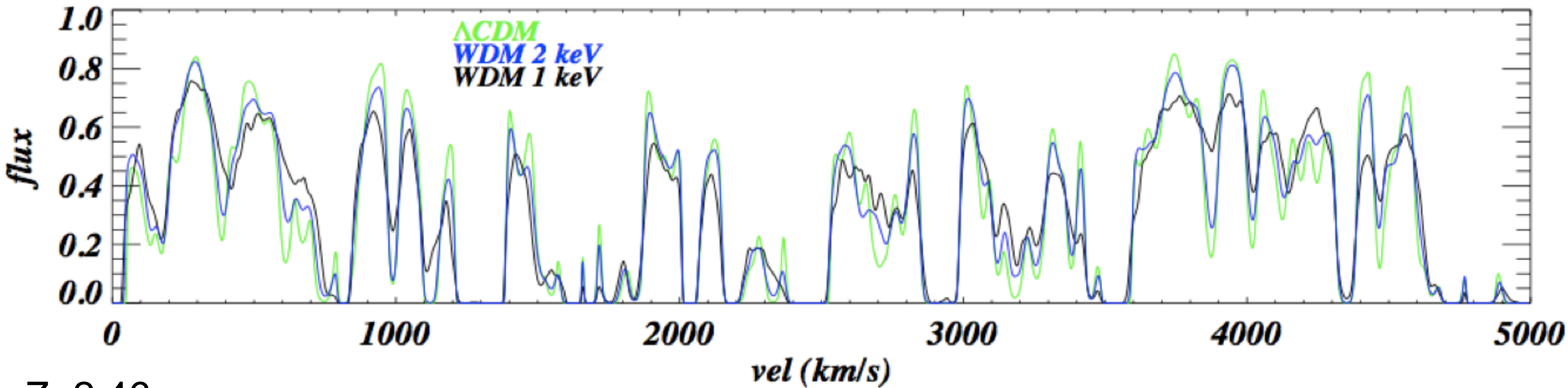
- We can anticipate that this stuff must have quite peculiar properties, since it behaves so differently from ordinary stuff. In the following, we'll learn what astrophysical and cosmological observations tell us about those!

Ly-α forest: probing structures during Universe evolution

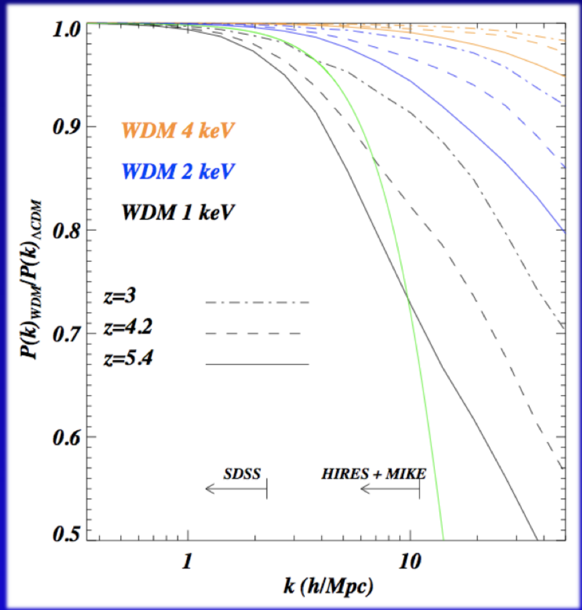




Ly-a forest to constrain the perturbation power spectrum

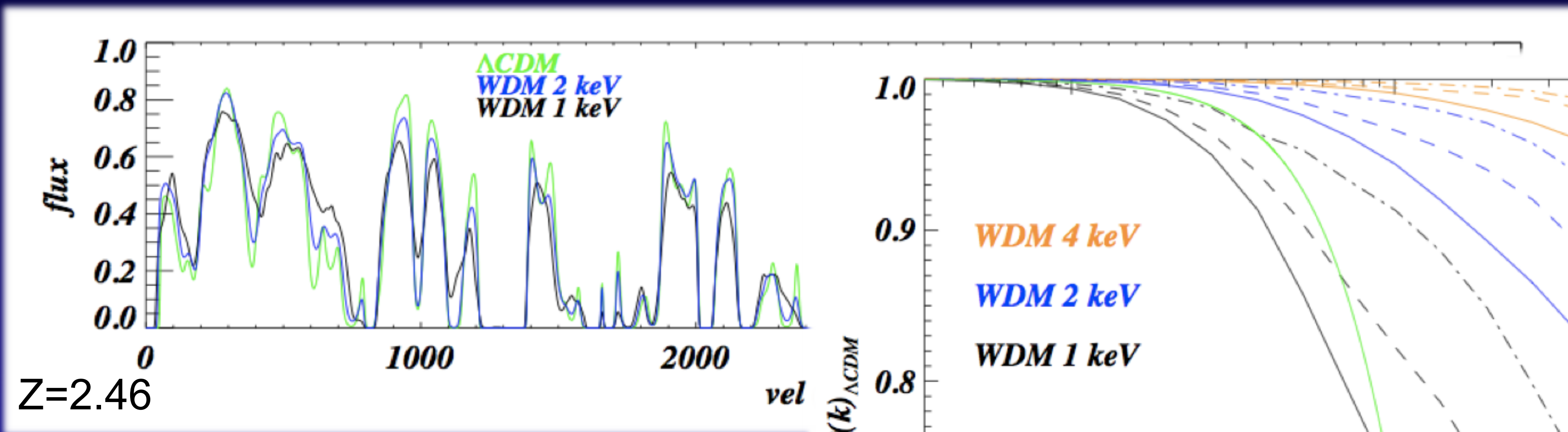


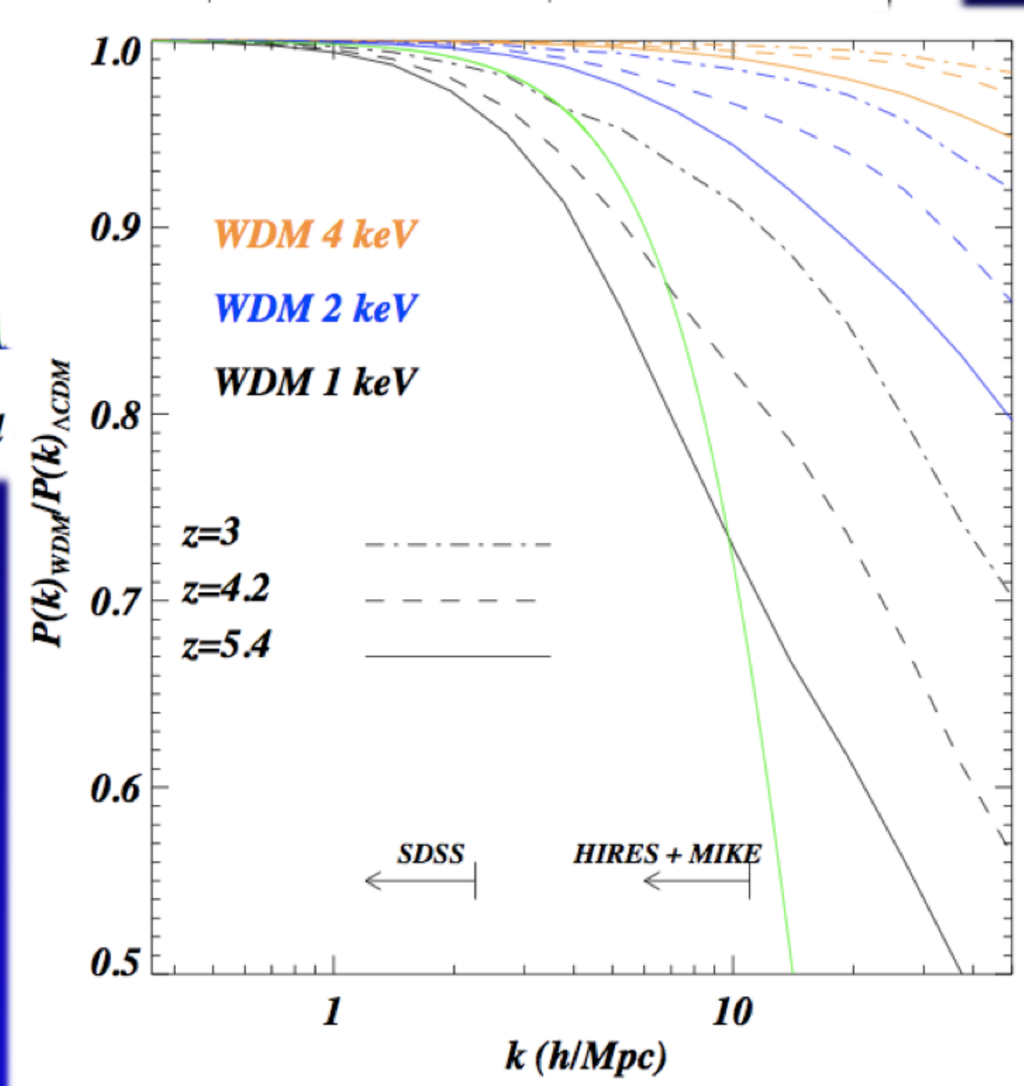
Z=2.46



[Viel et al., 2013]

Ly-a forest to constrain the perturbation power spectrum



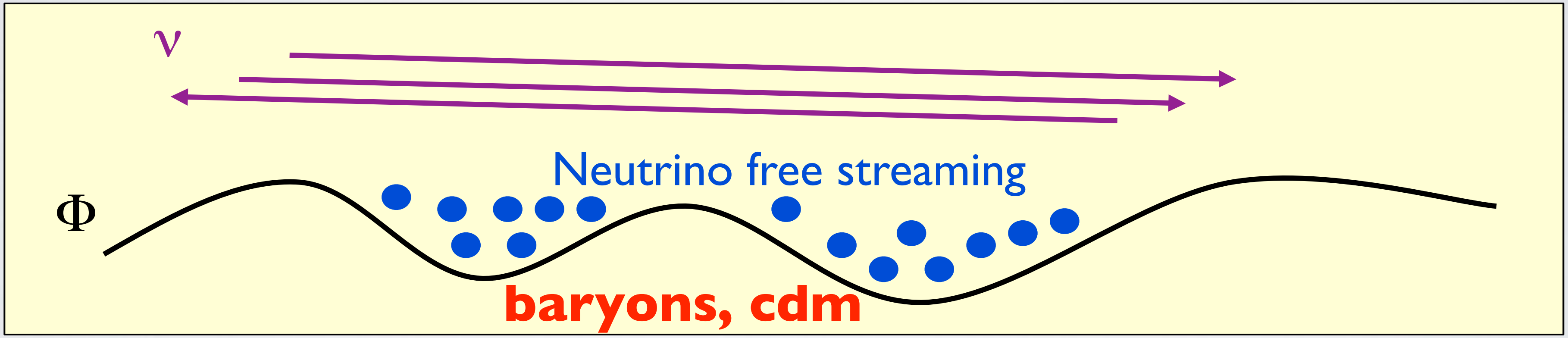


[Viel et al., 2013]

DM IS NOT "HOT" (IT IS NOT RELATIVISTIC)!

dark matter is not "hot": cannot have a relativistic velocity distribution (at least from matter-radiation equality for perturbation to grow)

This is the more profound reason why neutrinos would not work as DM, even if they had the correct mass: they were born with relativistic velocity distribution which prevents structures below O(100 Mpc) to grow till late!



Cartoon Picture:

ν's "do not settle" in potential wells that they can overcome by their typical velocity: compared with CDM, they suppress power at small-scales

More quantitative picture:

see R. Sheth on perturbation growth in radiation era (but some more notions in Lec. 4)

THE SMALLEST SCALES

The kinetic decoupling timescale (or temperature) controls different physical effects:

- damping of perturbations due to DM **collisional** effects ("viscosity")

$$k_{\rm coll}^{\rm comov} \simeq 1.8\sqrt{\frac{m_\chi}{T_{\rm kd}}\frac{a_{\rm kd}H_{\rm kd}}{a_0}} \simeq \frac{3.8\times 10^7}{\rm Mpc}\sqrt{\frac{m_\chi}{100\,{\rm GeV}}}\sqrt{\frac{T_{\rm kd}}{30\,{\rm MeV}}}$$

This can be computed by solving the time evolution of the perturbed real fluid (Navier-Stokes) eqs. including bulk and shear viscosity, proportional to the elastic relaxation time and temperature…

- damping of perturbations due to **free streaming** ("DM does not settle in potential wells whose depth can be overcome by its typical velocity dispersion")

$$k_{\rm fs}^{\rm comov} \simeq \sqrt{\frac{m_\chi}{T_{\rm kd}}\frac{a_{\rm eq}H_{\rm eq}}{a_0}}\,\frac{a_{\rm eq}/a_{\rm kd}}{\ln(4a_{\rm eq}/a_{\rm kd})} \simeq \frac{1.7\times 10^6}{\rm Mpc}\sqrt{\frac{m_\chi}{100\,{\rm GeV}}}\sqrt{\frac{T_{\rm kd}}{30\,{\rm MeV}}}$$

- damping of perturbations due to "**acoustic oscillations**" (DM-coupling with photons, in the kinematically coupled era) k_{ao} set by the size of the horizon at the time of kinetic decoupling, and is numerically similar (actually slightly smaller) than k_{fs}

M. Green, S. Hofmann and D. J. Schwarz, JCAP 0508, 003 (2005) [astro-ph/0503387]
A. Loeb and M. Zaldarriaga, Phys. Rev. D 71, 103520 (2005) [astro-ph/0504112]

COMPUTING THE FREE STREAMING LENGTH

- Take collisionless Boltzmann eq. in flat FLRW, whose leading terms are (η conformal time)

$$\frac{\partial f}{\partial \eta}+\frac{p_i}{a}\frac{\partial f}{\partial x_i}\simeq 0$$

- write the solution as homogeneous + "single mode" perturbation

$$f=f_0(p)[1+\delta(\vec{p},\eta)e^{i\vec{k}\cdot\vec{x}}]$$

where the unperturbed solution is e.g. Maxwell-Boltzmann at the kinetic decoupling

- Solve the (simplified) B. Eq. above for δ, with respect to initial time one (the ratio represents what is known as "transfer function")

- Average over momentum distribution $$\left\langle\frac{\delta f}{f_0}\right\rangle=\frac{\int d^3\vec{p}\, f_0(p)\,\delta(\vec{p},\eta)}{\int d^3\vec{p}\, f_0(p)}$$

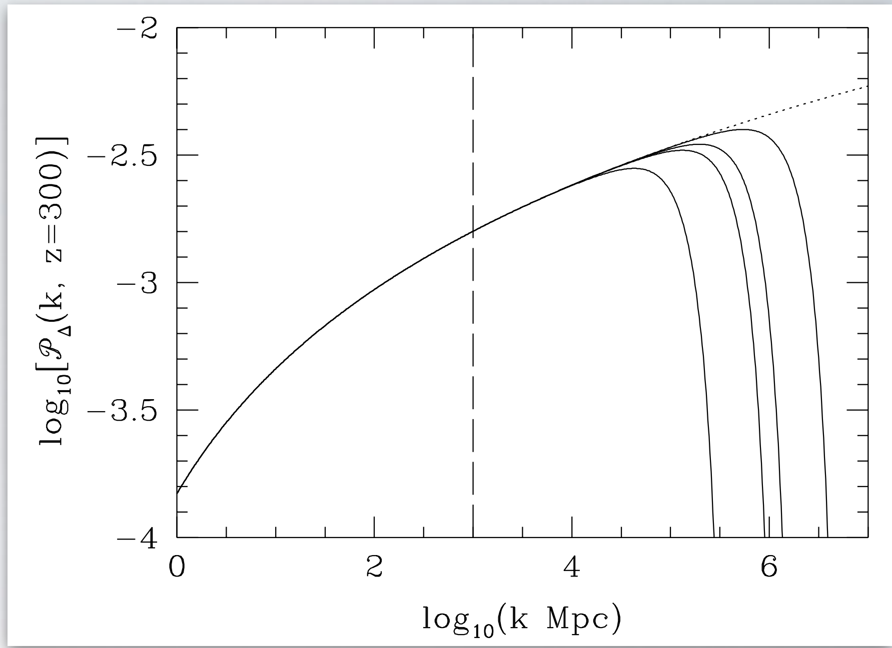
- Isolate the exponential suppression factor at large scales, "the free-streaming scale"

Exercise: follow these steps in detail, look e.g. in astro-ph/0504112, astro-ph/0503387

SMALLEST HALO MASSES

- Example PS for 4 benchmark WIMP models

A. M. Green, S. Hofmann and D. J. Schwarz, JCAP 0508, 003 (2005) [astro-ph/0503387]



- Often rephrased in the halo model language, via the corresponding smallest halo mass, i.e. the mass of a uniform sphere of radius π/k

$$M_{\min} \sim \frac{4\pi}{3}\left(\frac{\pi}{k_{\max}}\right)^3 \Omega_m \rho_c$$

yields about 3 x 10^{-6} $M_\odot$ (~Earth mass scale!) for fiducial free-streaming parameters above!

Can easily vary by 4 orders of magnitude in either sense even for WIMP models!

Note: This refers to a linear scale, e.g. useful to estimate the scale of smallest virialised objects that may have formed at early times… Non-linear post-processing (e.g. to infer indirect signals) could be very important!

FREE STREAMING WAVELENGTH

By performing the above exercise, you would find that the characteristic scale is

$$\lambda_{\rm fs} \equiv a(t)\,\lambda_{\rm fs}^{\rm comov} \simeq a(t)\int_{t_{\rm kd}}^{t}\frac{dt'}{a(t')}\bar{v}(t')$$

where

$$\bar{v}(t) = \frac{a(t_{\rm kd})}{a(t)}\sqrt{\frac{3\,T_{\rm kd}}{m_\chi}}$$

For a relic decoupling non-relativistically, in the radiation era one has $a(t) \sim t^{1/2}$ hence it grows logarithmically up to the matter-radiation equivalence, when it stops growing

Note: This quantity can be defined (and is physically relevant) in a more general context! Not only for relics once in kinetic equilibrium (i.e. with initial Max-Boltz.distributions)!

"MACRO" CANDIDATES

Phenomenologically, we only ask that DM interaction rate $\Gamma=\sigma\, n\, v$ is "small. But we only measure DM energy density ρ, not n. Hence **$\Gamma=(\sigma/m)\, \rho\, v$ small** only requires (σ/m) small!

Composite/macroscopic object may make the DM, if σ/m small enough. Also, must be done before BBN. 2 possibilities in the SM I am aware of

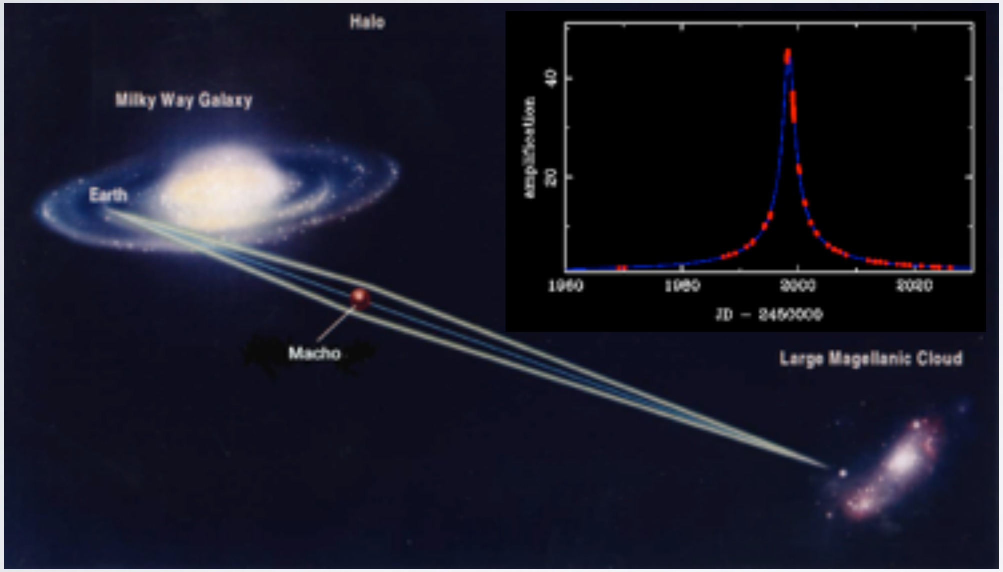
- **QCD strangelets** (*E. Witten, PRD 30, 272 (1984), See also J. Madsen, astro-ph/9809032*), require
  - that the most stable form of hadronic matter is one containing strange quarks (u-d-s "nuggets"), if the opening of a third "Fermi well" is not (over)compensated by the larger mass penalty for s quark
    answer to this conjecture still unknown
  - a first order QCD phase transition
    Lattice studies show that this is not realized Y. Aoki et al. Nature 443, 675 (2006) [hep-lat/0611014]
    ➟ Even if strangelets could exist, no mechanism present in the SM to make them the DM (might still make DM if BSM degrees of freedom alter early universe…)

- **Primordial Black Holes (PBHs)**
  Highly constrained & require new physics, anyway (more in a moment)

MICROLENSING

idea: Compact object crossing along the los acts as a gravitational lens, inducing a time-dependent magnification pattern depending on the geometry and mass. From limits to the rate of such events, DM fraction limits to the associated mass

e.g. L.Wyrzykowski et al., arXiv:1106.2925 & refs. therein



$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}$$

$u = \theta/\theta_E$

ang. distance source-lens

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_S - d_L}{d_S d_L}}$$

depends on lens mass and geometry

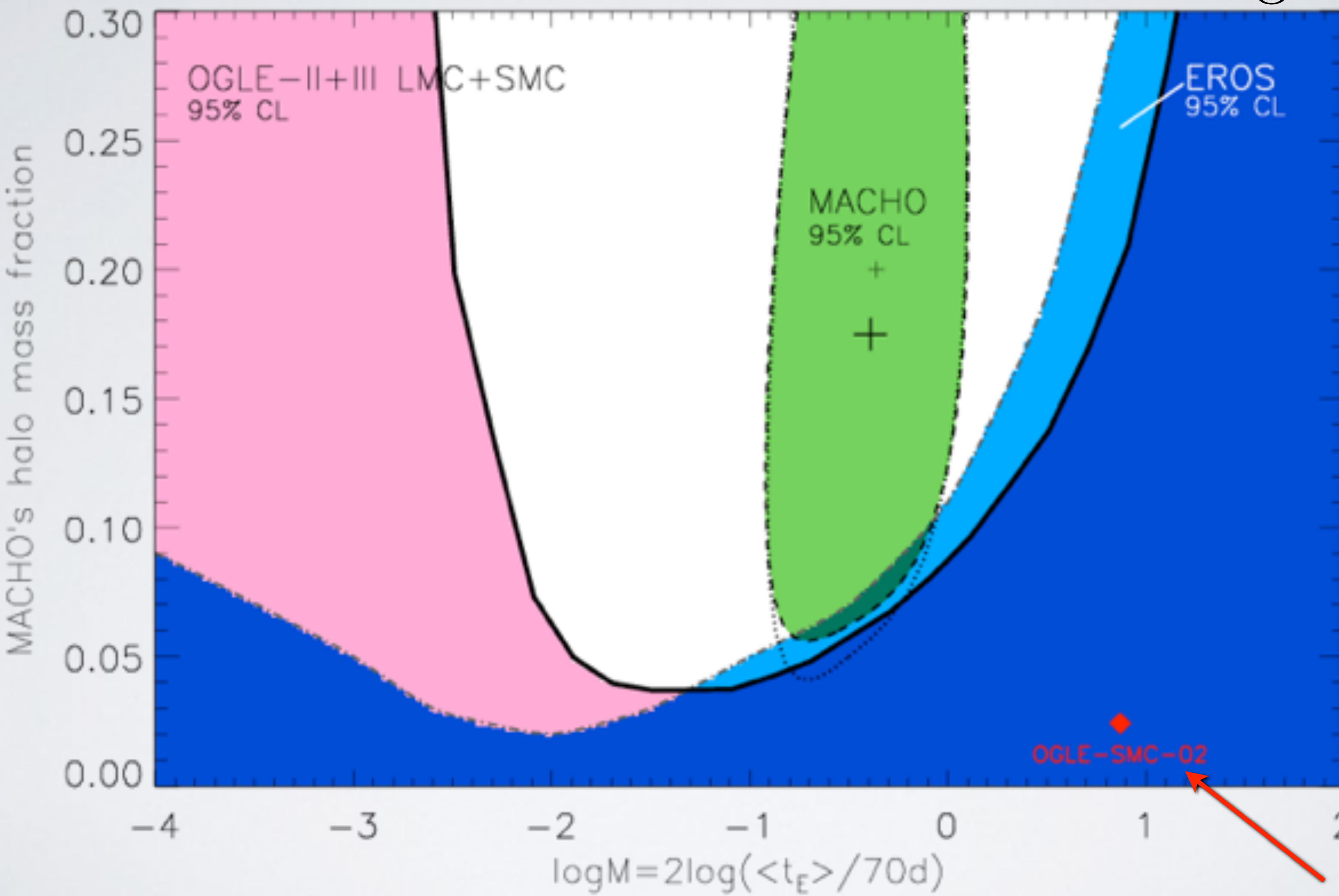
$$u(t) = \sqrt{u_{min}^2 + \left(\frac{t-t_0}{t_E}\right)^2}$$

t_E =time to cross Einstein angular size

Several searches (EROS, OGLE...) for μlensing events towards Magellanic Cloud exclude dominant MACHOs component as halo DM from 10^{-7} to 10 $M_\odot$

MICROLENSING CONSTRAINTS

← goes to $\simeq 10^{26}\mathrm{g}$ $2 \times 10^{34}\mathrm{g}$



some events expected
due to stellar BH

EXAMPLE OF LIMITS ON "MACHOS"

Too large DM "particle" would disrupt bound systems of different orbital sizes (function of mass) via associated time-dependent gravitational potentials

- thickness of disks: $M_X < 10^6\ M_\odot$

satellites, globular clusters: $M_X < 10^3\ M_\odot$

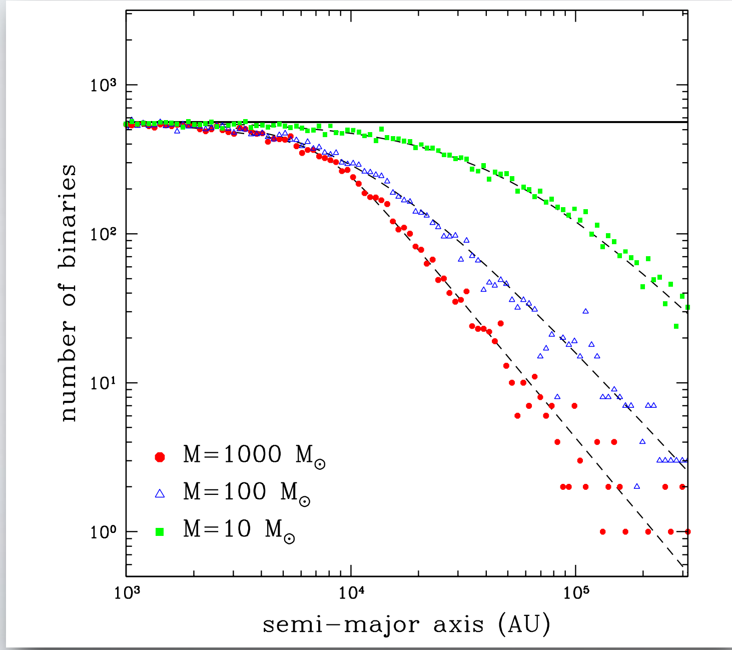
H-W.Rix and G. Lake, astro-ph/9308022 & refs. therein

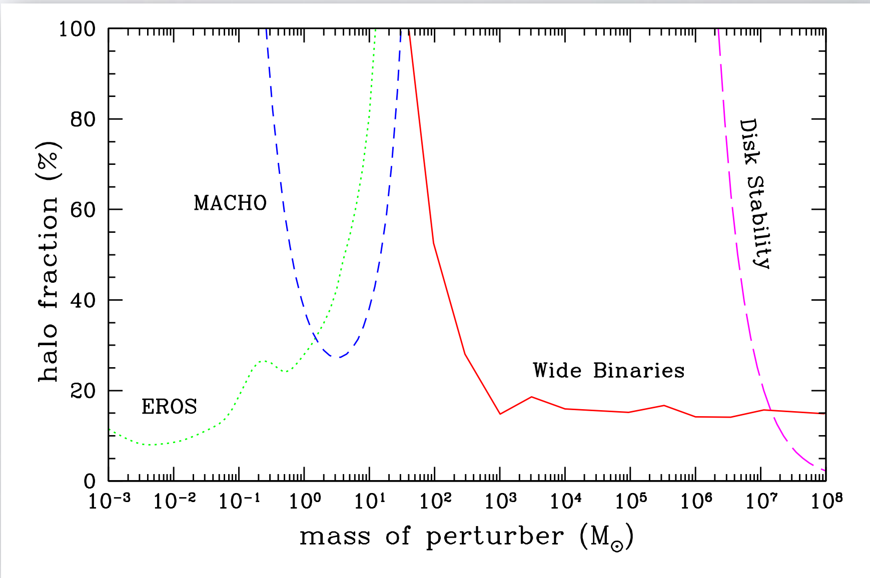
- Halo-wide binaries: Method proposed in *J.Yoo, J. Chaname, A. Gould, Astrophys. J. 601, 311 (2004)*

Latest bound $M_X \lesssim 100\ M_\odot$ to $\lesssim 5\ M_\odot$

(for higher and higher "binary quality" cuts)

M.A. Monroy-Rodríguez and C. Allen, ApJ J. 790 159 (2014) [1406.5169]



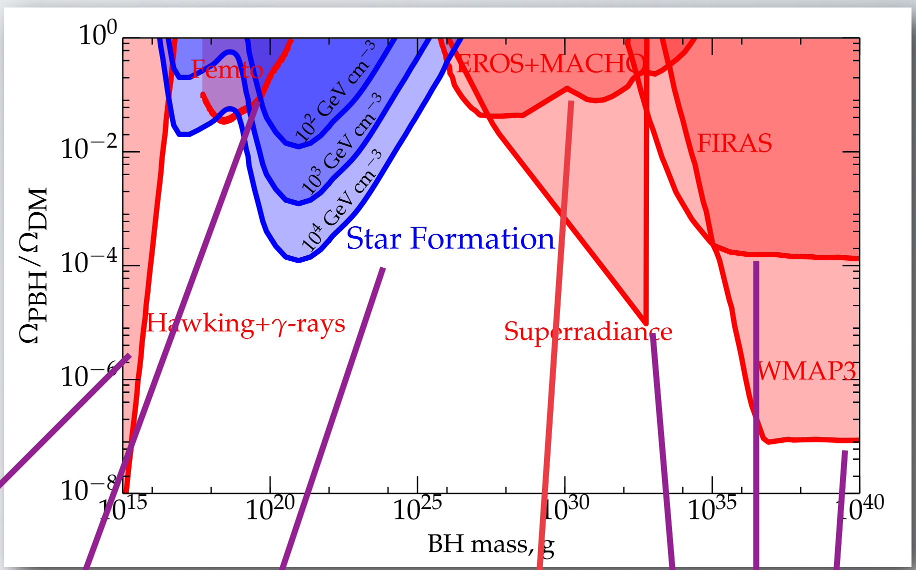


BOUNDS ON PBH

Even so, a number of constraints exist

see e.g. F. Capela, M. Pshirkov, P. Tinyakov, PRD 90, 083507 (2014) [arXiv:1403.7098] & refs. therein

which exclude a dominant "monochromatic" PBH contribution to DM at any mass but 10^{-14}-10^{-9} $M_\odot$ (potentially excluded as well)



BH evaporate (emitting gamma-rays) on times comparable or shorter than lifetime of Universe

BH would induce "interferometry" pattern in the energy spectrum of lensed GRBs

PBH capture in stars catalyze fast conversion in BH, while "old" evolved objects like WD or NS are observed (DM-density dependent bound)

direct searches via micro-lensing, plus other arguments (do not strictly require them to be BHs)

bounds from CMB spectral distortions, secondary anisotropies induced (e.g. reionization) either via accretion byproducts or by explosive runaway instability (if rotating, due to "plasma mass")

SUMMARY OF WHAT WE LEARNED

- Hopefully, some **clarification** on the (partially) misleading **dichotomy DM vs Modified Gravity:** the key is the need for some new degree of freedom.

- It turns out that this requires **new physics** (even for-the highly constrained-BHs, need some exotic production mechanism) with some specific properties.

- Astrophysical and cosmological arguments put some constraints on DM. Unfortunately, cannot get "too far" since "gravity is universal" → it does not tell us what the underlying new physics is.

- We need some "strategy" to identify what DM is. For that, first we need some extra input/constraint → must necessarily come from theory, i.e. let's try to define some classes of candidate: We Shall classify them via **production mechanisms**, the ***leitmotif*** of Lectures 3-4-5.

While staying agnostic on its very nature, a checklist for its properties (see later)

1. *Does it match the appropriate relic density?*
2. *Is it cold?*
3. *Is it neutral?*
4. *Is it consistent with BBN?*
5. *Does it leave stellar evolution unchanged?*
6. *Is it compatible with constraints on self-interactions?*
7. *Is it consistent with direct DM searches?*
8. *Is it compatible with gamma-ray constraints?*
9. *Is it compatible with other astrophysical bounds?*
10. *Can it be probed experimentally?*

[Taoso et al., 2007]