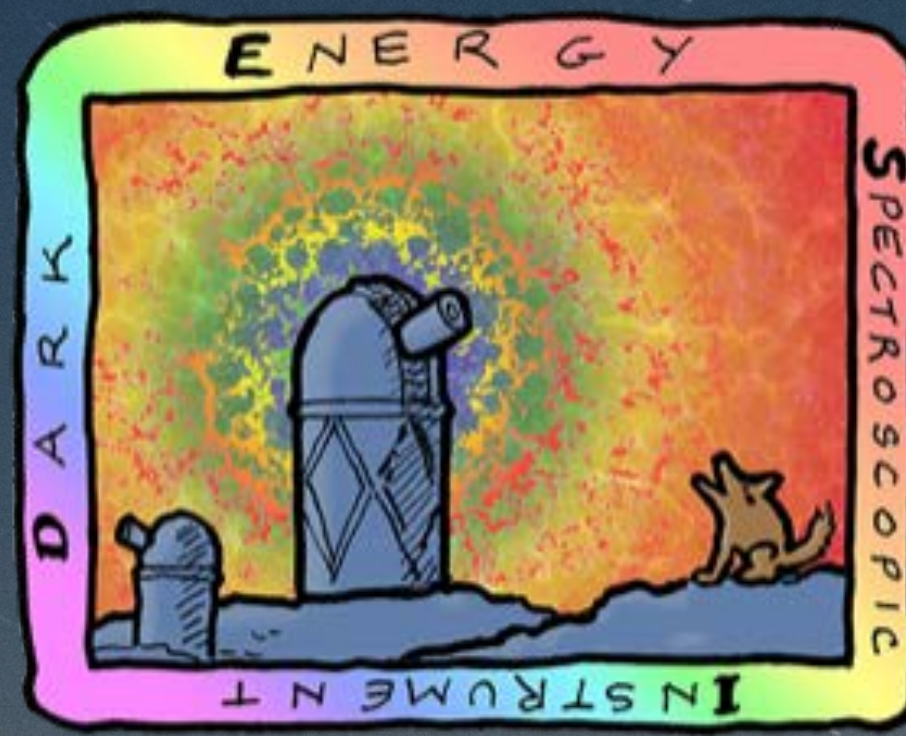


The background of the slide is a deep space image filled with numerous galaxies of various shapes and colors (yellow, orange, red, blue, and purple). Overlaid on this image is a network of bright blue lines that intersect to form a complex web-like pattern, representing the cosmic web or dark energy distribution.

First Results from the Dark Energy Spectroscopic Instrument (DESI)

David Schlegel
Lawrence Berkeley National Lab
DESI Project Scientist
12 July 2025



DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



Thanks to the Department of Energy,
our sponsors and
72 participating Institutions



April 4, 2024

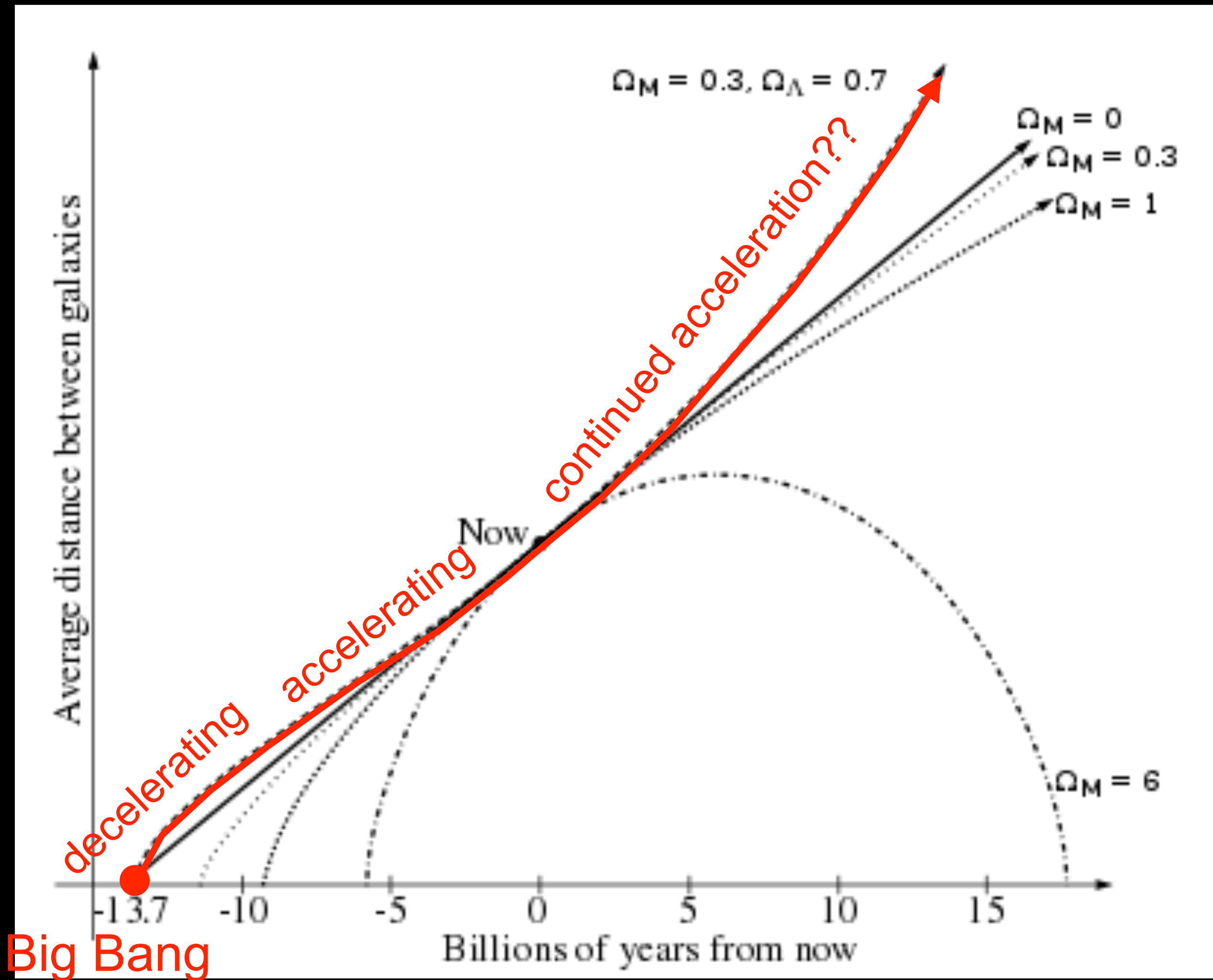
A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.



What is the Dark Energy Spectroscopic Instrument (DESI)?

- Largest 2-D map of the universe (until Rubin Observatory in the late 2020s)
- Largest 3-D map of the universe
- Dark Energy experiment, measuring Universe's expansion from $z=4 \rightarrow 0$

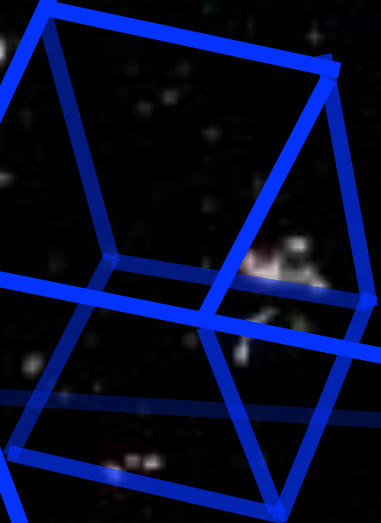


What is a map?

What is a map?

3-D positions of planets, stars, galaxies
3-D velocities

6 dimensions



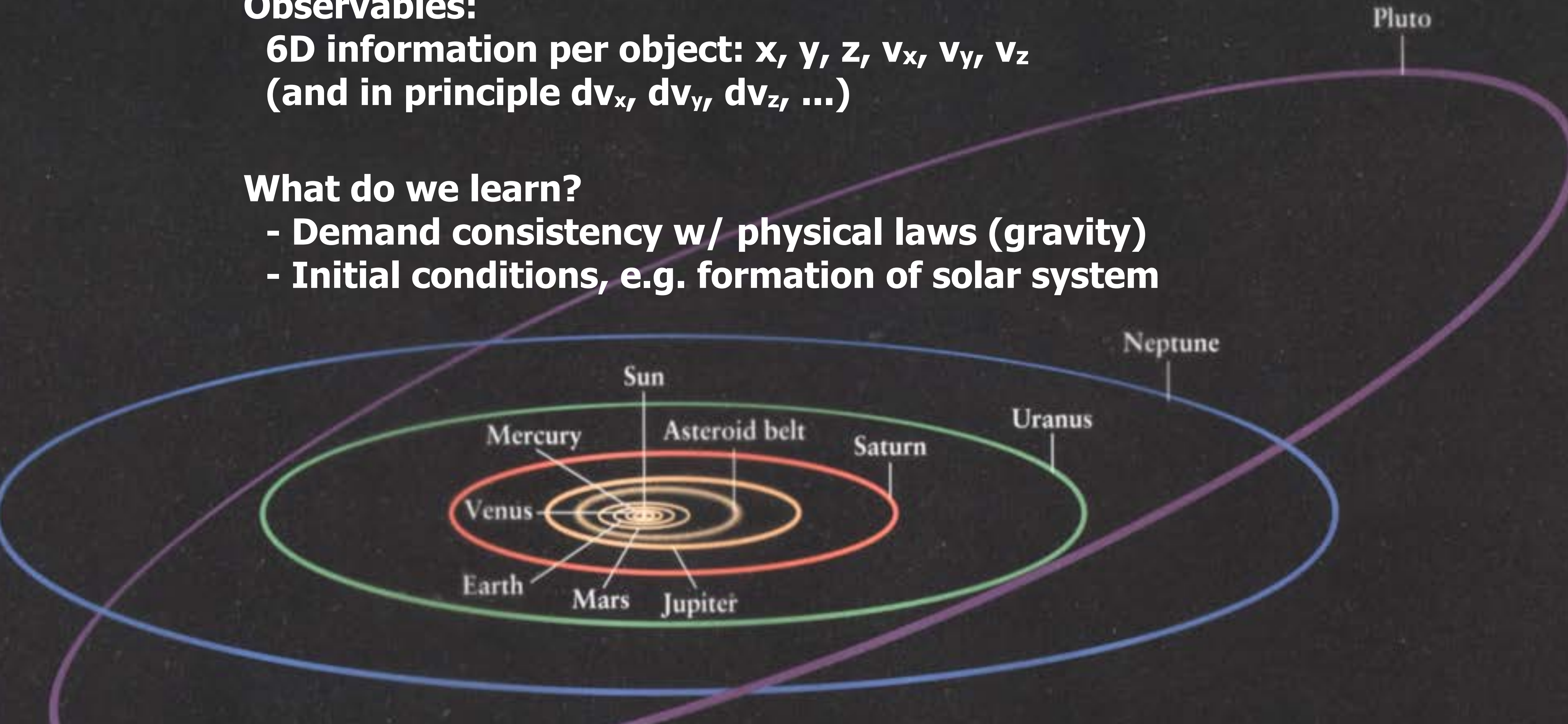
Maps of the Solar System

Observables:

6D information per object: x, y, z, v_x, v_y, v_z
(and in principle $dv_x, dv_y, dv_z, \dots$)

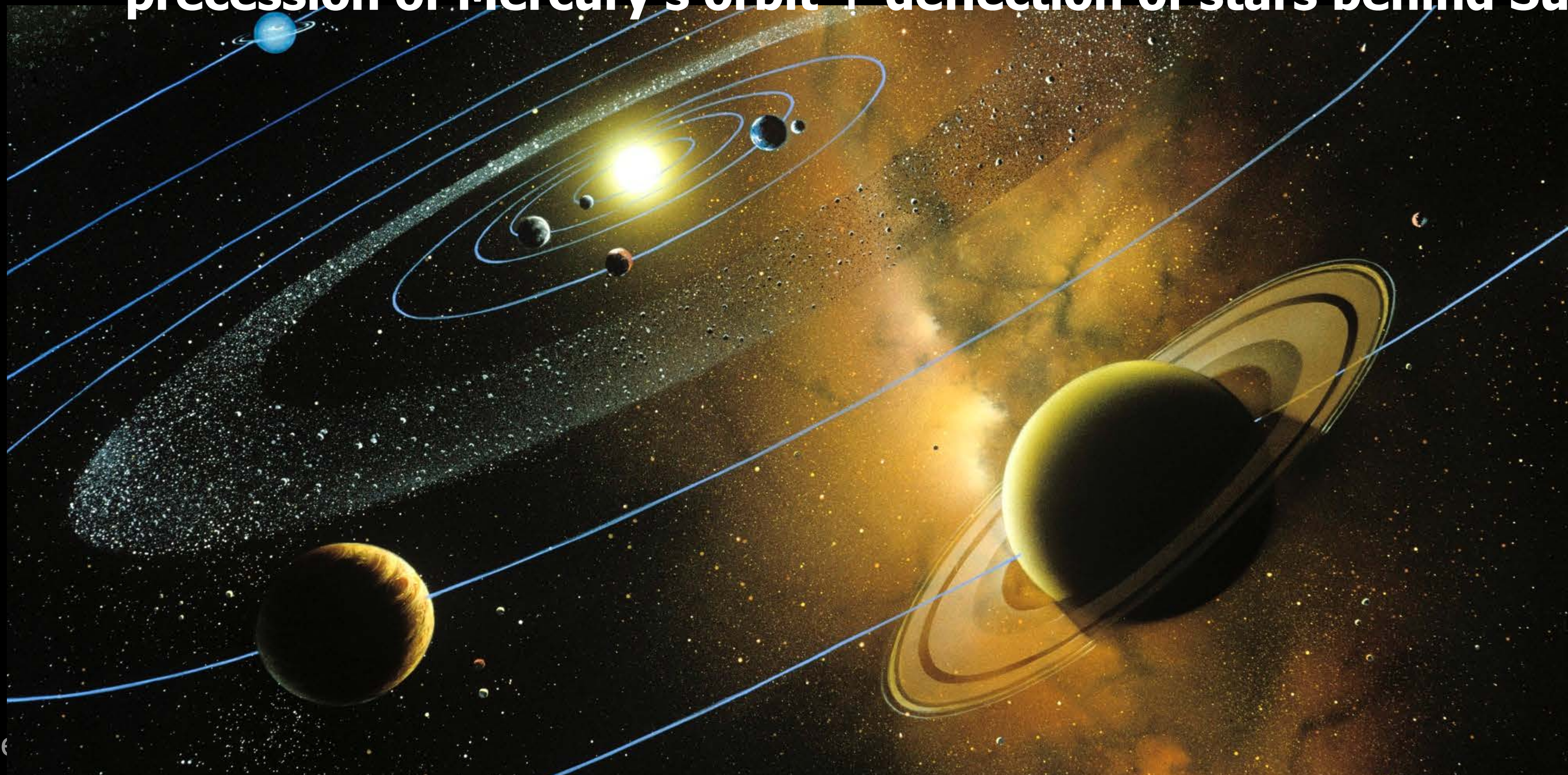
What do we learn?

- Demand consistency w/ physical laws (gravity)
- Initial conditions, e.g. formation of solar system



Maps of the solar system

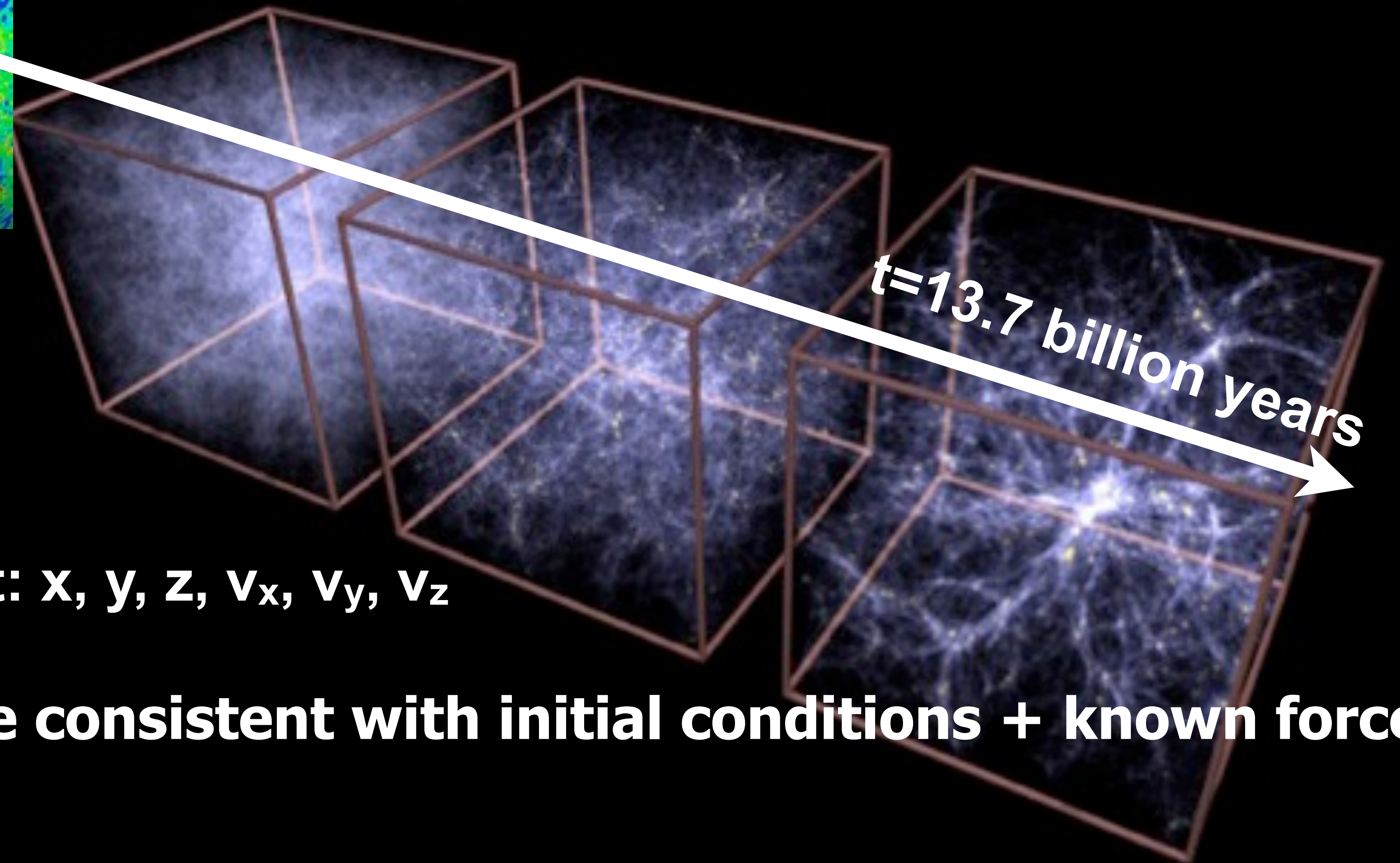
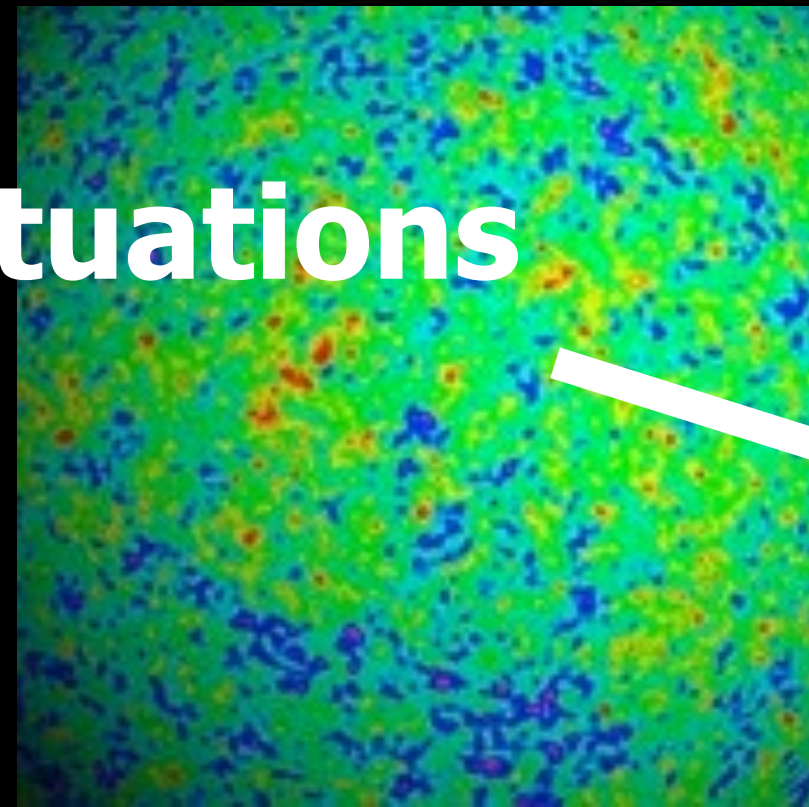
- The speed of light (1676; Jupiter's moons)
- Newton's laws of gravity (1687; planetary orbits)
- Scale of the solar system (1769; Venus transiting Sun)
- Confirmation of Einstein's general relativity (1916, 1919; precession of Mercury's orbit + deflection of stars behind Sun)



Maps of the Universe

$\mathcal{L}(\text{Our Universe} | \text{initial conditions, forces})$

quantum fluctuations



Observables:

6D information per object: x, y, z, v_x, v_y, v_z

These observables must be consistent with initial conditions + known forces
velocities = $\nabla\Phi$

What are the fundamental particles?

Standard Model of Elementary Particles											
three generations of matter (elementary fermions)						three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)		
		I	II	III			I	II	III		
mass		$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$			$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$			$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
spin		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS		u up	c charm	t top			$\bar{u}$ antiup	$\bar{c}$ anticharm	$\bar{t}$ antitop	g gluon	H higgs
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$			$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$			$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	
LEPTONS		d down	s strange	b bottom			$\bar{d}$ antidown	$\bar{s}$ antistrange	$\bar{b}$ antibottom	γ photon	
		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$			$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	0	
		-1	-1	-1			1	1	1	1	
		e electron	μ muon	τ tau			e^+ positron	$\bar{\mu}$ antimuon	$\bar{\tau}$ antitau	Z Z ⁰ boson	
		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$			$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino			$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W^+ W ⁺ boson	W^- W ⁻ boson
		$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$			$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$
		0	0	0			0	0	0	1	-1
										GAUGE BOSONS VECTOR BOSONS	
										SCALAR BOSONS	

What are the fundamental particles?

Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	$\bar{u}$ antiup	$\bar{c}$ anticharm	$\bar{t}$ antitop	g gluon	H higgs
	d down	s strange	b bottom	$\bar{d}$ antidown	$\bar{s}$ antistrange	$\bar{b}$ antibottom	γ photon	
	e electron	μ muon	τ tau	e^+ positron	μ^+ antimuon	τ^+ antitau	Z⁰ Z ⁰ boson	
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W⁺ W ⁺ boson	W⁻ W ⁻ boson

Periodic Table of the Elements

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Atomic Number → 13 ← Symbol Name → Aluminium ← Atomic Weight Electrons per shell → 2-8-3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
State of matter (color of name) GAS LIQUID SOLID UNKNOWN Subcategory in the metal-metalloid-nonmetal trend (color of background) Alkali metals Lanthanides Metalloids Alkaline earth metals Actinides Reactive nonmetals Transition metals Post-transition metals Noble gases Unknown chemical properties																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
<table><tr><td colspan="2">1 IA</td><td colspan="2">2 IIA</td><td colspan="12"></td><td colspan="2">13 IIIA</td><td colspan="2">14 IVA</td><td colspan="2">15 VA</td><td colspan="2">16 VIA</td><td colspan="2">17 VIIA</td><td colspan="2">18 VIIIA</td></tr><tr><td colspan="2">1 H</td><td colspan="2">4 Be</td><td colspan="12"></td><td colspan="2">5 B</td><td colspan="2">6 C</td><td colspan="2">7 N</td><td colspan="2">8 O</td><td colspan="2">9 F</td><td colspan="2">10 Ne</td></tr><tr><td colspan="2">3 Li</td><td colspan="2">9 Beryllium</td><td colspan="12"></td><td colspan="2">10.81</td><td colspan="2">12.011</td><td colspan="2">14.007</td><td colspan="2">15.999</td><td colspan="2">18.998</td><td colspan="2">20.180</td></tr><tr><td colspan="2">11 Na</td><td colspan="2">12 Mg</td><td colspan="12"></td><td colspan="2">13 Al</td><td colspan="2">14 Si</td><td colspan="2">15 P</td><td colspan="2">16 S</td><td colspan="2">17 Cl</td><td colspan="2">18 Ar</td></tr><tr><td colspan="2">22.98976928</td><td colspan="2">24.304</td><td colspan="12"></td><td colspan="2">26.982</td><td colspan="2">28.085</td><td colspan="2">30.974</td><td colspan="2">32.06</td><td colspan="2">35.45</td><td colspan="2">39.948</td></tr><tr><td colspan="2">2.3</td><td colspan="2">2.0</td><td colspan="12"></td><td colspan="2">2.3</td><td colspan="2">2.5</td><td colspan="2">2.5</td><td colspan="2">2.4</td><td colspan="2">2.7</td><td colspan="2">2.8</td></tr><tr><td colspan="2">19 K</td><td colspan="2">20 Ca</td><td colspan="2">3 Sc</td><td colspan="2">4 Ti</td><td colspan="2">5 V</td><td colspan="2">6 Cr</td><td colspan="2">7 Mn</td><td colspan="2">8 Fe</td><td colspan="2">9 Co</td><td colspan="2">10 Ni</td><td colspan="2">11 Cu</td><td colspan="2">12 Zn</td><td colspan="2">13 Ga</td><td colspan="2">14 Ge</td><td colspan="2">15 As</td><td colspan="2">16 Se</td><td colspan="2">17 Br</td><td colspan="2">18 Kr</td></tr><tr><td colspan="2">39.0983</td><td colspan="2">40.078</td><td colspan="2">44.955908</td><td colspan="2">47.88</td><td colspan="2">50.9415</td><td colspan="2">51.9961</td><td colspan="2">54.938044</td><td colspan="2">55.845</td><td colspan="2">58.933</td><td colspan="2">58.693</td><td colspan="2">63.546</td><td colspan="2">65.38</td><td colspan="2">69.723</td><td colspan="2">72.63</td><td colspan="2">74.9216</td><td colspan="2">78.9718</td><td colspan="2">79.904</td></tr><tr><td colspan="2">2.3</td><td colspan="2">2.0</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td></tr><tr><td colspan="2">37 Rb</td><td colspan="2">38 Sr</td><td colspan="2">39 Y</td><td colspan="2">40 Zr</td><td colspan="2">41 Nb</td><td colspan="2">42 Mo</td><td colspan="2">43 Tc</td><td colspan="2">44 Ru</td><td colspan="2">45 Rh</td><td colspan="2">46 Pd</td><td colspan="2">47 Ag</td><td colspan="2">48 Cd</td><td colspan="2">49 In</td><td colspan="2">50 Sn</td><td colspan="2">51 Sb</td><td colspan="2">52 Te</td><td colspan="2">53 I</td><td colspan="2">54 Xe</td></tr><tr><td colspan="2">85.468</td><td colspan="2">87.62</td><td colspan="2">88.906</td><td colspan="2">91.224</td><td colspan="2">92.90637</td><td colspan="2">95.95</td><td colspan="2">98</td><td colspan="2">101.07</td><td colspan="2">102.91</td><td colspan="2">106.42</td><td colspan="2">107.87</td><td colspan="2">112.41</td><td colspan="2">114.82</td><td colspan="2">118.71</td><td colspan="2">121.76</td><td colspan="2">127.60</td><td colspan="2">126.90</td><td colspan="2">131.29</td></tr><tr><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td 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colspan="2">189.23</td><td colspan="2">192.22</td><td colspan="2">195.08</td><td colspan="2">196.97</td><td colspan="2">200.59</td><td colspan="2">204.38</td><td colspan="2">207.2</td><td colspan="2">208.98</td><td colspan="2">209</td><td colspan="2">210</td><td colspan="2">222</td></tr><tr><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2"></td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td></tr><tr><td colspan="2">87 Fr</td><td colspan="2">88 Ra</td><td colspan="2">89-103 Actinides</td><td colspan="2">104 Rf</td><td colspan="2">105 Db</td><td colspan="2">106 Sg</td><td colspan="2">107 Bh</td><td colspan="2">108 Hs</td><td colspan="2">109 Mt</td><td colspan="2">110 Ds</td><td colspan="2">111 Rg</td><td colspan="2">112 Cn</td><td colspan="2">113 Nh</td><td colspan="2">114 Fl</td><td colspan="2">115 Mc</td><td colspan="2">116 Lv</td><td colspan="2">117 Ts</td><td colspan="2">118 Og</td></tr><tr><td colspan="2">223</td><td colspan="2">226</td><td colspan="2"></td><td colspan="2">261</td><td colspan="2">262</td><td colspan="2">266</td><td colspan="2">264</td><td colspan="2">277</td><td colspan="2">278</td><td colspan="2">281</td><td colspan="2">282</td><td colspan="2">285</td><td colspan="2">286</td><td colspan="2">289</td><td colspan="2">290</td><td colspan="2">293</td><td colspan="2">294</td><td colspan="2">294</td></tr><tr><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2"></td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td 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colspan="2">168.93032</td><td colspan="2">173.054</td><td colspan="2">174.967</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr><tr><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr><tr><td colspan="2">89 Ac</td><td colspan="2">90 Th</td><td colspan="2">91 Pa</td><td colspan="2">92 U</td><td colspan="2">93 Np</td><td colspan="2">94 Pu</td><td colspan="2">95 Am</td><td colspan="2">96 Cm</td><td colspan="2">97 Bk</td><td colspan="2">98 Cf</td><td colspan="2">99 Es</td><td colspan="2">100 Fm</td><td colspan="2">101 Md</td><td colspan="2">102 No</td><td colspan="2">103 Lr</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr><tr><td colspan="2">227</td><td colspan="2">232.0377</td><td colspan="2">231.03688</td><td colspan="2">238.02891</td><td colspan="2">237</td><td colspan="2">244</td><td colspan="2">243</td><td colspan="2">247</td><td colspan="2">247</td><td colspan="2">251</td><td colspan="2">252</td><td colspan="2">257</td><td colspan="2">258</td><td colspan="2">259</td><td colspan="2">260</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr><tr><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2">2.0-2</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr></table>																		1 IA		2 IIA														13 IIIA		14 IVA		15 VA		16 VIA		17 VIIA		18 VIIIA		1 H		4 Be														5 B		6 C		7 N		8 O		9 F		10 Ne		3 Li		9 Beryllium														10.81		12.011		14.007		15.999		18.998		20.180		11 Na		12 Mg														13 Al		14 Si		15 P		16 S		17 Cl		18 Ar		22.98976928		24.304														26.982		28.085		30.974		32.06		35.45		39.948		2.3		2.0														2.3		2.5		2.5		2.4		2.7		2.8		19 K		20 Ca		3 Sc		4 Ti		5 V		6 Cr		7 Mn		8 Fe		9 Co		10 Ni		11 Cu		12 Zn		13 Ga		14 Ge		15 As		16 Se		17 Br		18 Kr		39.0983		40.078		44.955908		47.88		50.9415		51.9961		54.938044		55.845		58.933		58.693		63.546		65.38		69.723		72.63		74.9216		78.9718		79.904		2.3		2.0		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		37 Rb		38 Sr		39 Y		40 Zr		41 Nb		42 Mo		43 Tc		44 Ru		45 Rh		46 Pd		47 Ag		48 Cd		49 In		50 Sn		51 Sb		52 Te		53 I		54 Xe		85.468		87.62		88.906		91.224		92.90637		95.95		98		101.07		102.91		106.42		107.87		112.41		114.82		118.71		121.76		127.60		126.90		131.29		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		55 Cs		56 Ba		57-71 Lanthanides		72 Hf		73 Ta		74 W		75 Re		76 Os		77 Ir		78 Pt		79 Au		80 Hg		81 Tl		82 Pb		83 Bi		84 Po		85 At		86 Rn		132.90545196		137.327				178.49		180.948		183.84		186.21		189.23		192.22		195.08		196.97		200.59		204.38		207.2		208.98		209		210		222		2.0-2		2.0-2				2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		87 Fr		88 Ra		89-103 Actinides		104 Rf		105 Db		106 Sg		107 Bh		108 Hs		109 Mt		110 Ds		111 Rg		112 Cn		113 Nh		114 Fl		115 Mc		116 Lv		117 Ts		118 Og		223		226				261		262		266		264		277		278		281		282		285		286		289		290		293		294		294		2.0-2		2.0-2				2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		57 La		58 Ce		59 Pr		60 Nd		61 Pm		62 Sm		63 Eu		64 Gd		65 Tb		66 Dy		67 Ho		68 Er		69 Tm		70 Yb		71 Lu								138.90547		140.12		140.90768		144.242		145		150.36		151.964		157.25		158.92532		162.50087		164.93032		167.259		168.93032		173.054		174.967								2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2								89 Ac		90 Th		91 Pa		92 U		93 Np		94 Pu		95 Am		96 Cm		97 Bk		98 Cf		99 Es		100 Fm		101 Md		102 No		103 Lr								227		232.0377		231.03688		238.02891		237		244		243		247		247		251		252		257		258		259		260								2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2		2.0-2							
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What are the fundamental particles?

Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
QUARKS	mass charge spin $\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	$\approx 2.2 \text{ MeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ $\bar{u}$ antiup	$\approx 1.28 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ $\bar{c}$ anticharm	$\approx 173.1 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ $\bar{t}$ antitop	0 0 1 g gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	$\approx 4.7 \text{ MeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ $\bar{d}$ antidown	$\approx 96 \text{ MeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ $\bar{s}$ antistrange	$\approx 4.18 \text{ GeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ $\bar{b}$ antibottom	0 1 γ photon	GAUGE BOSONS VECTOR BOSONS SCALAR BOSONS
	LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$\approx 0.511 \text{ MeV}/c^2$ 1 $\frac{1}{2}$ e^+ positron	$\approx 105.66 \text{ MeV}/c^2$ 1 $\frac{1}{2}$ $\bar{\mu}$ antimuon	$\approx 1.7768 \text{ GeV}/c^2$ 1 $\frac{1}{2}$ $\bar{\tau}$ antitau	
$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino		$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_e$ electron antineutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_\mu$ muon antineutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_\tau$ tau antineutrino	$\approx 80.39 \text{ GeV}/c^2$ 1 1 W⁺ W ⁺ boson	$\approx 80.39 \text{ GeV}/c^2$ -1 1 W⁻ W ⁻ boson

PERIODIC TABLE OF ANTIELEMENTS

The periodic table of antielements is organized into groups and periods. The elements are color-coded as follows:

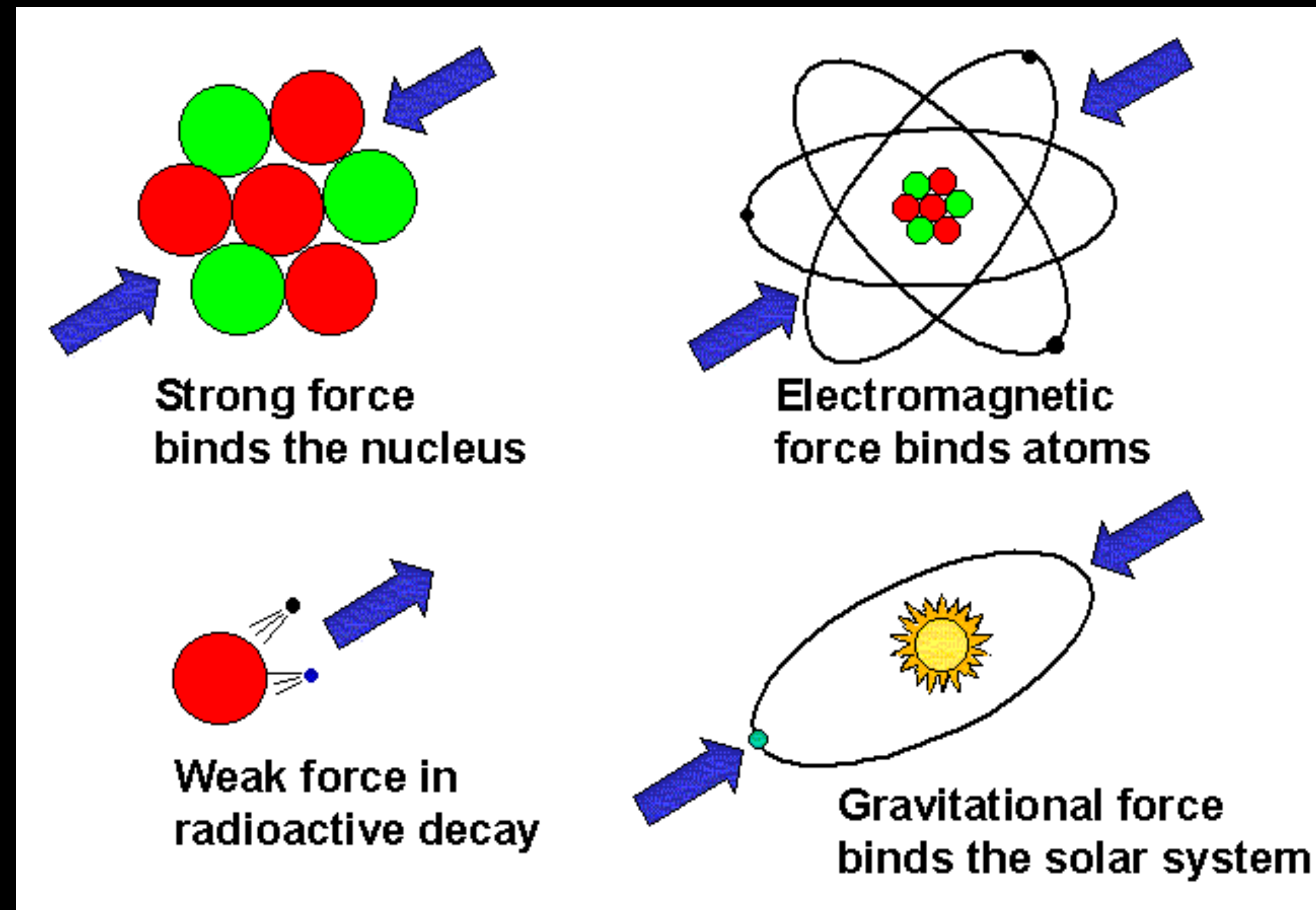
- Fluorine (Green): aH, aLi, aNa, aK, aRb, aCs, aFr, aCl, aBr, aI, aAt, aPo, aSb, aBi, aPb, aSn, aTe, aXe, aKr, aAr, aNe.
- Antimony (Orange): aB, aAl, aGa, aIn, aTl, aTm, aYb, aSc, aY, aLa, aCe, aPr, aNd, aPm, aSm, aEu, aGd, aTb, aDy, aHo, aEr, aTm, aYb.
- Cadmium (Blue): aBe, aMg, aCa, aSr, aBa, aRa, aAc, aTh, aPa, aU, aNp, aPu, aAm, aCm, aBk, aCf, aEs, aFm, aMd, aNo.

Other elements shown include aHe, aNe, aAr, aKr, aXe, aOg, aOs, aIr, aPt, aAu, aHg, aTl, aPb, aBi, aPo, aAt, aRn, aFr, aRa, aAc, aTh, aPa, aU, aNp, aPu, aAm, aCm, aBk, aCf, aEs, aFm, aMd, aNo.

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What are the fundamental forces?

The 4 known forces



This is the “standard model” of physics ... supposed to explain everything

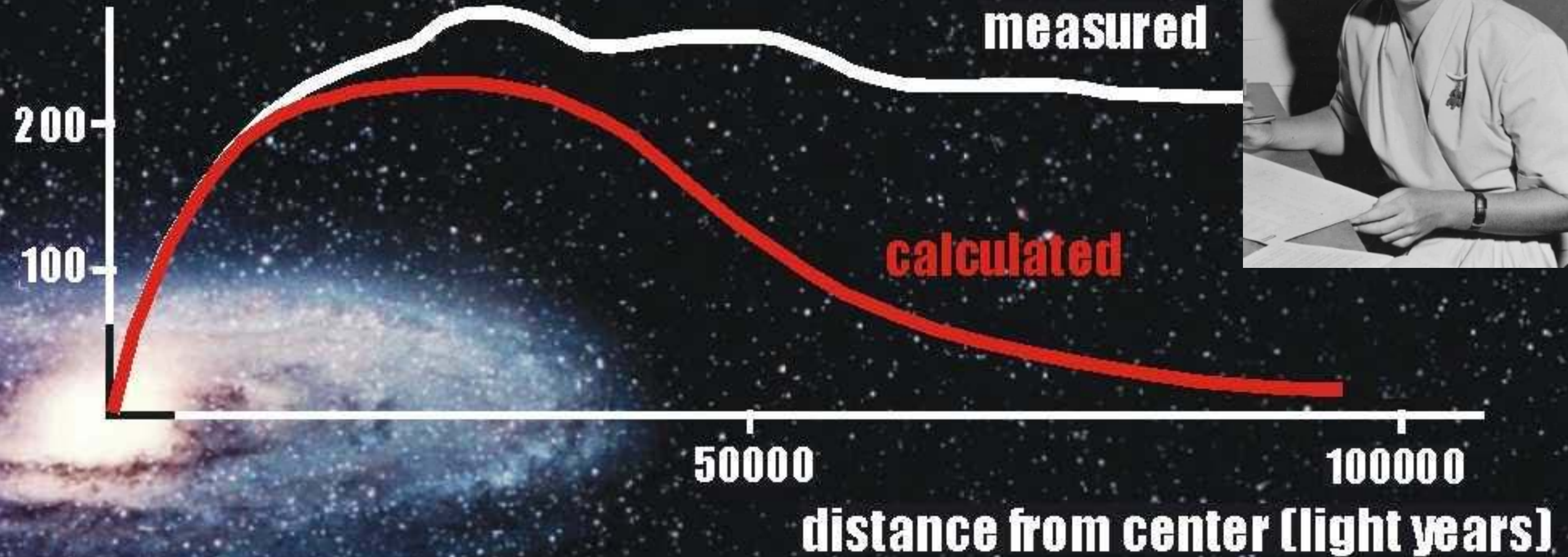
Standard Model of Elementary Particles											
three generations of matter (elementary fermions)						three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)		
	I	II	III	I	II	III					
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0			$\approx 124.97 \text{ GeV}/c^2$	
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0			0	
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			0	
	u up	c charm	t top	$\bar{u}$ antiup	$\bar{c}$ anticharm	$\bar{t}$ antitop	g gluon			H higgs	
QUARKS	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0				
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0				
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1				
	d down	s strange	b bottom	$\bar{d}$ antidown	$\bar{s}$ antistrange	$\bar{b}$ antibottom	γ photon				
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$				
	-1	-1	-1	1	1	1	0				
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1				
	e electron	μ muon	τ tau	e^+ positron	$\bar{\mu}$ antimuon	$\bar{\tau}$ antitau	Z Z^0 boson				
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$			$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	0	0	0	1			-1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W^+ W^+ boson			W^- W^- boson	

**Cosmic maps are not consistent with the
known fundamental particles + forces**

Dark Matter is most of the mass in the universe

Vera Rubin discovery in the 1970s, explains why galaxies gravitationally bound (oops — no Nobel Prize)

rotational velocity
(km/s)



Dark matter not yet found with “direct” searches

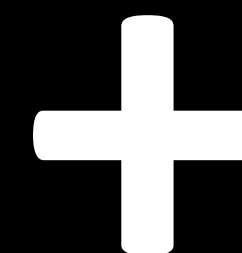


Lux-Zeplin experiment, 7 tons liquid Xenon 1 mile underground

**We can now map where the dark dark matter is gravitationally
... and we know it's not made of normal matter (baryons)**



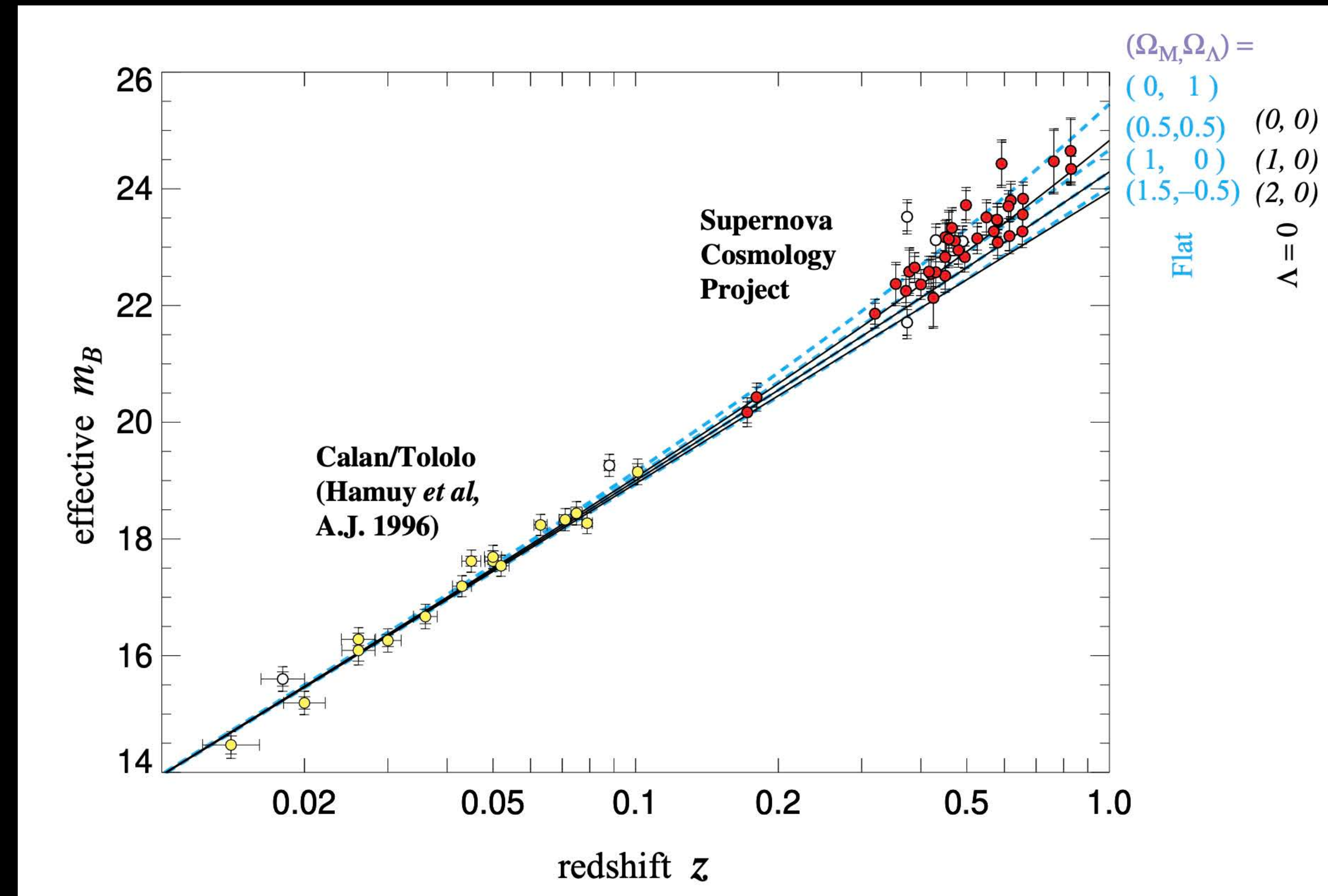
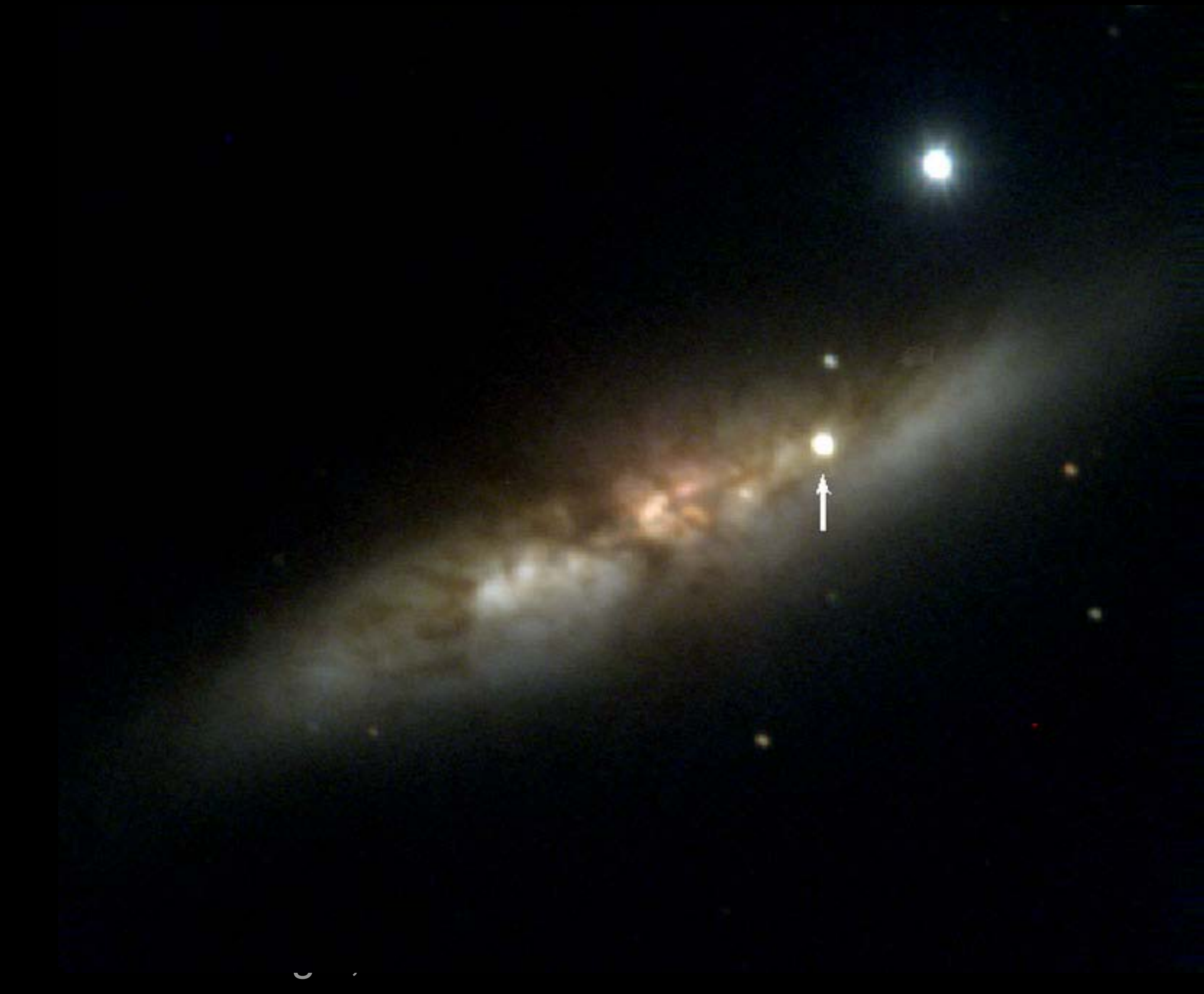
Known particles



Dark Energy is most of the mass-energy of the universe

Discovered in 1998

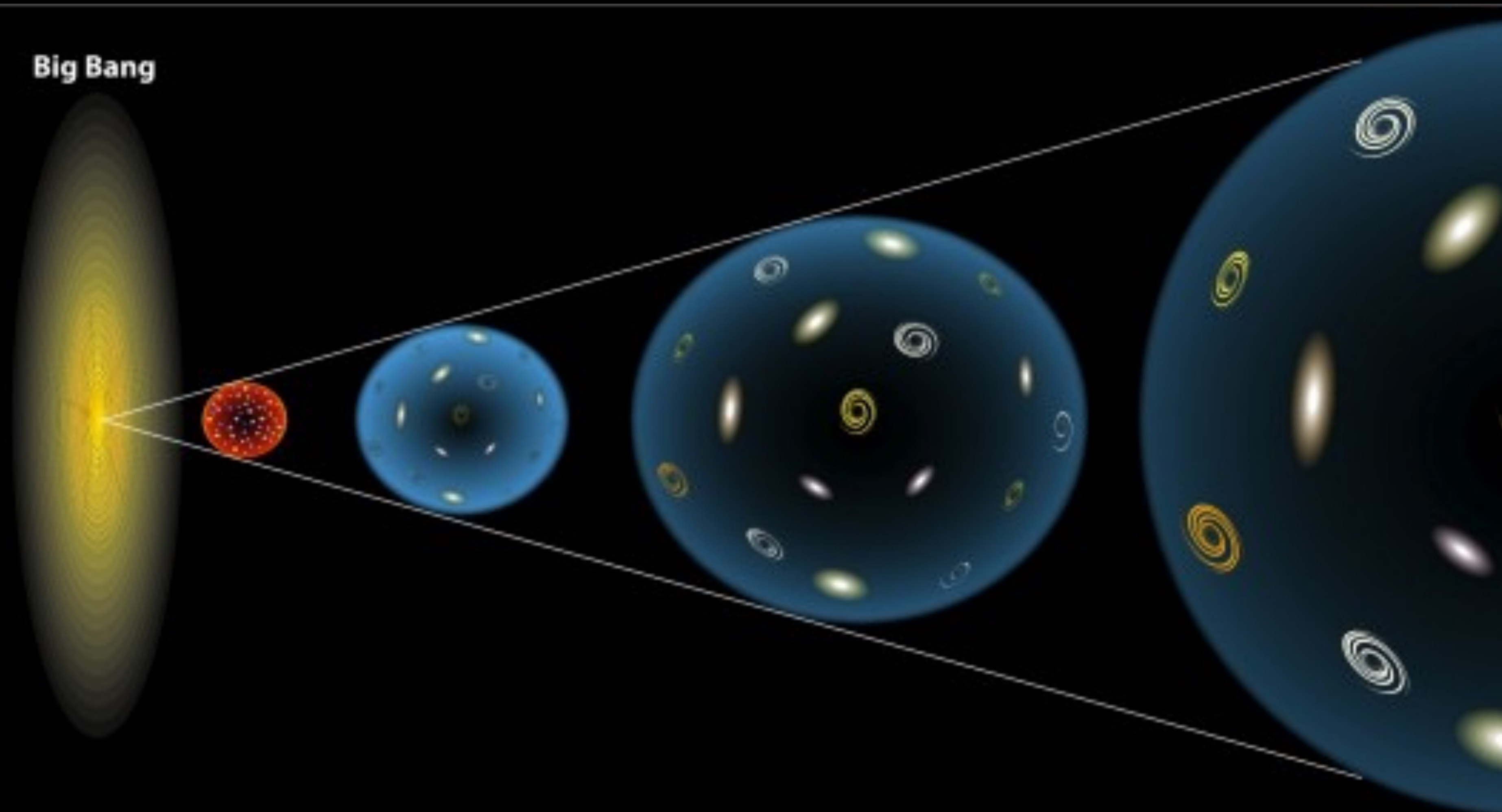
Distant supernova explosions are too faint
(Nobel Prize for Perlmutter, Schmidt, Reiss in 2011)



What is Dark Energy?

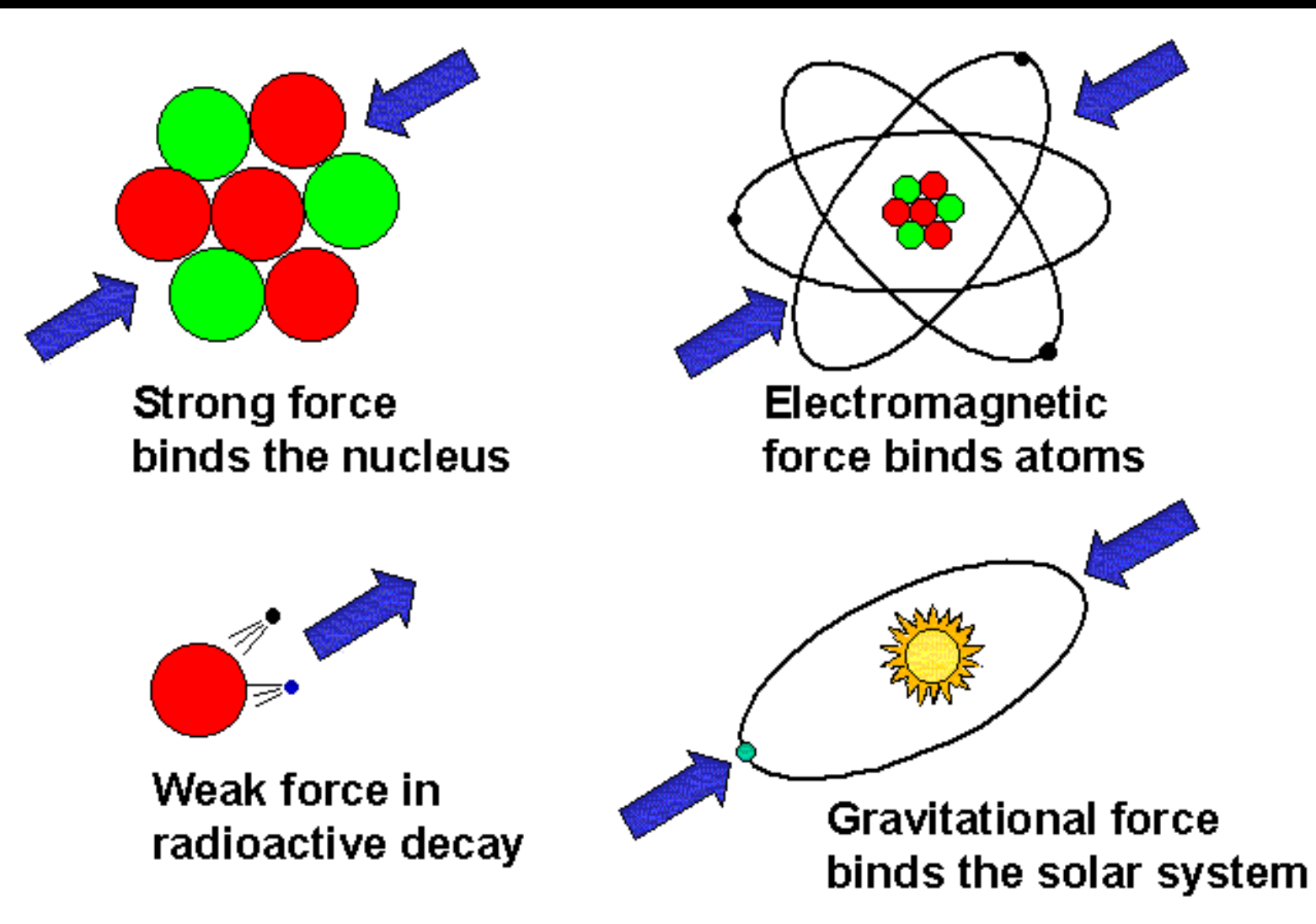
Too much “space” between us + distant galaxies

Apparent force accelerating expansion of universe



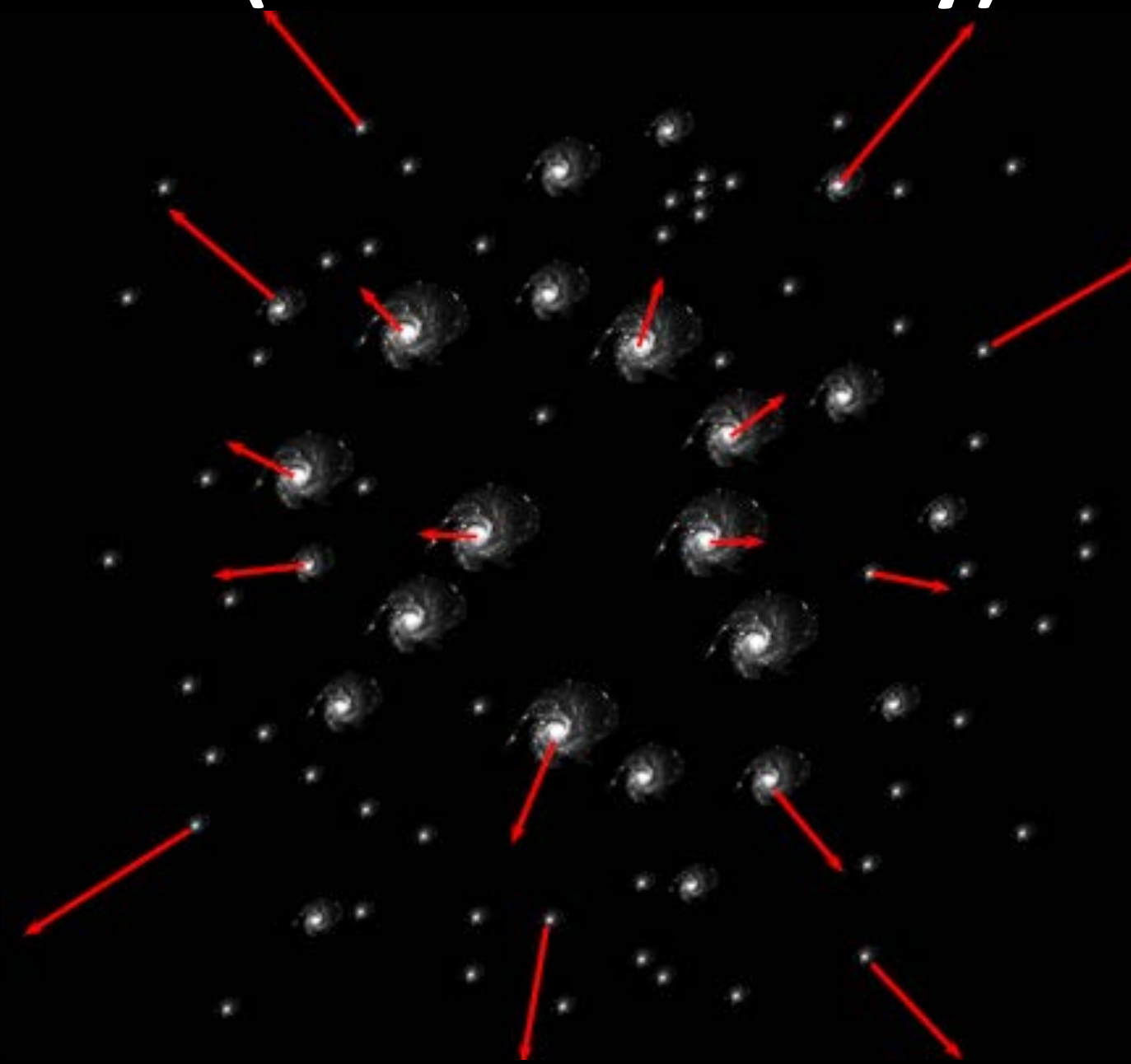
The Fundamental Forces

The 4 known forces



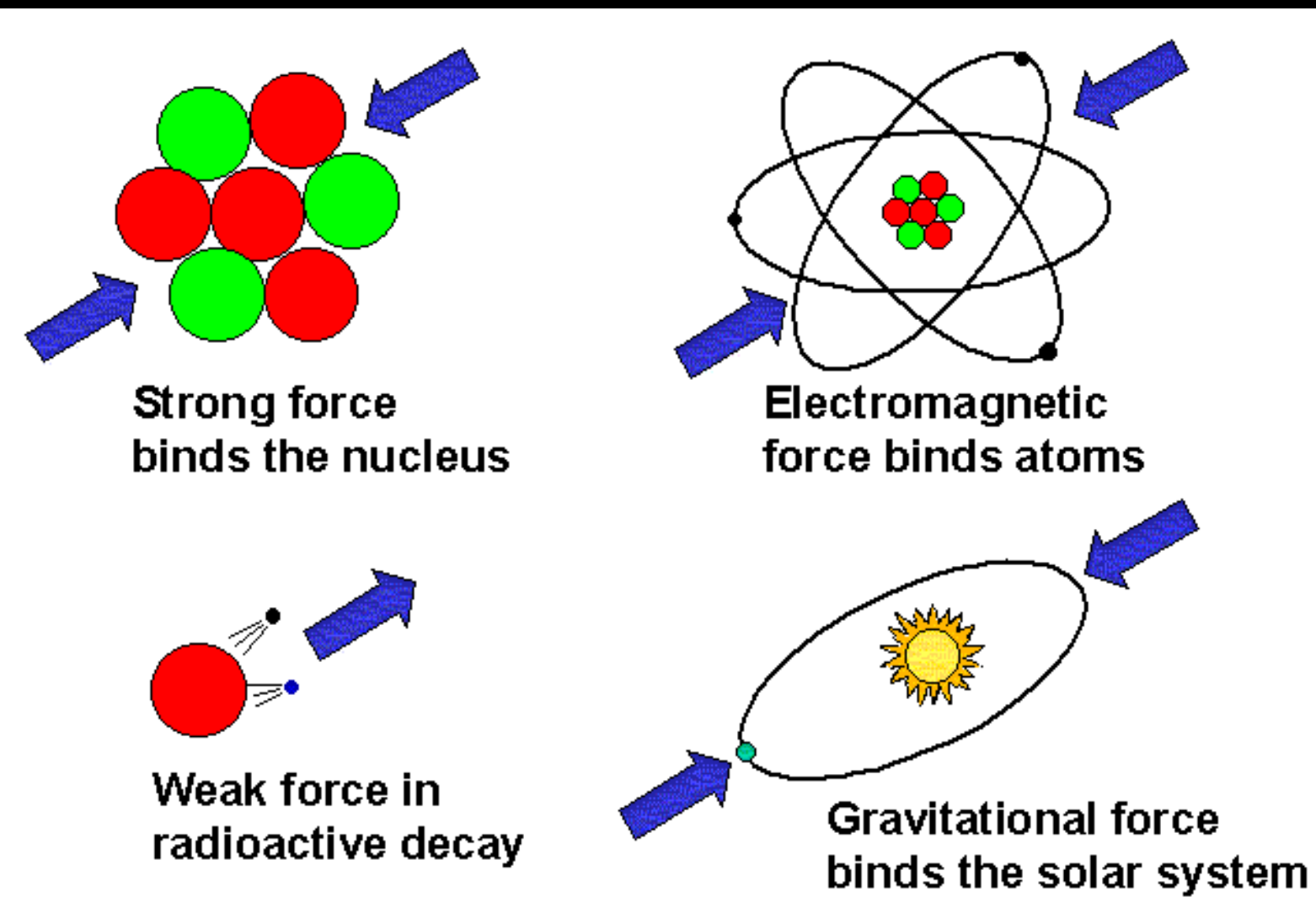
+

Dark energy (dominates today)

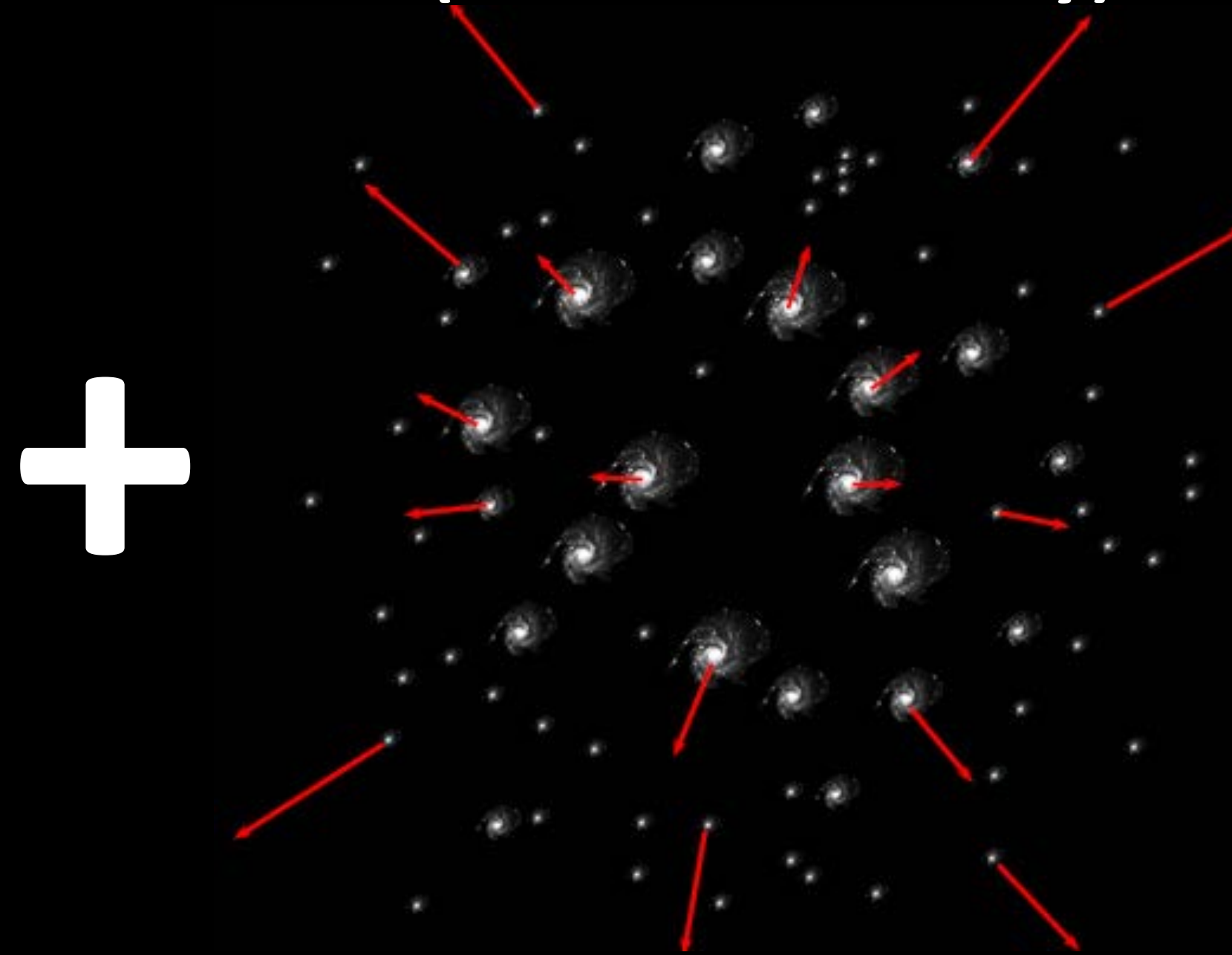


The Fundamental Forces

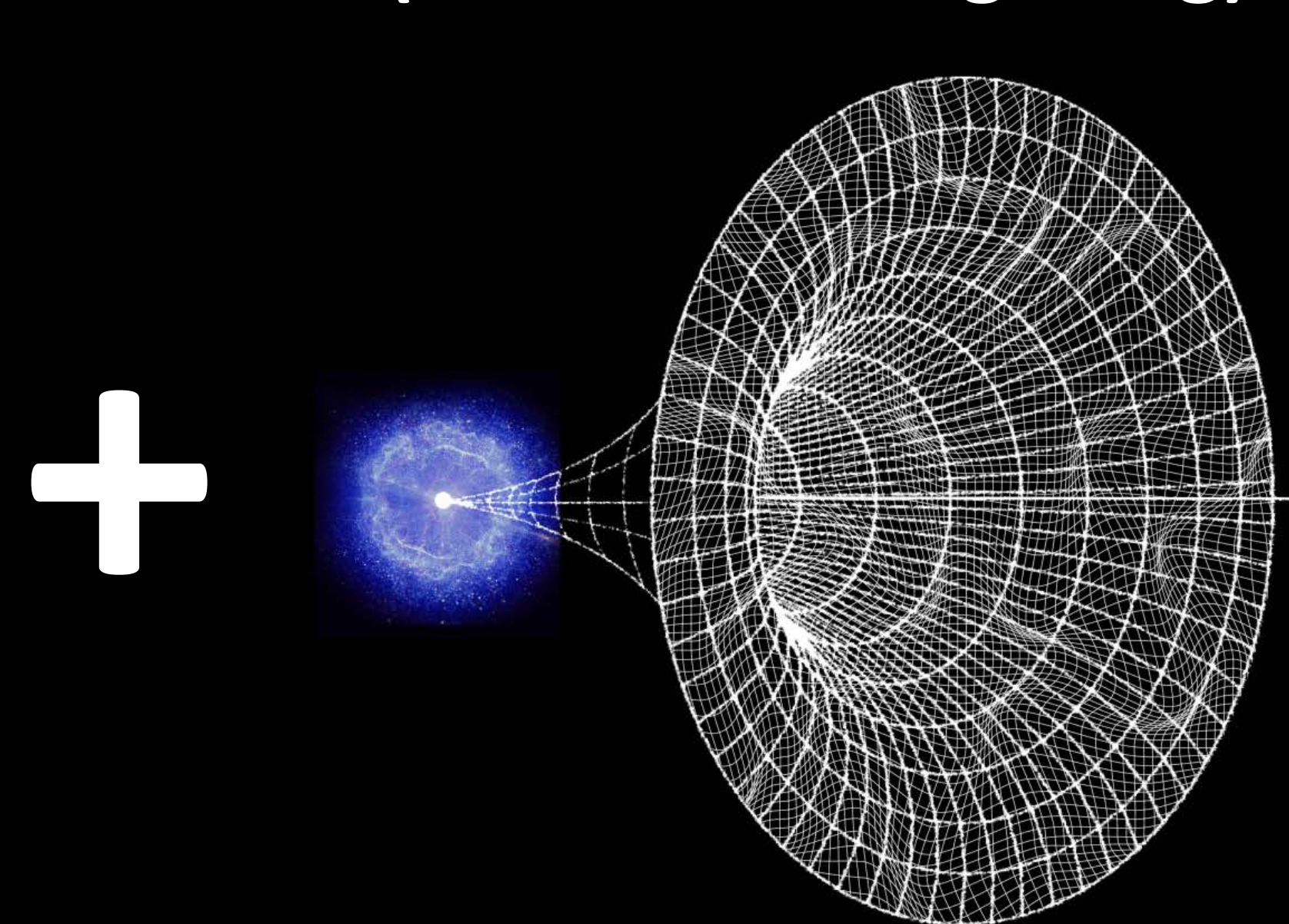
The 4 known forces



Dark energy
(dominates today)



Inflation
(<1 sec after Big Bang)



Most of the Universe's energy density is Dark Energy

Dark Energy is a component in the universe that can enter Einstein's equations of gravity like a cosmic fluid with a negative equation of state

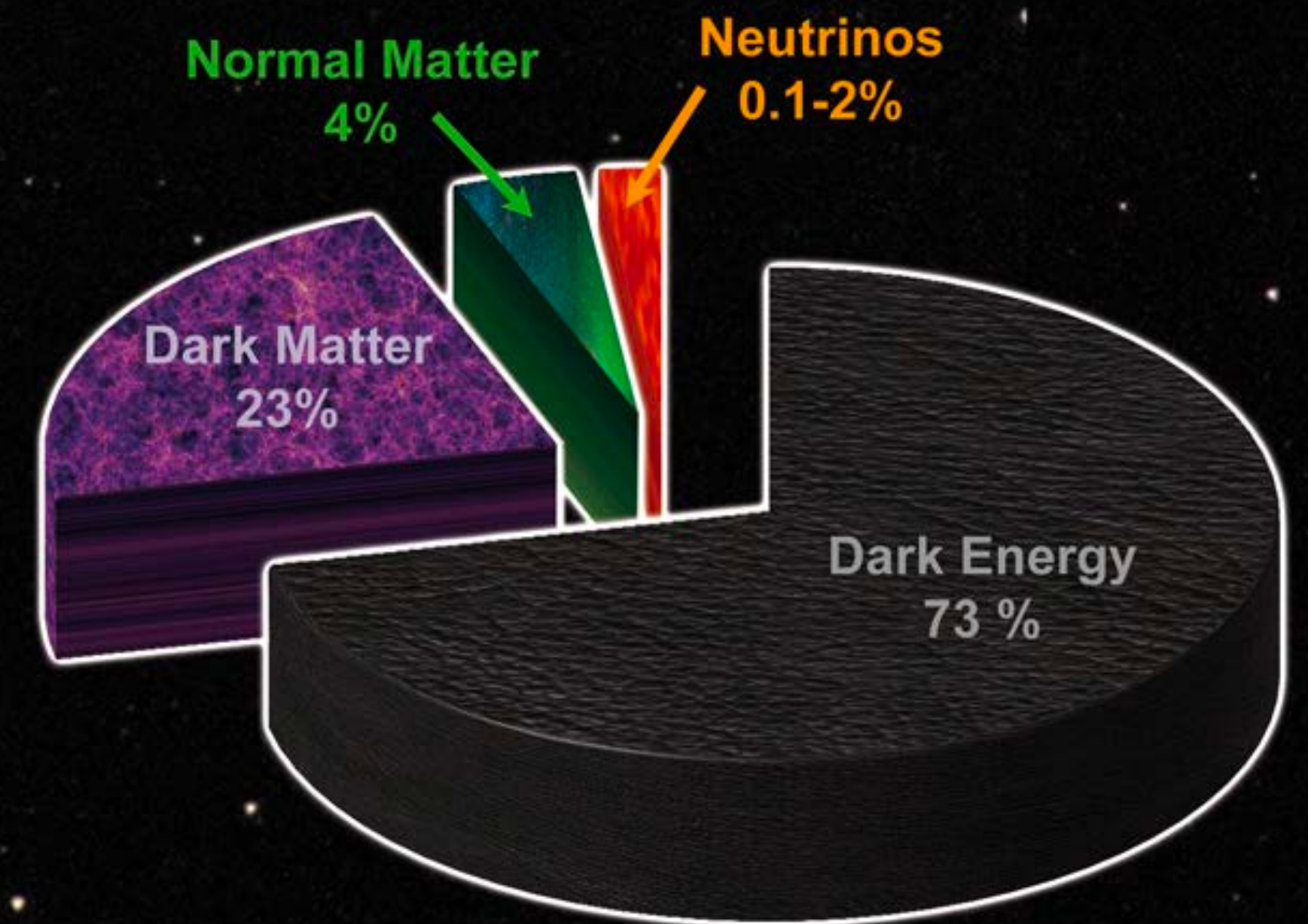
$$w \equiv \frac{p_{de}}{c^2 \rho_{de}}$$

Negative $w < -1/3$ gives an accelerating expansion

$$\frac{\ddot{a}}{a} = -4\pi G \rho_{de} \left(\frac{1}{3} + w \right)$$

Dark Energy candidates can have slightly different w values
Dark Energy may be dynamic, conventionally parameterized
by the scale factor a :

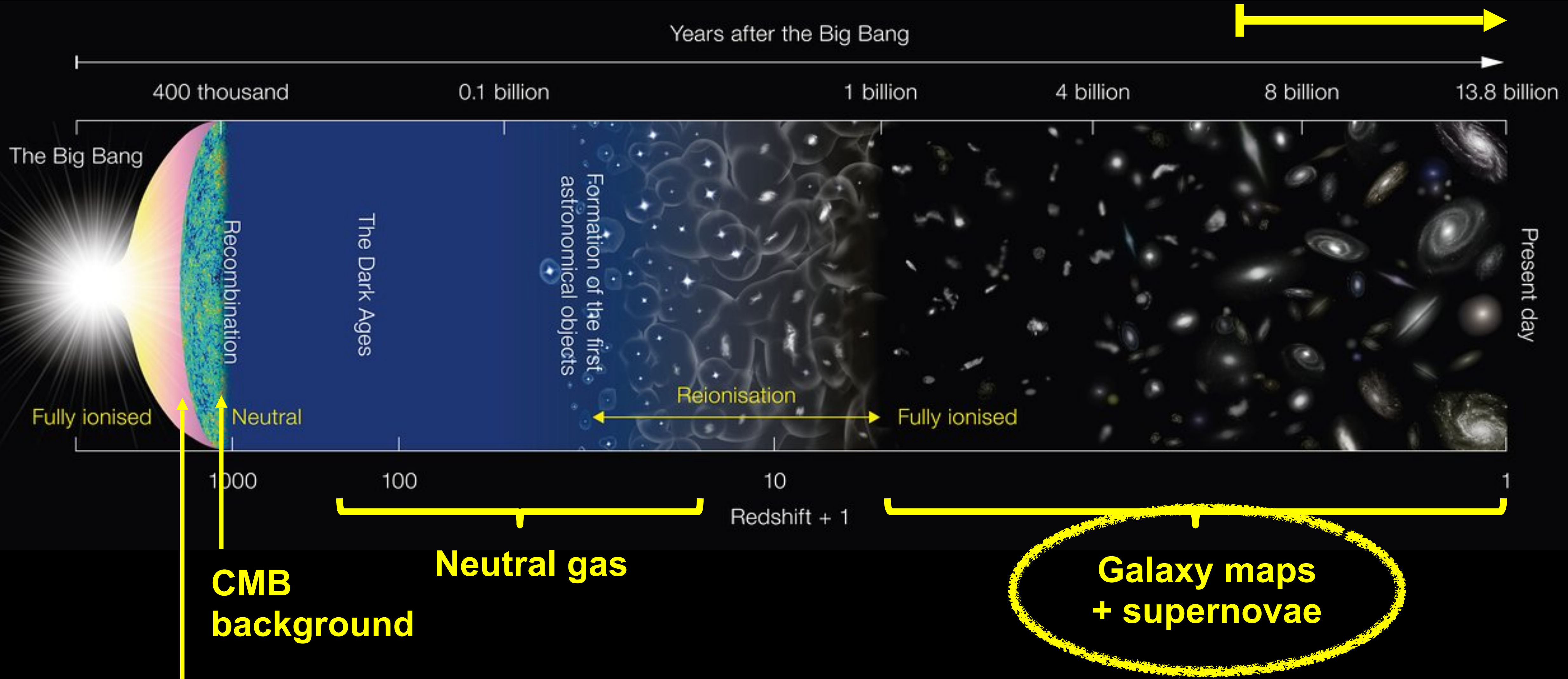
$$w(a) = w_0 + (1-a) w_a$$



Content of the Universe

Mapping the Universe

Dark Energy domination



Maps are never simply x,y,z

DESI maps in angular coordinates $(\alpha, \delta) + \text{redshift } (z)$

Maps are never simply x,y,z

gravity erases initial conditions on small (non-linear) scales

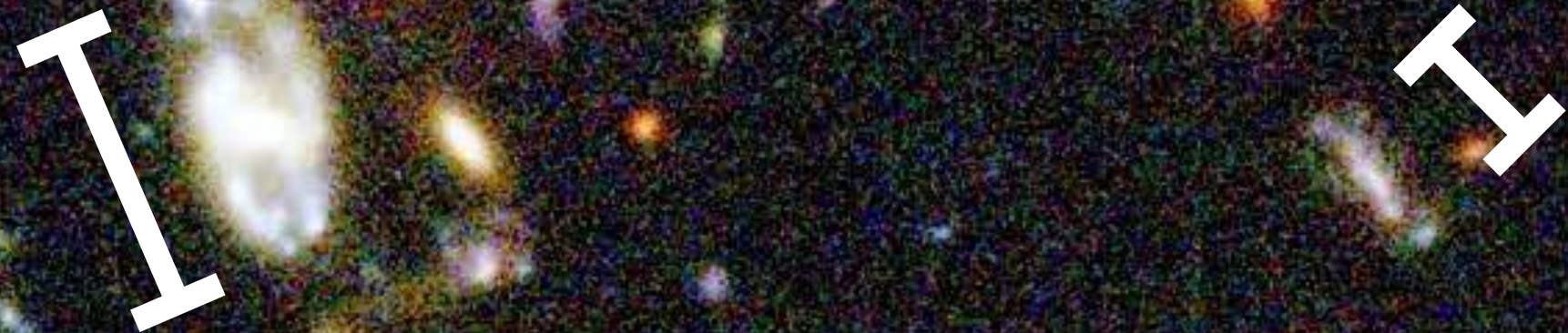
DESI maps in angular coordinates (α, δ) + redshift (z)
 z = distance + gravity-induced velocity

Mapping the Universe: **Point maps** vs. Statistical maps

Galaxies are not a good standard ruler!

$$d_A(z) = \frac{c}{\sqrt{|\Omega_{k,0}|} H_0 (1+z)} \cdot S_k \left(H_0 \sqrt{|\Omega_{k,0}|} \int_0^z \frac{dz}{H(z)} \right)$$

...though they have been proposed over the years as “standard-izable”,
(dating back to Carl Wirtz in 1924), as have galaxy clusters...



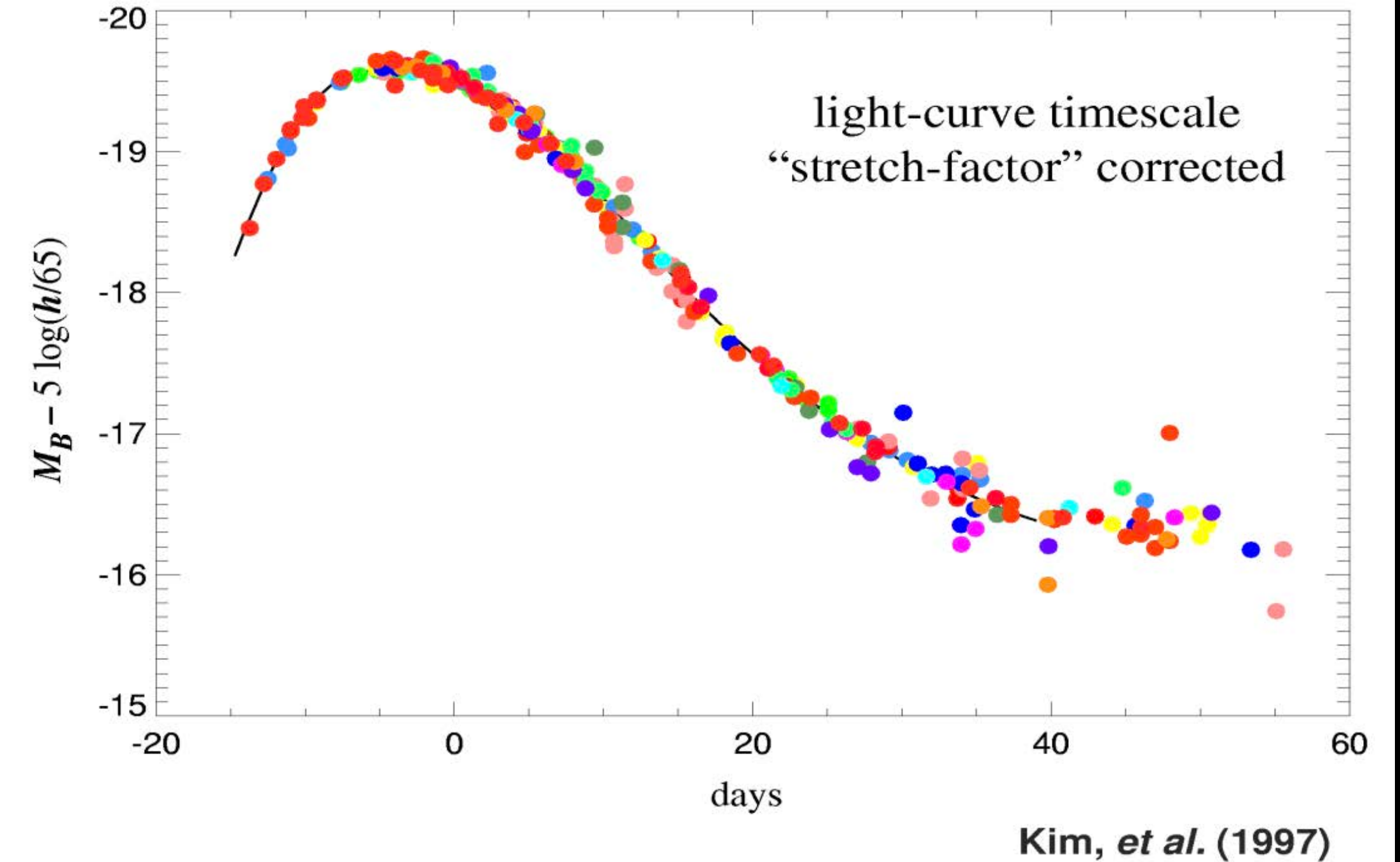
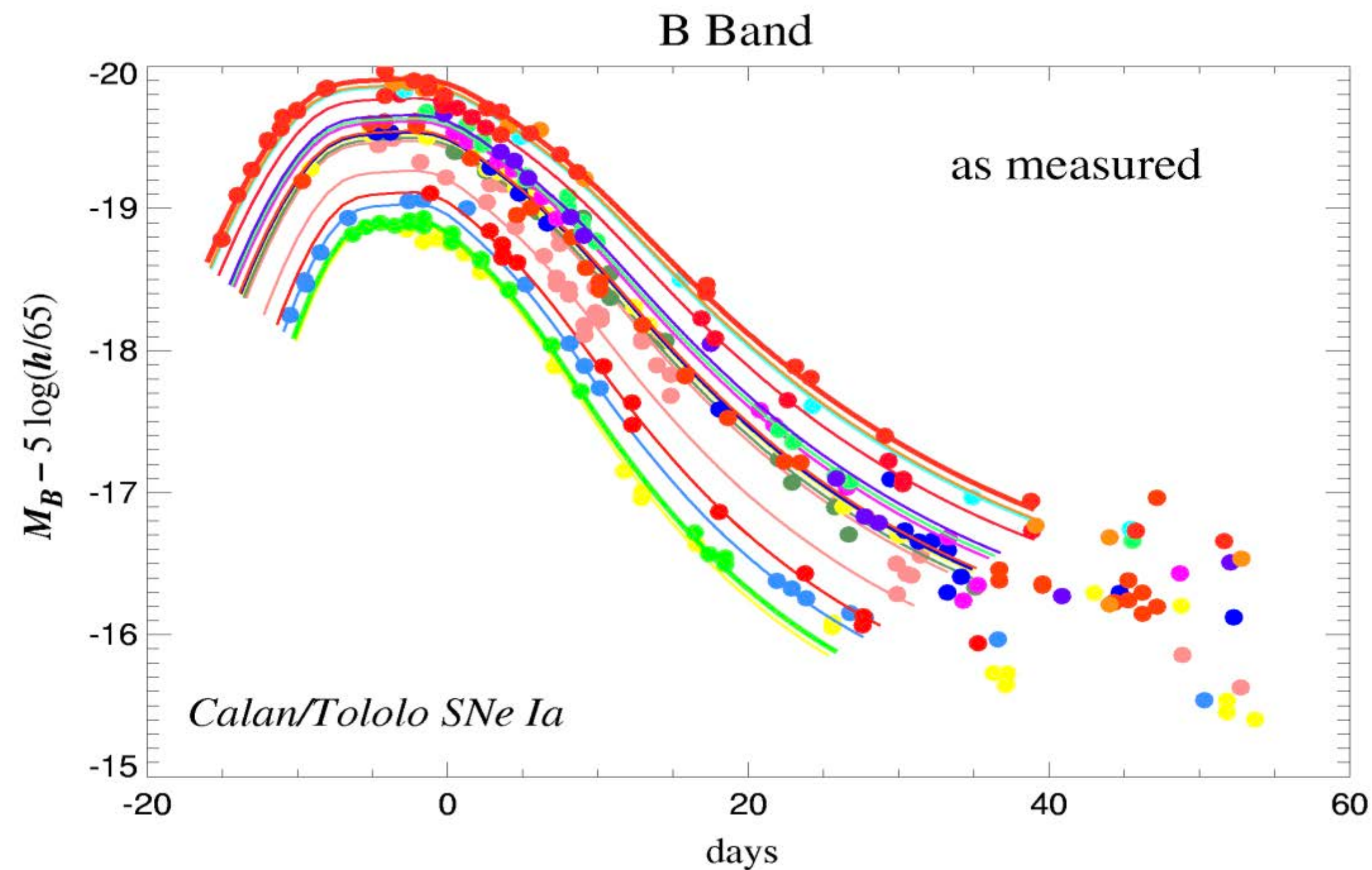
Mapping the Universe: **Point maps** vs. Statistical maps

Supernovae are an excellent “standard-izable” candle in intrinsic luminosity

$$d_L = \frac{r_1}{a} = (1+z)r_1 = (1+z)^2 \cdot d_A$$

Absolute mag Apparent mag

$$M - m = 2.5 \log \left(\frac{d_{L,0}}{d_L} \right)^2 = 5 \log \left(\frac{d_{L,0}}{d_L} \right)$$

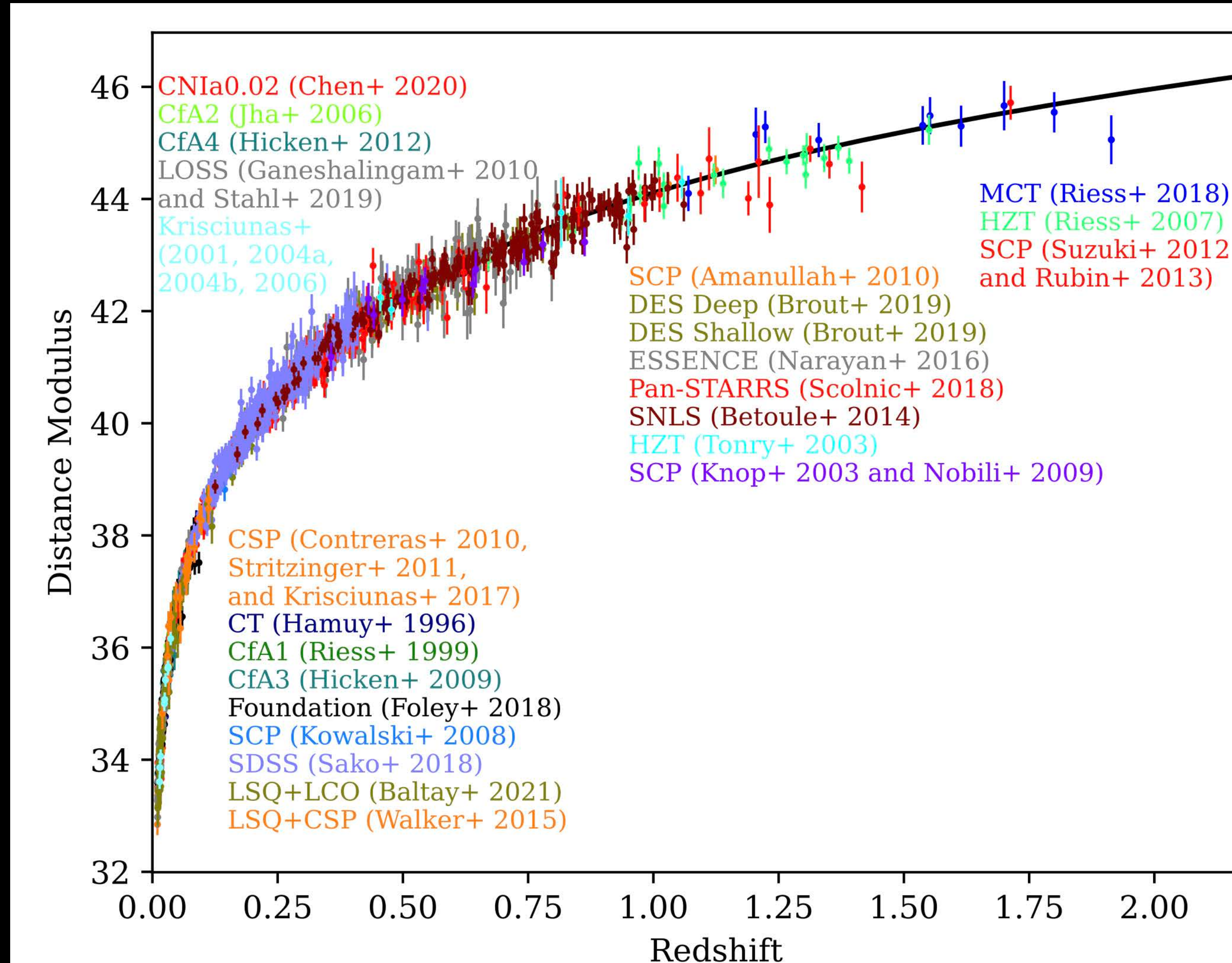


Mapping the Universe: **Point maps** vs. Statistical maps

Supernovae are an excellent “standard-izable” candle in intrinsic luminosity

Large compilations of supernova samples recently published

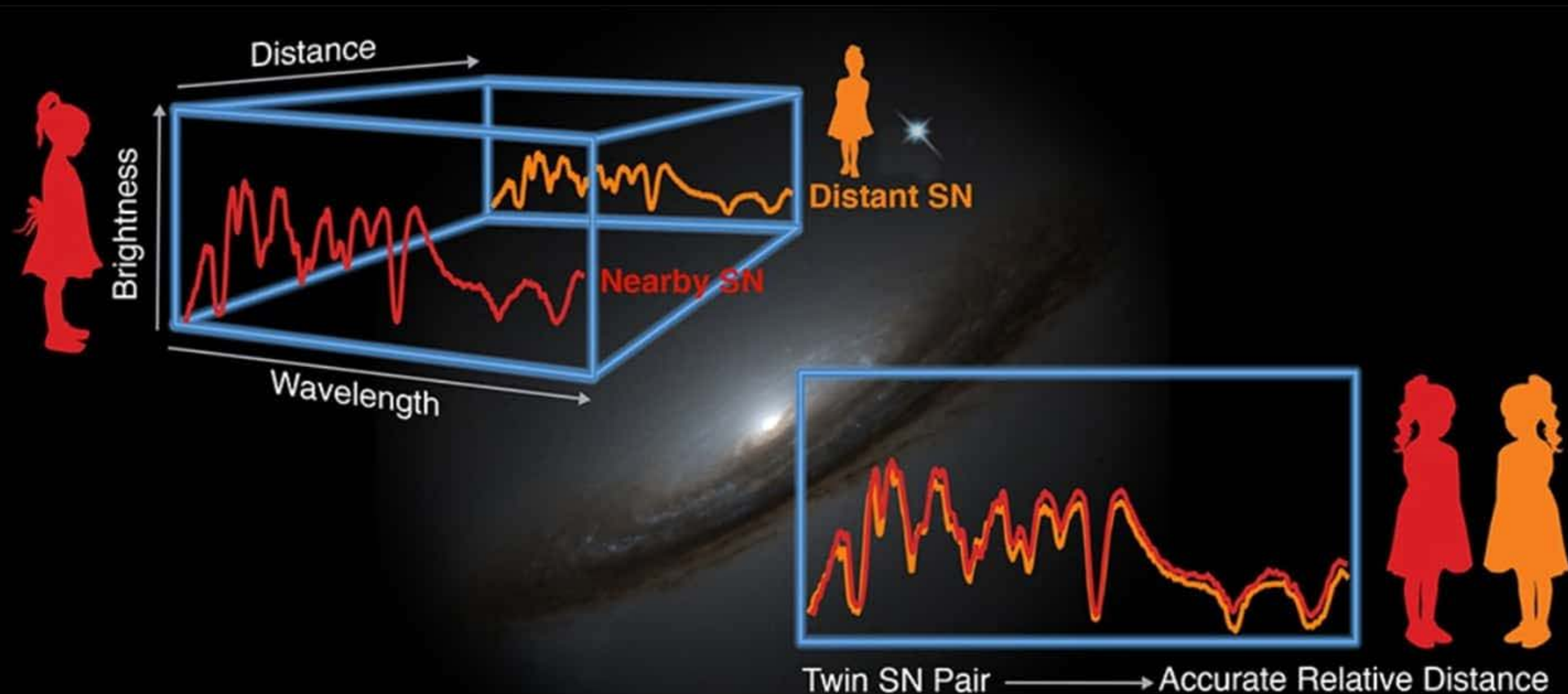
- Pantheon+(Scolnic+ 2022)
- Dark Energy Survey(DES-SN5YR 2023)
- Union 3 -> Unity (Rubin+ 2024)



Mapping the Universe: **Point maps** vs. Statistical maps

Supernovae are an excellent “standard-izable” candle in intrinsic luminosity

Supernova “twinning” can double the accuracy of each supernova distance



Mapping the Universe: **Point maps** vs. Statistical maps

Supernovae are an excellent “standard-izable” candle in intrinsic luminosity

Next generation of supernova projects starting

- Zwicky Transient Factory (0.6 Gpix)
- La Silla Schmidt Southern Survey (0.3 Gpix)
- Vera Rubin Observatory (3 Gpix)

Promised improvements with

- more statistics (millions!)
- improved flux calibration



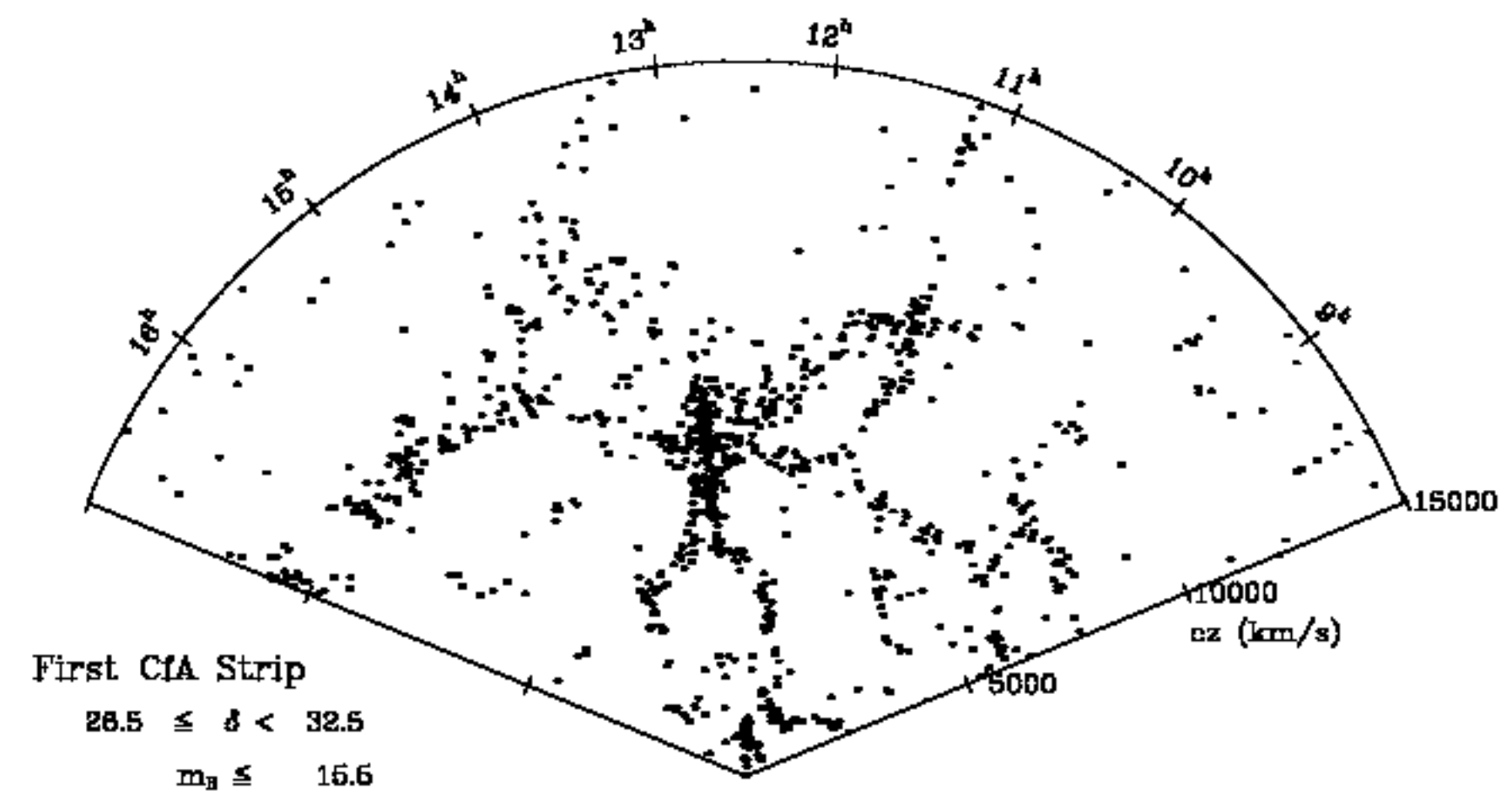
Mapping the Universe: Point maps vs. **Statistical maps**

The beginning of **redshift surveys**
for 3-dimensional maps in 1983

The “Z machine” (now in the Smithsonian)
Redshifted 2401 galaxies... 1 galaxy at a time...

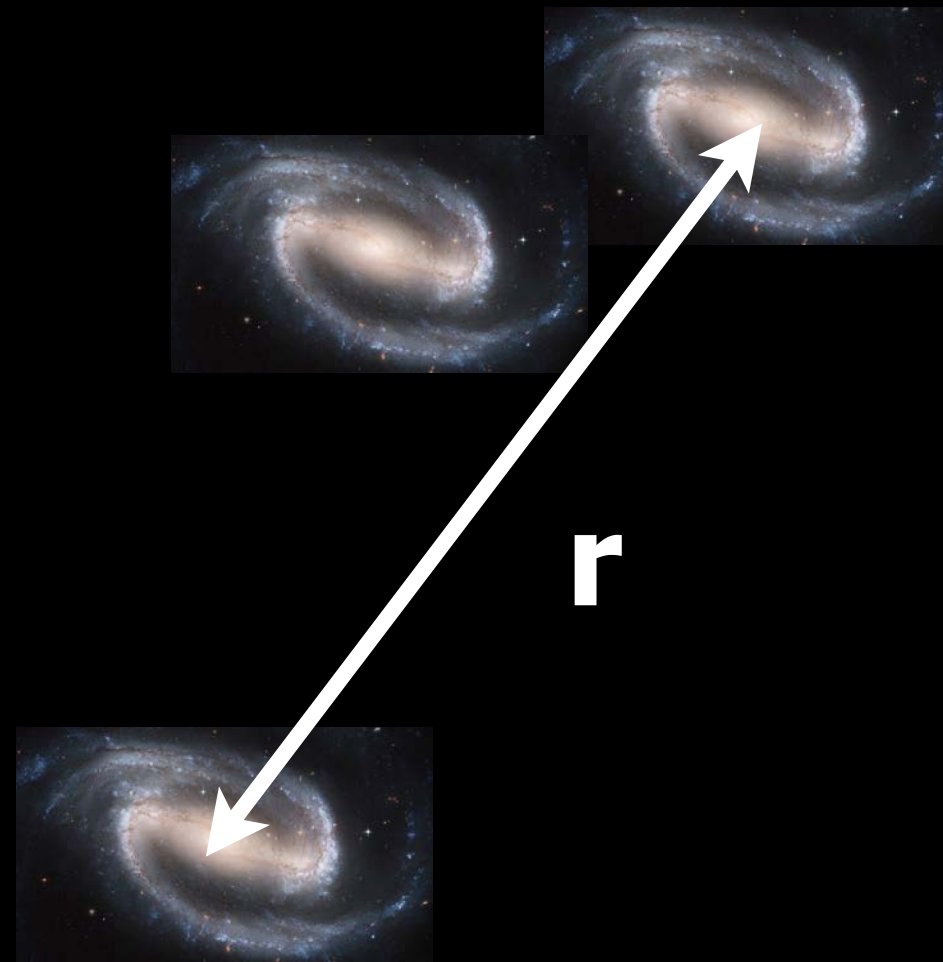


the famous “stick man”

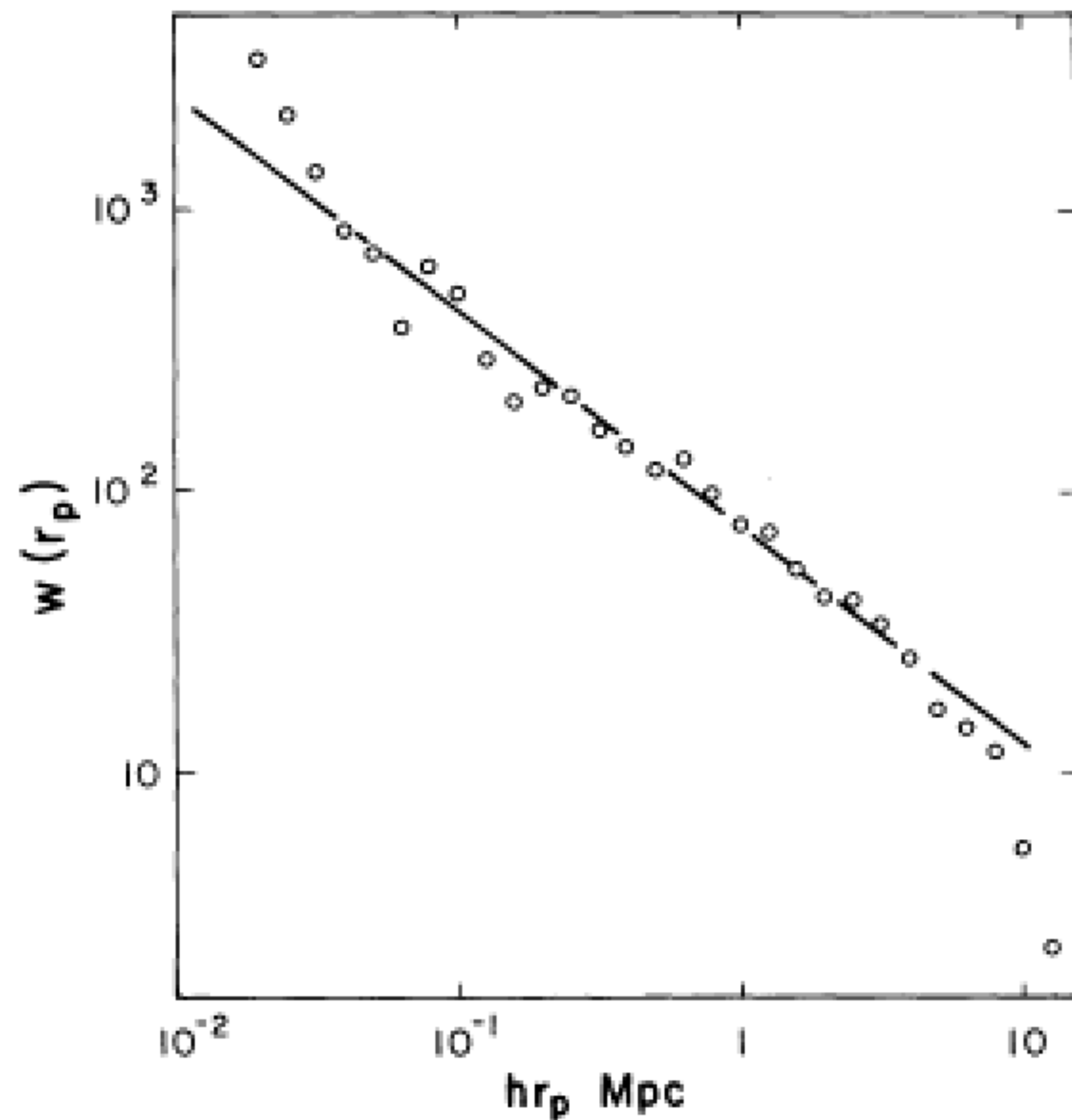


Copyright SAO 1998

**The start of measuring statistics of the clustering of galaxies
with the 2-point function == excess probability of galaxies at each r**



**The start of measuring statistics of the clustering of galaxies
with the 2-point function == excess probability of galaxies at each r**



**A SURVEY OF GALAXY REDSHIFTS. V. THE TWO-POINT POSITION
AND VELOCITY CORRELATIONS**

MARC DAVIS

Departments of Astronomy and Physics, University of California

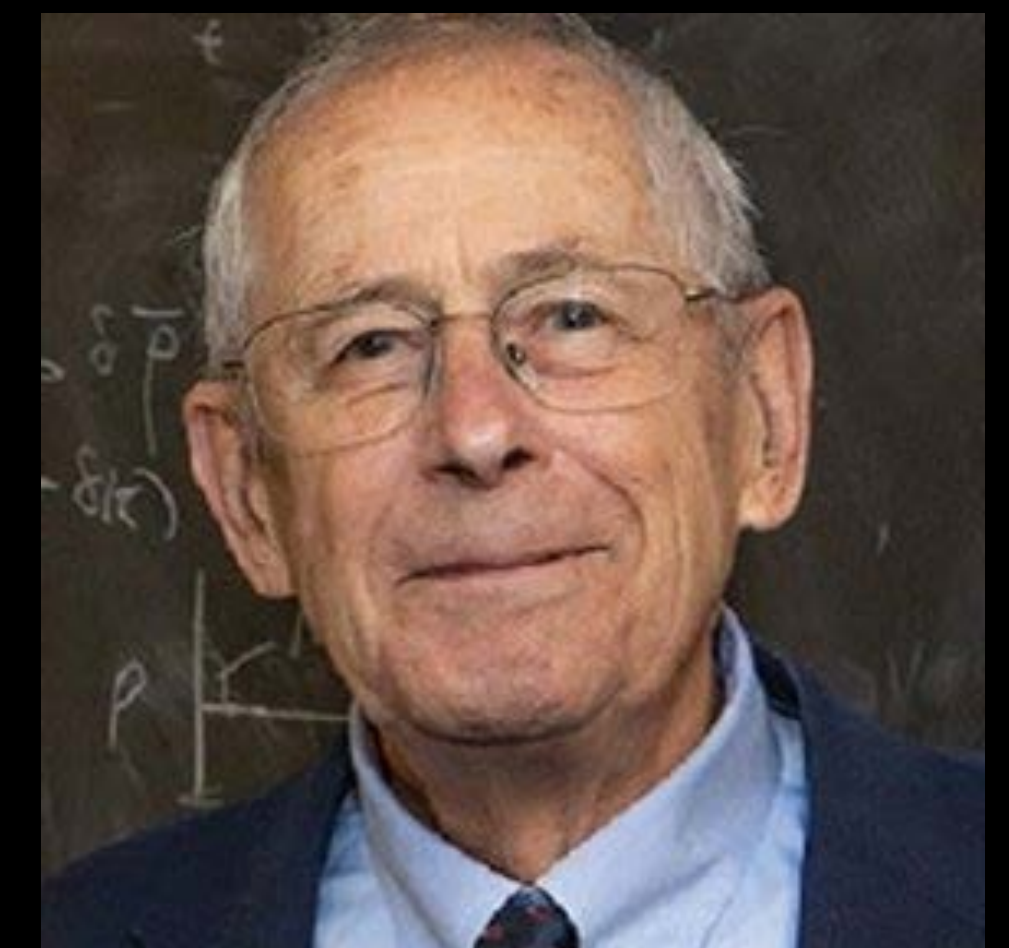
AND

P. J. E. PEEBLES

Joseph Henry Laboratories, Princeton University

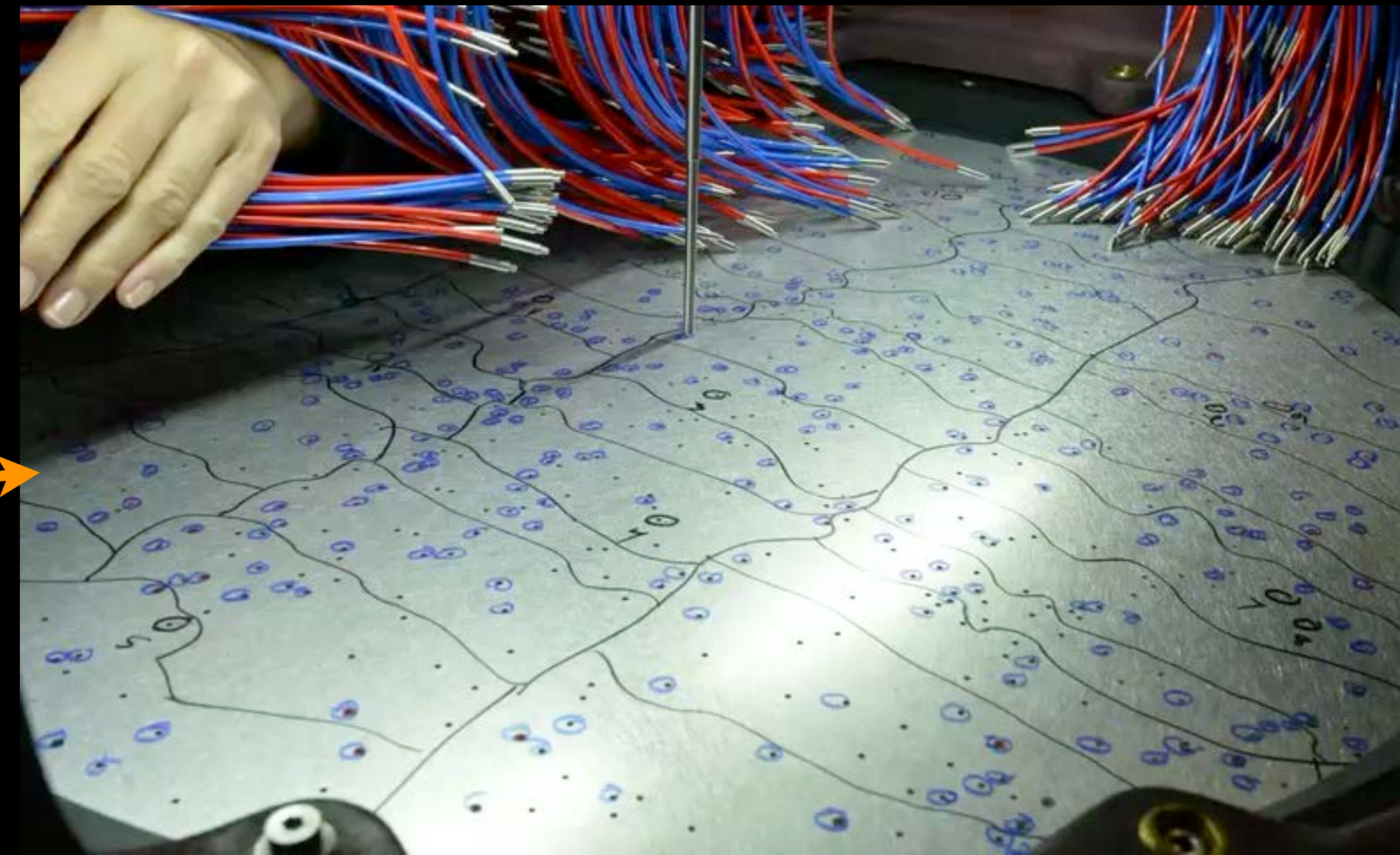
Received 1982 August 5; accepted 1982 October 12

**2019 Nobel Prize for
“contributions to for our
understanding of the
evolution of the universe”**



Sloan Digital Sky Survey (SDSS)

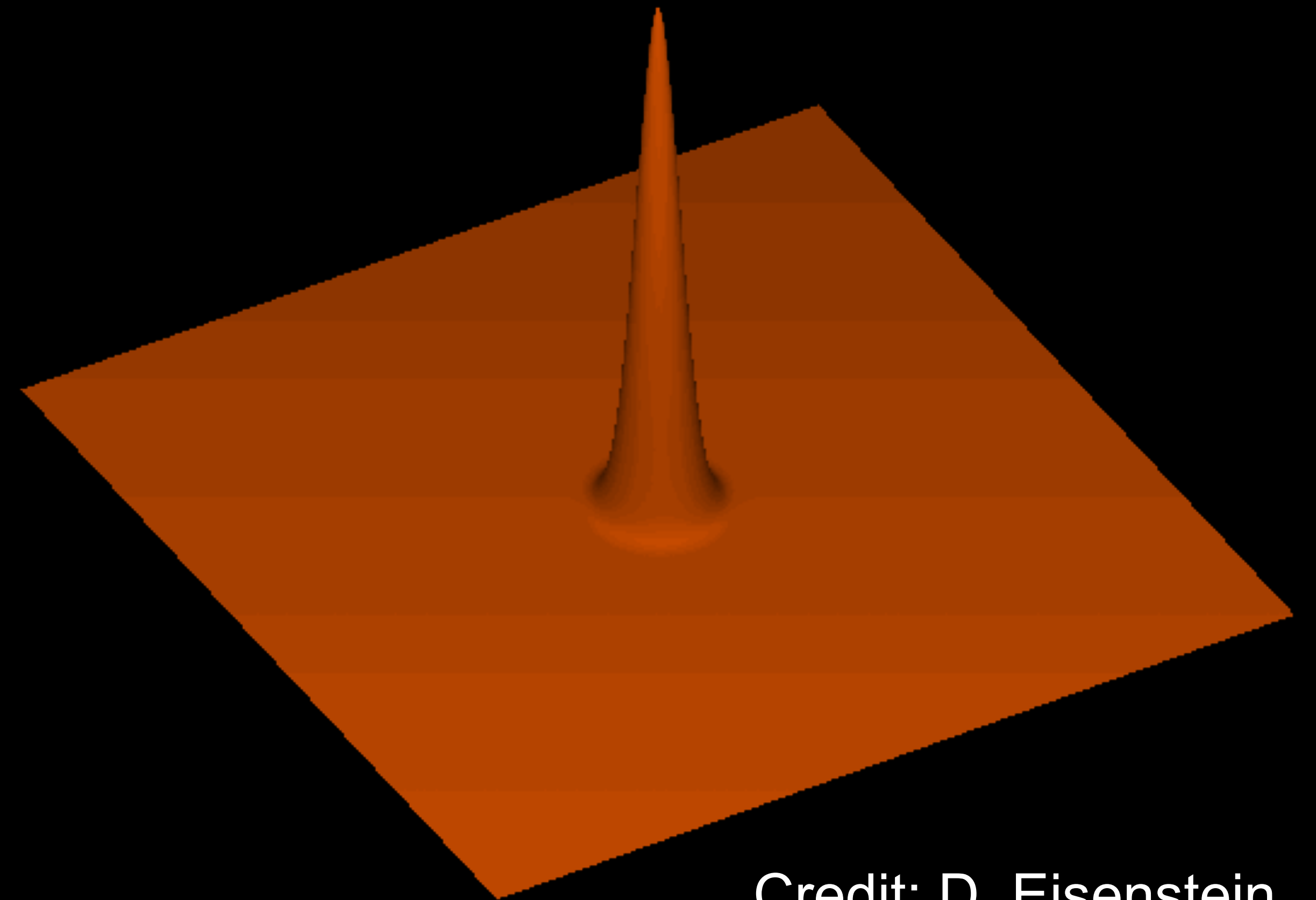
Multiplexing with fiber optic cables to observe 640 galaxies simultaneously
... later upgraded to 1000 ... up to 9000 galaxies/night



**SDSS — the first 3-dimensional map to make a good movie
with 1 million galaxies**

Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

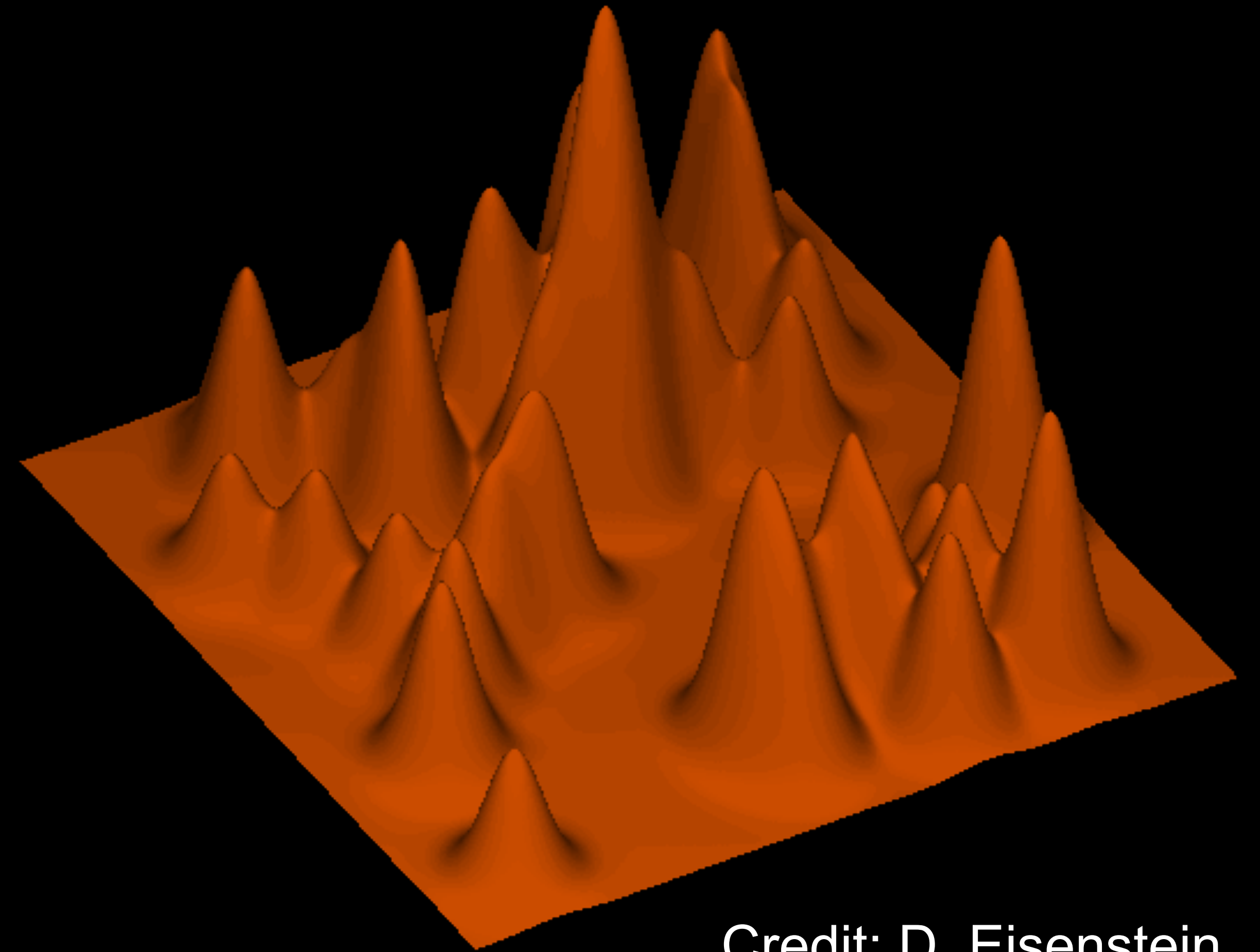
BAO imprinted in the microwave background at $z=1100$
... and forever more in galaxy maps



Credit: D. Eisenstein

Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

BAO imprinted in the microwave background at $z=1100$
... and forever more in galaxy maps



Credit: D. Eisenstein

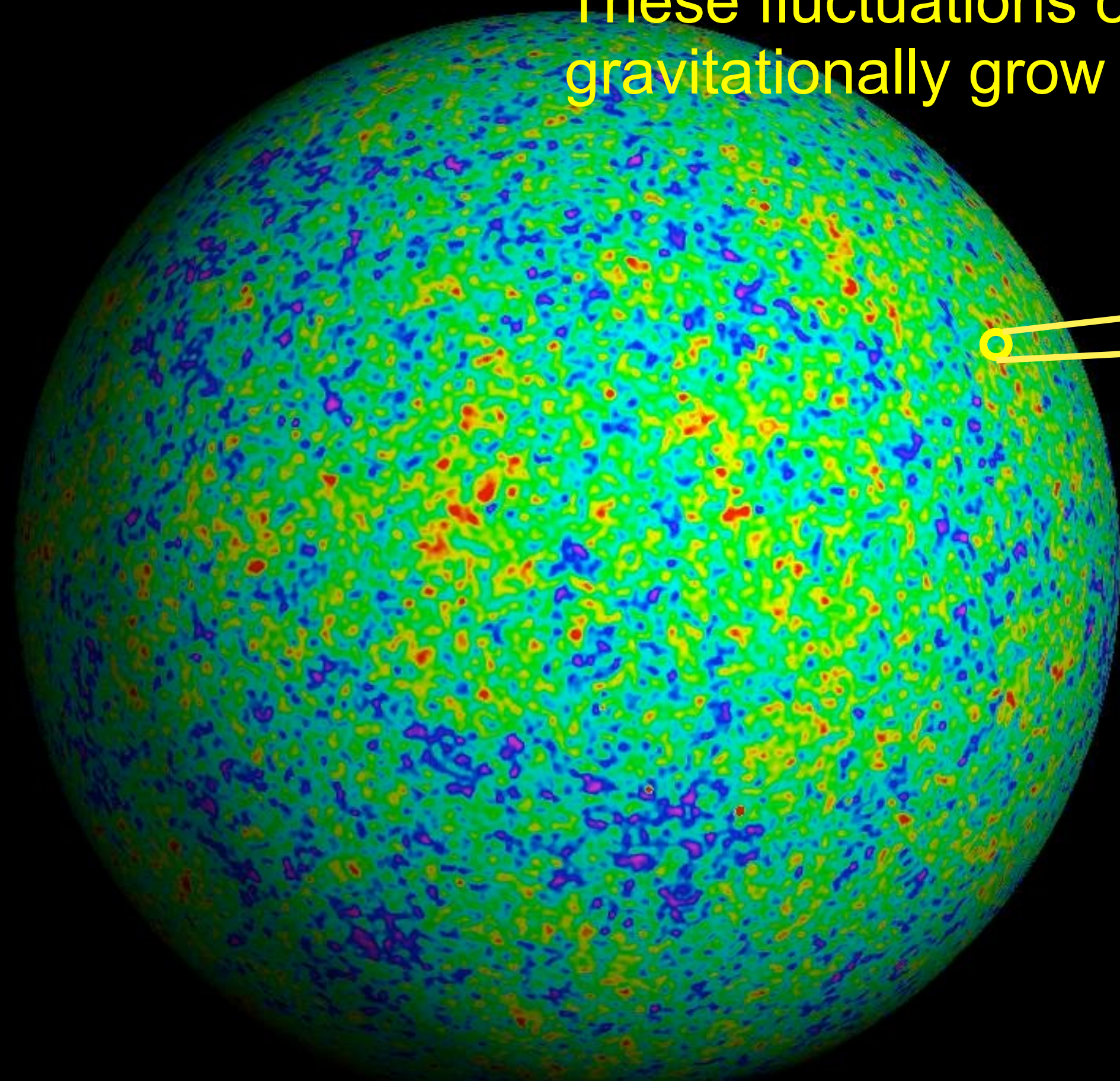
Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

BAO imprinted in the microwave background at $z=1100$
... and forever more in galaxy maps

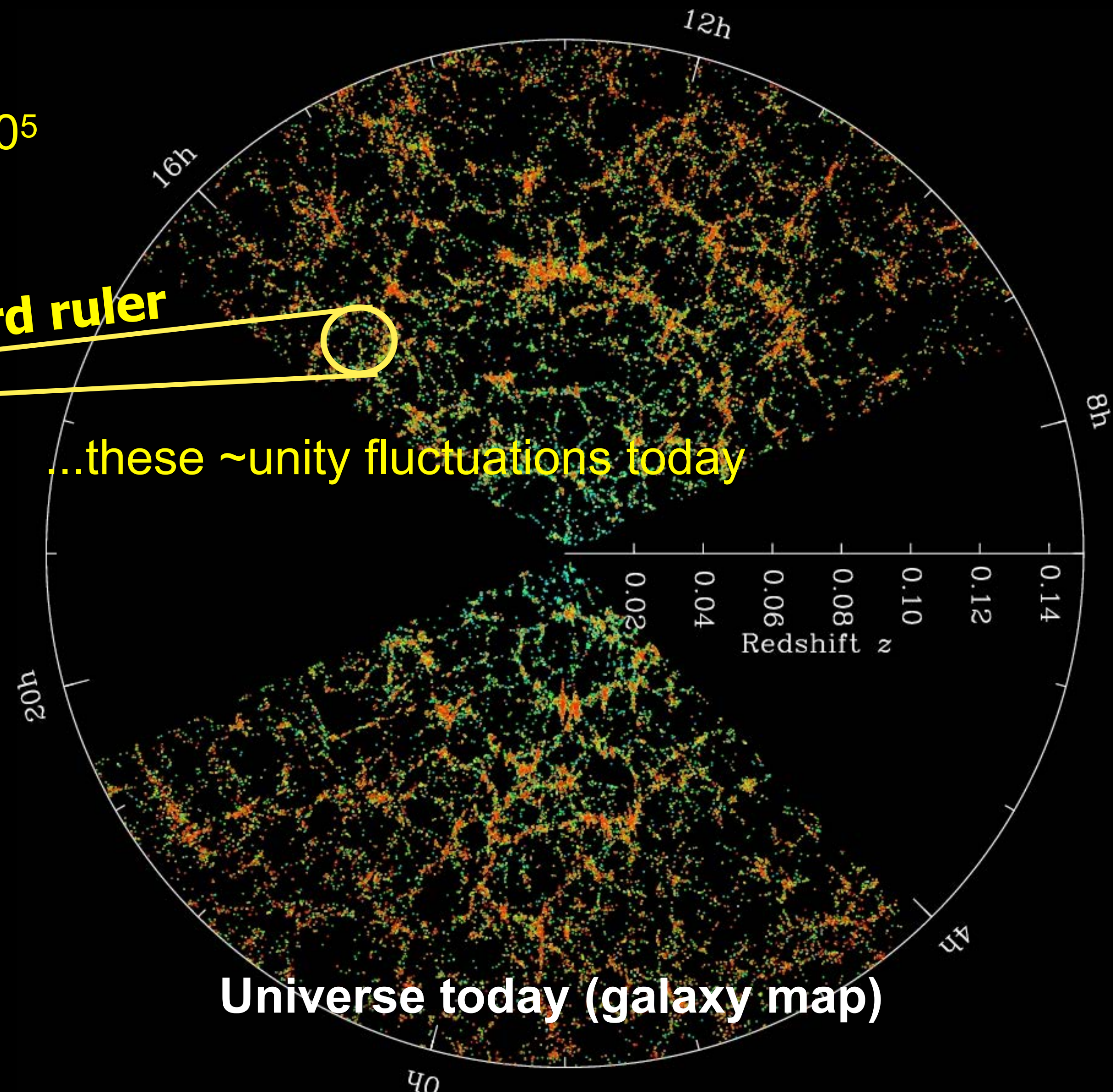
These fluctuations of 1 part in 10^5
gravitationally grow into...

standard ruler

...these ~unity fluctuations today



Universe at 380,000 years old (CMB)



Universe today (galaxy map)

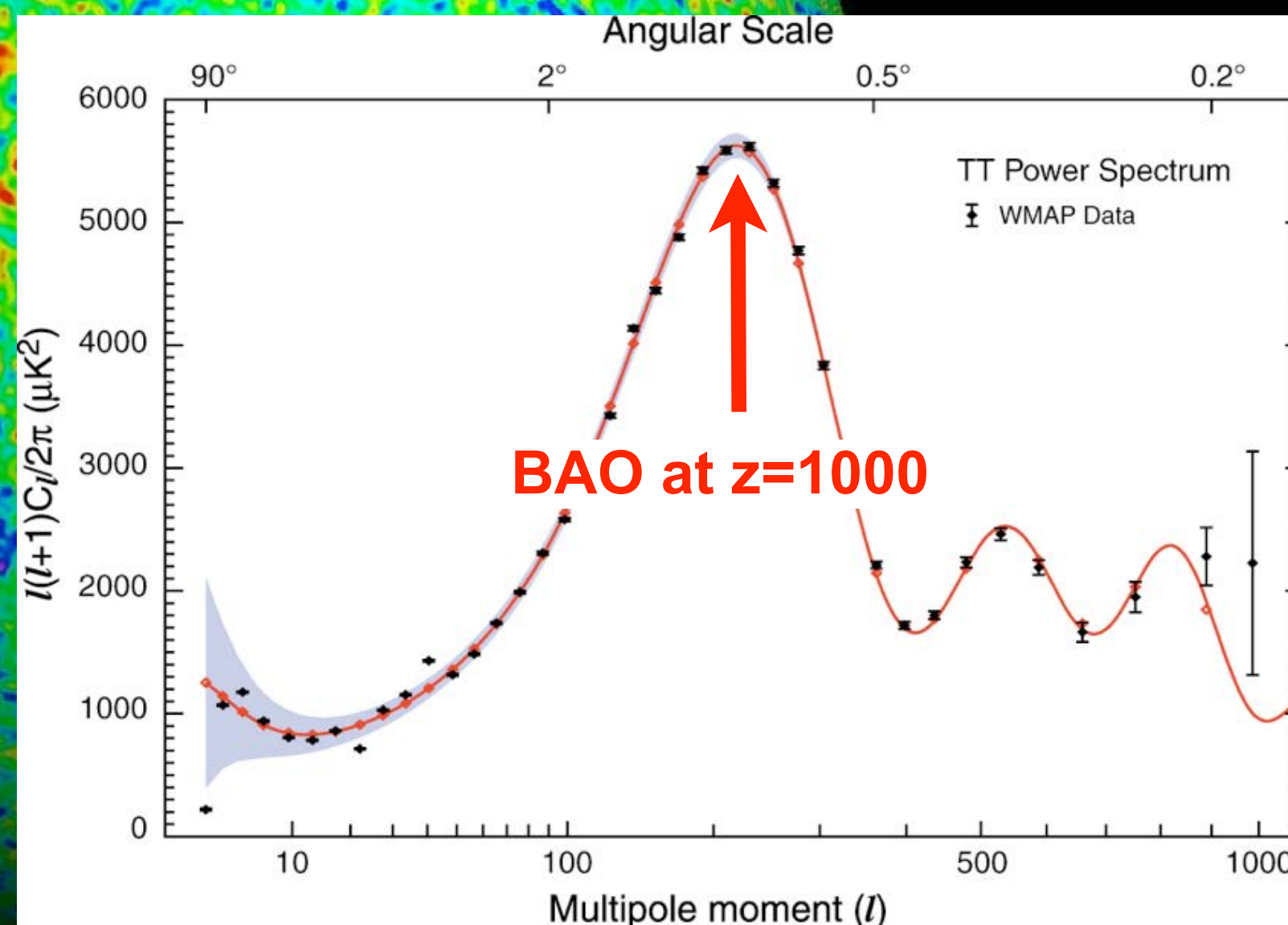
Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

BAO imprinted in the microwave background at $z=1100$
... and forever more in galaxy maps

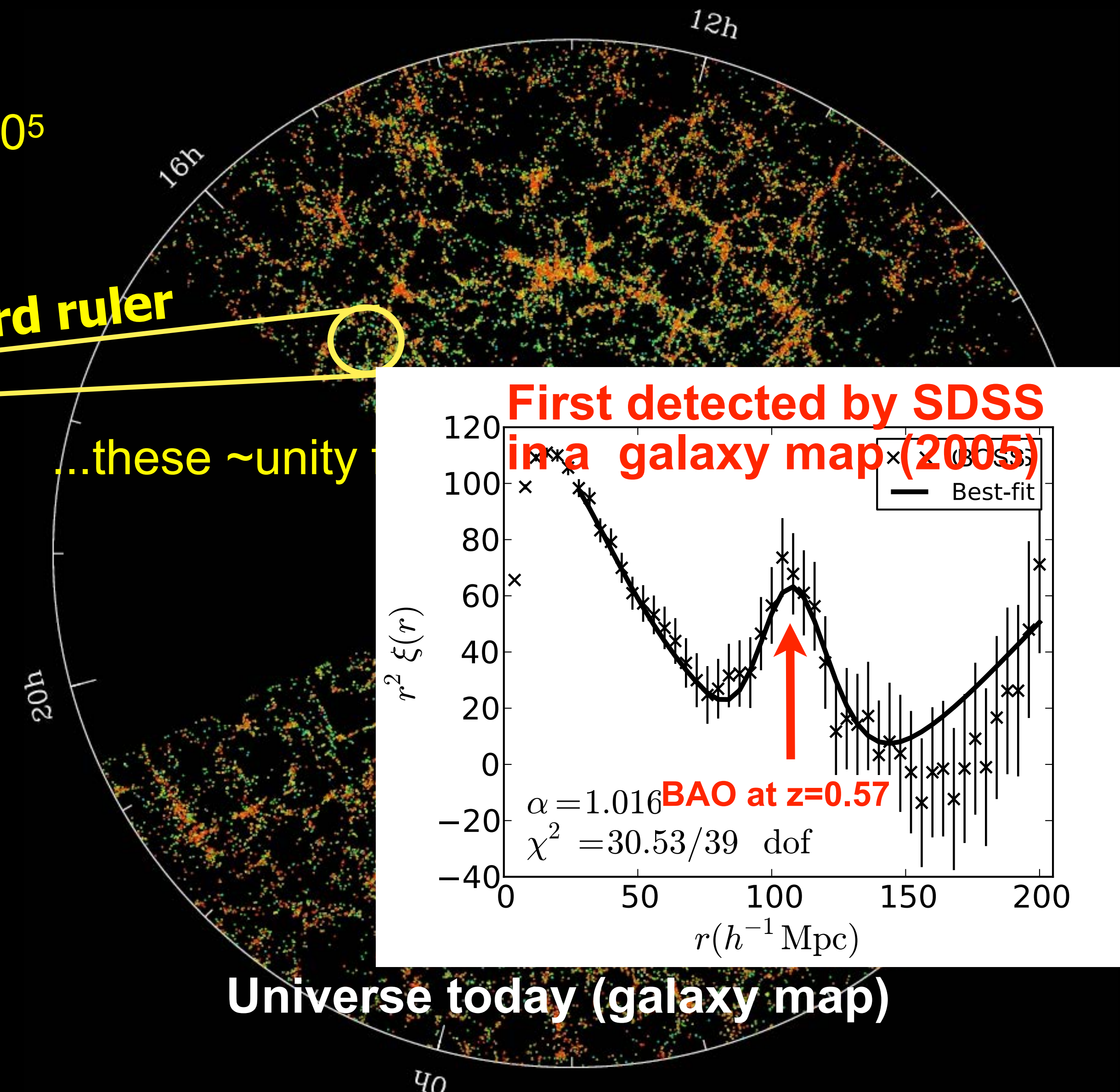
These fluctuations of 1 part in 10^5
gravitationally grow into...

standard ruler

...these ~unity



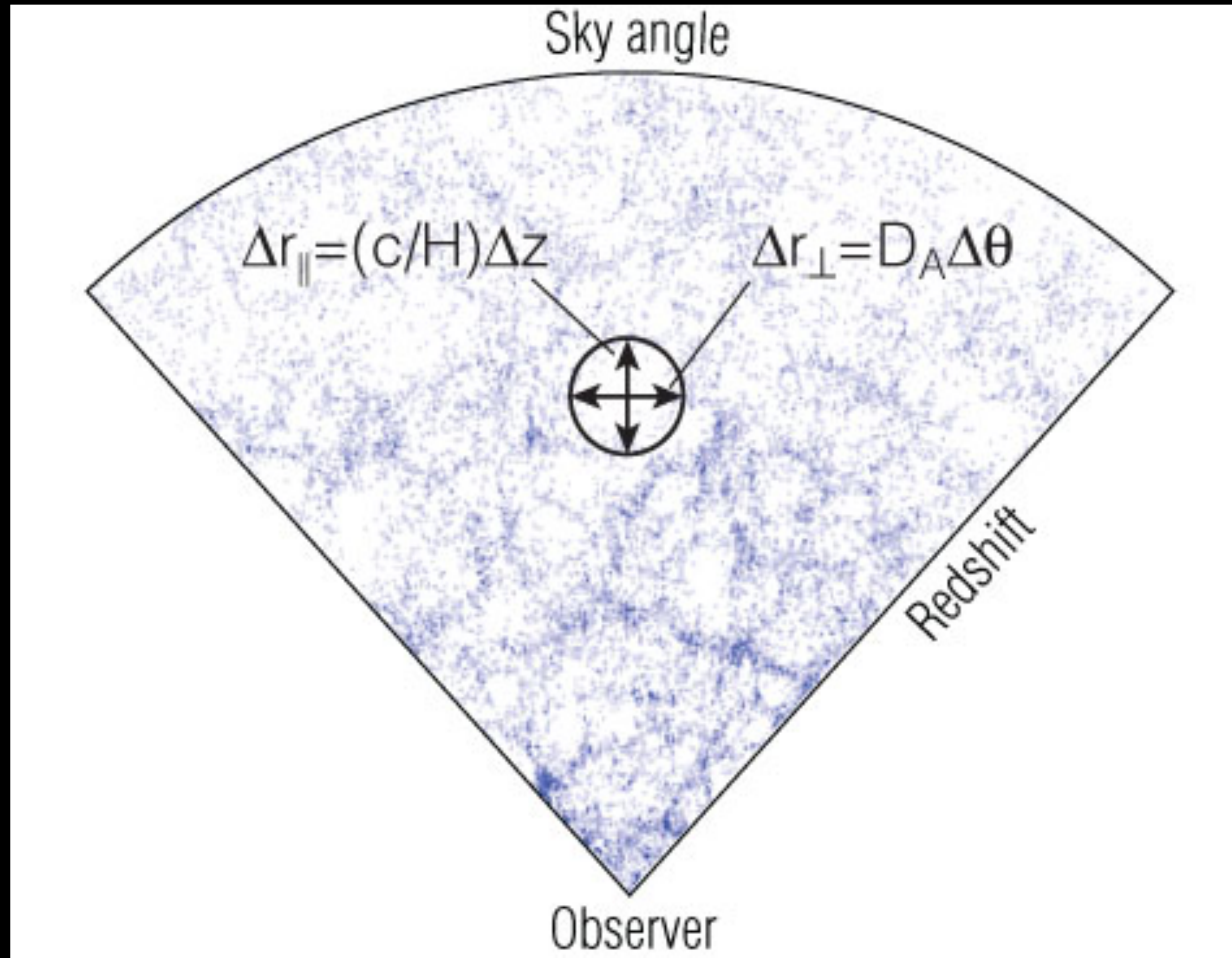
Universe at 380,000 years old (CMB)



Universe today (galaxy map)

Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

BAO imprinted in the microwave background at $z=1100$
... and forever more in galaxy maps



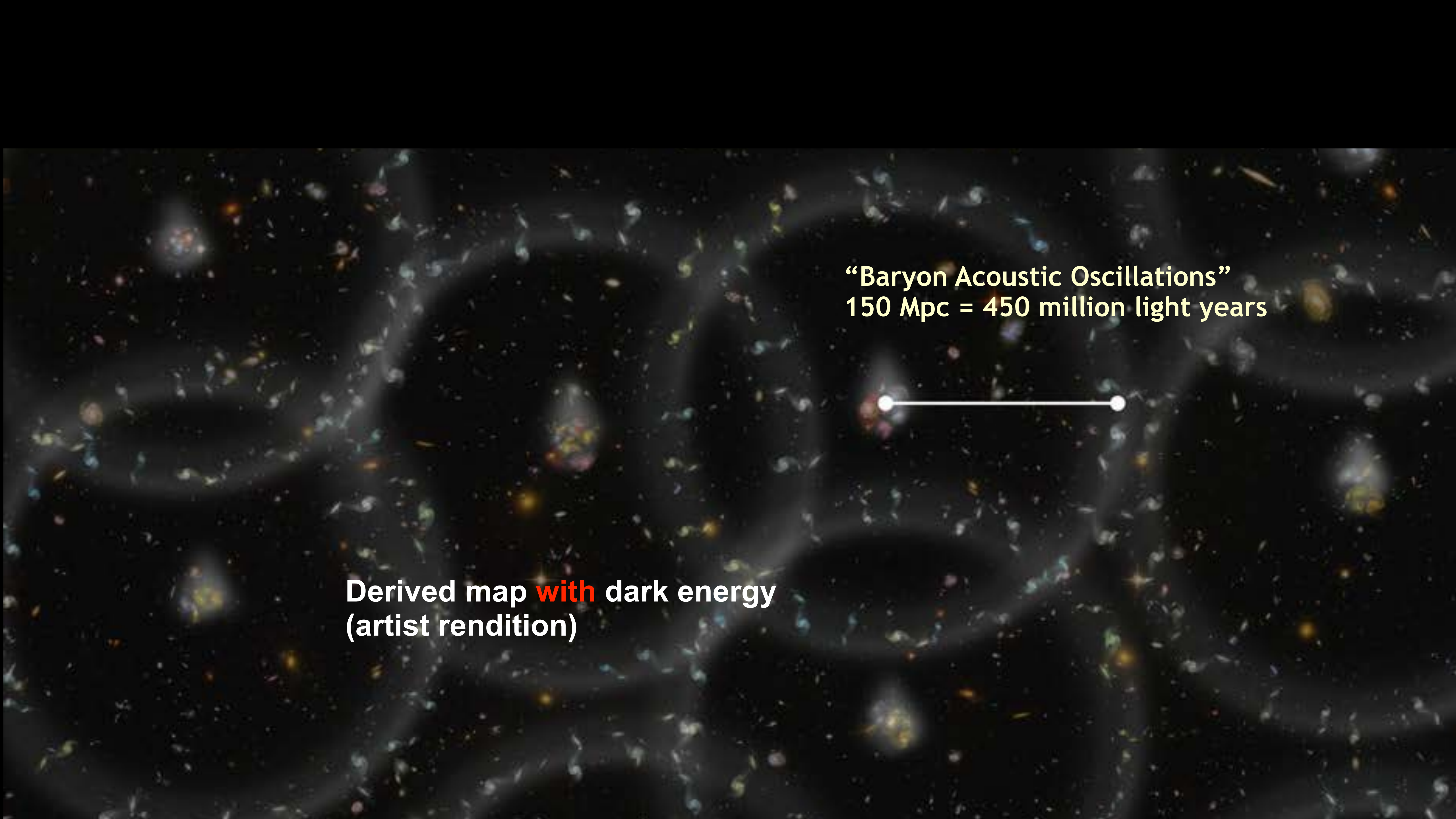
Galaxy maps give us two measures:
along the line of sight, $H(z)$,
+ perpendicular to the line-of-sight, $D_A(z)$

$$H(z) = \sqrt{\Omega_M(1+z)^3 + (1 - \Omega_M - \Omega_\Lambda)(1+z)^2 + \Omega_\Lambda}, \quad (2.4)$$

$$d_A(z) = \begin{cases} (-K)^{-1/2} \sinh[(-K)^{1/2}\chi(z)] & K < 0, \\ \chi(z) & K = 0, \\ K^{-1/2} \sin[K^{1/2}\chi(z)] & K > 0, \end{cases} \quad (2.5)$$

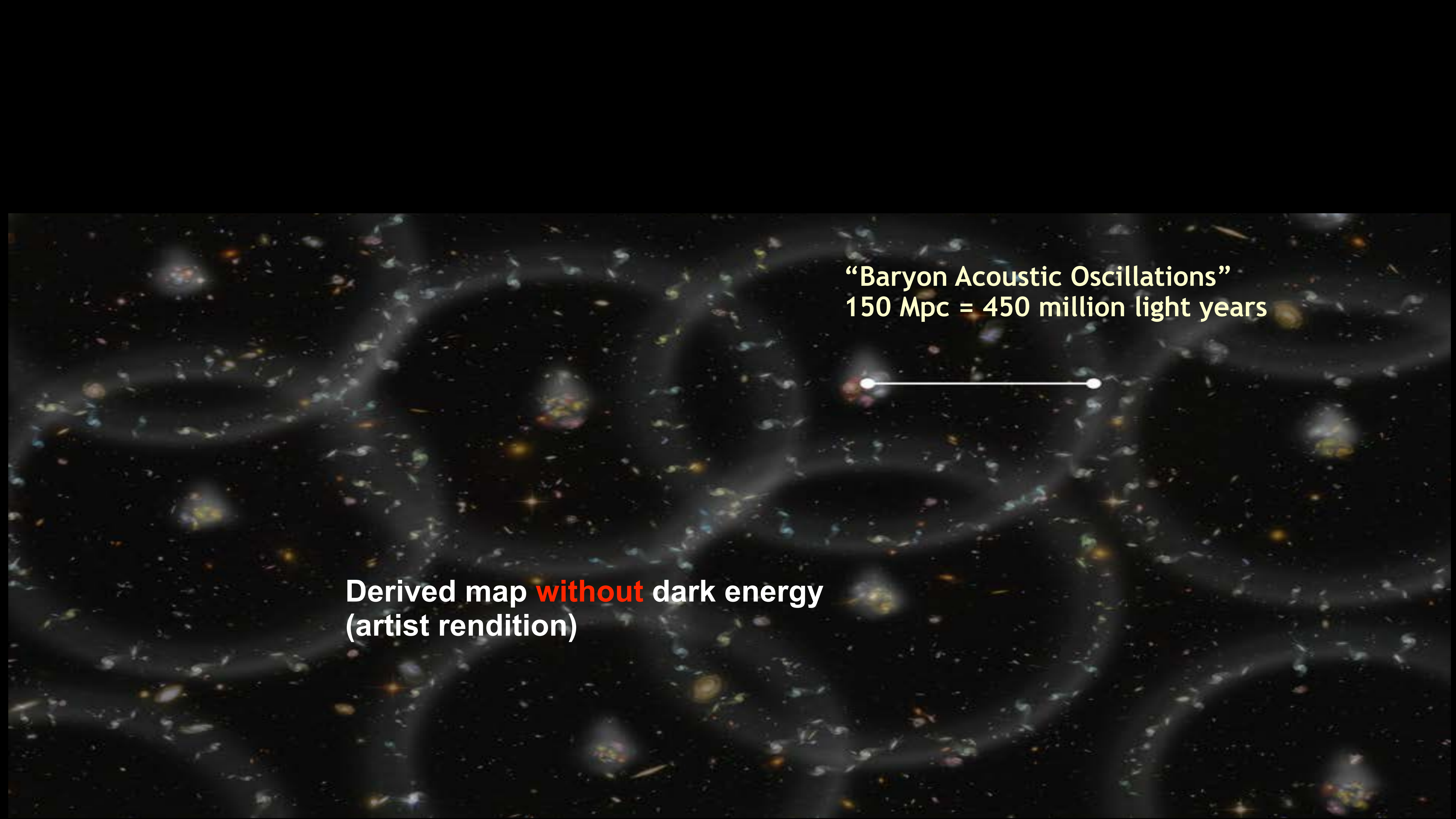
where

$$K = 1 - \Omega_M - \Omega_\Lambda, \quad \chi(z) = \int_0^z \frac{dz'}{H(z')} \quad (2.6)$$



“Baryon Acoustic Oscillations”
150 Mpc = 450 million light years

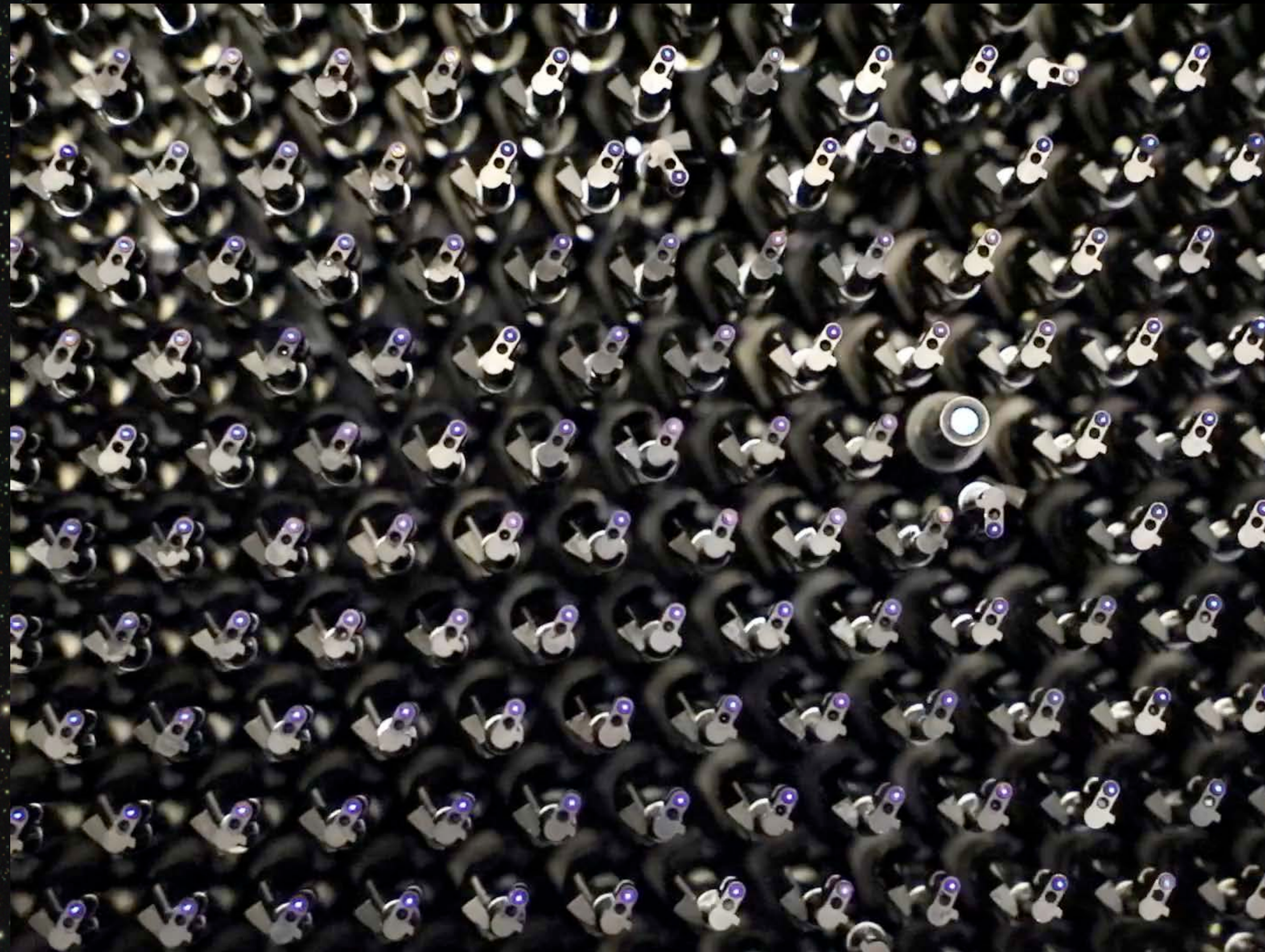
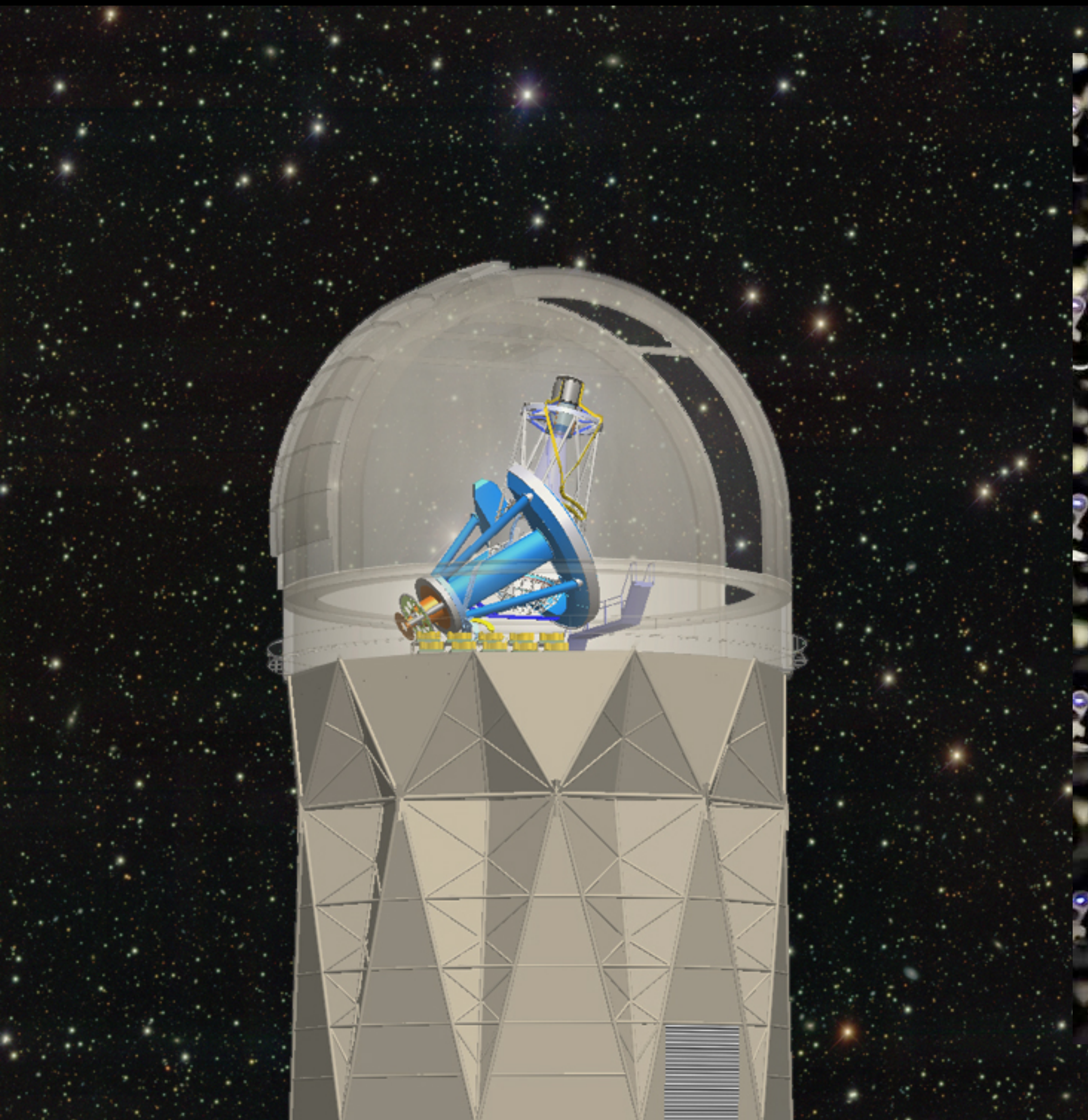
Derived map **with** dark energy
(artist rendition)

An artist's rendition of the universe showing large-scale structures. Concentric, semi-transparent, light-gray spherical shells are centered on a point in the upper right, representing the expansion of sound waves from the Big Bang. The background is a dense field of galaxies, depicted as small, colorful, multi-colored specks and clusters of light. The overall color palette is dark, with the galaxies providing points of light in various colors like yellow, orange, blue, and purple.

“Baryon Acoustic Oscillations”
150 Mpc = 450 million light years

Derived map **without** dark energy
(artist rendition)

Dark Energy Spectroscopic Instrument (DESI), 2021-2028 multiplexed with 5000 optical fibers on a robotic focal plane



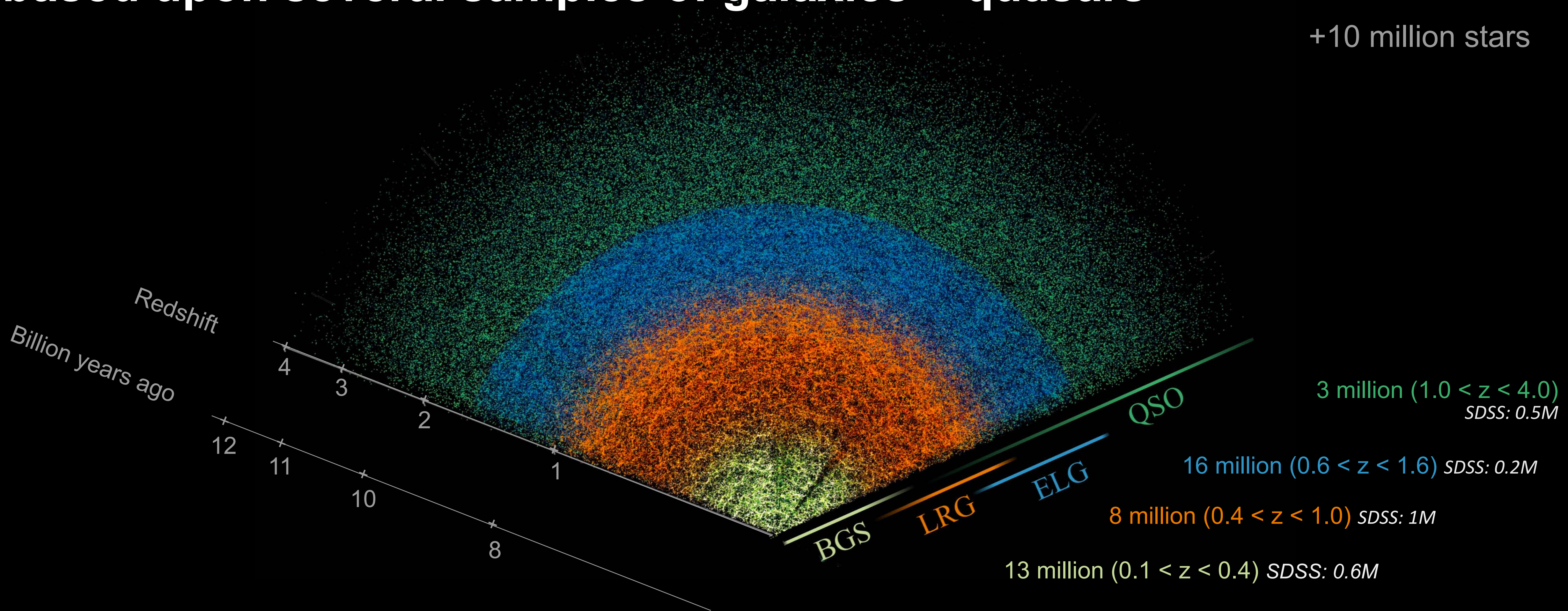
DESI — a much bigger map with 42 million galaxies... and counting...



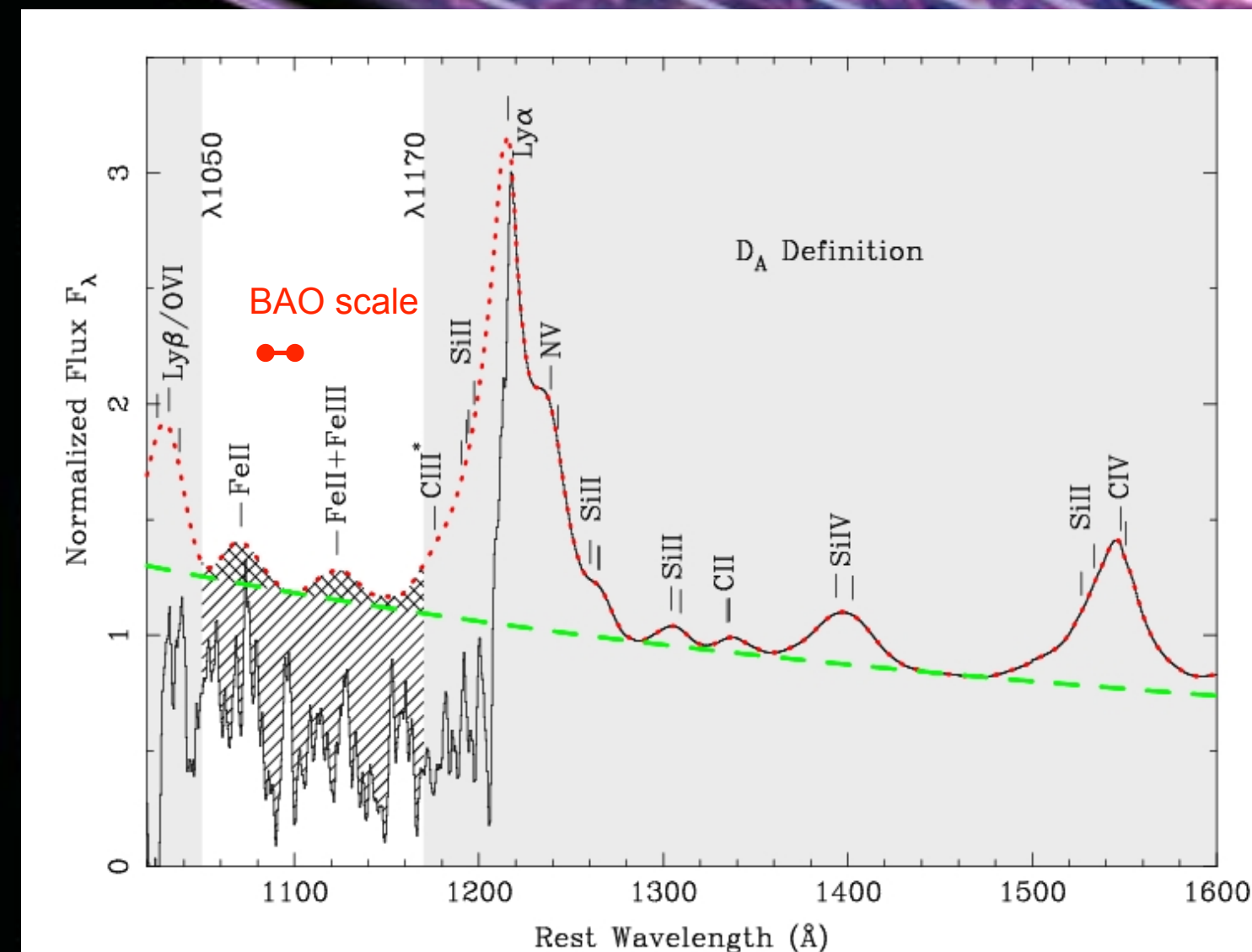
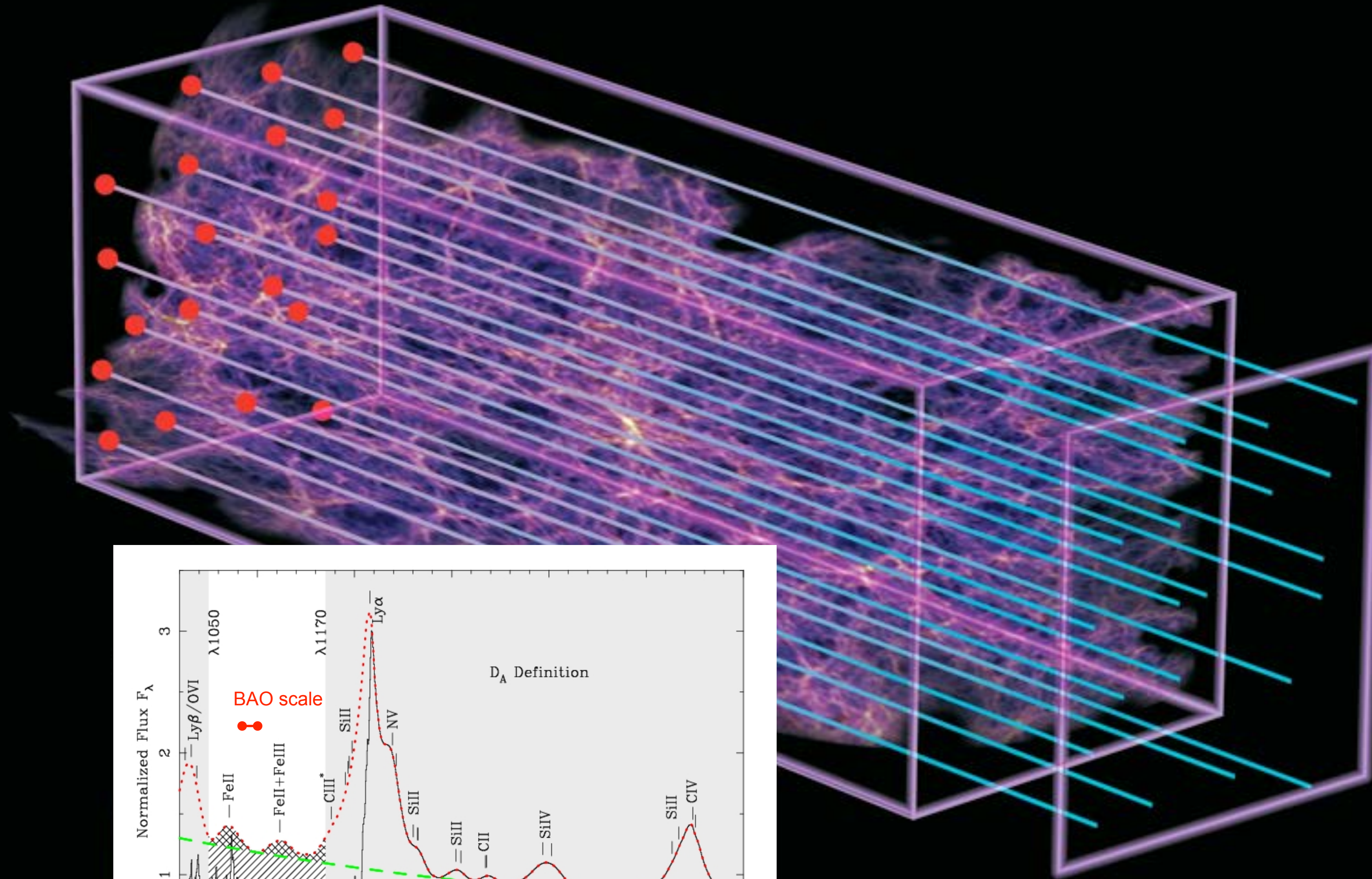
Credit: David Kirkby

DESI year 1 results published in April 2024,
DESI year 3 results published in March 2025,
based upon several samples of galaxies + quasars

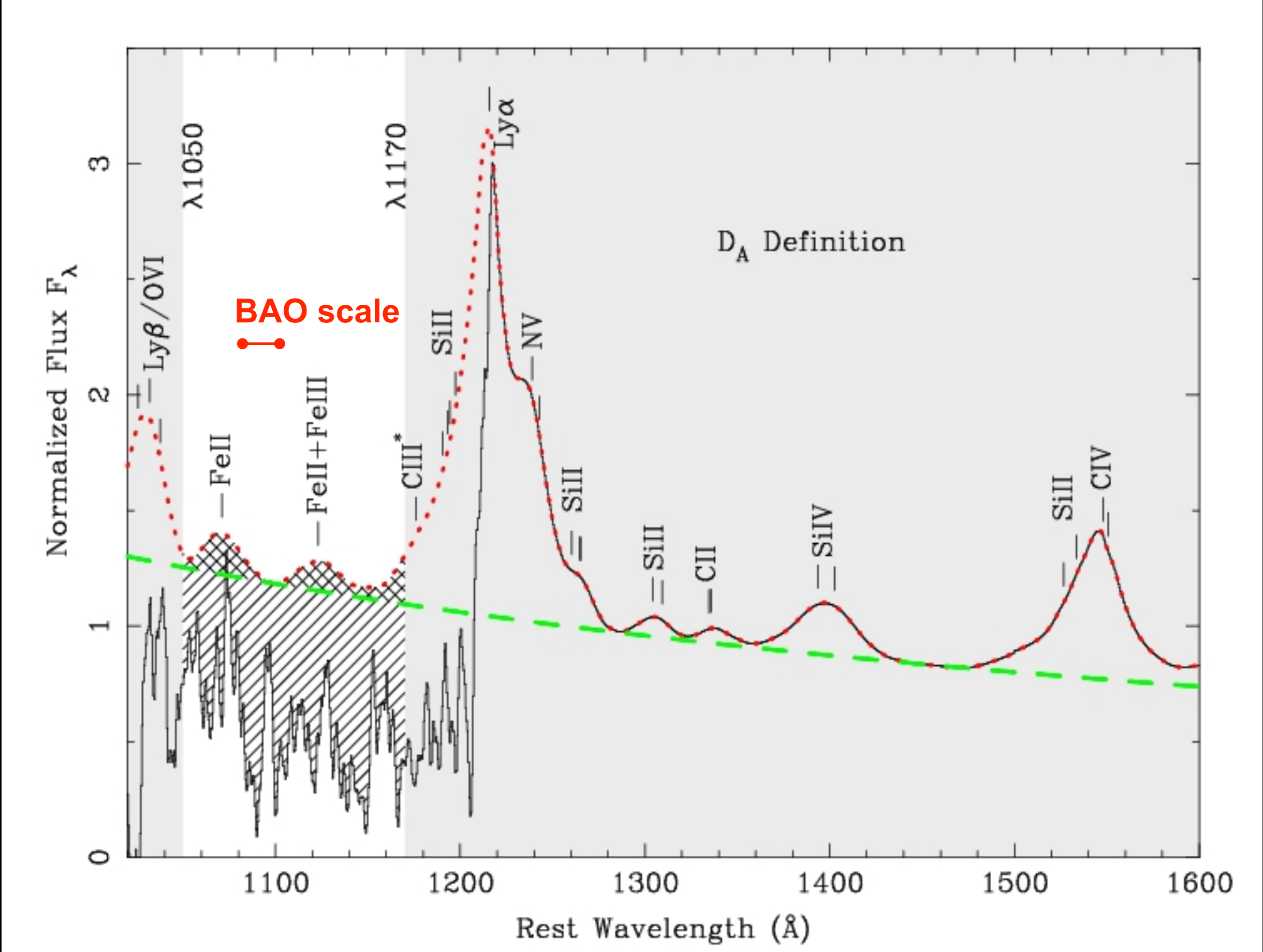
+10 million stars



Quasars at $z > 2.1$ used as a back-light for the Lyman-alpha forest



Quasars at $z > 2.1$ used as a back-light for the Lyman-alpha forest



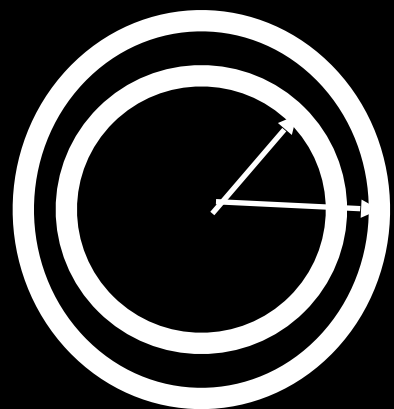
$$P_{\text{raw}}(\mathbf{k}) = \left[P_F(\mathbf{k}) + n^{-1} P_F^{1\text{D}}(k_{\parallel}) \right] W^2(k_{\parallel} R) + P_N^{\text{eff}}$$

Ideal 3D power (perfectly sampled) Sampling noise n =surface density of lines of sight (analogous to galaxy shot noise) Resolution Detector noise

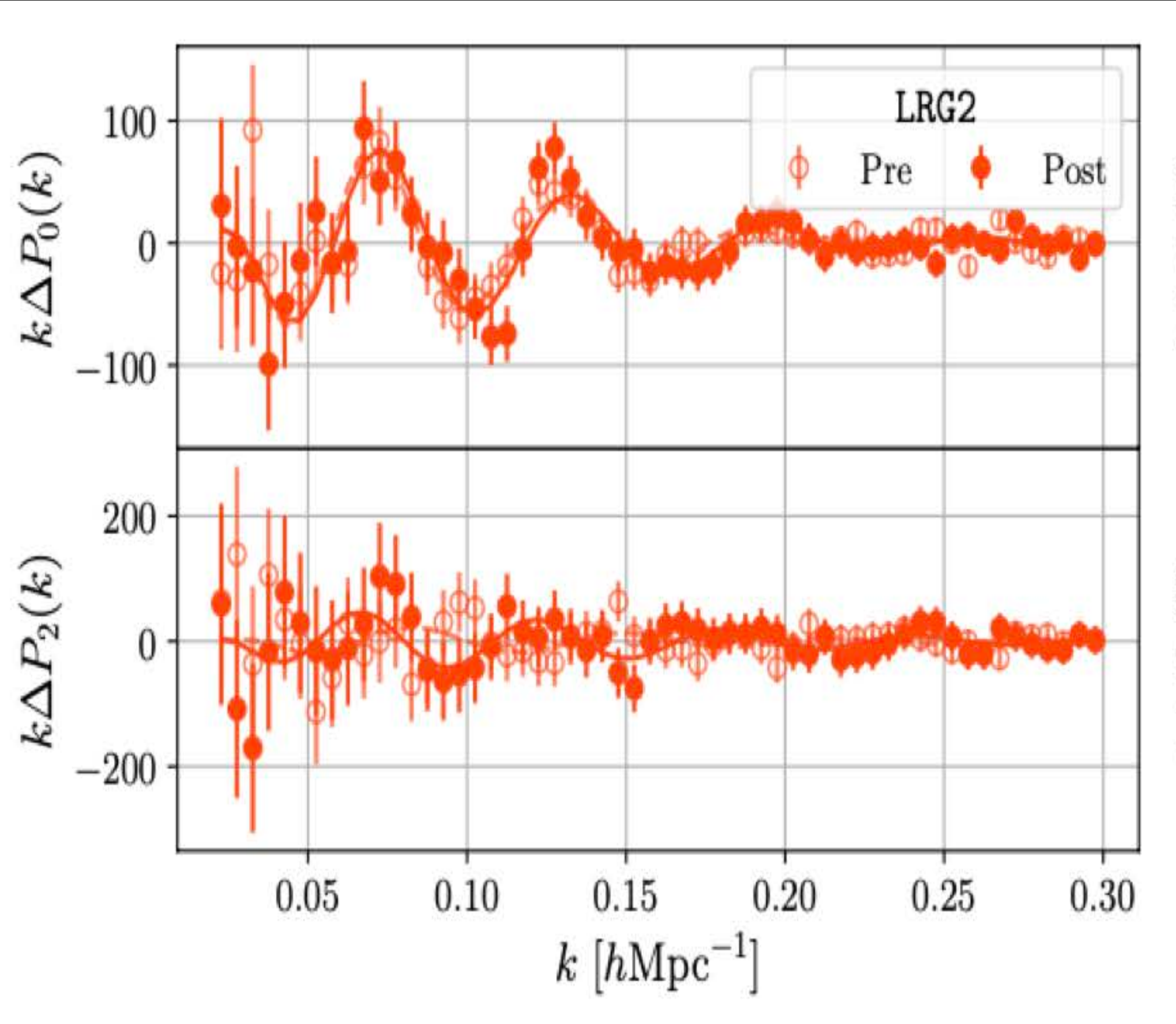
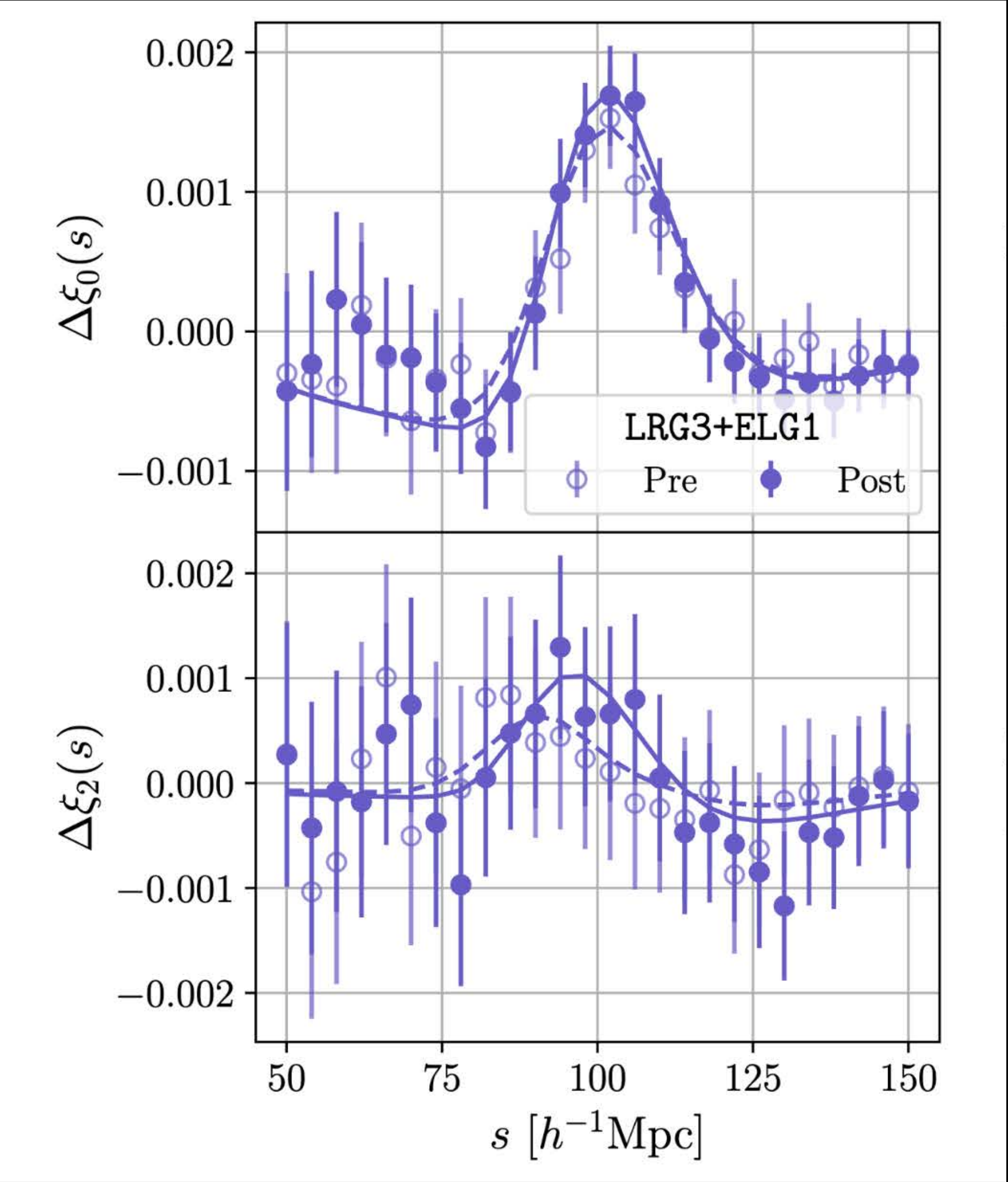
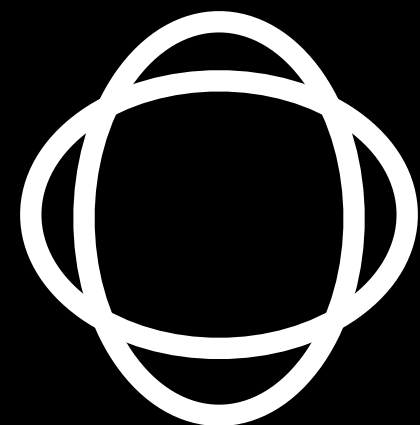
DESI analyses were all conducted blinded

BAO feature well-measured in 7 samples at 7 redshifts

Overall BAO size



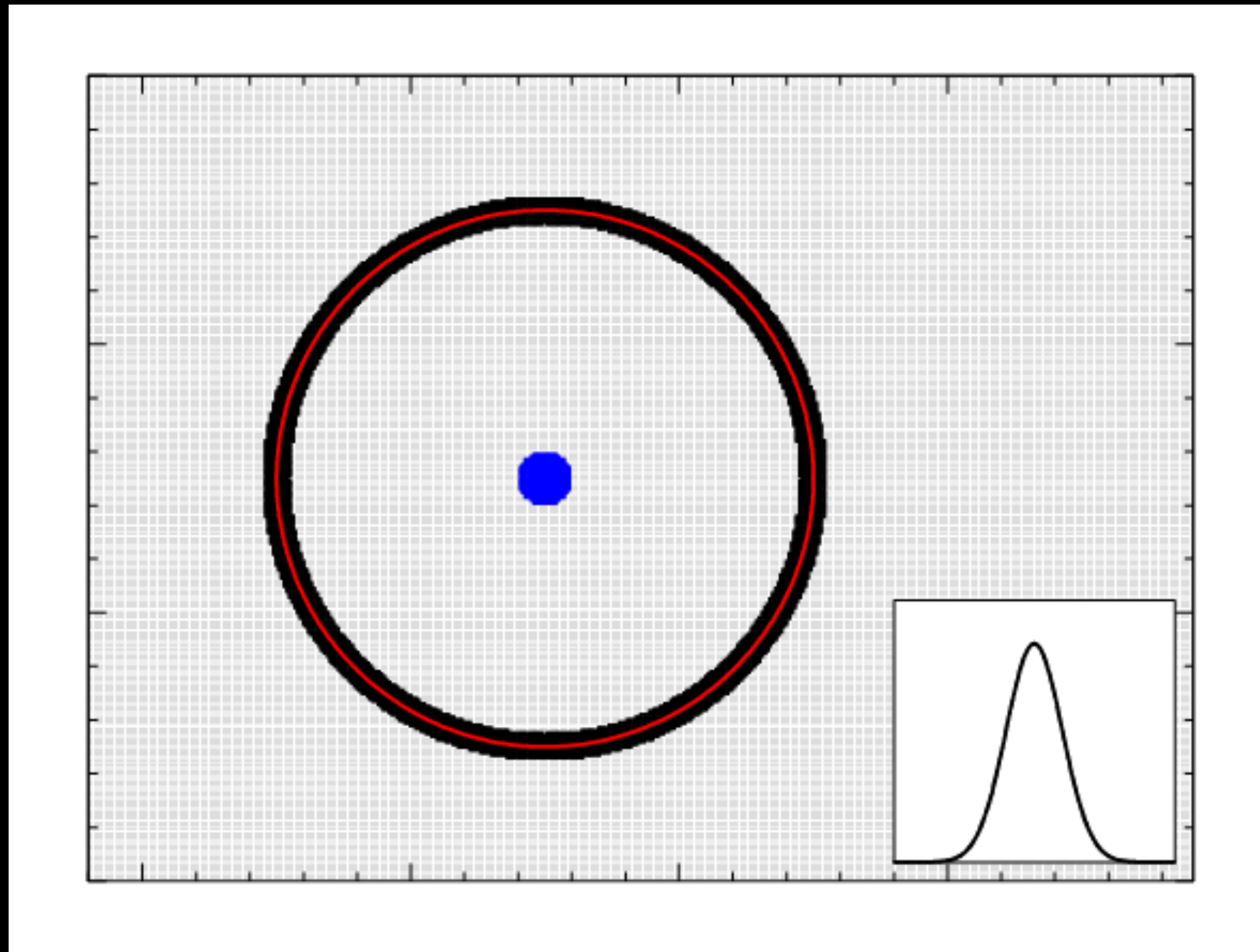
BAO anisotropy



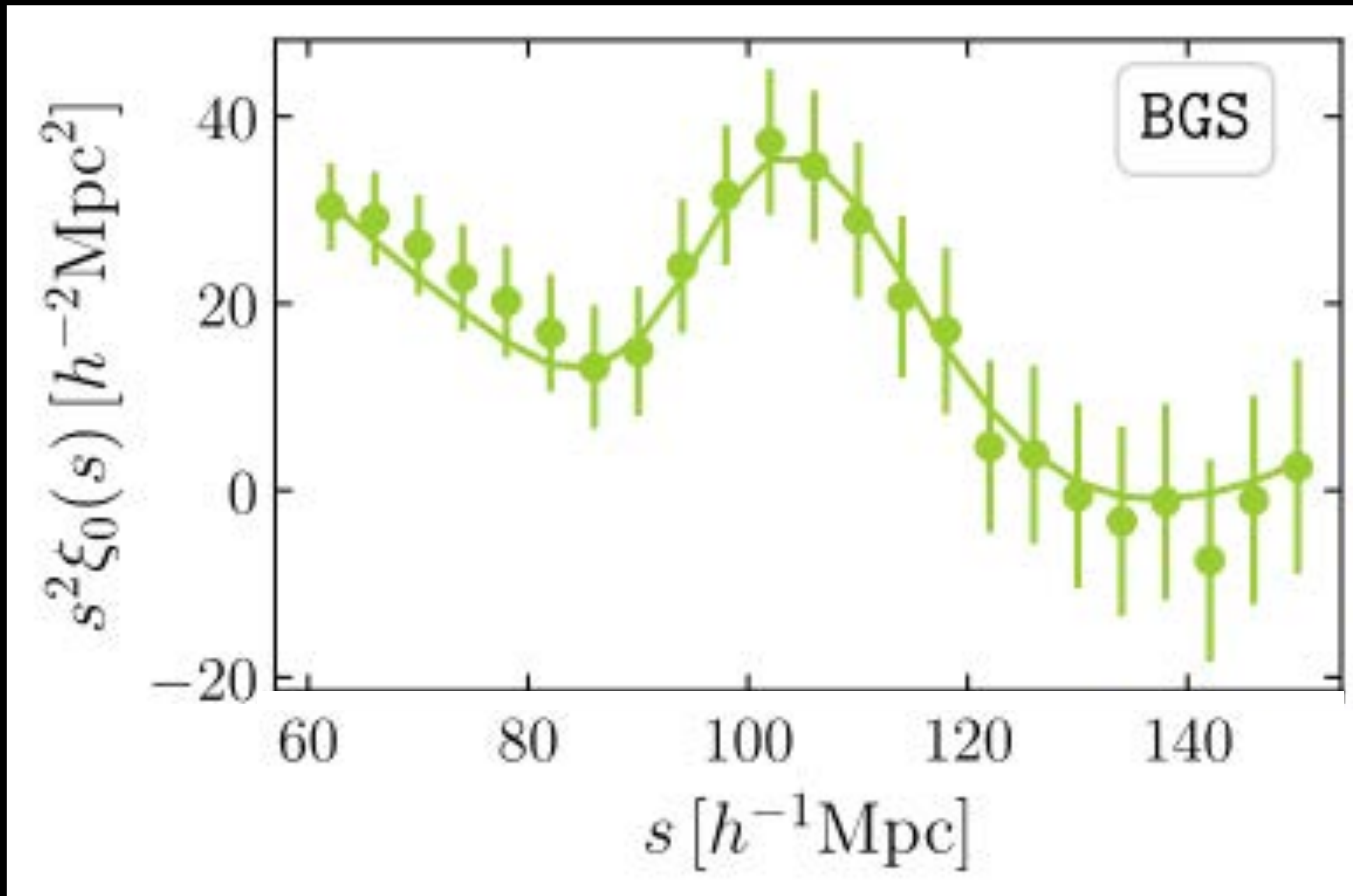
Fourier space

DESI analyses were all conducted blinded

Most of the maps underwent some “reconstruction”
to remove some of the non-linear gravitational growth

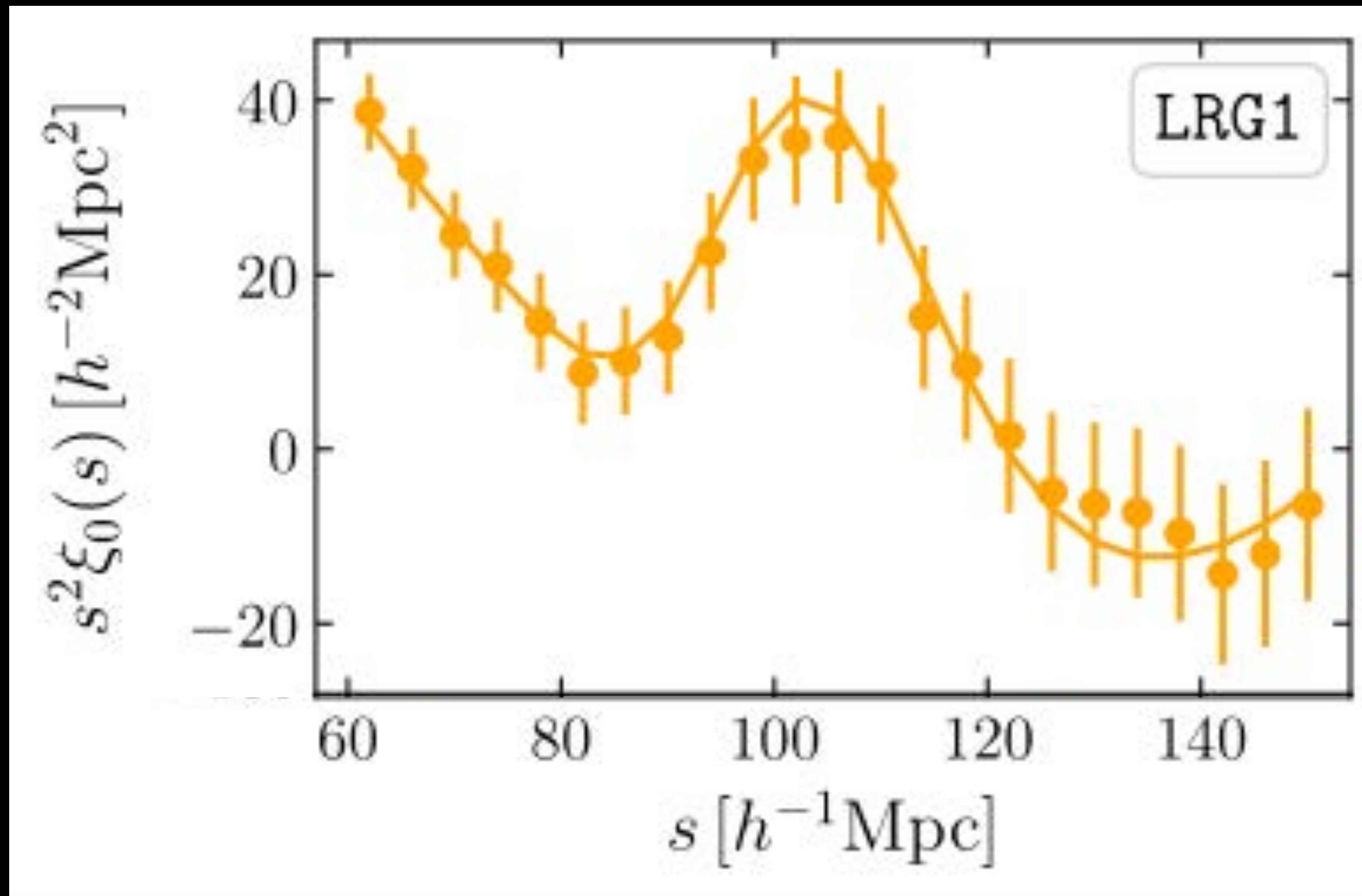


Bright Galaxy Sample, $z < 0.4$, 0.9% distance



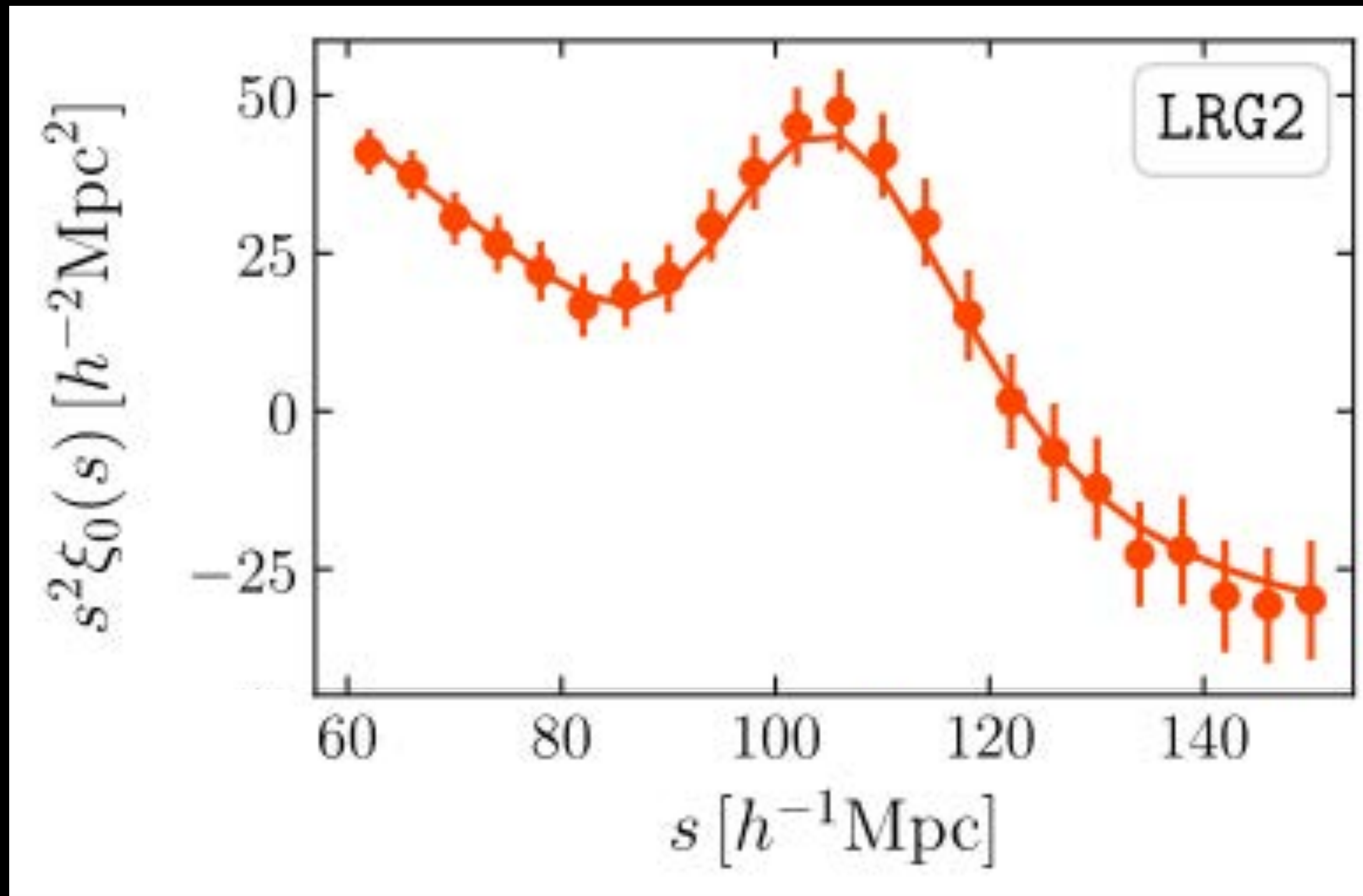
DESI Collaboration; arXiv:2503.14738

Luminous Red Galaxies, $0.4 < z < 0.6$, 0.8% distance



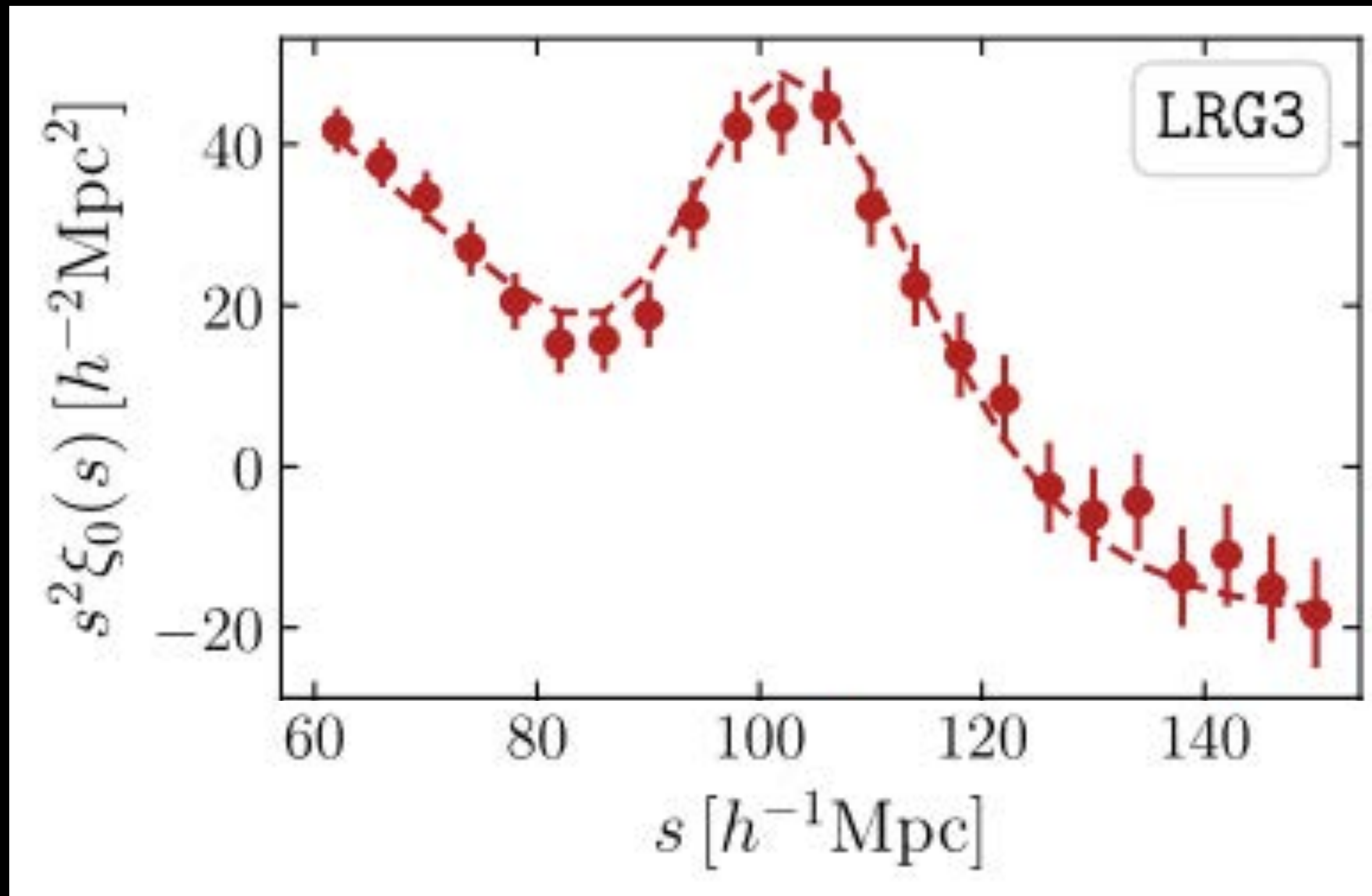
DESI Collaboration; arXiv:2503.14738

Luminous Red Galaxies, $0.6 < z < 0.8$, 0.7% distance



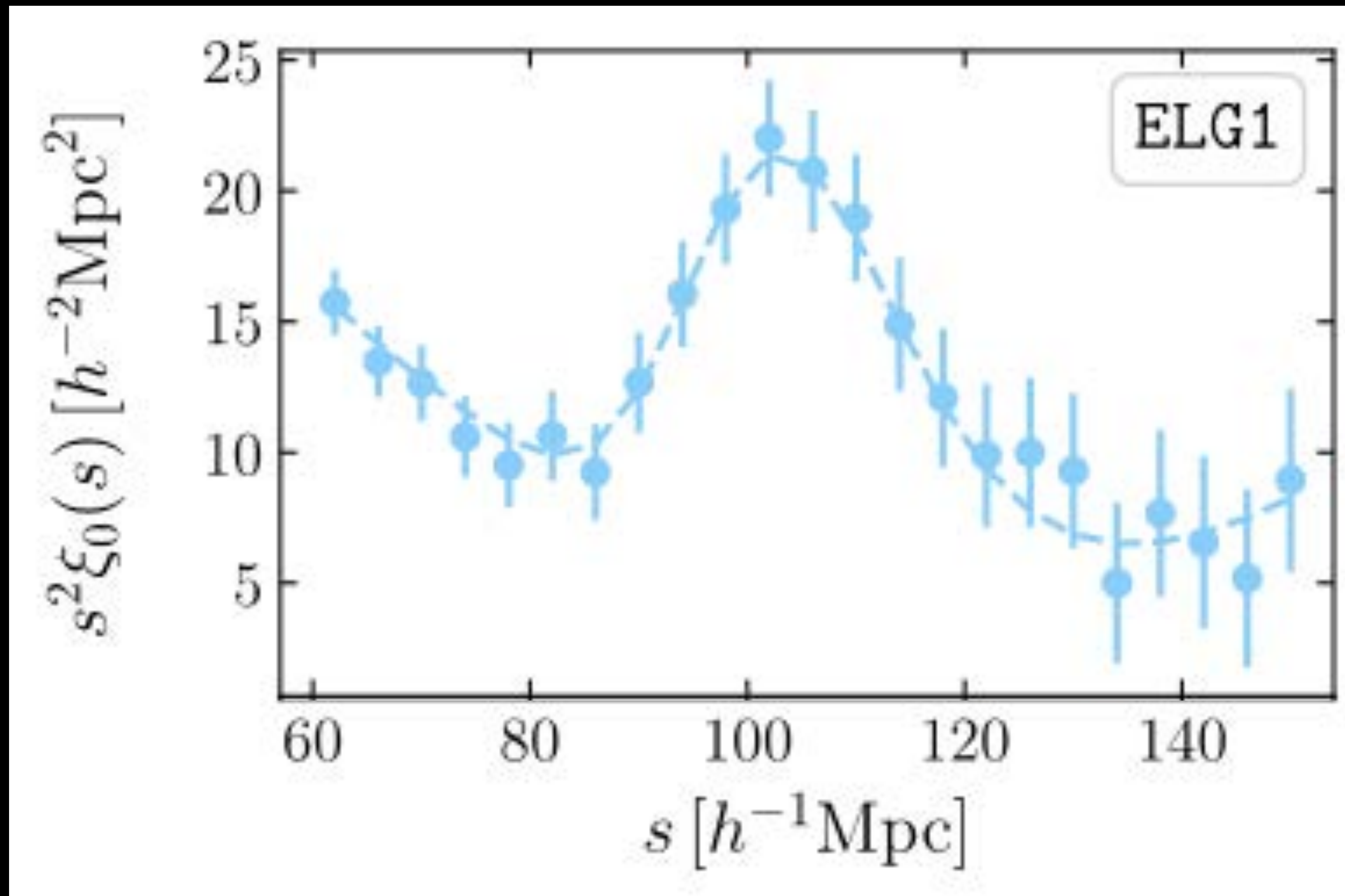
DESI Collaboration; arXiv:2503.14738

Luminous Red Galaxies, $0.8 < z < 1.1$, 0.5% distance



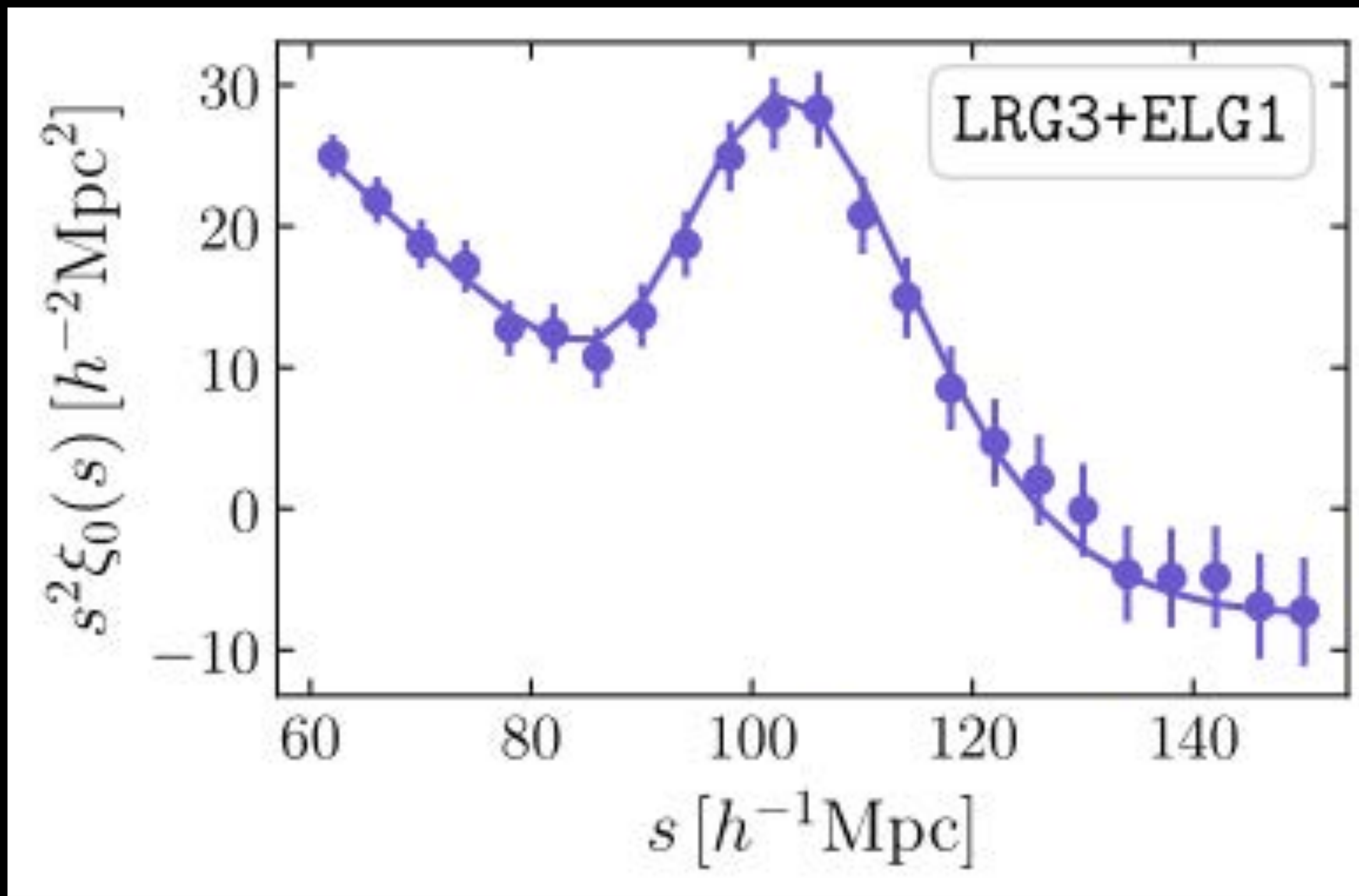
DESI Collaboration; arXiv:2503.14738

Emission Line Galaxies, $0.8 < z < 1.1$, 0.9% distance



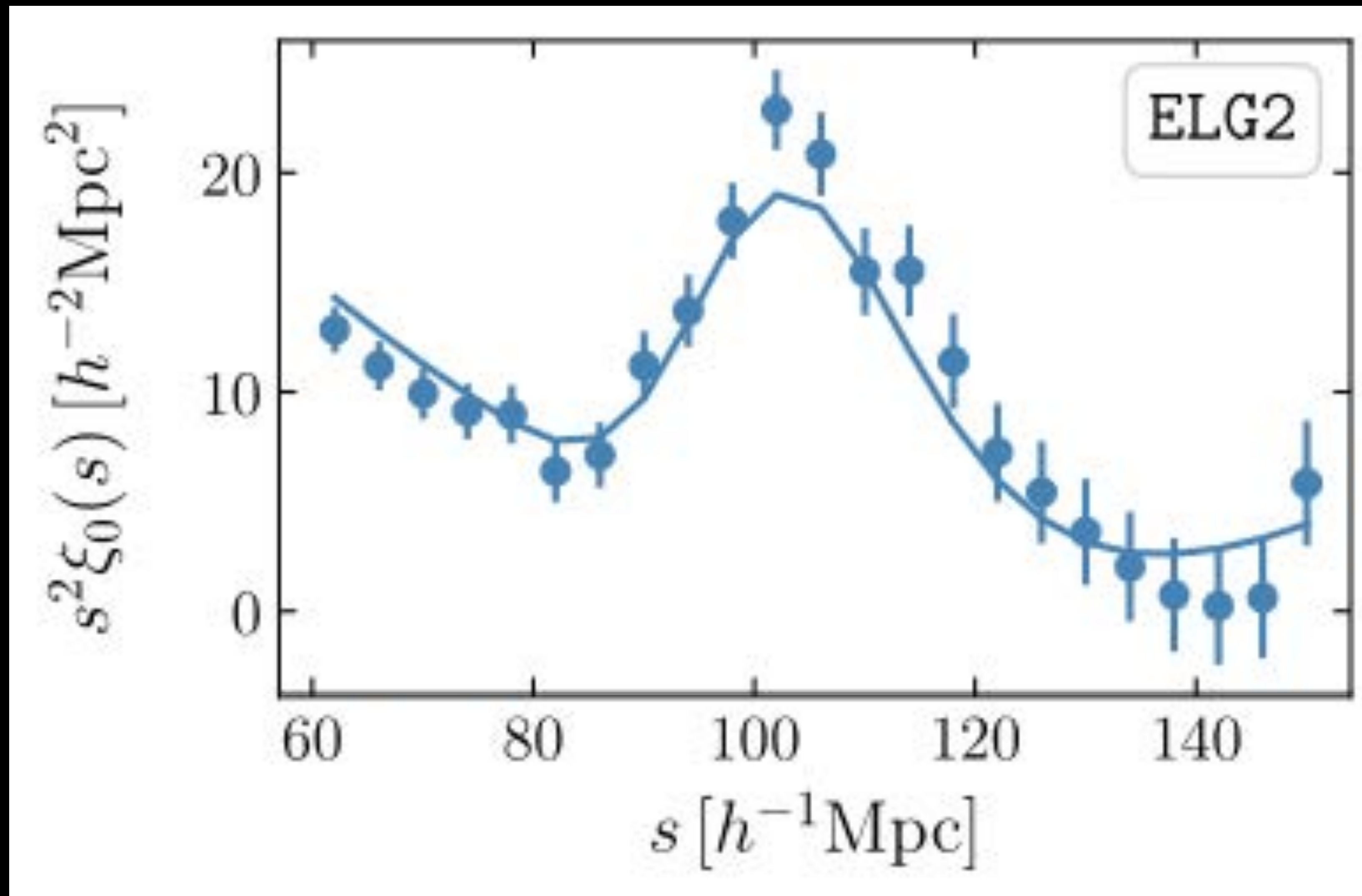
DESI Collaboration; arXiv:2503.14738

LRG3 + ELG1, $0.8 < z < 1.1$, 0.5% distance



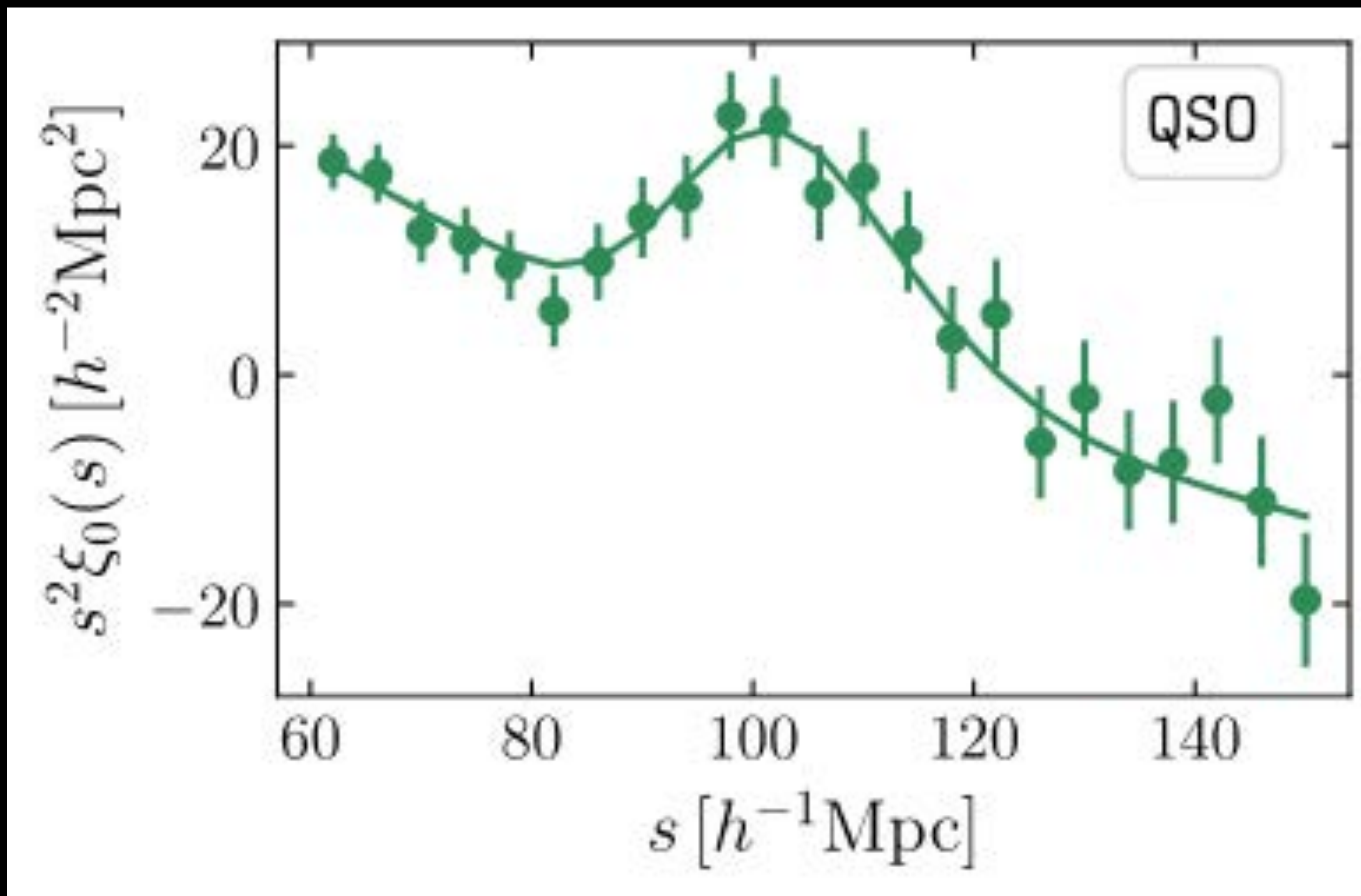
DESI Collaboration; arXiv:2503.14738

Emission Line Galaxies, $1.1 < z < 1.6$, 0.7% distance



DESI Collaboration; arXiv:2503.14738

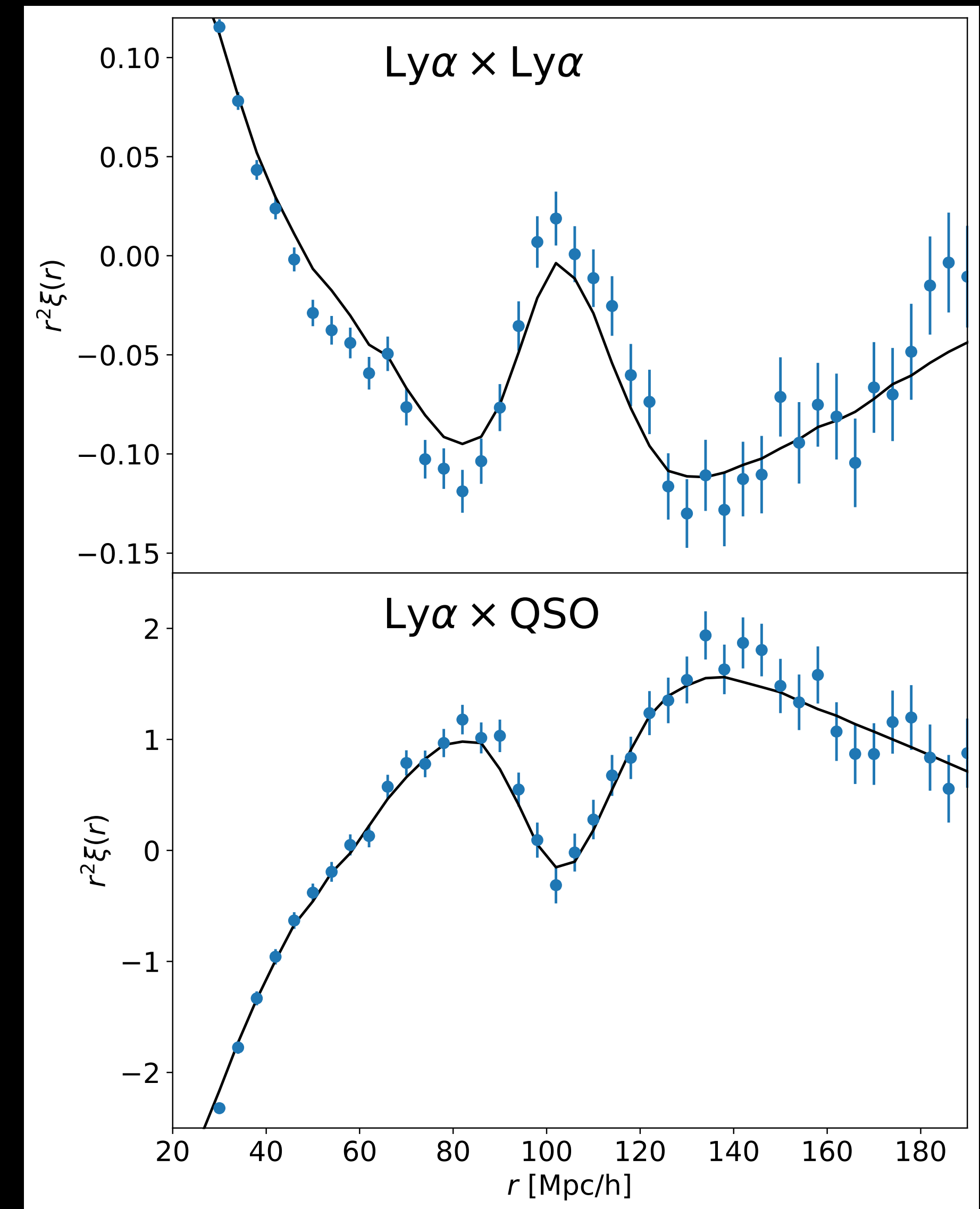
QSOs, $0.8 < z < 2.1$, 1.5% distance



DESI Collaboration; arXiv:2503.14738

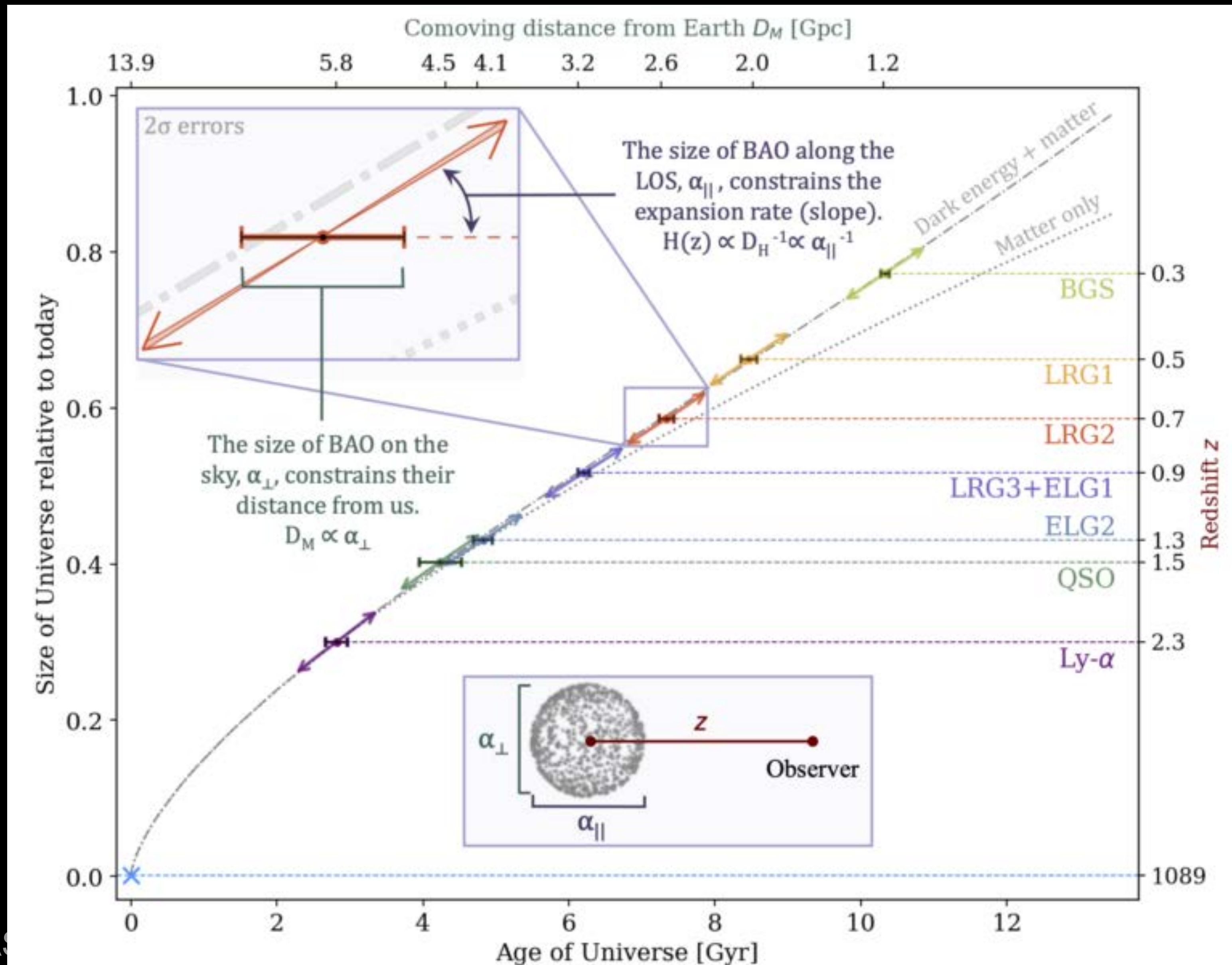
QSO Lyman-alpha forest, $z=2.3$, 0.65% distance

- Neutral hydrogen in the intergalactic medium leaves a distinctive signature in the spectrum of quasars
- Measure the density along the line of sight to each quasar, producing a 3-d map of neutral gas
- BAO peak 1.1% precision along LOS
- BAO peak 1.3% precision perpendicular

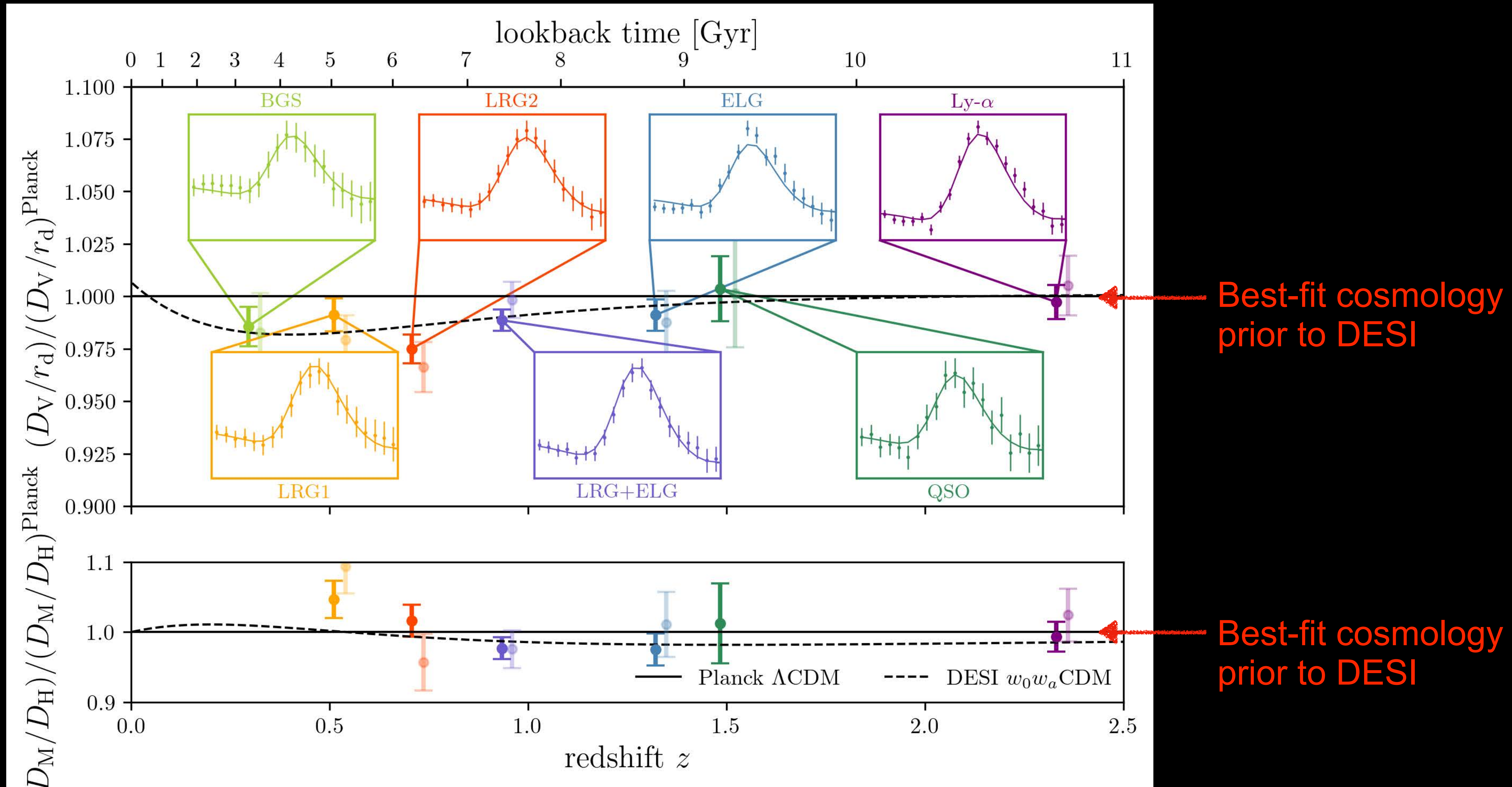


DESI Collaboration; arXiv:2503.14739

DESI gives a very precise history of the scale of the universe



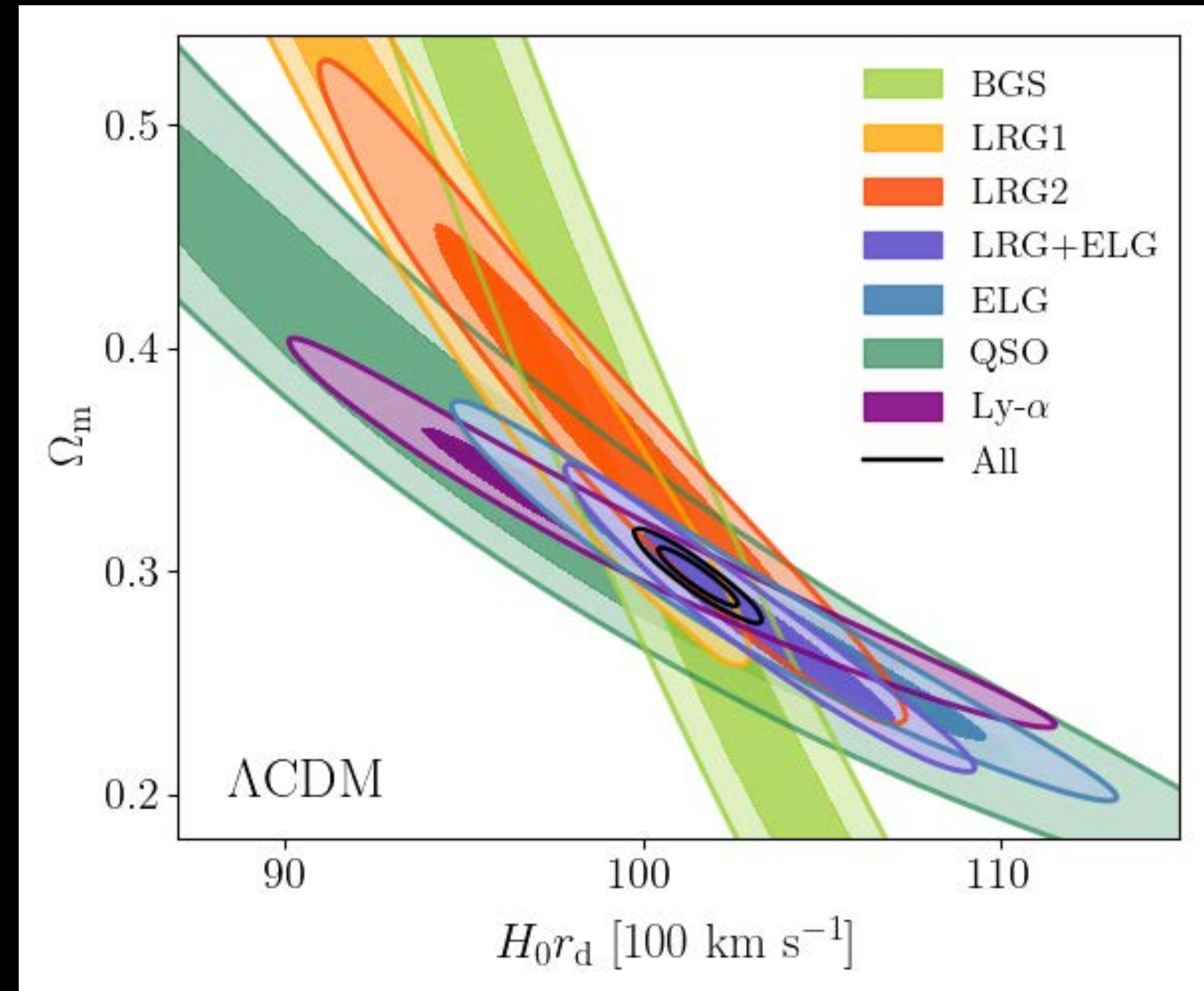
DESI DR2 results: Aggregate precision on BAO scale 0.3%



Interpretation in context of Lambda-CDM (Λ CDM) model

DESI galaxies at different redshifts are compatible and complementary

- Taking the acoustic scale as uncalibrated, the measurement of the acoustic peak at $z=0$ would measure $H_0 r_d$
- Measuring at non-zero redshift gives some Ω_m dependence
- Contours are bounded because we measure D_A and H at each redshift



Interpretation in context of Lambda-CDM (Λ CDM) model

DESI galaxies at different redshifts are compatible and complementary

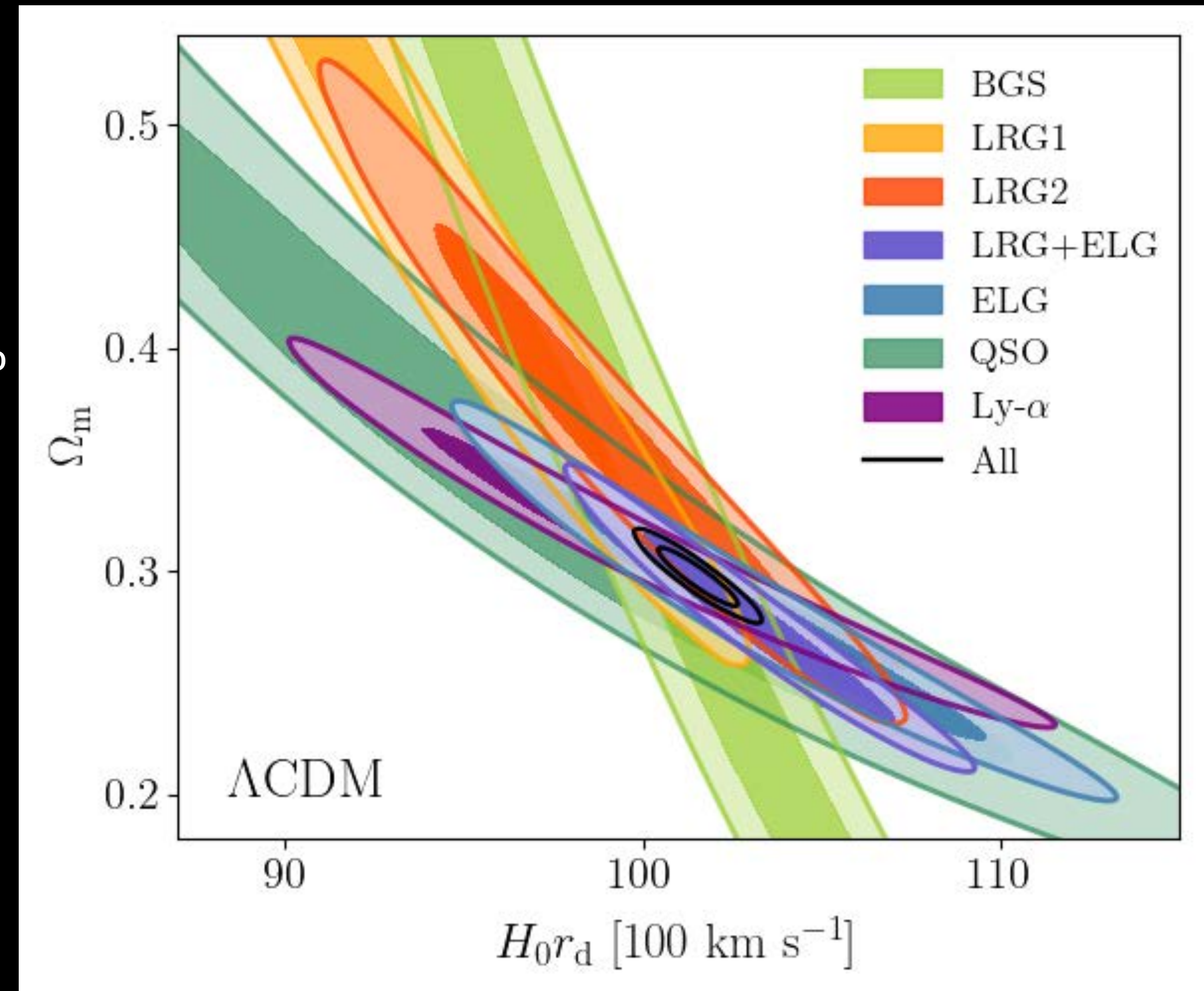
DESI BAO gives:

Matter density of the Universe measured to 2.9%

$$\Omega_m = 0.298 \pm 0.0086$$

Hubble constant X sound horizon measured to 0.7%

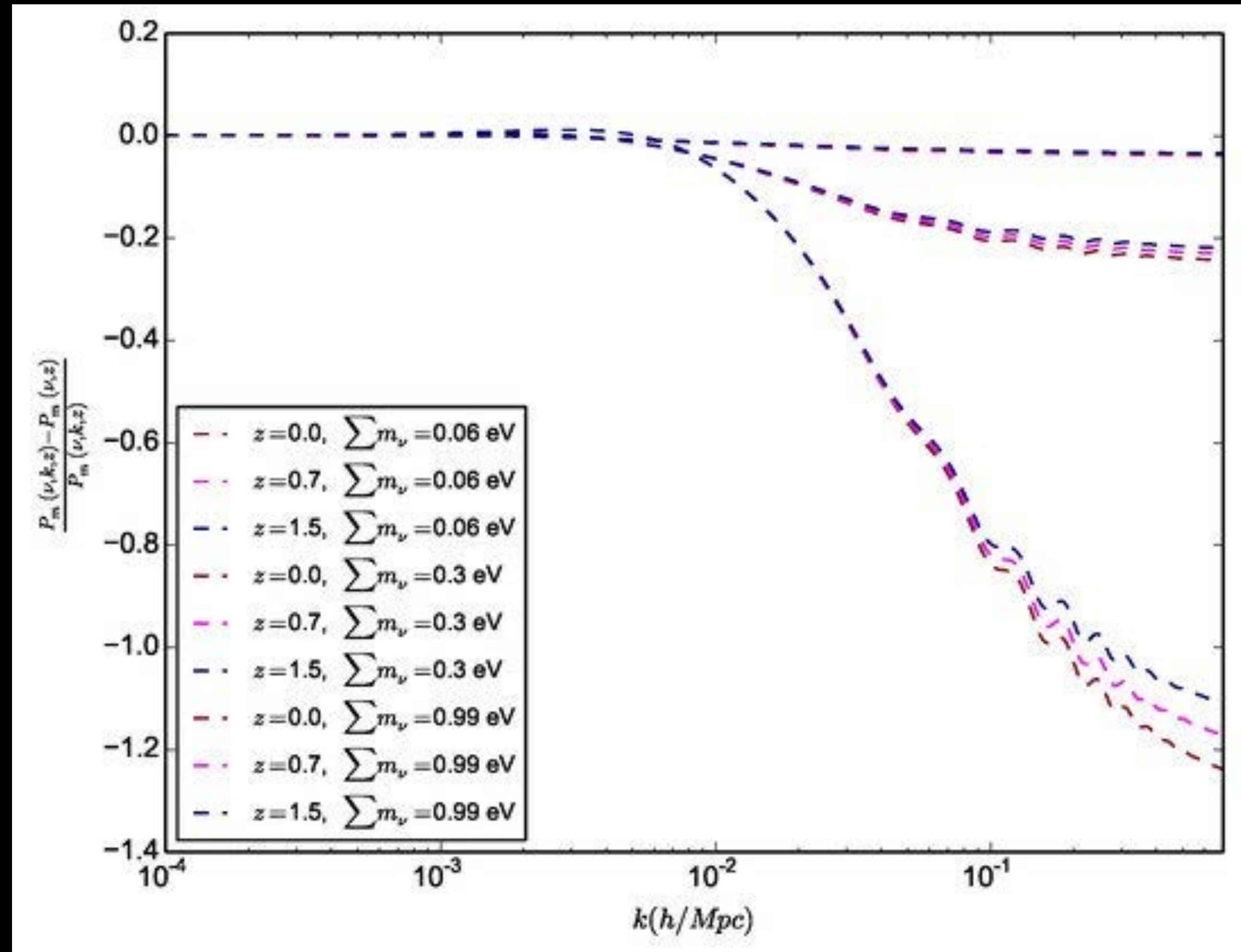
$$H_0 r_d = (101.54 \pm 0.73) [10^2 \text{ km s}^{-1}]$$



Constraints on neutrino mass in flat Λ CDM model

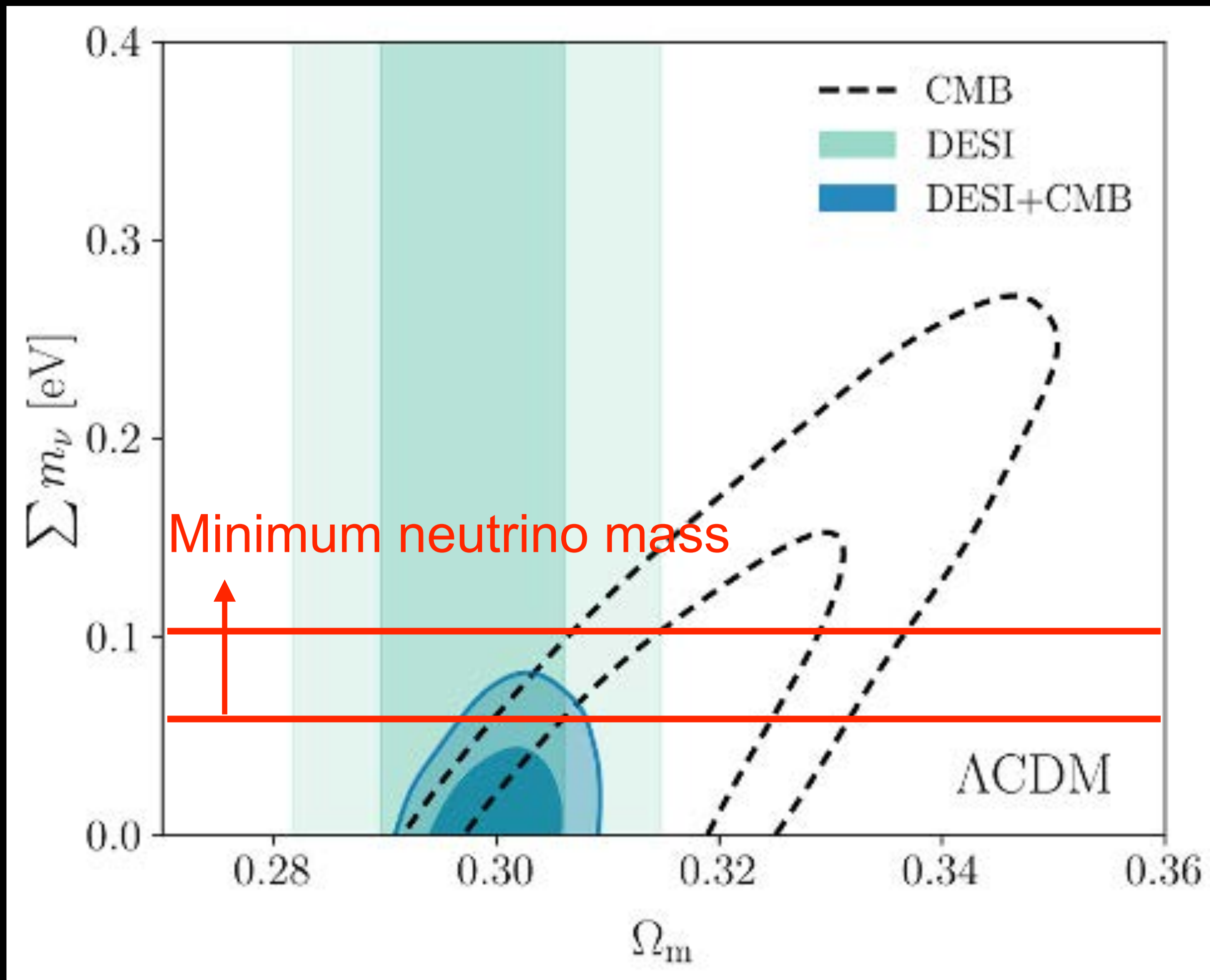
Neutrino mass both shifts the position of the last scattering surface (CMB peaks + BAO) and suppresses the growth of structure.

This analysis considers only the former...



Constraints on neutrino mass in flat Λ CDM model

DESI breaks parameter degeneracies in the CMB to further limit the sum of neutrino masses
... but those limits substantially relaxed if Dark Energy is dynamic



In Λ CDM model:

$$\Sigma m_\nu < 0.064 \text{ eV (95\%)}$$

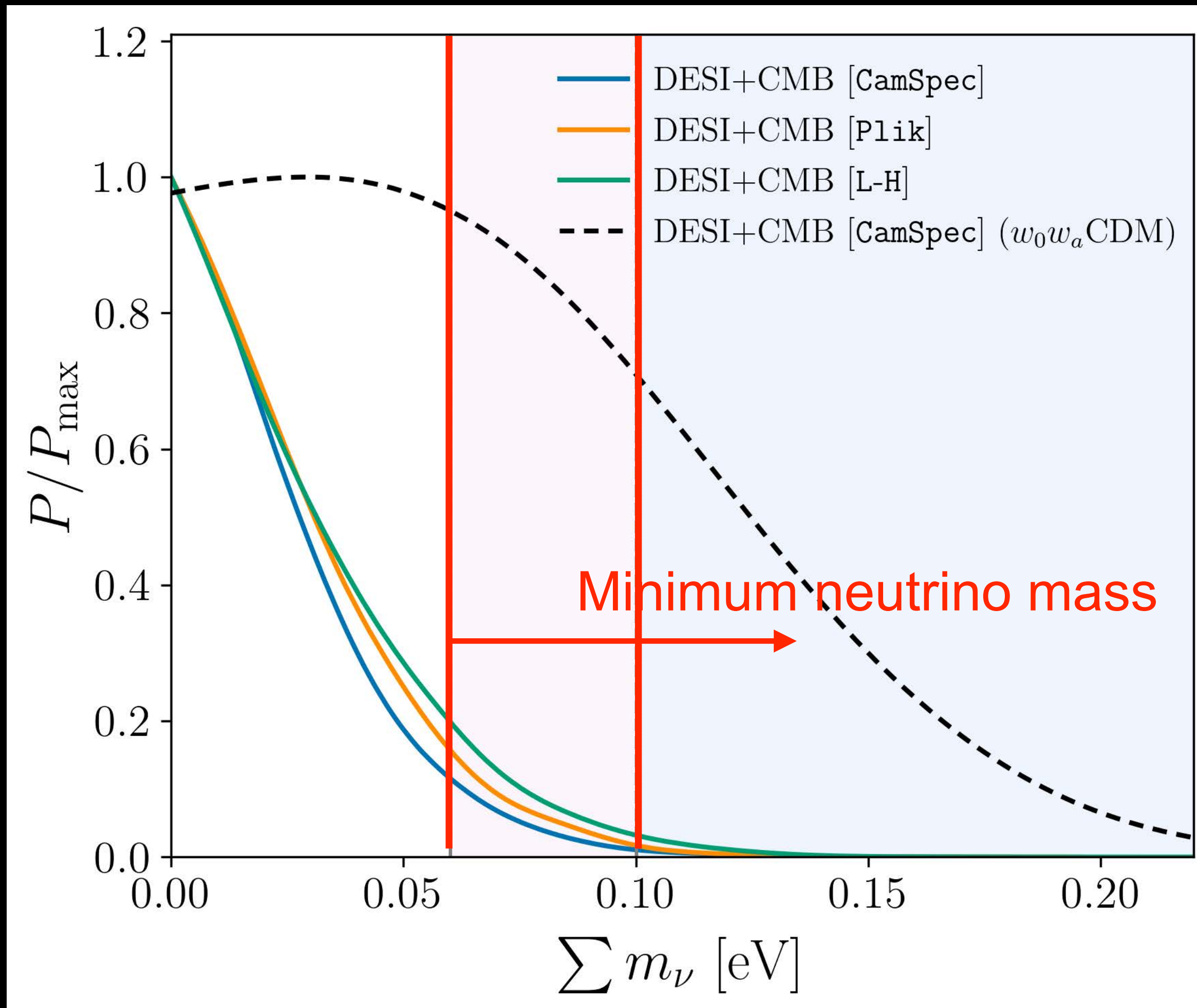
In w_0w_a CDM:

$$\Sigma m_\nu < 0.163 \text{ eV (95\%)}$$

Constraints are model and prior dependent

Constraints on neutrino mass in flat Λ CDM model

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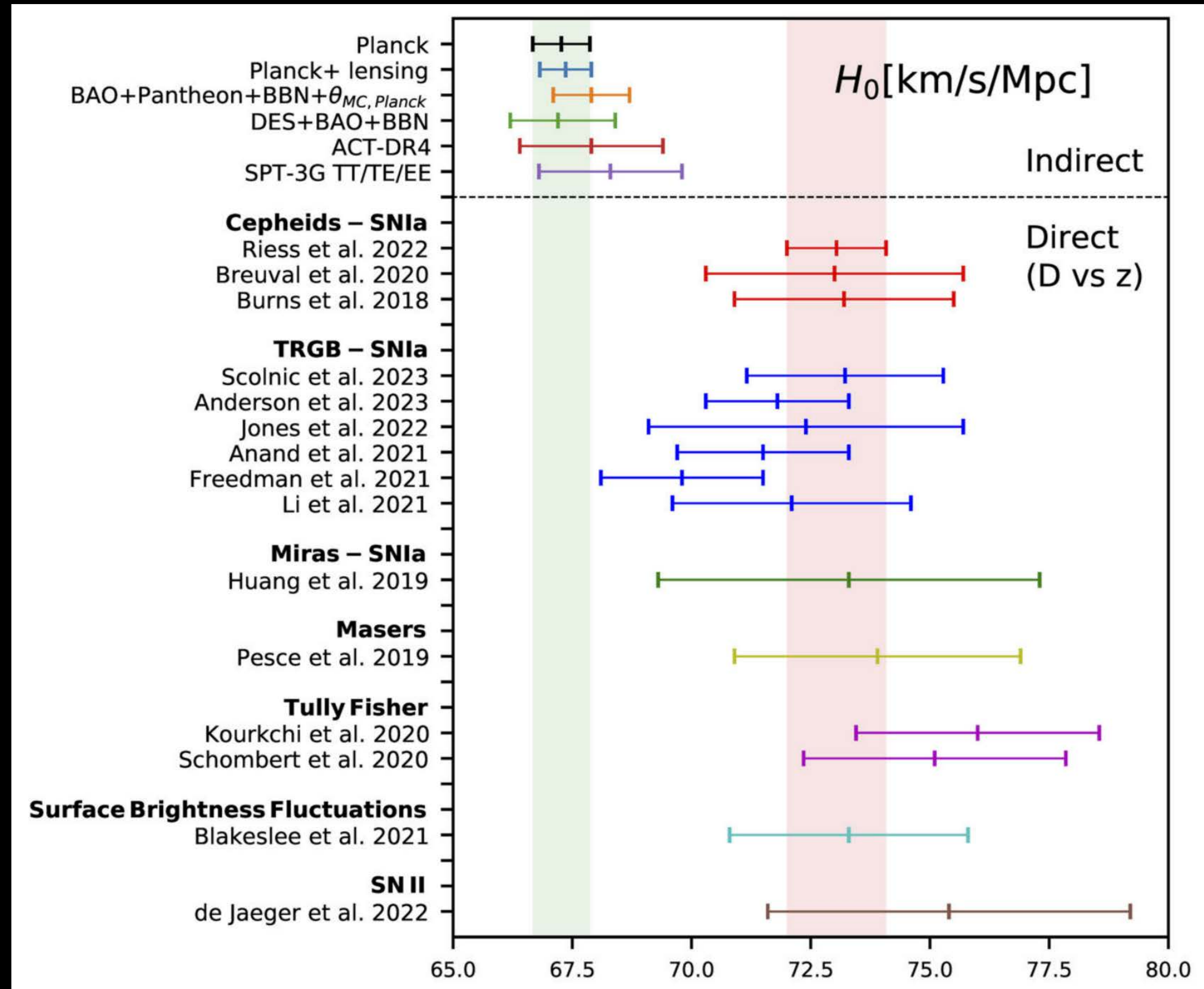
$$\Sigma m_\nu < 0.163 \text{ eV (95\%)}$$

Constraints are model and prior dependent

But we know neutrinos have mass!!

DESI in the context of the “Hubble tension controversy”

DESI BAO is consistent with previous results, however late-time measures of the Hubble expansion are still “in tension”

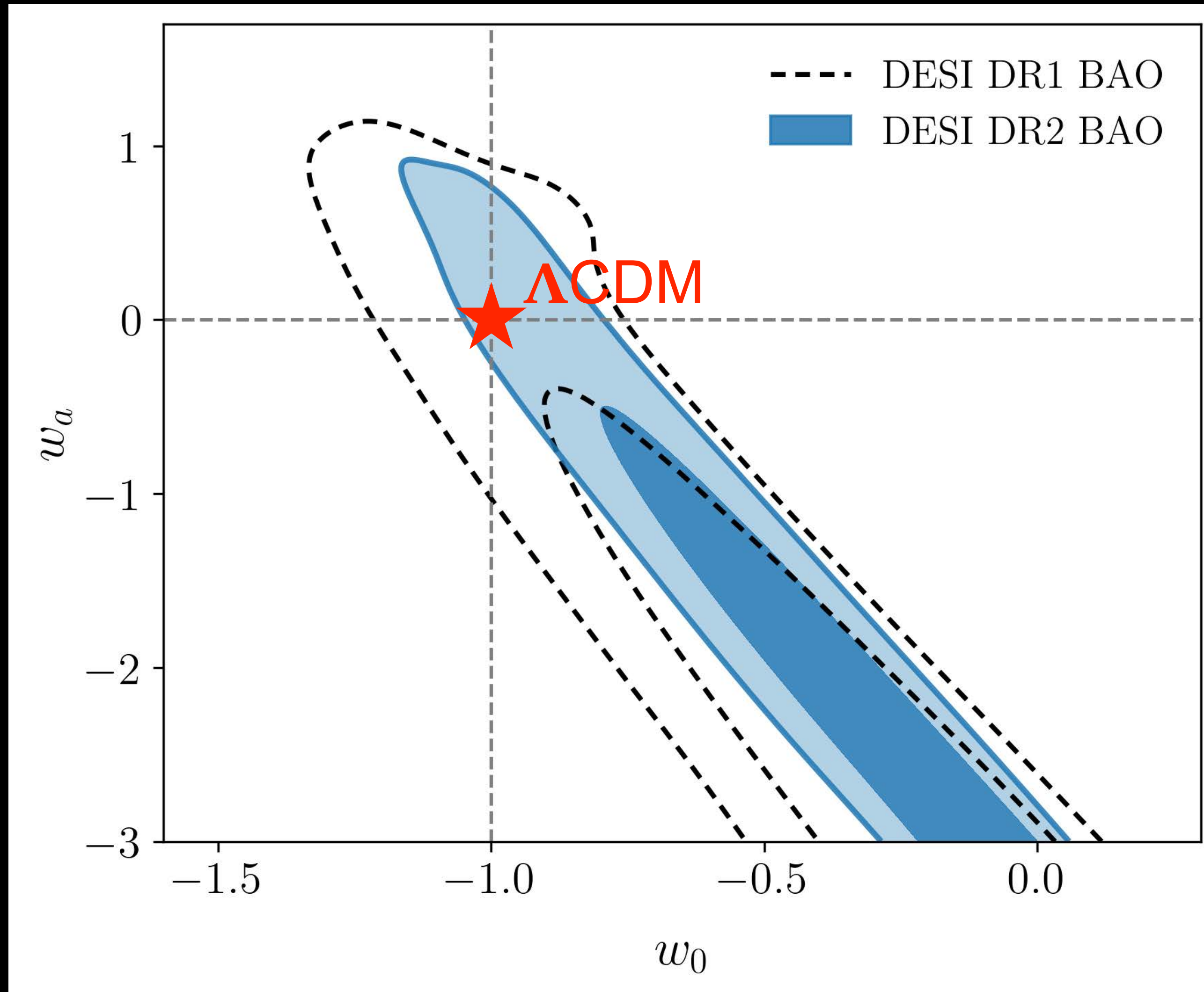


DESI + BBN constraints on physical baryon density, $\Omega_b h^2$, breaks the $H_0 r_d$ degeneracy:

$H_0 = (68.51 \pm 0.58) \text{ km s}^{-1} \text{ Mpc}^{-1}$
in 5.4σ tension with SH0ES

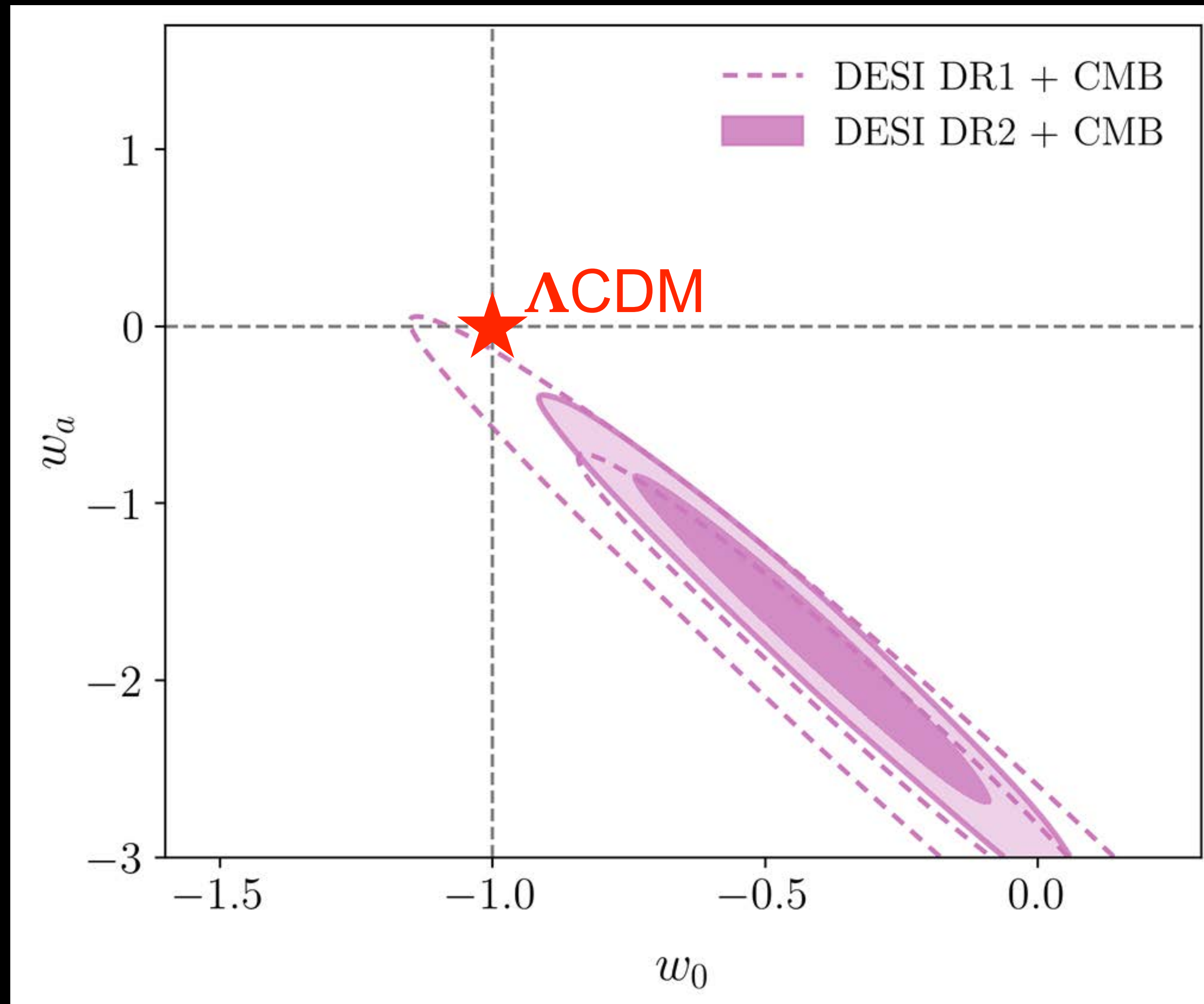
Either the nearby distance scale is wrong by 7% (15% in flux!!) or the sound horizon is actually 7% shorter than we infer!!??

DESI results alone consistent with Λ CDM (non-evolving dark energy)



DESI DR2 within 2- σ of Λ CDM

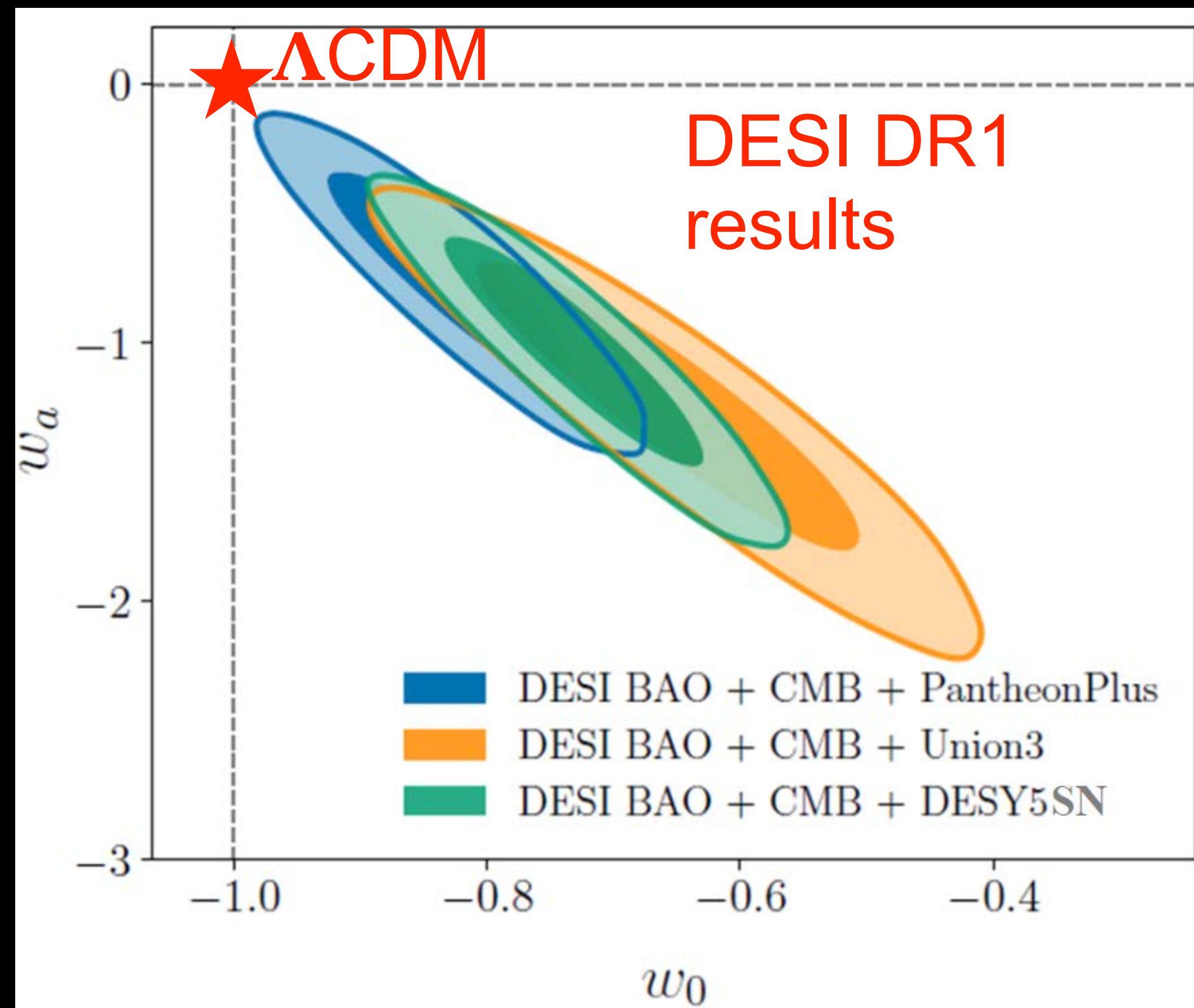
DESI results alone consistent with Λ CDM (non-evolving dark energy)



$$w(a) = w_0 + (1 - a) w_a$$

DESI DR2 + CMB prefers evolving dark energy by $3.1\text{-}\sigma$
($+0.5\sigma$ compared to DESI DR1)

Dark Energy with a time-varying equation of state w_0w_a CDM appears to fit the data better than Λ CDM when including supernova data



$$w(a) = w_0 + (1 - a) w_a$$

Combining DESI+CMB+Supernova increased preference for $w_0 > -1$ and $w_a < 0$

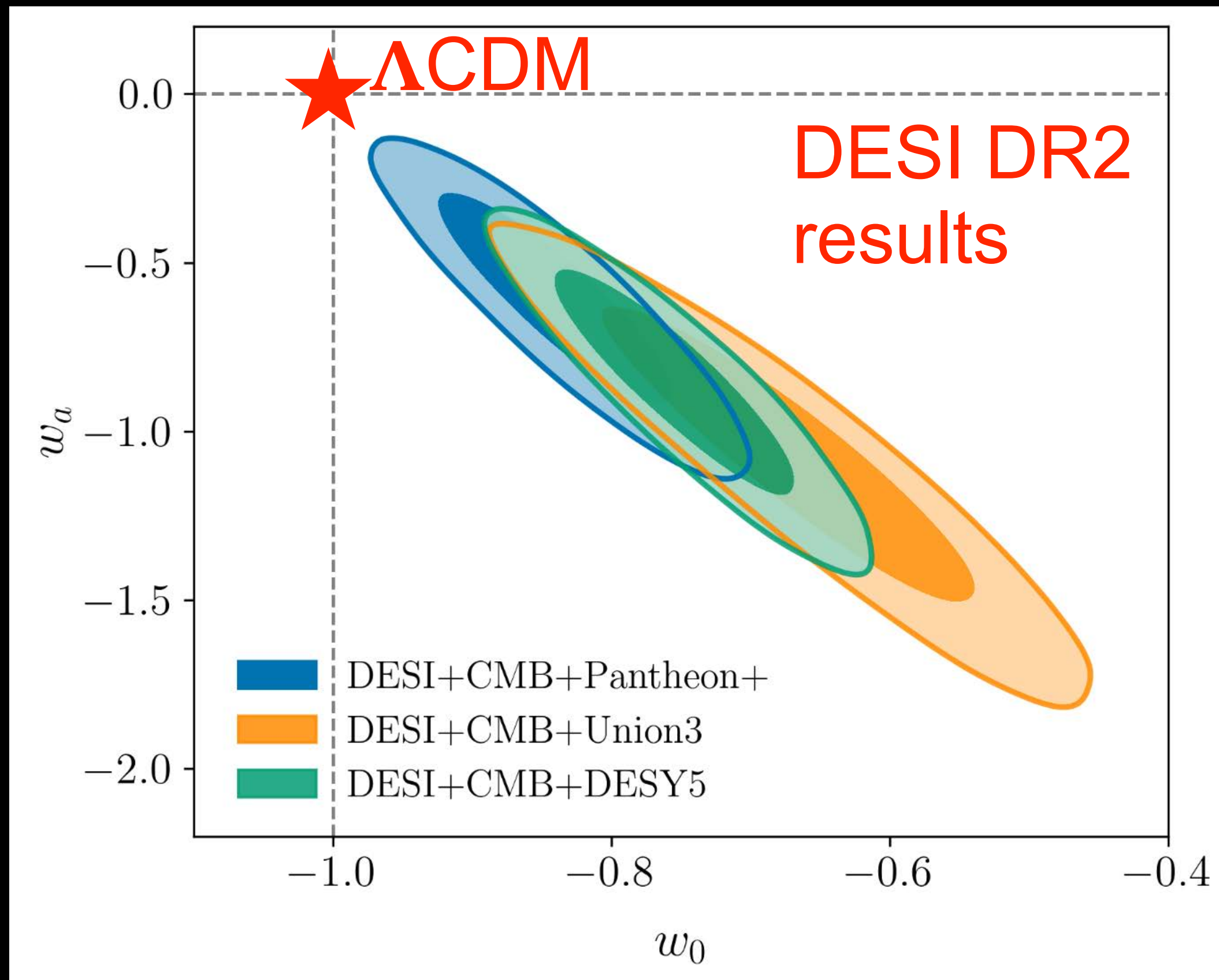
DESI+CMB+PantheonPlus: 2.5σ

DESI+CMB+Union3: 3.5σ

DESI+CMB+DESY5 SN: 3.9σ

Are we seeing first hints for a time-varying $w(a)$ rather than Λ CDM?

Dark Energy with a time-varying equation of state w_0w_a CDM appears to fit the data better than Λ CDM when including supernova data



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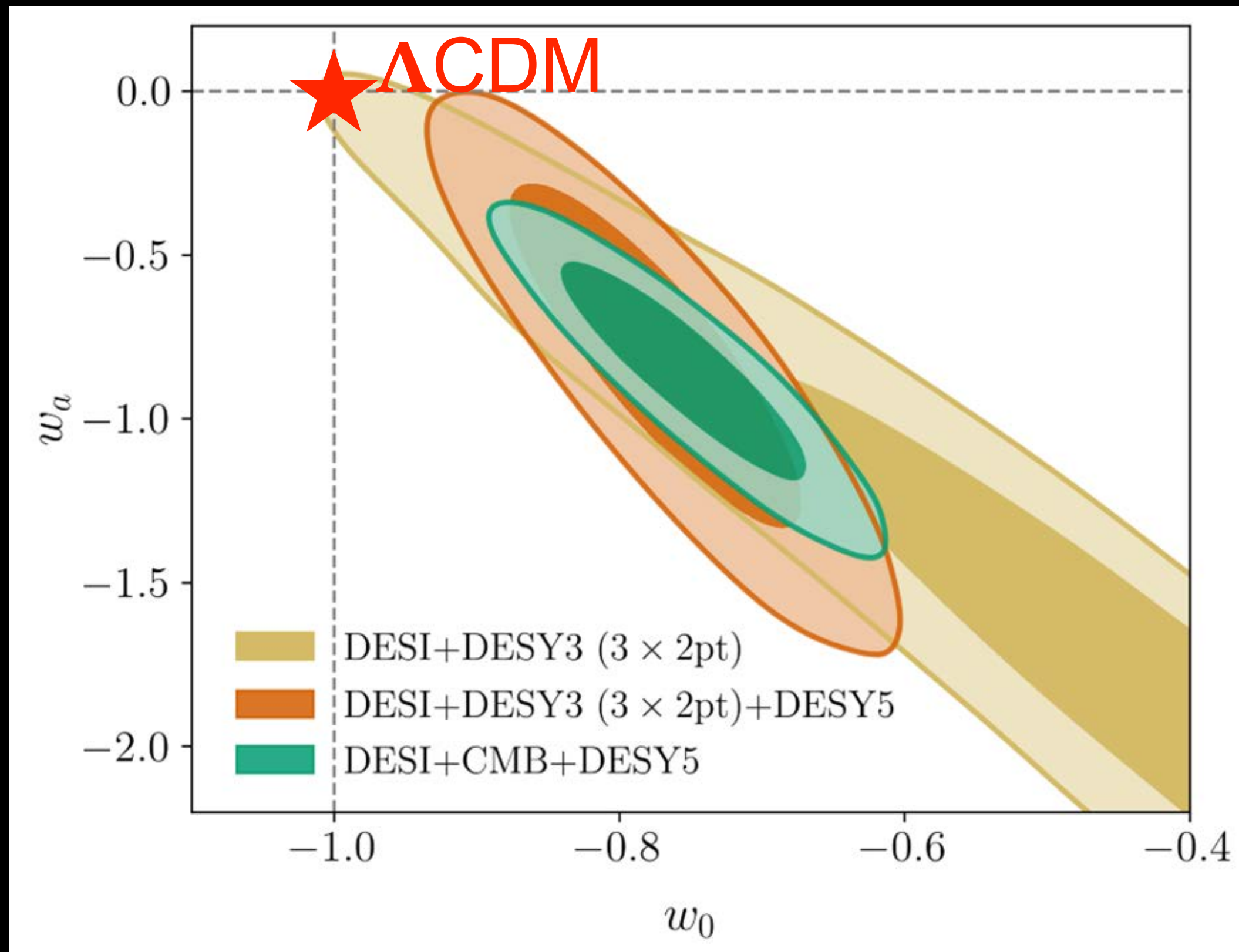
DESI+CMB+PantheonPlus: 2.8σ

DESI+CMB+Union3: 3.8σ

DESI+CMB+DESY5 SN: 4.2σ

Are we seeing first hints for a time-varying $w(a)$ rather than Λ CDM?

Dark Energy with a time-varying equation of state w_0w_a CDM still preferred when using low-redshift probes otherthan supernovae



$$w(a) = w_0 + (1 - a) w_a$$

Replacing CMB with DESY3 3x2pt
(weak lensing + galaxy clustering)

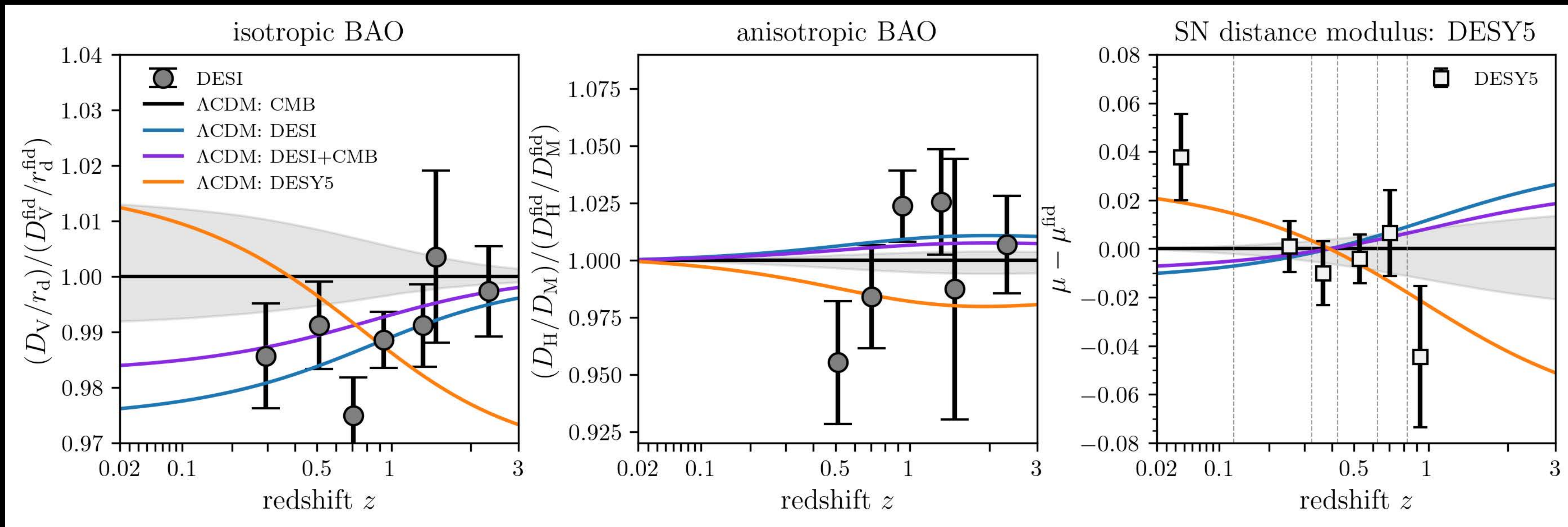
DESI + DESY3 (3x2pt) $\Rightarrow 2.2\sigma$

DESI + DESY3 (3x2pt) + DESY5 $\Rightarrow 3.3\sigma$

Are we seeing first hints for a time-varying $w(a)$
rather than Λ CDM?

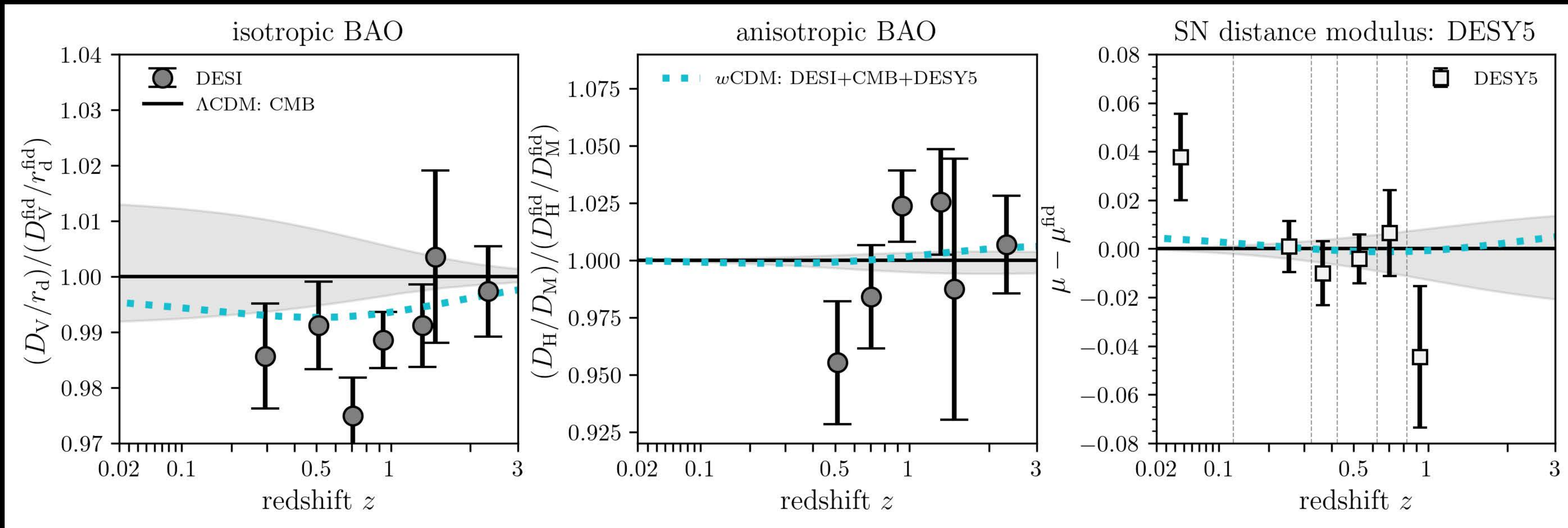
Evolving dark energy

The best-fit Λ CDM model in DESI+CMB doesn't match the trend in the SNe — would need an 0.05 mag shift



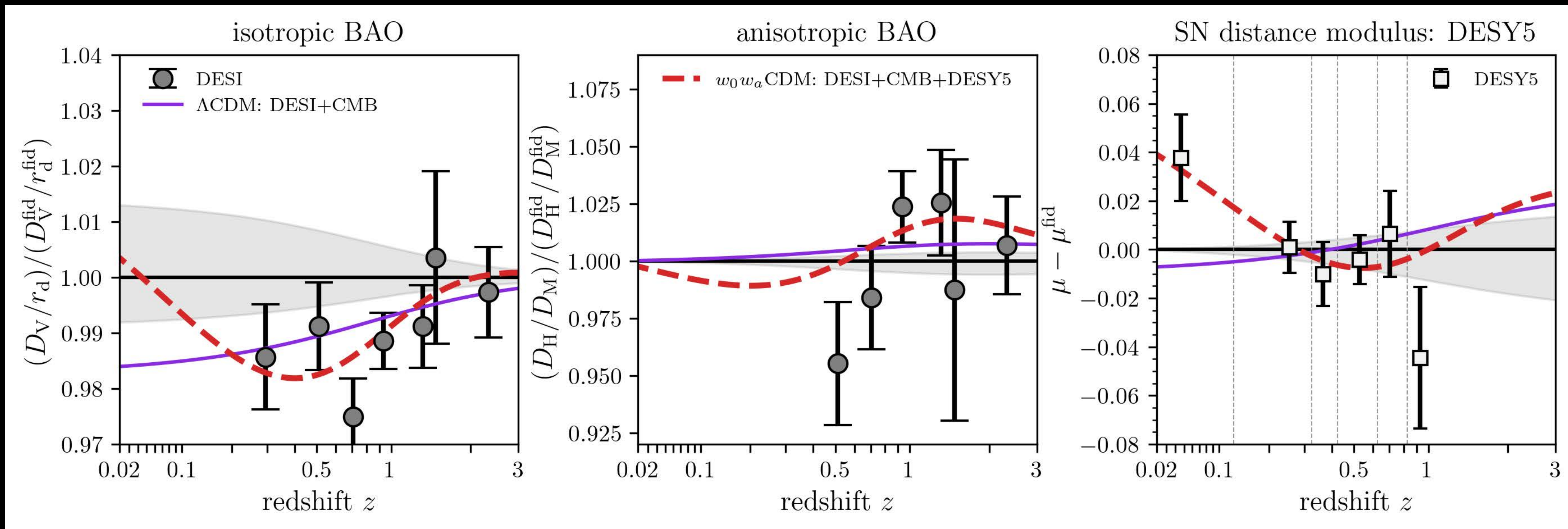
Evolving dark energy

A model of a constant w doesn't help...



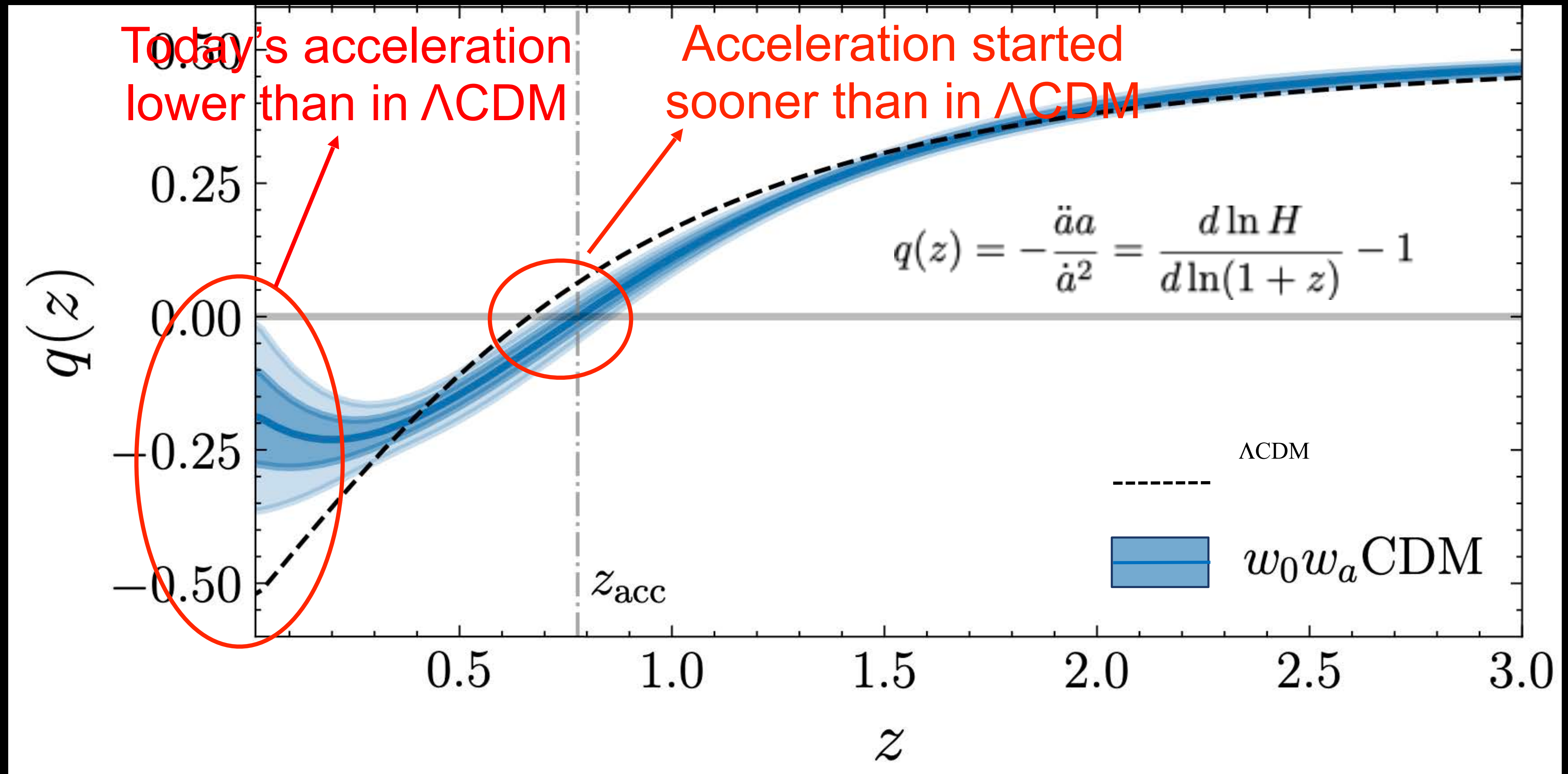
Evolving dark energy

...But a model with w_0, w_a is able to bend to steer through the tensions...



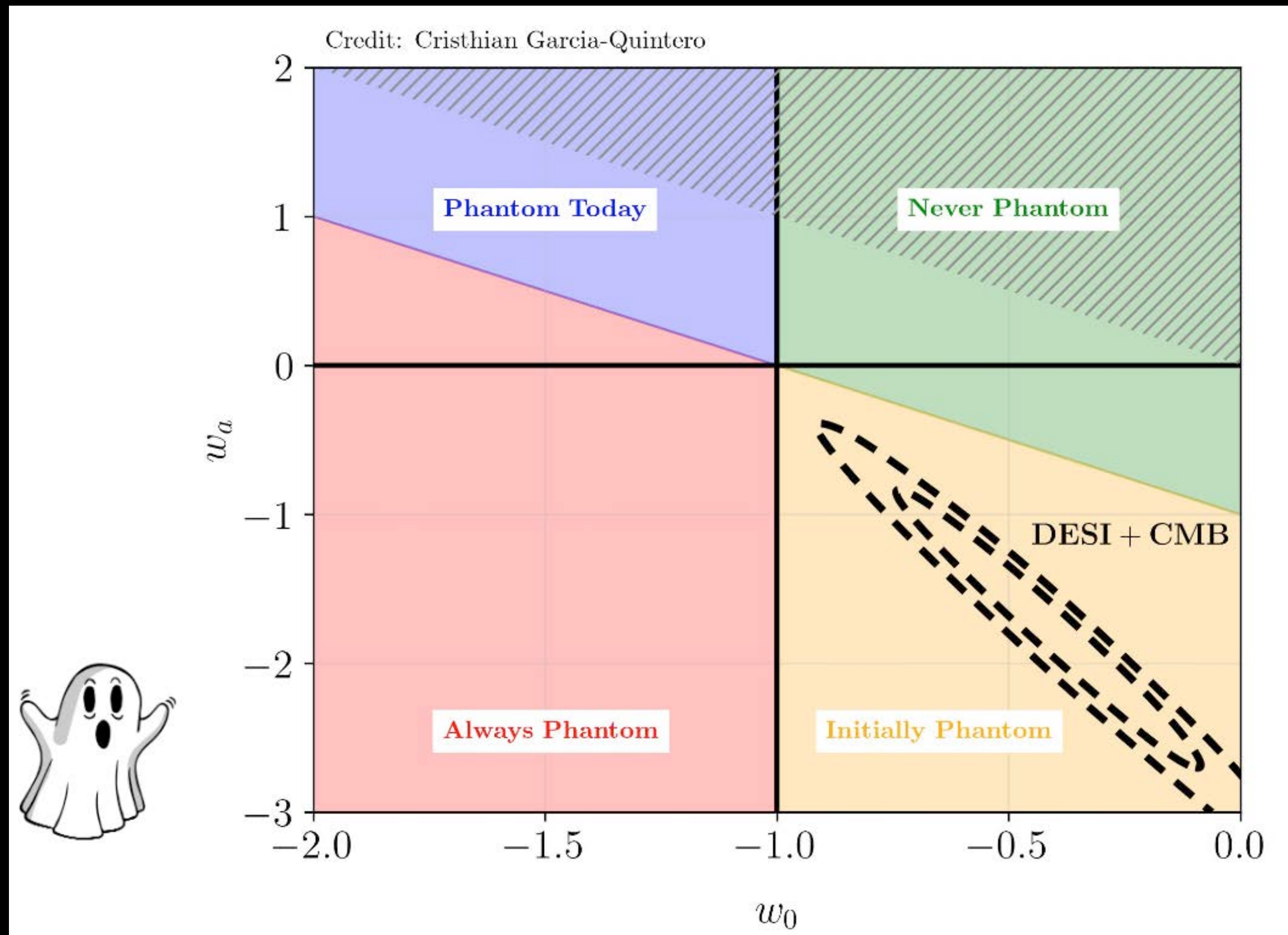
Apparent weakening of dark energy today when combining DESI + CMB + supernovae

Deceleration parameter



Weakening dark energy today

Ask the theorists what this means... they're writing ~3 papers/day...



Conclusions?

DESI has released the most precise BAO measurements

DESI in mild tension with Planck (2.3σ) and SN ($\sim 2\sigma$) when interpreted in Λ CDM

Evidence for evolving dark energy (increased by 0.3σ since DESI DR1)

3.1σ (DESI+CMB)

$2.8\sigma - 4.2\sigma$ (DESI+CMB+SN)

Tightest bound on Σm_ν

Growing tension with neutrino oscillations in Λ CDM

Tension reduced if evolving dark energy

Eagerly awaiting more data !!