Cosmological constraints from weak lensing, SNIa, and CMB, and Bayesian model selection

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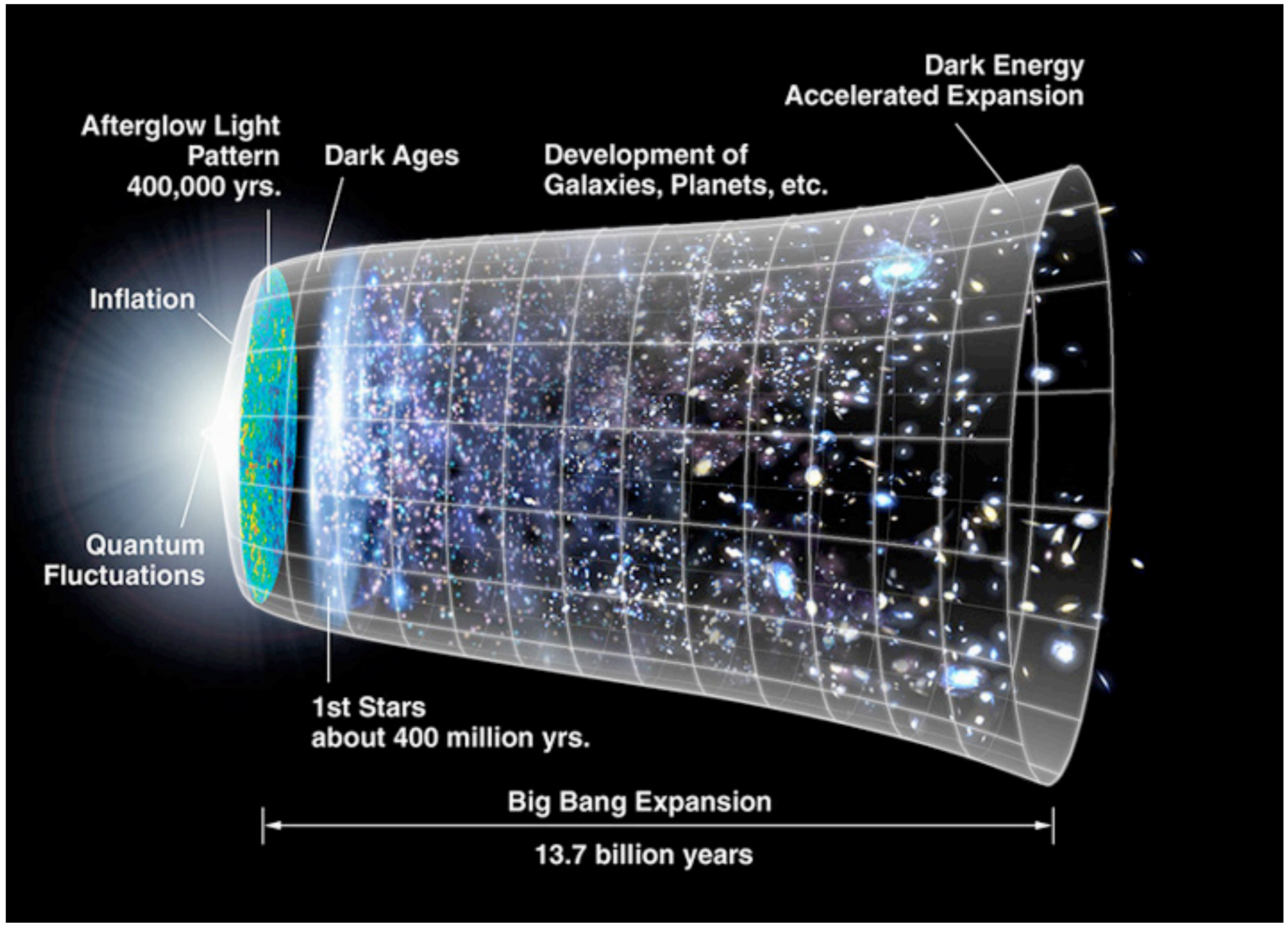
Outline

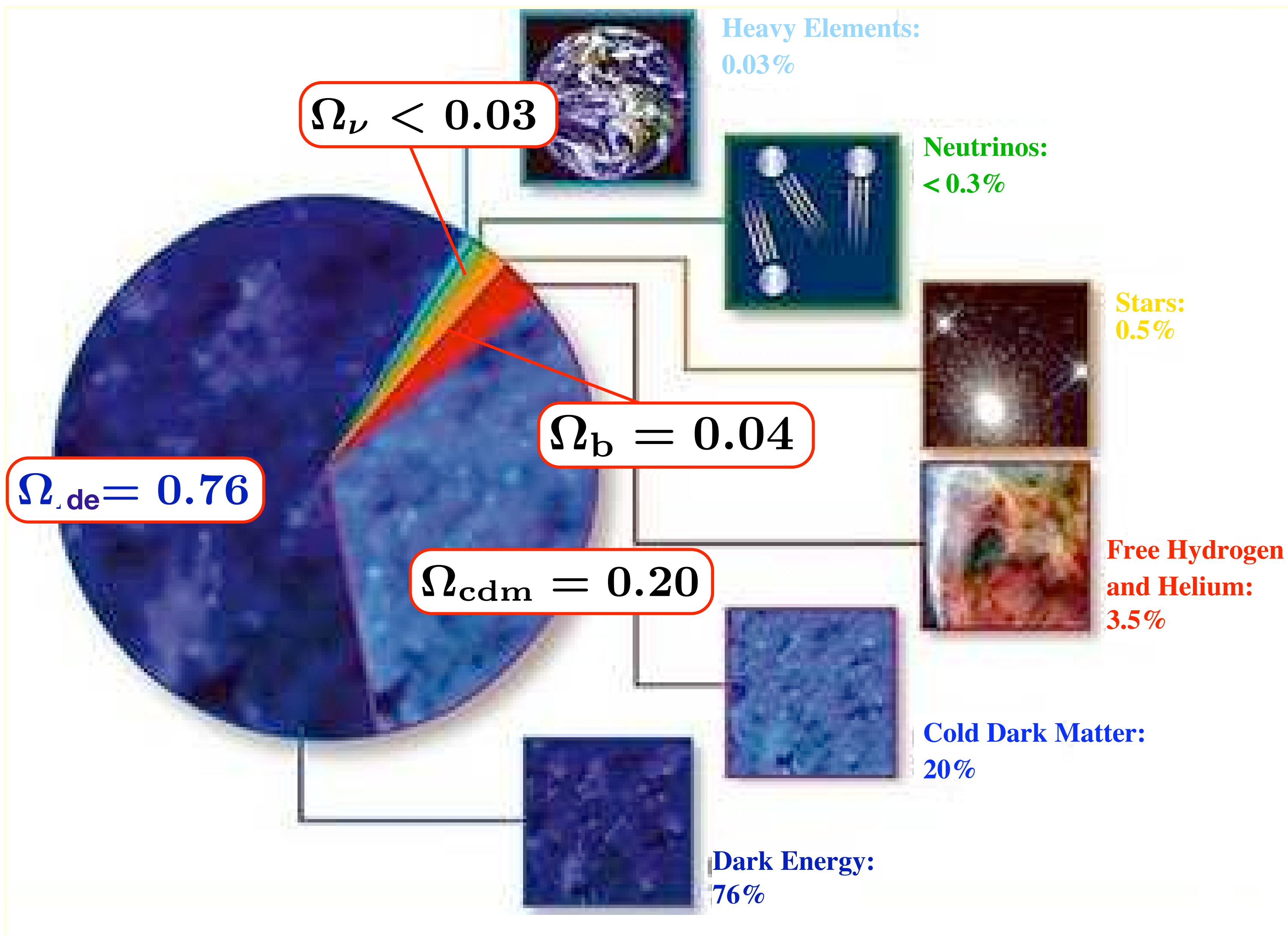
- Cosmology from Cosmic Microwave Background, weak gravitational lensing, and Supernovae type Ia
- Systematics in SNIa: photometric accuracy, dust reddening
- Model selection and Bayesian evidence
- A new method to sample the parameter space and compute the Bayesian evidence
- Results for model selection

Questions in cosmology



- How did the Universe begin, how does it evolve?
- What is it made of?
- How do structures form? (Dark matter, halos, galaxies, ...)

Composition of the Universe



density parameters $\Omega_i \equiv \rho_i/\rho_c$

critical density: $\rho_c = 3H_0^2/(8\pi G) = 10^{-29}\ \mathrm{g\,cm^{-3}}$

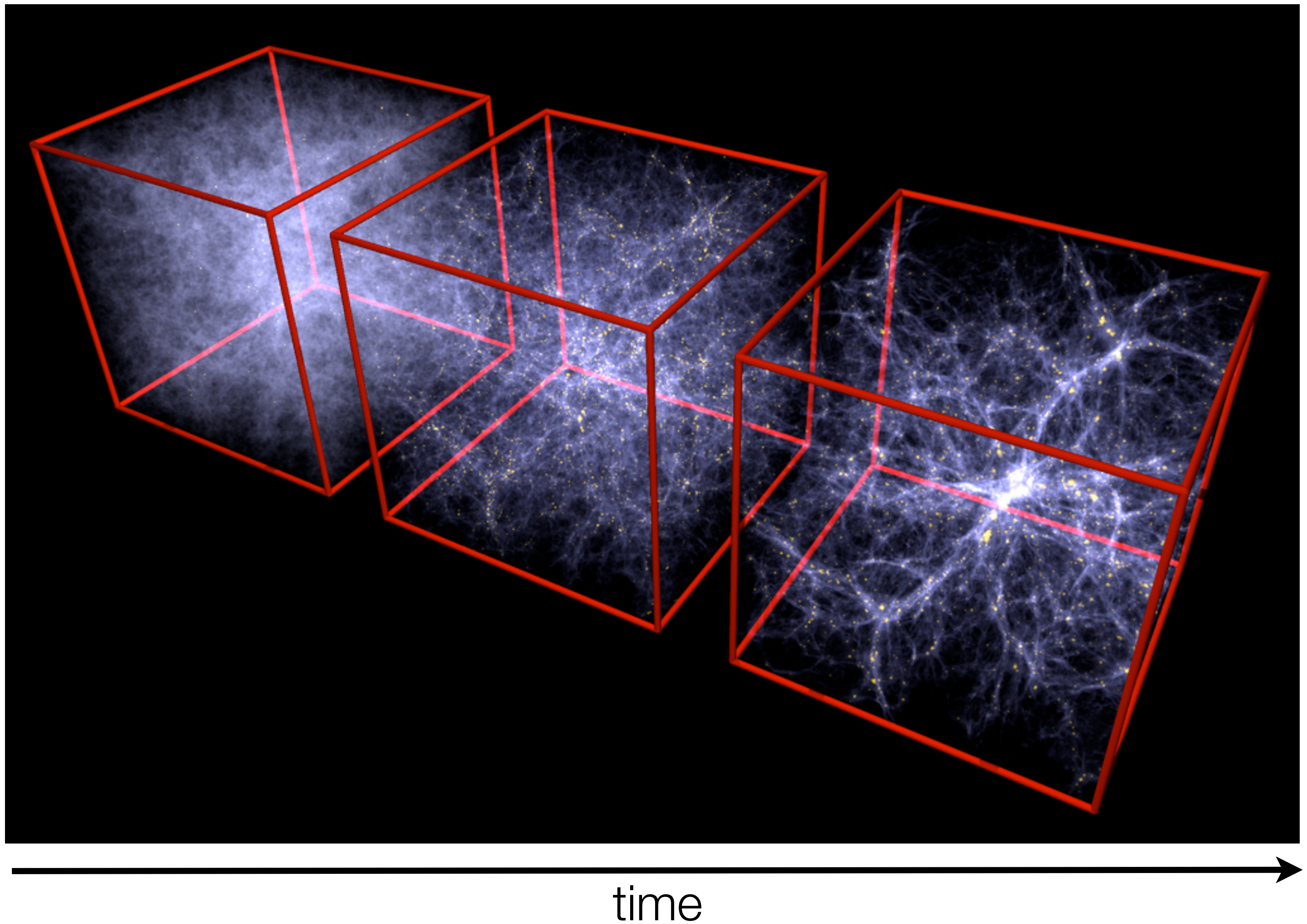
total matter density: $\Omega_m = \Omega_{cdm} + \Omega_b$

Dark energy or cosmological constant?

$w = p/(\rho c^2)$

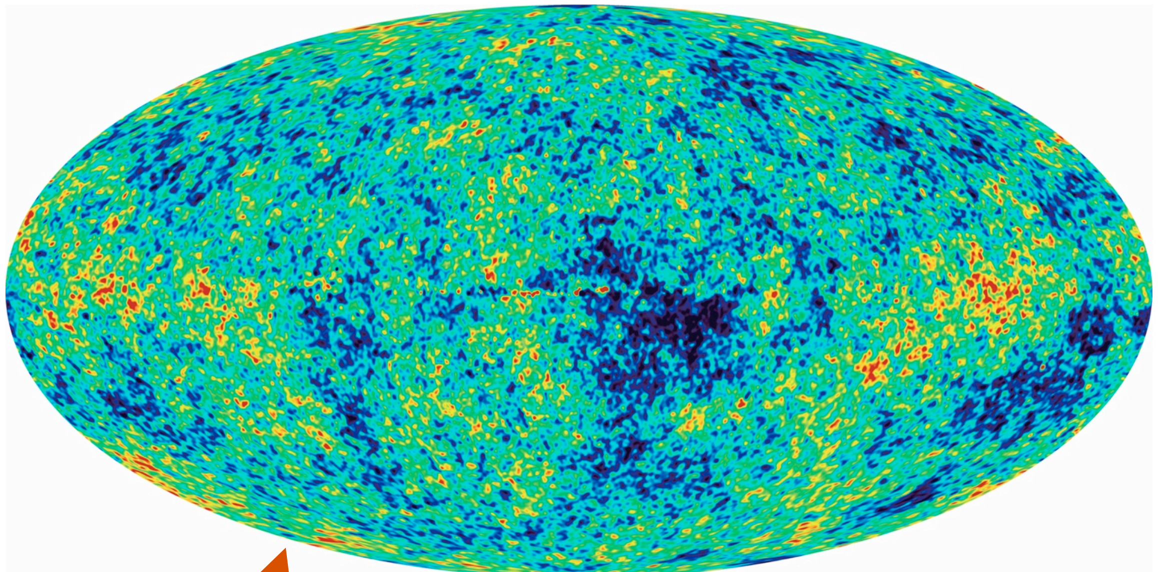
$w \neq -1$ $\quad$ $w = -1$

Structure formation

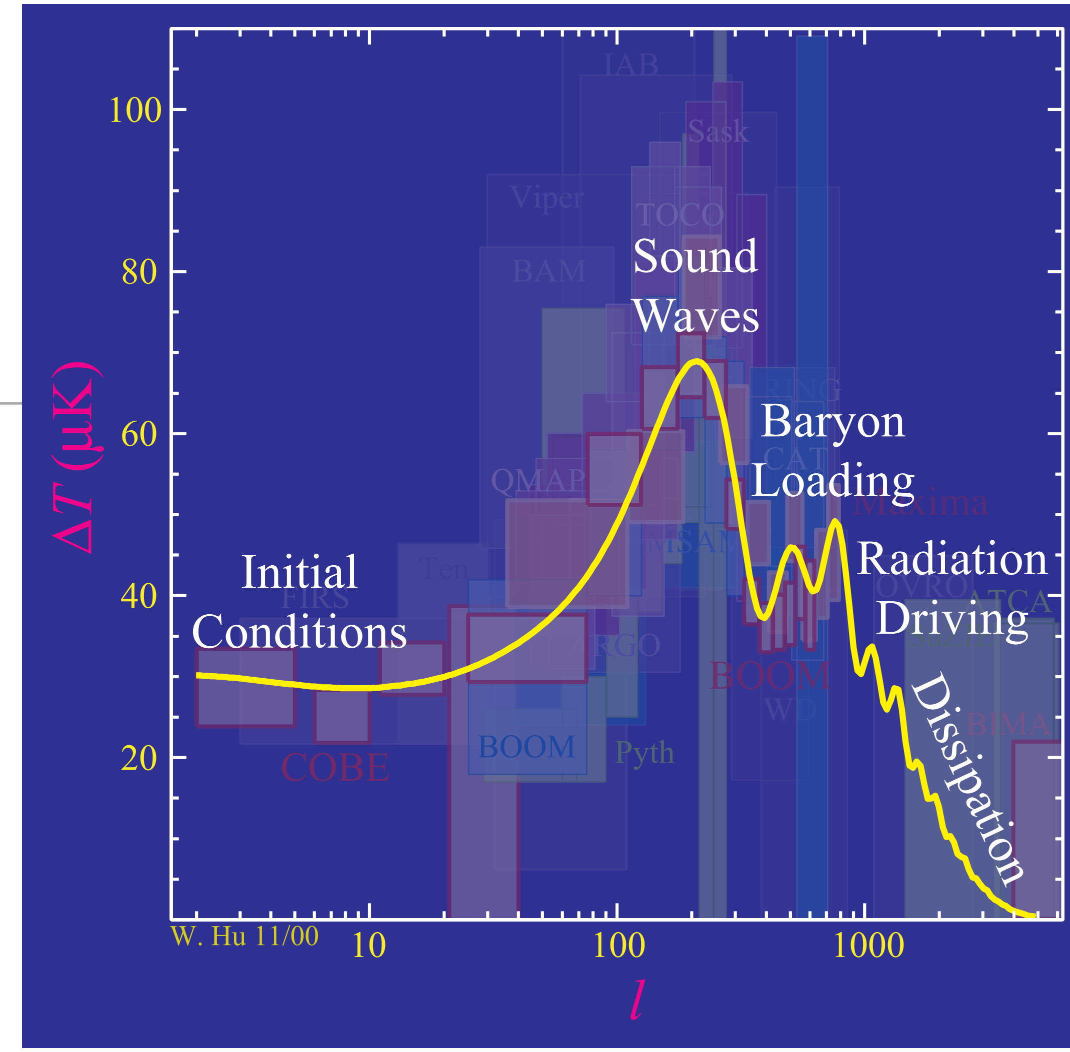


- Structure formation on large scales depends on cosmological parameters
- Structures consist mainly (80%) of invisible dark matter
- Galaxies as dark-matter tracers requires complex physics

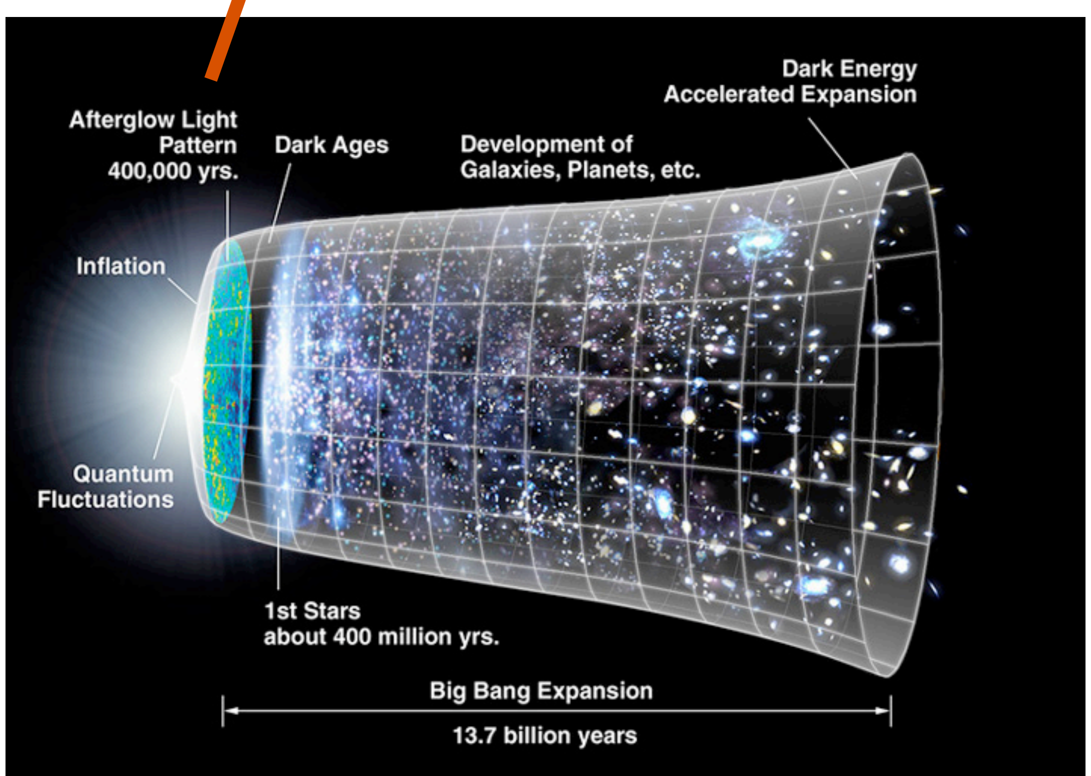
Cosmic Microwave Back-ground (CMB)

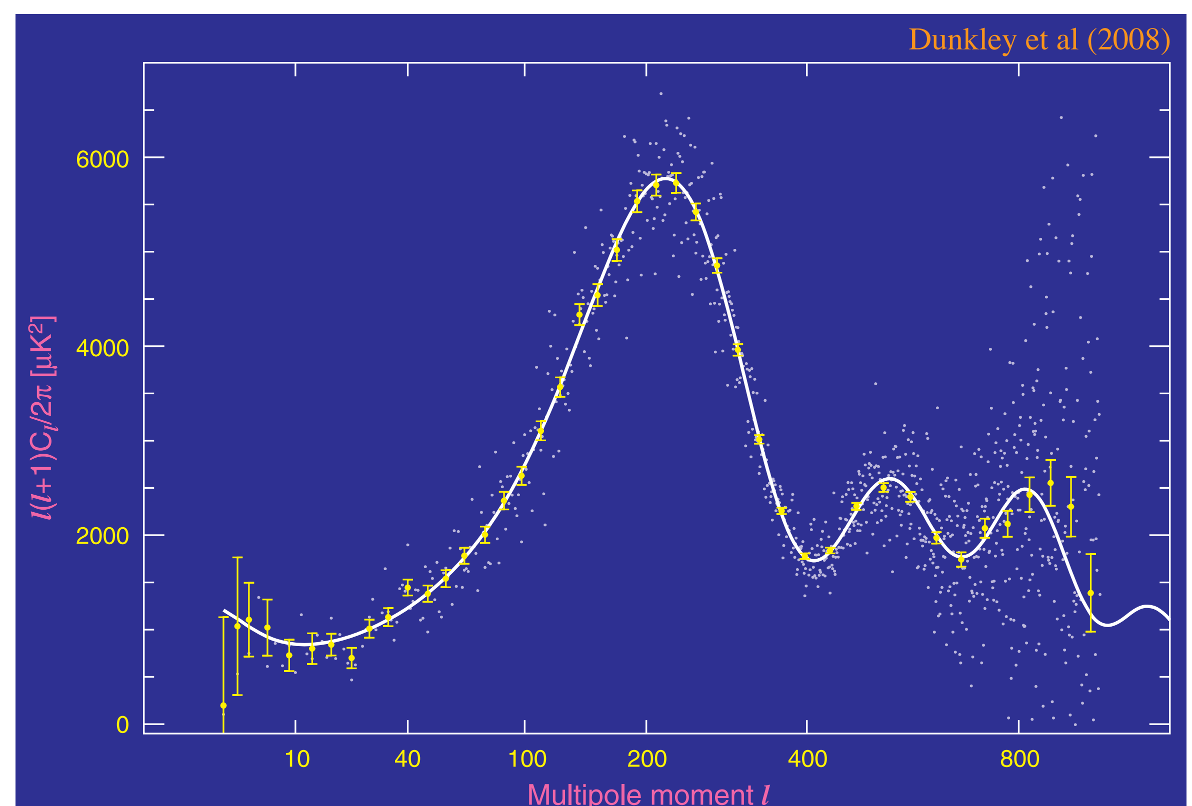


Temperature anisotropies



large scales small scales

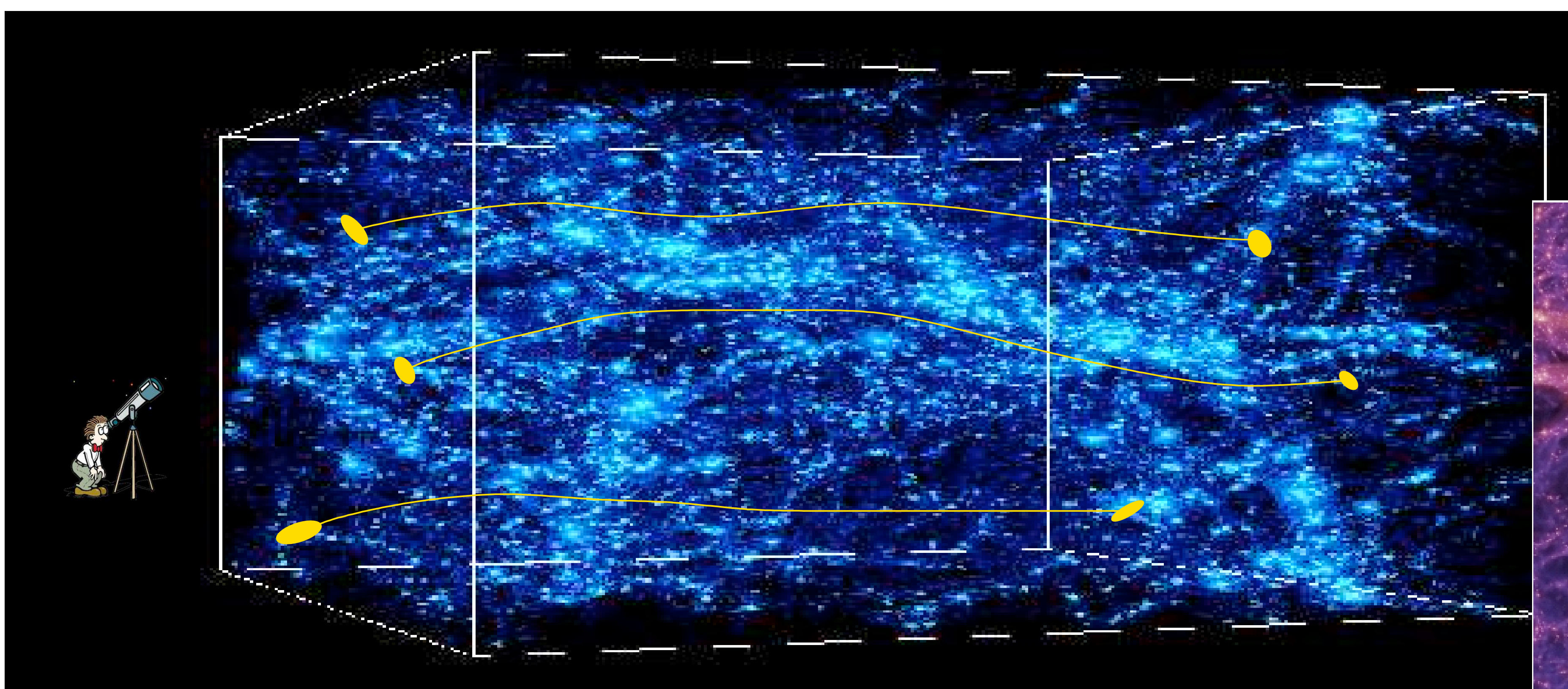


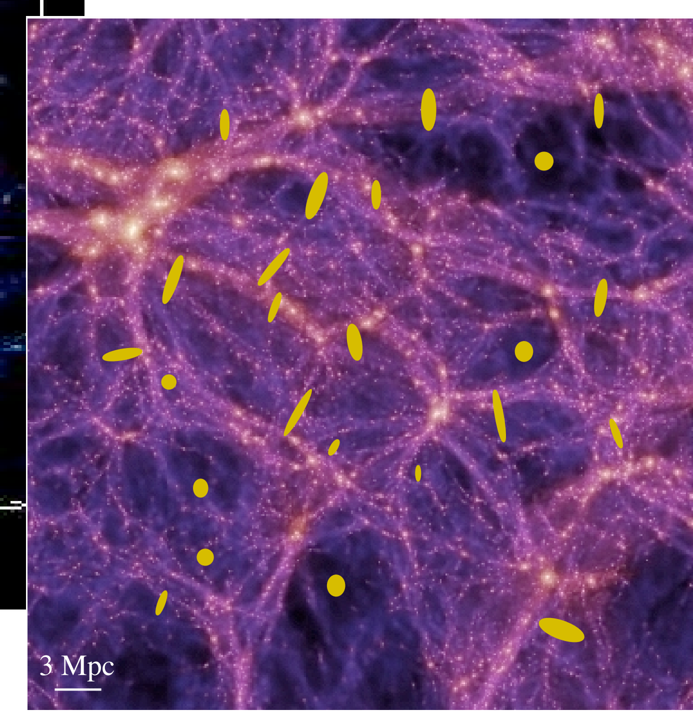


Angular power spectrum (WMAP5)

Gravitational lensing as probe of the large-scale structure

- Light from distant galaxies is continuously deflected along its path through the inhomogeneous Universe
- Light bundles are differentially ‘lensed’ by tidal matter field
- Galaxy images are coherently distorted → shape correlations, depending on statistical properties of (projected) large-scale structure

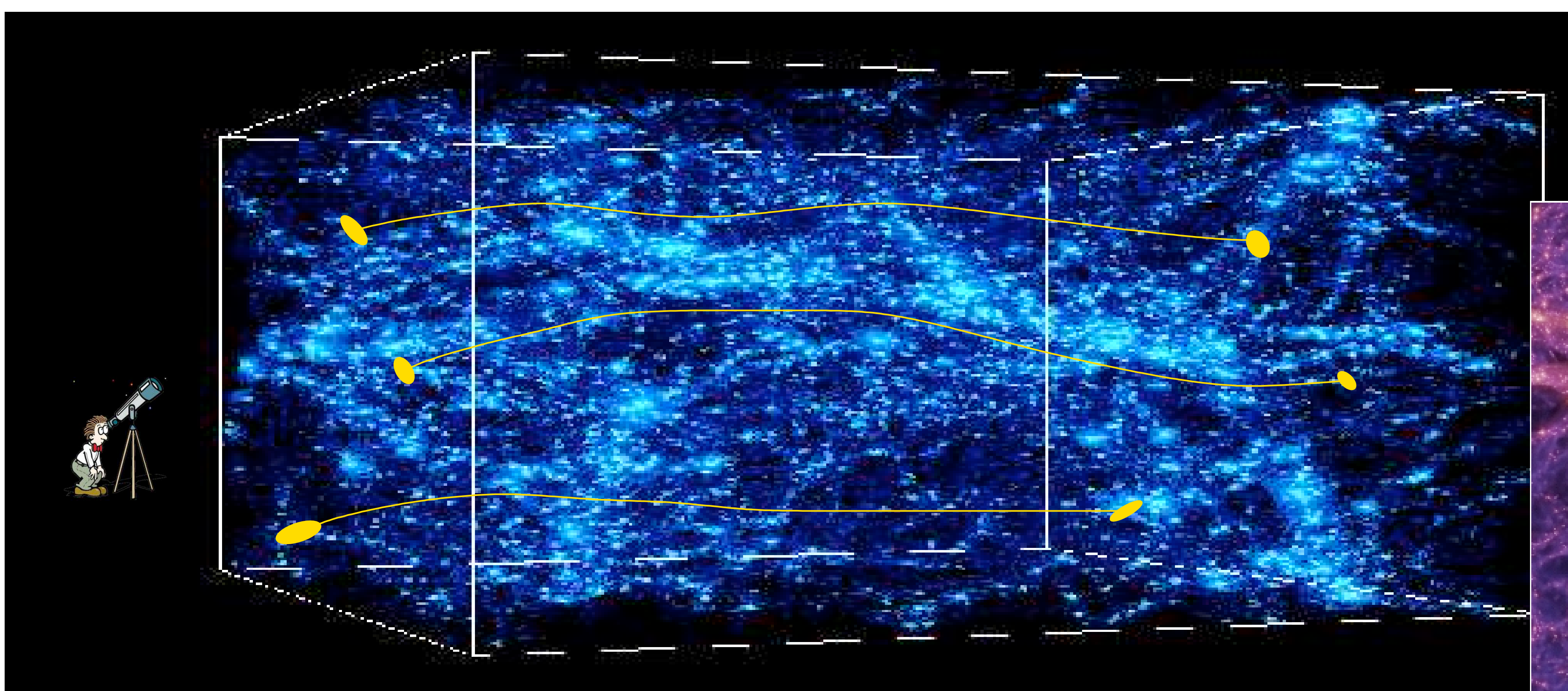


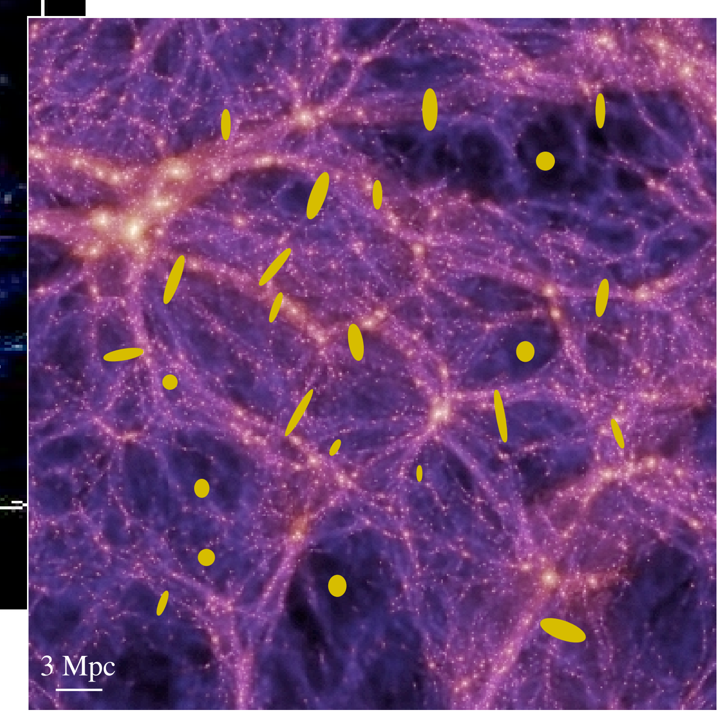


‘Cosmic shear’

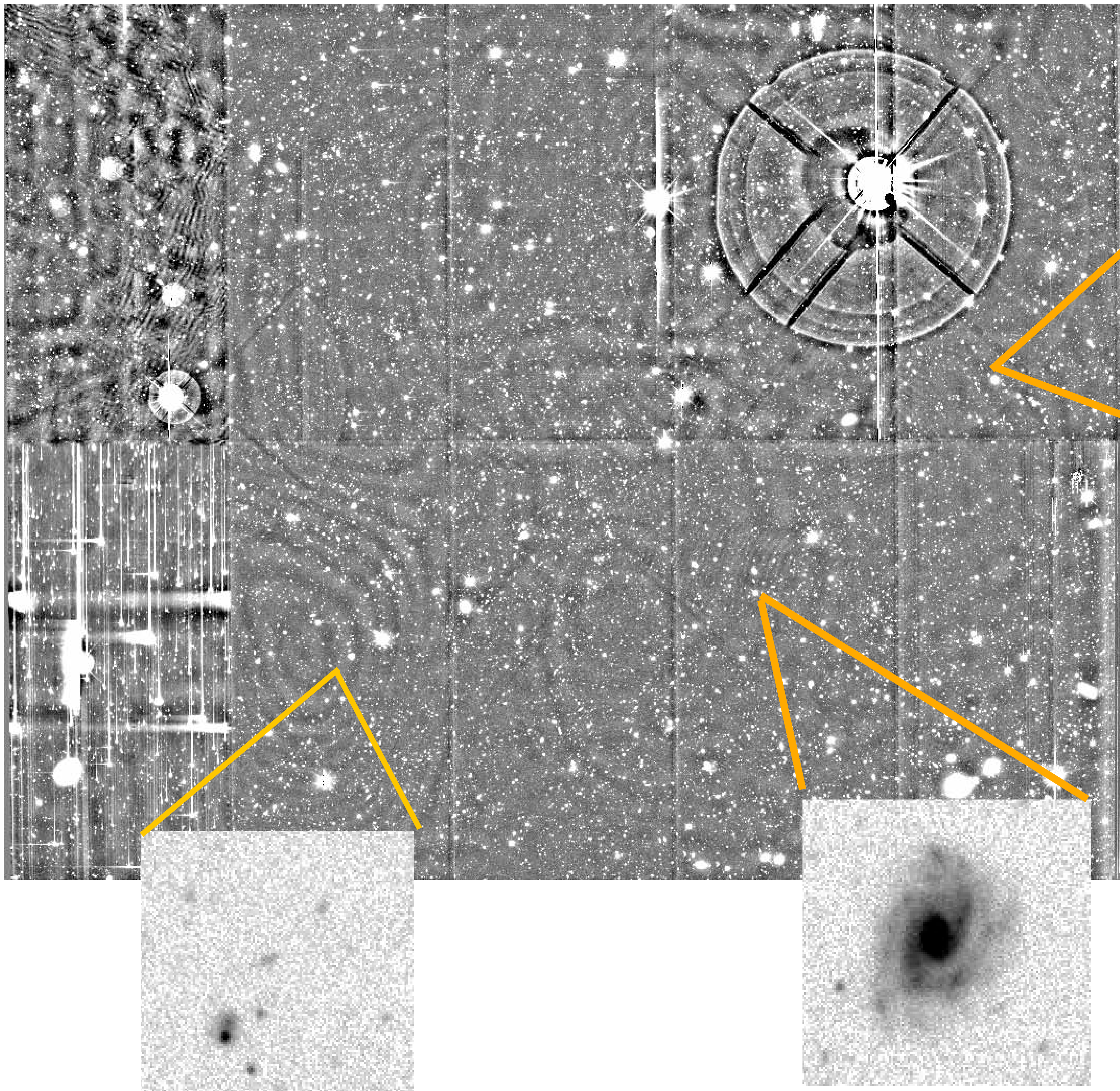
Weak cosmological lensing ...

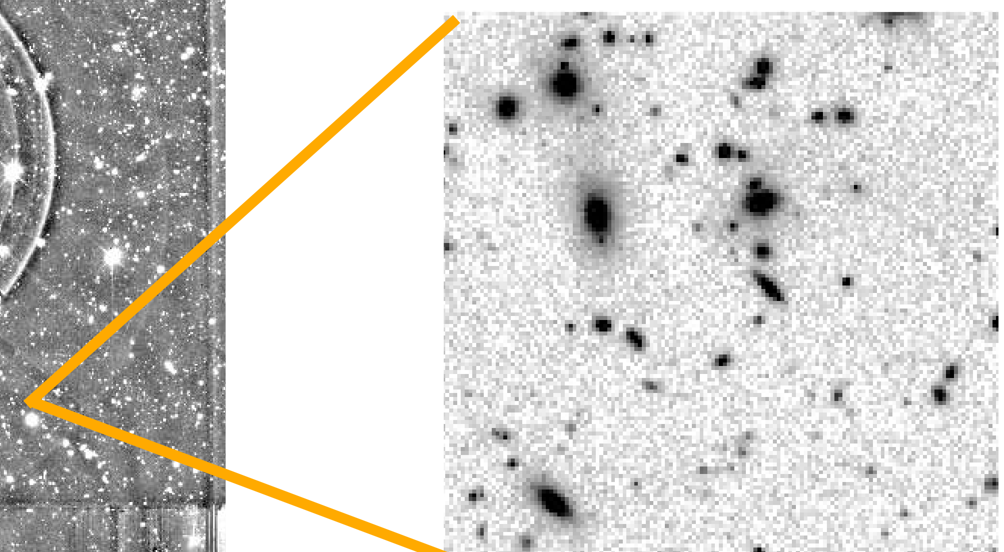
- probes structures @ z=0.3 ... 1, where accelerated expansion sets in
- probes both growth of structure and geometry of Universe → can distinguish between modified gravity and dark energy





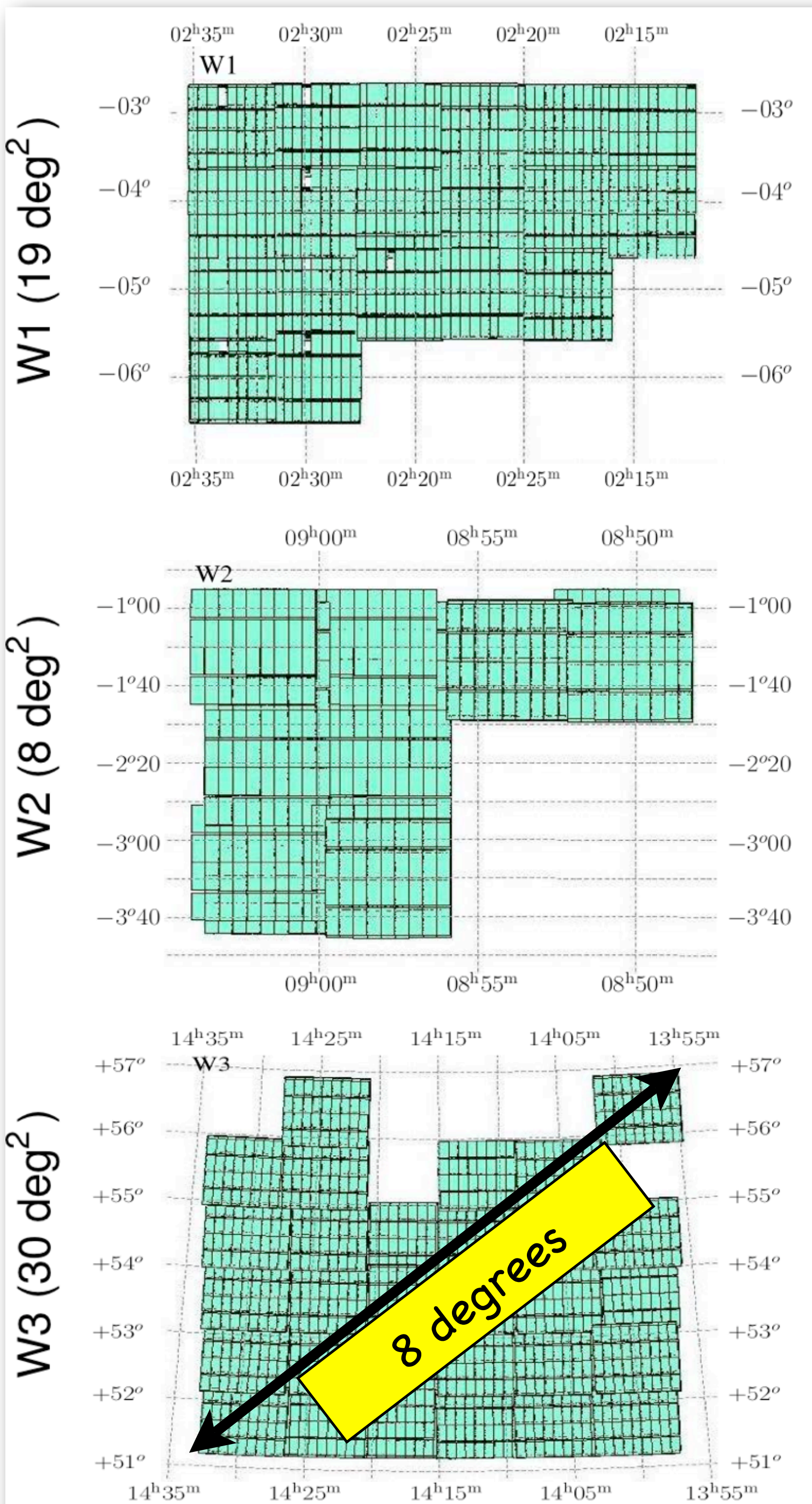
Weak lensing observations





- Gravitational lensing effect much smaller than intrinsic galaxy shapes or instrumental/atmospheric distortions
- Need to estimate accurate shapes of millions of galaxy images

Weak lensing data



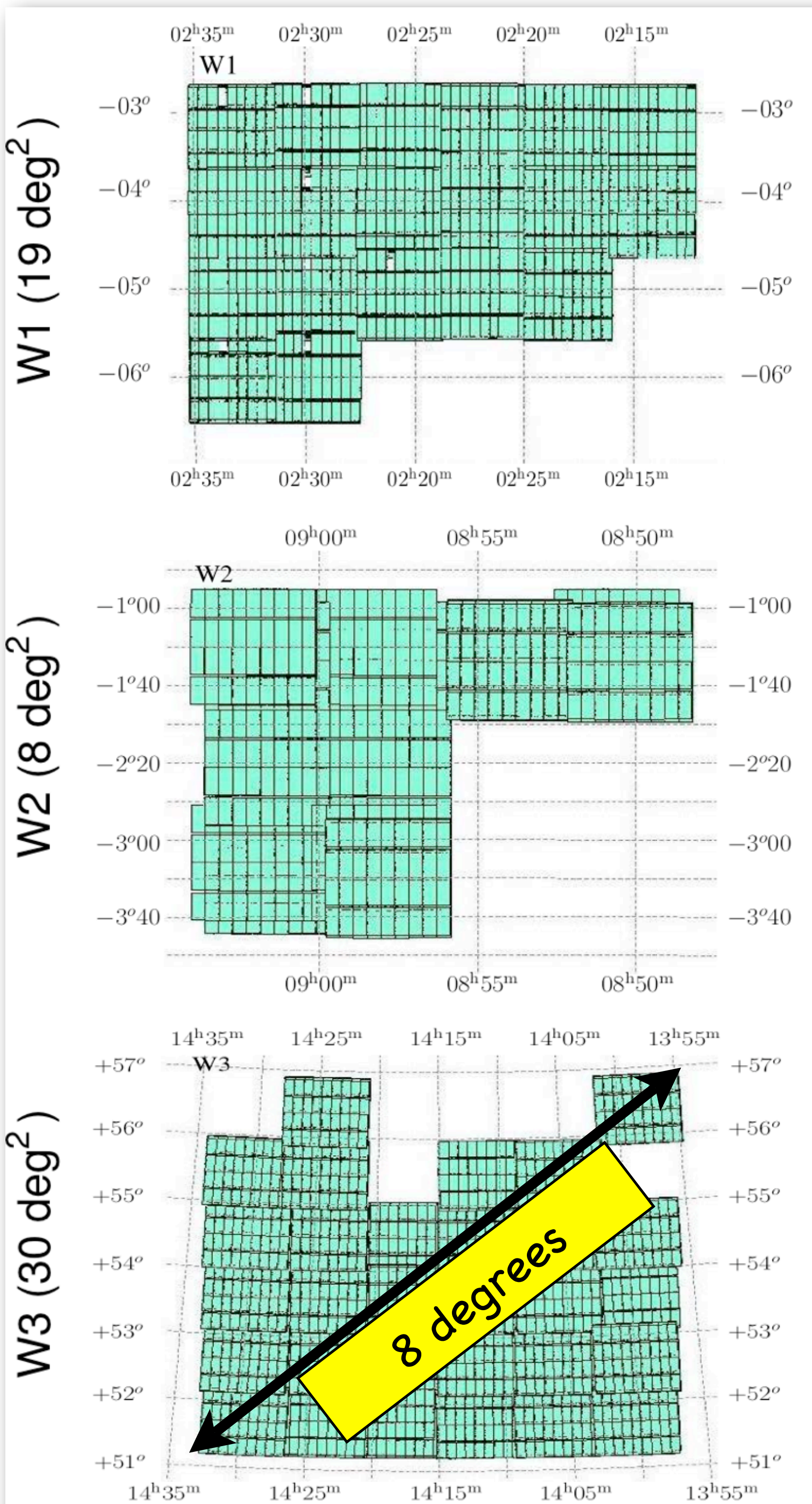
- Canada-France Hawaii Telescope (CFHT): 3.6m telescope
  MegaCam: 1 deg^2 field of view (4x full moon)

- Legacy Survey (LS): 500 nights (2003-2008), five optical bands, final area 170 deg^2

- 3[rd] data release: 57 deg^2, 2 million galaxies, only one band

[Fu, Hoekstra, Semboloni, MK et al. 2008]

Weak lensing data



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SUPRIME-33	SUBARU/ Suprime	33 deg^2	R	R=26	2003-?
VIKING	VISTA/	1500 deg^2	zYJHK	i_{AB}=22.9	2007-2010
Dark Energy Survey	CTIO DECam	5000 deg^2	griz	i_{AB}=24.5	2009-2014
DarkCam	VISTA	∼10,000 deg^2	ugriz	i_{AB}=24.	2010-2014
HyperCam	SUBARU/ Suprime	∼3500 deg^2	Vis.	?	>2012?
SNAP/JDEM	Space	100/1000/ deg^2 5000 deg^2	Vis.+NIR	-	>2013
DUNE	Space	∼20000 deg^2	ugriz+NIR?	i=25.5	∼2015?
LSST	Ground TBD	20000 deg^2	ugrizy	i_{AB}=26.5	>2014
Dome-C	SouthPole	? deg^2	?	?	∼2012?

CFHTLS lensing data used for:

- Modified gravity:

  Yukawa-, Uzan-Bernardeau potentials [Doré, Martig, Mellier, MK et al. 2009]
  no deviation from GR for 0.04 Mpc... 10 Mpc

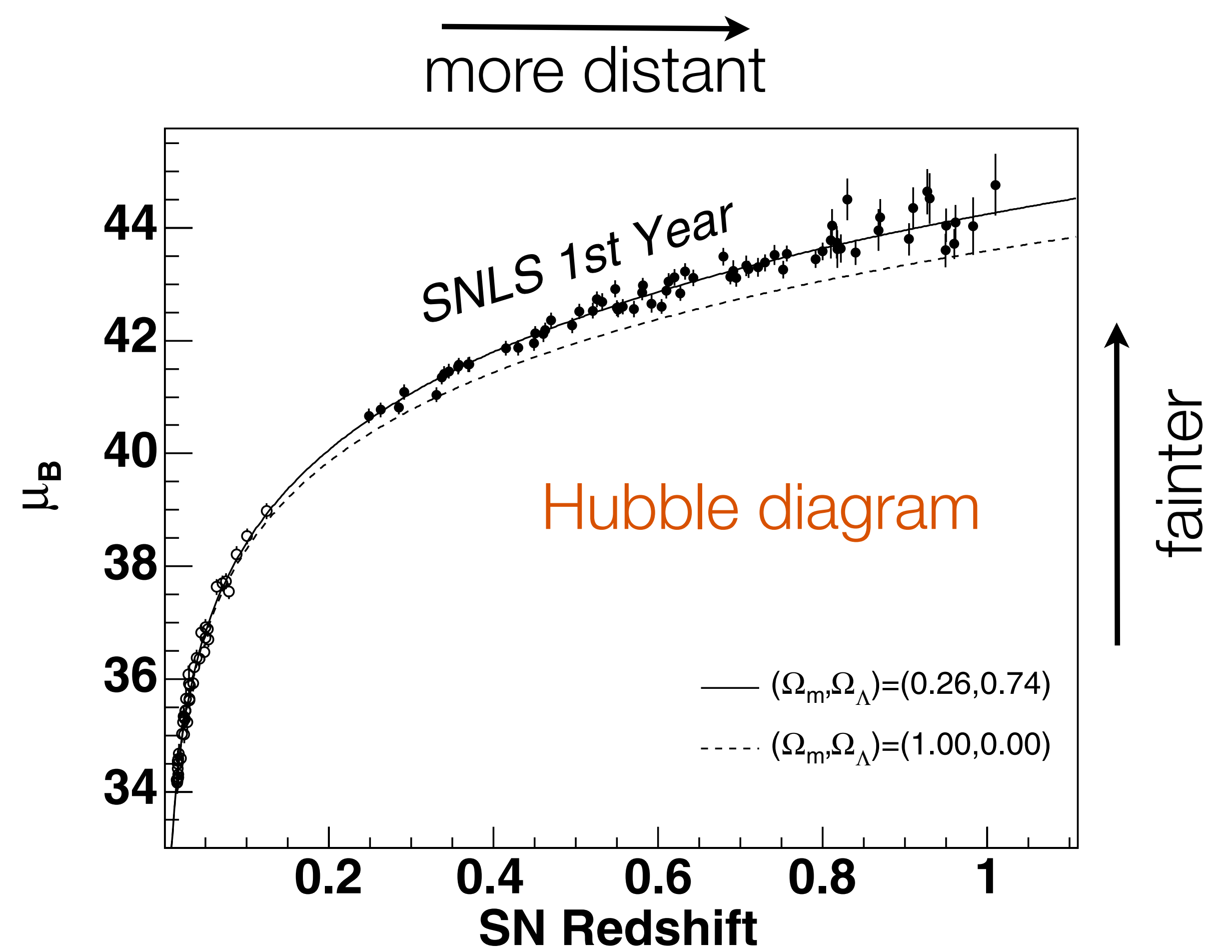
  Constraints on gravitational slip ($\psi \neq \varphi$) [Daniel, Caldwell, Cooray & Melchiorri 2008]
  DGP models excluded at 2σ [Thomas, Abdalla & Weller 2008]

- Dark energy constraints [MK, Benabed, Guy, Astier et al. 2009, Wraith, MK, Benabed, Cappé et al. 2009]
  no deviation from Λ

- Neutrino masses [Tereno, Schimd, Uzan, MK et al. 2009, Ichiki, Takada & Takahashi 2009]
  $\sum m < 0.54$ eV

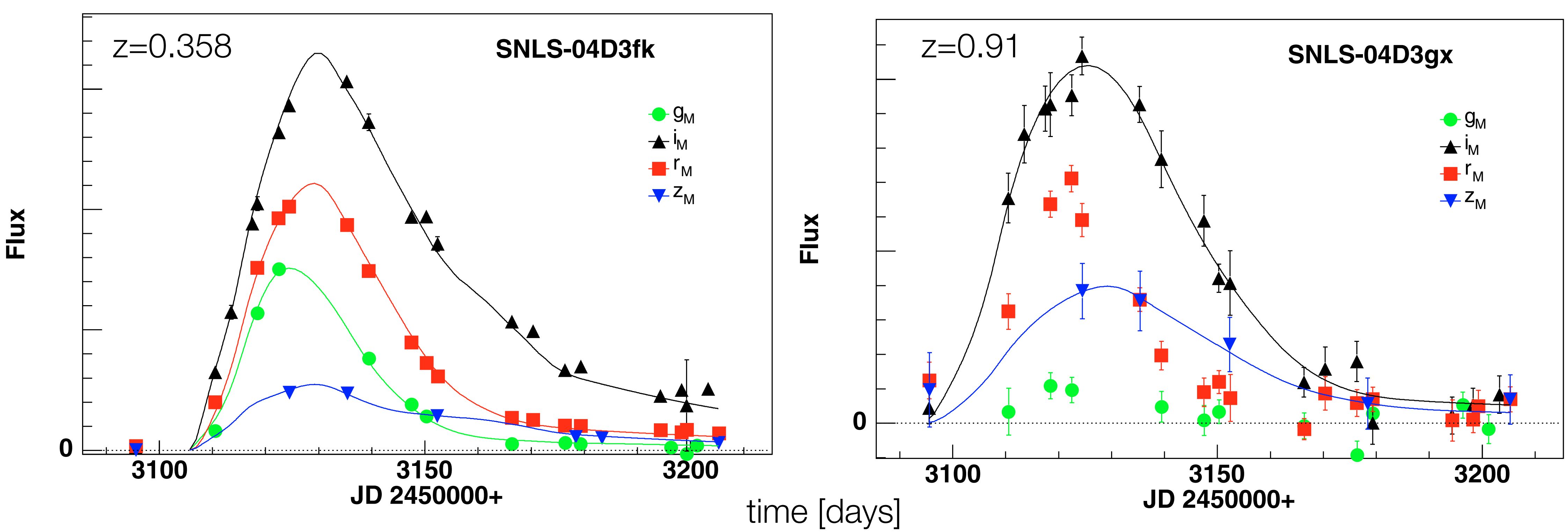
Supernovae of type Ia (SNIa)

- SNIa are thermo-nuclear explosions of a white dwarf with 1.4 solar masses
- They are standard candles: having universal intrinsic luminosity, observed luminosity only depends on distance
- Distance as function of redshift depends on expansion history of Universe



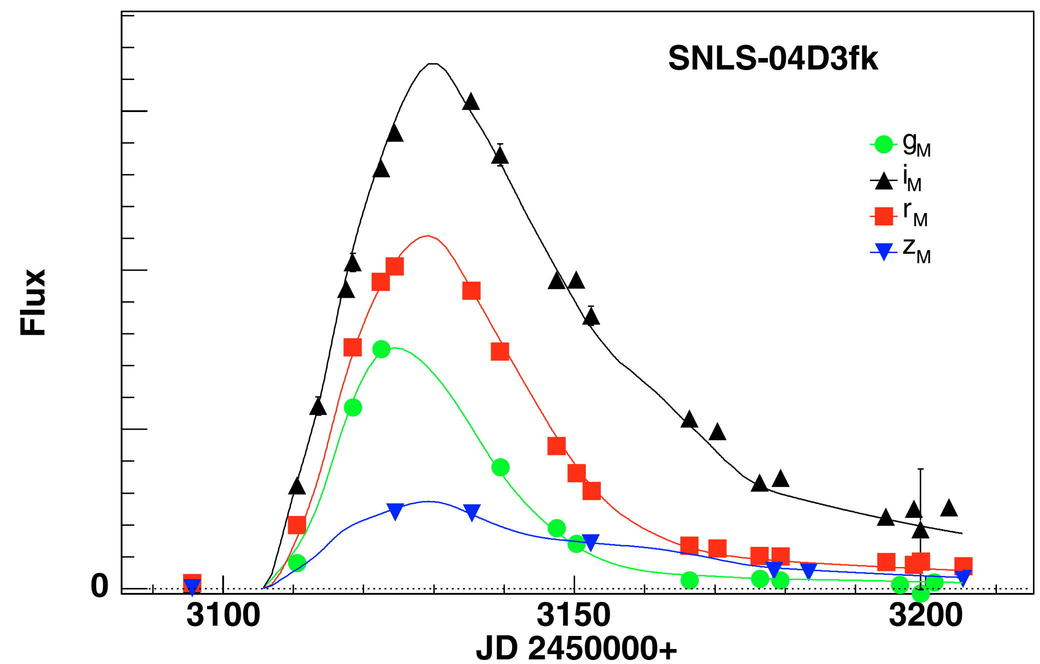
SNIa data

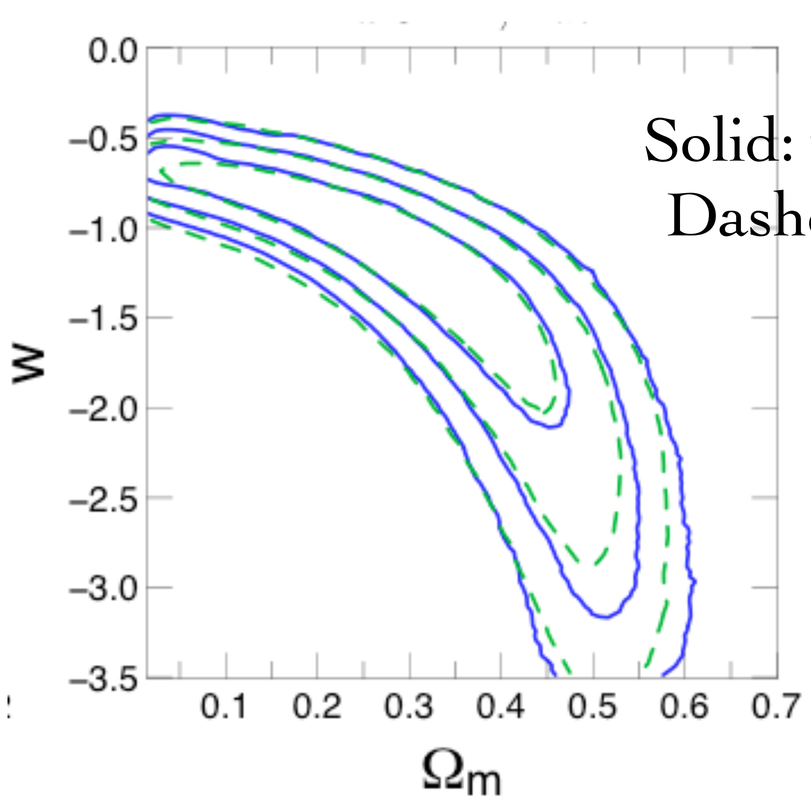
- SNLS: Supernova Legacy Survey [Astier et al. 2006]
- 1st year data: 71 distant (+ 44 nearby SNe)
- Imaging: CFHT in 5 optical bands, 4 deg^2
- Spectroscopy follow-up (for redshift, type): VTL, Gemini, Keck (8m class telescopes)



SNIa systematics: photometry

- Uncertainties in photometry
  → wrong distance estimate
  → biased cosmological parameters



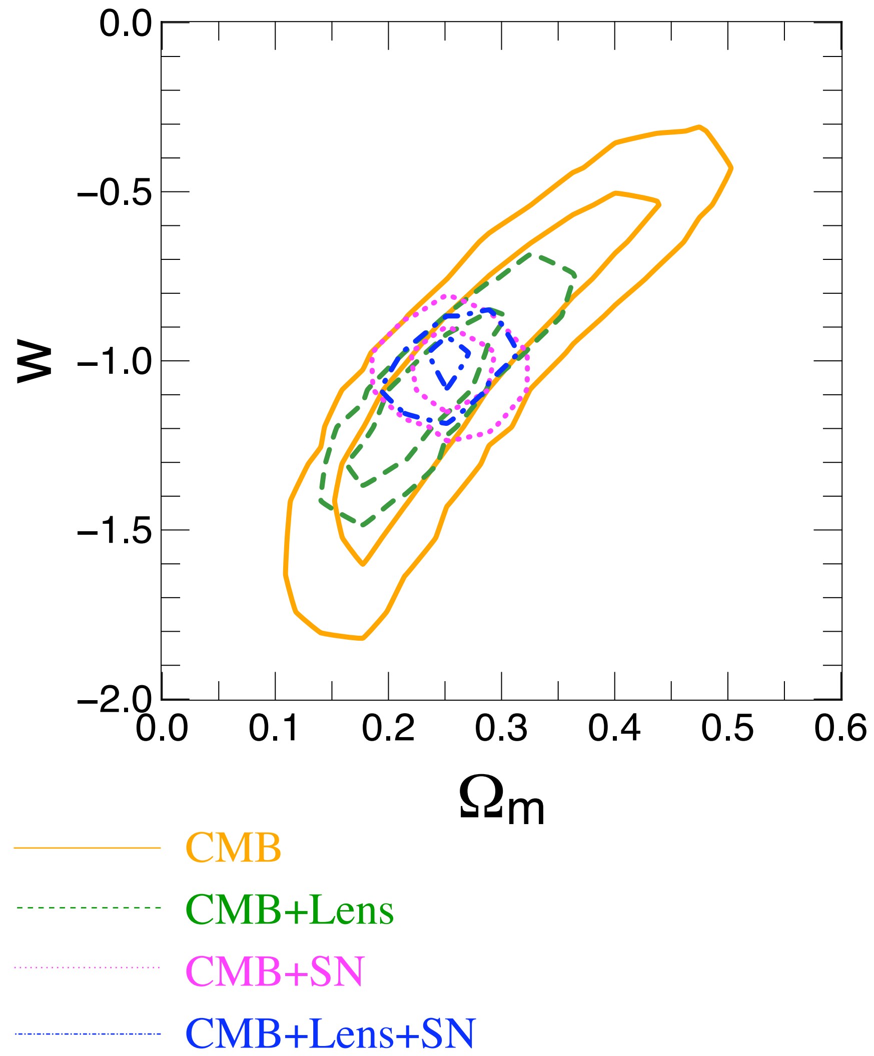


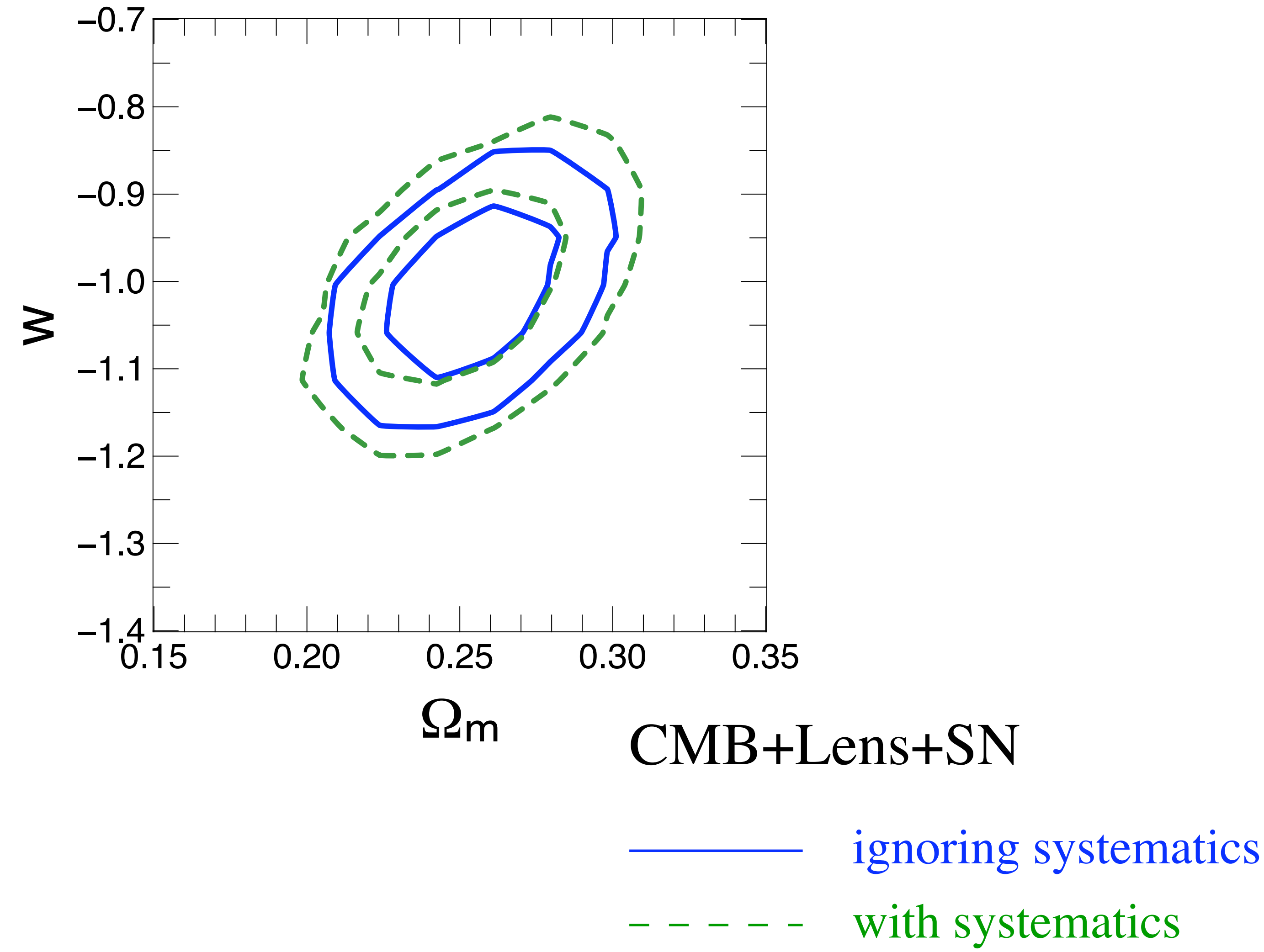
Solid: with systematics.
Dashed: ignoring sys.

Error bars underestimated by 10%-20%

	with systematics	ignoring systematics
$w(\Omega_{\rm m} = 0.25)$	$-1.00^{+0.12}_{-0.12}$	$-1.01^{+0.09}_{-0.10}$

Joint constraints on dark energy





	CMB	SNIa	BAO	lens	Lyα	clust	gal	w
MK et al. 2009	x	x		x				-0.18 < 1+w < 0.12
Mantz et al. 2009	x	x	x			x		-0.08 < 1+w < 0.04 (68%)
Seljak et al. 2005	x	x			x		x	-0.08 < 1+w < 0.10
Komatsu et al. 2008	x	x	x					-0.11 < 1+w < 0.14
Jarvis et al. 2006	x	x		x				-0.10 < 1+w < 0.27
Wang & Mukherjee 2006	x	x					x	-0.17 < 1+w < 0.16

SNIa systematics: dust absorption

- Dust (in Milky Way, inter-galactic medium, SN host galaxy) absorbs light, SNIa dimmer, has to be corrected for

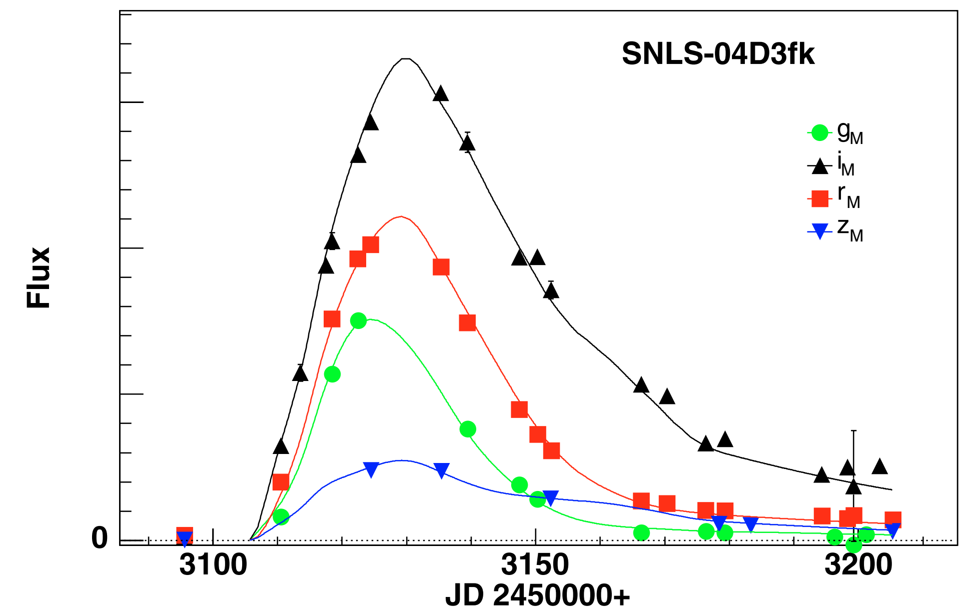
- More absorption at shorter wave-lengths (bluer bands)

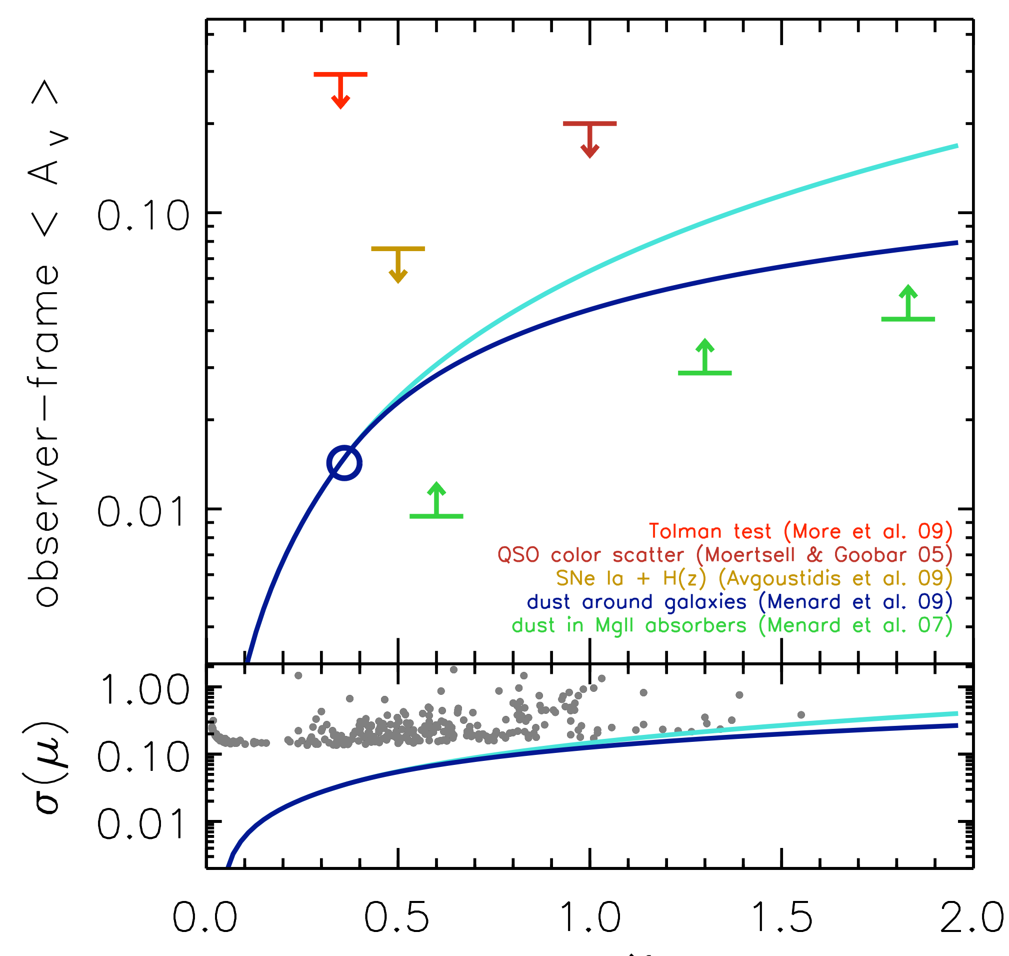
- Linear correction:

  Δ(brightness) = β × color

  β depends on dust properties

- Up to now:
  - color correction due to one dust comp.
  - inter-galactic medium neglected

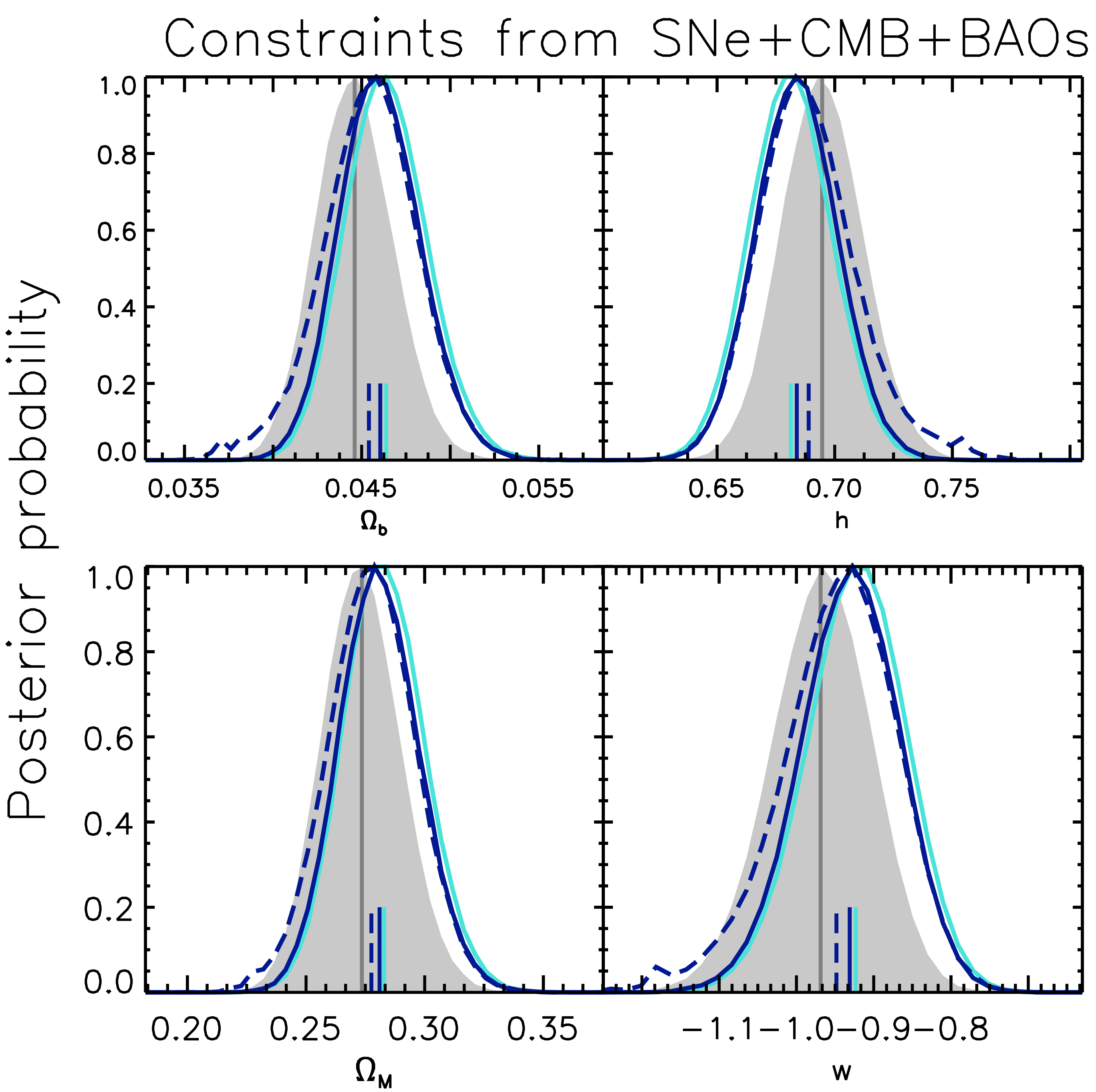




[Menard et al. 2009]

SNIa systematics: dust absorption

- β = 2.0 ... 2.5 up to now
- Menard et al. 2009:
  $\beta_{IGM} = 4.9 \pm 2.6$
- Ignoring this dust component leads to shifts in cosmological parameters
- Δw = 0.02 - 0.03, 25% to 30% of statistical error
- In future:
  - corrrection object by object
  - infrared less affected



[Menard, MK, Scranton 2009]

Model selection

- Traditional parameter estimation:
  Q: For a specific model with n parameters which is the most likely (best-fit) parameter and confidence interval given the data?
- Model selection:
  Q: Which of two or more models with parameters n_1, n_2, ... is the most likely to fit the data?
- Examples in cosmology:
  - ★ cosmological constant Λ vs. dark energy vs. modified gravity
  - ★ flat vs. curved
  - ★ Primordial fluctuations: scale-free (n_s=1) vs. n_s=const vs. running $n_s(k)$
- Other applications (Cluster profile reconstruction, exo-planets, ...)

Bayesian evidence

- Bayes' theorem

Likelihood, Prior

$$p(m,\theta|d) = \frac{\mathcal{L}(d|\theta,m)\pi(\theta|m)}{E(d|m)}$$

Posterior, Evidence

$m:$ model

$d:$ data

$\theta:$ model parameter

Posterior is normalised

$$E(d|m) = \int \mathrm{d}^n\theta\, \mathcal{L}(d|\theta,m)\,\pi(\theta|m)$$

- Bayes factor

$$B_{12} = \frac{E(d|m_1)}{E(d|m_2)}$$

- Ratio for two models m_1 and m_2:

$$\frac{p(m_1|d)}{p(m_2|d)} = B_{12}\frac{\pi(m_1)}{\pi(m_2)}$$

Jeffreys' scale

$\lvert\log_{10} B_{12}\rvert$	Odds	Strength
0 ... 0.5	1 ... 3	weak
0.5 ... 1	3 ... 10	substantial
1 ... 2	10 ... 100	strong
>2	>100	decisive

Approximations to the Evidence

- BIC (Bayesian Information Criterion) [Schwarz 1987]

$$\mathrm{BIC} = -2\ln\mathcal{L}_{\mathrm{max}} + k\ln N_{\mathrm{data}}$$

likelihood @ maximum

penalty for large parameter space
(Occam's razor)

(Similar: AIC, DIC)
Problem: Penalty independent whether parameters constrained by data or not

- Laplace approximation: likelihood Gaussian, priors large and uniform

[Lazarides, Ruiz de Austri & Trotta 2004, Heavens, Kitching & Verde 2007]

$$E \approx (2\pi)^{n/2}|F|^{-1/2}(\Delta\theta_1\ldots\Delta\theta_n)^{-1}\mathcal{L}_{\mathrm{max}}$$

volume allowed by data   initial volume (prior)

Occam's razor

Laplace: prios might be small (physical parameter boundaries)

Fisher matrix not good approx.

Monte-Carlo methods

- MCMC?
  Chain stays around high-likelihood, large regions of parameter space under-sampled.

- New method: PMC (Population MonteCarlo) [Cappé et al. 2004, 2007; Wraith, MK et al. 2009]

- Efficient integration over posterior:

$$\int \mathrm{d}^n\theta \, h(\theta)\mathcal{L}(\theta)\pi(\theta)$$

$$\begin{aligned} h(\theta) &= 1 : && \text{evidence} \\ h(\theta) &= \theta : && \text{mean} \\ h(\theta) &= 1_{68\%} : && \text{confidence region} \end{aligned}$$

Importance sampling

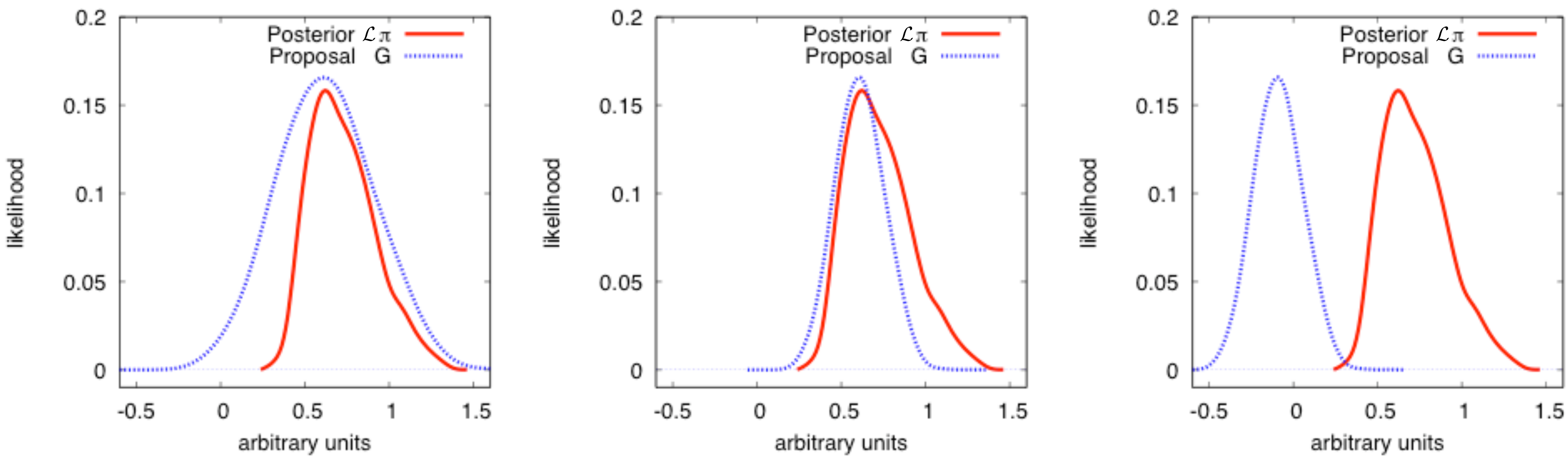
- Rewriting the integral:

$$\int \mathrm{d}^n\theta\, h(\theta)\mathcal{L}(\theta)\pi(\theta) = \int \mathrm{d}^n\theta\, h(\theta)\frac{\mathcal{L}(\theta)\pi(\theta)}{G(\theta)}G(\theta)$$

$$= \frac{1}{N}\sum_{\theta_i\sim G} h(\theta_i)\frac{\mathcal{L}(\theta_i)\pi(\theta_i)}{G(\theta_i)} = \sum_{\theta_i\sim G} h(\theta_i)\bar{w}_i$$

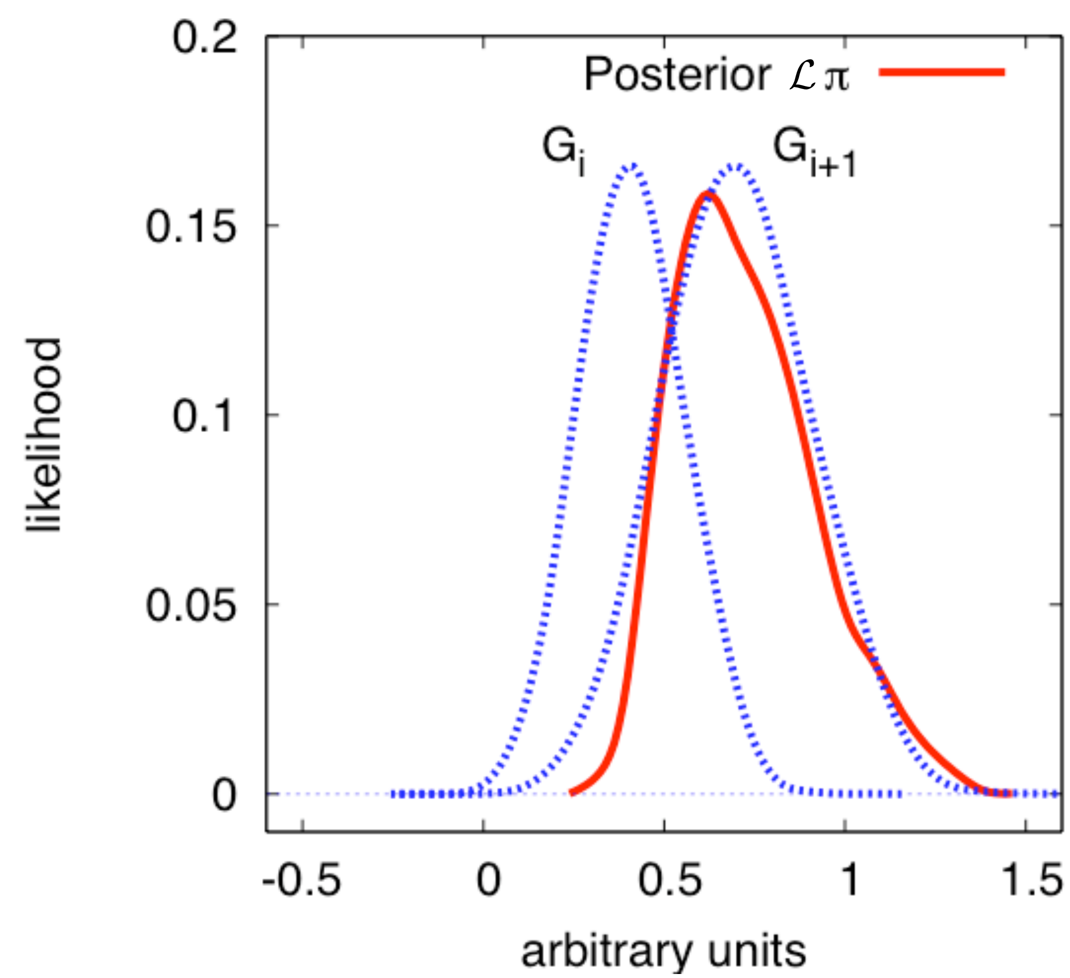
normalised importance weights

- *G*: Proposal distribution, easy to sample from (mixtures of Gauss, Student-t, ...)



Population MonteCarlo (PMC)

- Importance sampling performs poorly if proposal far from posterior
- Solution: adaptive importance sampling aka Population MonteCarlo
[Cappé et al. 2004, 2007]
- Iterative update of proposal G_i -> G_{i+1}
- Stop iterations when proposal and posterior 'close enough': Kullback-Leibler divergence



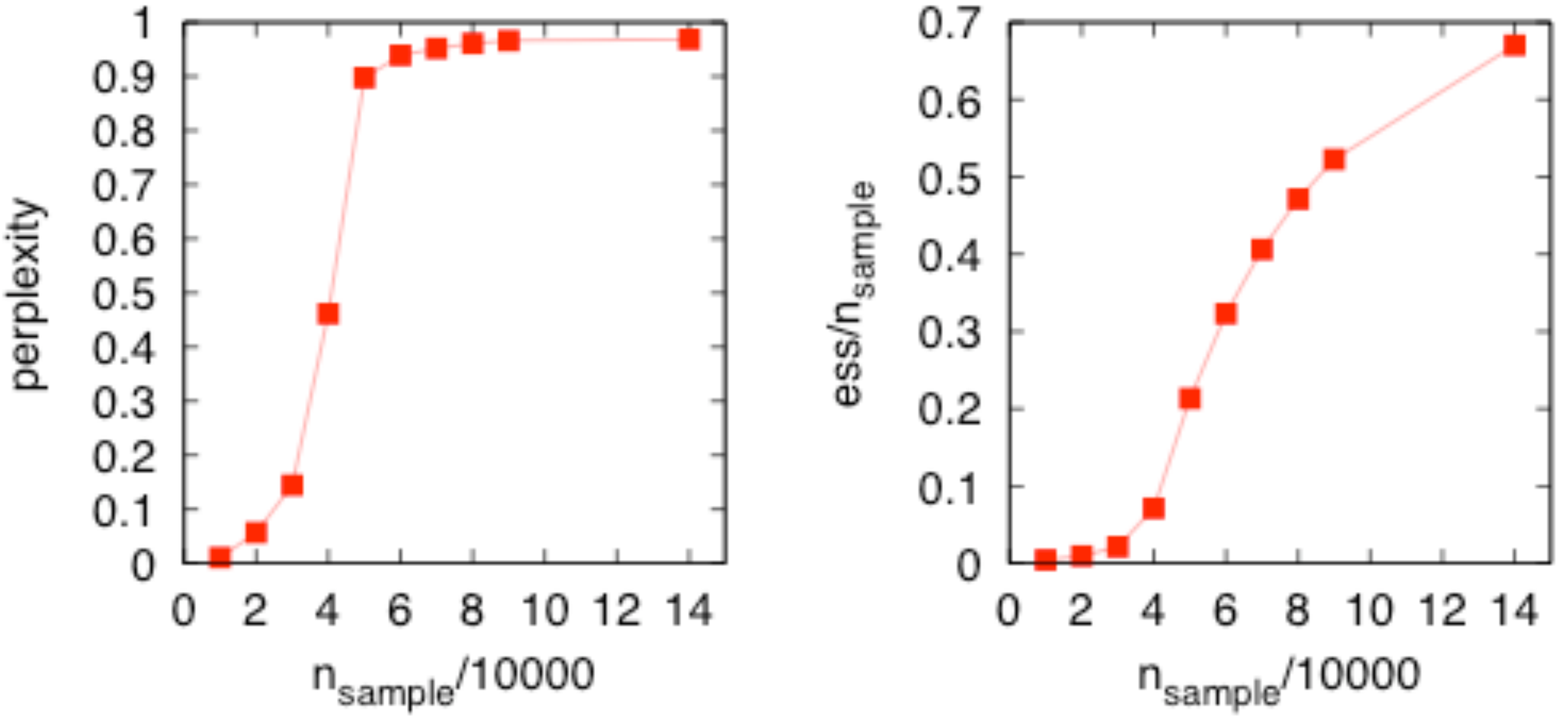
$$K = \int \mathrm{d}^n\theta \, \log\left[\frac{\mathcal{L}(\theta)\pi(\theta)}{G(\theta)}\right] \mathcal{L}(\theta)\pi(\theta)$$

$$K = \int \log\left[\frac{\mathcal{L}(\theta)\pi(\theta)}{G(\theta)}\right] \frac{\mathcal{L}(\theta)\pi(\theta)}{G(\theta)} G(\theta)\mathrm{d}\theta \approx \sum_{\theta_i \sim G} \log[\bar{w}_i]\, \bar{w}_i$$

PMC Performance

- Perplexity $p = \exp[-K]/N; \;\; p = 0 \ldots 1$

WMAP5 posterior, flat ΛCDM model, 6 parameters

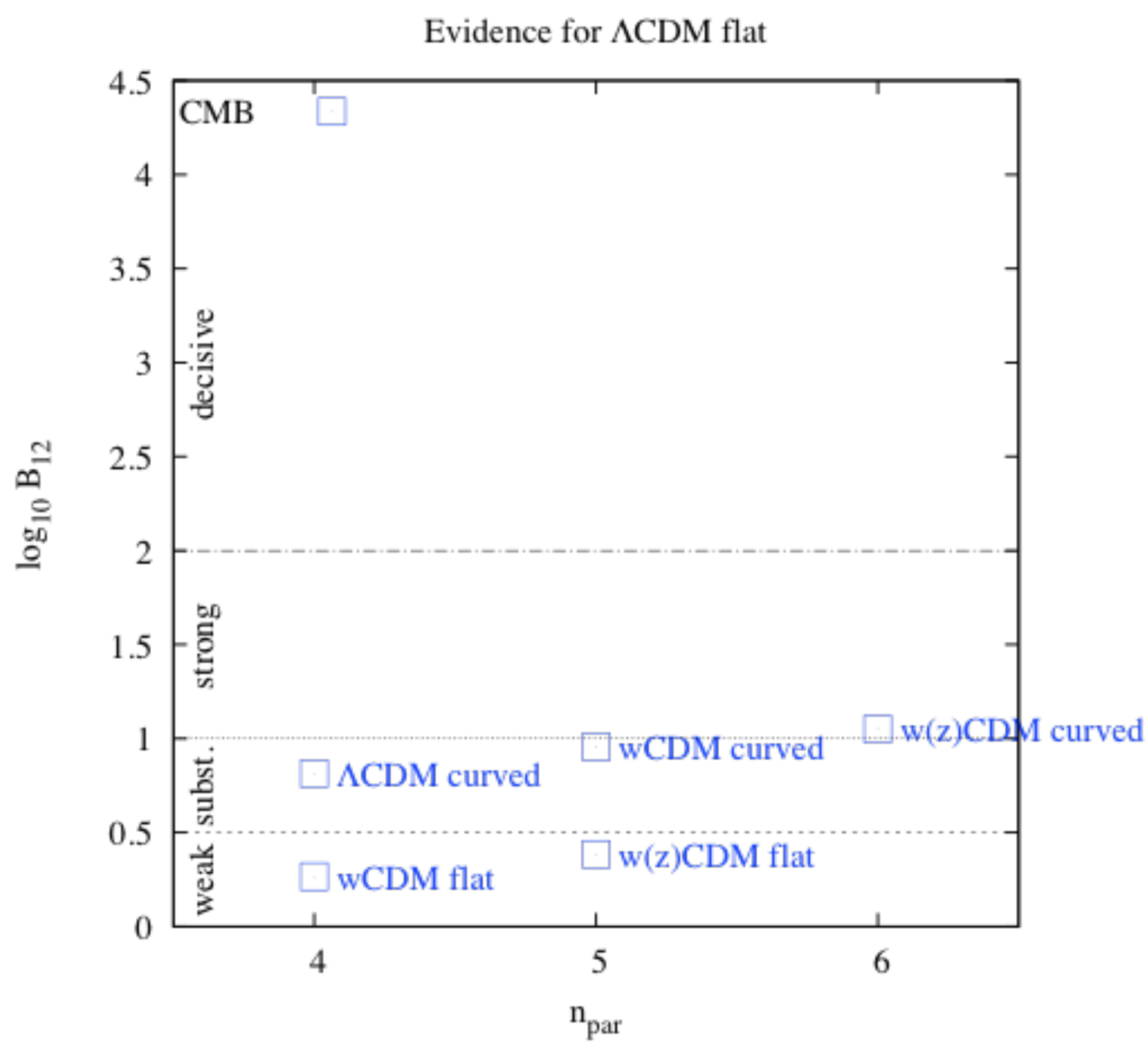


10 iterations

[Wraith, MK et al . 2009]

CMB+SNIa+BAO: Dark energy, curvature

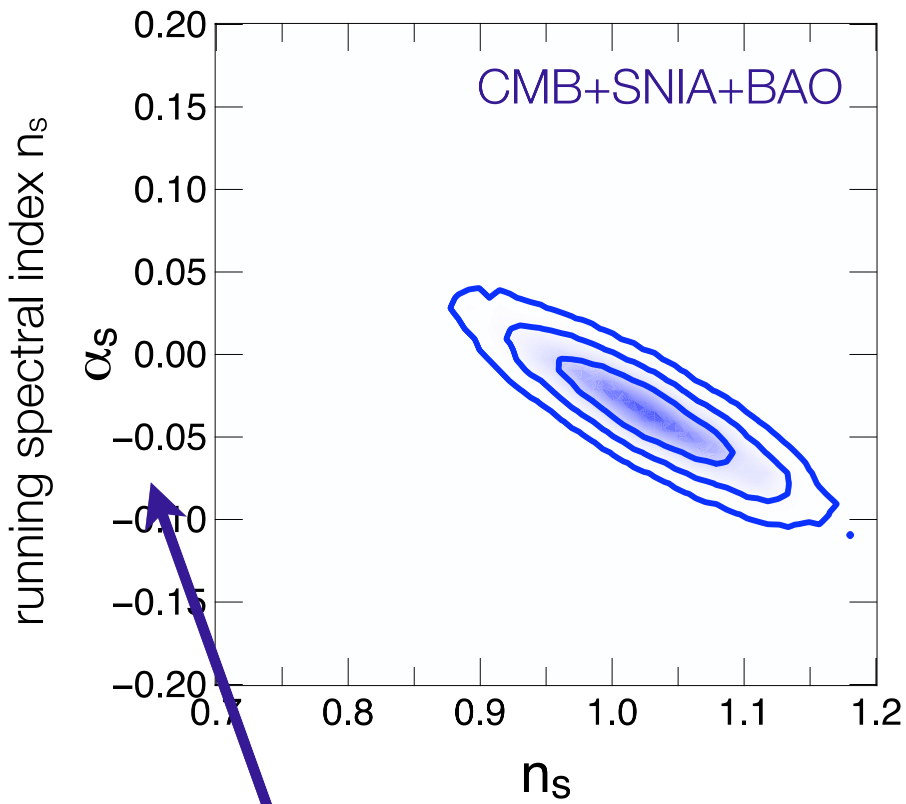
- Base model: flat ΛCDM, n_{par}=3 $(\Omega_\mathrm{m}, \Omega_\mathrm{b}, h)$
  Data: pure geometrical probes (WMAP5 distance priors, SNIa, BAO)

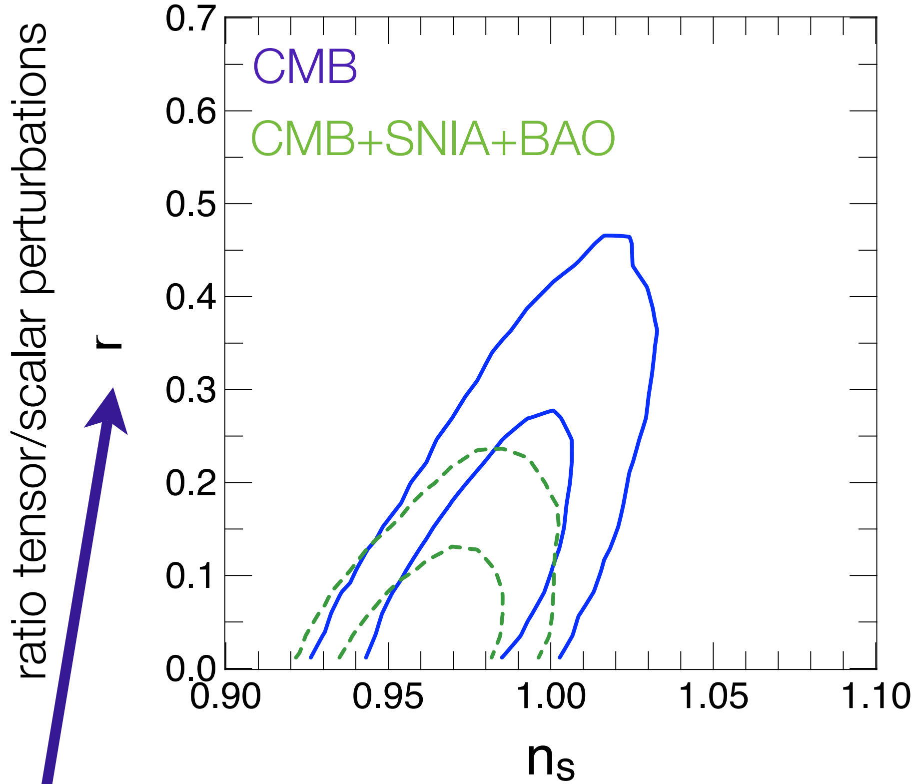


[MK, Wraith et al. in prep]

CMB+SNIa+BAO: Primordial perturbations

Primordial matter power spectrum:
$P_\delta(k) \propto k^{ns}$





Model	n_{par}	$\log E$
$n_S = 1$(HZ)	5	0.396
$n_S =$const	6	0.000
running	7	0.528
tensor	7	-1.599

Jeffreys' scale

$\lvert\log_{10} B_{12}\rvert$	Odds	Strength
0 ... 0.5	1 ... 3	weak
0.5 ... 1	3 ... 10	substantial
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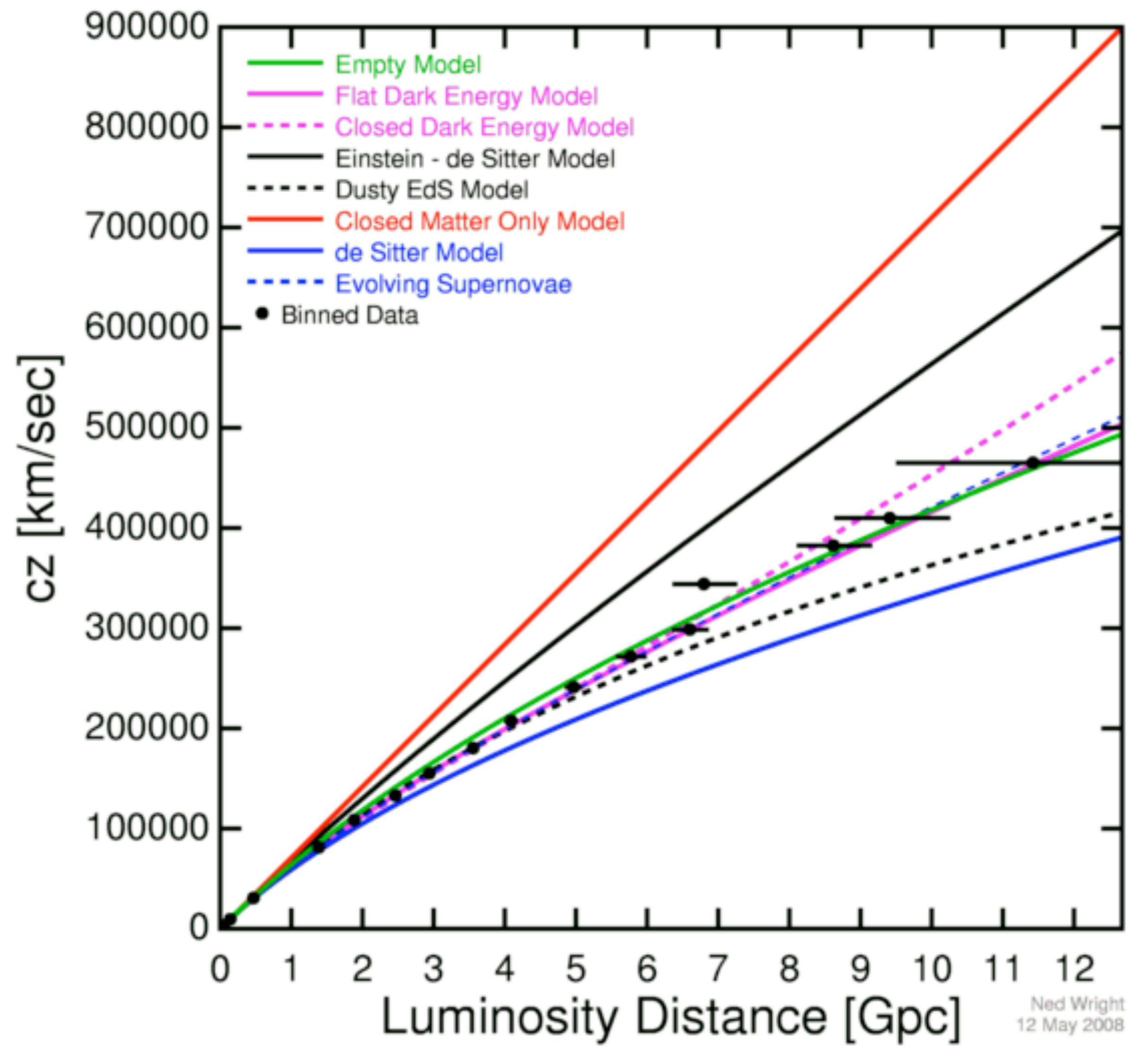
Summary & Conclusions

- Need multi-probe experiments to probe recent accelerated expansion of the Universe
  - ★ Control of systematics (e.g. dust absorption in SNIa, need large-scale structure observations)
  - ★ Distinguish between MoGR and dark energy
- Bayesian evidence
  - ★ powerful method to compare models
  - ★ important to design future experiments


900000
800000
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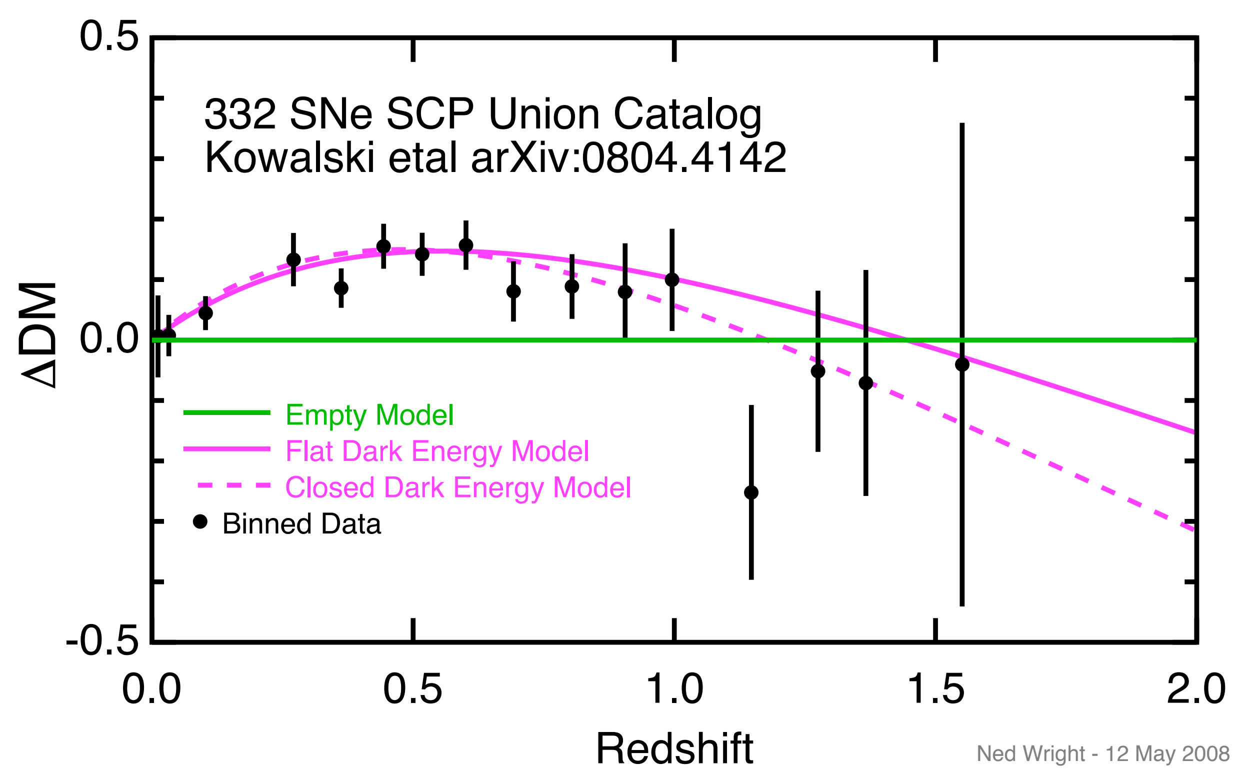
0
cz [km/sec]
Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned Data
0 1 2 3 4 5 6 7 8 9 10 11 12
Luminosity Distance [Gpc]
Ned Wright
12 May 2008


332 SNe SCP Union Catalog
Kowalski etal arXiv:0804.4142
0.5
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ΔDM
Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Binned Data
0.0 0.5 1.0 1.5 2.0
Redshift
Ned Wright - 12 May 2008