Figures of merit for the dark energy program

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Based on *Observational Probes of Cosmic Acceleration*, by DW, Michael Mortonson, Daniel Eisenstein, Chris Hirata, Adam Riess, Eduardo Rozo, in prep. for *Physics Reports*.

Plots in this presentation made by Michael Mortonson and Chris Hirata, including new calculations by Hirata.

Cosmic Acceleration

Two top-level questions:

1. Is cosmic expansion accelerating because of a breakdown of GR on cosmological scales or because of a new energy component that exerts repulsive gravity within GR?
2. If the latter, is the energy density of this component constant in space and time, consistent with fundamental vacuum energy?

General approach: Measure the expansion history and structure growth history with the highest achievable precision over a wide range of redshifts.

H(z) = expansion rate, D(z) = distance, G(z) = growth factor

Improve from 5% (now) to 1% (2018) to 0.1% (2025).

Friedmann Eqn. $$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\phi \frac{\rho_\phi(z)}{\rho_{\phi,0}}\right]^{1/2}$$

Matter Curvature Dark Energy

$$\frac{\rho_\phi(z)}{\rho_{\phi,0}} = \exp\left[3\int_0^z [1+w(z')]\,d\ln(1+z')\right] = (1+z)^{3(1+w)}$$

Comoving line-of-sight and angular diameter distances:

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}, \qquad D_A \approx D_C + \frac{1}{6}\Omega_k \left(\frac{c}{H_0}\right)^{-2} D_C^3$$

Growth rate of linear fluctuations:

$$\frac{G(z)}{G_0} \approx \exp\left(-\int_0^z \frac{dz'}{1+z'}\left[\Omega_m (1+z)^3 \frac{H_0^2}{H^2(z)}\right]^\gamma\right), \quad \gamma \approx 0.55$$

DETF FoM $= [\sigma(w_p)\sigma(w_a)]^{-1}$ where $w(a) = w_p + w_a(a_p - a)$.

Growth parameters: index deviation $\Delta\gamma$, multiplicative offset G_9

Leading Methods

Supernovae: D(z)

Ambitious Goal: 0.005 mag mean errors (0.25% in distance), statistical + systematic, in bins of $\Delta z = 0.2$ out to $z = 0.8$

Key systematics: photometric calibration, extinction, evolution

Baryon Acoustic Oscillations: D(z) and H(z)

Ambitious goal: Survey ¼ of the comoving volume to $z = 3$

Probably statistics limited, but non-linear corrections required

Weak Lensing: D(z) and G(z)

Ambitious goal: Achieve statistical limits of a 10^9 galaxy survey.

Key systematics: shape measurement calibration, photometric redshift calibration, intrinsic alignments

Keeping systematic ~ statistical requires control at $\sim 5\times10^{-4}$ level

Goals roughly those of Astro2010 CFP. Ambitious, but not maximal.

The WFIRST Contribution

Supernovae: D(z)

- Key systematics: photometric calibration, extinction, evolution
- Space-based photometric calibration with stable, sharp PSF
- Rest-frame near-IR: low extinction, homogeneous SN properties

Baryon Acoustic Oscillations: D(z) and H(z)

- Probably statistics limited
- Access to huge comoving volume at $z > 1.2$, hard from ground

Weak Lensing: D(z) and G(z)

- Key systematics: shape calibration, photo-z's, intrinsic alignment
- Keeping systematic ~ statistical requires control at ~ 5×10^{-4} level.
- IR photometry for photo-z's.
- Stable, high-resolution imaging.
- Coordinated program with LSST – combined optical/IR photo-z's, independent shape measurements allowing crucial cross-checks.

Complementarity of methods

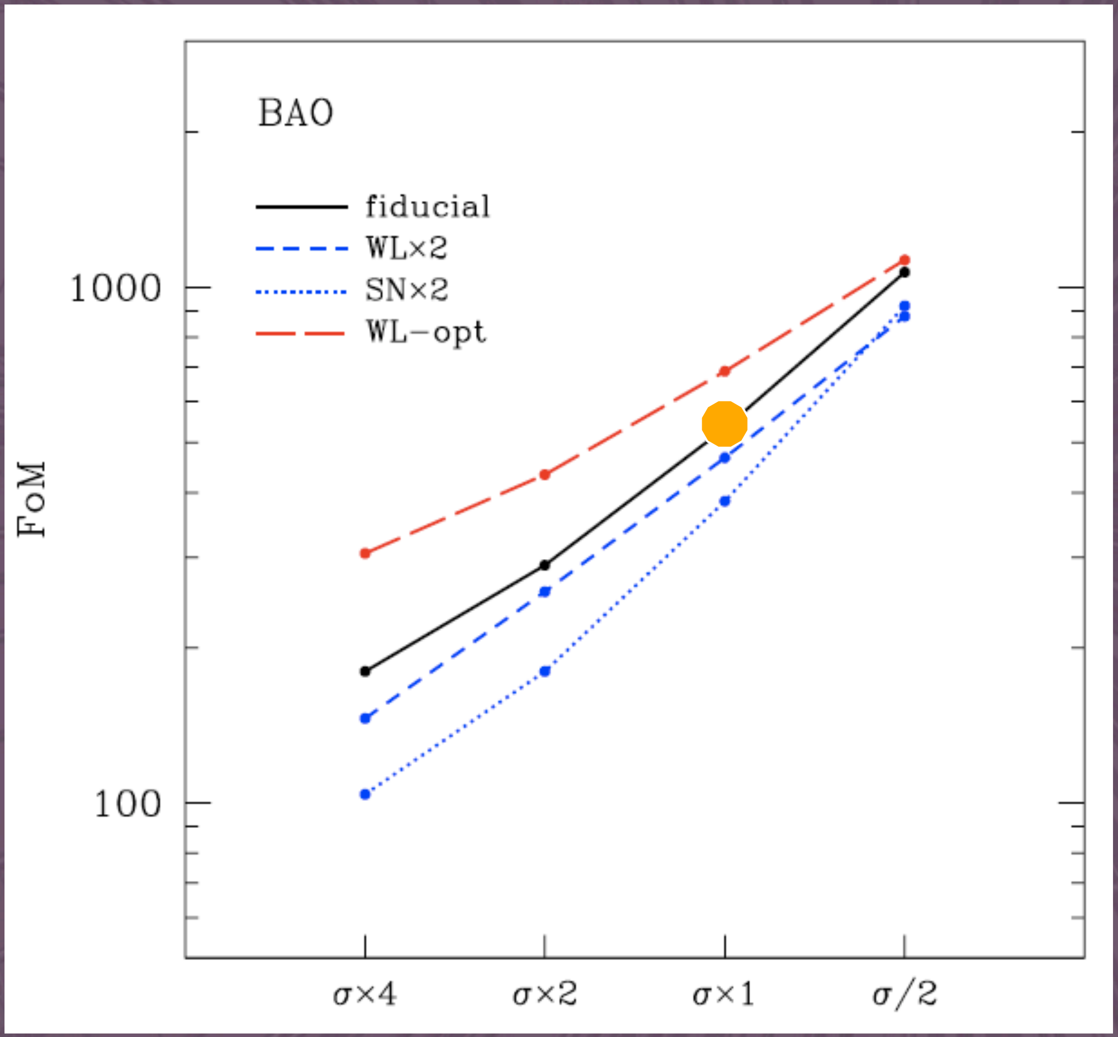
Supernovae have unbeatable precision at low redshift (roughly $z \leq 0.6$). Measure distances in h^{-1} Mpc.

Cosmic variance limited BAO precision increases to higher redshift, where there is more comoving volume. Measure distances in Mpc. Also measure H(z) directly.

Weak lensing measures growth of structure, as well as distance-redshift relation.

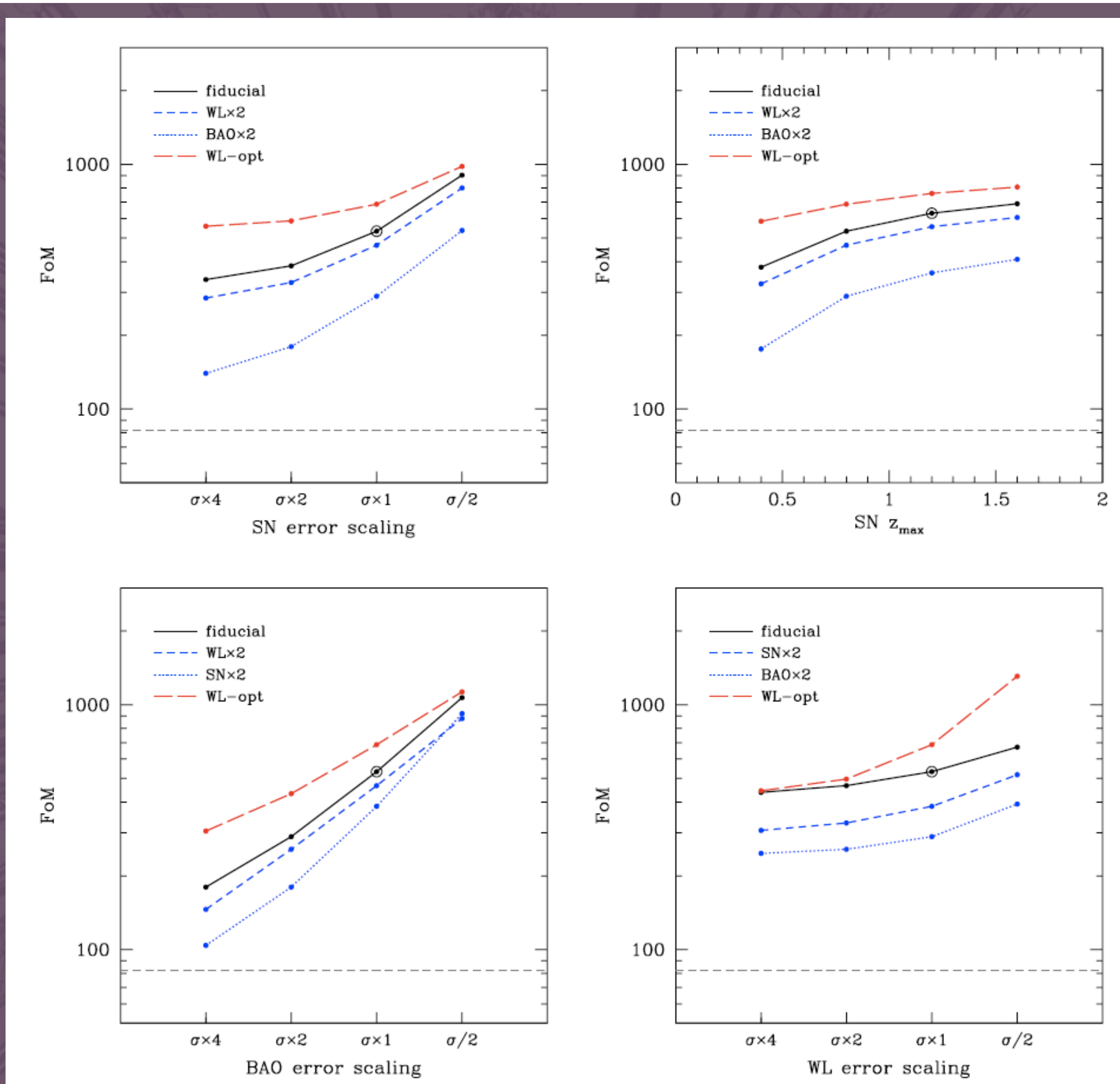
Systematic uncertainties of the three methods are different.

Forecasts of FoM = $[\sigma(w_p)\,\sigma(w_a)]^{-1}$ for a "fiducial" Stage IV program.

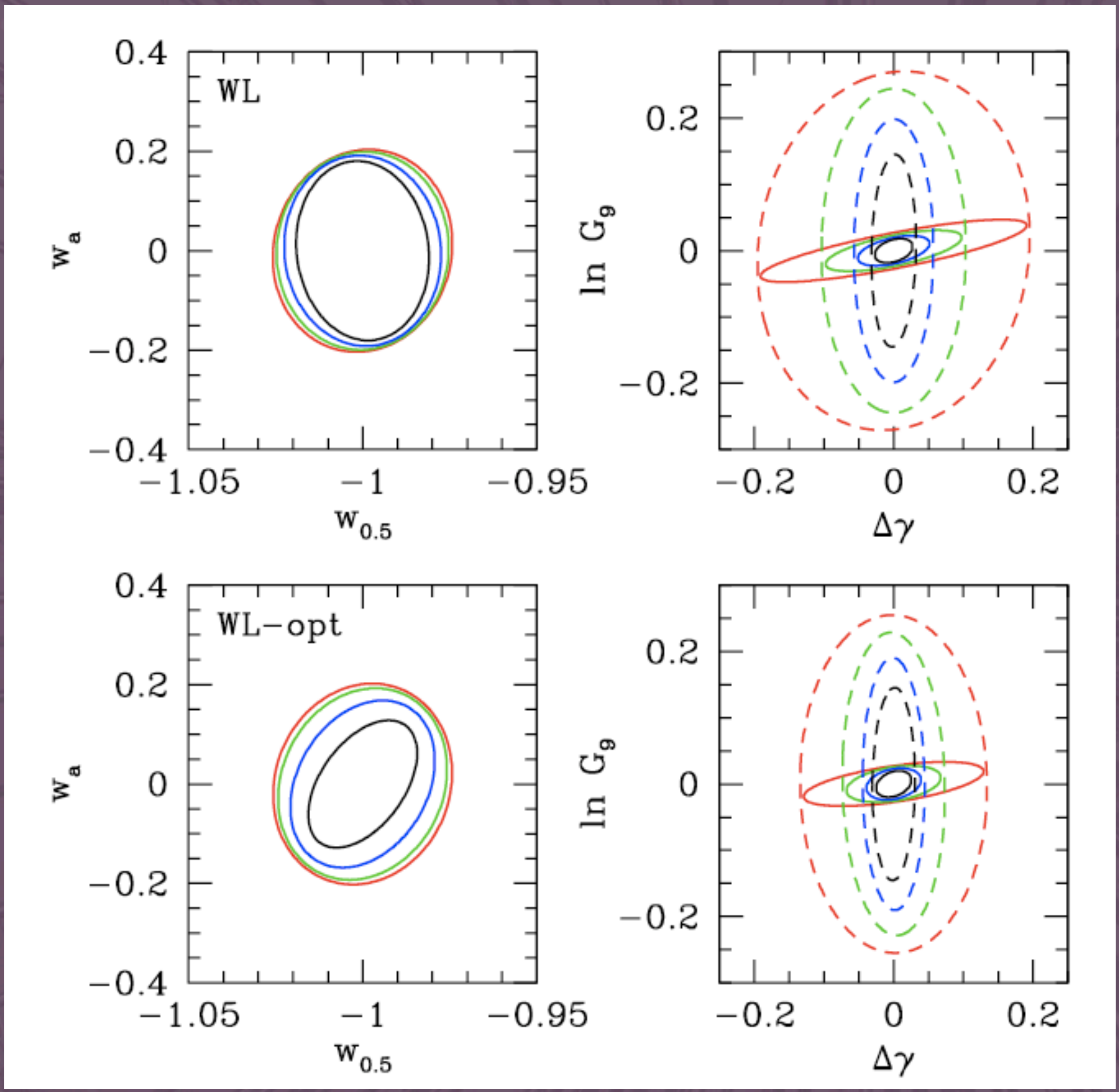


Multiplying factor for BAO errors

- Fiducial SN: 0.01 mag errors, uncorrelated, in bins of $\Delta z = 0.2$, out to $z_{max} = 0.8$
- Fiducial BAO: Errors of 1.8 × cosmic variance out to $z = 3$, for $f_{sky} = 0.25$.
- Fiducial WL: 10^4 deg^2, 23 gals. $arcmin^{-2}$ (total of 8.3e8 gals), shear calibration and photo-z calibration errors of 2×10^{-3}
- WL-opt has same gal numbers, total errors 2 × statistical errors

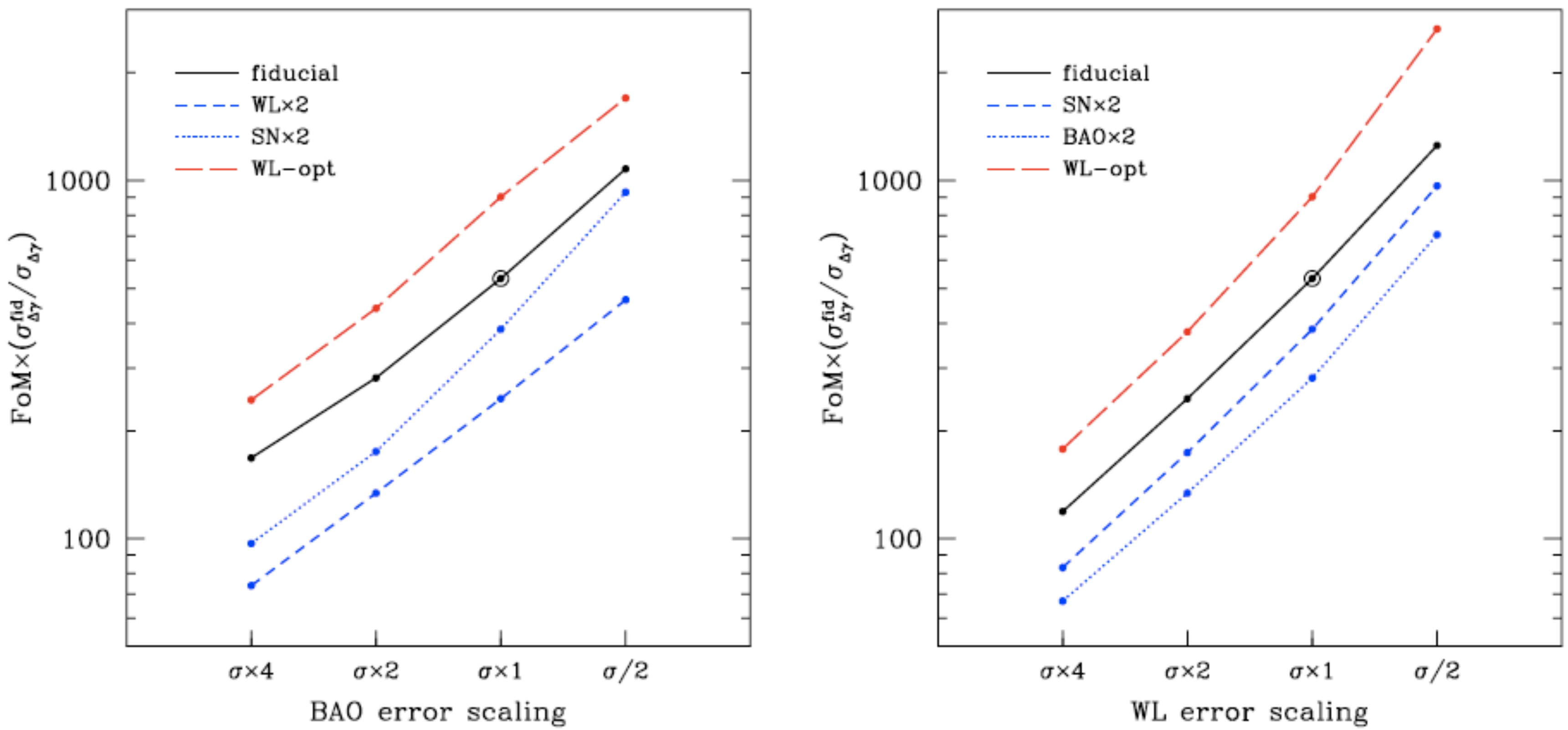


"Ambitious goals" of slide 4 correspond to SN/2, BAO×1, WLopt/2.



Left: Errors on $w(z=0.5)$ and w_a for fiducial SN and BAO and fiducial WL errors scaled by ×4, ×2, ×1, /2.

Right: Errors on G_9 and $\Delta\gamma$. Solid contours assume w_0-w_a model, dashed contours a general $w(a)$ model.



DETF FoM divided by σ(Δγ)

WFIRST/JDEMΩ vs Euclid Comparisons

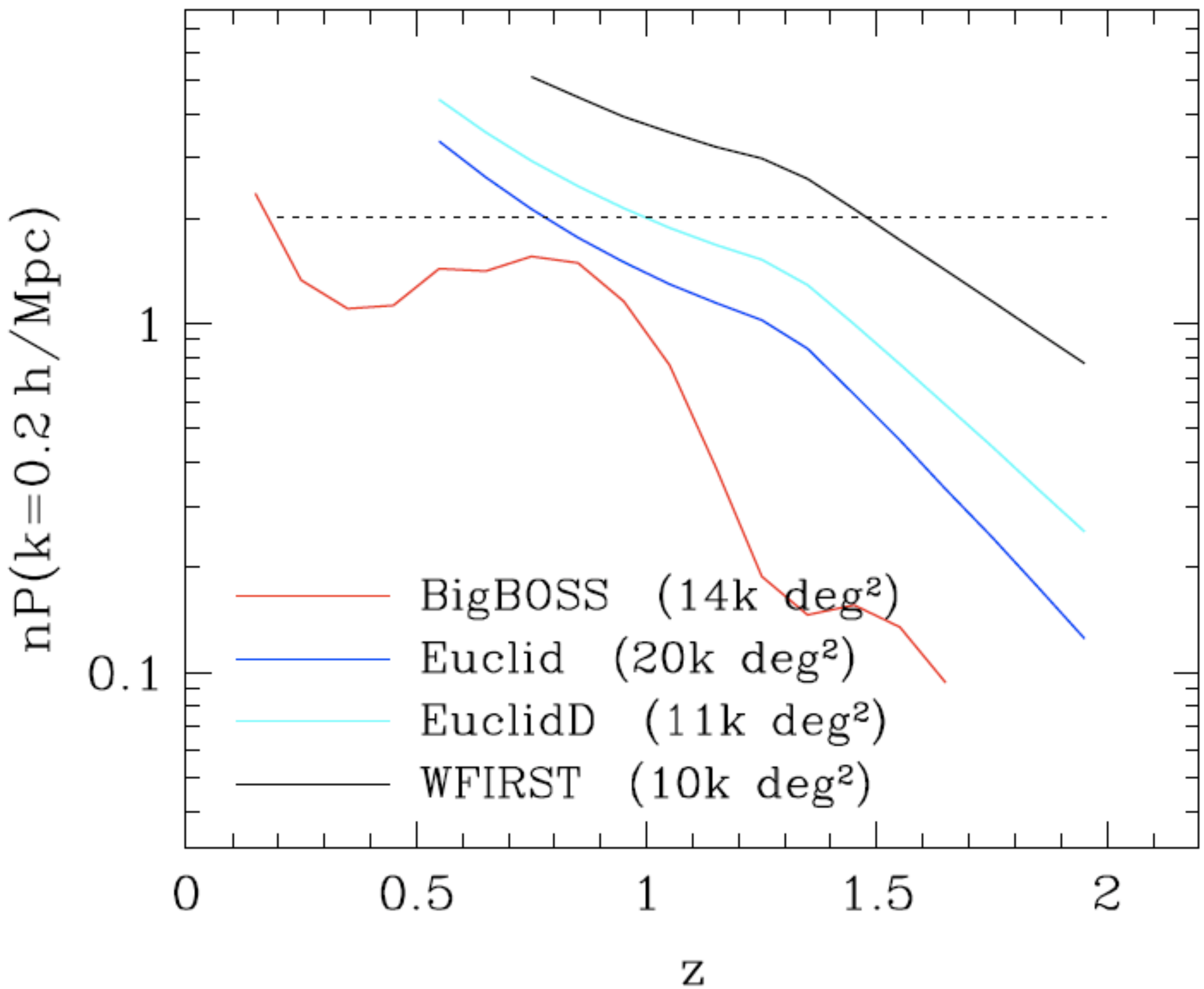
Christopher Hirata

Quick Reference Card™

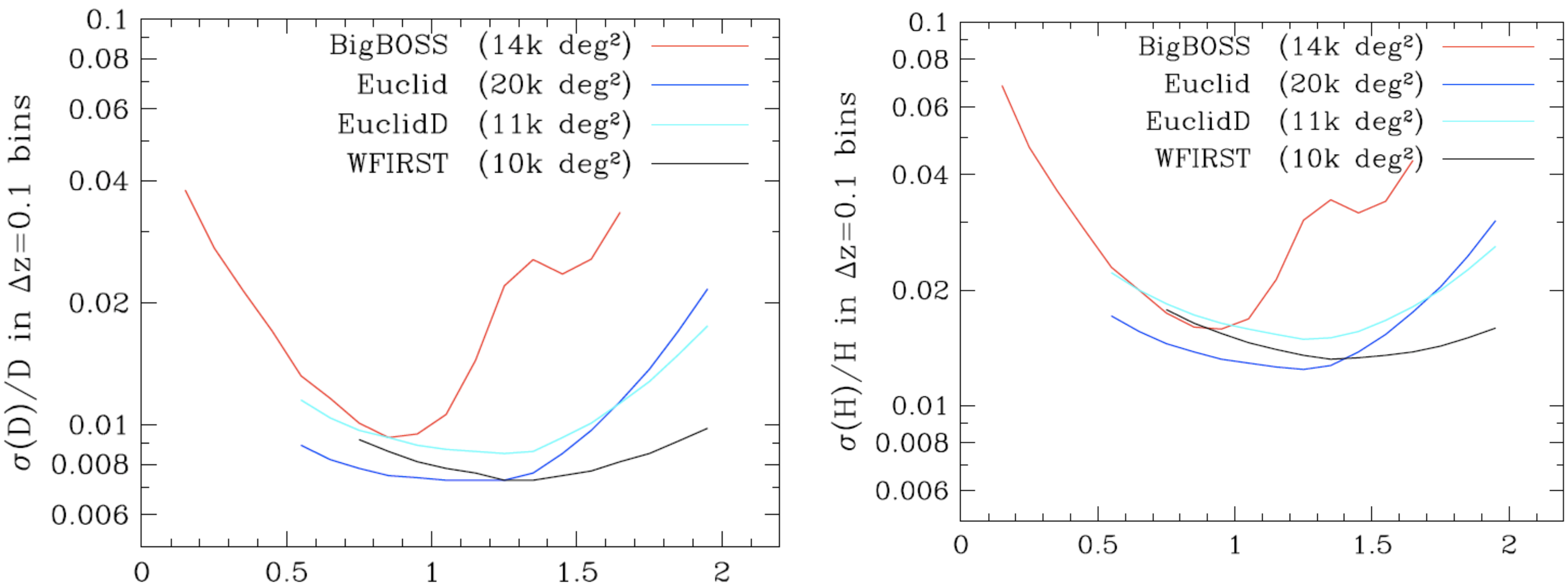
	WFIRST/JDEMΩ	Euclid
Telescope	D = 1.5 m, F = 20.6 m Folded on-axis TMA	D = 1.2 m, F = 24.5 m Folded on-axis TMA
NIR Imaging	24 2k×2k HgCdTe, 0.18" pixels with filter wheel	16 2k×2k HgCdTe, 0.3" pixels with filter wheel; refractive collimator + camera reduces focal length
Visible Imaging	No dedicated channel (WL shapes in NIR); HgCdTe detectors have response in visible	36 4k×4k CCD, 0.1" pixels Split from NIR by dichroic Currently 1 filter (0.55—0.92 μm), needs to increase
BAO Spectroscopy	2 channels: each is 6 2k×2k HgCdTe, 0.36" pixels, collimator + prism + camera (1.1—2.0 μm)	Same channel as NIR imager, grisms on wheel in collimated beam (1.0—2.0 μm)
SN Spectroscopy	Prism in imaging channel	N/A

Part I: BAO

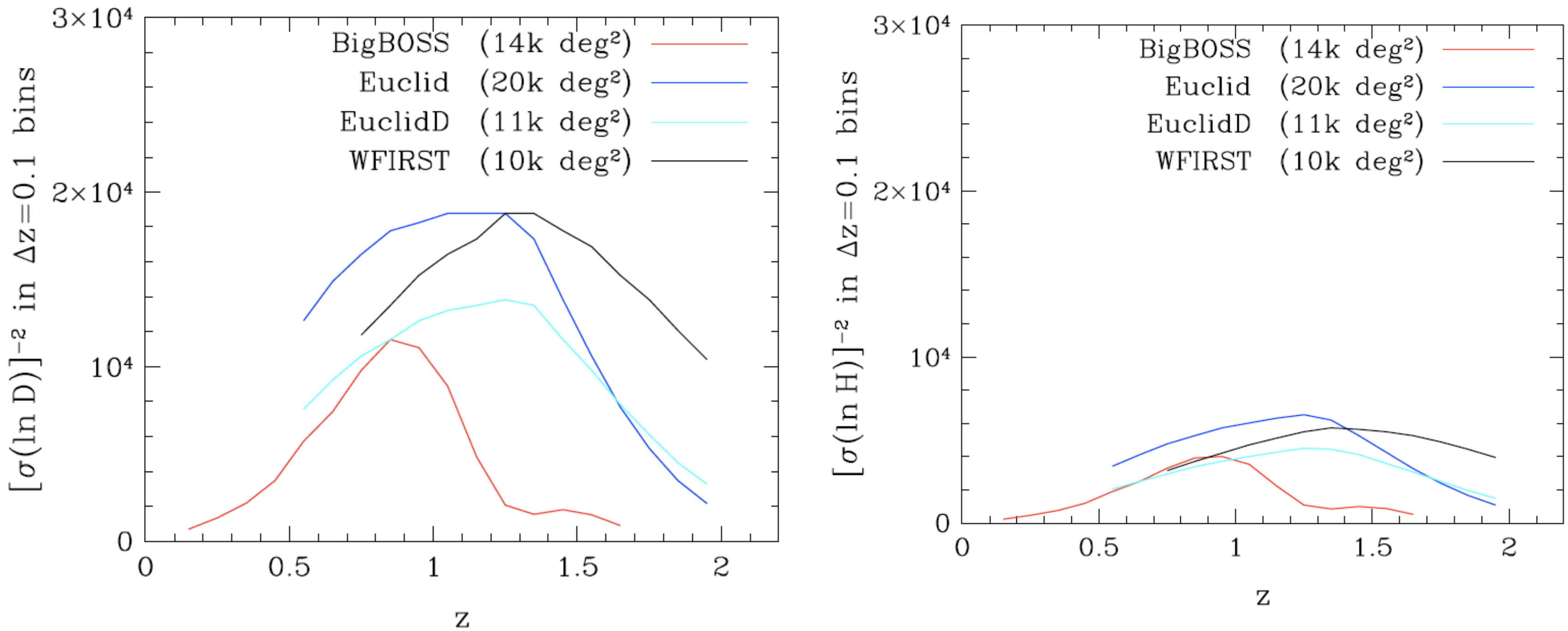
- Both cases: slitless spectroscopy to observe Hα in NIR
- JDEMΩ dedicates more resources to BAO than Euclid
  - Dedicated channels with 100% of observing time in BAO mode
  - Prism (instead of grism) increases 1^{st} order throughput, avoids background and confusion from 0^{th} order
- Flux sensitivity is also helped by:
  - Larger telescope
  - Narrower bandpass
- JDEMΩ reaches lower flux limits: 1.6×10^{-16} mW/m^2/s (Euclid: 4×10^{-16}) at similar survey rate.
- But WFIRST as presently conceived would not be a dedicated dark energy mission – e.g. with 1 year of BAO + 1 year in BAO/WL parallel mode, would get ~10k deg^2



Galaxy shot noise becomes important compared to cosmic variance at nP <~ 2.



BAO distance and H(z) errors



BAO distance and H(z) inverse variance

What's Happening?

- Euclid is suffering from low ratio of clustering:shot noise (nP) at z>1.5. This loss is rapid for limiting flux > L_*.
- Could gain this back if:
  - Sacrifice sky coverage, e.g. 20k → 10k deg^2
  - Reduce BAO λ range, e.g. 1.4—2.0 μm (lower z → ground)
- This gets Euclid down to the green curve at z>1.15. Not part of current Euclid plan, and would impose changes on WL, but may happen. WFIRST could try a similar strategy.
- All of the 3 surveys mentioned have uncomfortably thin margins. Highest nP is least sensitive to degradation.

Part II: Weak Lensing

- Euclid is a WL-optimized mission. JDEMΩ classified WL as a "goal."
- Euclid has smaller EE50 despite smaller primary and charge diffusion.
- Pixel scale: 0.1" vs 0.18".
- Imaging pixel count in shape channel: 576M vs 96M.
- Implications for:
  - Number of resolved + detected galaxies
  - Image sampling issues
  - Color dependent PSF
- Both require ground visible imaging for photo-z's. Only planned project that would fully meet this requirement over large f_{sky} (including depth and u band) is LSST. Coverage in northern hemisphere may be limited.

Depths, Number of Exposures, etc.

- JDEMΩ Fiducial survey: 150 s exposures ×4 random dithers ×3 colors (3300 deg^2/yr), 5000 deg^2 total
- Euclid: 542 s exposures (fiducial ~5000 deg^2/yr)
  - Reference case: 1 filter, ×4 random dithers (3 in chip gaps)
  - Will have to be changed to 2 filters. If restricted to LSST area, can retain number of dithers.
- Half-light radius of PSF (EE50):
  - JDEMΩ: 0.17” (F115W), 0.20” (F150W), 0.23” (F177W)
  - Euclid: 0.12” (RIZ)
  - LSST: 0.40” (r or i)
- Sampling of JDEMΩ insufficient in F115W in most of area based on Fisher analysis of reconstructing Fourier modes.
  - Euclid, IDECS, and several ISWG options pass this test.

Galaxy Yields

- Forecasts from Gary Bernstein:
  - JDEMΩ with fiducial strategy reaches n_{eff} = 22 gal/am^2.
    - Gary's ETC did not include degradation due to aliasing degeneracies so this may be too optimistic.
    - Improves to 30 for unobstructed option (D=1.3m) since more light is in central peak instead of diffraction rings.
  - Euclid reaches 30 gal/am^2 at 4 exposures.
    - Increases to 37 gal/am^2 at 7 exposures.
    - No significant aliasing degeneracies (MTF cutoff @ 0.68 cycles/pix; can measure shapes from the unaliased Fourier modes, multiple implementations possible.)

Color Dependence Issue

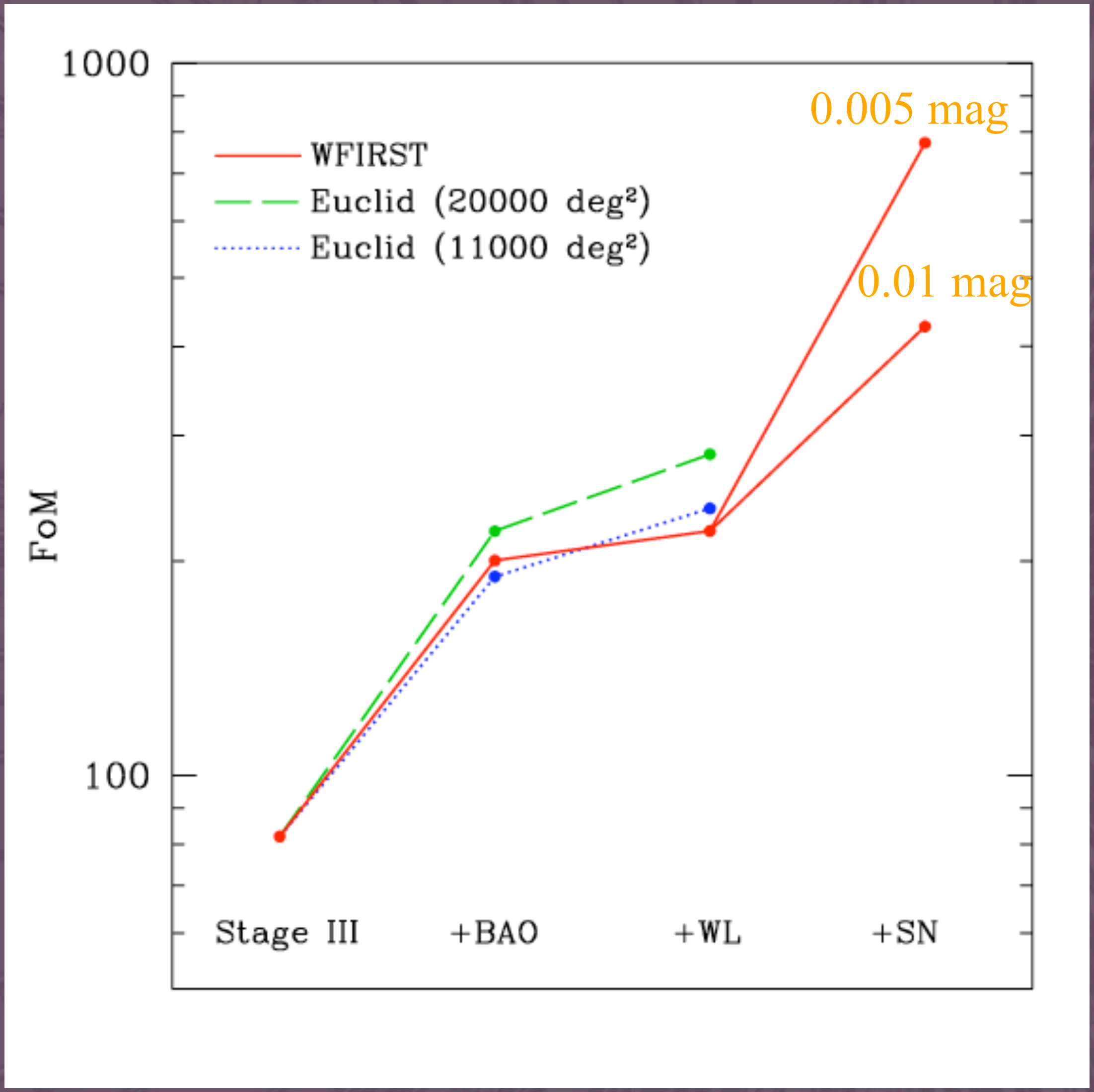
- WL shape estimation is just math; but it assumes:
  - Real space: Observed galaxy is intrinsic galaxy sheared and then convolved with PSF.
  - Fourier space: Observed FT[galaxy] is intrinsic FT[galaxy] (anti)sheared and then multiplied by FT[PSF].
- If PSF = PSF(λ), we are forced to do an operation with no unique solution.
  - Real space: The observed image is a superposition with different PSFs, must estimate SED in each pixel.
  - Fourier space: Each Fourier mode is observed through a different effective filter (higher spatial frequency = bluer). Must color-correct each Fourier mode of the galaxy.
- At least 2 filters required, mitigation techniques in progress and look promising.

Sources of λ-dependent PSF

- Diffraction spot (~λ/D)
  - Should include aberrations if present
- Turbulent seeing disk ($\sim\lambda^{-0.2}$ if Kolmogorov)
- Chromatic aberration (on both PSF centroid and size) if refractive elements are used (or atmospheric dispersion)
- Filters in a converging beam
  - Will introduce amplitude & phase dependent on λ and angle of incidence
  - This is a generic feature of interference devices
- Finite mean free path effects in CCD
  - Redder λ = longer mfp
  - Introduces chromatic defocus (low f/ratio); centroid shift (if central ray is at non-normal incidence); change in charge diffusion
  - Fringing of emission lines (perhaps not as scary)

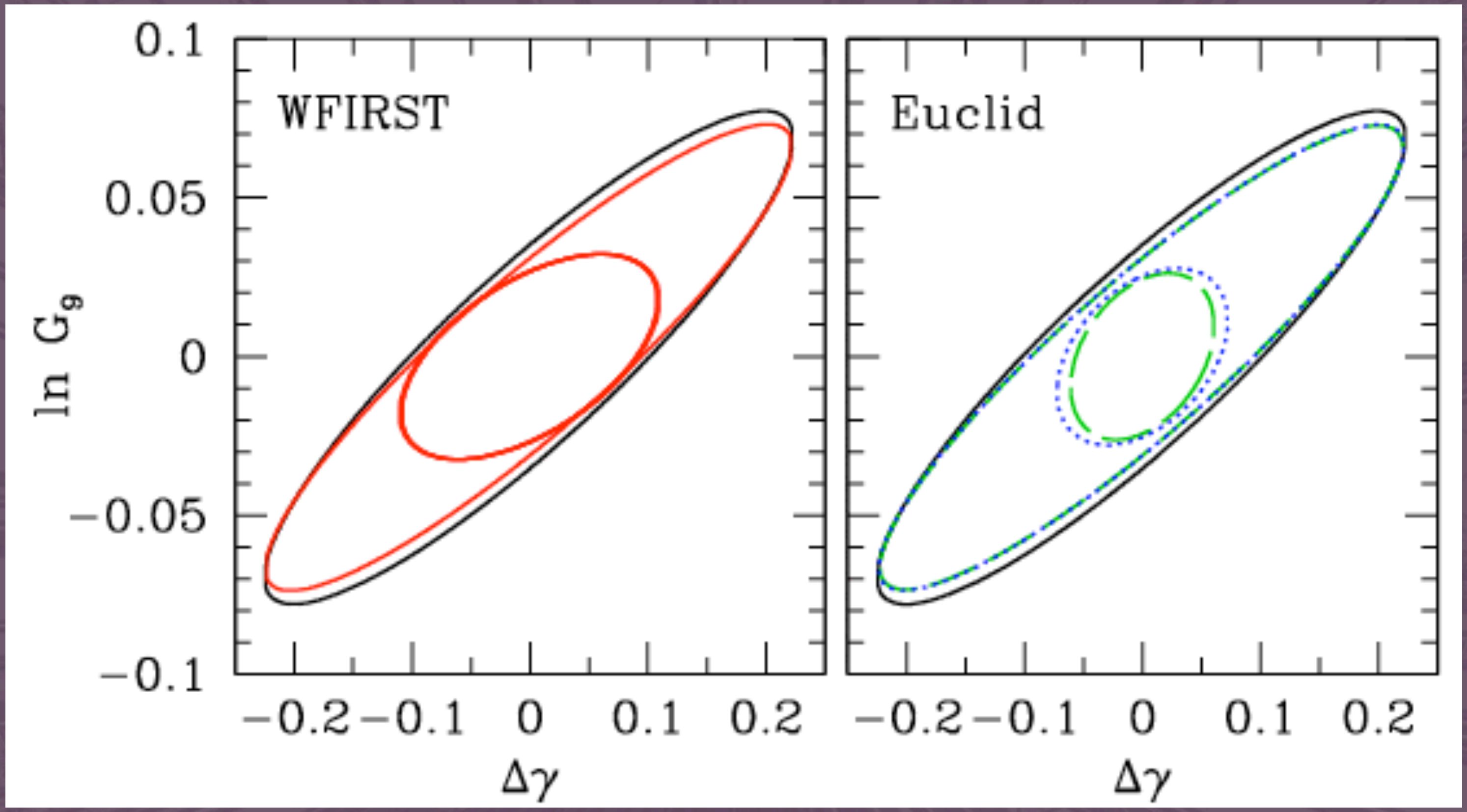
Lessons for WFIRST

- Euclid (if 2nd filter is added) is a much more powerful WL mission than JDEMΩ.
  - Remember that JDEMΩ was a descope of the SCG WL-enabled space mission (IDECS).
- If WFIRST is to do WL, the first challenge(s) is(are):
  - Need to fully sample the bluest NIR filter and may want to consider the unobstructed option. It is doubtful that EE50 = 0.20” is sufficient advance over LSST to justify space WL mission.
  - Do this while covering enough sky and not being swamped by read noise, and maintaining sufficient S/N margin.
  - If we descope JDEMΩ detector count the WL program is unlikely to be viable.



Growth of DETF FoM from adding WFIRST or Euclid programs to anticipated Stage III.

We assume Stage III SN errors of 0.03 mag (uncorrelated) in bins of $\Delta z = 0.2$ to $z_{max} = 0.8$. We assume WFIRST will decrease errors to 0.01 mag or 0.005 mag, with same z_{max}.



Adding WFIRST/Euclid constraints to Stage III. Outer contours show BAO only, inner contours show addition of WL (and SN for WFIRST). Euclid contours are for 20K deg^2 (green) or 11K deg^2 (blue).

Editorial comments: Figures of Merit

Combination of DETF FoM and $\Delta\gamma$ error gives adequate guidance. Typically $\sigma(w_a) \approx 10 \times \sigma(w_p)$.

General w(z) is useful for understanding sensitivity and degeneracies, but doesn't lead to a better idea of what to optimize.

Editorial comments: Supernovae

There is clearly more to be gained by improving precision at $z < 0.8$ than by pushing beyond $z = 0.8$.

All effort should go to minimizing systematic error. When this is saturated, can gain by going to higher z, but slowly.

Spending WFIRST time on $z > 1$ SNe will require a strong argument.

Coordination with ground will need to be carefully thought through. Consider all phases – discovery, monitoring, spectroscopic confirmation --- and ask where WFIRST is needed and where it adds the most.

Editorial comments: Time Division

My advice: At this stage, give each method 1/3 of the dark energy observing time. (Need to figure out what this means with WL/BAO co-observing.)

Set down expectation that, in the end, each method will get $\geq 1/6$ and $\leq 2/3$ of the dark energy time, with division decided close to launch, based on what we have learned about ground-based progress, systematics of methods, possible departures from ΛCDM.

WFIRST will be time-limited. Each community (SN, BAO, WL) should be trying to develop ground-based approaches that *minimize* the time needed on WFIRST. In an ideal world (hah!), NASA would pay them to do so …

Editorial comments: Coordination

The reach of the WFIRST BAO and WL programs will be limited by observing time. May be true for SN as well.

There are large potential gains from optimizing the coordination of WFIRST programs with Euclid, especially if this allows longer dark energy observing programs.

There are also large potential gains from optimizing the coordination with ground-based programs.

	Forecast case	z_p	σ_{w_p}	FoM	$\sigma_{w(z>1)}$	$10^3\,\sigma_{\Omega_k}$	σ_{H_0}	$\sigma_{\Delta\gamma}$	$\sigma_{\ln G_9}$
1	[SN,BAO,WL,CMB]	0.51	0.015	533	0.052	0.55	0.61	0.034	0.015
2	[SN,BAO,WL-opt,CMB]	0.43	0.013	687	0.049	0.64	0.47	0.026	0.016
3	[BAO,WL,CMB]	0.63	0.017	321	0.054	0.56	0.99	0.034	0.015
4	[SN-III,BAO,WL,CMB]	0.61	0.017	351	0.054	0.56	0.91	0.034	0.015
5	[SN×4,BAO,WL,CMB]	0.62	0.017	338	0.054	0.56	0.94	0.034	0.015
6	[SN×2,BAO,WL,CMB]	0.59	0.016	385	0.053	0.56	0.83	0.034	0.015
7	[SN/2,BAO,WL,CMB]	0.38	0.011	903	0.050	0.55	0.37	0.034	0.015
8	[SNz_{max},BAO,WL,CMB]	0.46	0.012	690	0.051	0.55	0.47	0.034	0.015
9	[SNz_{min},BAO,WL,CMB]	0.61	0.017	356	0.053	0.56	0.90	0.034	0.015
10	[SNc4,BAO,WL,CMB]	0.51	0.015	534	0.052	0.55	0.60	0.034	0.015
11	[SNc8,BAO,WL,CMB]	0.48	0.014	604	0.051	0.55	0.54	0.034	0.015
12	[SNc16,BAO,WL,CMB]	0.47	0.014	632	0.051	0.55	0.52	0.034	0.015
13	[SN,WL,CMB]	0.30	0.025	107	0.32	2.2	0.79	0.039	0.023
14	[SN,BAO-III,WL,CMB]	0.38	0.021	224	0.12	1.2	0.68	0.035	0.017
15	[SN,BAO×4,WL,CMB]	0.35	0.023	180	0.15	1.2	0.74	0.037	0.018

Table by Michael Mortonson