Achieving the potential of weak lensing observations

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What we owe the Universe and ourselves

- Statistical reach of surveys
- Resolution and sampling
- Shear algorithmic systematics
- PSF measurement systematics
- Photometric redshift calibration
- Photo-z outlier rates

Statistical limits of WL

- Surveys bounding present & future projects' plans/claims
- Total S/N on the shear signal:

$$S/N \approx \frac{0.02}{0.3/\sqrt{N}}$$

- Total S/N on power spectrum:

$$\frac{P}{\delta P} \approx \sqrt{\frac{N_{\rm modes}}{2}} = \ell_{\rm max}\sqrt{f_{\rm sky}/2}$$

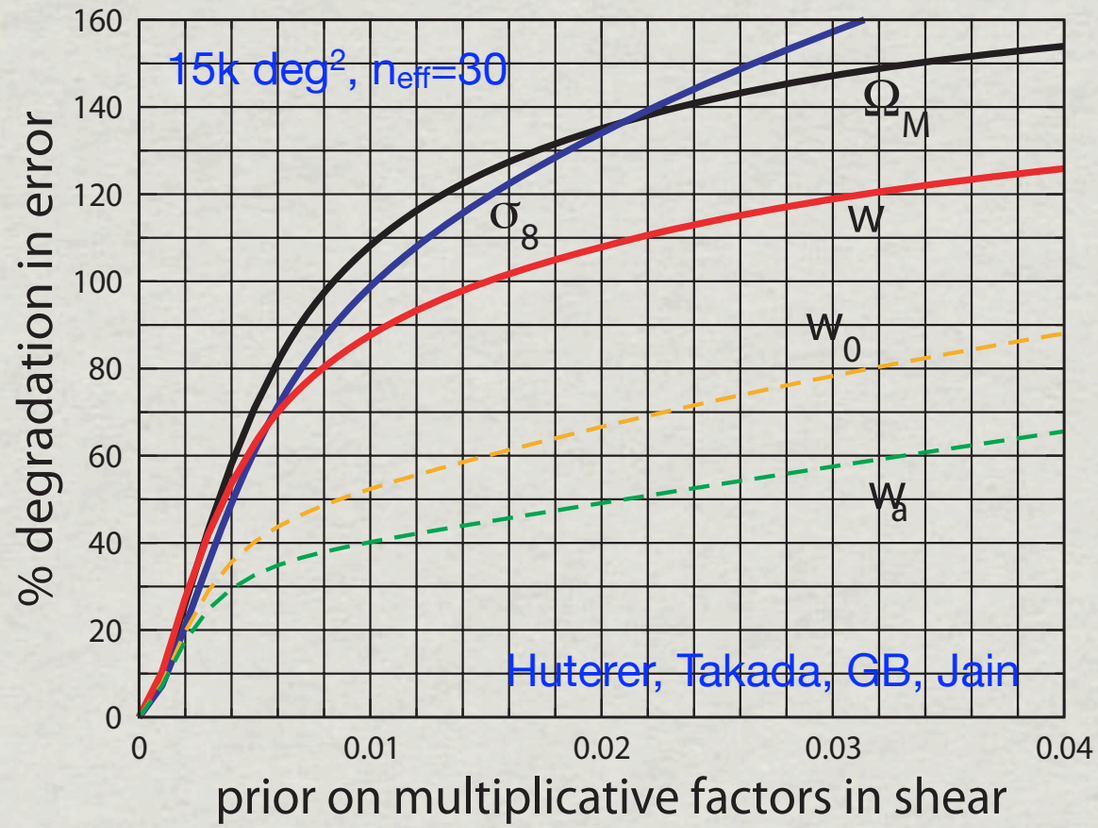
- Spurious shear signal:

$$\langle \gamma^2_{\rm sys}\rangle < \delta P \approx \frac{2(0.02)^2}{N_{\rm modes}}$$

Survey	CFHLS	DES	Euclid
n_{eff} $(arcmin^{-2})$	10	10 (?)	30 (?)
f_{sky}	0.004	0.12	0.5
N_{eff}	6×10^6	2×10^8	2×10^9
Shear S/N	160	900	3000
N_{modes} $(l<1000)$	4×10^3	1×10^5	5×10^5
Power S/N	50	250	500
Scaling error	<0.01	0.001	<0.0003
Spurious shear RMS	<0.003	<0.0013	<0.001

Preserving WL statistical power requires:

- Shear scaling accuracy (multiplicative errors) of
  - <0.01 (now)
  - <0.001 (DES, KIDS, HSC?)
  - <0.0003 (LSST, Euclid, WFIRST?)
- Somewhat relaxed in more rigorous analysis of tomography



- Shear algorithms, undersampling must cause <0.001 multiplicative errors.
- PSF size must be known to 1 part in 1000 if galaxy size is ~PSF size
- Mean of photo-z's must be known to ~0.001
- Rate of *O(1)* errors in photo-z must be known to +-0.001

Preserving WL statistical power requires:

- Spurious shear signals (uncorrelated with lensing shear) must be
  - <0.003 RMS (now)
  - <0.001 (future)

- PSF *ellipticity* must be known to +-0.001 if galaxy size is ~PSF size
  - Tighter specification if galaxies are poorly resolved
  - Looser if galaxy half-light radii well above PSF's

- CFHLS team has worked very hard for several years and is struggling to be statistics-limited.

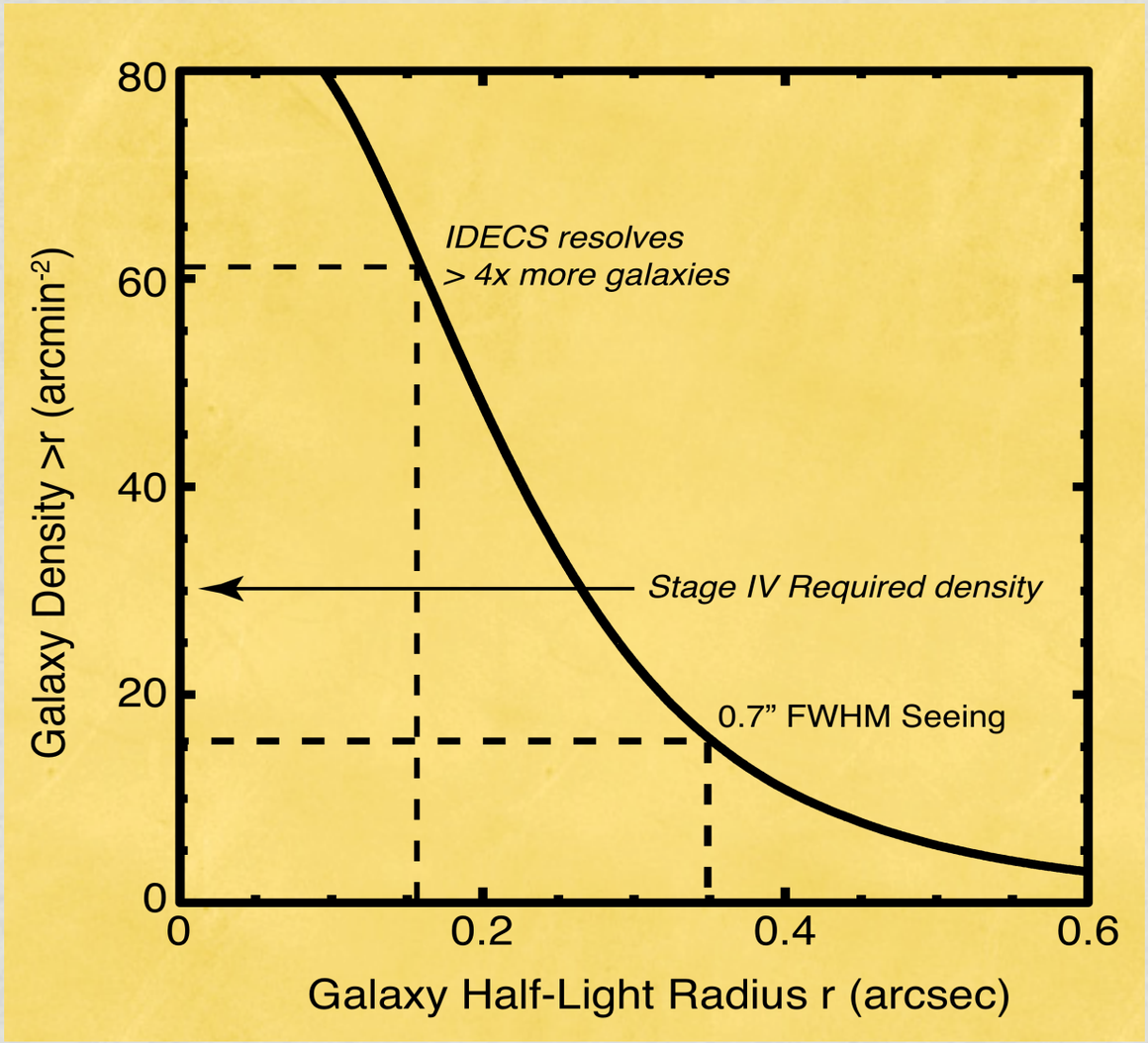
- ***What will your future WL survey do to improve upon the performance of CFHLS??***

  - Getting more data is not a **solution**, it makes the problem **harder!**

  - Better seeing is not a solution unless you limit yourself to galaxies >> PSF size!

Resolution & Sampling

- Very difficult & expensive to dig high-precision shears out of poorly resolved galaxies.
- Ideally should have “headroom” in resolution vs typical galaxy size.



Resolution & Sampling

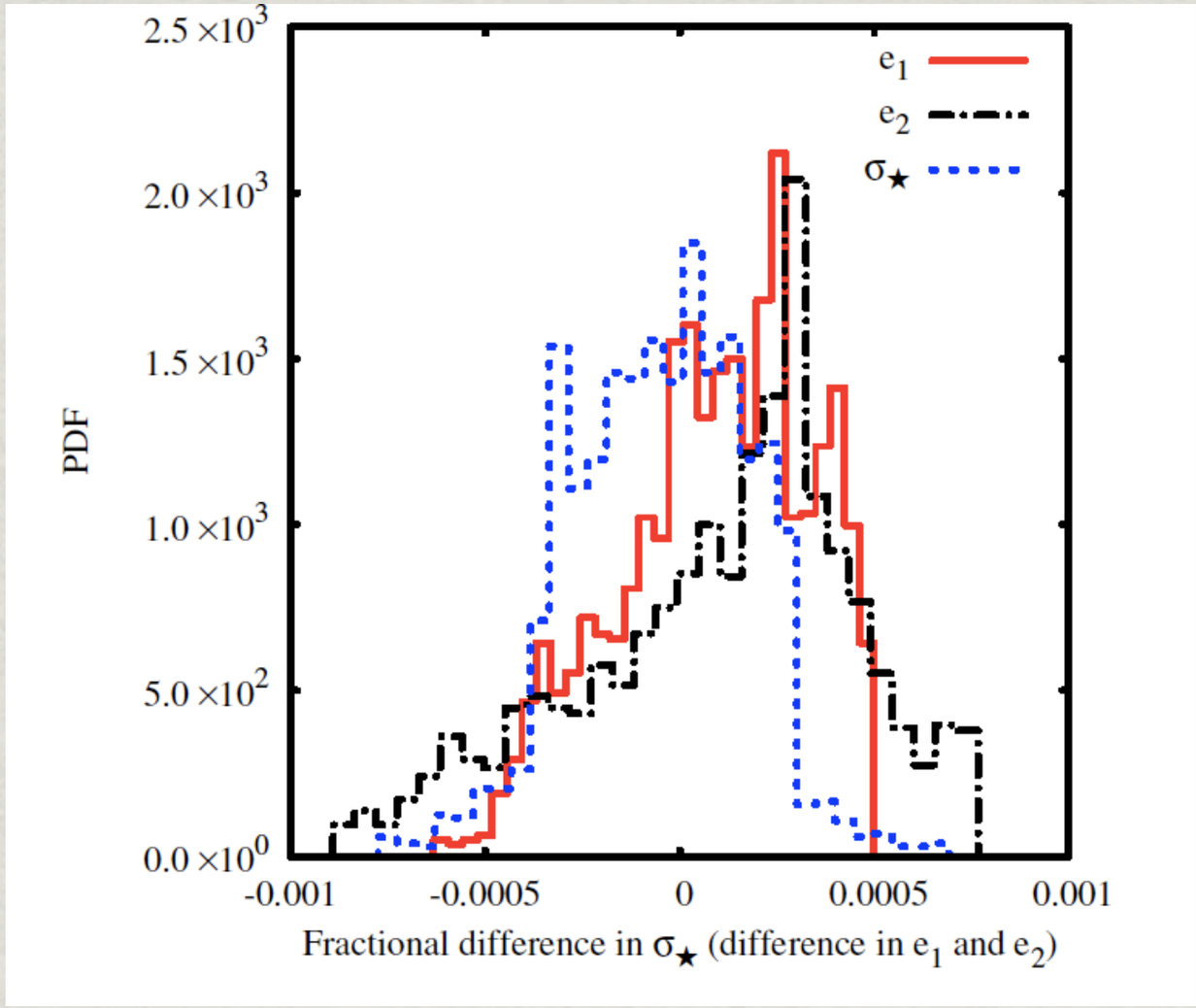
- If telescope delivers resolution: don't throw it away by aliasing! Need sufficient ***sampling***.
- Note that sampling pitch is (pixel size) / (# of exposures) if the PSF is stable!
  - and don't forget to subtract samples lost to cosmic rays, chips gaps, etc.
- There are well-defined mathematical criteria for aliasing, involving k_{max} of optical system. Sampling rates are *not* well described by FWHM for non-Gaussian PSFs.
- Ask Chris Hirata & Barney Rowe...

PSF Knowledge

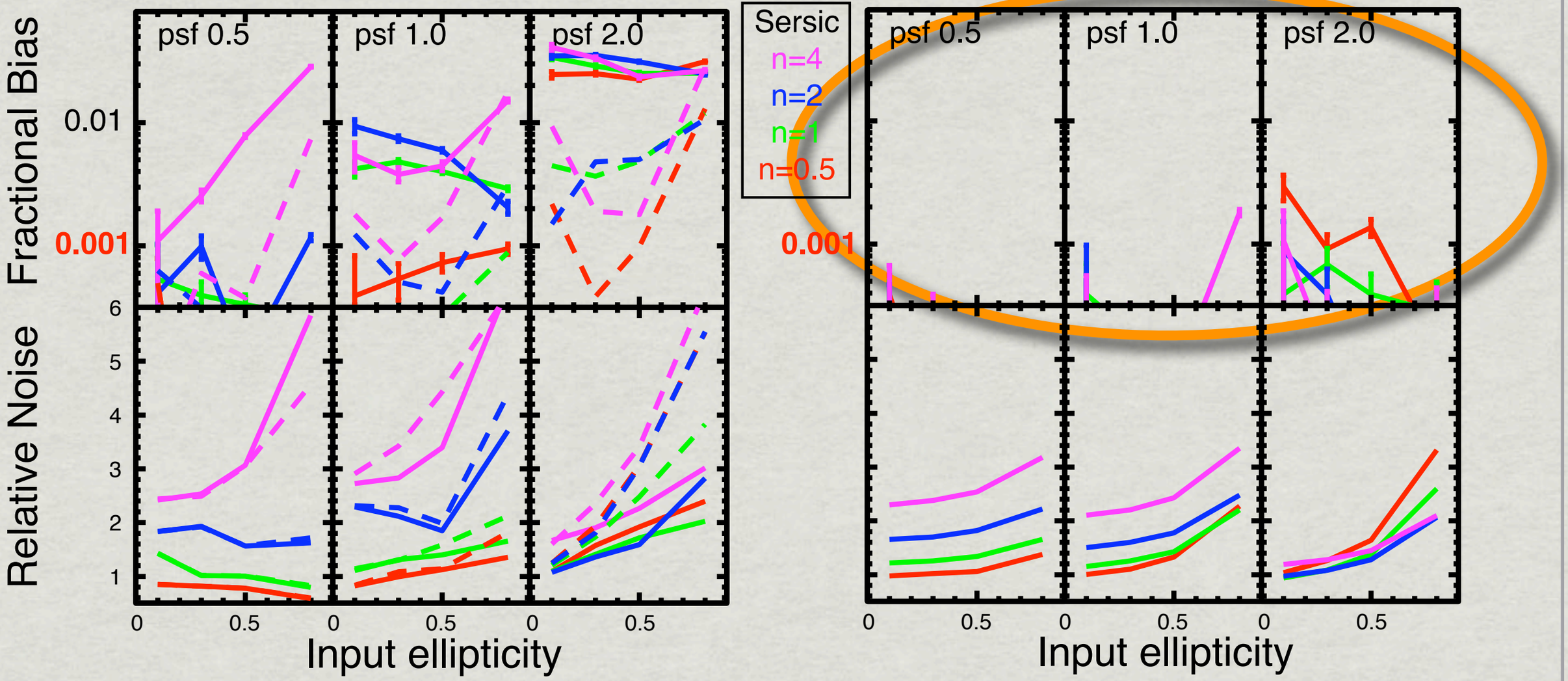
- Challenging to know your PSF to 1 part per 1000 in size, shape for each galaxy!
- Are stellar images sufficient to tell you this?
  - How many degrees of freedom are in the PSF pattern *per exposure* - optics flexure, thermal drifts, pointing jitter, atmospheric wavefront, detector effects? Highly non-linear model?
  - What is total S/N of stellar images per exposure?
  - Are you scraping for poorly-resolved galaxies?

PSF Knowledge

- Example: Ma *et al.* (2008)
- *SNAP* design
- PSF has:
  - static optical model
  - + wandering secondary mirror (5 DOF)
  - + pointing jitter (6 DOF)
- Stellar data recovers all 11 DOF and high-precision PSF.



Shape algorithmic progress



Nakajima & Bernstein:

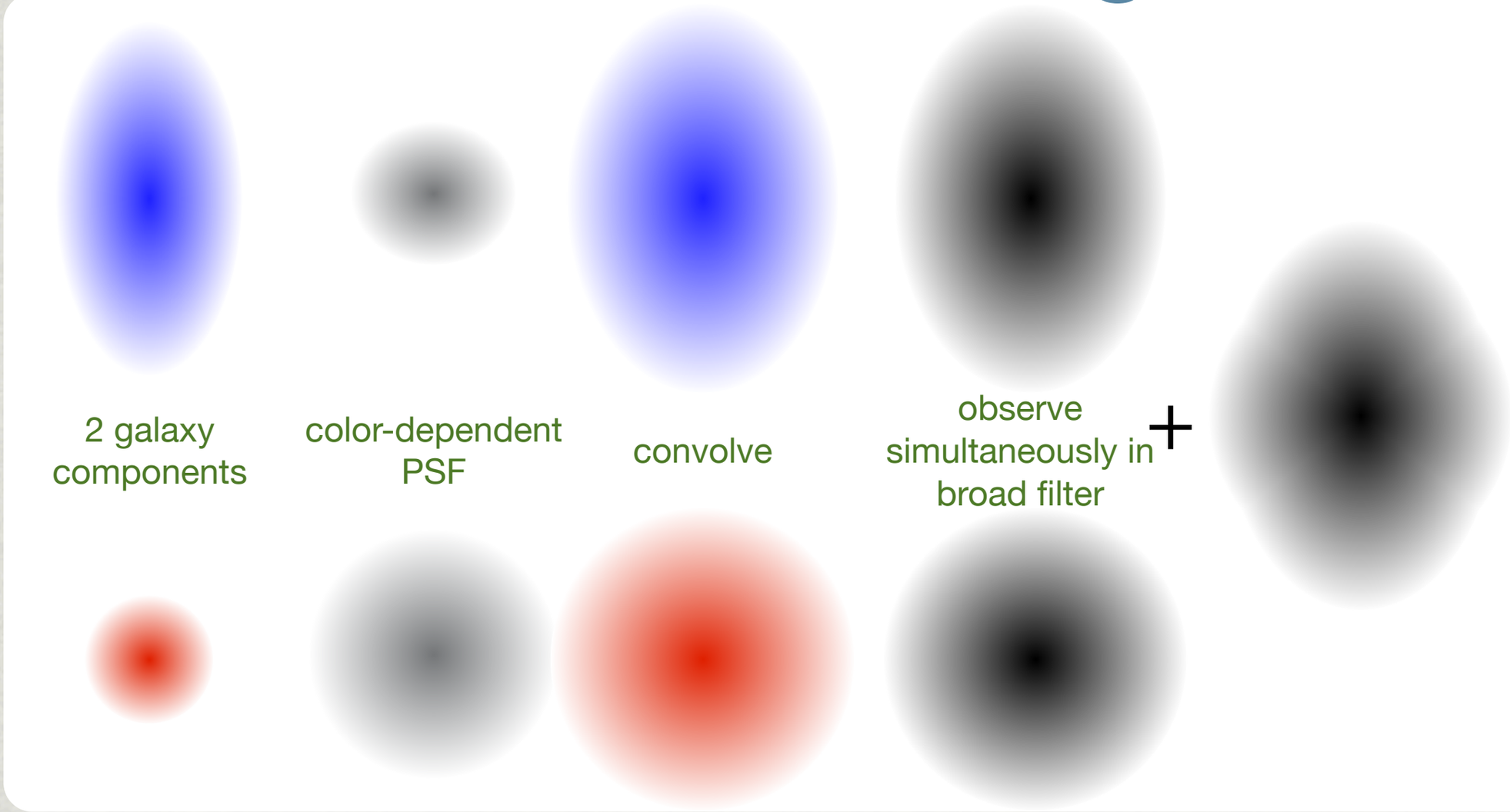
Elliptical Gauss-Laguerre fitting.
Notice >0.01 errors for n=4 Sersic or high ellipticity.

FDNT:

Multiplicative errors below 0.001, even for high Sersic indices, poor resolution, high ellipticity!

These tests use pure elliptical Sersic galaxies convolved with elliptical Gaussian PSF.

Future issue: color gradients



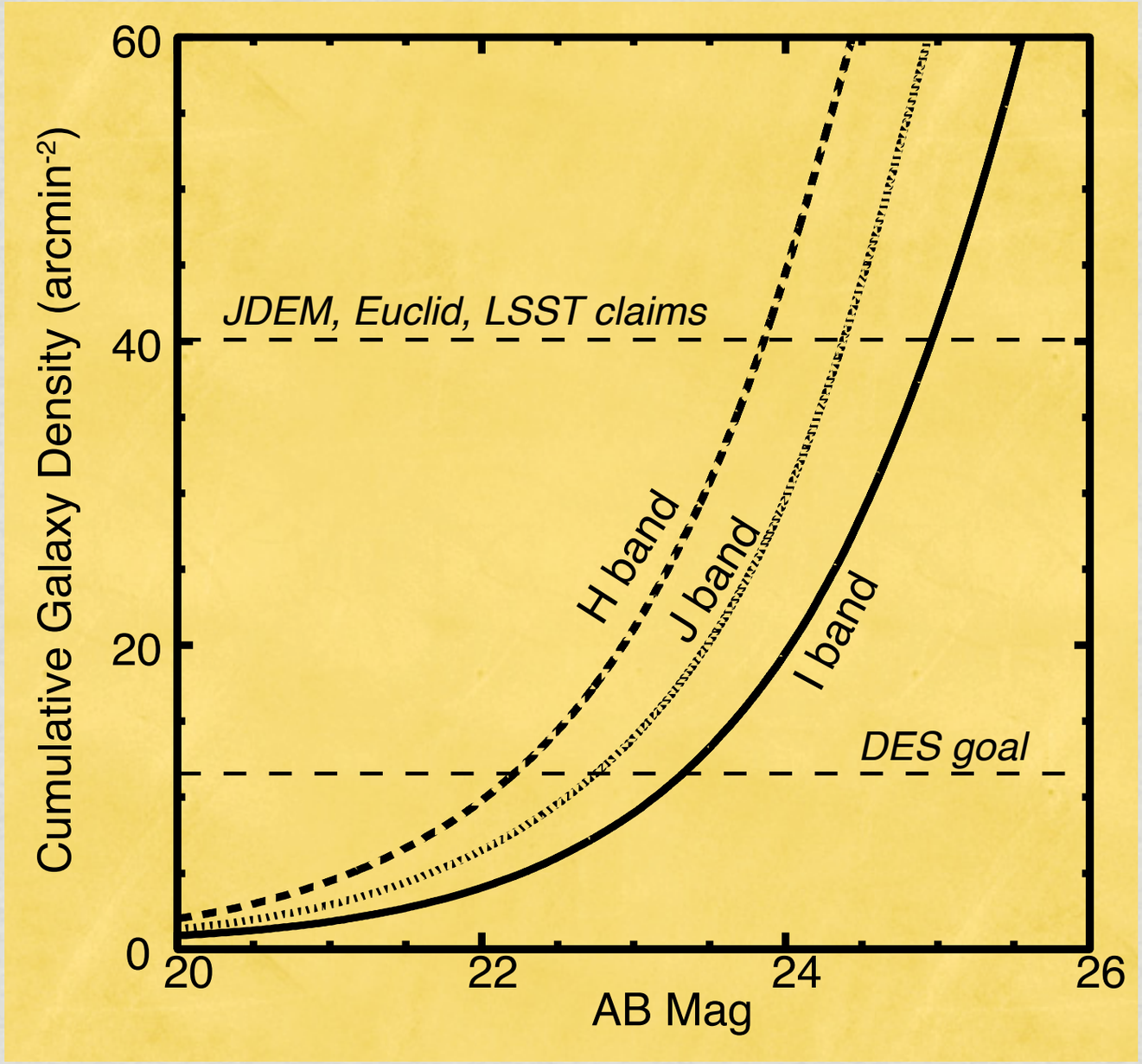
- ***Deconvolution is ambiguous without knowing whether each photon was blue or red!***
- Not just issue for FDNT!
- Easily percent-level.
- Essential to obtain some info on color gradients.

Photo-z calibration

- Measuring <z> and outlier rates to 0.001 accuracy requires redshift survey with 99.9% completeness!
  - unless you have some other knowledge of the z's of the redshift failures.
- Photo-z's are trained *and validated* on spectroscopic surveys that are typically i<23 mag and/or only 70% complete.
- Inconceivable to me that we would simply trust that the calibration is precise for the other 30% of galaxies and those too faint for the spectro survey!

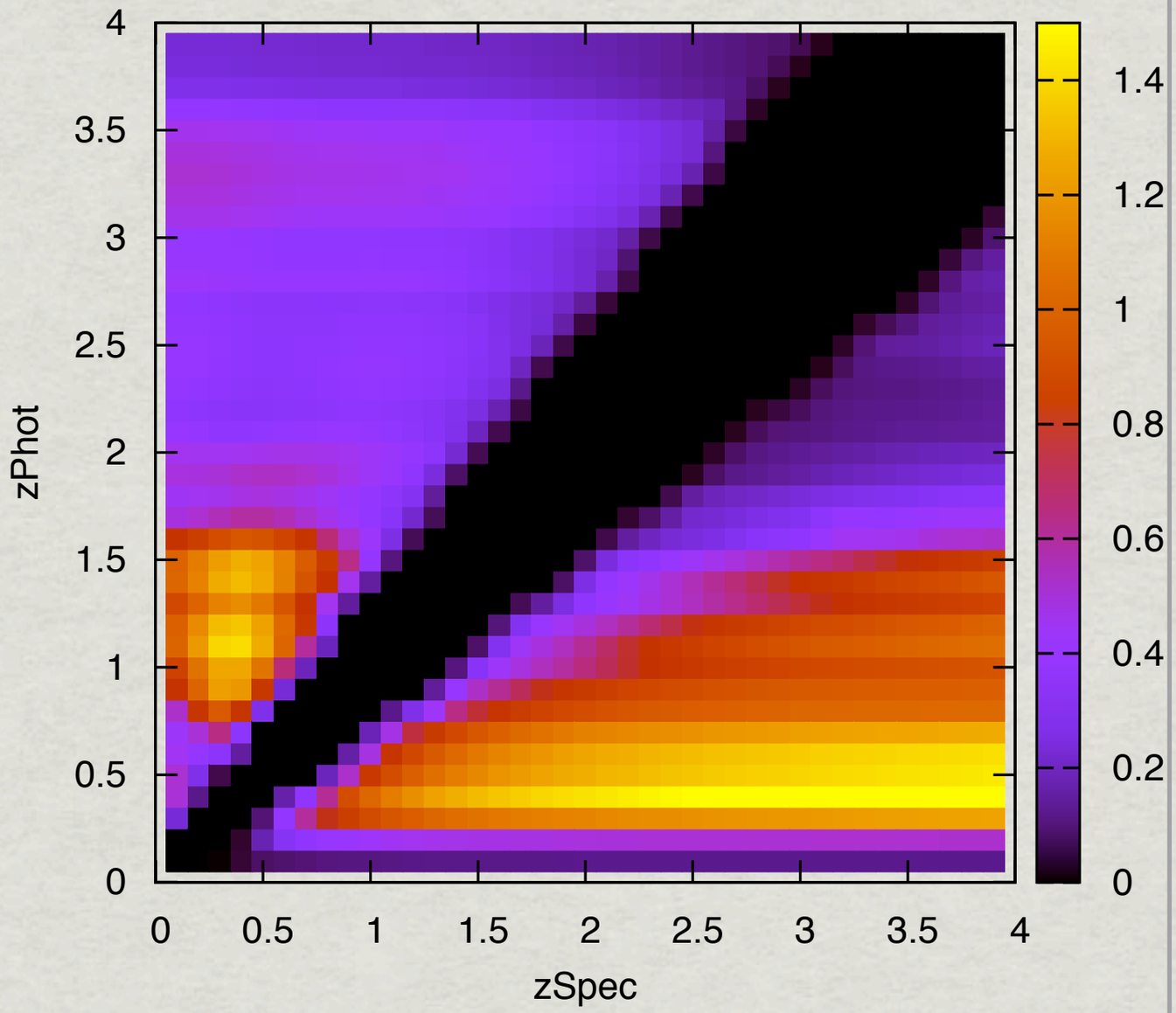
Photo-z calibration

- Only KIDS, DES are operating within range of current deep spectro-z surveys.



Outlier trouble

- From GMB & Huterer (2009):
- Shows size of dark energy bias induced by 0.001 error in outlier rate - relative to the statistical errors of Stage IV surveys.
- Outlier rate must be known to 1-3 parts per thousand!



Outliers the hard way:

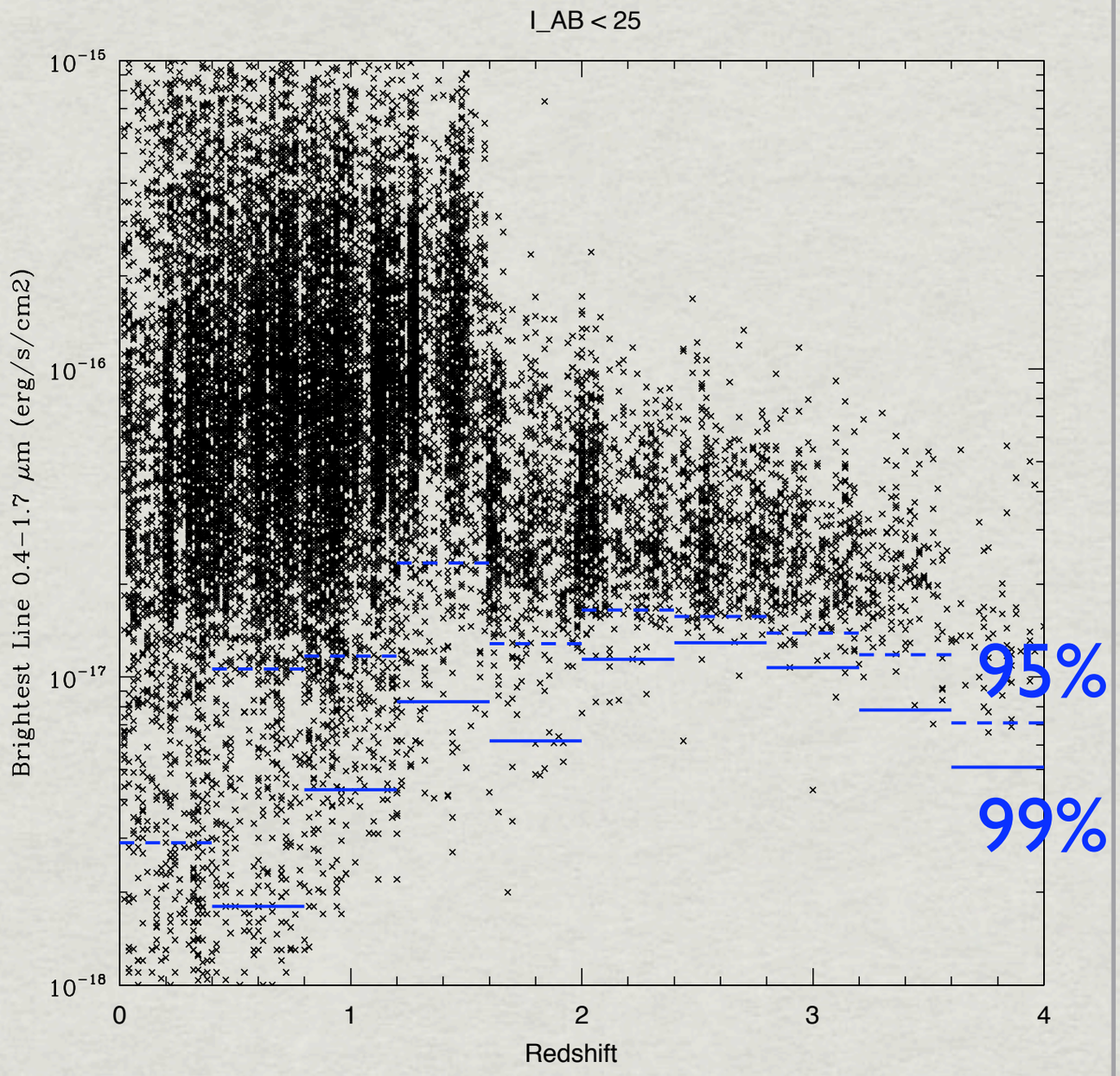
- Suppose that in a redshift bin, fraction *f* are outliers.
- Complete spectra of *N* galaxies will yield an *average* of *fN* outliers.
- Statistical fluctuations are $\sqrt{fN}$.
- Uncertainty in outlier rate is $\sqrt{(f/N)}$, so $N > f/(0.001)^2$
- For $f=0.02$: need $N=20{,}000$.
- Higher outlier rate forces larger spectroscopic sample for calibration.

Photo-z calibration survey

- High completeness spec-z survey of ~20k galaxies needs detection of ~10^{-17} cgs emission lines across visible + NIR

- **This will require (at least) high-multiplex visible spectrograph on 8m telescope**

- **PLUS high-multiplex NIR spectra, WFIRST or Euclid deep surveys**



USING ILBERT ET AL SIMULATION

Outliers: shortcuts?

- Newman (2008), Matthews & Newman (2010): Find photo-z *dn/dz* by cross-correlating with incomplete spectro-z survey (see also Zhang *et al* 2010, GMB & Huterer 2010).
- Problem 1: magnification bias creates a cross-correlation even with no physical overlap (also crowding effects - Hartlap *et al.* 2010). Must subtract such signals to high accuracy somehow.
- Problem 2: x-corr signal is $\propto b(z)(dn/dz)r(z)$, with b and r being bias of outliers, and r is correlation coefficient of outliers w.r.t. spectro sample. How would we know these???

Benefits of spectroscopic cross-correlation

- Substantial systematic-error reduction in WL analyses (as per Newman, even if not an outlier solution)
- Known substantial gains in potential cosmological accuracy:
  - WL x-corr gives bias of the spectro sample (Pen)
  - Spectro-sample reduces much of the projection loss in simple shear tomography
- New tests of gravity enabled (*e.g.* Reyes *et al.*)
- "De-clustification" of the density field may alleviate the "information saturation" problem
- Calibration of galaxy cluster statistics (Oguri & Takada)
- Things we have not thought of yet!!

What the Dark Energy Survey(s) of the Future Need:

- A spectroscopic survey over much of the same volume - not just for BAO!
- Sufficient color info to keep a small photo-z outlier rate
- A highly complete spectro-z survey to the full photo-z depth, to calibrate photo-z & outlier rates
- Sufficient resolution to resolve the galaxies being used for shear measurement!
- A plan for determining the PSF to part-per-thousand accuracy on each exposure
- Sufficient sampling for rigorous de-aliasing
- Color information on a per-galaxy basis to defeat color gradient ambiguity.
- Shape-measurement algorithms better than currently available.

Being big is not enough to make use of the opportunity that Nature is handing us!