What scares me about weak lensing with NIR detectors

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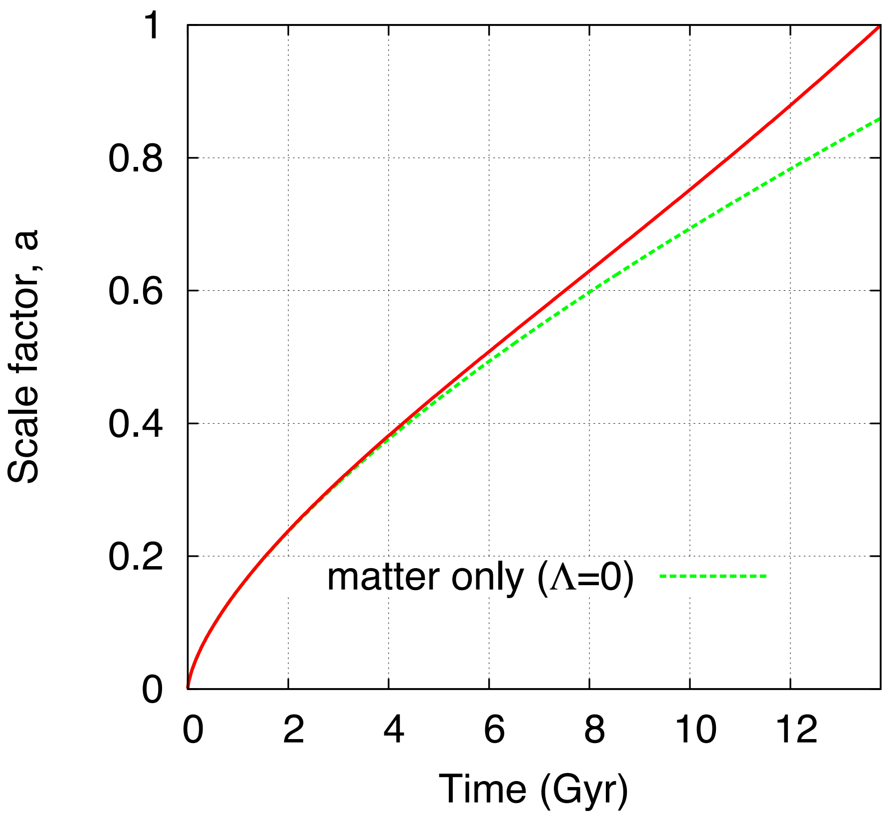
Two Key Functions

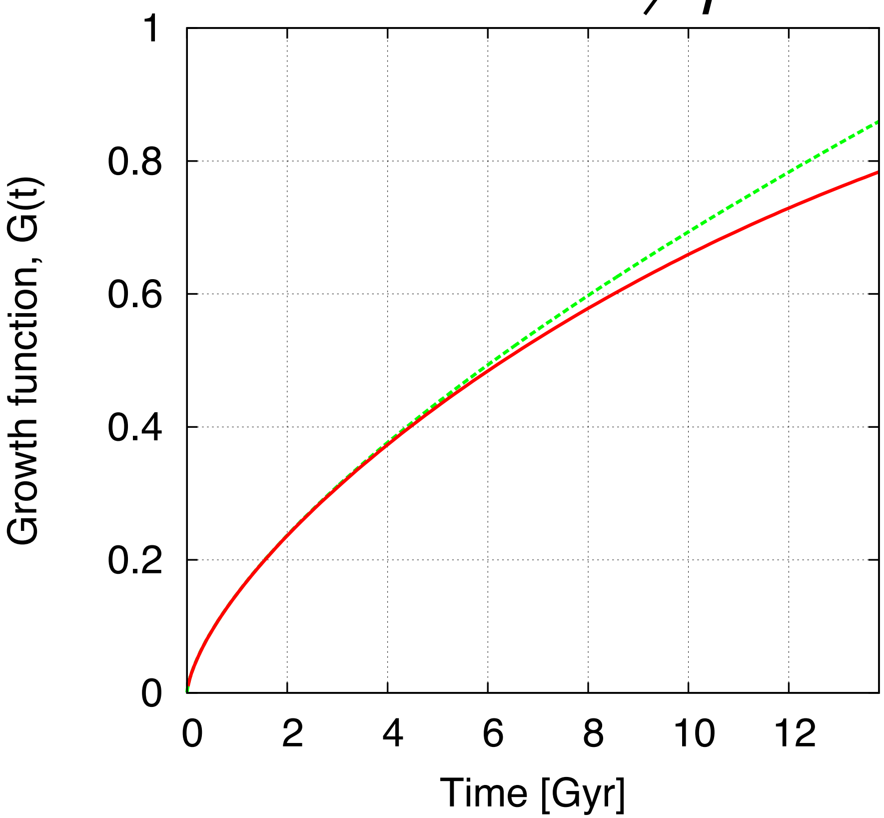
Expansion rate of the Universe

physical separation $\propto a(t)$



Growth of perturbations

density perturbation $\delta\rho / \bar{\rho} \propto G(t)$



Stage IV Weak Lensing

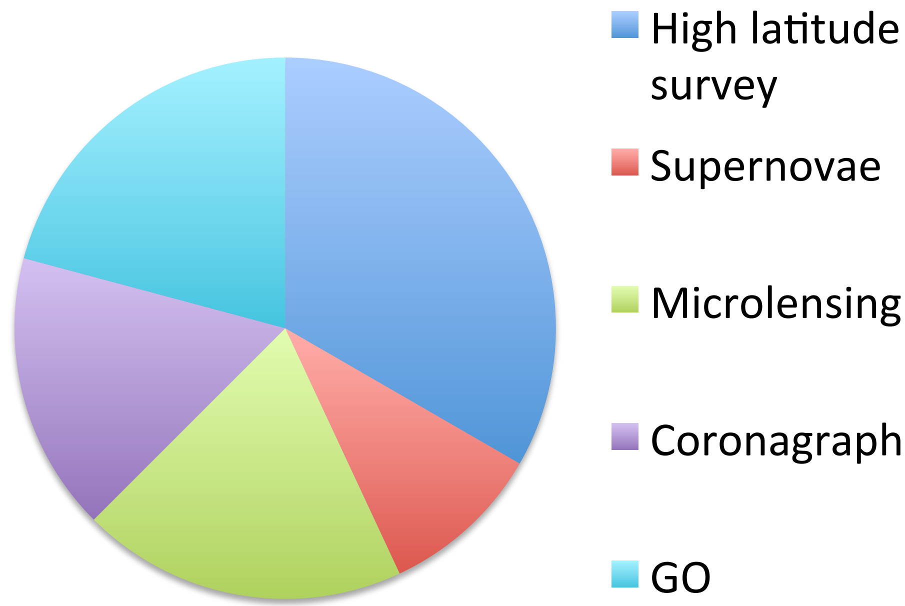
- Weak lensing shear is great!
  - Sensitive to both expansion history and growth of structure
  - Directly connected to mass distribution
  - … but a tiny signal.

- 3 "flagship" programs for the 2020s – LSST, Euclid, WFIRST
- I'll focus on the WFIRST weak lensing program in this talk:
  - in space for stability and to avoid atmospheric effects on PSF
  - multiple (~6) passes over the footprint for redundant measurements
  - shape measurement in NIR (combined with photo-z imaging)
  - will be embedded in LSST footprint

WFIRST Programs

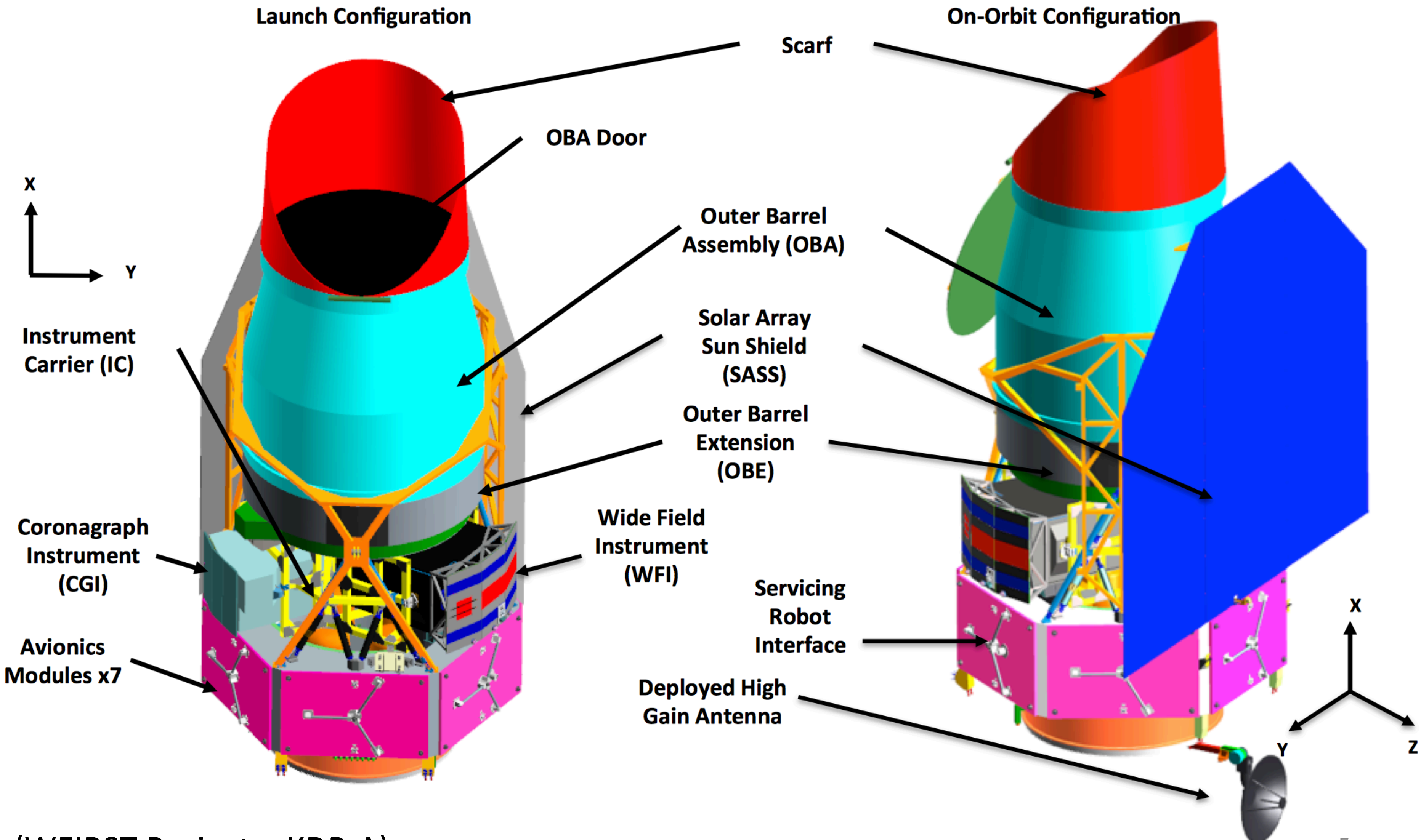
- 2.36 m primary mirror
- Wide Field Channel:
  - 18x H4RG detectors
  - 3×10^8 pix total
- Also: IFC & coronagraph (not this talk)
- Launch: mid-2020s
- 6 year nominal mission

Notional breakdown of observing programs



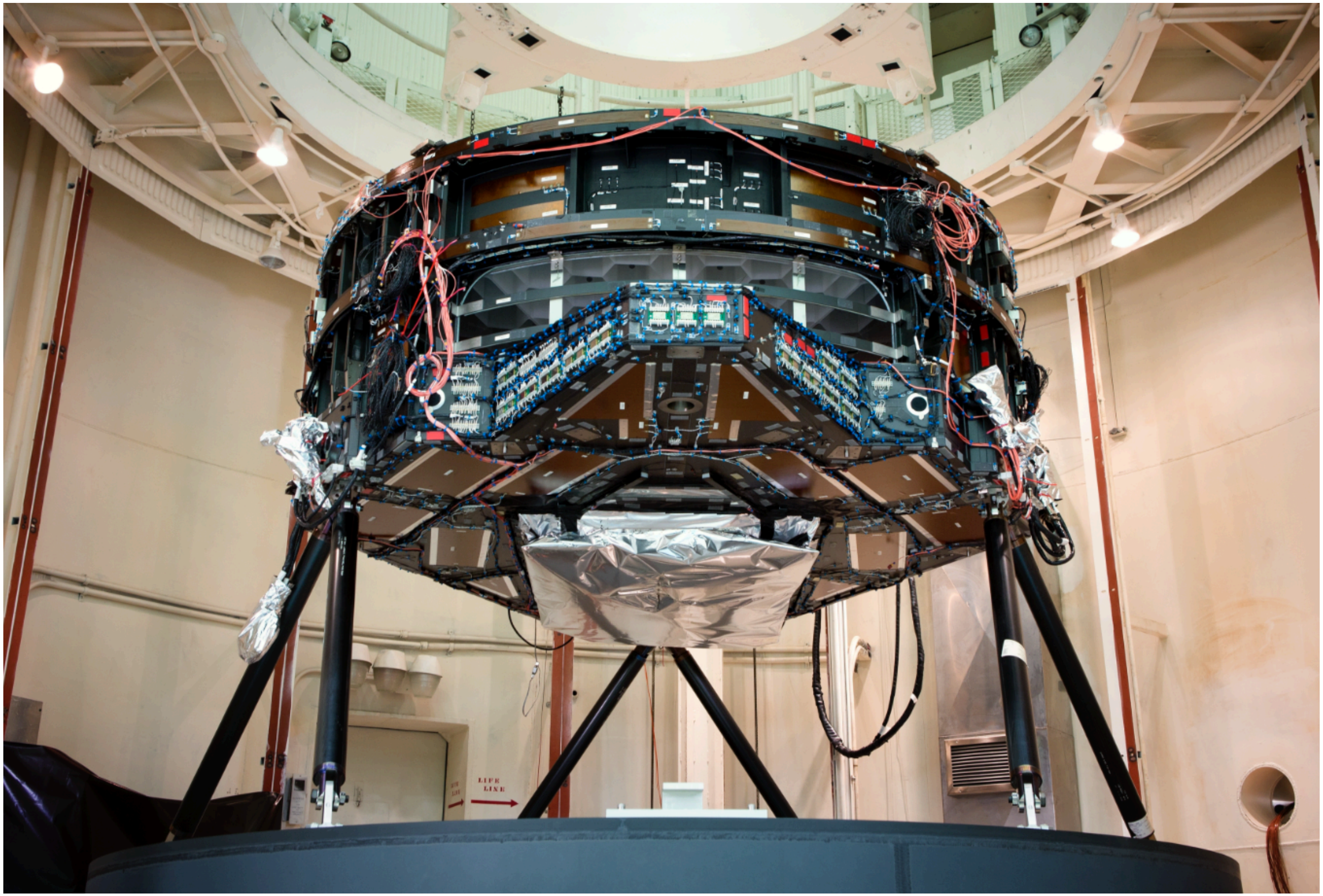
High latitude survey (Science Investigation Team: PI Doré) includes both imaging and grism spectroscopy.

WFIRST Configuration



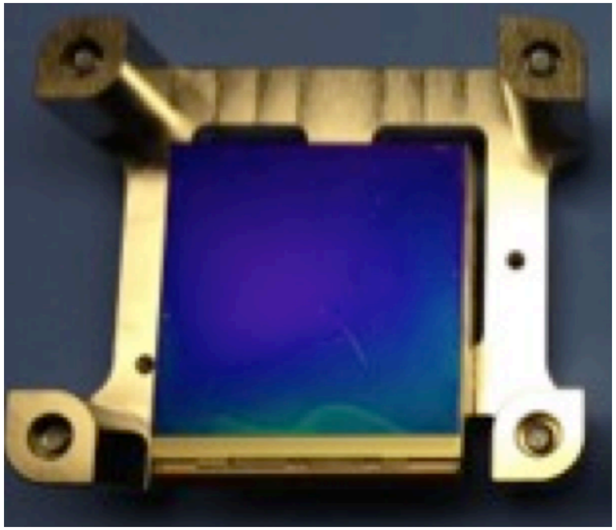
(WFIRST Project – KDP-A)

Primary Mirror Assembly

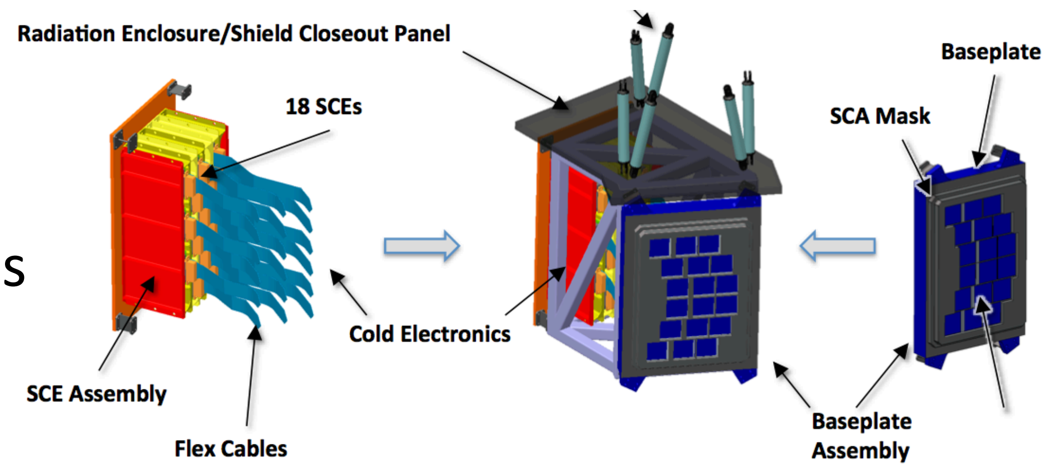


Harris Corporation / TJT Photography

WFIRST Detectors



- Sensor Chip Array:
  - 4k x 4k array of p-n junctions in HgCdTe (light sensitive material; band gap tunable, ~2.3 μm cutoff for WFIRST)
  - In interconnect to Si readout circuit/ multiplexer
- Flex cable
- Sensor Cold Electronics
  - Signal is digitized here
- These detectors are **not** CCDs
  - FET on each pixel, charge not transferred, read-out is non-destructive



WFIRST SDT Report 2015

Detector Technology Milestones

#		Date
√ 1	Produce, test, and analyze **2 candidate passivation techniques** (PV1 and PV2) in **banded arrays** to document baseline performance, inter-pixel capacitance, and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, and QE greater than 60% (over the bandpass of the WFI channel) at nominal operating temperature.	7/31/14 **Passed 8/7/14**
√ 2	Produce, test, and analyze **1 additional candidate passivation technique** (PV3) in **banded arrays** to document baseline performance, inter-pixel capacitance, and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, and QE greater than 60% (over the bandpass of the WFI channel) at nominal operating temperature.	12/30/14 **Passed 12/1/14**
√ 3	Produce, test, and analyze **full arrays with operability > 95%** and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, QE greater than 60% (over the bandpass of the WFI channel) , inter-pixel capacitance ≤3% in nearest-neighbor pixels at nominal operating temperature.	9/15/15 **Passed 10/8/15**
4	Produce, test, and analyze final selected recipe in **full arrays demonstrating a yield of > 20%** with operability > 95% and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, QE greater than 60% (over the bandpass of the WFI channel) , inter-pixel capacitance ≤3% in nearest-neighbor pixels, persistence less than 0.1% of full well illumination after 150 sec at nominal operating temperature.	9/15/16 **Passed 9/22/16**
5	Complete environmental testing (vibration, radiation, thermal cycling) of one SCA sample part, as per NASA test standards.	12/1/16

(from the WFIRST NIR Detector Technology Report)

Summary from WFIRST Project NIR Detector Milestone #4 Report

Detector	Pixels with Nominal Photo Response (%)	Median Dark Current (e/s)	Median CDS Noise (electrons)	QE (%) (av. 800-2350nm)	Crosstalk (%) (nearest neighbor)	Persistence (% of FW in 150 sec. after 150 sec.)
	95%	< 0.1	< 20	> 60	$\leq$ 3	< 0.10
18237	99.99	0.001	11.9	95	2.3	0.02
18238	99.3	0.001	15.1	96	2.6	0.01
18239	99.8	0.001	15.2	89	1.8	0.03
18240	99.97	0.001	15.7	93	2.3	0.01
18241	99.9	0.004	15.2	92	1.9	0.02
18242	99.9	0.040	16.0	93	1.8	0.02
18243	99.9	0.064	16.3	90	1.8	0.03
18244	99.9	0.003	15.1	90	1.9	0.20
18438	99.98	0.001	13.2	86	1.9	0.01
18440	99.96	0.001	14.4	81	2.4	0.01
18441*	99.97					
18442	99.96	0.35	16.2	93	1.9	0.02
18443	99.95	0.003	12.8	87	2.2	0.02

*18441 was not fully analyzed due to an electrical coupling between Vreset and DSUB bias lines

The WFIRST weak lensing program has the raw statistical power to measure σ_8 to ±0.1%. Similar advances will be made on the other parameters relative to current weak lensing programs.

Trying to measure a 1% shear signal to 0.1% accuracy. Reliable results at this level will require 1-2 order of magnitude improvement in systematic error control in shape measurements. Other big WL programs (LSST, Euclid) face similar issues.

Improvements also needed in other areas, e.g. photo-z training → but that's another talk

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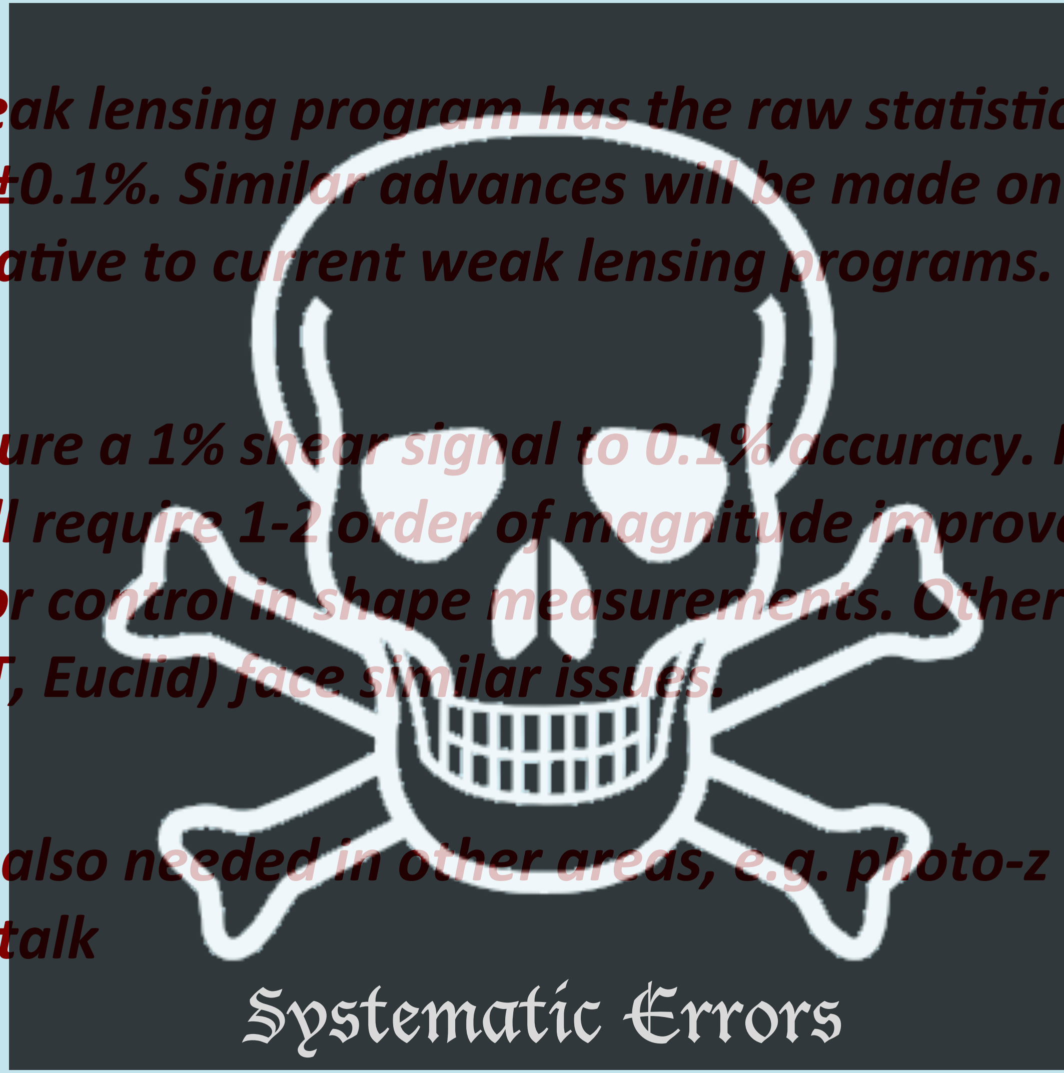
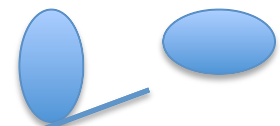
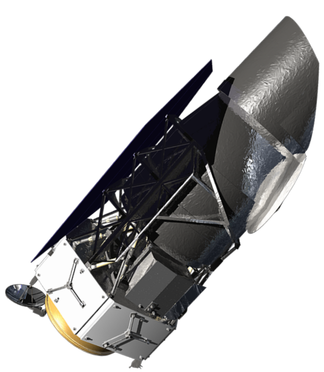


The Major Systematic Errors

Intervening matter:
- Nonlinear power spectrum?
- Baryonic corrections?
- Higher-order lensing corrections?



Source galaxies:
- Redshifts?
- Intrinsic alignments?



Telescope/instrument:
- Point spread function?
- Flats, astrometry … ?
- **Detector non-idealities?**

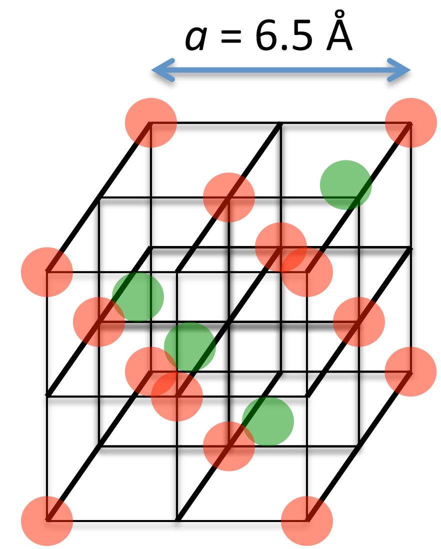
Data analysis:
- Image processing algorithms?
- Source selection?
- Shape measurement?

We are sensitive to very small signals!

- Trying to measure a 1% signal to 0.1% accuracy.

$$0.01 \times \sqrt{0.001} \approx 0.0003$$

- “Stage IV” additive systematic error requirement = 0.0003 in shear
- e.g. for WFIRST:
  - “Typical” galaxy radius = 1.8 pixels
  - 1 pixel = 10 μm
  - Change in radius = 1.8 x 0.0003 x 10 μm = 54 Å
  - … or the size of ~8 lattice cubes in HgCdTe!



Layers of Systematic Control

LAYER	PROCESS
1	*Eliminate the physics causing the effect (but not always possible).*
2	*Develop a first-principles model (but again, not always possible).*
3	*Develop an empirical model based on stars or external calibration data (may capture multiple pieces of physics simultaneously).*
4	*Mask affected data (if a small number of pixels are affected, e.g. persistence, cosmic rays …).*
5	*Statistical corrections based on science galaxies (e.g. de-trending with respect to position on focal plane).*
6	*Cross-correlations of successive passes over the sky at different roll angles (tile 2x per filter, 3 shape measurement filters).*

Different effects may be more amenable to mitigation at different layers.

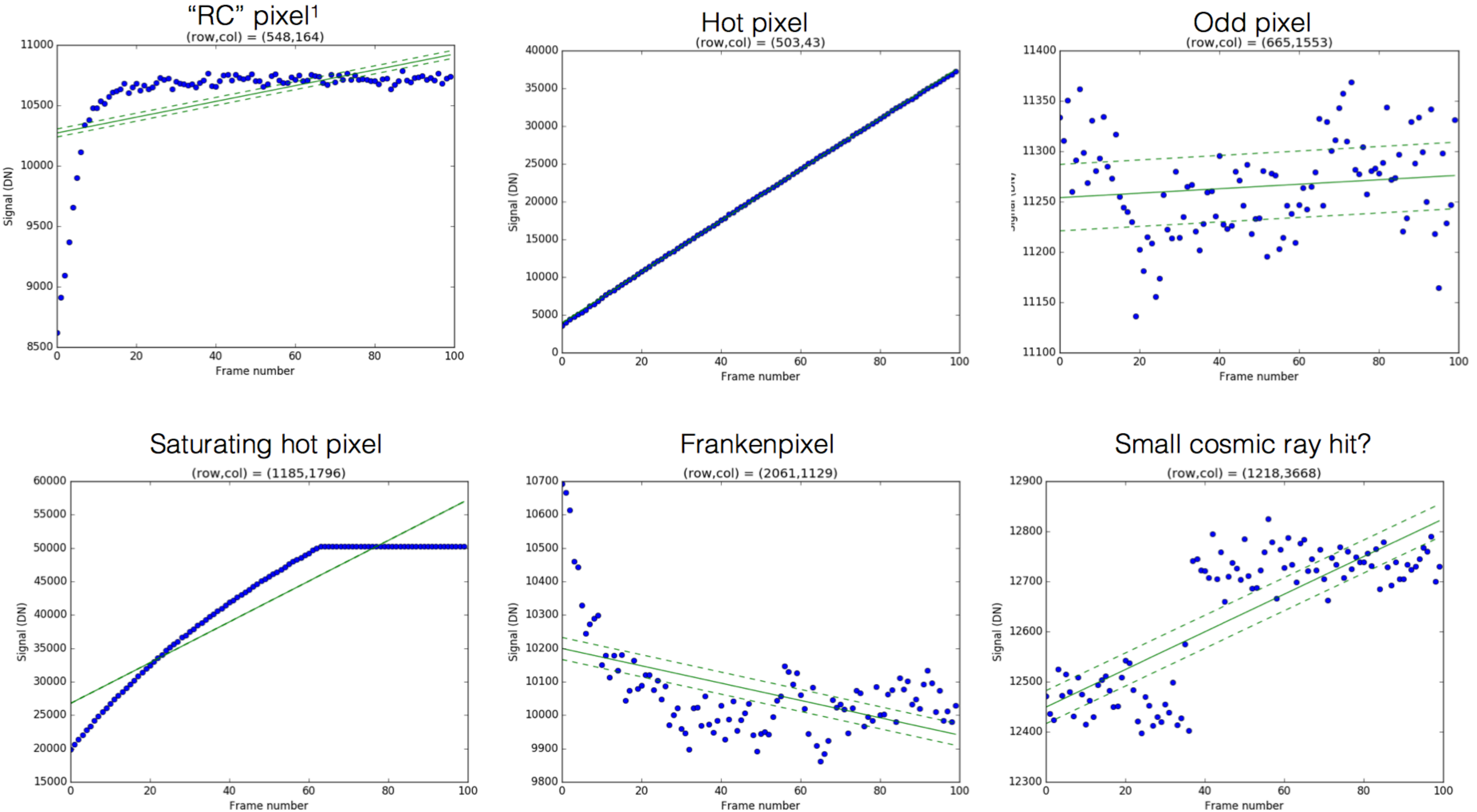
Want to avoid premature reliance on layers 5 and (especially) 6 – these are there if 1—4 are not sufficient, or when (not if) unexpected problems arise.

Some considerations

- Read-out architecture different from CCDs:
  - Every pixel is (potentially) special, including its own amplifier!
    - Compare to SDSS (my WL experience) – drift scan, many quantities inherently 1D
    - "Point and stare" CCD – 2D array but only a few amplifiers
  - Multiple reads
    - WFIRST can download ~6 linear combinations per pixel per exposure
- Very sensitive to environmental perturbations (e.g. thermal)
- Charge traps!
  - symptoms such as persistence, reciprocity failure, …
- Some CCD "problems" not present
  - Most notably charge transfer inefficiency
- (Maybe the biggest worry?) New detectors → probably many surprises in the future!

Weird Pixels

(chart from Bernie Rauscher – these are from H4RG detectors)



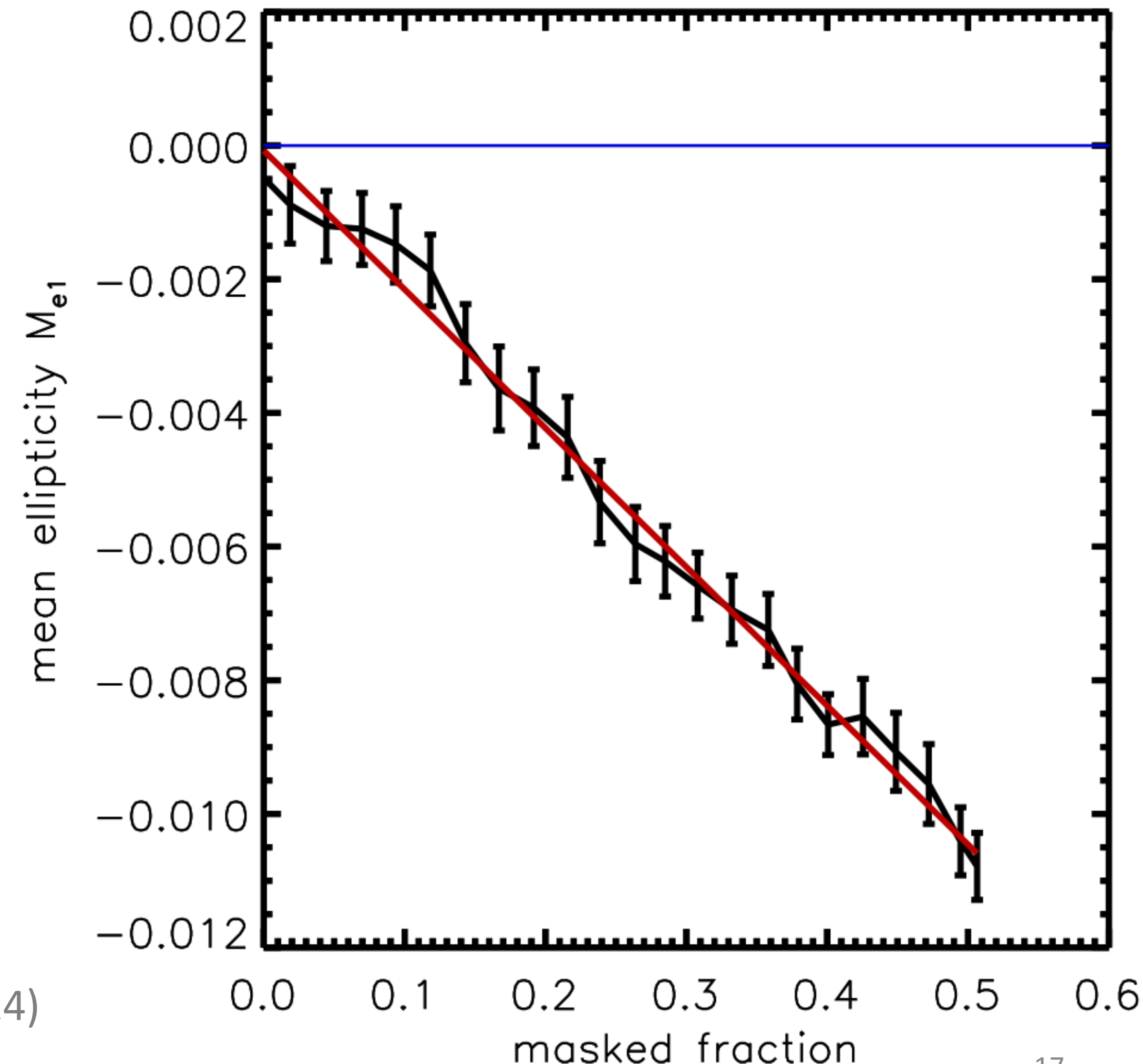
Would not use these for science, but need to be careful as masking can itself introduce biases!

Masking bias in SDSS simulations

This was for masking bad ***columns*** in a Sloan CCD.

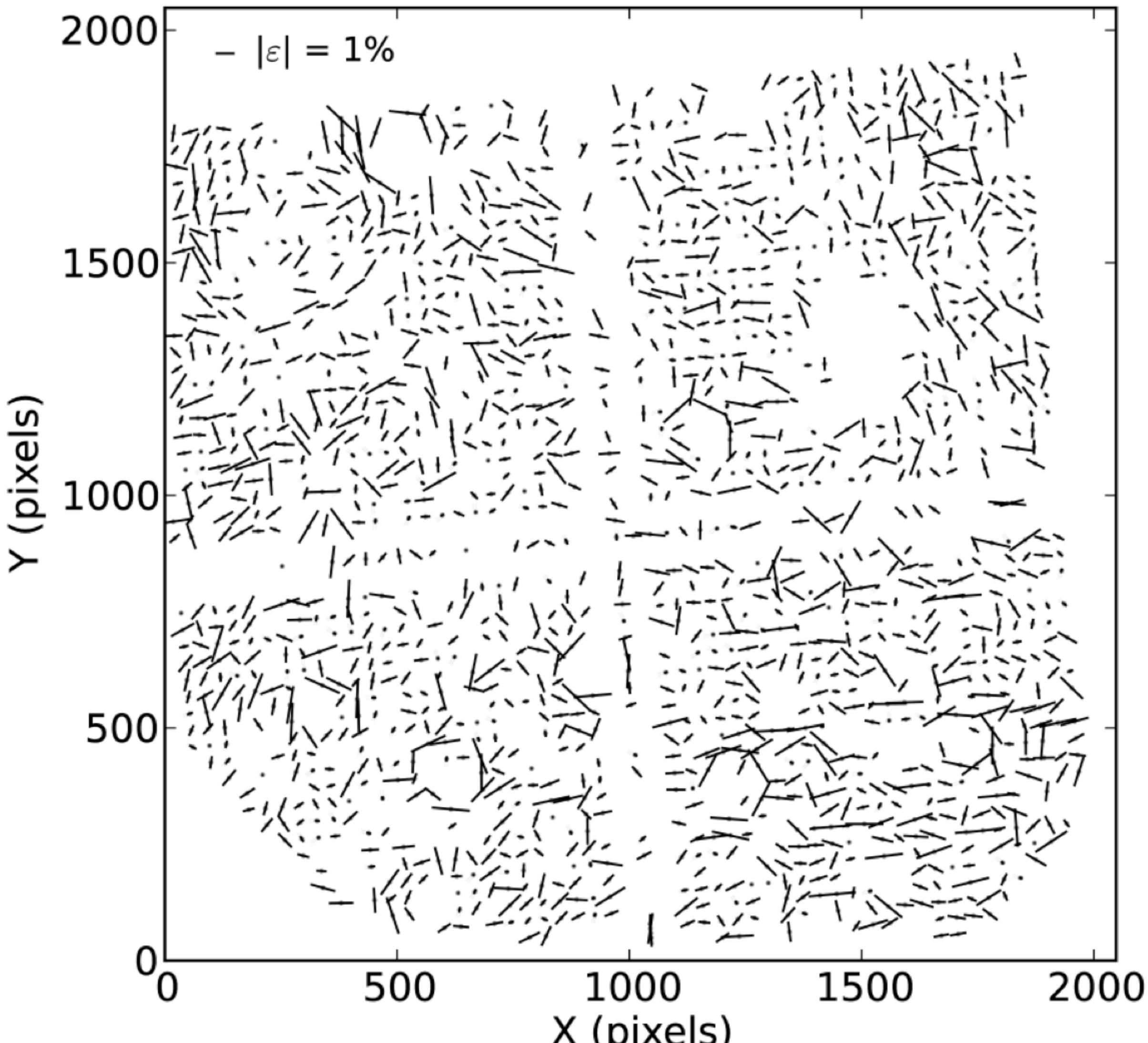
Masking patterns for weird pixels likely not so severe …

but requirements are much tighter!



Huff et al. (2014)

Contributions to image ellipticity



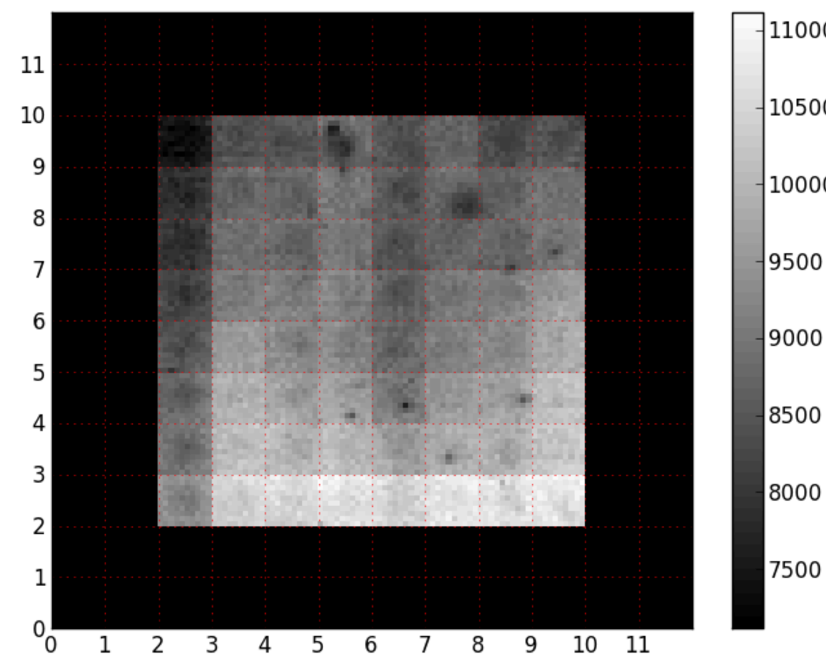
Whisker diagram for H2RG at Caltech Precision Projector Lab (Seshadri et al. 2013)

Correlated structure is present

Individual Pixel Response Functions

- Stars are bright, galaxies are faint

- Stars have high S/N per pixel
  – Pixel response functions differ from one pixel to another
    - QE, area, centroids, shapes, higher moments
  – Not visible in individual galaxies (at S/N=10 per image, care most about mean behavior on >1 arcmin scales)
  – … but a big deal for PSF stars as we may be interpolating based on ~1000 stars each at S/N~100
    - This is where the tightest requirements on high spatial frequency flats, etc. will come from on WFIRST!



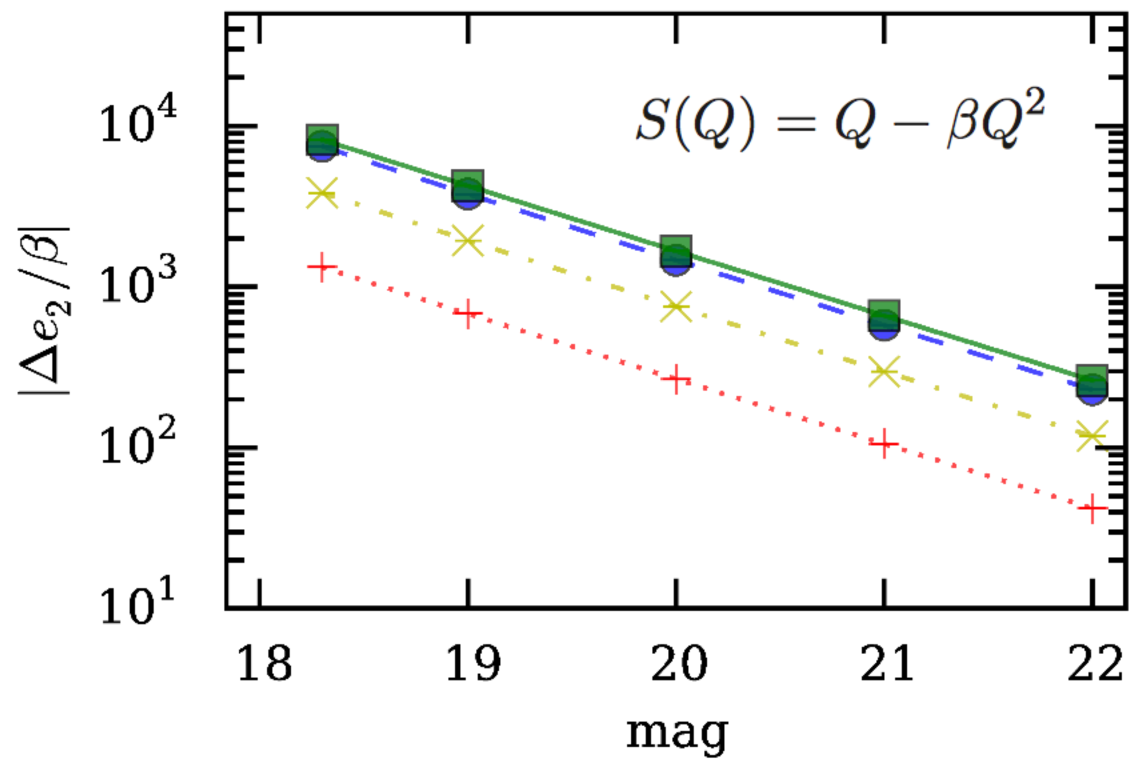
Hardy et al. (2014)
SPIE 9154, 9154D-12
H1RG, 5μm cutoff

Nonlinearity effect on stars

Non-linearity both:

Changes the PSF size
→ multiplicative shear error

Couples to aberrations to modify PSF ellipticity
→ additive shear error



A. Plazas Malagón et al. (2016)

"Nominal" $\beta = 5 \times 10^{-7}$

Correlated Noise

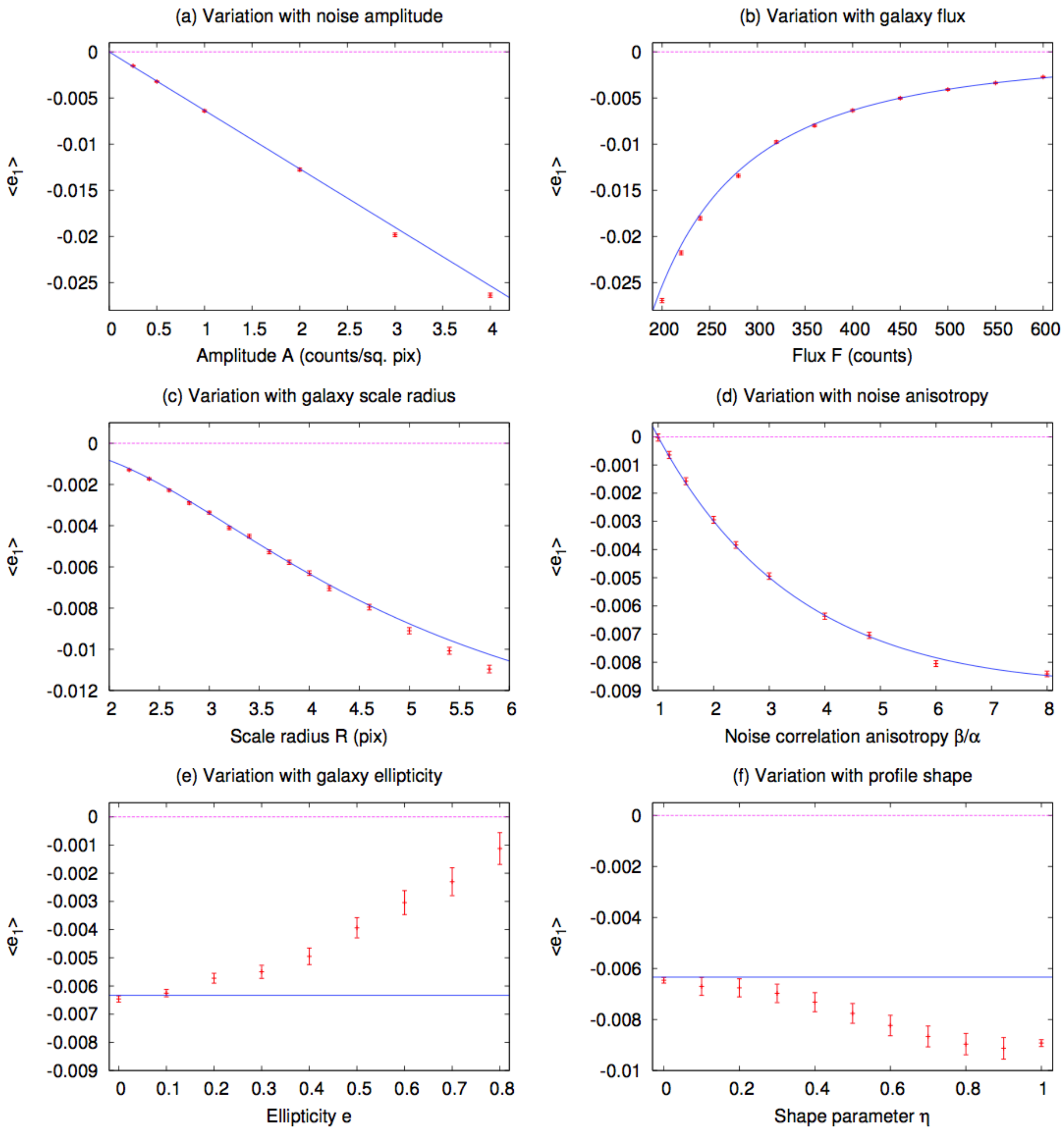
- Noise correlations imprinted at multiple stages in the readout chain

- Anisotropic correlations have the same symmetry as shear and are of concern for weak lensing.

- We don't have data yet for WFIRST detectors with flight-like electronics.

Rauscher (2015) PASP 127:1144

Semi-analytic model for the effects of correlated noise on shape measurement

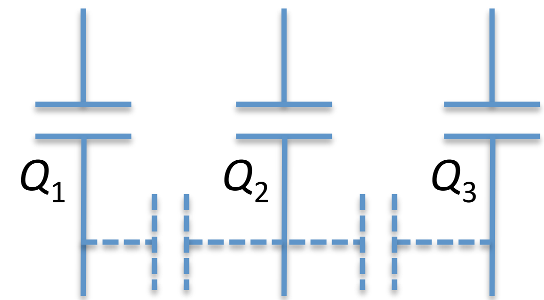


- We are using these models to set requirements on the knowledge of the noise correlation structure

blue = semi-analyic model
red = simulation

Inter-pixel capacitance (IPC)

- Capacitive coupling between neighboring pixels, since in NIR detectors the pixels are read out in place.
- Part of the effective PSF for signal, but not for noise.
- For WFIRST, will have to know the IPC to 0.01% on scales down to ~500 pixels
  - or absorb any errors at this level into ePSF model



$$V[i,j] = \sum_m \sum_n \frac{1}{C_{\rm node}} Q[m,n] K[i-m, j-n]$$

K = IPC kernel

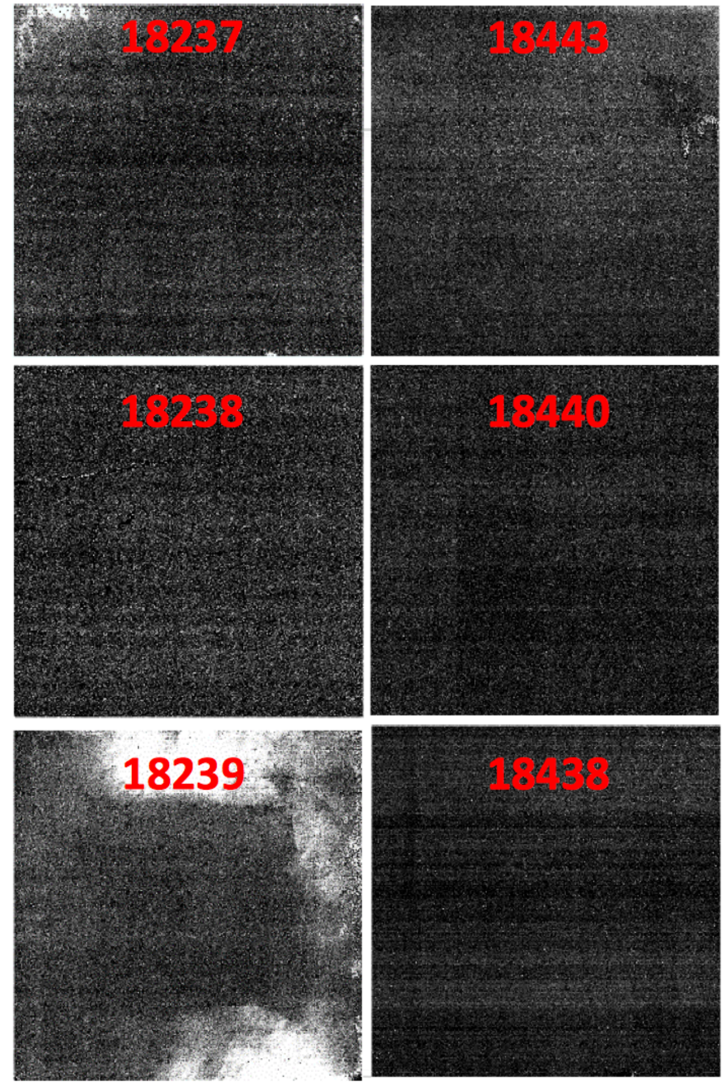
0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.2%	**1.9%**	0.2%	0.0%
0.1%	**2.0%**	**91.5%**	**2.0%**	0.1%
0.0%	0.2%	**1.8%**	0.2%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%

18438

See e.g. Kannawadi et al. (2016)
H4RG data from WFIRST Project Technology Report #4

Persistence

- Pixels in NIR detectors show excess current following exposure to a bright source.
- Small effect as a fraction of stimulus, (in modern detectors) but of concern due to:
  - High precision demanded of WFIRST
  - Large dynamic range between science targets (galaxies) and bright stars
- What effect on weak lensing?
  - Approach thus far – treat unmasked persistence as a correlated noise field.



H4RG data from WFIRST Project Technology Report #4
Linear scale: 0 to 0.1% of full well from t = 150-300 s after 8xFW illumination

Persistence from Slews

- No cold shutter in WFIRST, so detectors see a “streak” from every bright star during slews.
  - Mask the worst stars (baseline: <9th mag) and accept remaining contamination
- Semi-analytic estimates of the effect were completed this fall
  - “Low” and “high” roughly correspond to regions seen on previous slide.
  - Next steps are to optimize masking algorithms and insert slew persistence into pixel-level simulations.

	Low model		**High model**	
ACS error (arcsec rms per axis)	**Masked pixel fraction**	**Systematic shear per component**	**Masked pixel fraction**	**Systematic shear per component**
1.0	0.16%	3.4E-5	0.68%	8.6E-5
2.0	0.32%	3.4E-5	1.31%	8.6E-5
4.0	0.62%	3.4E-5	2.58%	8.6E-5

Summary

- A weak lensing experiment is going to be very challenging, even from space.
  - If history is a guide, that includes some systematics we haven't considered yet.
  - After you get rid of the atmosphere, the detectors are perhaps the scariest part of the problem.
- Much recent progress on WFIRST detector development and characterization.
  - More to come; the formulation science team received its first H4RG test data this year.
  - Detector characterization plans and calibration plan are being formulated now – decisions made in the next 1—2 years will be critical.