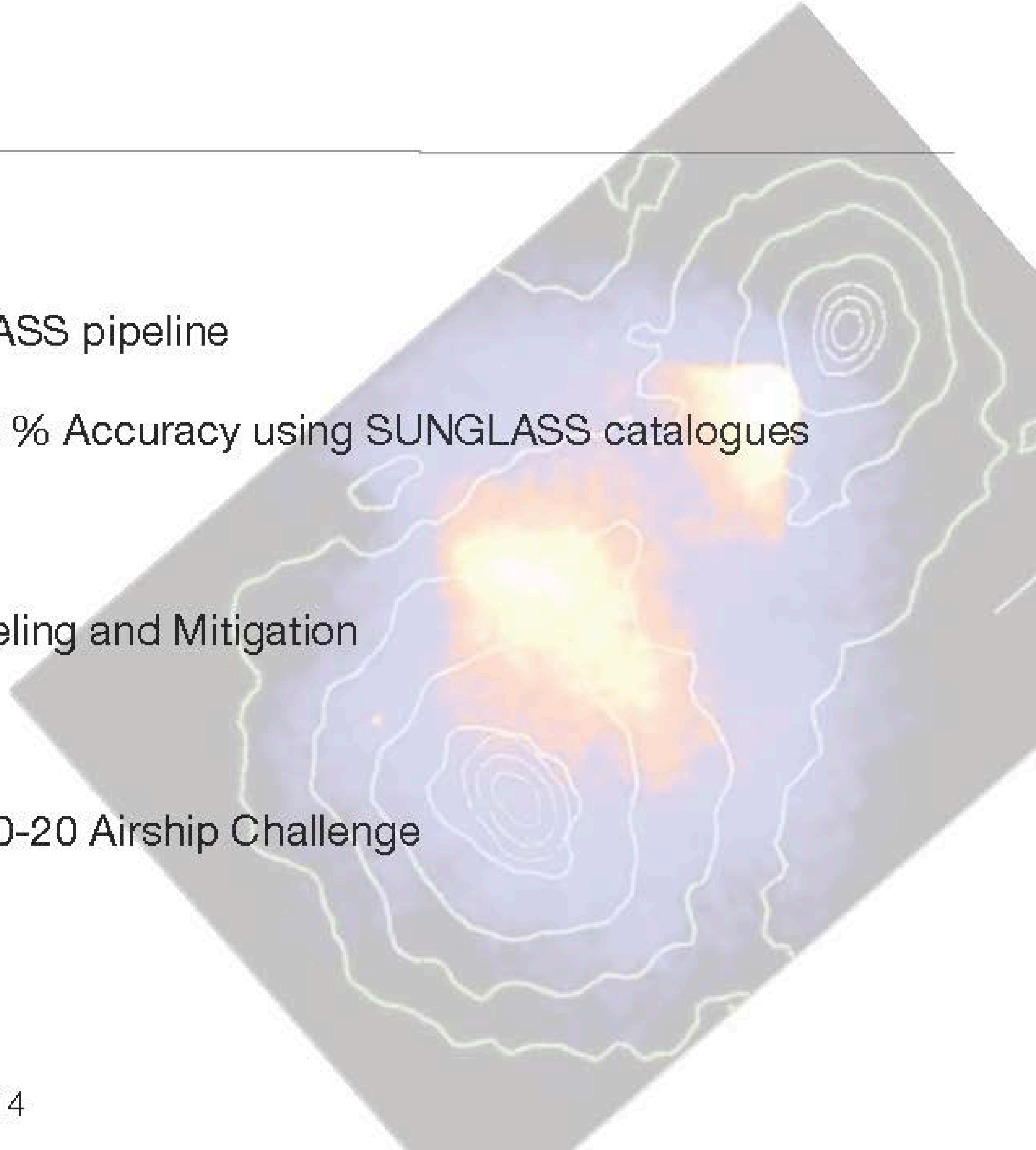
Measuring Dark Energy to 1% Accuracy with Cosmological Simulations

Alina Kiessling
Jet Propulsion Laboratory / CalTech

Astrophysics Seminar, IPMU, Oct 2014

Outline

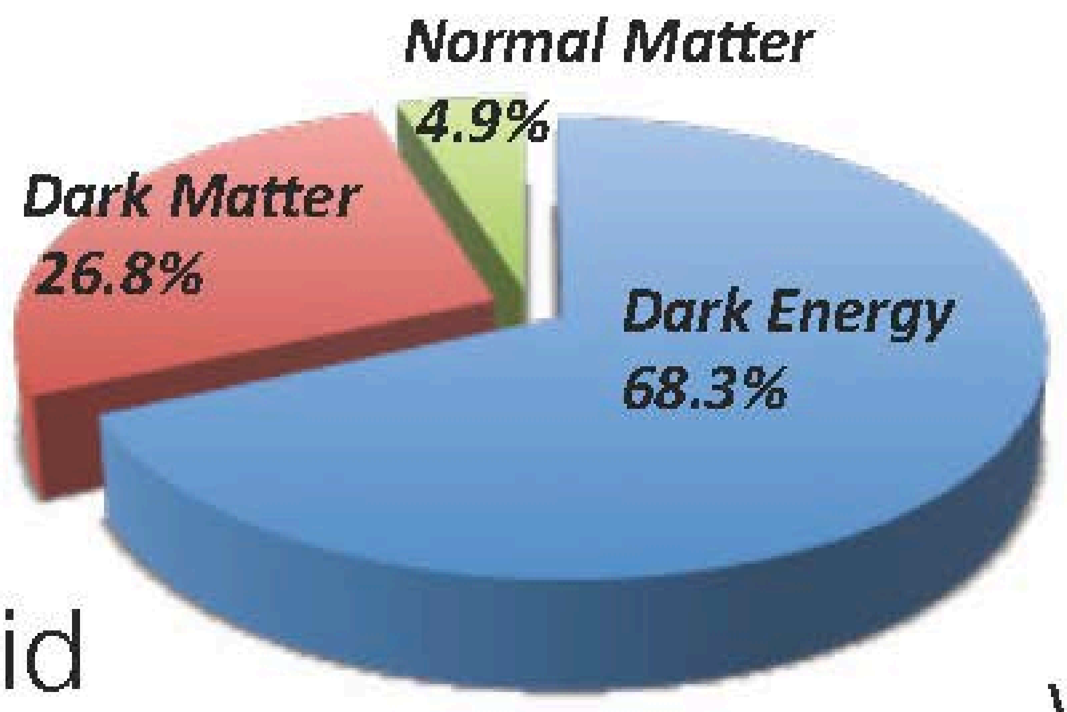
- Motivation
- Introduction to the SUNGLASS pipeline
- Measuring Dark Energy to 1% Accuracy using SUNGLASS catalogues
    - Covariance matrices
    - Intrinsic Alignment Modeling and Mitigation
- Summary
- The NASA Centennial 20-20-20 Airship Challenge



Motivations

What is the nature of gravity?

What is the nature of Dark Matter Ω_{DM}?



What are the Cosmological parameters of the Universe?

How did structures form?

What is Dark Energy Ω_{Λ}?

A Solution

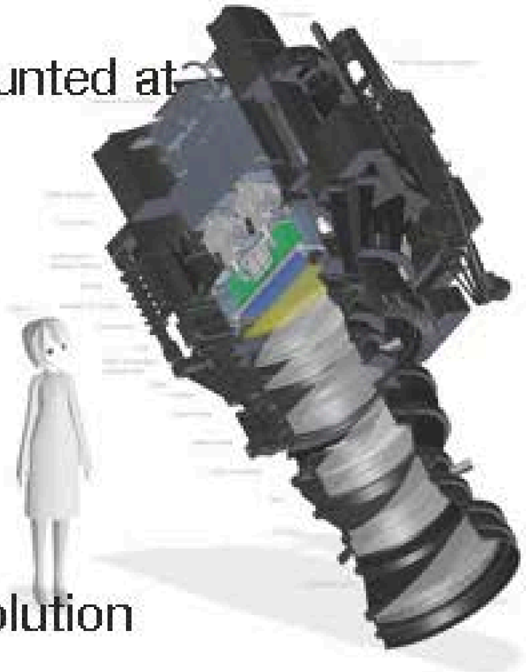
Weak Gravitational Lensing

- Sensitive to both Dark and Luminous Matter
- Probes the growth rate of structure
- Has greatest statistical power to probe cosmological parameters - in particular the Dark Energy equation of state
- Is independent of galaxy bias

- Intrinsic alignments of galaxies are still not well understood
- Observational shape measurement is difficult

HSC: 2014 - 2019

- Wide-field mosaic camera mounted at the prime focus of the Subaru telescope (8.2m)
- 1.5 deg diameter FoV
- 1400 sq deg wide survey
- 27 sq deg deep survey
- 2 FoV ultra deep survey
- WL + LSS + SNe + Galaxy Evolution



Euclid: 2020 - 2026

Euclid

- A cosmic vision ESA/NASA mission
- 1.2m satellite telescope
- 0.5 sq deg FOV
- 15,000 sq deg
- Weak Lensing + Galaxy Clustering

WFIRST

Wide-Field Infrared Survey Telescope

- Proposed launch date 2022++
- Microlensing + NIR + WL + BAO + SNe
- 2.4m NRO telescope available
- 2500 sq deg survey
- HST quality imaging quality

LSST: 2021 - 2031

LSST
Large Synoptic Survey Telescope

- An NSF and DOE joint project
- 6.5m effective diameter mirror
- 9.6 sq deg FoV
- 20,000 sq deg
- u-g-r-i-z-y
- WL + LSS + SN + SL + Cl

Motivation

- Simulations can test weak lensing analysis techniques by providing a data set with known parameters.
- Simulations can characterize the effects of source clustering and galaxy alignments, as well as other systematics and real world effects, better than theory can.
- Simulations can be used perform Monte Carlo analysis to provide precision matrices and statistical properties required for data analysis.

Large, high resolution single realisations:

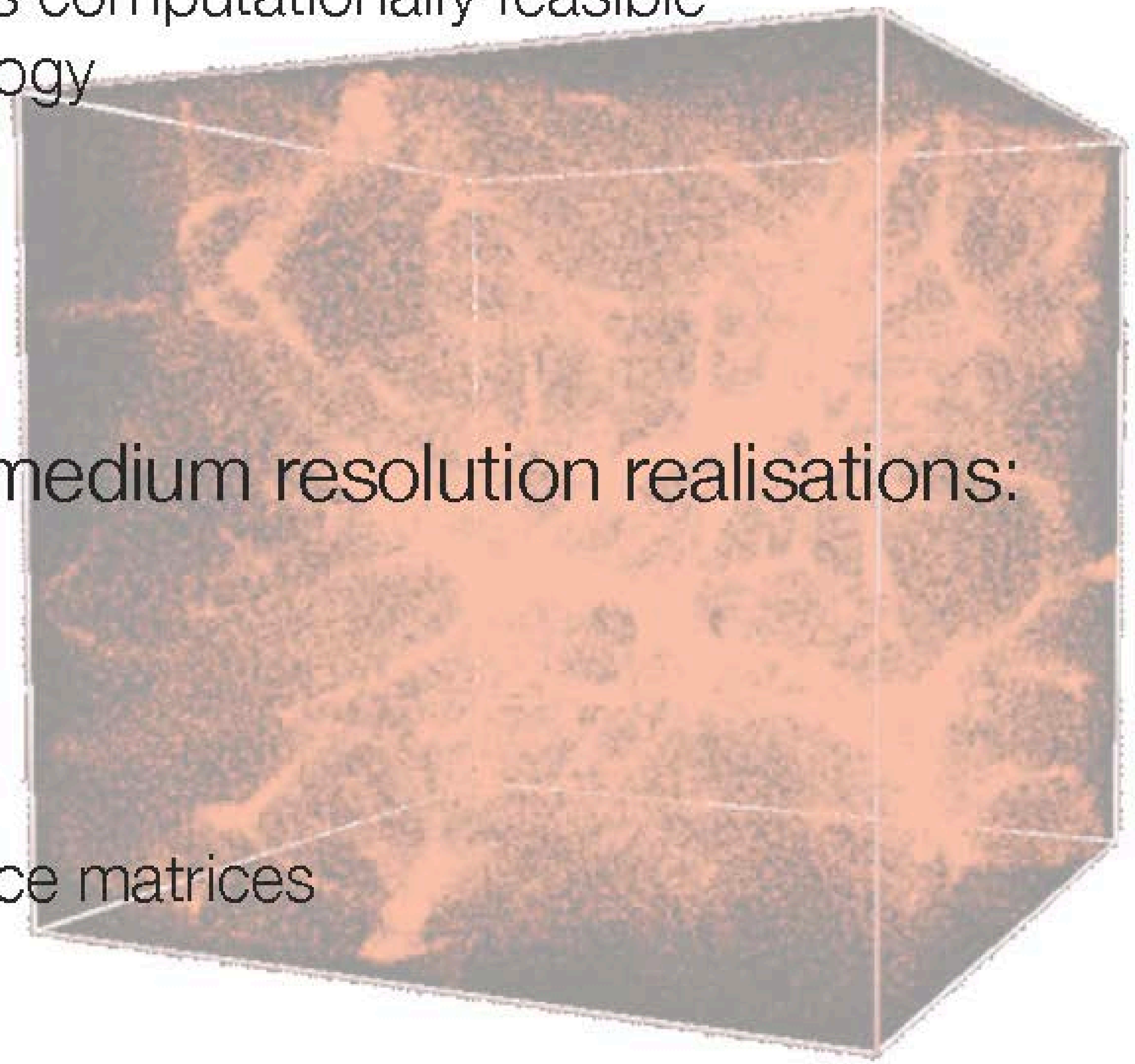
- Pushes the limits of what is computationally feasible
- Currently favoured cosmology

  - ☆ Halo properties
  - ☆ Galaxy formation

Multiple, Monte Carlo, medium resolution realisations:

- Computationally cheap
- Any cosmology

  - ☆ Testing of methods
  - ☆ Generation of covariance matrices



The SUNGLASS pipeline - Kiessling et al, 2011

SUNGLASS -

Simulated UNiverses for Gravitational Lensing Analysis and Shear Surveys

A pipeline that rapidly generates Monte Carlo simulated universes for weak lensing and cosmic shear analysis

Kiessling et al 2011, MNRAS, 414, 2235

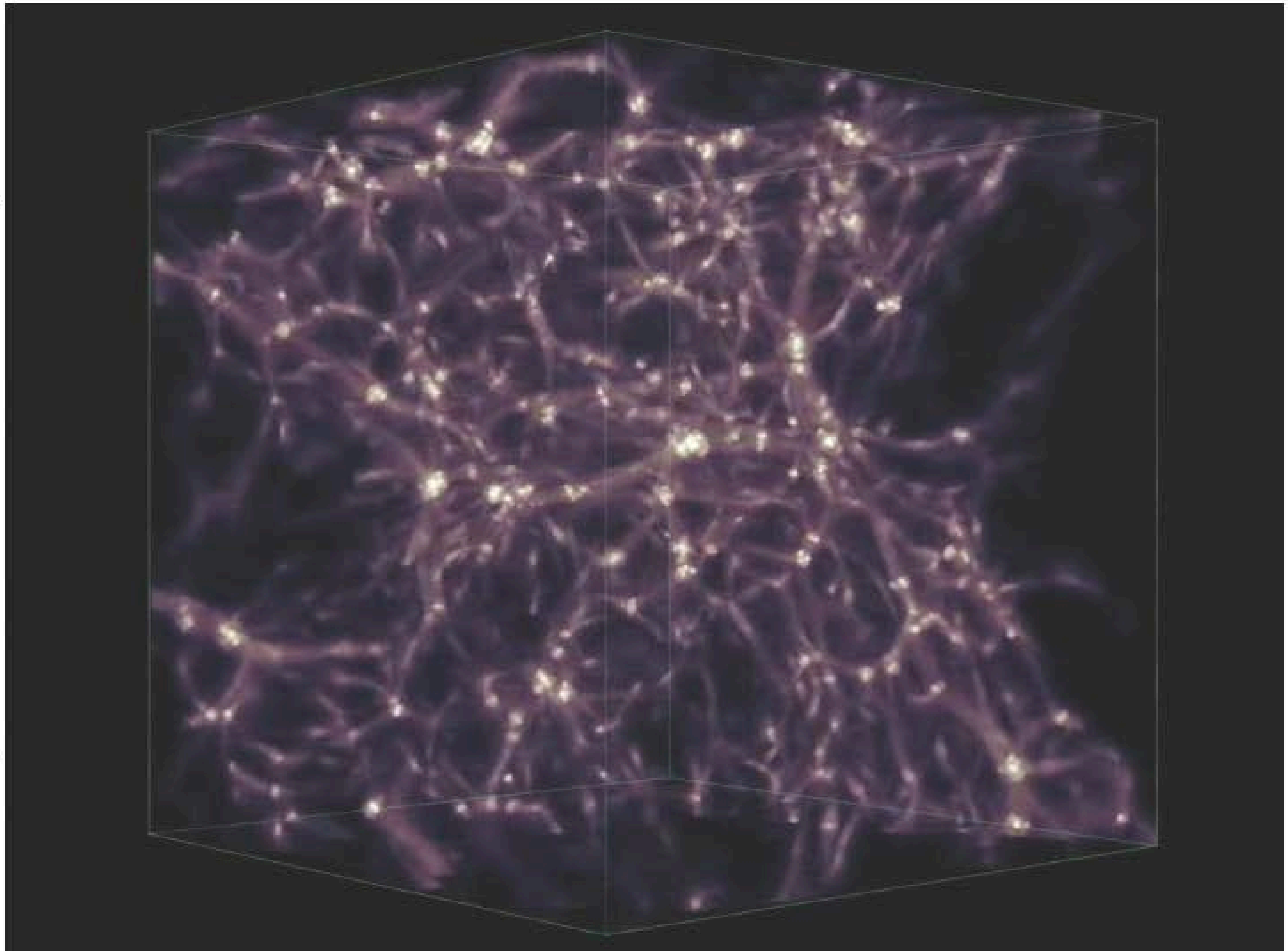
Summary of the SUNGLASS pipeline

Use Cosmological N-Body simulations to test weak lensing analysis techniques and run data analysis on telescope survey data sets.

Method

- Create multiple cosmological N-Body simulations with N-GenIC and GADGET2 (Springel 2005)
- Generate a light cone through the simulation output
- Calculate the shear & convergence and their power spectra for multiple lensing source redshifts
- Generate mock galaxy catalogues with a realistic source redshift distribution and assign each galaxy a shear, convergence and photo-z
- (Add systematics and real world effects to the simulation data)
- Generate precision matrices and test weak lensing analysis techniques

The Simulations - GADGET2



512^3 particles
512 h^{-1}Mpc
$\Omega_m = 0.27$
$\Omega_\Lambda = 0.73$
$\Omega_b = 0.05$
$h = 0.71$
$\sigma_8 = 0.81$
$z_0 = 60$
$m_p = 7.5 \times 10^{10} M_\odot$

Generating the light cone

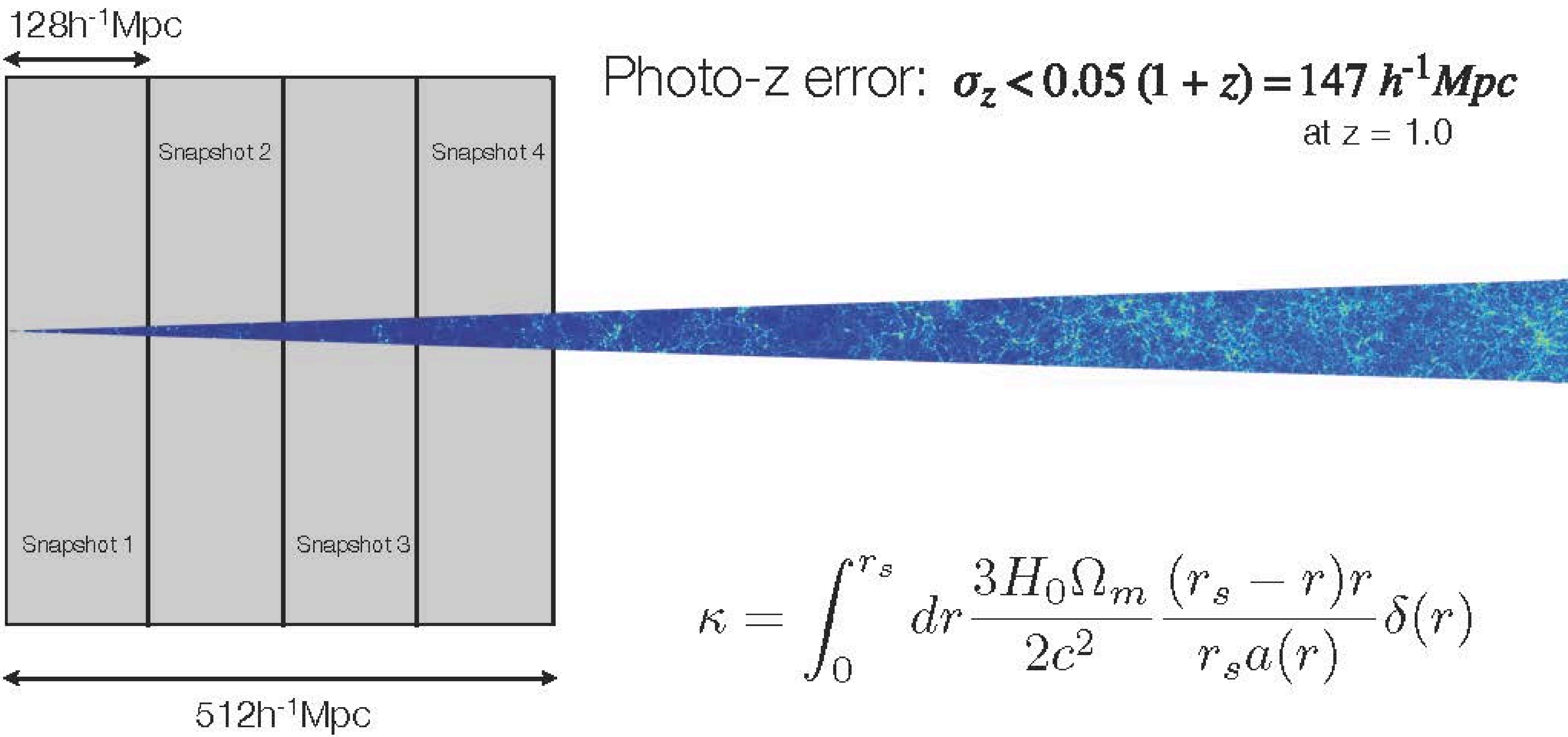
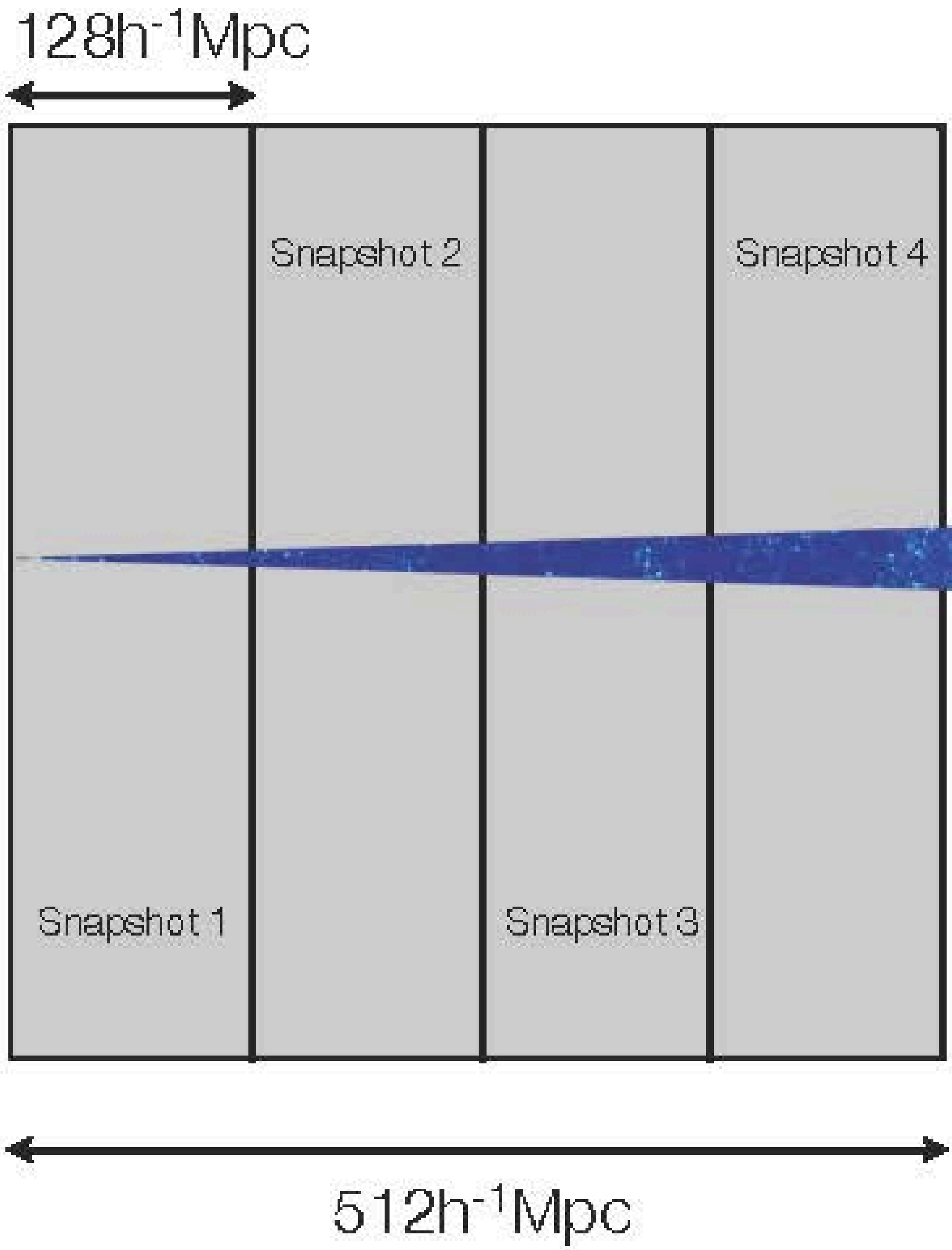


Photo-z error: $\sigma_z < 0.05\,(1+z) = 147\ h^{-1}Mpc$

at z = 1.0

$$\kappa = \int_0^{r_s} dr \frac{3H_0\Omega_m}{2c^2} \frac{(r_s - r)r}{r_s a(r)} \delta(r)$$

Generating the light cone



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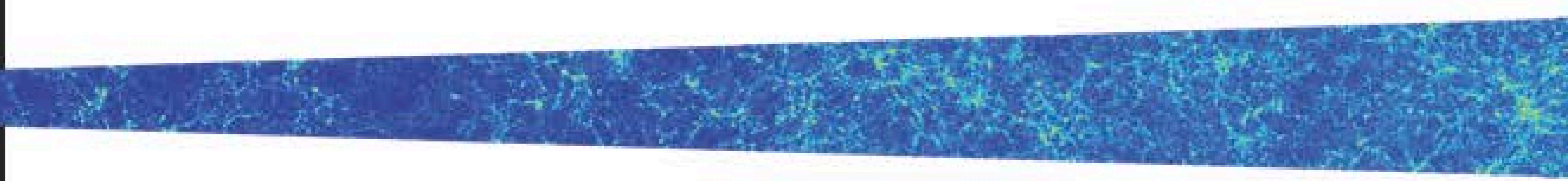
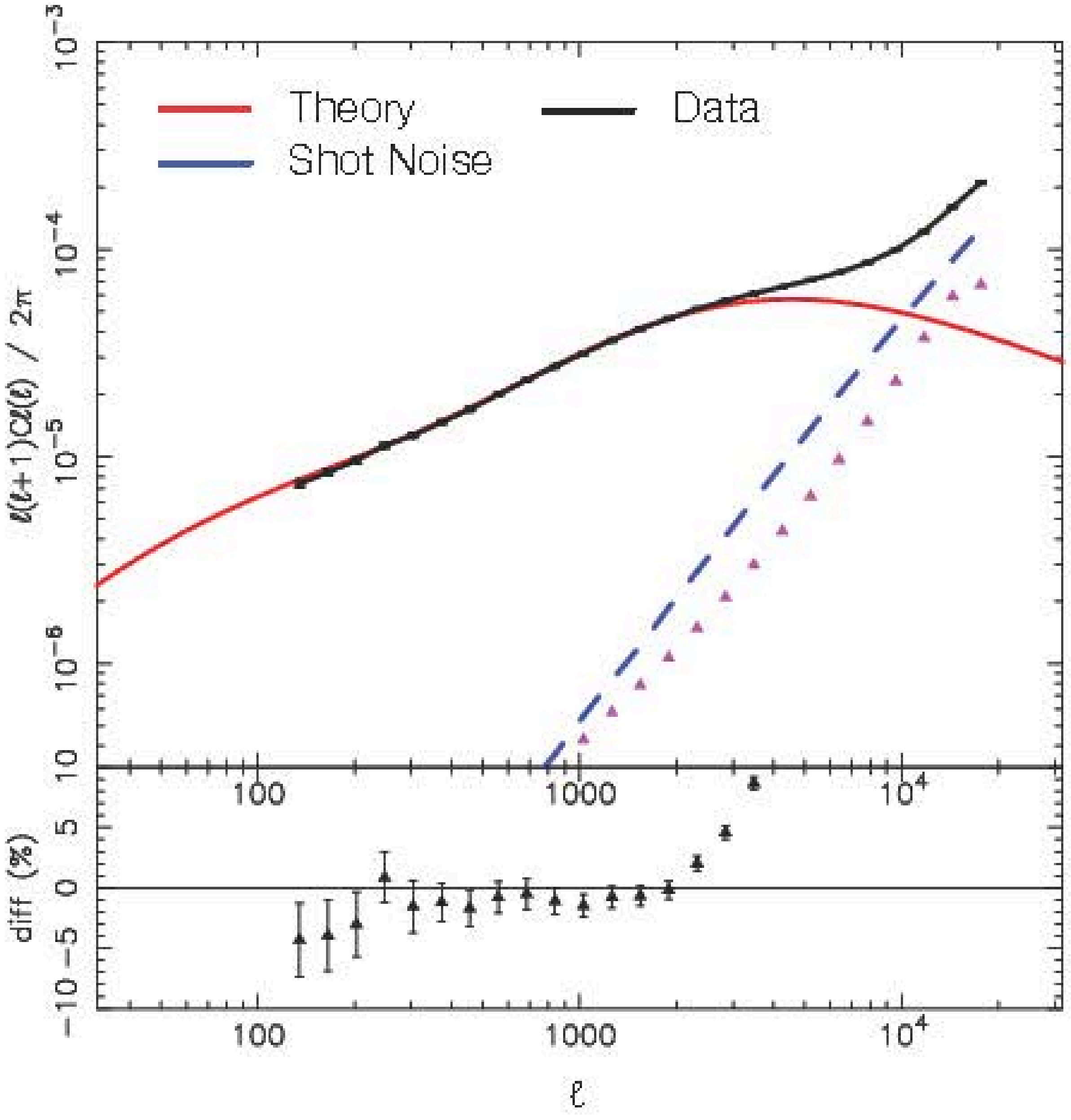


Line of sight integration using no radial binning

$$\kappa(p) = \sum_i \frac{k(r_i, r_s)}{\Delta\Omega_p \bar{n}(r_i) r_i^2} - \int_0^{r_s} dr\ k(r, r_s)$$

$$k(r, r_s) = \frac{3\Omega_m H_0^2}{2c^2} \frac{(r_s - r)r}{r_s a(r)} \qquad \Delta\Omega_p = \Delta\theta_x \Delta\theta_y$$

SUNGLASS reproduces theoretical expectations



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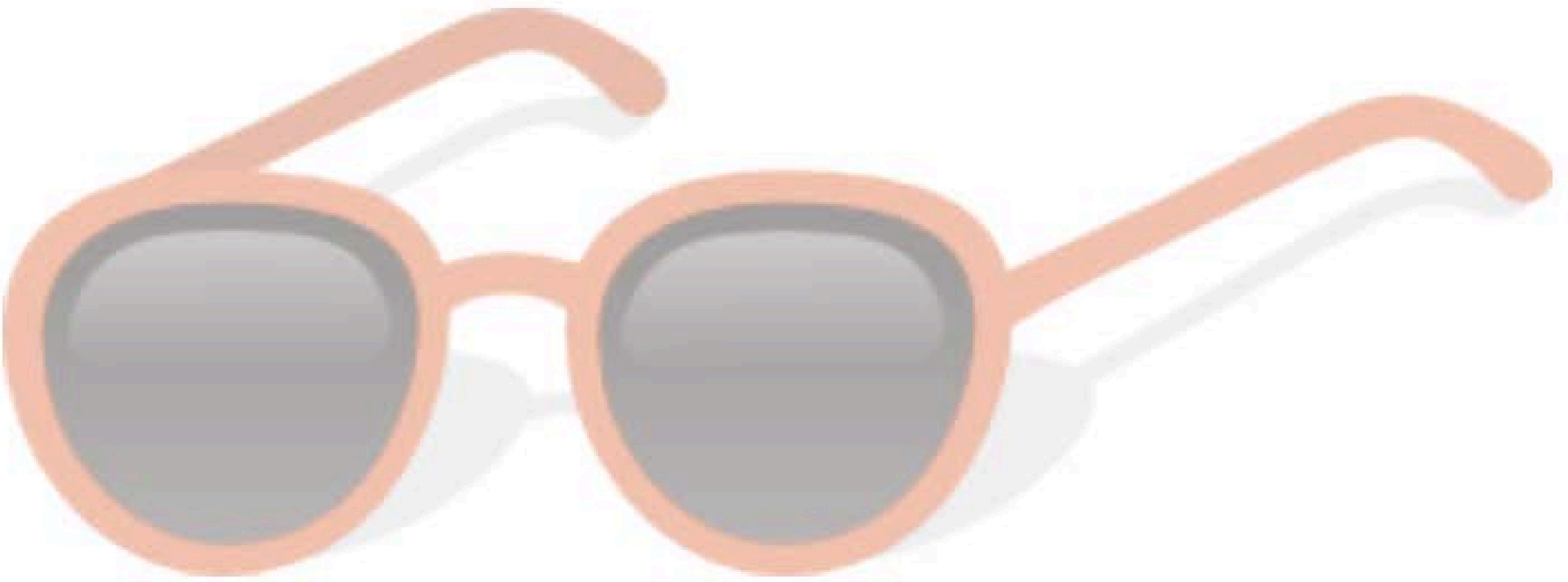
Kiessling et al 2011, MNRAS, 414, 2235

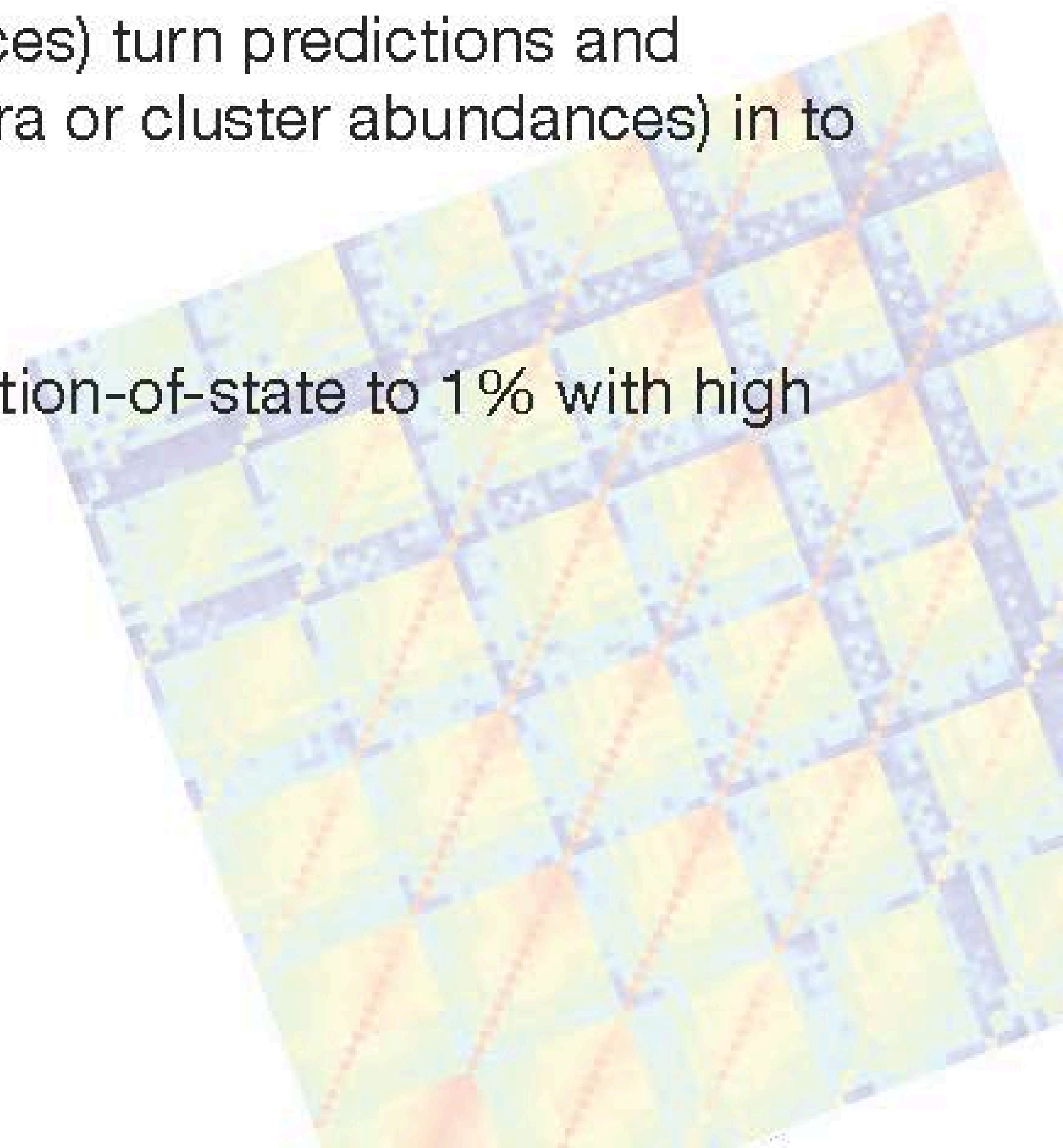


What can we use the mock galaxy shear catalogues generated by SUNGLASS for?

Covariance & Precision Matrix Generation

Why are covariance matrices important?

- A covariance matrix tells us how correlated our data points are with each other (e.g. power spectrum bandpower modes)
- Inverse covariance matrices (precision matrices) turn predictions and observations (e.g. weak lensing power spectra or cluster abundances) in to cosmological parameter estimates
- We can only determine the dark energy equation-of-state to 1% with high accuracy precision matrices

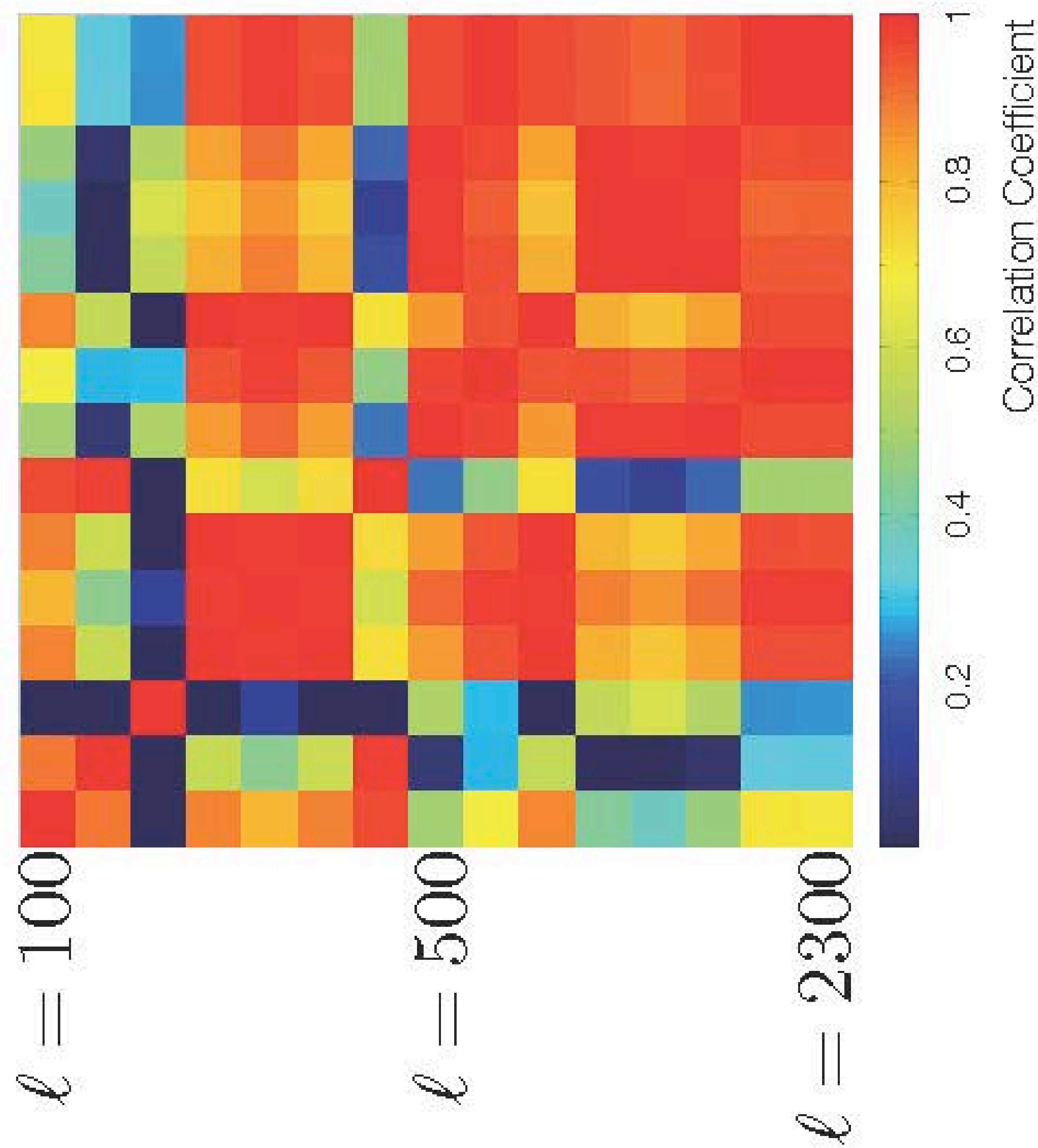


Correlation Coefficient Matrix

$$r_{\ell\ell'} = \frac{M_{\ell\ell'}}{\sqrt{M_{\ell\ell}M_{\ell'\ell'}}}$$

where

$$M_{\ell\ell'} = \langle \Delta C_\ell^{\gamma\gamma} \Delta C_{\ell'}^{\gamma\gamma} \rangle$$



More realisations gives a more stable matrix

Kiessling et al 2011, MNRAS, 414, 2235

Correlation Coefficient Matrix

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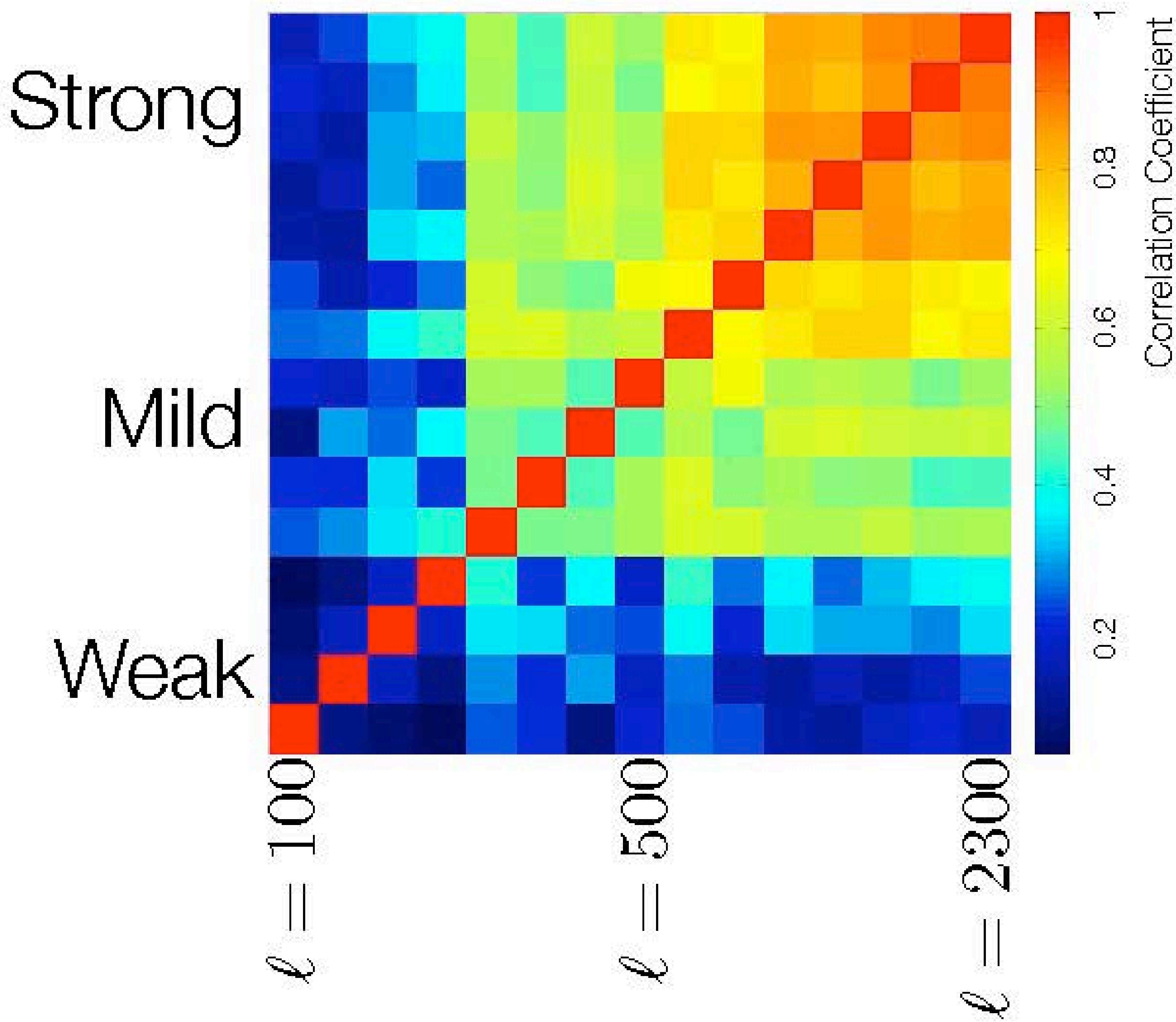
100 realisations



Kiessling et al 2011, MNRAS, 414, 2235

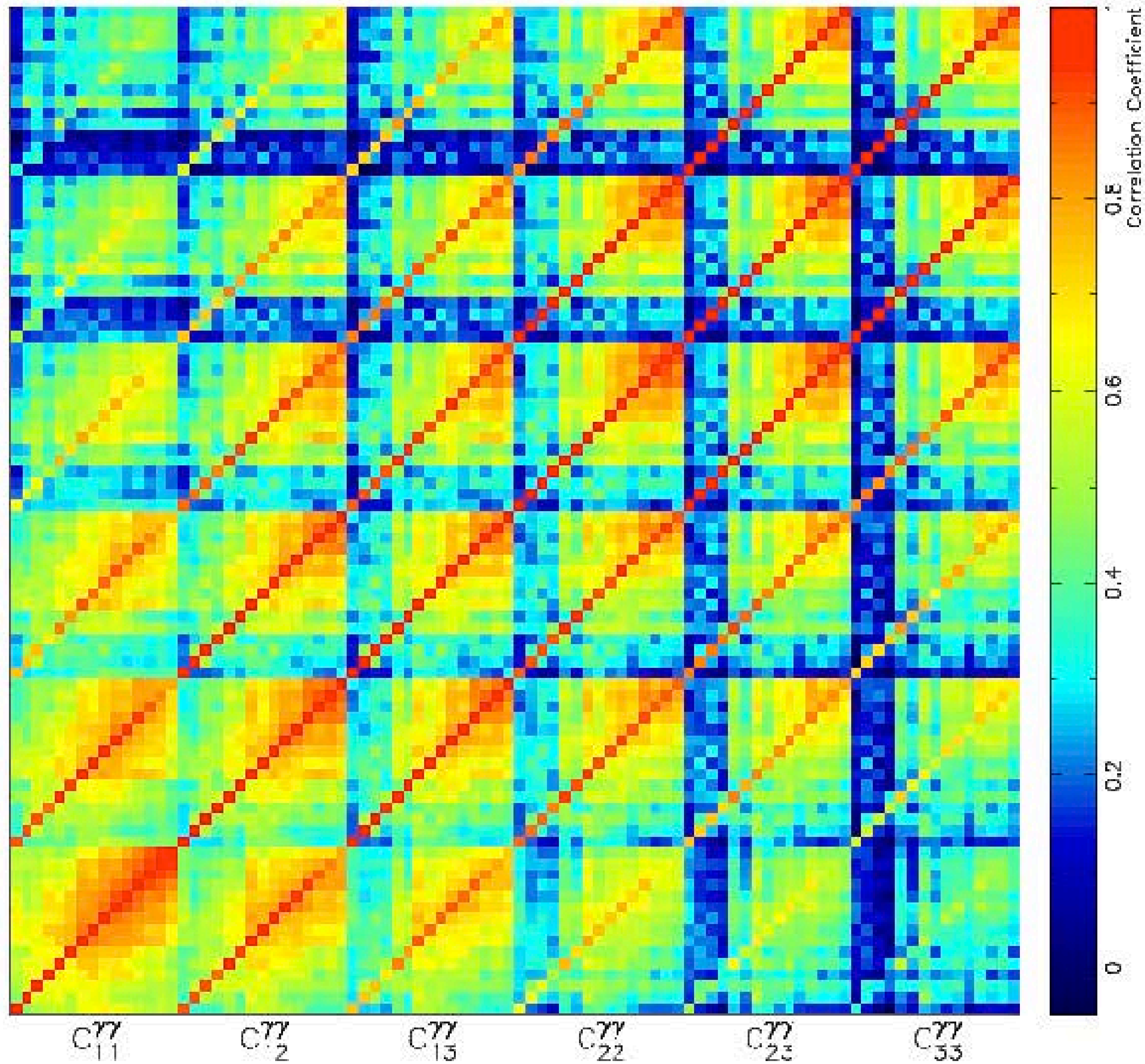
Correlation Coefficient Matrix - Tomography

$$r_{\ell\ell'} = \frac{M_{\ell\ell'}}{\sqrt{M_{\ell\ell} M_{\ell'\ell'}}}$$

where

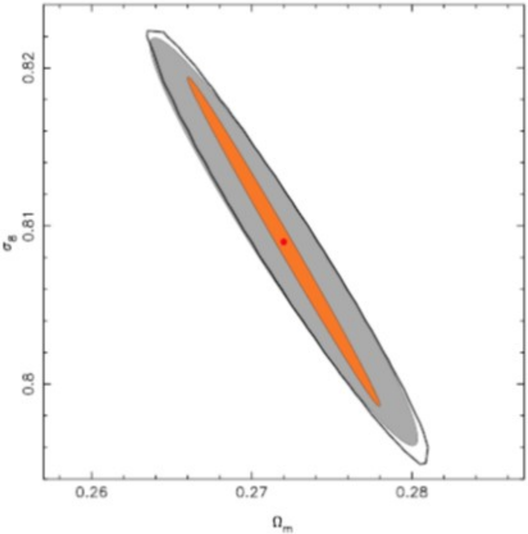
$$M_{\ell\ell'} = \langle \Delta C_\ell^{\gamma\gamma} \Delta C_{\ell'}^{\gamma\gamma} \rangle$$

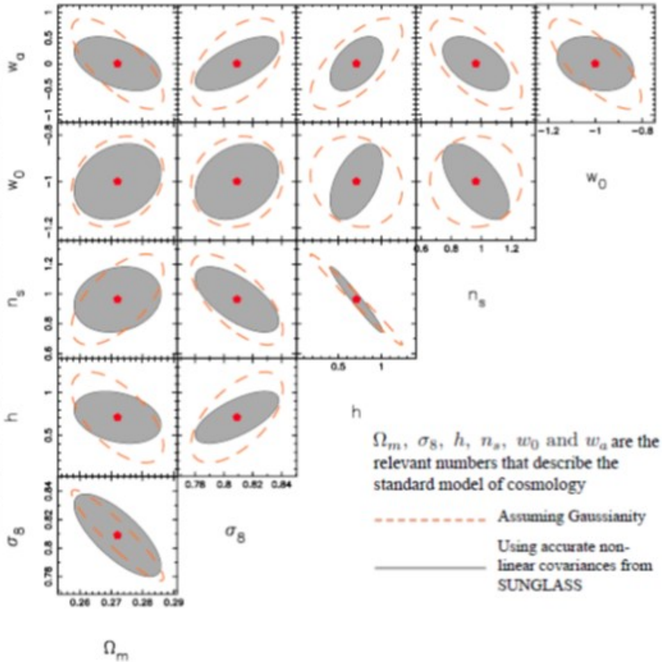
100 realisations



Kiessling et al 2011, MNRAS, 414, 2235

An application of SUNGLASS: Cosmological Parameter Error Estimates

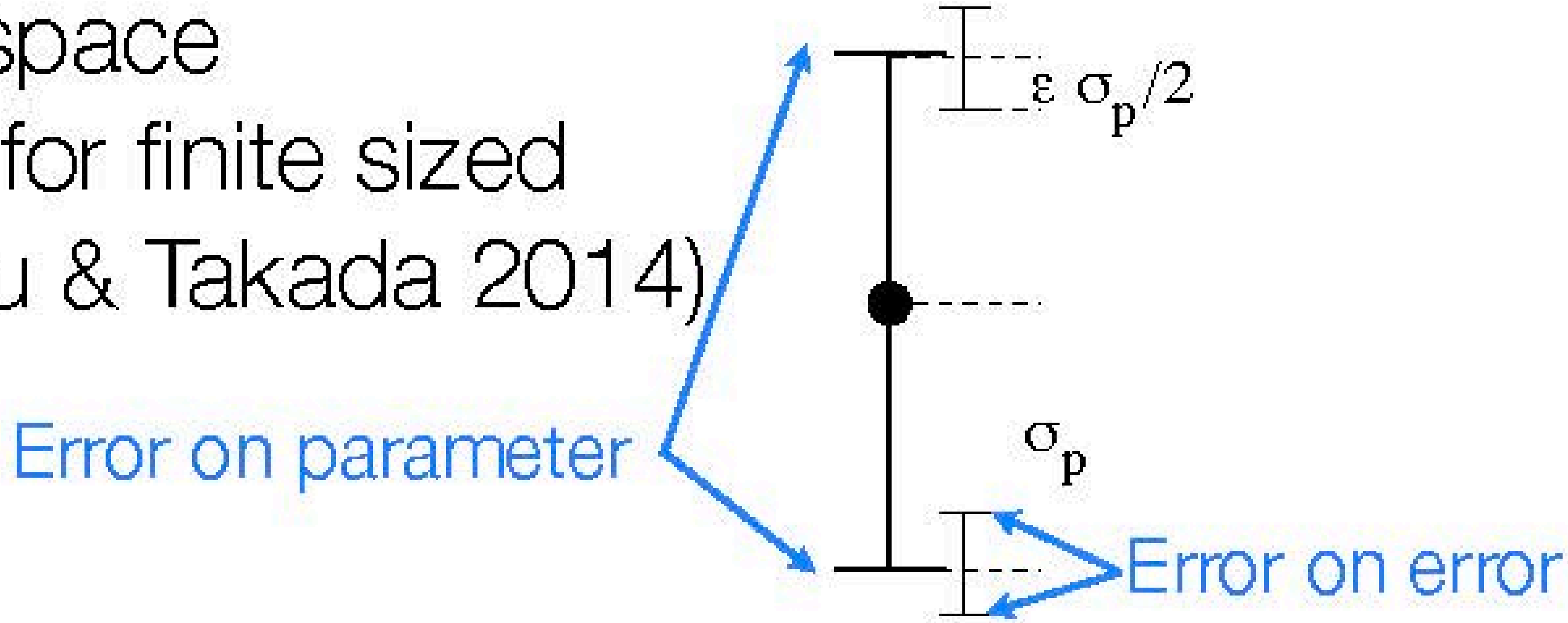




Kiessling et al 2011, MNRAS, 416, 1045

Precision Matrix Requirements for w~1%

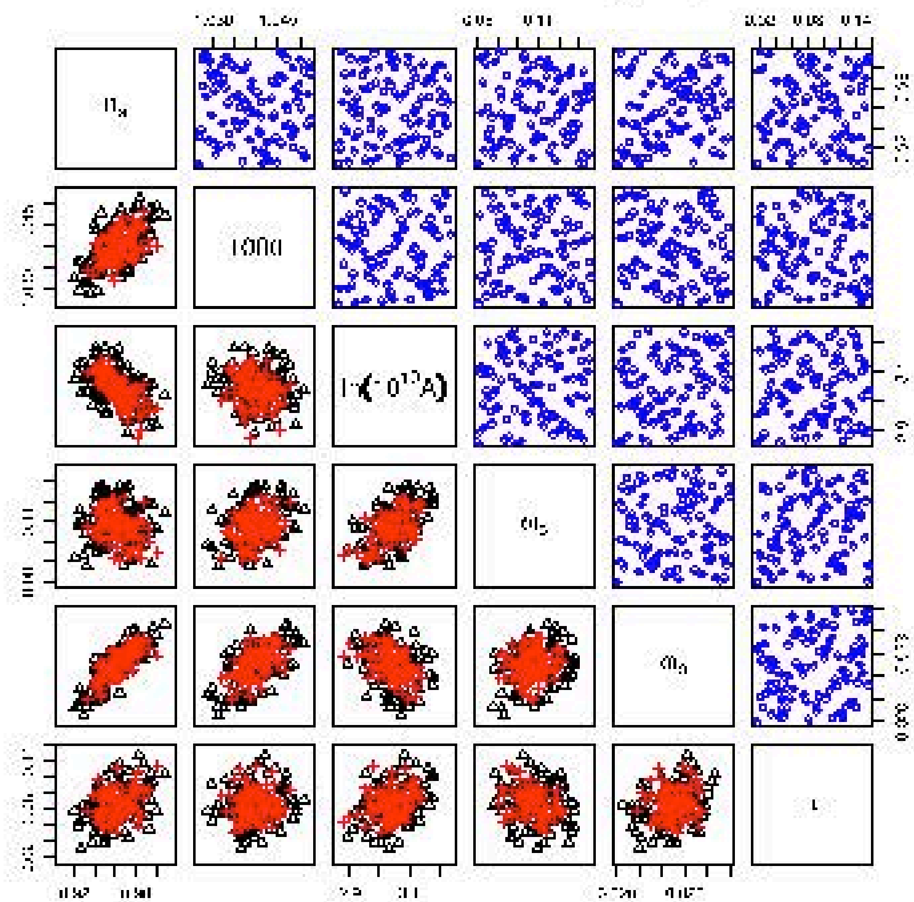
- Upcoming telescope missions want to measure w~1%
- What error can the precision matrix have to reach this accuracy?
- Taylor, Joachimi & Kitching 2013 define equations to determine the error on precision matrices.
- $N_S > (2/\epsilon^2) + N_D + 4$ $\epsilon = \sqrt{\frac{2}{N_S - N_D - 4}}$
- They estimate 10^6 realizations required per point in parameter space
- Also need to account for finite sized surveys (SSC e.g. Li, Hu & Takada 2014)



Precision Matrix Requirements for w~1%

- What area of cosmological parameter space do we need to cover?

- Schneider, Holm & Knox 2011discuss an intelligent way to populate parameter space - but how many points are sensible?



Precision Matrix Requirements for w~1%

- Brute Force Approach -
  - 10^6 realizations
  - 100 points in parameter space
  - 50 CPUs x 48 hrs per realization
  - Total: 240 billion CPU hrs
  - This is 18 years using all 1.5 million processors on the Sequoia supercomputer

- This problem exceeds the computational resources available in the world today

Precision Matrix Requirements for w~1%

- What techniques can we use to reduce the number of realizations required?
    - Emulators (e.g. Schneider & Heitmann)
    - Power Spectrum Mode Resampling (e.g. Schneider)
    - Shrinkage (e.g. Joachimi, Pope & Szapudi)
    - Data Compression (e.g. Taylor, Kitching & Joachimi)

Precision Matrix Requirements for w~1%

$$N_S = N_D \times N_{PS}^{P} \times N_{PS}^{NP} \times f_{shrink}$$

N_S = Total number of simulation realizations required

N_D = Total number of data points (power spectrum bins, redshift bins, cross bins, probes)

N_{PS} = Number of realizations per point in parameter space

P = Number of cosmological parameters

NP = Number of Nuisance Parameters

f_{shrink} = Factor that we can reduce the required number of simulation by using emulators, shrinkage etc

Precision Matrix Requirements for w~1%

$$N_S = N_D \times N_{PS}^{P} \times N_{PS}^{NP} \times f_{shrink}$$

$$10^{6} = 10^{5} \times 2^{6} \times 2^{4} \times 10^{-2}$$

N_S = Total number of simulation realizations required

20 10

N_D = Total number of data points (power spectrum bins, redshift bins, cross bins, probes)

10 2

N_{PS} = Number of realizations per point in parameter space

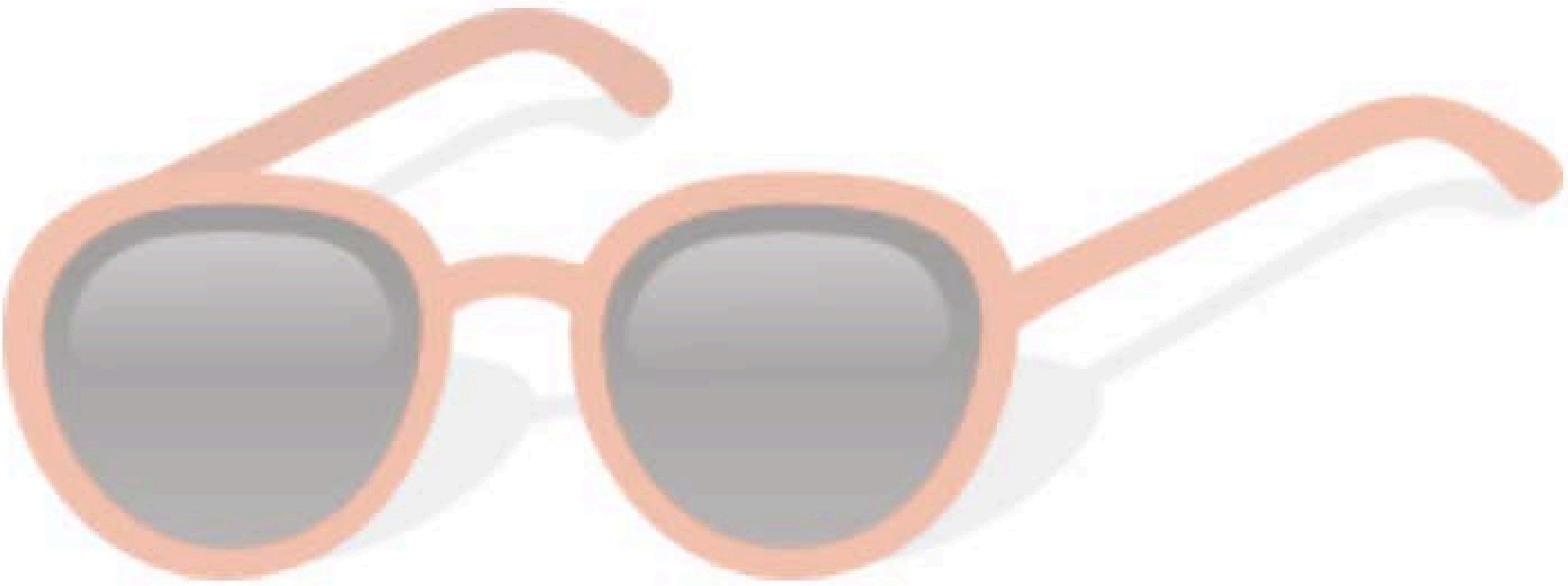
P = Number of cosmological parameters

NP = Number of Nuisance Parameters

f_{shrink} = Factor that we can reduce the required number of simulation by using emulators, shrinkage etc

Open Questions

- How many points in parameter space do we need to sample and how do we fill that parameter space?
  - What nuisance parameters (e.g.IA) do we need to include in the covariance matrices?
  - How many parameters do we have in total when considering cosmological parameters and nuisance parameters?
- How many N-body realizations do we require to achieve an accuracy on the precision matrix that will enable us to measure DE to 1%?
- What wavenumbers do we need to resolve in the simulations in order to measure DE to 1%
- What techniques can we develop that will reduce the number of N-body simulations required to a reasonable amount?
  - Do we need to combine techniques (emulator, shrinkage, data compression, mode resampling, other) or will a single technique be enough?
- What probes and joint probes do we need to generate precision matrices for?
- What computational resources do we need to generate all the required precision matrices for upcoming telescope missions?

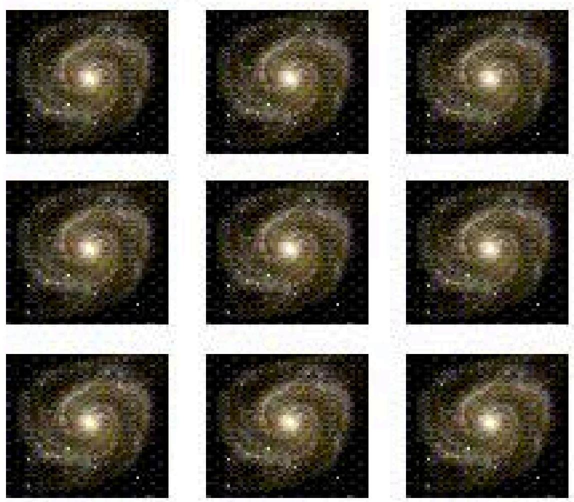


What can we use the mock galaxy shear catalogues generated by SUNGLASS for?

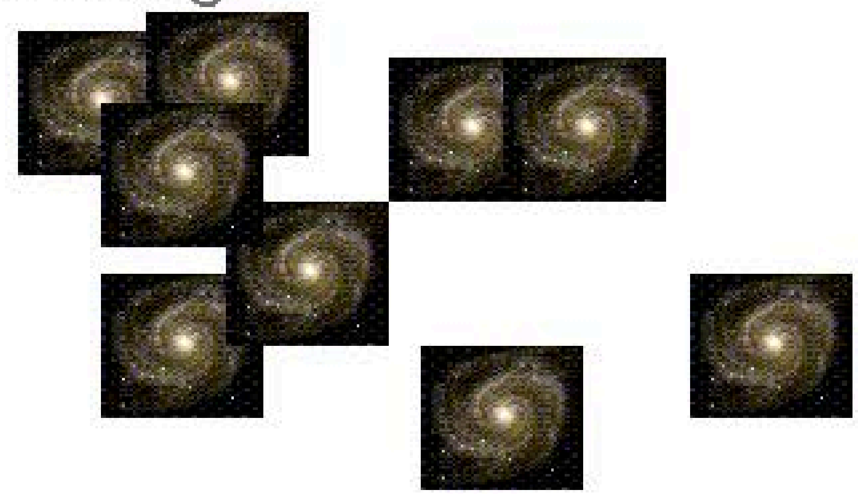
Intrinsic Alignment Modeling and Mitigation

Lensing assumptions

- Homogeneous background sources - Clustering

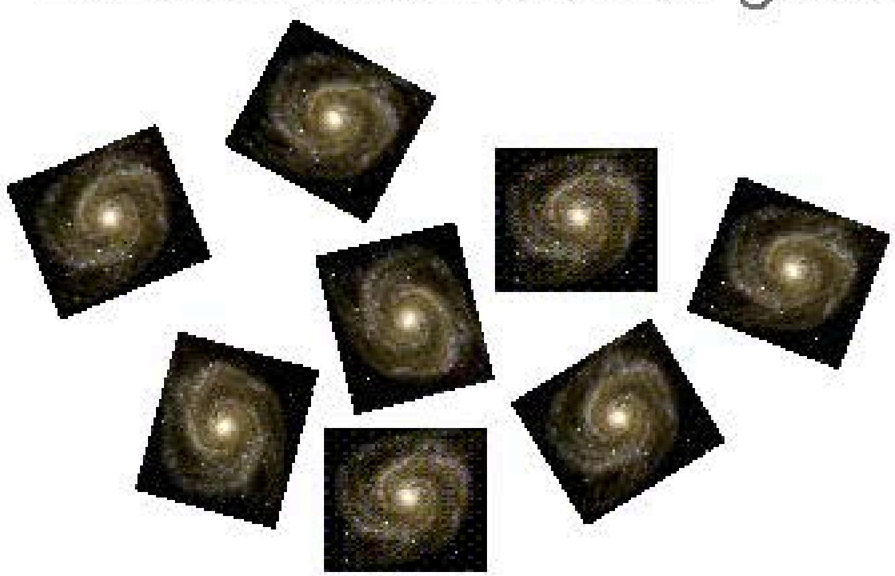


Assumption



Reality

- Random orientation of galaxy shapes - Intrinsic Alignments



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Reality

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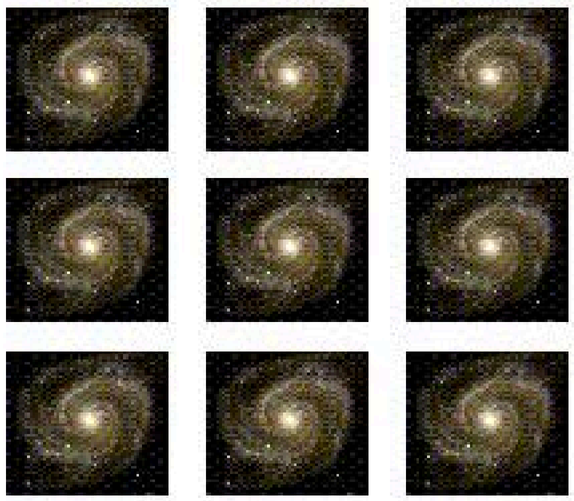
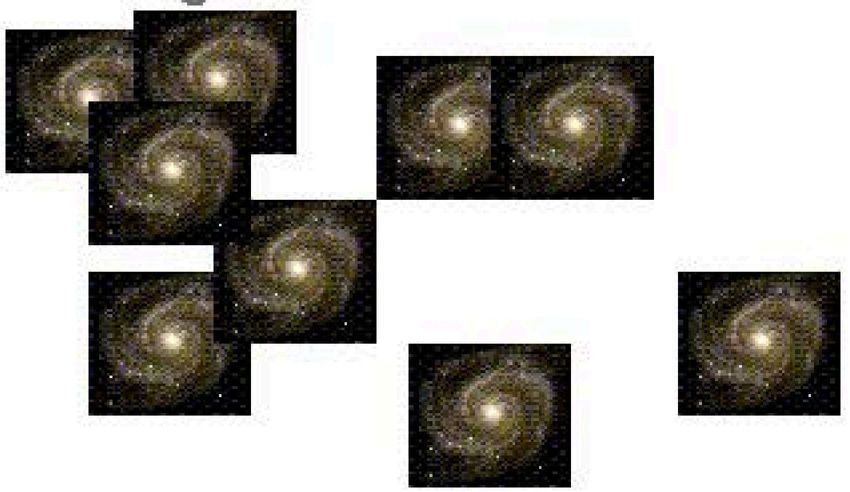


Assumption



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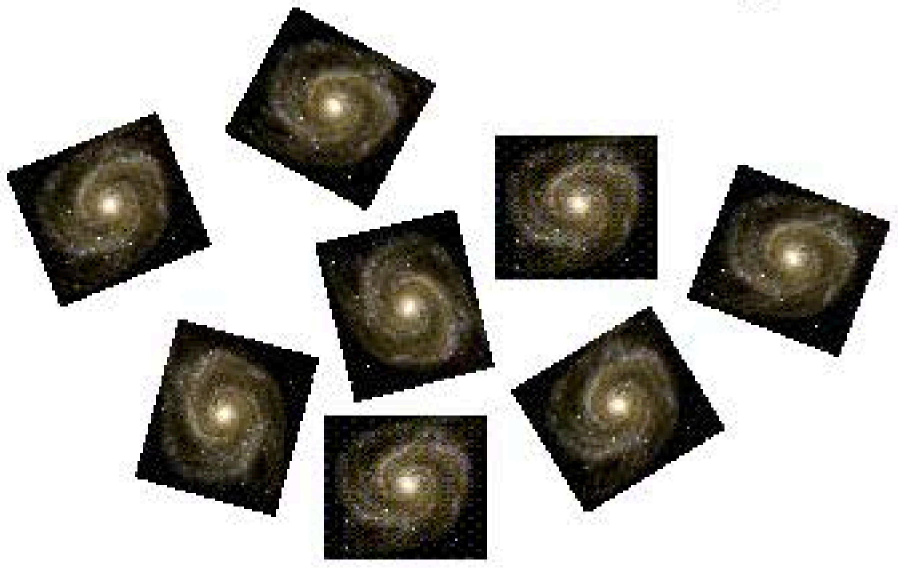
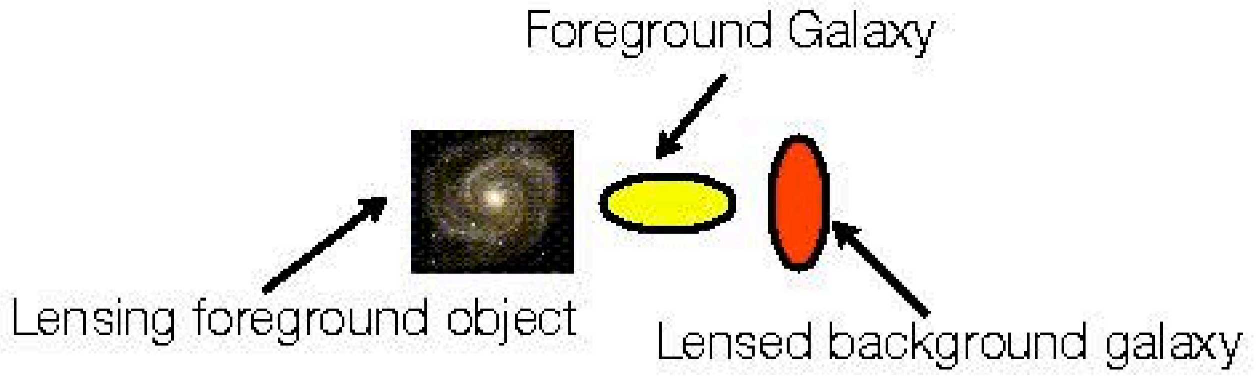


Assumption



Reality

Intrinsic Alignments

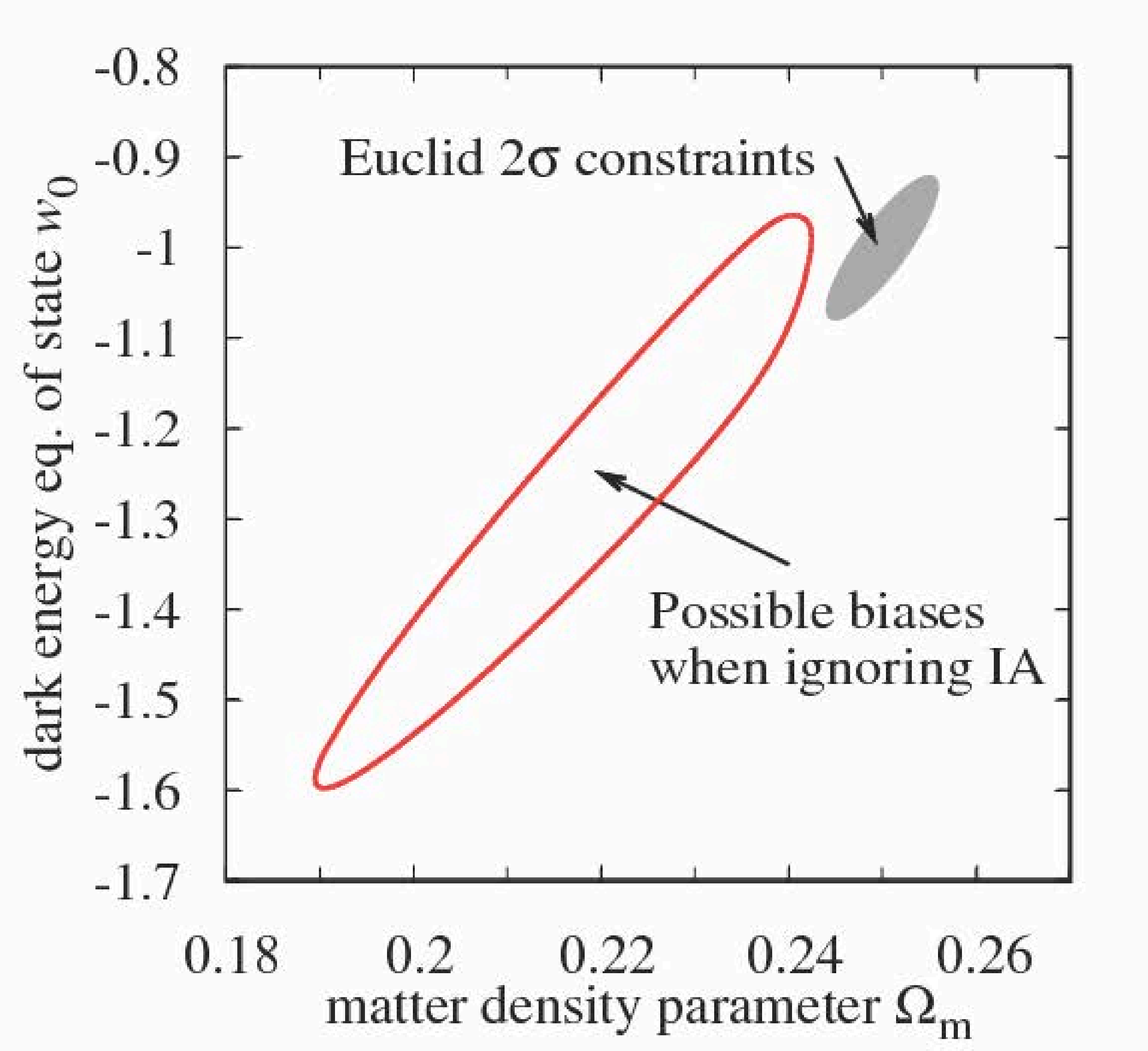
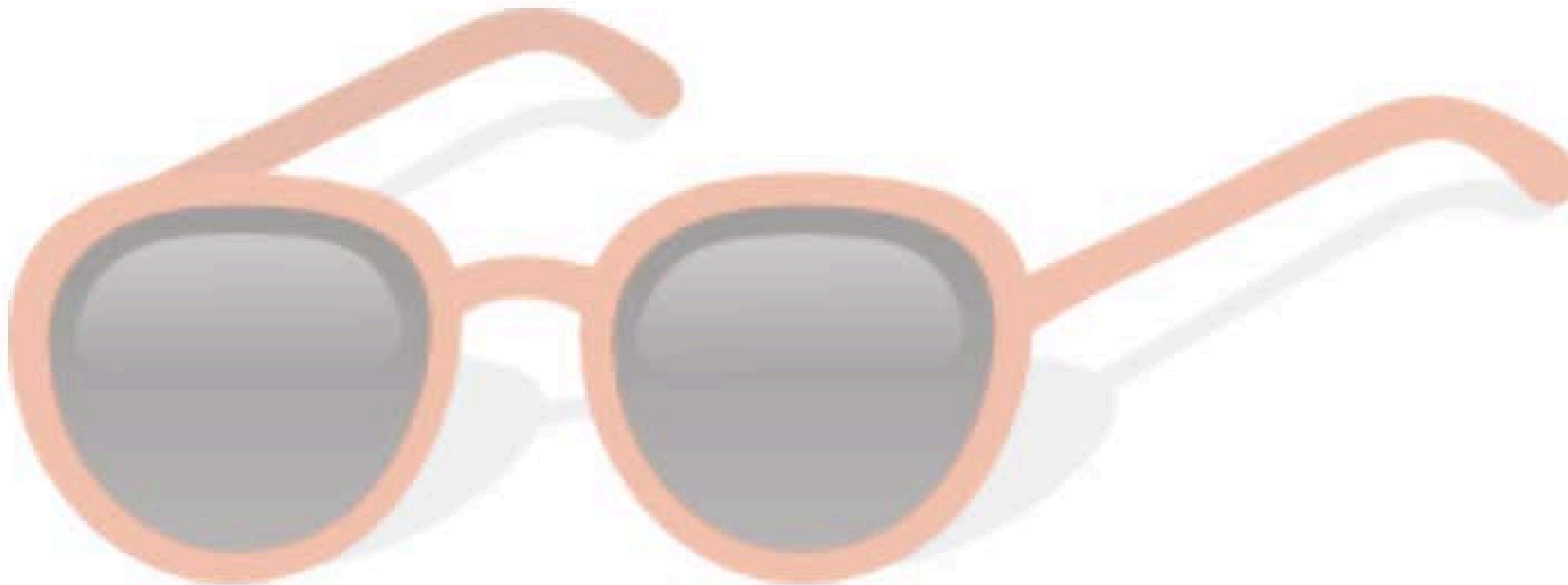


Figure Credit: Benjamin Joachimi

Galacticus - see Benson (2012)

- Populate the SUNGLASS catalogues with realistic galaxy properties such as
  - Color
  - Morphology
  - Magnitude
  - Luminosity
  - etc
- Include semi-analytic IA based on Galacticus galaxy shapes and the linear alignment model (e.g. Joachimi et al 2012)

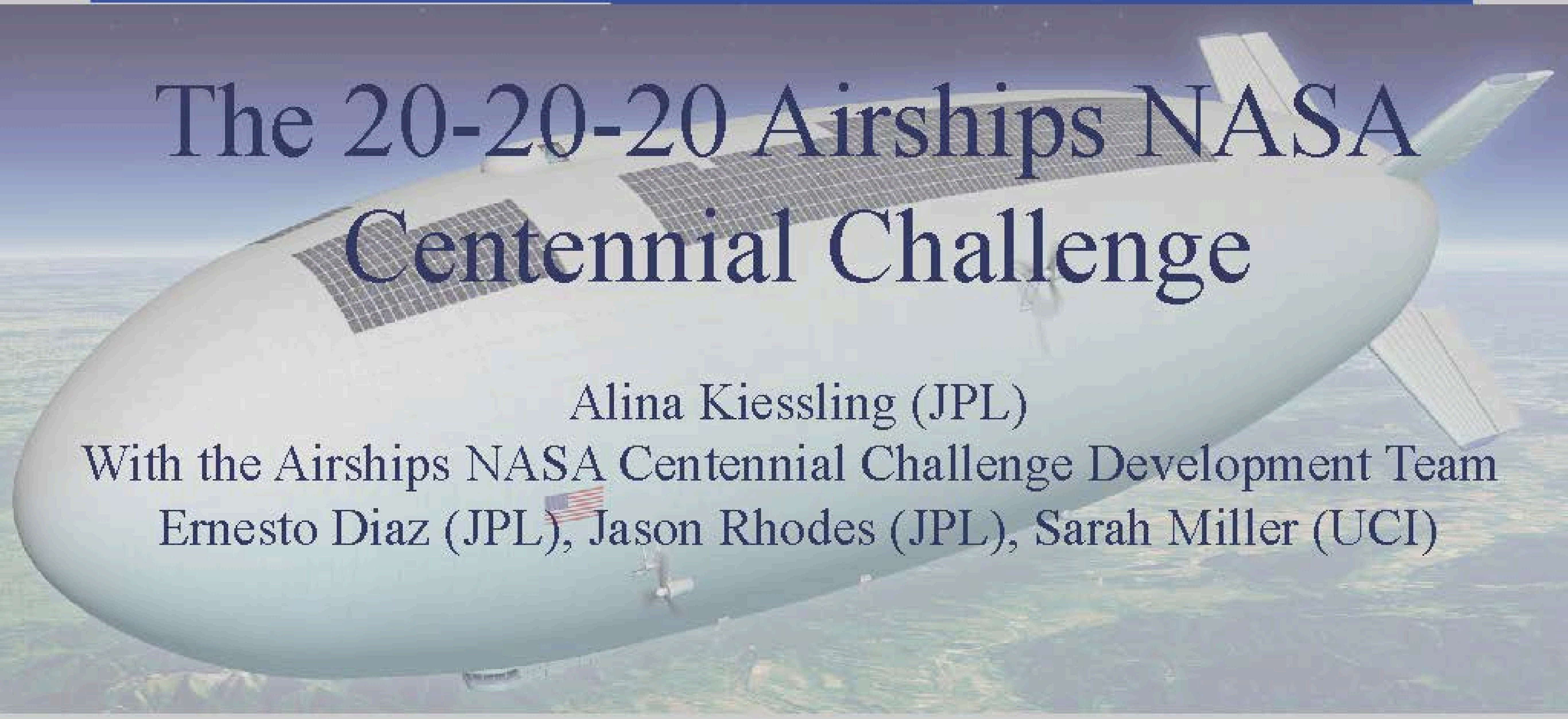
- Also useful for galaxy clustering and photo-z studies



Summary

Summary

- Simulations are essential for survey analysis - e.g. HSC, LSST, Euclid & WFIRST. SUNGLASS simulations are currently available for use - please contact me if you are interested Alina.A.Kiessling@jpl.nasa.gov
- SUNGLASS simulations will include galaxy properties within the next 6 months making them useful for both weak lensing and galaxy clustering analysis
- Monte Carlo suites of simulations are essential for generating stable covariance matrices for both data analysis and parameter estimation
- Research in to Intrinsic Alignment modeling and mitigation is essential to minimize astrophysical systematics in upcoming weak lensing missions
- Still much work to be done to reach precision required for upcoming telescope missions



The 20-20-20 Airships NASA Centennial Challenge

Alina Kiessling (JPL)

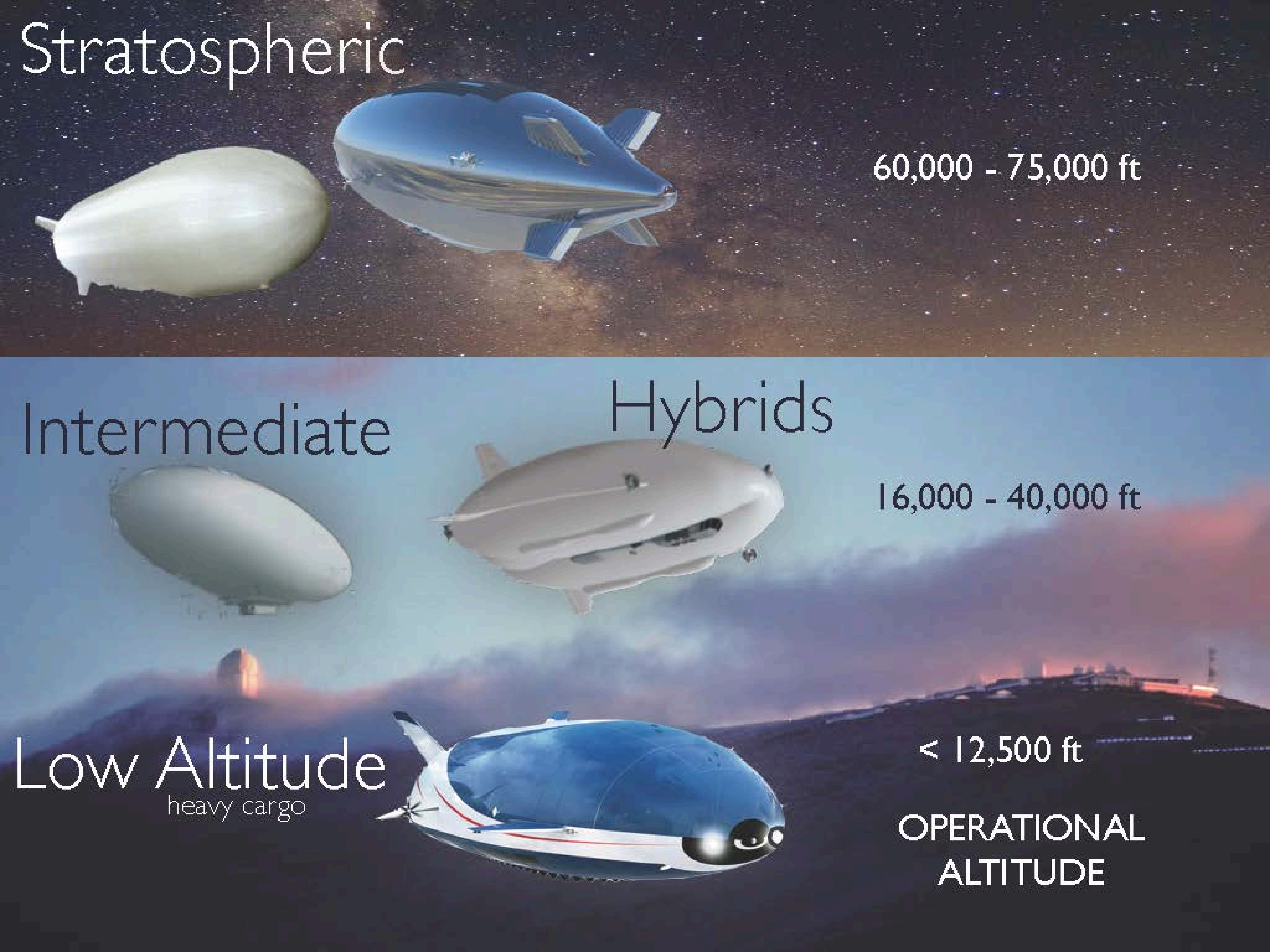
With the Airships NASA Centennial Challenge Development Team

Ernesto Diaz (JPL), Jason Rhodes (JPL), Sarah Miller (UCI)

What is an airship?

An airship is a powered, maneuverable, lighter-than-air vehicle

At 20 km, you're above 95% atm


Stratospheric
60,000 - 75,000 ft
Intermediate
Hybrids
16,000 - 40,000 ft
Low Altitude
heavy cargo
< 12,500 ft
OPERATIONAL
ALTITUDE

HIGH-ALTITUDE AIRSHIP RESEARCH STATION

Multi-wavelength Astrophysics and Cosmology

Planetary Science from Earth and Beyond

Multi-vantage Earth-sensing and Atmospheric Studies

Interferometry of proto-planetary disks or black holes	*Persistent* stare on any part of sky or Earth	Molecules **hidden** from ALMA	Discover **THz** sky	Vertical profiles of the **carbon-cycle**

http://adsabs.harvard.edu/abs/2014arXiv1402.6706M

Atmospheric Wavelength Absorption

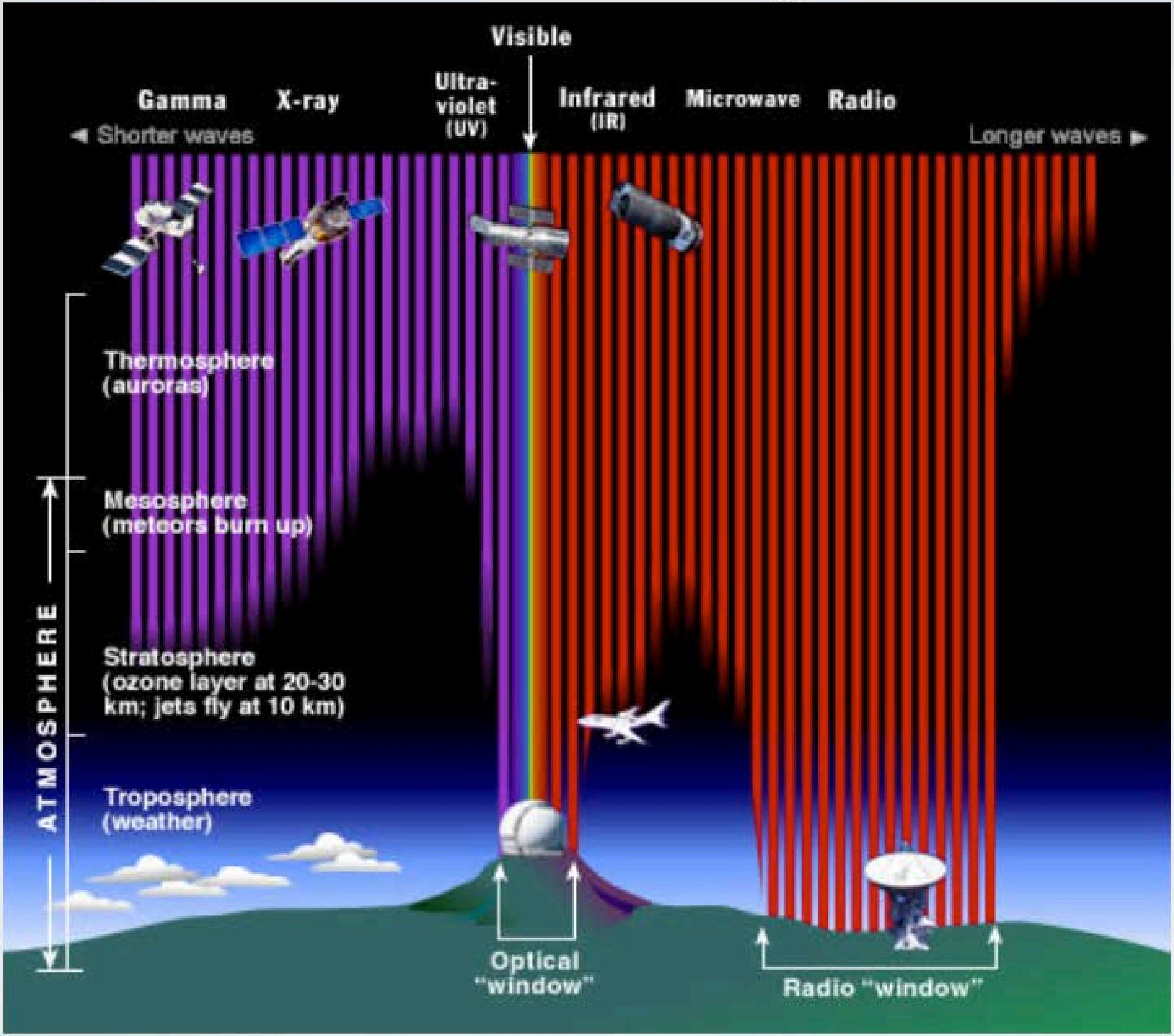
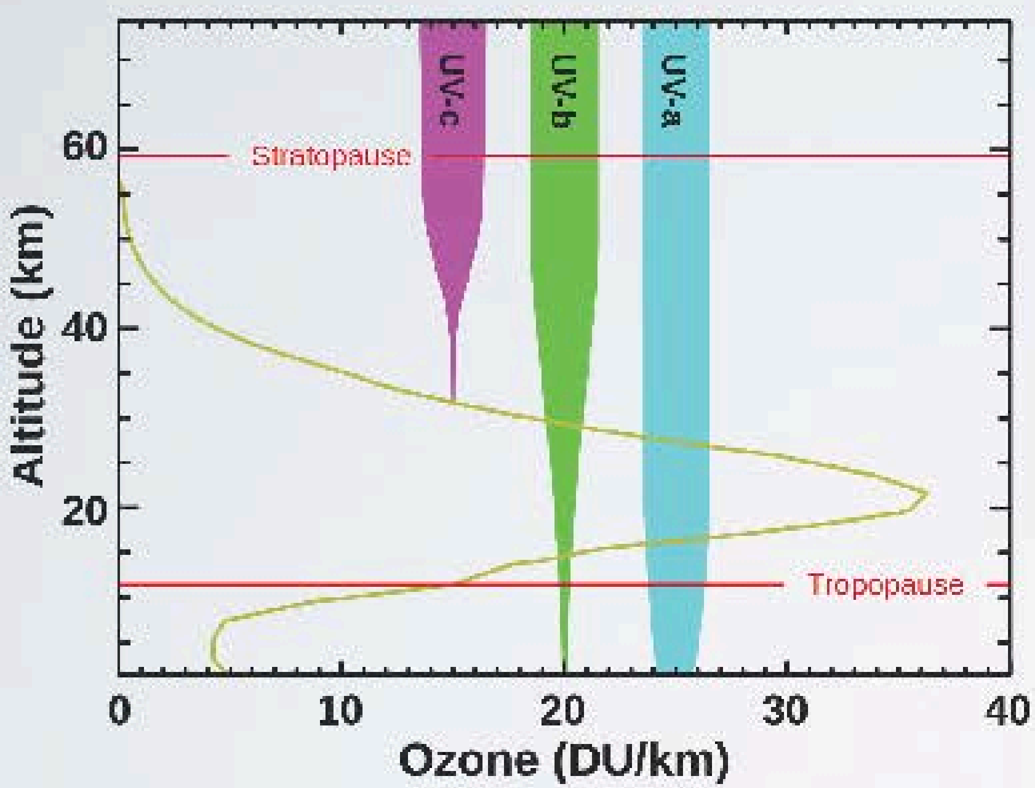
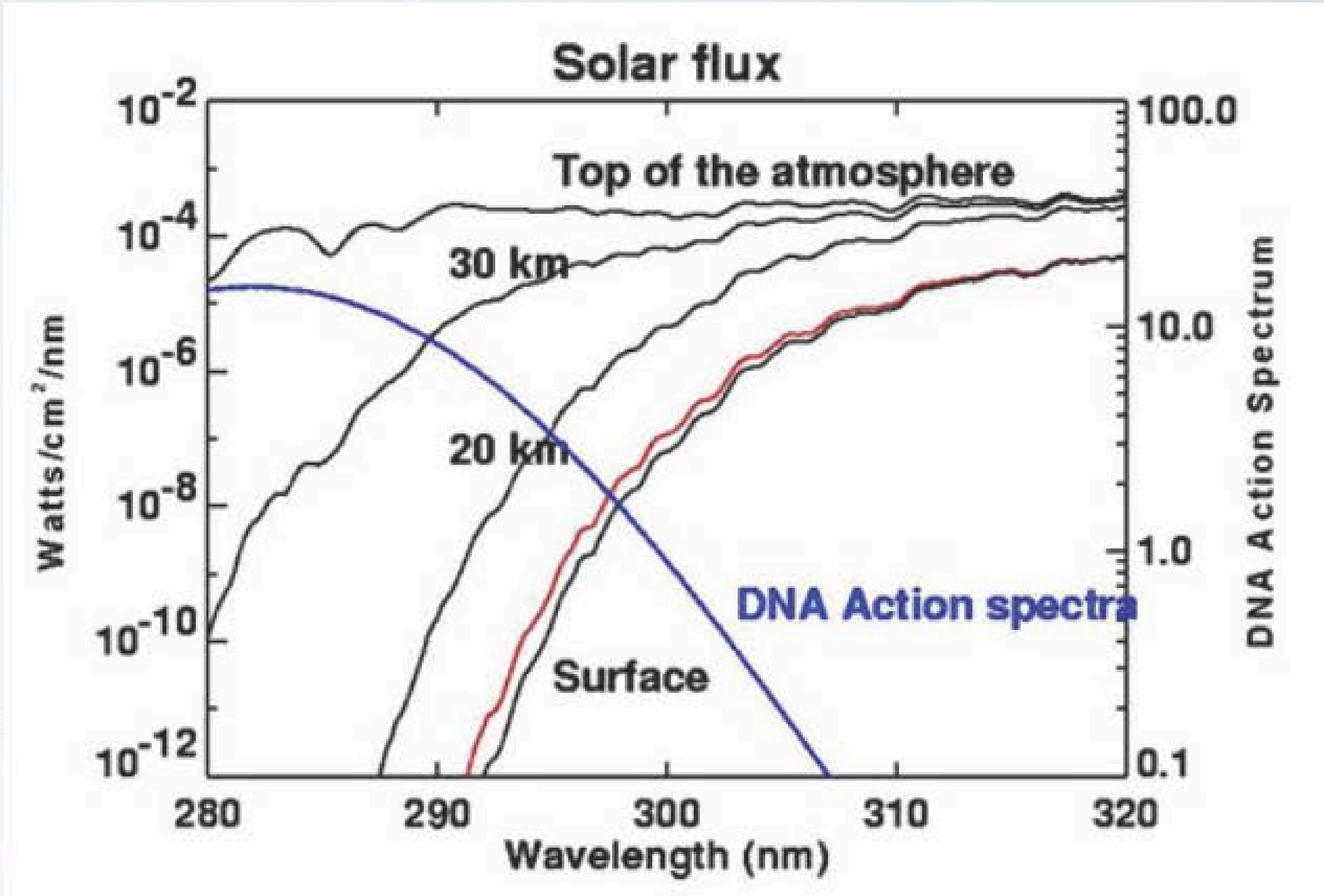


Figure Credit: STScI/JHU/NASA

Atmospheric Wavelength Absorption





Near to ~Middle UV Observations should be possible at 20km

Figure Credit: NASA

Airship Interferometry

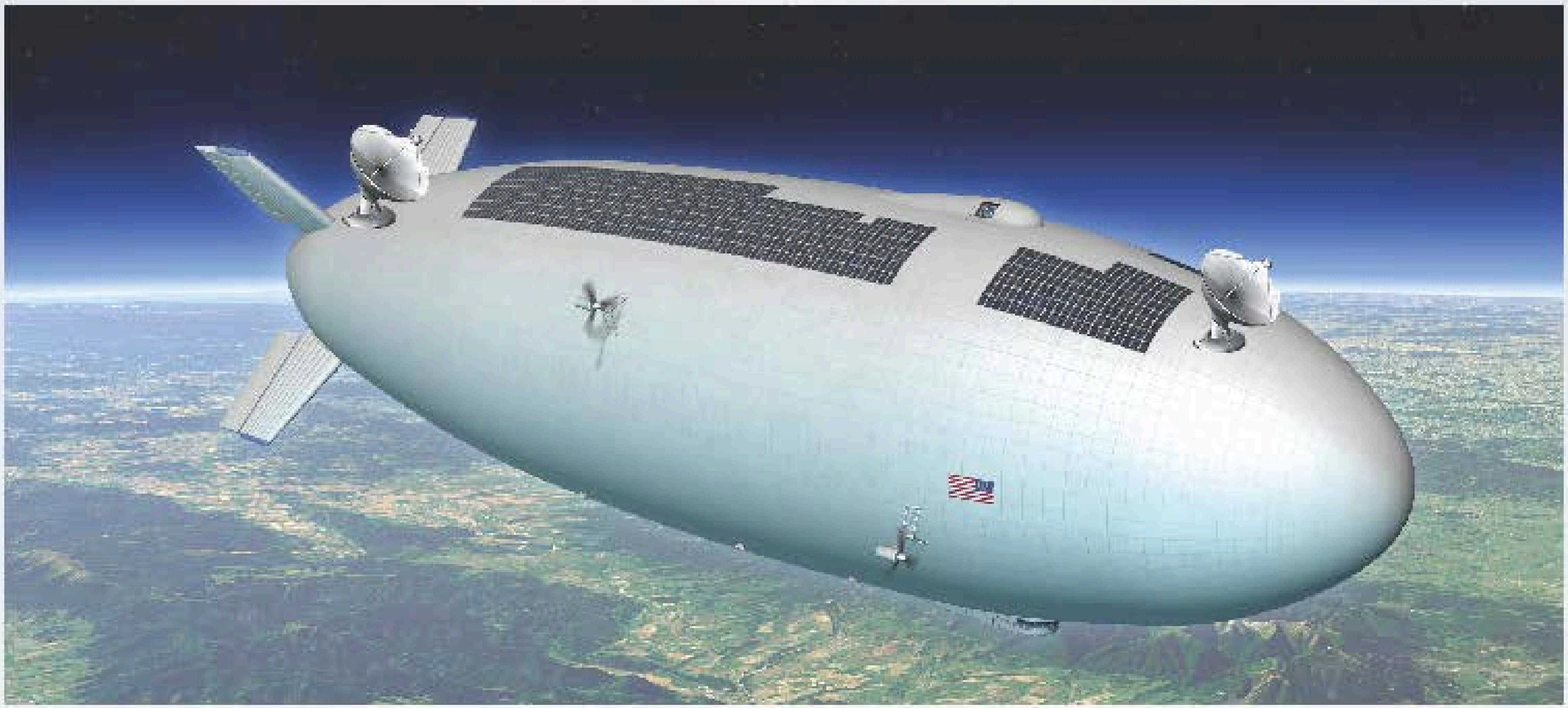


Figure Credit: Keck Institute for Space Studies / Eagre Interactive

NASA Centennial Challenges

- "NASA Centennial Challenges were initiated in 2005 to directly engage the public in the process of advanced technology development"

- The program offers incentive prizes to generate revolutionary solutions to problems of interest to NASA

- The **20-20-20 Airships Challenge** is currently under development and we are in the process of raising public awareness of the challenge

The 20-20-20 Airship NASA Centennial Challenge

Motivation

- There are few opportunities for space missions in astronomy and Earth science.
- *Airships* (powered, maneuverable, lighter-than-air vehicles) could offer significant gains in observing time, sky and ground coverage, data downlink capability, and continuity of observations over existing suborbital options at competitive prices.
- We seek to spur private industry to demonstrate the capability for sustained airship flights as astronomy and Earth science platforms.
- Technology is also desirable to industry for telecommunications, oil and gas (alarm monitoring, asset tracking, field communication), and transport companies (satellite tracking in remote regions).

For more information, contact challenge development leads:
Alina Kiessling Alina.A.Kiessling@jpl.nasa.gov
Ernesto Diaz Ernesto.Diaz@jpl.nasa.gov

The Challenge

- **NASA Centennial Challenge** in development to build a stratospheric airship as a science platform (www.centenntialchallenges.nasa.gov)
- Airships Challenge Team: Jason Rhodes (PI), Alina Kiessling, Ernesto Diaz, Jeff Booth, Randy Friedl, Jeff Hall (JPL); Sarah Miller (UCI)
- Anticipated \$2M-\$3M prize pool
- Anticipated challenge launch ~2015
- Competitors must fly a powered airship that remains stationary at **20km** (65,000ft) altitude for over **20 hours** with a **20 kg** payload. The design must be scalable to longer flights with more massive payloads

Requirements

- Must demonstrate 20 hr at 20 km altitude while carrying a 20 kg payload (Tier 1).
- Must demonstrate 200 hr at 20 km altitude while carrying a 200 kg payload (Tier 2).

- Must demonstrate controlled descent and successful payload recovery.
  - Originally intended to require controlled descent of the entire airship.
  - Requirement will be for controlled descent of only the rigid components but most importantly, the payload.
  - Most concepts of stratospheric airships have consumable hulls, and only the rigid components are reusable.
- Airship must be "scalable" to longer durations and larger payloads.
  - Teams are not to rely on expendables for station keeping (inflation/attitude control afloat). If a concept uses too much propellant or other consumable to stay afloat then it may not scale to weeks at altitude.
  - Better option would be replenishable power sources. Teams will have to show their scalable designs at PDR/CDR type review where panel of experts will determine if the feasibility of scalability.
  - Must be operable at wide range of latitude
  - Must be able to follow a simple course (A to B) in Tier 2

Request for Information (RFI)

- Draft is under review by HQ/Centennial Challenge Office
- Expect release in late-October
- 30 day response period
- Development team has a list of contacts to inform/ask for responses
- Seek responses from:
    - Astronomy/Astrophysics/Space Science
    - Earth & Atmospheric Science
    - Potential Competitors
    - Potential Commercial Community (e.g. telecom and Google)
    - Allied Organizations (want to sponsor and/or administer the Challenge)
    - Partners for Tier 2 Payload Development

Discussion Questions

JPL

Airships could provide a low-cost, long duration platform above 95% of the Earth's atmosphere for cosmology missions at a fraction of the cost of a space mission.

- Are you interested in using airships as a scientific platform for cosmology?
- What scientific goals would you hope to achieve with an airship?
- What technological requirements must the airship have and/or demonstrate in order to meet your scientific goals (e.g. altitude, station keeping, payload capacity, platform stability etc.)?
- Would you be interested in providing a scientific instrument as part of the payload for our Tier 2 competition?

Forbes

Astronomy From High Altitude Airships

Sometimes the edge of space can almost be as good as space itself — that is, when it comes to telescopes riding airships at the top of Earth's tenuous and rarefied stratosphere.

High Altitude Airships (HAAs), until now largely the purview of defense-related research, may ultimately find their rightful place as vehicles of science and industry.

http://www.forbes.com/sites/brucedorminey/2014/07/29/astronomy-from-high-altitude-airships/

The New York Times

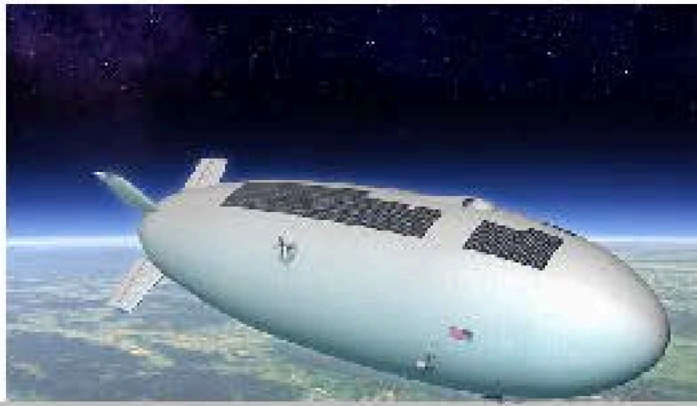
SCIENCE

Modern Research Borne on a Relic

Airships That Carry Science Into the Stratosphere

Airships are dusty relics of aviation history. Lighter-than-air vehicles conjure images of the Hindenburg, in its glory and destruction, and the Goodyear Blimp, a floating billboard that barely resembles its powerful predecessors.

But now engineers are designing sleek new airships that could streak past layers of cloud and chart a course through the thin, icy air of the stratosphere, 65,000 feet above the ground — twice the usual altitude of a jetliner. Steered by scientists below, these aerodynamic balloons might be equipped with onboard telescopes that



http://www.nytimes.com/2014/08/26/science/airships-that-carry-science-into-the-stratosphere.html?_r=0