New Generation of Large Imaging Surveys

- **Science Goals** (varying, but common themes):
  - Cosmology/Dark Energy
  - Galaxy Formation and Evolution
  - Time-Domain Studies
  - Local (Galactic) Structure
  - ...

- Billions of targets for ELT Follow-up
- Immense synergies to be exploited
Brief Survey of New Imaging Surveys

- Dark Energy Survey (2013-18)
- Hyper Suprime-cam surveys (2014-18)
- LSST (2021-31)
- Euclid (2020-26)
- WFIRST/AFTA (early 2020’s?)
- With apologies to PanSTARRS, Skymapper,…
- Dates are notional survey start dates, based on recent information from participants/proponents
optical imaging surveys heading toward deep, wide

future
ongoing
completed

Takada
Dark Energy

• What is the physical cause of cosmic acceleration?
  – Dark Energy or modification of General Relativity?
    • If Dark Energy, is it $\Lambda$ (the vacuum) or something else?
      – What is the DE equation of state parameter $w$ and (how) does it evolve?

![Pie chart showing the distribution of dark energy, matter, and normal matter.]

- 75% Dark Energy
- 21% Dark Matter
- 70% 25%
- 4% Normal Matter
What can we probe?

Require both to disentangle Dark Energy from Modified Gravity

- Weak Lensing cosmic shear
- Supernovae
- Baryon Acoustic Oscillations
- Cluster counting
- Redshift Distortions

Distance vs. Redshift

Distance + growth

Distances

Distances and \( H(z) \)

Distances + growth

Growth
I. Clusters

- Clusters are proxies for massive halos and can be identified optically to redshifts $z > 1$
- Galaxy colors provide photometric redshift estimates for each cluster
- Observable proxies for cluster mass: optical richness, SZ flux decrement, weak lensing mass, X-ray flux

**Challenge**: determine mass-observable relation $p(O|M,z)$ with sufficient precision

$$\frac{d^2N}{dzd\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z)dO \int p(O|M,z) \frac{dn(z)}{dM} dM$$

$$\frac{dN(z)}{dzd\Omega} = \frac{dV}{dzd\Omega} n(z)$$

$w = -1.0$
$w = -0.8$
$w = -0.6$
II. Weak Lensing: Cosmic Shear

- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure
Cosmic Shear Tomography
III. Large-scale Structure
Baryon Acoustic Oscillations

Galaxy angular power spectrum in photo-z bins (relative to model without BAO)

Photometric surveys provide angular measure

Radial modes require spectroscopy
SDSS-II: 500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III
Photometric SN Cosmology

- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts.
- Future surveys will have SN spectra for only a small subsample.
VST and VISTA

250 nights: VIKING

VISTA
4m telescope
0.6 sq.deg. InfraRed camera
16 2kx2k detectors
0.35” pixels

Kuijken

440 nights: KiDS

VST
2.6m telescope
1 sq.deg. optical camera (OmegaCAM)
32 2kx4k detectors
0.21” pixels
ESO Public Surveys

VST:
- ATLAS (SDSS-like)
- VPHAS+ (plane)
- KiDS

VISTA:
- VHS—VIKING—VIDEO—UltraVISTA
- VVV (plane, variables)
- VMC (Clouds)
The Dark Energy Survey

Survey project using 4 complementary techniques:
I. Cluster Counts
II. Weak Lensing
III. Large-scale Structure
IV. Supernovae

Two multiband imaging surveys:
5000 deg$^2$ $grizY$ to 24th mag
30 deg$^2$ repeat $griz$ (SNe)

New 3 deg$^2$ FOV camera on the Blanco 4m telescope
Survey 2013-2018 (525 nights)
Facility instrument for astronomy community (DES 30% time)

DECam on the Blanco 4m at CTIO
Four Probes of Dark Energy

- **Galaxy Clusters**
  - ~100,000 clusters to $z > 1$
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry

- **Weak Lensing**
  - Shape measurements of 200 million galaxies
  - Sensitive to growth of structure and geometry

- **Baryon Acoustic Oscillations**
  - 300 million galaxies to $z = 1$ and beyond
  - Sensitive to geometry

- **Supernovae**
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to $z \sim 1$
  - Sensitive to geometry
DECam CCDs

- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels
570-Mpix DECam imager
DECam First Light

September 12, 2012

Covered in 258 publications in 36 countries, plus Jay Leno’s monologue
DECam
1x1deg
grizY co-add
image of SPT
cluster
$z=0.32$

~50,000 galaxies
in this image
High Redshift Cluster Discovered by DES

from DES Science Verification data in November
Cluster Weak Lensing

- Stacked (statistical) Weak Lensing cluster shear profiles will calibrate cluster mass-observable relations

- Preliminary cluster mass map from DES Science Verification data
DECam composite image of deep SN field will be visited many times during survey, resulting in very deep co-add
First Confirmed SNe from DES

Nov. 7
SN Ia at z=0.2 confirmed at AAO
100 nights on AAO awarded for follow-up (OzDES)

Dec. 15
DES Survey Strategy

Science Verification: few x 100 sq deg to full DES depth (10 exposures in each band). Nov. 2012-Feb. 2013

Full survey area to be covered by Vista Hemisphere Survey (JHK)

- SPT SZ area (2500 sq deg)
- Stripe 82
- 2 Deep SN fields
- 8 Shallow SN fields
- Full Survey: 5000 sq deg
- 10x90s exposures in each filter (shorter Y)
Subaru telescope

- 8.2 meter primary mirror
- Mauna Kea
- Excellent imaging conditions
**Hyper Suprime-Cam**

Expand field of view to increase survey speed

- HST
- Suprime-Cam
- HSC

1.5 deg

0.5 deg

0.05 deg

Picture credit: S. Miyazaki
HSC is on the telescope!

First Light Sept. 2012
Looking good!

Seeing variation across FOV

104 Science, 4 Guide, 8 Focus CCDs
870 Megapixels (0.17”/pixel)

Raw image of Andromeda
3-layer HSC survey

- **Wide:** ~1400 deg², i<25.8 (grizy)
  - Weak lensing, z<1.5 galaxy populations

- **Deep:** ~26 deg², 1 mag deeper, 5 wide+3 NB filters
  - Ly-α emitters, quasars, deeper galaxy populations, lensing systematics, ...

- **Ultradeep:** 3 deg², 1 mag deeper, 5 wide+6 NB filters
  - Supernovae, galaxies to z<7

- **Important synergies:** CMB (ACT+ACTPol), redshifts (BOSS + assorted other), NIR, u band, ...

- **Surveys starting 1st semester of 2014** (300 nights over 5 yrs)
The HSC fields are selected based on …

- Synergy with other data sets: SDSS/BOSS, The Atacama Cosmology Telescope CMB survey (from Chile), X-ray (XMM-LSS), spectroscopic data sets
- Spread in RA
- Low dust extinction
The Large Synoptic Survey Telescope

Steven M. Kahn

Sidney Wolff

Victor Krabbendam

Nadine Kurita

Zeljko Ivezic

Cerro Pachon, Chile
Basic idea behind LSST: a uniform sky survey

- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night.
- After 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky.
- ~100 PB of data: about a billion 16 Mpix images, enabling measurements for 20 billion objects!

**LSST in one sentence:**
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

**Left:** A 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of equatorial coordinates).
## Summary of High Level Requirements

<table>
<thead>
<tr>
<th>Survey Property</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Survey Area</td>
<td>18000 sq. deg.</td>
</tr>
<tr>
<td>Total visits per sky patch</td>
<td>825</td>
</tr>
<tr>
<td>Filter set</td>
<td>6 filters (ugrizy) from 320-1050nm</td>
</tr>
<tr>
<td>Single visit</td>
<td>2 x 15 second exposures</td>
</tr>
<tr>
<td>Single Visit Limiting Magnitude</td>
<td>u = 23.9; g = 25.0; r = 24.7; I = 24.0; z = 23.3; y = 22.1</td>
</tr>
<tr>
<td>Photometric calibration</td>
<td>&lt; 2% absolute, &lt; 0.5% repeatability &amp; colors</td>
</tr>
<tr>
<td>Median delivered image quality</td>
<td>~ 0.7 arcsec. FWHM</td>
</tr>
<tr>
<td>Transient processing latency</td>
<td>&lt; 60 sec after last visit exposure</td>
</tr>
<tr>
<td>Data release</td>
<td>Full reprocessing of survey data annually</td>
</tr>
</tbody>
</table>
The modified Paul-Baker optical design provides a large field of view with high image quality.

8.4m primary mirror diameter, 6.7m effective aperture
The telescope mount has been optimized for fast slew and settle.

- Points to new positions in the sky every 37 seconds
- Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 seconds
The 3.2 billion pixel camera enables a 9.6 square degree field in a tight enclosure.
Recent Progress: M1/M3

- Final Optical Polishing has commenced – the final and most challenging step.
- Final acceptance testing scheduled for late 2013.
- 5 tons of excess material already removed to generate rough optical surface of M1/M3.
- Loose abrasive grinding resulted in initial optical shapes.
- Interferogram shows surface deviations on the order of microns, aiming for nanometers.
- Work enabled by private funds.
Project timeline enables “first light” in 2019, survey start 2022
Euclid Mission: baseline and options

<table>
<thead>
<tr>
<th>SURVEYS</th>
<th>In ~6 years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wide Survey</strong></td>
<td>Area (deg²)</td>
</tr>
<tr>
<td></td>
<td><strong>15,000 deg²</strong></td>
</tr>
<tr>
<td><strong>Deep Survey</strong></td>
<td><strong>40 deg²</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PAYLOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
</tr>
<tr>
<td>Instrument</td>
</tr>
<tr>
<td>Field-of-View</td>
</tr>
<tr>
<td>Capability</td>
</tr>
<tr>
<td>Wavelength range</td>
</tr>
<tr>
<td>Sensitivity</td>
</tr>
</tbody>
</table>

Shapes + Photo-z of \( n = 1.5 \times 10^9 \) galaxies z of \( n = 5 \times 10^7 \) galaxies

Weak Lensing | Photo-z | BAO

Ref: Euclid RB Laureijs et al arXiv:1110.3193

Euclid slides from Yannick Mellier
The VIS instrument

Courtesy: S. Pottinger, R. Cole, M. Cropper and the VIS team

- Large area imager – a 'shape measurement machine'
- 36 4kx4k CCDs with 12 micron pixels
- 0.1 arcsec pixels on sky
- Bandpass 550-900 nm (wide band channel)
- Limiting magnitude for wide survey of magAB = 24.5 for 10σ (extended)
- Data volume - 520Gbit/day
The NISP Instrument

16 2kx2k H2GR NIR detectors

0.3 arcsec/pixel

3 NIR filters: H,J,H,

4 Grisms (2 « B»; 2 « R »)

Lim. mag: AB 24.0 ; 5 σ pt source

Data volume: 180 Gbit/day

Courtesy: T. Maciaszek and the NISP team
15,000 deg$^2$ in 5.5 years
Photometric redshifts with Euclid

Requirements: accuracy
= 0.05x(1+z)
→ 4 optical band needed
→ U-band not needed.

Visible data obtained from ground based telescopes

Nearinfrared data from Euclid NIR images.
# Euclid Legacy:
a gold mine for astronomy for 2020-2040

<table>
<thead>
<tr>
<th>Objects</th>
<th>Euclid</th>
<th>Before Euclid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxies at 1&lt;z&lt;3 with precise mass measurement</td>
<td>~2x10^8</td>
<td>~5x10^6</td>
</tr>
<tr>
<td>Massive galaxies (1&lt;z&lt;3))</td>
<td>Few hundreds</td>
<td>Few tenss</td>
</tr>
<tr>
<td>Hα Emitters with metal abundance measurements at z~2-3</td>
<td>~4x10^7/10^4</td>
<td>~10^4/~10^2 ?</td>
</tr>
<tr>
<td>Galaxies in clusters of galaxies at z&gt;1</td>
<td>~2x10^4</td>
<td>~10^3 ?</td>
</tr>
<tr>
<td>Active Galactic Nuclei galaxies (0.7&lt;z&lt;2)</td>
<td>~10^4</td>
<td>&lt;10^3</td>
</tr>
<tr>
<td>Dwarf galaxies</td>
<td>~10^5</td>
<td></td>
</tr>
<tr>
<td>T_{eff} ~400K Y dwarfs</td>
<td>~few 10^2</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Lensing galaxies with arc and rings</td>
<td>~300,000</td>
<td>~10-100</td>
</tr>
<tr>
<td>Quasars at z &gt; 8</td>
<td>~30</td>
<td>None</td>
</tr>
</tbody>
</table>
Astrophysics Focused Telescope Assets (AFTA)

Presentation to P. Hertz  April 19, 2013

Neil Gehrels (GSFC)  SDT Co-Chair
David Spergel (Princeton)  SDT Co-Chair
Kevin Grady (GSFC)  Study Manager & Project Team

SCIENCE DEFINITION TEAM
James Breckinridge, Caltech
Megan Donahue, Michigan State Univ.
Alan Dressler, Carnegie Observatories
Chris Hirata, Caltech
Scott Gaudi, Ohio State Univ.
Thomas Greene, Ames
Olivier Guyon, Univ. Arizona
Jason Kalirai, STScI
Jeremy Kasdin, Princeton
Warren Moos, Johns Hopkins
Saul Perlmutter, UC Berkeley / LBNL
Marc Postman, STScI
Bernard Rauscher, GSFC
Jason Rhodes, JPL
Yun Wang, Univ. Oklahoma
David Weinberg, Ohio State U.
Joan Centrella, NASA HQ Ex-Officio
Wes Traub, JPL Ex-Officio
“Discover how the universe works, explore how it began and evolved, and search for Earth-like planets”

NASA Strategic Plan (p. 14)

AFTA-2.4m
- Dark energy
  * Accelerating expansion of the universe
  * Growth of structure
- Exoplanet microlensing
- Exoplanet coronagraphy (optional)
- Galactic and extragalactic astronomy
- Guest Investigator & Observer program
AFTA Instruments

Wide-Field Instrument
- **Imaging & spectroscopy** over 1000s sq deg.
- **Monitoring** of SN and microlensing fields
- 0.7 – 2.0 micron bandpass
- 0.28 sq deg FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 4 filter imaging, grism + IFU spectroscopy

Coronagraph (study option)
- **Imaging of ice & gas giant exoplanets**
- **Imaging of debris disks**
- 400 – 1000 nm bandpass
- $10^{-9}$ contrast
- 100 milliarcsec inner working angle at 400 nm

*Requires focused tech. development ASAP for 2021 launch*
Evolution of WFIRST Concepts to AFTA

- **DRM1**
  - 1.3 meter off-axis telescope
  - 150 Mpixels, 0.4 deg$^2$
  - 5 year mission (15% GO time)

- **DRM2**
  - 1.1 meter off-axis telescope
  - 234 Mpixels, 0.6 deg$^2$
  - 3 year mission (15% GO time)

- **2.4m AFTA**
  - 2.4 meter on-axis telescope
  - 288 Mpixels, 0.3 deg$^2$
  - Additional IFU for SN slit spectroscopy
  - Additional coronagraph for exoplanet imaging
  - 5 year mission (25% GO time)
AFTA is a more capable dark energy mission than previous DRMs

- Larger telescope + integral field channel enable high S/N spectrophotometry
  - More supernovae out to higher redshift
  - Systematic errors addressed: eliminate K-correction, improved calibration, measure SN spectral diagnostics.

- Deeper weak lensing survey
  - 3x fainter, 1.9x smaller PSF, 2x \( n_{\text{eff}} \)
  - More accurate lensing maps to higher redshift
  - Better sampling for higher-order WL statistics
  - Lensing masses for 40,000 M \( \geq 10^{14} M_{\odot} \) clusters in the 2000 deg\(^2\) area of the high-latitude survey

- Much deeper galaxy redshift survey at 1 < z < 2, [OIII] extends redshift range to z =3.
  - Can use multiple tracers.
  - Improve redshift-space distortion measurements, test systematics.
  - Better measurements of high-order clustering.
Frontiers of Knowledge

As envisioned in NWNH, AFTA uses multiple approaches to measure the growth rate of structure and the geometry of the universe to exquisite precision. These measurements will address the central questions of cosmology.

**Imaging Survey**
- Map over 2000 square degrees of high latitude sky
- 500 million lensed galaxies (70/arcmin²)
- 40,000 massive clusters

**Supernova Survey**
- wide, medium, & deep imaging + IFU spectroscopy
- 2700 type Ia supernovae
  - $z = 0.1–1.7$

**Spectroscopic Survey**
- 20 million Hα galaxies, $z = 1–2$
- 2 million [OIII] galaxies, $z = 2–3$

**Measure the Distance Redshift Relationship**

**Trace the Distribution of Dark Matter Across Time**

- Why is the universe accelerating?
- What are the properties of the neutrino?
- What is Dark Matter?

Multiple measurement techniques each achieve 0.1-0.4% precision.

- Red shift space distortion
**AFTA:**

**Deep Infrared Survey (2000 sq. deg)**

**Lensing:**
- High Resolution (70 - 250 gal/arcmin²)
- 5 lensing power spectrum

**Supernovae:**
- High quality IFU spectra of 2700 SN

**Redshift survey**
- High number density of galaxies
- Redshift range extends to \( z = 3 \)

---

**Euclid:**

**Wide optical Survey (15000 sq. deg)**

**Lensing:**
- Lower Resolution (30 gal/arcmin²)
- 1 lensing power spectrum

**No supernovae program**

**Redshift survey:**
- Low number density of galaxies
- Significant number of low redshift galaxies

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**Deep AFTA SURVEY (250)**

**Wide AFTA SURVEY (70)**

**Euclid (30 gal arcmin⁻²)**

**More Accurate Dark Matter Maps**

---

AFTA and Euclid have complementary strengths for dark energy studies
AFTA and Euclid have complementary strengths for dark energy studies

**AFTA:**

**Deep Infrared** Survey (2000 sq. deg)

*Lensng:*
- High Resolution (70 - 250 gal/arcmin²)
- 5 lensing power spectrum

*Supernovae:*
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- High number density of galaxies
- Redshift range extends to $z = 3$

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**Wide optical** Survey (15000 sq. deg)

*Lensng:*
- Lower Resolution (30 gal/arcmin²)
- 1 lensing power spectrum

*No supernovae program*

*Redshift survey:*
- Low number density of galaxies
- Significant number of low redshift galaxies

---

**Graph:**

- 10x more sensitive in GRISM mode

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AFTA will have the sensitivity and the control of systematics to enable a major discovery of the nature of dark energy!

By measuring the relationship between distance and redshift, we will be able to determine the properties of dark energy.

These properties are often characterized by $w$ and its time derivative, $dw/da$.

If $w < -1$, the universe will someday be torn apart in a “big rip” that destroys spacetime.
Sensitivities of LSST, WFIRST, and Euclid

- LSST (10 yr, S Hemisphere, AM 1.2)
- WFIRST (1.6k deg²/yr, ref zodi)
- Euclid (15-20k deg², β=45°)

Labels indicate PSF half light radius in units of 0.01 arcsec

50 pt src threshold (AB mag) vs λ (µm)
## WFIRST-2.4 Design Reference Mission Capabilities

<table>
<thead>
<tr>
<th>Imaging Capability</th>
<th>0.281 deg²</th>
<th>0.11 arcsec/pix</th>
<th>0.6 – 2.0 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters</td>
<td>Z087</td>
<td>Y106</td>
<td>J129</td>
</tr>
<tr>
<td></td>
<td>H158</td>
<td>F184</td>
<td>W149</td>
</tr>
<tr>
<td>Wavelength (μm)</td>
<td>0.760-0.977</td>
<td>0.927-1.192</td>
<td>1.131-1.454</td>
</tr>
<tr>
<td></td>
<td>1.380-1.774</td>
<td>1.683-2.000</td>
<td>0.927-2.000</td>
</tr>
<tr>
<td>PSF EE50 (arcsec)</td>
<td>0.11</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>Spectroscopic Capability</td>
<td>Grism (0.281 deg²)</td>
<td>IFU (3.00 x 3.15 arcsec)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.35 – 1.95 μm, R = 550-800</td>
<td>0.6 – 2.0 μm, R = ~100</td>
<td></td>
</tr>
</tbody>
</table>

## Baseline Survey Characteristics

<table>
<thead>
<tr>
<th>Survey</th>
<th>Bandpass</th>
<th>Area (deg²)</th>
<th>Depth</th>
<th>Duration</th>
<th>Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exoplanet Microlensing</td>
<td>Z, W</td>
<td>2.81</td>
<td>n/a</td>
<td>6 x 72 days</td>
<td>W: 15 min Z: 12 hrs</td>
</tr>
<tr>
<td>HLS Imaging</td>
<td>Y, J, H, F184</td>
<td>2000</td>
<td>Y = 26.7, J = 26.9</td>
<td>1.3 years</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H = 26.7, F184 = 26.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLS Spectroscopy</td>
<td>1.35 – 1.95 μm</td>
<td>2000</td>
<td>0.5x10⁻¹⁶ erg/s/cm² @ 1.65 μm</td>
<td>0.6 years</td>
<td>n/a</td>
</tr>
<tr>
<td>SN Survey</td>
<td>Wide</td>
<td>27.44</td>
<td>Y = 27.1, J = 27.5</td>
<td>0.5 years (in a 2-yr interval)</td>
<td>5 days</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>8.96</td>
<td>J = 27.6, H = 28.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td>5.04</td>
<td>J = 29.3, H = 29.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Synergies with ELTs

• Wider, faster, deeper optical/NIR surveys on the way
• Deep imaging surveys require large, deep(?) spectroscopic samples for photo-z calibration (see Jeff Newman’s talk)
• Imaging surveys provide sources for value-added follow-up: radial velocities, line strengths, unusual objects…
• Time-domain surveys: rapid follow-up for identification/characterization
• Multi-layered follow-up program, with varying depth, sample size, spectral resolution, and timescale requirements: wide, fast, deep spectroscopy needed
• Piecemeal vs. coherent program?