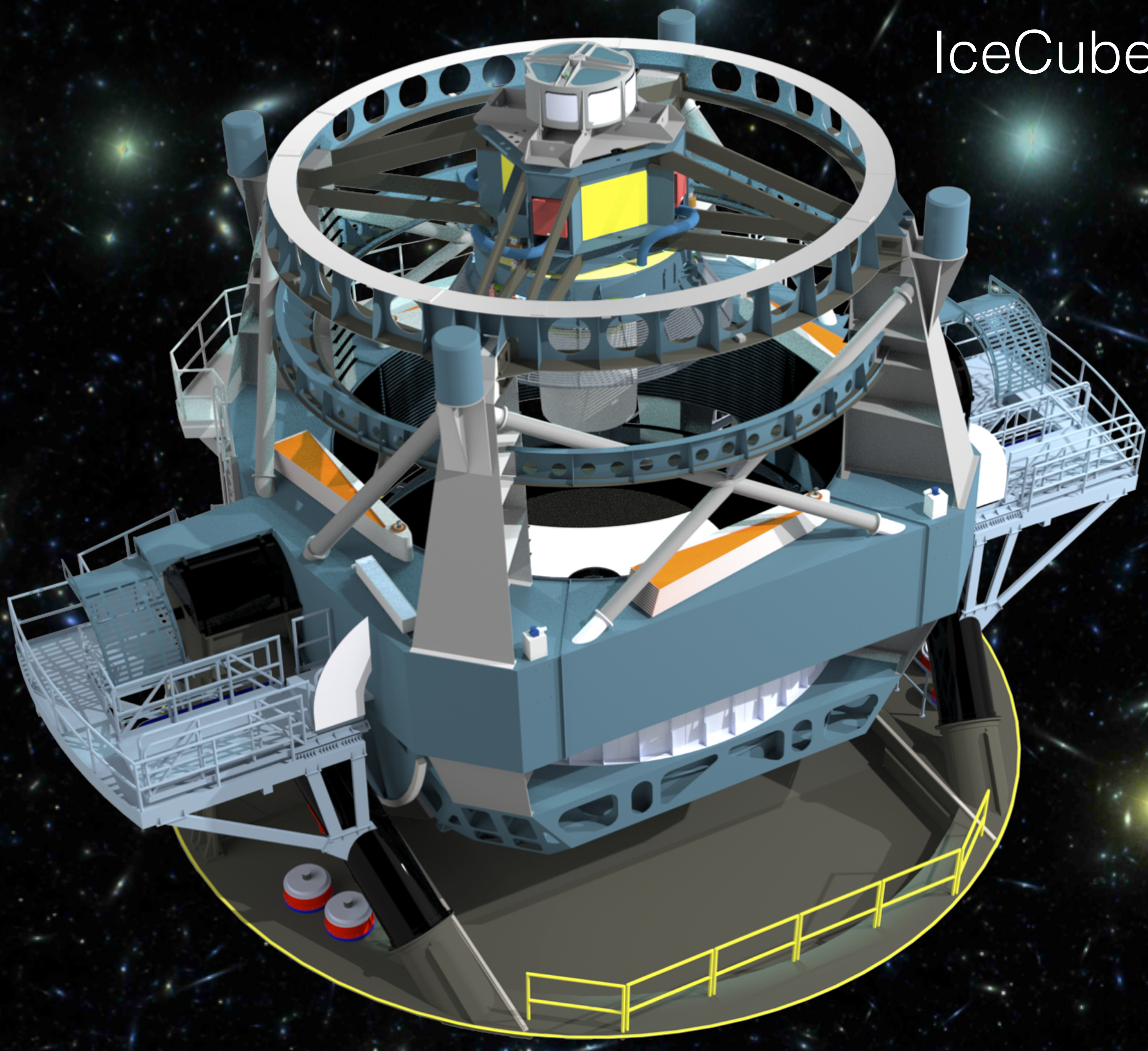
# Optical Surveys and Particle Astrophysics: Prospects in the LSST Era

**Keith Bechtol**
LSST
IceCube Particle Astrophysics Symposium
10 May 2017

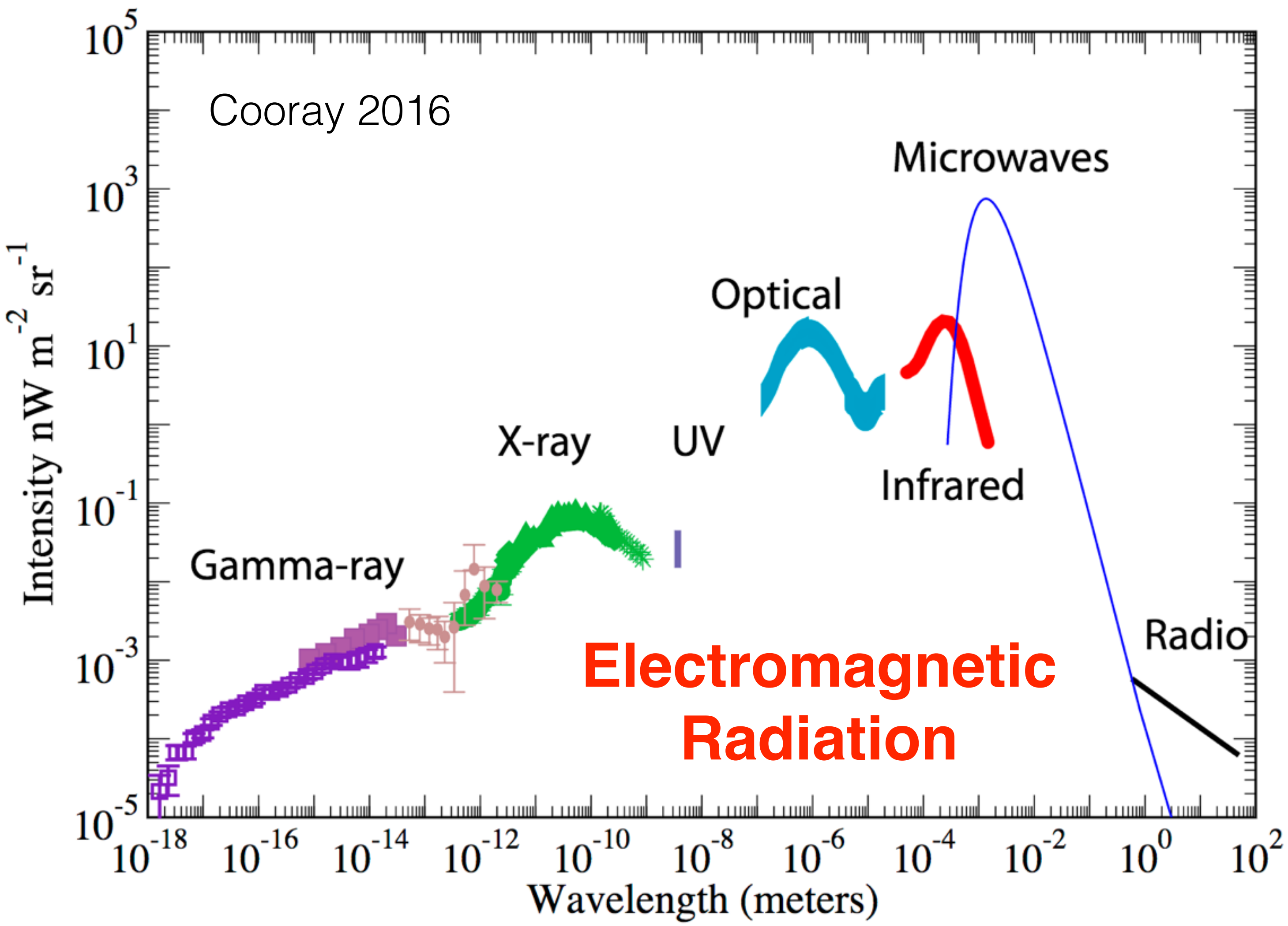


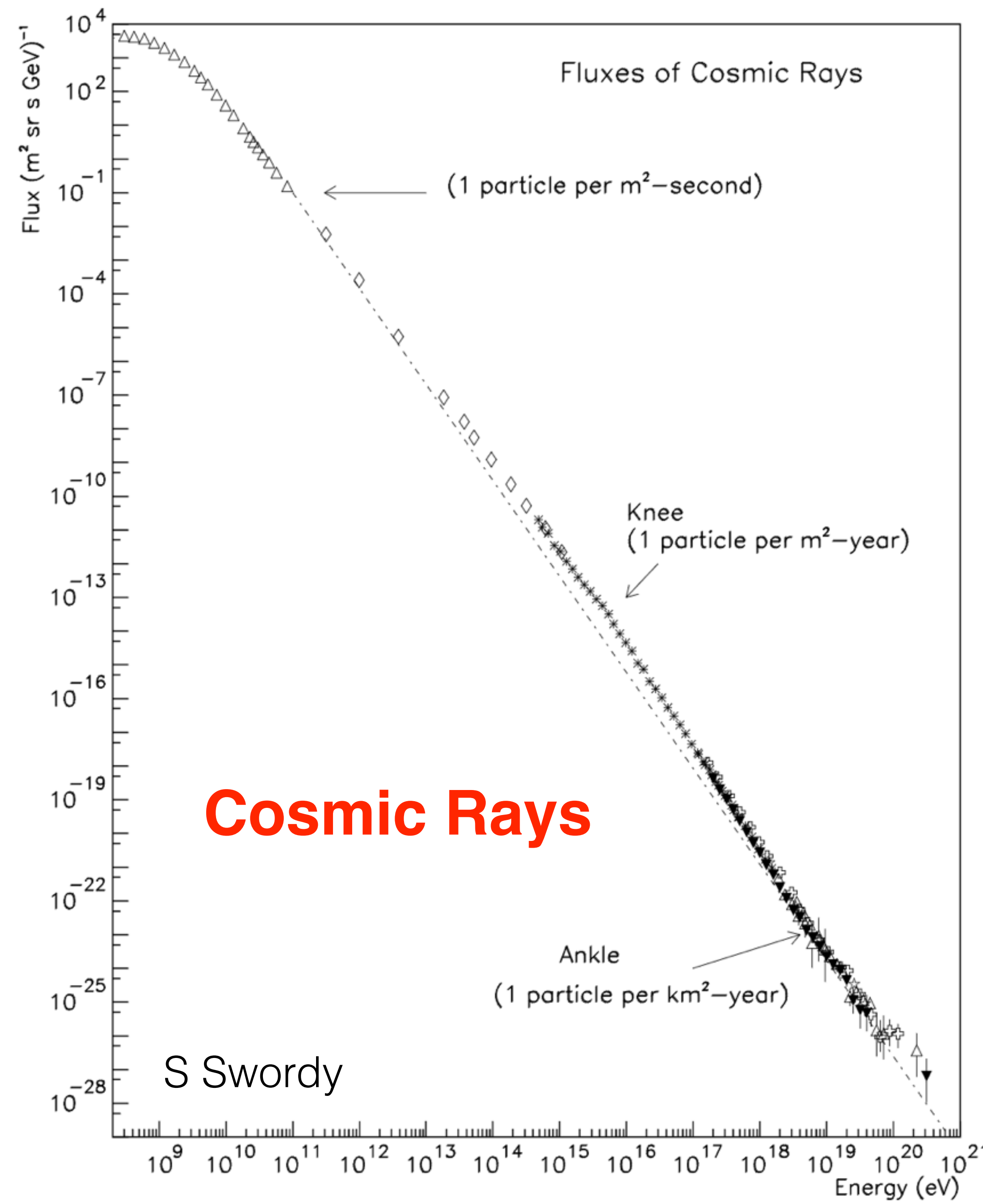
# *Large Synoptic Survey Telescope (LSST)*

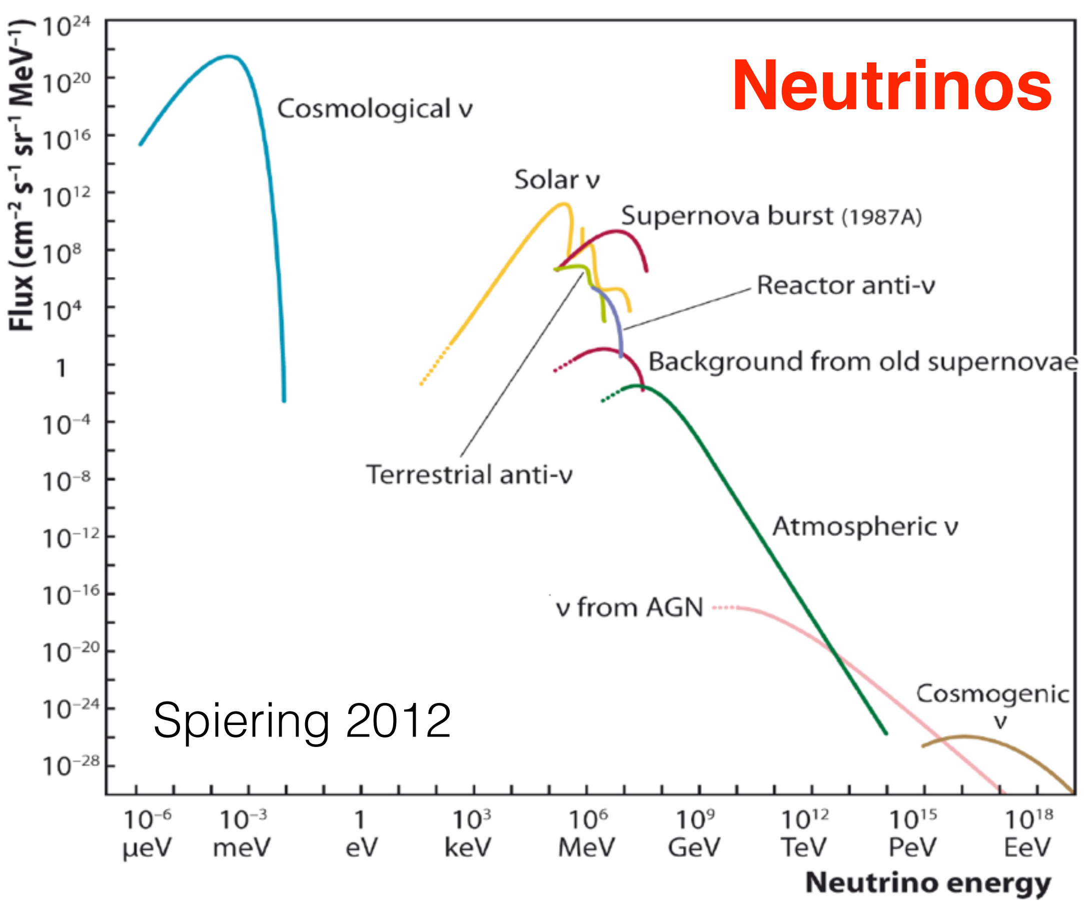
**New optical telescope + camera under construction in Chile optimized for survey astronomy, scheduled to begin a decade of science operations in 2022**

**Open data access for the US and Chilean scientific community + partner institutions**

**Construction Video**
https://youtu.be/VAu61viS7p0




**+ Gravitational Waves**

*How can **optical surveys** advance our understanding of the **non-thermal** universe?*

# Role of Optical Surveys in Particle Astrophysics

**Catalogs for multiwavelength / multimessenger science**

- Source association / classification, redshifts, optical EBL

**Mapping the (dark) matter distribution**

- Cosmic expansion history and growth of structure
- Targets for indirect dark matter searches
- Local dark matter density
- Interstellar dust (+gas)

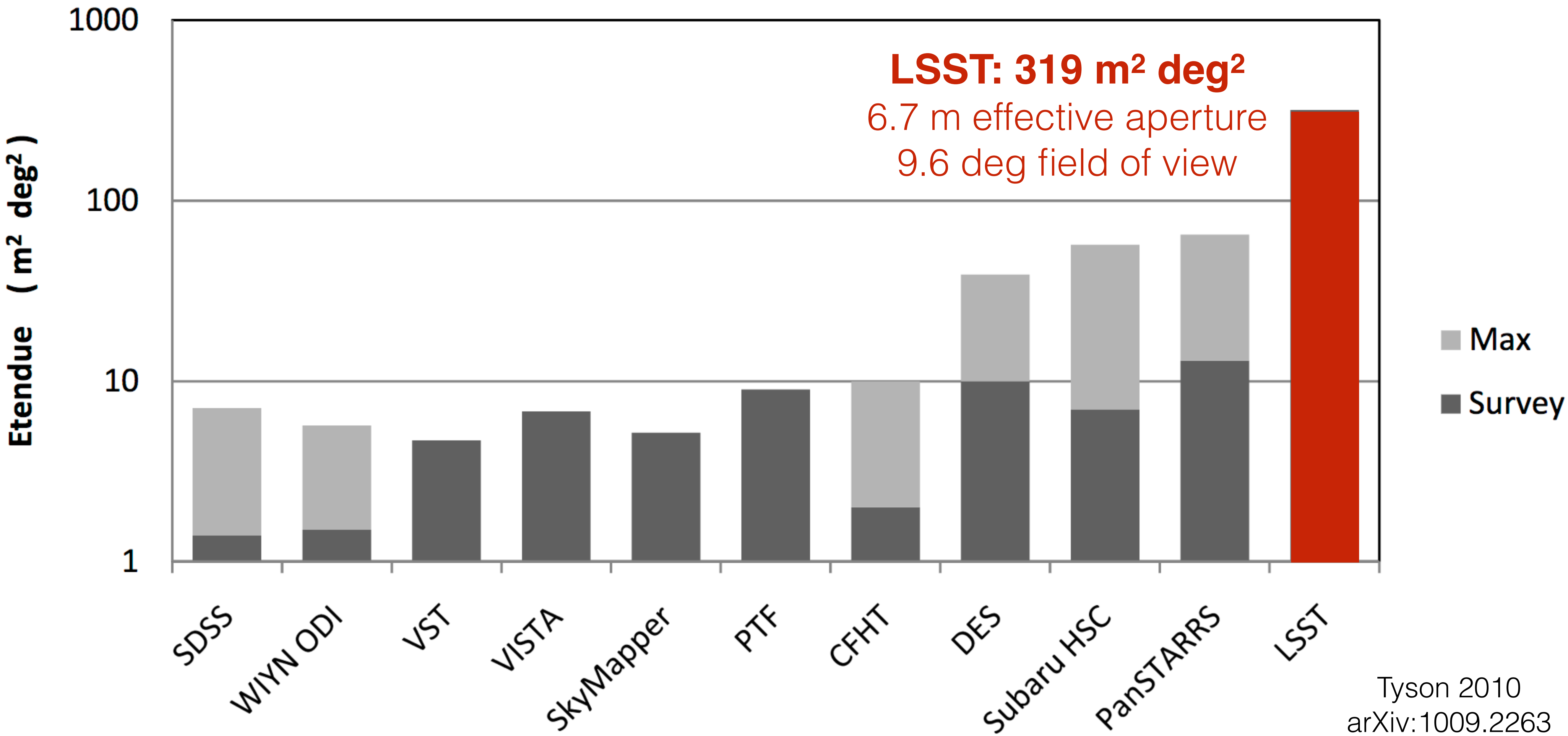
**Electromagnetic counterparts for explosive transients**

- Supernova neutrinos
- TeV-PeV neutrinos
- Gravitational waves

All of these science topics are ***already*** being pursued, and will be substantially advanced by next-generation surveys, including LSST

# Photon Collecting Power

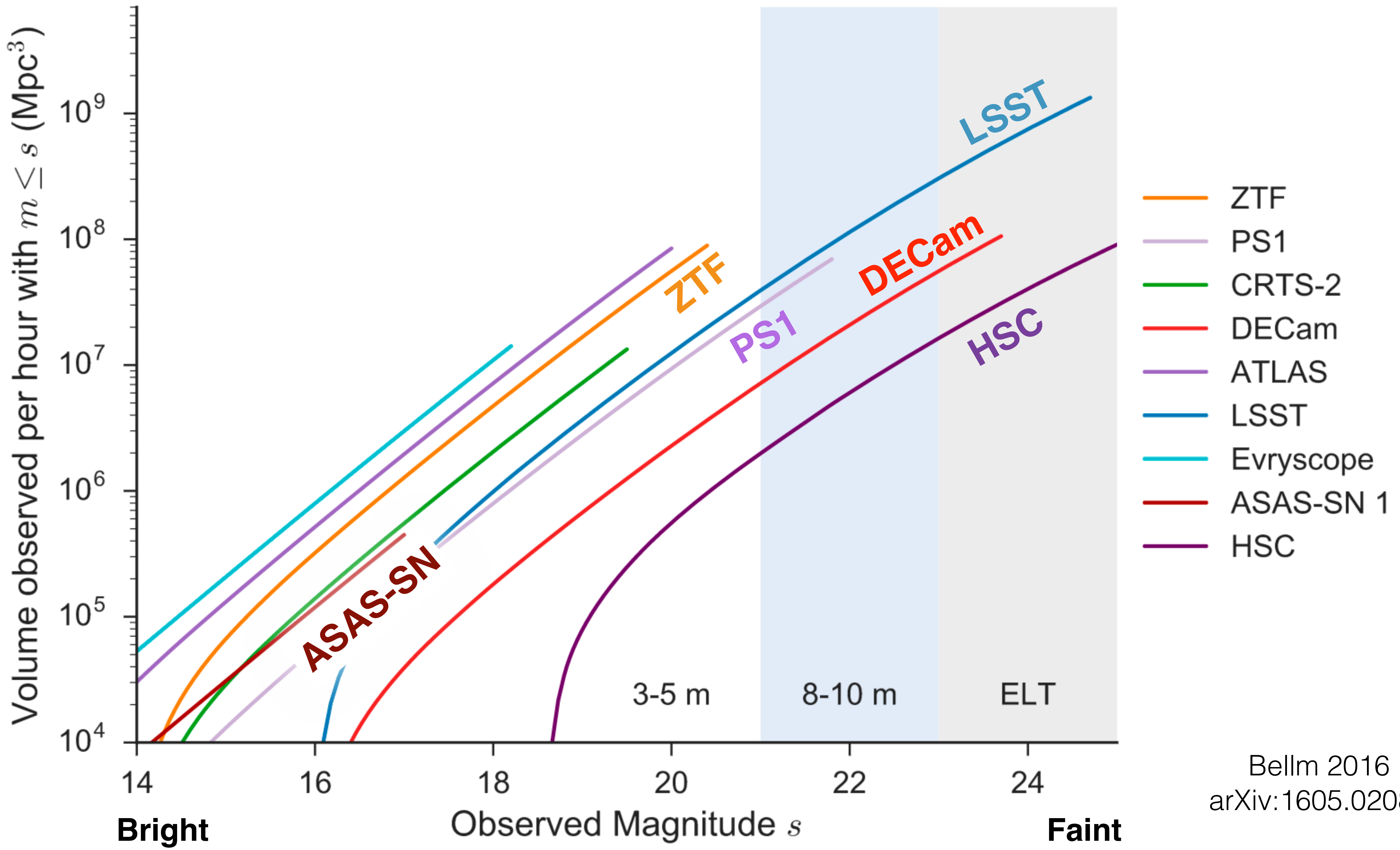
Etendue = Field of View × Effective Aperture (× Efficiency)




Tyson 2010
arXiv:1009.2263

**Etendue measures to how fast a telescope + camera can map the sky**

# Volumetric Survey Speed




Bellm 2016
arXiv:1605.02081

Shaded regions indicate required aperture for spectroscopic follow-up
(Example for $M_V$ = 19 mag, typical of type Ia SN)

# Optimized for Survey Science

**90%** observing time in "universal" cadence: **Wide-Fast-Deep**
**10%** for special projects (e.g., deep drilling fields, Galactic plane)

## Single Epoch

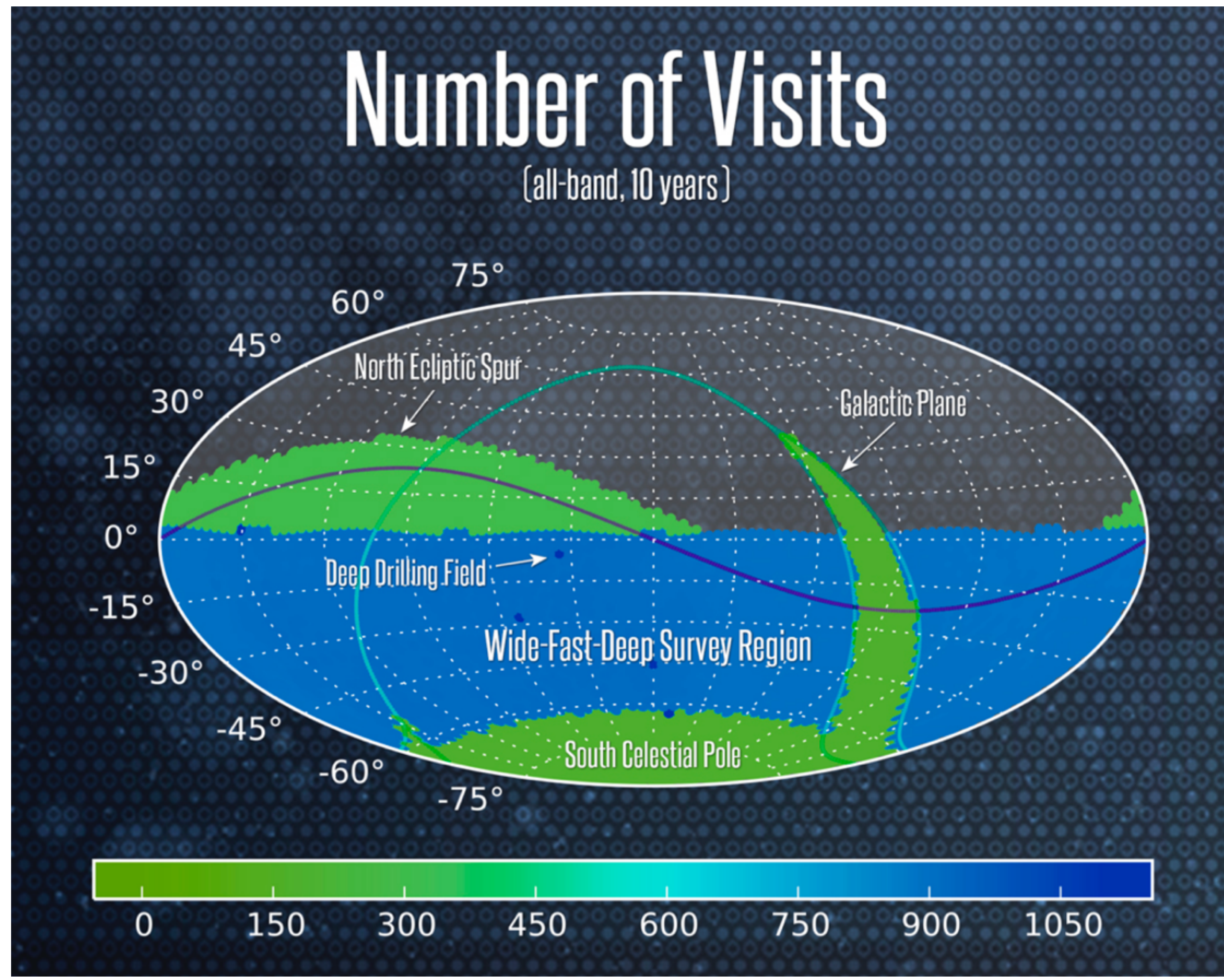
Each patch visited ~800 times over 10 years with a broad range of time sampling ($r \sim 24.7$)

**➔ Level 1 data products (within 60 sec)**

## Image Stack

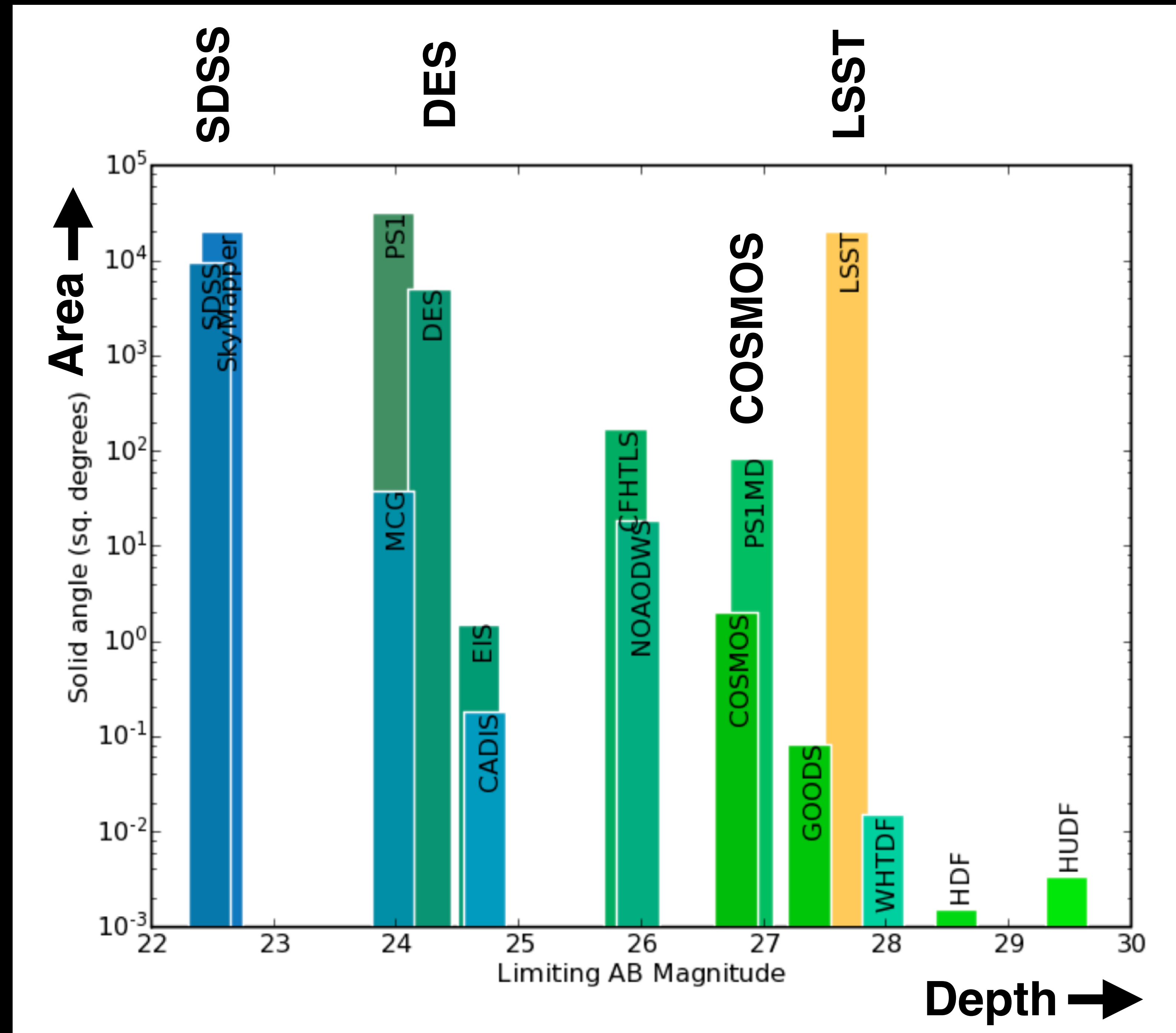
Combined analysis of all images in 6 broadband optical filters: colors, shapes, proper motion, statistical variability (~30x deeper; $r \sim 27.5$)

**➔ Level 2 data products (annual release)**




Visit = 2 x (15 sec exposure + 2 sec readout)
New field every ~40 seconds
~1000 visits per night ➔ ~10K $deg^2$ per night

# Catalogs for Multiwavelength / Multimessenger Science




**100x deeper than SDSS**

**>10x deeper than DES**

Comparable depth to *Hubble* COSMOS, but over an area **10⁴** larger (in **6** filters)

LSST Science Book
arXiv:0912.0201

**LSST will catalog more stars and galaxies (~40 billion) than all previous astronomical surveys combined**

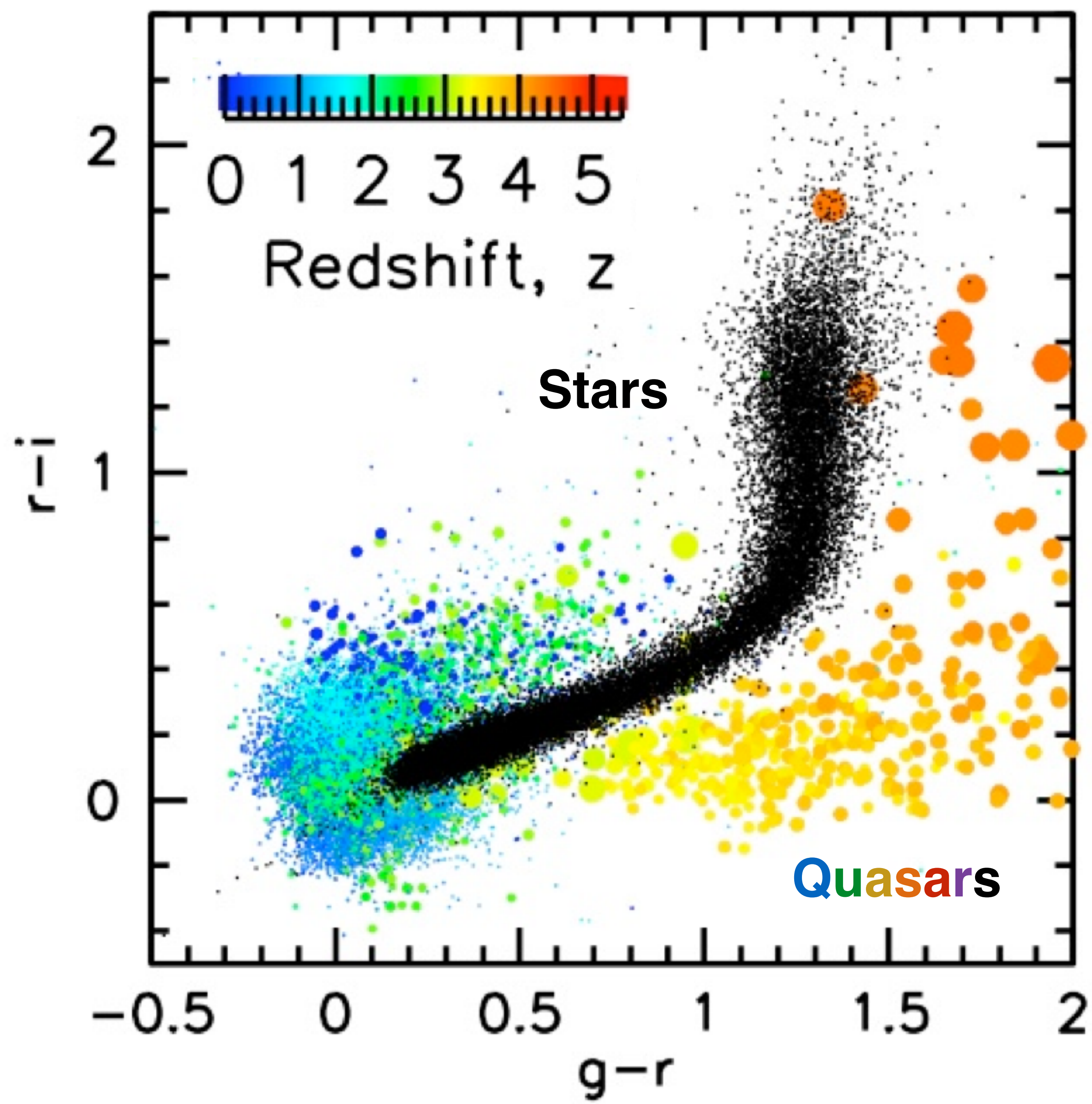
# AGN Classification, Demographics, and Evolution

### LSST AGN Sample

- >500 deg$^{-2}$, >10 M in full survey
- Typically a factor 1000 range in luminosity at a given redshift
- Extending to z ~ 7, w/ Δz = ±0.1 for 90% of quasar sample

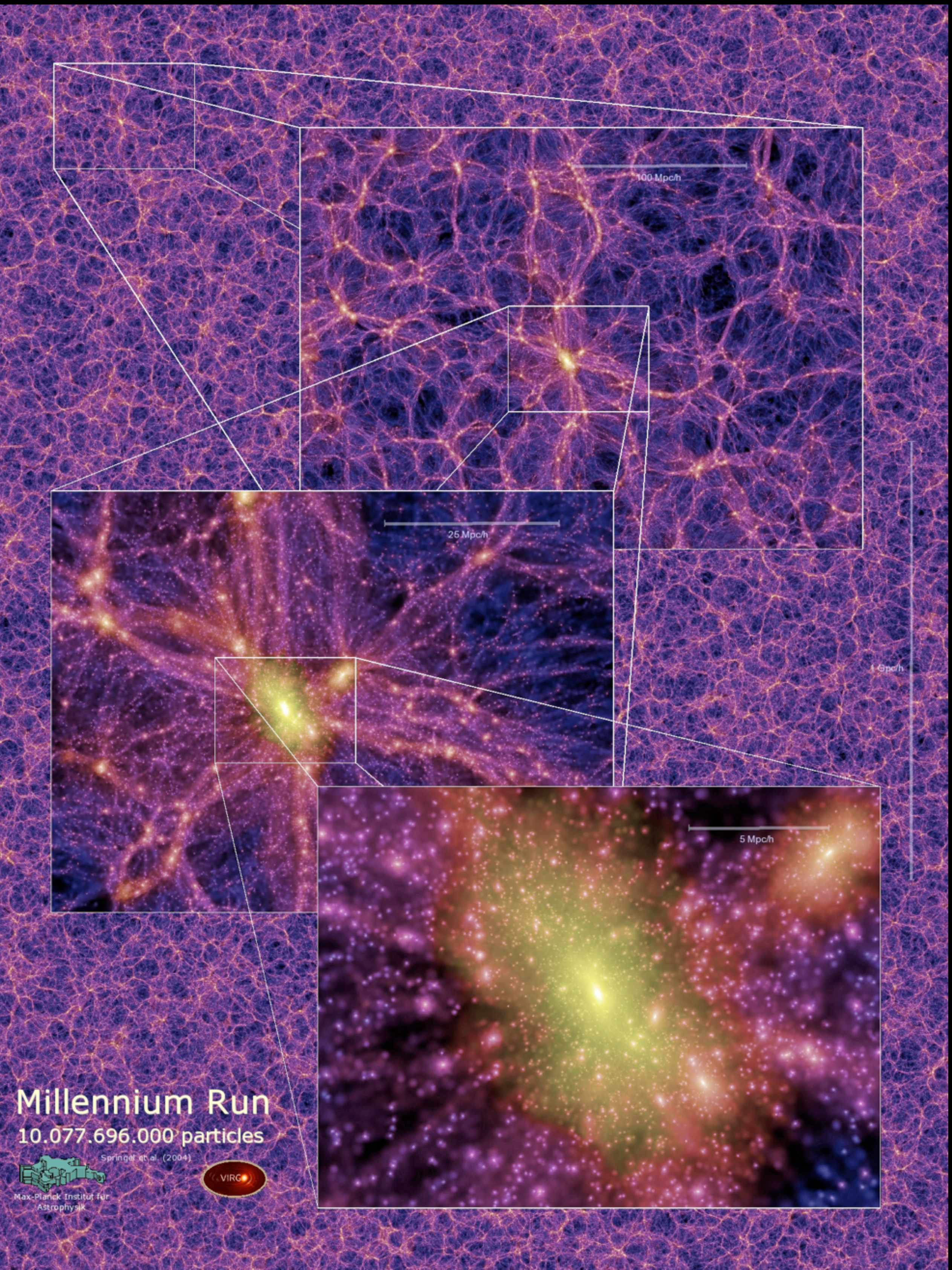
### Multiple detection strategies

- Colors (*ugrizy*)
- Lack of proper motion (relative to foreground stars)
- Variability (~20 epochs per year in a given band)




LSST Science Book
arXiv:0912.0201

# Mapping the (Dark) Matter Distribution




**From large scale structure …**

**… to Galactic subhalos**

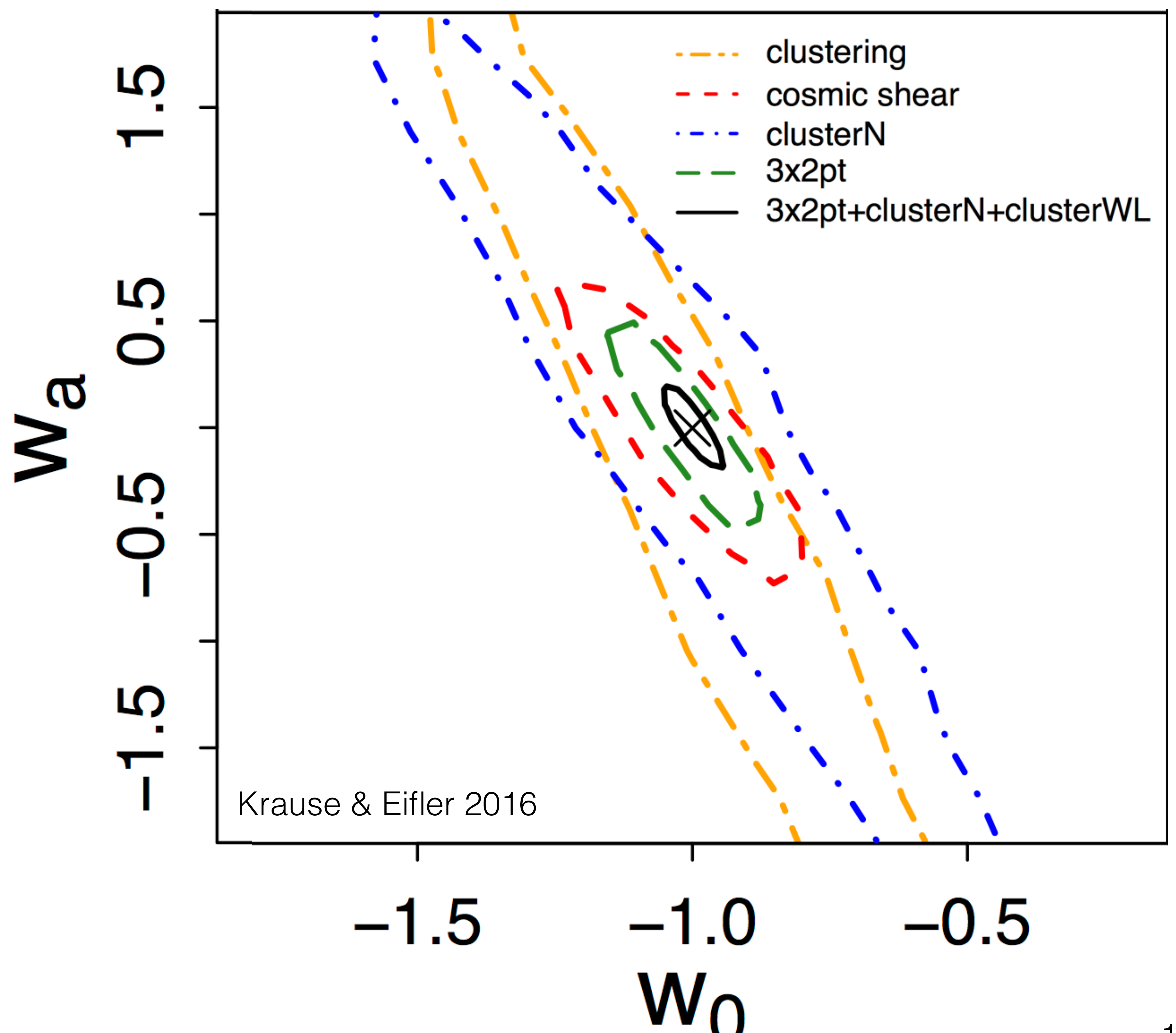
# Cosmic Acceleration ($w_o$, $w_a$, …)

**LSST combines multiple complementary probes of cosmic expansion history and growth of structure to explore parameter space beyond ΛCDM**

- Type Ia Supernova
- Galaxy Clusters
- Baryon Acoustic Oscillations
- Weak Lensing
- Strong Lensing

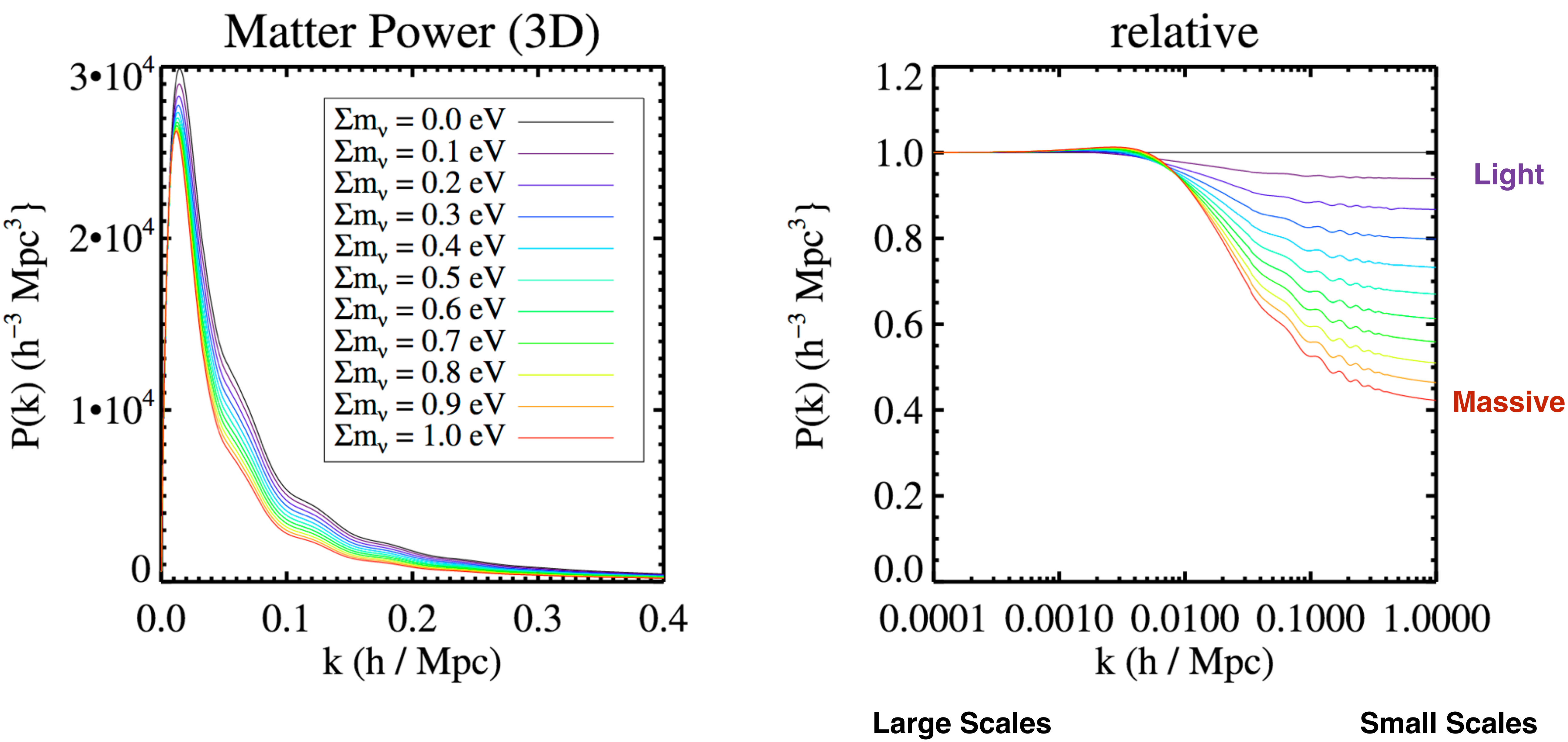
**Further calibration of systematic uncertainties from CMB, spectroscopic, 21cm surveys, …**

**Combined Probes of Large Scale Structure**



# Massive Neutrinos ($\sum m_\nu$)

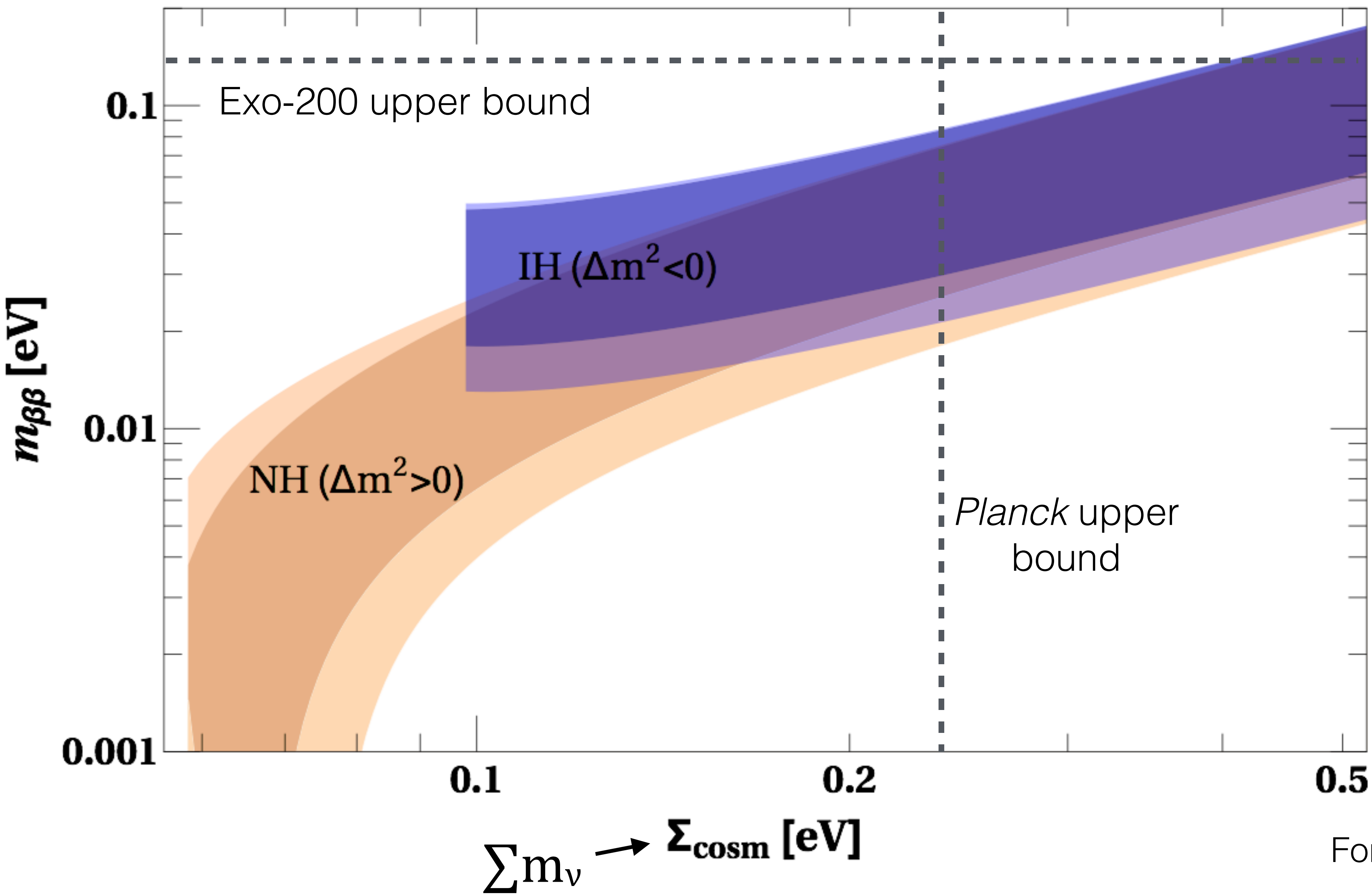
## Massive neutrinos suppress structure formation on small scales




CMB-S4 Science Book
1610.02743

# Massive Neutrinos ($\sum m_\nu$)

**Combination of neutrino-less double beta-decay experiments + cosmology could determine mass hierarchy and dirac/majorana nature of neutrinos**




Dell'Oro et al. 2016
arXiv:1601.07512

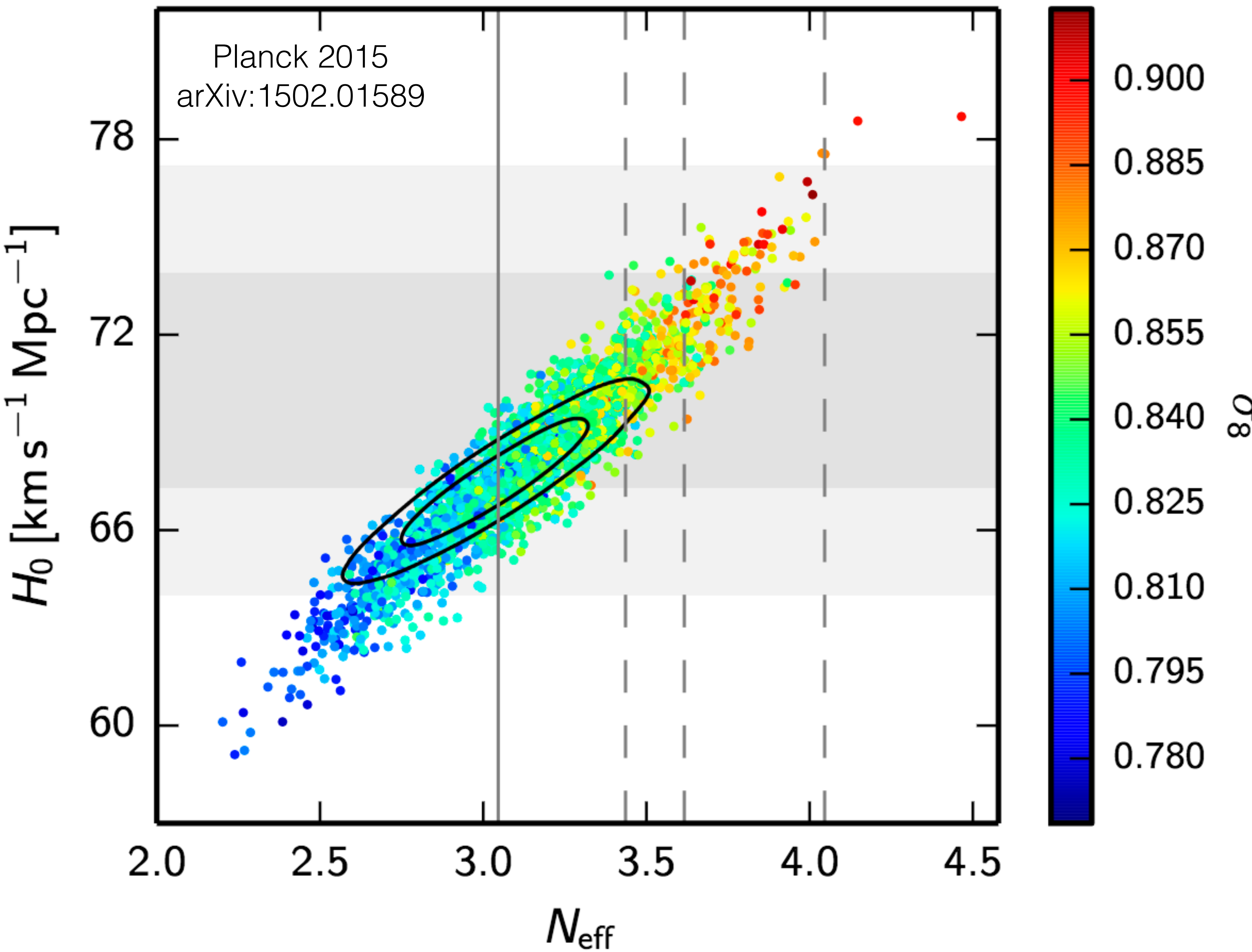
Font-Ribera et al. 2013
arXiv:1308.4164

Oscillation experiments: $\sum m_\nu > 0.058$ eV

LSST: $\sigma(\sum m_\nu) = 0.02$ eV

# Light Relics ($N_{eff}$)

**Sensitive not only to Standard Model neutrinos,**
**but to ALL relativistic species in the early universe**
**(axions, sterile neutrinos, hidden photons, gravitinos, …)**

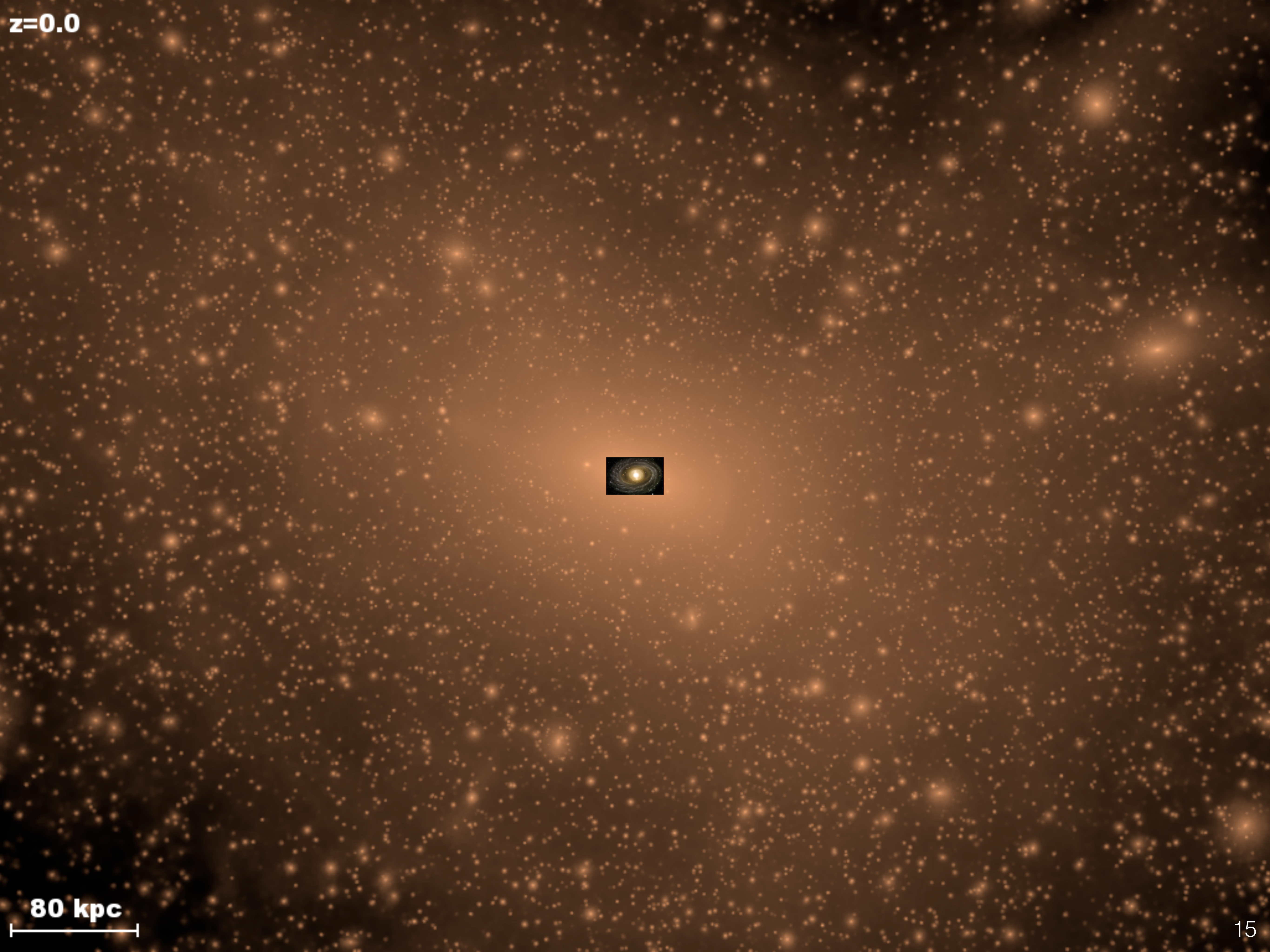



$N_{eff}$ = 3.046 (Standard Model)

$N_{eff}$ = 3.04 ± 0.18
(Planck + BAO)

Font-Ribera et al. 2013
arXiv:1308.4164

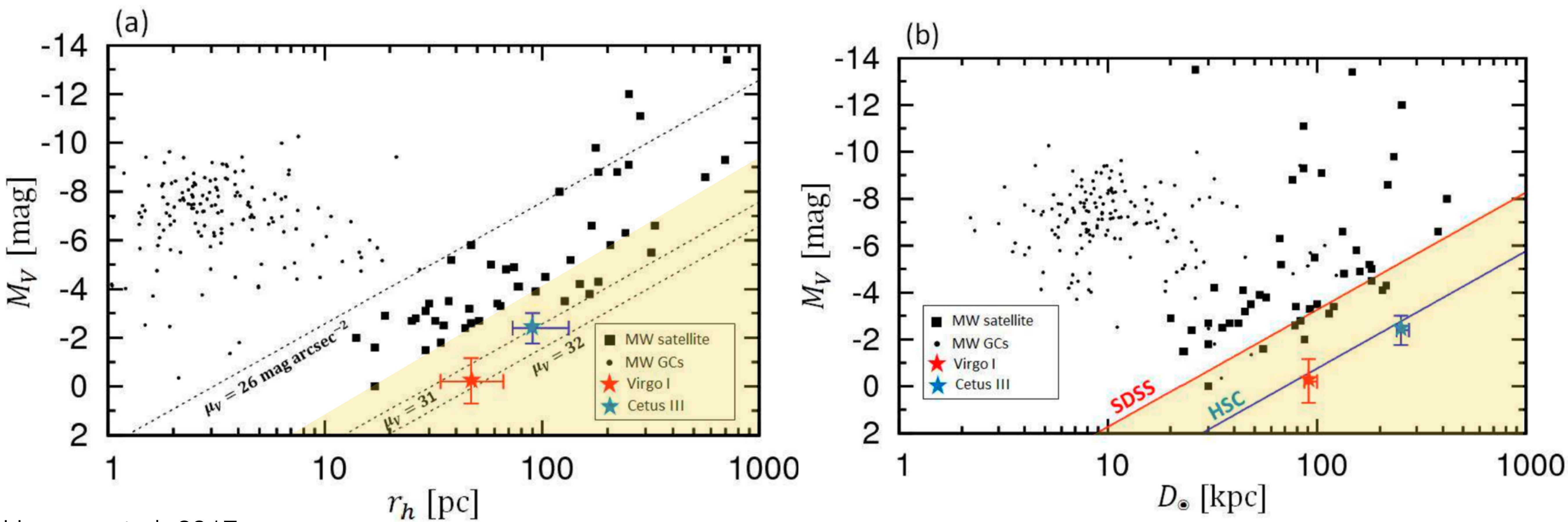
LSST: $\sigma(N_{eff})$ = 0.06


z=0.0
80 kpc

# Closer to Home:
# Searching for the Darkest Galaxies

**Our current census of Milky Way satellites is highly incomplete**

**Two new ultra-faint galaxy candidates** found in first **300 deg²** of HSC SSP data that were likely not detectable in any previous wide-field survey ( <1% of 4$\pi$ celestial sphere)

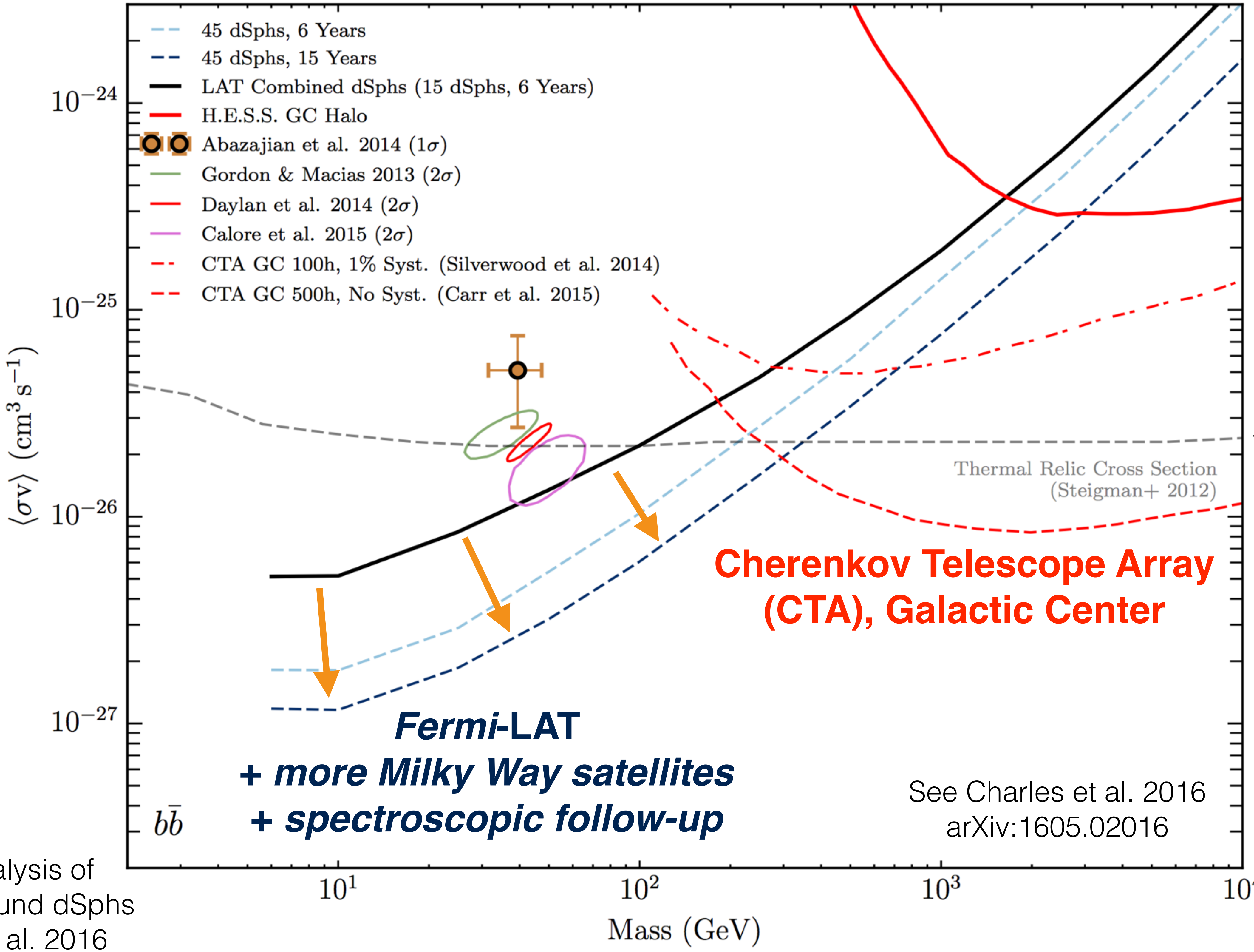



Homma et al. 2017

Similarly, we estimate that ~half of the ultra-faint galaxy candidates found with DES would not have been detected in a survey of SDSS depth

Bechtol et al. 2015, Drlica-Wagner et al. 2015

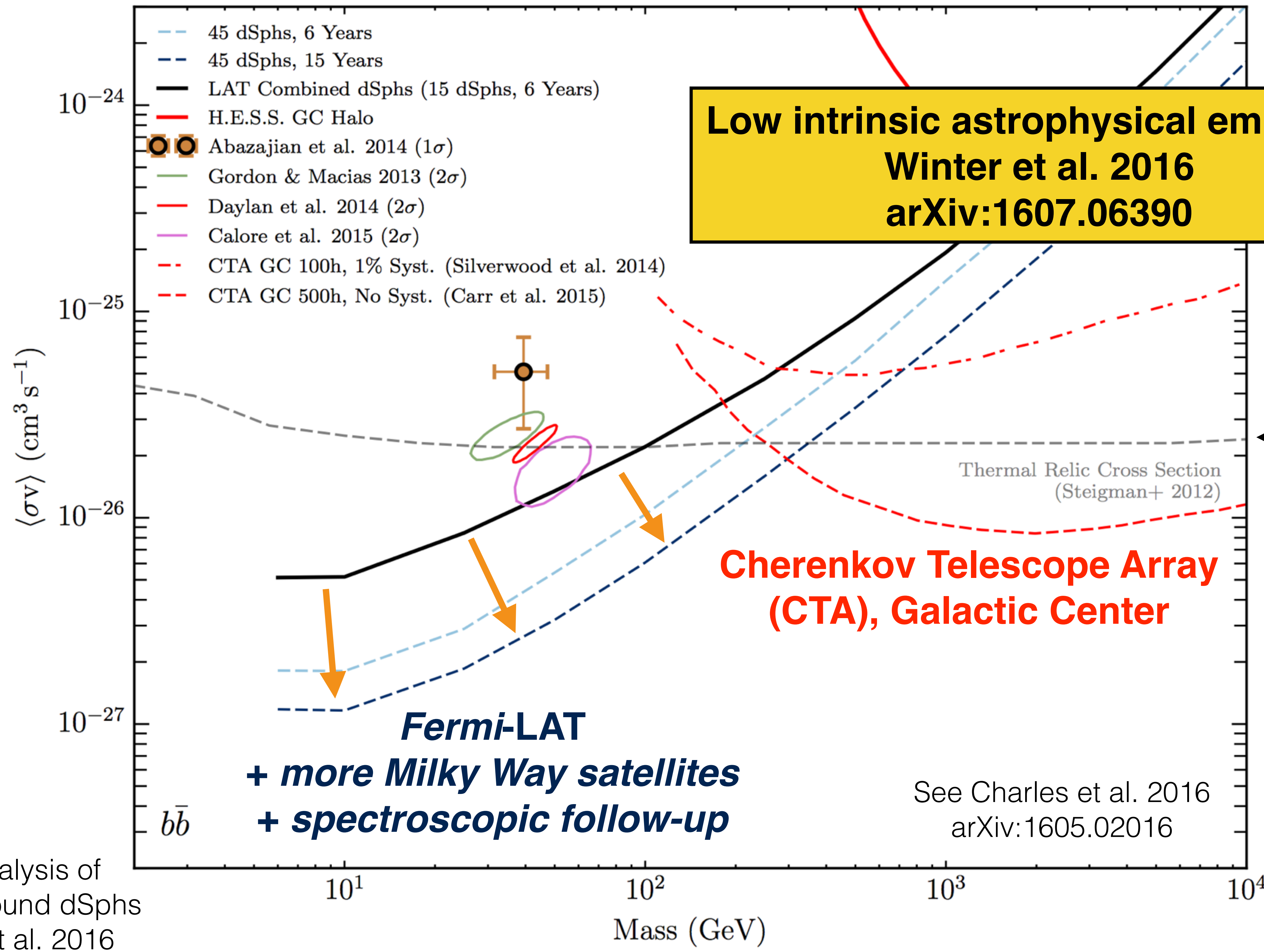
# Indirect Dark Matter Searches Targeting dSph Galaxies




Thermal Relic Cross Section

LAT analysis of recently found dSphs Albert et al. 2016 arXiv:1611.03184

# Indirect Dark Matter Searches Targeting dSph Galaxies

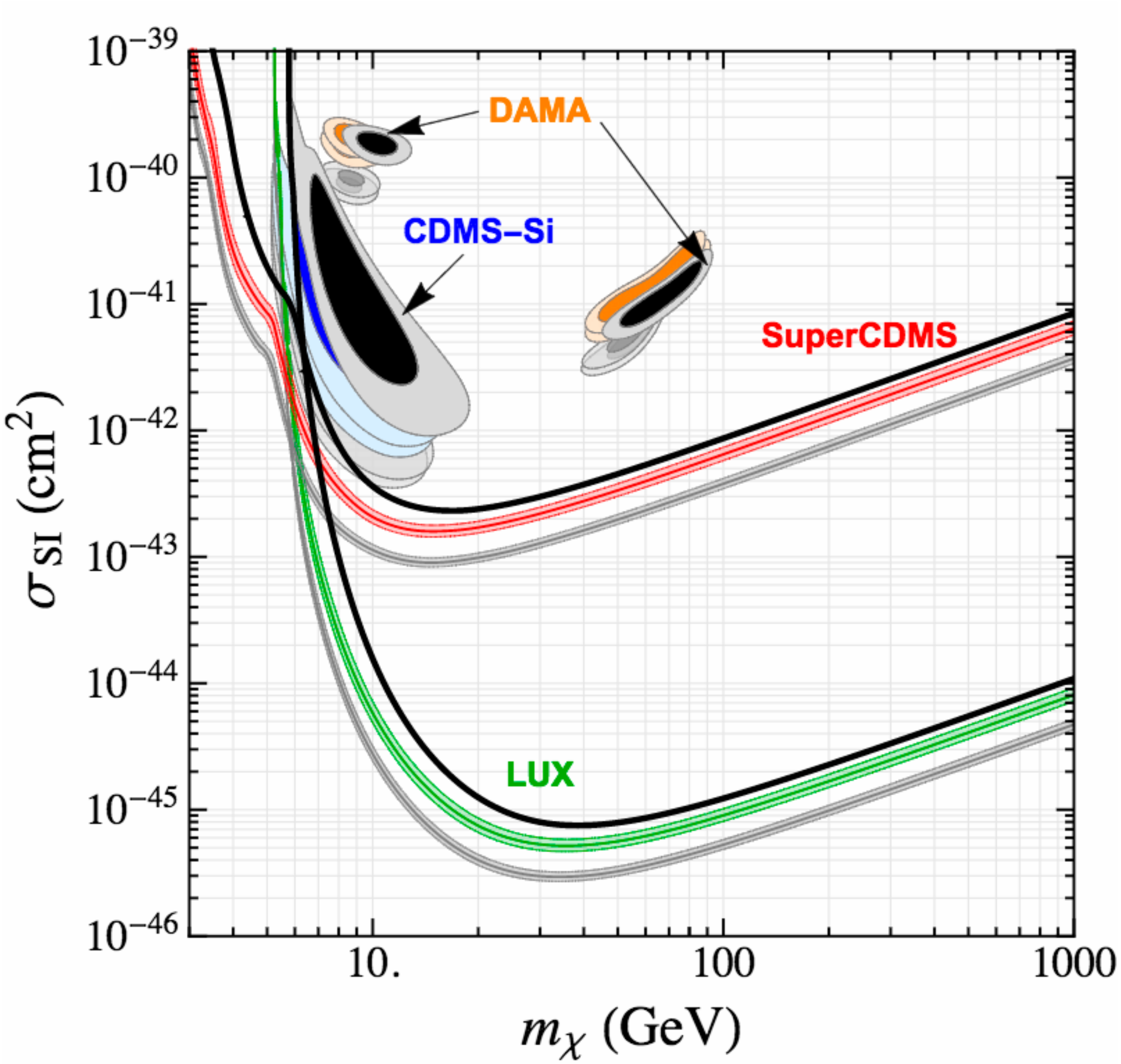



Thermal Relic Cross Section

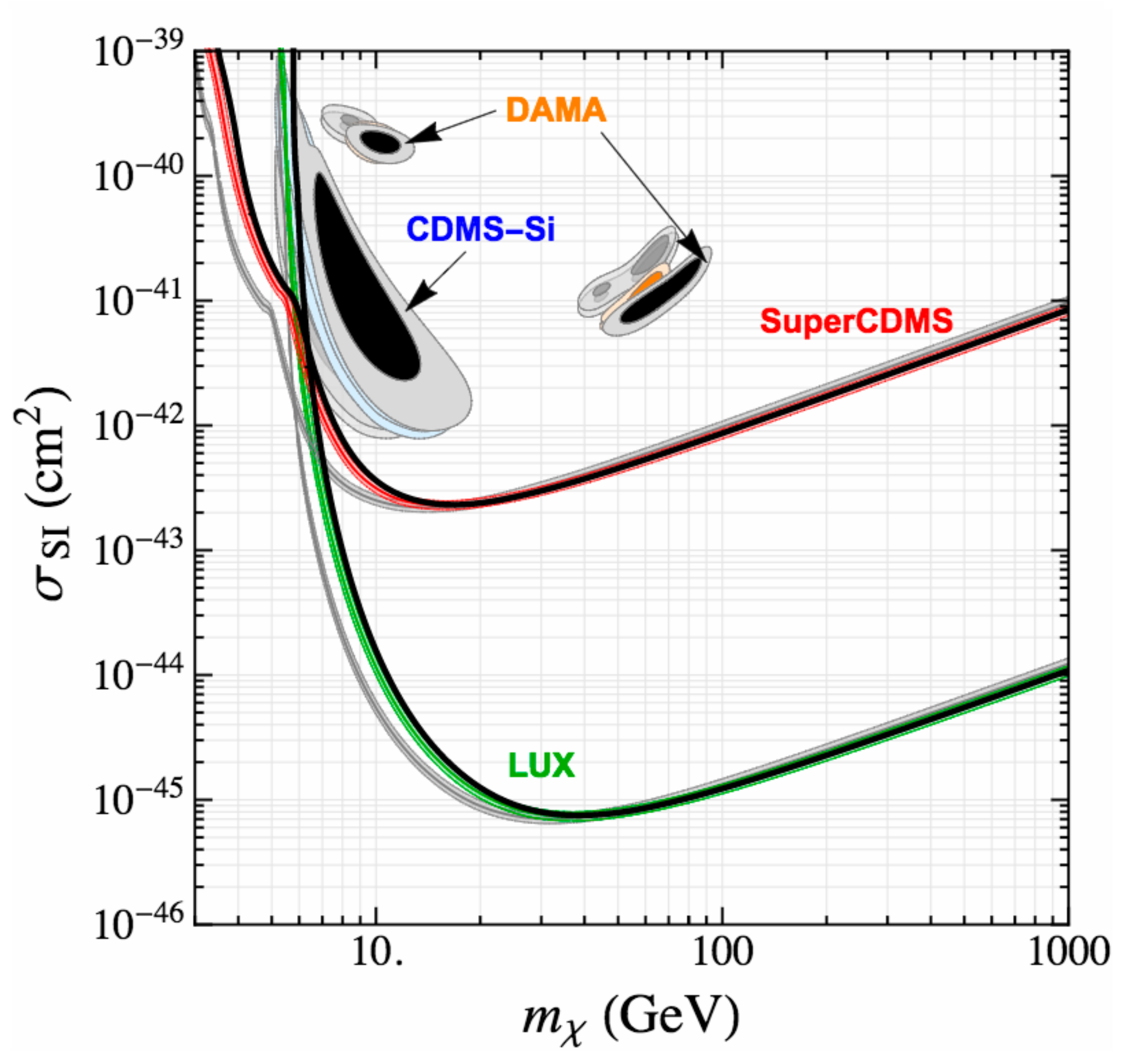
LAT analysis of recently found dSphs
Albert et al. 2016
arXiv:1611.03184

# Impact of Galactic Halo Uncertainty on Direct Detection Searches

**Varying local dark matter density**

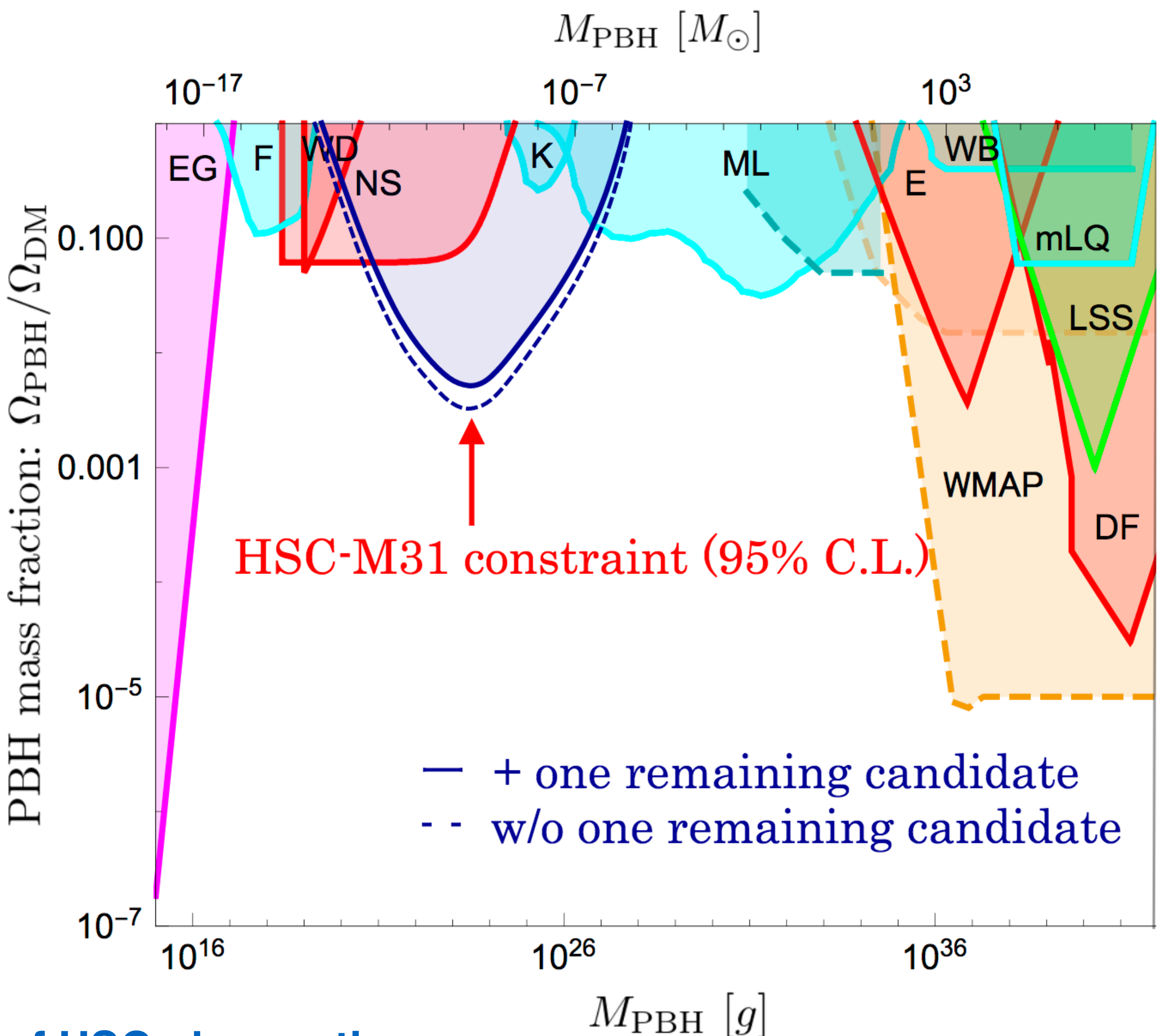



**Varying dark matter velocity distributions**




Bozorgnia et al. 2016, arXiv:1601.04707
See also
Kelso et al. 2016, arXiv:1601.04725
Sloane et al. 2016, arXiv:1601.05402

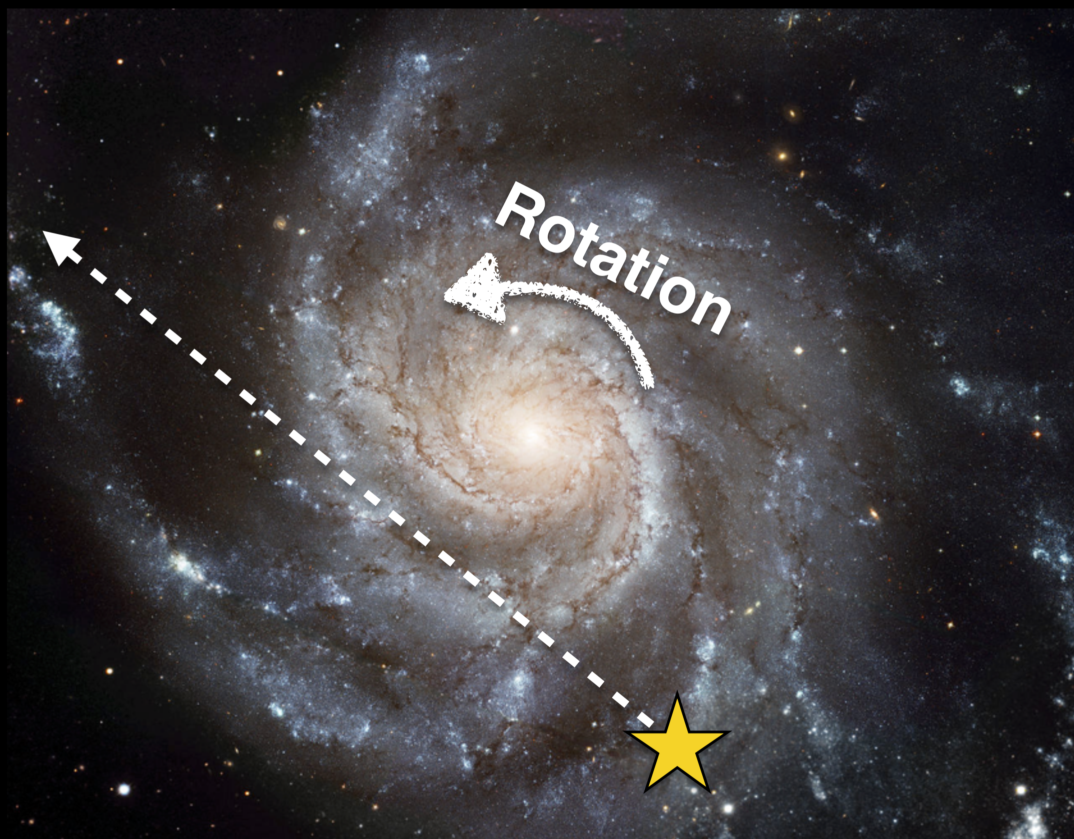
# Dark Matter Constraints from Gravitational Microlensing (MACHOs)




Niikura et al. 2017
arXiv:1701.02151

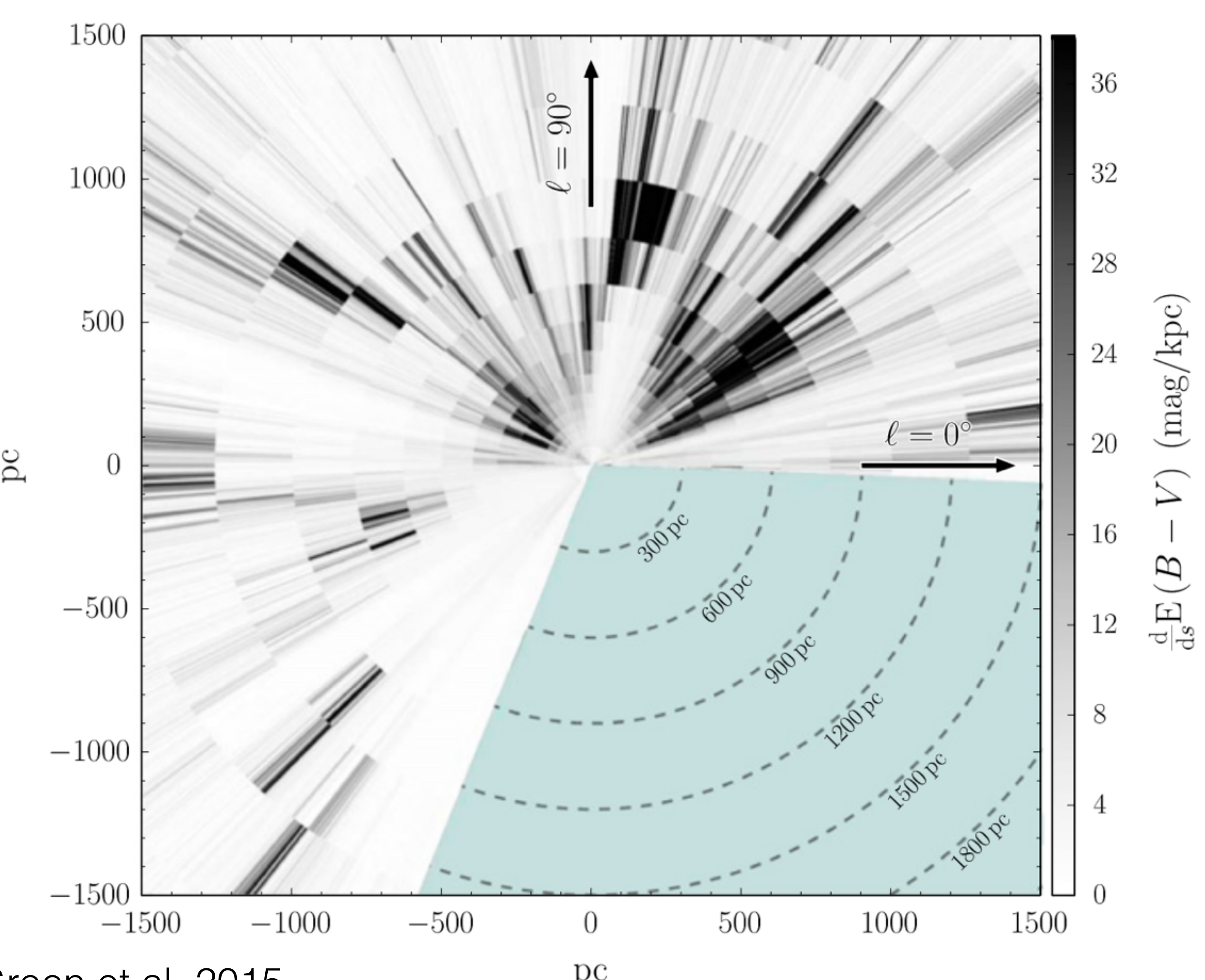
**Single night of HSC observations**

# A Different Kind of Dark Matter: Three-Dimensional Dust Maps




**Gamma-ray interstellar emission maps are typically created from gas maps where radial velocity is translated to distance assuming a galactic rotation curve (with degenerate solutions)**

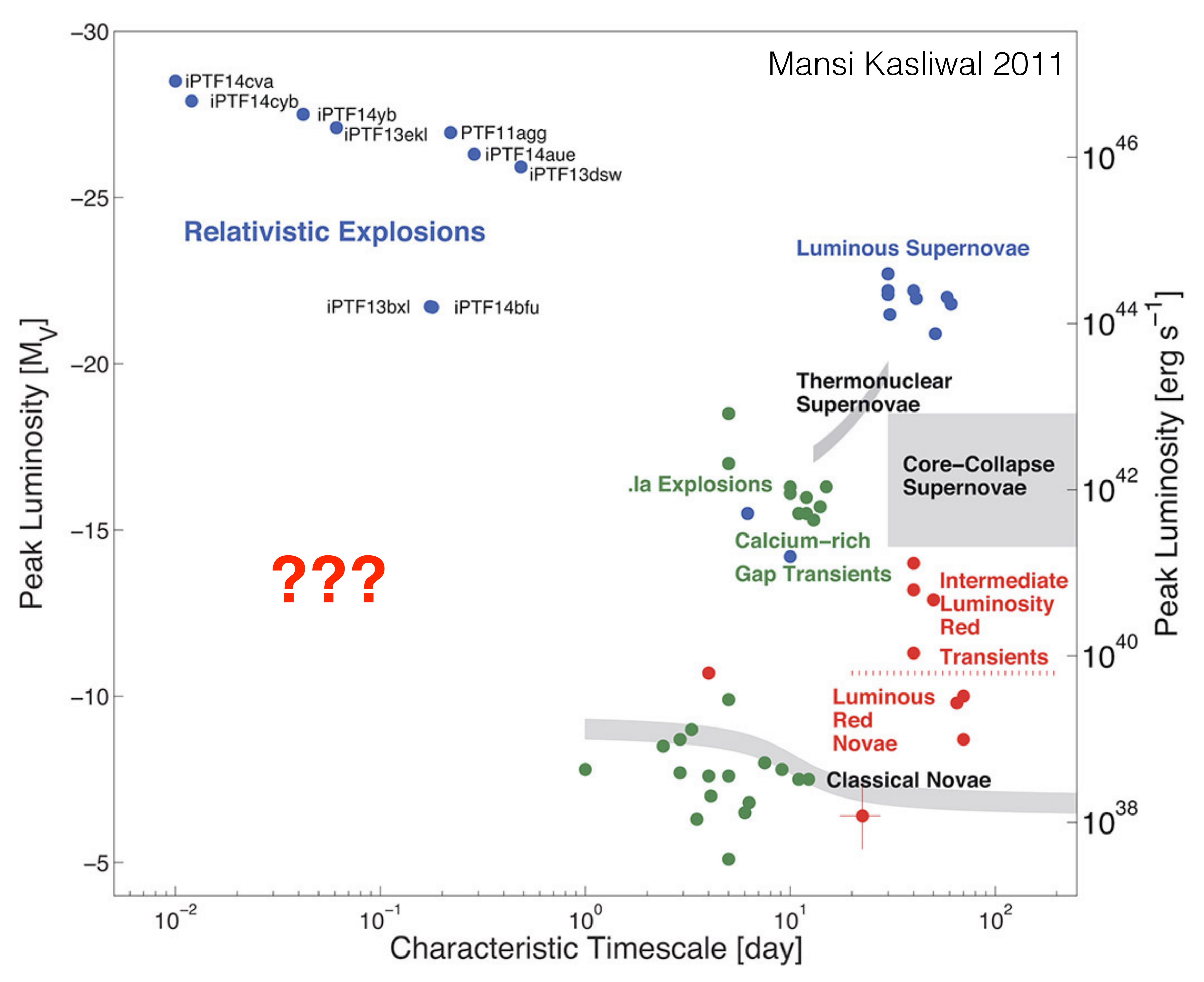
**Differential extinction along line of sight measured for stars at a range of heliocentric distances**
(thin slice of map)




Green et al. 2015

More visualiztions:
http://argonaut.skymaps.info/

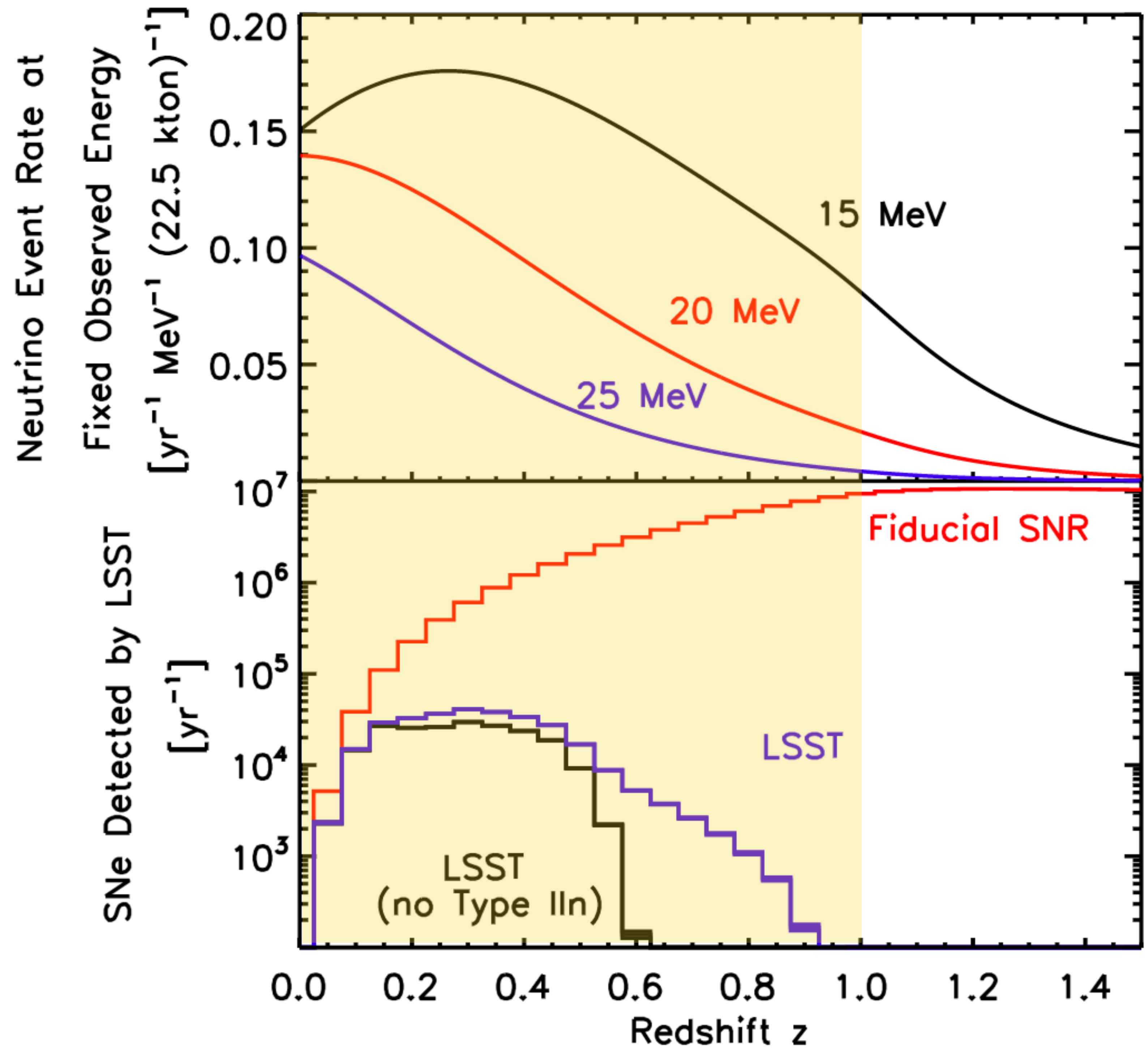
# Electromagnetic Counterparts for Multi-messenger Transients




**LSST will explore parameter space for fast transients with timescales <1 day that is now largely unexplored, along with rare and/or faint event classes**

# Diffuse Supernova Neutrino Background (MeV)

- ~90% of diffuse SN neutrino background events from 10-26 MeV (positron energy) produced at z < 1
- **LSST to detect ~$10^5$ CC SN per year to z ~ 1 in main survey**
- Directly measure the CC SN rate at z ~ 0.3 to precision of ±5%
- Probe fraction of invisible SN events

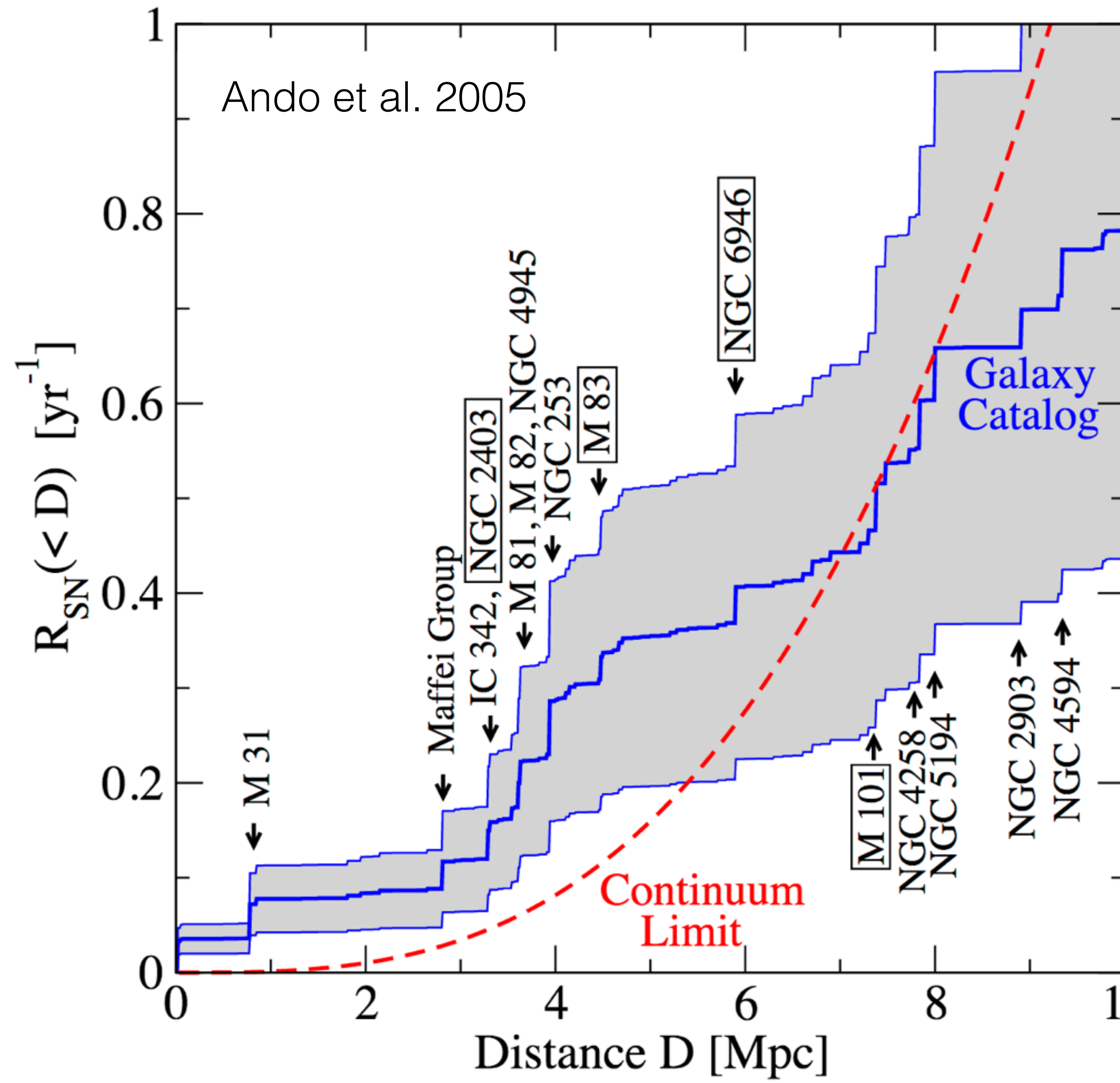



Lien et al. 2010

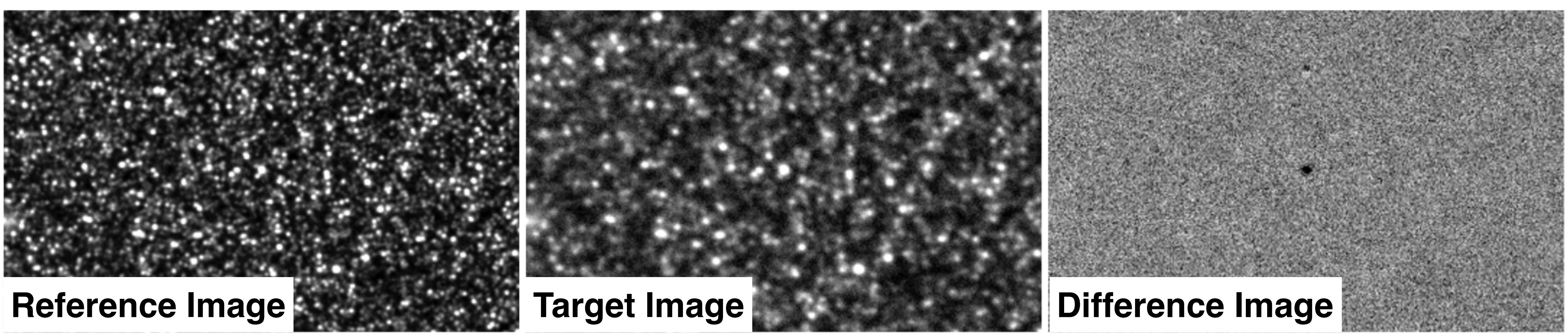
# Detecting "Invisible" Supernovae?

**What about a star that collapses *without* producing excess electromagnetic radiation?**

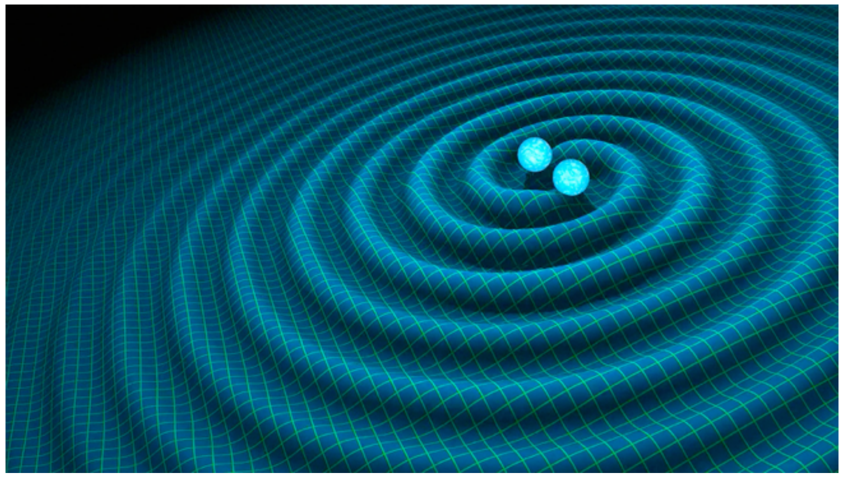
**"Invisible" SN (a disappearing star) detected via difference image analysis as a *negative* point-like source coincident with galaxies within ~10 Mpc**




Example analysis from LSST proto-pipeline
Niikura et al. 2017
arXiv:1701.02151



# Electromagnetic Counterparts to Gravitational Wave Events

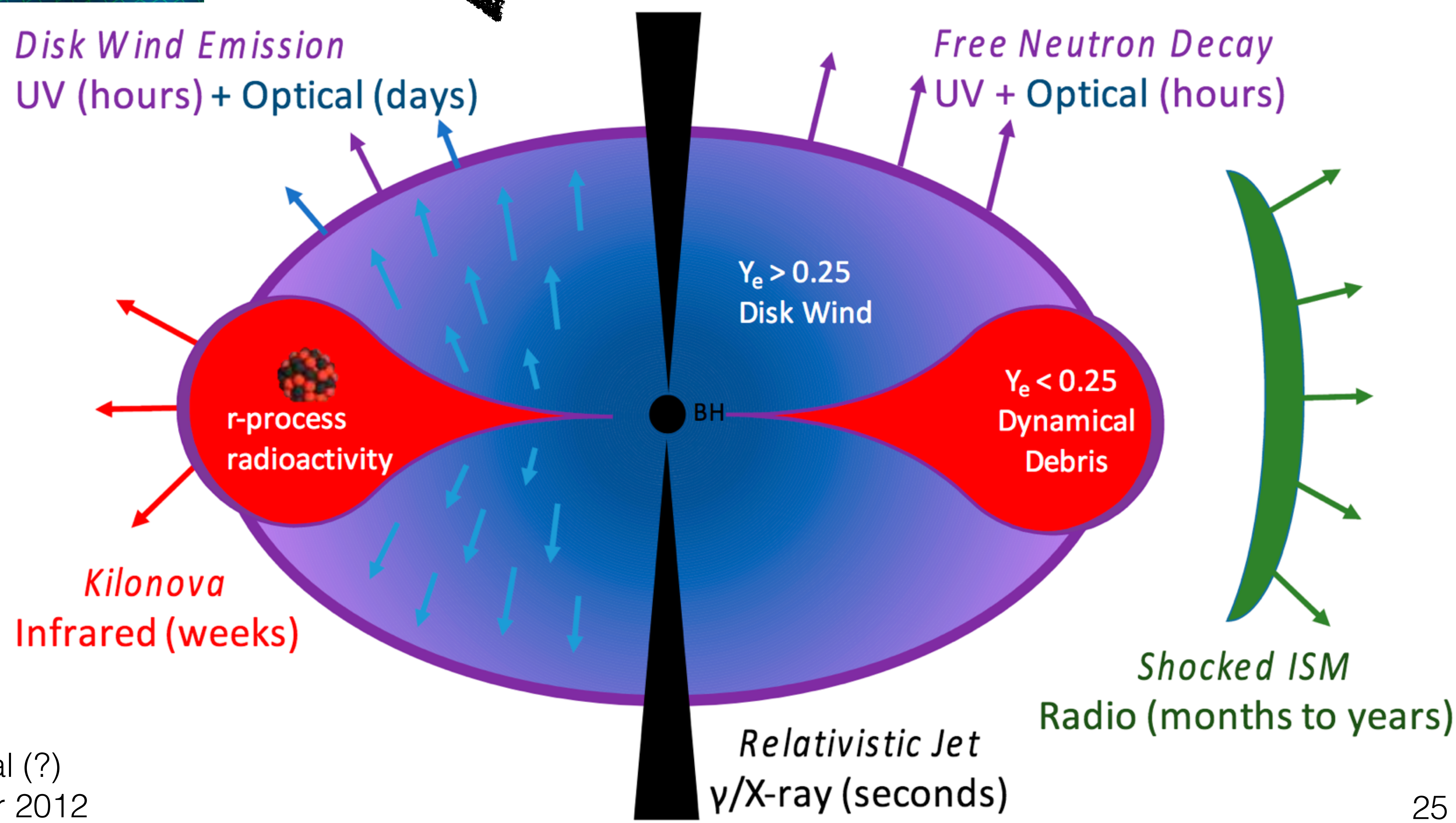


*Gravitational Waves*

*Binary Neutron Star Coalescence*

**Electromagnetic counterpart can provide**

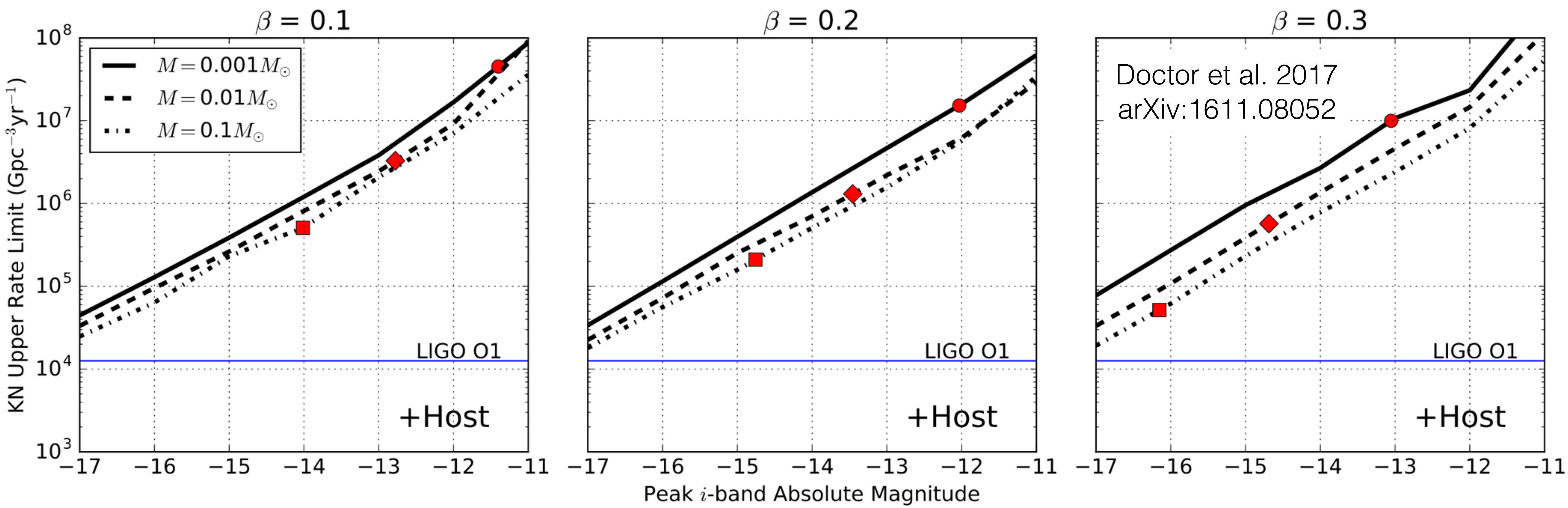
- ✓ Confirmation
- ✓ Localization
- ✓ Redshift
- ✓ Yield of heavy elements (r-process)
- ✓ …




Adapted from M. Kasliwal (?)
See also Metzger & Berger 2012

# Upper Limits on Kilonova Event Rate from an Unbiased Search

**Use 10 supernova fields (30 deg²) from Dark Energy Survey (DES)**




**Upper bounds from optical search compatible with current GW search**

See also
Cowperthwaite 2016
arXiv:1606.04538

# Electromagnetic Counterparts to Gravitational Wave Events

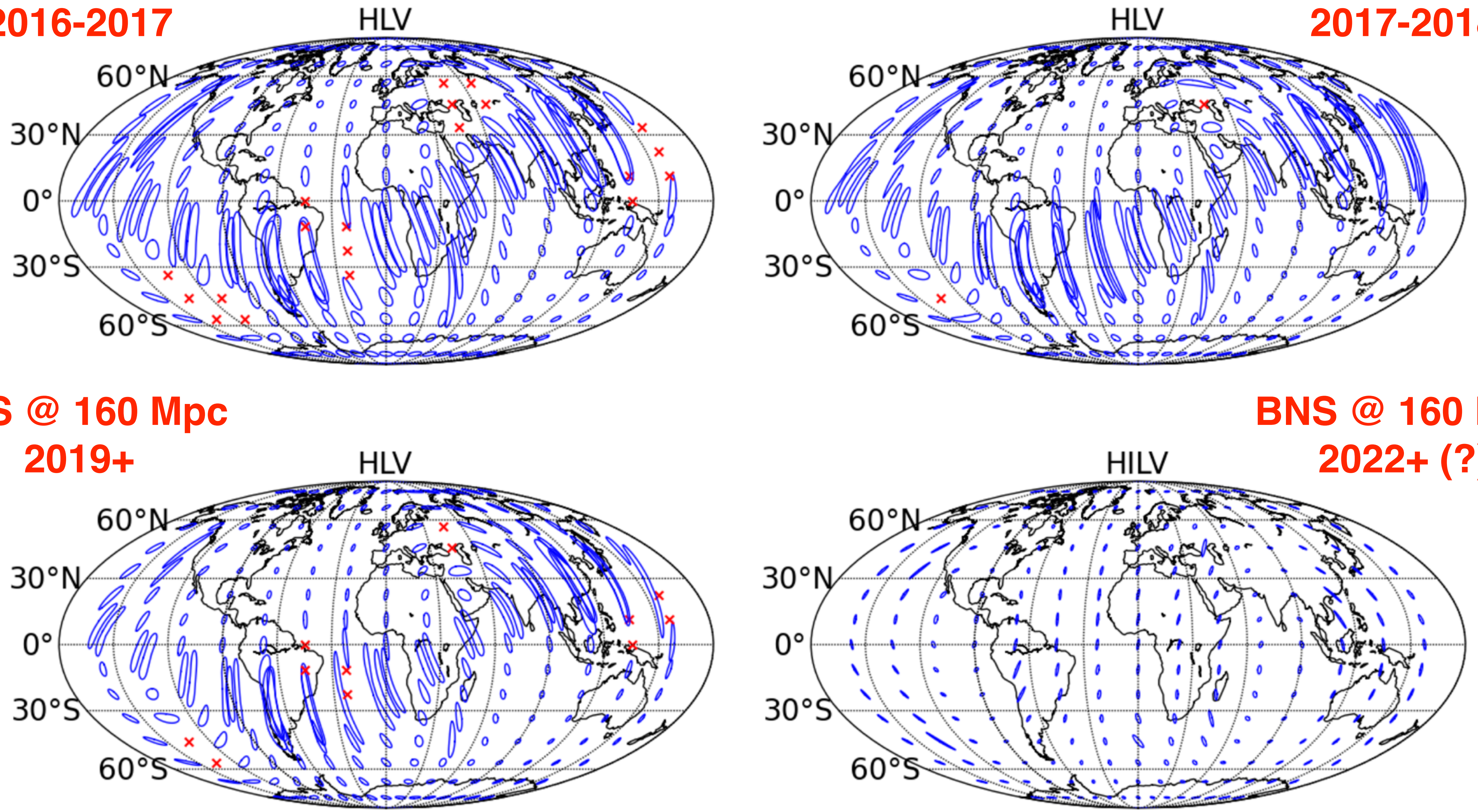
**Expected Localization 90% Confidence Regions**

**BNS @ 80 Mpc 2016-2017**

**BNS @ 80 Mpc 2017-2018**

**BNS @ 160 Mpc 2019+**

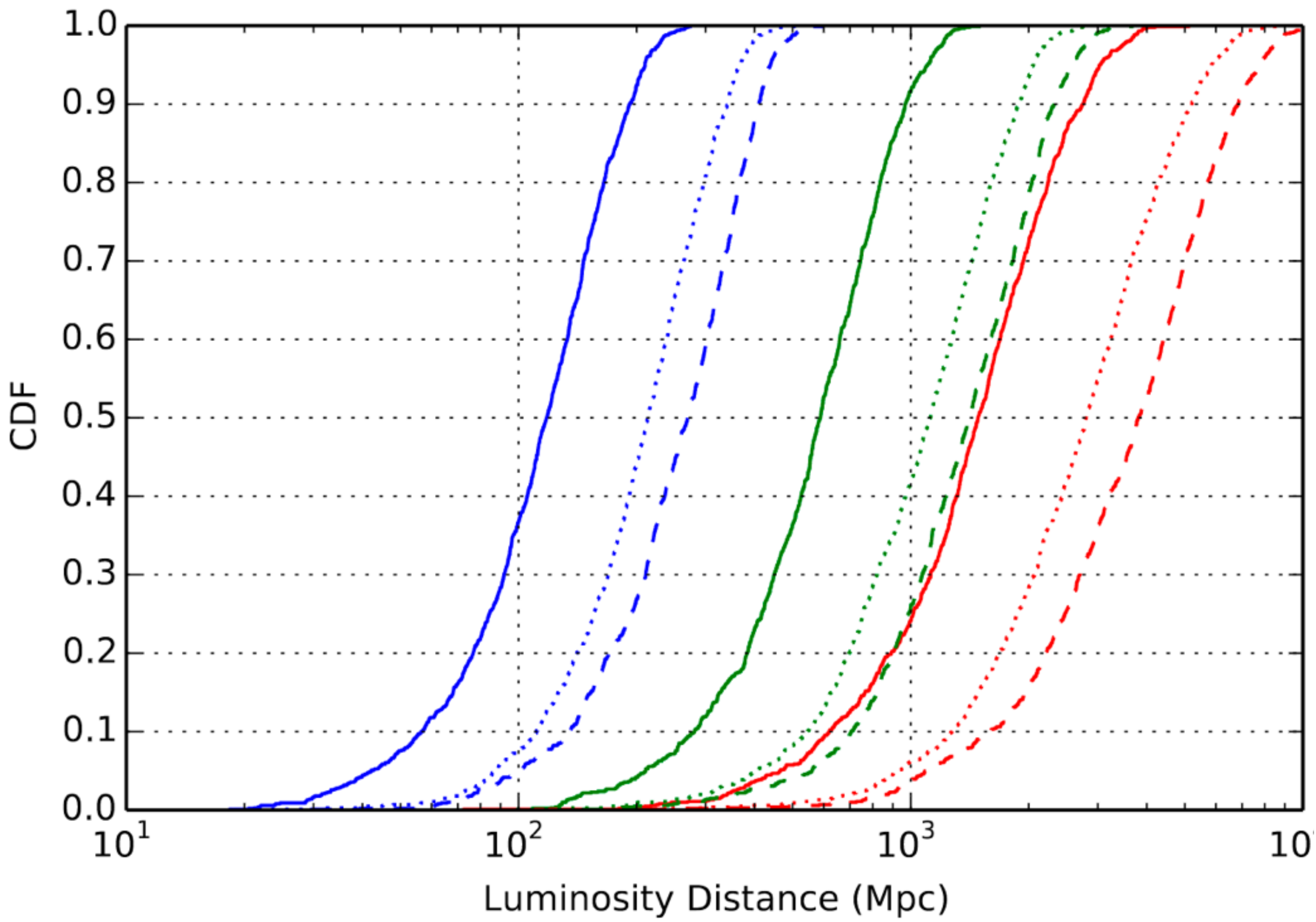
**BNS @ 160 Mpc 2022+ (?)**



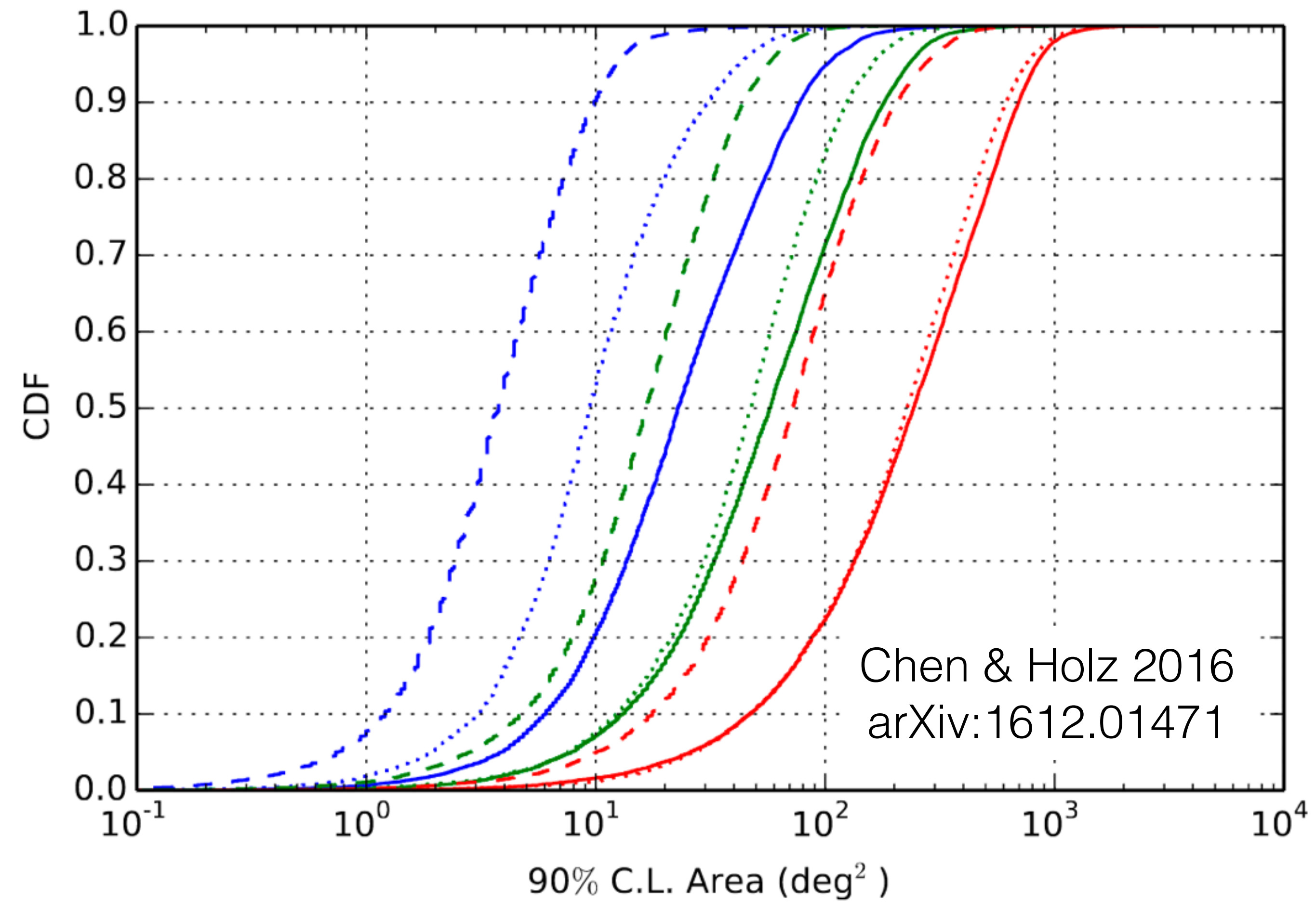

Abbott et al. 2016 (version 2)
arXiv:1304.0670

# Electromagnetic Counterparts to Gravitational Wave Events

**Luminosity Distance**




**90% Confidence Localization Area**



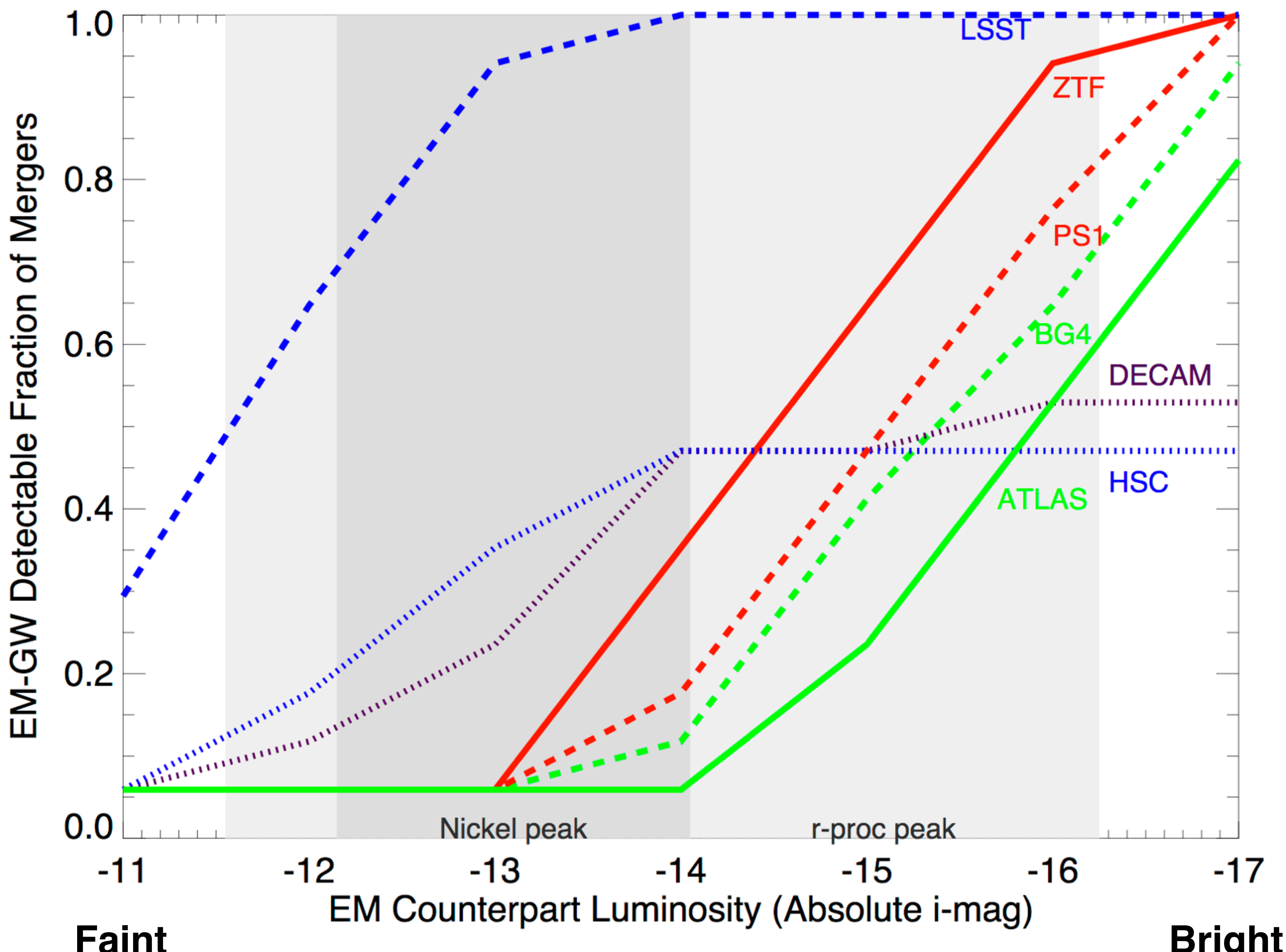

**Solid = HLV O3 sensitivity**
**Dotted = HLV design sensitivity**
**Dashed = HLVJI**

**1.4 $M_\odot$ - 1.4 $M_\odot$**
**10 $M_\odot$ - 10 $M_\odot$**
**30 $M_\odot$ - 30 $M_\odot$**

**By early 2020s, we expect that a substantial fraction of BNS merger events will be localized to an area of ~10 $deg^2$, comparable to a single LSST pointing**

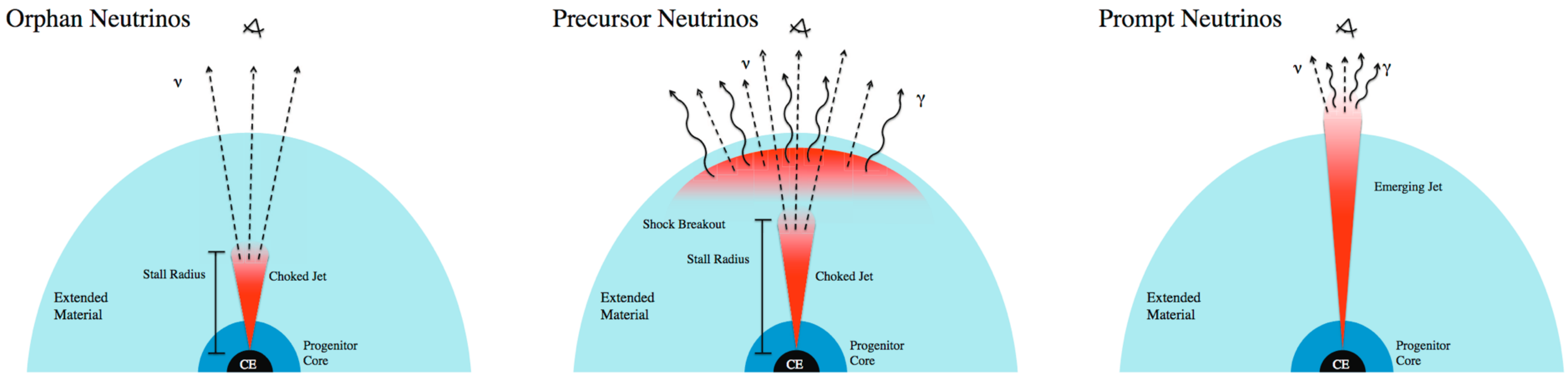
Also, limited GW detection horizon is an advantage for EM counterpart identification

# Electromagnetic Counterparts to Gravitational Wave Events




Kasliwal & Nissanke 2014

# TeV Supernova Neutrinos




Senno, Murase, & Meszaros 2016

**Choked Jet**

Meszaros & Waxman 2001

Ando & Beacom 2005

Senno, Murase, & Meszaros 2016

**Low luminosity GRB**

Murase et al. 2006

Murase & Ioka 2013

Tamborra & Ando 2016

**Prompt (1-100 sec)**

**See next talk by Anna Frankowiak**

**Type IIn SN**

Murase et al. 2011

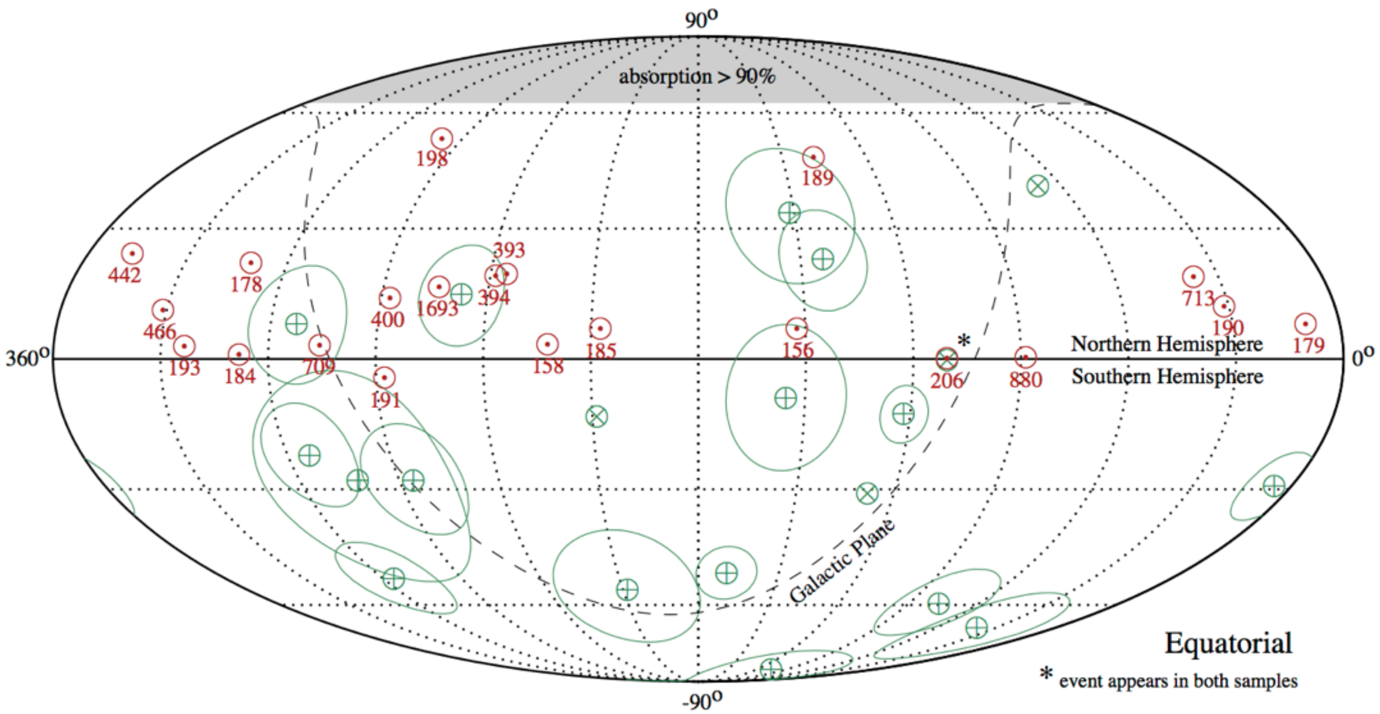
Katz, Sapir, & Waxman 2011

Zirakashvili & Ptuskin 2016

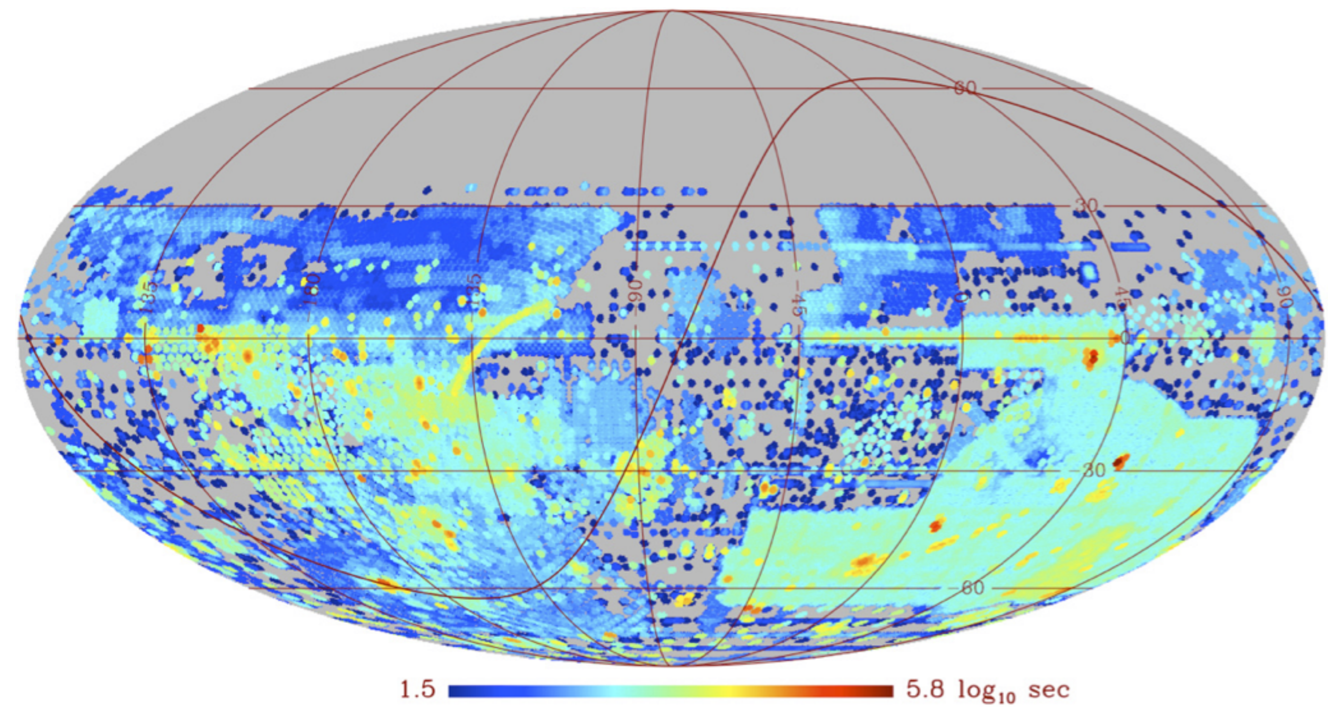
**Interactions with dense circumstellar wind (~months)**

# Optical Follow-up of IceCube Tracks: Access to the Southern Hemisphere

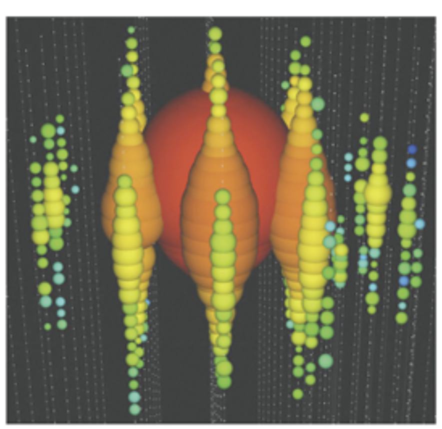
**IceCube HESE (3yr) and NuMu (2y) Events**



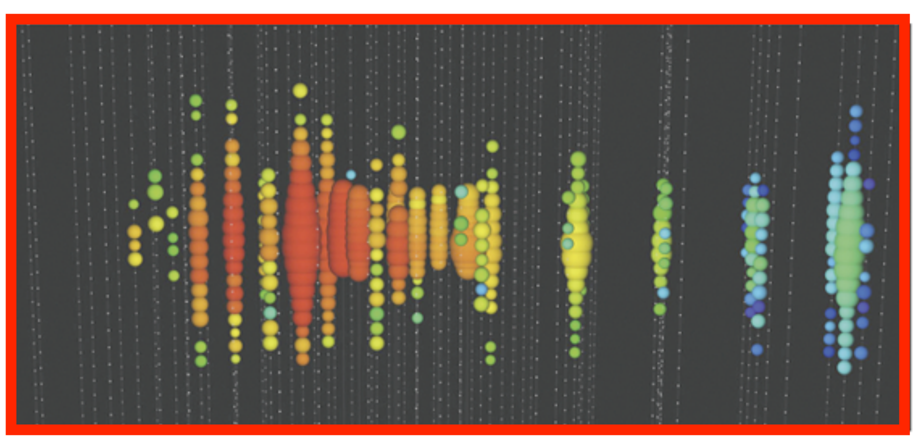

**All DECam exposures up to June 2016**




**Cascade**



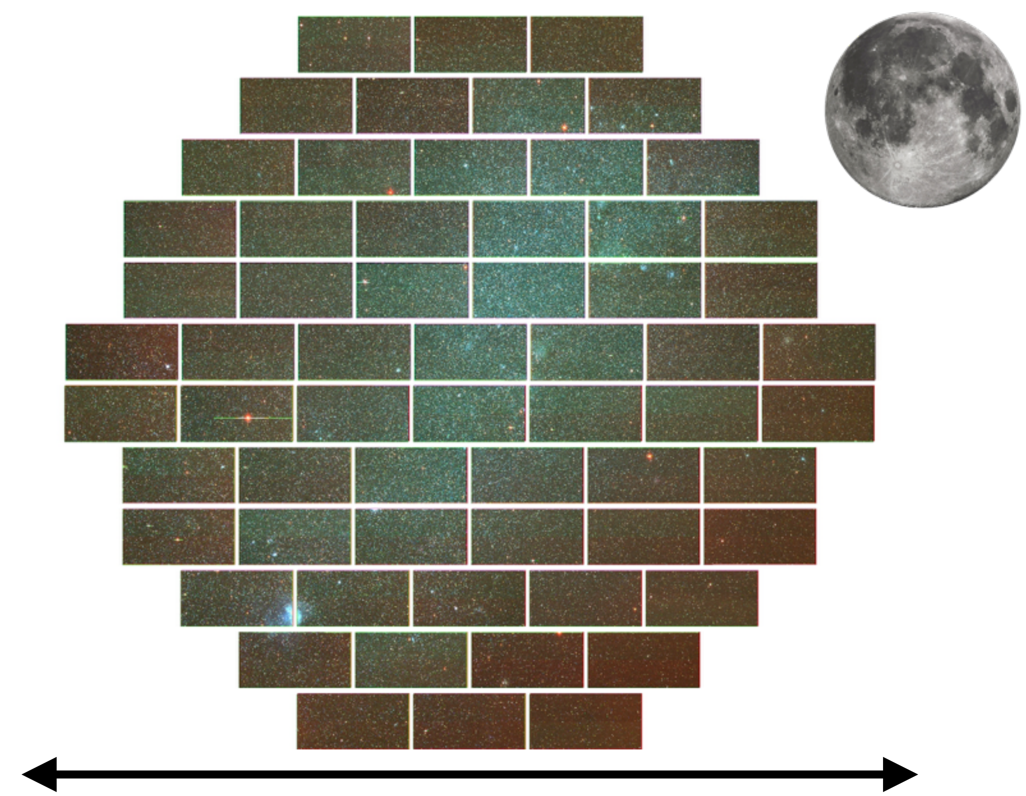
**Track**



IceCube, arXiv:1406.6757

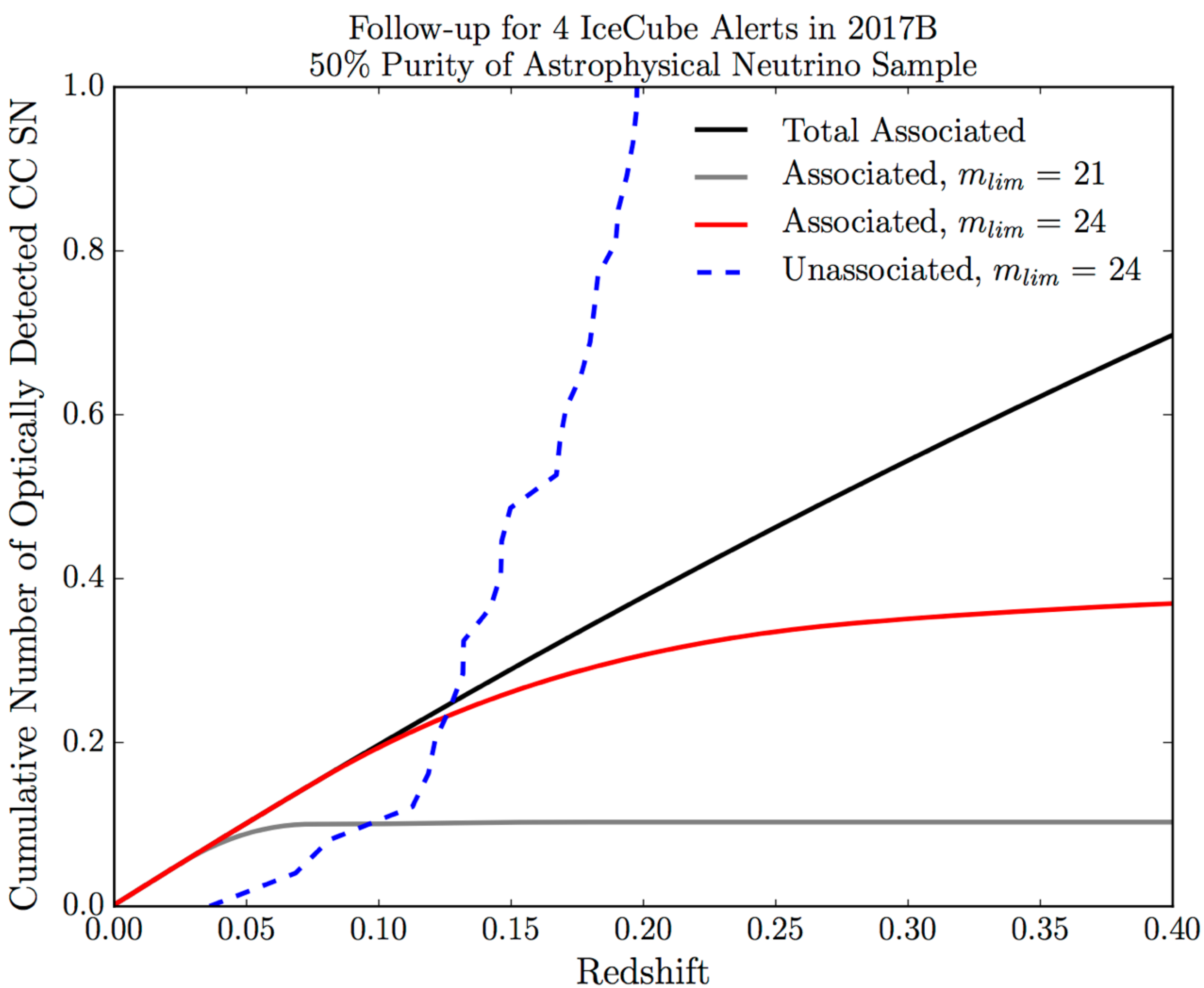
**Angular Resolution**

| Cascade | Track |
|---|---|
| ~15 deg | ~1 deg @ 1 TeV<br>~0.4 deg @ 100 TeV |



2.2 deg

# Optical Follow-up of IceCube Tracks: Benefits of a Larger Aperture




**Proposed follow-up of 4 IceCube alerts in 2017B w/ DECam**

**$m_{lim}$ ~ 24 achieved in**
**~300 sec w/ DECam (3 deg$^2$)**
**~30 sec w/ LSST (10 deg$^2$)**

**Baseline Pan-STARRS / ZTF**

Estimate coincidence rate of unassociated CC SN in full DECam field of view (3 deg$^2$) using a 10 day window centered on neutrino event

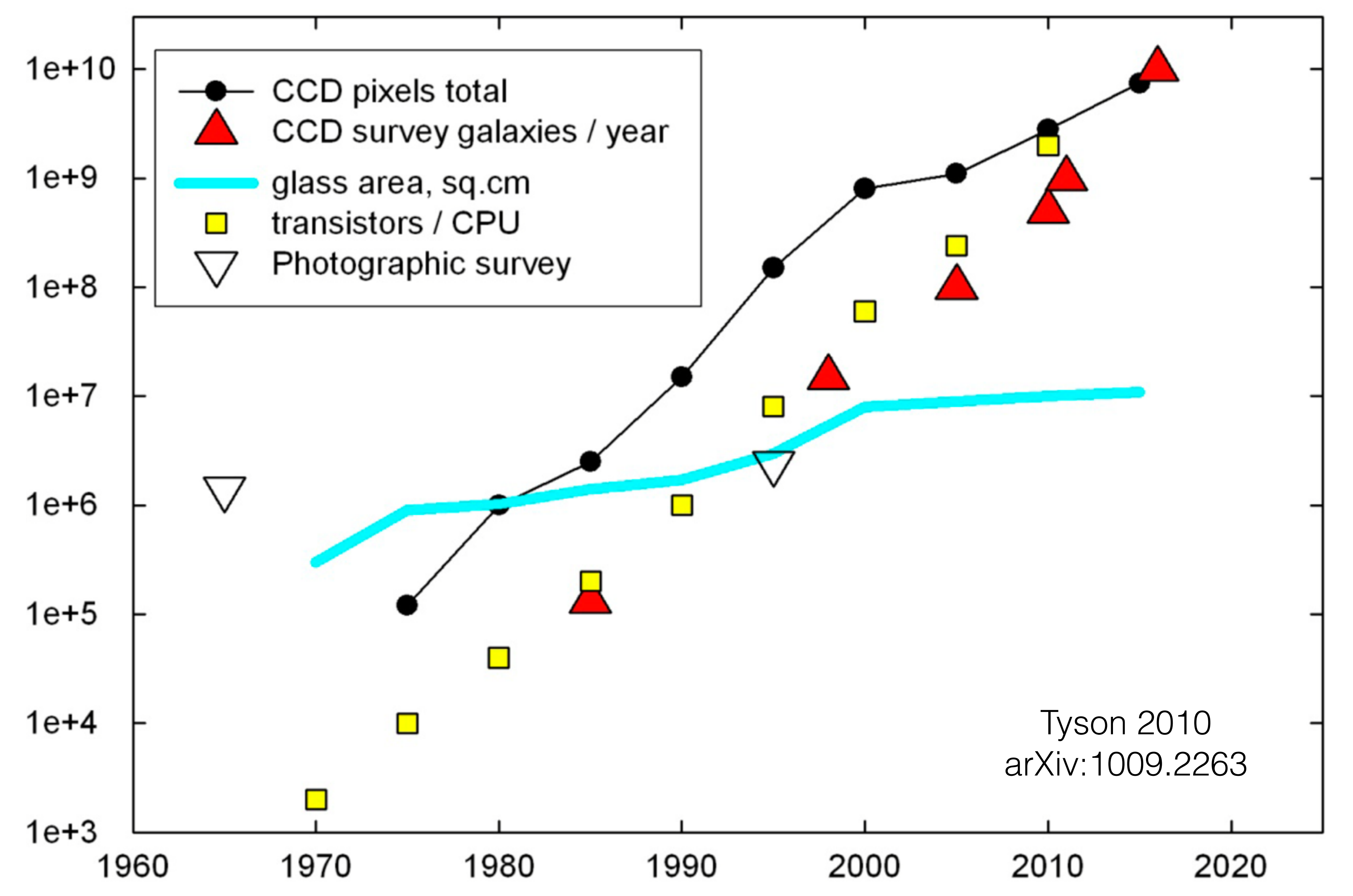
# Takeaways

- Optical imaging surveys: wider, faster, deeper
- LSST will soon (~2022) join the growing ensemble of wide-field, time-domain, and multi-wavelength / multi-messenger experiments
- Public dataset, broad scientific reach
- Optimal implementation of LSST observing strategy is currently being discussed, including possibility for a limited ToO program

***What can LSST do for particle astrophysics?***

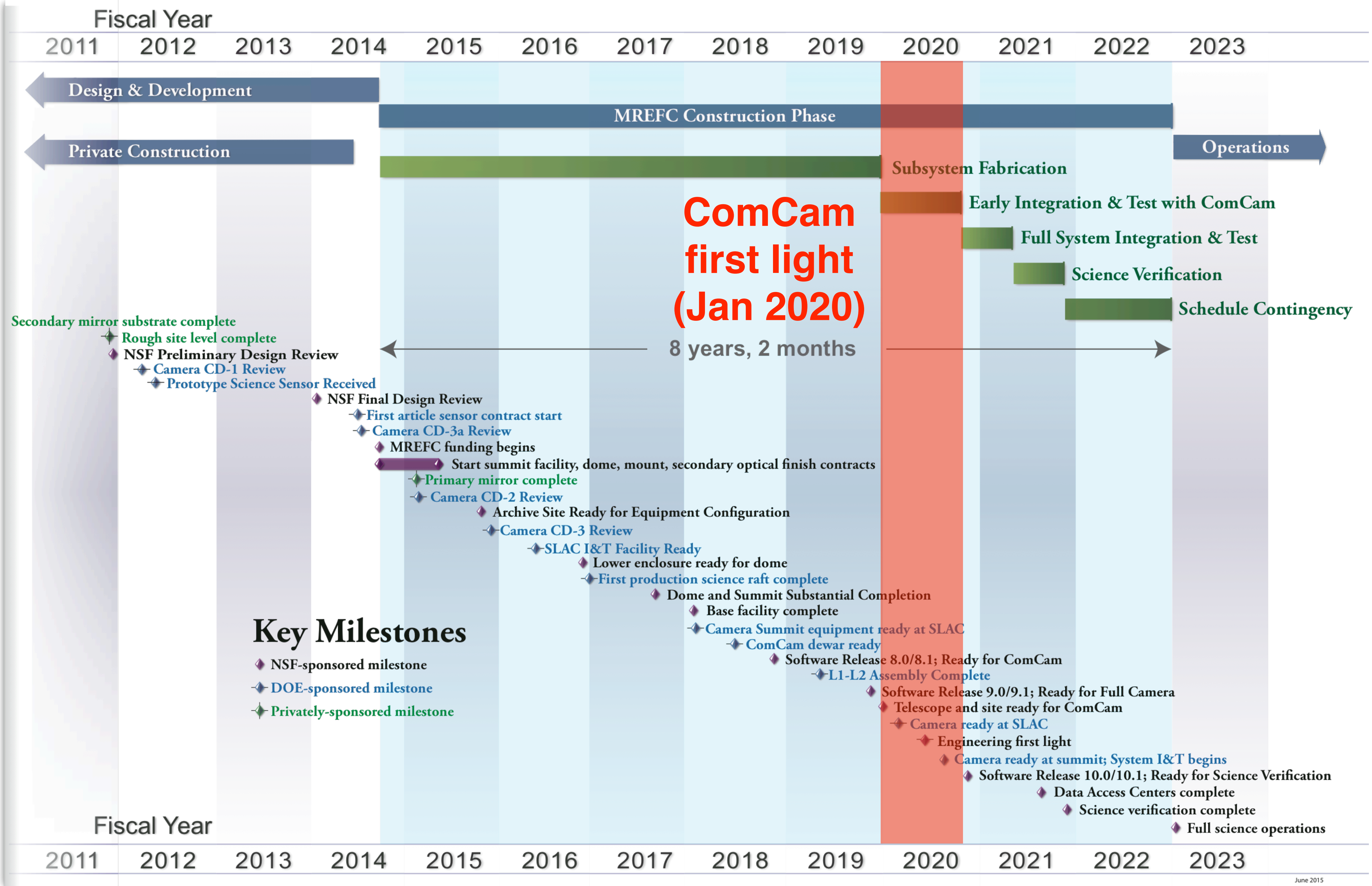
# Bonus Slides

# Confluence of Enabling Technologies



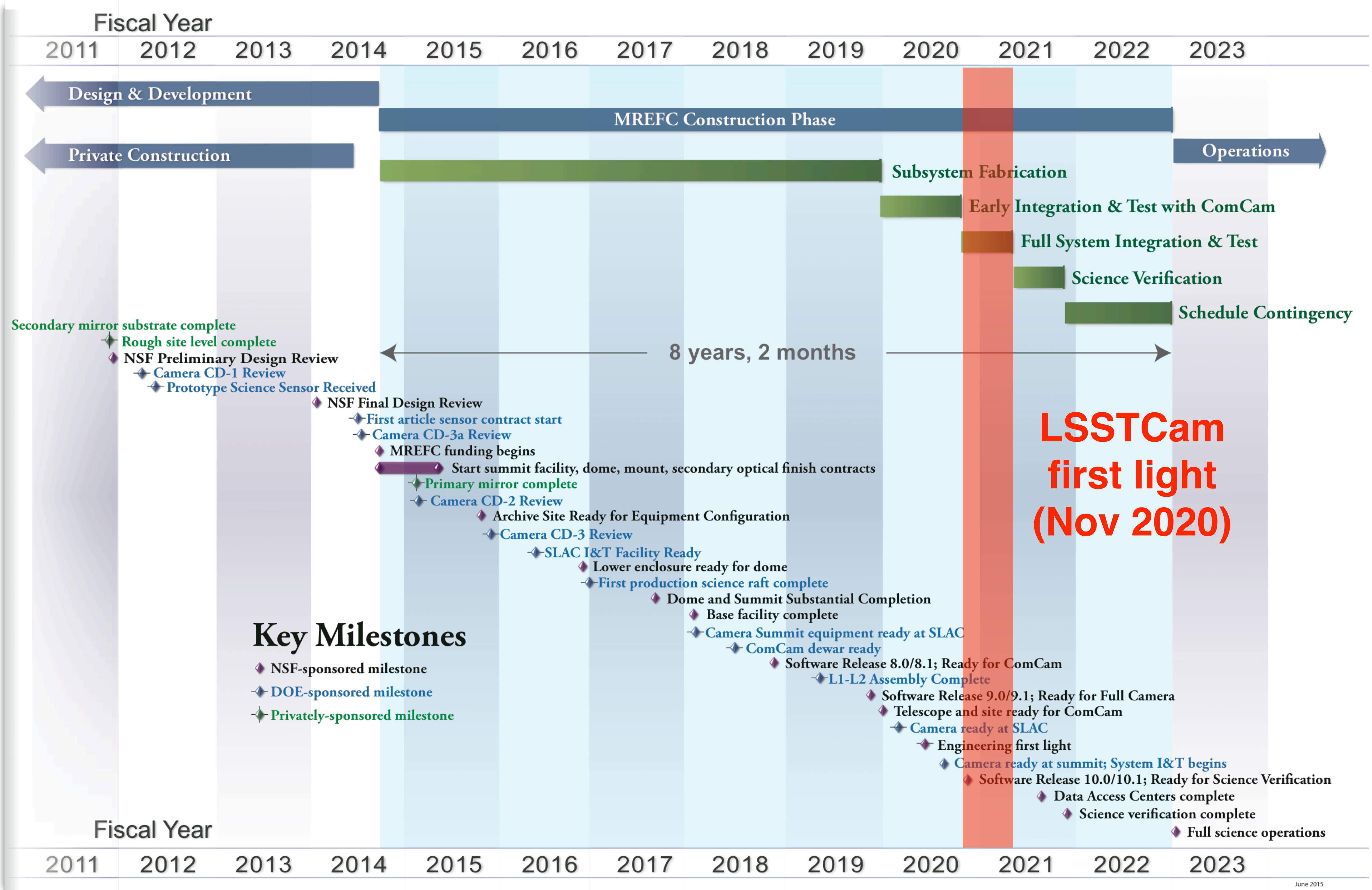

- ✓ 8 m class aspheric mirrors
- ✓ Mosaic of high quantum efficiency CCDs w/ near-IR sensitivity
- ✓ Increasing computational power

# Project Construction Schedule




**The project is on track to achieve first light in 2020, and to formally begin the decade of operations on 1 October 1 2022**

# Project Construction Schedule

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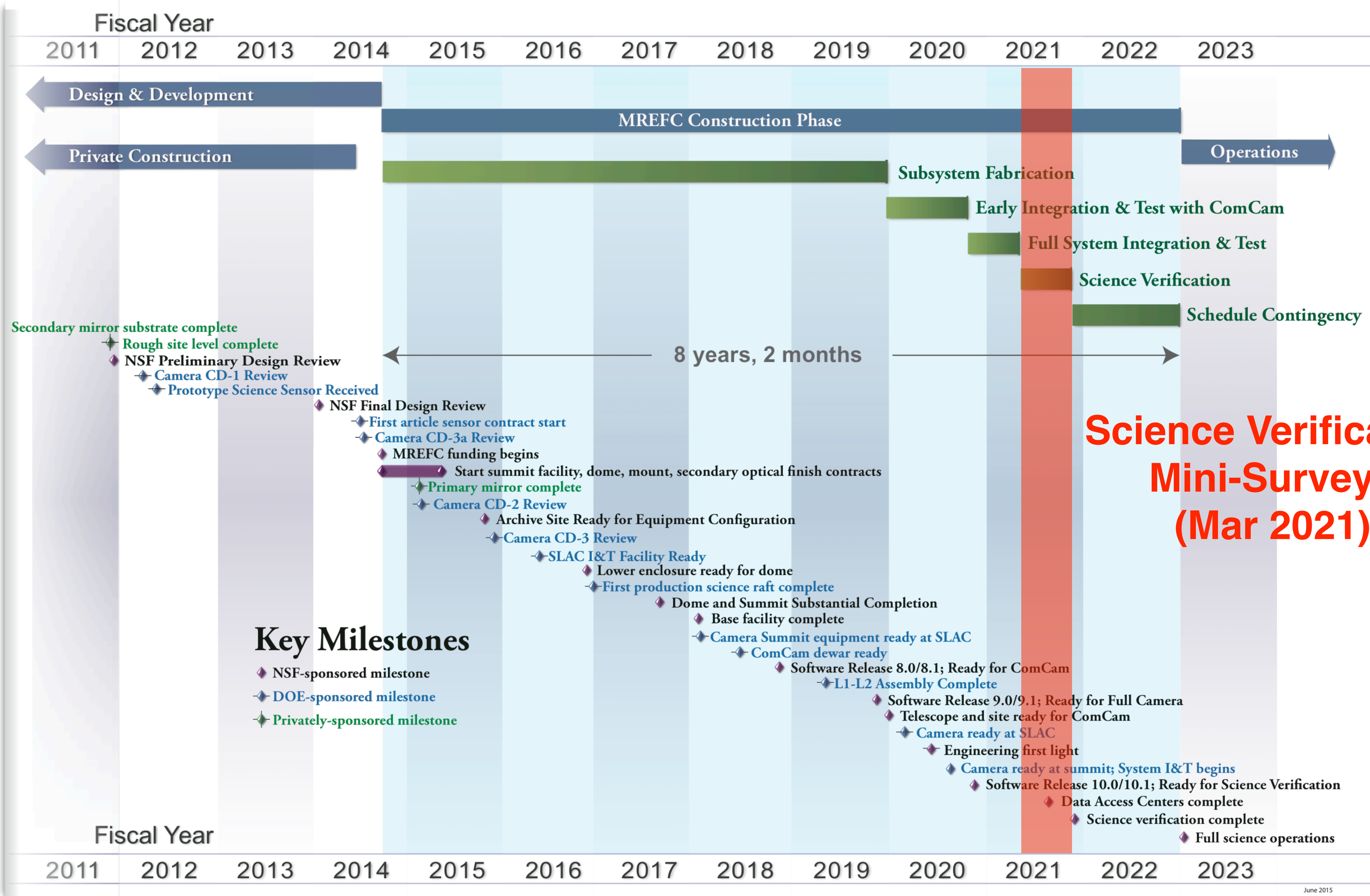
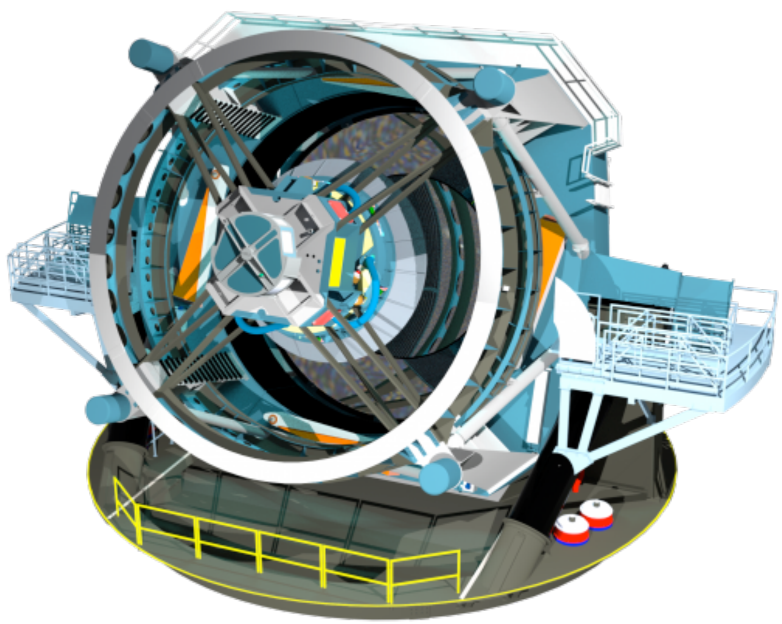



**Science Verification Mini-Surveys (Mar 2021)**

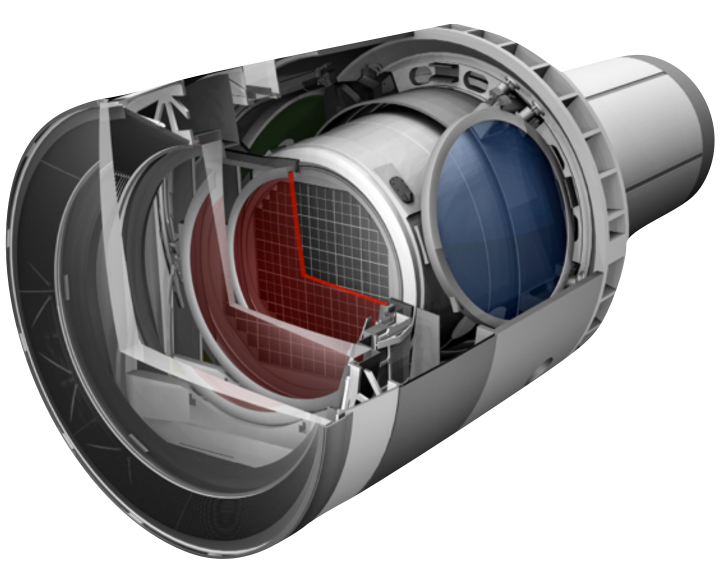
**The project is on track to achieve first light in 2020, and to formally begin the decade of operations on 1 October 1 2022**

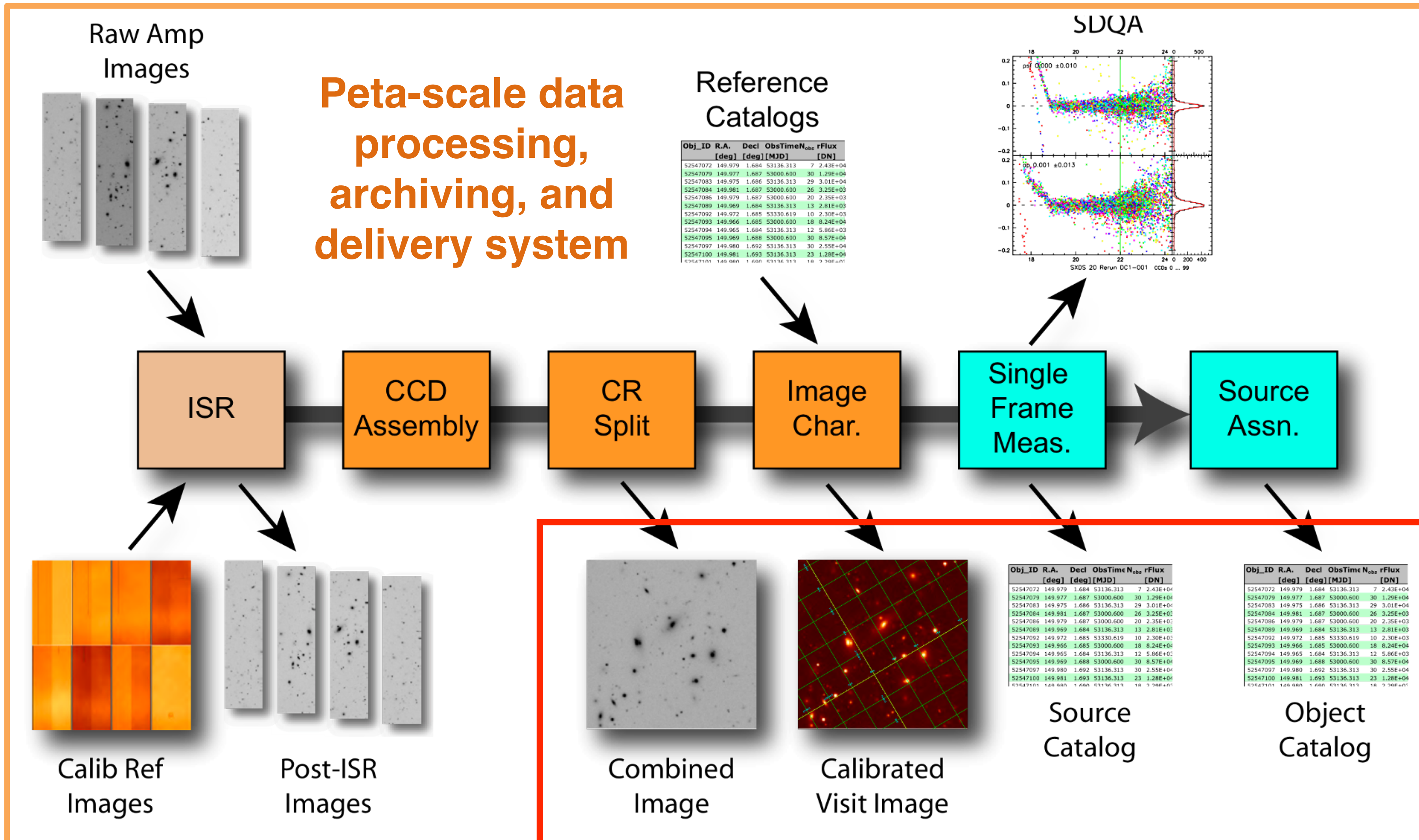
# Overview of the LSST System

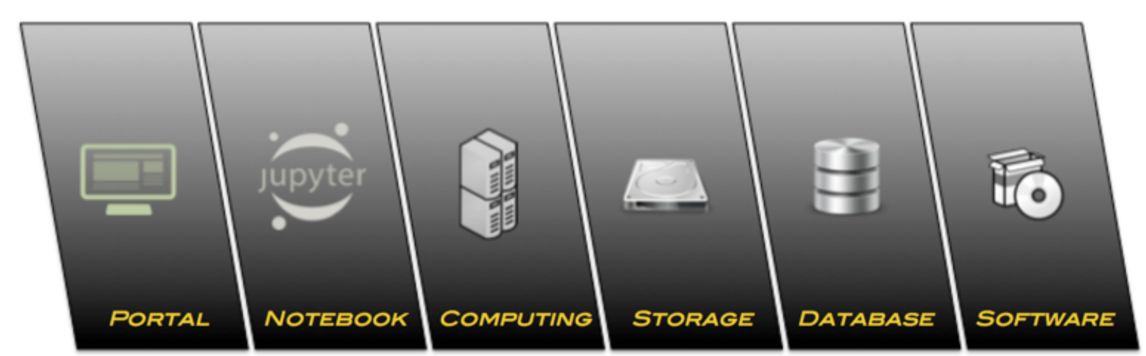
**8.4 m telescope + observatory**



**3.2 Gpix camera**

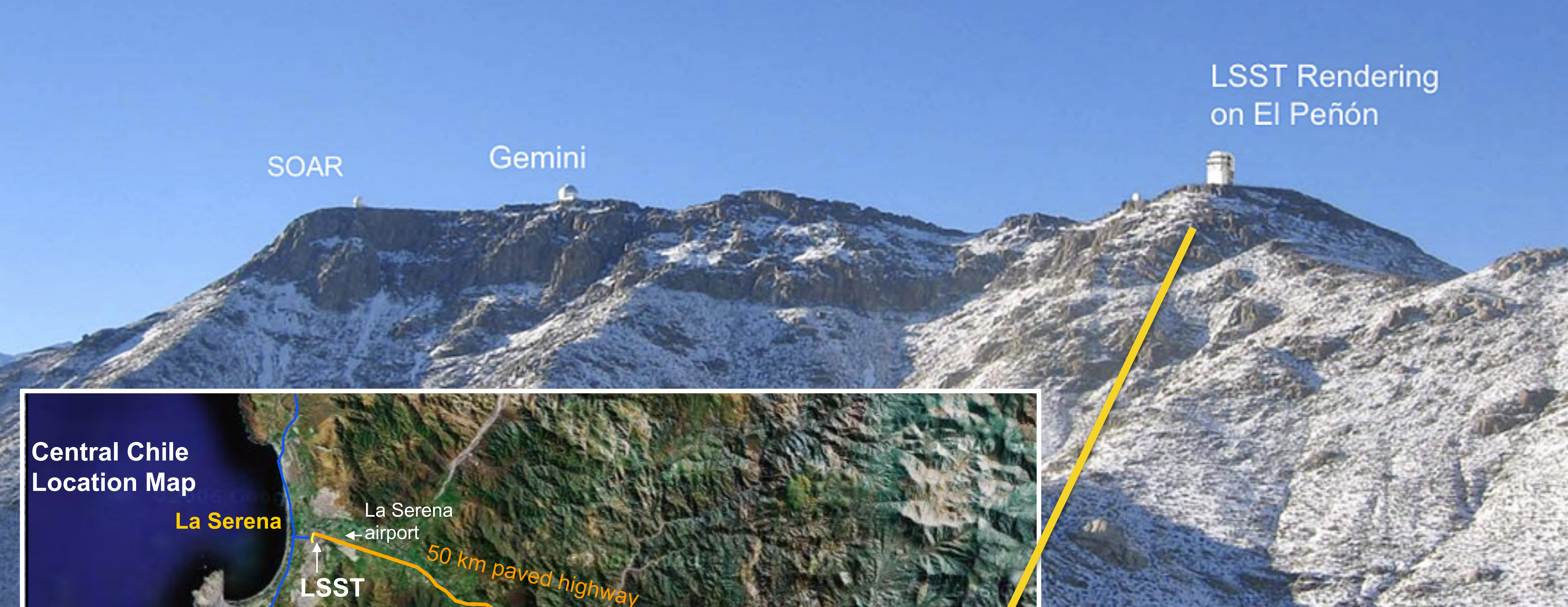





**LSST Science Platform provides community access services**

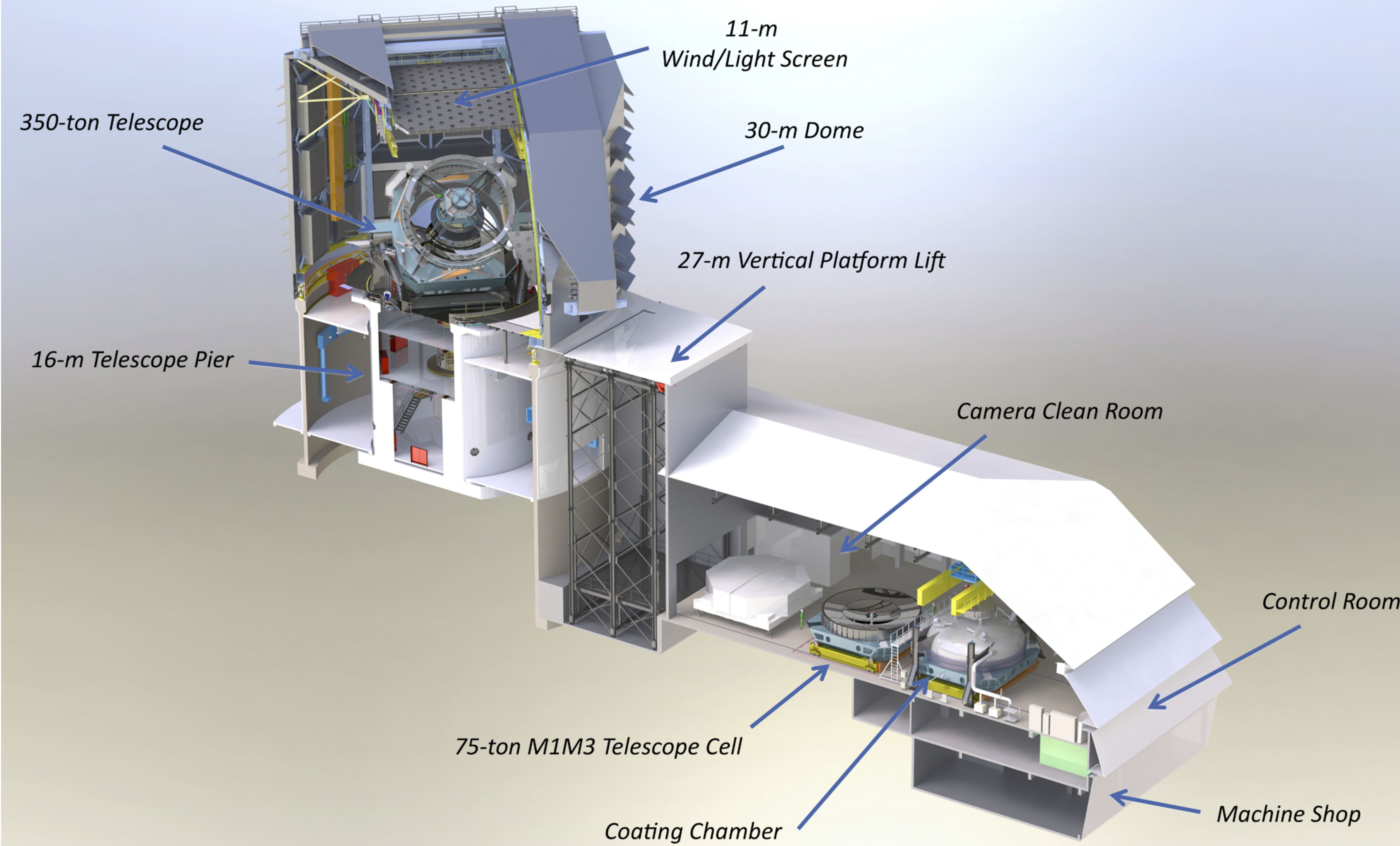
# Cerro Pachón – Future site of the LSST



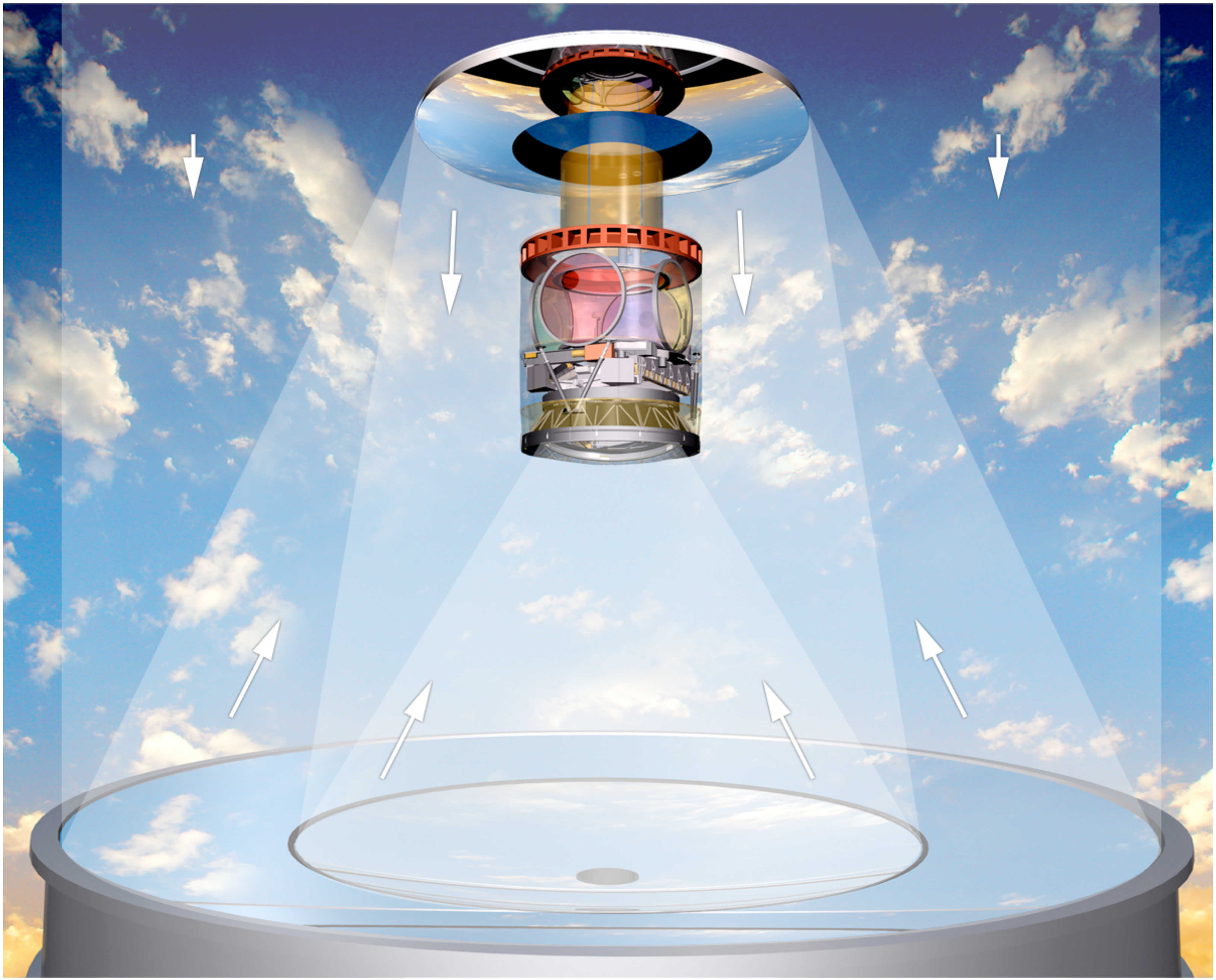


LSST coordinates
(30° 14′ S, 70° 44′ W)
Elevation 2,700 m

La Serena is 400 km
north of Santiago, Chile


11-m
Wind/Light Screen
350-ton Telescope
30-m Dome
27-m Vertical Platform Lift
16-m Telescope Pier
Camera Clean Room
Control Room
75-ton M1M3 Telescope Cell
Coating Chamber
Machine Shop

# Three Mirror Optical System



**Primary mirror**
**8.4 m**

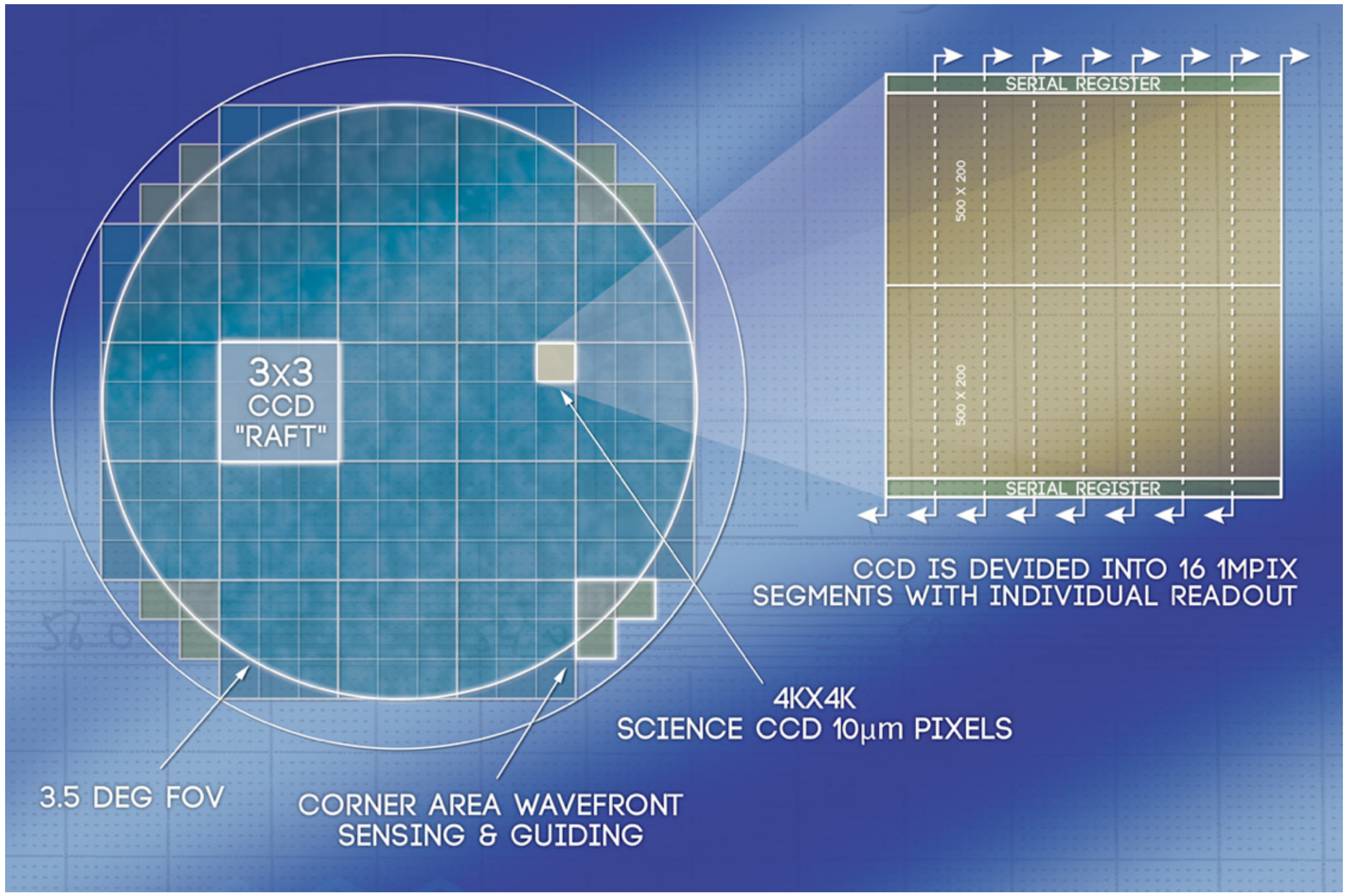
**Effective aperture**
**6.7 m**

**Focal length**
**f/1.23**

**Plate scale**
**50.9 µm/″**

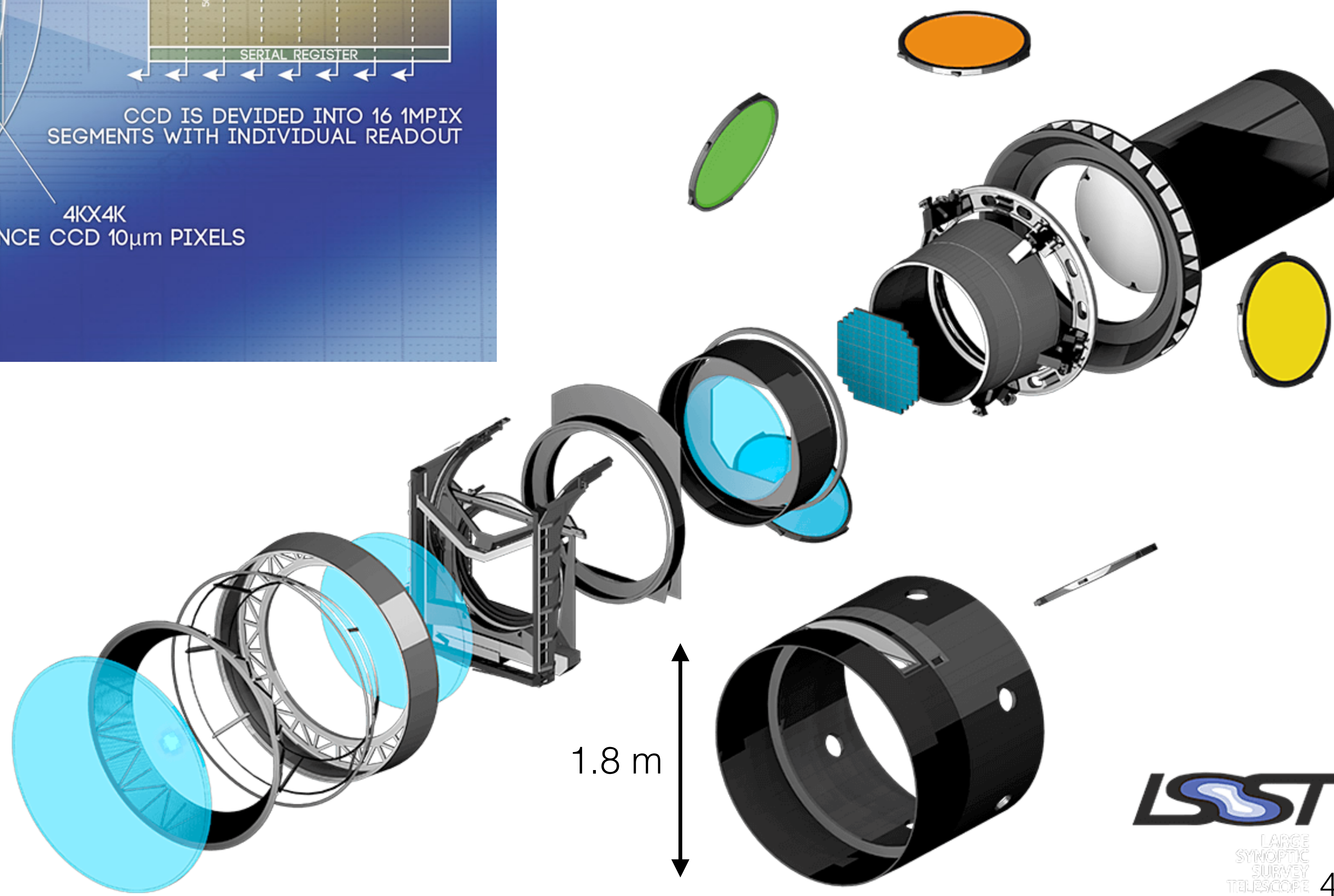
**Etendue**
**319 m² deg²**

# World's Largest Camera for Astronomy




**Total of 189 CCDs in 21 rafts (3 x 3)**
**Each CCD: 4k x 4k pixels (13.3′ x 13.3′)**
**16 readout channels**

**3.2 Gpix**
**0.2″ pixels (10μm)**
**64 cm diameter**
**2 sec readout**



# LSST Key Numbers

**Survey:**

- **Telescope field of view = 9.6 deg$^2$**
- **Main survey area = 18,000 deg$^2$**
- **Filters = *ugrizy* (6)**
- **Visits per night = 1000**
- **Survey Duration = 10 yr**
- **Total visits per pointing = 825**

**Imaging depth:**

- **Single visit (*r*, S/N=5) = 24.7 mag**
- **Stack depth (*r*, S/N=5) = 27.5 mag**

**Expected number of objects:**

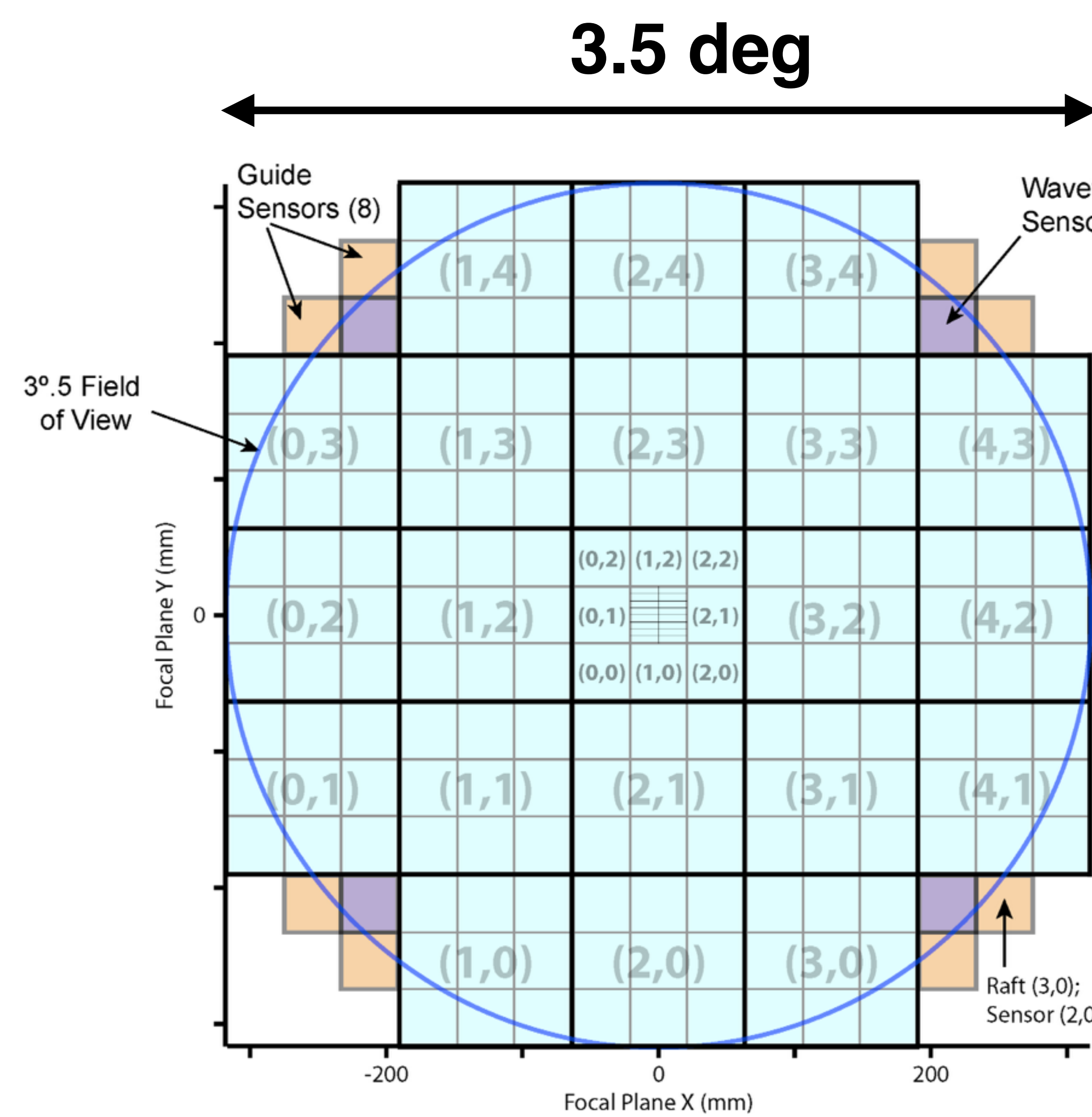
- **Galaxies = 20 billion**
- **Stars = 17 billion**
- **Sources (single-epoch) = 7 trillion**
- **Forced sources = 30 trillion**

**Alert production:**

- **Real-time alert latency = 60 sec**
- **Throughput = 10 million per night**

**Data (Data Release 11):**

- **Data collected per 24 hr = 15 TB**
- **Total image collection = 0.5 EB**
- **Database size = 15 PB**




**Full moon for scale**

*Hubble* has field of view of ~0.003 deg$^2$
(i.e., LSST is >1000 times larger)

# LSST Key Numbers

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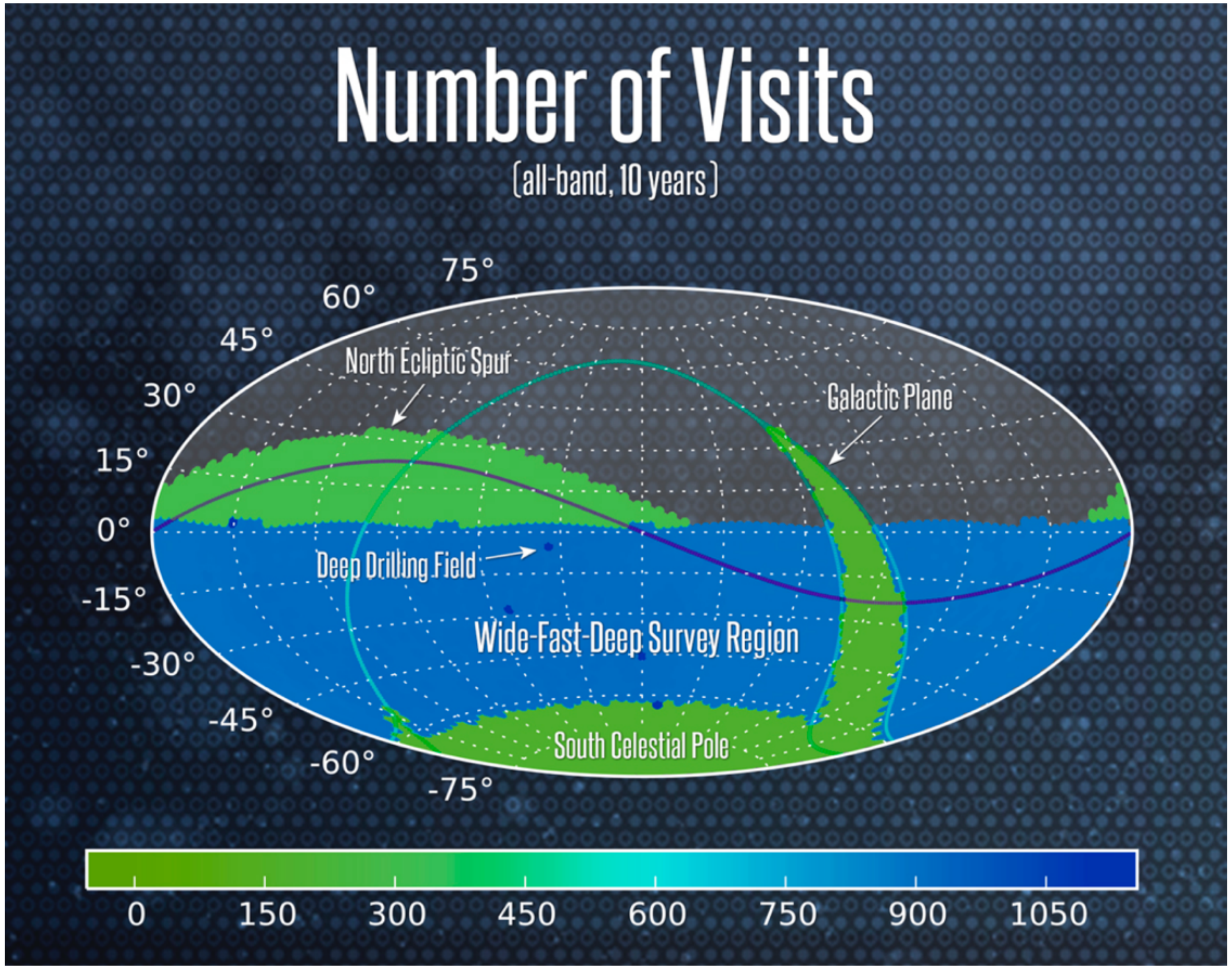
**90% of observing in "Universal Cadence"**
**10% for special projects**




**Coverage over the entire southern hemisphere**

"Visit" = 16 second exposure
+ 2 second readout
+ 16 second exposure

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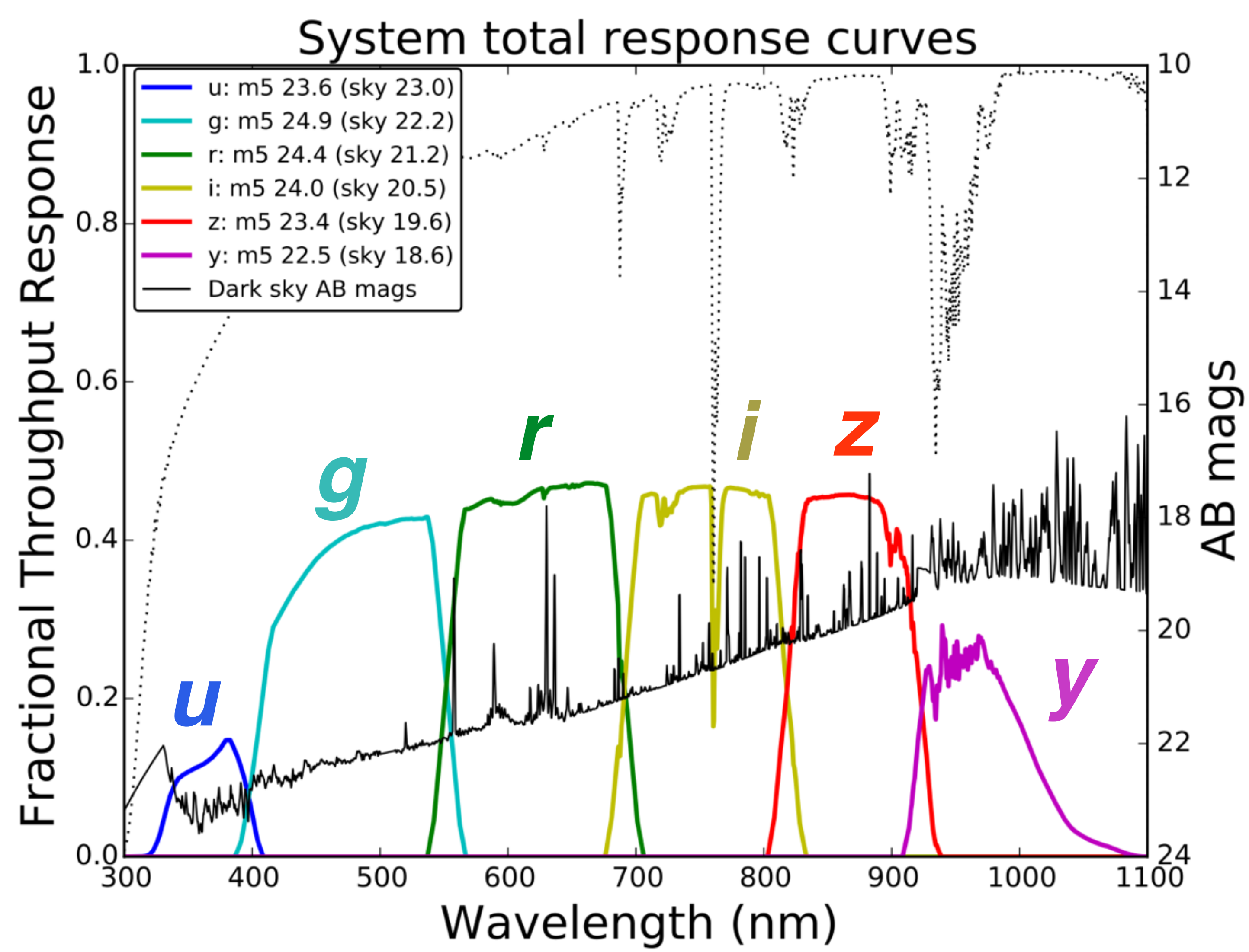


**6 broad-band filters spanning 320-1050 nm near-UV to near-IR**

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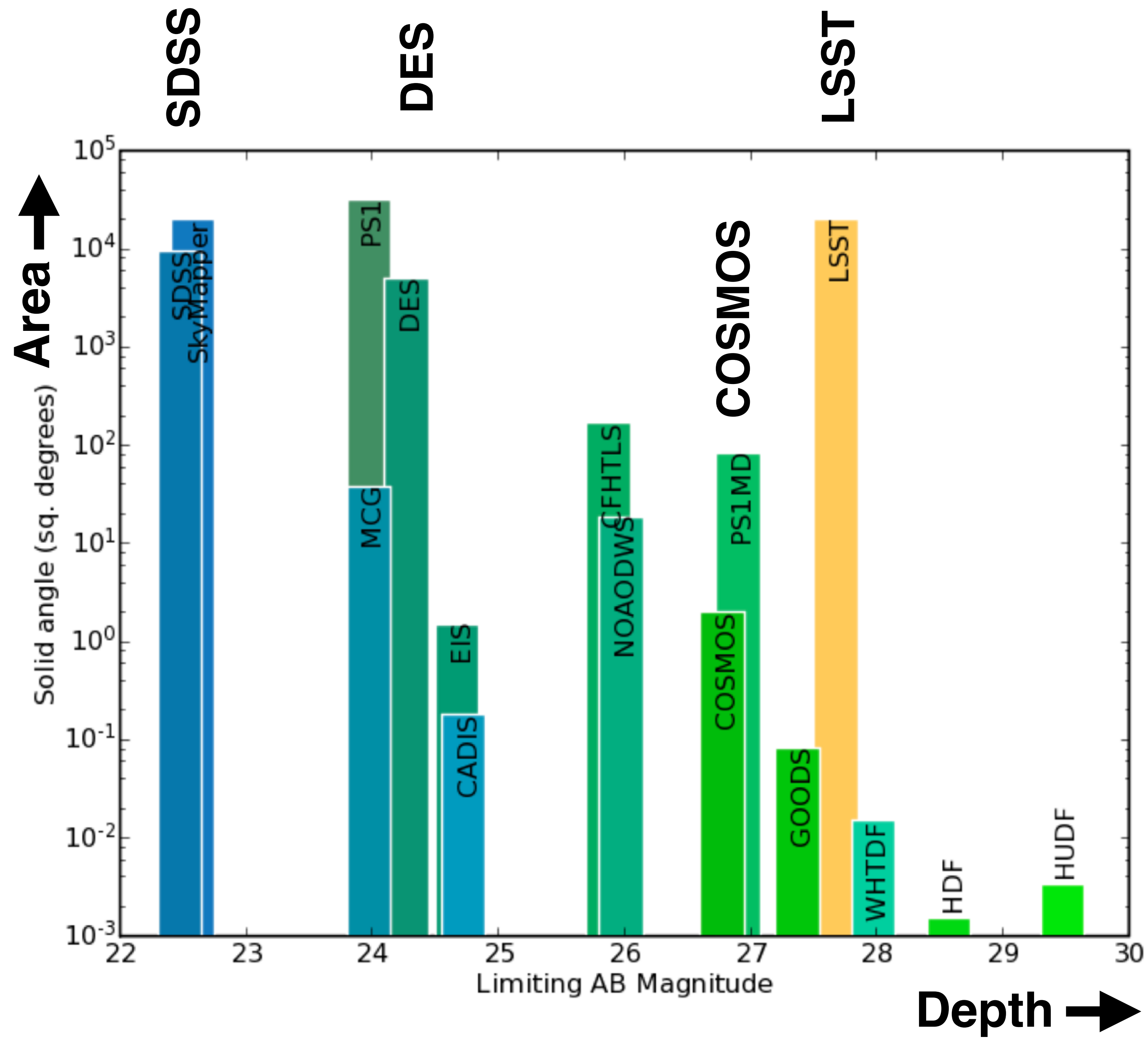


**100x deeper than SDSS**

**>10x deeper than DES**

Comparable depth to *Hubble* COSMOS, but over an area $10^4$ larger (in 6 filters)

# LSST Key Numbers

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**LSST will catalog more stars and galaxies than all previous astronomical surveys combined**

…but perhaps even more important is the anticipated ***quality*** and ***richness*** of the data, as well as ***homogeneous*** processing

# LSST Key Numbers

Survey:
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**"Big Data" aspect of LSST draws upon expertise of computer scientists, statisticians, and high-energy physics community**

# LSST Data Products and Services

**Difference imaging analysis**

- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Nightly (Level 1)

**Direct image analysis**

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion single-epoch detections ("sources"), and ~30 trillion forced sources, produced annually, accessible through online databases. Includes proper motion, size and shape measurements (w/ posteriors), photometric redshift (w/ posteriors), and statistical variability metrics.
- Deep co-added images.

Annual Release (Level 2)

**Co-located data and processing resources**

- Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
- Software and APIs enabling development of analysis codes.

Value Added (Level 3)

Data Products Definition Document: https://docushare.lsstcorp.org/docushare/dsweb/Get/LSE-163/

# A Selection of High-level Science Requirements

| Survey Property | Performance (design value) |
|---|---|
| **Image Depth (single visit)** | 24.7 mag in *r*-band at SNR = 5 |
| **Median Delivered Seeing** | 0.7″ FWHM |
| **Photometry (single visit)** | 0.5% repeatability, 1% relative, 1% absolute, 0.5% color |
| **Astrometry (single visit)** | 10 mas relative, 50 mas absolute |
| **Proper Motion** | 0.2 mas yr |
| **Residual PSF Ellipticity Power** | 2 x 10 |
| **Transient Detection** | 95% purity at 90% detection efficiency for SNR > 6 |

Note that many of the requirements are specified in terms of a *distribution* (e.g., median and outlier fraction)

“mas” = milliarcsecond

# Comparing Wide-field Optical Survey Cameras

Comparison of Existing and Planned Wide-field Optical Survey Cameras

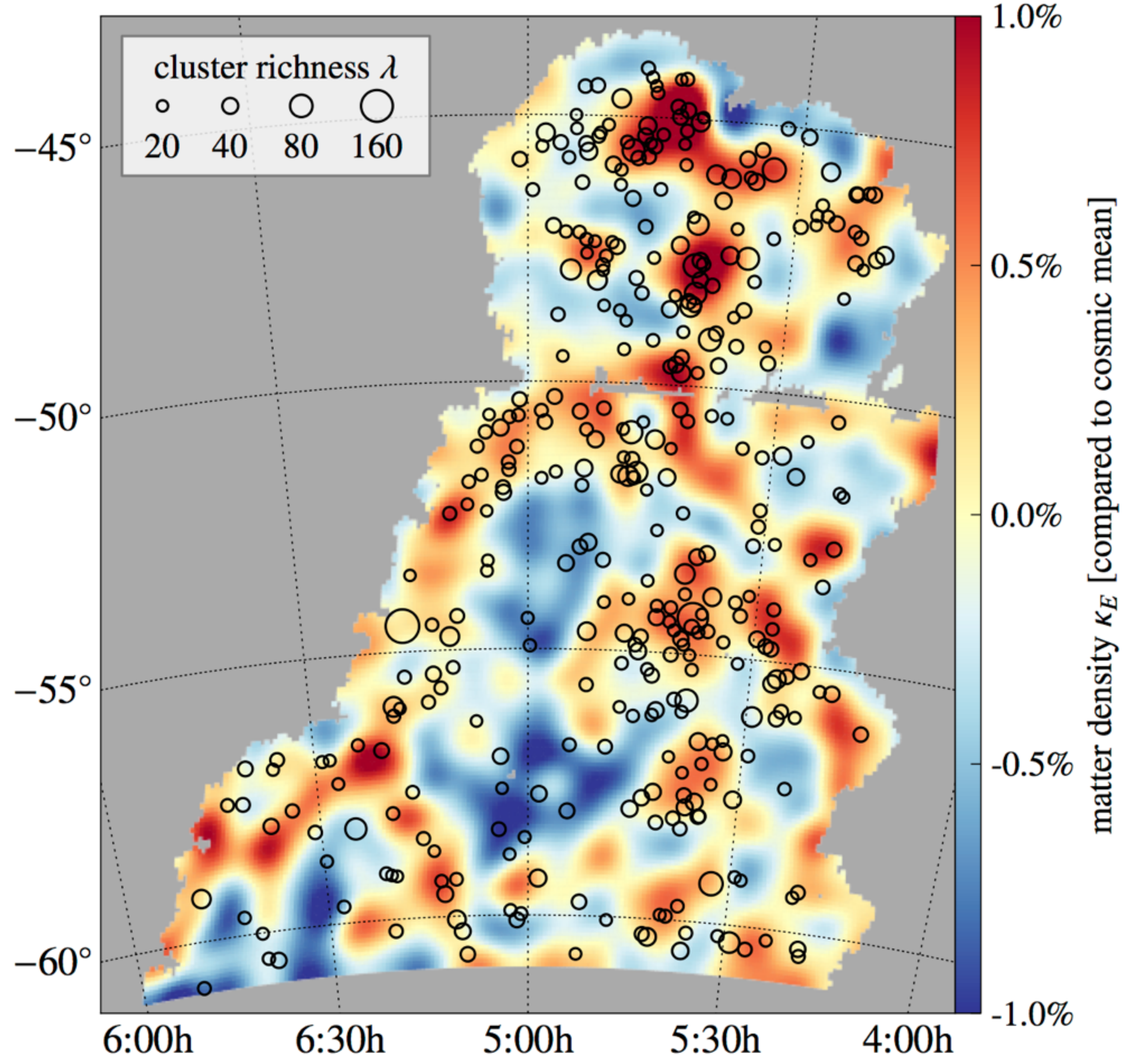
| Survey Camera | $D$ (m) | $\Omega_{fov}$ (deg$^2$) | Etendue (m$^2$ deg$^2$) | Pixels ($''$) | $t_{exp}$ (s) | $t_{OH}$ (s) | $m_{lim}$ | $\dot{\Omega}$ (deg$^2$ hr$^{-1}$) | $N_{obs}$ (yr$^{-1}$) | $\dot{V}_{-19}$ (Mpc$^3$ s$^{-1}$) | $f_{spec}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Evryscope | 0.06(27×) | 8660 | 26.5 | 13.3 | 120 | 4 | 16.4 | 251419 | 19279 | $1.1 \times 10^4$ | 1.00 |
| ASAS-SN 1 | 0.14(4×) | 73 | 1.1 | 7.8 | 180 | 23 | 17 | 1294 | 99 | $1.2 \times 10^2$ | 1.00 |
| ATLAS | 0.5(2×) | 60 | 11.8 | 1.9 | 30 | 8 | 20.0 | 5684 | 435 | $2.3 \times 10^4$ | 1.00 |
| CRTS | 0.7 | 8.0 | 3.1 | 2.5 | 30 | 18 | 19.5 | 600 | 46 | $1.4 \times 10^3$ | 1.00 |
| CRTS-2 | 0.7 | 19.0 | 7.3 | 1.5 | 30 | 12 | 19.5 | 1628 | 124 | $3.7 \times 10^3$ | 1.00 |
| LSQ | 1.0 | 8.7 | 6.8 | 0.9 | 60 | 40 | 20.5 | 313 | 24 | $2.3 \times 10^3$ | 1.00 |
| PTF | 1.2 | 7.3 | 8.2 | 1.0 | 60 | 46 | 20.7 | 246 | 18 | $2.3 \times 10^3$ | 1.00 |
| Skymapper | 1.3 | 5.7 | 7.5 | 0.5 | 110 | 20 | 21.6 | 157 | 12 | $3.9 \times 10^3$ | 0.52 |
| PS1 $3\pi$ | 1.8 | 7.0 | 17.8 | 0.3 | 30 | 10 | 21.8 | 630 | 48 | $1.9 \times 10^4$ | 0.42 |
| *SST* | 2.9 | 6.0 | 39.6 | 0.9 | 1 | 6 | 20.7 | 3085 | 236 | $2.7 \times 10^4$ | 1.00 |
| MegaCam | 3.6 | 1.0 | 10.2 | 0.2 | 300 | 40 | 22.8 | 10 | 0.8 | $8.8 \times 10^2$ | 0.16 |
| DECam | 4.0 | 3.0 | 37.7 | 0.3 | 50 | 20 | 23.7 | 154 | 11 | $2.9 \times 10^4$ | 0.07 |
| HSC | 8.2 | 1.7 | 89.8 | 0.2 | 60 | 20 | 24.6 | 76 | 5 | $3.1 \times 10^4$ | 0.03 |
| BlackGEM* | 0.6(4×) | 2(4×) | 11.3 | 0.6 | 30 | 5 | 20.7 | 822 | 63 | $7.6 \times 10^3$ | 1.00 |
| ZTF* | 1.2 | 47 | 53.1 | 1.0 | 30 | 15 | 20.4 | 3760 | 288 | $2.5 \times 10^4$ | 1.00 |
| LSST* | 6.7 | 9.6 | 319.5 | 0.2 | 30 | 11 | 24.7 | 842 | 64 | $3.7 \times 10^5$ | 0.03 |

Bellm 2016
arXiv:1605.02081

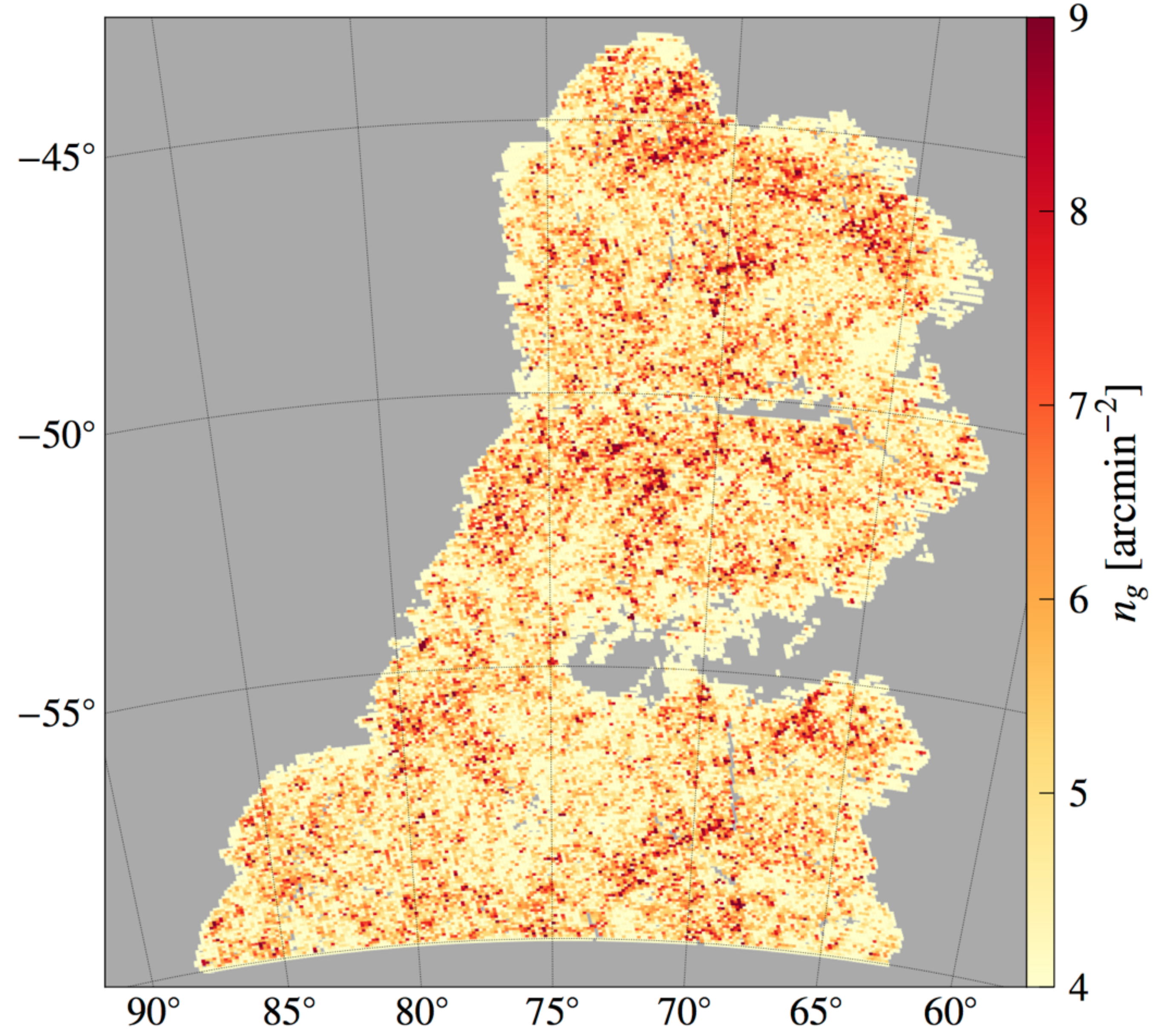
# Cross-correlating Large Scale Structure w/ Extragalactic Gamma-ray Background

Example from DES Science Verification data
140 deg$^2$

**Weak Lensing Mass Map**
(w/ galaxy cluster positions overlaid)



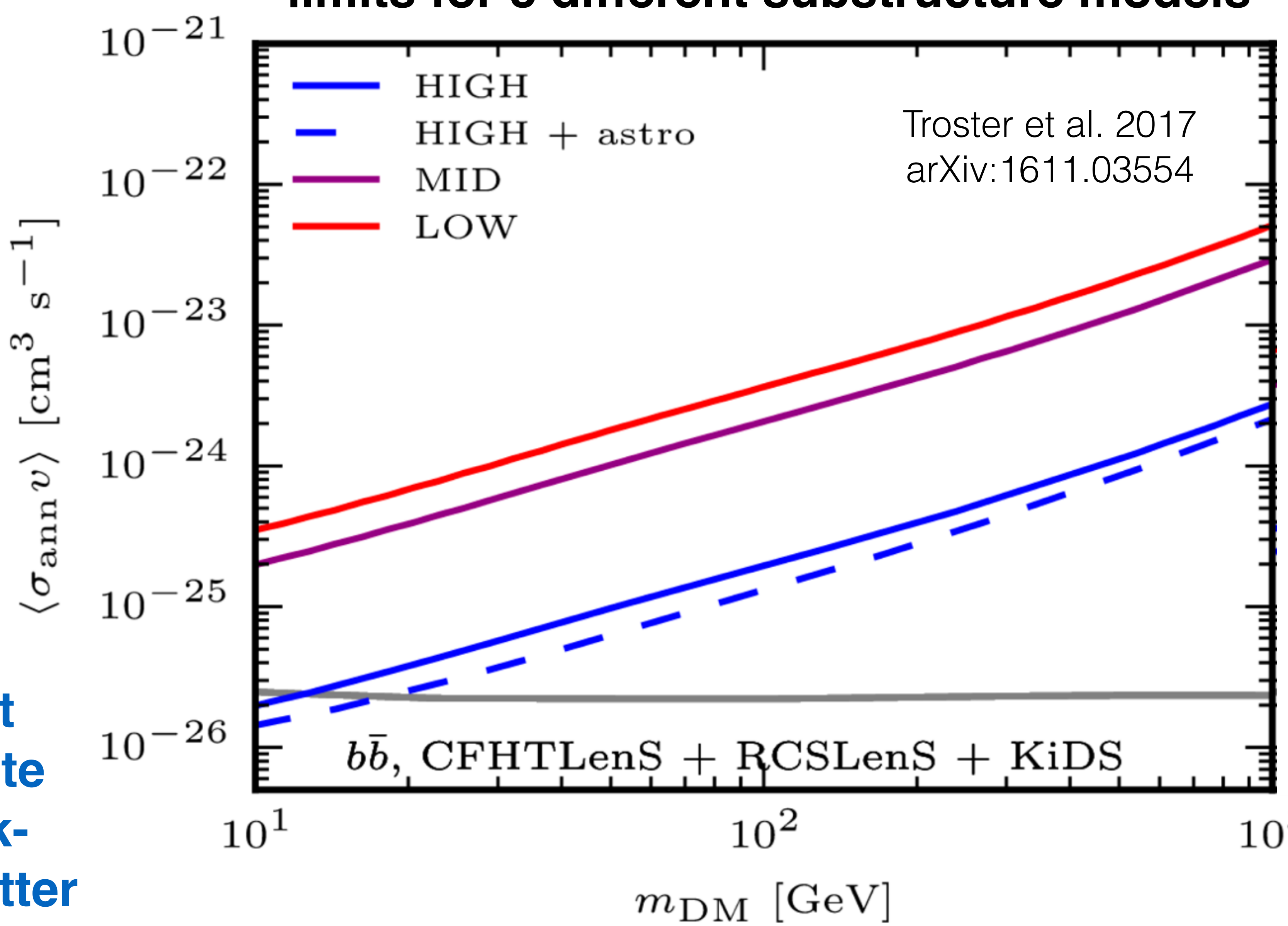

**Galaxy Density Map**



# Cross-correlating Large Scale Structure w/ Extragalactic Gamma-ray Background

Combined analysis of lensing mass maps from CFHTLenS, RCSLenS, KiDS
(total ~1000 deg$^2$, compared to LSST ~ 18000 deg$^2$)

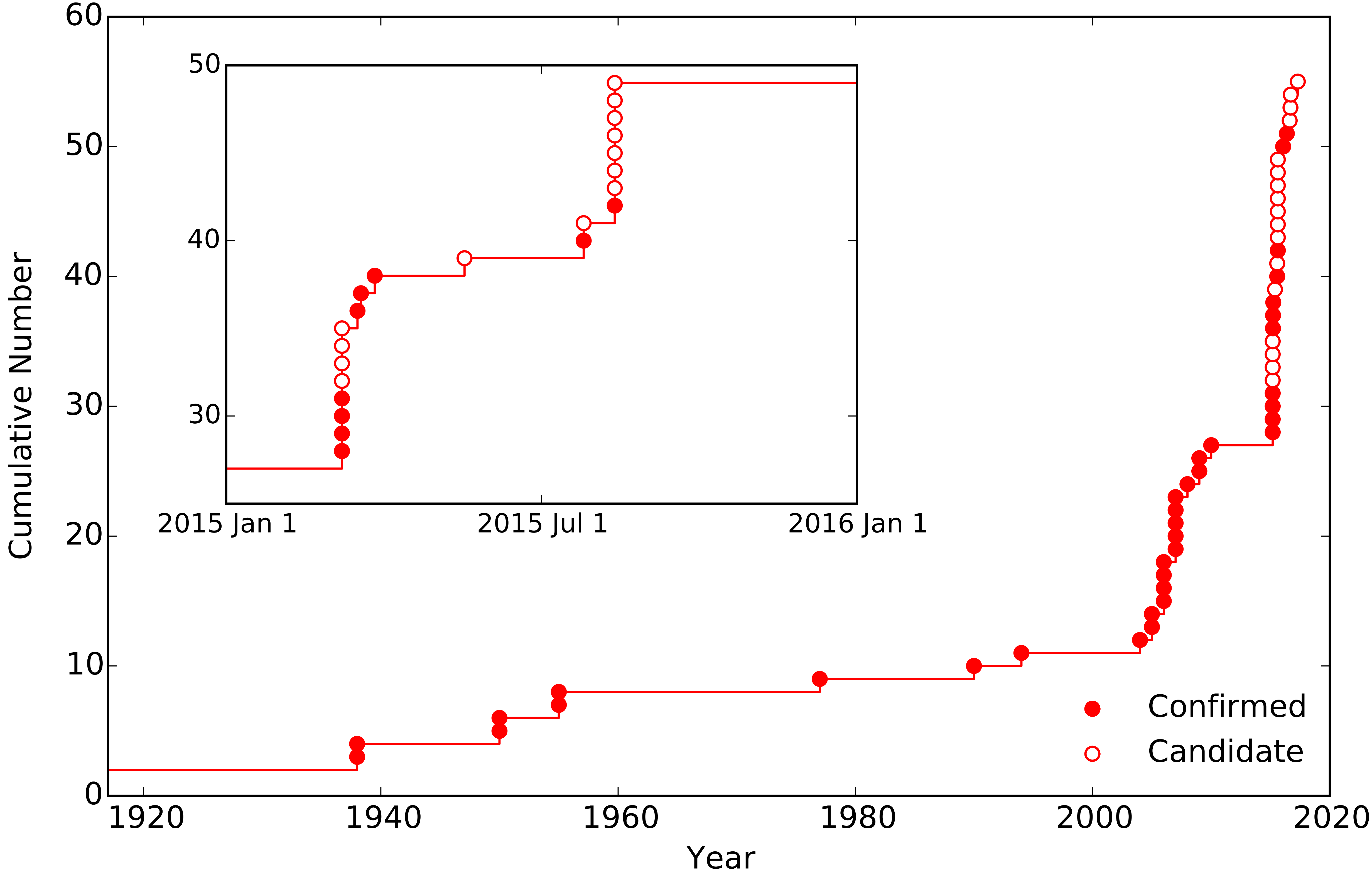
**DM annihilation cross section upper limits for 3 different substructure models**



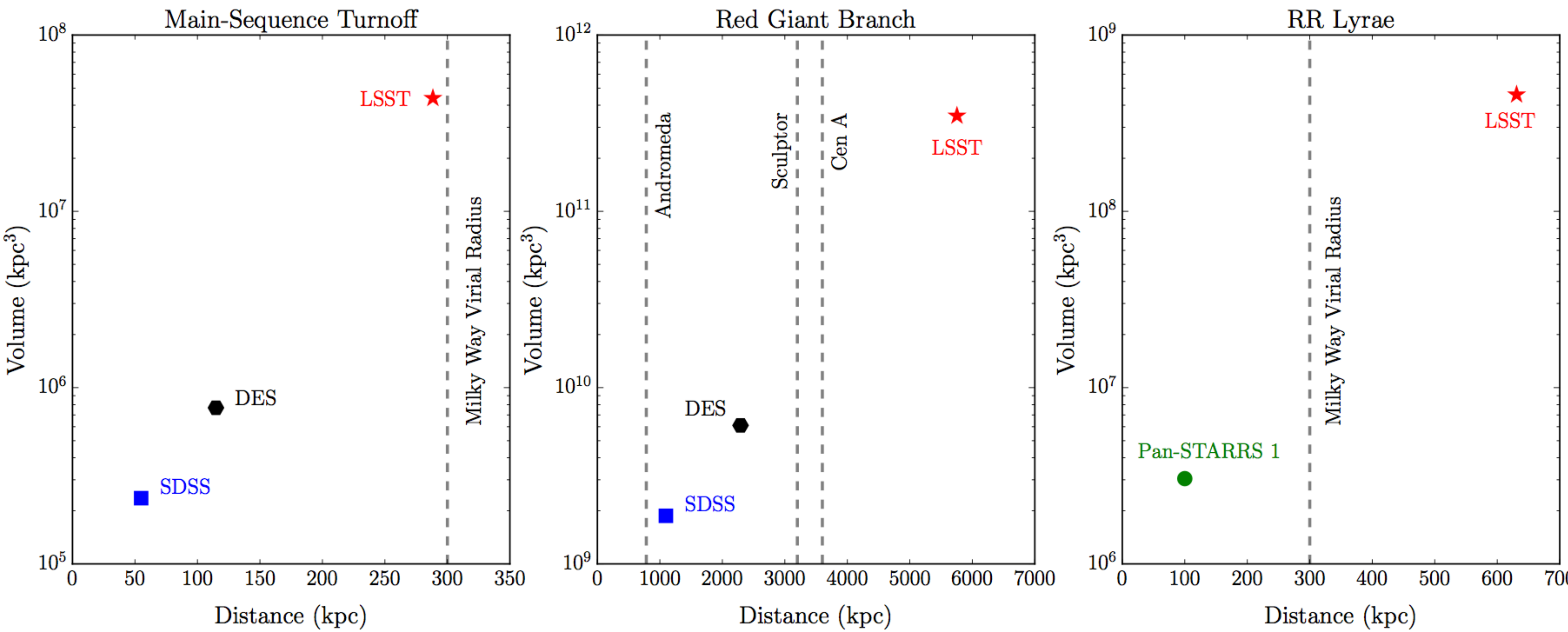

See also, e.g.,
Cuoco et al. 2015
arXiv:1506.01030
for cross-correlation against galaxy catalogs

**The most sensitive and robust analysis would likely incorporate both galaxy catalogs and weak-lensing to constrain the dark matter halos hosting the target galaxies**

# Milky Way Satellite Galaxy Discovery Timeline



# Extending Search Throughout the Milky Way Halo and Beyond

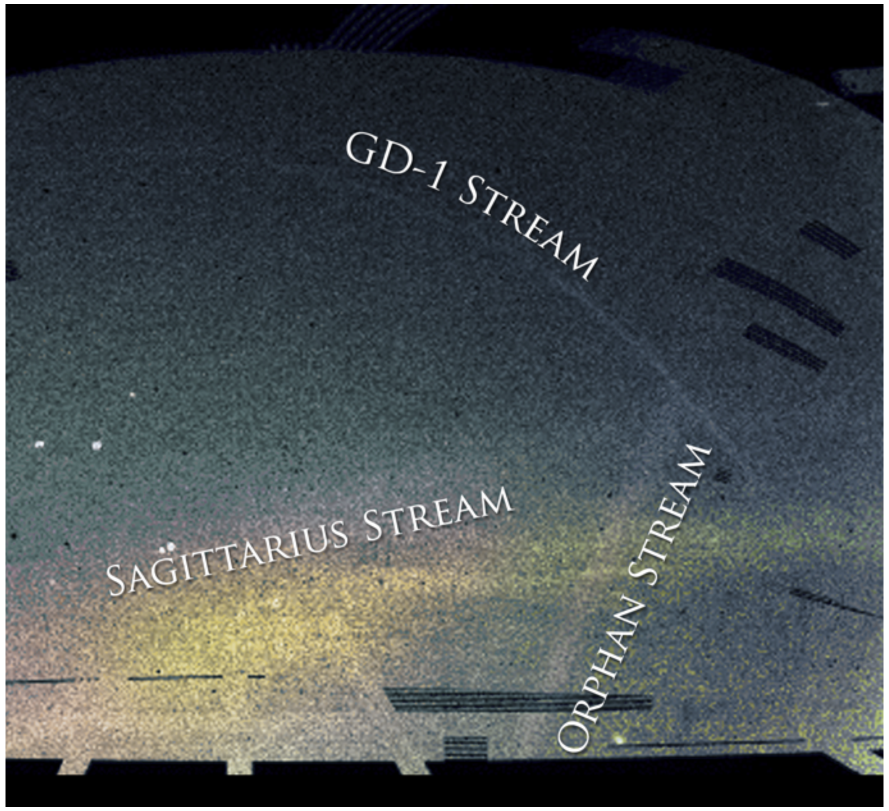



## Consider multiple observational handles

- Colors ➔ star/galaxy separation, distinct stellar populations
- Variability ➔ variable stars as three-dimensional tracers of halo substructures
- Proper motion ➔ star/galaxy separation, foreground stars, constrain Milky Way potential
- Diffuse light ➔ dwarf galaxies in the field

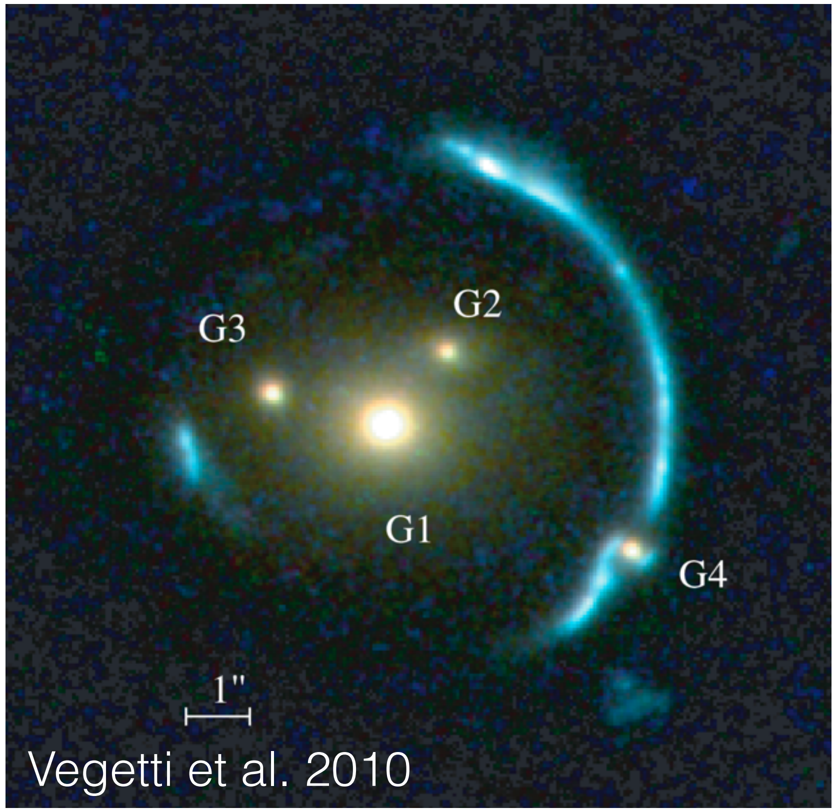
# Identifying Dark Subhalos

## Stellar Stream Gaps



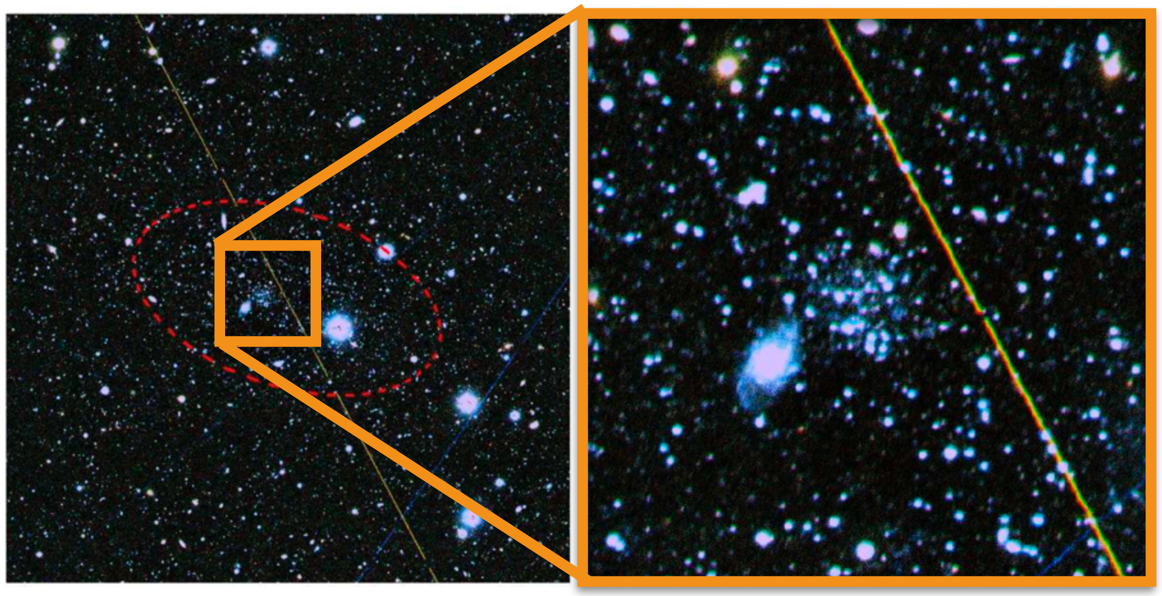

- Dark satellites perturb stellar stream
- Statistical detection of low-mass subhalos around the Milky Way
- Active theoretical work on interpretation

## Strong Gravitational Lensing




- Subhalos detected as spatial, temporal, or flux ratio anomalies in lensed images
- Ability to detect dark subhalos around lens galaxies at cosmological redshifts
- LSST will detect ~$10^4$ galaxy-galaxy lenses and ~$10^3$ lensed quasar systems

# Being ready for surprises…
# MACHO Dark Matter constraints



The dwarf galaxy Eridanus II (discovered w/ DES) has it's own small star cluster.

Crnojevic et al. 2016
arXiv:1604.08590

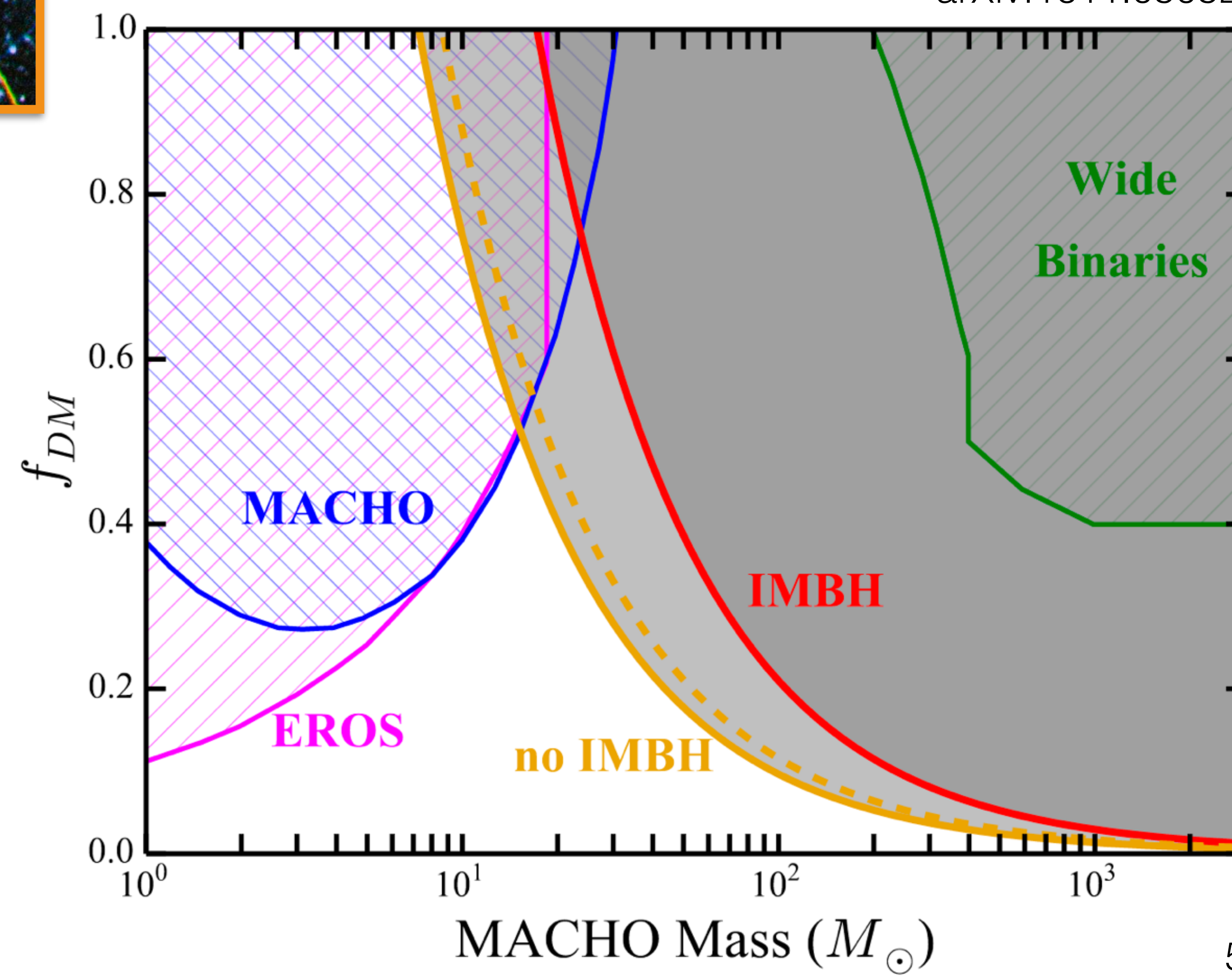
With follow-up spectroscopy, we infer a large mass-to-light ratio in the central regions of Eridanus II

$$M\,/\,L_V = 420^{+210}_{-140}\ \mathrm{M_{sol}}\,/\,\mathrm{L_{sol}}$$

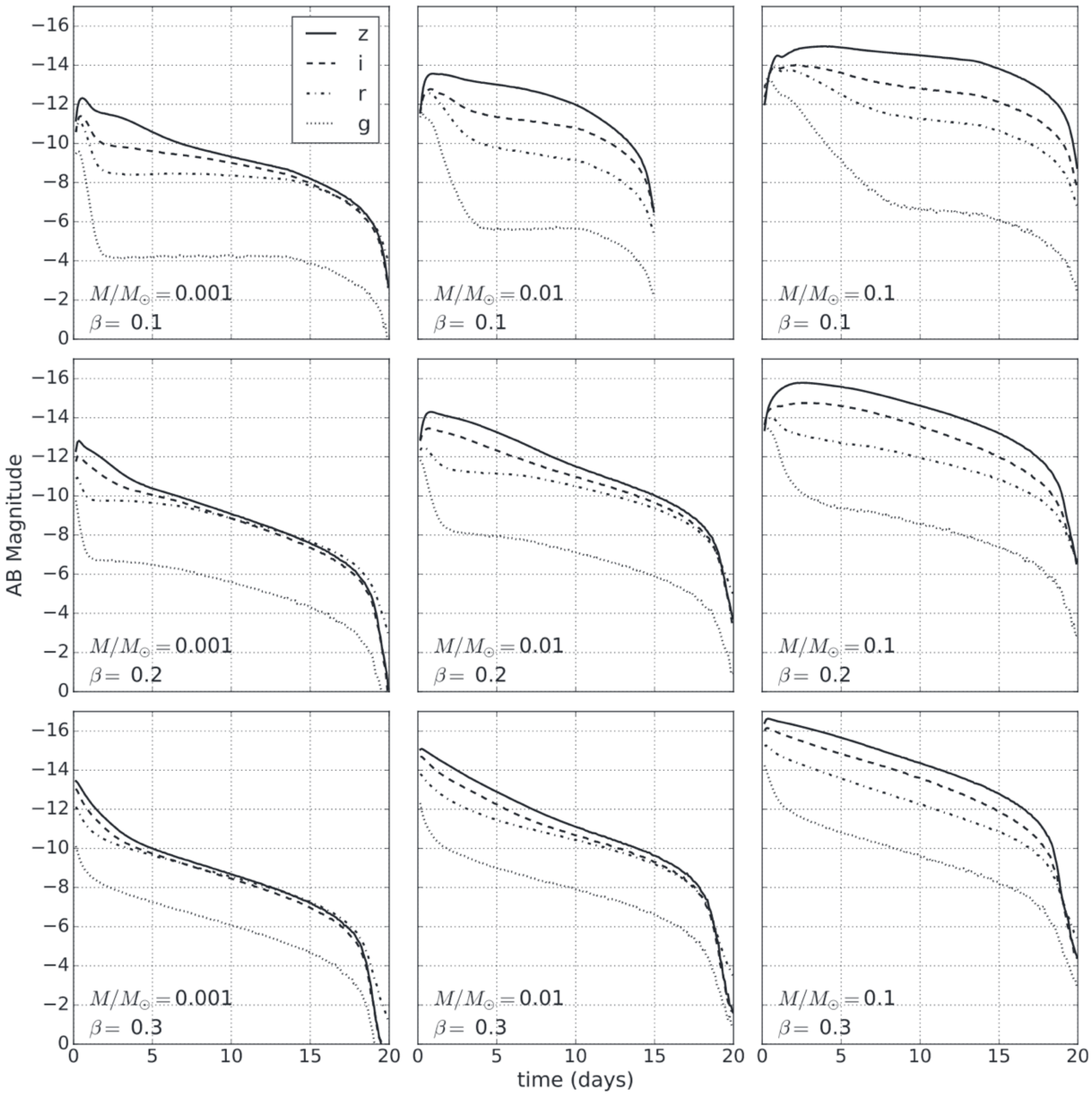
(i.e., large dark matter density)

**We can use the survival of this star cluster to place upper limits on the mass of individual dark matter particles.** High-mass dark matter particles would disrupt the cluster.

Li et al. 2016
arXiv:1611.05052



# Theoretical Kilonova Lightcurves



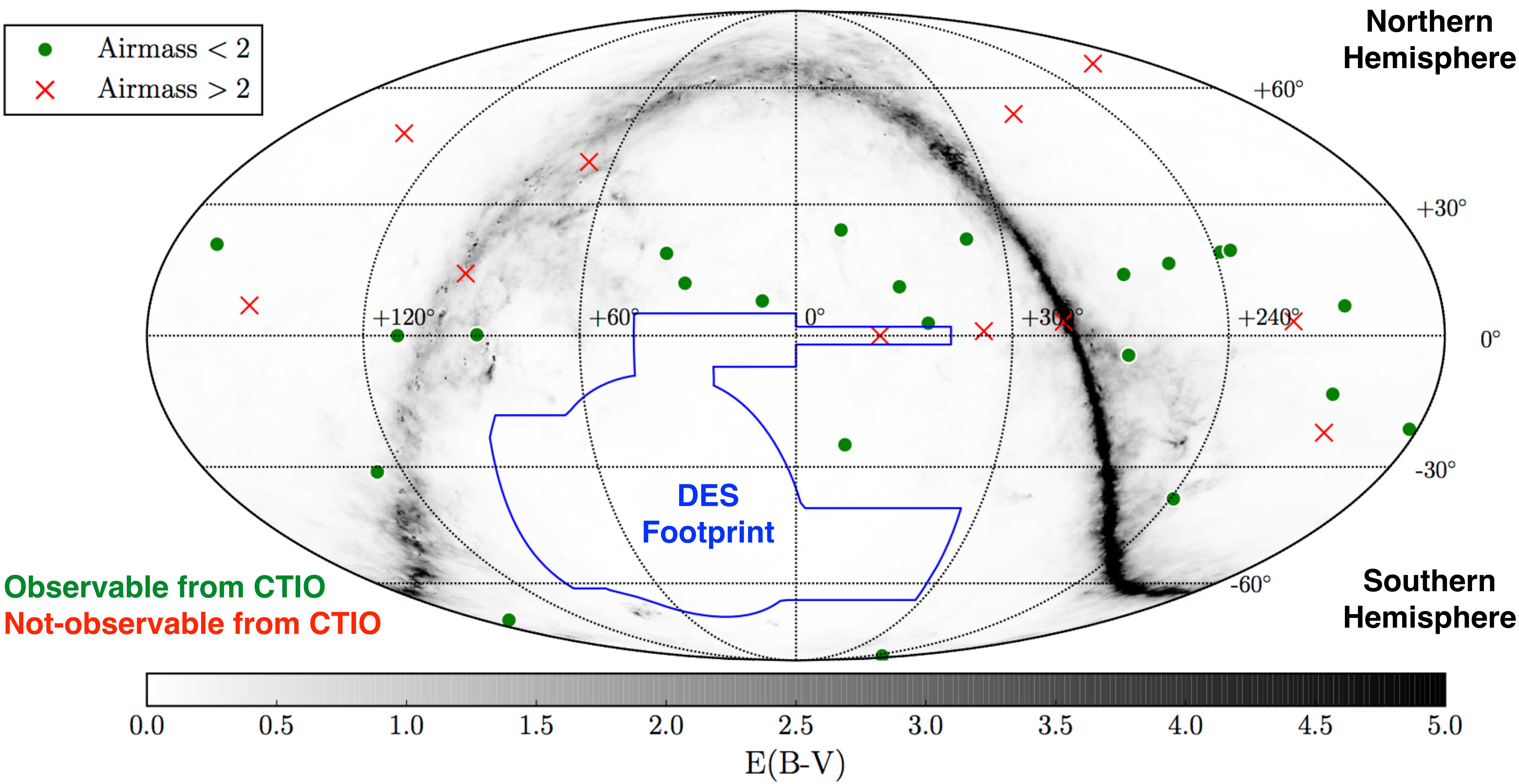

Typical distance of 200 Mpc
(m - M = 36.5)

Doctor et al. 2017
arXiv:1611.08052

Barnes & Kasen 2013 model set

# Optical Follow-up of IceCube Tracks: Access to the Southern Hemisphere

**Selection of IceCube High-Energy Track Events**




**Observable from CTIO**

**Not-observable from CTIO**

**Dark Energy Camera (DECam) and LSST situated on neighboring peaks in Chile at latitude = -30 deg south**

# Searching for Explosive Optical Transients Associated w/ IceCube Events

$$\frac{dN_\nu(E_\nu)}{dE_\nu d\Omega dt_{\rm obs} dA} = \int_0^{z_{\rm max}} \frac{dV}{dz d\Omega} \frac{1}{4\pi D_L^2} \frac{dN_\nu(E_\nu(1+z))}{dE_\nu} \frac{1}{1+z} \mathcal{R}(z) dz$$