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Charting New Physics Territory with Time-Domain Optical Astronomy

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Stockholm University

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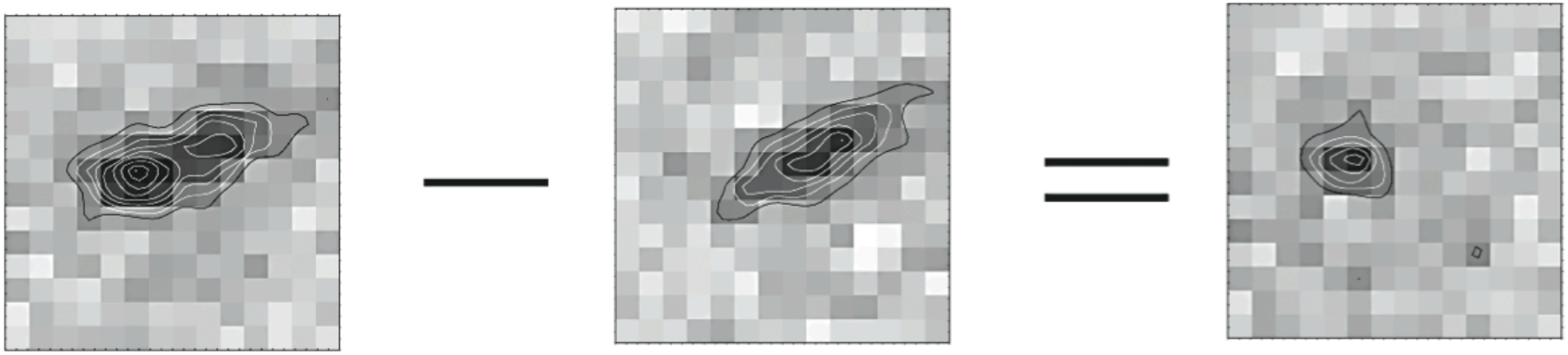
What's new?

- technological advances!

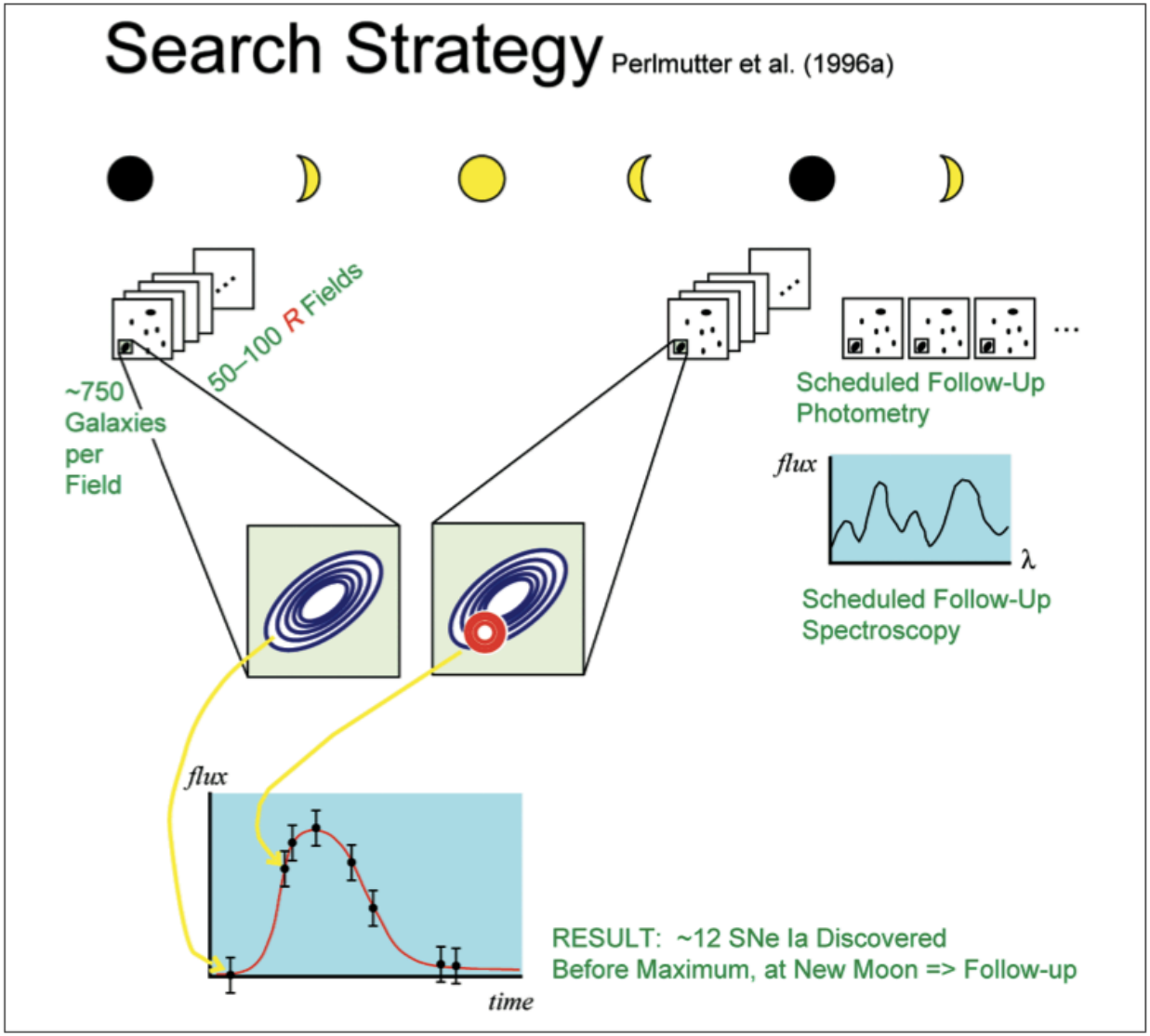
- Very large field of view: nightly monitoring of nearly the whole sky.
- Study transients with shorter time-scales than ever before, down to seconds.
- Potential to discover very rare
  - and possibly yet unknown phenomena.
- Implications for astrophysics, cosmology and fundamental physics.

Transient astronomy 101



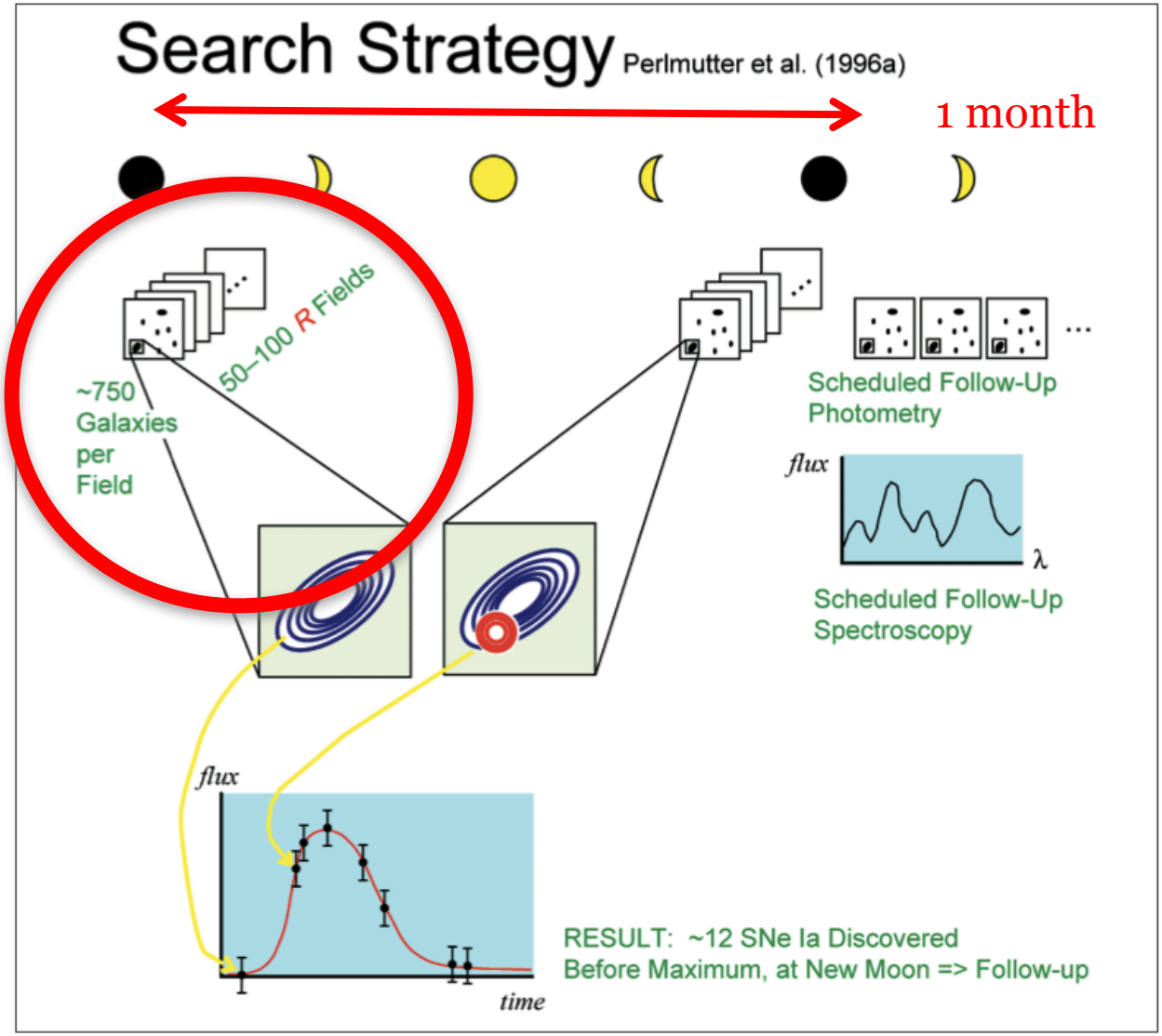
SN +Galaxy — Galaxy = SN

SNIa searches in the 90's and the discovery of dark energy



From Saul's Nobel Lecture (2011)

SNIa searches in the 90's and the discovery of dark energy



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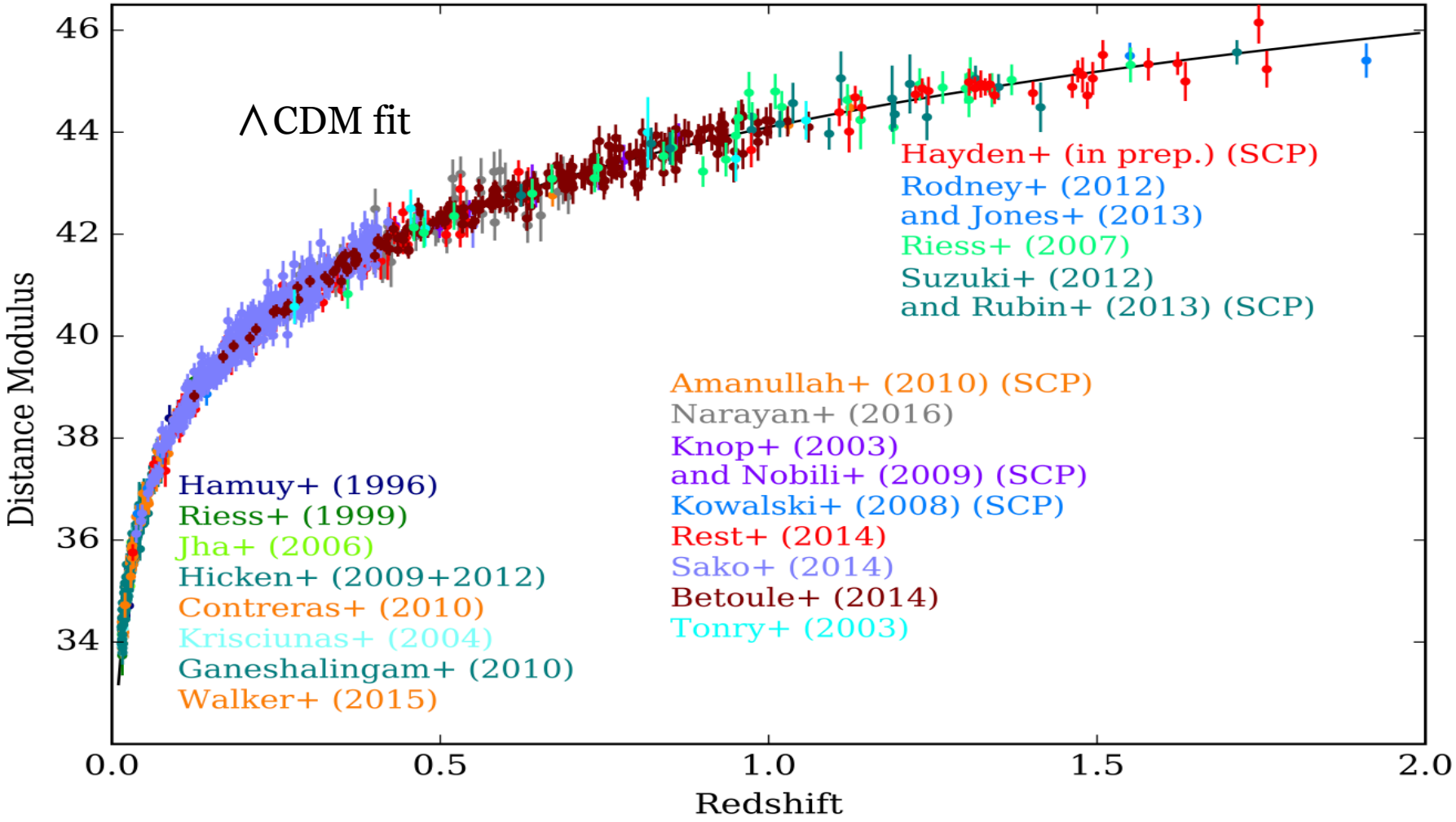
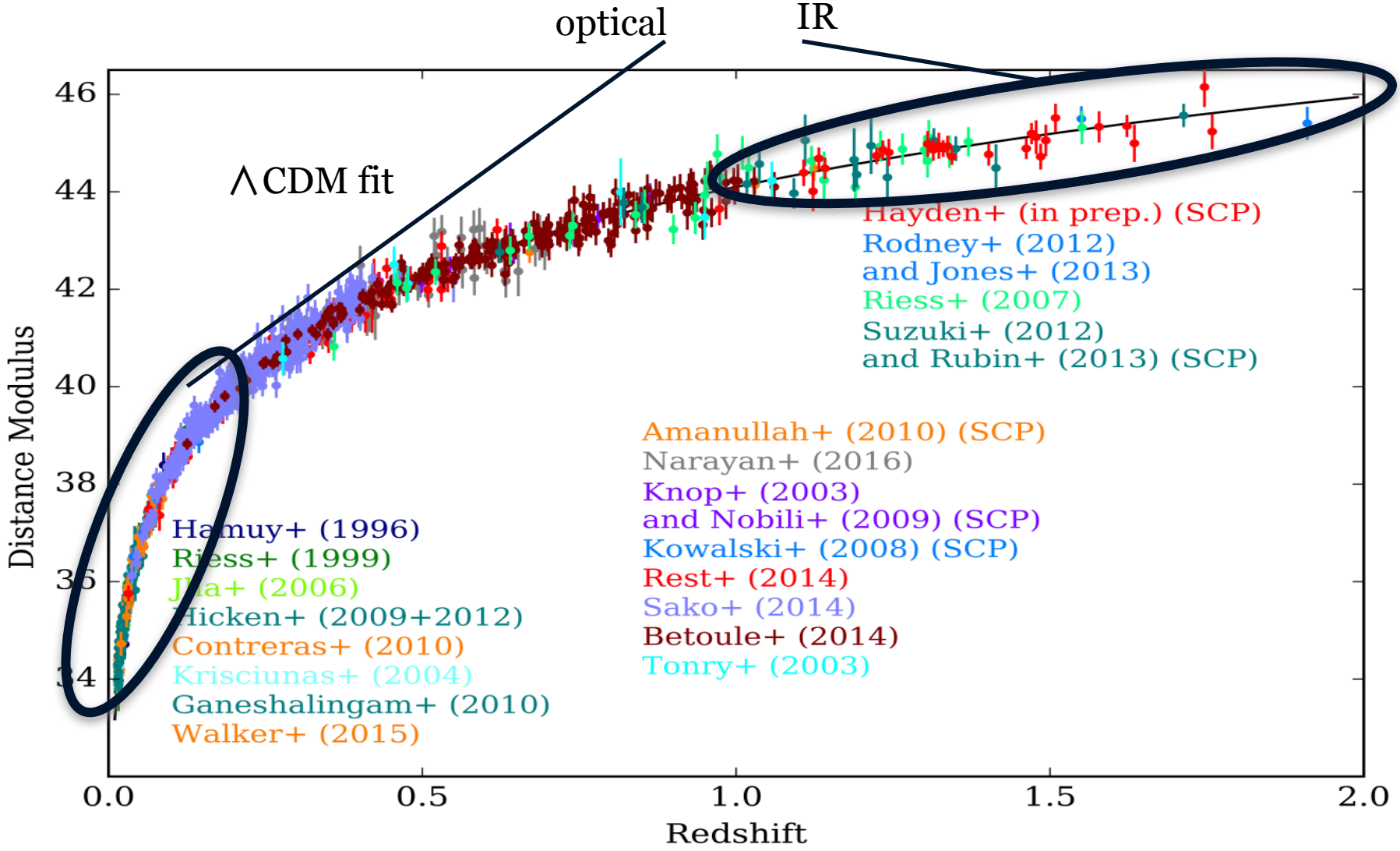
SNIa Hubble diagram: *v2017.9*



Further progress requires wide-field surveys



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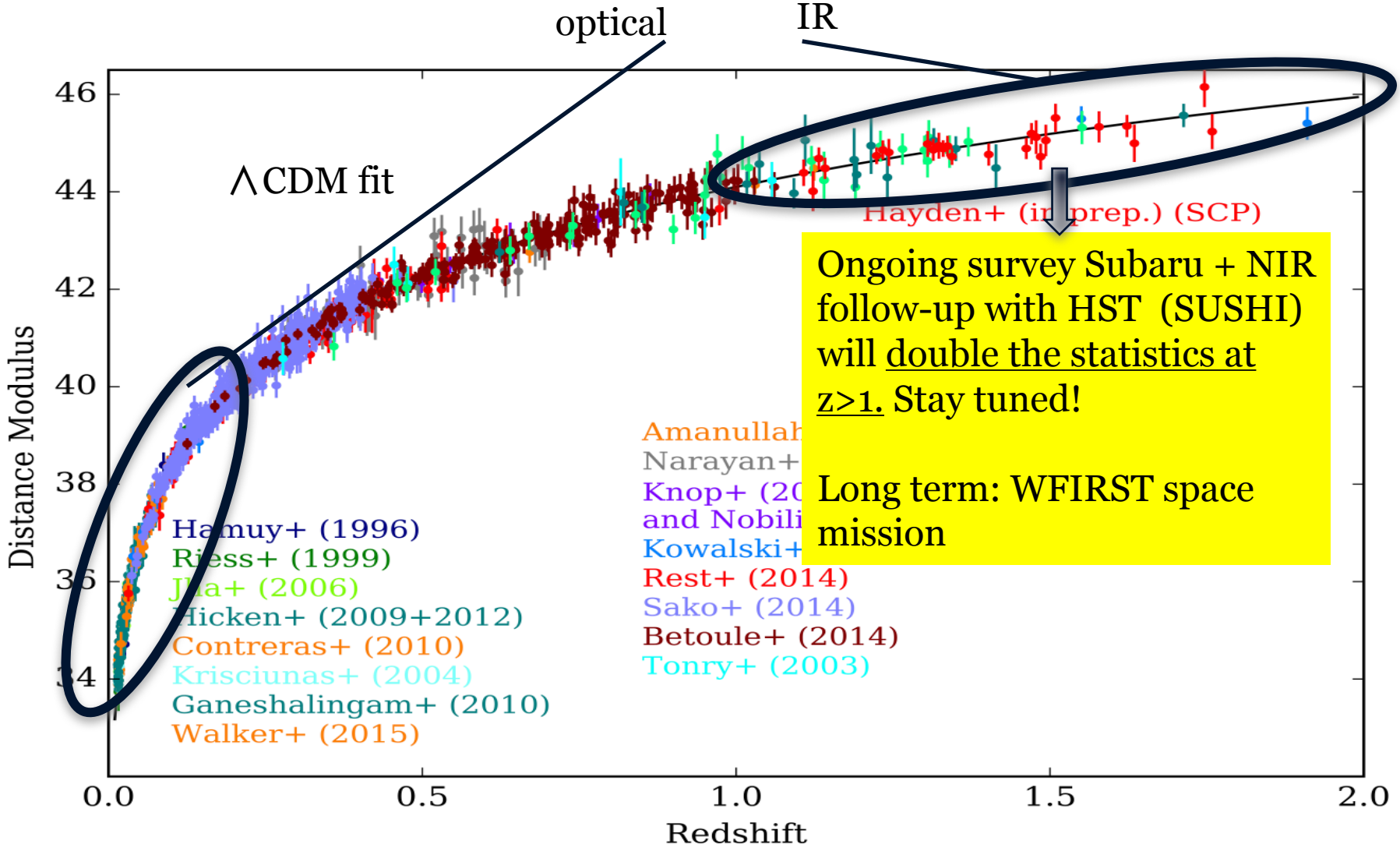

Important technological improvements

Larger CCD arrays: Field-of-view of cameras has changed from just a few sq.*arcminutes* to many sq.*degrees*

Large statistics and improved chances to catch very rare transient phenomena.

(Example will follow shortly)

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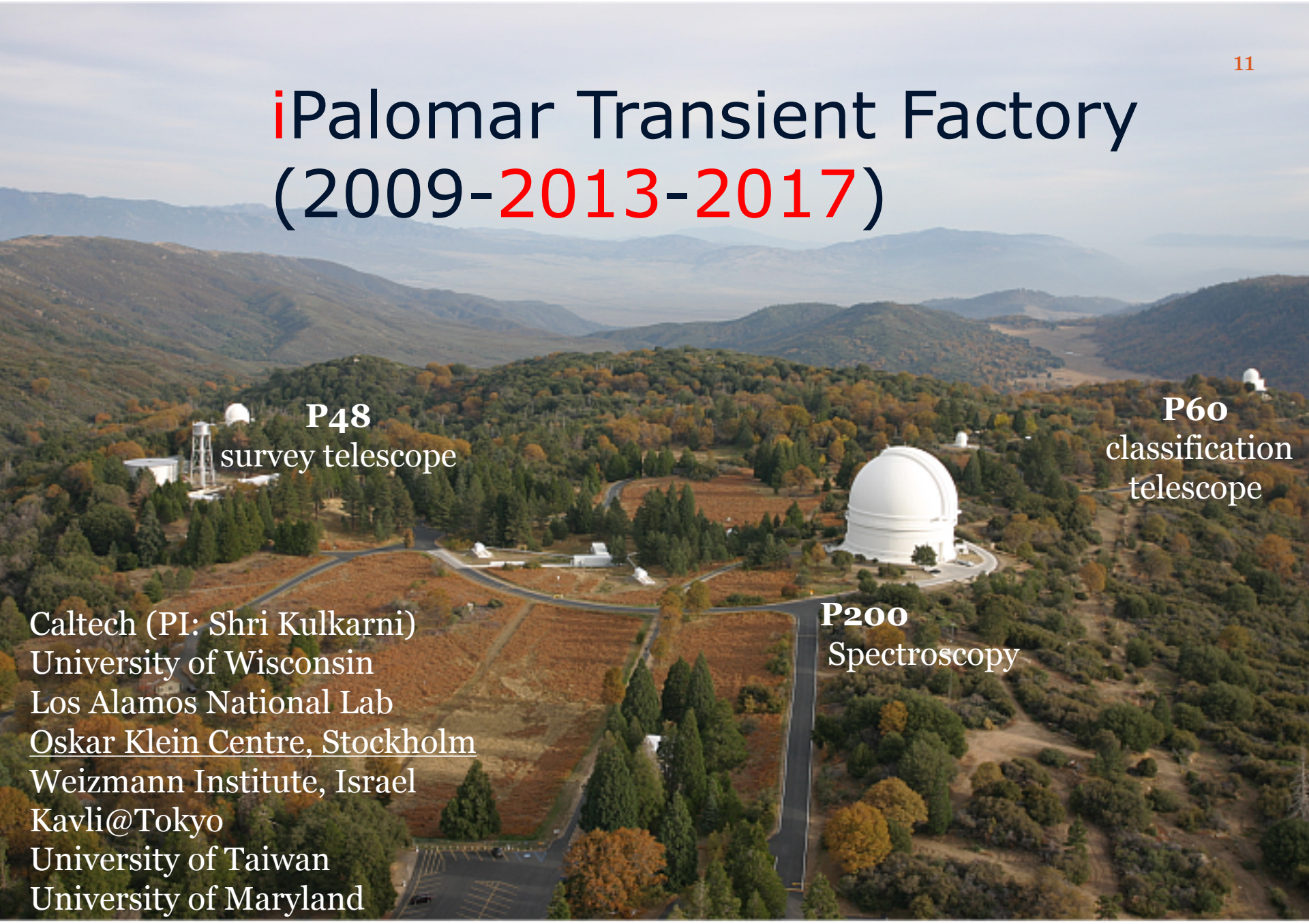
Other implications:

High "cadence", i.e., frequency by which the same piece of sky is revisited:

1) ability to discover transients/supernovae much earlier in the lightcurve and trigger follow-up observations with specialized instruments (e.g., from space)

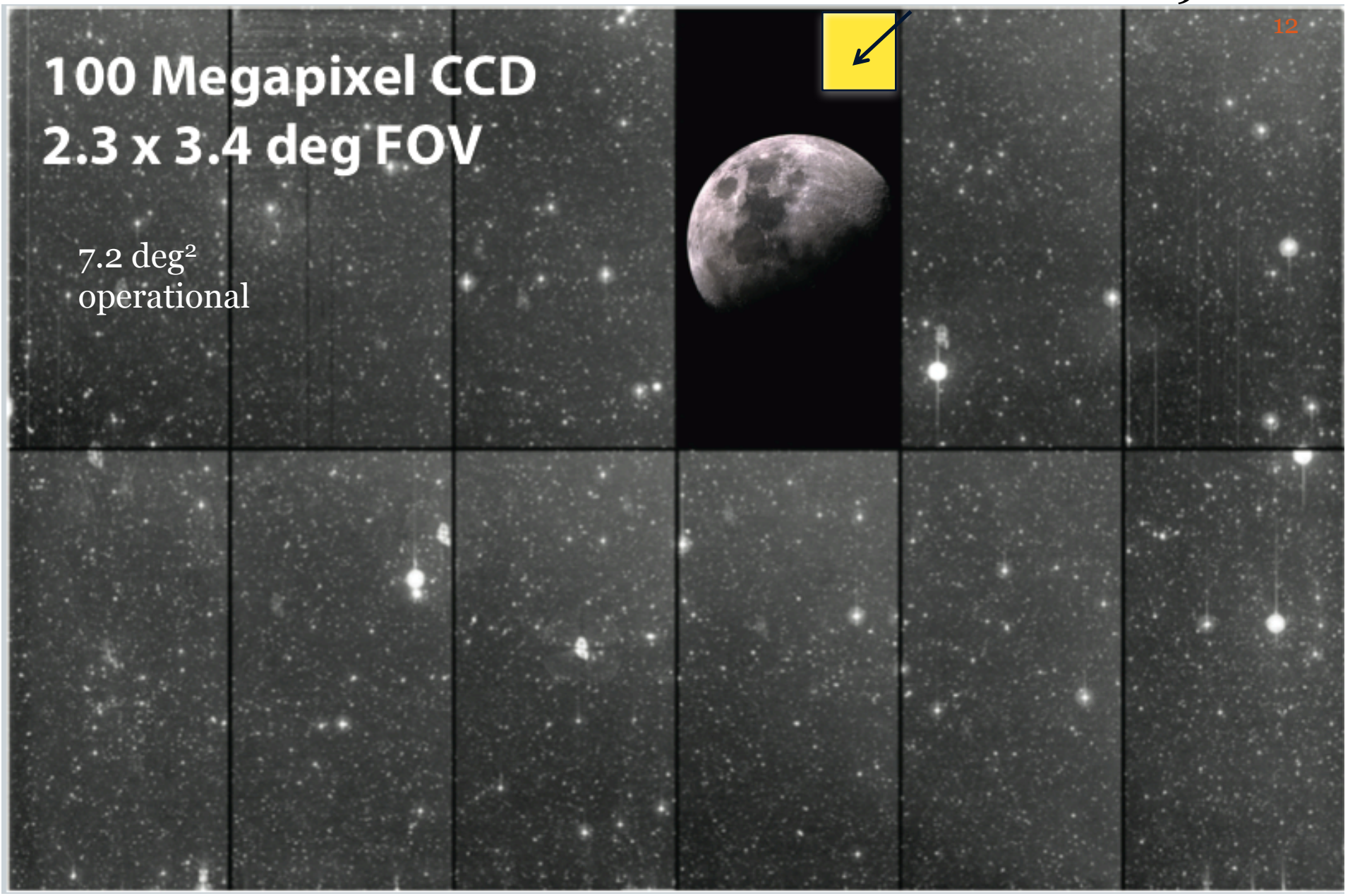
2) Possibility to find *new* transient phenomena, with much shorter time scales

iPalomar Transient Factory (2009-2013-2017)

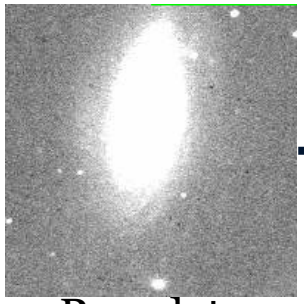


Caltech (PI: Shri Kulkarni)
University of Wisconsin
Los Alamos National Lab
Oskar Klein Centre, Stockholm
Weizmann Institute, Israel
Kavli@Tokyo
University of Taiwan
University of Maryland

State of the art in the 90's



Pipeline flow-chart

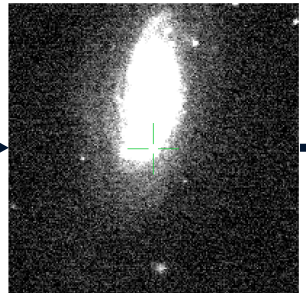


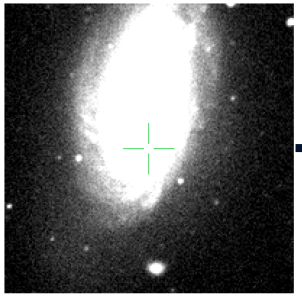
Raw data

(Palomar -> Caltech -> LBL)

processing

3 min

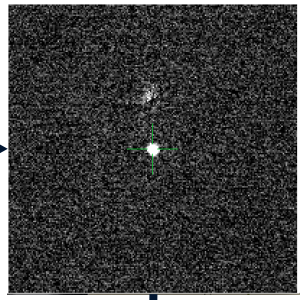




Reference Image

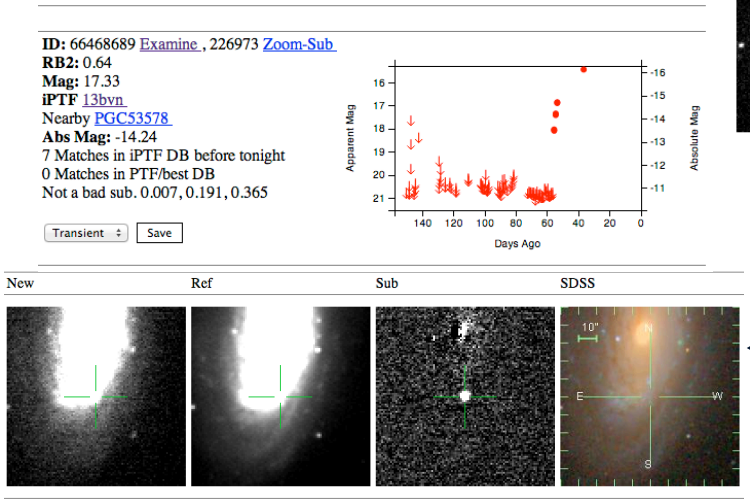
1.5 min/ image

Image Subtraction



Real-Bogus (reject false alarms) 0.5 min/ image

Load candidates Into database



Scanning Page: human screening mainly in Israel and Stockholm

Star/asteroid Identification

Local galaxy match

0.5 min/image

Database

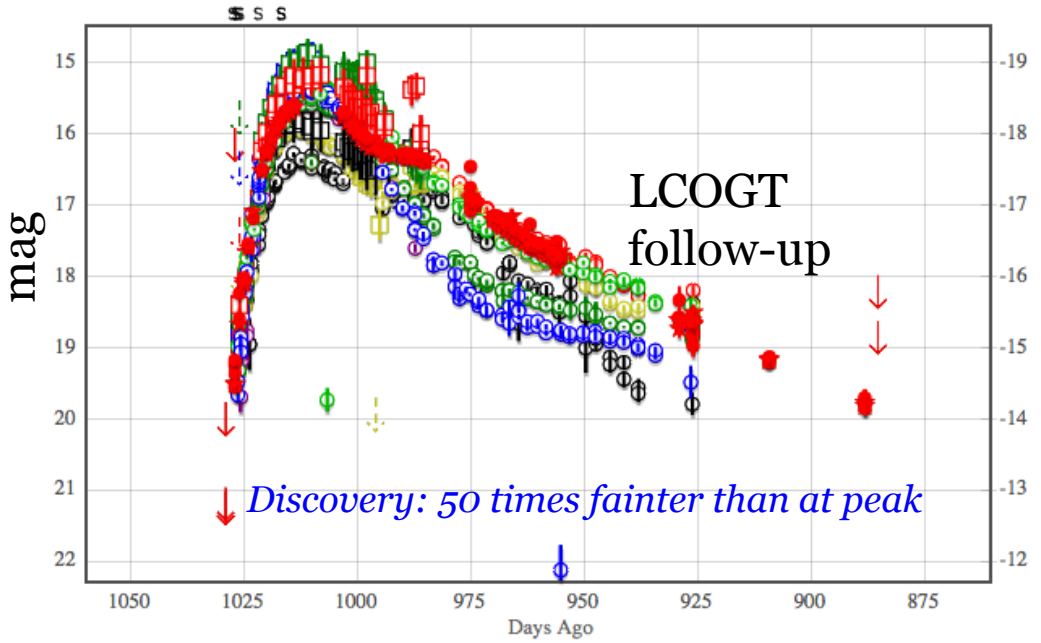
COURTESY OF YI CAO & MANSI KASLIWAL

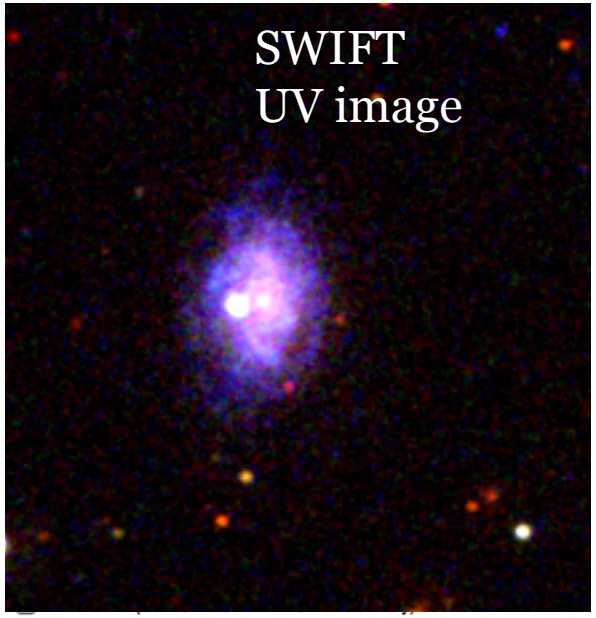
13dge SN Ia

Examples of iPTF early detections

D~100 Mpc (z=0.0159)

OVERVIEW PHOTOMETRY SPECTROSCOPY FOLLOWUP OBSERVABILITY FINDING CHART EXAM

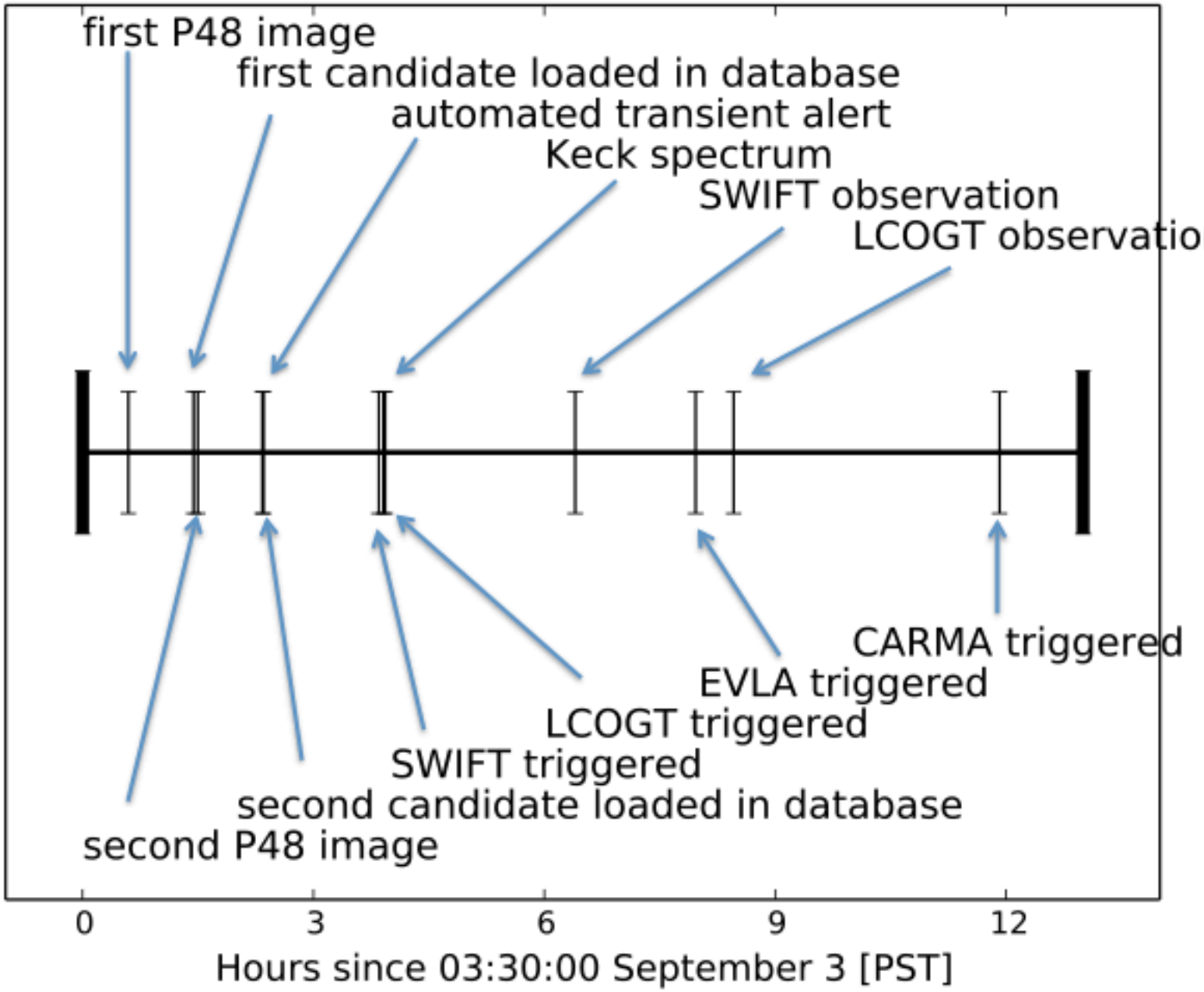




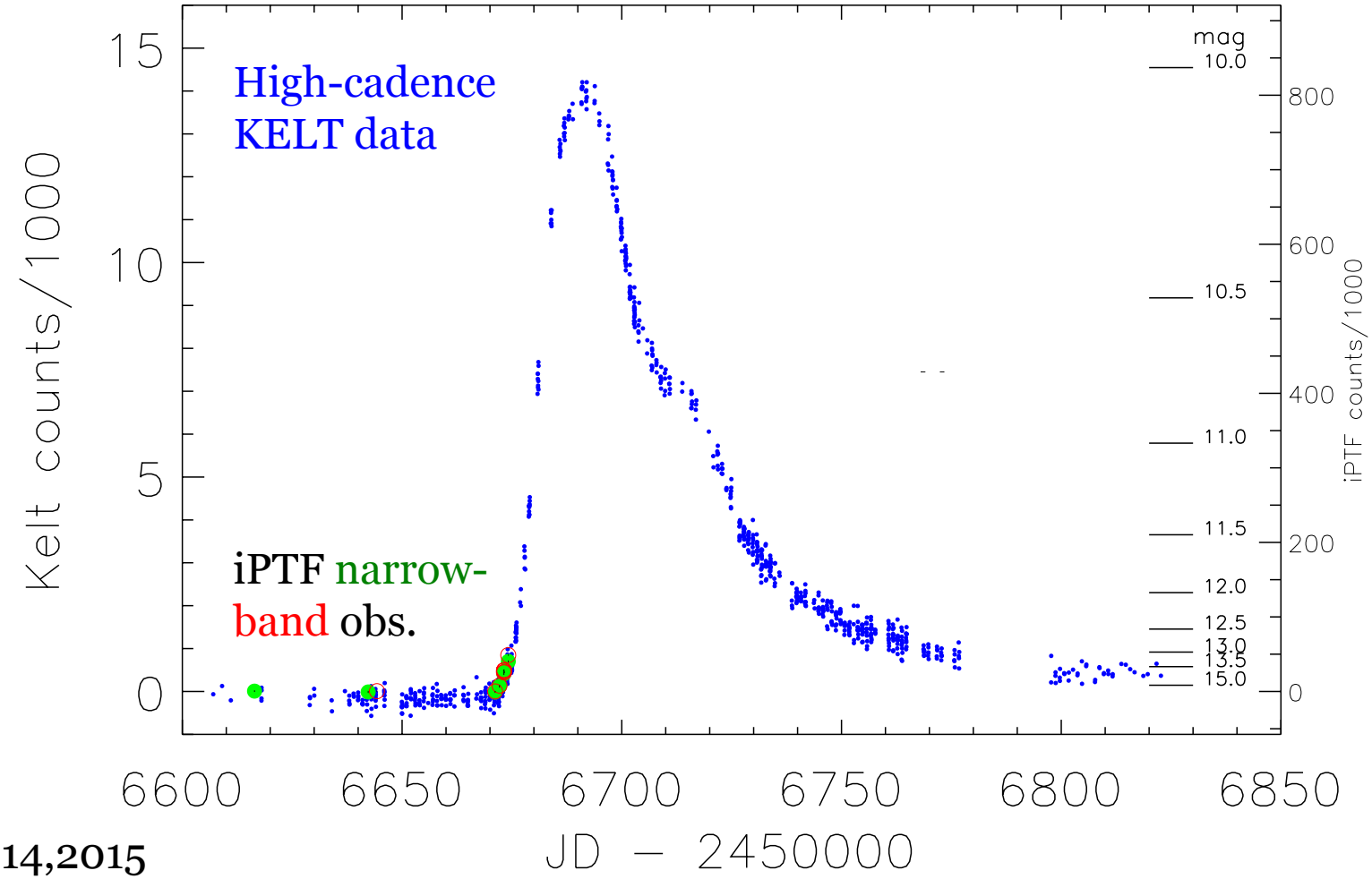
Early observations of SNe – astrophysical unknowns:

- Search for evidence of shock heating of outer layers of exploding star, interaction with companion star, circumstellar medium, surface radioactivity, etc
- Multi-wavelength follow-up observations to study extinction along line of sight.

Time-line of follow-up of iPTF13dge



SN2014J in M82: see explosion *as it happens*!

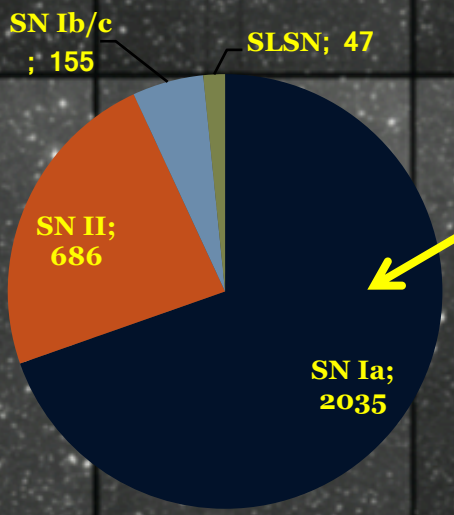


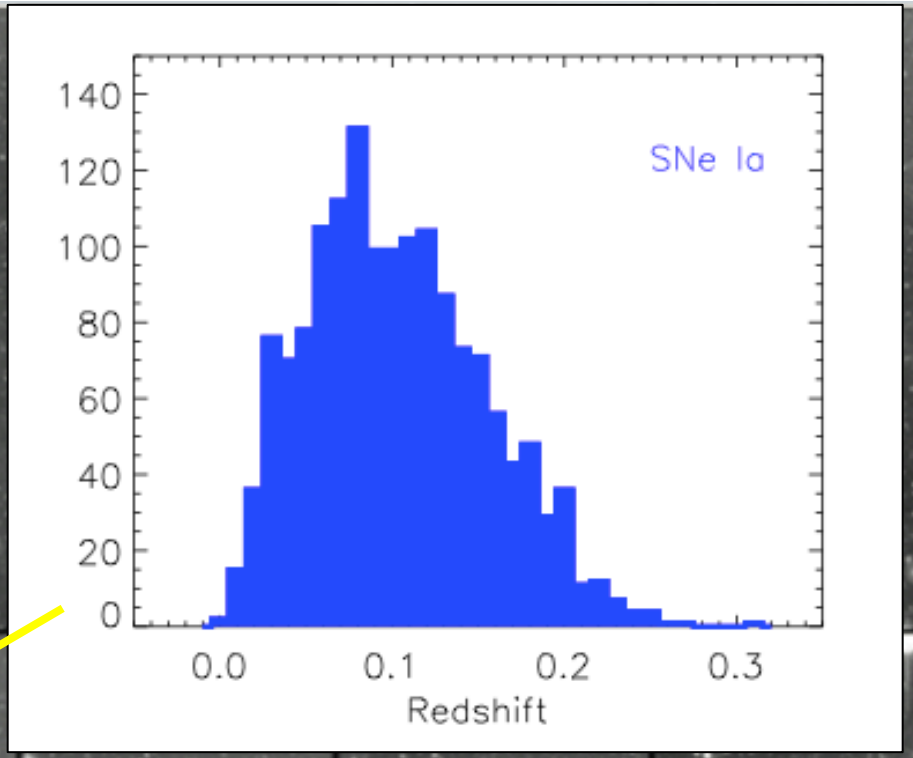
AG+2014,2015
Siverd, AG+2015

Lots of follow-up observations/analysis!

100 Megapixel CCD
2.3 x 3.4 deg FOV

7.2 deg^2
operational





Typical operation: 60 s exposures + 36 s readout:
Pixel size: 1”, S/N=5 for 21 mag in R and g

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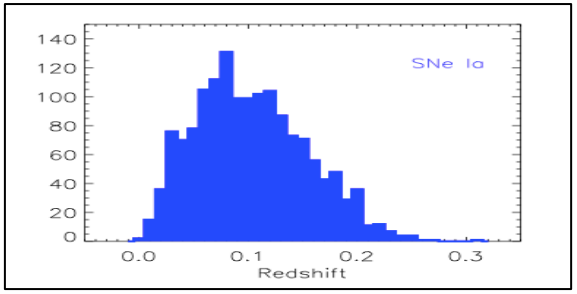
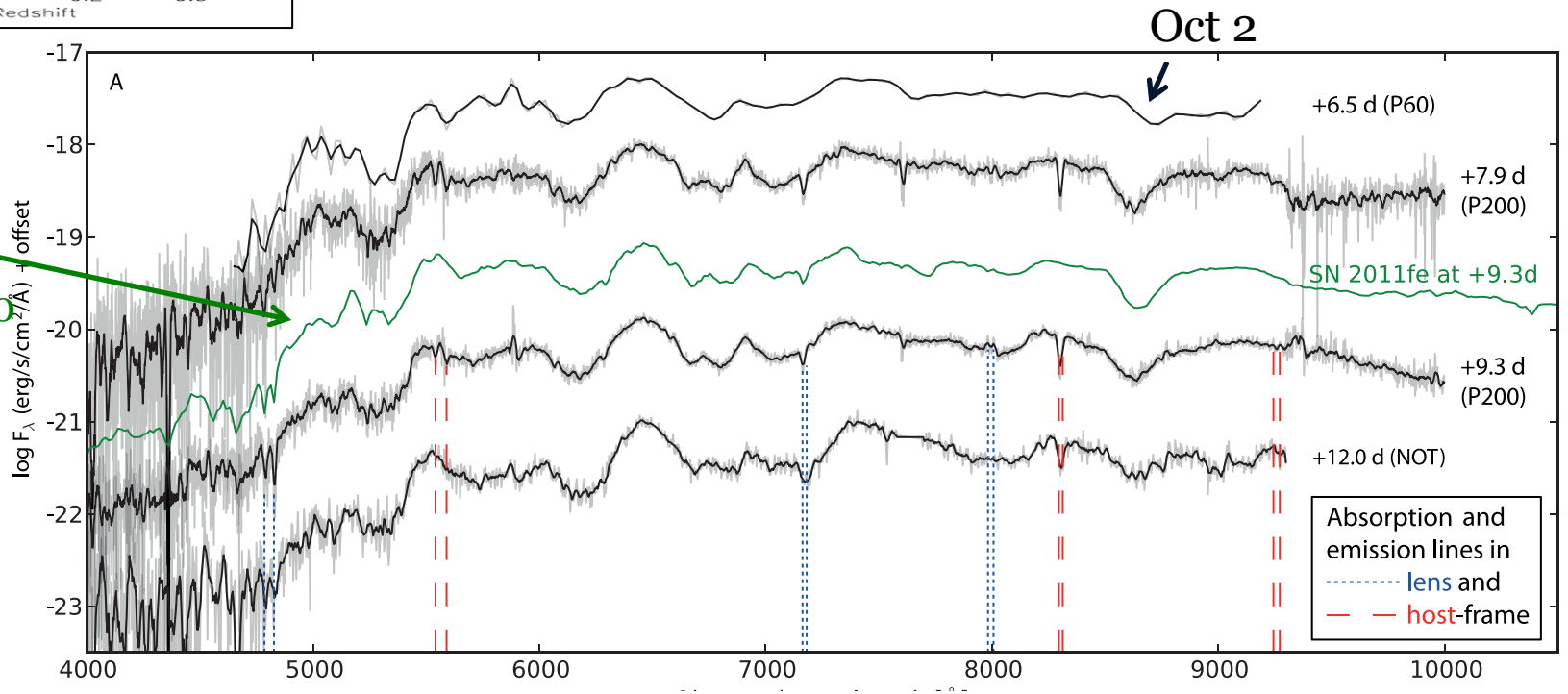
On Oct 2, 2016, something quite unexpected happened…



Perfect match to z=0.409 SN Ia

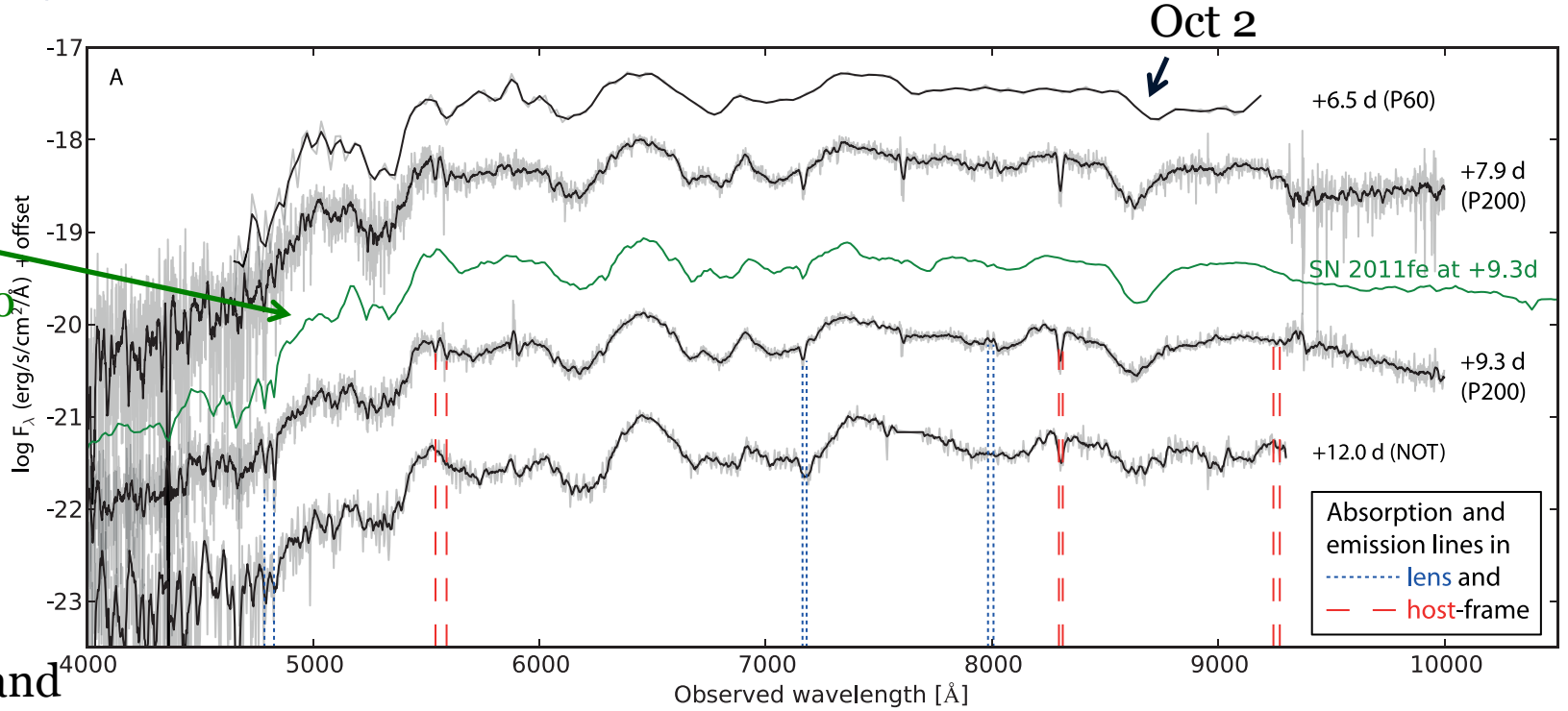
"Typical" SNIa redshifted to z=0.409



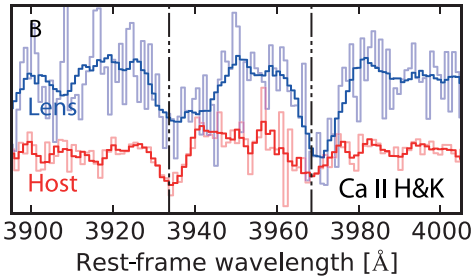
AG et al 2017, *Science*

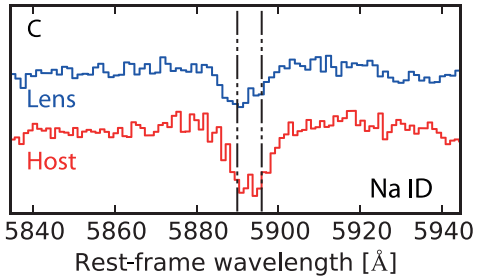
Perfect match to z=0.409 SN Ia + intervening galaxy at z=0.216

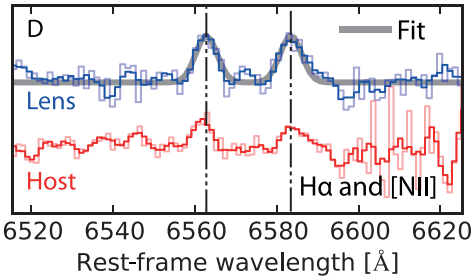
"Typical" SNIa redshifted to z=0.409



Absorption and emission lines at two redshifts: the SN host galaxy and other galaxy in line-of-sight







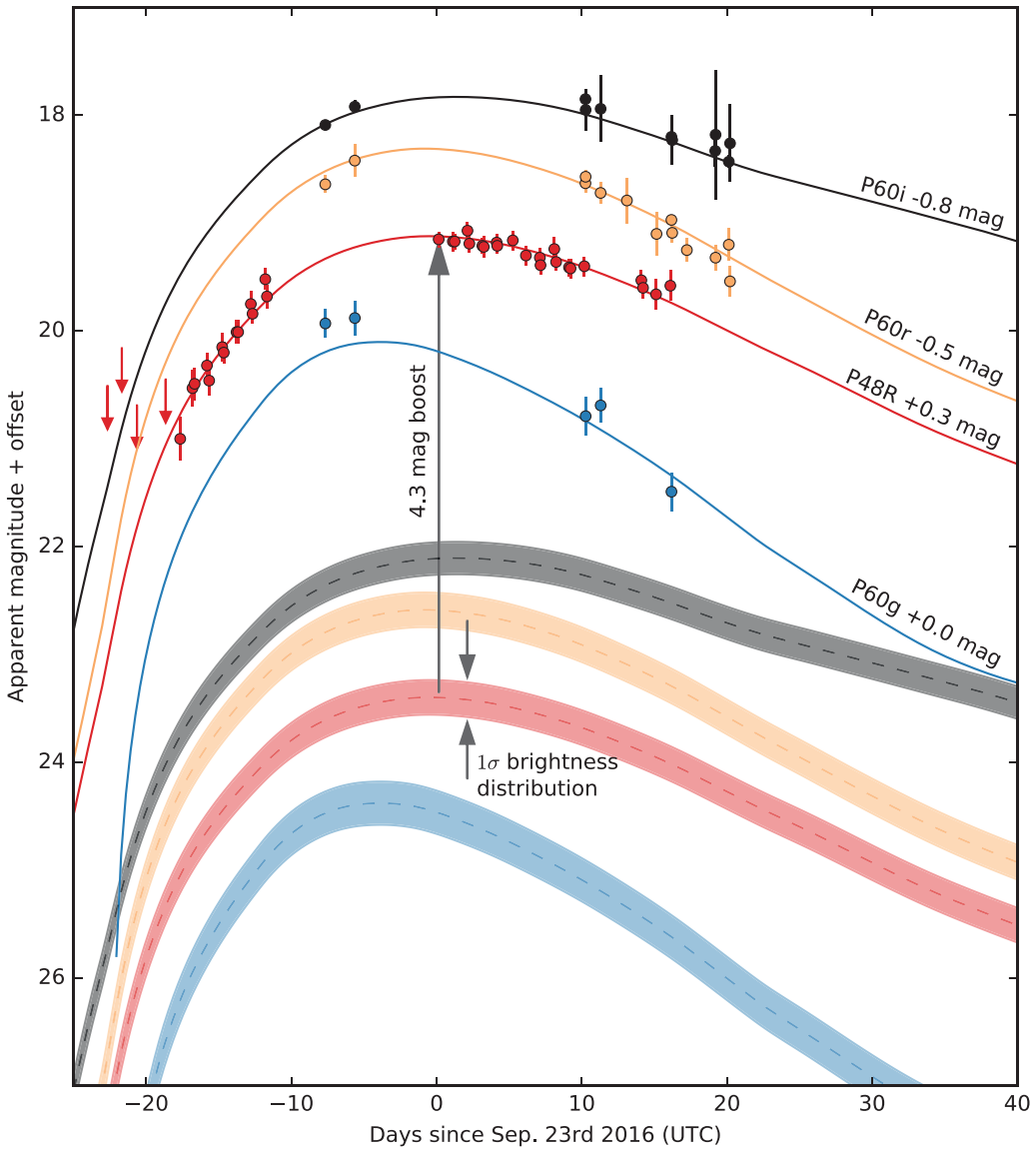
AG et al 2017, *Science*

~52 times brighter than normal SNIa at z~0.4: a 30σ outlier!

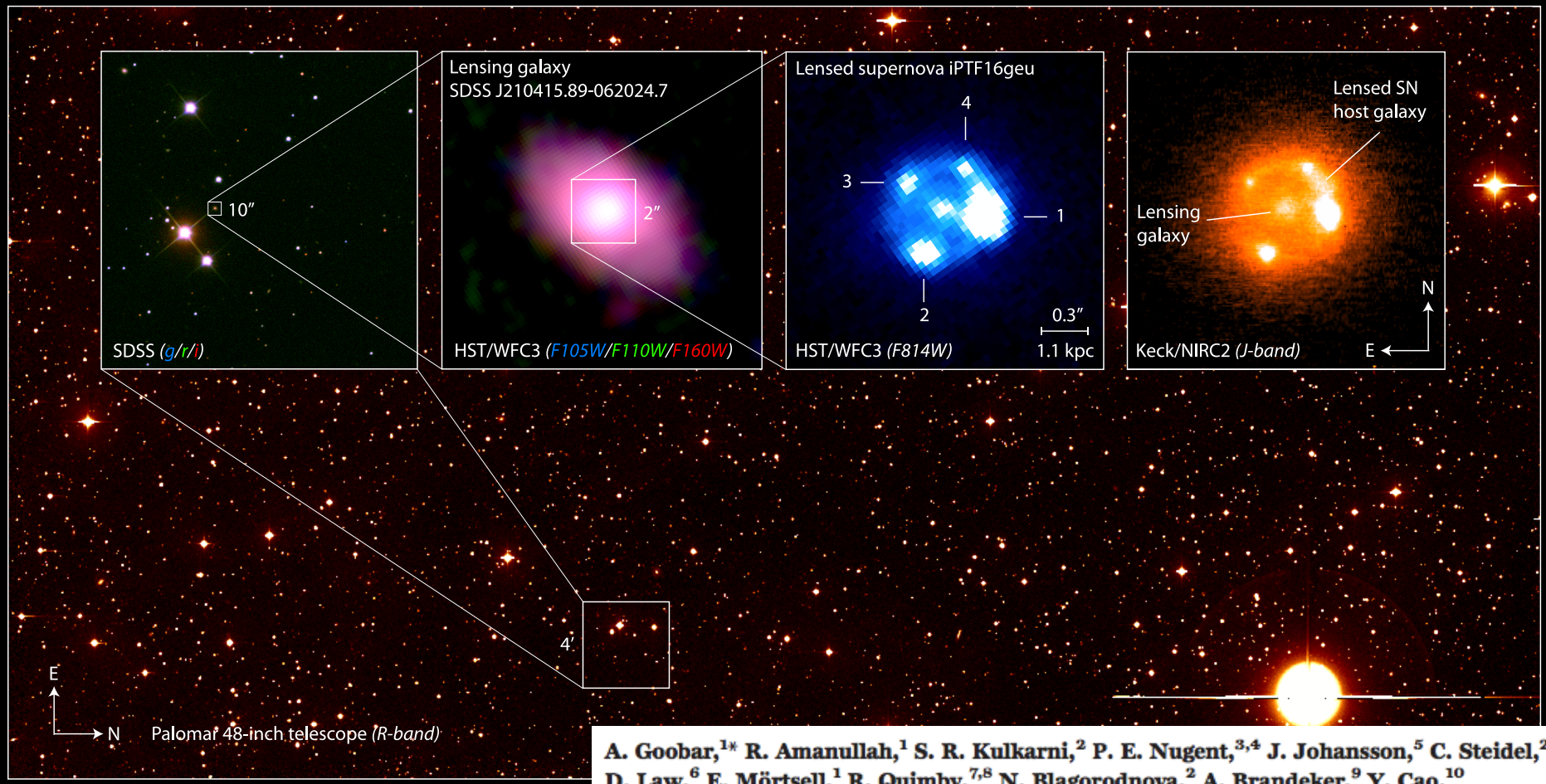
Only possible with SNe Ia: "standard candles"

Must be lensed by the intervening galaxy!

High-resolution imaging with HST requested + Adaptive Optics from VLT and Keck.



A quadrupole lens!



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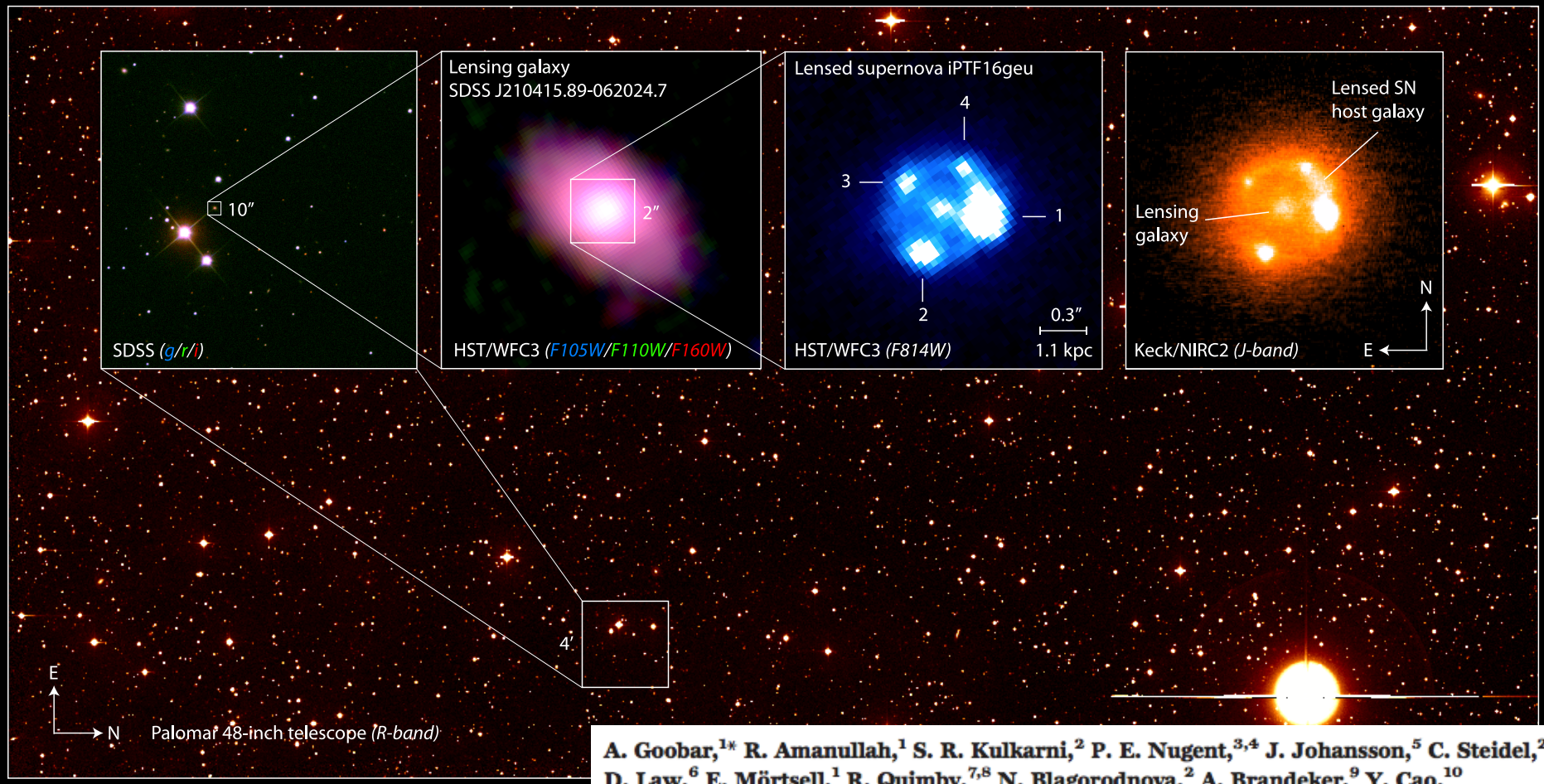
Time-delay measurement in progress... (H_0)



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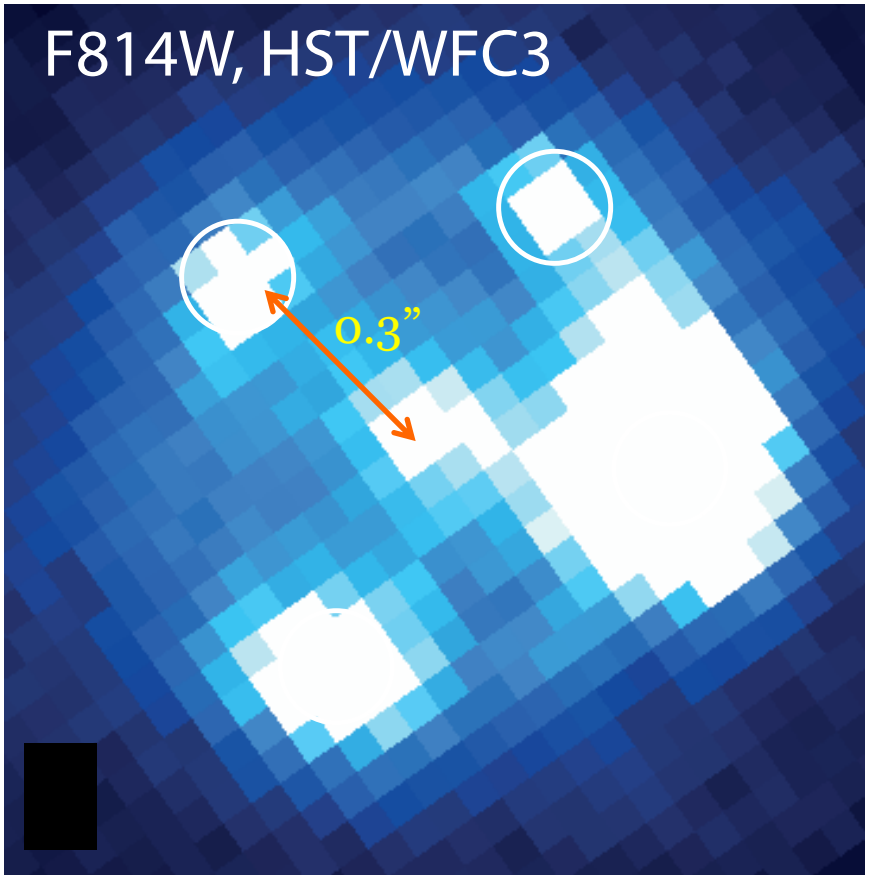
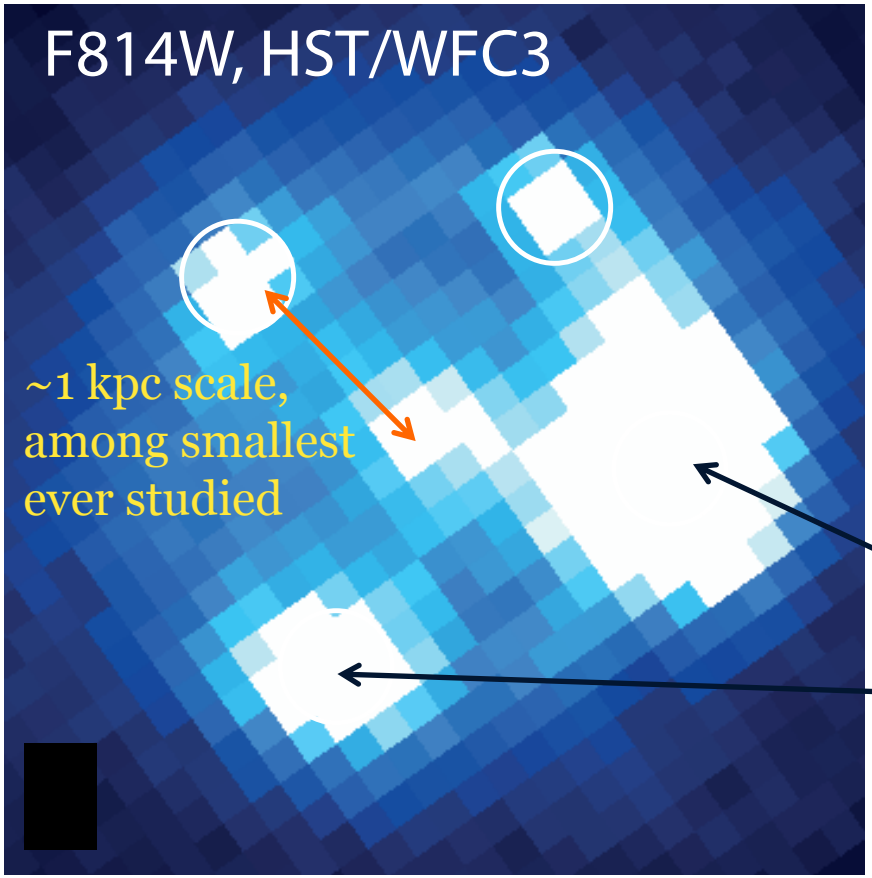
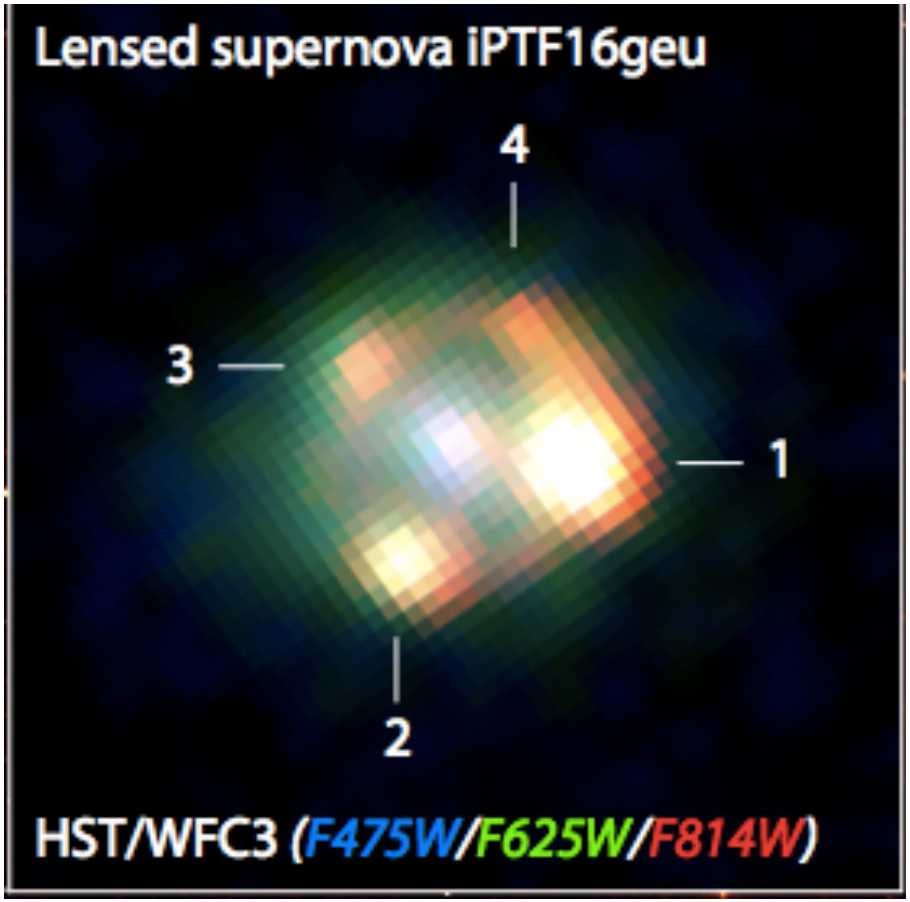
Discovery *not limited by spatial resolution: it was the SN lightcurve that gave it away, 2" seeing!*





Large magnification and symmetry while very different intensities suggestive of added "compact" lenses in l-o-s

Microlensing by substructures?

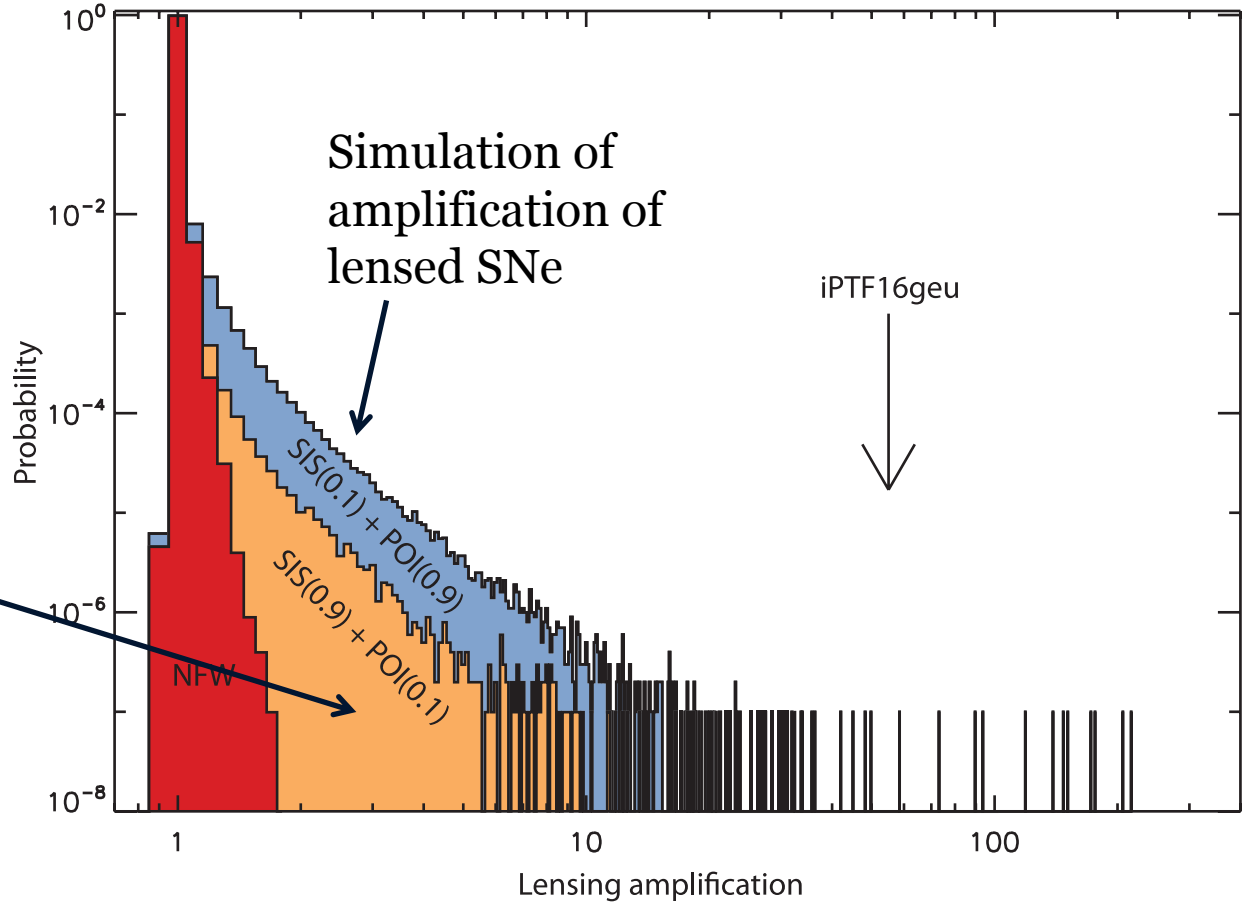


Evidence for reddening/extinction. But images 1 & 2 are ~4x brighter than expected compared to 3 & 4.

Large magnification and symmetry while very different intensities suggestive of added “compact” lenses in l-o-s

Very strong magnification...

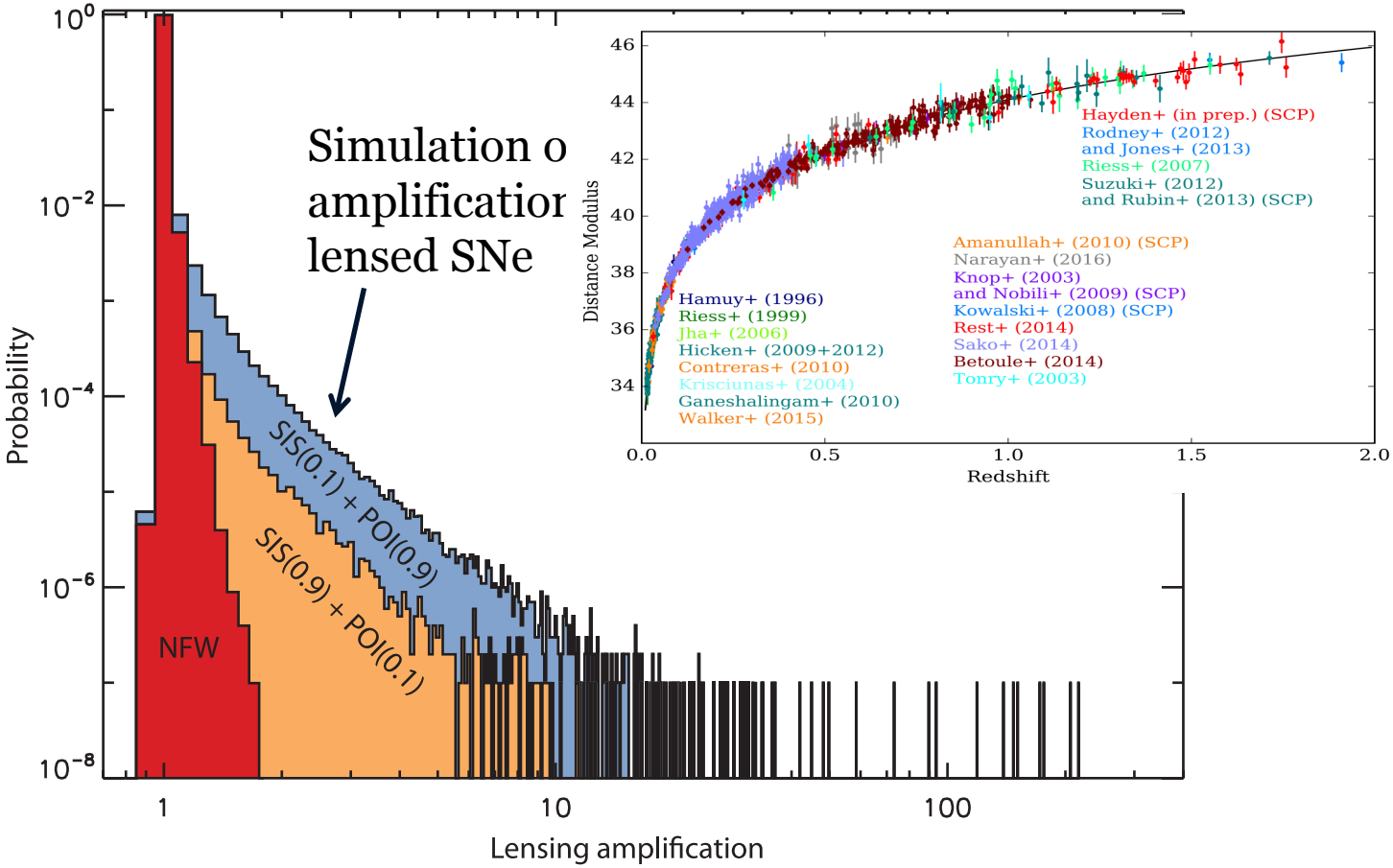
Added "graininess"



Measured amplification requires extraordinary alignment of source and lens – also suggests lensing by substructures in addition to a smooth matter component from the galaxy (e.g., network of stars, black holes, ...).

Just "lucky" or something profound?

No lensed SN in high-z sample



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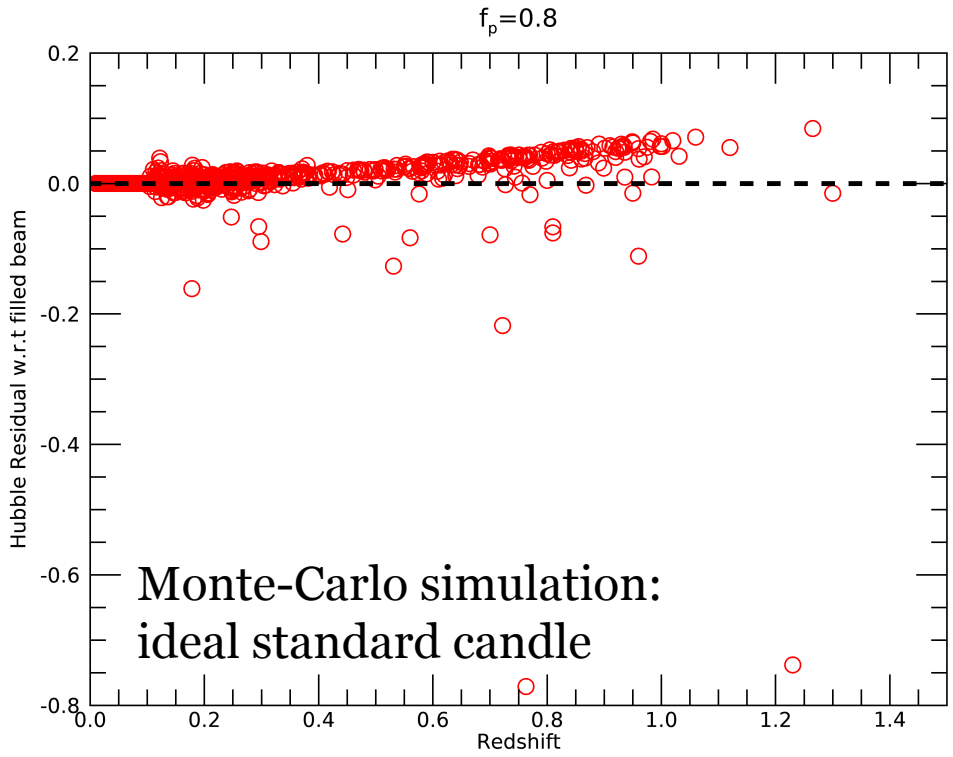
What can be said about clumping and inhomogeneities of DM from JLA sample?



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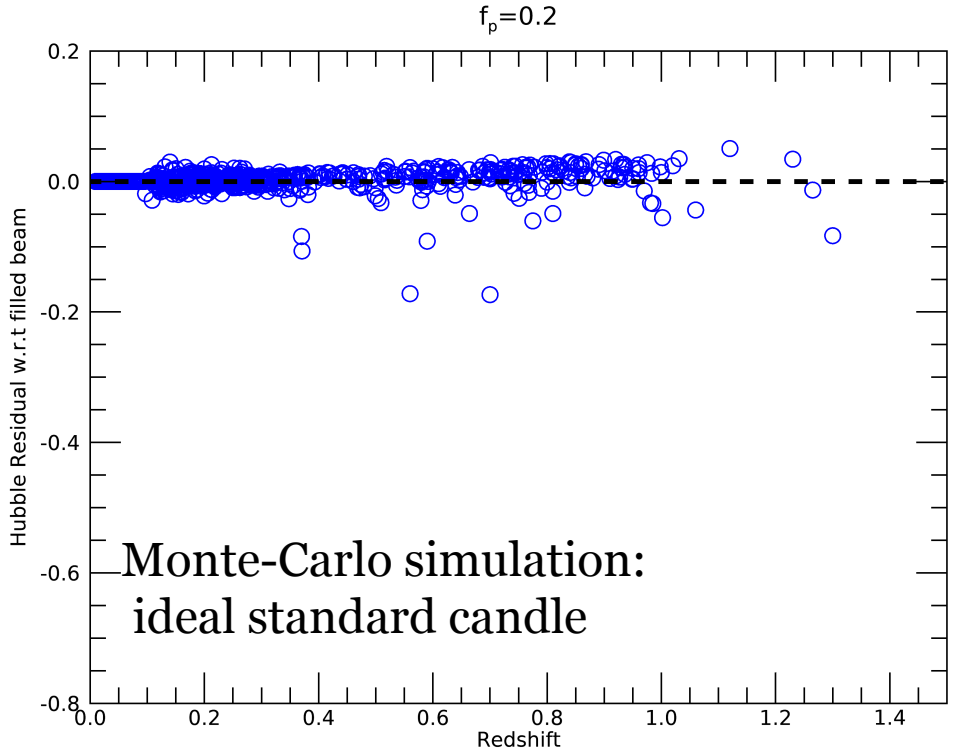

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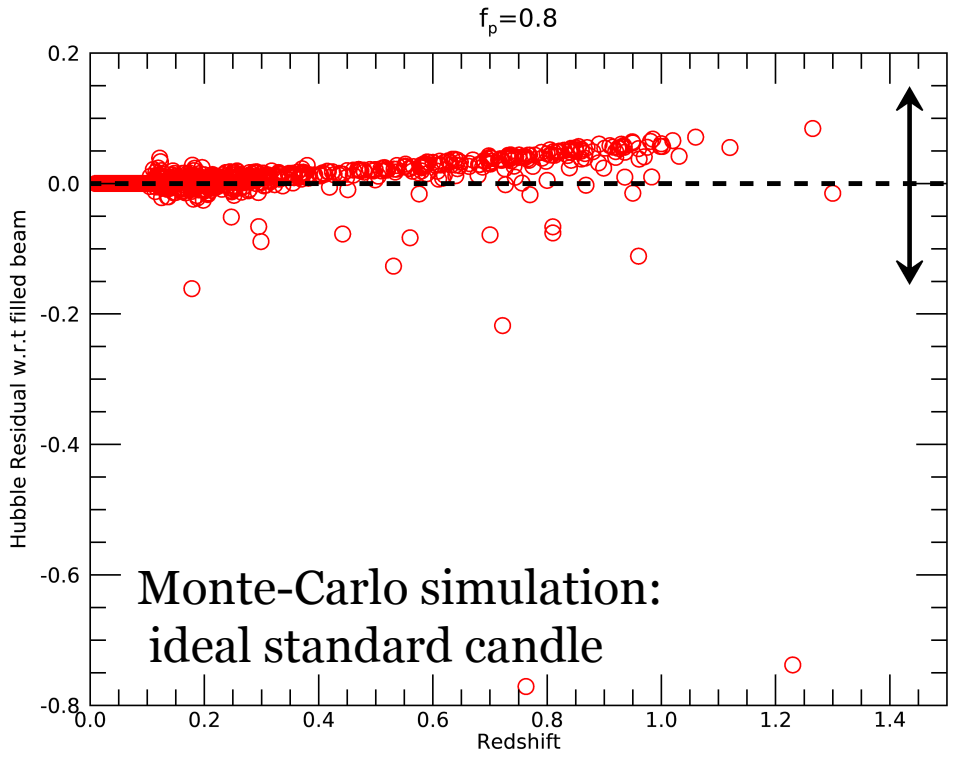
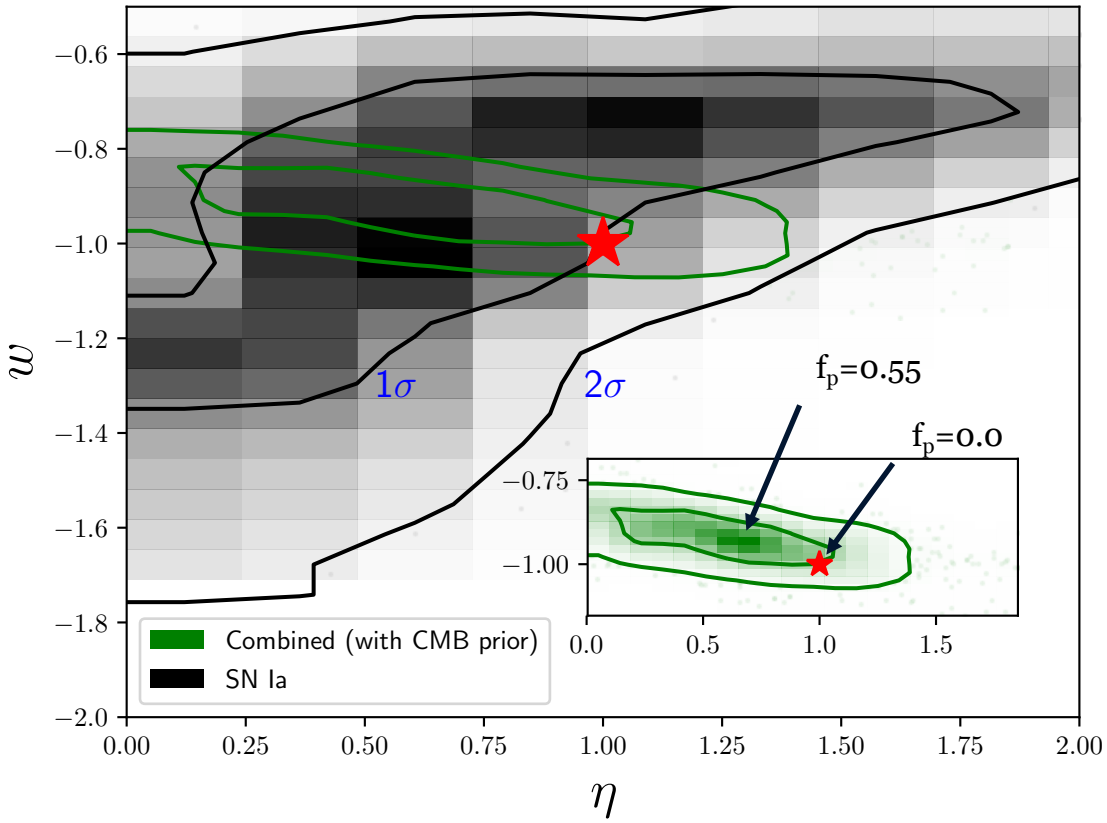


Typical measurement error for 1 SN.

A quantitative study of JLA sample

- The distance-redshift Dyer-Roeder equation (Dyer & Roeder 1973) offers a way to quantify the level of inhomogeneous space-time probed by SN line of sight.
- The DR approximation assumes that the expansion rate of the Universe is governed by the total matter density whereas the focusing of light is only affected by a fraction η of the total matter density. η=1 implies homogeneous matter distribution ('filled beam').
- Fitting for η (+ all other cosmological parameters) shows some degeneracy with Dark Energy equation of state, w.

Bounds on inhomogenious matter distribution



Planck + JLA SNIa

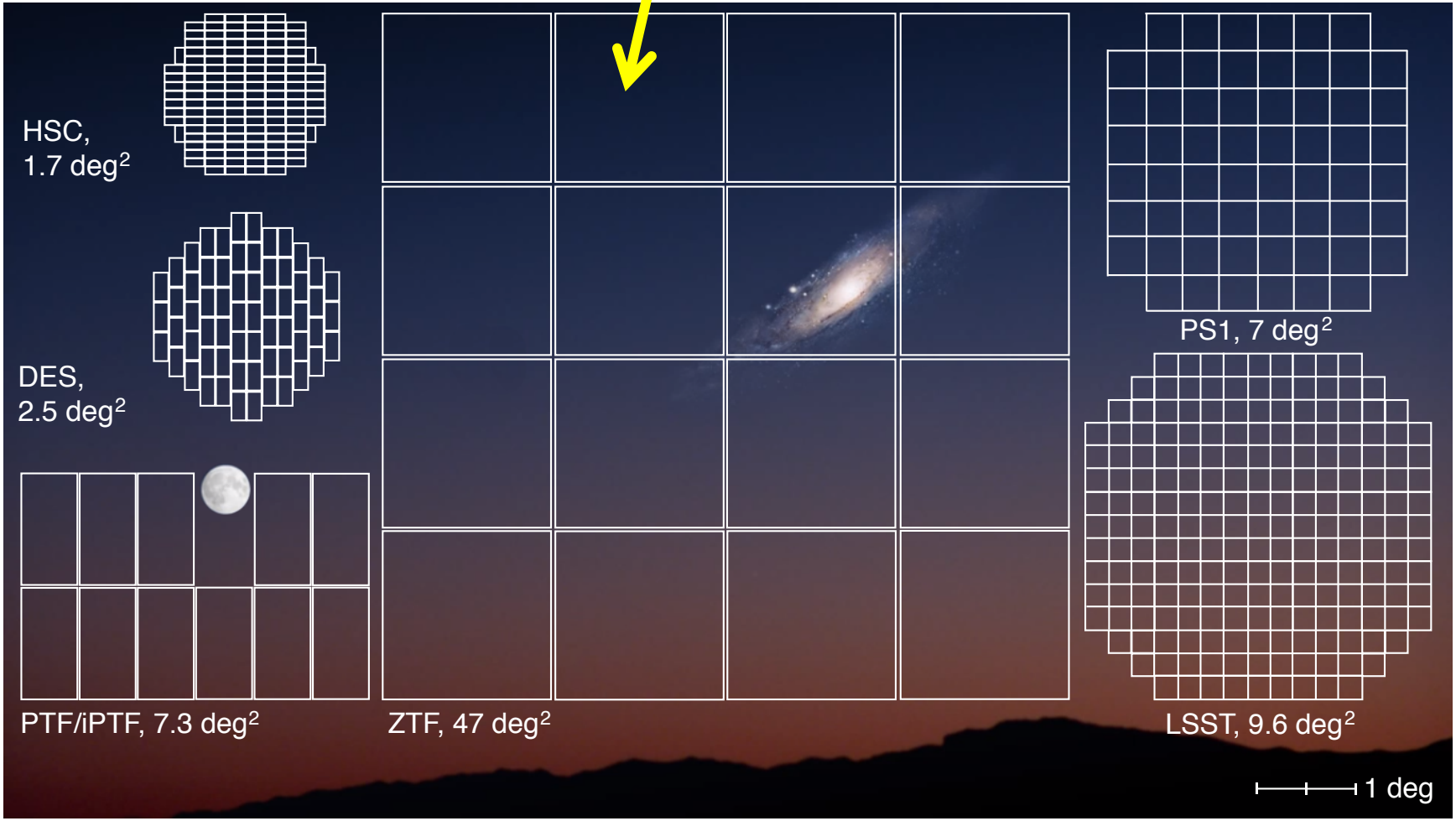
Current data **not yet sensitive enough**

Dhawan, AG, Mörtsell, *in prep*

New horizons in time-domain astrophysics.

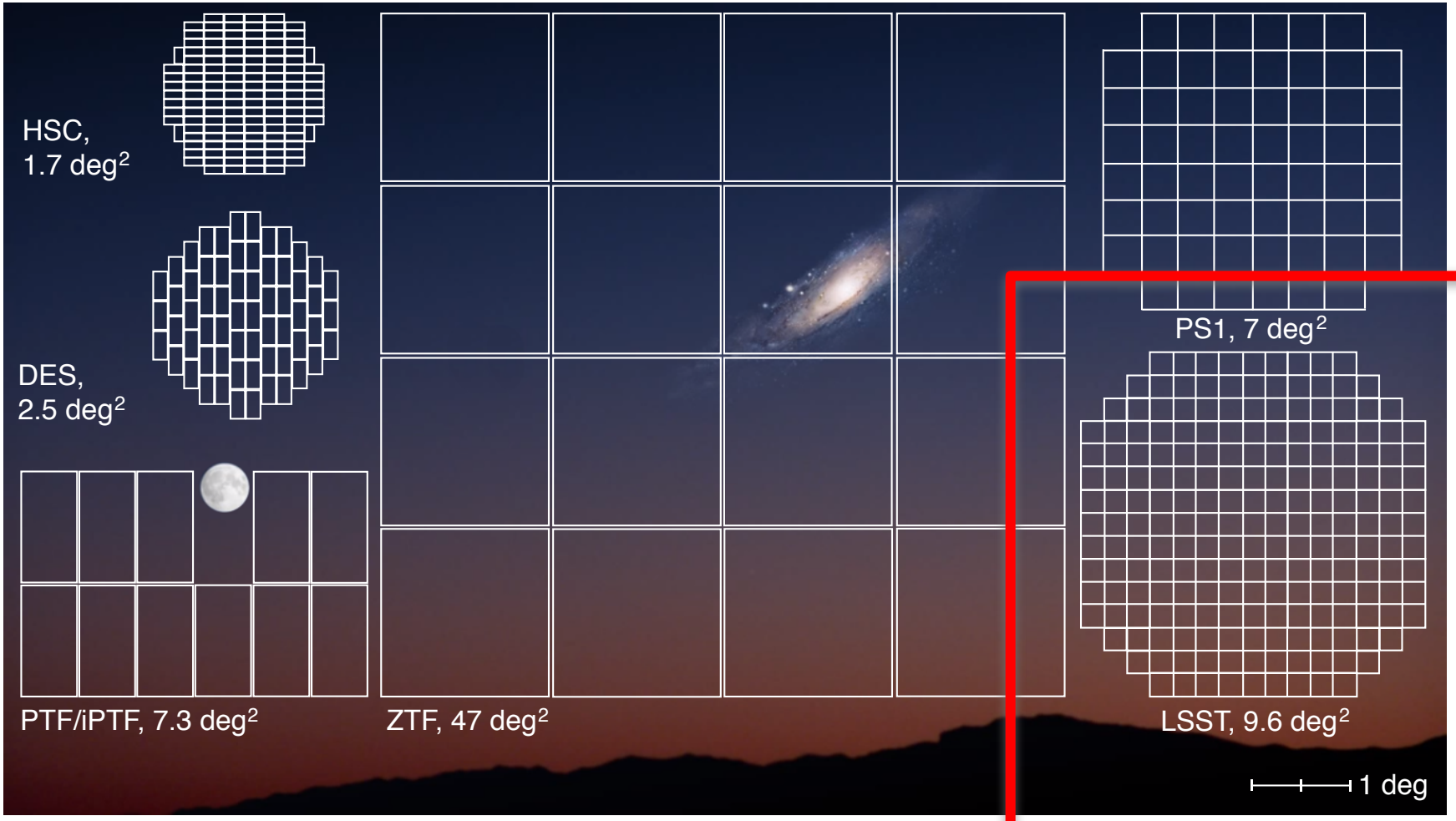
- Zwicky Transient Facility (ZTF) is being installed @Palomar. Same telescope as iPTF, but much larger FoV and new camera. 3-year survey funded. Will collect all the low-hanging fruits at low redshifts. “Stepping stone” for LSST in TDA.
- Large Synoptic Survey Telescope (LSST) to see first light in 2020. 10-year “all sky” optical survey with suitable cadence for high-z SNe Ia.
- WFIRST (2025?) will operate at Near-IR wavelengths, sensitivity to detect first generation of cosmic explosions, besides doing “bread and butter” SNIa science.

Zwicky Transient Facility: 12 x faster than iPTF!



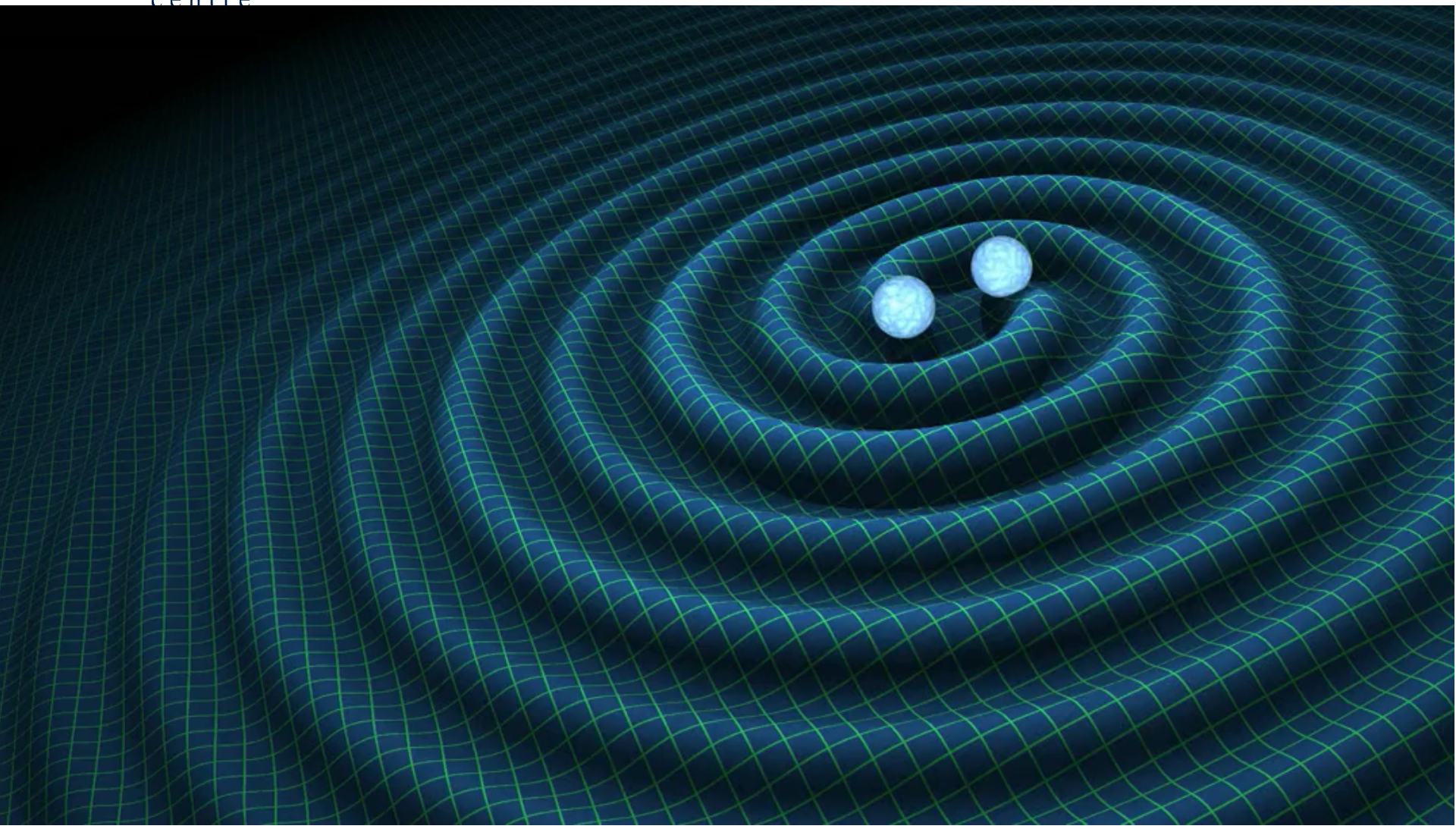
First light: one week from today!!

LSST: 8.4m mirror –> substantially deeper



Survey start: ~2023

Next big leap?
GW-EM counterparts?



GW-EM counterparts: "Macronovae"

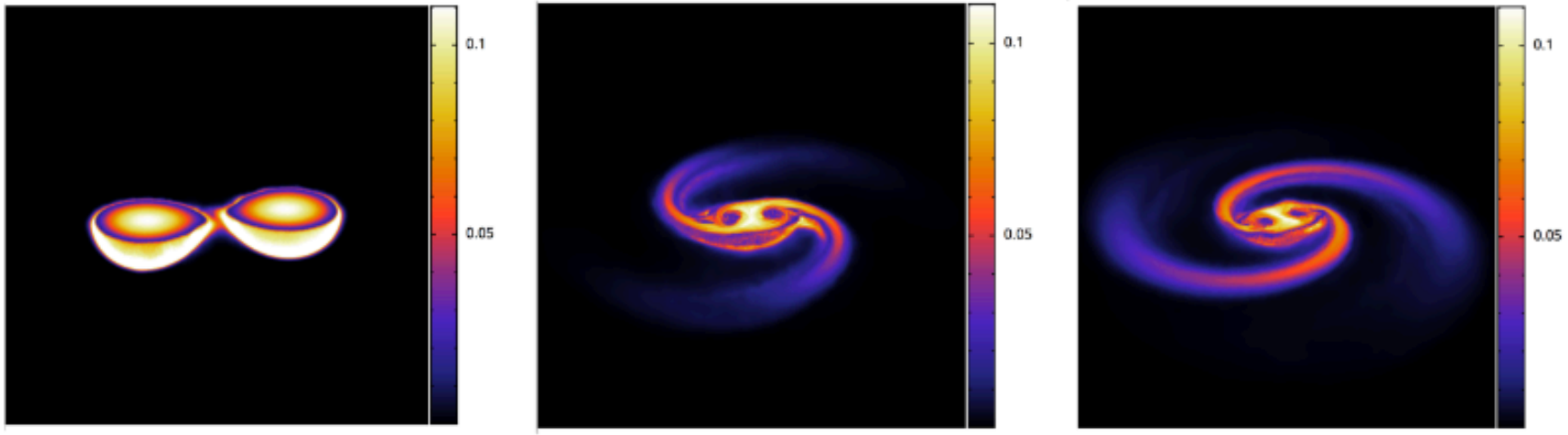
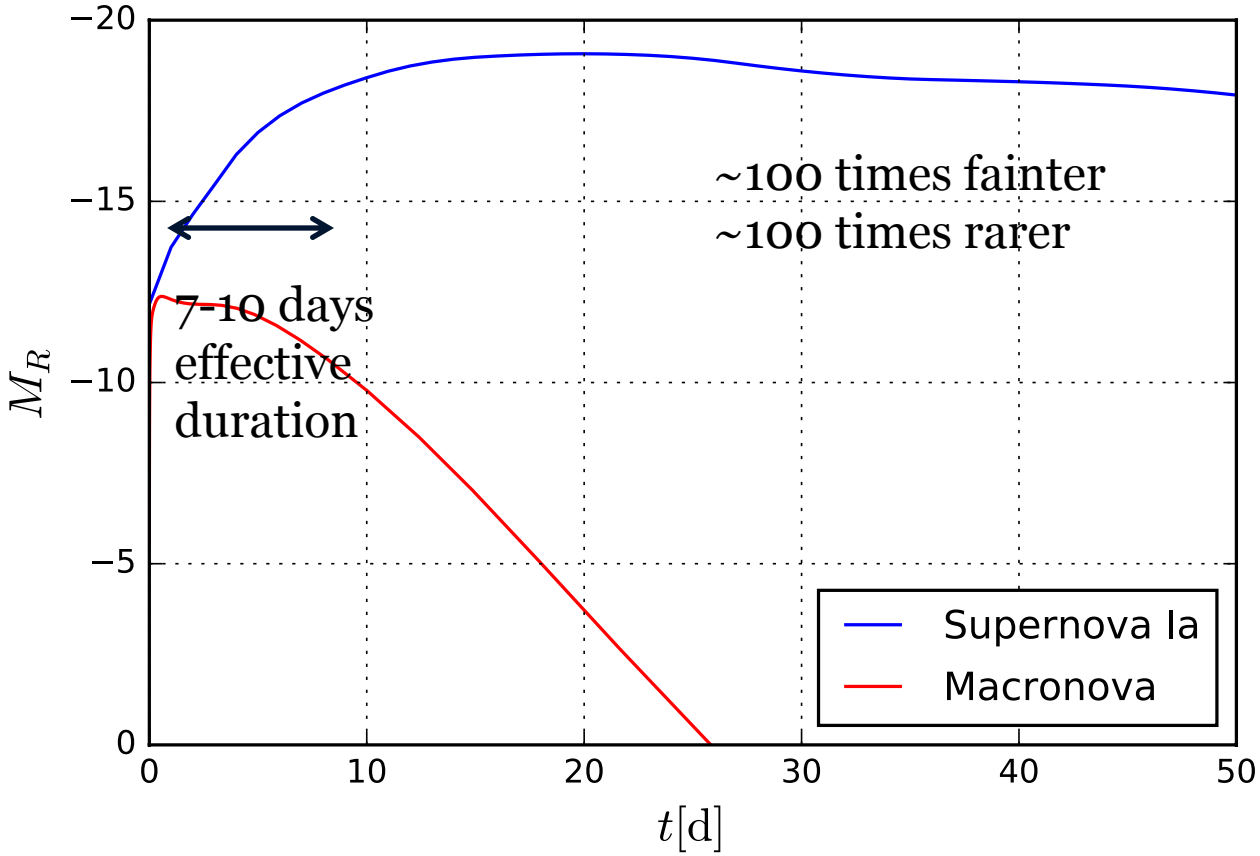


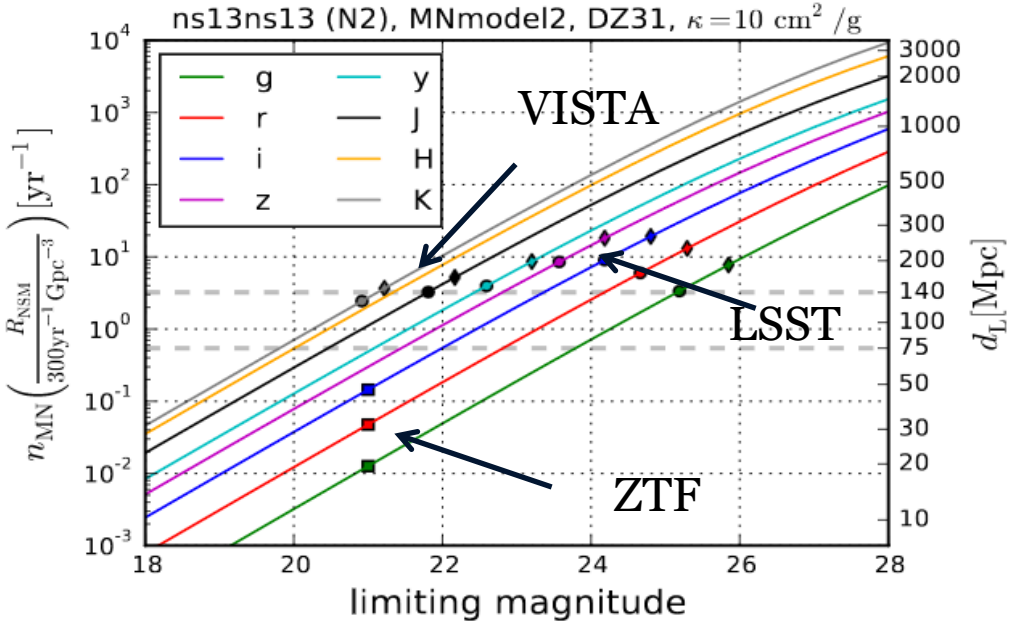
Figure 3. Electron fraction in a 1.3-1.3 $M_{\odot}$ merger (model N2; only matter below orbital plane shown) at t= 7.06, 11.6 and 12.4 ms.

Merger of
neutron star- neutron star or
black hole- neutron star

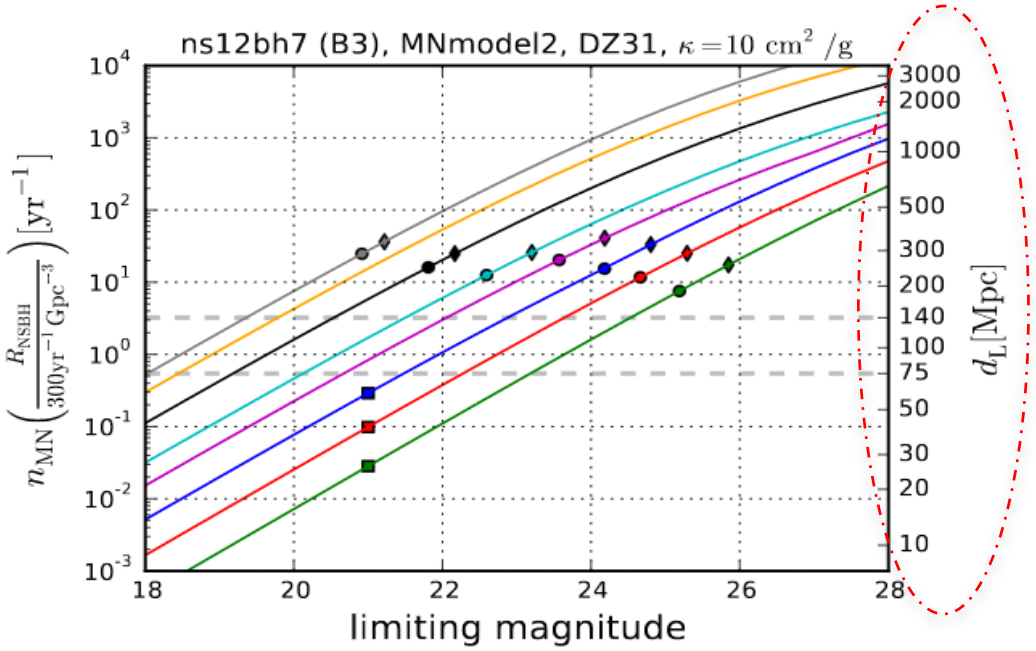
Rosswog et al 2017

Model prediction: Rare, Faint, Red and Fast!





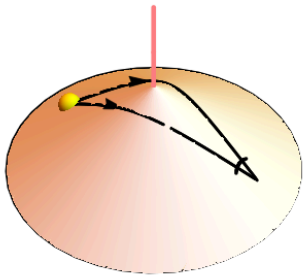
Rosswog et al 2017

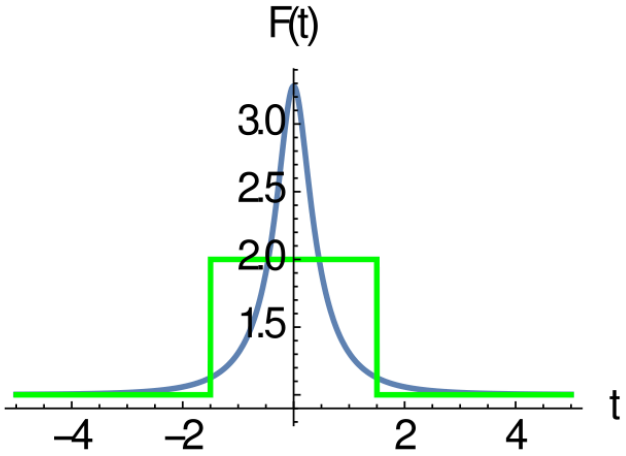


Exotic transients?

- Microlensing of stars by *early universe relics*. Very short time scales (**seconds or minutes!**) may be expected.

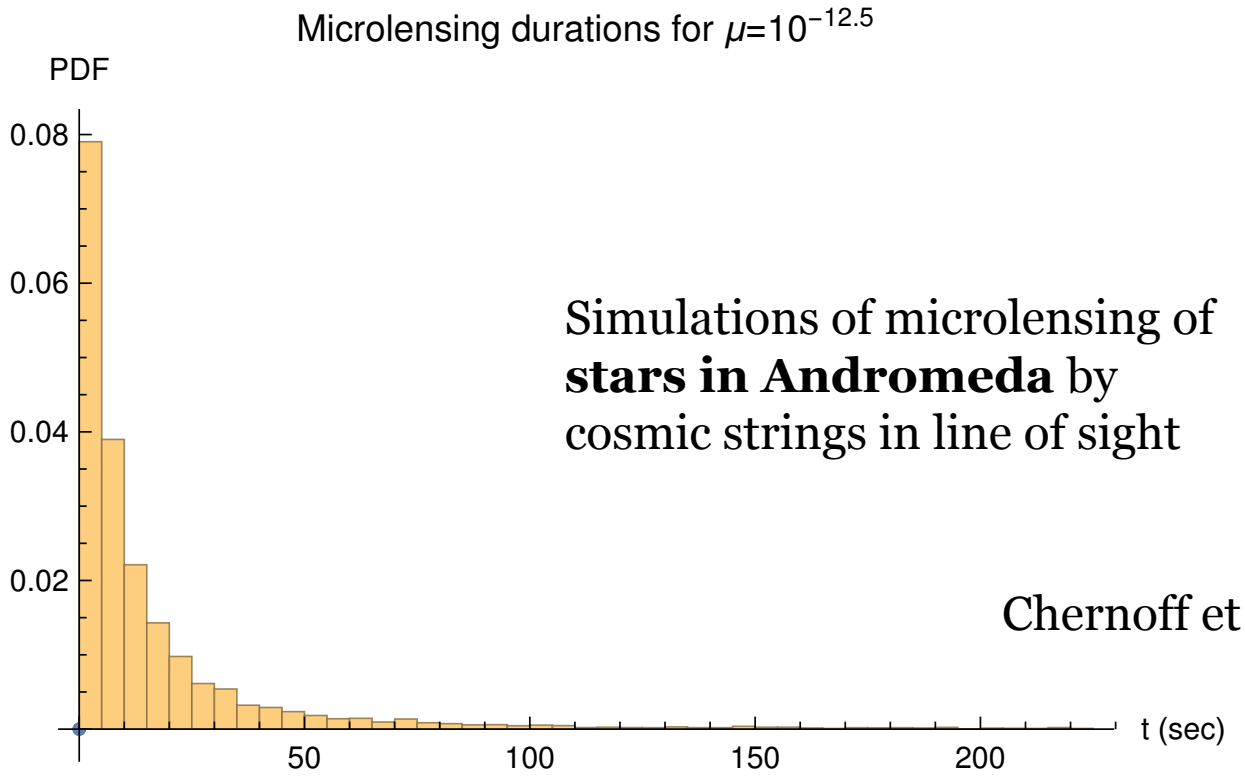
- **Cosmic Strings**, cosmological defects from Early Universe.





Chernoff & Tye

Short time scales: new frontier (I)



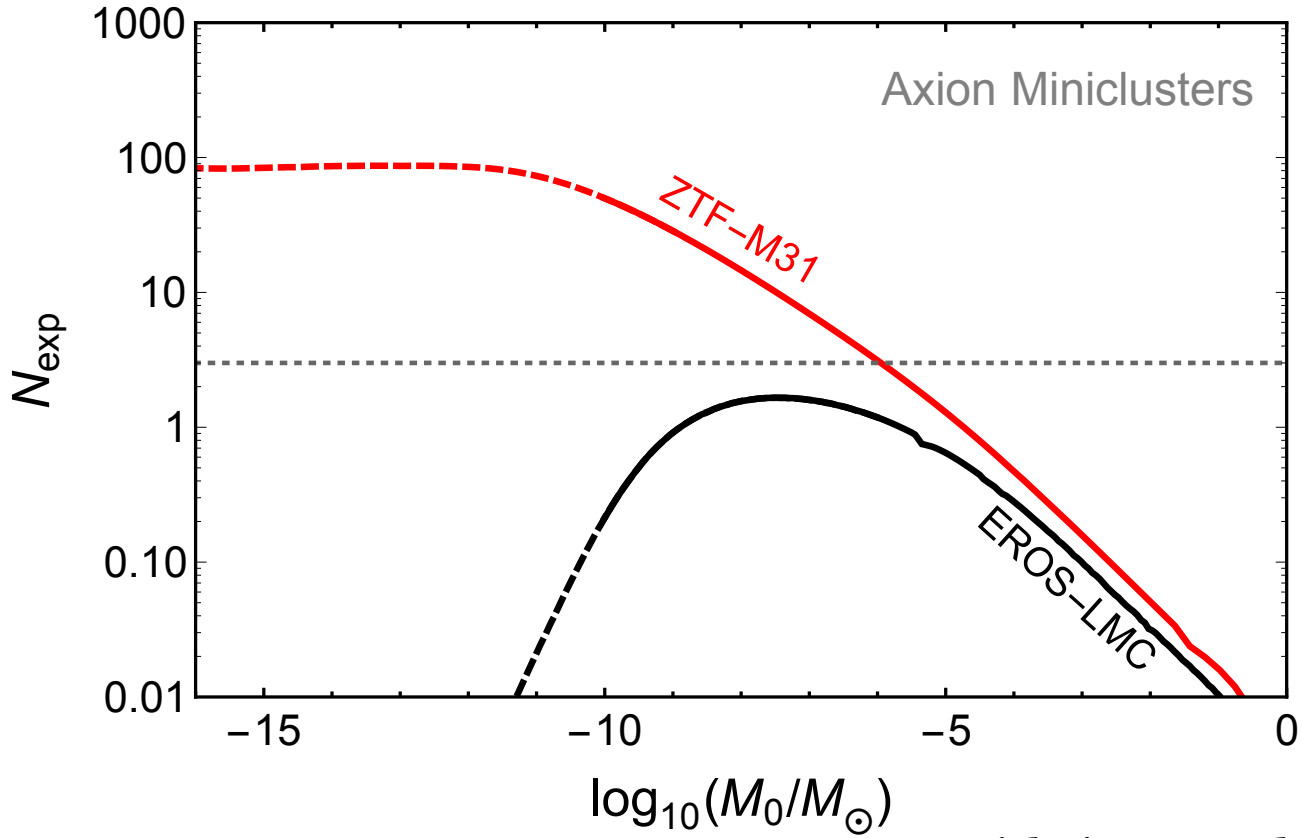
Simulations of microlensing of **stars in Andromeda** by cosmic strings in line of sight

Chernoff et al, *in prep*

Time scale depends on string tension, μ

Short time scales: new frontier (II)

- Gravitational microlensing by **Axion "miniclusters" (+ similar efficiency for light PBHs)**



Fairbairn, Marsh & Quevillon

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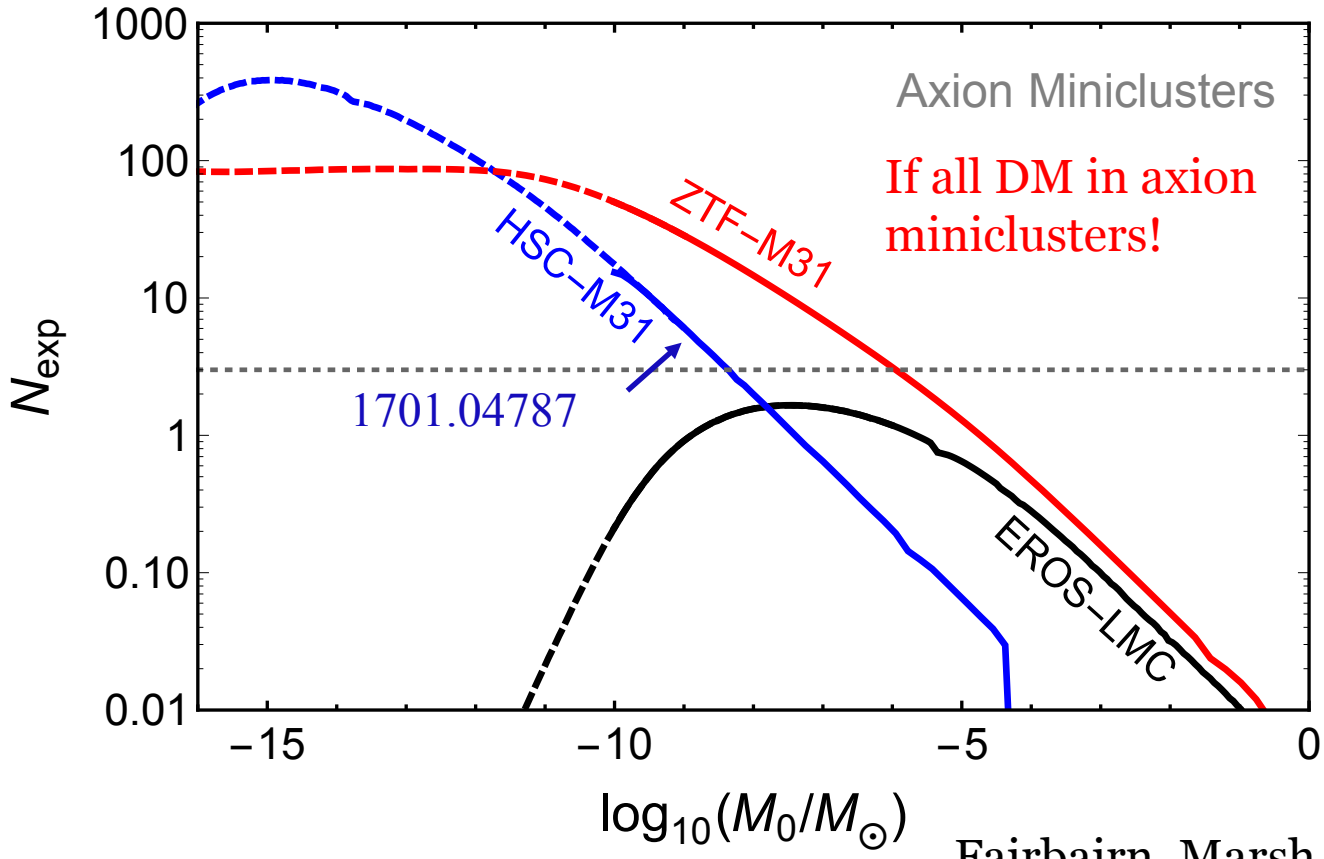

Fairbairn, Marsh & Quevillon

What's new?

- Monitoring of nearly the whole sky over much shorter time scales than ever before, down to seconds. *E.g., short time microlensing, onset of supernovae, anchor sample for SNIa cosmology + systematics.*

- Potential to discover very rare and possibly yet unknown phenomena. *E.g., gravitational lensing of standard candles in poorly explored length scales + H_0; GW-EM counterparts, microlensing by early universe relics, etc.*

- Bottle-neck? limited resources to follow-up the large number of discoveries. Have a telescope? Want to collaborate?

Oskar Klein centre

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- **Please talk to me if you have other ideas for what we should be looking for with ZTF/LSST!**

Thank you!