EXCELENCIA SEVERO OCHOA

DARK ENERGY SURVEY

Prospects and reasons for finding Planet 9 in **DES** data

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IFAE

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Non-DE physics with the DES

DES 2015-0085
FERMILAB-PUB-16-003-AE

Mon. Not. R. Astron. Soc. 000, 1–?? (2002) Printed 27 January 2016 (MN LaTeX style file v2.2)

The Dark Energy Survey: more than dark energy - an overview

Dark Energy Survey Collaboration: T. Abbott[1], F. B. Abdalla[2], S. Allam[3], J. Aleksić[50], A. Amara[4], D. Bacon[6], E. Balbinot[49], M. Banerji[7,8], K. Bechtol[59,60], A. Benoit-Lévy[15,2,14], G. M. Bernstein[10], E. Bertin[14,15], J. Blazek[16], S. Dodelson[3,29,61], C. Bonnett[17], D. Brooks[2], S. Bridle[18], R. J. Brunner[44,22], E. Buckley-Geer[3], D. L. Burke[11,19], D. Capozzi[6], G. B. Caminha[54,55], J. Carlsen[6], A. Carnero-Rosell[20,21], M. Carollo[57], M. Carrasco-Kind[22,23], J. Carretero[9,50], F. J. Castander[9], L. Clerkin[2], T. Collett[6], C. Conselice[58], M. Crocce[9], C. E. Cunha[11], C. B. D'Andrea[6], L. N. da Costa[21,20], T. M. Davis[52], S. Desai[26,27], H. T. Diehl[3], J. P. Dietrich[28,26], P. Doel[2], A. Drlica-Wagner[3], J. Etherington[6], J. Estrada[3], A. E. Evrard[24,31], J. Fabbri[2], D. A. Finley[3], B. Flaugher[3], P. Fosalba[9], R. J. Foley[23,44], J. Frieman[29,3], J. García-Bellido[46], E. Gaztanaga[9], D. W. Gerdes[24], T. Giannantonio[8,7], D. A. Goldstein[47,40], D. Gruen[19,11], R. A. Gruendl[22,23], P. Guarnieri[6], G. Gutierrez[3], W. Hartley[4], K. Honscheid[16,34], B. Jain[10], D. J. James[1], T. Jeltema[56], S. Jouvel[2], R. Kessler[29], A. King[52], D. Kirk[2], R. Kron[29], K. Kuehn[35], N. Kuropatkin[3], O. Lahav[2,⋆], T. S. Li[25], M. Lima[21,37], H. Lin[3], M. A. G. Maia[21,20], M. Makler[54], M. Manera[2], C. Maraston[6], J. L. Marshall[25], P. Martini[16,38], R. G. McMahon[7,8], P. Melchior[5], A. Merson[2], C. J. Miller[31,24], R. Miquel[39,50], J. J. Mohr[32,27,26], X. Morice-Atkinson[6], K. Naidoo[2], E. Neilsen[3], R. C. Nichol[6], B. Nord[3], R. Ogando[21,20], F. Ostrovski[7,8], A. Palmese[2], A. Papadopoulos[6,51], H. Peiris[2], J. Peoples[3], A. A. Plazas[30], W. J. Percival[6], S. L. Reed[7,8], A. K. Romer[41], A. Roodman[19,11], A. Ross[16], E. Rozo[62], E. S. Rykoff[11,19], I. Sadeh[2], M. Sako[10], C. Sánchez[50], E. Sanchez[33], B. Santiago[48], V. Scarpine[3], M. Schubnell[24], I. Sevilla-Noarbe[33,23], E. Sheldon[43], M. Smith[53], R. C. Smith[1], M. Soares-Santos[3], F. Sobreira[3,21], M. Soumagnac[2], E. Suchyta[10], M. Sullivan[53], M. Swanson[63], G. Tarle[24], J. Thaler[44], D. Thomas[6,45], R. C. Thomas[40], D. Tucker[3], J. D. Vieira[23,44,22], V. Vikram[36], A. R. Walker[1], R. H. Wechsler[11,19], W. Wester[3], J. Weller[32,26,28], L. Whiteway[2], H. Wilcox[6], B. Yanny[3], Y. Zhang[24], J. Zuntz[18]

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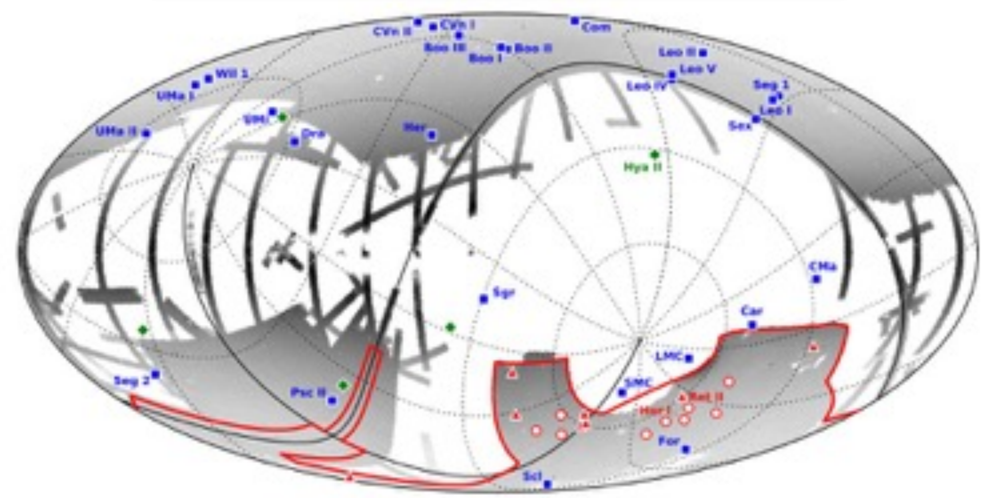
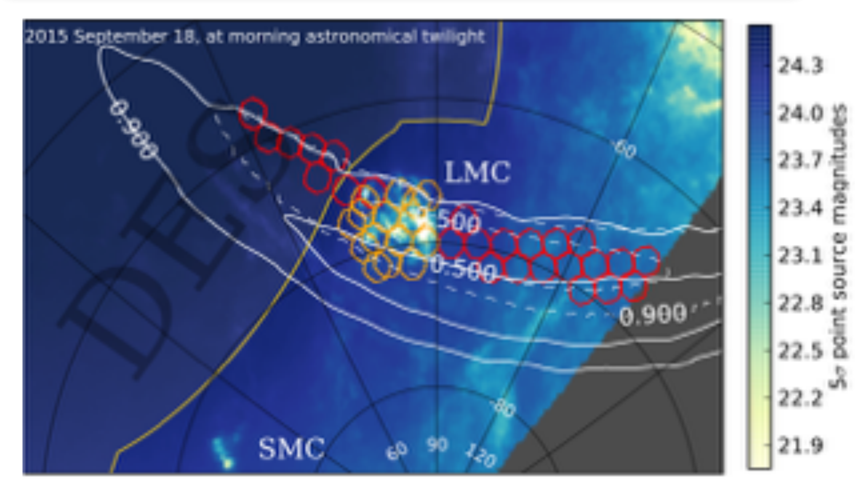
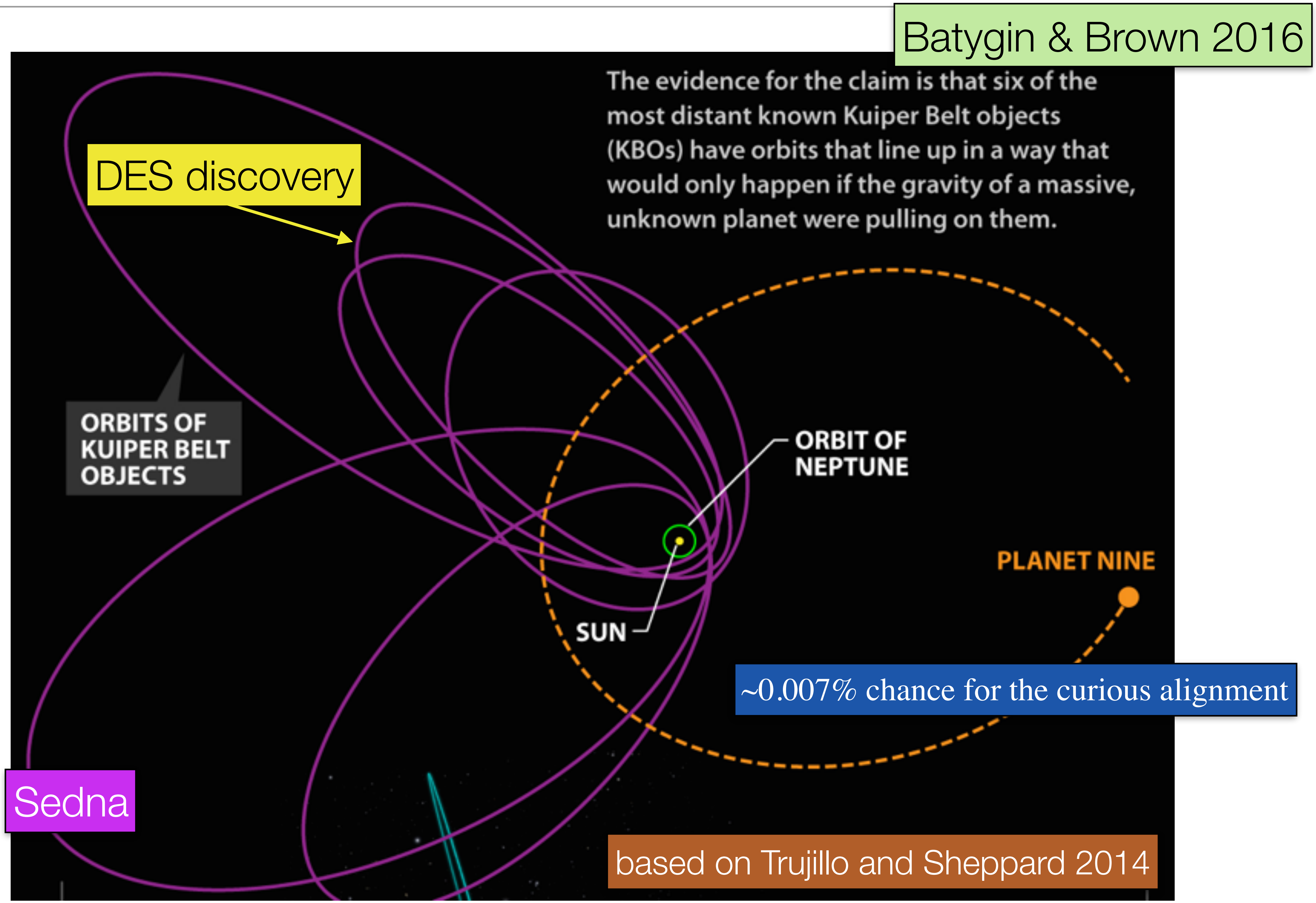
MW dwarf galaxies



GW150914 follow-up

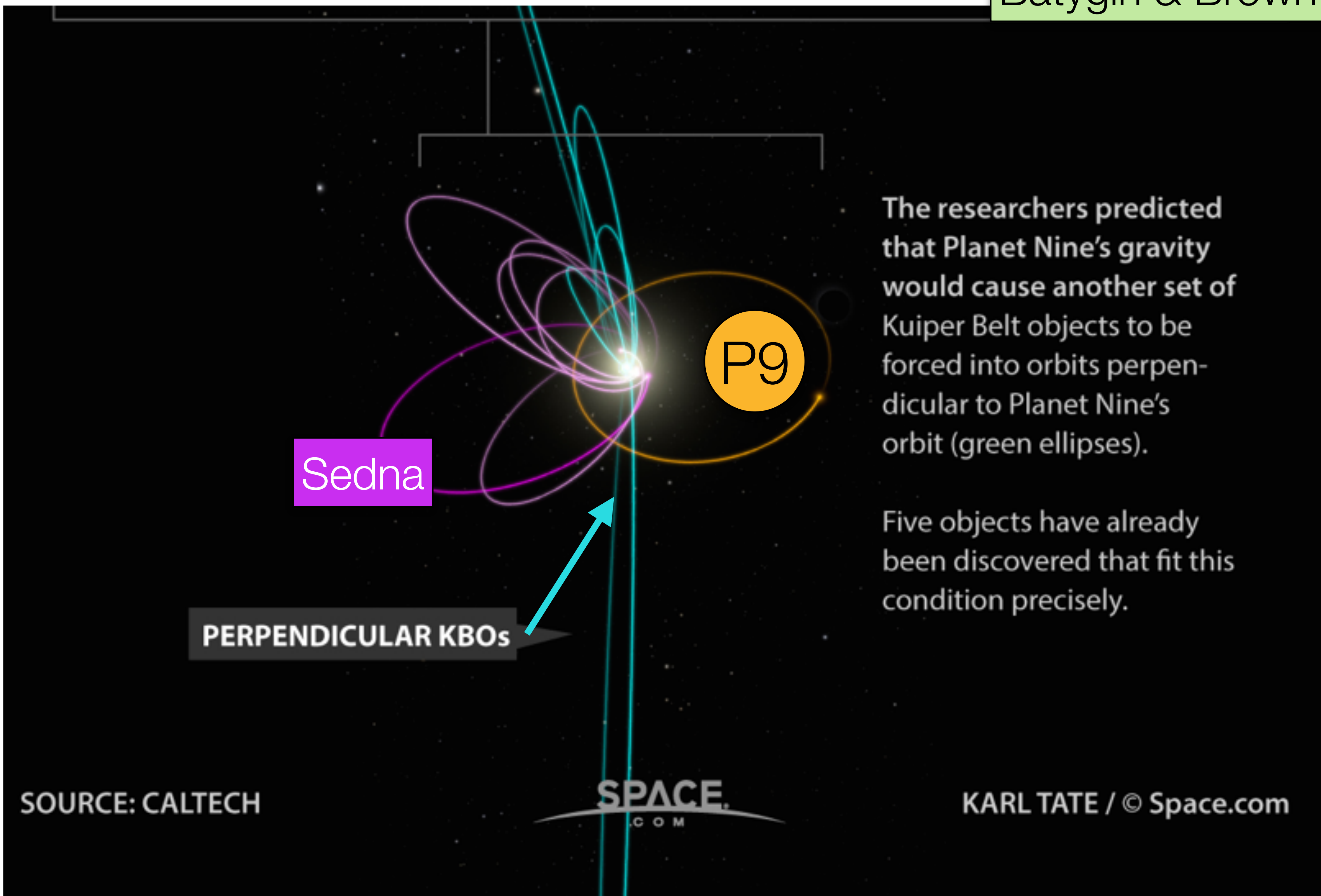


Existing evidence for P9

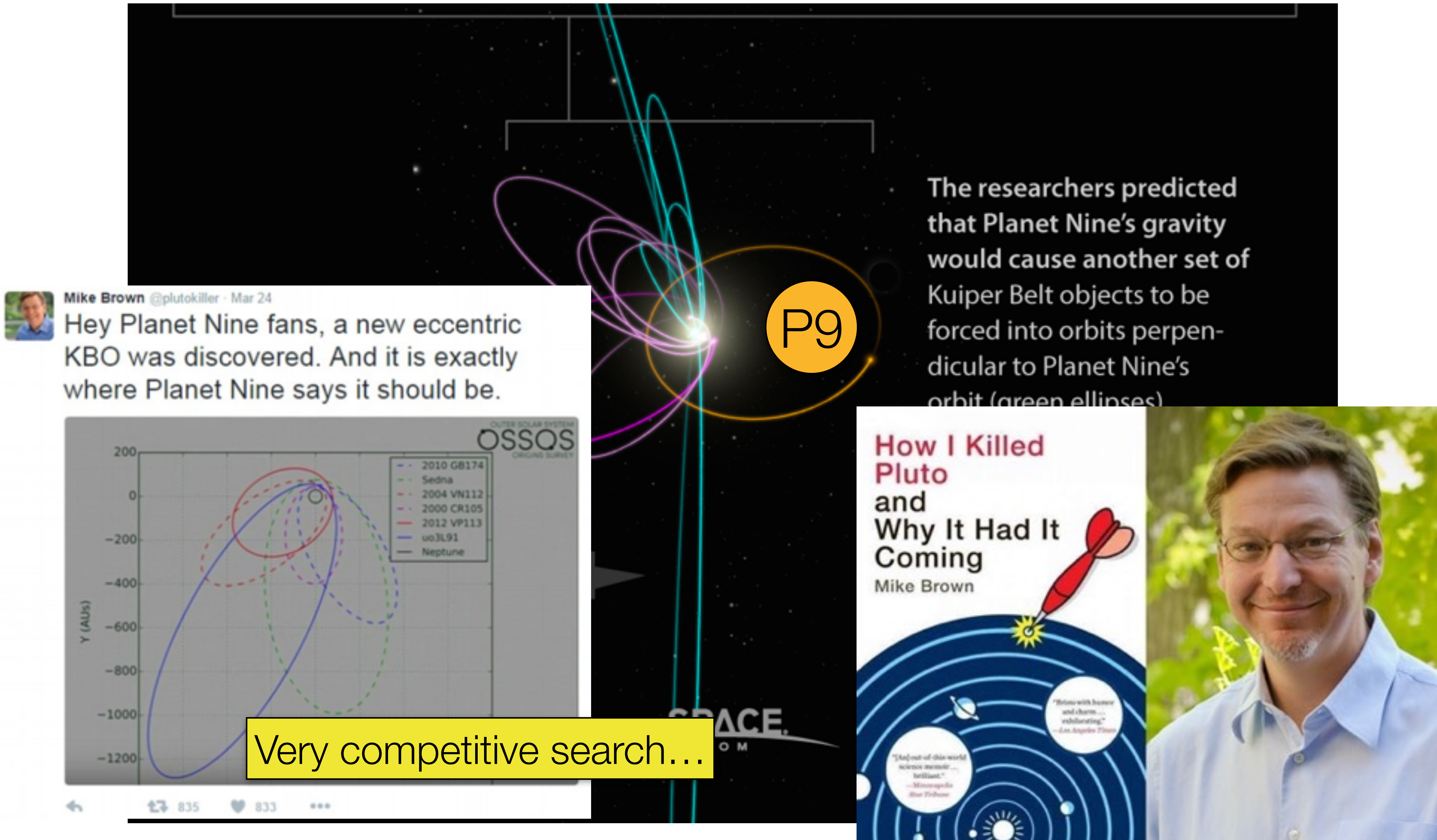


Possible evidence for P9

Batygin & Brown 2016



Possible evidence for P9



Very competitive search…

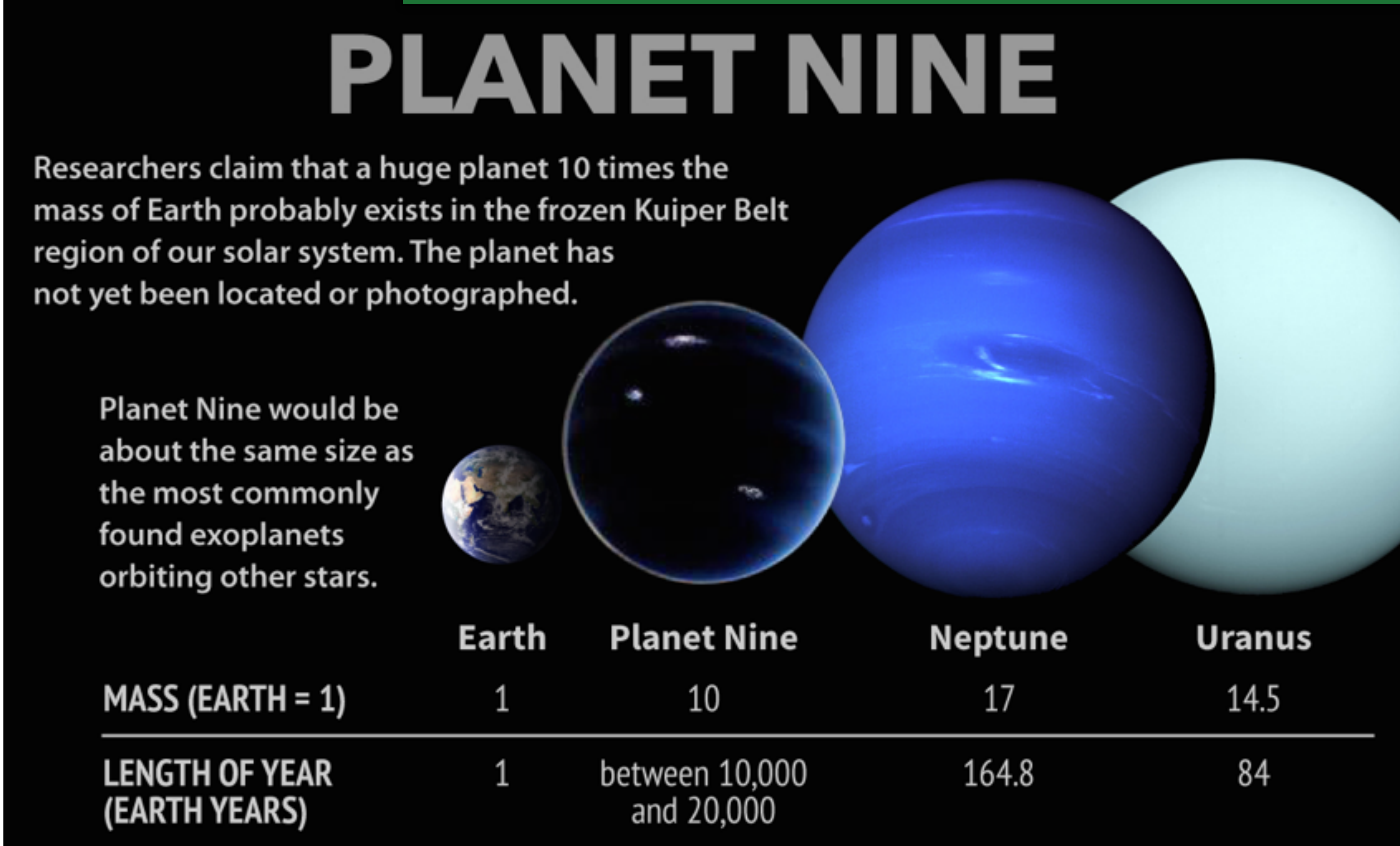
What Is Planet Nine?

- A ~10 earth-mass planet with a~700 AU, e~0.6, i~30 deg., whose orbit is anti-aligned with the observed distant, aligned TNOs.
- Stabilizes the observed alignment on timescales comparable to the age of the Solar System.
- Its present position in its orbit is *a priori* unknown.

slides by David Gerdes

Is this a big deal? What does it look like?

Strong constraints from the WISE infrared all-sky survey



Three Key Predictions

- Distant TNOs with a>250 AU should all cluster in physical space (non-clustering objects should be swept out by P9). DES can address this!

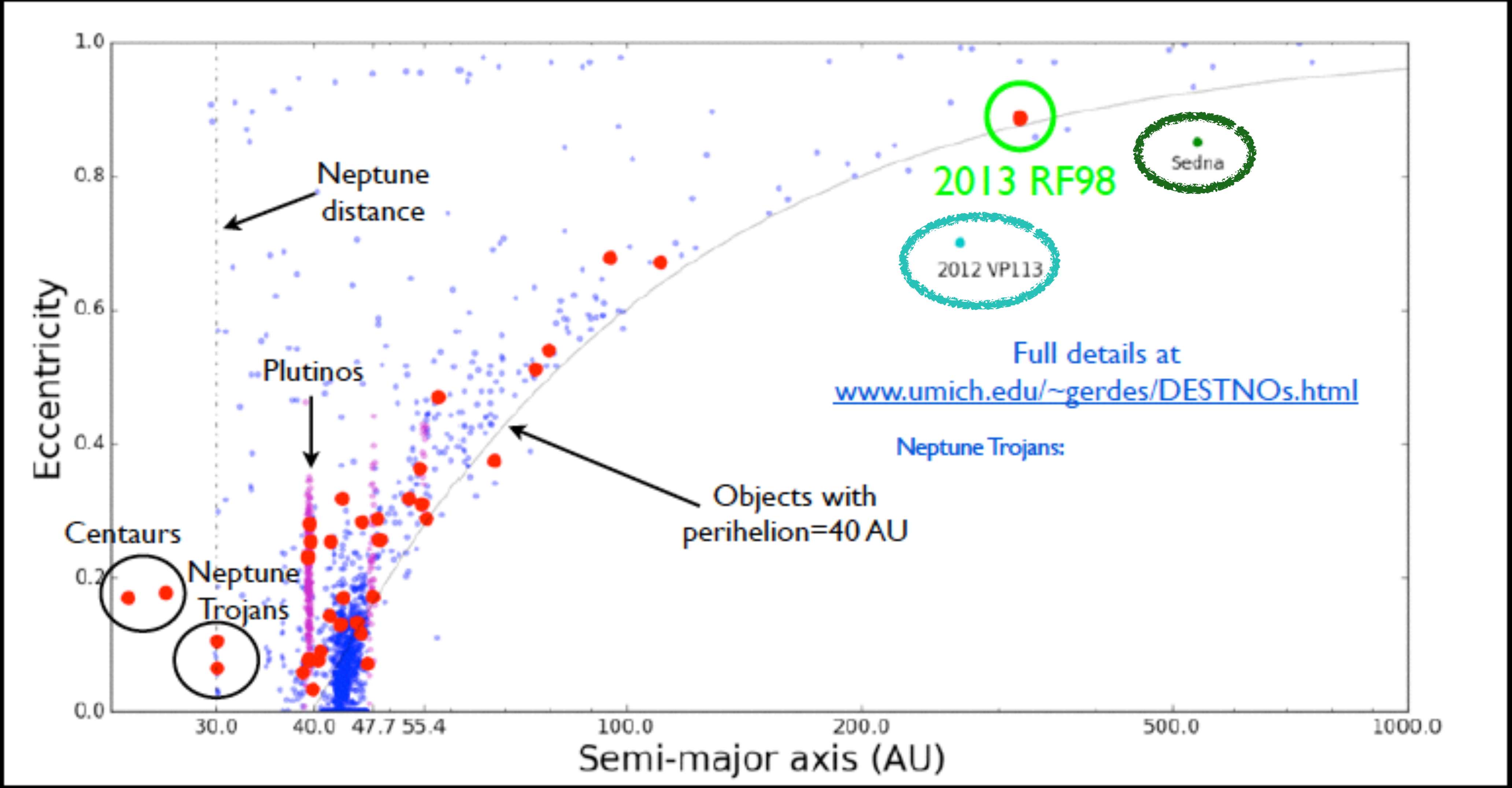
- There exists a population of very distant, detached objects (a>100 AU) that are aligned with P9.
  No such objects known; these are very hard to find.

- There exists a population of very high-inclination (even retrograde) objects on very eccentric orbits that may reach the inner solar system. A few are known; DES can find more given our broad off-ecliptic coverage.

slides by David Gerdes

TNO Search Through Y3

Search initially developed in the SNe fields.
34 (+2 WS) new objects reported to the Minor Planet Center.



slides by David Gerdes

Search in the Wide Survey

- This is where DES can have a transformative impact on the field.

Survey	Dates	Area (deg.^{2})	Depth (r-mag)	Rel. discovery power
Deep Ecliptic Survey	1998-2003	550	22.5	1
Palomar DSSS	2007-8	12,000	21.3	2.4
CFEPS	2003-9	321	23.2	6.2
NGVS	2009-12	76	24.6	6.6
OSSOS	2013-16	168	24.5	12
Sheppard-Trujillo DECam	2012-	800	24.5	58
Pan-STARRs 1	2010-	30,000	22.5	54
DES-SN, conventional	2012-2018	24 shallow, 6 deep	24.1, 24.7	1.5
DES-SN, digital tracking	2012-2018	24 shallow, 6 deep	25.0, 25.6	7.7
DES wide	2012-2018	5000	23.9	**230**

Stephanie Hamilton

- Particularly sensitive to high-inclination TNOs
- Challenges: sparse, irregular cadence; extending difference imaging to wide survey.

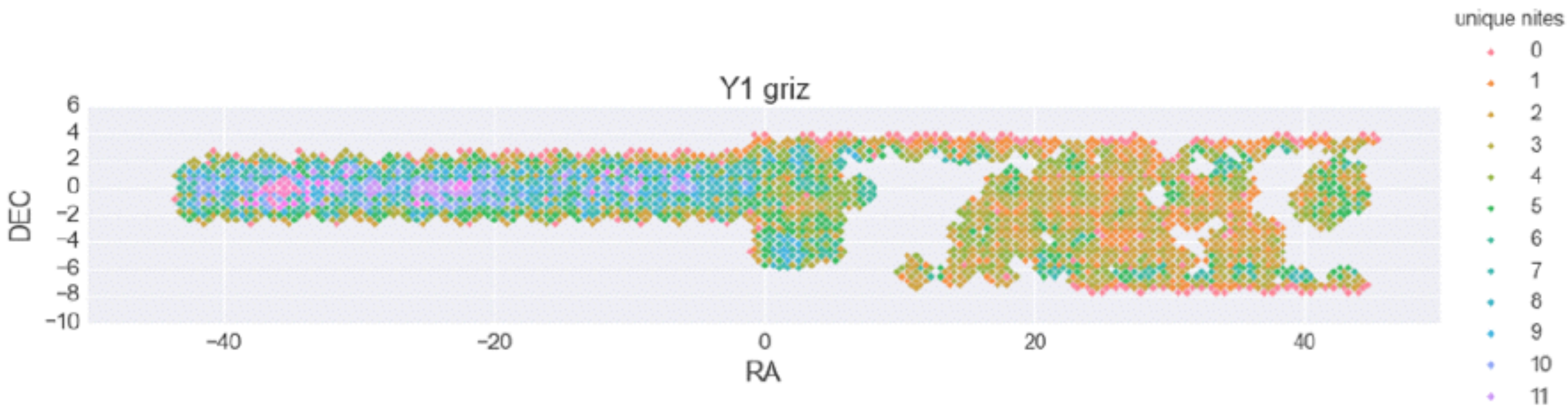
slides by David Gerdes

First Look: Stripe 82

Difference imaging adaptation to WS data by Rick Kessler, Masao Sako and students. A big effort!

2815 exposures in Y1-Y3
3.1 million individual transient detections
240 million triplets to consider

Connect the dots!



Debiasing this selection function will be a challenge!

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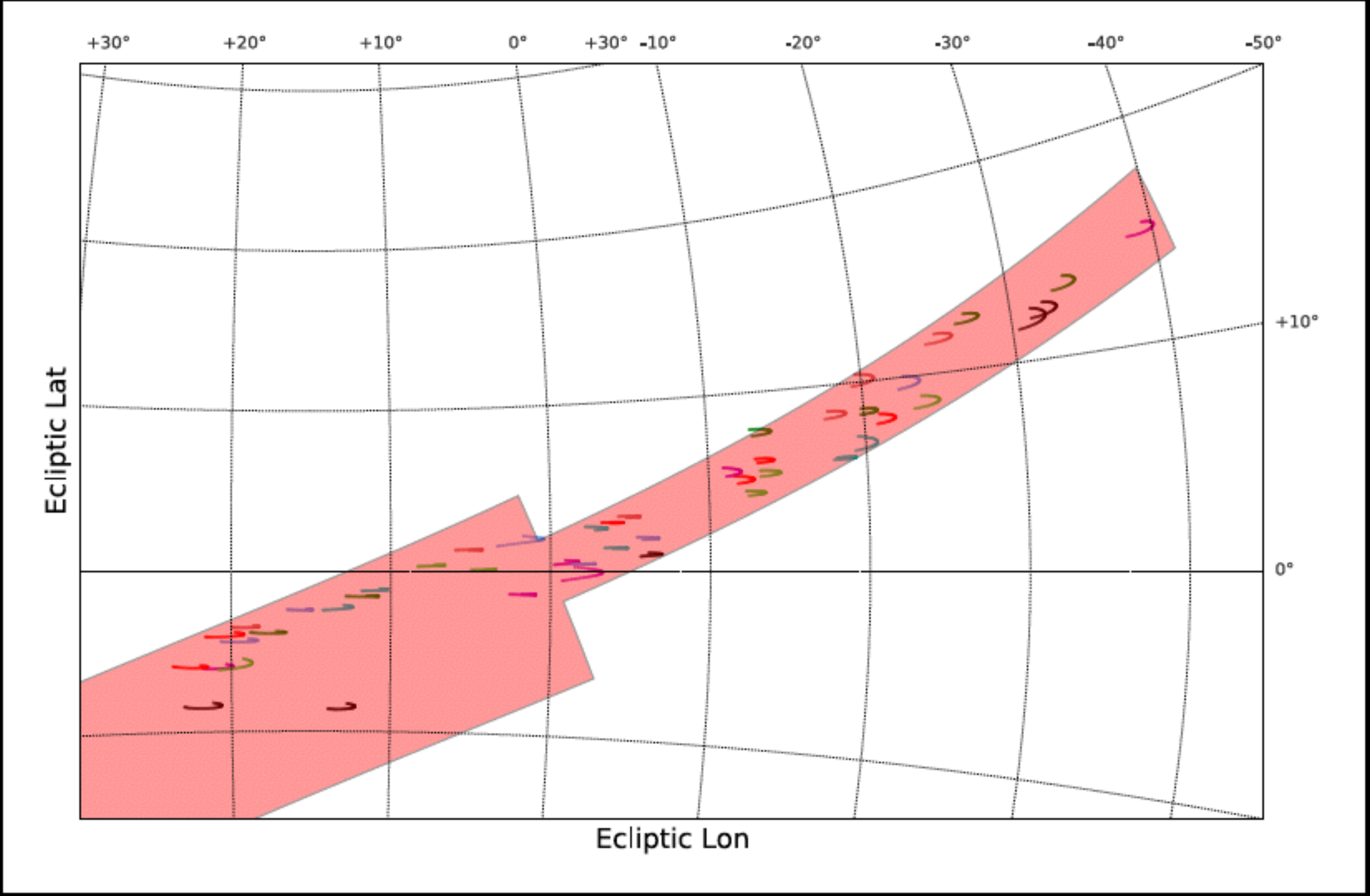
Location within Stripe 82



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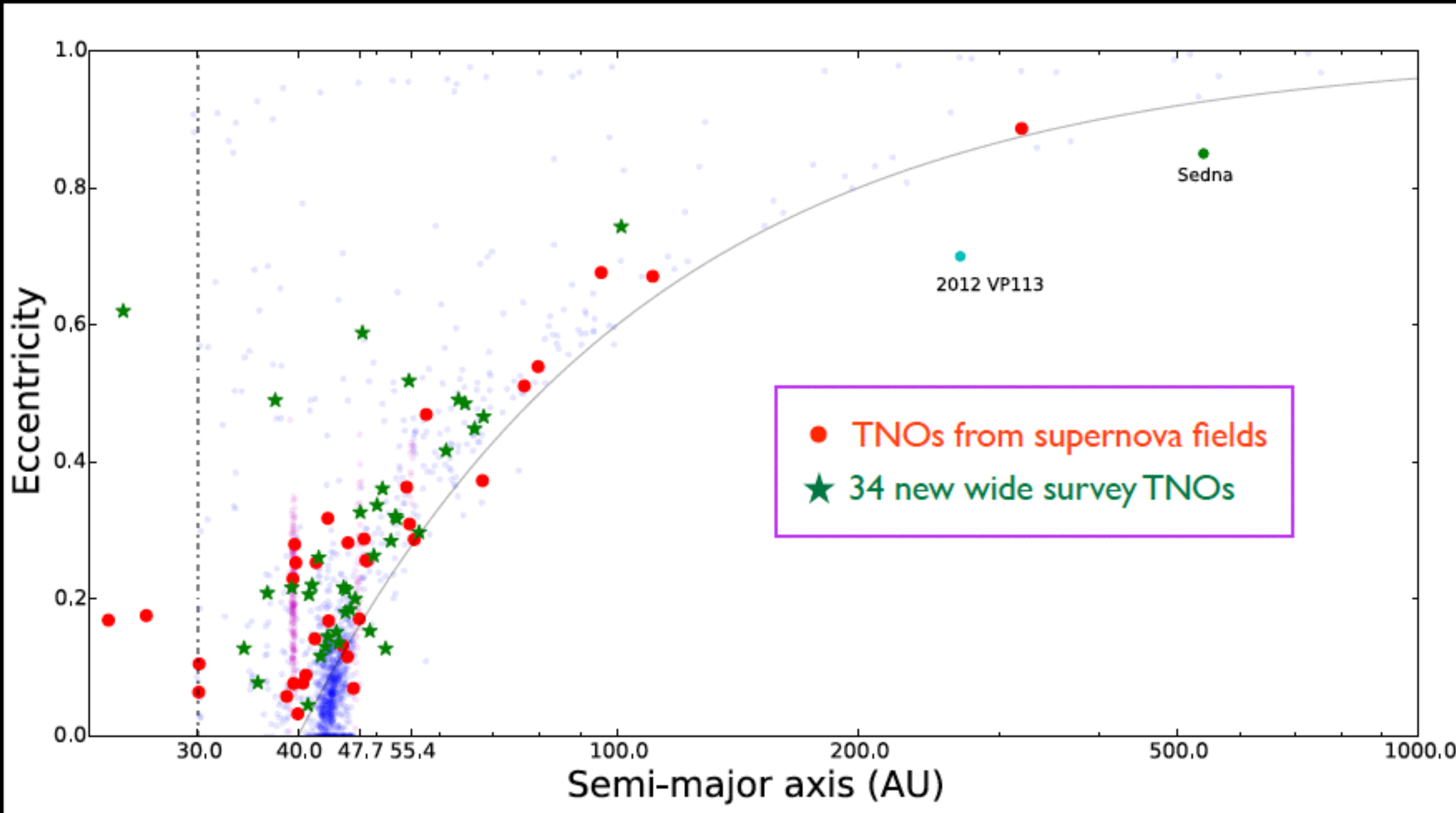
New TNOs in DES data



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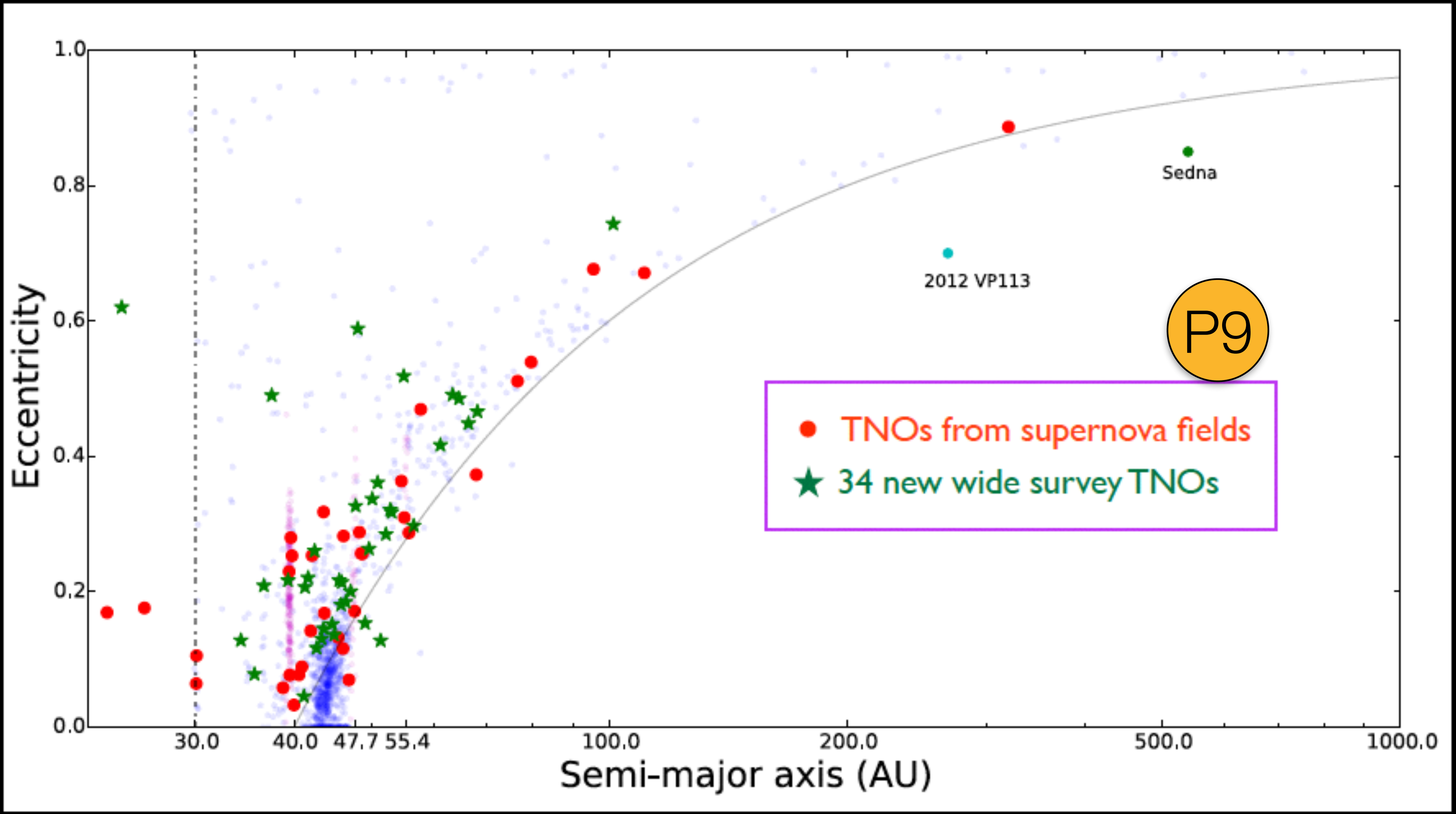
New TNOs in DES data



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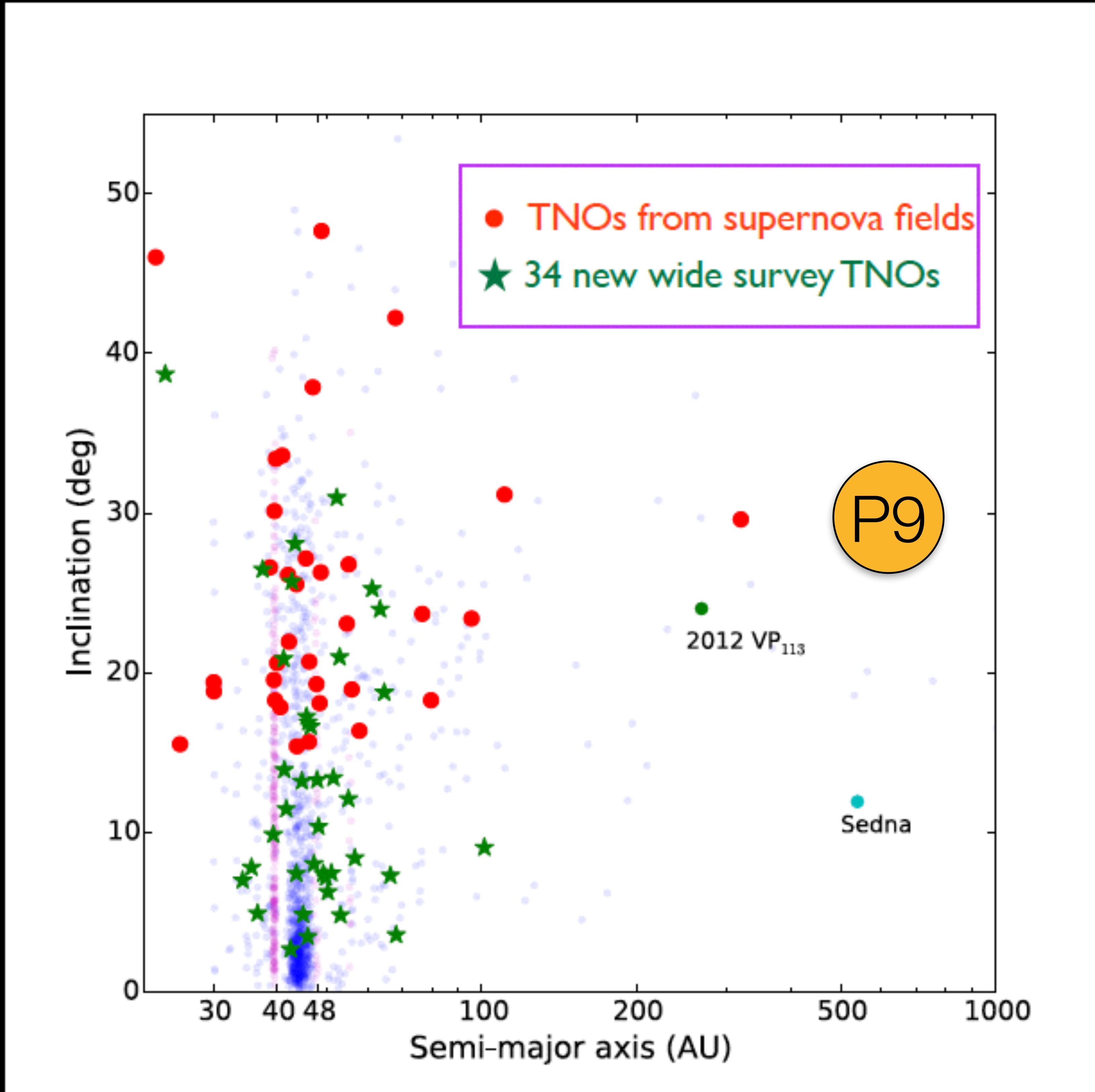
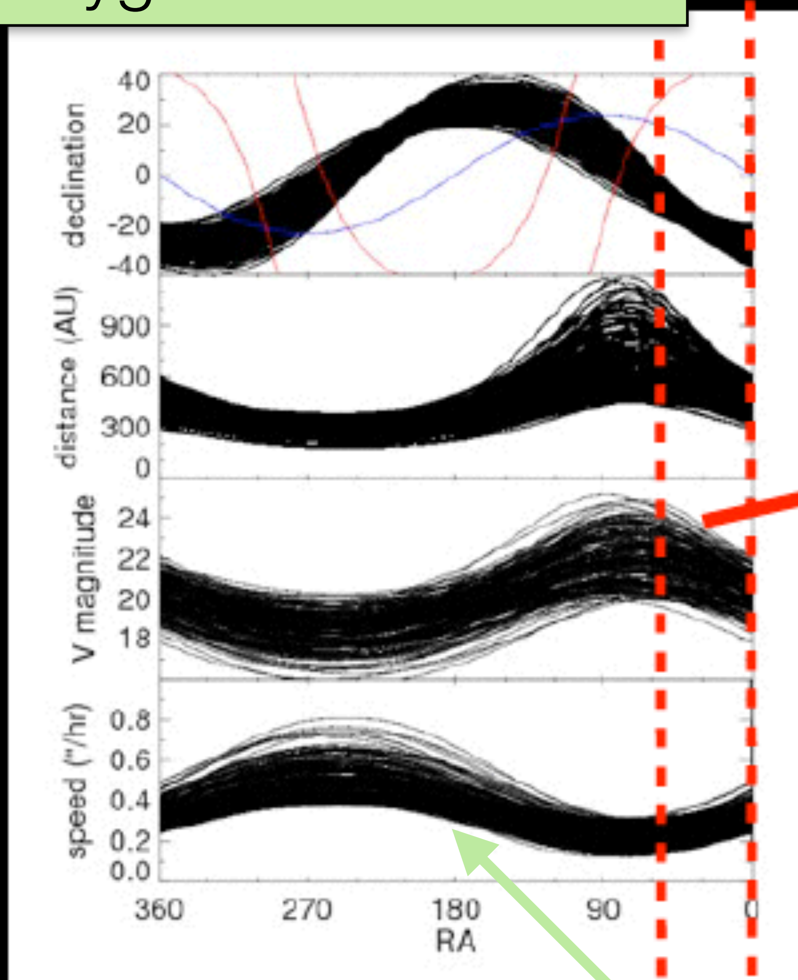
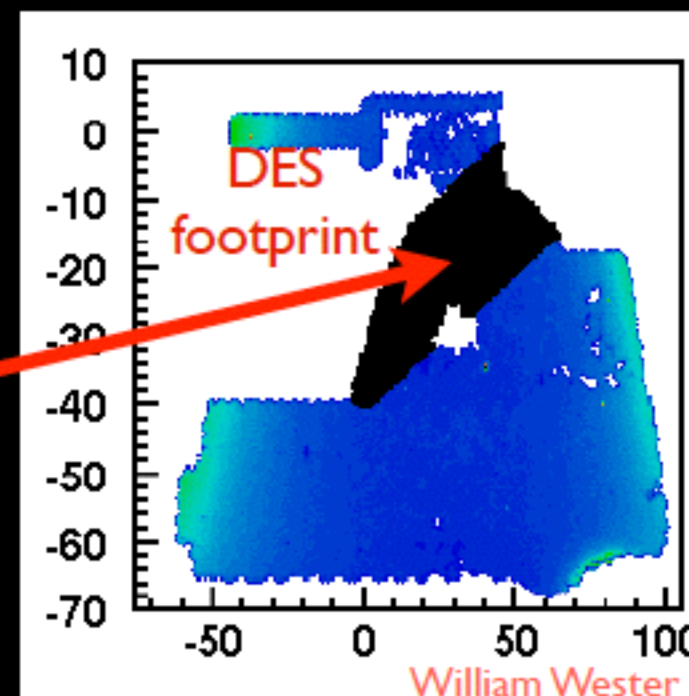

TNOs from supernova fields
34 new wide survey TNOs
P9
2012 VP_{113}
Sedna
Inclination (deg)
Semi-major axis (AU)
0
10
20
30
40
50
30
40 48
100
200
500
1000

Planet Nine
"Treasure Map"

Batygin & Brown 2016





5688 exposures from Y1-Y3

possible orbits from simulations

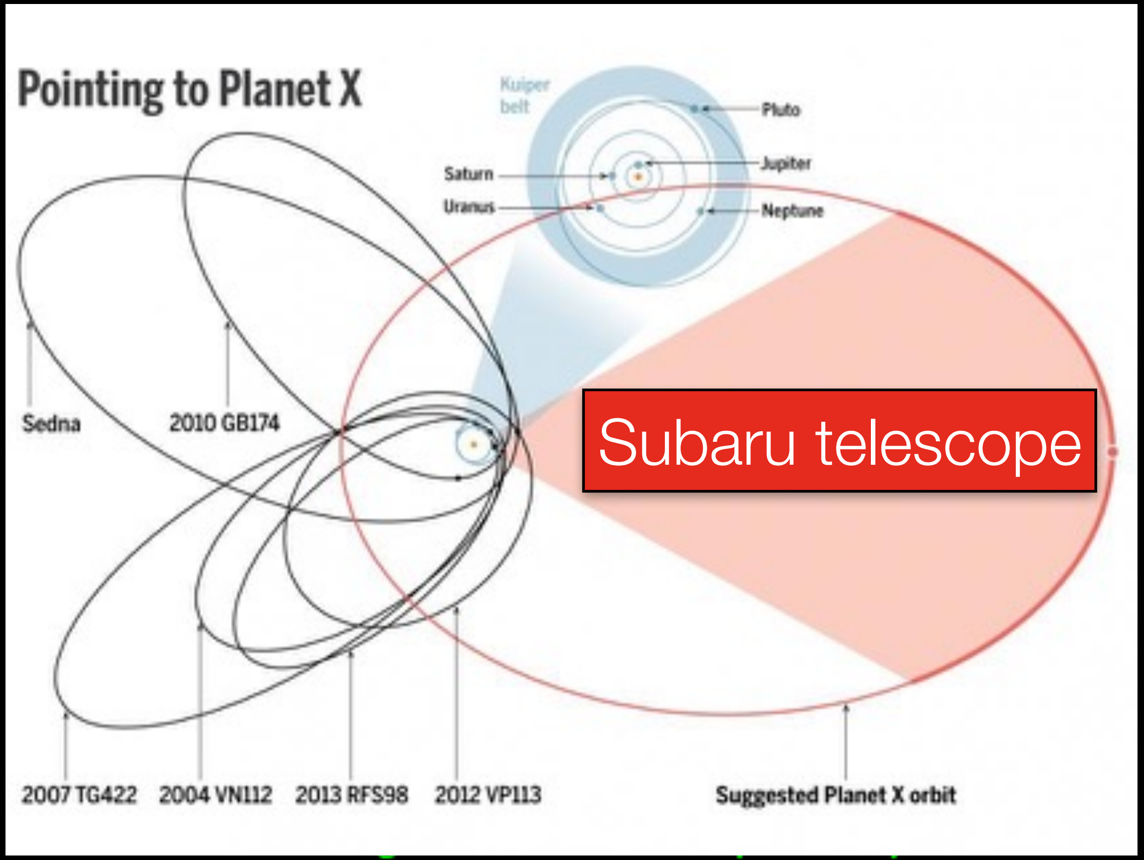
findplanetnine.com

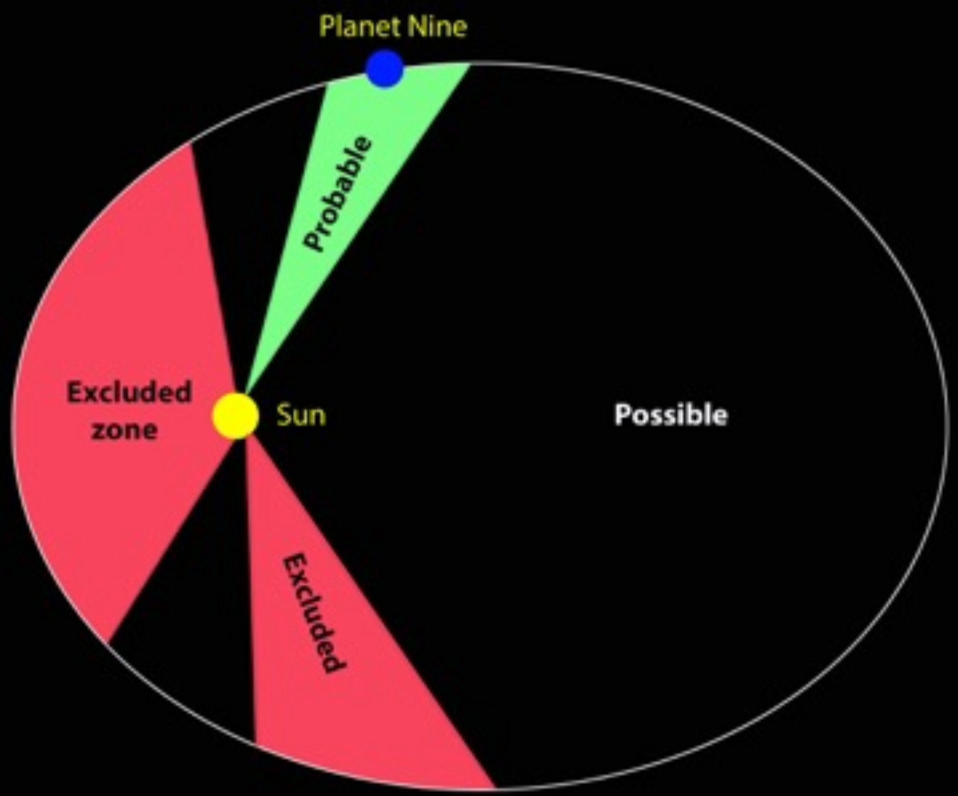
slides by David Gerdes

Constraints from Cassini

Fienga et al. 2016

The Cassini spacecraft has been orbiting the Saturnian system since 2004. Consequently, Earth-Saturn ranging data is good to ~30 meters. Compare residuals to a full post-Newtonian Solar System model with and without Planet 9.





Excluded and possible locations for Planet Nine based on new research

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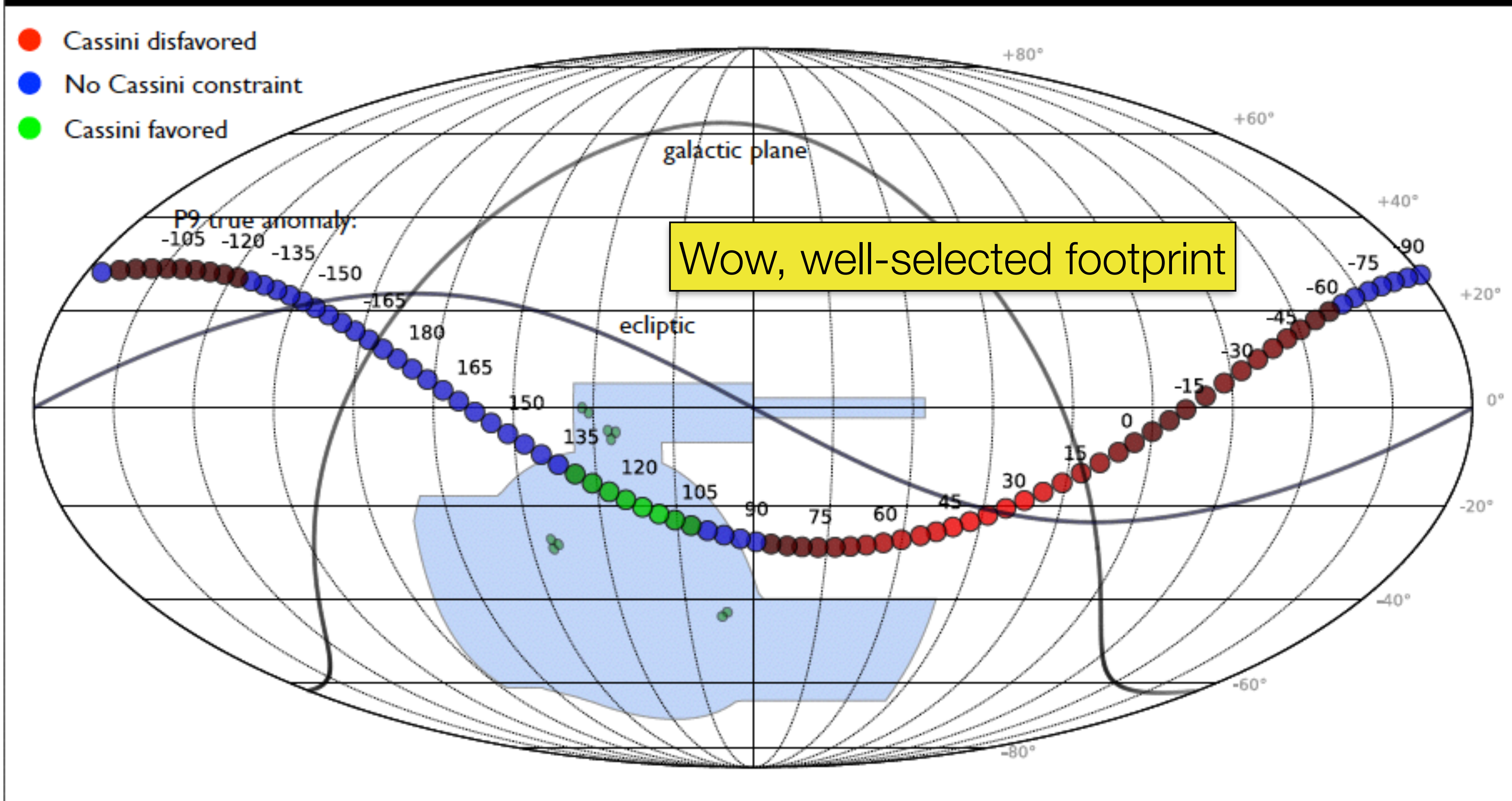
DES footprint vs. P9 position constraints



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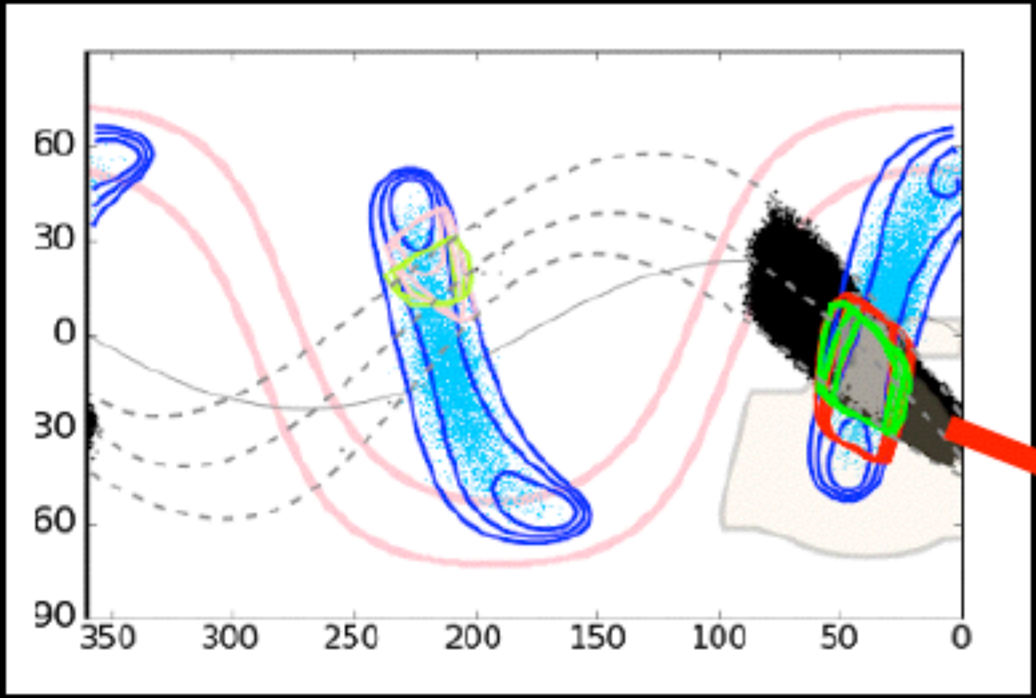
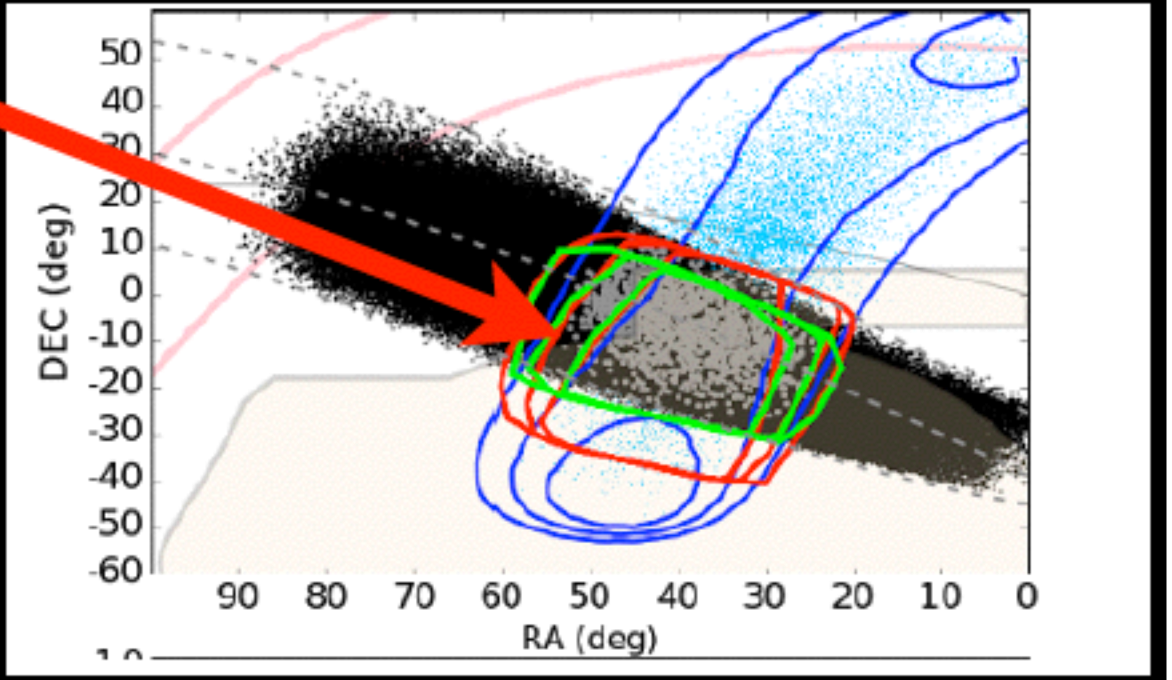
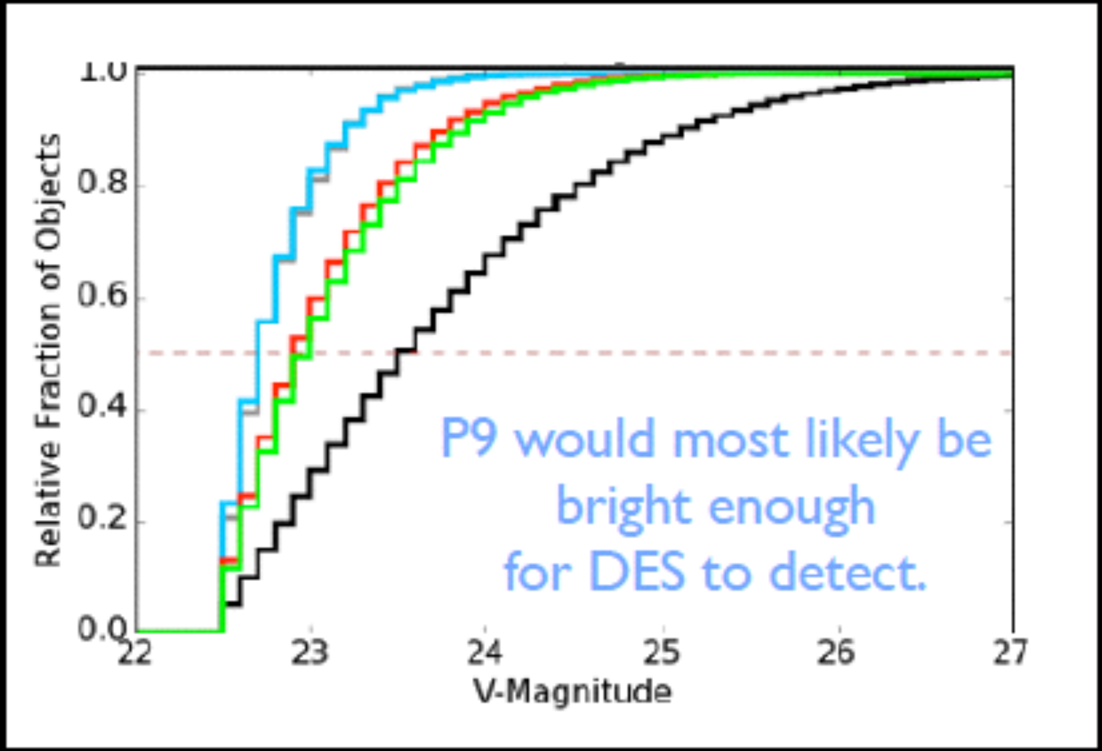
It Gets Better...



Holman & Payne (2016) analyze the same data in the context of a more general tidal perturbation, then fold in the P9 orbital pdfs from Batygin & Brown (2016b).





Let's look **here**.

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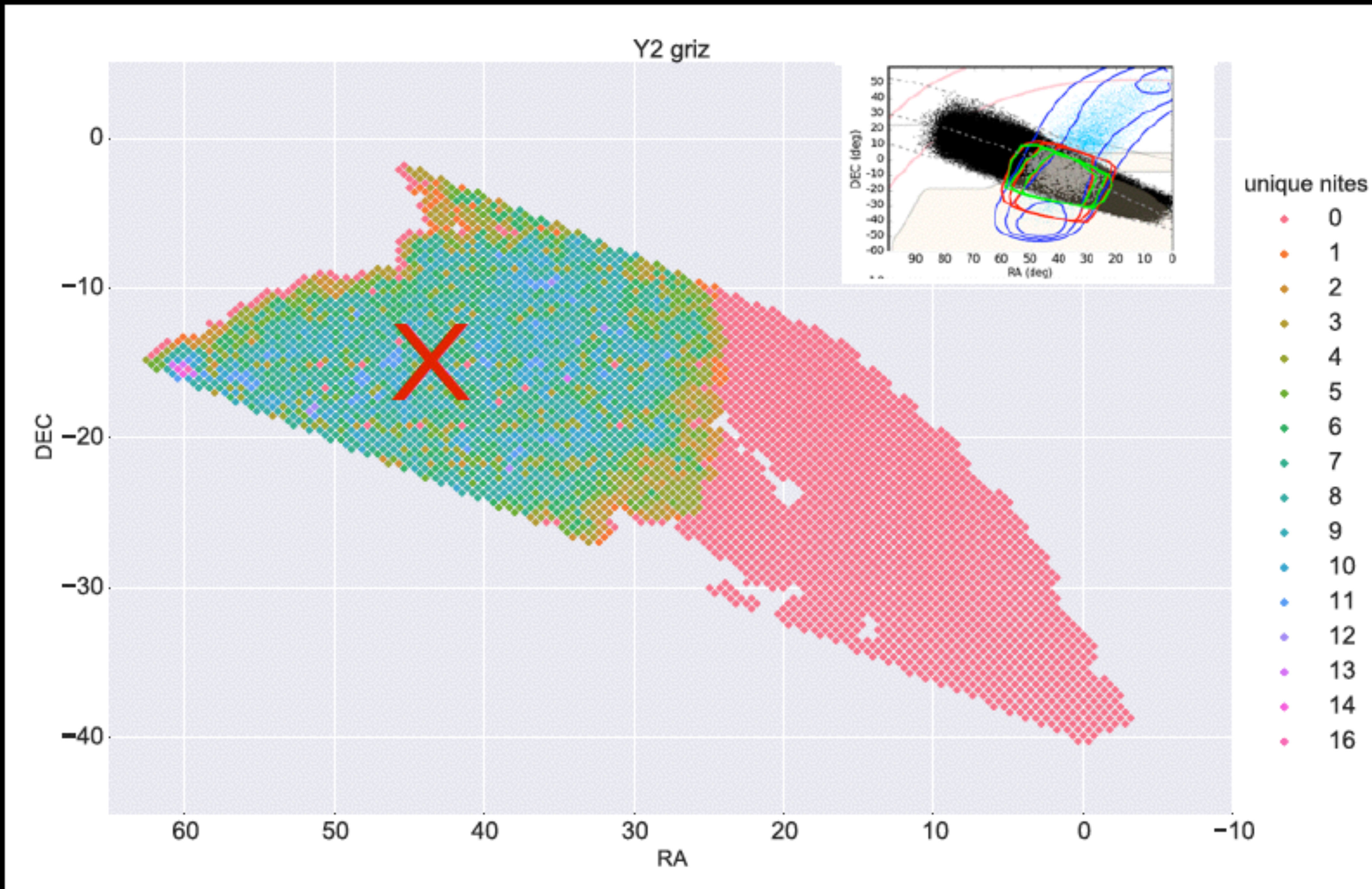
Y2 Coverage



slides by David Gerdes

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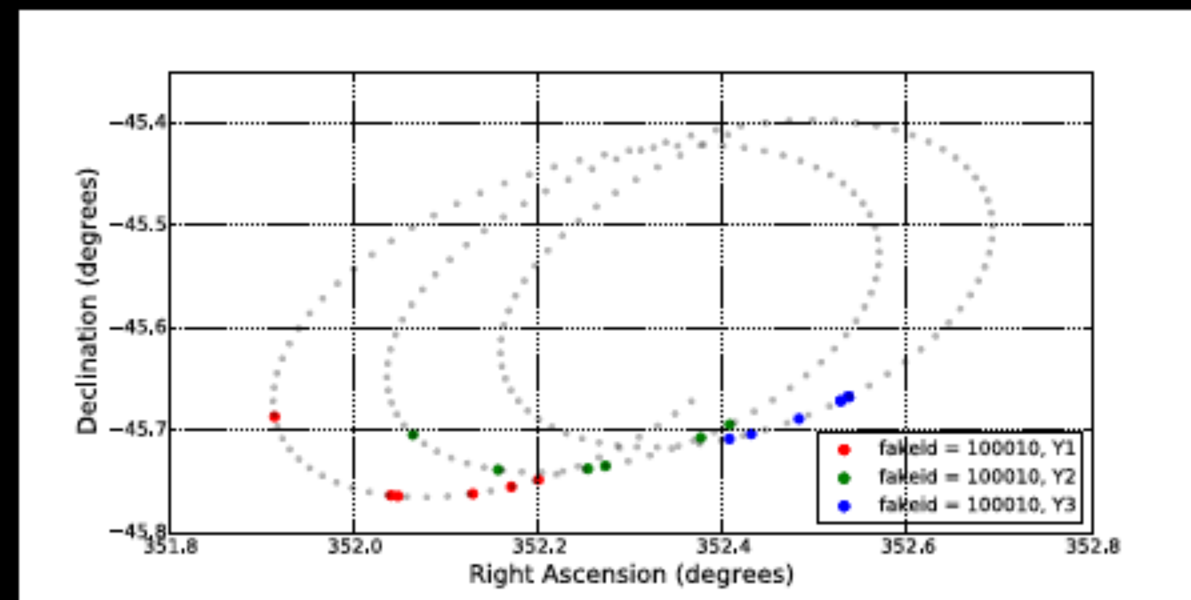
Fake Planet Nines

- 400 < a < 1000 AU
- 0 < i < 40 deg.
- 0.3 < e < 0.8, q_{min}=200 AU
- -8 < H < 0 (mag > ~22)
- Simple color model



motion is 4-8 arcsec/day

Pass these objects through the Y2A1 exposures and generate observations. Positions smeared by 0.15”.

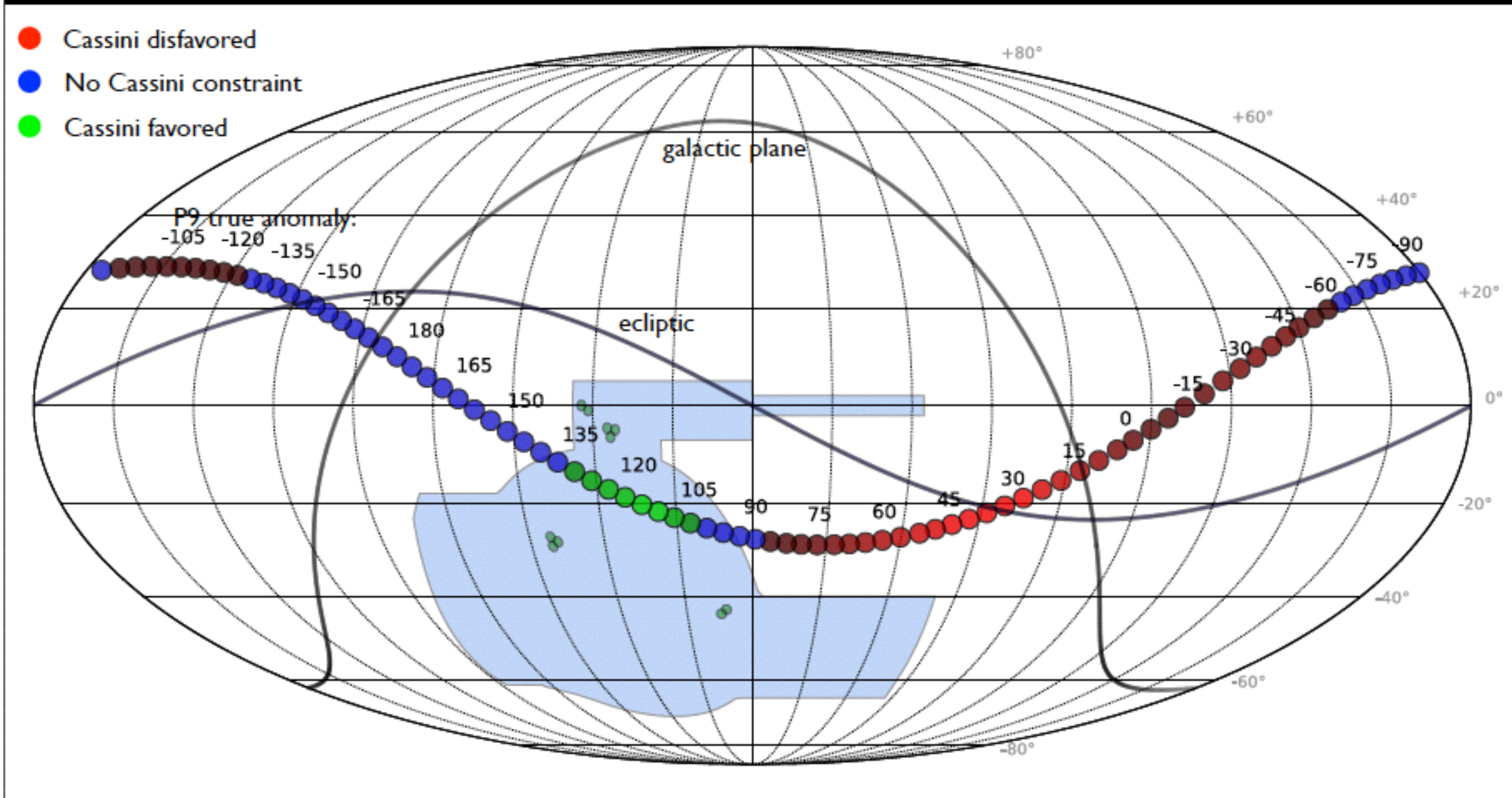
Parameters: number of bands, number of nights, time difference…

Summary

- We have demonstrated the ability to detect TNOs efficiently in both the SNe and Wide Survey fields: 34 in SN fields + 36 and counting in Wide Survey (S82)
- Have found many interesting objects already, including one that adds to the evidence for a distant ninth planet.
- A significant part of the Planet Nine probability map overlaps with our survey, including the region favored by Cassini data.
- If Planet Nine is in our data, we will find it soon! If not, we will place tight constraints.
- In any case, we are almost certain to find more objects that belong to dynamical classes that will test this hypothesis (as well as hundreds of other TNOs).
- Catalog production is in progress. Results on full data set coming this summer.

slides by David Gerdes

DES footprint vs. P9 position constraints



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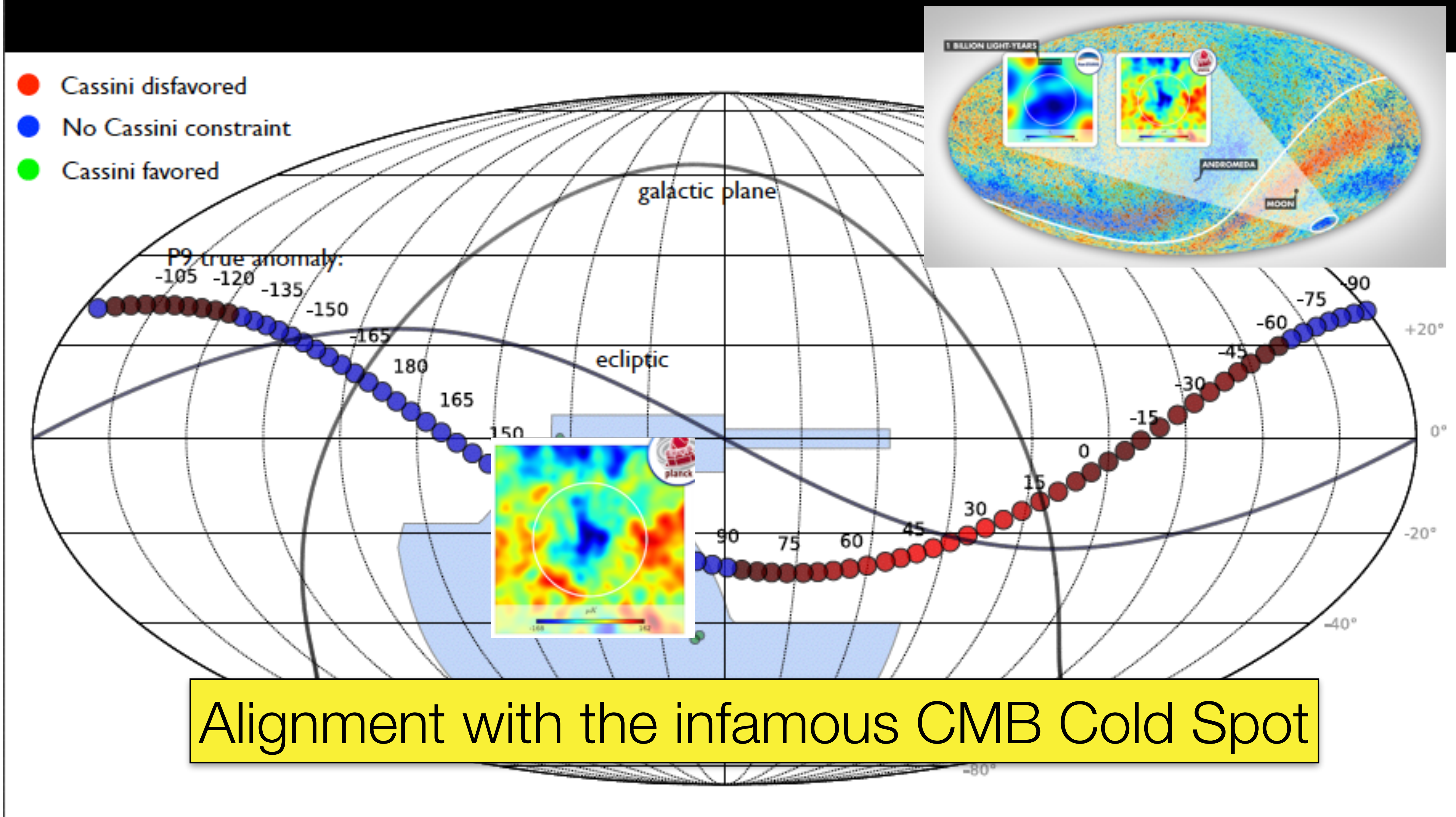
DES footprint vs. P9 position constraints



Alignment with the infamous CMB Cold Spot

slides by David Gerdes

Planets vs. paradigm shifts

1: Examples of new entity vs new theory

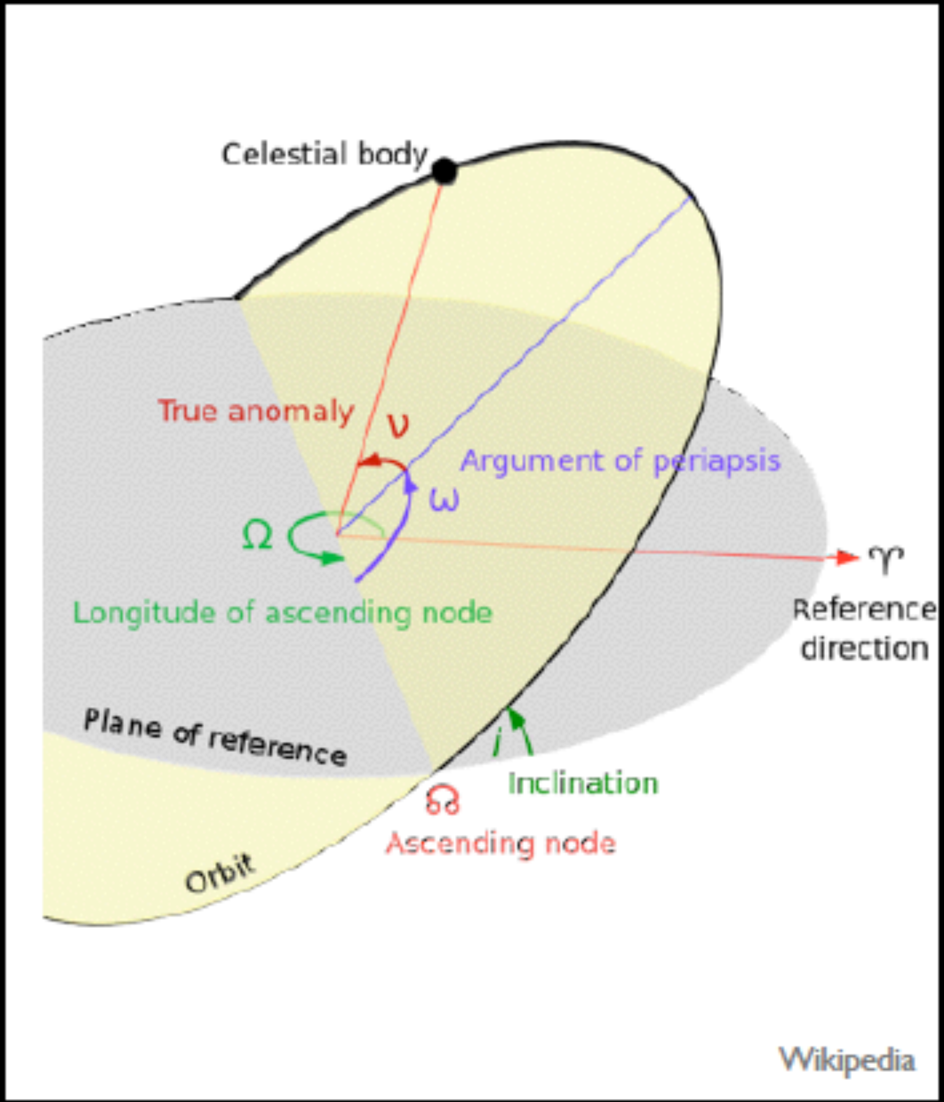
phenomenon	new entity	new theory
Uranus's orbit	Neptune	(Bessel's specific gravity ruled out)
Mercury's orbit	(hypothetical planet Vulcan ruled out)	general relativity
beta decay	neutrino	(violation of angular momentum ruled out)
galaxy flat rotation curves	dark matter?	modified Newtonian dynamics?
accelerating universe (SN Ia and other data)	dark energy?	modified general relativity?

P9

Table by Ofer Lahav

Thanks and enjoy
your pizza!

Describing an Orbit

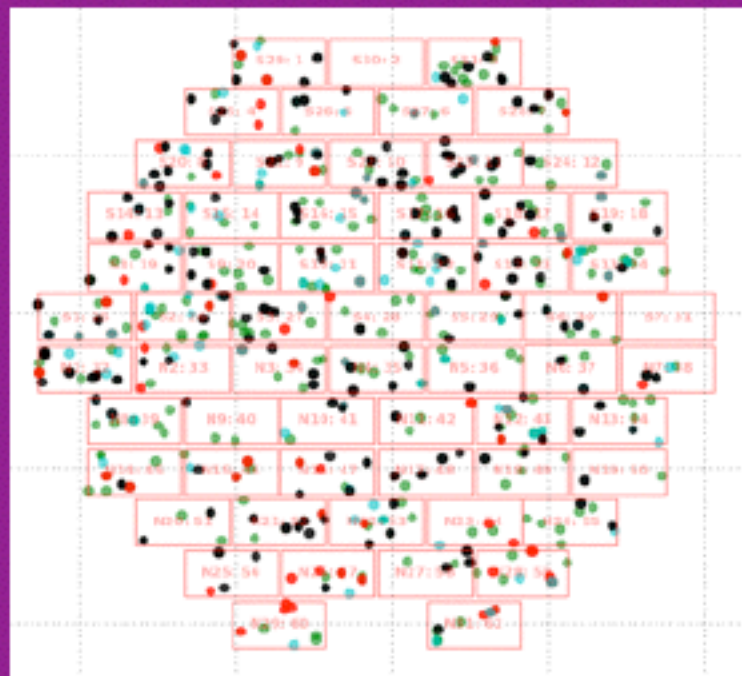


6 parameters needed

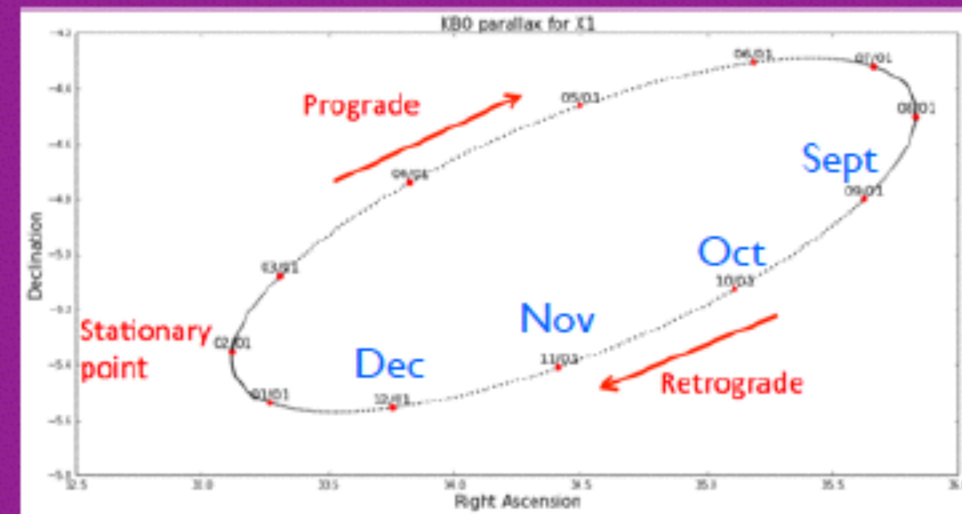
- semi-major axis, eccentricity — size and shape
- inclination, longitude of ascending node, argument of periapsis — orientation
- true anomaly — location of object at a given epoch

Minimal requirement:
observations on 3 different nights

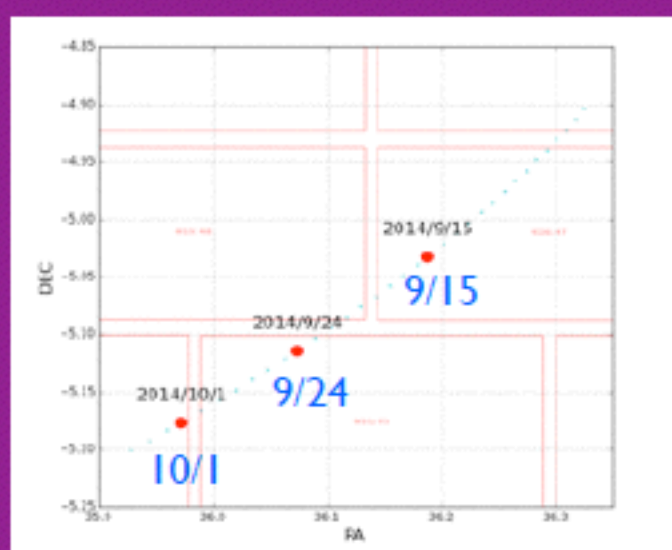
Diffimg candidates from each exposure



Look for matches in nearby exposures consistent with seasonally-appropriate parallax motion

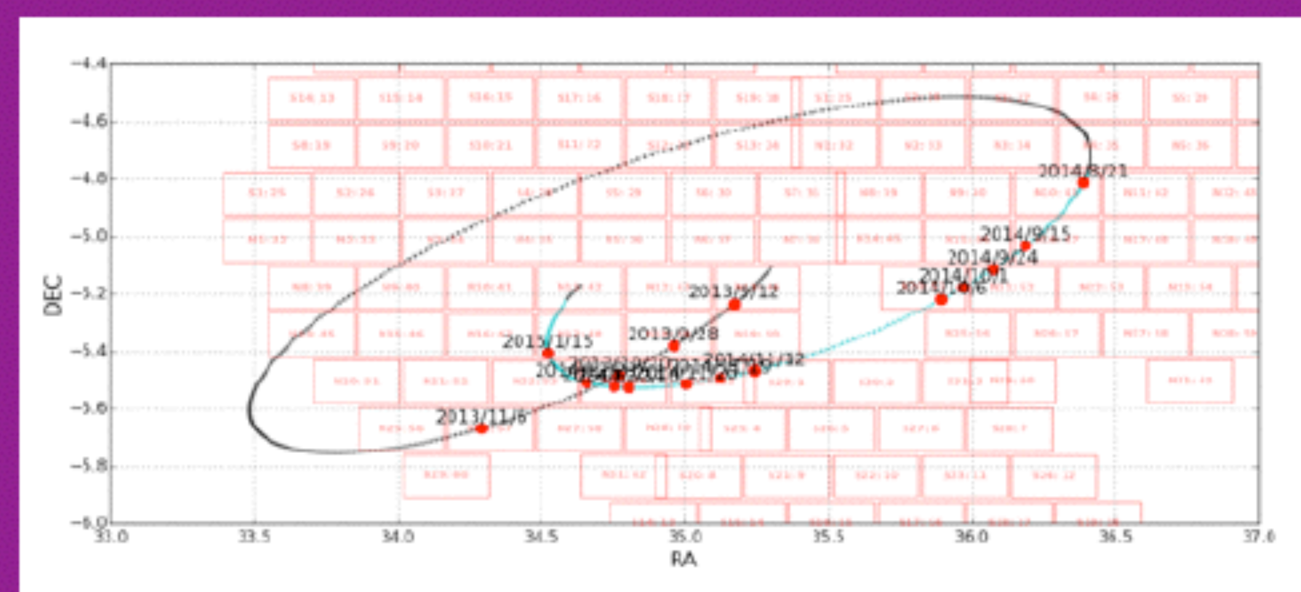


Identify triplets that fit to TNO-like orbit



Bernstein & Khushalani 2000

Use preliminary orbit to add observations, refine fit



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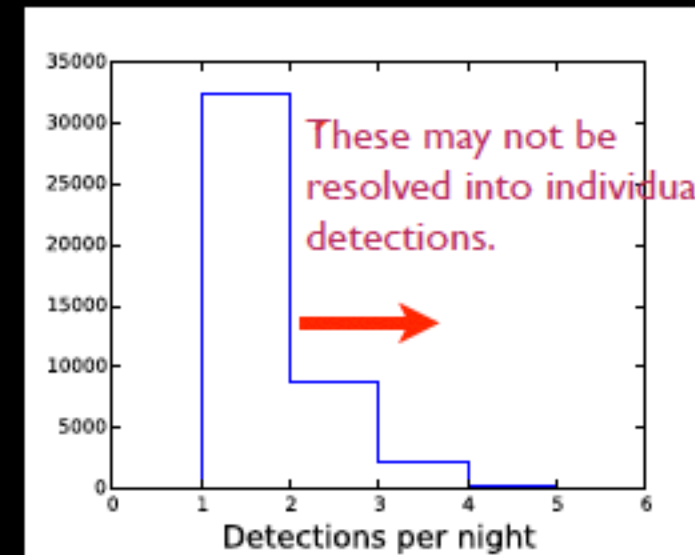
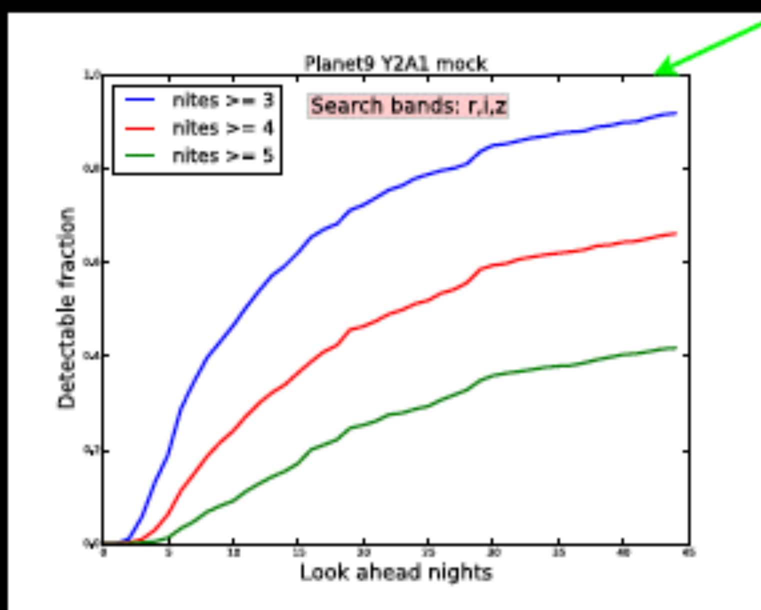
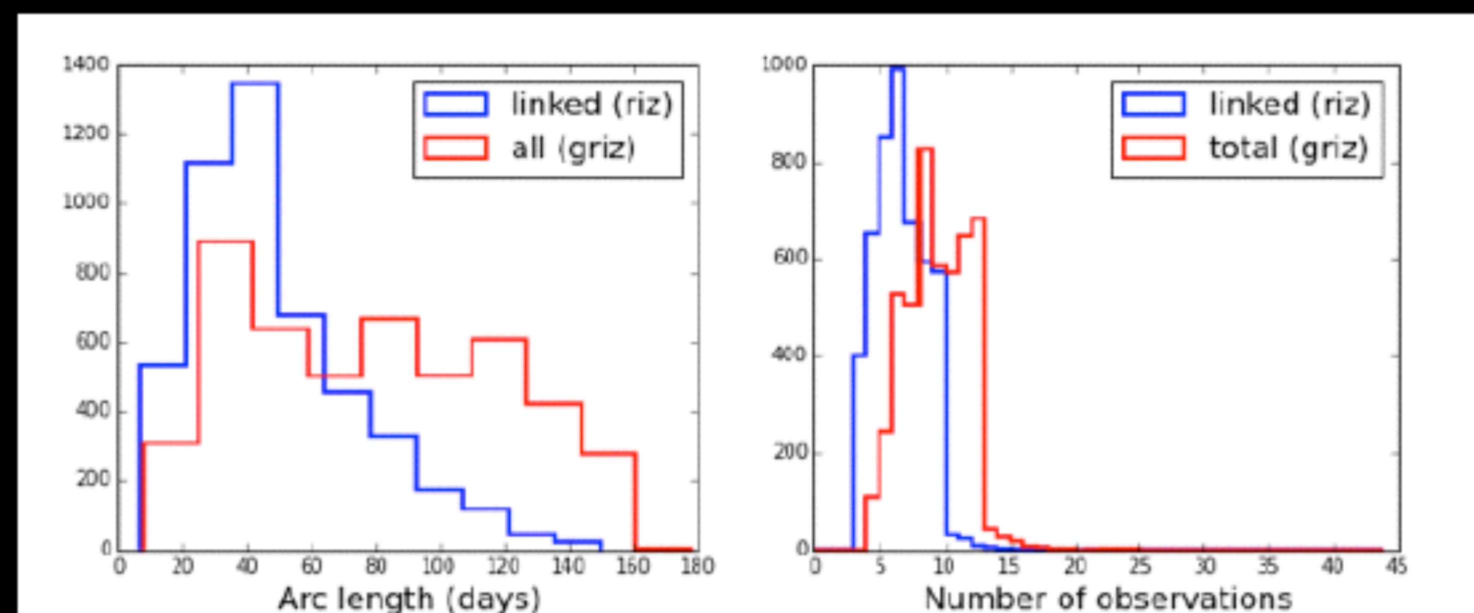
Factors Influencing Detectability

- Number of nights with detections
- Time between detections
- Bands chosen for search



90% detection efficiency





More search bands, longer search window = higher efficiency, but also higher combinatoric backgrounds.

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How Well Do We Reconstruct the Orbit of Fake P9s?

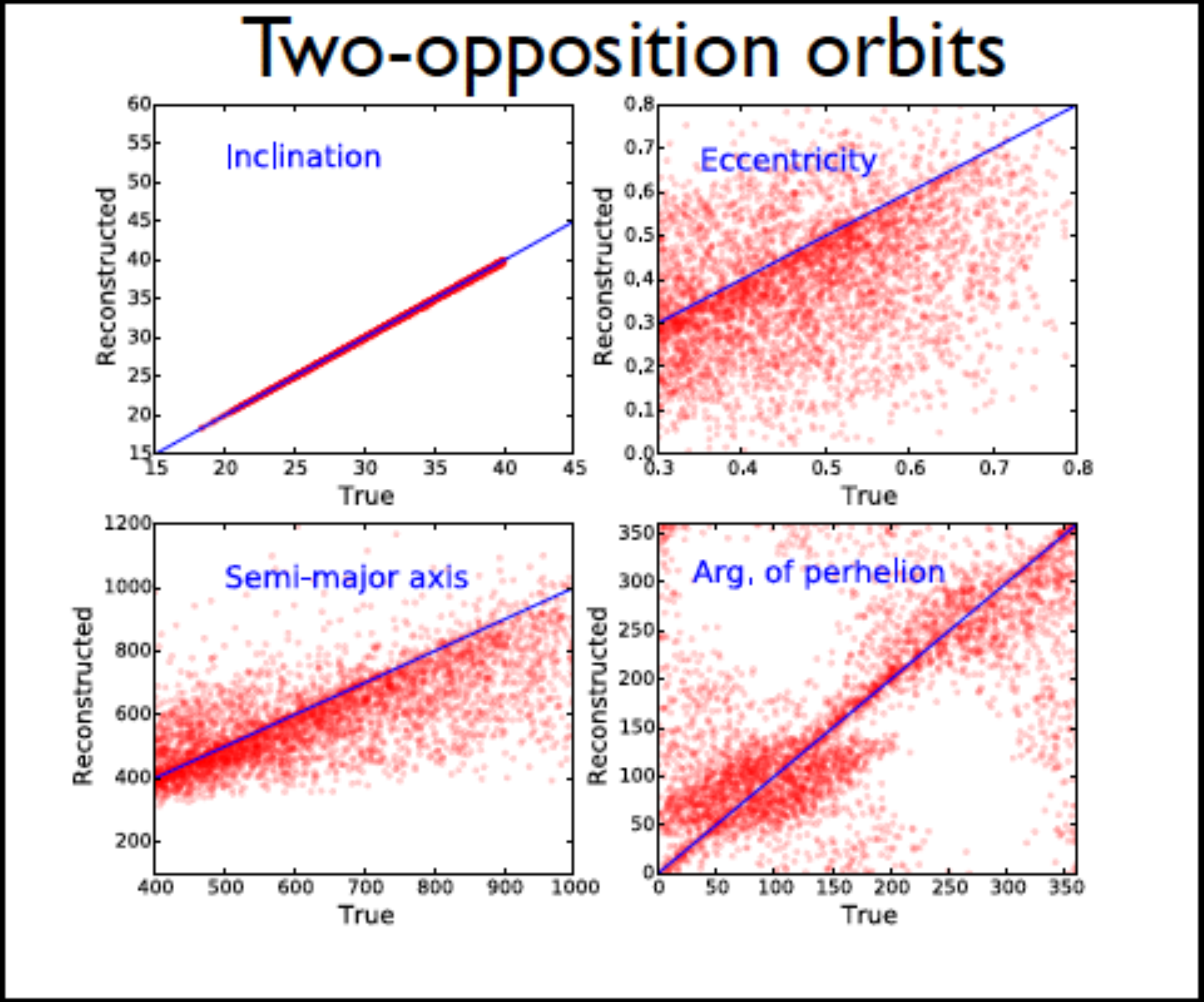
Inclination: well reconstructed

Semi-major axis: can tell it's very distant, but tend to under-estimate *a*.

Eccentricity: big scatter

Arg. of peri: big scatter and evidence of bias

(Note that for P9, arg. of peri. is expected to be ~180 deg.)



To establish "Planet Nine-ness" will require observations at multiple oppositions.

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