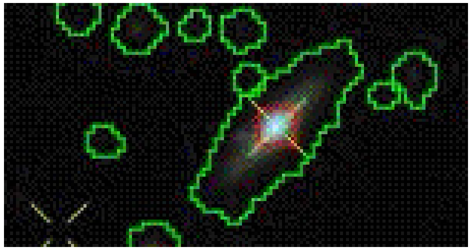
# The SDSS and the Era of Astronomical Surveys

Alex Szalay



# Big Data in Science

- Data growing exponentially, in all science
- All science is becoming data-driven
- This is happening very rapidly
- Data becoming increasingly open/public
- Non-incremental!
- Convergence of physical and life sciences through Big Data (statistics and computing)
- The “long tail” is important
- A scientific revolution in how discovery takes place

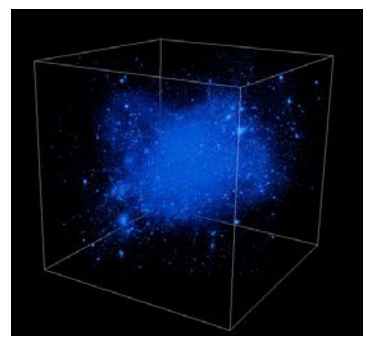
  => a rare and unique opportunity

# Science is Changing

THOUSAND YEARS AGO
science was empirical
describing natural phenomena

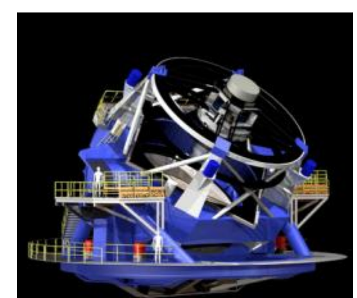
LAST FEW HUNDRED YEARS
theoretical branch using models, generalizations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{4\pi G\rho}{3} - \mathrm{K}\frac{c^2}{a^2}$$



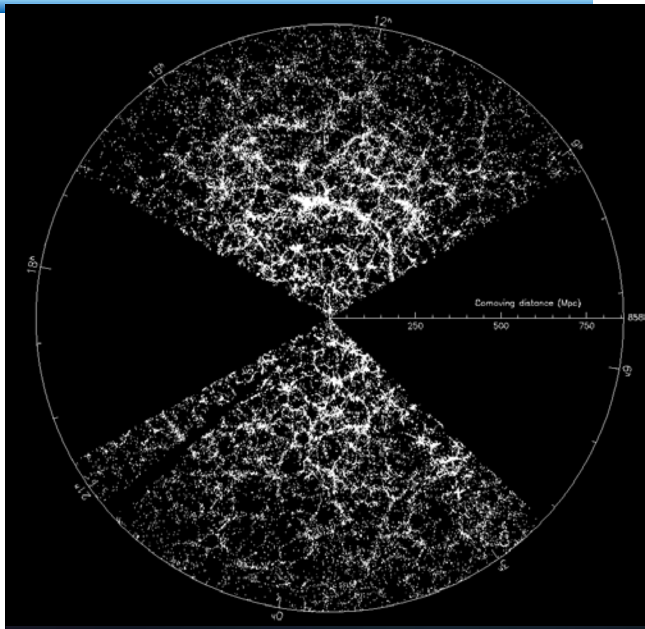
LAST FEW DECADES
a computational branch simulating complex phenomena

TODAY
data intensive science, synthesizing theory, experiment and computation with statistics
►new way of thinking required!



# Sloan Digital Sky Survey

- **"The Cosmic Genome Project"**
- Started in 1992, finished in 2008
- Data is public
  - 2.5 Terapixels of images => 5 Tpx
  - 10 TB of raw data => 120TB processed
  - 0.5 TB catalogs => 35TB in the end
- Database and spectrograph built at JHU (SkyServer)
- Data served from FNAL
- Now SDSS-3, imaging completed
- SDSS-3 data served from JHU



# The Telescope

**Special 2.5m telescope**

*3 degree field of view*

*Wind screen moved separately*

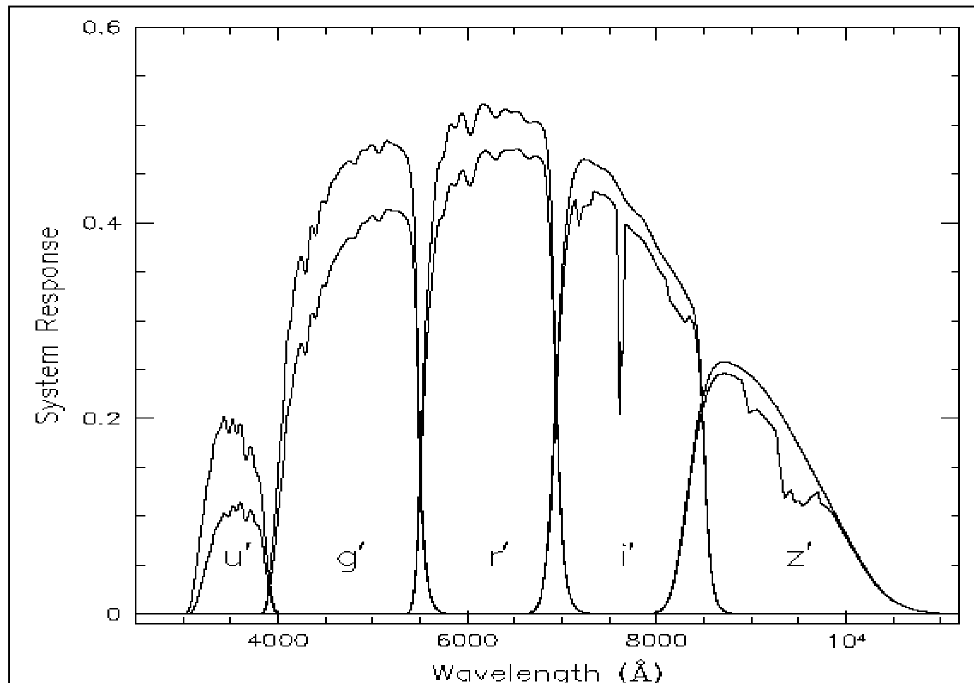
# The Photometric Survey

**Continuous data rate of 8 Mbytes/sec**

**Northern Galactic Cap**

drift scan of 10,000 square degrees
5 broad-band filters
exposure time: 55 sec
pixel size: 0.4 arcsec
astrometry: 60 mas
calibration: 2% at r'=19.8
done only in best seeing
(20 nights/year)

| *u'* | *g'* | *r'* | *i'* | *z'* |
|---|---|---|---|---|
| *22.3* | *23.3* | *23.1* | *22.3* | *20.8* |




**Southern Galactic Cap**

multiple scans (> 30 times)
of the same stripe

# The Spectroscopic Survey

**SDSS Redshift Survey**

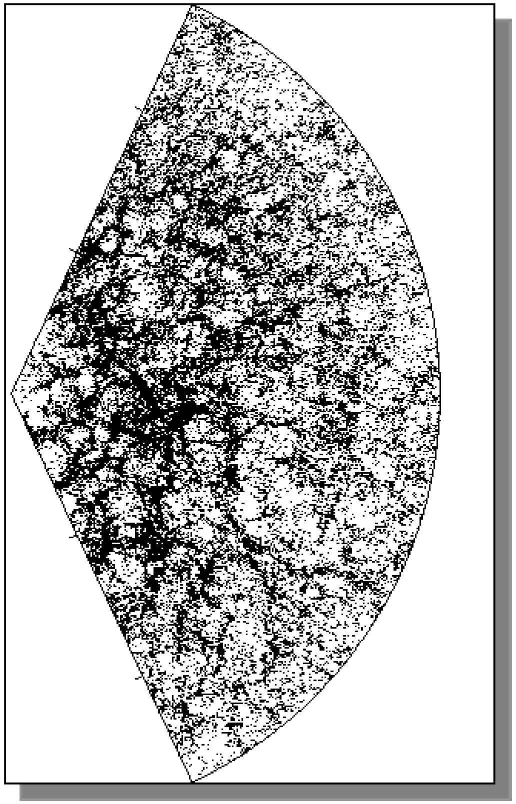
- *1 million galaxies*
  - *900,000 r' limited*
  - *100,000 red galaxies*
    - *volume limited to z=0.45*
- *100,000 quasars*
- *100,000 stars*

**Two high throughput spectrographs**

- *spectral range 3900-9200 Å*
- *640 spectra simultaneously*
- *R=2000 resolution, 1.3 Å*

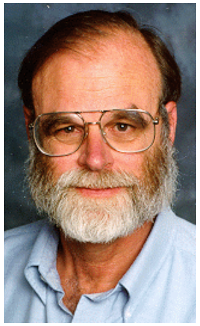
**Features**

- *Automated reduction of spectra*
- *Very high sampling density and completeness*
- *Objects in other catalogs also targeted*



# Skyserver


- Prototype in 21st Century data access
  - *1.2B web hits in 12 years*
  - *200M external SQL queries*
  - *4,000,000 distinct users vs. 15,000 astronomers*
  - *The emergence of the "Internet scientist"*
  - *The world's most used astronomy facility today*
  - *Collaborative server-side analysis done by 7K astronomers*



Jim Gray

# GalaxyZoo

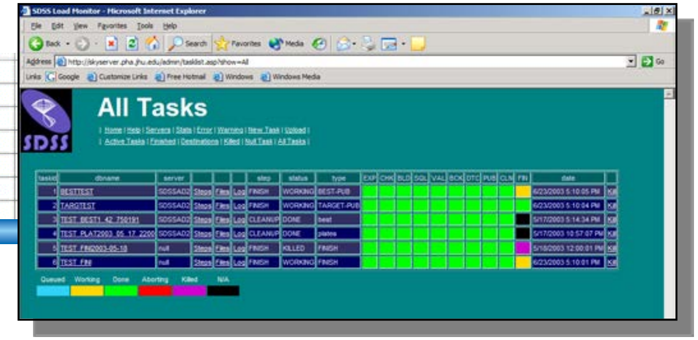
- 40 million visual galaxy classifications by the public
- Enormous publicity (CNN, Times, Washington Post, BBC)
- 300,000 people participating, blogs, poems…
- Original discoveries by the public
  (Voorwerp, Green Peas)

*Chris Lintott et al*

# SkyServer Goals

- Provide easy, visual access to exciting new data
  - *"hot off the press"*
- Illustrate that advanced content does not mean a cumbersome interface
- Understand new ways of publishing scientific data
- Demonstrate how to take analyses inside the DB
  - *Heavy use of user defined functions*
- Target audience
  - *Advanced high-school students, amateur astronomers, wide public*
- Multilingual capabilities built in from the start
  - *Heavy use of stylesheets, language branches*

# DB Loading




- Wrote automated table driven workflow system for loading
  - *Two-phase parallel load*
  - *Over 16K lines of SQL code, mostly data validation*
- Loading process was extremely painful
  - *Lack of systems engineering for the pipelines*
  - *Lots of mismatches*
  - *Fixing files corrupted in data processing (RAID5 disk errors)*
  - *Most of the time spent on scrubbing data*
- Once data is clean, everything loads in 1 week
- Reorganization of data is <1 week

# Data Delivery

- Small requests (<100MB)
  - *Anonymous, putting data on the stream*
- Medium requests (<1GB)
  - *Queues with resource limits*
- Large requests (>1GB)
  - *Save data in scratch area and use async delivery*
  - *Only practical for large/long queries*
- Iterative requests/workbench
  - *Save data in temp tables in user space*
  - *Let user manipulate via web browser*
- **Paradox:** if we use web browser to submit, users want immediate response even from large queries

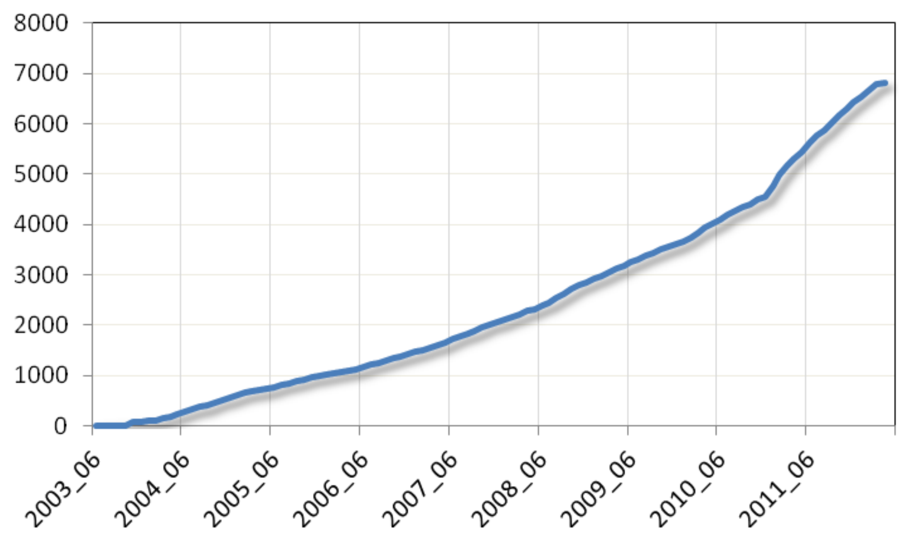
# CASJOBS/MyDB: Workbench

- Need to register ‘power users’, with their own DB
- Query output goes to ‘MyDB’
- Can be joined with source database
- Results are materialized from MyDB upon request
- Users can do:
  - *Insert, Drop, Create, Select  Into, Functions, Procedures*
  - *Publish their tables to a group area*
- Data delivery via the CASJobs (C# WS)
  - *Batch scheduler for large queries*
- First example of “cloud computing” in science (2003)

**=> Sending analysis to the data!**

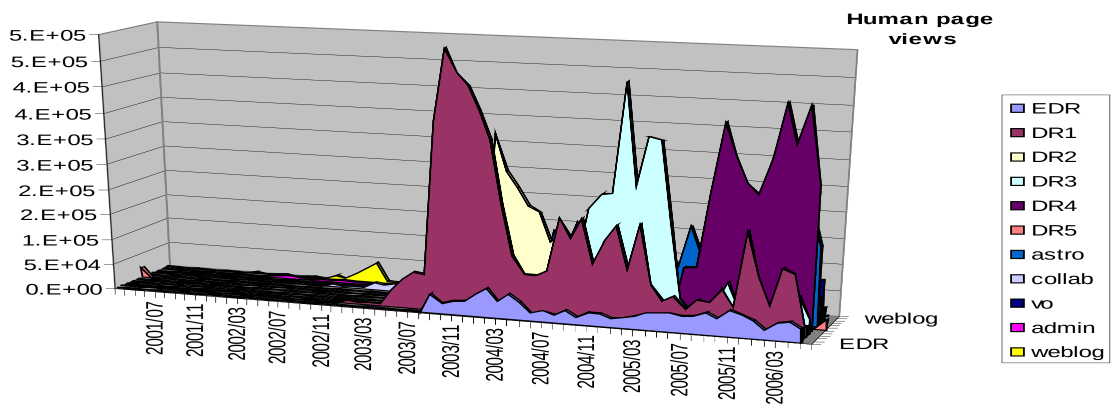
# MyDB

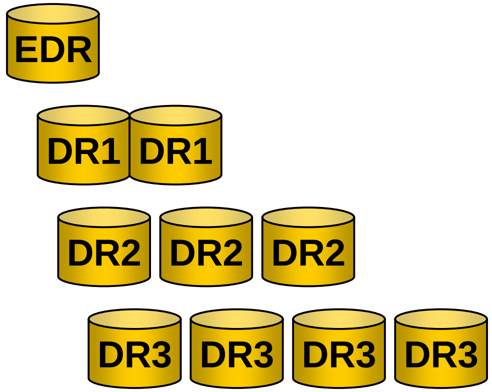
- Implemented by Nolan Li, from user feedback
- Results are materialized from MyDB upon request
- Users can collaborate!
  - *Insert, Drop, Create, Select Into, Functions*
  - ***Publish/share** their tables to a group area*
  - *Flexibility "at the edge"/ Read-only big DB*
- 6,800 registered users



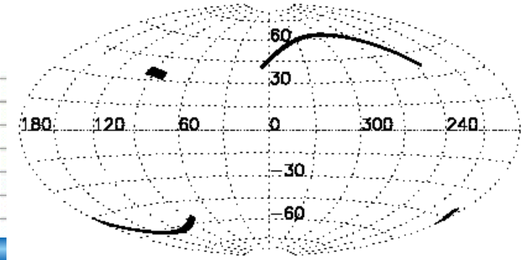
# Data Versions

- June 2001: EDR with 100GB
- 2003 DR2, 2004: DR3, 2005 DR4
- 2006 DR5, with 2.4TB, 2007: DR6, 2008: DR7, with 10TB
- 3 versions of the data
  - *Target, Best, Runs*
  - *Total catalog volume 5TB*
- Data publishing: once published, must stay
- SDSS: DR1 is still used



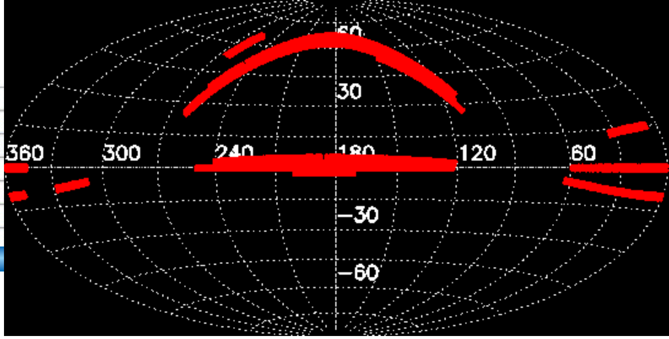
# EDR: Early Data Release



Imaging Sky Coverage (Galactic Coordinates)

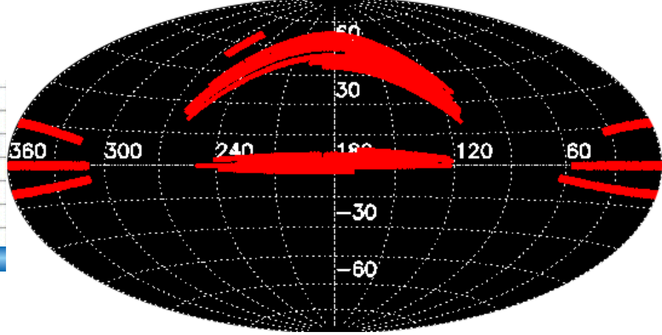
- SDSS Early Data Release (June 6, 2001)
- 100 GB catalogs, few hundred square degrees
- SkyServer aimed solely at public outreach
- Built in 2 weeks by Szalay and Gray (20 hour days)
- Web site design by Szalay
- Images converted in PhotoShop scripts
- Content writing by Stephen Landy
- Hardware donated by Compaq
- Highly interactive, using browser independent DHTML (“browser hell”)

# DR1: Data Release 1

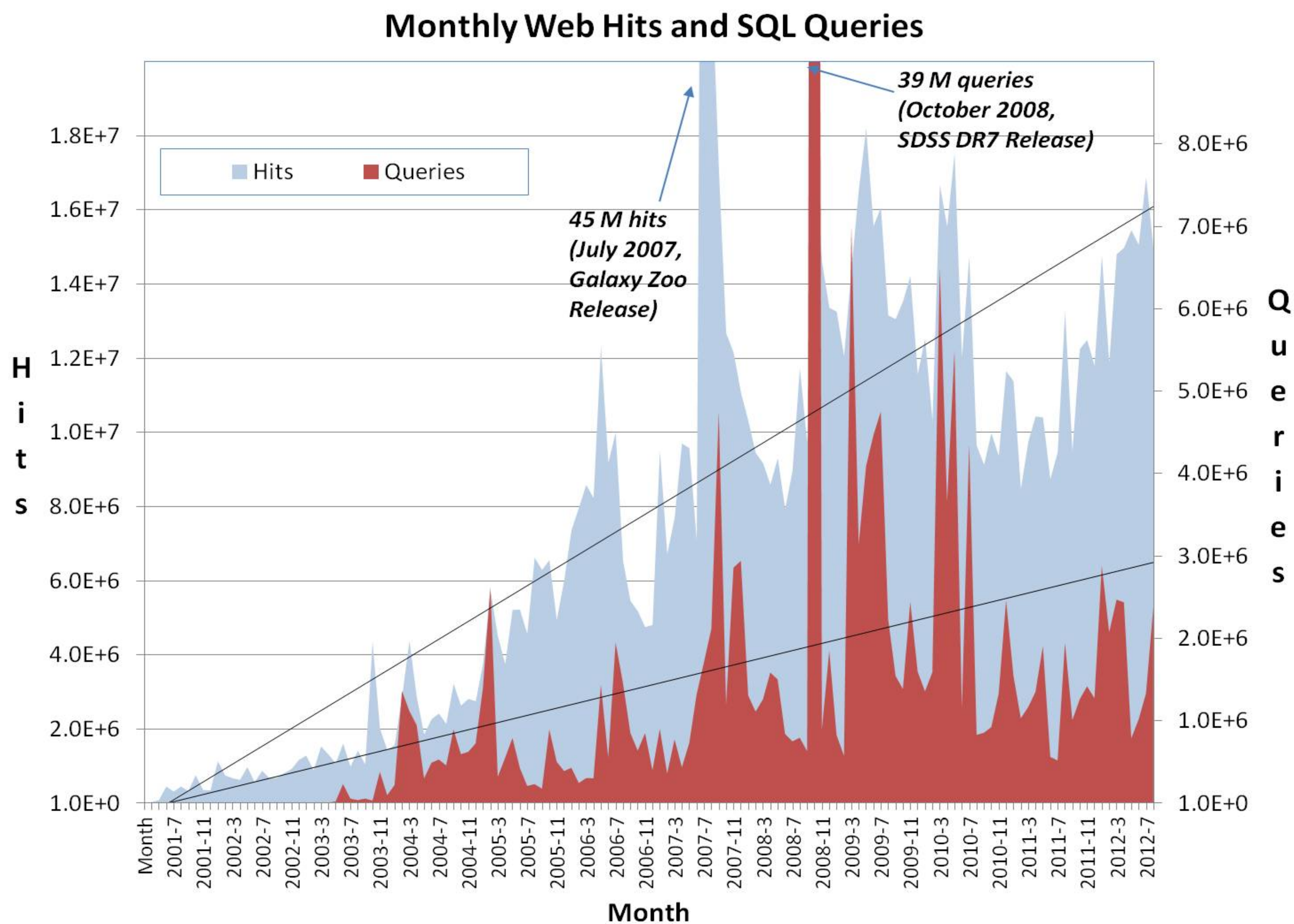



- The first main data release of SDSS (May 2003)
- 1.1TB of catalogs, linked to 6TB of low level data
- SkyServer has undergone a major facelift
  - *New graphic design by Curtis Wong, Asta Roseway (MS)*
  - *Modified stylesheets  and embedded scripts only*
  - *Web site translated in 2 days*
- New visual tools using Web Services
  - *Szalay, Gray, Maria Nieto-SantiSteban*
- API's published
- Formal helpdesk in place
- Created MySkyServer
  - *0.65GB laptop version*

# DR2: Data Release 2




- Live in March 15, 2004, with 2.2 TB of catalogs
- Only incremental changes in interface
- Web site under source control
- Color images dramatically improved
- New translations under way
  - *Japanese, French, German, Spanish, Hungarian*
- Tools overhauled
  - *now embraced by professional astonomers*
- Enormously increased traffic
- Moving to 3-way web front end + 3 DB servers
- Collaborative tools: MyDB with group access



Monthly Web Hits and SQL Queries
Hits
Queries
45 M hits (July 2007, Galaxy Zoo Release)
39 M queries (October 2008, SDSS DR7 Release)
Hits
Queries
Month
1.8E+7
1.6E+7
1.4E+7
1.2E+7
1.0E+7
8.0E+6
6.0E+6
4.0E+6
2.0E+6
1.0E+0
8.0E+6
7.0E+6
6.0E+6
5.0E+6
4.0E+6
3.0E+6
2.0E+6
1.0E+6
1.0E+0
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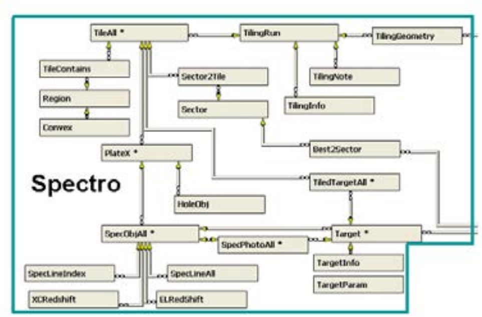
2011-7
2011-11
2012-3
2012-7

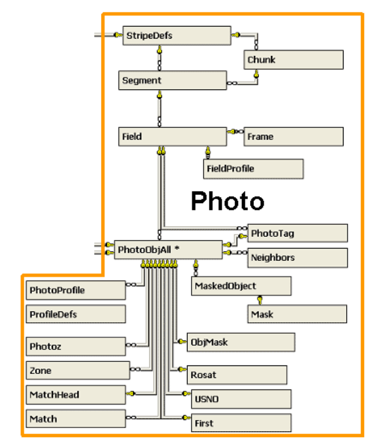
# Visual Tools

- Goal:
  - *Connect pixel space to objects without typing queries*
  - *Browser interface, using common paradigm (MapQuest)*
- Challenge:
  - *Images: 200K x 2K x1.5K resolution x 5 colors = 3 Terapix*
  - *300M objects with complex properties*
  - *20K geometric boundaries and about 6M 'masks'*
  - *Need large dynamic range of scales (2^13)*
- Assembled from a few building blocks:
  - *Image Cutout Web Service*
  - *SQL query service + database*
  - *Images+overlays built on server side -> simple client*

# User Level Services

- Three different applications on top of the same core
  - *Finding Chart (arbitrary size)*
  - *Navigate (fixed size, clickable navigation)*
  - *Image List (display many postage stamps on same page)*
- Linked to
  - *One another*
  - *Image Explorer (link to complex schema)*
  - *On-line documentation*



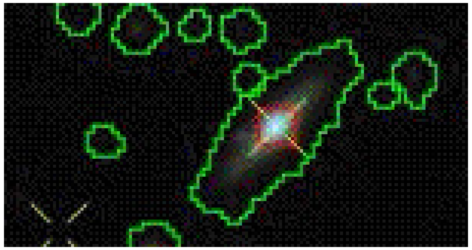



# Images

- 5 bands, 2048x1489 resolution (u,g,r,i,z), 6MB each
  - *Raw size 200Kx6MB = 1.2TB*
  - *For quick access they must be stored in the DB*
  - *It has to show well on screens, remapping needed*
  - *Remapping must be uniform, due to image mosaicking*
- Built composite color, using lambda mapping
  - *(g->B, r->G, i->R), u,z was too noisy*
- Many experiments, discussions with Robert Lupton
  - *Asinh compression*
- Resulting image stored as JPEG
  - *From 30MB->300kB : a factor 100 compression*

# Object Overlays

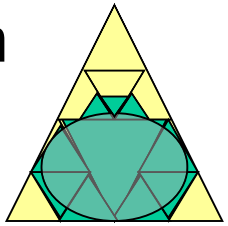
- Object positions stored in (ra,dec)
- At run time, convert (ra,dec)-> (screen_x, screen_y)
- Plotting pixel space quantities, like outlines:
  - *We could do (x,y)->(ra,dec)->(screen)*
  - *For each field we store local affine transformation matrix:*
    - (x,y) -> (screen)
- Apply local projection matrix and plot in pixel coordinates
  - *GDI plots correctly on the screen!*



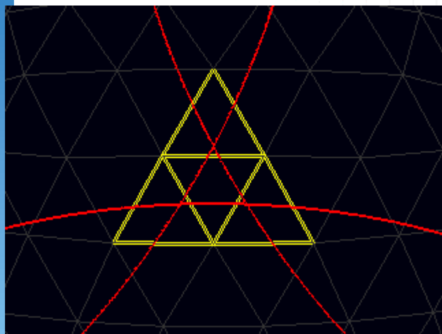
- Whole web service less than 1500 lines of C# code

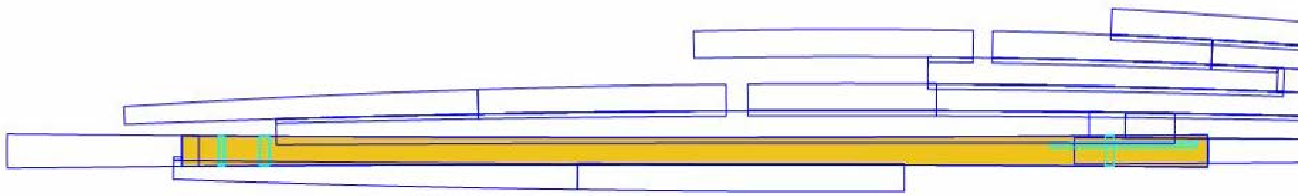
# Geometries

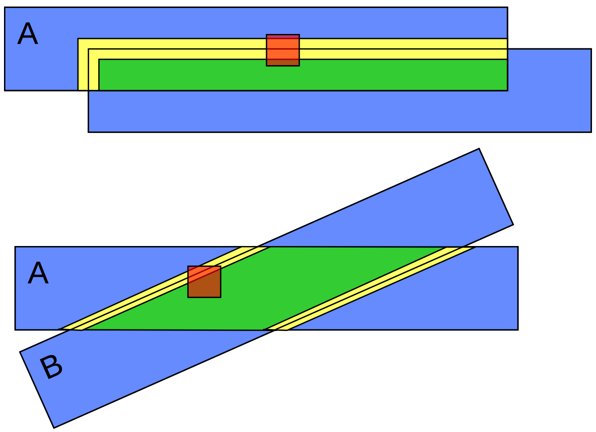
- SDSS has lots of complex boundaries
  - *60,000+ regions*
  - *6M masks, represented as spherical polygons*
- A GIS-like computational geometry library built in SQL, then converted to C++
- Converted to C# for direct plugin into SQL Server2005 (17 times faster than C++)
- Precompute arcs and store in database for rendering
- Functions for point in polygon, intersecting polygons, polygons covering points, all points in polygon
- Using spherical quad-tree index (HTM)

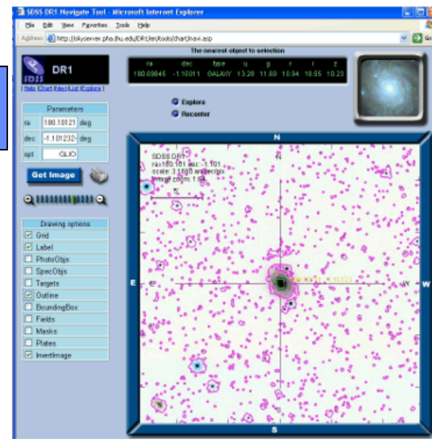


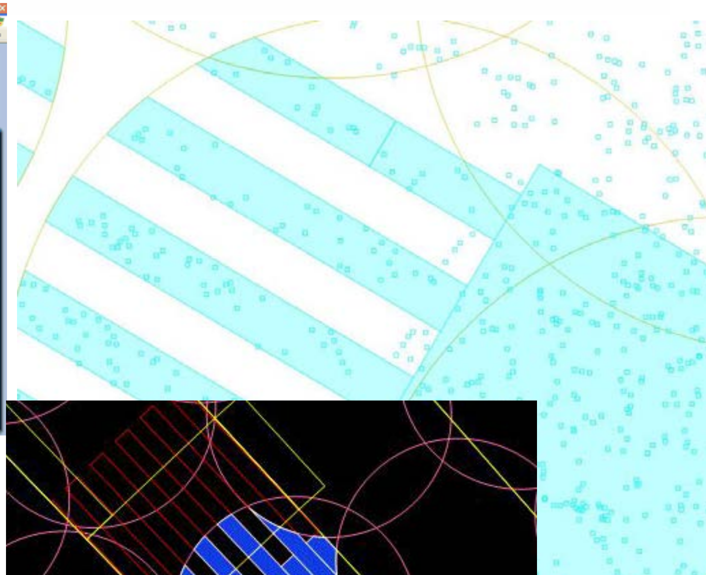
# Things Can Get Complex

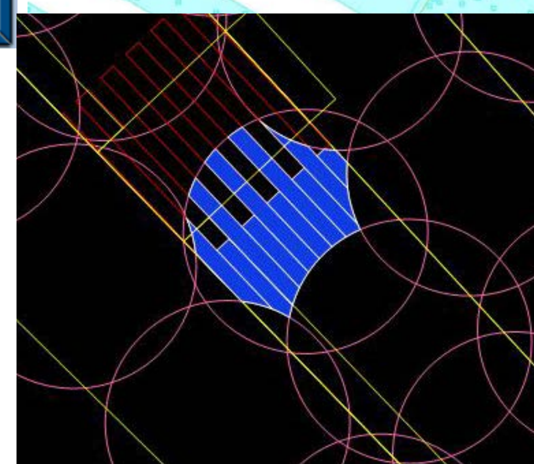




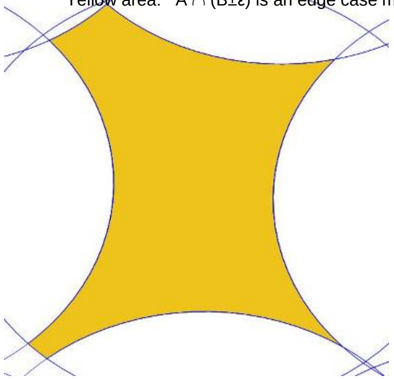




Green area: A ∩ (B- ε) should find B if it contains an A and not masked
Yellow area: A ∩ (B±ε) is an edge case may find B if it contains an A.

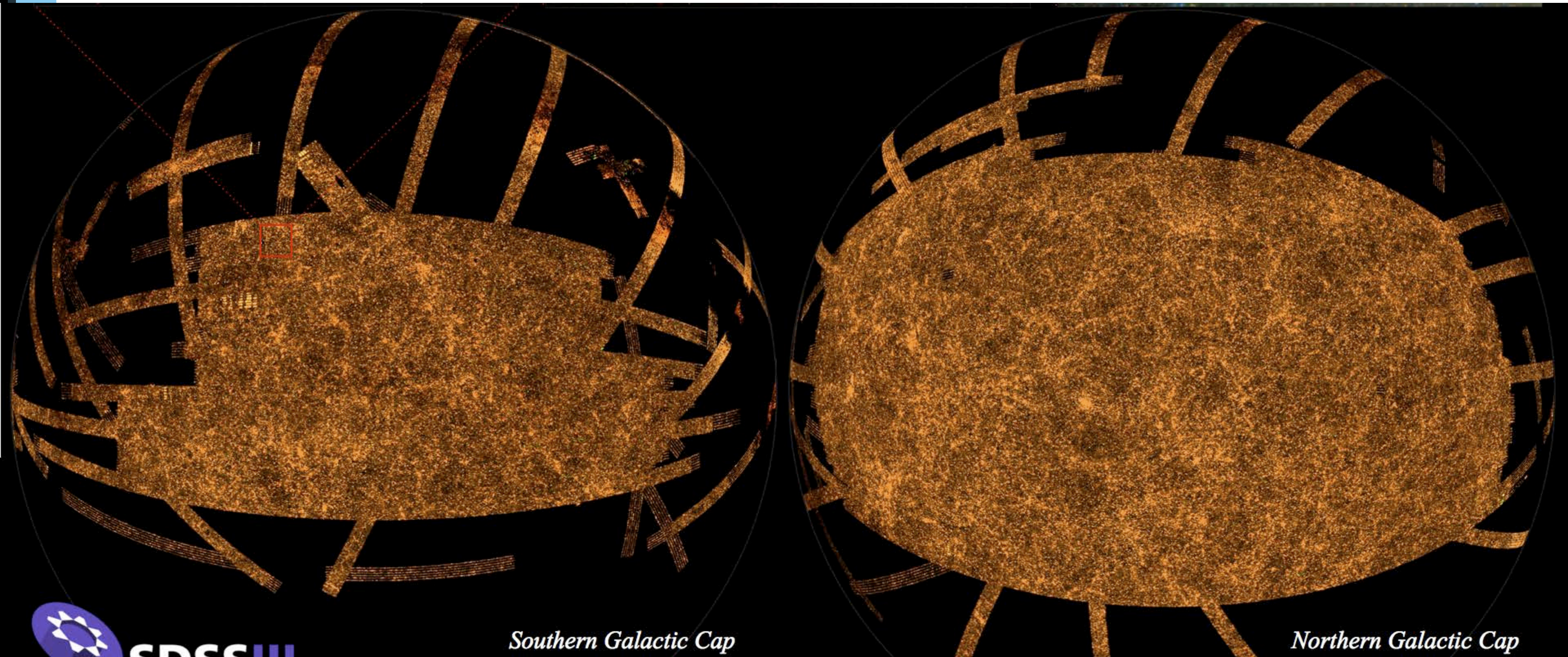


# Current Status

- SDSS-II finished with DR7
  - *Database a bit over 10TB*
- SDSS-III
  - *One last run of imaging, completed area between Southern stripes, then turned off imaging camera*
  - *Rebuilt spectrographs, mostly LRG (BOSS)*
  - *DR8 in 2011, DR9 in July 2012, DR10 in June 2013*
  - *Database over 12TB*
- AS3 (After Sloan 3) is in the formation process
  - *New special instruments (Integral field spectrograph unit)*

# SDSS III

14,555 square degrees
2,674,200 specObj



# Numerous Science Projects

- 5,000 publications, 200,000 citations
- More papers from outside the collaboration
- From cosmology/LSS to galaxy evolution, quasars, stellar evolution, even time-domain
- Combination of 5-band photometry and matching spectroscopy provided unique synergy
- Overall, seeing not as good as originally hoped for, but systematic errors extremely well understood
- Very uniform, statistically complete data sets
- Photometry entirely redone for DR9, using cross-scans to calibrate the zero points across the stripes

# The Broad Impact of SDSS

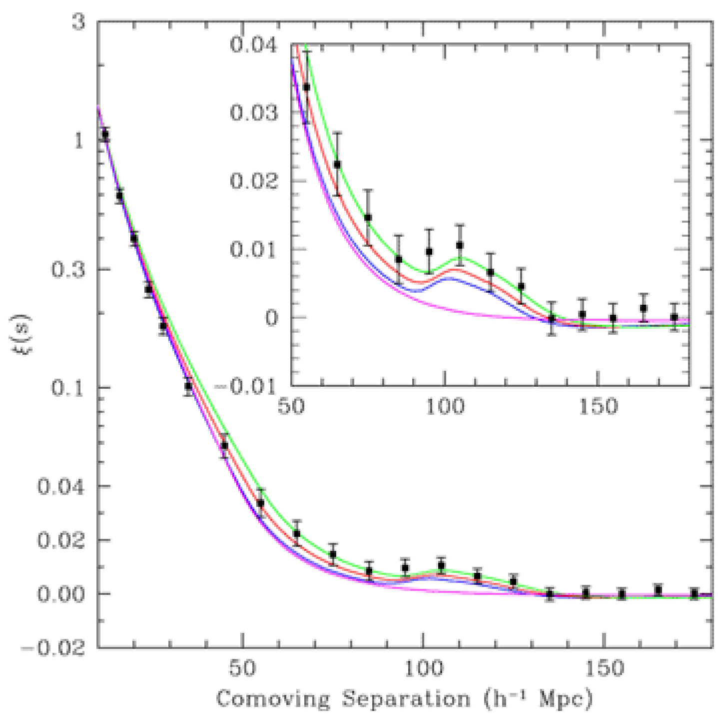
- Changed the way we do astronomy
- Remarkably fast transition seen for the community
- Speeded up the first phase of exploration
- Wide-area statistical queries easy
- Multi-wavelength astronomy is the norm
- SDSS earned the TRUST of the community
- Enormous number of projects, way beyond original vision and expectation
- Many other surveys now follow
- Established expectations for data delivery
- Serves as a model for other communities of science

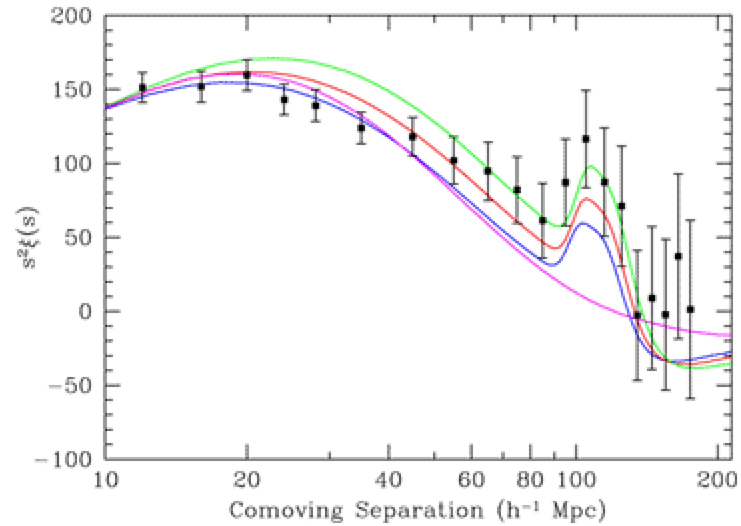
# Astro-Statistical Challenges

- The crossmatch problem (multi-$\lambda$, time domain)
- Photometric redshifts (prediction/regression problem)
- Correlations (auto/cross, higher order)
- Outlier detection in many dimensions
- Statistical errors vs systematics
- Comparing observations to models
  - *comparing distributions, updating models*
- The “unknown unknown”, when we have no models
- …..
- Scalability!!!

# Finding the Bumps – DR4

- Eisenstein et al (2005) – LRG sample



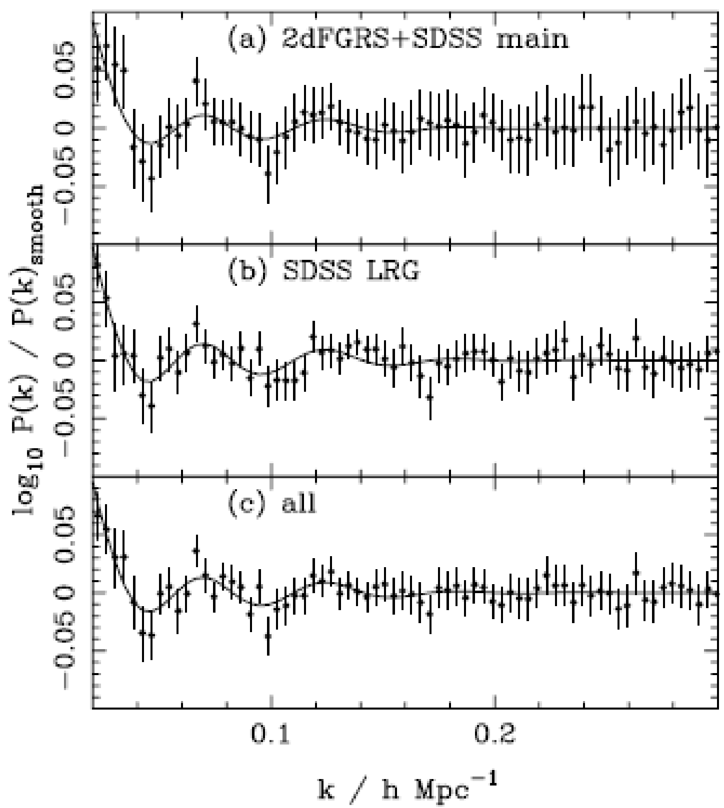

Correlation function

# Primordial Sound Waves in SDSS

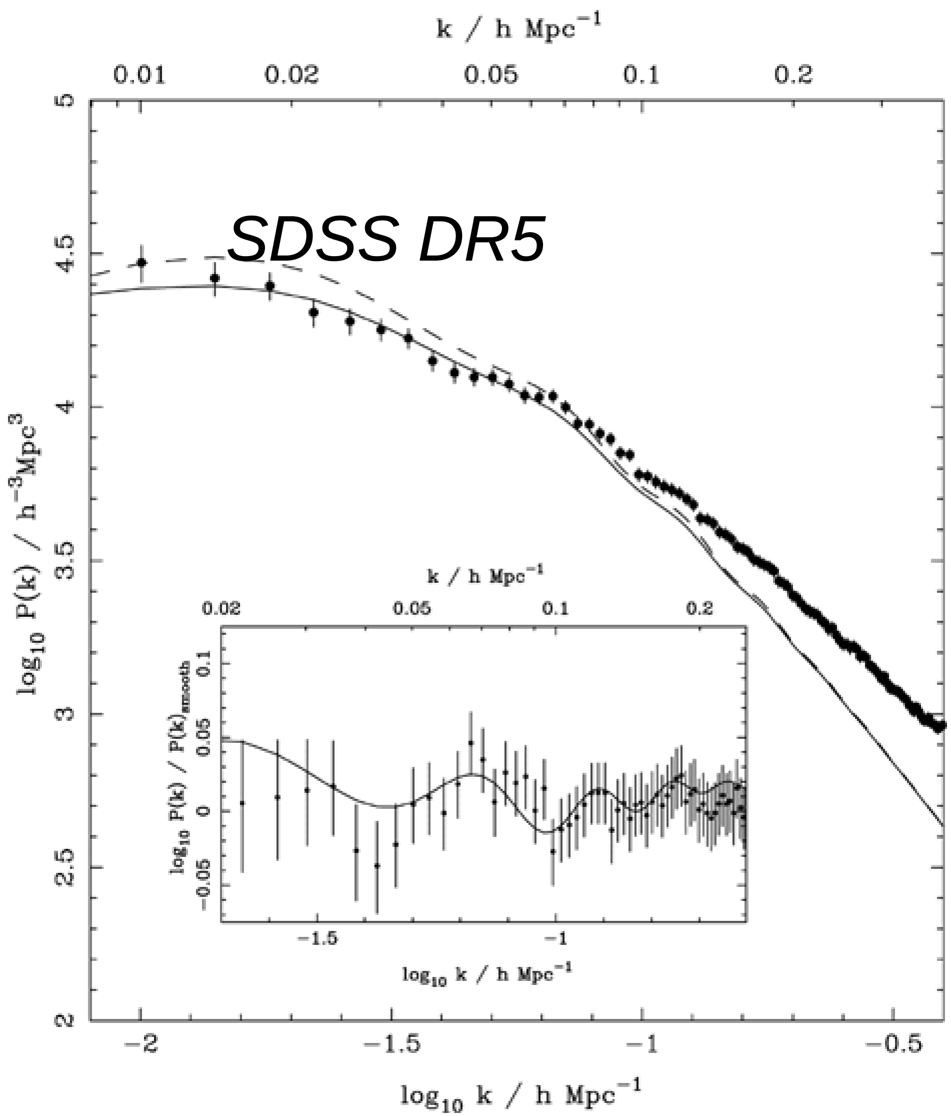
Power Spectrum

(Percival et al 2006, 2007)

*SDSS DR6+2dF*

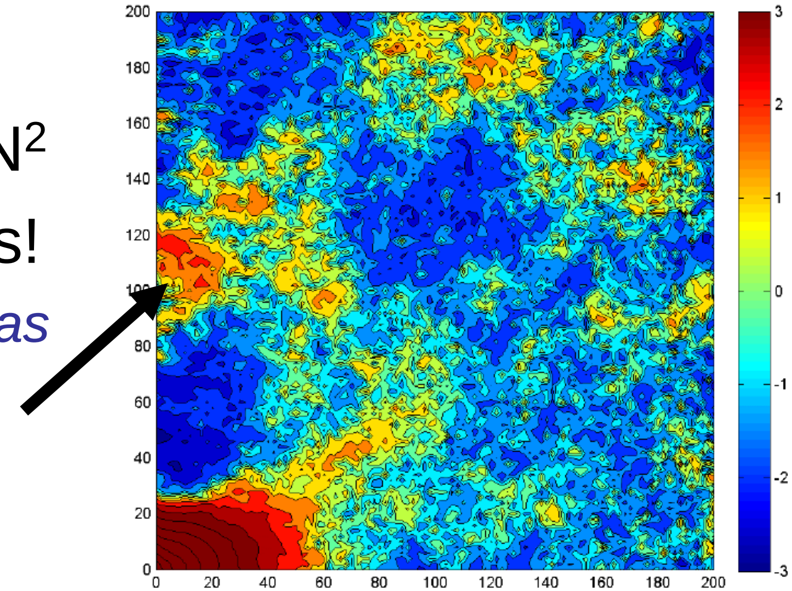



800K galaxies



# The Impact of GPUs

- We need to reconsider the N logN only approach
- Once we can run 100K threads, maybe running SIMD $N^2$ on smaller partitions is also acceptable
- Recent JHU effort on integrating CUDA with SQL Server, using SQL UDF
- Galaxy spatial correlations: **600 trillion real and random** galaxy pairs using brute force $N^2$
- Much faster than the tree codes!
  - *This is because high resolution was needed…*



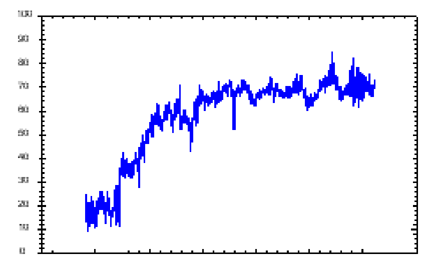

Tian, Budavari, Neyrinck, Szalay 2010

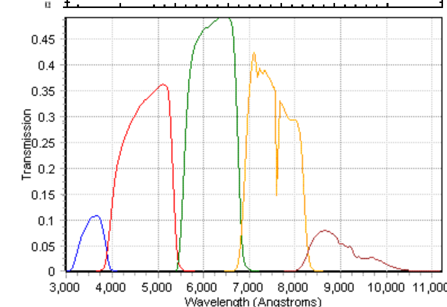
# Photometric Redshifts

- Normally, distances from Hubble's Law

$$v = H_0 r$$

- Measure the Doppler shift of spectral lines
  - *distance!*
- But spectroscopy is very expensive
  - *SDSS: 640 spectra in 45 min vs. 300K 5 color images in 1min*
- Future big surveys will have no spectra
- Idea:
  - *Multicolor images are like a crude spectrograph*
  - *Statistical estimation of the redshifts/distances*

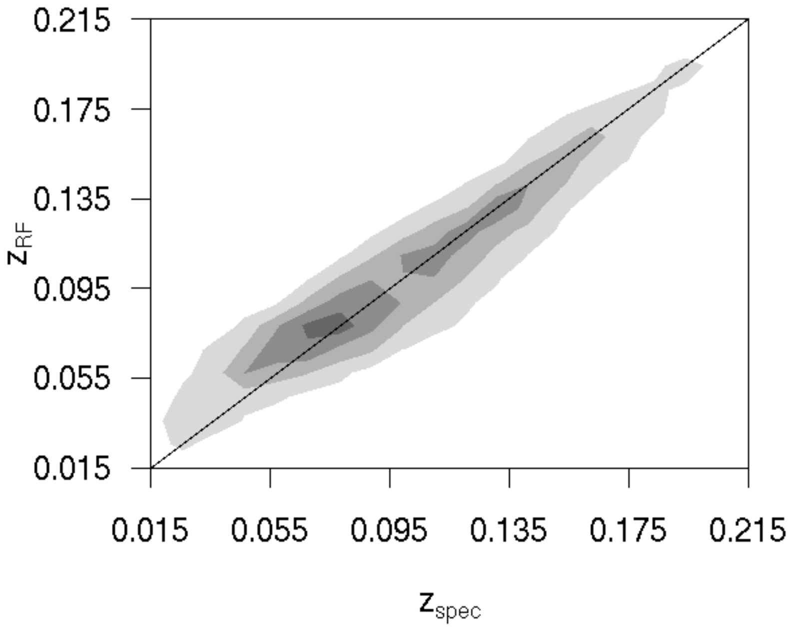


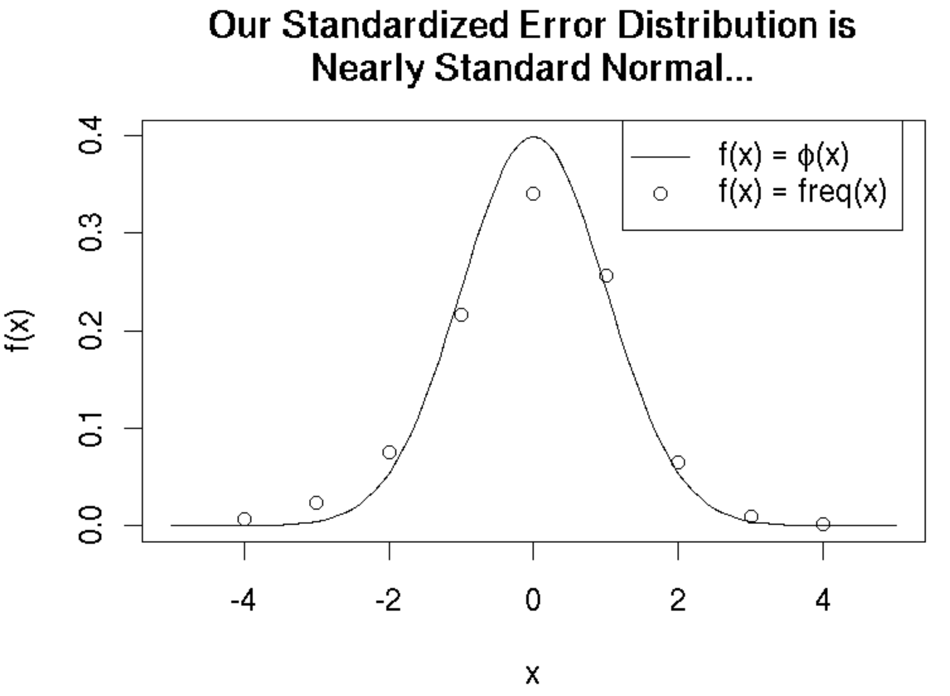


# Random Forest

- Recent effort at JHU
  - *S. Carliles, C. Priebe, A. Szalay, T. Budavari, S. Heinis*
- RF: Leo Berman and Adele Cutler
- Create many (~500) random subsamples of training set (about 2/3 each)
- Build a piecewise linear regression *Tree* for each
- These Trees make up the *Forest*: each provides an estimated parameter value
- Their mean and sigma is the value and error of the final estimate → *robust!*

# Zspec vs Zrf



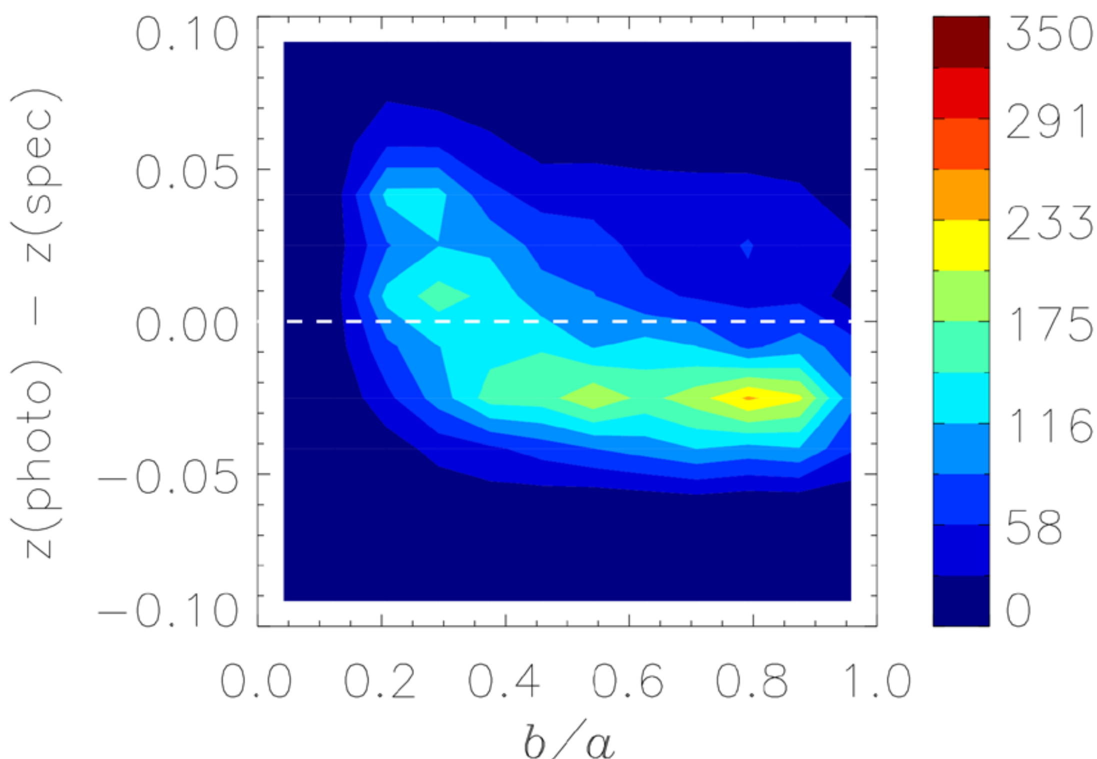

Carliles et al 2009

# RF on Cyberbricks

- 36-node Amdahl cluster using 1200W total
- Zotac Atom/ION motherboards
  - *4GB of memory, N330 dual core Atom, 16 GPU cores*
- Aggregate disk space 43.6TB
  - *63 x 120GB SSD = 7.7 TB*
  - *27x 1TB Samsung F1 = 27.0 TB*
  - *18x.5TB Samsung M1= 9.0 TB*
- Blazing I/O Performance: 18GB/s
- Amdahl number = 1 for under $30K
- Using the GPUs for data mining:
  - *6.4B multidimensional regressions (photo-z) in 5 minutes over 1.2TB of data*
  - *Running the Random Forest algorithm inside the DB*

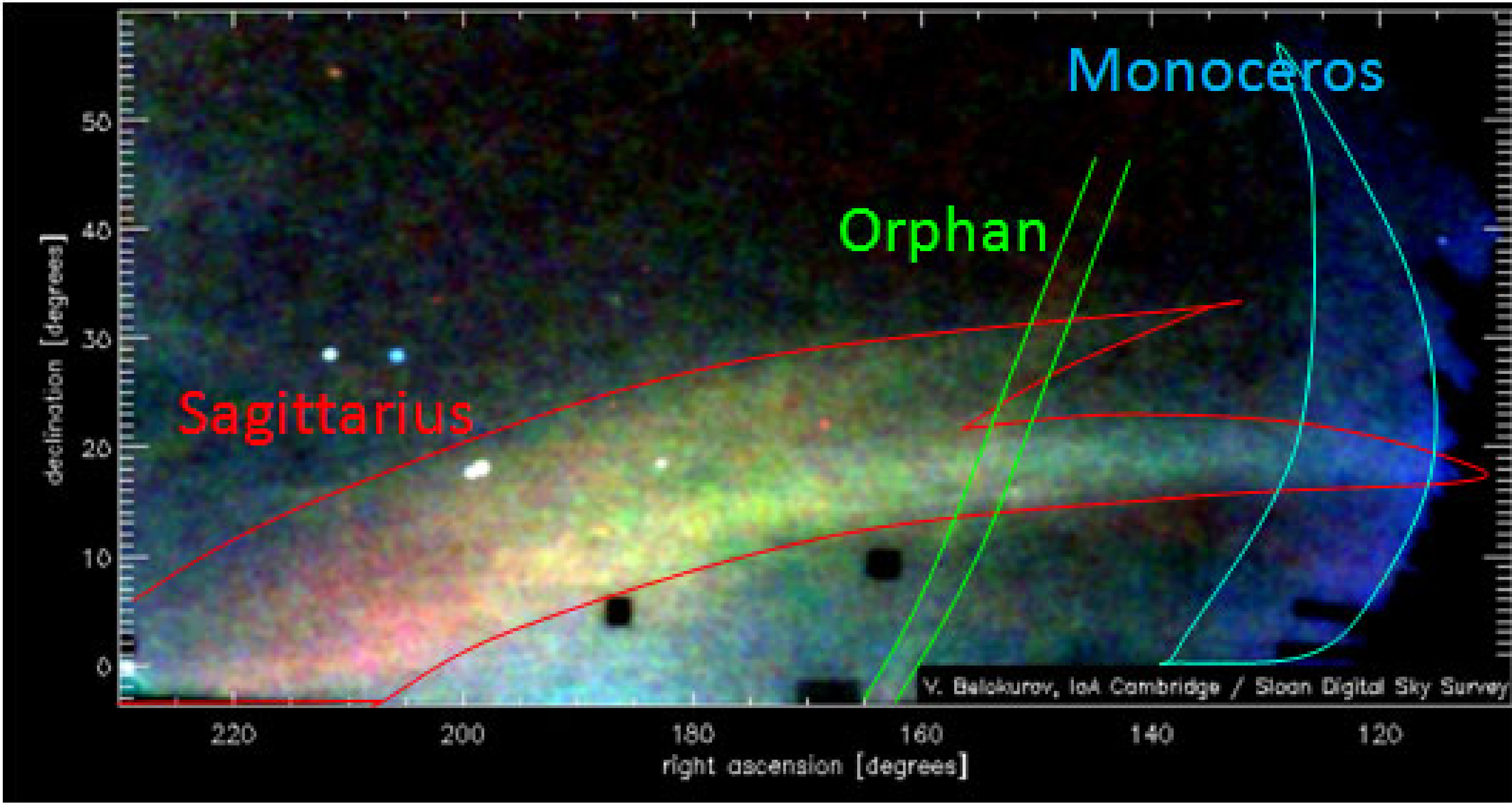
# Photo-z Bias vs. Galaxy Inclination

- Edge-on galaxies are redder, mimic higher redshift galaxies
- Photo-z bias is -0.02 for face-on galaxies
- SDSS disk galaxiess, Spec-z = 0.065-0.075, a 30% effect!
- Once axial ratio is included in RF training, bias goes away



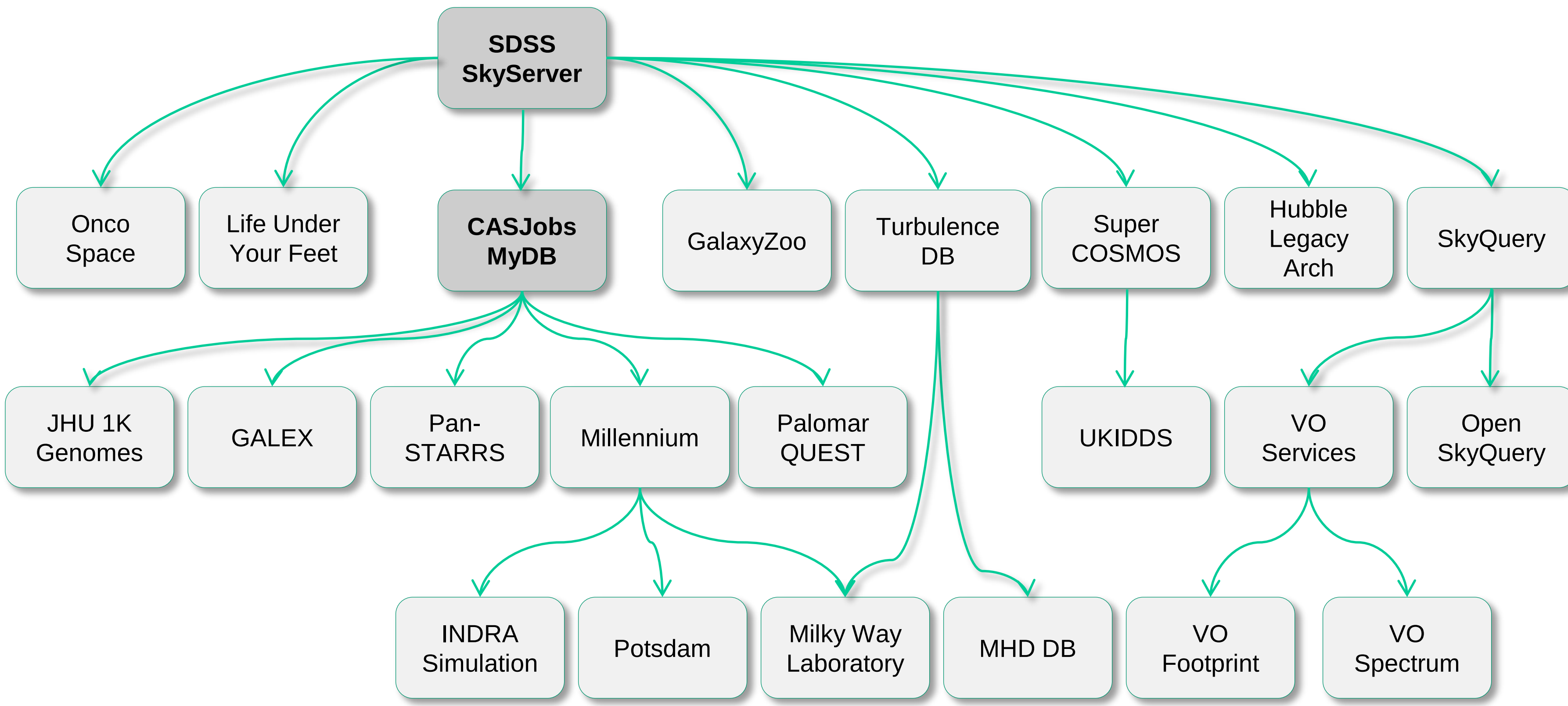

C-W Yip et al. 2011

# Field of Streams




Belokurov et al 2006

# The SDSS Genealogy



# Trends

***CMB Surveys***

| | | |
|---|---|---|
| 1990 | COBE | 1000 |
| 2000 | Boomerang | 10,000 |
| 2002 | CBI | 50,000 |
| 2003 | WMAP | 1 Million |
| 2008 | Planck | 10 Million |

***Angular Galaxy Surveys***

| | | |
|---|---|---|
| 1970 | Lick | 1M |
| 1990 | APM | 2M |
| 2005 | SDSS | 200M |
| 2008 | VISTA | 1000M |
| 2012 | PS1 | 1500M |
| 2018 | LSST | 3000M |

**Time Domain**

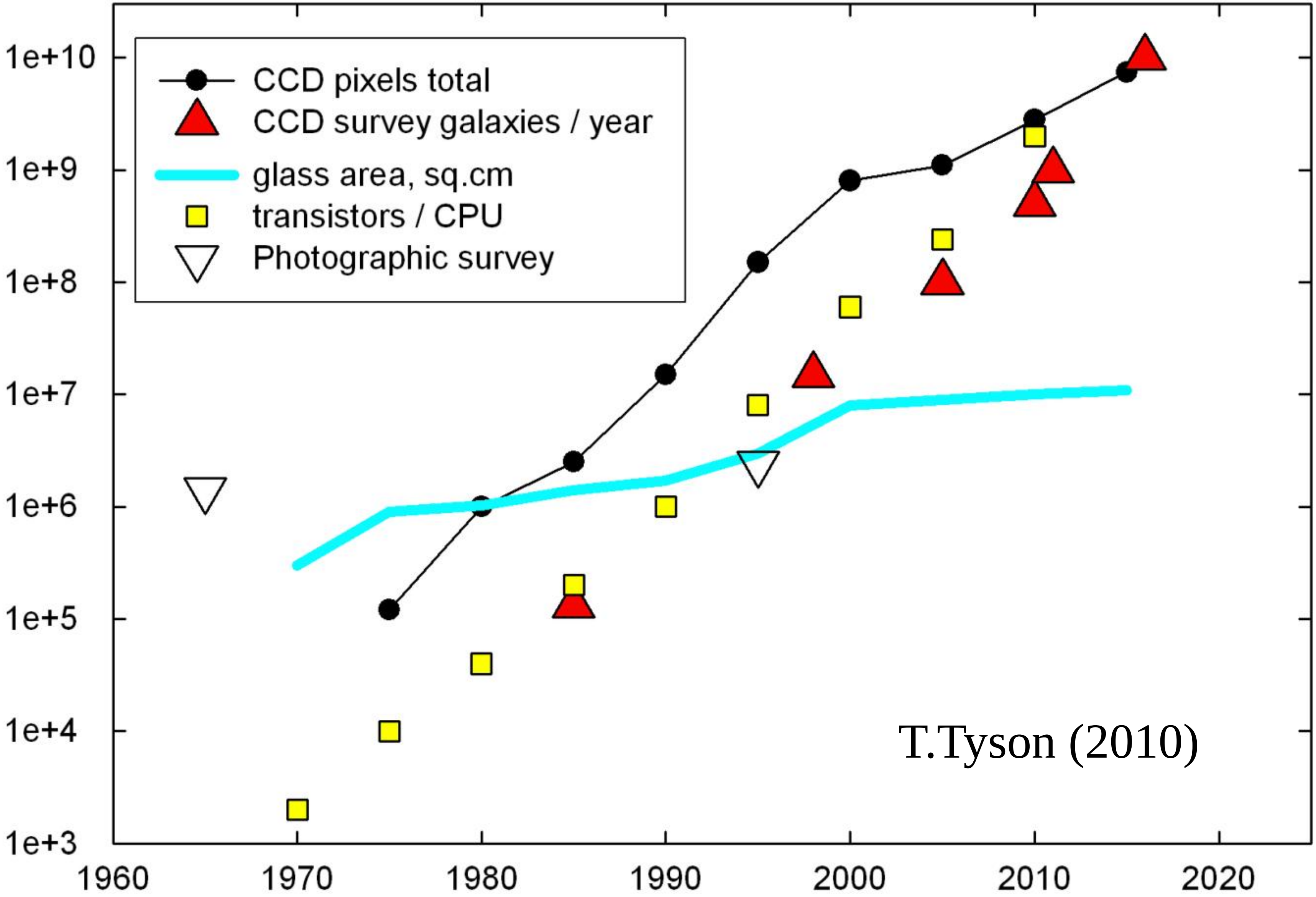
- QUEST
- SDSS Extension survey
- Dark Energy Survey
- Pan-STARRS
- LSST…

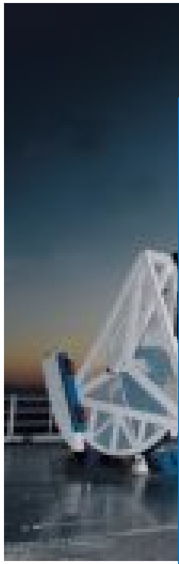
***Galaxy Redshift Surveys***

| | | |
|---|---|---|
| 1986 | CfA | 3500 |
| 1996 | LCRS | 23000 |
| 2003 | 2dF | 250000 |
| 2006 | SDSS | 500000 |
| 2012 | BOSS | 1000000 |

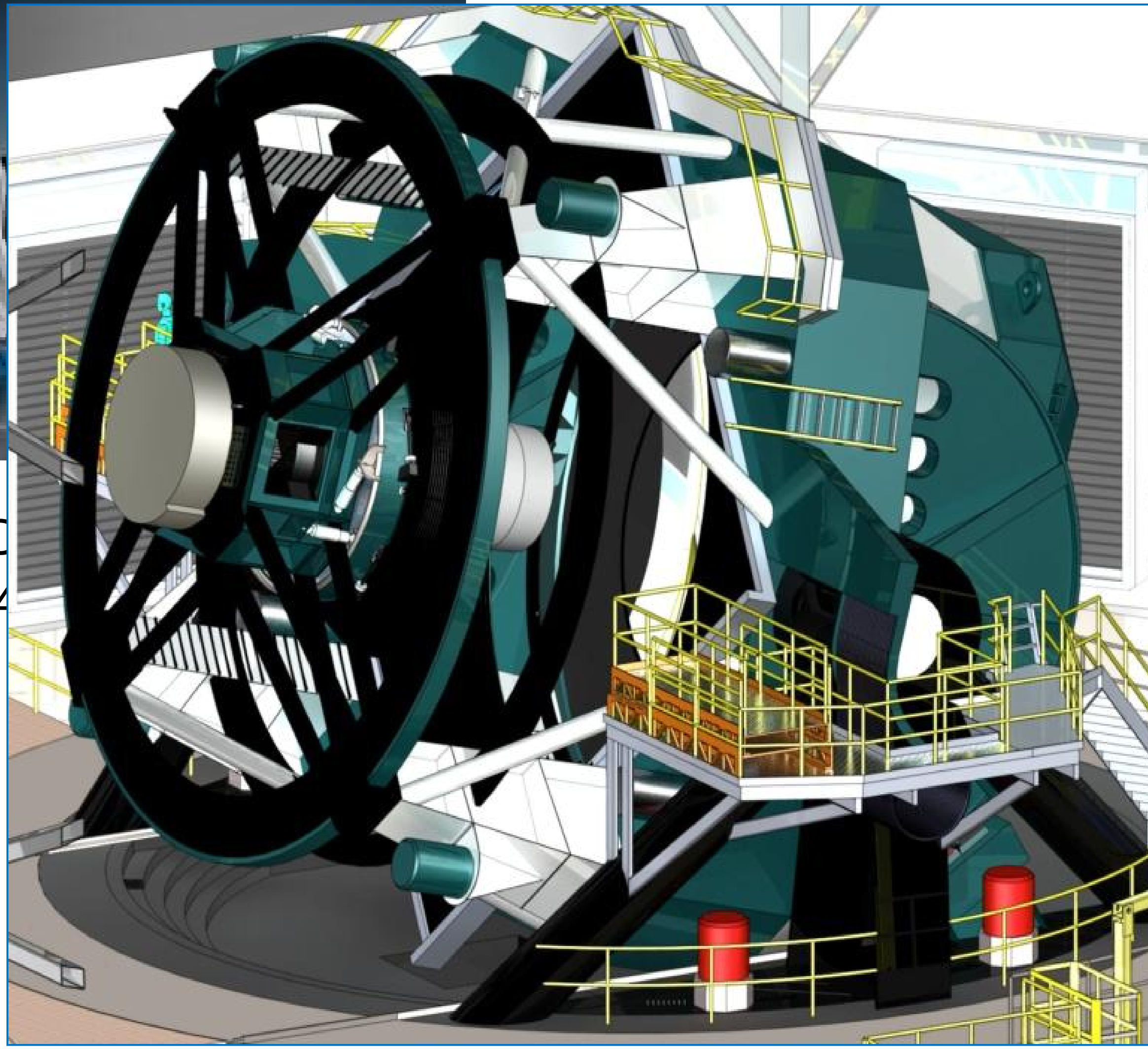
1 Petabyte/year today…

# Survey Trends

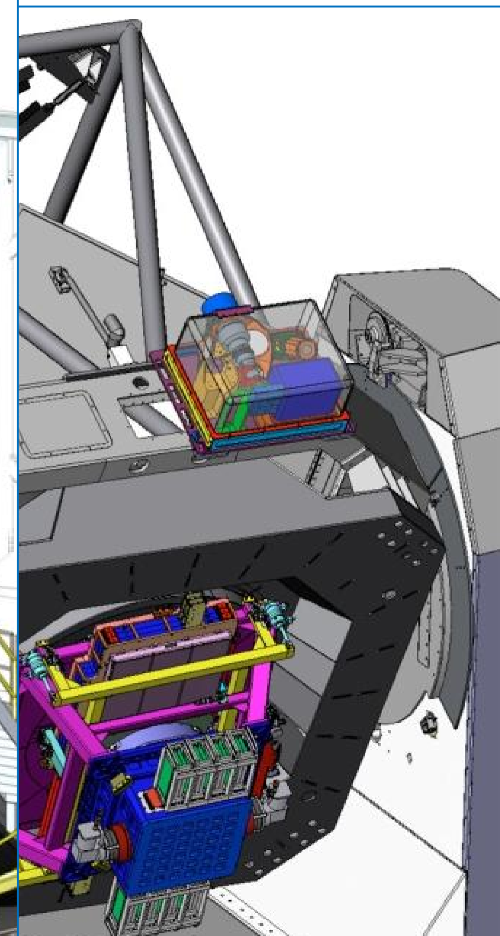




SD
2.4



LSST
8.4m  3.2Gpixel

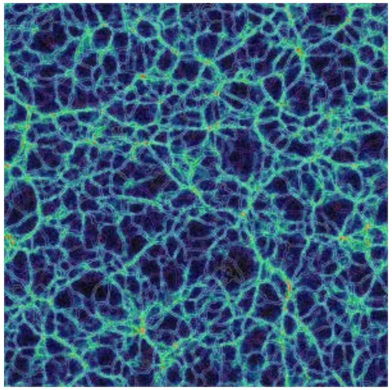


PanSTARRS
1.8m  1.4Gpixel

# Continuing Growth

**How long does the data growth continue?**

- High end always linear
- Exponential comes from technology + economics
  - *rapidly changing generations*
  - *like CCD's replacing plates, and become ever cheaper*
- How many generations of instruments are left?
- Are there new growth areas emerging?
- **Software is becoming a new kind of instrument**
  - *Value added data*
  - *Hierarchical data replication*
  - ***Large and complex simulations***



# Why Is Astronomy Interesting?

- Approach inherently and traditionally data-driven
  - *Cannot do experiments in the lab…*
- Important spatio-temporal features
- Very large density contrasts in populations
- Real errors and covariances
- Many signals very subtle, buried in systematics
- Data sets large, pushing scalability
  - *LSST will be 100PB*

*"Exciting, since it is **worthless**!"*

*— Jim Gray*

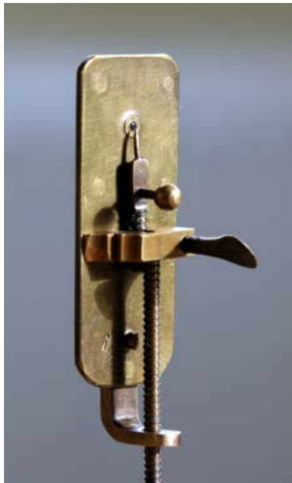
# Non-Incremental Changes

- Science is moving increasingly from hypothesis-driven to data-driven discoveries
- Data collection in collaborations, increasingly separate from analyses by small groups
- Need new randomized, incremental algorithms
  - *Best result in 1 min, 1 hour, 1 day, 1 week*
- New computational tools and strategies

… not just statistics, not just computer science, not just astronomy, not just genomics…

- Need new data intensive scalable architectures

**Astronomy has always been data-driven…. now becoming more generally accepted**



# Summary

- Science is increasingly driven by data (large and small)
- Changing sociology – surveys analyzed by individuals
- From hypothesis-driven to data-driven science
- We need new instruments: “microscopes” and “telescopes” for data
- There is a challenge on the “long tail”
- Data changes not only science, but society
- A new, Fourth Paradigm of Science is emerging…
- SDSS has been at the cusp of this transition

***A convergence of statistics, computer science, physical and life sciences…..***