Stellar flares

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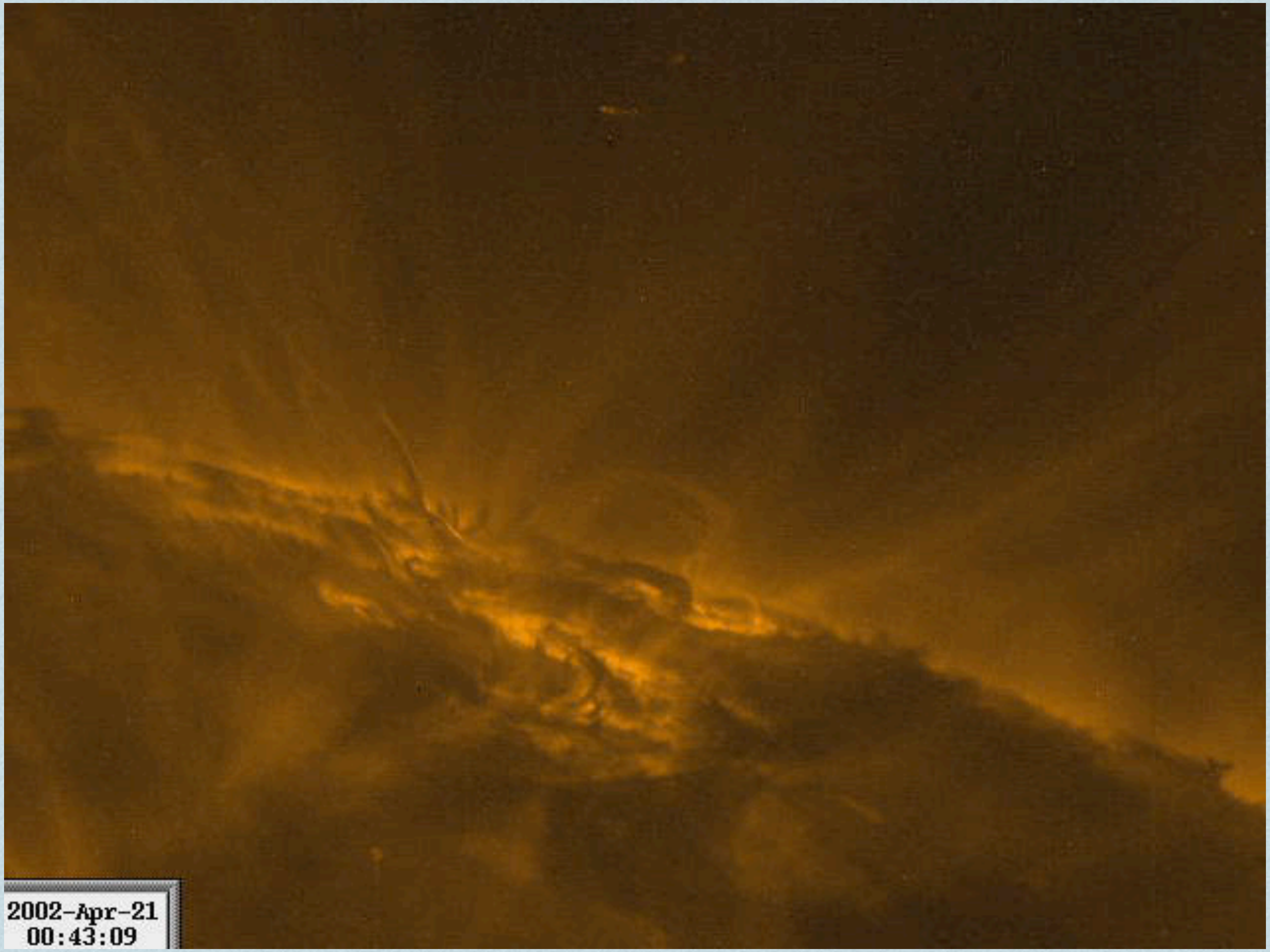
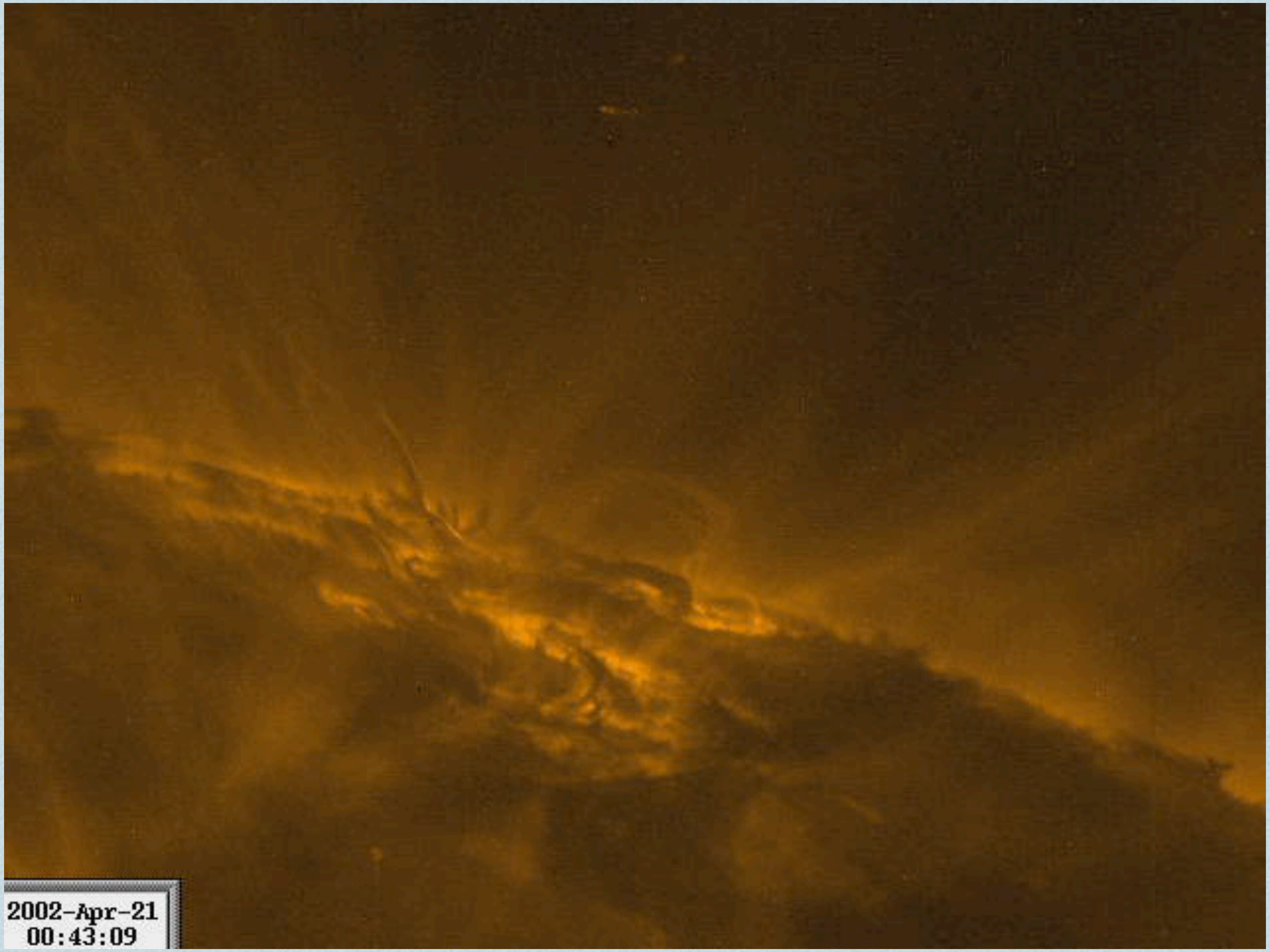
Why solar physicists love the Sun



Why astronomers hate the Sun

A star ➔ ·



Flares on stars

- Discovery
- Anecdotal observations: Phenomenology
- Systematic data: A potential context for the Sun
- Why study stars? What can we hope to learn?
    - Stars provide different environments to study and examples of solar phenomena in extremes. That helps elucidate the physics.
    - We have sunspot records for centuries and space (physical) data for decades, but that's $<10^{-7}$ of the Sun's life. There are many more stars out there to observe.
    - The Sun and stars evolve, but only the stars let us see the Sun at different life phases.

Some basics

- What makes the Sun the Sun: its convective envelope
- Convective stars are types FGKM (~1.3 to 0.1 M_{Sun}):
  - F stars: ~1.4 to 1.1 M_{Sun} or 6500-6000 K
  - G stars: ~1.1 to 0.9 M_{Sun} or 6000-5000 K
  - K dwarfs: ~0.9 to 0.7 M_{Sun} or 5000-4000 K
  - M: ~0.7 to 0.1 M_{Sun} or <4000K (at ~0.3 M_{Sun} stars become fully convective)
- The Sun: an "early" G dwarf
  - "Dwarf" means it is still on the main sequence, converting H to He in its core
  - Sun is ~4.5 Gyr old, half way through its main sequence life
  - The Sun is central to all of astrophysics: Only star with an age
- "Solar-type" or "solar-like" a loose term
  - To me "solar-type" means a G dwarf
  - To some it means a star with a convective envelope, including evolved stars

The paradigm of solar-type behavior

- The paradigm:
  - Solar-type stars have convective envelopes
  - Convection + rotation (esp. diff. rot.) ➔ dynamo
  - Dynamo ➔ magnetic field regeneration
  - Magnetic field ➔ activity
  - Magnetic field + solar wind ➔ AM loss
  - Higher rotation ➔ higher B ➔ higher AM loss rate
  - Hence AM loss is deterministic and rotation rates converge
- This is based on observed properties of the Sun and young stars
- The convergence occurs by ~0.5 Gyr
- Very young solar-type stars (<200 Myr) exhibit a wide range of rotation (>20x), with periods from 0.25 day (100x solar) to ~1 week

Stellar flares

- Evidence as early as 1924, but van Maanen is credited with first detections ca. 1940 (V1396 Cyg, AT Mic, YZ CMi).
- The big event: in 1949 a massive (~70x) flare on Luyten 726-8, dM6e (in a long-period binary with a M5.5e star), seen spectroscopically by A. H. Joy and M. L. Humason (PASP, 61, 133). This was to be called UV Ceti, the eponym for the class.
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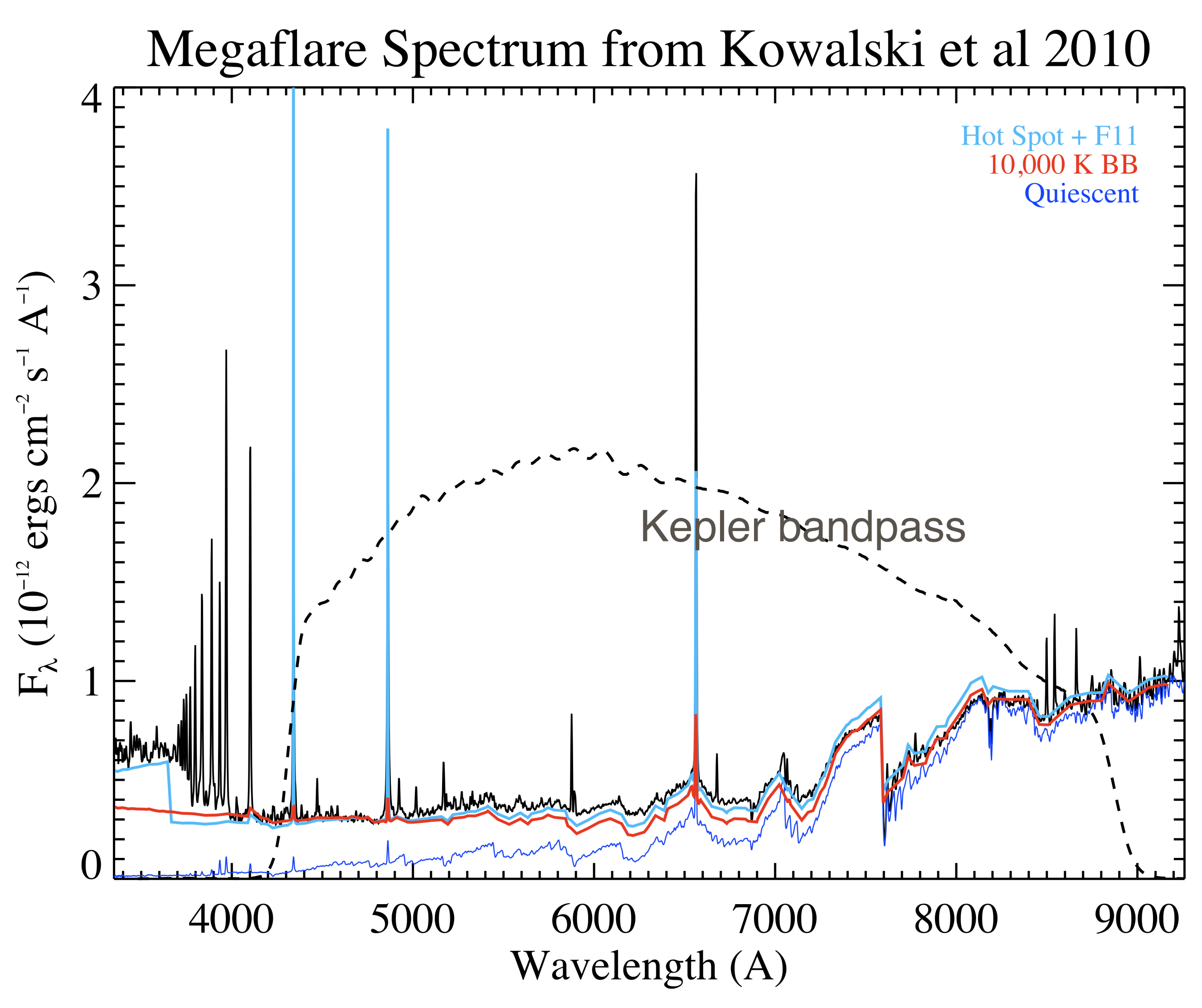
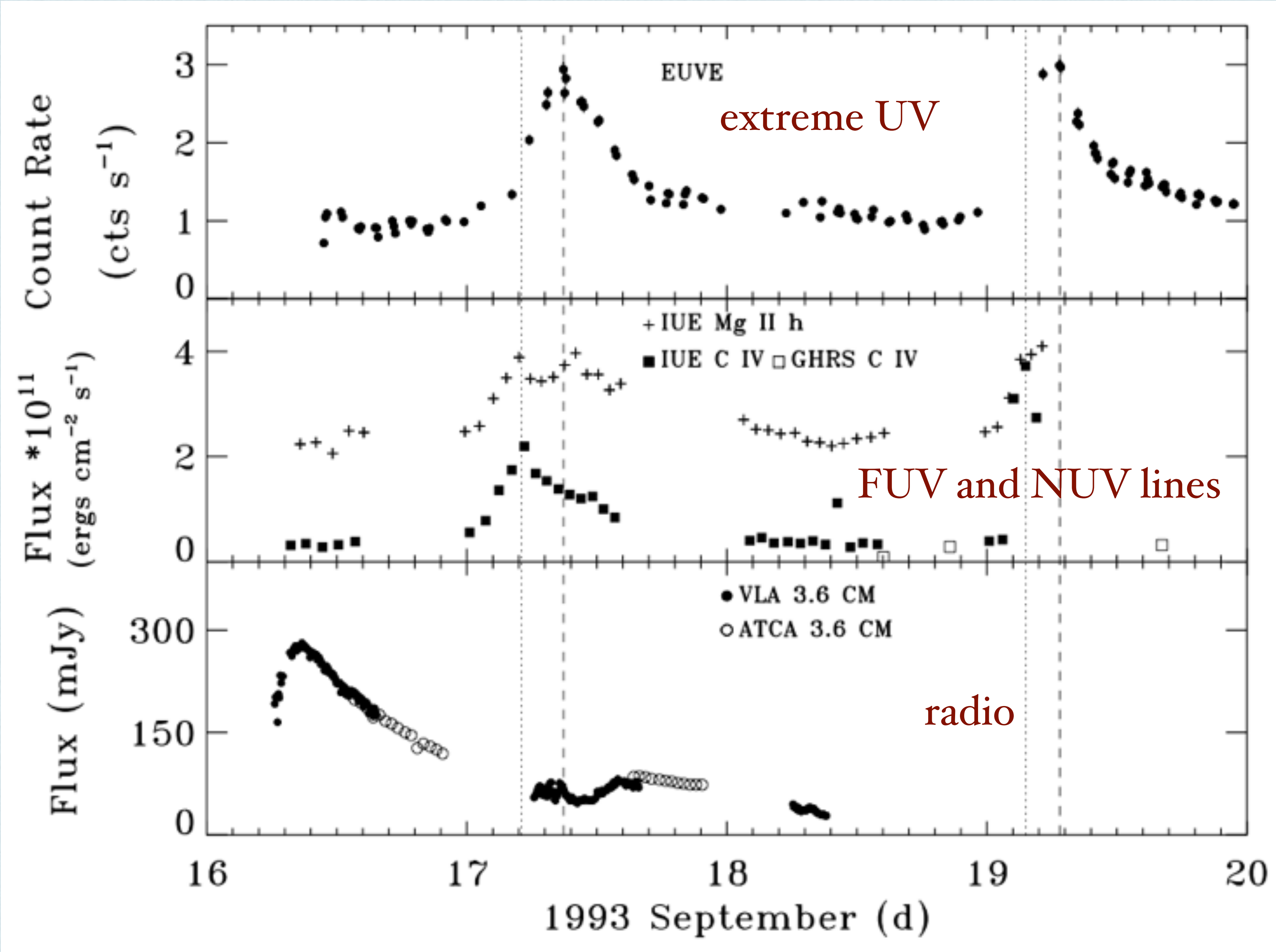
- Note that most flare energy lies outside the Kepler bandpass except for Hα, Hβ, Hγ.



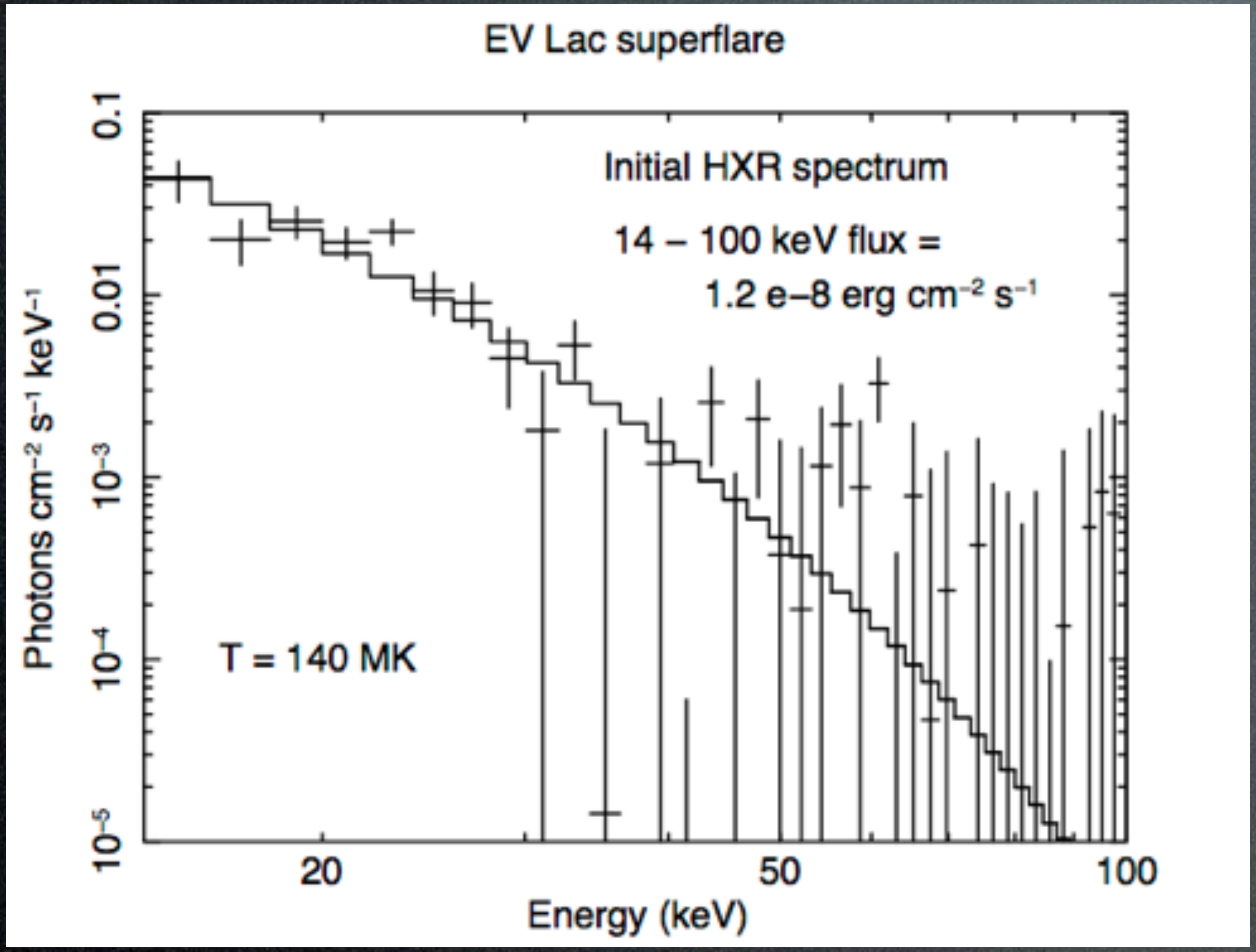
Spectrum of flare in YZ CMi (dM4e)

Stellar flares are multi-wavelength



HR 1099 (G5IV+K1V); Osten et al. 2004

a "GRB" at 5 pc!



Osten et al. (2010)

In highly active (young) solar-type stars, log L_x/L_{bol} ~ −3

EV Lac (dM4, d=5 pc) Swift trigger April 25, 2008

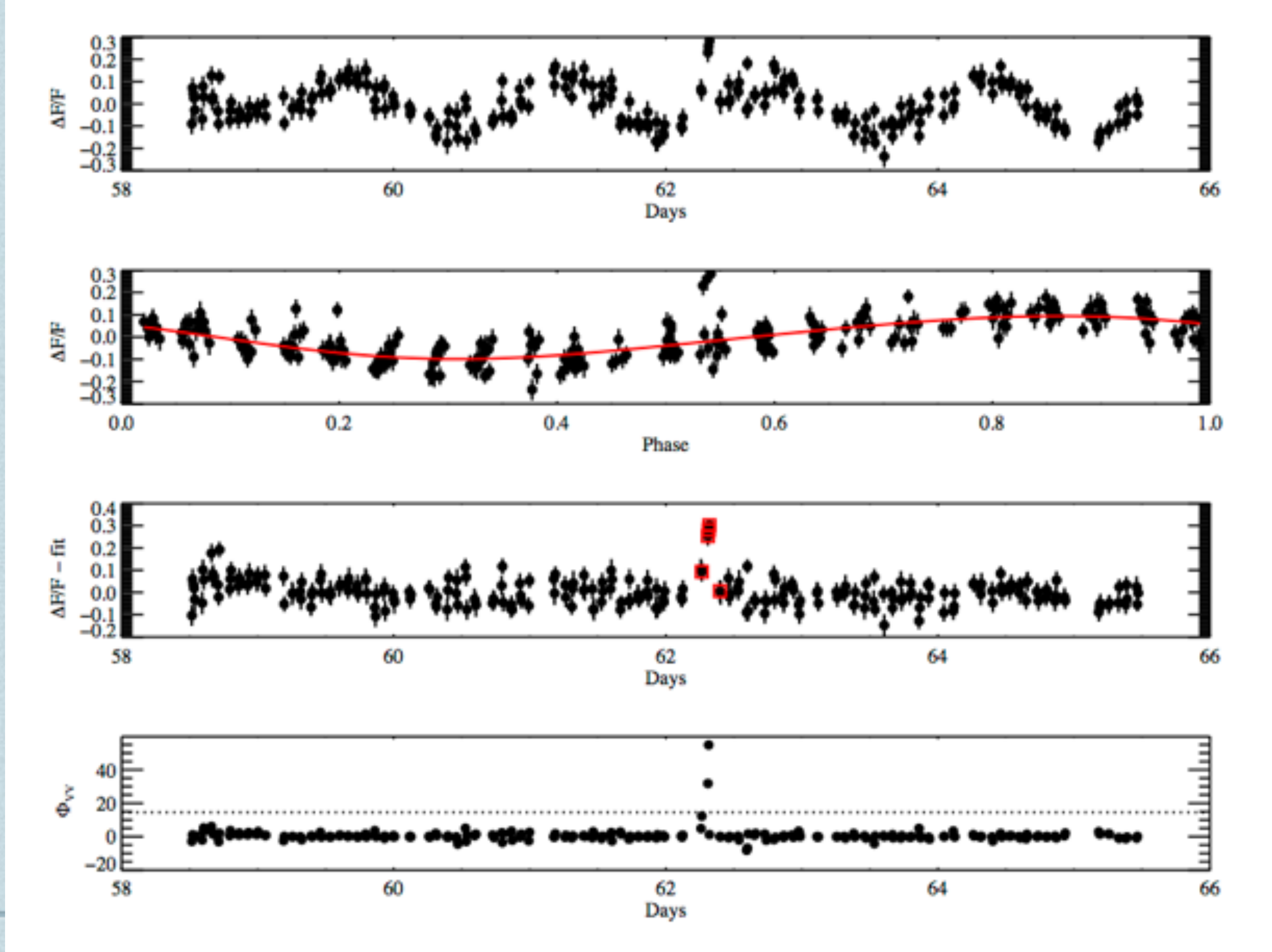
➜F(0.3-100 keV) = 5.3×10^{-8} ergs/cm^2/s

➜factor of 7000 increase over quiescent value

➜peak estimated L_X/L_{bol} ~+3.1

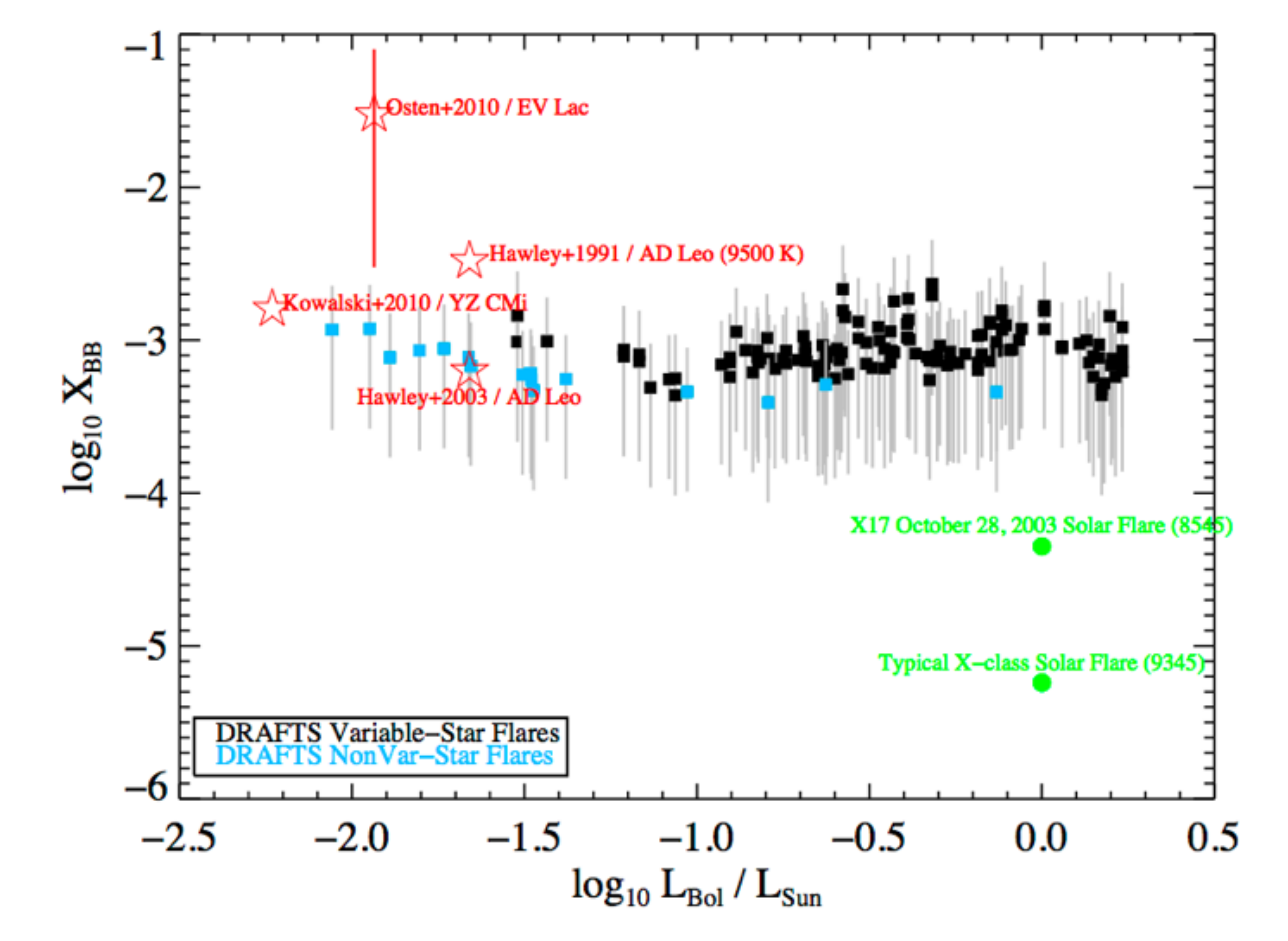
Flares in the Galactic Bulge (DRAFTS)

- 7 days continuous coverage with HST in broad-band visible light
- ~200,000 stars, ~10 Gyr old (plus younger)
- Flaring stars appear to be close binaries (RS CVns)



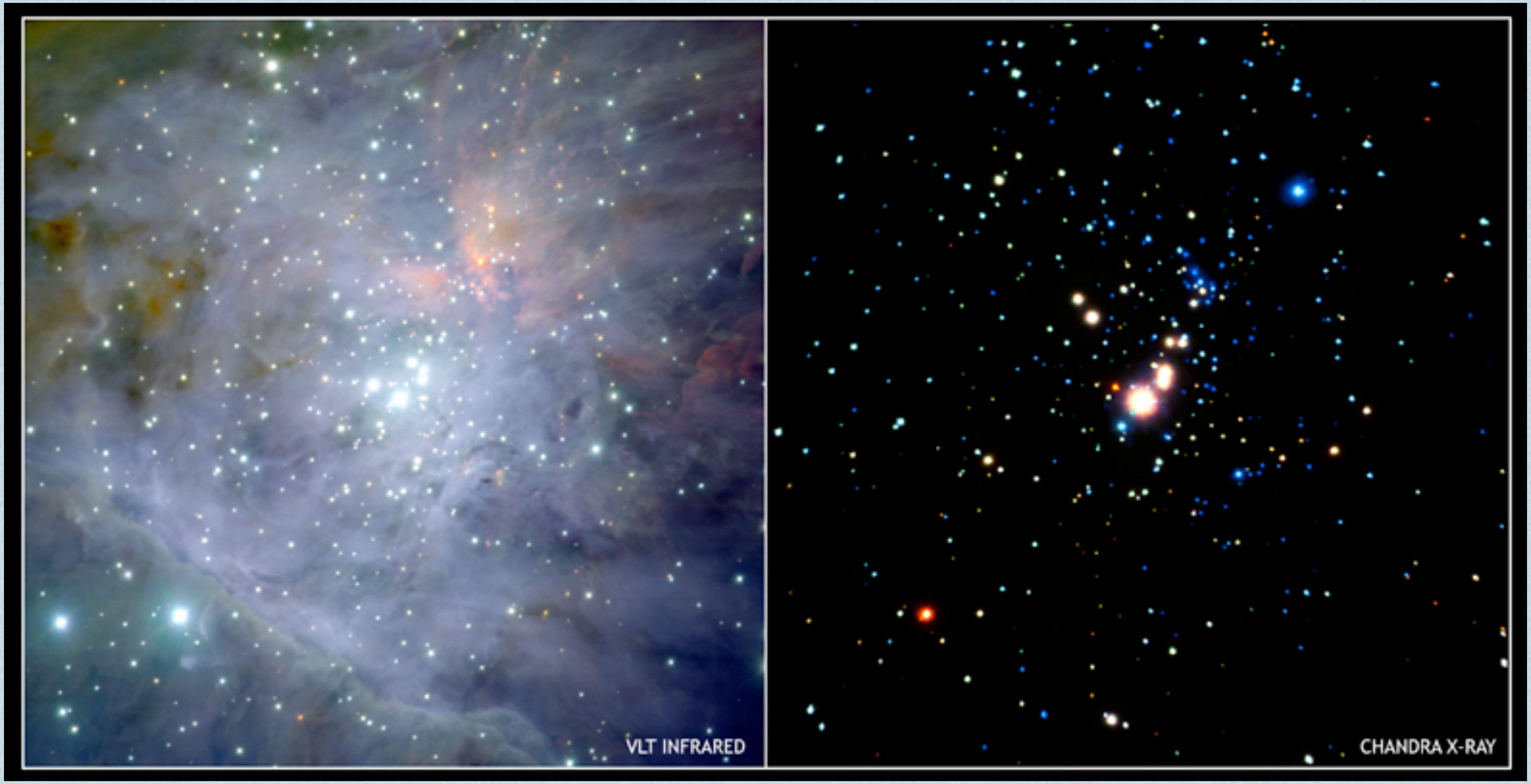
Coverage fractions

❖ Flaring stars compared to the Sun

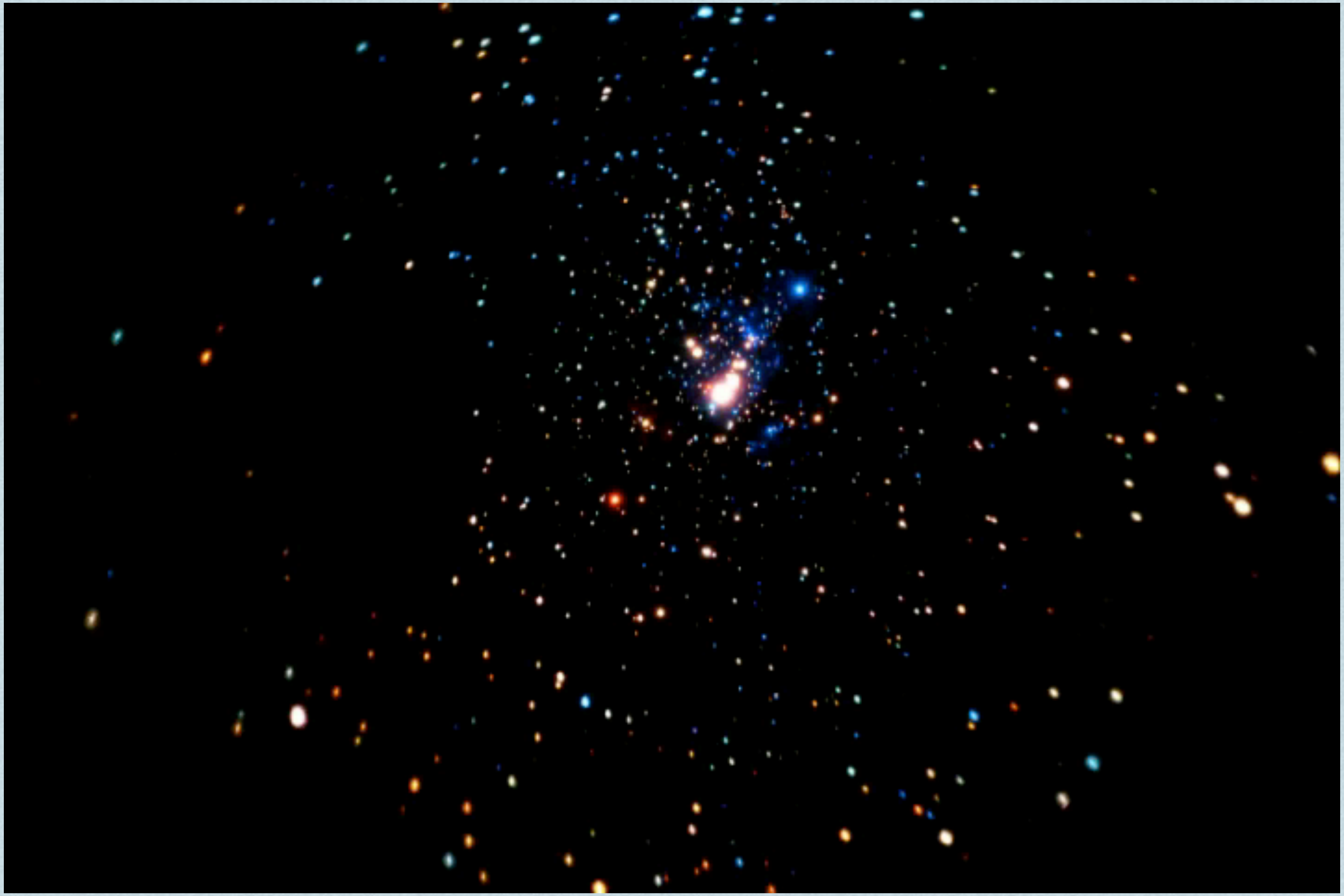


The Orion Nebula Cluster

- ~1 Myr old
- Infrared (left) and x-rays (right)
- On a solar scale, Orion x-ray flares are class X300 – X40,000



Orion in x-rays



Stellar flares pre-Kepler

- Observational data mostly anecdotal or at least incomplete:
  - Sometimes sheer luck
  - Or surveys in regions expected to yield a payoff (very young clusters)
  - Subject to social, administrative, and technical factors
- Important physical data, though:
  - Maximum flare energy seen consistently at $\sim 10^{36-37}$ ergs
    - How can the star store that much energy before it's released?
    - Maximum seen for RS CVn stars, which are evolved.
      Smaller stars have smaller E_{max}.
  - Stellar events seen vividly at non-thermal wavelengths (radio, x-rays, UV).
    - Potentially effective way to find flare stars, but sensitivity still too low.
  - Flares associated with rapidly-rotating stars (very young or close binaries).

The Kepler mission

- Primary goal: Detect Earth-sized transiting planets around Sun-like stars via ultra-high-precision photometry.
- Statistics of transits are poor even if planets are ubiquitous
  - ~1:200 for Earth+Sun
  - Hence observe ~100,000 stars total, meaning ~100 square degree field
  - Observed for 4 years to detect ~1-year periods (see the event >3 times)
  - Reject false positives (esp. binaries)
- Need relative photometric precision of 20 ppm over ~6.5 hours for V =12 (4σ)
  - Instantaneous diminution from transit is 80 ppm
  - Kepler photometry is not absolutely calibrated
  - Variations with time-scales more than ~week can be problematic
- Prelaunch (descoped) plan would only have sampled stars over 30-minute intervals to keep data rate down.
- Actual operations allow ~500 targets to be sampled in one-minute intervals, and that list changed monthly. This enabled seismology (KASC).
- Kepler went far beyond previous photometric precision by ~10^2 and observed ~10^5 solar-type stars for years.

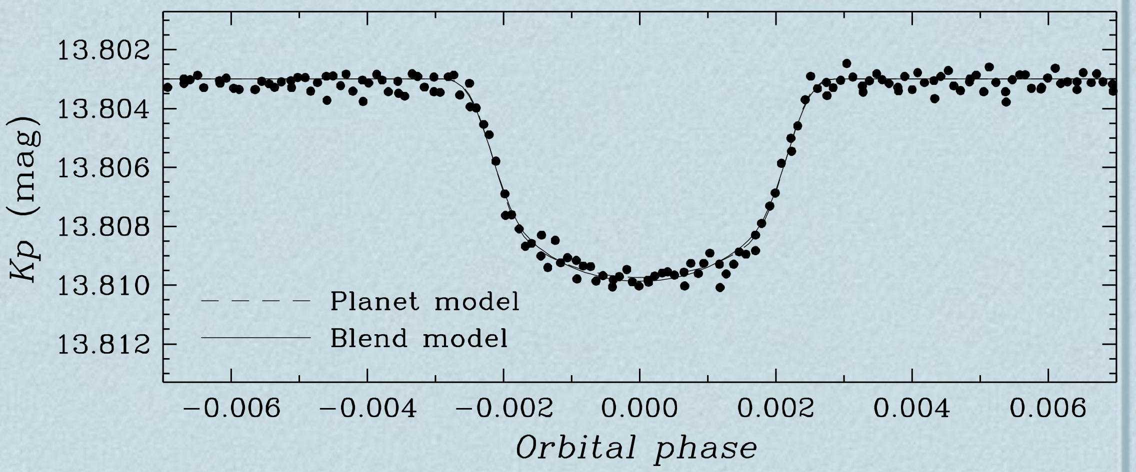
Kepler: A stealth solar physics mission

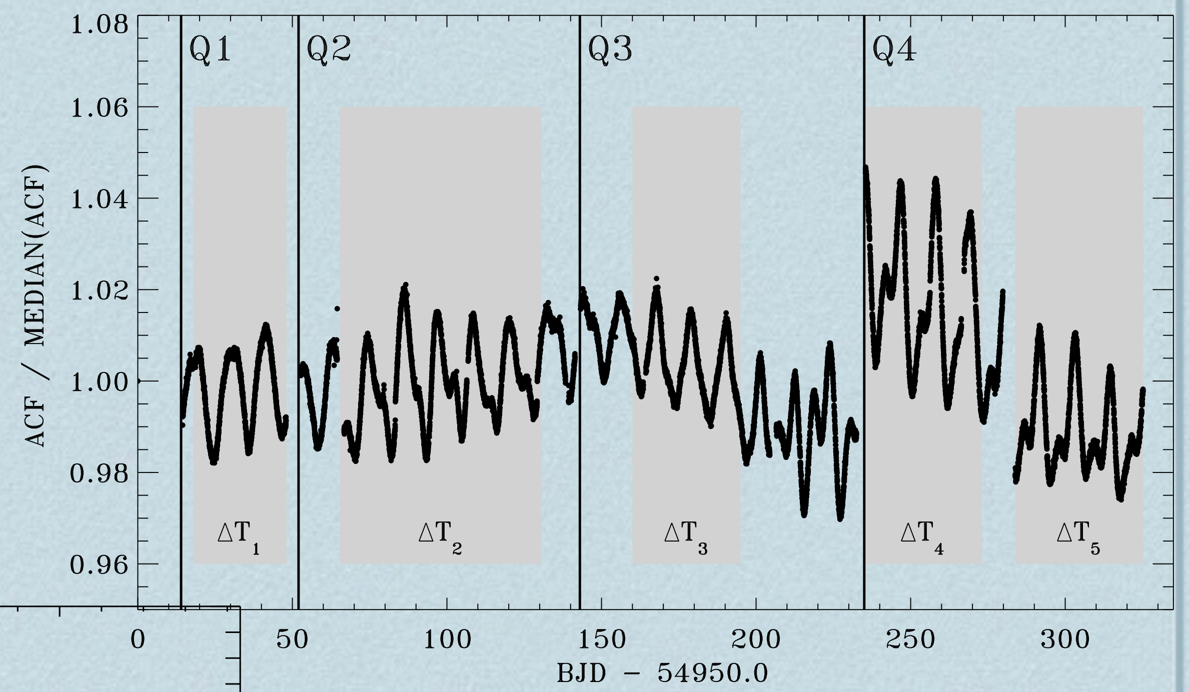
❖ Built for dips: transits and eclipses (planets and binaries)

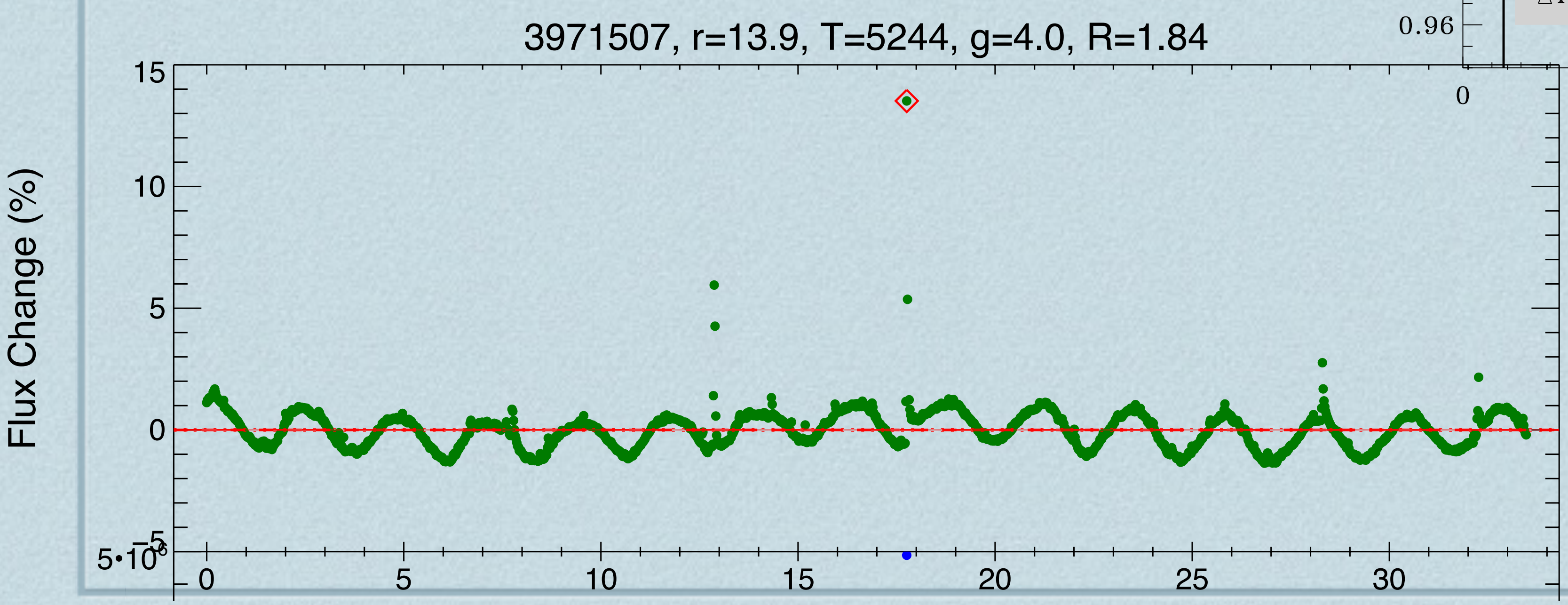
❖ Adapted for wiggles:

- ❖ Gross scale: spots, rotation & differential rotation
- ❖ Fine scale: oscillations

❖ But then there's bumps: flares and other transients

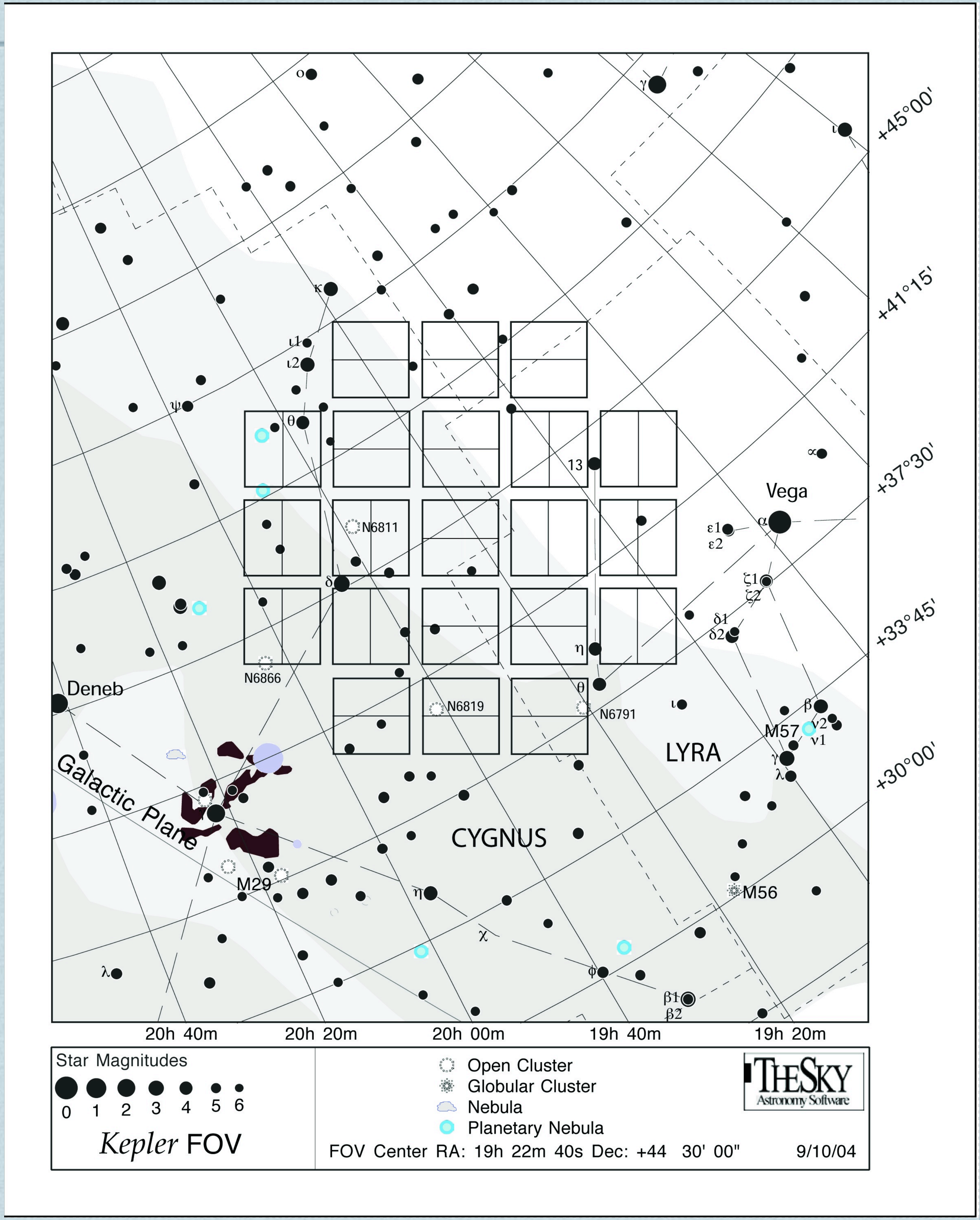






Kepler FOV

- Cygnus/Lyra
- $b \approx +13.5^{\circ}$
- ~100 square degrees
- G dwarfs at ~300 pc for $V \approx 12$; this means $Z \approx 100$ pc, or one scale height.
  - Recently-formed stars <u>not</u> expected in this field.
  - No star-forming regions or young clusters seen.
- ~150,000 selected targets in field are observed.
- ~100,000 are "solar-type."

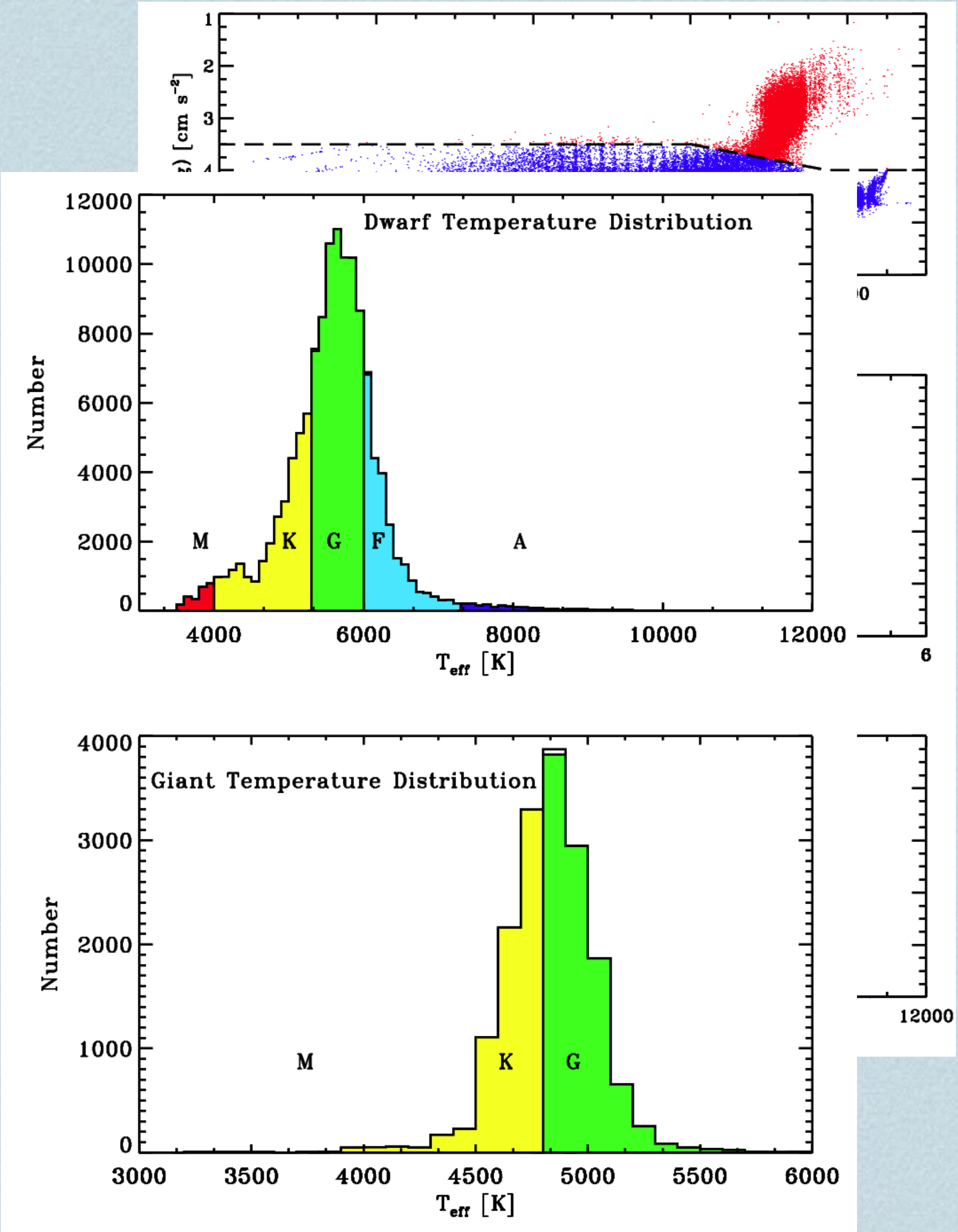


Kepler target sample

- Intended to be predominantly G dwarfs
  - Gs are photometrically quiet (Sun is ~10 ppm); Ks and Ms suspected to be noisier
  - Gs provide a good balance between frequency and luminosity
    - Stars get fainter much faster than they get numerous
    - Need brightness to get photons for S/N (detecting planets)
    - Need brightness for high-resolution spectra to confirm planets
  - G spectra ideal for RV follow-up (many narrow lines)
  - We understand the Sun
- Pre-launch ground-based photometry to estimate stellar properties: Kepler Input Catalog (KIC)
  - SDSS *griz* plus DDO 5180 Å (Mg b-band)
  - Temperature is easy (±100 K), but KIC temp's may be systematically low
  - Gravity is hard and imprecise (but essential to cull non-dwarfs)
- Sample changed slowly with time
  - 5,000+ dropped each quarter
  - Some dwarfs turn out to be giants (can often tell from photometry alone)
  - Some targets not good for planet detection (noisy)
- Sample includes examples of almost every stellar type
- ~1,000 observed at 1-minute cadence (remainder at 30-minute)

The Kepler sample

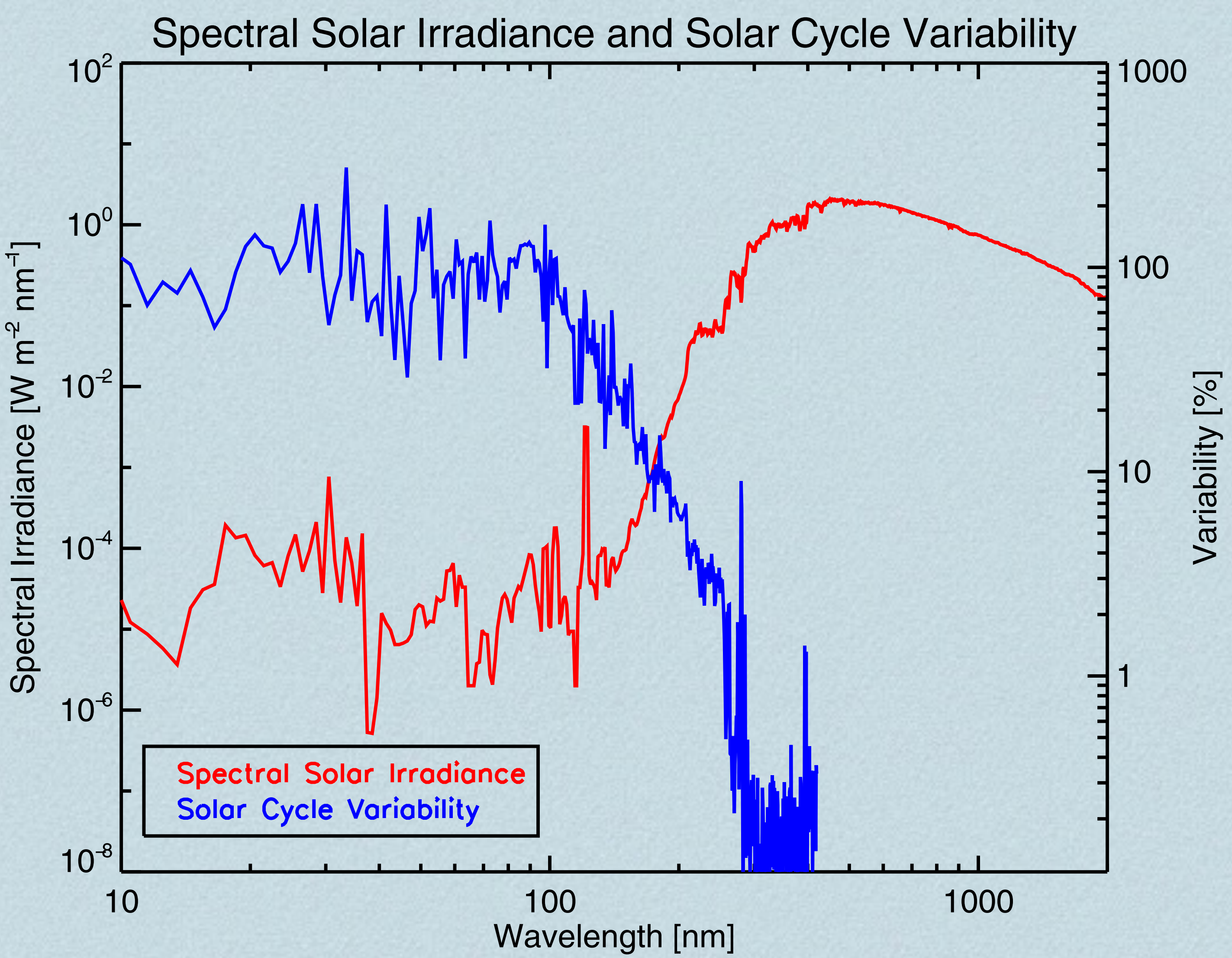
- Clean distinction between dwarfs (blue) and giants (red).
- $N_{\mathrm{dwarfs}}/N_{\mathrm{giants}}$ ~ 7.
- Temperature distribution the inverse of what's ideal for flare studies.



Ciardi, von Braun et al. 2011, AJ, 141, 108

Solar variability vs. wavelength

- Very little solar flux below 1000 Å, but most of the solar-cycle variability is there.



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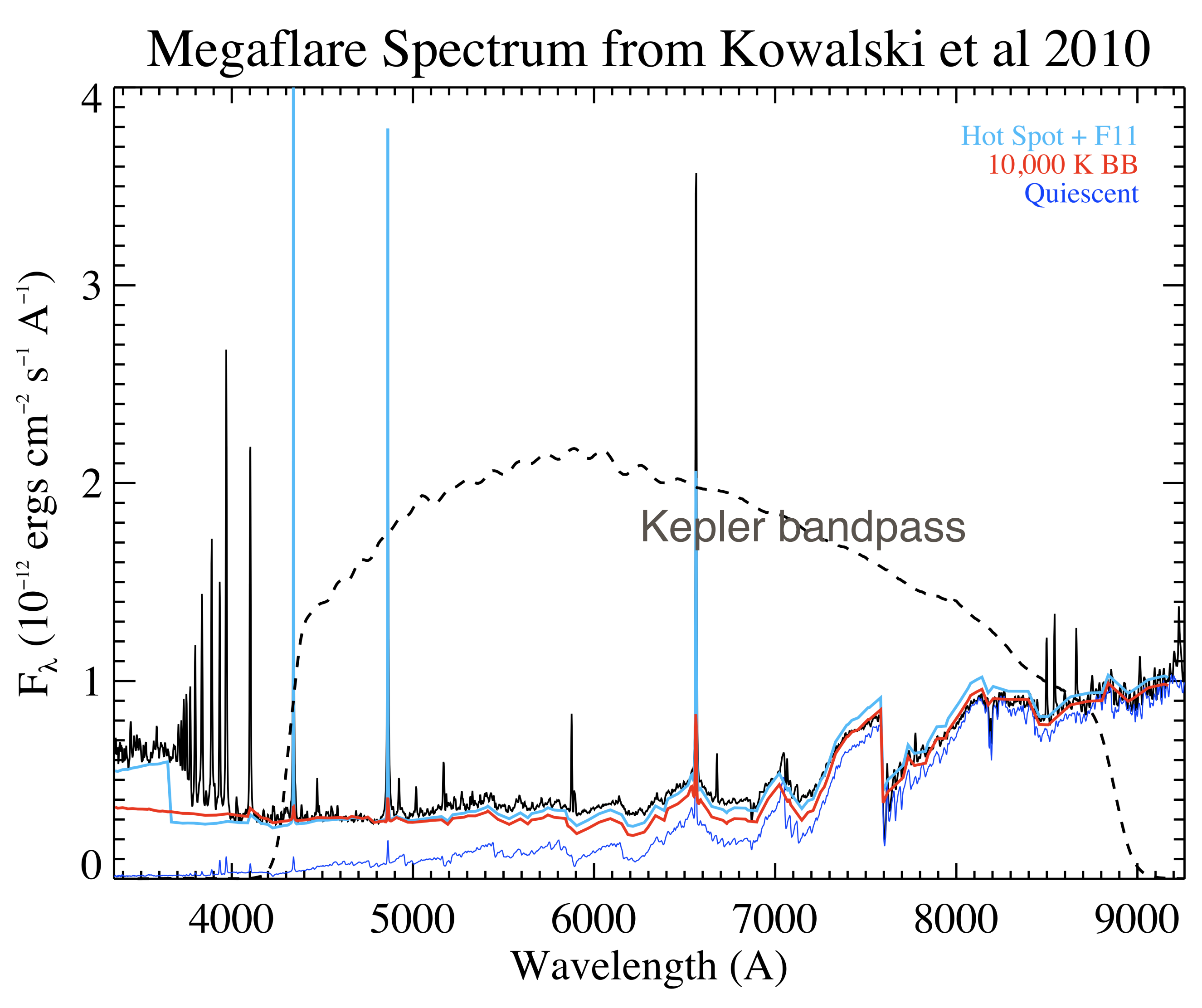
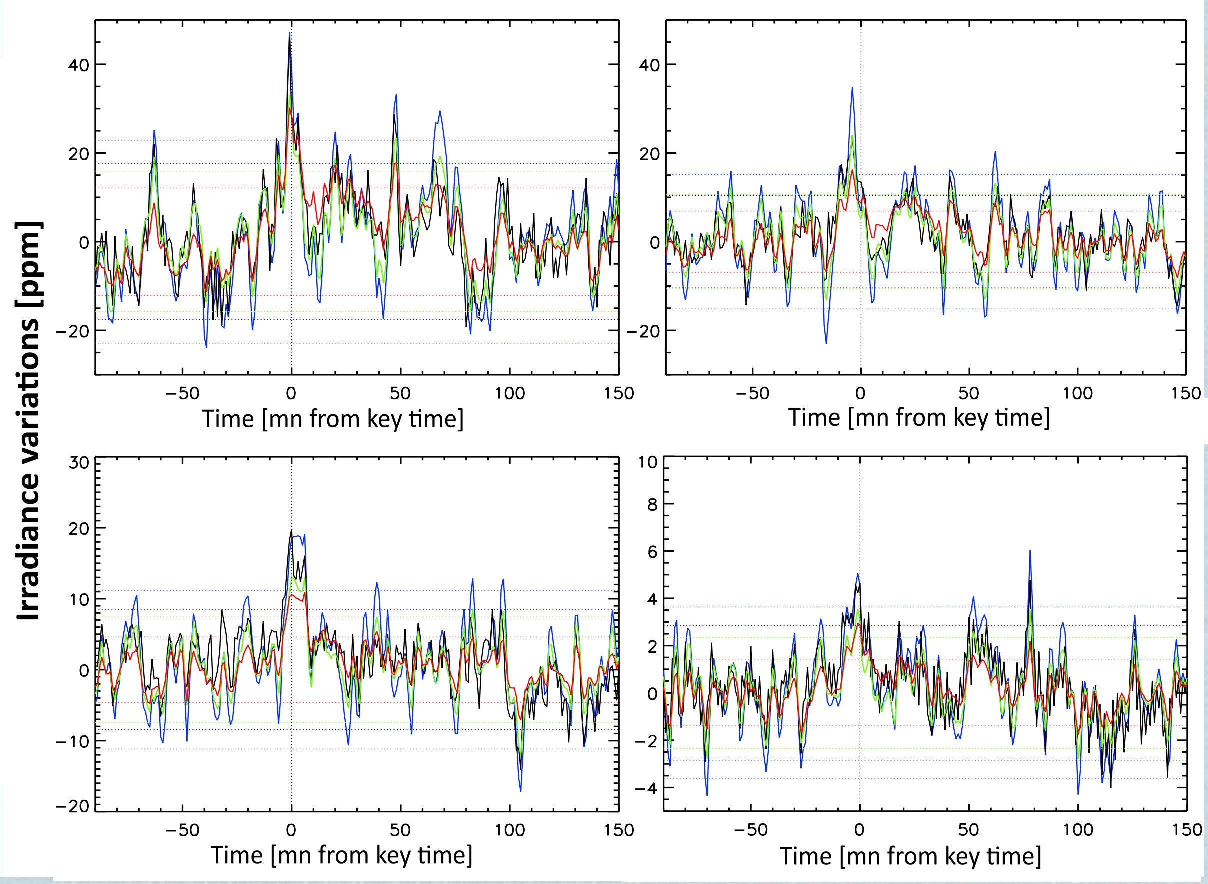


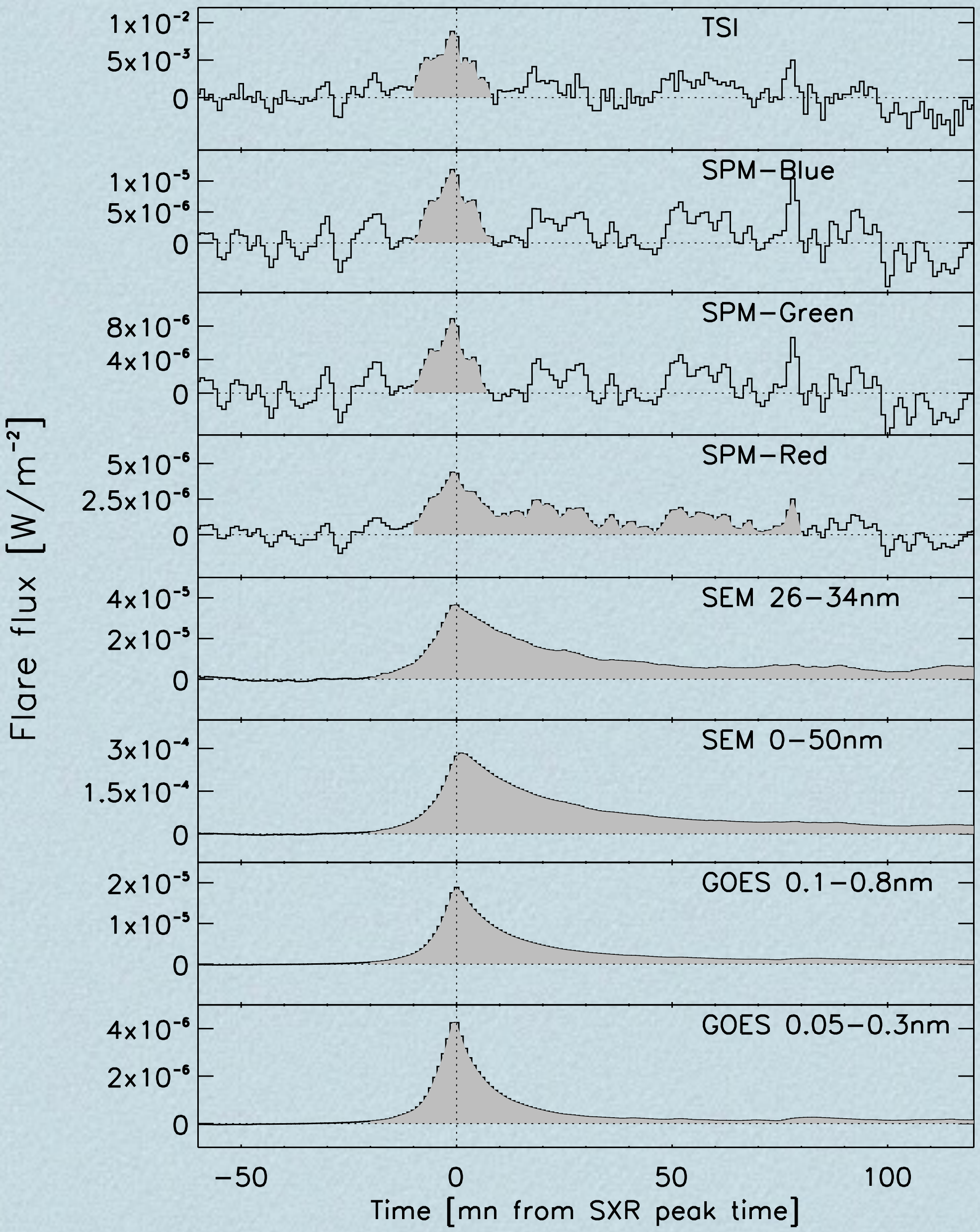
Spectrum of flare in YZ CMi (dM4e)

Solar flares in integrated light

Are they seen in white light?

- Yes (discovery!), but spatially resolved. *Are they seen in TSI?*
- Barely, when many flares co-added (Kretzschmar et al. 2011, A&A).
- Different behavior for flares in optical compared to x-rays.

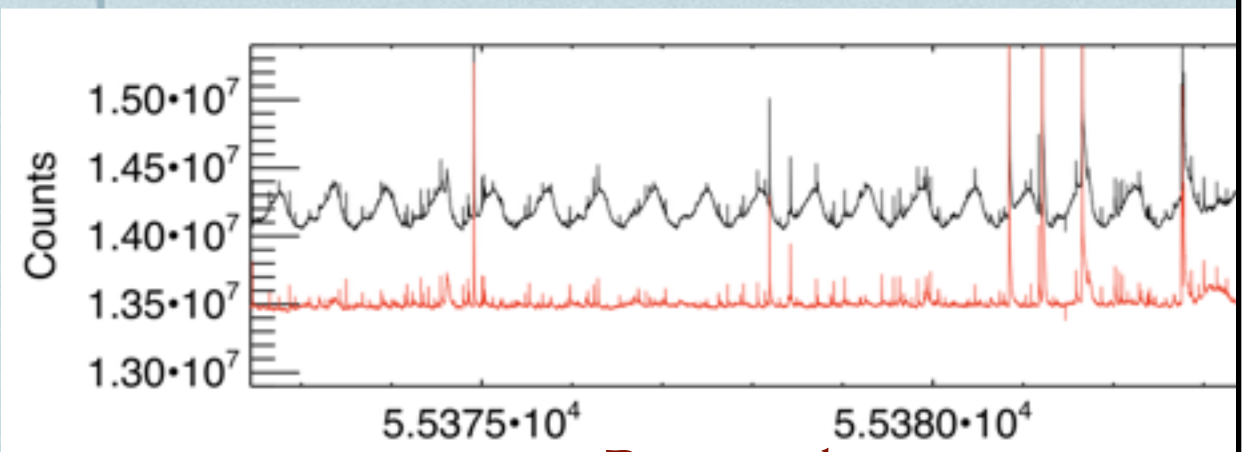




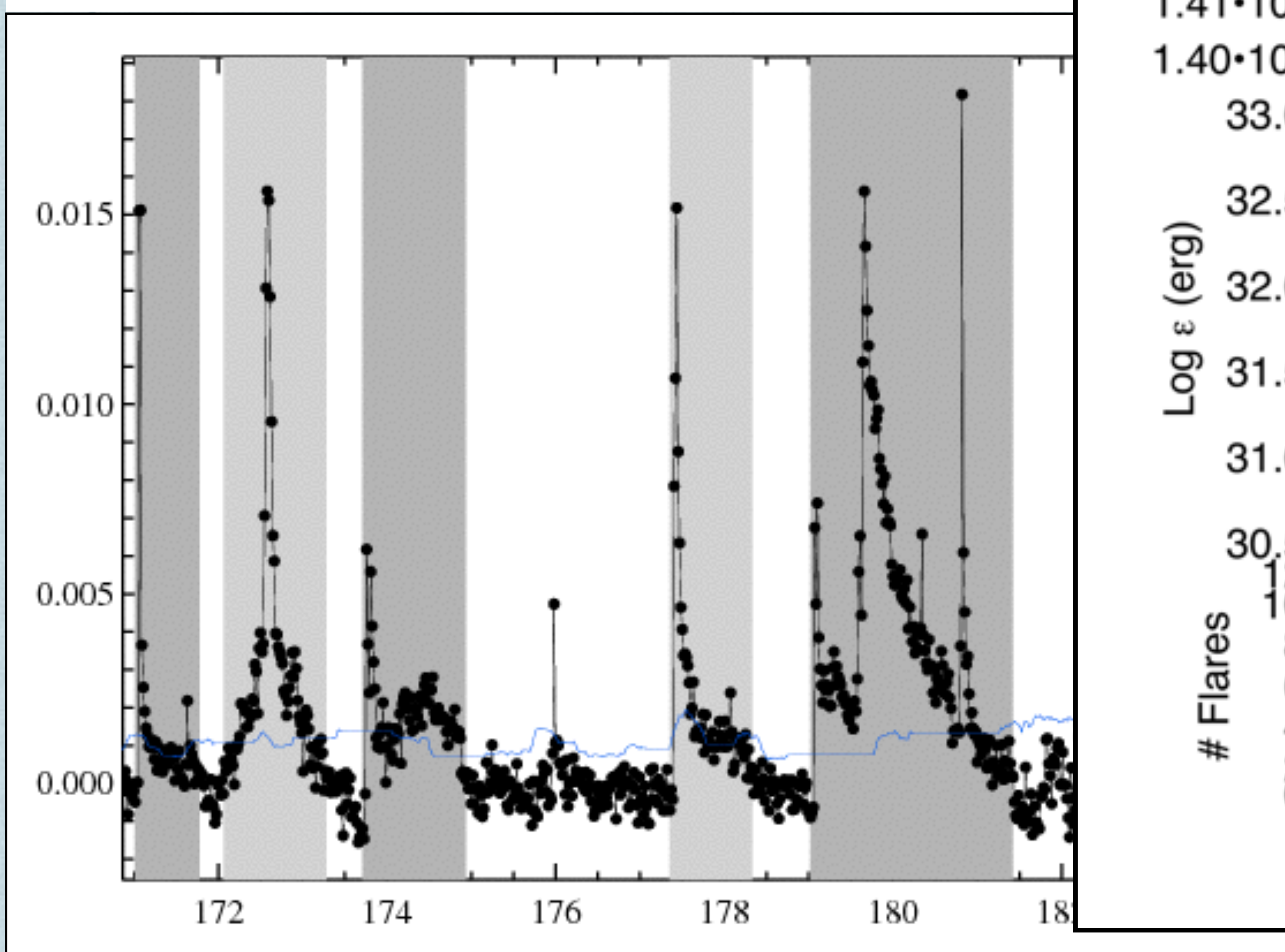
Stellar flares with Kepler?

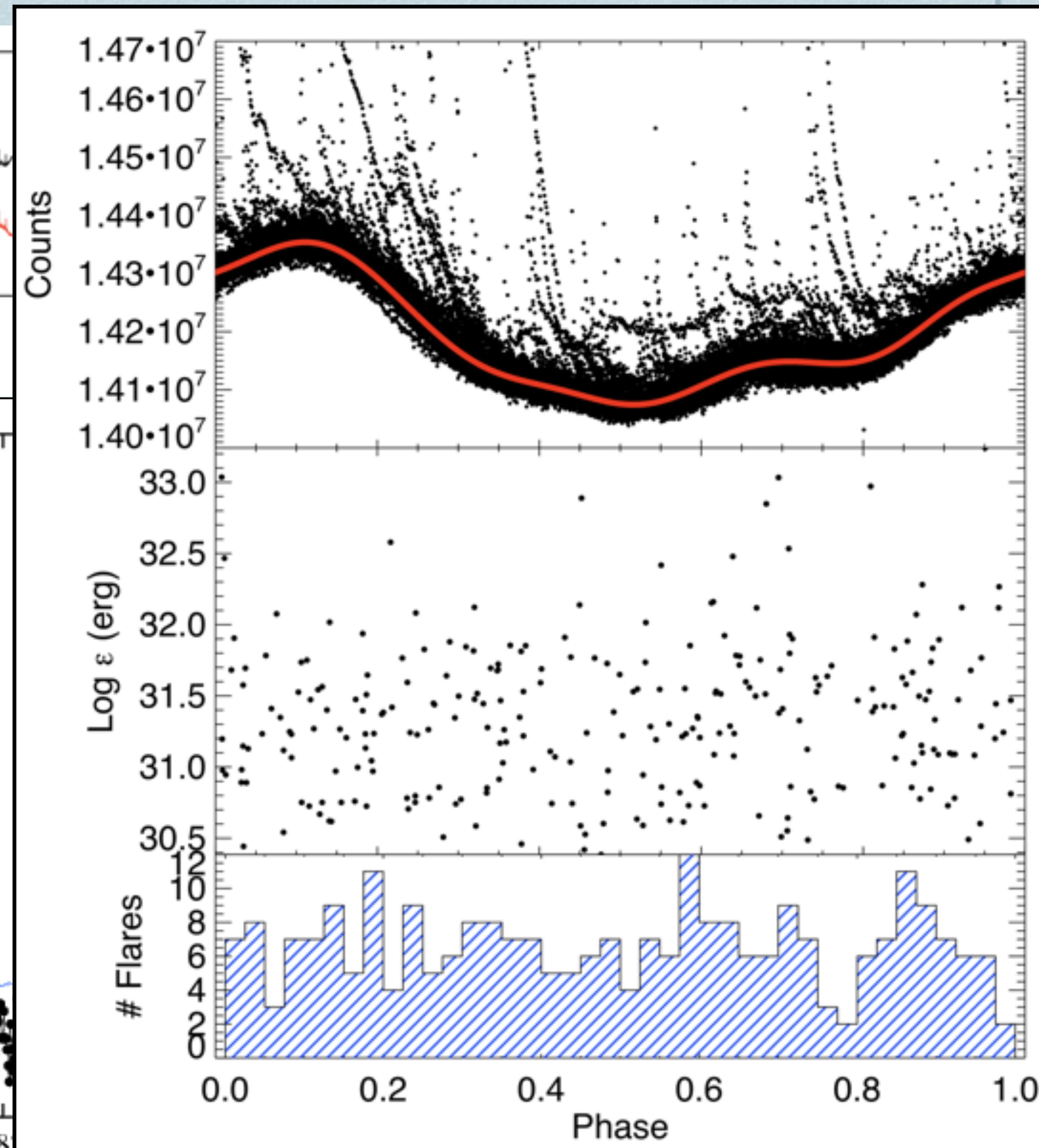
- All this suggests Kepler would be less than ideal for detecting and studying stellar flares:
  - Kepler sample strongly emphasizes G stars; only a few with T < 5000 K.
  - Kepler is white light but favors red (5000 Å+; CCD response), so flares are diluted.
  - No color information.
  - 30-minute sampling means even the largest solar flares would never be reliably seen (one barely deviant data point).
    [10^{32} ergs at 1 L_{Sun} over 30 minutes is 1:50,000 in just one data point.]
- But:
  - Very large sample (> 100,000 stars), which favors luck.
  - Continuous, long-term sampling, which favors luck.
  - Extraordinary photometric precision.
  - There are a not-small number (>10^4) of K & M stars observed by Kepler.
- And, we've gotten lucky.

Gliese 1243, 1-minute (Hawley et al. 2011)



P = 0.59^{d}



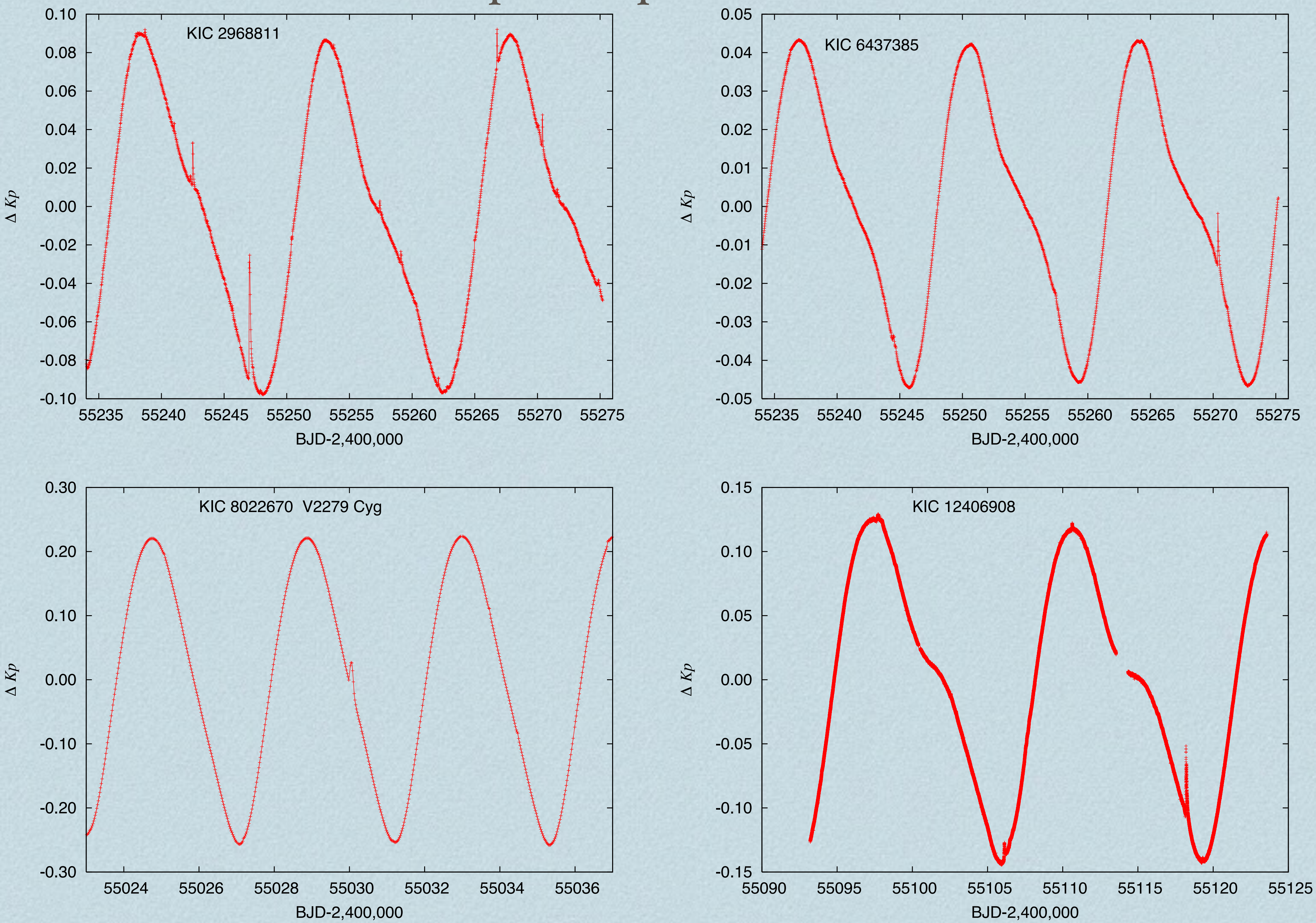


Gl 1243 (Hawley et al. 2011)

- Star varies with strict 0.59-day period (binary?).
- Multi-sine fit to light curve to remove overall spot variations.
- Flares found by positive excursion >2.5σ.
- Flares occur many times per day.
  - Is the star ever quiescent?
- No relation of flare frequency or energy to phase.

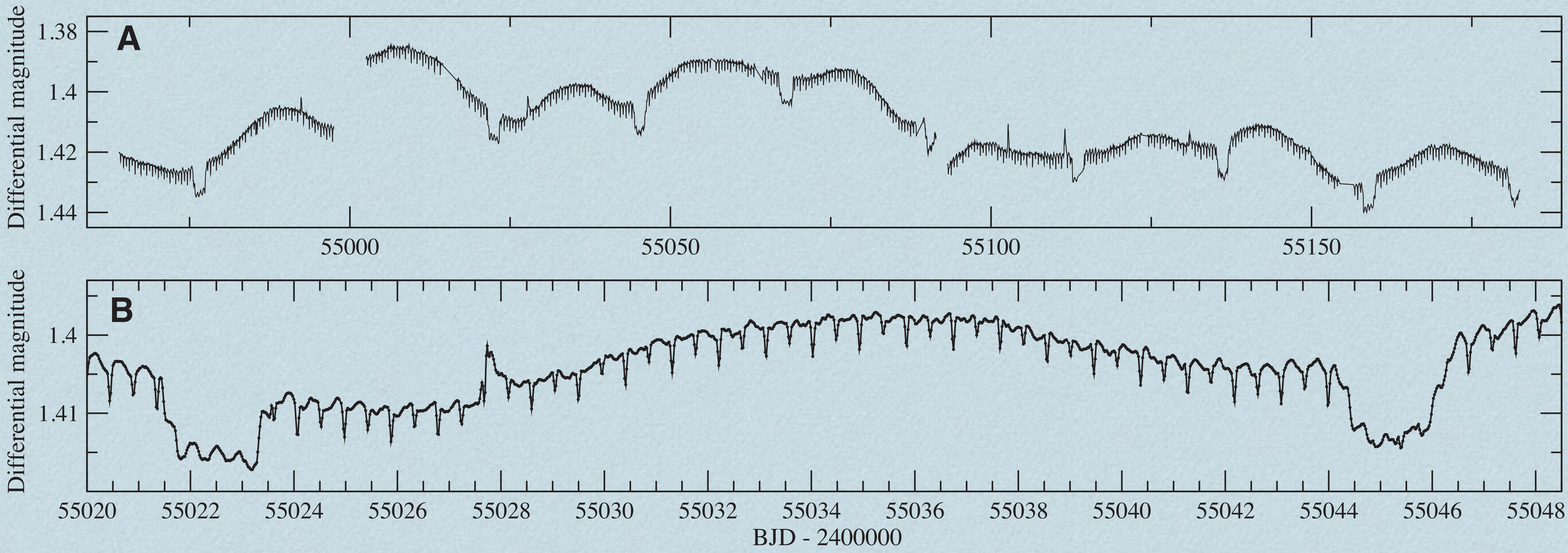
More Kepler examples

❖ Szabó et al. (2011): Kepler Cepheid candidates



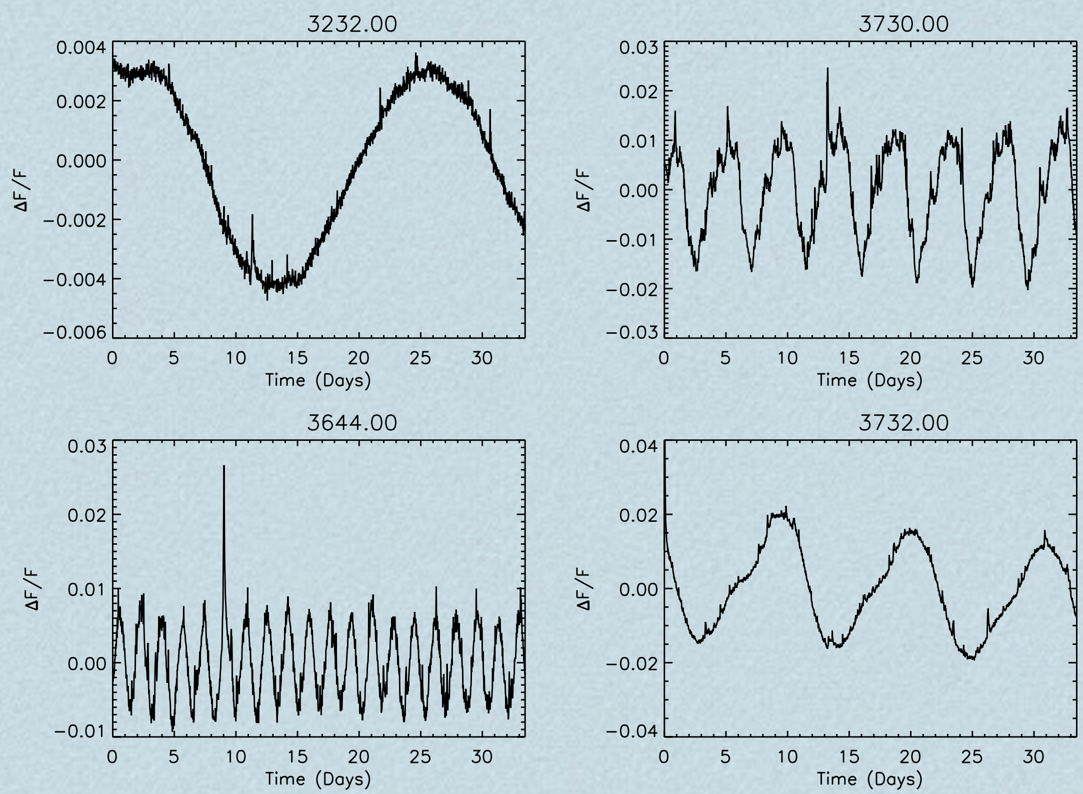
Yet another example

- Derekas, Kiss, et al., 2011, Science: "HD 181068: A Red Giant in a Triply Eclipsing Compact Hierarchical Triple System"



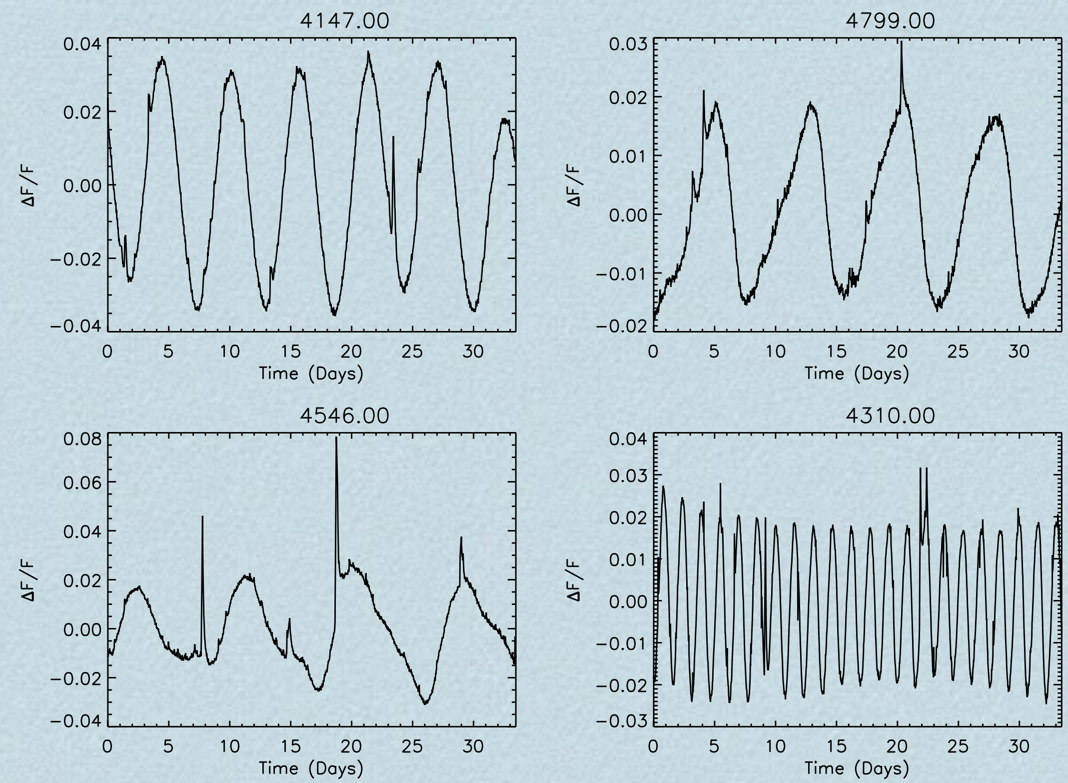
Kepler light curves with flares

- Examples of flaring M dwarfs (Walkowicz, Basri, et al. 2011):
  - Note the broad range of apparent rotation periods: ~1 day to ~20.
  - Similar ~10x range in amplitude, both of rotational modulation, and flares.



M

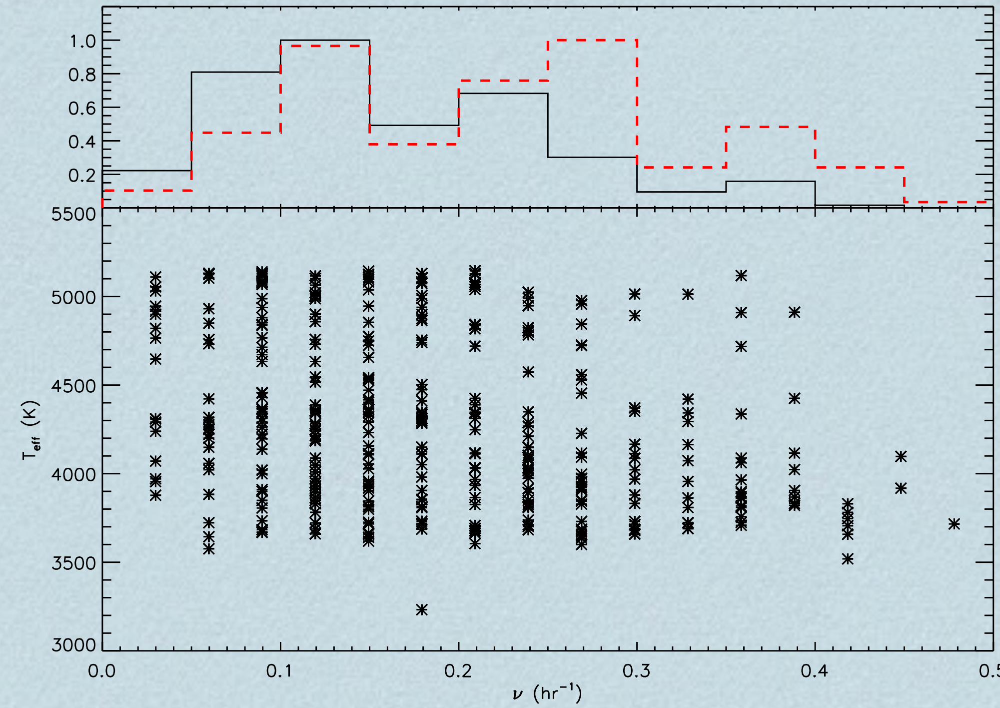
- K dwarfs:
  - Ditto.
- The overall variability is enough to detect from the ground, and some flares would be too.

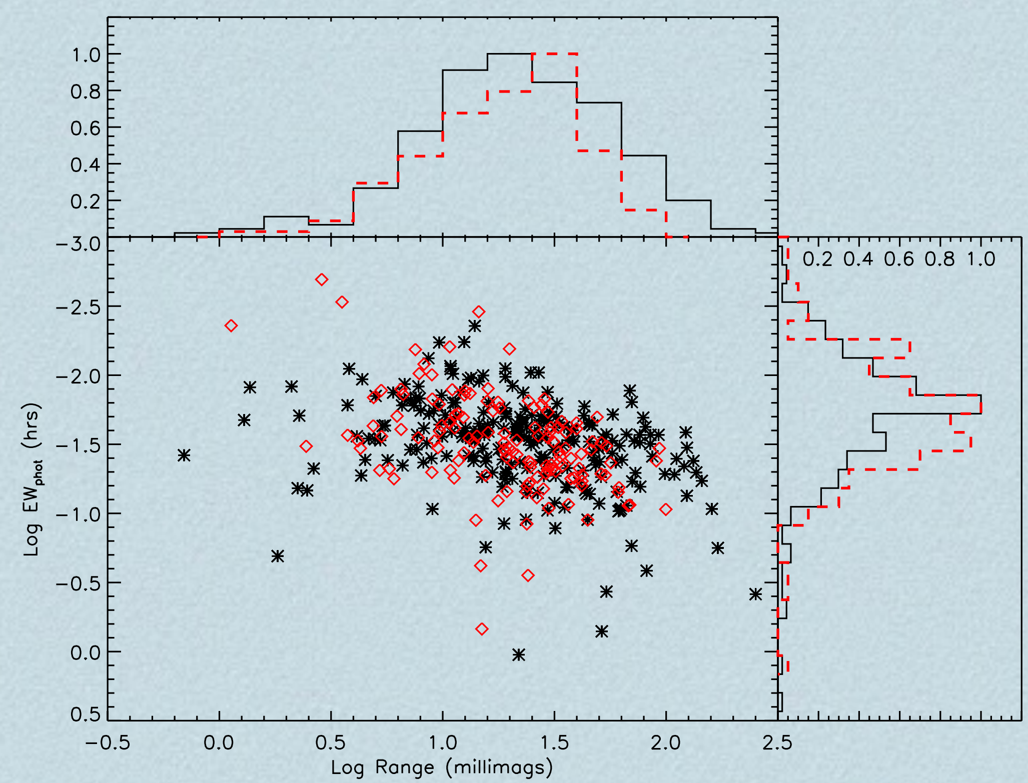


K

K and M dwarf flare stats (WB+11)

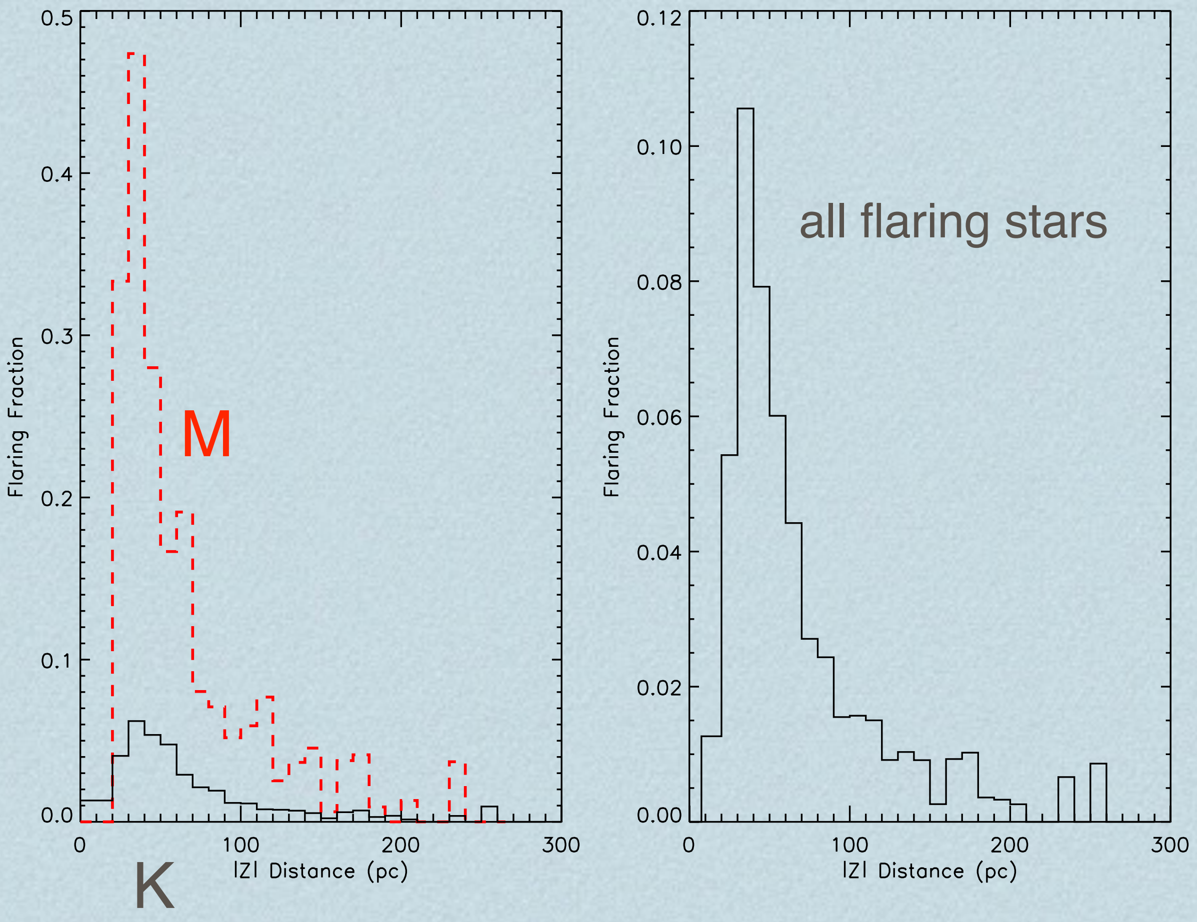
- Flaring frequency (per hour) versus Teff:
  - M stars (red dashed line) dominate the frequent flarers.
  - K stars (black solid line) flare less often.
- Flare EW (time units) versus star variability range:
  - Ks and Ms little different.
  - Overall variability and flaring not highly correlated.





Flares and Galactic Z

- Flaring stars concentrated in Galactic plane.
- Offset from zero due to Kepler pointing (about 15 degrees latitude at center).



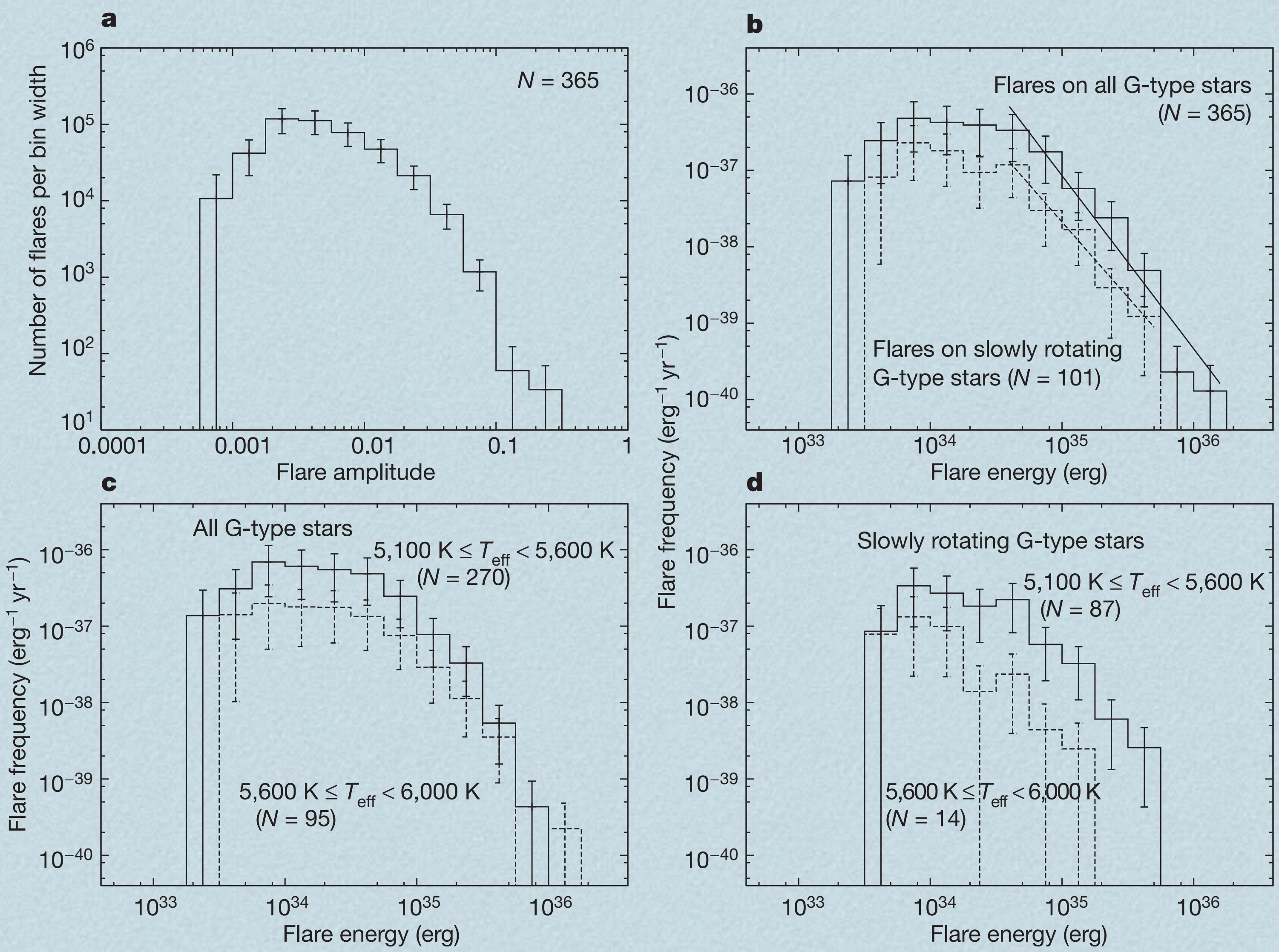
"Superflares" on G stars

Maehara et al., 2012, *Nature*

❖Only examined 30-min data

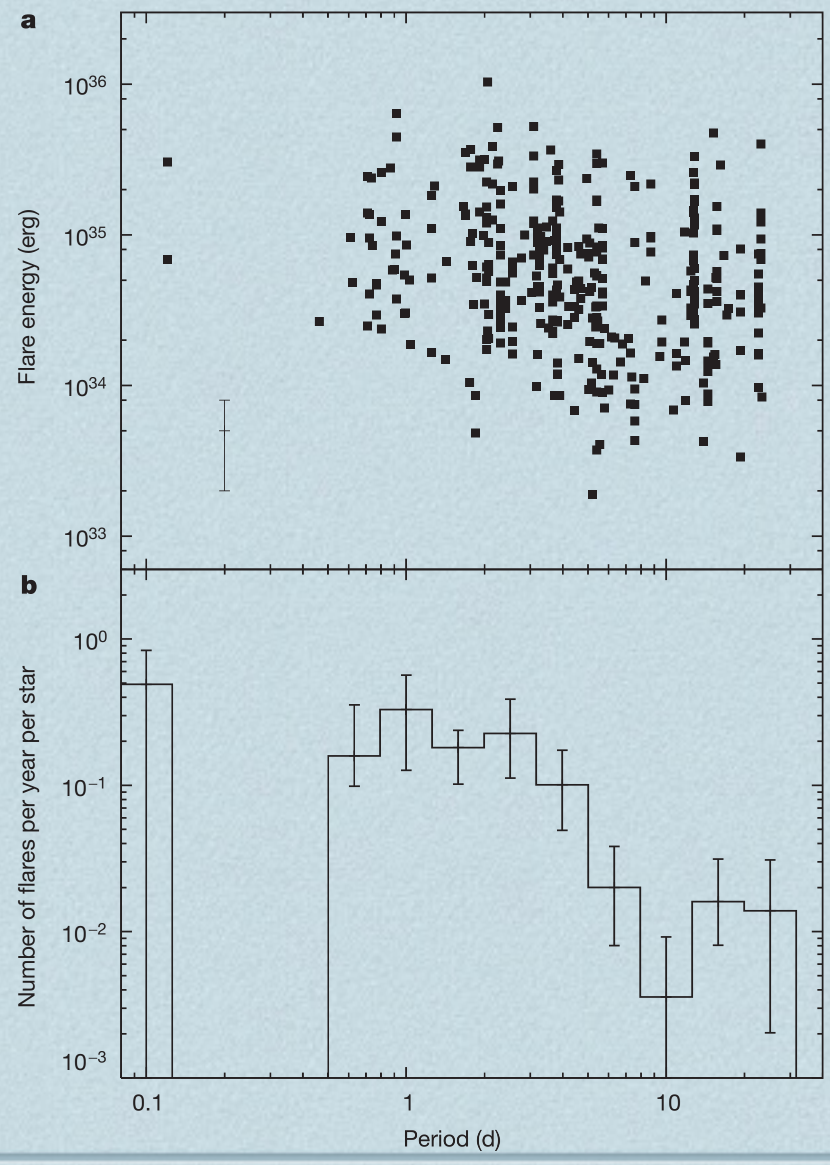
❖Dist's over all stars

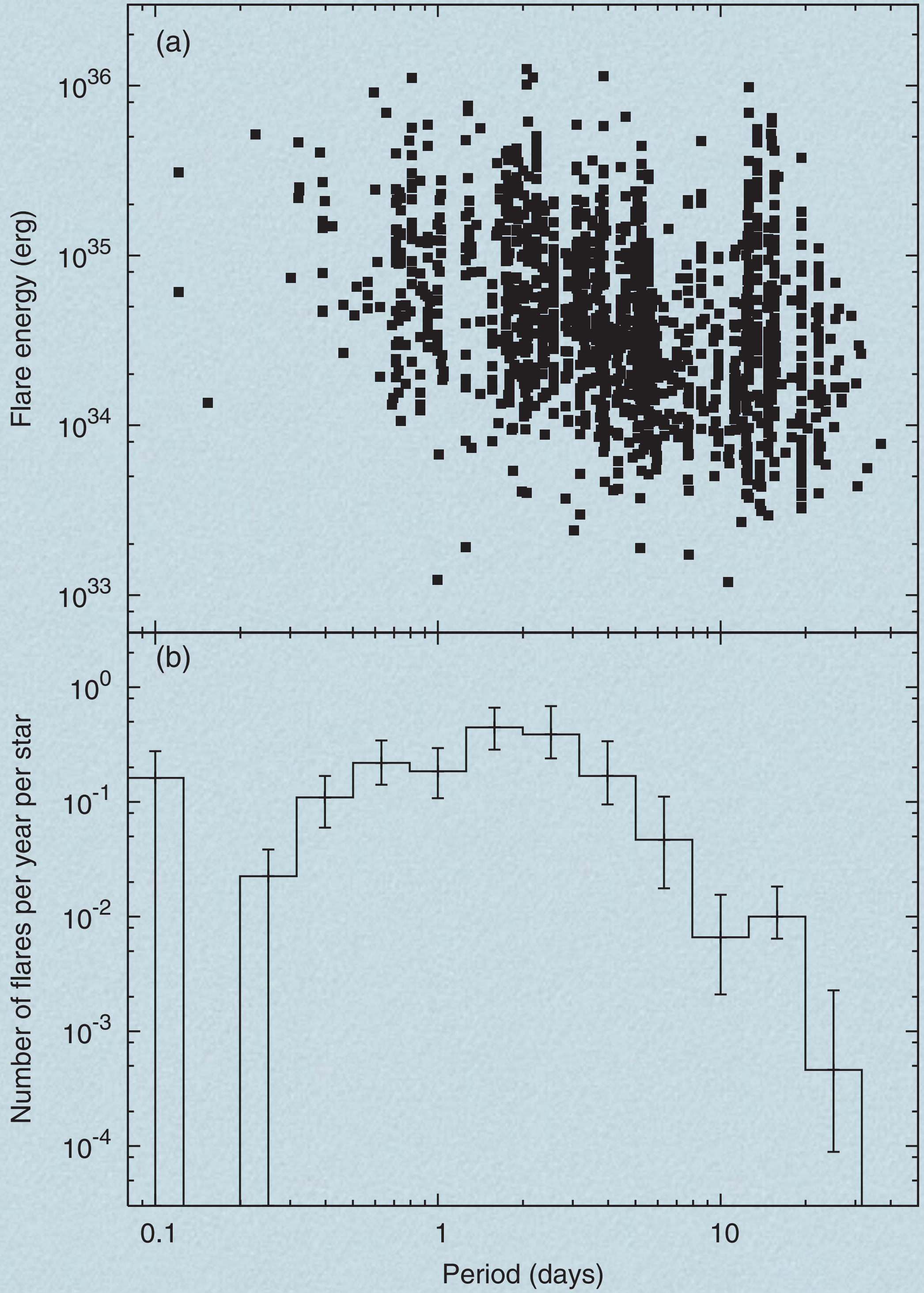
slope = −2.3



Notsu et al. (2013) update

- Poor correlation with rotation:





Shibayama et al. (2013)

- Note excess of short period rotators, due to close binaries.

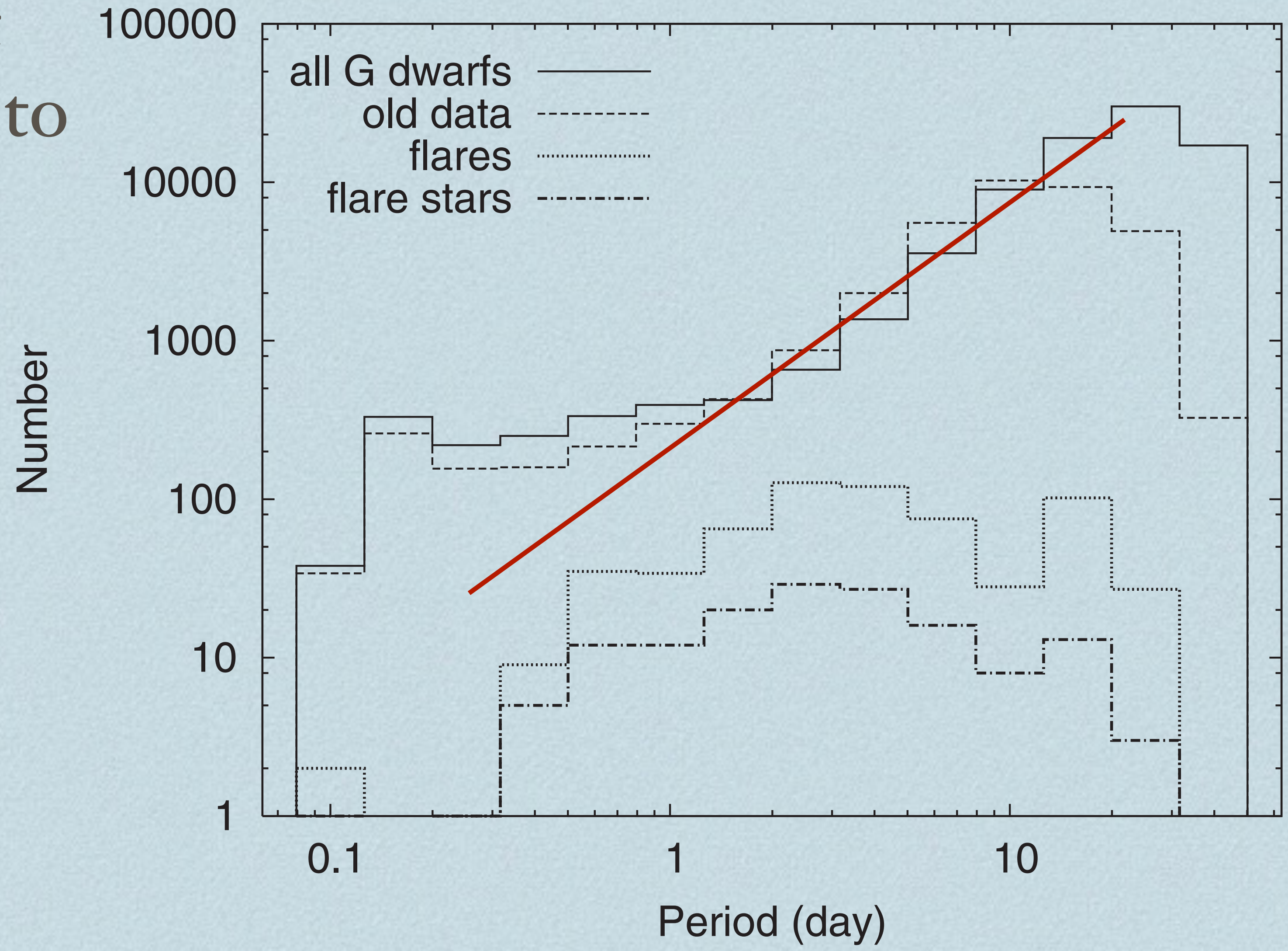
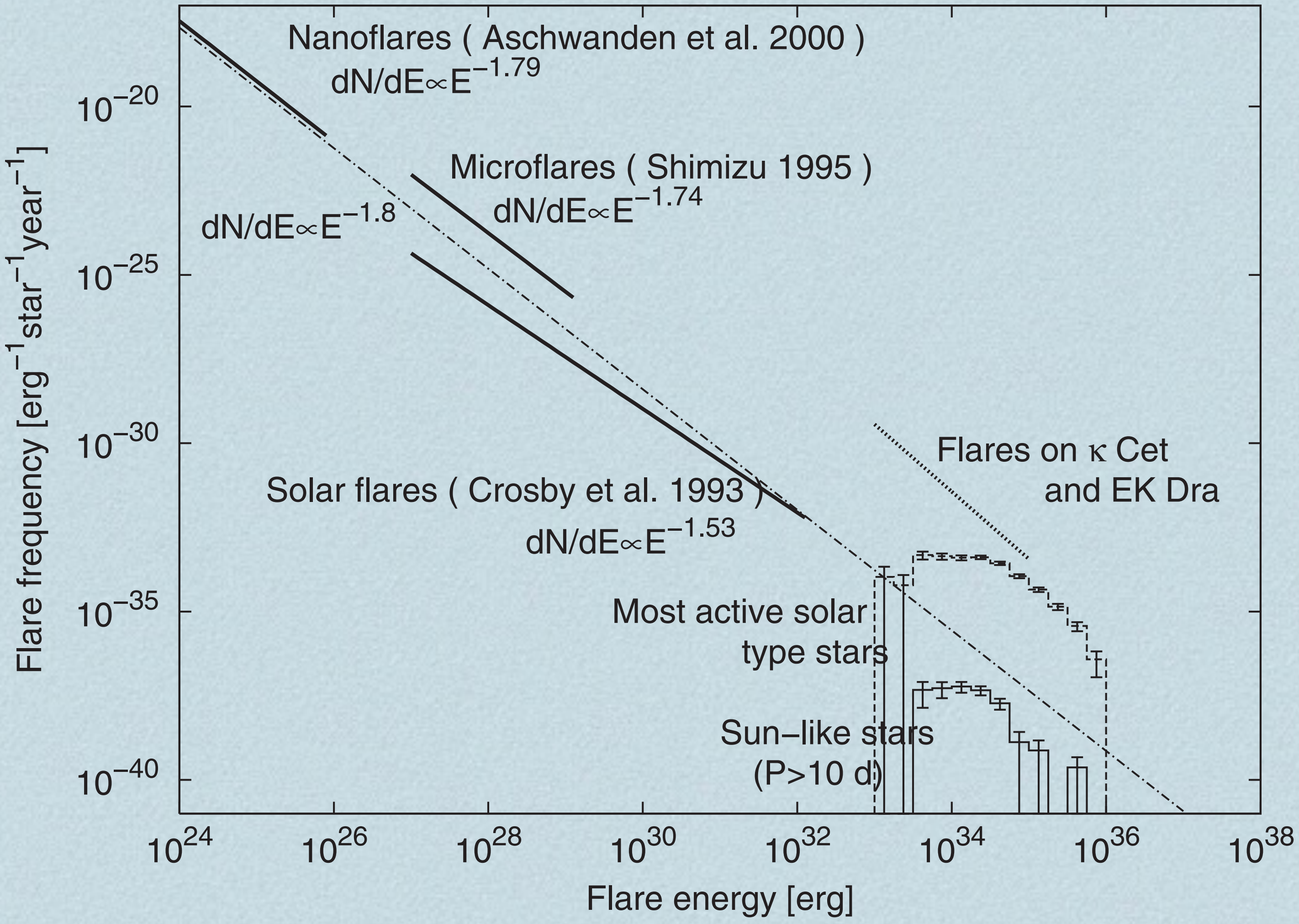


Figure 2. Number distributions of all G-type dwarfs (solid line), flare stars (dash–dotted line), and flares (dotted line) observed by *Kepler* as a function of rotational period. The periods of these stars are calculated from new data. We selected flares whose total energy are larger than 5×10^{34} erg. The dashed line indicates the distribution of period calculated from the old data, which is calibrated by the pipeline of the previous version.

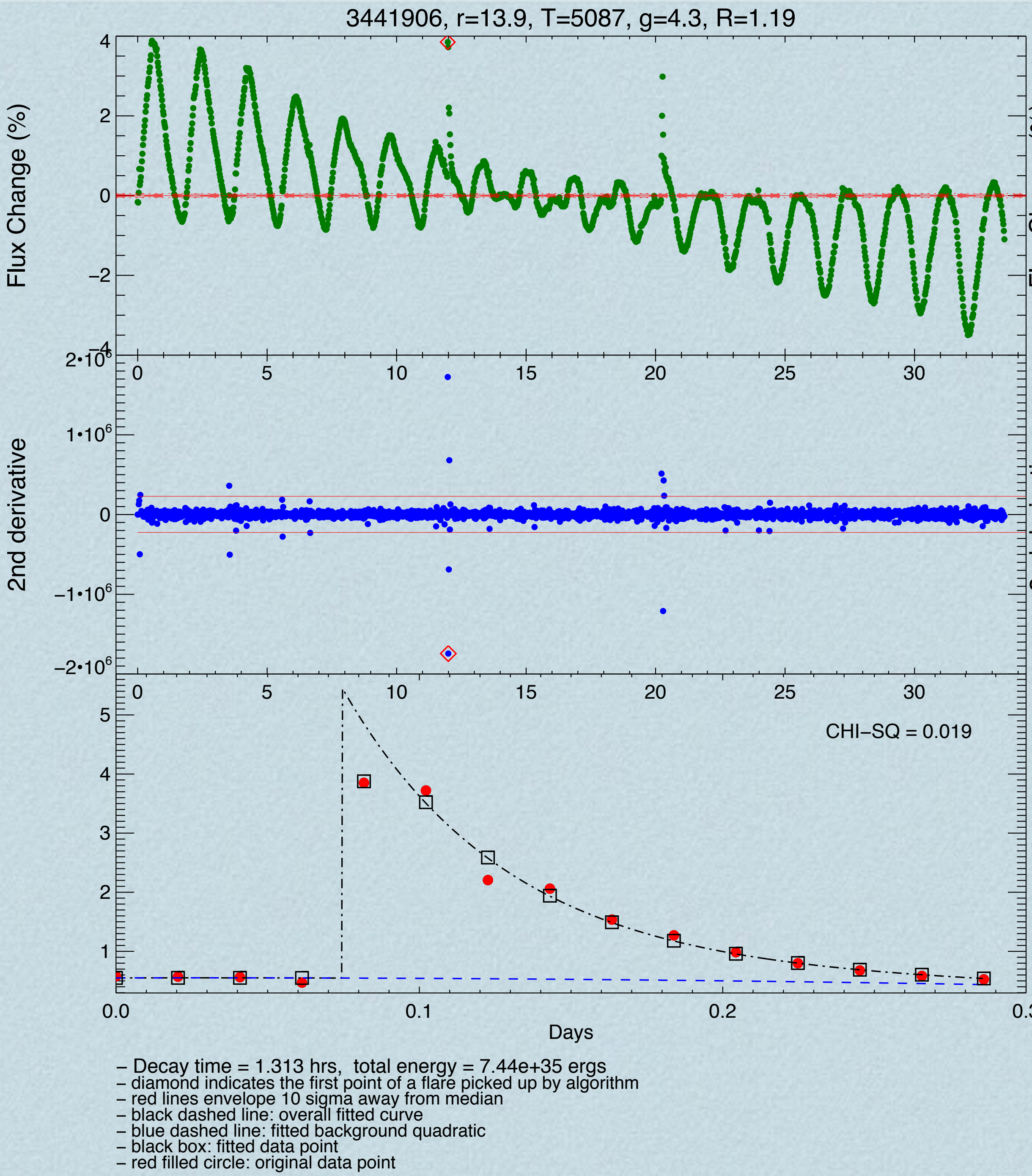
Shibayama: occurrence rates

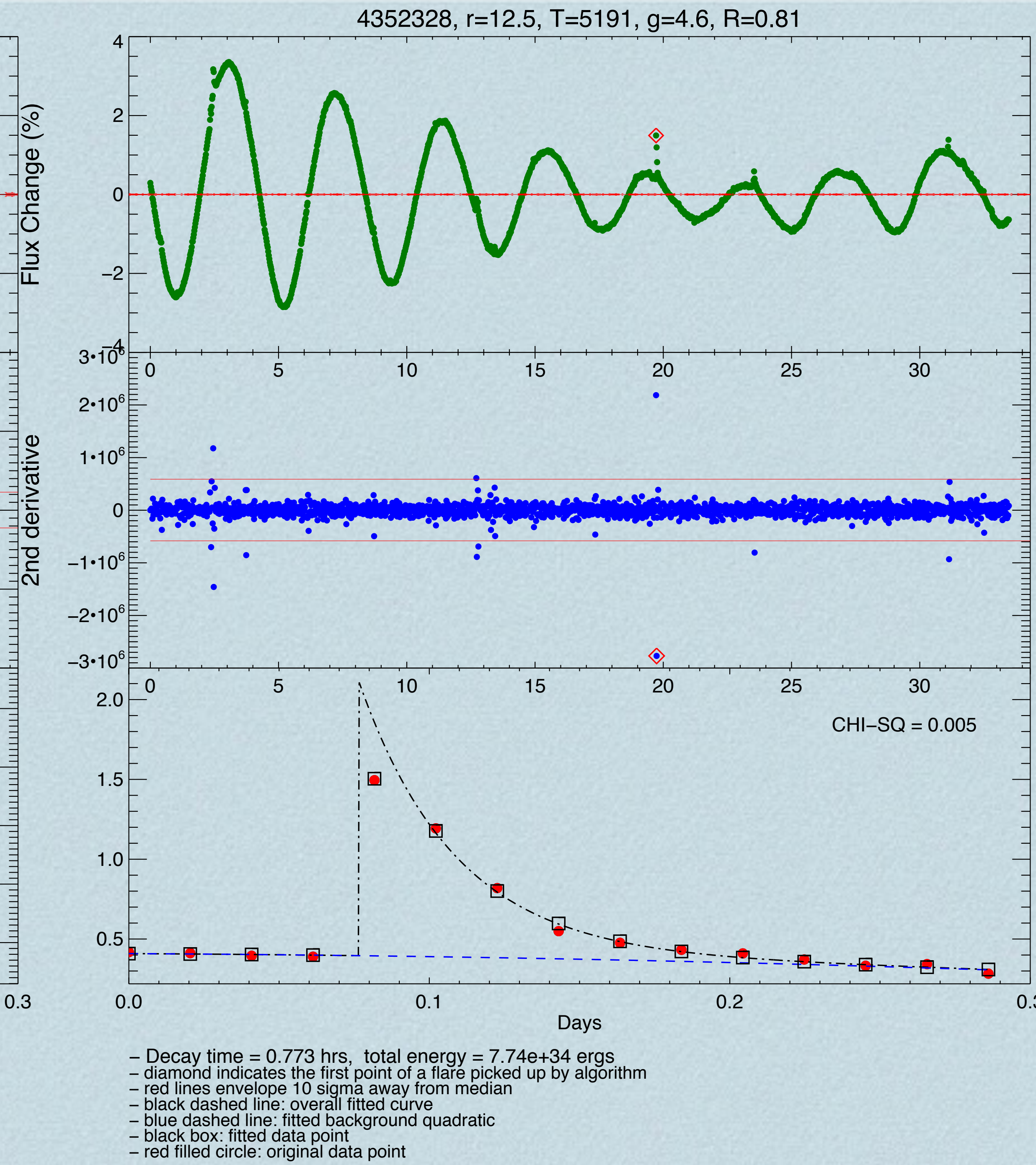
- The most active stars have rates in excess of solar extrapolation by ~0.5 dex.



Flares on G stars (T > 4500 K)

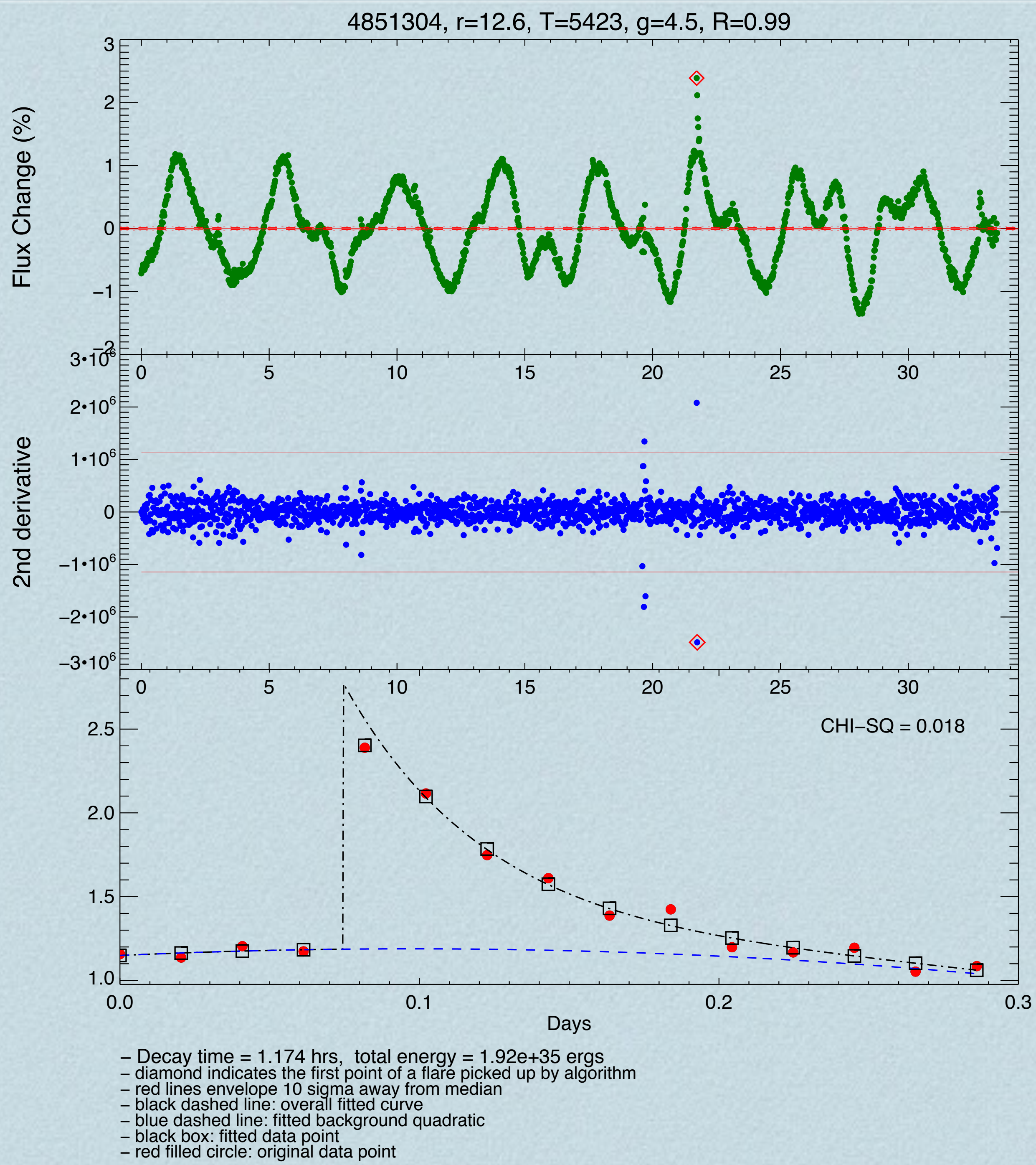
- Kepler data G stars that show flares:
  - Any radius
  - Kepmag < 14 for good photometry
  - ~20,000 stars have $K_p < 14$
  - ~100 of those show flares (½%)
- Used second-derivative technique to identify outliers while moderating false positives.
- Required 3-point events.
- Fit identified and confirmed flares with simple FRED curves.
- Do these tell us anything about the Sun? Stellar evolution? The physics of flaring?

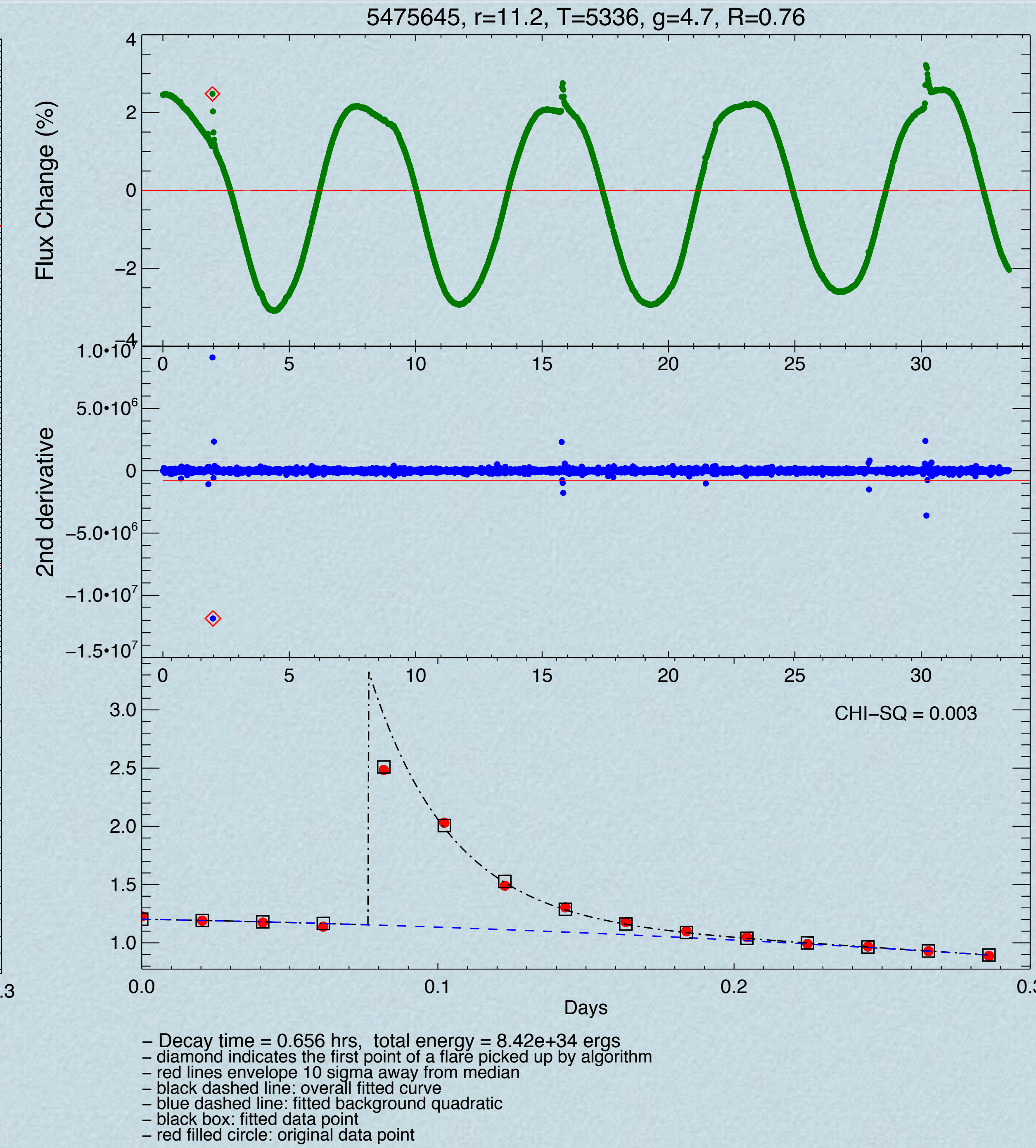




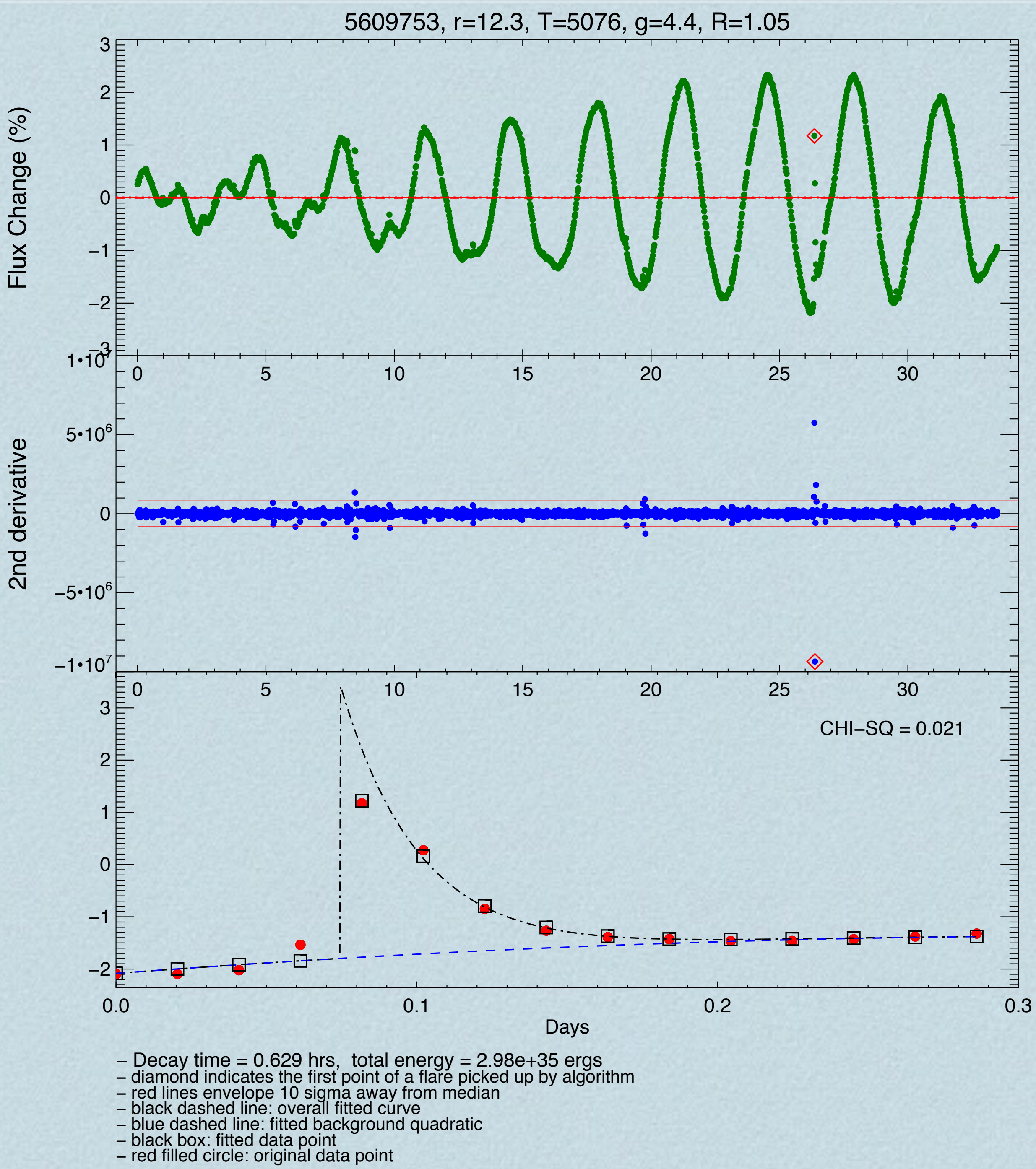
~10^{36} erg total energy
1.3 hr decay time
P = 1.7 d

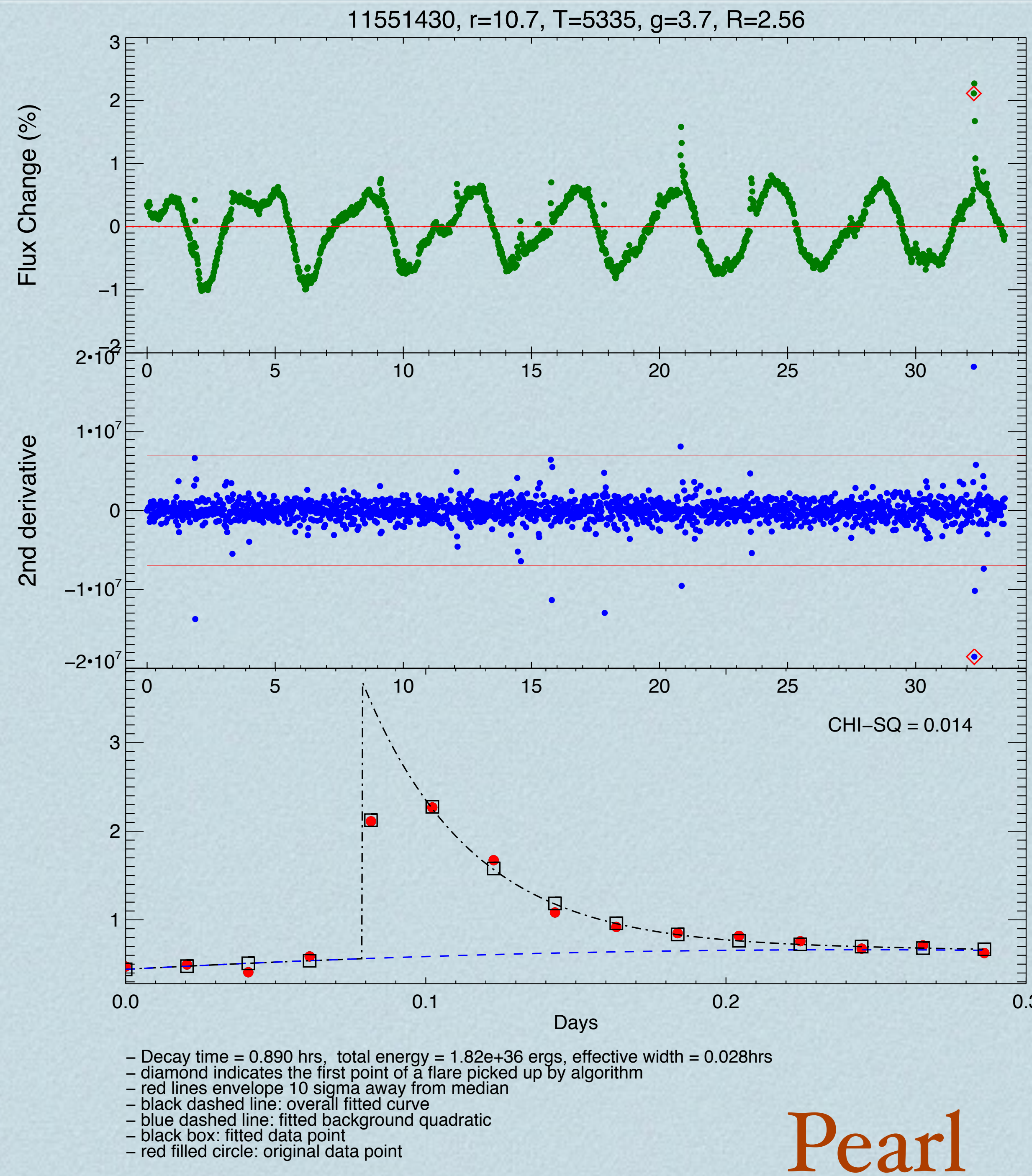
~10^{35} erg
0.8 hr
P = 4 d





~10^{35} erg	~10^{35} erg
1.2 hr	0.7 hr
P = 4 d	P = 8 d

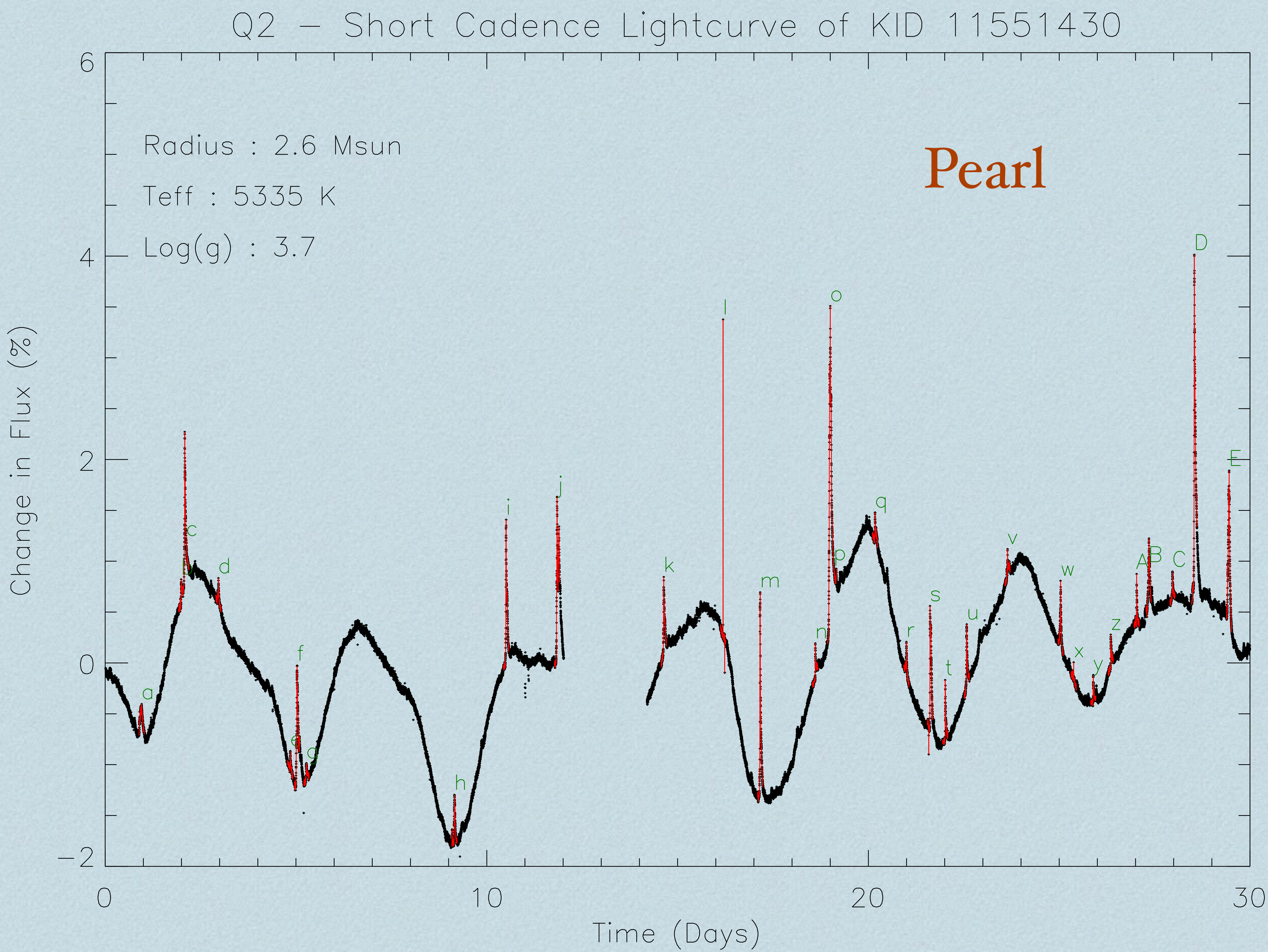




Pearl

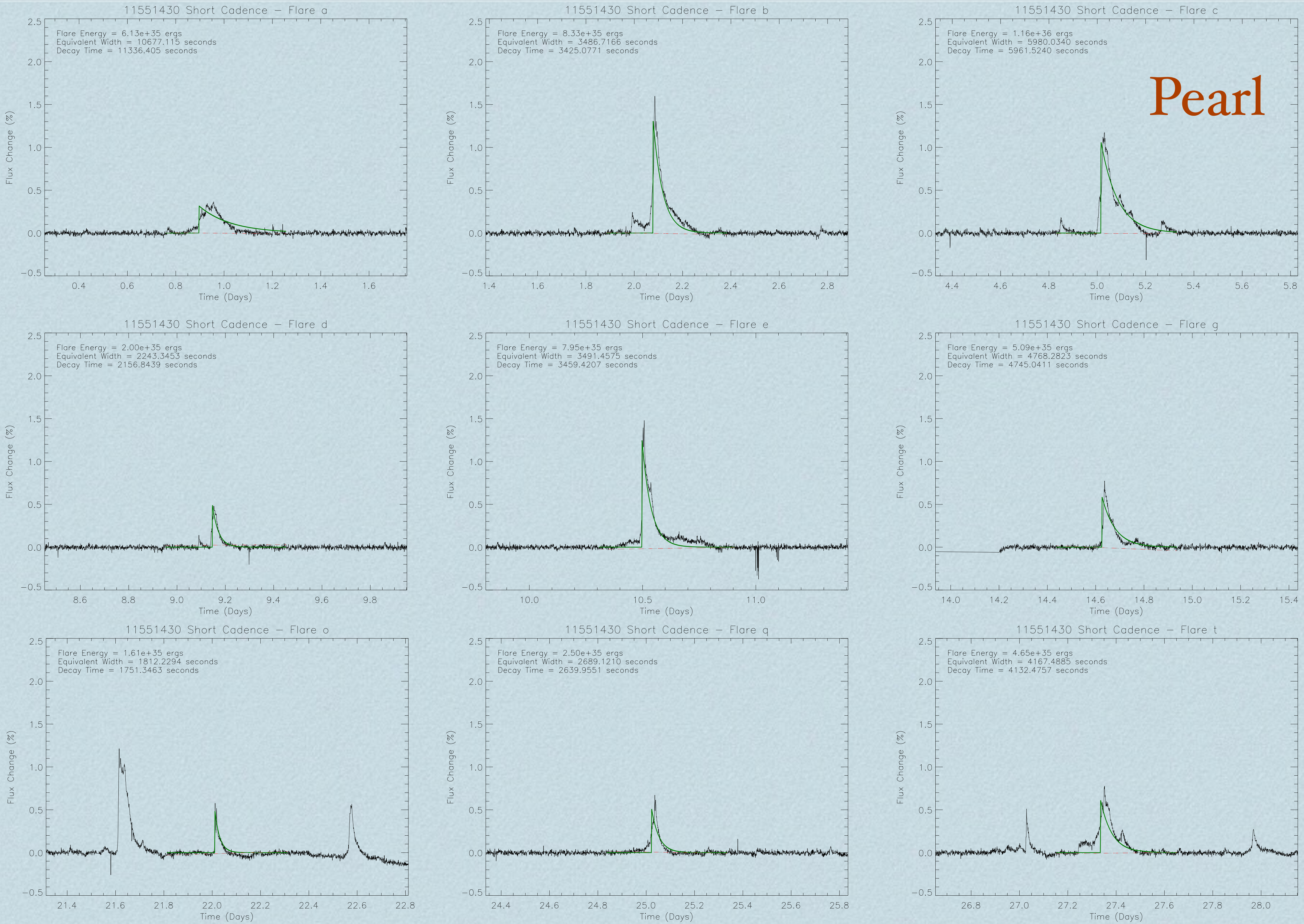
~10^{35} erg
0.6 hr
P = 3 d

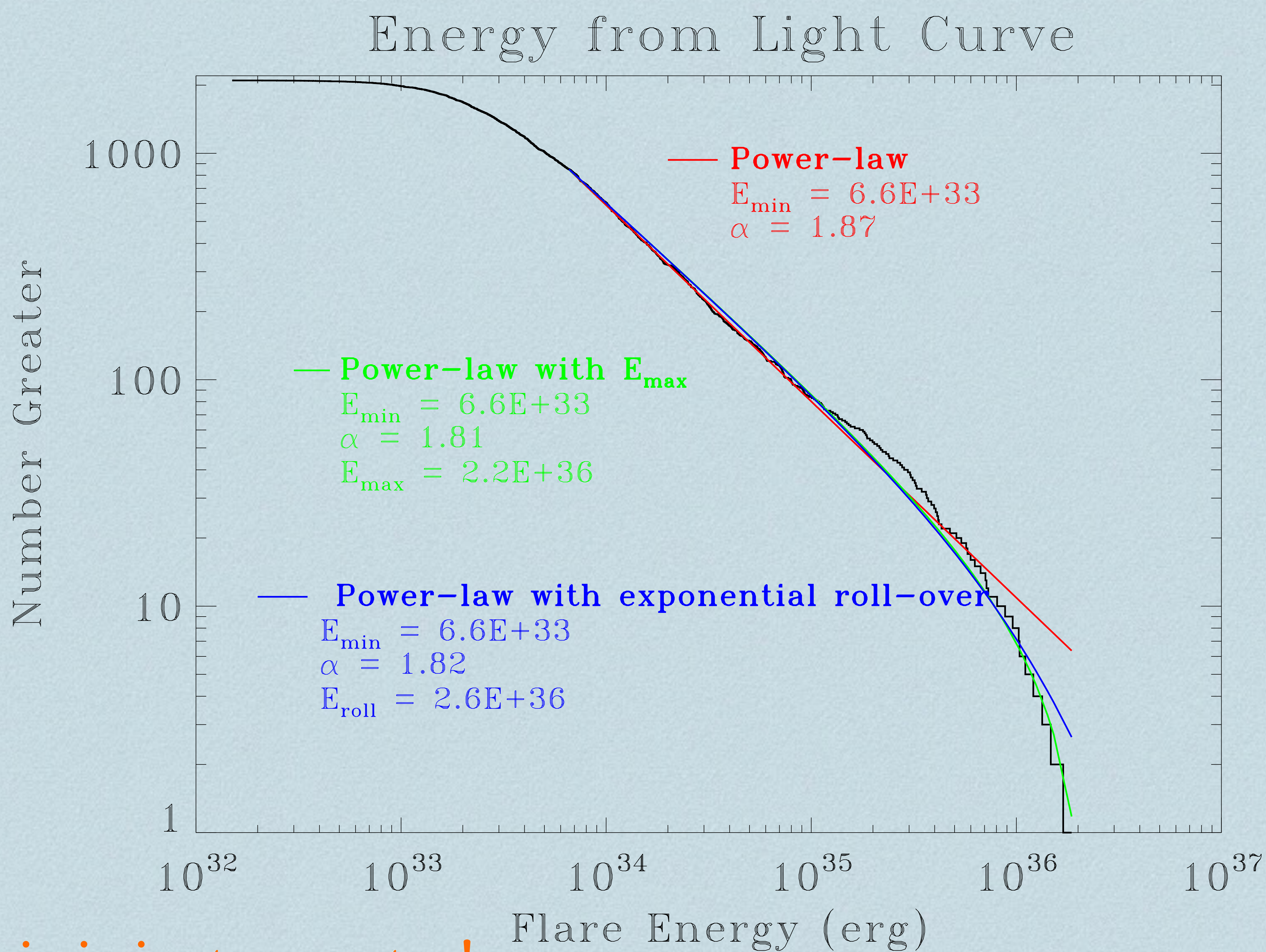
~10^{36} erg
0.9 hr
P = 4.2 d


Q2 – Short Cadence Lightcurve of KID 11551430
Radius : 2.6 Msun
Teff : 5335 K
Log(g) : 3.7
Change in Flux (%)
Time (Days)

Pearl

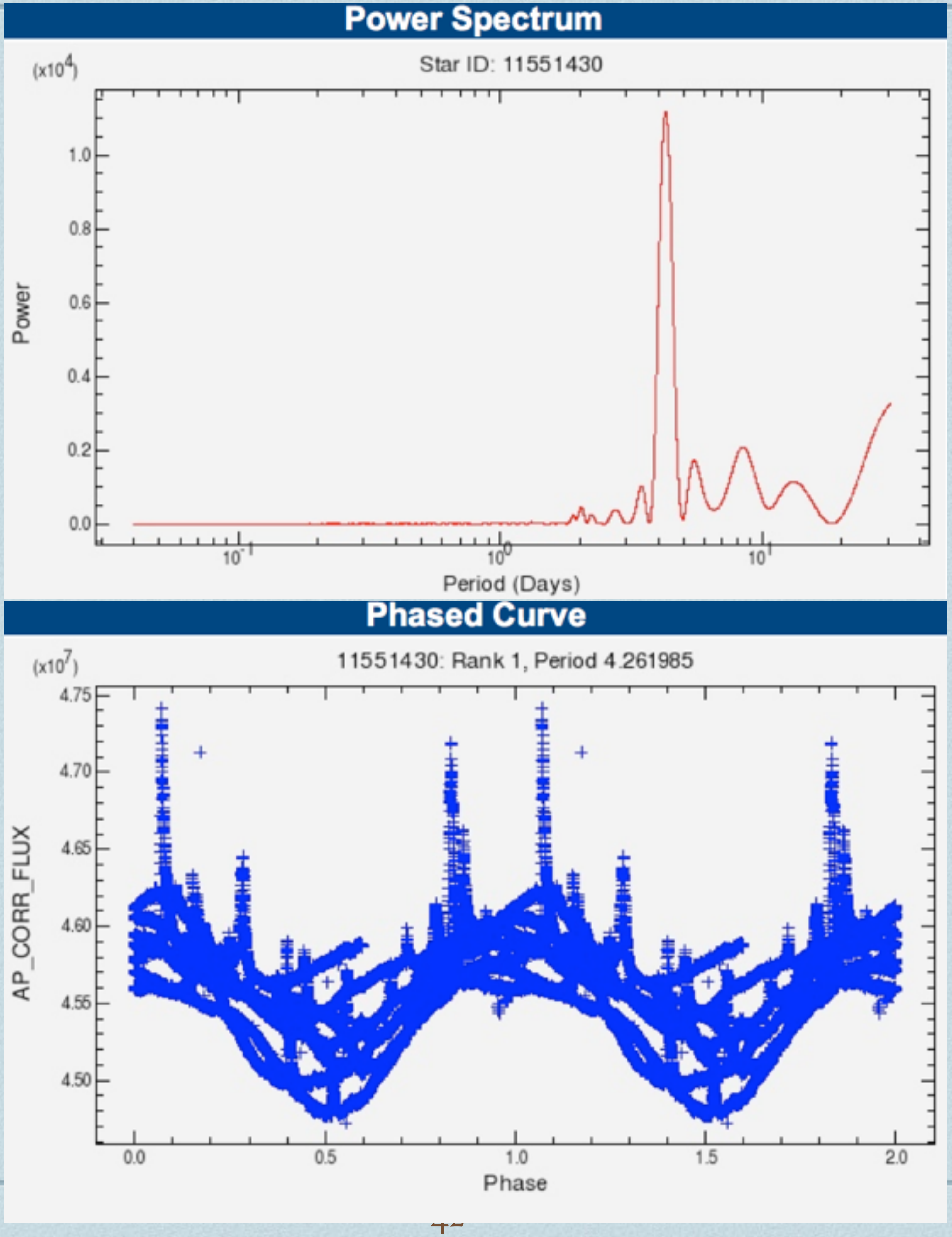
Pearl


11551430 Short Cadence – Flare a
Flare Energy = 6.13e+35 ergs
Equivalent Width = 10677.115 seconds
Decay Time = 11336.405 seconds
11551430 Short Cadence – Flare b
Flare Energy = 8.33e+35 ergs
Equivalent Width = 3486.7166 seconds
Decay Time = 3425.0771 seconds
11551430 Short Cadence – Flare c
Flare Energy = 1.16e+36 ergs
Equivalent Width = 5980.0340 seconds
Decay Time = 5961.5240 seconds
11551430 Short Cadence – Flare d
Flare Energy = 2.00e+35 ergs
Equivalent Width = 2243.3453 seconds
Decay Time = 2156.8439 seconds
11551430 Short Cadence – Flare e
Flare Energy = 7.95e+35 ergs
Equivalent Width = 3491.4575 seconds
Decay Time = 3459.4207 seconds
11551430 Short Cadence – Flare g
Flare Energy = 5.09e+35 ergs
Equivalent Width = 4768.2823 seconds
Decay Time = 4745.0411 seconds
11551430 Short Cadence – Flare o
Flare Energy = 1.61e+35 ergs
Equivalent Width = 1812.2294 seconds
Decay Time = 1751.3463 seconds
11551430 Short Cadence – Flare q
Flare Energy = 2.50e+35 ergs
Equivalent Width = 2689.1210 seconds
Decay Time = 2639.9551 seconds
11551430 Short Cadence – Flare t
Flare Energy = 4.65e+35 ergs
Equivalent Width = 4167.4885 seconds
Decay Time = 4132.4757 seconds
Flux Change (%)
Time (Days)



This is just one star!

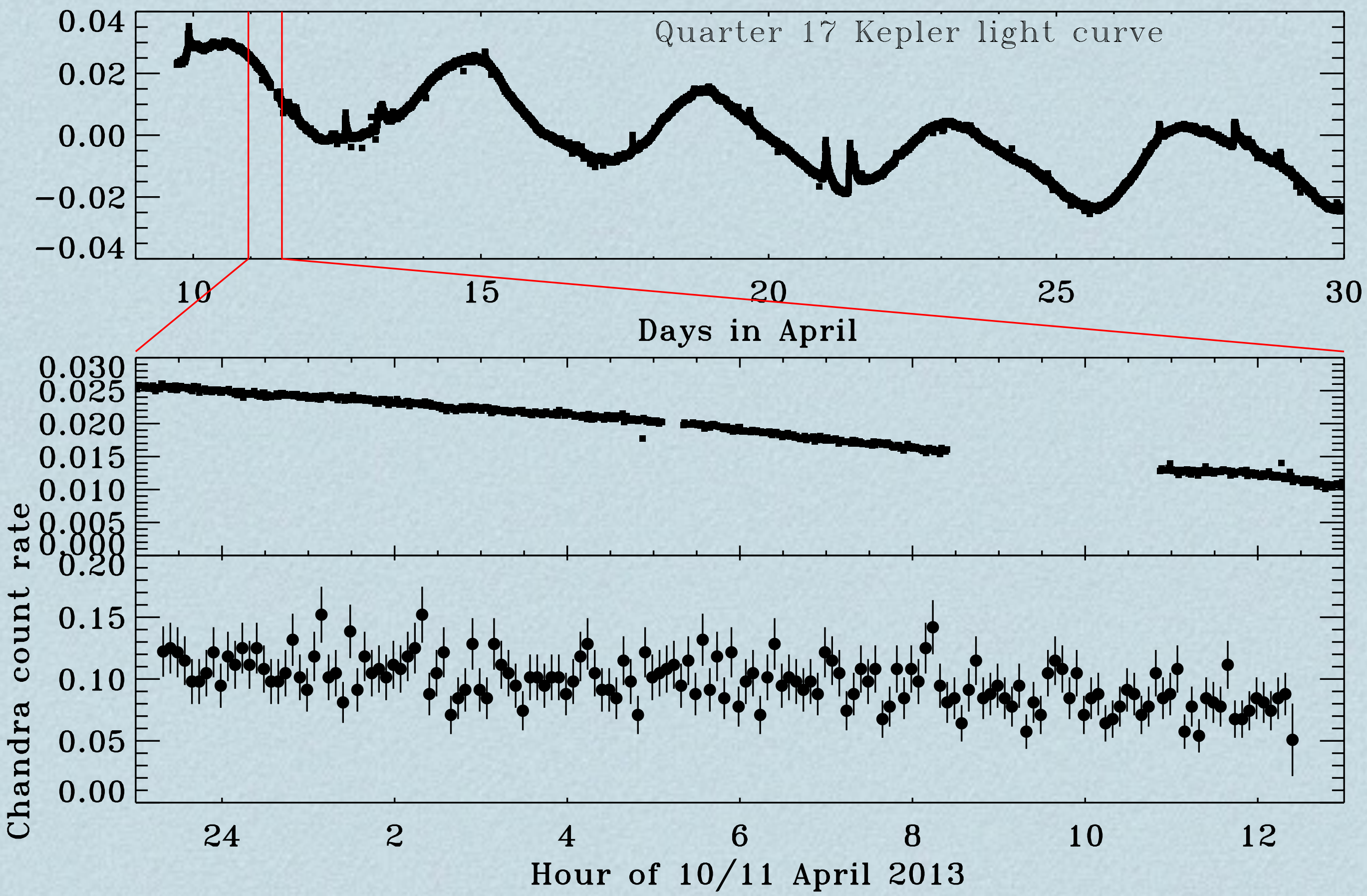
Pearl



Power Spectrum
Star ID: 11551430
(x10^4)
Power
1.0
0.8
0.6
0.4
0.2
0.0
10^-1
10^0
10^1
Period (Days)
Phased Curve
11551430: Rank 1, Period 4.261985
(x10^7)
AP_CORR_FLUX
4.75
4.70
4.65
4.60
4.55
4.50
0.0
0.5
1.0
1.5
2.0
Phase

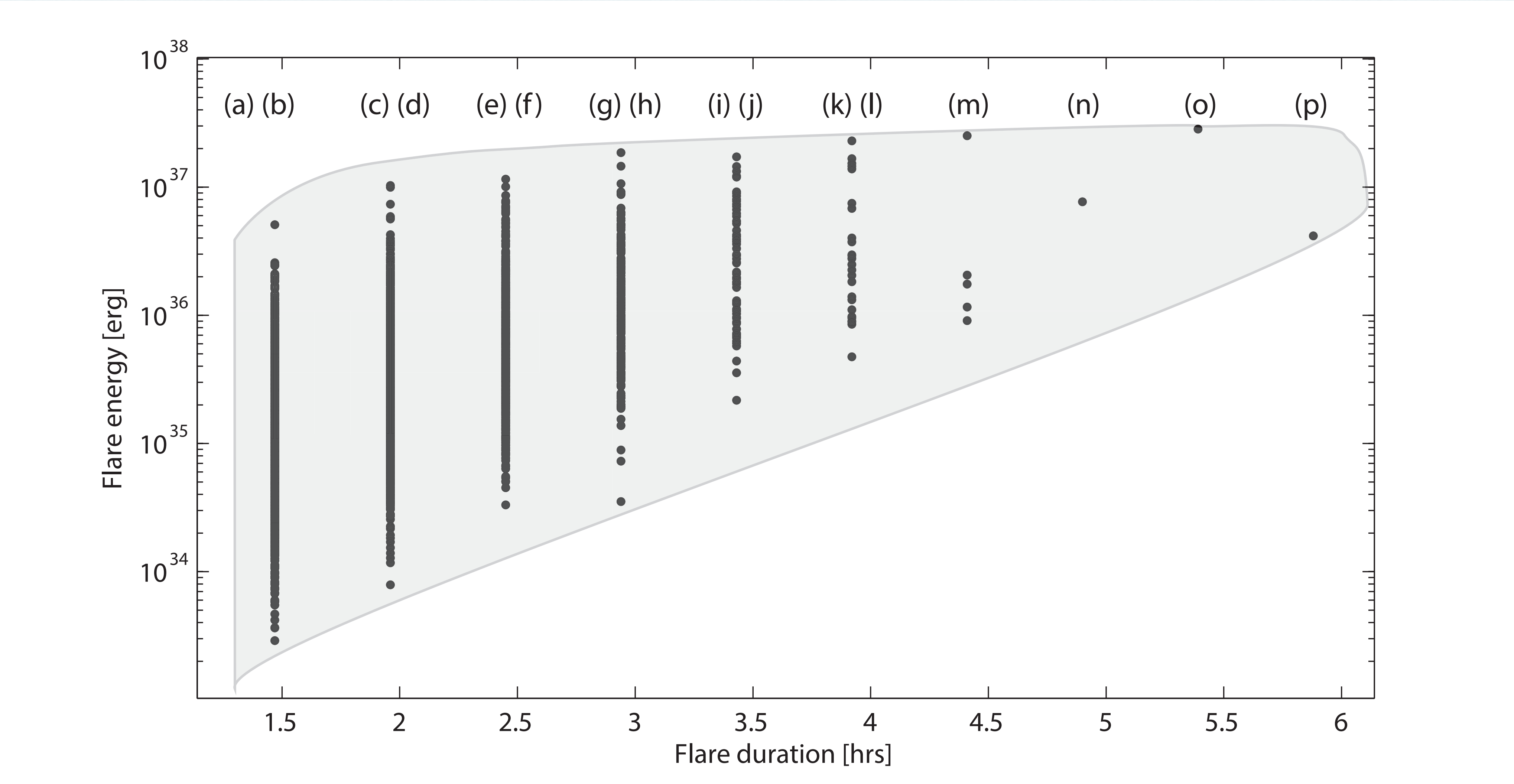
Flares in x-rays?

- Two attempts with Chandra to catch Pearl flaring.
- Try #1: Kepler in safemode.
- Try #2: Just before Kepler's demise, but…
- Keck optical spectra show an outburst in Balmer lines.



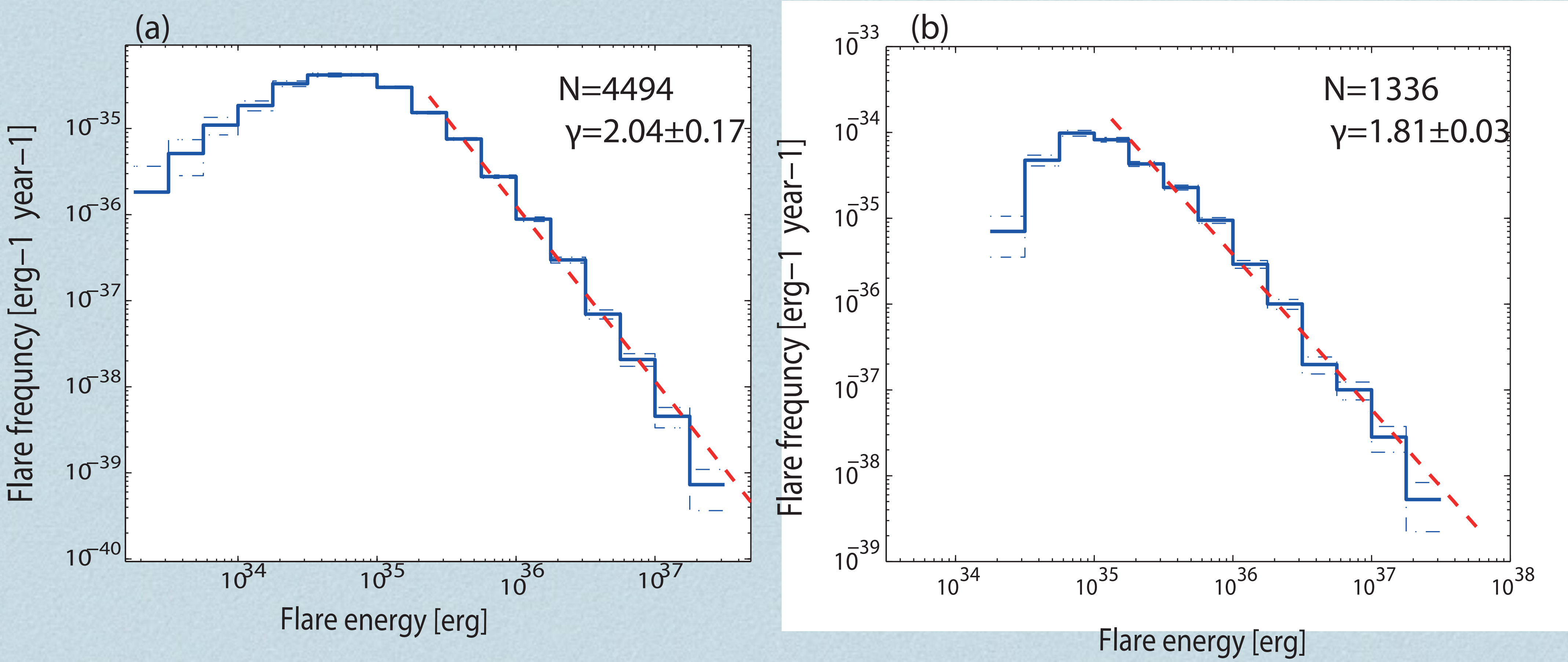
Other studies: Wu et al. (2014)

- Flare energy vs. duration



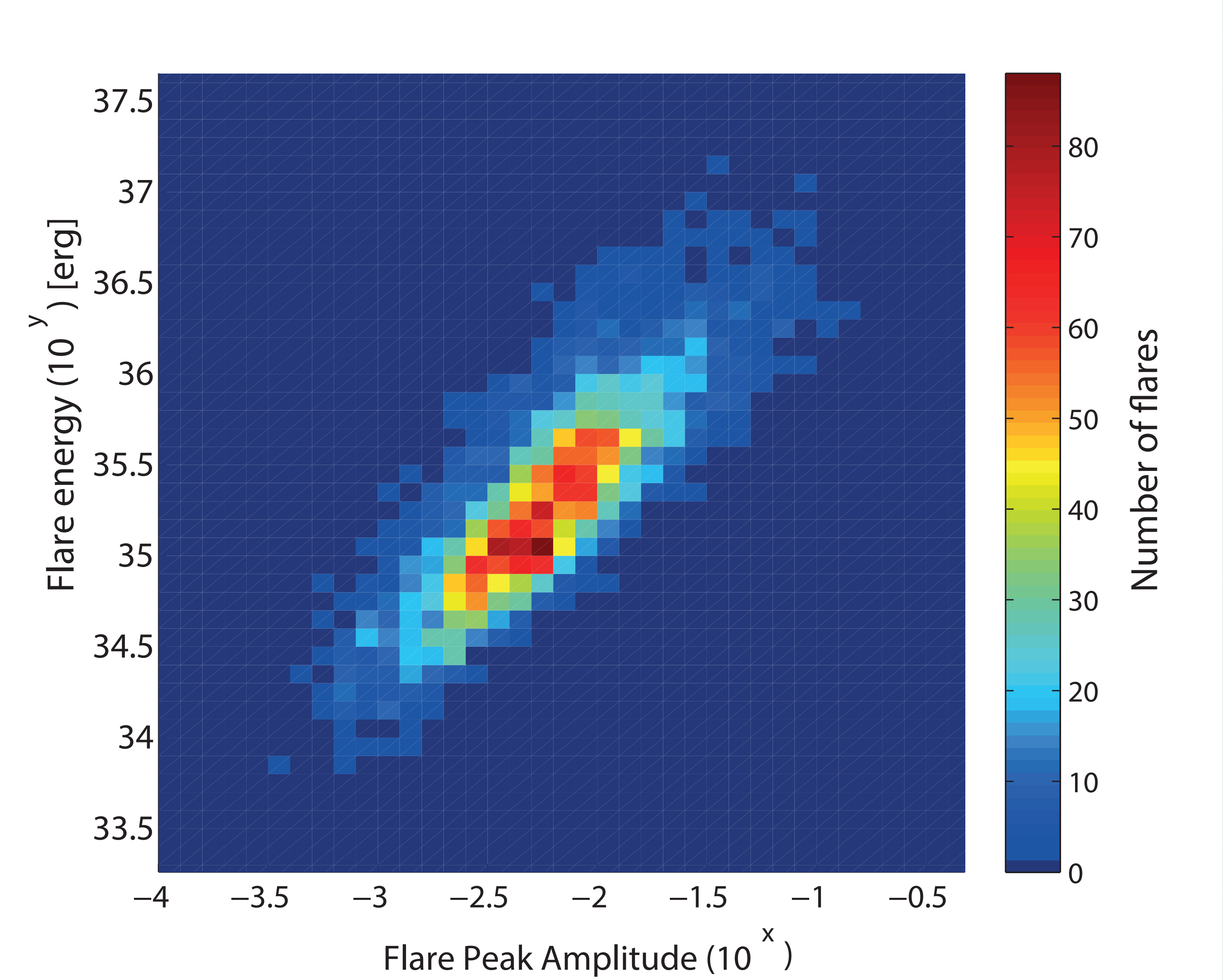
Other studies: Wu et al. (2014)

- Energy distributions for (a) all G stars; (b) 8 frequent flarers:



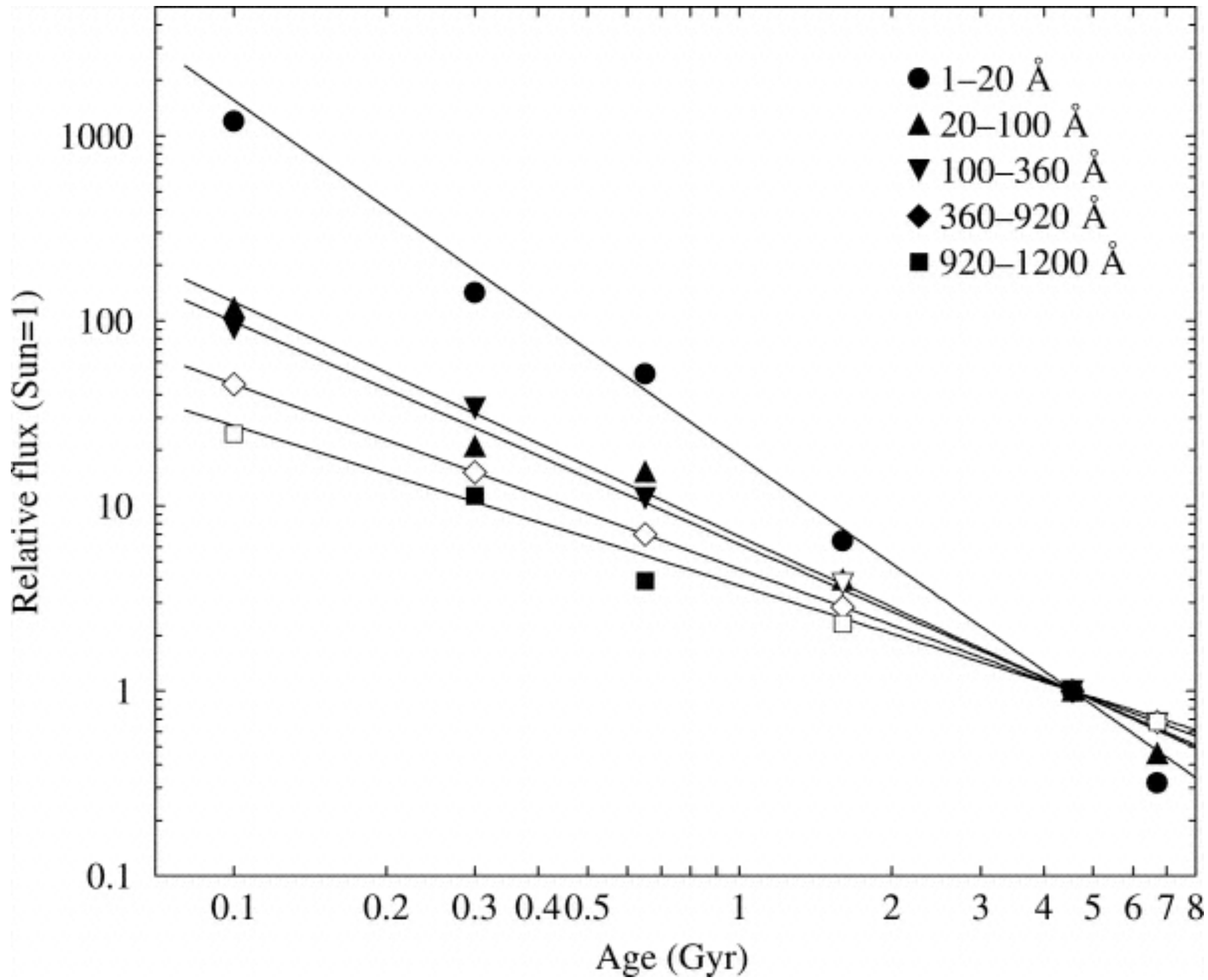
Other studies: Wu et al. (2014)

- Flare energy vs. amplitude

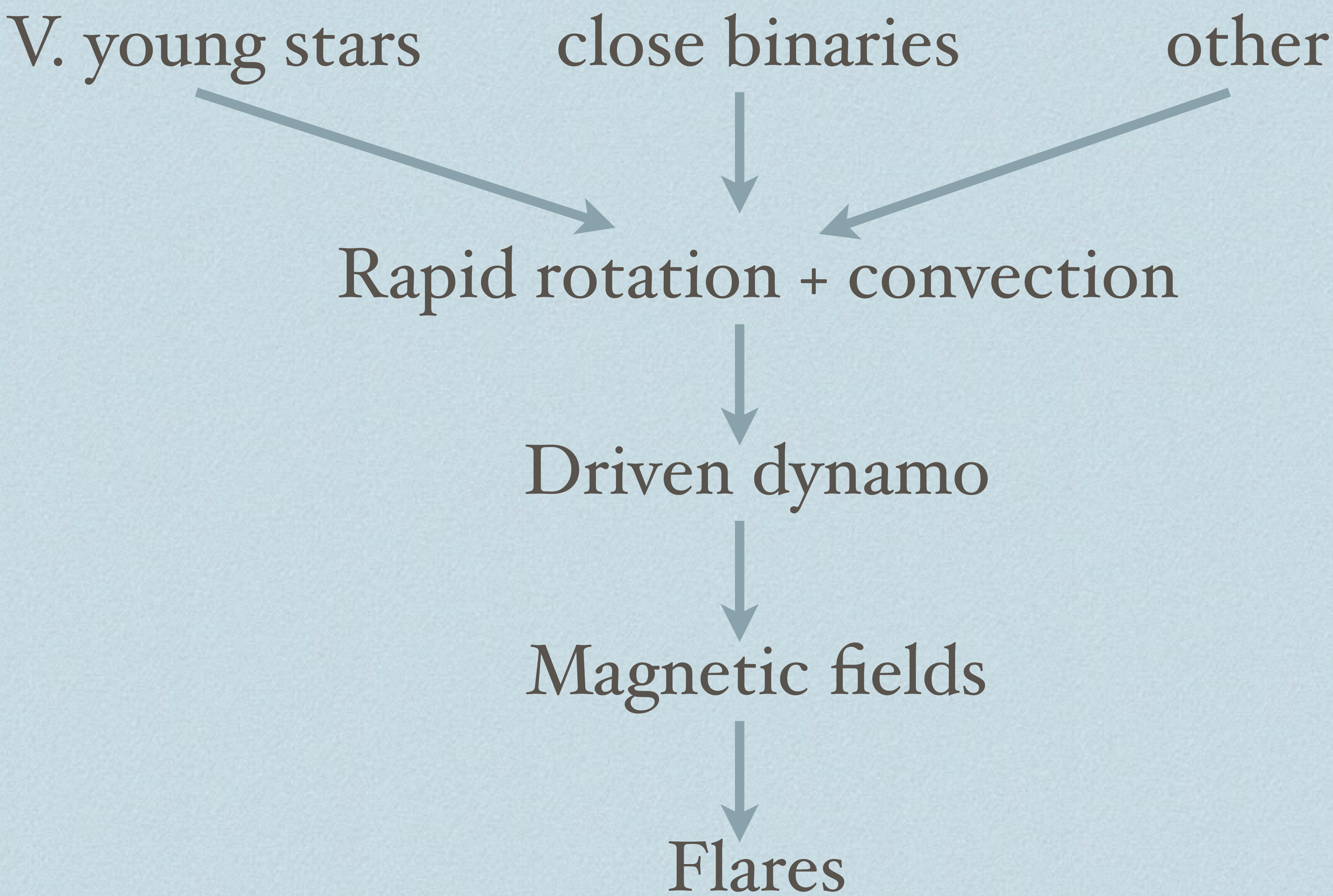


X-ray flux and UV versus age

- Power-law trends
- But variability may be as important



What kinds of stars are these?



The flaring stars as stars

- Flares represent a magnetically-related phenomenon:
  - We expect them on stars with magnetic field and dynamos and other forms of magnetically-related activity (spots, HK emission, x-rays, ...).
  - We presume they occur on stars with convective envelopes, a necessary ingredient of a dynamo.
- At least two kinds of stars have the high activity levels we expect to go with flaring:
  - Very young stars, because of rapid rotation.
  - RS CVn and BY Dra systems, as close binaries enforcing rapid rotation.
  - Or maybe former close binaries that have coalesced?
  - Or a close-in planet generating Alfven waves (MacGregor & Pinsonneault)?
    - Up to 10^{27} erg/sec atmospheric heating.
  - Or M dwarf companions that we cannot see except for their flares?

Studies of stars

- Nogami et al. (2014): *Two sun-like superflare stars rotating as slow as the Sun*
  - Two flare stars studied at high resolution with Subaru.
  - Both are inactive, slow rotators.
  - <u>But</u>: Flare energies ~10^{34}, so source could be companion M dwarf.
- Notsu et al. (2013): High-dispersion spectroscopy of KIC 6934317
  - Also small $v\sin i$ but short rotation period (2.54 d), so pole-on
  - Highly active
  - Flares at 6 x 10^{35}
  - Binary? No RV change seen, but limited time span, and pole-on: inconclusive.
- Kitze et al. (2014, MN) Superflares on KIC 10524994 and 7133671
  - 8-sigma photocenter shift for 7133671 during flares, so it's not the G star
  - That leaves exactly one star with $E > 10^{35}$ erg from Maehara et al. (2012).

How big do they come?

- Can the Sun do a big one on us?
  - Schaefer, King & Deliyannis, 2000, ApJ, 529, 1026; "Superflares on ordinary solar-type stars"
    - They list 9 events seen historically on main sequence stars, F8V-G8V, with energies estimated from 10^{34}-10^{38} ergs. A couple of their objects are definitely young-ish, but several are definitely not and appear to be single.
- Available data on stellar flares consistently show none larger than ~10^{37} ergs.
  - M dwarfs
  - Hyper-active stars (RS CVns)
  - G stars seen by Kepler
- Stars flaring at that level are <u>not</u> old, like the Sun, but exceptional for one reason (youth) or another (duplicity).

Summary

- White-light flares have not been seen on G stars until Kepler.
- Kepler enables the detection of G star flares down to ~10^{33}-10^{34} ergs.
- Flares are seen on dwarfs and evolved stars (subgiants mostly).
- Maximum flare energy of ~10^{37} ergs.
  - Energies quoted are lower bounds:
    - Kepler temperatures underestimated
    - No accounting yet for flare energy outside Kepler bandpass.
- In one-minute data events are fully resolved:
  - Rise times ~10 minutes
  - Decay times of hours
  - Frequent secondary events during decay phase
- Many of these stars are being studied further, both to understand the stars and the flares.

The future: K2

- "K2" is the repurposed Kepler spacecraft.
- Must point along its ecliptic to maintain pointing stability with 2 reaction wheels.
- ~80-90 days at any one pointing.
- BUT: The fields include:
  - Pleiades (100 Myr)
  - Praesepe (600 Myr)
  - M67 (4 Gyr)
  - and other interesting populations.

WHY ARE WE HERE?

- George Herbig, 1920 – 2013
  - Best known for work on newly-formed stars.
  - Also observed interstellar medium, diffuse interstellar bands, comets, and ordinary solar-type stars.
- Jack Eddy, 1931 – 2009
  - Best known for "Maunder minimum"
  - An historian of solar behavior, with an omnivorous appetite.