Millisecond Pulsar Discovery via Gamma-Ray Pulsations

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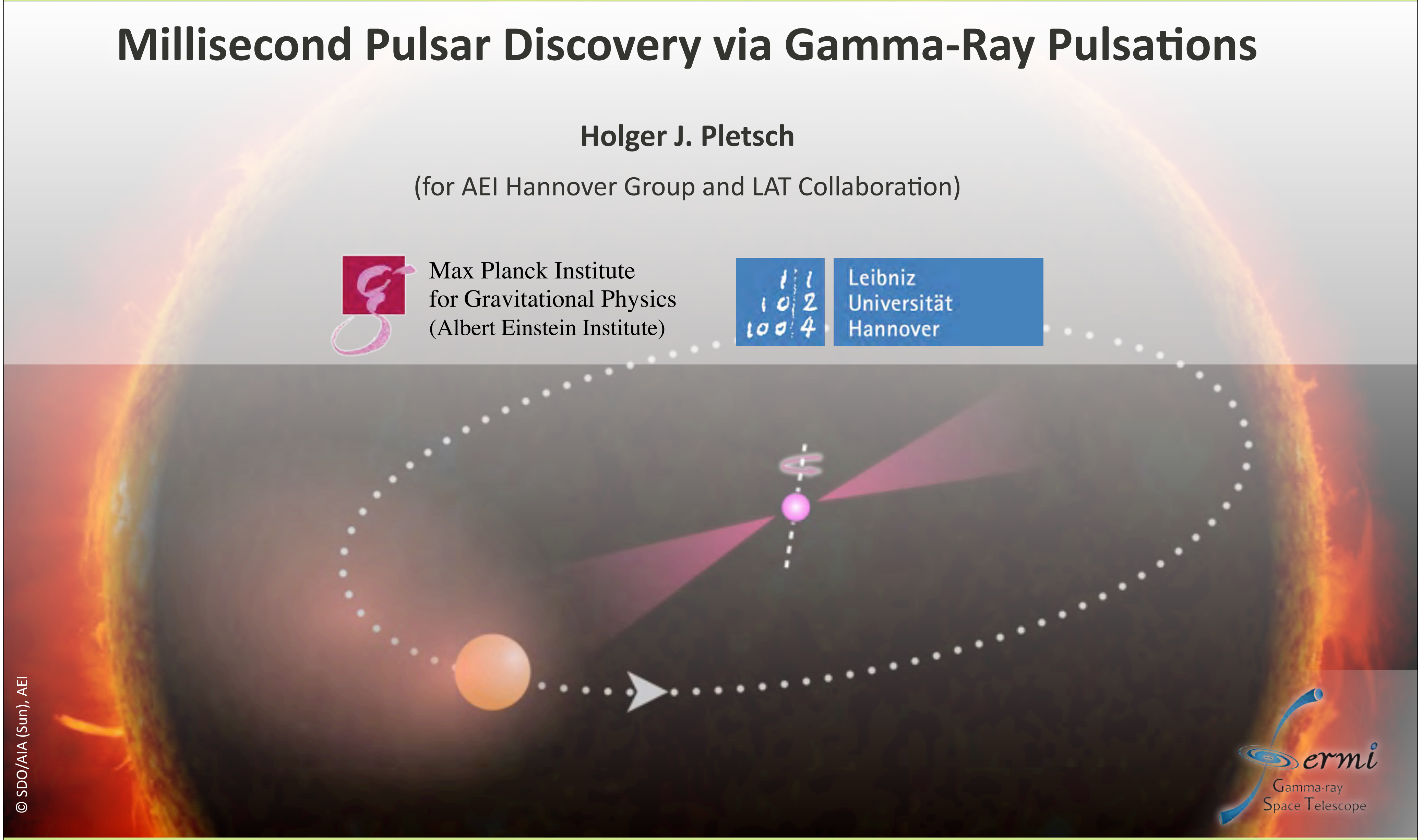

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Executive summary

- **Millisecond pulsars** (MSPs):
  - old neutron stars, spun up by accreting matter from companion star,
  - reach high rotation rates of several hundreds of Hertz.
- Previously: ALL such MSPs ("recycled" pulsars) discovered by spin-modulated **radio** emission.

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Binary Millisecond Pulsar Discovery via Gamma-Ray Pulsations

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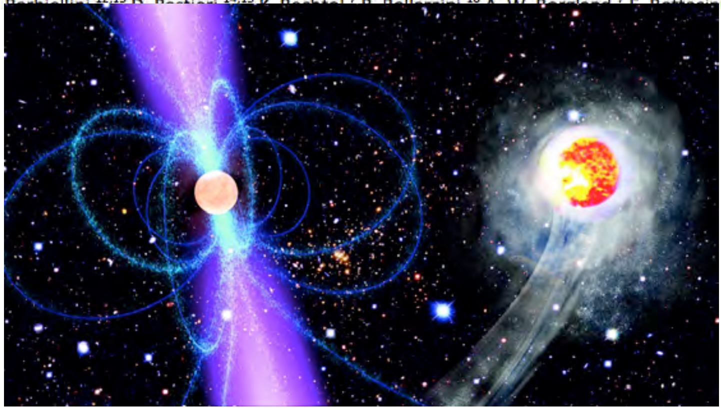

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- **Computing-intensive blind search** in *Fermi*-LAT data using advanced methods (with partial constraints from optical data):
  ⇒ Discovery of **PSR J1311-3430**
  - First **MSP** found via **gamma-ray** pulsations!
  - Extremely **compact** binary:
    Shortest orbital period!
  - Clarifies nature of decade-long enigma.

Background

- **30 years ago:** First MSP detected in radio observations.

Backer et al., Nature 1982

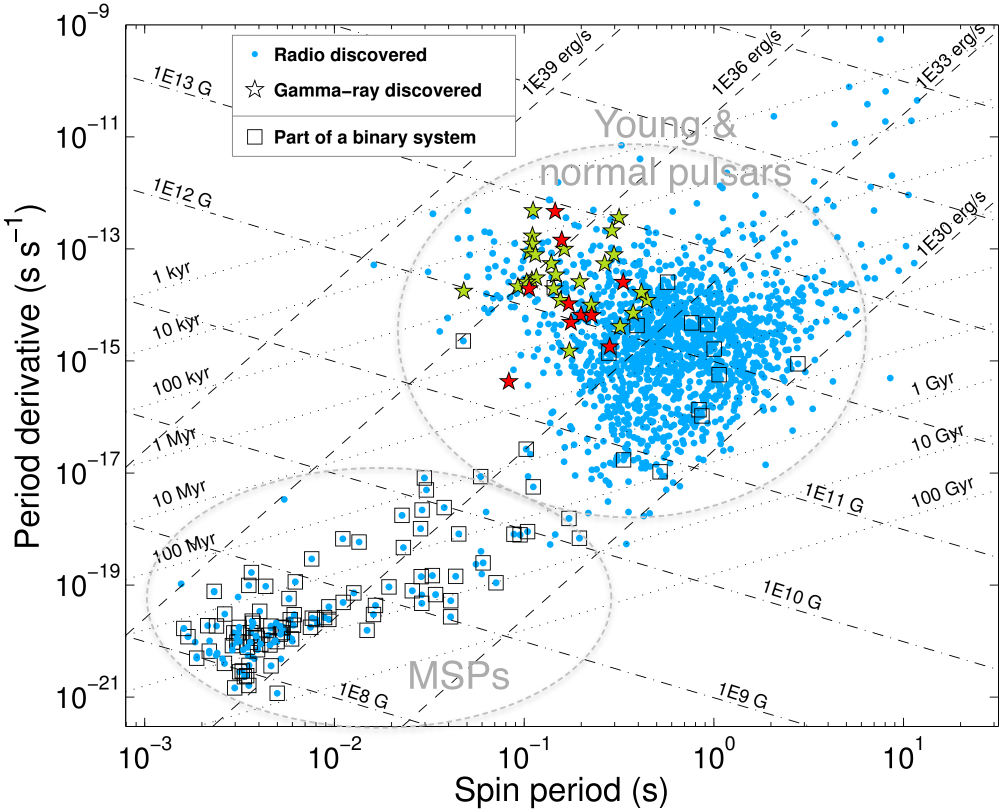
- *Fermi* LAT confirmed that many radio-detected MSPs also pulsate in gamma-rays:

Abdo et al., Science 2009

→ Gamma-ray pulsations revealed only by rotation parameters obtained from radio telescopes.

e.g., Smith et al., A&A 2008

- Successful blind searches for gamma-ray pulsars in LAT data:
  - 24 (with 1 year) Abdo et al., Science 2009; Saz Parkinson et al. ApJ 2010
  - 10 (with 3 years) HJP et al. ApJ & ApJL 2012
    - → Large fraction of young pulsars
    - → Most are radio-quiet Ray et al. 2012



- No MSP previously found in blind search of gamma-ray data.

Computational Challenge

- Blind-search problem for gamma-ray pulsars:
  - **Computationally demanding** since pulsar parameters **unknown** a priori
    - → Must be explicitly searched on dense **grid**
      (for isolated pulsars: spin frequency, frequency derivative & sky position)
    - → For multiple-year observation times:
      number of **grid points** tremendously large

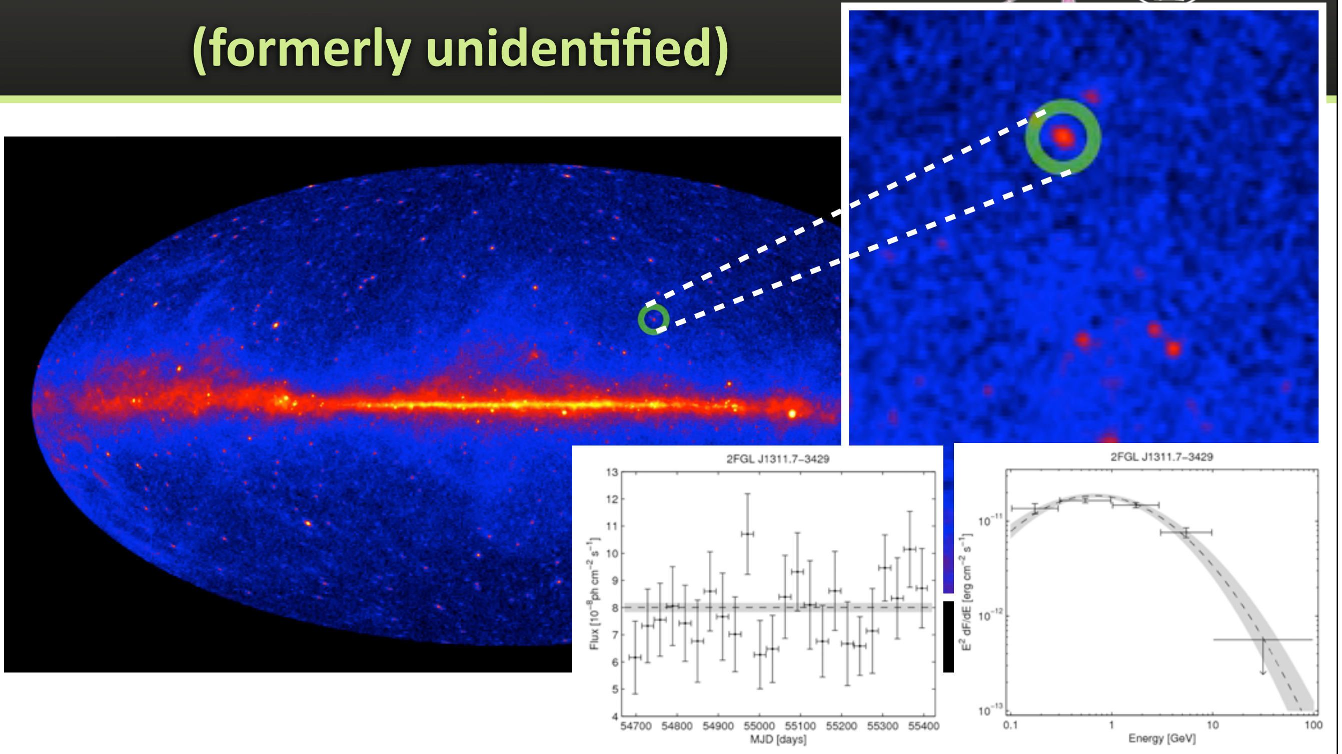
Brady et al., 1998
Chandler et al., 2001
Atwood et al., 2006
Ziegler et al., 2008
HJP et al., 2012

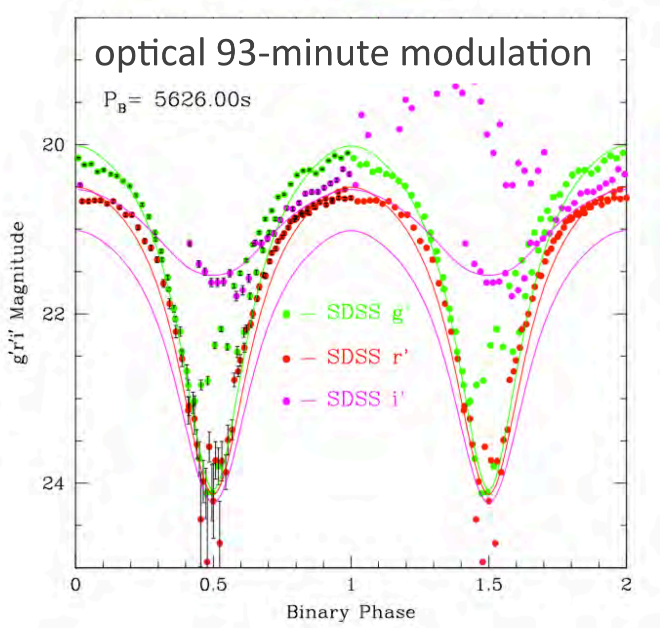
- Blind searches for **MSPs** vastly more difficult:
  - Must scan up to **higher spin frequencies** [to and beyond 716Hz]
  - Plus, most MSPs are in binaries:
    - → Additionally unknown **orbital** parameters
    - → Increases computational complexity by orders of magnitude
  - Blind binary-MSP searches in LAT data were hitherto virtually unfeasible

Target source: 2FGL J1311.7-3429

(formerly unidentified)

- First seen by **EGRET.** (e.g., 2EG J1314-3430)
- Most significant (43σ) unidentified **LAT** source in 2FGL.
- Good pulsar candidate:
  - low flux variability
  - very curved spectrum

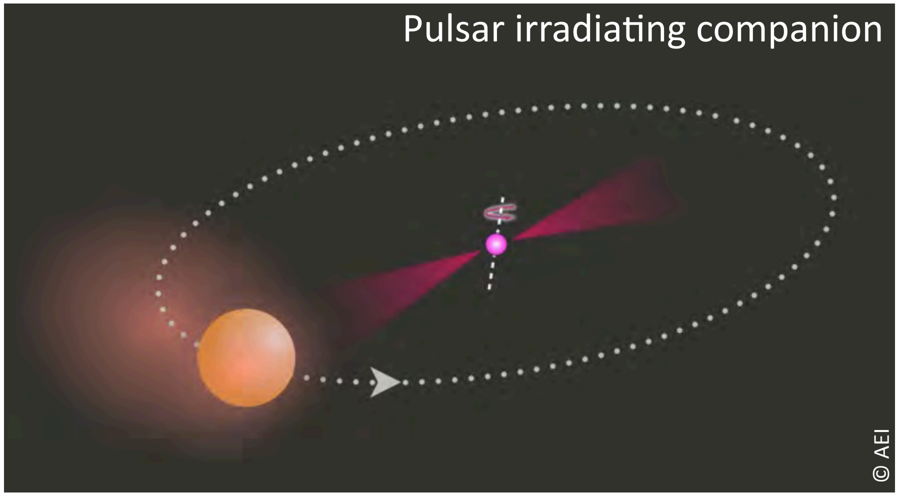




- Crucial: In search for **optical counterparts**, Romani (2012) identified quasi-sinusoidal optical flux modulation. (Romani ApJL 2012, Kataoka et al. ApJ 2012)

  → Conjecture: **"black widow" pulsar binary**
  - MSP irradiates companion star
  - Heating one side of companion, explains optical brightness variation

The search space



Pulsar irradiating companion

© AEI

- **"Black widow" pulsar interpretation:**
  - Optical variation associated with period of circular orbit.
  - Confines sky position.

  → These constraints made **blind binary-MSP search** **feasible**.

  BUT: still enormous computational challenge, because uncertainties on orbital parameters by far larger than required for pulsar detection (and f, $\dot{f}$ unknown)

→ **Pulsar search parameter space left 5-dimensional:**

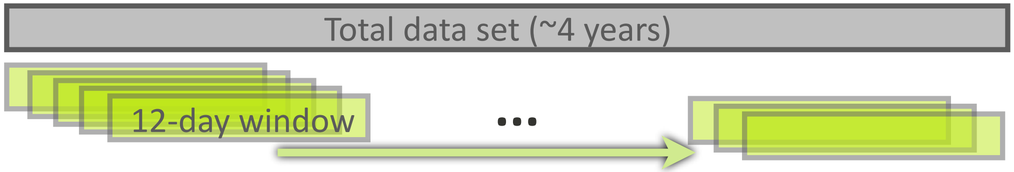
1. Spin frequency: $0 < f < 1400$ Hz
2. Its rate of change: -5×10^{-13} Hz/s $< \dot{f} < 0$
3. Orbital period: $P_{\mathrm{orb}} = 5626.0 \pm 0.1$ s
4. Time of ascending: $T_{\mathrm{asc}} = 56009.131 \pm 0.012$ MJD
5. Projected semi-major axis: $0 < x < 0.1$ lt-s

Hierarchical search strategy

Hierarchical, 3-staged search scheme:

- Goal: discarding unpromising regions in parameter space as early as possible.
- Previously enabled detection of 10 young (non-MSP) pulsars in blind searches.

HJP et al. ApJ & ApJL 2012




Dr. Timo Mappes, www.musoptin.com.

Zooming in

Most **compute cycles** spent at this stage.

1. Semi-coherent stage:

- **Sliding coherence window,** summing coherent Fourier power;
- Coarse graining: Least sensitive, but most efficient to ***scan entire search space***
- Incorporates photon weights (à la Kerr, ApJ 2011)
- Uses heterodyning to process in bands of *f* using FFT

extending Atwood et al., ApJL 2006; HJP, PRD 2011

2. Coherent follow-up:

- For every **semi-coherent candidate** compute fully coherent Fourier power over entire data set, on significantly **refined grid**.

3. Including higher signal harmonics (*H*-test):

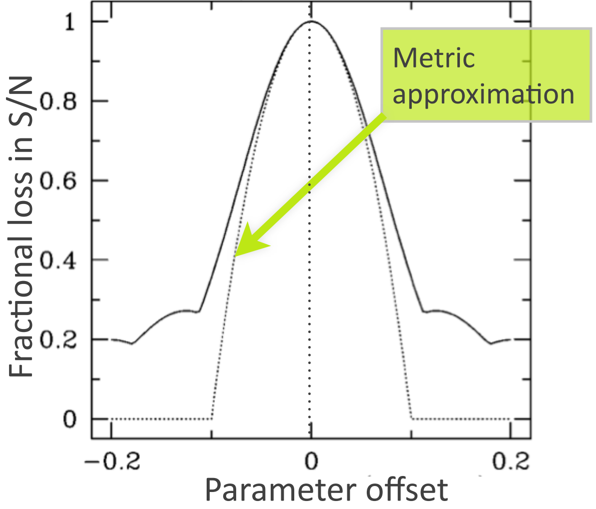
de Jager et al. 1989

- Typically pulse profile non-sinusoidal, also Fourier power at harmonics.
- For every **coherent candidate** sum power (over entire data) from harmonically related frequencies, using a **further refined grid**.

Key novelty: metric search grids

- Based on concepts from gravitational-wave searches.
- Define a distance **metric** on search parameter space:
  - Measure of expected **fractional loss** in S/N for given signal at nearby grid point.
  - Local **Taylor-expansion** of fractional loss around signal location to 2nd order gives the metric.

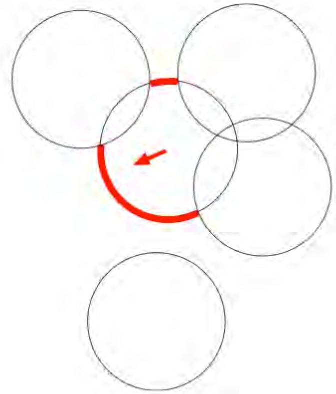
Brady et al., PRD 1998; HJP & Allen, PRL 2009; HJP, PRD 2010



Brady et al. PRD 1998

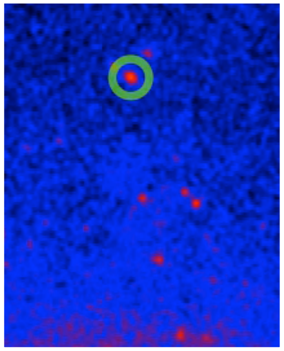
- Problem: Metric **orbital** components explicitly depend on parameters (unlike metric in $\dot{f}$ and f)
  → Simple lattice would either over- or undercover

- Solution: New grid construction algorithm to utilize metric
  - First place orbital grid points **at random**.
    (fast MC integration using metric provides total number of grid points required)
  - Then move those that are too close or too far apart by **barycentric shifts** towards optimal coverage.
  - Designed to never lose > 30% in S/N for any signal.



Fehrmann & HJP, in prep

Searching 4 years of LAT data



- **Input LAT data** for the search:
  - 1437-day time span; LAT photons within 15° around target.

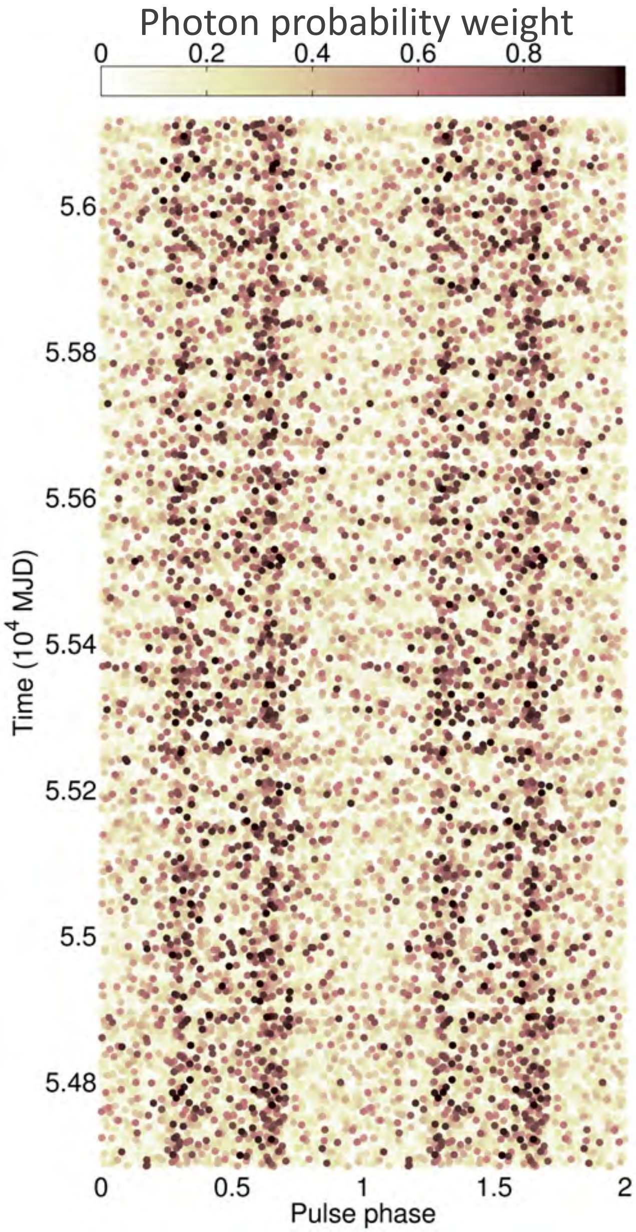
- **Computing** done on the **ATLAS** cluster (6780 CPU-cores)
  - Analyzed full spin-frequency range in **bands** of 128 Hz each (via heterodyning):
    - → accommodates memory limitations
    - → adapt orbital search to each band (points increase as f^3)
  - For example, a band near 700Hz Number of grid points:
    f: 10^8, $\dot{f}$: 10^2, orb: 10^7
    → total: 10^{17}

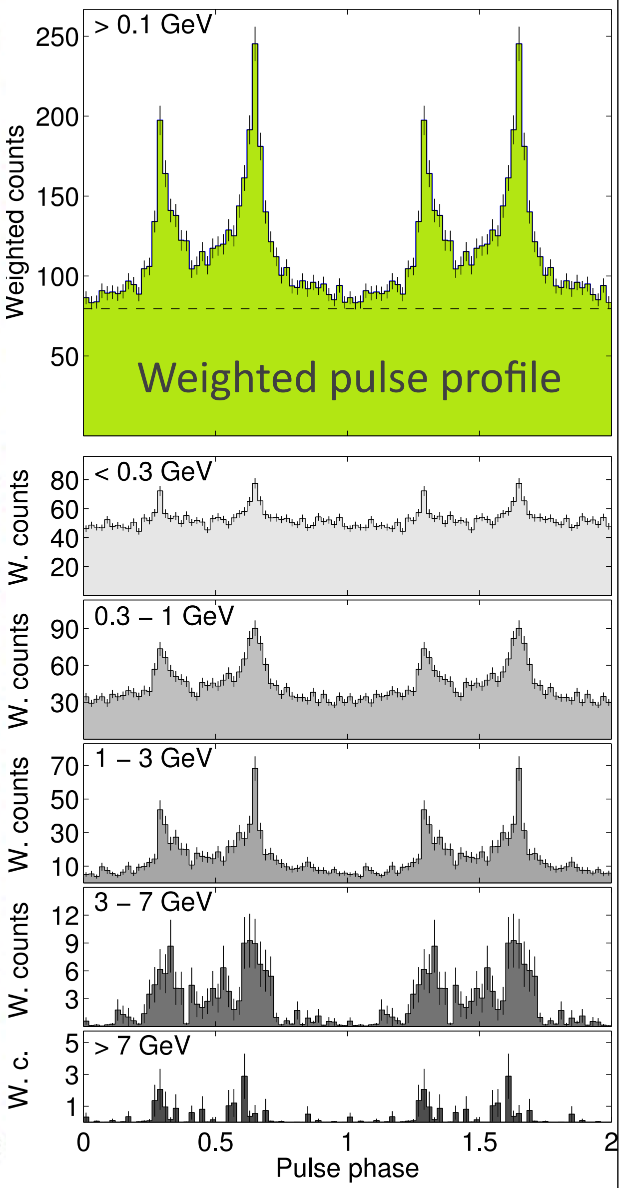
ATLAS computing facility, Hannover

The PSR J1311-3430 system (1/2)

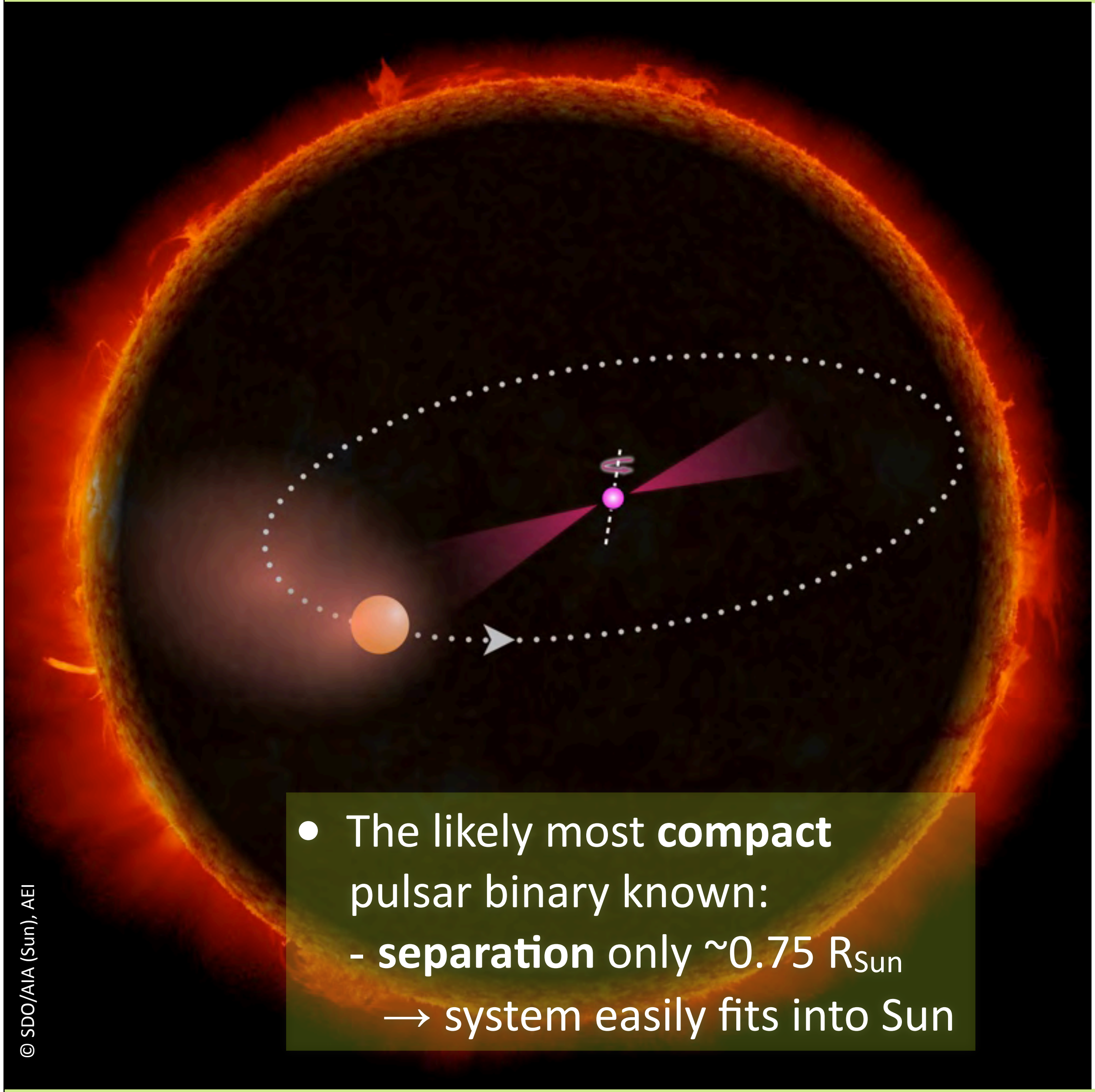
- Following the discovery:
  → pulsar timing to precisely measure the system parameters (🟧)

Parameter		Value
Right ascension (J2000.0) (hh:mm:ss)	🟧	13:11:45.7242(2)
Declination (J2000.0) (dd:mm:ss)	🟧	−34:30:30.350(4)
Spin frequency, f (Hz)	🟧	390.56839326407(4)
Frequency derivative, $\dot{f}$ (Hz s^{-1})	🟧	$-3.198(2) \times 10^{-15}$
Reference time scale		TDB
Reference time (MJD)		55266.90789575858
Orbital period P_{orb} (d)	🟧	0.0651157335(7)
Projected pulsar semi-major axis x (lt-s)	🟧	0.010581(4)
Time of ascending node T_{asc} (MJD)	🟧	56009.129454(7)
Eccentricity e		< 0.001
Data span (MJD)		54682 - 56119
Weighted RMS residual (μs)		17
Derived Quantities		
Companion mass m_c ($M_\odot$)		> 0.0082
Spin-down luminosity $\dot{E}$ (erg s^{-1})		4.9×10^{34}
Characteristic age τ_c (yr)		1.9×10^{9}
Surface magnetic field B_S (G)		2.3×10^{8}
Gamma-Ray Spectral Parameters		
Photon index, Γ		1.8 ± 0.1
Cutoff energy, E_c (GeV)		3.2 ± 0.4
Photon flux above 0.1 GeV, F (10^{-8} photons cm^{-2} s^{-1})		9.2 ± 0.5
Energy flux above 0.1 GeV, G (10^{-11} erg cm^{-2} s^{-1})		6.2 ± 0.2





The PSR J1311-3430 system (2/2)



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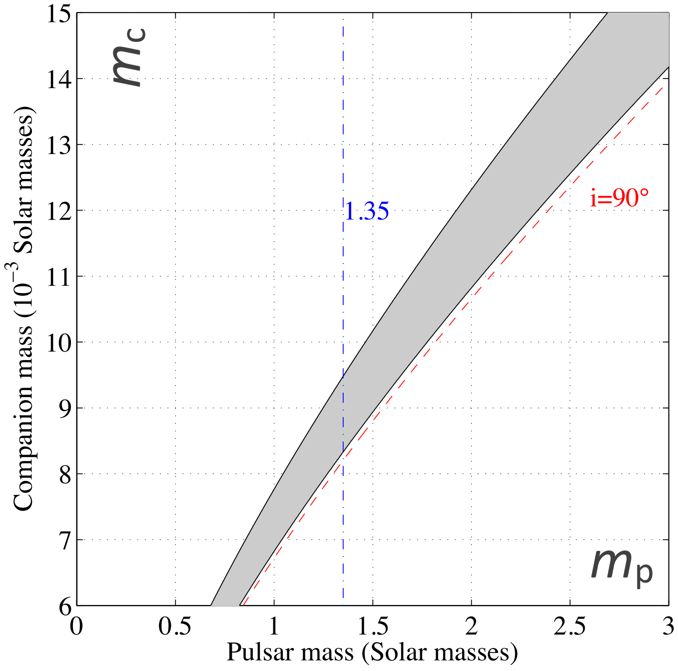
- The likely most **compact** pulsar binary known:
  - **separation** only ~0.75 R_{Sun}
  → system easily fits into Sun

- Rotational ephemeris also constrains **companion mass**:

  $m_c > 0.0083\ M_{Sun}$ (~8 $M_{Jupiter}$)

  [for $m_p = 1.35\ M_{Sun}$, i=90°]

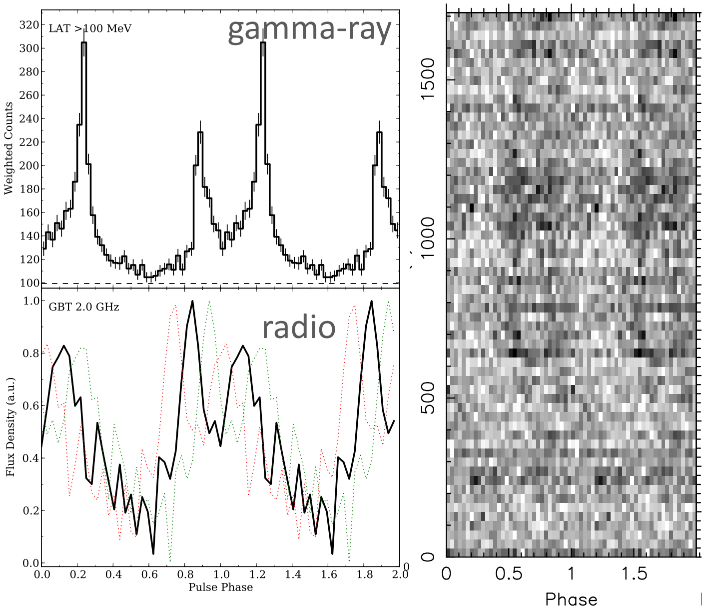


- Companion Roche lobe radius: ~0.63 $R_{Jupiter}$
- Mean density: ~45 g cm^{-3}
  → 30 times higher than Jupiter

Further studies at other wavelengths

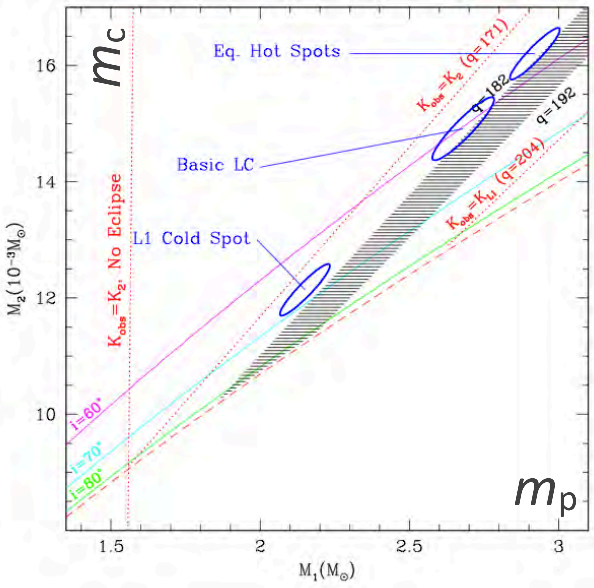
- **Radio follow-up observations**

  see *Ray et al.*, arXiv:1210.6676
  - Several targeted searches with gamma-ray ephemeris gave no detection
  - BUT: intermittent **radio detection** with GBT in one 2GHz observation
    ⟶ Dispersion-measure distance: 1.4kpc

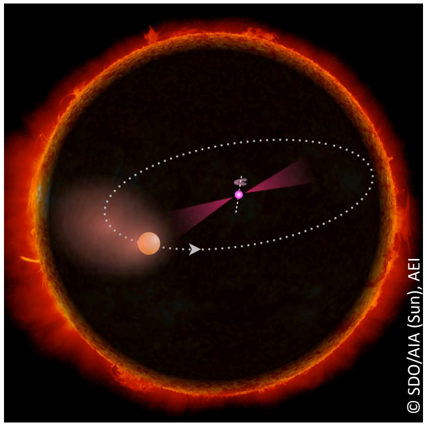


- **Further optical observations**

  see *Romani et al.*, arXiv:1210.6884
  - Radial velocity measurements of companion
  - Additional constraint in mass-mass diagram
    ⟶ Neutron star might have very large mass



Conclusion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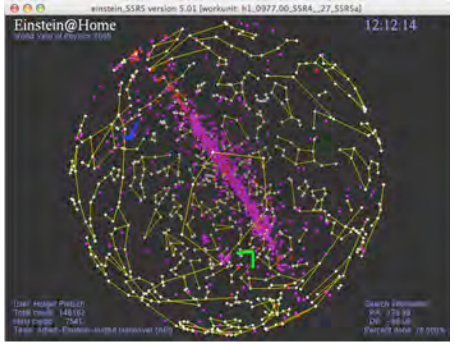
- With partial constraints from optical, binary gamma-ray MSPs can be found in blind search with *Fermi* LAT.

- **PSR J1311-3430:**
  First MSP discovered solely via gamma-ray pulsations
  - Compact "black widow" pulsar binary, with shortest P_{orb} known.
  - Broader relevance: potential key probe for binary evolution; its high neutron star mass can constrain behavior of ultra-dense matter.

- New possibilities for future searches & studies:
  - More MSPs might exist among LAT unidentified sources, which are too radio-faint or obscured for typical radio searches.
  - Hunt for the first radio-quiet MSP continues.



- Blind searches in LAT data for solitary MSPs also with volunteer computing system **Einstein@Home**
  http://einstein.phys.uwm.edu/