# University of Wisconsin-Milwaukee Proposal

Bruce Allen, Patrick Brady, Jolien Creighton, and Alan Wiseman

LIGO Program Advisory Committee
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# Who We Are
# U. Of Wisconsin-Milwaukee

- One of two Ph.D.-Granting institutions in the university of Wisconsin system
- Center for Gravitation and Cosmology:
  - » 4 professors, 1 visiting professor, 4 postdocs, 5 grad students
  - » Founded in 1967
  - » Received continuous NSF funding for > 30 years
- LSC group at UWM
  - » 2 professors, 1 visiting professor, 2 postdocs, 1 grad student, 4 undergraduate students
  - » Received ~ $300k in equipment and salary match from UWM over the past three years alone

# Who We Are
# UWM LSC Group Members

- Bruce Allen (professor)
  - » GW detection (stochastic, inspiral, pulsars), early universe, curved space QFT
- Patrick Brady (professor)
  - » GW detection (pulsars, inspiral, bursts), singularities, numerical simulations, gravitational back-reaction
- Jolien Creighton (Postdoc)
  - » GW detection (inspiral, stochastic, bursts, ringdown), black hole thermodynamics
- Alan Wiseman (visiting Prof)
  - » GW detection (inspiral), waveform generation, gravitational back-reaction
- Scott Koranda (staff scientist)
  - » GRID computing expert, PhD in early universe cosmology
- Ben Owen (Postdoc)
  - » GW detection (inspiral, pulsars), r-mode instability, spinning binaries
- Duncan Brown (grad student)
  - » Hierarchical, templated inspiral search code
- Flasch, Gallistel, Hammer
  - » Undergraduate students
  - » Beowulf software and hardware maintenance
- Stone
  - » Physics undergrad research

# Results From Prior Support Inspiral Searches

- Prototype inspiral search demonstrated matched filtering in presence of non-Gaussian noise
- Tools developed:
  - » Time-frequency discrimination
  - » Loudest event method of setting conservative upper limit
- Recent activities
  - » LAL code to perform matched filtering and vetoing
  - » Hierarchical search engine (Brown)
  - » Filtered 5000 sec of E5 data through about 10 templates to enable det. char. activities

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## Observational Limit on Gravitational Waves from Binary Neutron Stars in the Galaxy

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Using optimal matched filtering, we search 25 hours of data from the LIGO 40-m prototype laser interferometric gravitational-wave detector for gravitational-wave chirps emitted by coalescing binary systems within our Galaxy. This is the first test of this filtering technique on real interferometric data. An upper limit on the rate $R$ of neutron star binary inspirals in our Galaxy is obtained: with 90% confidence, $R < 0.5\ h^{-1}$. Similar experiments with LIGO interferometers will provide constraints on the population of tight binary neutron star systems in the Universe.

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A worldwide effort is underway to test a fundamental prediction of physics (the existence of gravitational waves) using a new generation of gravitational-wave detectors capable of making astrophysical observations. These efforts include the US Laser Interferometer Gravitational-wave Observatory (LIGO) [1], VIRGO (French/Italian) [2], GEO-600 (British/German) [2], TAMA (Japanese) [2], and ACIGA (Australian) [3]. The detectors are laser interferometers with a beam splitter and mirrors suspended on wires. A gravitational wave displaces the mirrors, and shifts the relative optical phase in two perpendicular paths. This causes a shift in the interference pattern at the beam splitter [4]. Within the next decade, these facilities should be sensitive enough to observe gravitational waves from astrophysical sources at distances of tens to hundreds of megaparsecs (Mpc).

During the past 15 years, the LIGO project has used a 40-m prototype interferometer at Caltech to develop optical and control elements for the full-scale detectors under construction in Hanford, Washington, and Livingston, Louisiana [5]. In 1994, this instrument was configured as a modulated Fabry-Perot interferometer: light returning from the two arms was independently sensed [6]. In this configuration, the detector had its best differential displacement sensitivity of $\sim 3.5 \times 10^{-19}$ m Hz$^{-1/2}$ over a bandwidth of approximately a kHz centered at 600 Hz.

A week-long test run of the instrument was made in November 1994 prior to a major reconfiguration. Figure 1 shows the data-taking periods. The run yielded 44.8 hours of tape; both arms were in optical resonance for 39.9 hours (89% of the time). Although the data was taken for diagnostic purposes, it provides an excellent opportunity to obtain observational limits on gravitational-wave sources, and to examine analysis techniques.

A major challenge arises because the real detector noise does not satisfy the usual simplifying assumptions: stationary and Gaussian. The 40-m data have the expected colored broadband background but with significant deterministic components (spectral peaks), including $\sim 10^{2}$ sinusoidal components arising from the vibration of the

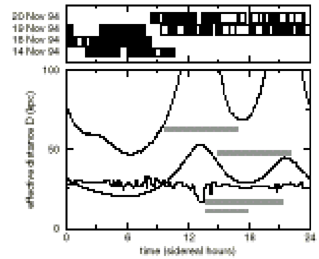


FIG. 1. Top: boxes show data collection times. Dark bars show data actually filtered. Bottom: effective distance $D$ [Eq. (1)] to 90% (50%) of sources varies as the detector antenna pattern sweeps past the Galactic center. The dip at 6 h is when the nadir of the detector (turning with the Earth) points closest to the Galactic center where the potential sources are clustered. Fortuitously, much of the data was taken near such times. Jagged line: effective distance $D$ at which a $2 \times 1.4 M_{\odot}$ optimally oriented coalescing system would give SNR $= \rho = 10$. This depends on the average sensitivity of the instrument. The small fluctuations indicate stable sensitivity.

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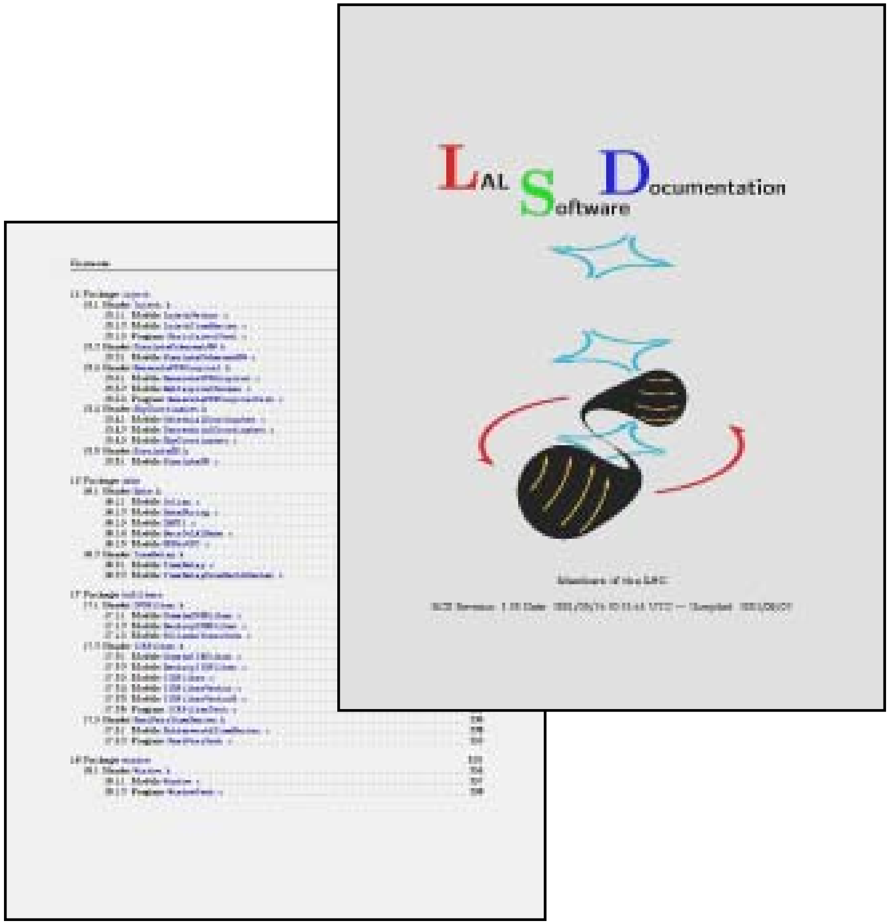
# Results From Prior Support Contributions to LSC Software

- LSC software coordinator
  - » Alan Wiseman
- LSC algorithm library (LAL)
  - » Librarian: Jolien Creighton
  - » Lead authors on:
    - – `Std`, `support`, `utilities`, `inject`, `tdfilters`, `window`, `fft`, `pulsar stack-slide`, `framedata`, `comm`, `findchirp` `findchirp`
  - » Contribute to:
    - – `Factories, burstsearch`
- Data monitoring tool
  - » Teviet Creighton (ex post-doc at UWM, now at Caltech) contributed routines for filtering



# Results From Prior Support Burst Detection Methods

- Need for burst detection methods
  - » Intermediate mass binary black holes: no accurate templates
- Approach 1: (W. Anderson and R. Balasubramanian)
  - » Explored a variety of time-frequency transforms (used Beowulf)
  - » Implemented line-feature identification in time-frequency plane
  - » Calibrated the method using white Gaussian noise and mock black hole merger signals
  - » Implemented in LAL
- Approach 2: (W. Anderson, P. Brady, J. Creighton and E. Flanagan)
  - » Excess power time-frequency search method (Flanagan/Hughes)
  - » Developed algorithmic implementation
  - » Extended theory to multiple detectors
  - » Implemented in LAL and available through LDAS

# Results From Prior Support Using LAL in LDAS

- MPI working group
  - » Brady & Blackburn (co-chairs)
  - » UWM group was core, now expanded (and expanding)
- UWM contributions
  - » Helped design uniform interface
  - » Implemented as LALWrapper by J. Creighton and D. Brown
  - » Implemented inspiral search code (Brown)
  - » Implemented power search code (Brady)
  - » Produced HOWTO for developers
  - » Mock Data Challenge 3: successful in Jan 2001

# Results From Prior Support UWM LSC Computing Facilities

- Beowulf compute clusters
- March 1998
  - » Allen, Anderson, Balasubramanian
  - » 48 nodes, 30 Gflops, $75k
- System uses:
  - » Binary inspiral search project
  - » To develop/test robust methods to search for intermediate-range black holes (Anderson & Balasubramanian)
  - » Modeling galactic distribution of binary NS systems by matt Evans (Caltech)
  - » Parameter space study for wide-area pulsar seach method J Sylvestre (MIT)
  - » To develop inspiral search code by D. Brown (UWM)

# Results From Prior Support
# UWM LSC Computing Facilities

## Medusa cluster (2001) designed for GW analysis work

- 296 nodes, each with
  - 1 GHz Pentium III
  - 512 MBytes memory
  - 100baset Ethernet
  - 80 Gbyte disk
  - On-board hardware health monitoring
- 1.2 TByte RAID array
- 1.5 TByte tape robot
- UPS power
- Fully-meshed switch

**Storage: 22 TBytes**

**CPU: 296 Gflops**

Completed in August 2001

NSF MRI and UWM matching funds

# Results From Prior Support
# Other Highlights

- Robust filtering for stochastic backgrounds
  - » Allen, J. Creighton, Flanagan and Romano. (gr-qc/PRD)
  - » Method is insensitive to non-Gaussian noise bursts
- Astrophysical Source Identification and Signatures
  - » Allen chairs this group providing active interface to astrophysics
- Upper Limit groups:
  - » Coordinated effort: Wiseman as software coordinator
  - » Inspiral: Brady co-chairs with Gonzalez. Allen, Brady, Brown, Creighton and Wiseman will contribute search code in LAL/LALWrapper, simulation code in LAL, statistical methods
  - » Stochastic: Allen and J. Creighton contributing simulation and search codes
  - » Pulsar: Owen contributing template placement code
  - » Burst: Brady contributing power search code.

# Proposed Research Preface

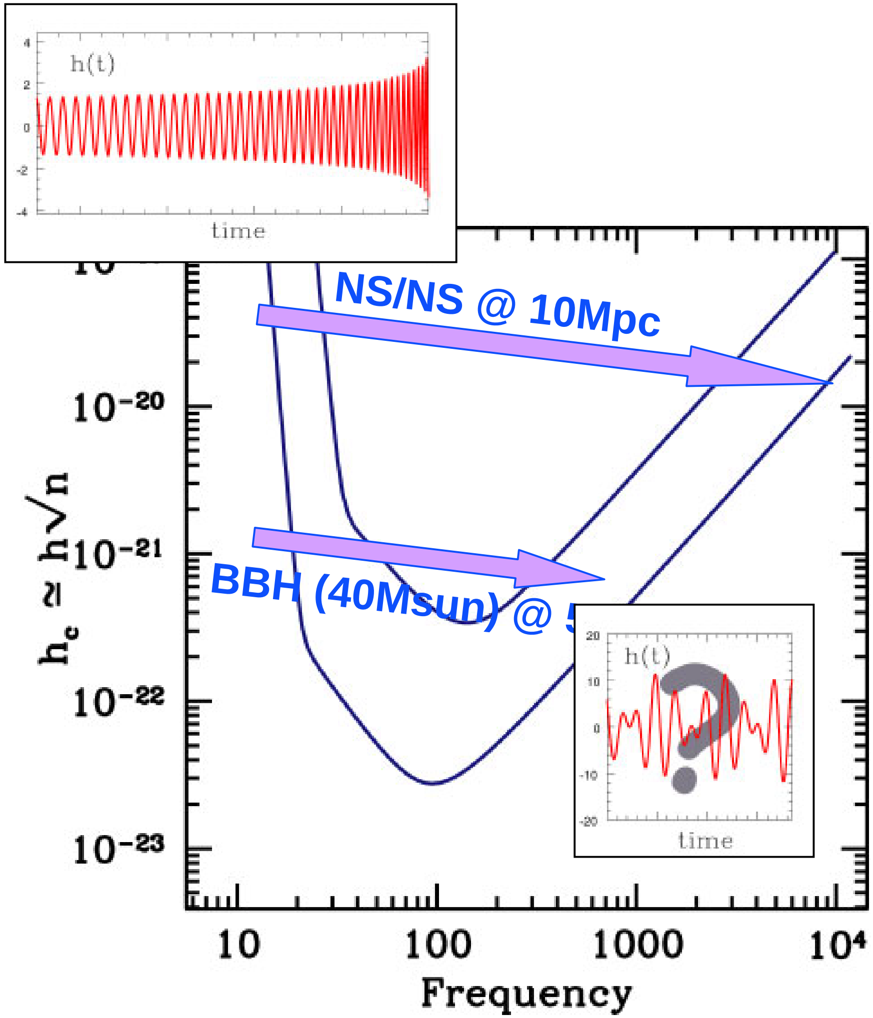
- This proposal extends group's activities for 2002-2007
  - » Four principal investigators, two experienced PhD level scientists, excellent facilities, demonstrated teamwork and commitment
  - » This proposal would build on and subsume three existing funded gravitational-physics/LIGO grants to enhance flexibility and simplify the administrative burden.
- New requests in the proposal:
  - » support for an additional post-doctoral associate
  - » computer systems administrative support commensurate with the group's growing role in LSC production computing
  - » one additional graduate student
  - » increased travel funds to participate in LSC & LIGO Lab. activities
- UWM will add new faculty to the group next year and provide significant matching funds.

# Proposed Research Service and Boiler Plate

- LSC service activities …..
  - » **Software coordinator**: Wiseman
  - » **ASIS**: Allen (chair), Wiseman (meeting coordinator)
  - » **LAL librarian**: J. Creighton
  - » **Software Change Control board**: Wiseman and J. Creighton
  - » **LSC computing facility**: Managed by Allen, Brady, Wiseman
  - » **MPI working group**: Brady and Blackburn
    - – Note: transition to LSC Software Users Group imminent
  - » **CVS software archives and web pages:** Brady, Brown, J. Creighton
- All software products will be produced to LSC coding specification
- All science within LSC proposal mechanism

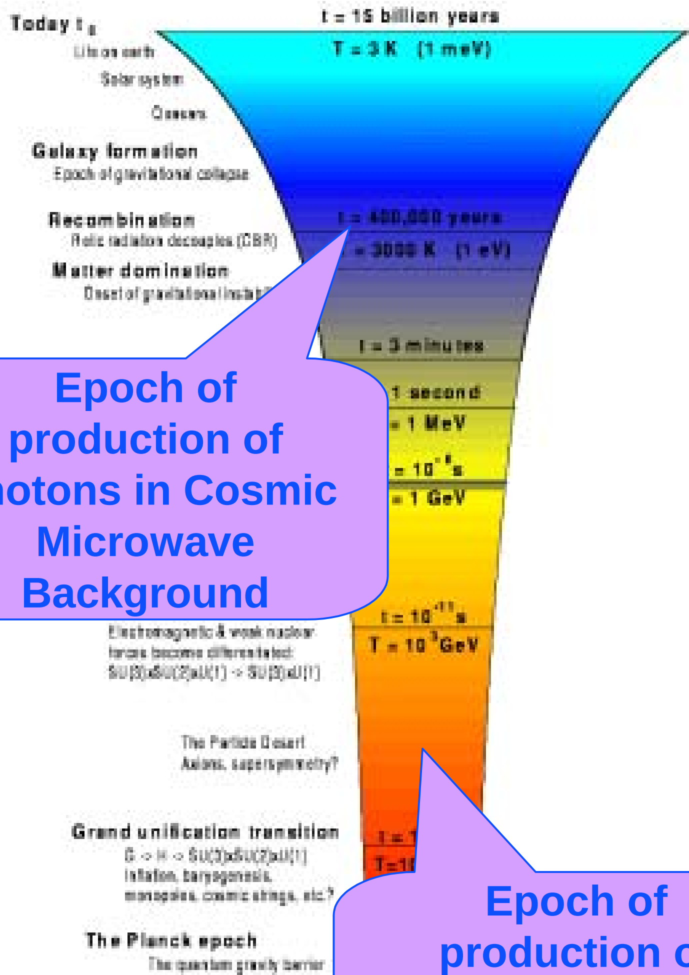
# Proposed Research
# Binary Inspiral





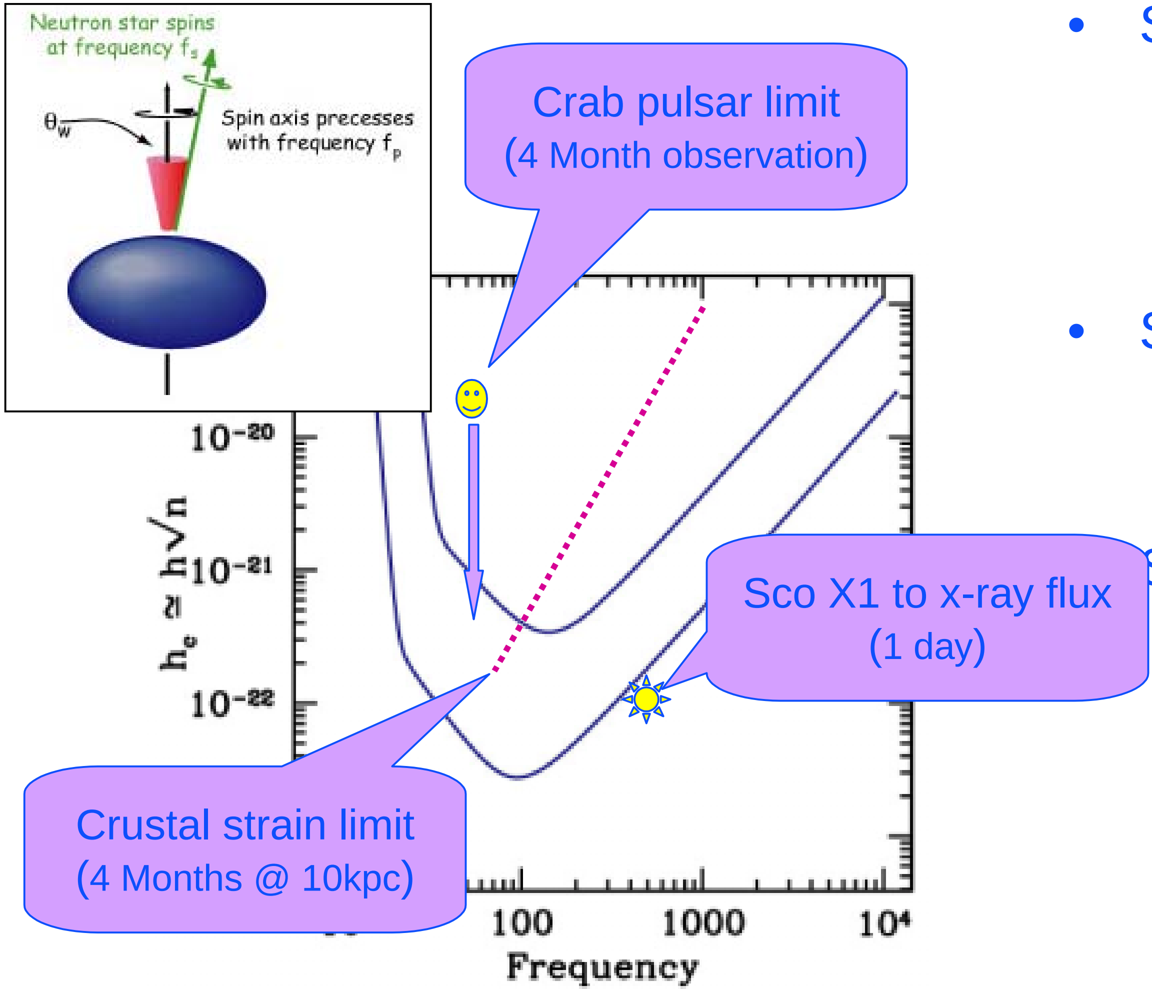

- Science goals:
  - » To determine upper limits on binary inspiral rates in the universe
  - » Detect waves from inspiral and merger on compact binaries
- Develop inspiral search code
  - » Develop robust, efficient hierarchical search code
  - » Explore different hierarchical strategies
- Other activities
  - » Detection & information extraction using multiple instruments
  - » Statistical determination of upper limits
  - » Precessing binary detection

# Proposed Research
# Stochastic Background



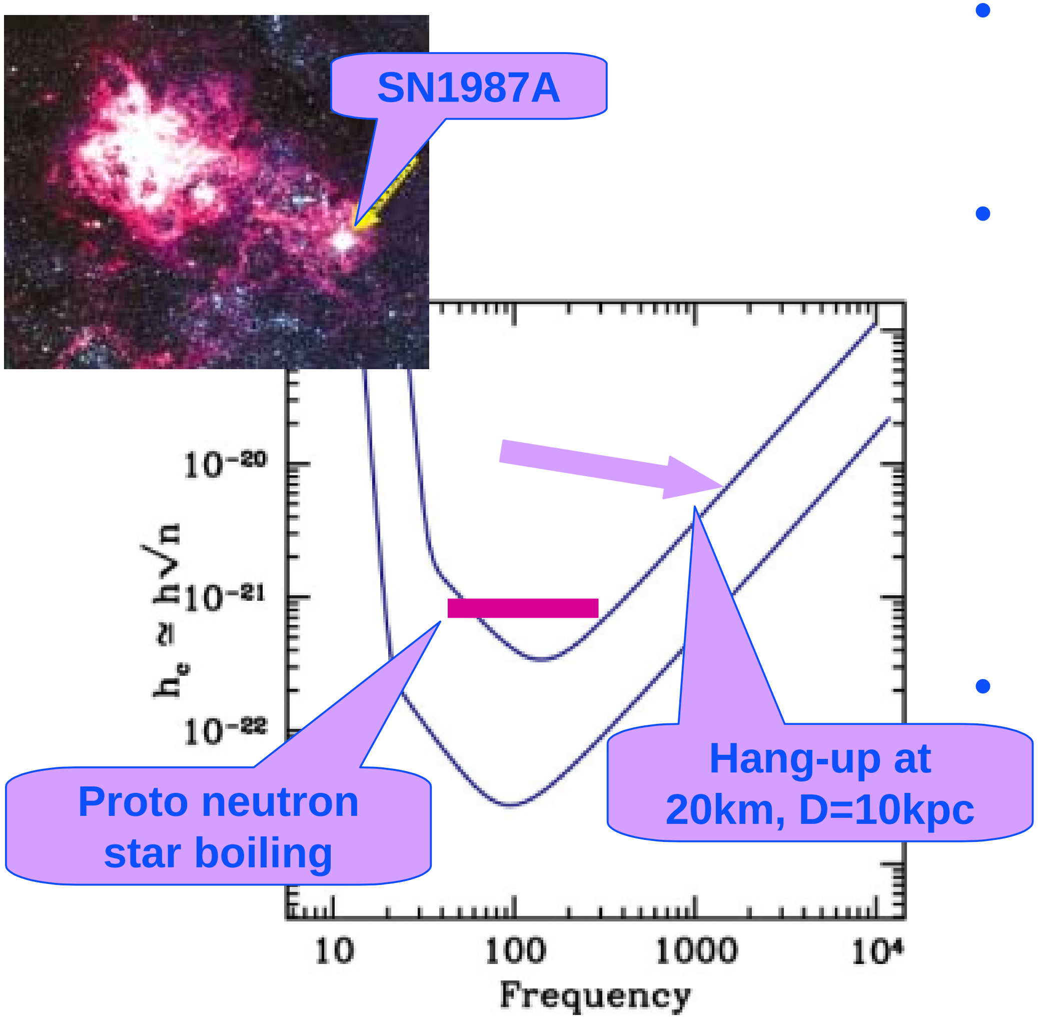

- Scientific Goals
  - » Determine upper limits on energy density in a gravitational-wave background and implications for cosmology
  - » Limits for backgrounds with a variety of statistical properties and spectra
- Modeling of early universe
  - » Study non-gaussian statistics from kinks on cosmic strings and unresolved supernovae and cosmic binaries.
- Analysis tools
  - » Develop and extend robust detection methods which are locally optimal and encorporate them into the stochastic search code
  - » Develop methods to analyze noise correlations between detectors and multi channel analyses to discriminating between gravitational waves and non-gravitational channels.

# Proposed Research
# Spinning Neutron Stars




- Scientific Goals
  - » Determine upper limits on strain from spinning neutron stars
  - » Constrain/detect possible EM silent populations
- Search code development
  - » Develop/implement stack-slide search algorithm as hierarchical search method
- Source modeling
  - » Continue to study nature of gravitational waves from r-modes
  - » Explore needs to search for gravitational waves from x-ray binaries
  - » Implement search methods for both types of source

# Proposed Research
# Burst Sources




- Scientific goals
  - » To determine upper limits on rate and strength of gravitational wave bursts
- Software products
  - » Maintain and develop the excess power code which currently runs under LDAS
  - » Implement the multi-detector version of the excess power code
  - » Implement searches for ringdown waves
- Information extraction
  - » Explore use of time-frequency techniques for information extraction
  - » Develop coincidence strategy between inspiral, burst (merger) and ringdown to detect binary black holes

# Proposed Research
# LIGO Data Analysis on the Grid

- Question: How do 100’s of LSC scientists analyze 100’s of Tbytes of LIGO data?
  - » Answer: Grid computing
- Analogy with the electrical power grid
  - » you don’t care where or how power for your toaster is generated
  - » you just want results (toast!)
- Grid computing to provide robust, uniform, access to distributed high performance computing resources
  - » don’t necessarily know (or care) from where cycles are delivered
  - » you just want to do science

# Proposed Research
# UWM LSC Grid Activities

- GriPhyN and iVDGL
  - » Allen, Brady, Koranda, (funding not part of this proposal)
  - » research and prototyping of grid and virtual data tools
  - » UWM is an LSC Tier-2 data analysis facility
- Activities exploiting the Grid
  - » Monte-Carlo simulations of all search codes mentioned above. (Inspiral, Bursts, Stochastic, Pulsar)
  - » Already started:
    - – J. Sylvestre using condor to run simulations for burst group
    - – D. Brown using condor to run simulations for inspiral group.
- Sys. Admin Request
  - » As a Tier-2 center, increased support of LSC users requires increased system support
  - » iVDGL provides some support, but not nearly enough.

# Training and Outreach

- Previous LSC postdocs
  - » Teviet Creighton ('99-'01)
    - – Now postdoc at Caltech
  - » Warren Anderson ('98-'00)
    - – Now professor at UTB
  - » R. Balasubramanian ('98-'00)
    - – Now staff with GEO600
  - » Joseph Romano ('96-'98)
    - – Now professor at UTB
- Other postdocs
  - » Jorma Louko (faculty, Nottingham); Sharon Morsink (faculty, Alberta); Atsushi Higuchi (faculty, Bern)
- Recent UWM graduate students in relativity:
  - » S. Bose (faculty, Pulman)
  - » N. Stergioulas (faculty, Greece)
  - » K. Lockitch (postdoc,Illinois)
  - » R. Caldwell (postdoc, Princeton)
  - » W. Hua (LSC group, Stanford)
- REU undergraduate students:
  - » D. Hammer
  - » K. Flasch
  - » G. Gallistel
  - » A. Ruja