Title: Probing frontiers of fundamental physics and astrophysics with numerical relativity

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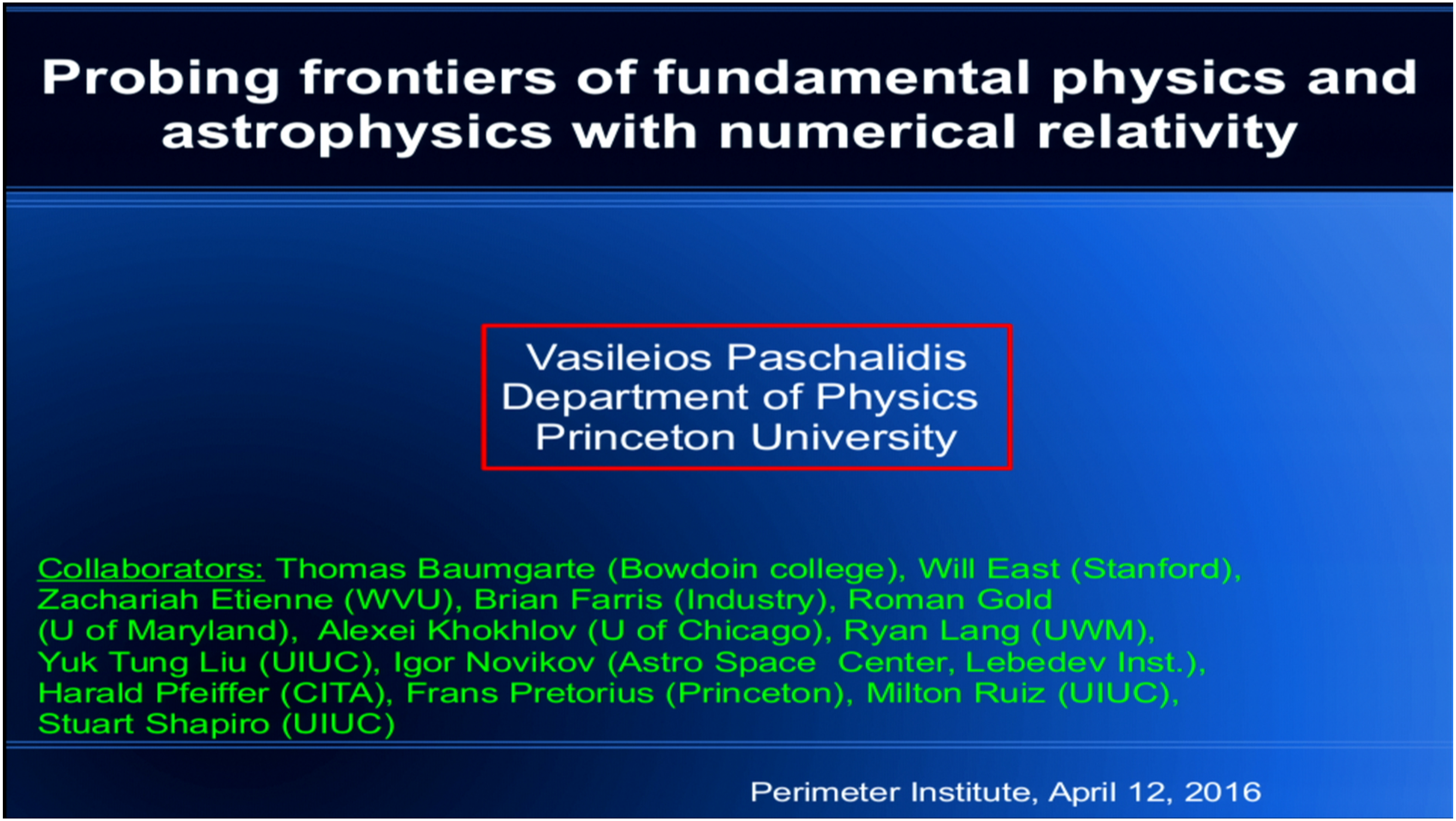
Abstract: <p>The coalescence of black hole-black hole (BHBH), black hole-neutron star (BHNS) and neutron star-neutron star (NSNS) systems are among the most promising sources of gravitational waves (GWs) detectable by Advanced LIGO/Virgo and NANOGrav. In addition, distinct observable electromagnetic radiation may accompany these GWs. Such "multi-messenger" sources can be powerful probes of fundamental physics such as the state of matter under extreme conditions, cosmology, as well as our theories of gravity. However, the identification, detection and interpretation of multimessenger signals from such sources requires careful theoretical modeling through the last stages of the compact binary inspiral, during which all approximations to general relativity break down. The only avenue to theoretically understanding these highly non-linear systems is solving the Einstein equations with the aid of supercomputers. This task is far from trivial: ill-posed formulations of the Einstein equations, gauge issues, the presence of singularities, shocks, and large range of length and time scales inherent to these systems pose strong theoretical and computational challenges. In this talk I will review these challenges, describe state-of-the-art numerical relativity techniques that overcome them, and present results from recent supercomputer simulations of binary NSNSs, and BHBHs around magnetized disks. I will conclude by discussing future directions and applications of numerical relativity.</p>



Probing frontiers of fundamental physics and astrophysics with numerical relativity

Vasileios Paschalidis
Department of Physics
Princeton University

Collaborators: Thomas Baumgarte (Bowdoin college), Will East (Stanford), Zachariah Etienne (WVU), Brian Farris (Industry), Roman Gold (U of Maryland), Alexei Khokhlov (U of Chicago), Ryan Lang (UWM), Yuk Tung Liu (UIUC), Igor Novikov (Astro Space Center, Lebedev Inst.), Harald Pfeiffer (CITA), Frans Pretorius (Princeton), Milton Ruiz (UIUC), Stuart Shapiro (UIUC)

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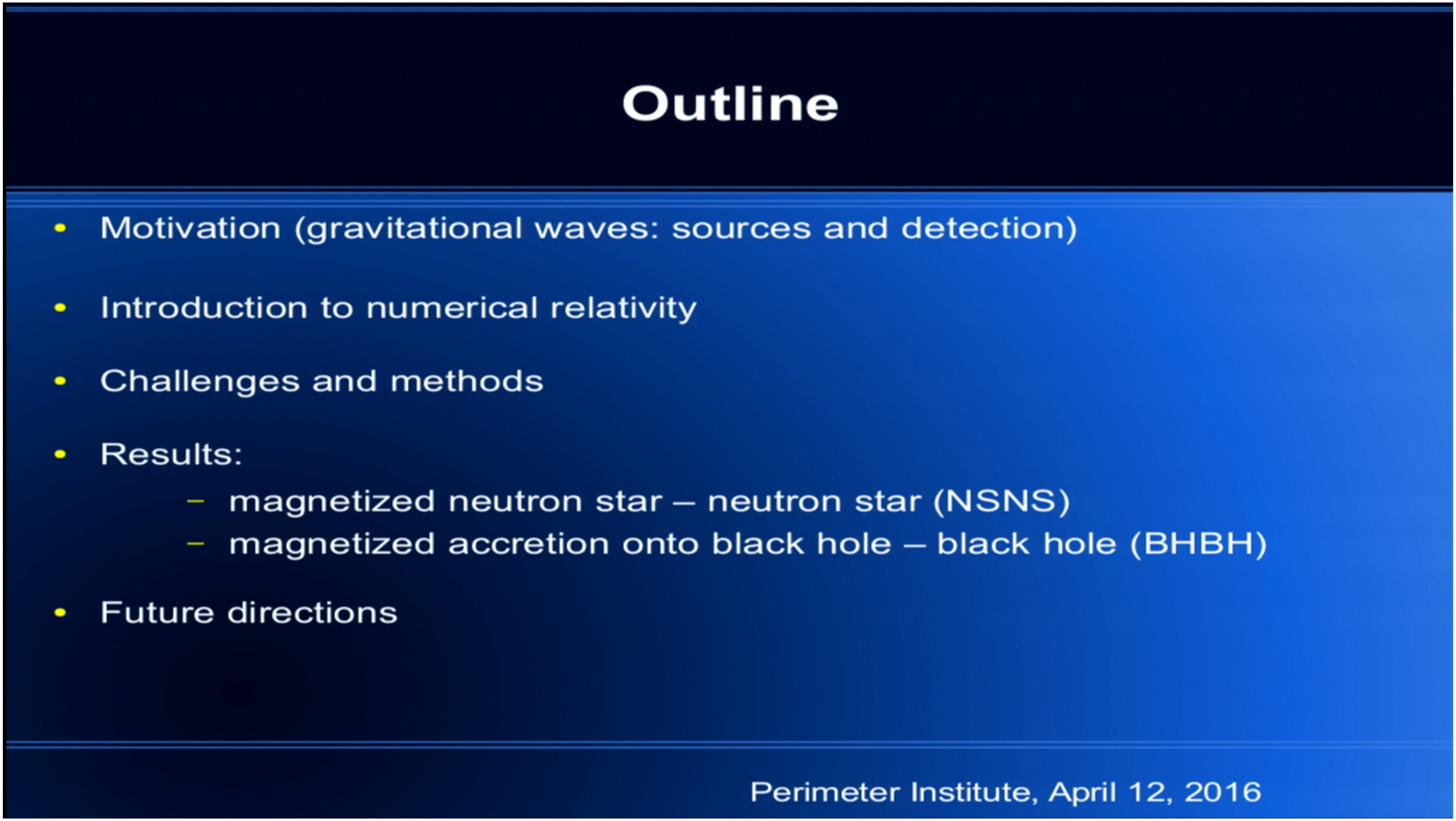
Outline

- Motivation (gravitational waves: sources and detection)
- Introduction to numerical relativity
- Challenges and methods
- Results:
    - magnetized neutron star – neutron star (NSNS)
    - magnetized accretion onto black hole – black hole (BHBH)
- Future directions



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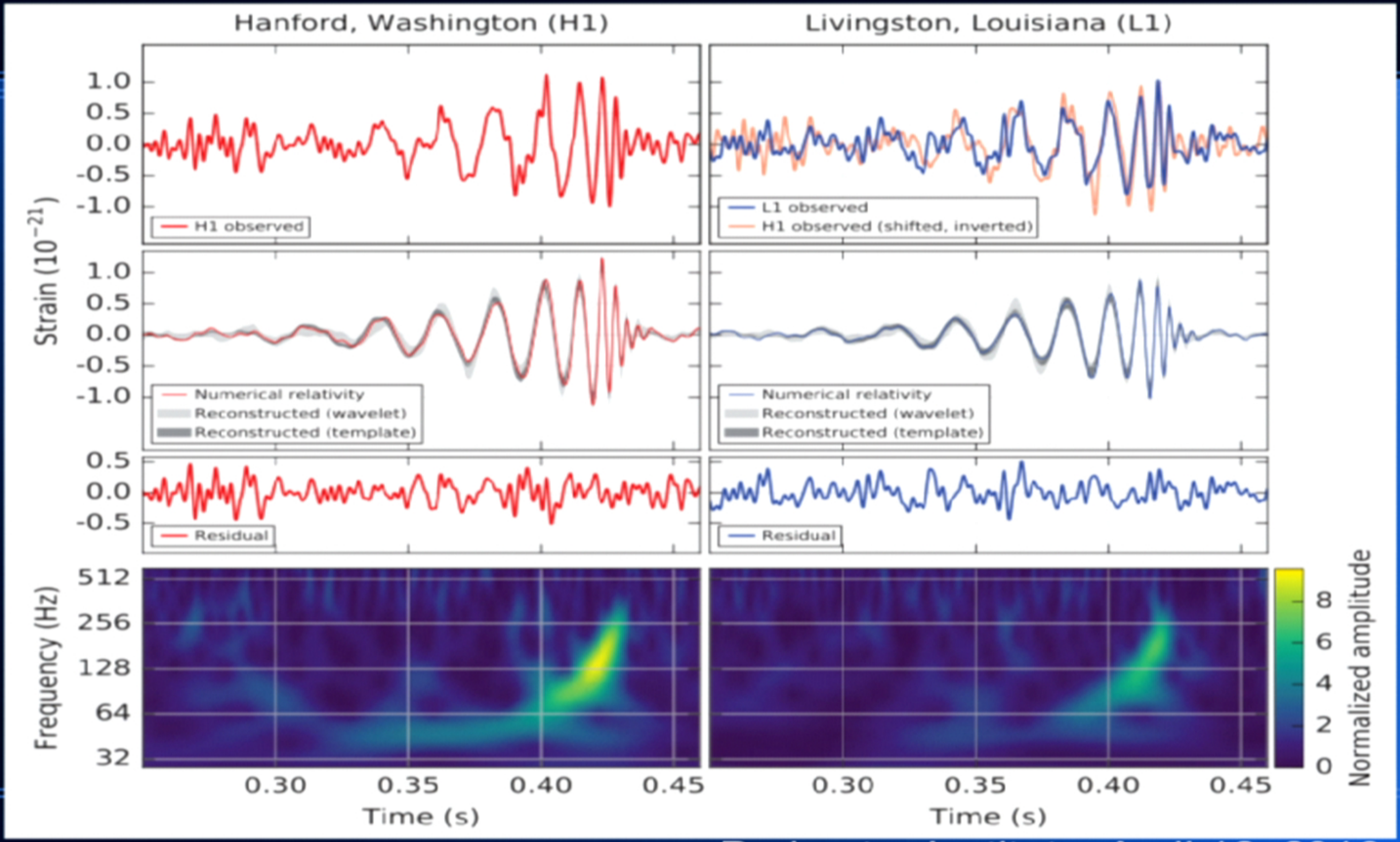
Gravitational waves exist! GW150914



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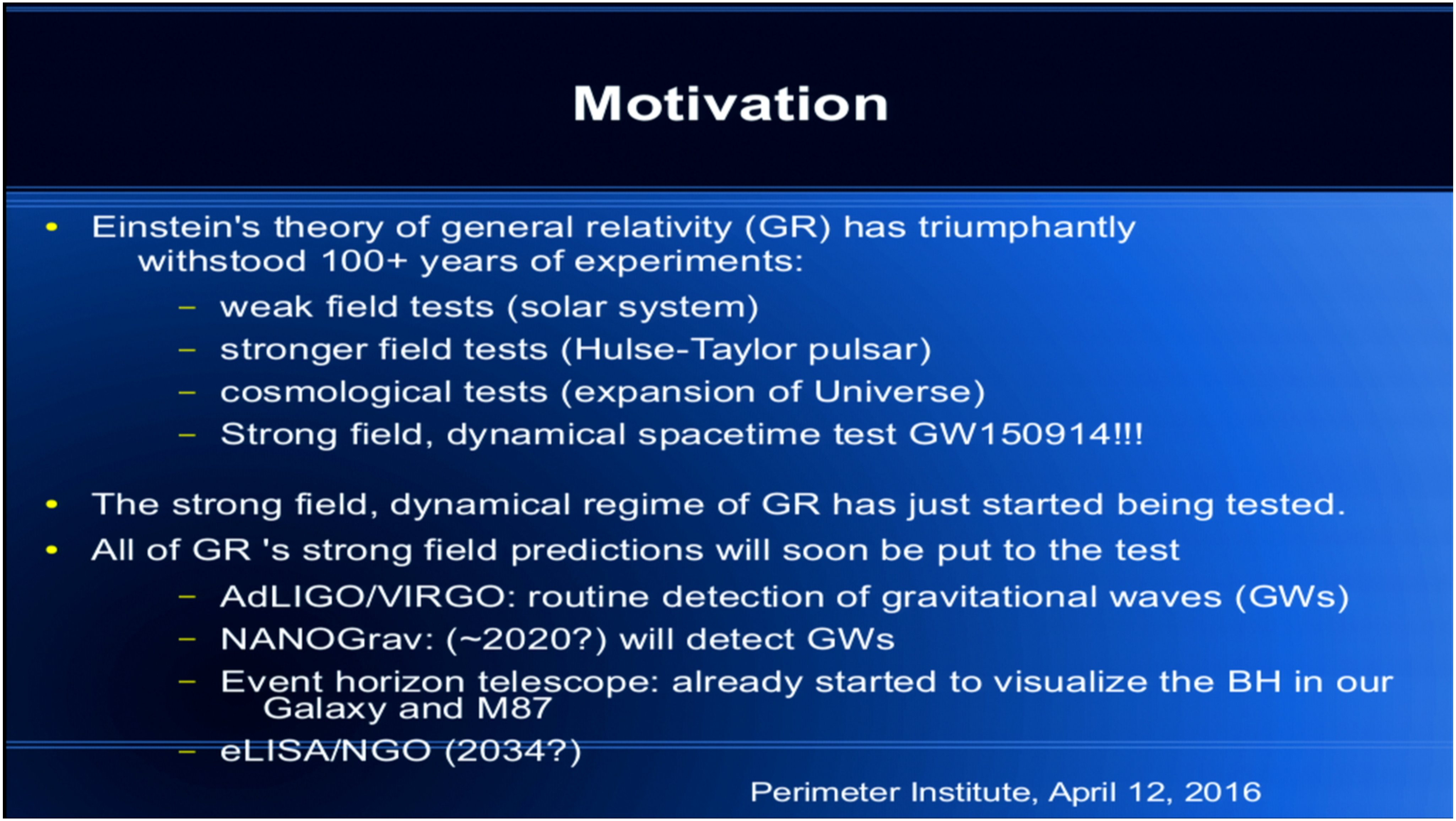

Motivation

- Einstein's theory of general relativity (GR) has triumphantly withstood 100+ years of experiments:
  - weak field tests (solar system)
  - stronger field tests (Hulse-Taylor pulsar)
  - cosmological tests (expansion of Universe)
  - Strong field, dynamical spacetime test GW150914!!!
- The strong field, dynamical regime of GR has just started being tested.
- All of GR 's strong field predictions will soon be put to the test
  - AdLIGO/VIRGO: routine detection of gravitational waves (GWs)
  - NANOGrav: (~2020?) will detect GWs
  - Event horizon telescope: already started to visualize the BH in our Galaxy and M87
  - eLISA/NGO (2034?)

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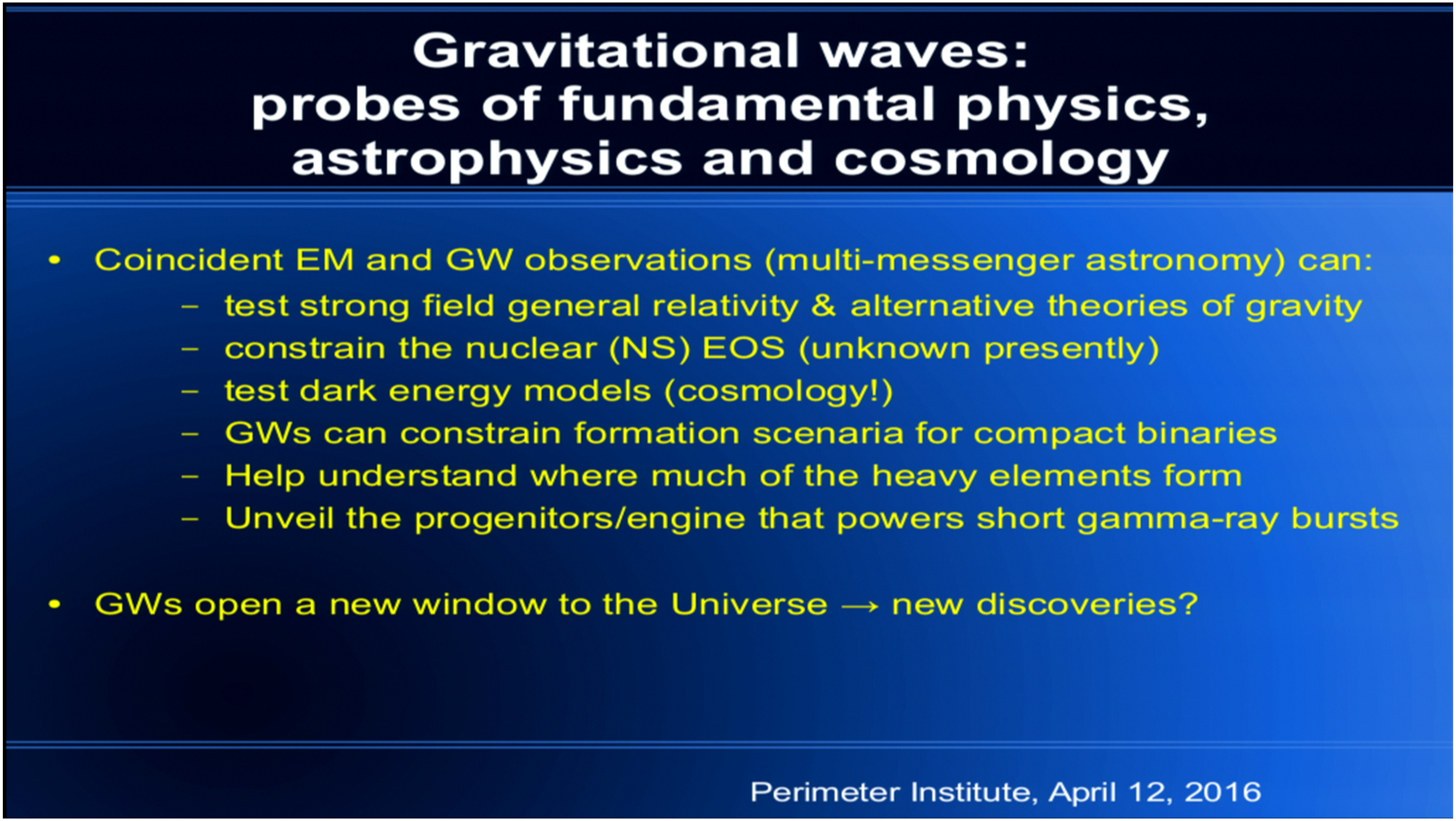
Gravitational waves:
most promising sources and rates

- Most promising GW sources: coalescing compact binaries - binaries involving black holes or neutron stars
- aLIGO will detect 0.4-400 events/yr [Abadie et al. (2010), Dominik et al. 2012)]
- From GW150914 → ~2-400 BHBH events/yr [Abott et al. (2016)]



Gravitational waves: probes of fundamental physics, astrophysics and cosmology

- Coincident EM and GW observations (multi-messenger astronomy) can:
  - test strong field general relativity & alternative theories of gravity
  - constrain the nuclear (NS) EOS (unknown presently)
  - test dark energy models (cosmology!)
  - GWs can constrain formation scenaria for compact binaries
  - Help understand where much of the heavy elements form
  - Unveil the progenitors/engine that powers short gamma-ray bursts
- GWs open a new window to the Universe → new discoveries?

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On the verge of a global GW network

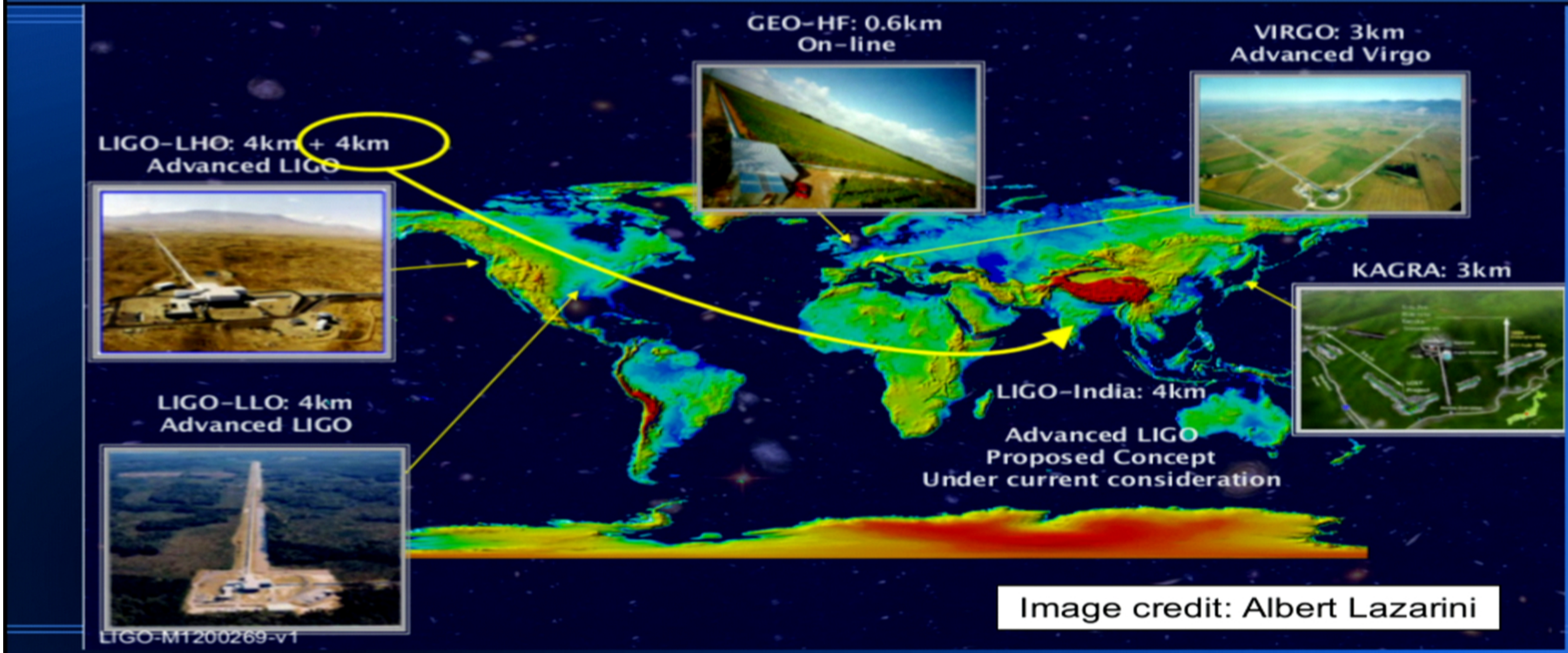


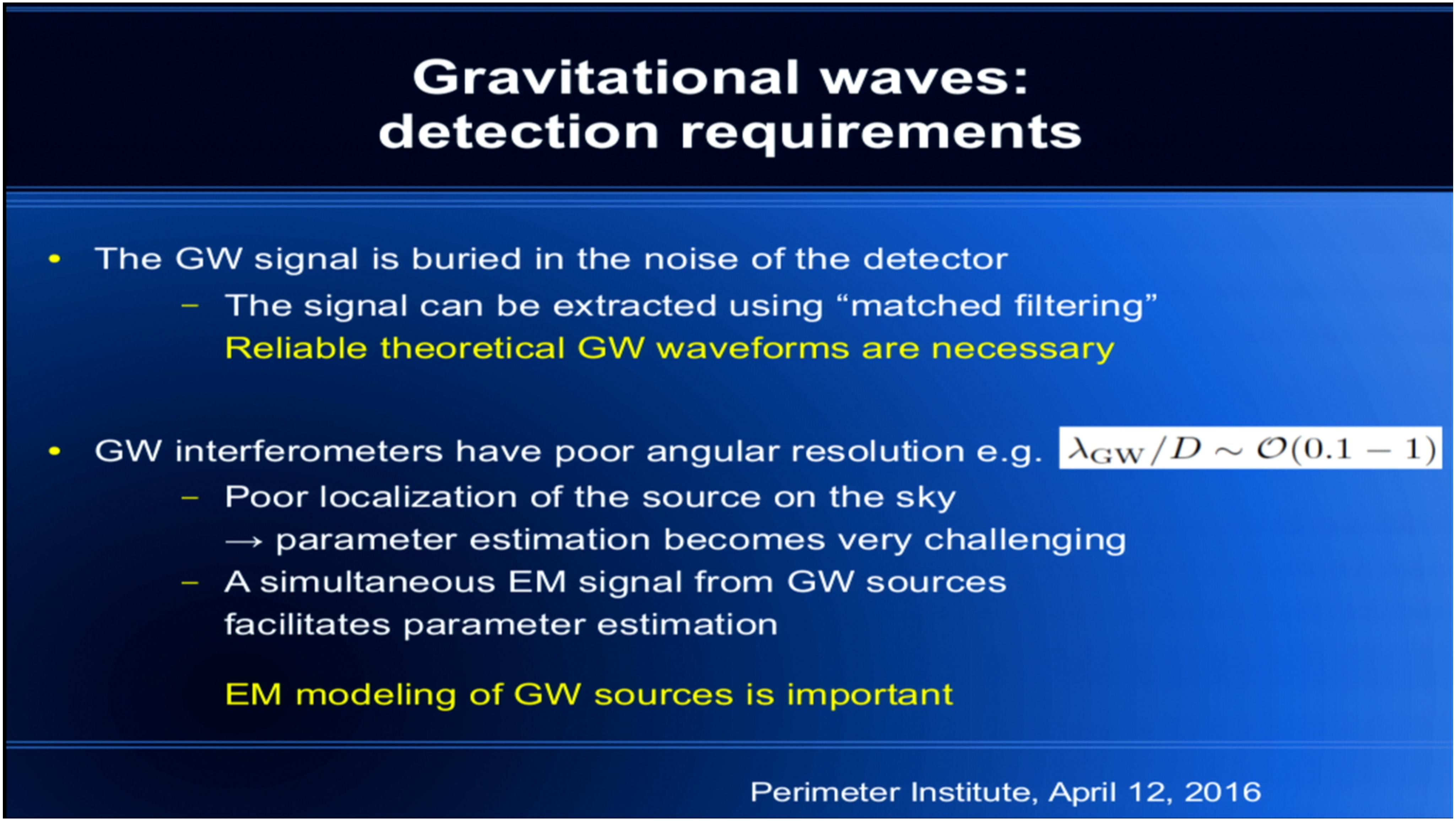
Image credit: Albert Lazarini

Gravitational waves: detection requirements

- The GW signal is buried in the noise of the detector
    - The signal can be extracted using “matched filtering”
      Reliable theoretical GW waveforms are necessary

- GW interferometers have poor angular resolution e.g. $\lambda_{\rm GW}/D \sim \mathcal{O}(0.1-1)$
    - Poor localization of the source on the sky
      $\longrightarrow$ parameter estimation becomes very challenging
    - A simultaneous EM signal from GW sources facilitates parameter estimation

      EM modeling of GW sources is important



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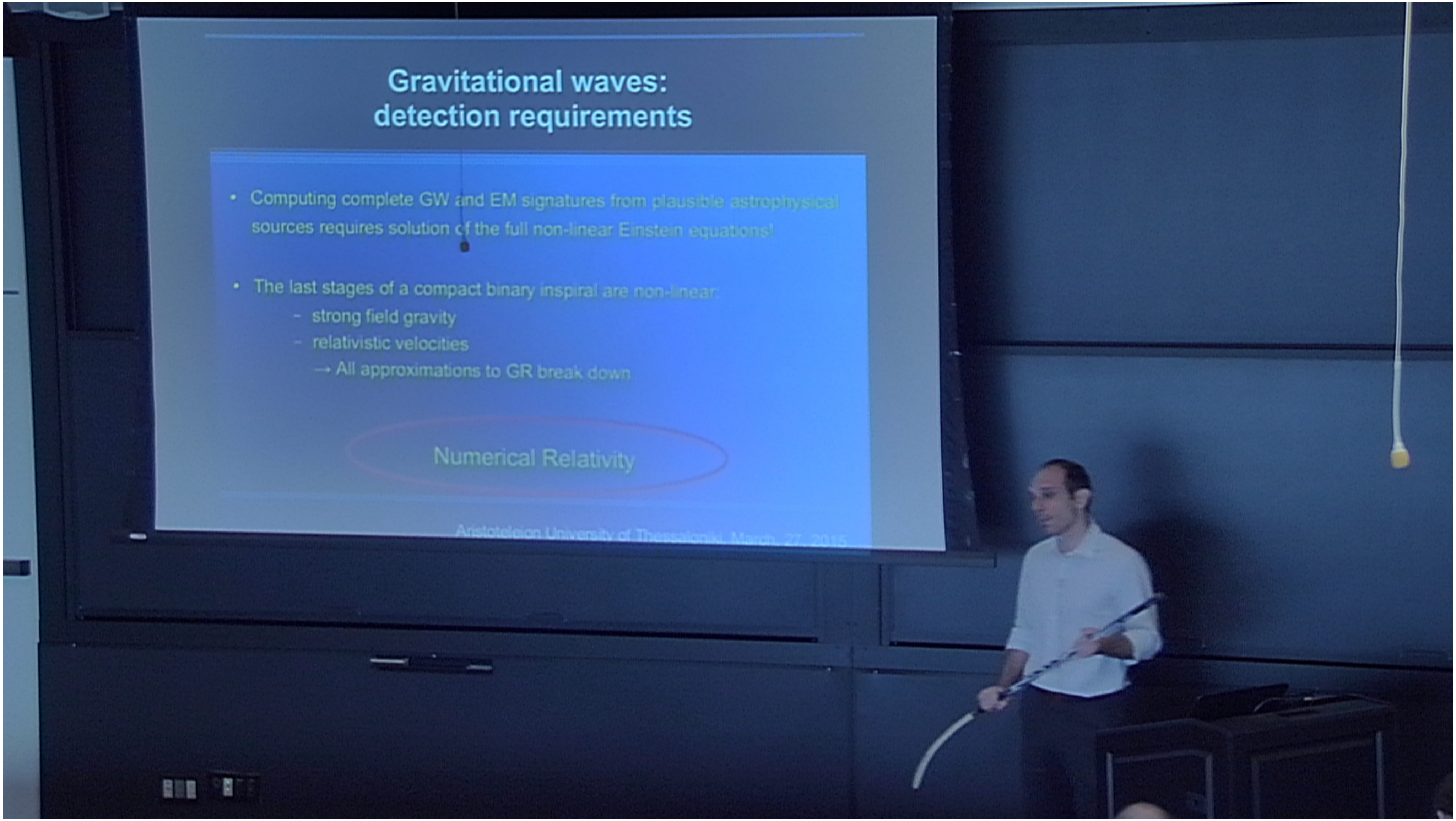


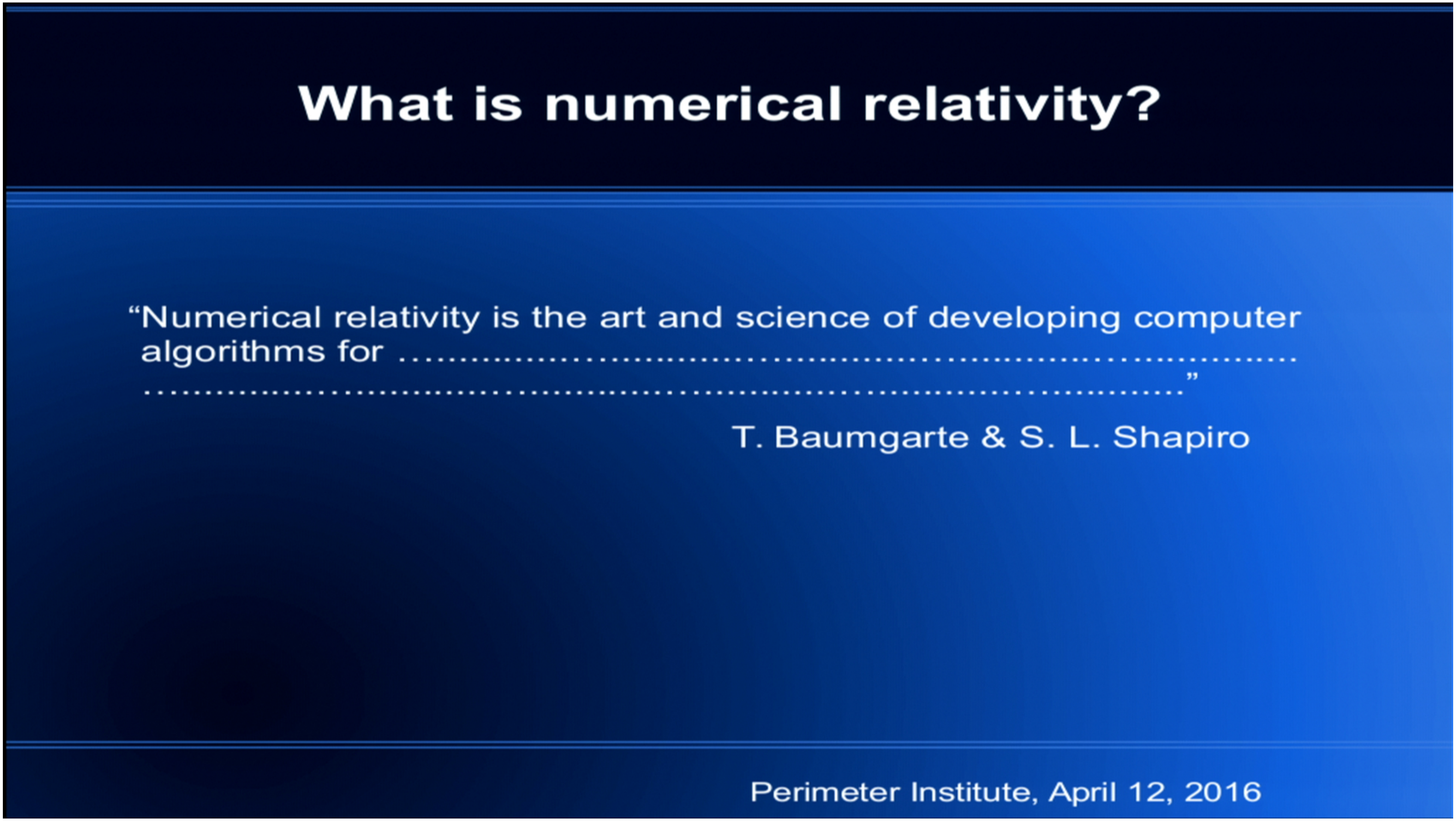
Gravitational waves: detection requirements

- Computing complete GW and EM signatures from plausible astrophysical sources requires solution of the full non-linear Einstein equations!
- The last stages of a compact binary inspiral are non-linear:
  - strong field gravity
  - relativistic velocities

  → All approximations to GR break down

Numerical Relativity

Aristoteleion University of Thessaloniki, March, 27, 2015



What is numerical relativity?

"Numerical relativity is the art and science of developing computer algorithms for ....
...."

T. Baumgarte & S. L. Shapiro

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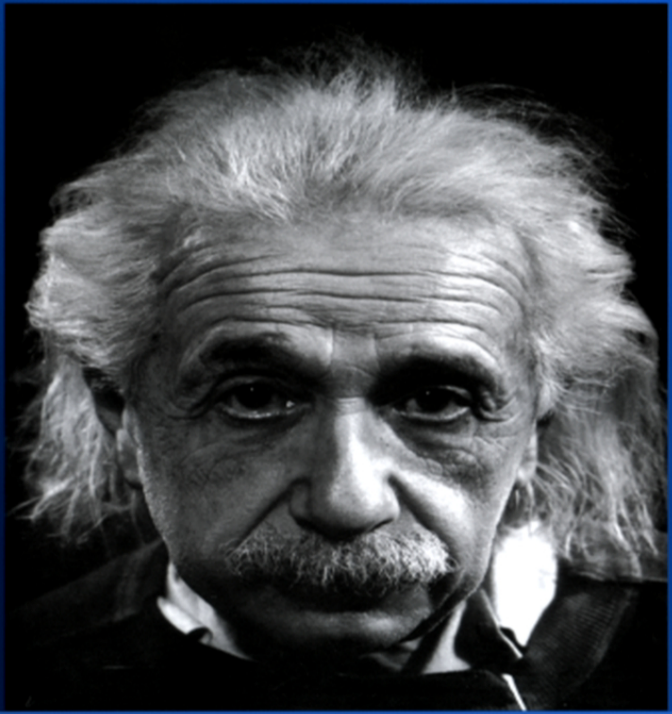
So, you want to do numerical relativity?



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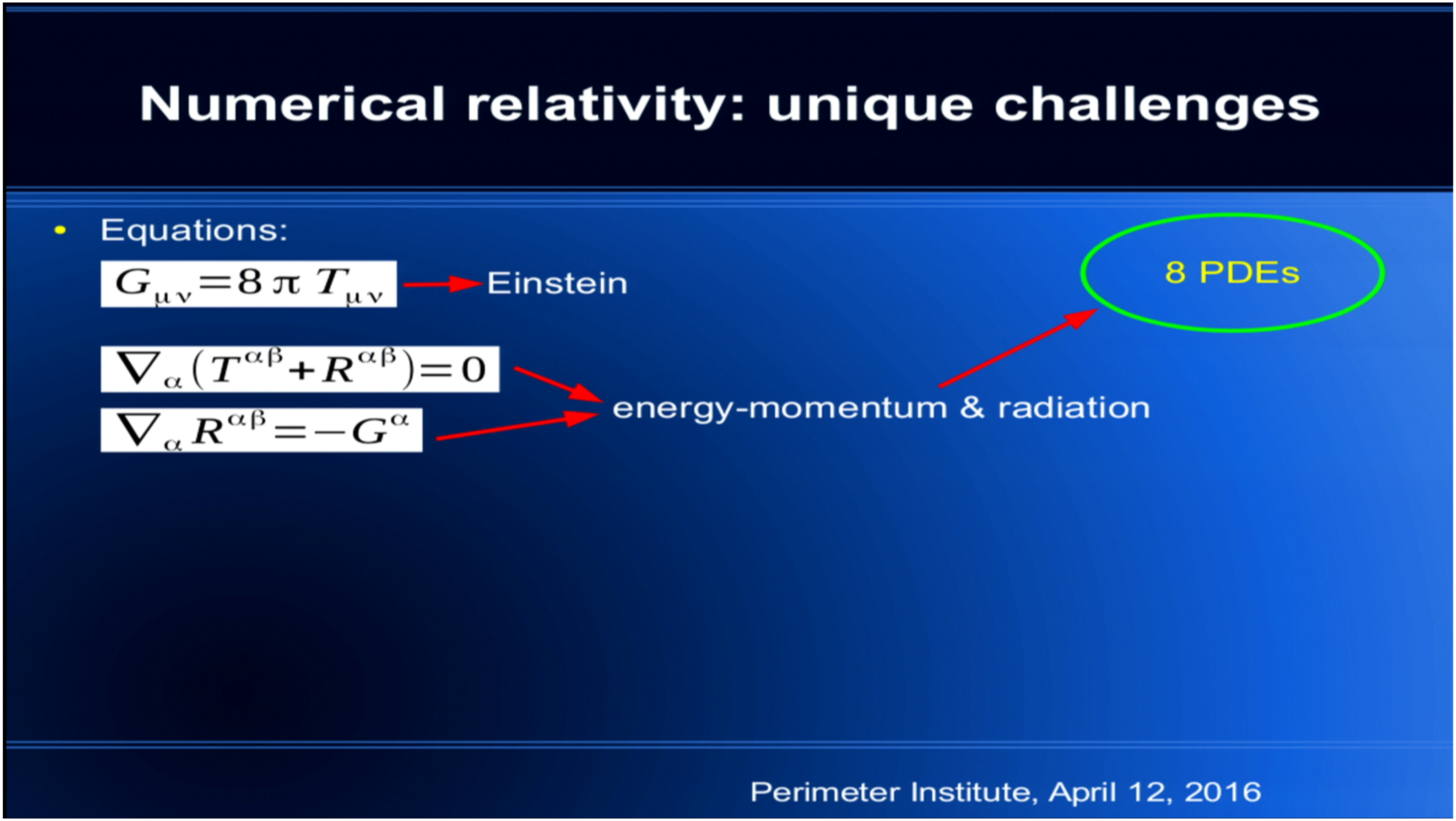

Numerical relativity: unique challenges

- Equations:

$$\boxed{G_{\mu\nu} = 8\pi T_{\mu\nu}} \longrightarrow \text{Einstein}$$

$$\boxed{\nabla_\alpha (T^{\alpha\beta} + R^{\alpha\beta}) = 0}$$

$$\boxed{\nabla_\alpha R^{\alpha\beta} = -G^\alpha}$$

$\longrightarrow$ energy-momentum & radiation $\longrightarrow$ 8 PDEs

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Numerical relativity: unique challenges

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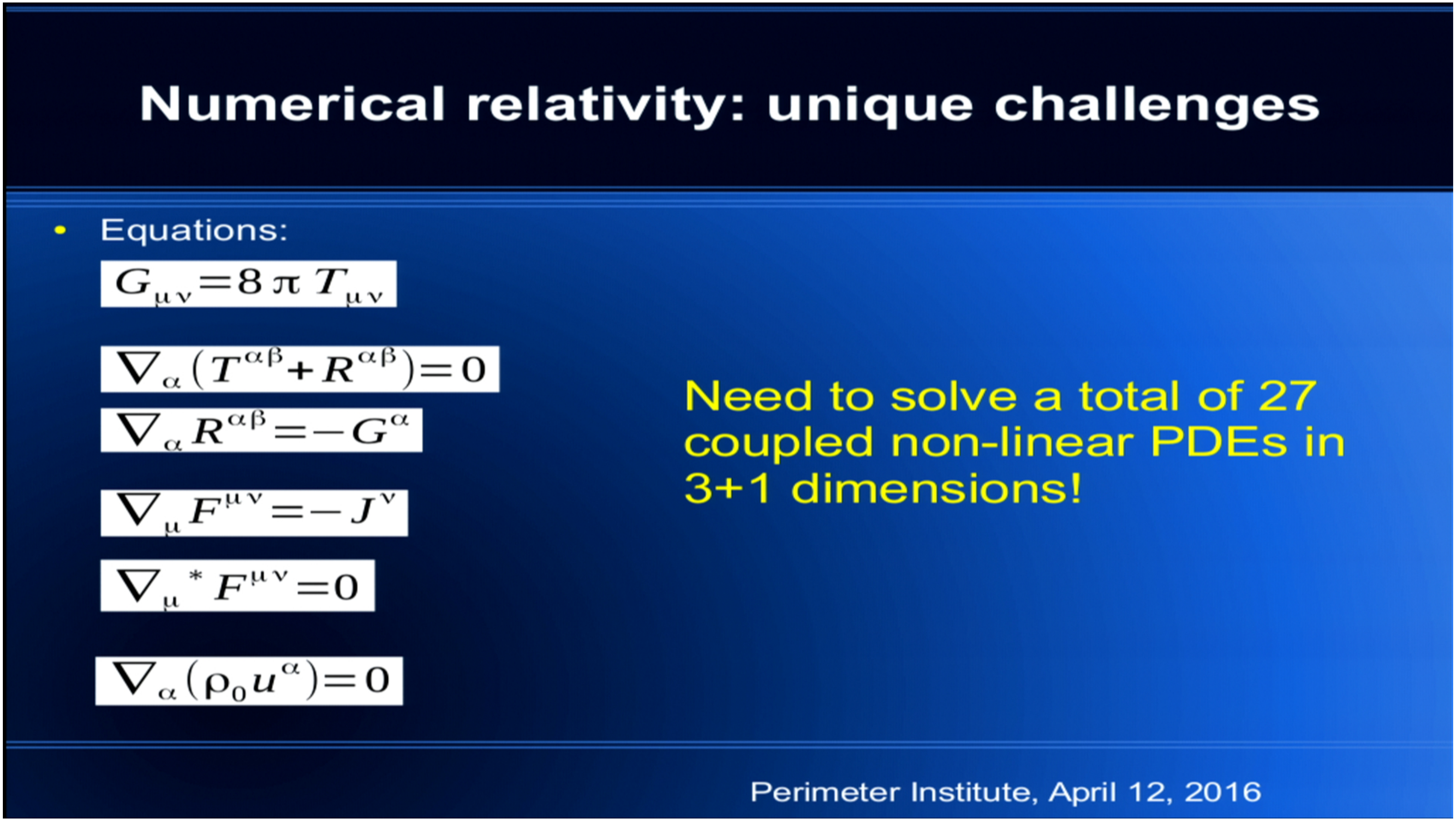
$\boxed{\nabla_\mu F^{\mu\nu} = -J^\nu}$ → Maxwell

$\boxed{\nabla_\mu {}^{*}F^{\mu\nu} = 0}$ → Maxwell

$\boxed{\nabla_\alpha (\rho_0 u^\alpha) = 0}$ → Baryon conservation → 1 PDE



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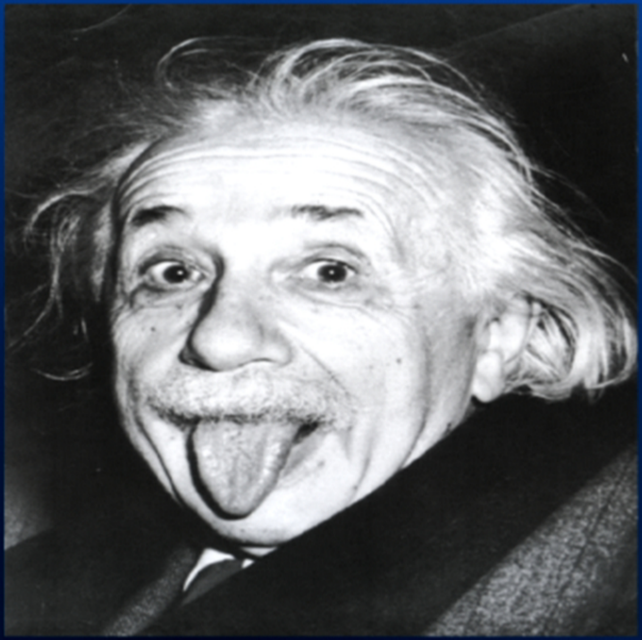
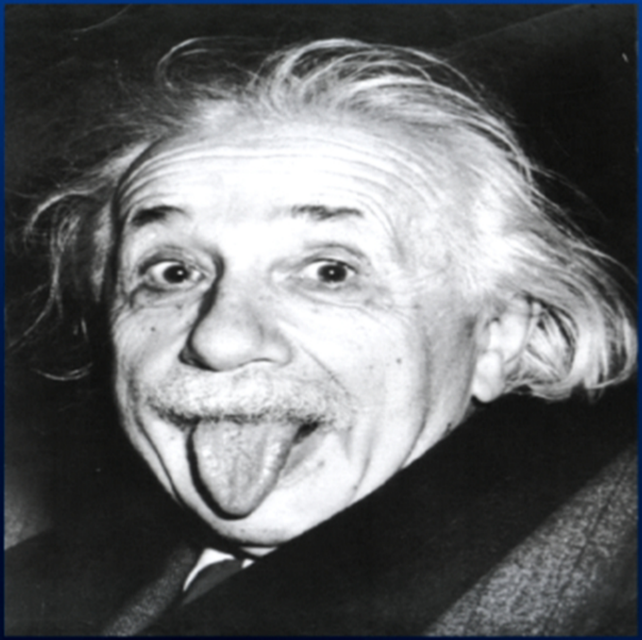
$$\nabla_\mu {}^*F^{\mu\nu}=0$$

$$\nabla_\alpha (\rho_0 u^\alpha)=0$$

Need to solve a total of 27 coupled non-linear PDEs in 3+1 dimensions!



Hmmm....this looks kind of tough!



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Is numerical relativity (NR) really necessary for GW detection and science?

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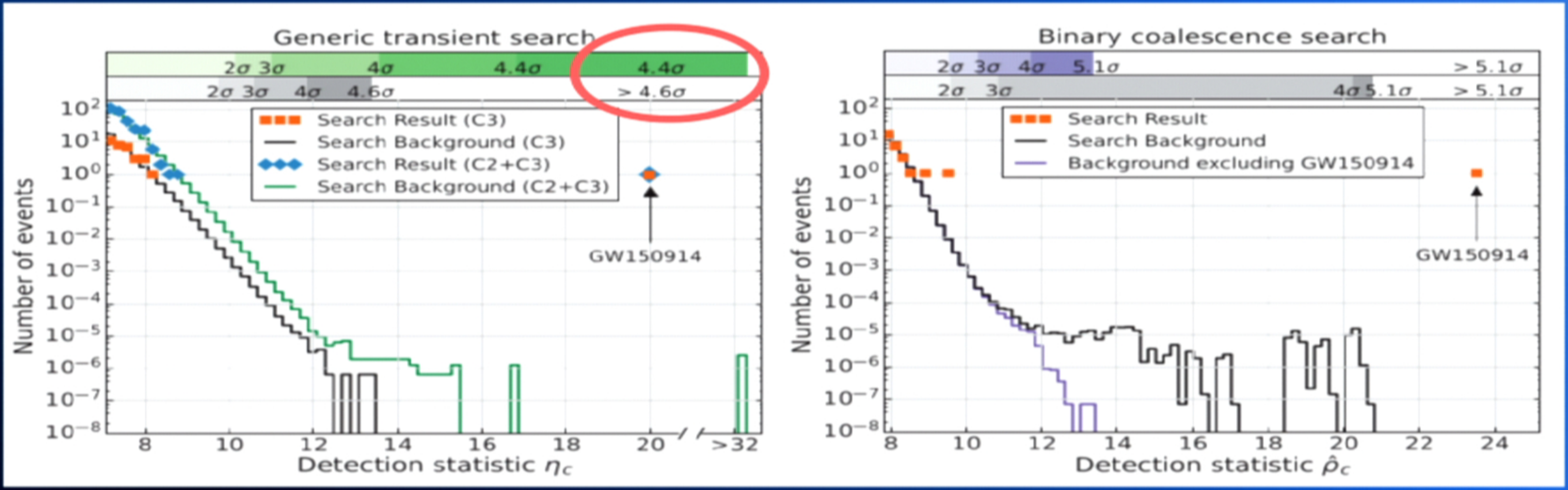
- Statistical significance of the GW150914 detection



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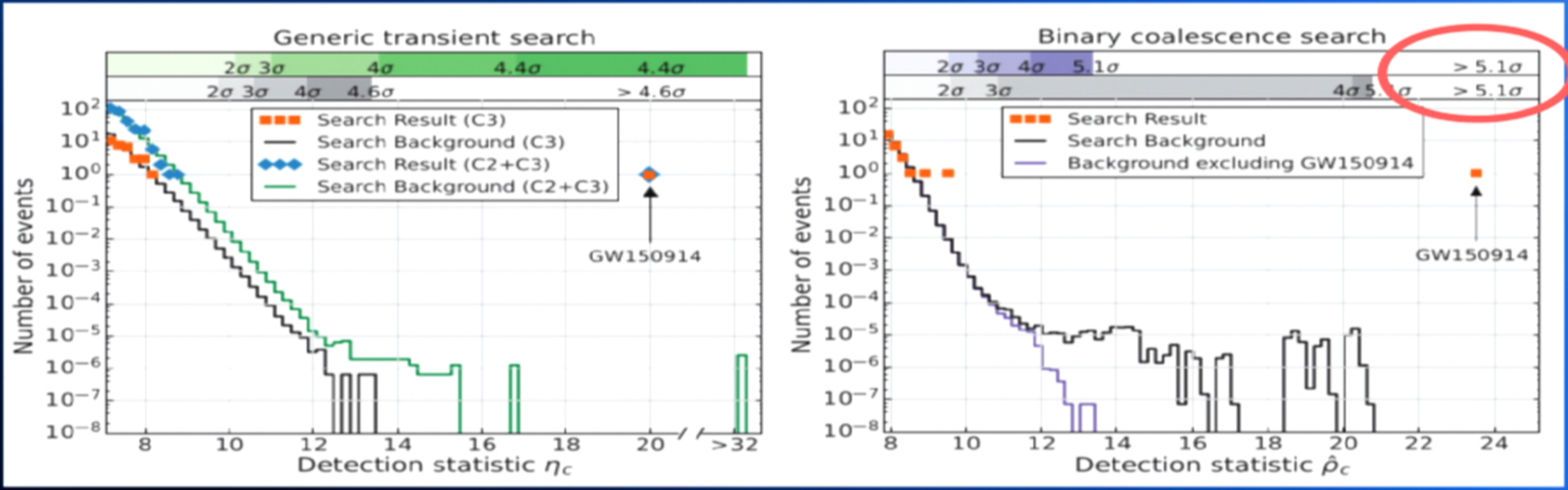
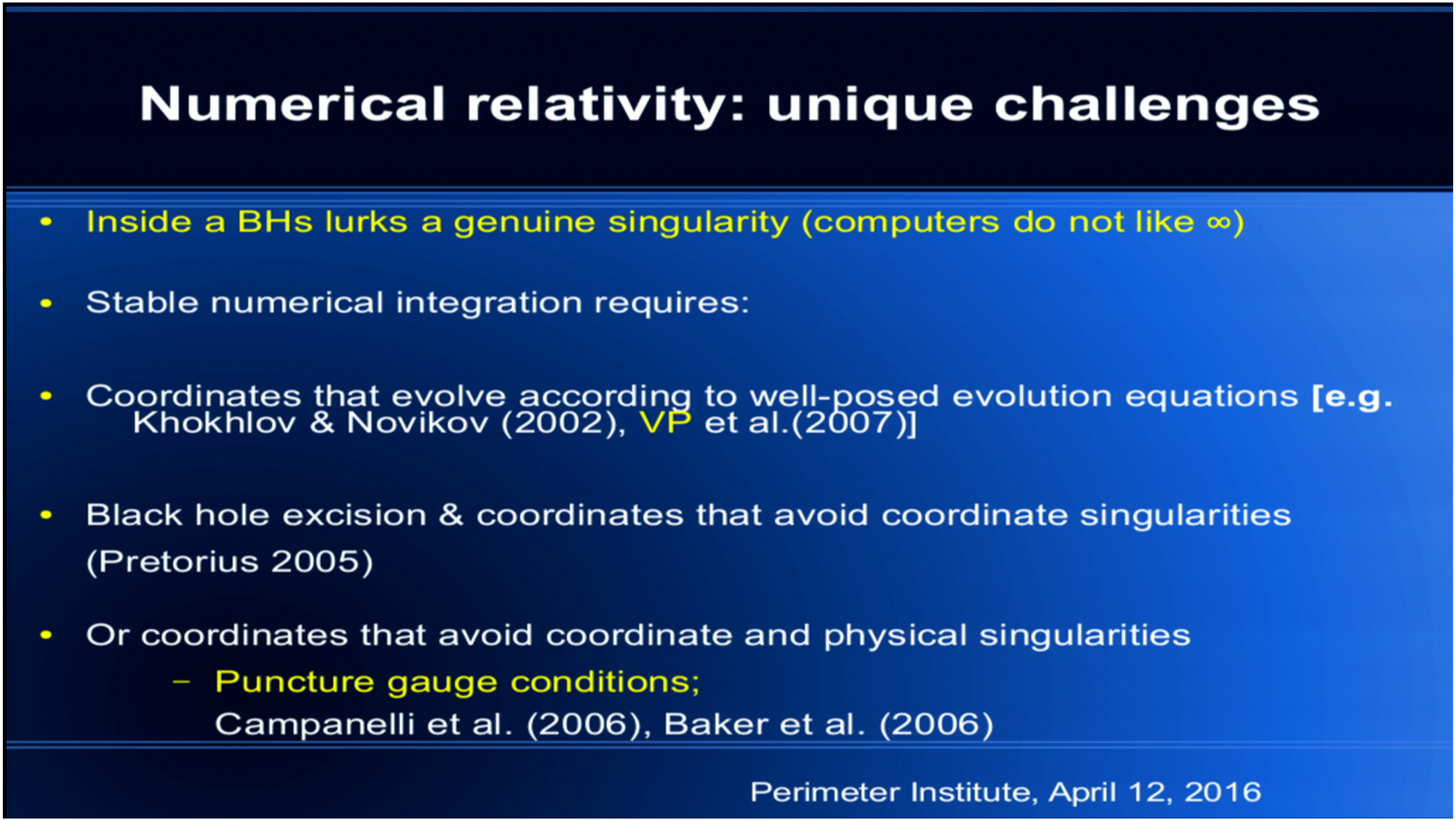


- Parameter estimation would have been impossible without NR



Numerical relativity: unique challenges

- Inside a BHs lurks a genuine singularity (computers do not like ∞)
- Stable numerical integration requires:
- Coordinates that evolve according to well-posed evolution equations **[e.g.** Khokhlov & Novikov (2002), VP et al.(2007)]
- Black hole excision & coordinates that avoid coordinate singularities (Pretorius 2005)
- Or coordinates that avoid coordinate and physical singularities
  - Puncture gauge conditions;
    Campanelli et al. (2006), Baker et al. (2006)

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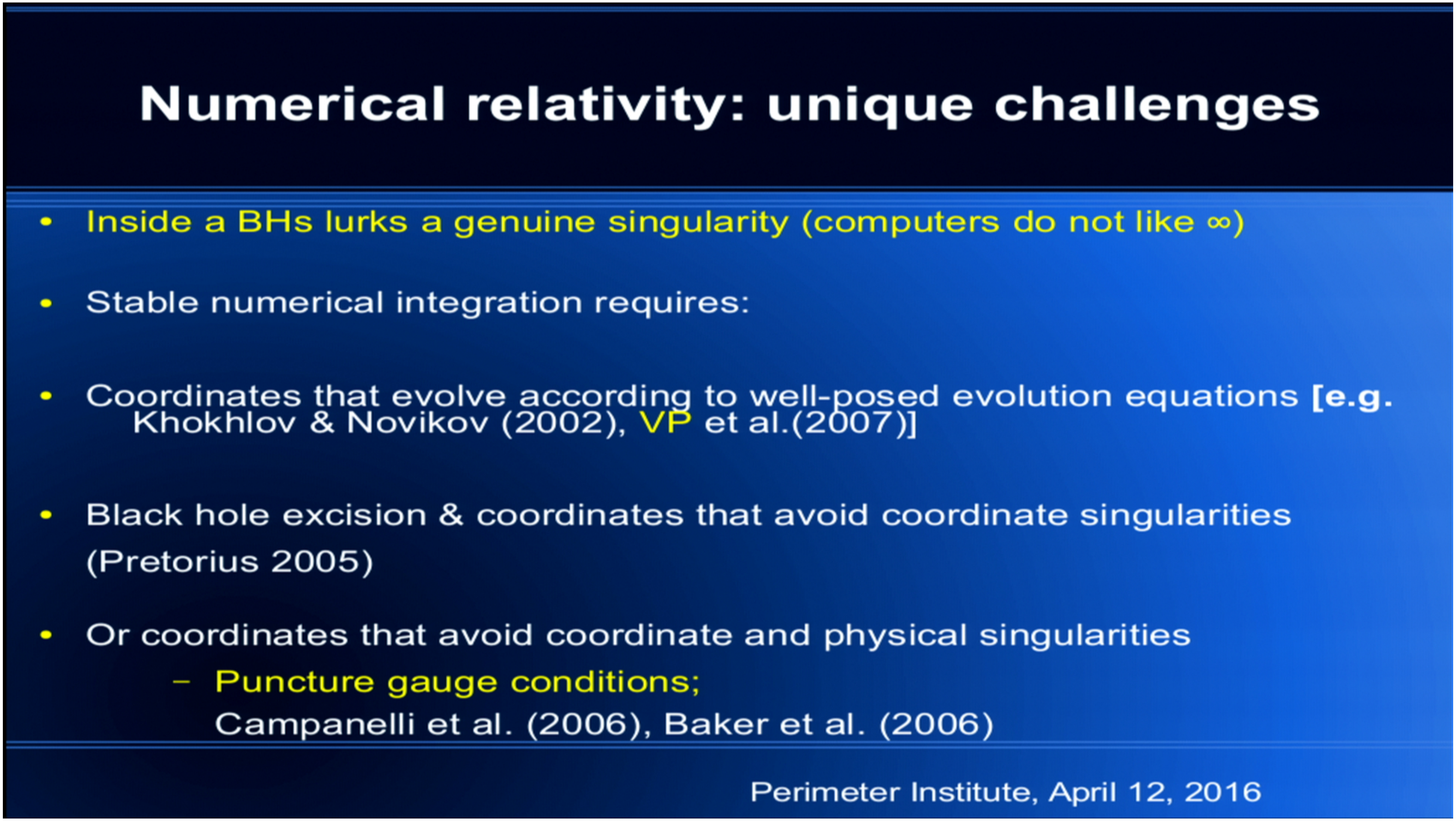

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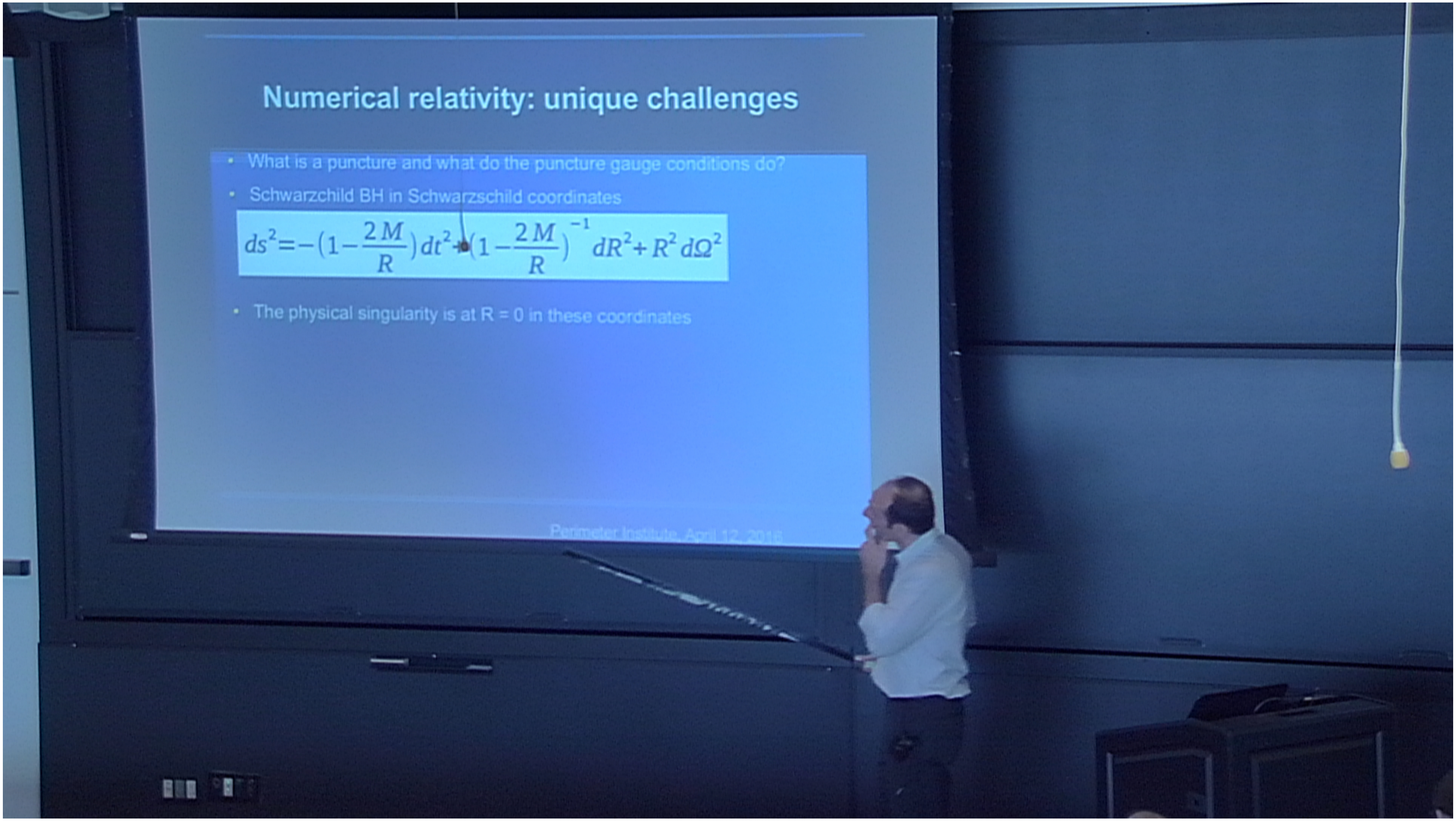

Numerical relativity: unique challenges

- What is a puncture and what do the puncture gauge conditions do?
- Schwarzchild BH in Schwarzschild coordinates

$$ds^2 = -\left(1 - \frac{2M}{R}\right) dt^2 + \left(1 - \frac{2M}{R}\right)^{-1} dR^2 + R^2 d\Omega^2$$

- The physical singularity is at R = 0 in these coordinates

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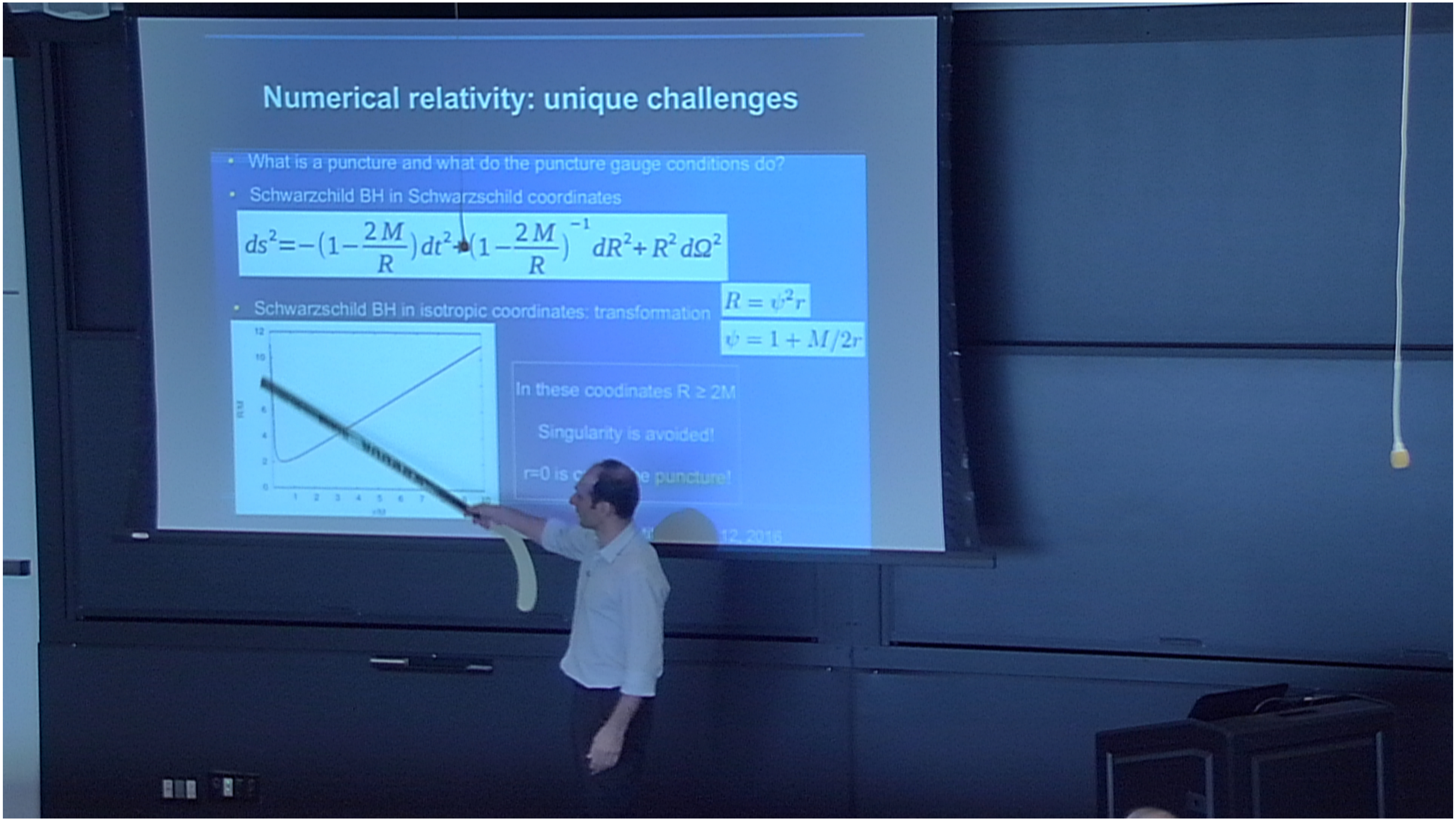
- Schwarzschild BH in isotropic coordinates: transformation

$$R = \psi^2 r$$

$$\psi = 1 + M/2r$$

$$ds^2 = -\left(\frac{1 - \frac{M}{2r}}{1 + \frac{M}{2r}}\right)^2 dt^2 + \psi^4 \left(dr^2 + r^2 d\Omega^2\right)$$



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$$R = \psi^2 r$$

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In these coodinates R ≥ 2M

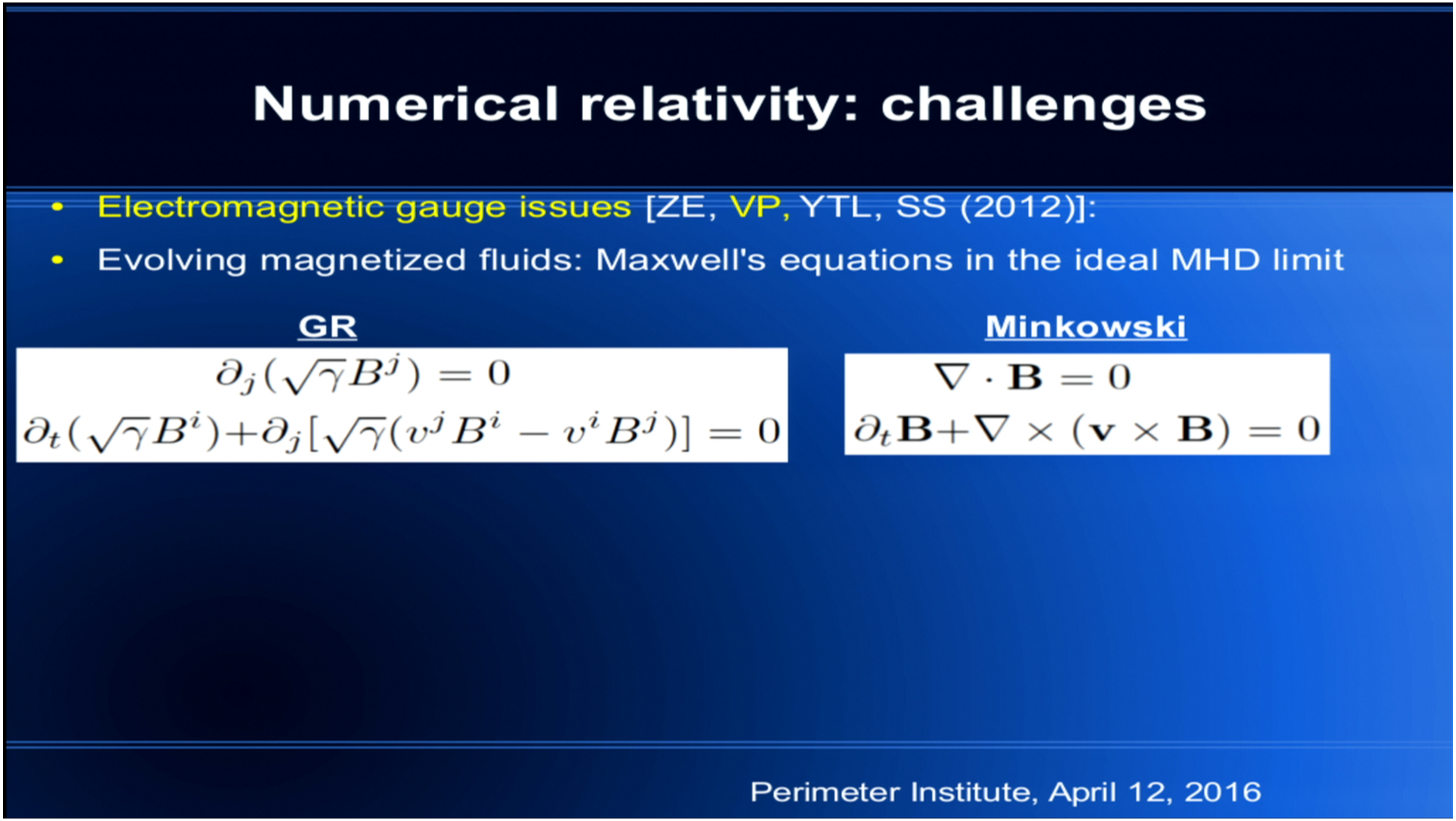
Singularity is avoided!

r=0 is c[illegible]e puncture!

12, 2016

Numerical relativity: challenges

- Discontinuities due to shocks
    - Colliding neutron stars
    - Accretion onto (binary) BH → tidal/turbulent shocks
- Employ high-resolution shock capturing methods (Riemann solvers):
    - Shocks are captured automatically



Numerical relativity: challenges

- Electromagnetic gauge issues [ZE, VP, YTL, SS (2012)]:
- Evolving magnetized fluids: Maxwell's equations in the ideal MHD limit

GR

$$\partial_j(\sqrt{\gamma}B^j) = 0$$

$$\partial_t(\sqrt{\gamma}B^i)+\partial_j[\sqrt{\gamma}(v^j B^i - v^i B^j)] = 0$$

Minkowski

$$\nabla \cdot \mathbf{B} = 0$$

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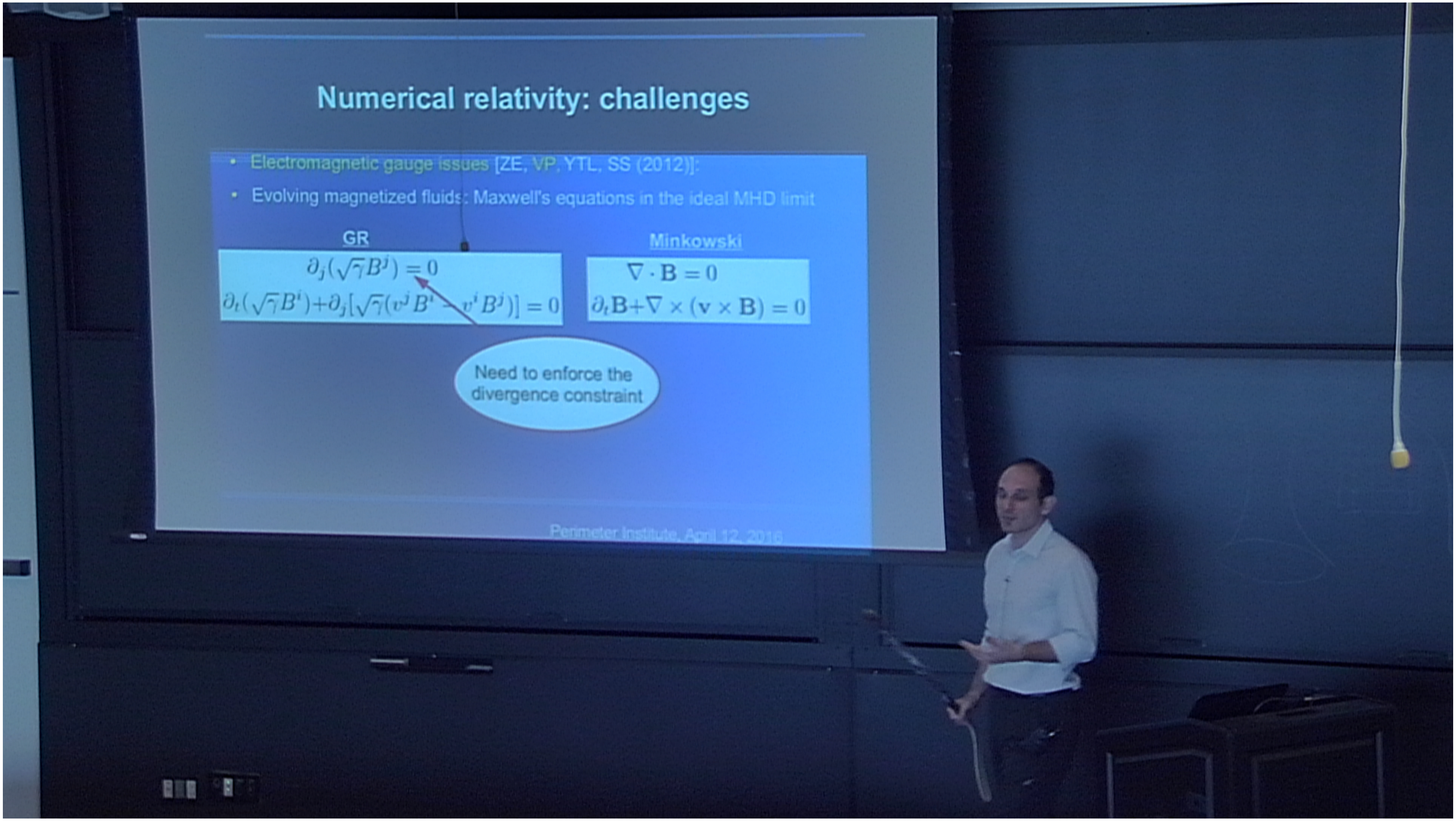

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Need to enforce the divergence constraint

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Numerical relativity: challenges

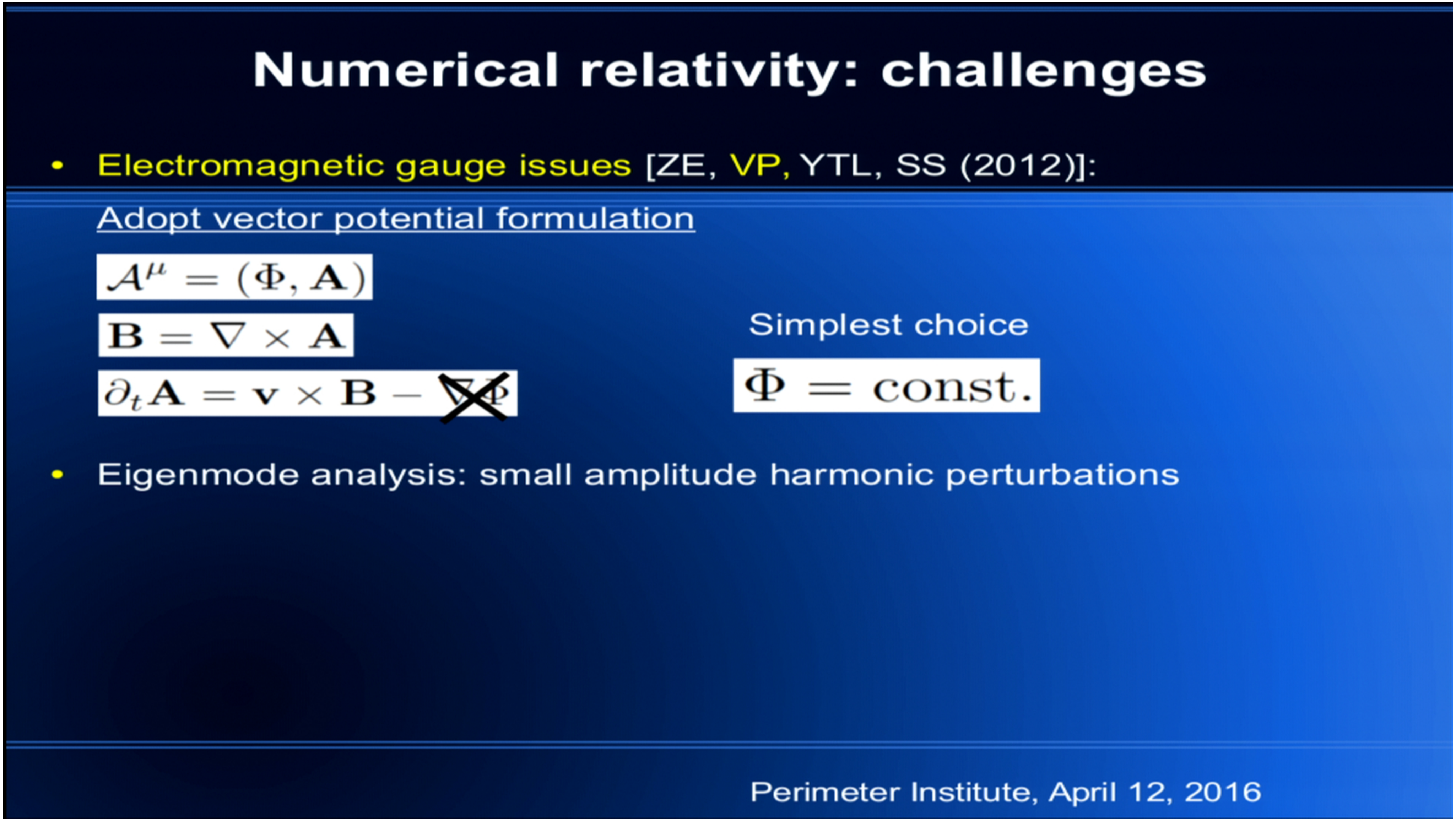
- Electromagnetic gauge issues [ZE, VP, YTL, SS (2012)]:

  Adopt vector potential formulation

$$\mathcal{A}^\mu = (\Phi, \mathbf{A})$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\partial_t \mathbf{A} = \mathbf{v} \times \mathbf{B} - \nabla\Phi$$



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Simplest choice

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- Eigenmode analysis: small amplitude harmonic perturbations

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$$\partial_t \mathbf{A} = \mathbf{v} \times (\nabla \times \mathbf{A}) \quad , \quad \nabla \rightarrow \mathbf{k} \;\; \text{wavevector with } |\mathbf{k}| = 1$$

$$\Rightarrow \partial_t \mathbf{A} = \mathbf{M}\mathbf{A} \quad , \quad M_{ij} = k_i v_j - (\mathbf{v} \cdot \mathbf{k})\delta_{ij}$$

- Eigenvalues $\mathbf{M} : \quad \boxed{\lambda_1 = 0,} \quad \lambda_2 = \lambda_3 = \mathbf{v} \cdot \mathbf{k}$

Zero speed mode!

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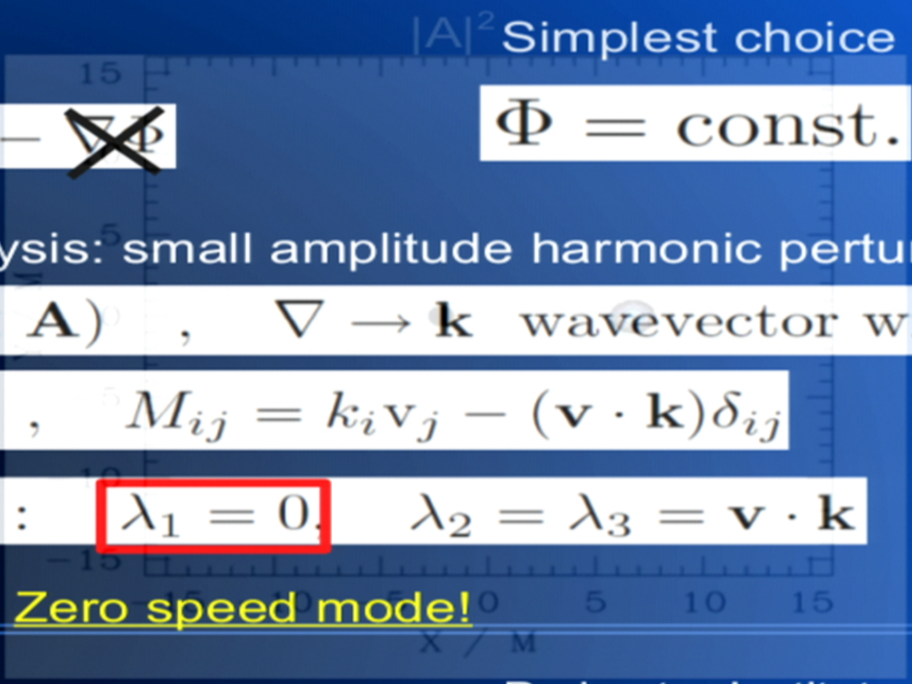
Numerical relativity: challenges

- Electromagnetic gauge issues [ZE, VP, YTL, SS (2012)]:

Adopt vector potential formulation

- Evolution of a magnetized binary BHNS in the "algebraic" gauge with AMR



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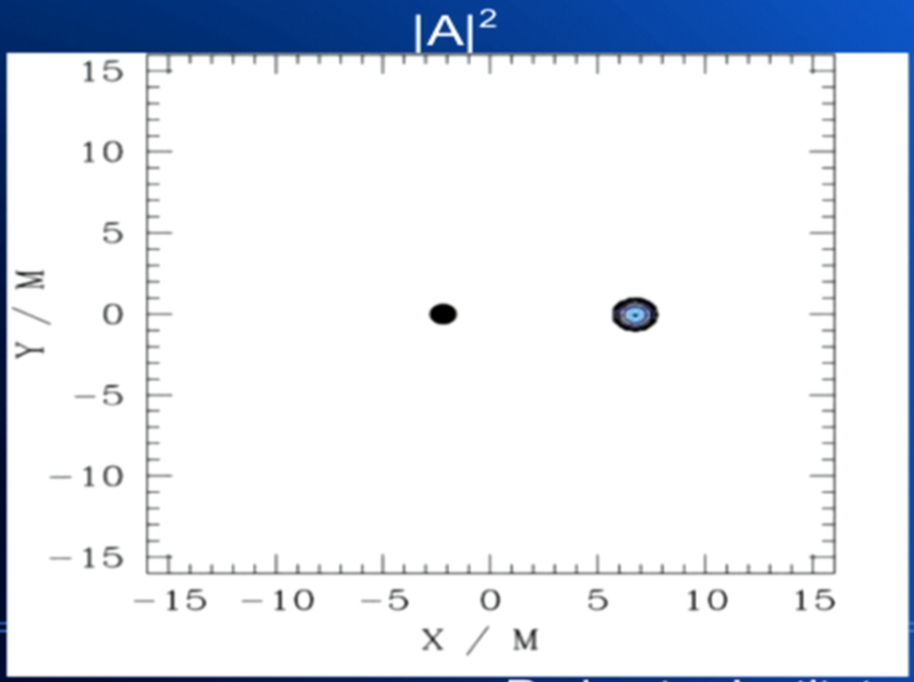
$|A|^2$

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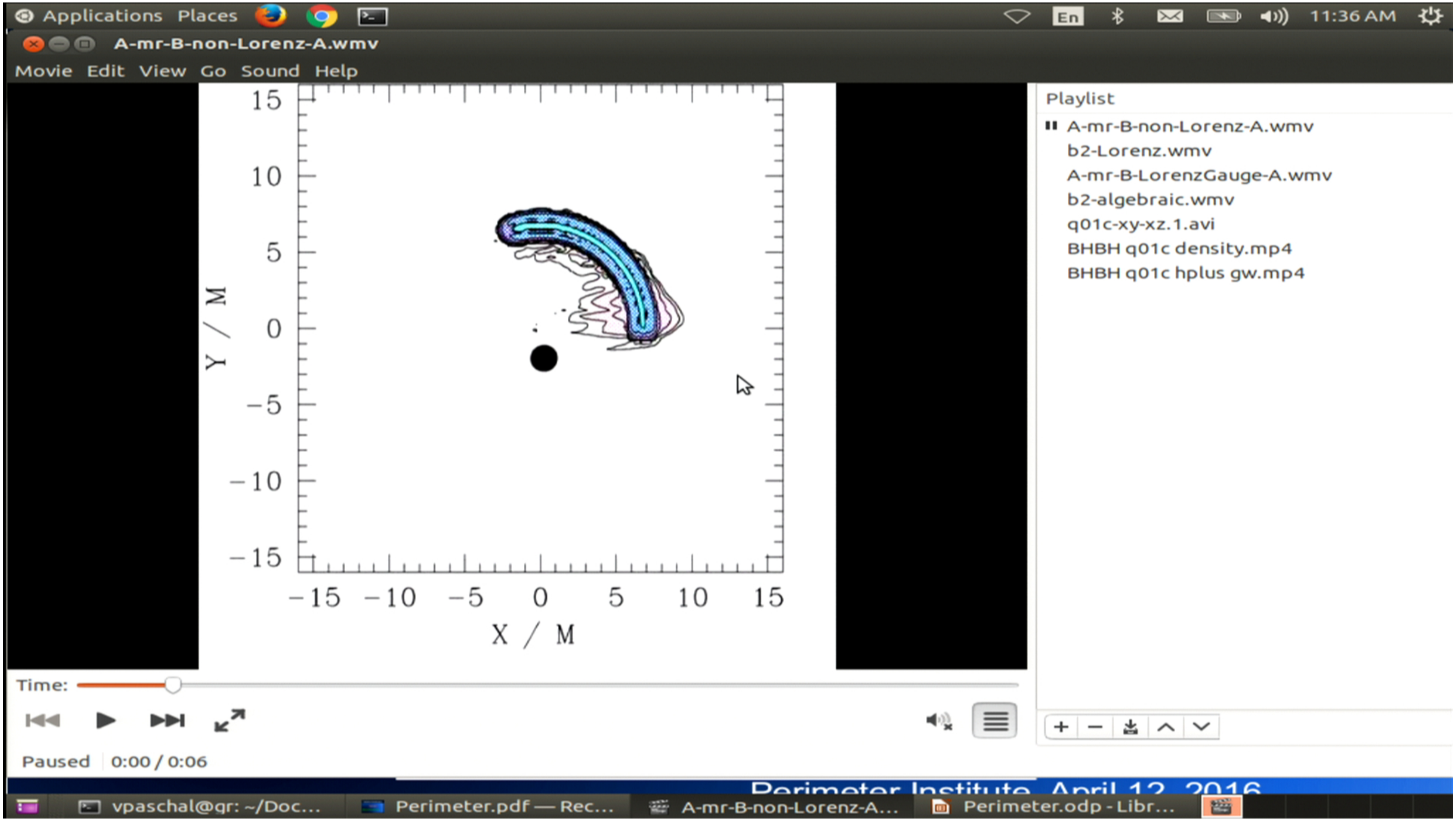
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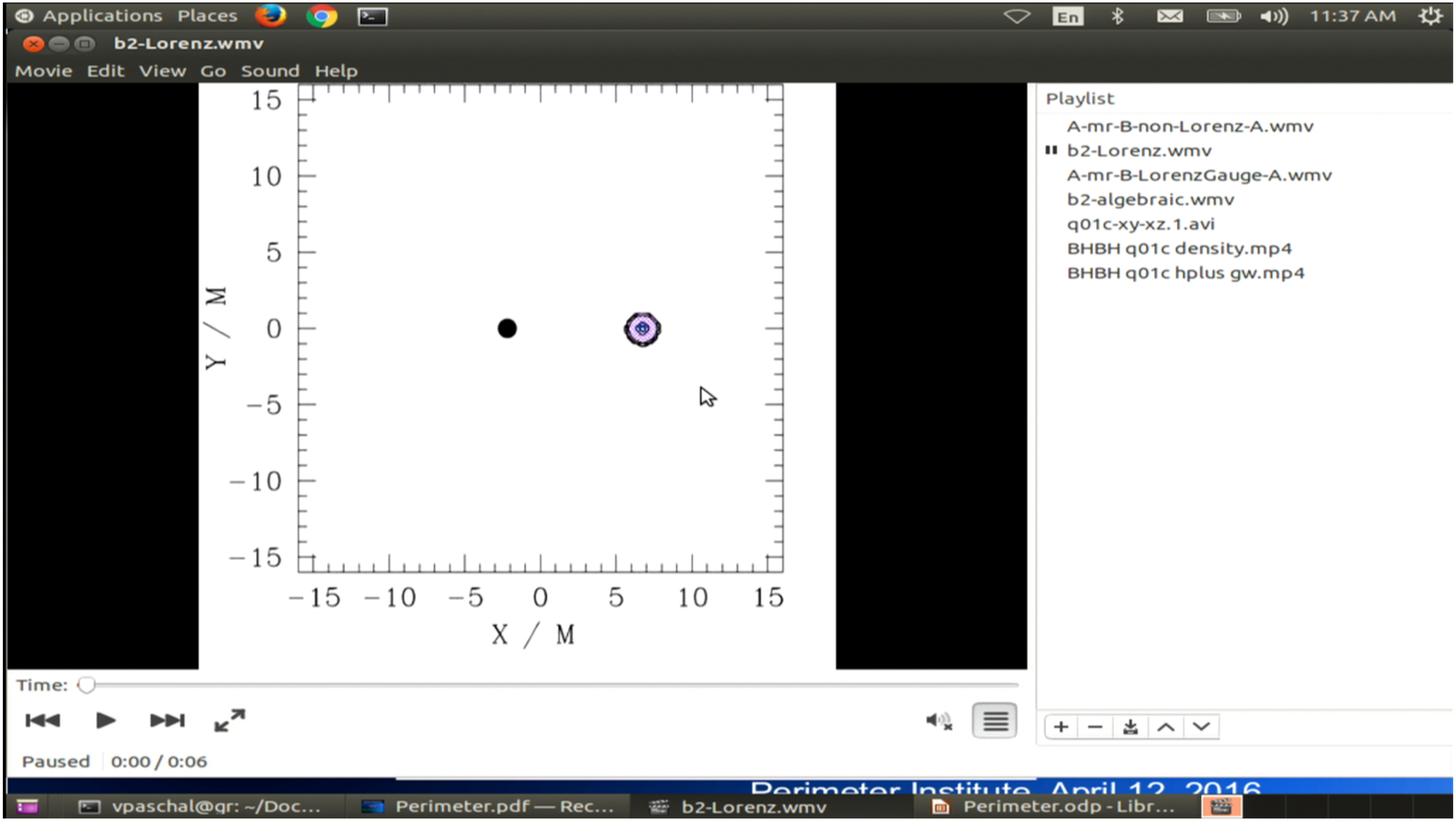

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q01c-xy-xz.1.avi
BHBH q01c density.mp4
BHBH q01c hplus gw.mp4

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Numerical relativity: challenges

- Electromagnetic gauge issues [ZE, VP, YTL, SS (2012)]:

  What about the Lorenz gauge condition?

$$\nabla_\mu \mathcal{A}^\mu = 0 \quad \Rightarrow \quad \partial_t \Phi + \nabla \cdot \mathbf{A} = 0$$

- Induction eq. $\partial_t \mathbf{A} = \mathbf{v} \times \mathbf{B} - \nabla \Phi$

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No zero speed mode!

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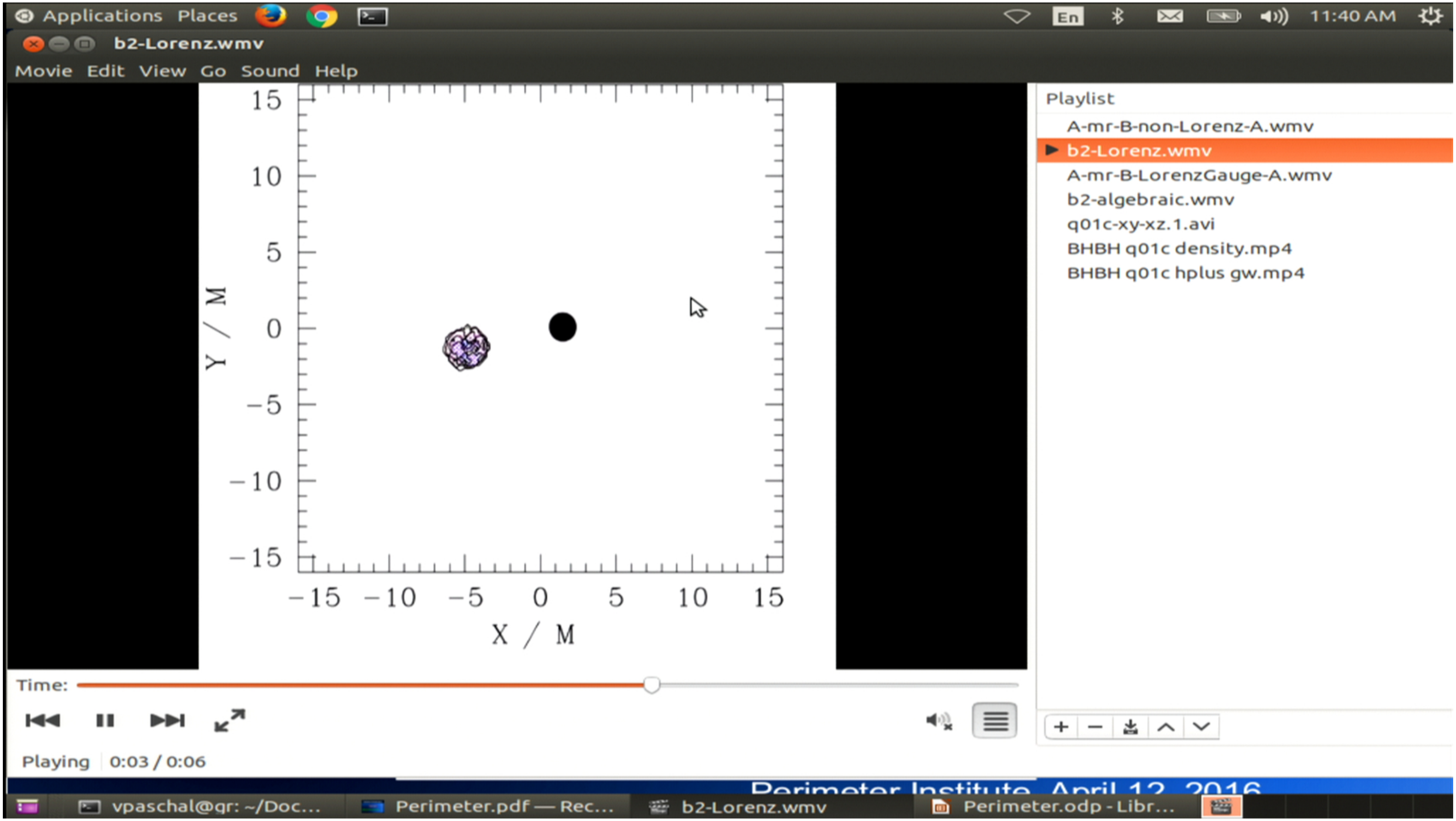
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BHBH q01c hplus gw.mp4
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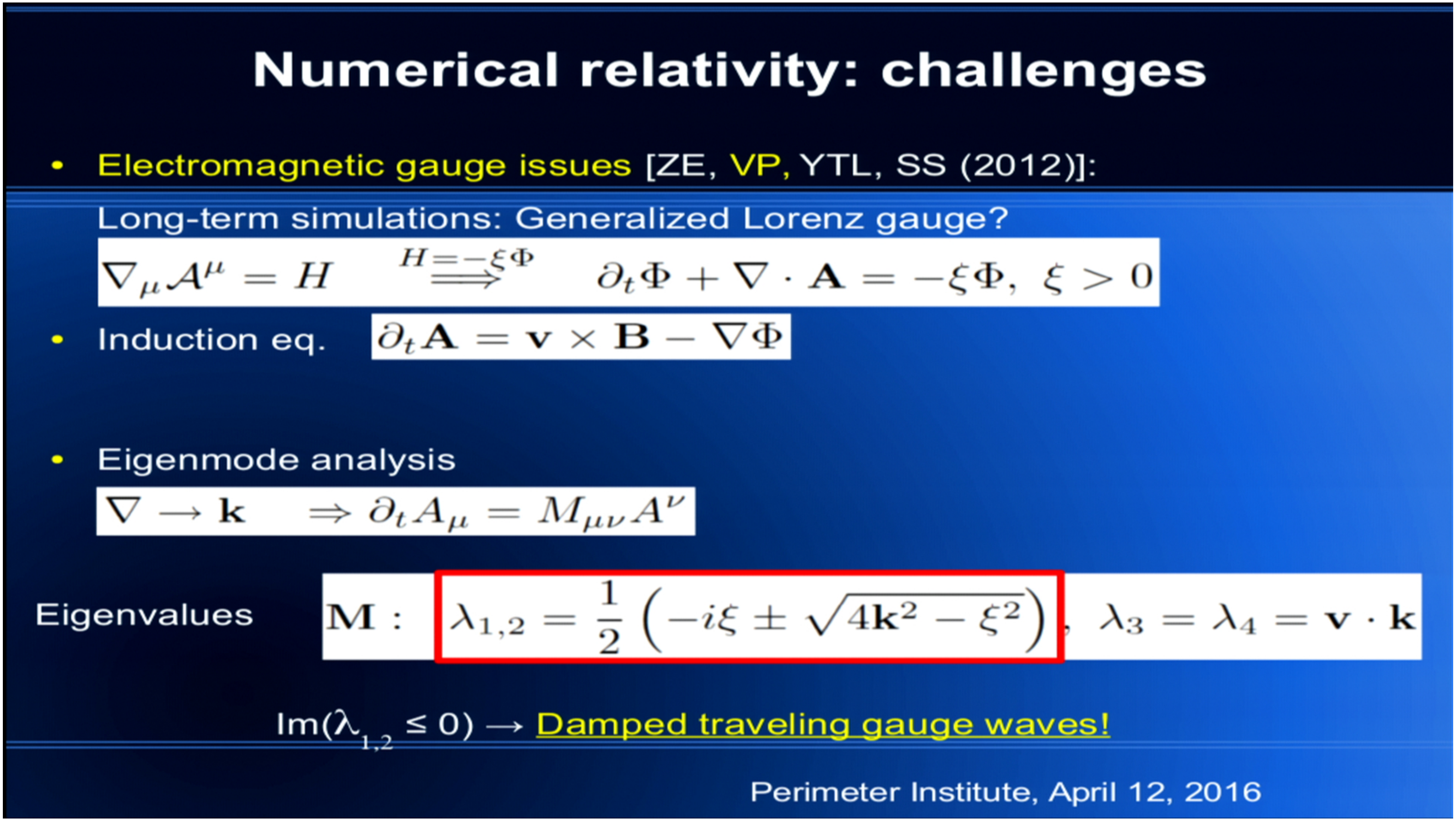
Numerical relativity: challenges

- Electromagnetic gauge issues [ZE, VP, YTL, SS (2012)]:

  Long-term simulations: Generalized Lorenz gauge?

  $$\nabla_\mu \mathcal{A}^\mu = H \quad \overset{H=-\xi\Phi}{\Longrightarrow} \quad \partial_t \Phi + \nabla \cdot \mathbf{A} = -\xi\Phi, \ \xi > 0$$

- Induction eq. $\partial_t \mathbf{A} = \mathbf{v} \times \mathbf{B} - \nabla\Phi$



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- Eigenmode analysis

$$\nabla \rightarrow \mathbf{k} \quad \Rightarrow \partial_t A_\mu = M_{\mu\nu} A^\nu$$

Eigenvalues $\mathbf{M}: \ \boxed{\lambda_{1,2} = \frac{1}{2}\left(-i\xi \pm \sqrt{4\mathbf{k}^2 - \xi^2}\right)}, \ \lambda_3 = \lambda_4 = \mathbf{v} \cdot \mathbf{k}$

$\mathrm{Im}(\lambda_{1,2} \leq 0) \longrightarrow$ Damped traveling gauge waves!

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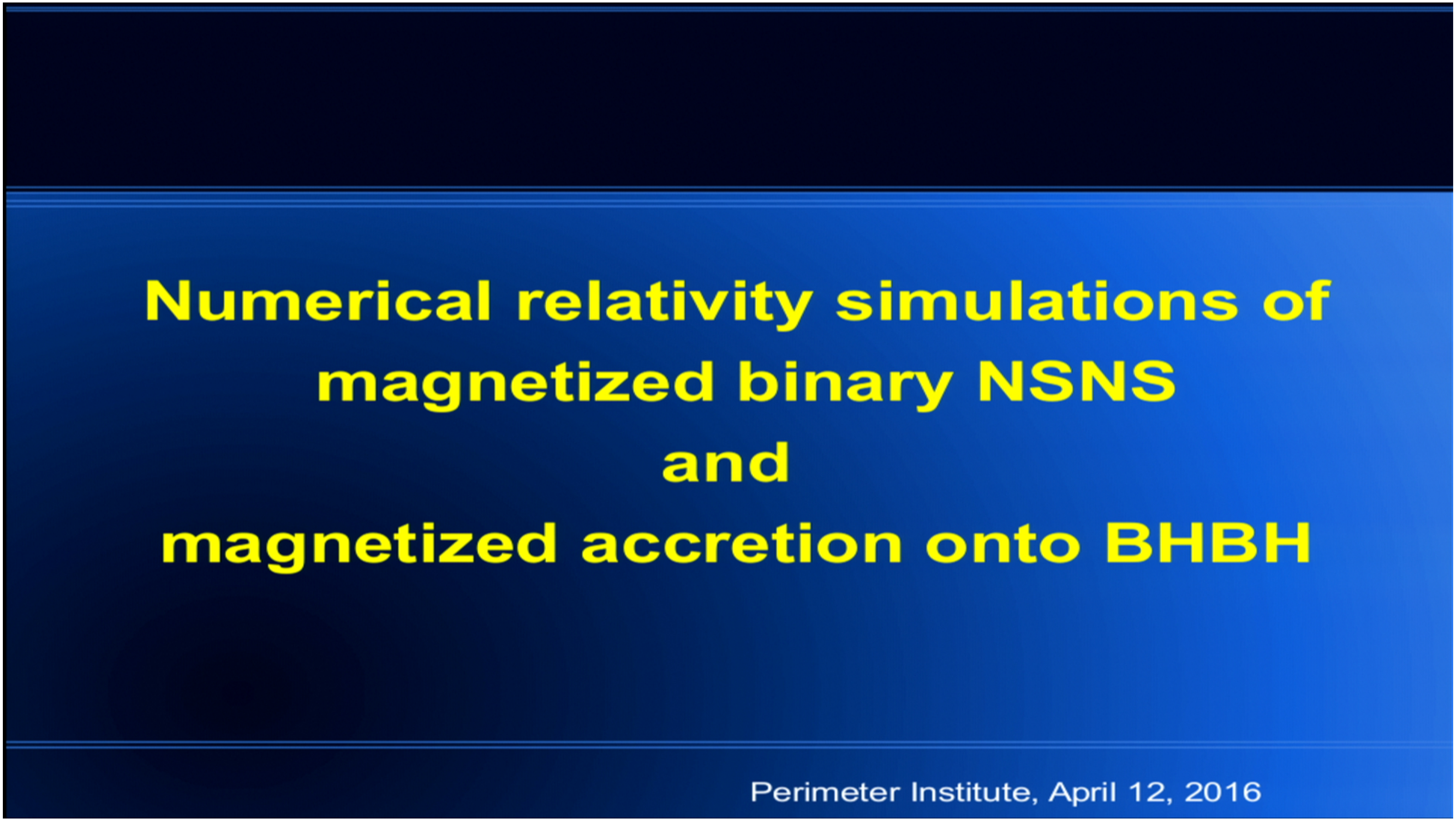

Numerical relativity simulations of magnetized binary NSNS and magnetized accretion onto BHBH

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Short Gamma-ray bursts in a nutshell

- Flashes of gamma rays of extra-galactic origin
- Instruments: BATSE, Swift, HETE-2, Fermi, Hubble, Liverpool & Faulkes...
- Timescales: $T_{90} \leq 2s$; $\langle T_{90} \rangle = 0.2s$;
- Gamma ray luminosities: 10^{50} - 10^{52} erg/s (10erg = 1 joule)
- Host galaxies: spirals & gas depleted ellipticals → (old stars)
- Popular model: relativistic jet (fireball); $\Gamma \geq 100$ (Piran 2004)
- Plausible engine: BH + accretion disk (with twin relativistic jets)
- Progenitor: NS-NS? Eichler et al. 1989; BH-NS? Paczynski 1991

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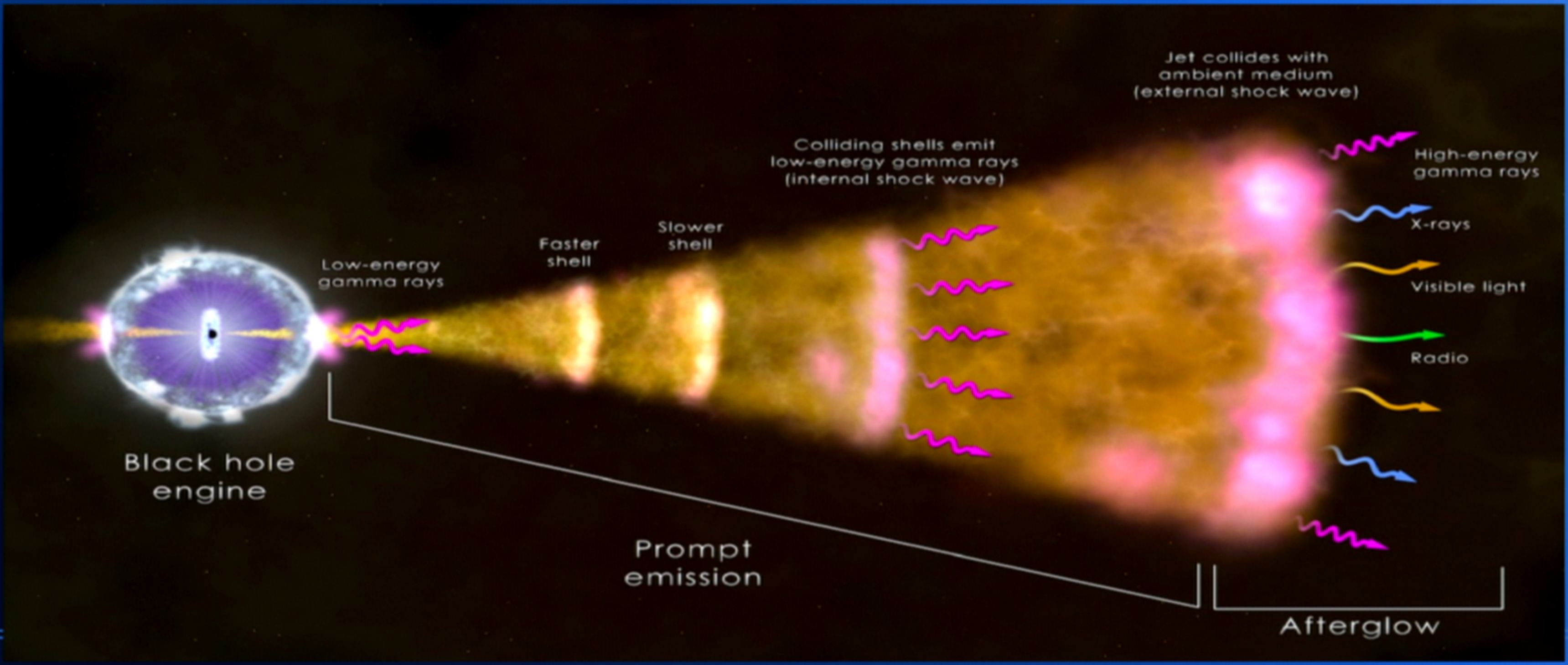
Short Gamma-ray bursts in a nutshell

Artist's conception (NASA)



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Numerical Relativity simulations of neutron star – neutron star systems as short GRB engines

- The Merger of neutron star – neutron star (NSNS) systems is considered a leading candidate progenitor for the engine that powers a short gamma-ray burst
- Setting: NSNS → collapse to BH → magnetized accretion → relativistic jet

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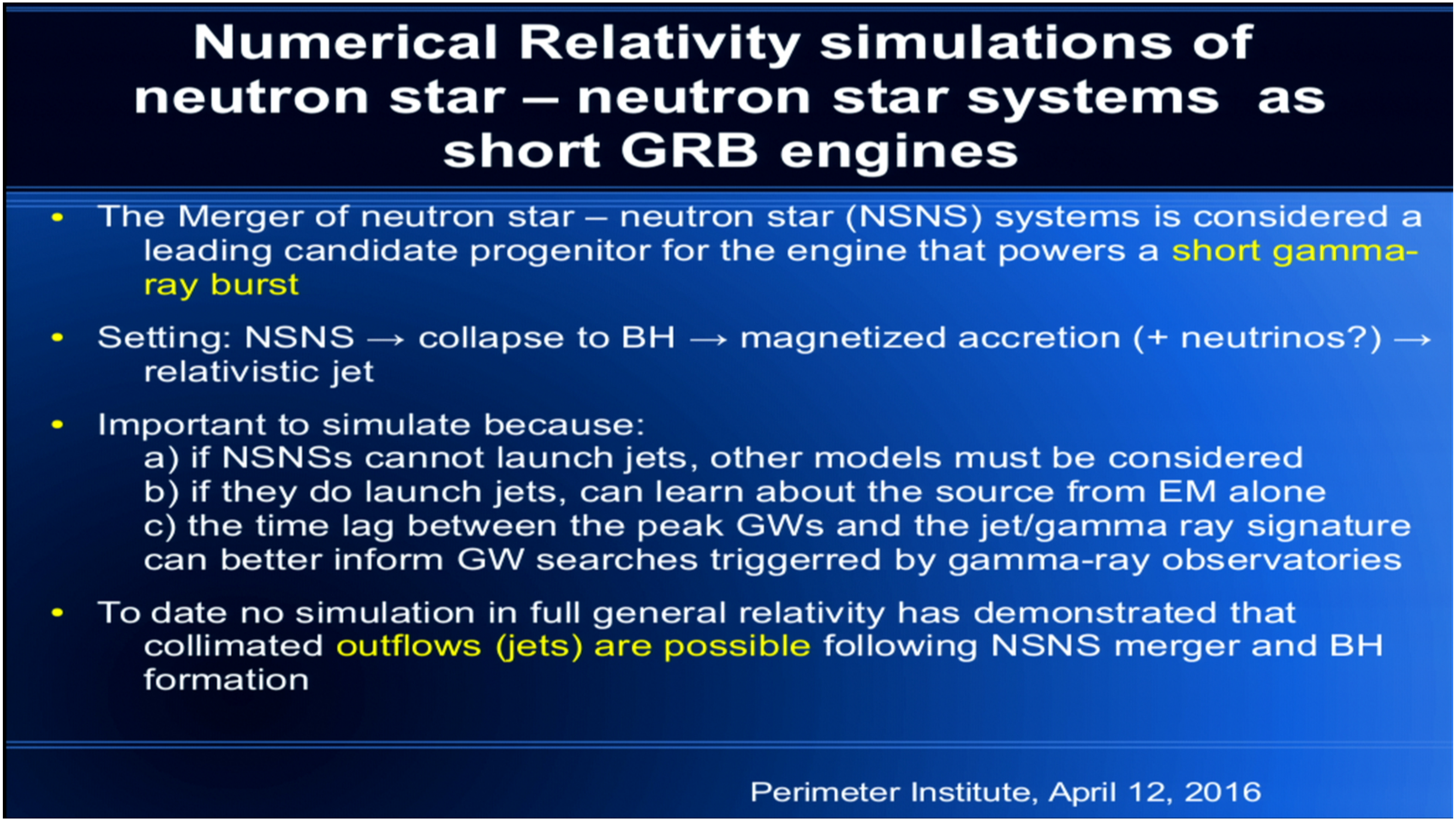
- Important to simulate because:
  a) if NSNSs cannot launch jets, other models must be considered
  b) if they do launch jets, can learn about the source from EM alone
  c) the time lag between the peak GWs and the jet/gamma ray signature can better inform GW searches triggerred by gamma-ray observatories



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- To date no simulation in full general relativity has demonstrated that collimated outflows (jets) are possible following NSNS merger and BH formation

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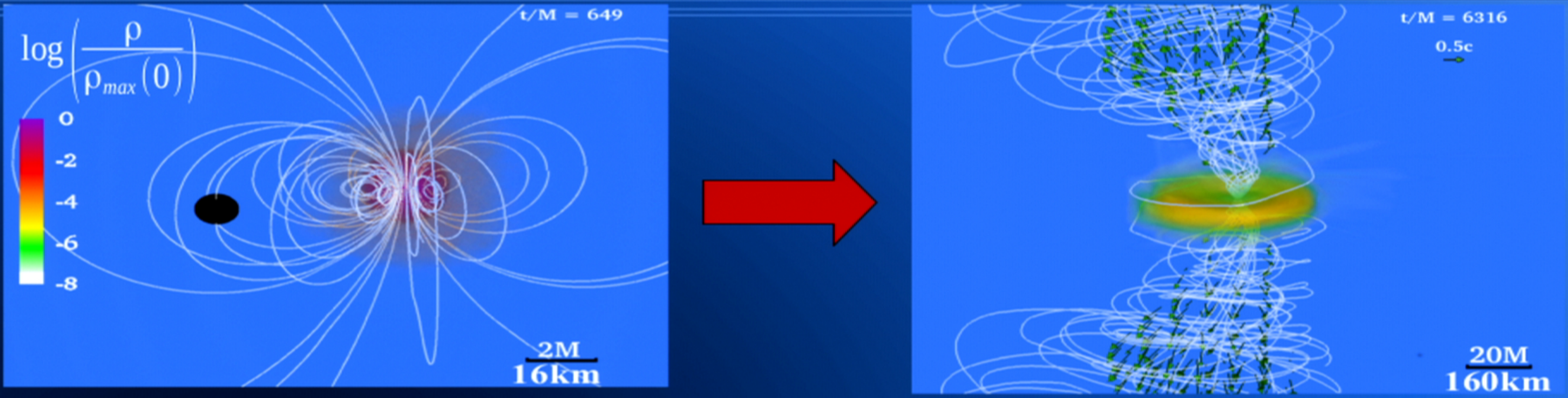
Numerical Relativity simulations of neutron star – neutron star systems as short GRB engines

- Two ideal magnetohydrodynamic (MHD) studies in full GR find:

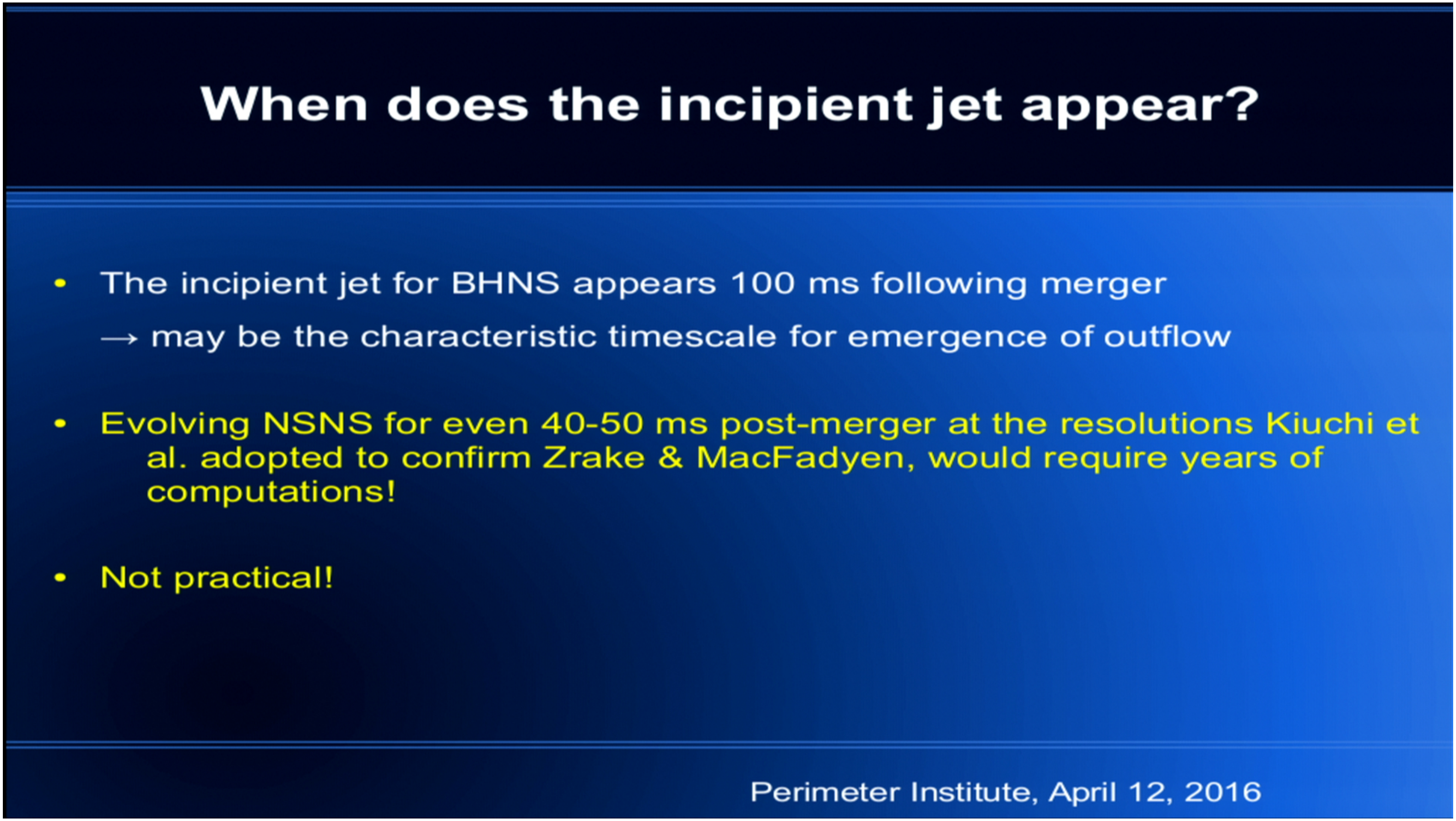
  a) Rezzolla et al. (2011) “jet like” structures are possible → no collimated outflow


20M
160km
2016
r = R + r₀

BHNS → incipient jets!

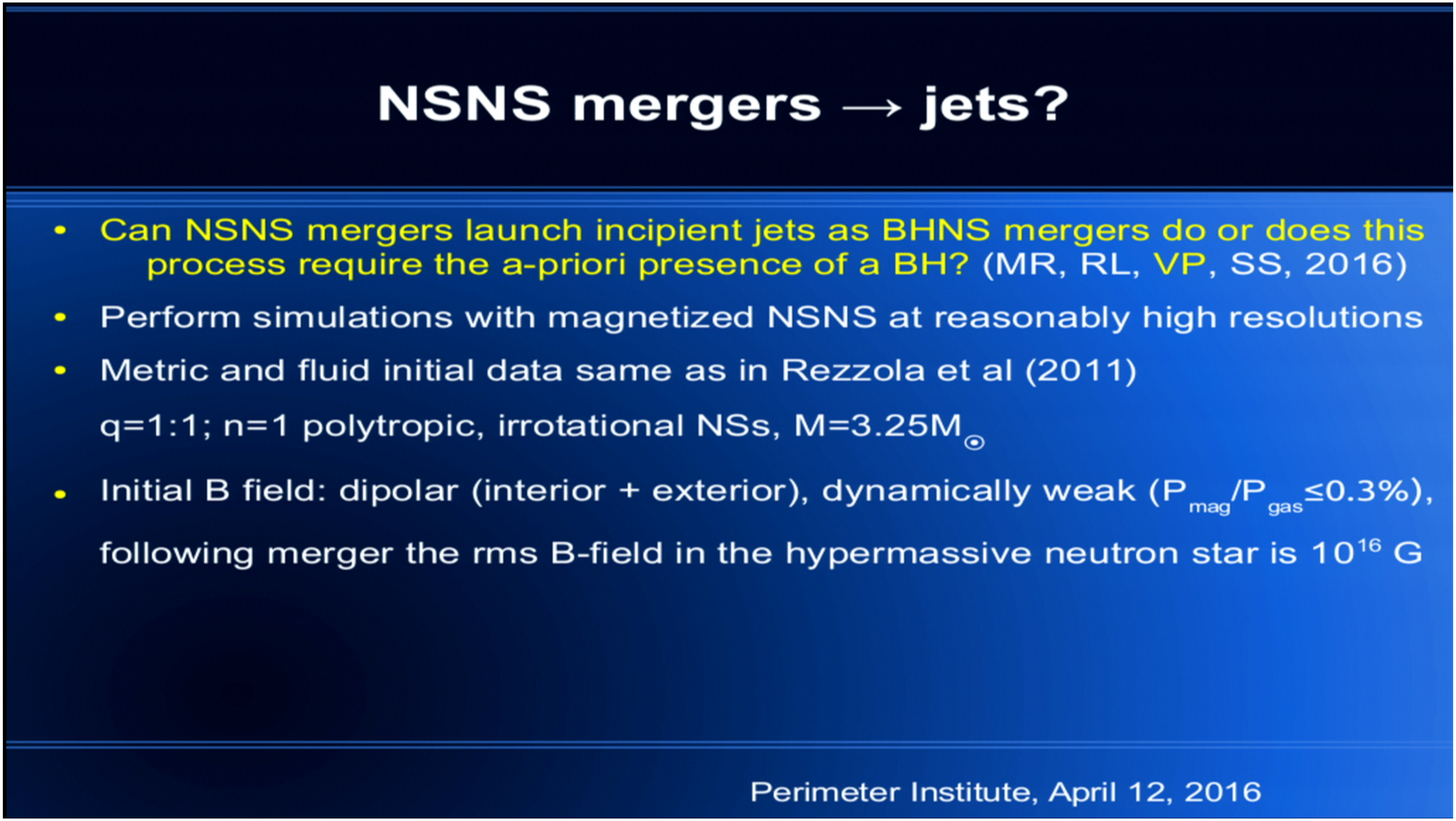


25 ms=1000M



When does the incipient jet appear?

- The incipient jet for BHNS appears 100 ms following merger
  → may be the characteristic timescale for emergence of outflow
- Evolving NSNS for even 40-50 ms post-merger at the resolutions Kiuchi et al. adopted to confirm Zrake & MacFadyen, would require years of computations!
- Not practical!



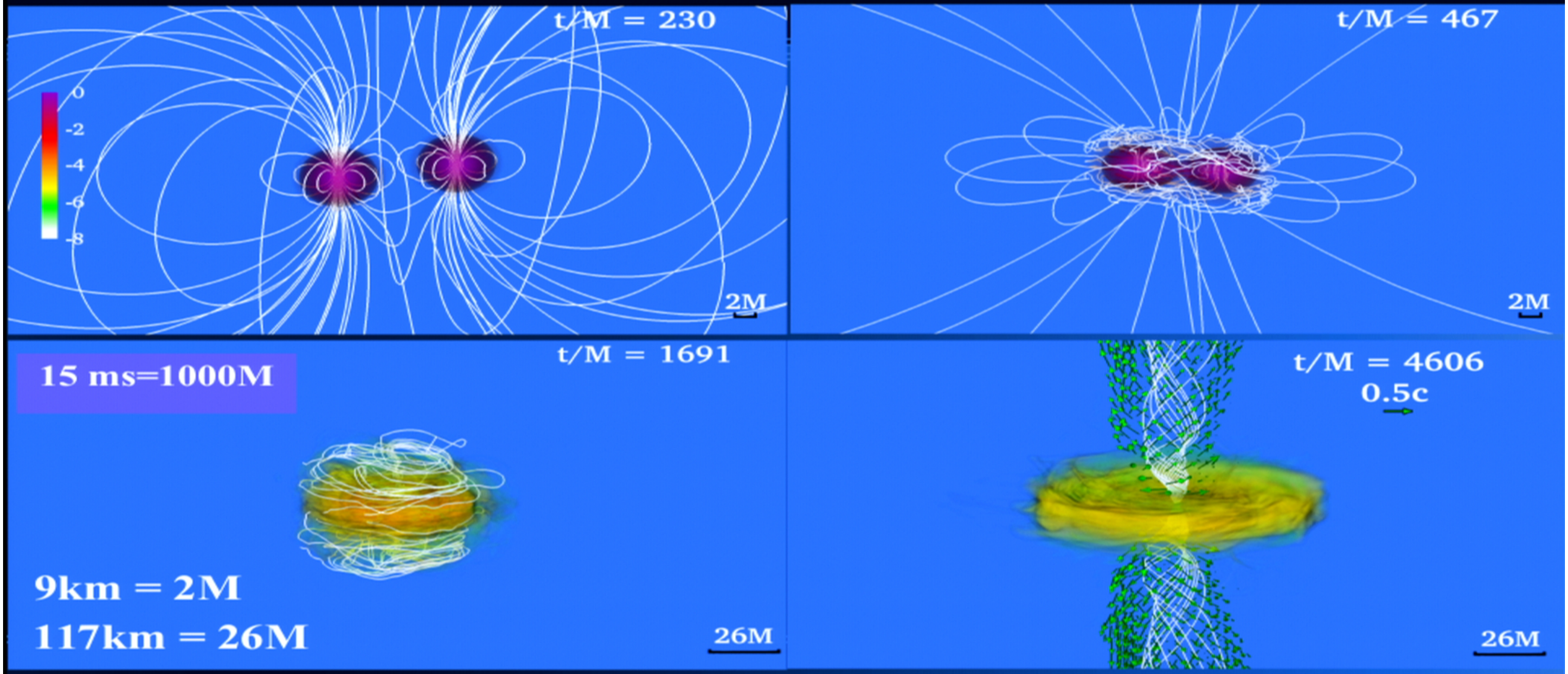
NSNS mergers → jets?

- Can NSNS mergers launch incipient jets as BHNS mergers do or does this process require the a-priori presence of a BH? (MR, RL, VP, SS, 2016)
- Perform simulations with magnetized NSNS at reasonably high resolutions
- Metric and fluid initial data same as in Rezzola et al (2011)

  q=1:1; n=1 polytropic, irrotational NSs, $M=3.25M_\odot$
- Initial B field: dipolar (interior + exterior), dynamically weak ($P_{mag}/P_{gas} \leq 0.3\%$),

  following merger the rms B-field in the hypermassive neutron star is 10^{16} G

NSNS mergers → incipient jets



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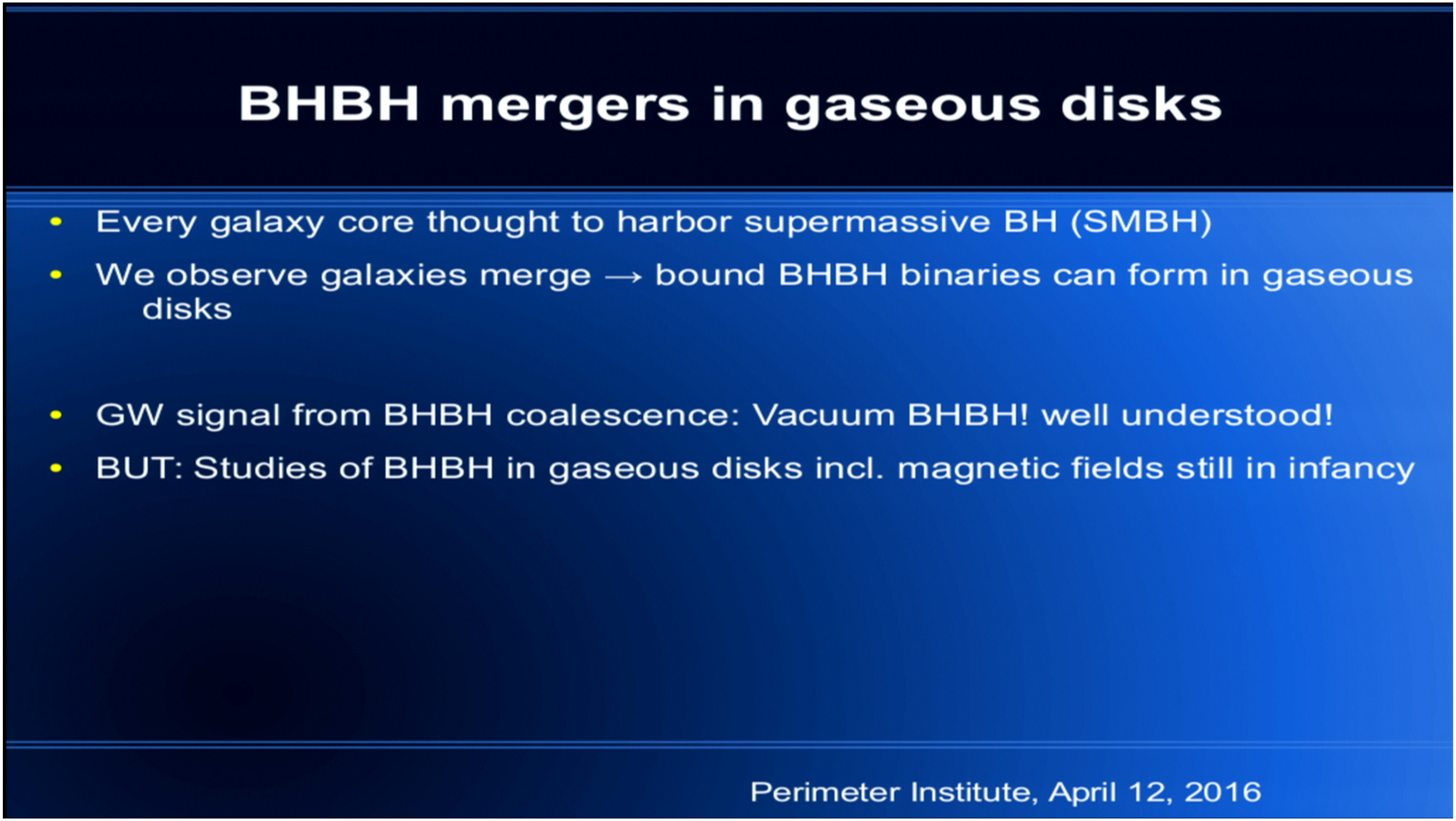
An incipient jet emerges

- Max. magnetization in the outflow: $\frac{B^2}{8\pi\rho c^2} \sim 100$ ~ terminal Lorentz factor
- Disk lifetime: $t_{disk} \sim \frac{M_{disk}}{\dot{M}} \sim 0.1\, s$ ~ consistent with very short sGRB T_{90}
- Outgoing poynting flux: $L_{EM} \sim 10^{51}\, erg/s$ ~ consistent with typical sGRB
- NSNS mergers seem viable sGRB engines as long as B-fields can be amplified in the remnant to >$10^{15.7}$ G!



BHBH mergers in gaseous disks

- Every galaxy core thought to harbor supermassive BH (SMBH)
- We observe galaxies merge → bound BHBH binaries can form in gaseous disks

- GW signal from BHBH coalescence: Vacuum BHBH! well understood!
- BUT: Studies of BHBH in gaseous disks incl. magnetic fields still in infancy

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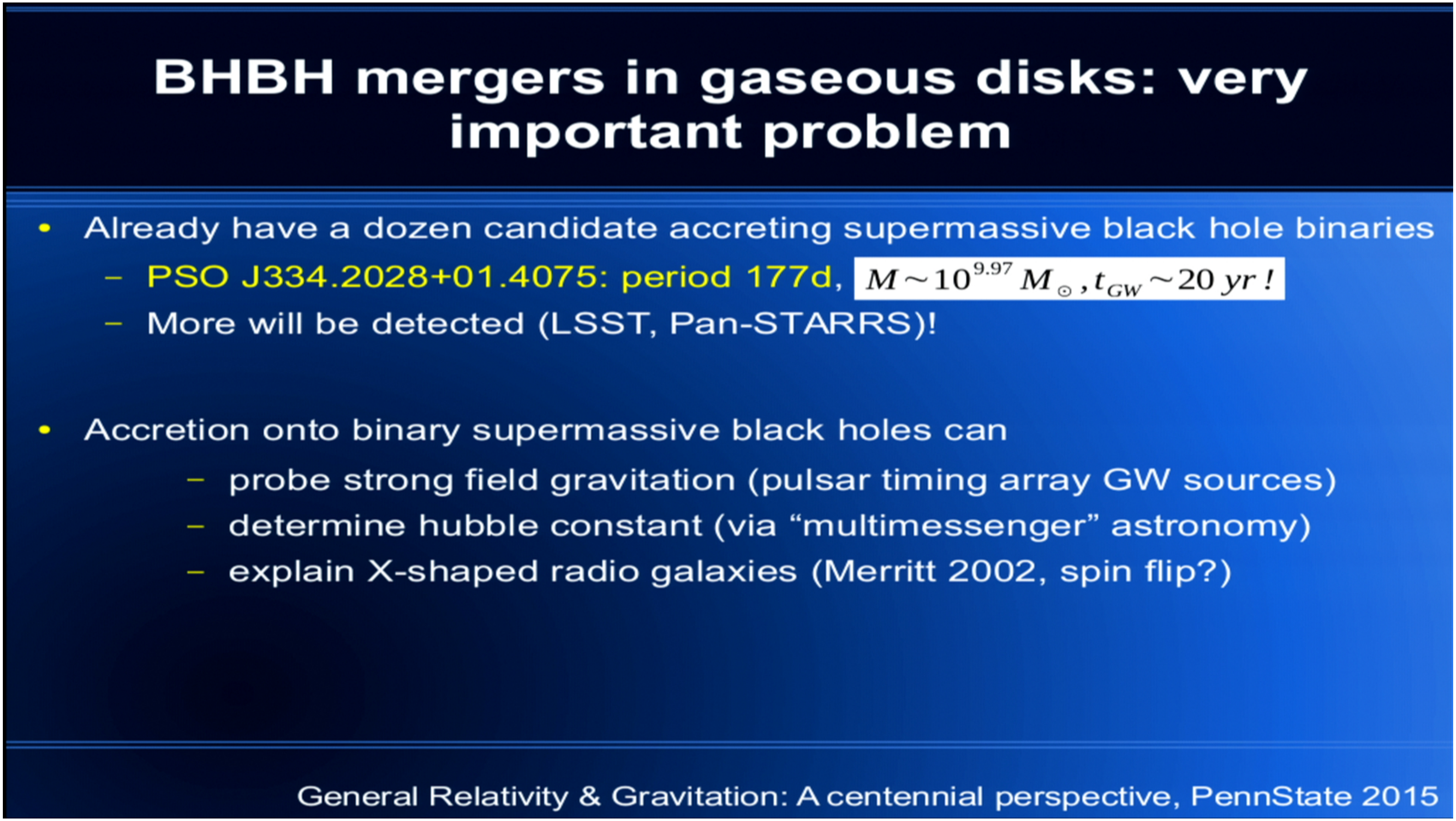
- Goal: Identify EM signatures that accompany GW signal
- Involves: MHD accretion onto inspiraling/merging BHBH

- This is intrinsically a GR problem



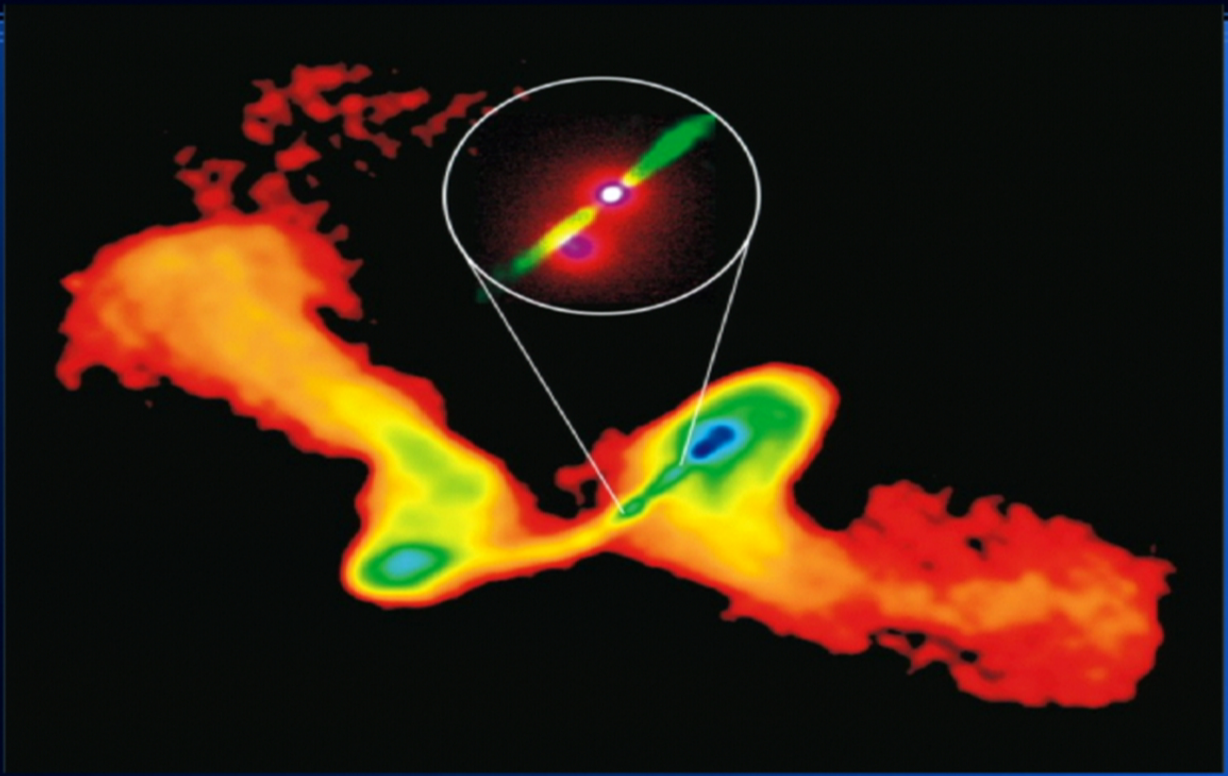
BHBH mergers in gaseous disks: very important problem

- Already have a dozen candidate accreting supermassive black hole binaries
  - PSO J334.2028+01.4075: period 177d, $M \sim 10^{9.97} M_{\odot}, t_{GW} \sim 20\, yr\,!$
  - More will be detected (LSST, Pan-STARRS)!

- Accretion onto binary supermassive black holes can
  - probe strong field gravitation (pulsar timing array GW sources)
  - determine hubble constant (via “multimessenger” astronomy)
  - explain X-shaped radio galaxies (Merritt 2002, spin flip?)

General Relativity & Gravitation: A centennial perspective, PennState 2015

X-shaped radio galaxies



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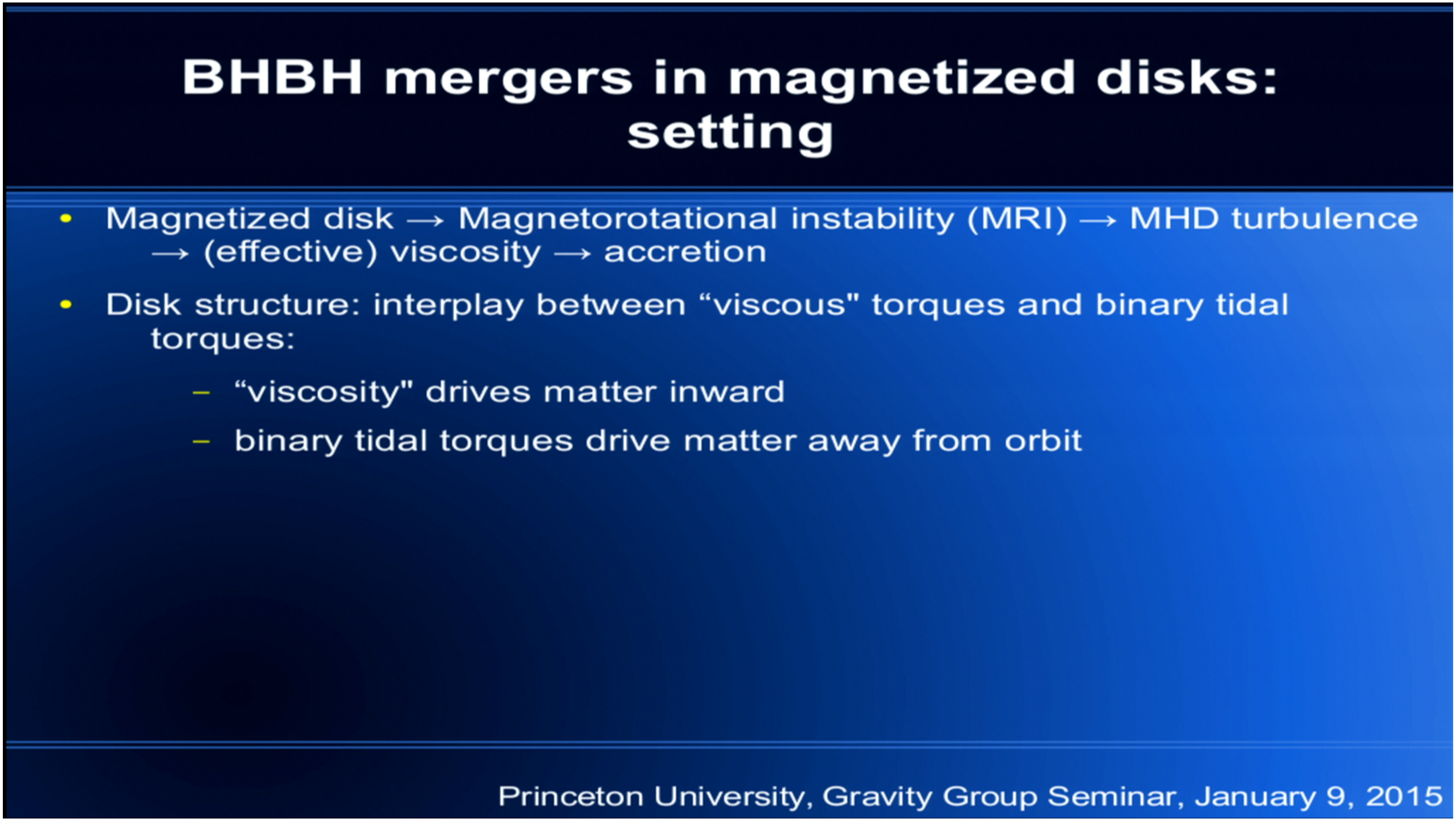
  - explain X-shaped radio galaxies (Merritt 2002, spin flip?)
  - explain periodicities in the light curves of some quasars
  - help understand formation and evolution of supermassive BHs

General Relativity & Gravitation: A centennial perspective, Penn State 2015



BHBH mergers in magnetized disks: setting

- Magnetized disk ⟶ Magnetorotational instability (MRI) ⟶ MHD turbulence ⟶ (effective) viscosity ⟶ accretion
- Disk structure: interplay between “viscous" torques and binary tidal torques:
  - “viscosity" drives matter inward
  - binary tidal torques drive matter away from orbit

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- Disk structure: interplay between "viscous" torques and binary tidal torques:
  - "viscosity" drives matter inward
  - binary tidal torques drive matter away from orbit
- Evolution has two regimes:
  - pre-decoupling: $t_{GW} >> t_{vis}$ (can neglect inspiral)
  - post-decoupling: $t_{GW} << t_{vis}$ (must evolve spacetime)

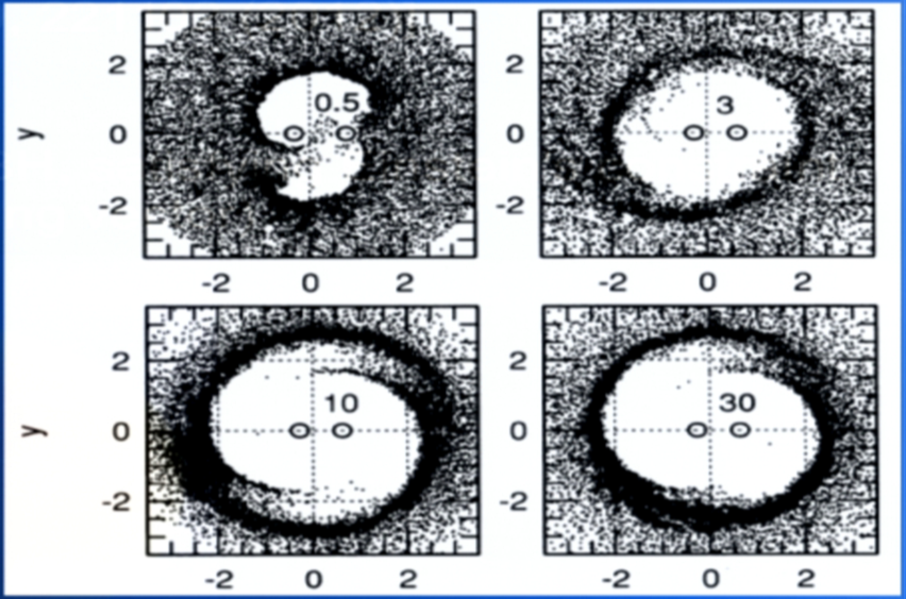
$$t_{\mathrm{GW}} = t_{\mathrm{vis}} \Rightarrow \frac{a_{\mathrm{d}}}{M} \approx 13\left(\frac{\alpha}{0.13}\right)^{-2/5}\left(\frac{H/R}{0.3}\right)^{-4/5}$$

$$a_{\mathrm{d}} \approx 0.25\mathrm{AU}\left(\frac{\mathrm{M}}{2\cdot 10^{6}\mathrm{M}_{\odot}}\right)\left(\frac{\alpha}{0.13}\right)^{-2/5}\left(\frac{\mathrm{H/R}}{0.3}\right)^{-4/5}$$

BHBH mergers in magnetized disks: early work

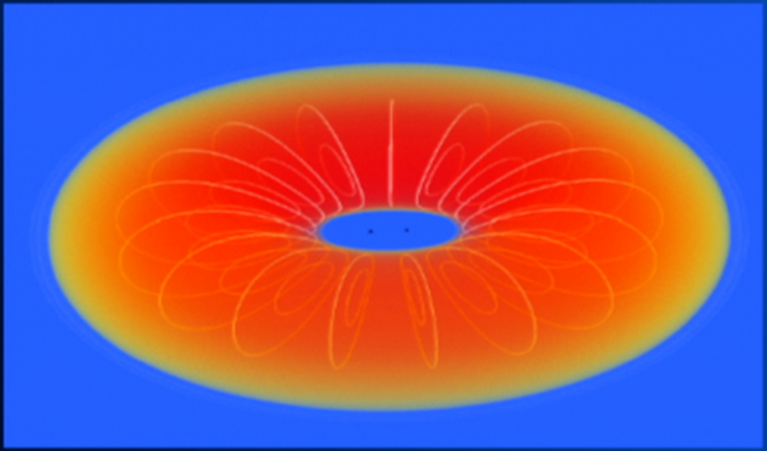
- Early Newtonian equal-mass binary & thin disk [Artymowicz, Lubow (1994)]
  - Hollow/gap
  - Diminished accretion
  - Low chances for EM signals

- What if we consider 3D thick(e)r disks?



BHBH mergers in magnetized disks

- Performed the first study of magnetized disk accretion onto BHBH in full 3+1 GR [BF, RG, VP, ZE, SS PRL109, 221102 (2012)]
- Initial data:
  - Spacetime: quasiequilibrium BHBH, satisfying Einstein's constraint equations (possess helical Killing vector)
  - Disk:



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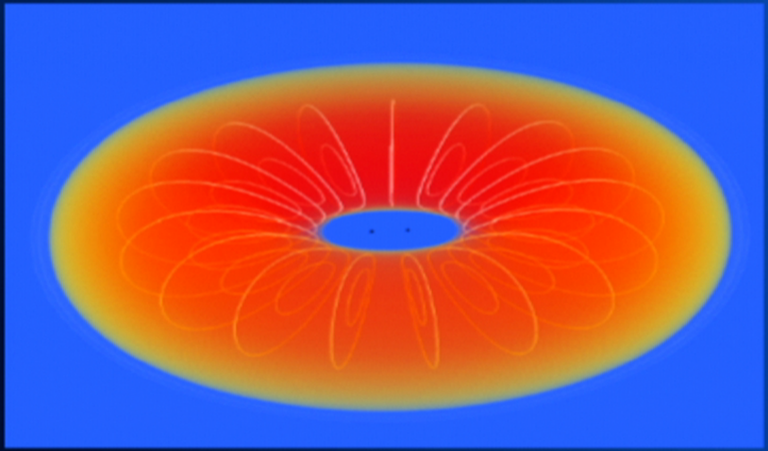

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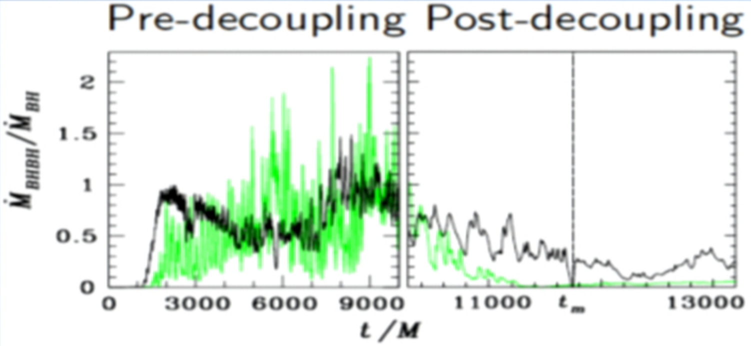
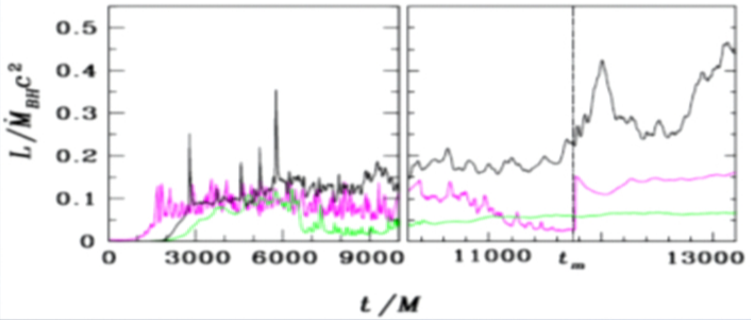
What do astrophysicists/observers want to learn from our simulations?

- E.g. accretion rates and luminosities



- $\dot{M}_{BHBH}$ comparable to $\dot{M}_{BH}$

t_m: merger time



black: $L_{Poynting}$ "no-cooling"

magenta: L_{Λ} (matter cooling)

- $L_{Poynting}$ and L_{Λ} peak just after merger!

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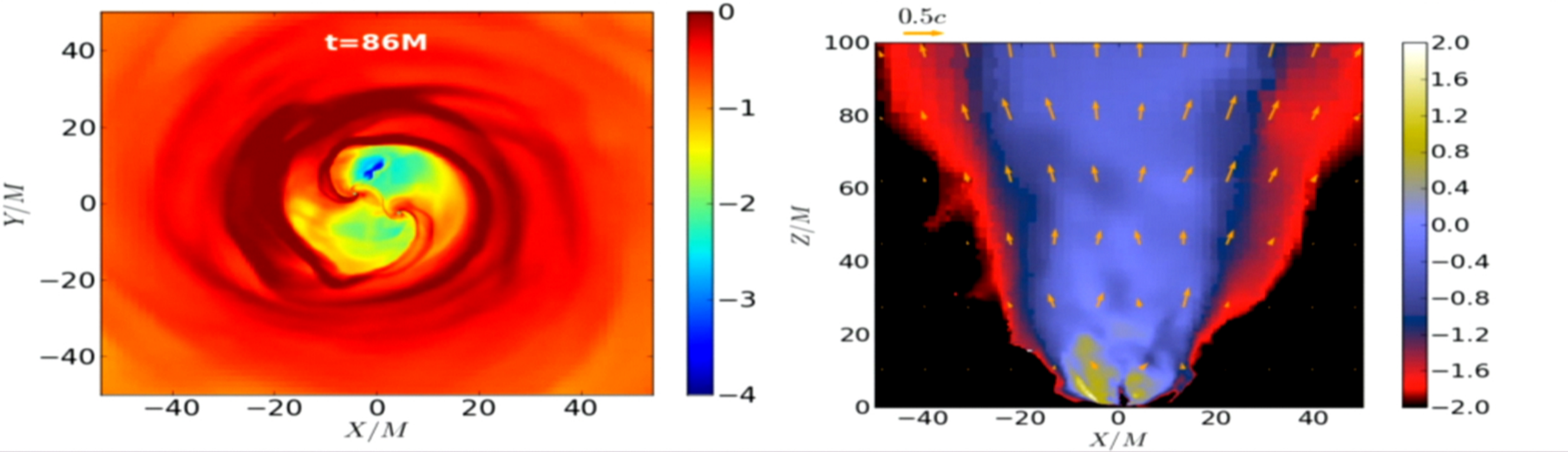
Outflows/Incipient Jets?

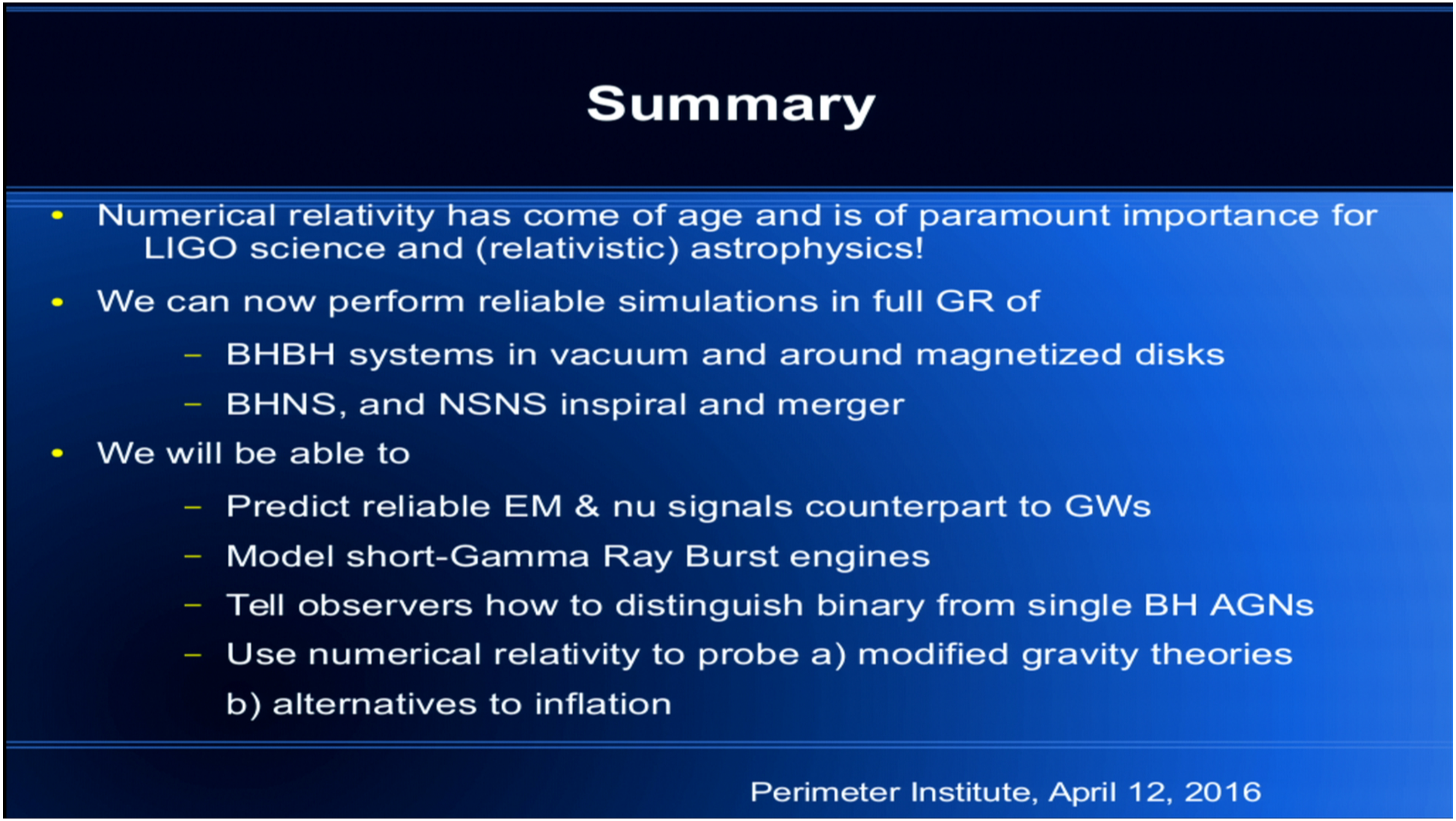
Density (log scale)

Magnetic pressure/ Density (log scale)



→ highly magnetized, mildly relativistic outflows

Gold, VP, et. al. 2014



Summary

- Numerical relativity has come of age and is of paramount importance for LIGO science and (relativistic) astrophysics!
- We can now perform reliable simulations in full GR of
  - BHBH systems in vacuum and around magnetized disks
  - BHNS, and NSNS inspiral and merger
- We will be able to
  - Predict reliable EM & nu signals counterpart to GWs
  - Model short-Gamma Ray Burst engines
  - Tell observers how to distinguish binary from single BH AGNs
  - Use numerical relativity to probe a) modified gravity theories

    b) alternatives to inflation

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