Multi-messengers from transient candidates of UHECRs
necessary condition for successful particle acceleration

\[ L_B = \frac{\Gamma_w R^2 B^2}{2} > 10^{45} Z^{-2} E_{20}^2 \text{ erg s}^{-1} \]

\( \Gamma_w \) lower bound of the bolometric luminosity of source

\( E \geq 60 \text{ EeV} \quad \alpha \leq 8^\circ \)

\( E \geq 80 \text{ EeV} \quad \alpha \leq 30^\circ \)

level of anisotropy in the sky in Auger data \textit{Abreu et al. 2013}

\( \text{apparent number density of sources} \) @ given energy and angular deflection \( \alpha \)

Required for UHE Protons

Ke Fang's talk (Tuesday AM)

\( n_s (>L) \text{ [Mpc}^{-3}] \)

\[ L \text{ [erg s}^{-1}] \]

\[ F_{\text{agg}} \text{ [erg s}^{-1}] \]
The transient energy budget

Level of anisotropy in the sky in Auger data

- **Apparent number density of sources** $n_0$ @ given energy and angular deflection $a$

For transient sources: **Real number density** of UHE proton sources

- $\rho_0 \sim n_0 / (\text{CR time spread } \tau_d)$
  - $\tau_d$ depends on extragalactic + Galactic magnetic fields (not known)  
  
**Observed energy budget in UHECRs** $E_{\text{UHECR}} \rho_0 = 10^{44.5}$ erg Mpc$^{-3}$ yr$^{-1}$
The transient energy budget

level of anisotropy in the sky in Auger data

- **apparent number density of sources** $n_0$ @ given energy and angular deflection $\alpha$

for transient sources: **real number density** of UHE proton sources

$\rho_0 \sim n_0 / (\text{CR time spread } \tau_d)$

$\tau_d$ depends on extragalactic + Galactic magnetic fields (not known)  

*Murase & Takami 09*

**Observed energy budget in UHECRs** $E_{\text{UHECR}} \rho_0 = 10^{44.5} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$

![Diagram showing energy budget for various transient sources compared to UHECR energy budget.](Image)
The transient energy budget

- Level of anisotropy in the sky in Auger data
- **Apparent number density of sources** $n_0$ @ given energy and angular deflection $\alpha$

For transient sources: **Real number density** of UHE proton sources

$\rho_0 \sim n_0 / (\text{CR time spread } \tau_d)$

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**Observed energy budget in UHECRs** $E_{\text{UHECR}} \rho_0 = 10^{44.5} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$

**Diagram**

- Upper limit on intergalactic magnetic fields
- Lower limit on time delays from Galactic magnetic field
- Only few candidates/observations or no observation yet
- Many objects observed at various wavelengths

**References**

- Murase & Takami 09
- KK & Murase, in prep.
The transient energy budget

level of anisotropy in the sky in Auger data

- **apparent number density of sources** $n_0$ @ given energy and angular deflection $\alpha$

for transient sources: **real number density** of UHE proton sources

$\rho_0 \sim n_0 / (\text{CR time spread } \tau_d)$

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**Murase & Takami 09**

- **Observed energy budget in UHECRs** $E_{\text{UHECR}} \rho_0 = 10^{44.5}$ erg Mpc$^{-3}$ yr$^{-1}$
Particle acceleration in pulsars/magnetars

**Charge density**

Induced electric field

\[ \mathbf{E} = -\frac{\mathbf{v}}{c} \times \mathbf{B} = \frac{1}{c} (\Omega \times \mathbf{r}) \times \mathbf{B} \]

Implies a charge density (Goldreich-Julian 69)

\[ \rho = \frac{1}{4\pi} \nabla \cdot \mathbf{E} \approx - \frac{\Omega \cdot \mathbf{B}}{2\pi c} \equiv \rho_{GJ} \]

- e.g.
  - Blasi et al. (2000)
  - Arons et al. (2003)
  - Bednarek & Bartosik (2006)
  - Fang, KK & Olinto (2012, 2013)
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Arons et al. (2003)
Bednarek & Bartosik (2006)
Fang, KK & Olinto (2012, 2013)
Lemoine, KK & Pétri (2015)

---

### outflow energetics

**Total energy**

\[ E_p = \frac{I \Omega_i^2}{2} \approx 1.9 \times 10^{52} \text{ erg} \]

**Neutron star luminosity**

\[ L_p(t) = \frac{E_p}{t_p} \frac{1}{(1 + t/t_p)^2} \]

---

\[ B = 10^{13} \text{ G} \]

\[ t_p \approx \text{a few years for ms pulsars} \]
Particle acceleration in pulsars/magnetars

**Charge density**

Induced electric field

\[ \mathbf{E} = -\frac{\mathbf{v}}{c} \times \mathbf{B} = -\frac{1}{c} (\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B} \]

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**outflow energetics**

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Neutron star luminosity

\[ L_p(t) = \frac{E_p}{t_p} \frac{1}{(1 + t/t_p)^2} \]

Conversion of pulsar electromagnetic into kinetic energy

Particles accelerated to maximum Lorentz factor:

\[ \gamma M \sim \frac{L_p}{\dot{N}mc^2} \]

Goldreich-Julian charge density

Maximum energy:

\[ E_0 \sim 1.5 \times 10^{20} \text{ ev} A_{56} \eta^{-1} \kappa_{45}^{-1} P_{13}^{-2} B_{18}^2 R_{10}^3 \]

Fraction of luminosity into particle kinetic energy

Pair multiplicity

---

e.g.

Blasi et al. (2000)
Arons et al. (2003)
Bednarek & Bartosik (2006)
Fang, KK & Olinto (2012, 2013)
Lemoine, KK & Pétri (2015)
Particle acceleration in pulsars/magnetars

**Charge density**

Induced electric field

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\mathbf{E} = -\frac{\mathbf{v}}{c} \times \mathbf{B} = -\frac{1}{c} (\Omega \times \mathbf{r}) \times \mathbf{B}
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Implies a charge density (Goldreich-Julian 69)

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Arons et al. (2003)
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**outflow energetics**

Total energy

\[
E_p = \frac{I \Omega_i^2}{2} \sim 1.9 \times 10^{52} \text{ erg } I_{45} P_{i,-3}^2
\]

Neutron star luminosity

\[
L_p(t) = \frac{E_p}{t_p} \frac{1}{(1 + t/t_p)^2}
\]

\[
B = 10^{15} \text{ G}
\]

\[
\gamma_M \approx \frac{L_p}{N mc^2}
\]

Goldreich-Julian charge density

Maximum energy:

\[
E_0 \sim 1.5 \times 10^{20} \text{ eV } A_{56} \eta \kappa_4^{-1} P_{i,-3}^2 B_{13}^{1/3} R_{*,6}^3
\]

fraction of luminosity into particle kinetic energy
pair multiplicity

---

Pulsars born with ms periods and magnetars are good candidates of UHECR sources
Particle acceleration in pulsars/magnetars

- **Charge density**

  Induced electric field
  \[ \mathbf{E} = -\frac{\mathbf{v}}{c} \times \mathbf{B} = -\frac{1}{c}(\Omega \times \mathbf{r}) \times \mathbf{B} \]

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  *Blasi et al. (2000)*
  *Arons et al. (2003)*
  *Bednarek & Bartosik (2006)*
  *Fang, KK & Olinto (2012, 2013)*
  *Lemoine, KK & Pétri (2015)*

- **Composition**

  neutron stars have metal-rich surfaces: ideal site for heavy nuclei production

- **Pulsars born with ms periods and magnetars are good candidates of UHECR sources**

- **Outflow energetics**

  total energy
  \[ E_p = \frac{I \Omega_i^2}{2} \sim 1.9 \times 10^{52} \text{ erg} \]

  neutron star luminosity
  \[ L_p(t) = \frac{E_p}{t_p} \frac{1}{(1 + t/t_p)^2} \]

  conversion of pulsar electromagnetic into kinetic energy

  particles accelerated to maximum Lorentz factor:
  \[ \gamma_M \sim \frac{L_p}{\dot{N}mc^2} \]

  maximum energy:
  \[ E_0 \sim 1.5 \times 10^{20} \text{ eV} A_{56} \eta^{-1} \kappa_4^{-1} \left( \frac{P_{13}}{1} \right)^2 B_{13} R_{6,3}^3 \]

  fraction of luminosity into particle kinetic energy
  \[ \frac{\eta}{\dot{N}} pc^2 \]

  pair multiplicity
  \[ \kappa_4 \]
Cosmic ray acceleration in pulsars

- Acceleration region?

- Gaps close to star

Accelerating cosmic rays is a key aspect of understanding pulsar physics. The acceleration region is typically associated with the interaction between the pulsar's magnetic field and the surrounding interstellar medium. This interaction is thought to lead to the acceleration of particles to very high energies through processes such as diffusive shock acceleration or Fermi acceleration.

Several theories have been developed to explain the acceleration mechanisms, including those reviewed in Harding (2007) and Hirotani (2008). These theories often involve the presence of gaps in the magnetosphere, such as the polar cap and outer gap, which are critical for the acceleration process.

The schematic view of the magnetosphere within the light cylinder, shown in Figure 5, illustrates the presence of various gaps and slots. The sizes of these gaps are not to scale. Charges and current distributions present outside the light cylinder can be superluminal even if the particles themselves remain subluminal. Such motions generate radiation that is referred to as Schott radiation by da Costa & Kahn (1985) and to be distinguished from Čerenkov radiation. An analogy with Čerenkov emission was nevertheless put forward by Ardavan (1981).

In a series of papers by Ardavan (1976a, b, d, c) it was claimed that the transition between the corotating magnetosphere and the wind should go through a shock discontinuity and not via a continuous MHD flow. Singular surfaces in the magnetosphere were also found by Buckley (1976).
Cosmic ray acceleration in pulsars

**Acceleration region?**

- pulsar
- relativistic pulsar wind
- blast (at rest)
- pulsar wind nebula
- reverse shock
  - termination shock
- contact discontinuity
- forward shock
- cold SN ejecta

Gaps close to star


Figure 5. Schematic view of the magnetosphere within the light-cylinder. Sizes of the gaps are not to scale.

Charges and current distribution present outside the light-cylinder are superluminal even if the particles themselves remain subluminal. Such motions generate radiation qualified as Schott radiation by da Costa & Kahn (1985) and to be distinguished from Čerenkov radiation. An analogy with Čerenkov emission was nevertheless put forward by Ardavan (1981). This flow outside the light-cylinder will be discussed in the pulsar wind theory sec. 7.

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3. Theory of pulsar magnetospheres

Establishing a consistent model of pulsar physics requires an accurate and quantitative description of the magnetospheric structure, the dynamics and radiative outputs, that is, the magnetic field topology, the current flowing inside and outside the light-cylinder and particle acceleration mechanisms. Such a study in the general case is very difficult to conduct. Simple situations are instead treated but keeping the problem interesting from a physical point of view. The hypotheses usually accepted are the following:

- the magnetosphere is filled with a pair plasma screening the electric field such that $E \cdot B = 0$ everywhere. This means that all charged particles adapt their motion to maintain $E_\parallel = 0$. Spatially localized slight deviations from this rigorous $E_\parallel = 0$ fulfillment are expected to ignite electromagnetic activity in the magnetosphere. Subleties in achieving $E_\parallel \neq 0$ lead to different plasma regimes involving a plethora of gap and cap models.

- particles follow an electric drift motion superposed to a translation along field lines.

- the regime is stationary and at least for earlier models assumed axisymmetric (aligned rotator).

- primary particles emanate from the surface of the star, there is no pair creation.

- the plasma is quasi-neutral, which means that the space charge is overwhelmed by a background much more dense neutral plasma.
Cosmic ray acceleration in pulsars

**Acceleration region?**

- pulsar
- reverse shock
  - termination shock
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- forward shock
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Figure 5. Schematic view of the magnetosphere within the light-cylinder. Sizes of the gaps are not to scale.
Cosmic ray acceleration in pulsars

Acceleration region?

- pulsar
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- forward shock
- reverse shock
- termination shock
- blast (at rest)
- pulsar wind nebula

Wind region

- cold SN ejecta
- cold Poynting flux dominated?
Cosmic ray acceleration in pulsars

- **Acceleration region?**

  - **pulsar**
  - **contact discontinuity**
  - **forward shock**
  - **reverse shock**
  - **termination shock**
  - **blast (at rest)**
  - **pulsar wind nebula**

- **Wind region**

  - **cold Poynting flux dominated?**

- **Nebula**

  - **cold**
  - **radiative kinetic energy**

---

**Figure 5.** Schematic view of the magnetosphere within the light-cylinder. Sizes of the gaps are not to scale.

- **charges and current distribution present outside the light-cylinder** are superluminal even if the particles themselves remain subluminal. Such motions generate radiation qualified as Schott radiation by da Costa & Kahn (1985) and to be distinguished from Cerenkov radiation. An analogy with Cerenkov emission was nevertheless put forward by Ardavan (1981). This flow outside the light-cylinder will be discussed in the pulsar wind theory sec. 7.

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**3. Theory of pulsar magnetospheres**

Establishing a consistent model of pulsar physics requires an accurate and quantitative description of the magnetospheric structure, the dynamics and radiative outputs, that is, the magnetic field topology, the current flowing inside and outside the light-cylinder and particle acceleration mechanisms. Such a study in the general case is very difficult to conduct. Simple situations are instead treated but keeping the problem interesting from a physical point of view. The hypotheses usually accepted are the following:

- **the magnetosphere is filled with a pair plasma screening the electric field such that** $E \cdot B = 0$ everywhere. This means that all charged particles adapt their motion to maintain a vanishing acceleration along field lines, thus $E_{\parallel} = 0$. Spatially localized slight deviations from this rigorous $E_{\parallel} \neq 0$ fulfillment are expected to ignite electromagnetic activity in the magnetosphere. Subleties in achieving $E_{\parallel} \neq 0$ lead to different plasma regimes involving a plethora of gap and cap models.

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**J. Pétri (2016)**
Cosmic ray acceleration in pulsars

### Acceleration region?

- **Pulsar**
- **Contact discontinuity**
- **Forward shock**
- **Reverse shock**
- **Termination shock**
- **Blast (at rest)**
- **Pulsar wind nebula**
- **SN ejecta**
- **Cold**

### Wind region

- **Relativistic pulsar wind**
- **Polar cap**
- **Outer gap**
- **Slot gap**
- **Closed magnetosphere**
- **Open field lines**

### Nebula

- **Cold**
- **Radiative**
- **Kinetic energy**

### Dissipation of e-m to kinetic energy?

- Related to "sigma-problem"

  *e.g., Kirk et al. 2009*
Cosmic ray acceleration in pulsars

**Acceleration region?**
- reverse shock
- termination shock
- contact discontinuity
- forward shock

**Wind region**
- relativistic pulsar wind
- blast (at rest)
- pulsar wind nebula

**Nebula**
- cold SN ejecta

**Acceleration mechanism?**
- « linear » $E \propto r$
- Fermi @ TS
- reconnection wind region
- and/or close to TS in striped wind or in nebula?

- e.g., Chen et al. 92, Arons 03
- e.g., Lemoine, KK, Pétri 15
- e.g., Sironi & Spitkovsky 12
- Lemoine, KK, Pétri 15

**Wind region dominated?**
- cold Poynting flux dominated?

**Dissipation of e-m to kinetic energy?**
- related to "sigma-problem"

- e.g., Kirk et al. 2009

---

5
Interaction backgrounds for neutrino production

- **nubula non-thermal γ**
  - Amato et al. (2003)
  - Lemoine, KK, Pétri (2015)

- **star's thermal γ**
  - Bednarek & Protheroe (1997)
  - Link & Burgio (2006)

- **SN thermal γ**
  - Amato et al. (2003)
  - Fang, KK, Murase & Olinto (2016)

- **SN ejecta matter**
  - Amato et al. (2003)
  - Bednarek (2003)
  - Murase et al. (2009)
  - Fang, KK, Murase & Olinto (2015, 2016)

- **Crab flares non-thermal γ**
  - Guépin & Kotera (in prep.)

Most promising for UHECRs: interactions in SN.
IceCube constraints on neutron stars as sources of UHECRs

Population of newborn pulsars as sources of UHECRs following star formation rate excluded at 90% C.L. population of pulsars with realistic (P,B) distribution

Fang, KK, Murase & Olinto 2013

Aartsen et al. 2016
IceCube constraints on neutron stars as sources of UHECRs

- **Population of newborn pulsars as sources of UHECRs following star formation rate** excluded at 90% C.L.
- **Population of pulsars with realistic (P,B) distribution**

**Aartsen et al. 2016**

**Fang, KK, Murase & Olinto 2013**

- **Model dependent 90% C.L. limits**

<table>
<thead>
<tr>
<th>Model</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahlers best-fit 3EeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ahlers best-fit 10EeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kotera FRII</td>
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<tr>
<td>Kotera SFR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murase AGN s=2.3</td>
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</tr>
<tr>
<td>Padovani all BL Lac</td>
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<td></td>
</tr>
<tr>
<td>Fang Pulser SFR</td>
<td></td>
<td></td>
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</tbody>
</table>

**Fang, KK, Murase & Olinto 2016**

- **Neutrino fluxes @ break energy, if normalized to UHECR spectrum**

<table>
<thead>
<tr>
<th>Model</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_{jet}=0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_{jet}=0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_{jet}=0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_{jet}=0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Population of neutron stars with same characteristics (P,B)**
- Magnetar jet puncturing SN ejecta

- **f_{jet} = "jet fraction"**
  - Fraction of accelerated particles that can escape without crossing a dense environment

  - Magnetars not excluded if escape fraction > 10%
  - UHECR production and escape possible

**Komissarov & Barkov (2007)**

**Discussion, conclusions**
Superluminous supernovae due to central pulsar/magnetar

- superluminous supernovae lasting over a few days/months/years

\[ E_{\text{rot}} \sim 10^{52} \text{ erg} \gg E_{\text{SN}} \sim 10^{51} \text{ ergs} \]

injection of pulsar rotational energy into SN ejecta

change radiation emission from SN?

KK, Phinney, Olinto. 2013
Superluminous supernovae due to central pulsar/magnetar

- Superluminous supernovae lasting over a few days/months/years

\[ \text{injection of pulsar rotational energy into SN ejecta} \]
\[ E_{\text{rot}} \sim 10^{52} \text{ erg} >> E_{\text{SN}} \sim 10^{51} \text{ ergs} \]

\[ \begin{align*}
B = 3 \times 10^{12} \text{ G} & \quad \text{ultraluminous} \\
B = 10^{13} \text{ G} & \quad \text{standard SN} \\
B = 10^{14} \text{ G} & \\
B = 10^{15} \text{ G} &
\end{align*} \]

\[ \begin{align*}
L_{\text{tot}} \left[ \text{erg/s} \right] & \quad \text{magnetars} \\
10^{45} & \quad P = 1 \text{ ms}
\end{align*} \]

\[ \begin{align*}
t \left[ \text{days} \right] & \quad 0 \quad 100 \quad 200 \quad 300 \quad 400
\end{align*} \]

\[ \begin{align*}
0 & \quad 10^{42} \\
10^{43} & \quad 10^{44} \\
10^{45} &
\end{align*} \]

\[ \text{Fig. 7.— High-energy photon spectra of the early PWN embedded in the SN ejecta for } P_t = 2 \text{ ms at } t = 10^{7.5} \text{ s } \approx 316 \text{ d. Different magnetic field strengths are considered. Detections with CTA are possible for } B_{\text{dip}} = 10^{13} \text{ G}. \]

\[ \text{Murase et al. 2015} \]
Superluminous supernovae due to central pulsar/magnetar

- Superluminous supernovae lasting over a few days/months/years

![Graph showing ultraluminous versus standard SN over time](image)

**Figure 5.** High-energy photon spectra of the early PWN embedded in the SN ejecta for $P_i = 2$ ms at $t = 10^7.5$ s $\sim 316$ d. Different magnetic field strengths are considered. Detections with CTA are possible for $B_{\text{dip}} = 10^{13}$ G.

**Murase et al. 2015**

**Figure 7.** High-energy photon spectra of the early PWN embedded in the SN ejecta for $P_i = 2$ ms at $t = 10^7.5$ s $\sim 316$ d. Different magnetic field strengths are considered. Detections with CTA are possible for $B_{\text{dip}} = 10^{13}$ G.

** KK, Phinney, Olinto. 2013 **
Superluminous supernovae due to central pulsar/magnetar

Superluminous supernovae lasting over a few days/months/years

![Graph showing luminosity over time for different magnetic field strengths and rotation periods.](image)

- Injection of pulsar rotational energy into SN ejecta
  \( E_{\text{rot}} \sim 10^{52} \text{ erg} \gg E_{\text{SN}} \sim 10^{51} \text{ ergs} \)

- Systematic search with Fermi LAT @ location of SLSNe
  Strong constraints on central object

Murase et al. 2015
sample of 39 SLSNe
Fermi Pass-8 data
3+1 and 7+1 bands in E: 0.6-600 GeV
4 different time windows

Individual analysis
only source detected above 3-sigma level: SN2011ke
constraints on SLSNe luminosities: \(< ~ 10^{44} \) erg/s

Joint likelihood analysis (stacking)

Table 4: Luminosities from joint likelihood analysis measurements with the 7+1 energy band set and all sources.

<table>
<thead>
<tr>
<th>Time window</th>
<th>Sig(_{0.6-600.0, \text{GeV}}) (\sigma) units</th>
<th>(L_{0.6-10.2, \text{GeV}}) erg s(^{-1})</th>
<th>(L_{\text{sum}}^{0.6-600.0, \text{GeV}}) erg s(^{-1})</th>
<th>Sig(_{\text{best bnd}}^{\text{E1-E2}}) (\sigma) units</th>
<th>E1 GeV</th>
<th>E2 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_{\text{peak}}) to (t_{\text{peak}} + 3) months</td>
<td>0.1</td>
<td>(&lt; 2.0 \times 10^{39})</td>
<td>(2.3 \times 10^{38}) (2.0 \times 10^{39}) 1.8(10^{38})</td>
<td>2.9</td>
<td>171.50</td>
<td>600.00</td>
</tr>
<tr>
<td>(t_{\text{peak}}) to (t_{\text{peak}} + 6) months</td>
<td>0.0</td>
<td>(&lt; 1.6 \times 10^{39})</td>
<td>(2.5 \times 10^{38}) (1.5 \times 10^{39}) (2.3 \times 10^{38})</td>
<td>2.8</td>
<td>171.50</td>
<td>600.00</td>
</tr>
<tr>
<td>(t_{\text{peak}}) to (t_{\text{peak}} + 1) year</td>
<td>0.2</td>
<td>(&lt; 7.2 \times 10^{38})</td>
<td>(&lt; 9.5 \times 10^{38})</td>
<td>1.5</td>
<td>67.04</td>
<td>171.50</td>
</tr>
<tr>
<td>(t_{\text{peak}}) to (t_{\text{peak}} + 2) years</td>
<td>0.0</td>
<td>(&lt; 6.6 \times 10^{38})</td>
<td>(1.2 \times 10^{38}) (6.0 \times 10^{38}) (1.2 \times 10^{38})</td>
<td>3.8</td>
<td>67.04</td>
<td>171.50</td>
</tr>
<tr>
<td>SN off-peak period</td>
<td>1.6</td>
<td>(&lt; 3.5 \times 10^{38})</td>
<td>(9.6 \times 10^{37}) (4.6 \times 10^{38}) (8.8 \times 10^{37})</td>
<td>2.2</td>
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Search for Superluminous Supernovae with Fermi-LAT

Follows approximately a power-law of index

The layout of the table is identical to Table 4.

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Black Hole mergers as sources of UHECRs: neutrinos and FRBs

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- **Fast Radio Bursts!**
  (very bright radio bursts, routinely detected, of unknown cosmological origin)
  Debris/bodies required around merging black holes/final black hole ——> model of *Mottez & Zarka (2013)*

A body immersed in a highly magnetized outflow generates 2 stationary Alfvén wings

\[ B_0 \]

\[ v_0 \]

Wind velocity

**NB: asteroids and planets can orbit at close distance from the central object without being evaporated/destroyed (Mie Theory)**

- plasma instabilities in Alfvén wings (e.g., cyclotron maser instability):
  - radio emission

- strongly beamed radio emission @ 10 MHz-10^3 GHz
  - with high flux (Jansky level)
How to look for multi-messenger transient signals

- UHECRs
- neutrinos
- photons
- GW
- real-time analysis (alerts/follow-up)

hotspot could be signature of Galactic transient source occurred $10^{3-4}$ yrs ago or extragalactic transient at few 10s Mpc $10^5$ yrs ago

Fang et al. 2015
Fargion 2015
He et al. 2016
Renault-Tinacci, KK, Olinto in prep.

a hotspot? TA hotspot?

identify best detector characteristics for neutrino astronomy

boom in time-domain astronomy (PTF, Pann-STARRS, LSST, ...)
gamma-rays: Fermi, HESS, CTA

next slide

H. He and D. Ryu's talks
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- **GW**

- **real-time analysis (alerts/follow-up)**

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**Example: HESE-160427A**, on April 27 2016

[Diagram showing the event timeline and detection process]

---

Naoko Kurahashi Neilson, Drexel University

from N. Kurahashi-Neilson, TeVPA 09/2016
How to search for multi-messenger transient signals: neutrino sources?

- no deflection, no time delay, ideal?
- BUT: no horizon —→ possible to spot source on top of background?
  
e.g., difficult to identify sources for IceCube neutrinos…

>1000 events and <1 deg. angular resolution required
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**Giant Radio Array for Neutrino Detection**
- 200'000 radio antennas over 200'000 km²
- >1000 events in 10 yrs (E>10^{17} eV)
- < 0.3 deg. angular resolution

Fang, KK, Murase, Miller, Oikonomou, submitted